Detection of the cosmic neutrino background: an extreme challenge for neutrino physics and experimentalists

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Joint Cosmo/Neutrino Club
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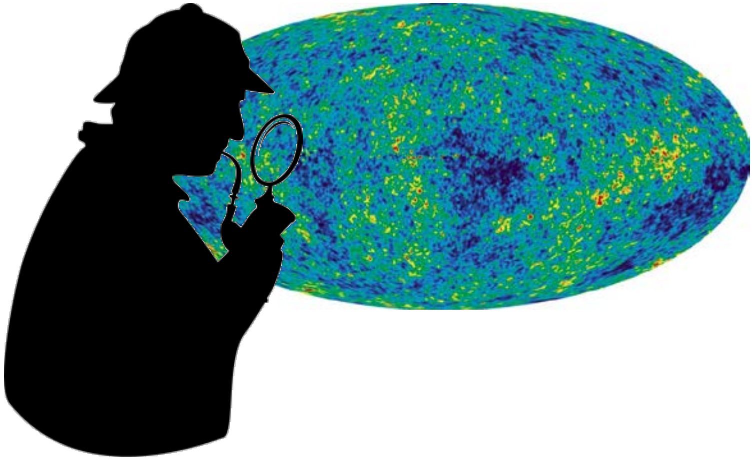
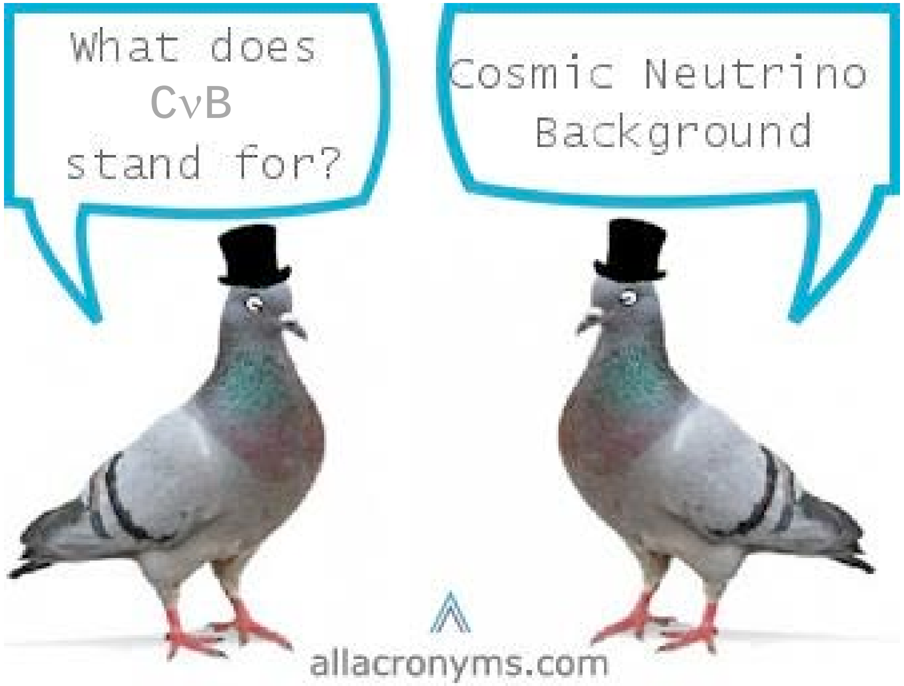
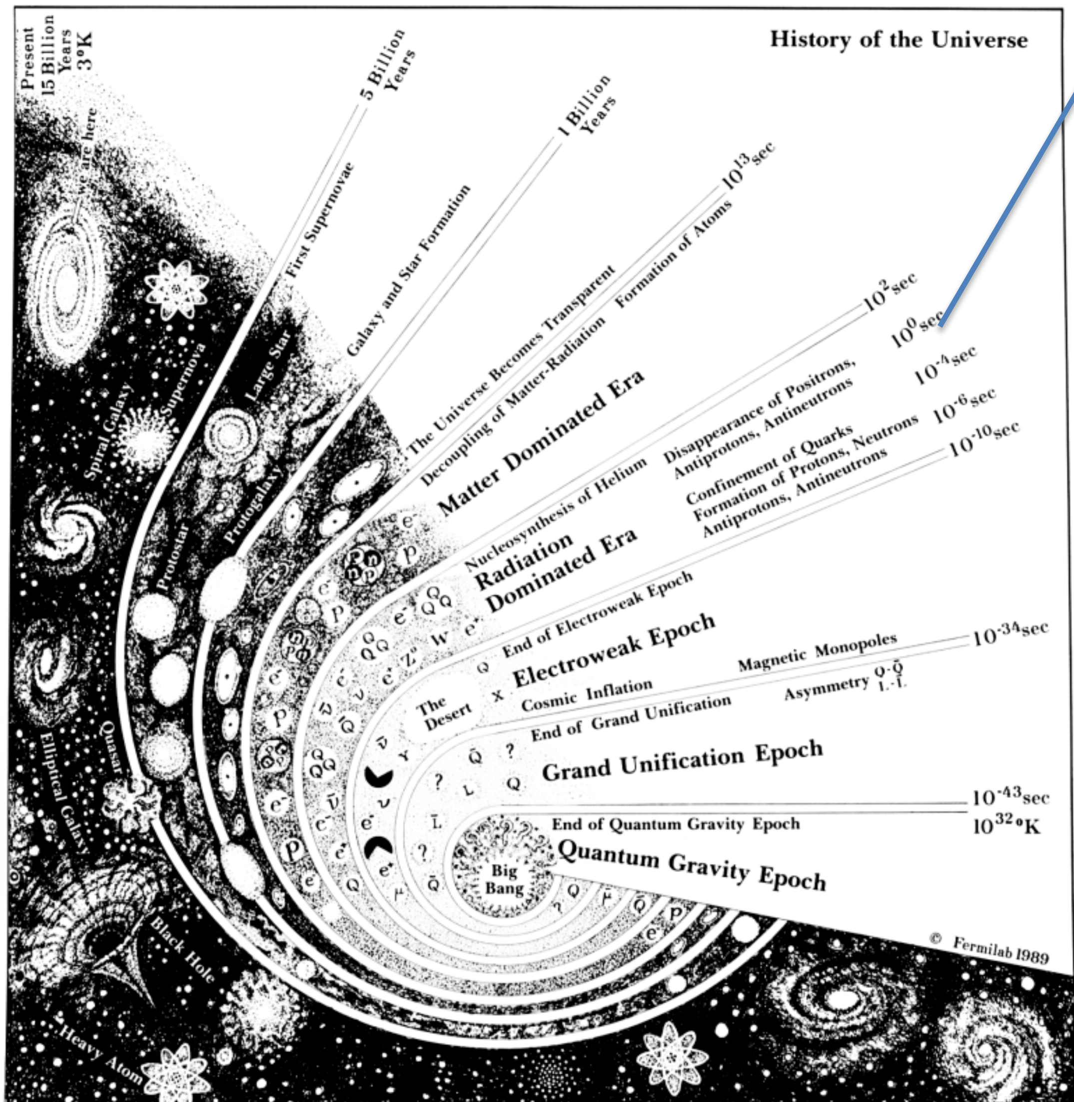


Outline

- Cosmic neutrino Background (CνB): overview
- Neutrino Capture on Beta-decaying nuclei (NCB)
- The PTOLEMY experiment and the detection of the CνB
- Discussion on the physics potential:
  - Annual modulation of CνB terrestrial detection *Phys. Rev. D 90, 043001 (2014)*
  - Measuring anisotropies of CνB via a polarized target *arXiv:1407.0393 [astro-ph.CO]*



Cosmic Neutrino Background (CνB)



Neutrino decoupling

- It is a central prediction of standard thermal cosmology.
- It is similar to the cosmic microwave background (CMB) as both are relic distributions created shortly after the Big Bang.
- However, while the CMB formed when the Universe was roughly 400,000 years old, the CνB decoupled from the thermal Universe only 1 second after the Big Bang.
- Observation of the cosmological neutrinos would provide a window into the 1st second of creation (0.18 s – $z=1x10^{10}$).

Thermal history of CνB

Neutrinos in **thermal equilibrium with the primordial thermal soup** through reactions

$\nu e \longleftrightarrow \nu e$ and $e^+e^- \longleftrightarrow \nu\bar{\nu}$ $\Rightarrow$ **Rate:** $\Gamma \approx G_F^2 T^5$

to be compared with the **Hubble expansion rate:** $H \approx T^2/M_P$

Γ* ≥ *H $\Rightarrow$ neutrinos decouple from the thermal soup and freeze out (T ≤ ~1 MeV)

Since that time (t=0.18 s), they free-stream until the present epoch

As fermions, they follow a **Fermi-Dirac thermal distribution** $\Rightarrow$ $\tilde{g}_{\mathrm{C}\nu\mathrm{B}}(p_\nu) = \frac{1}{1+e^{p_\nu/T_\nu}}$

Integrating over mementum gives the number density per degree of fredom (flavor and spin)

$$n_\nu(T) = \frac{3\zeta(3)}{4\pi^2}T^3$$

Thermal history of CνB

We know however that $T_\nu < T_\gamma$, as photons have been re-heated by $e^+ - e^-$ annihilation

Today: T_γ = 0.235 meV = *2.725* K (CMB)

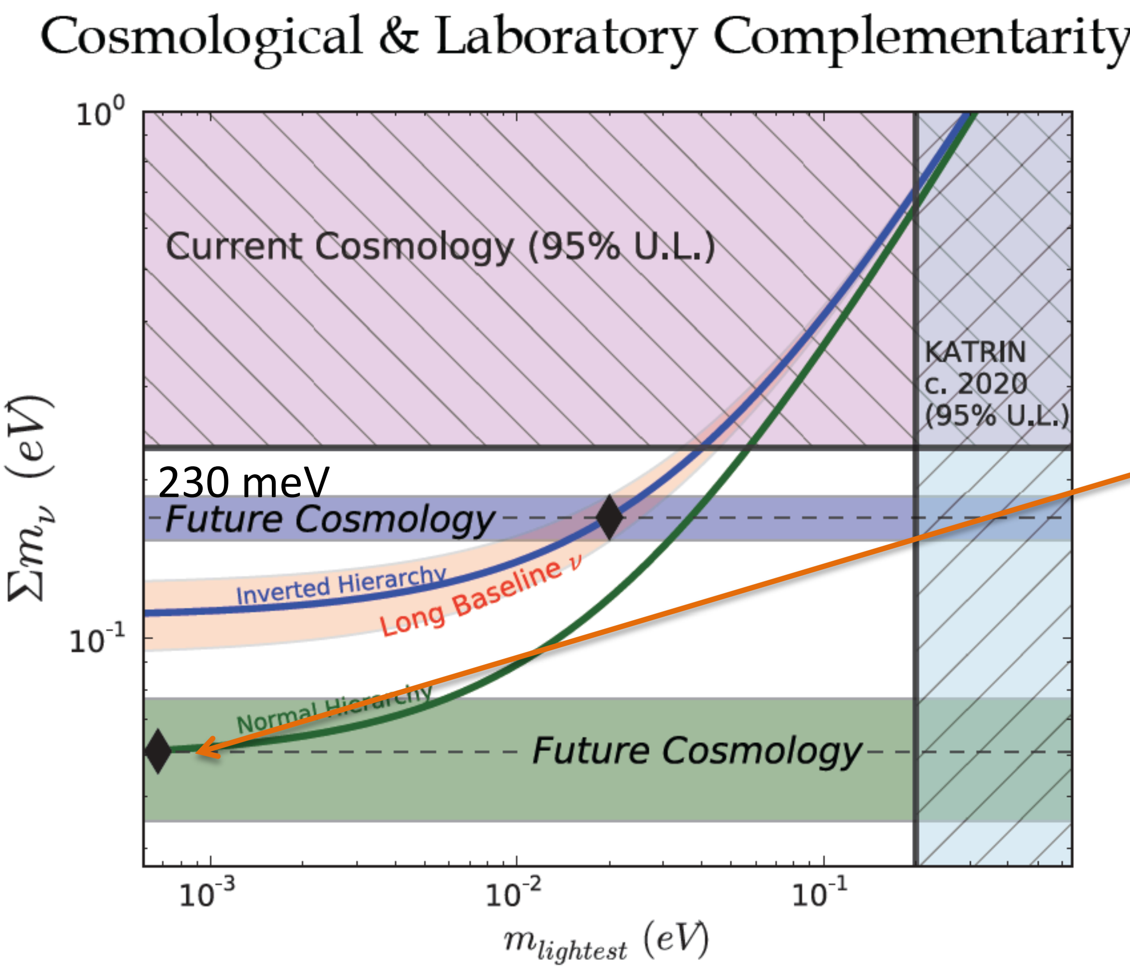
$$T_\nu \approx (4/11)^{1/3} T_\gamma$$

T_ν = 0.168 meV = *1.945* K

Inserted in $n_\nu(T) = \frac{3\zeta(3)}{4\pi^2} T^3$ we get

$n_0 \approx 56\,\mathrm{cm}^{-3}$ per degree of freedom (flavor and spin) in the present epoch

Neutrino masses



We know (from ν oscillation) that at least one neutrino state has

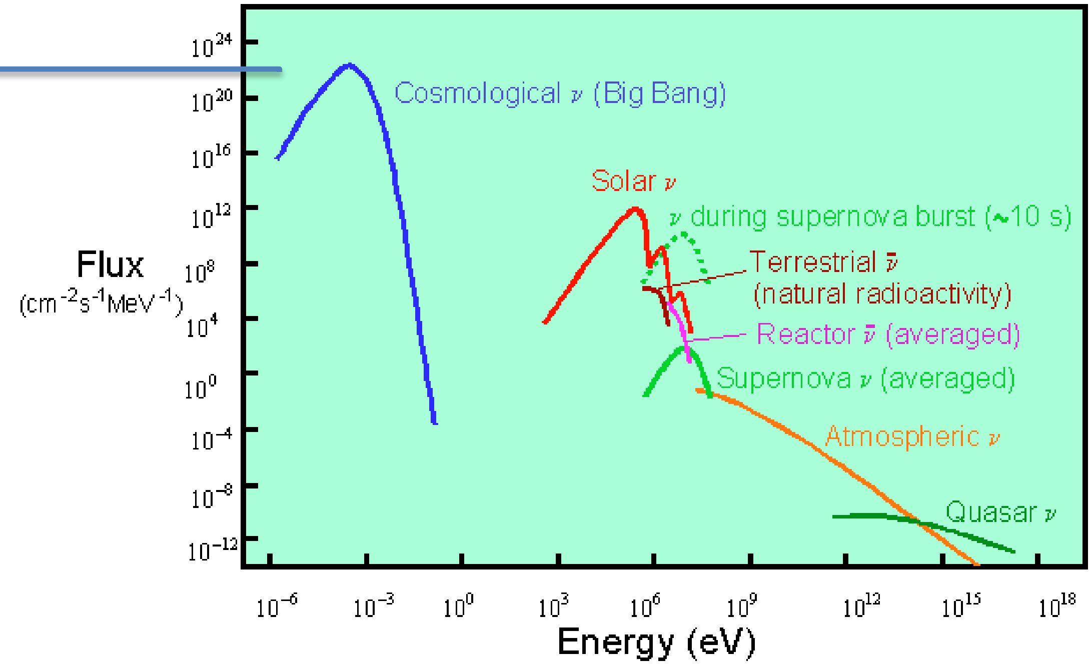
m_ν > ~ 50 meV

comparing with $\boldsymbol{T_\nu}$ **= 0.168 meV**

CνB are extremely non-relativistic

the only known source of non-relativistic neutrinos!

CνB and other astrophysical neutrinos



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

Cardinal feature of early universe cosmology

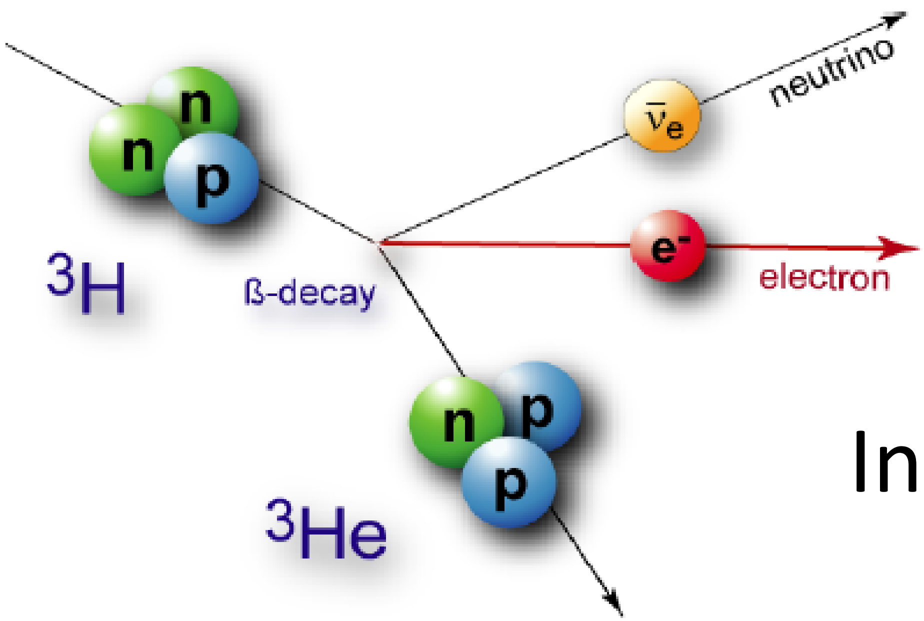
Direct detection is the **"holy grail"** of neutrino physics

- It would confirm that relic neutrinos are still present in the universe today (we do not have an empirical proof)
- It would constitute the first probe of non-relativistic neutrinos
- It could reveal the neutrino nature (through measurement of modulations / asymmetries)

Neutrino Capture on β-decaying nuclei (NCB)

$$^{3}H \rightarrow {}^{3}He^{+} + e^{-} + \bar{\nu}_e$$

Q-value = M(^{3}H) – M(^{3}He) - m_e

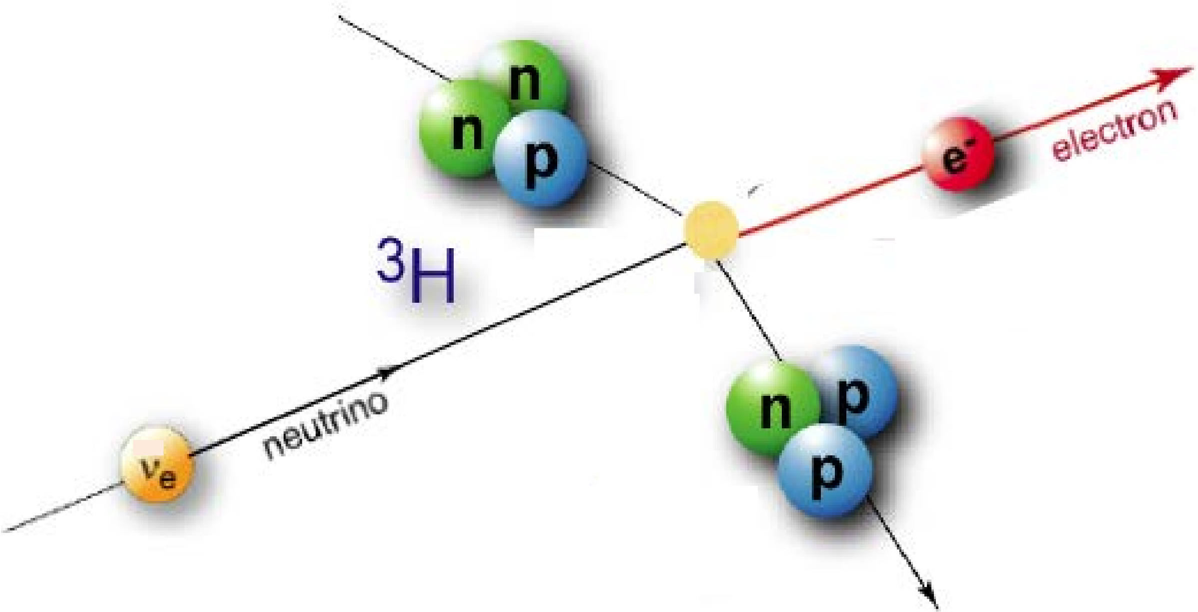


Instead of β-decay…

...ν is captured by a β-instable nucleus

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

Q-value = $M(^{3}H) - M(^{3}He) - m_e$



Remarkable property: **no energy thresholds** on the value of the incoming neutrino energy

Neutrino Capture on β-decaying nuclei (NCB)

$$\nu_e + A_Z \to e^- + A^*_{Z+1}$$

Since the process can occur even for vanishing ν energies, this is ideal to investigate CνB (average energy amount to **~0.5 meV**)

Detecting the impossible! …

…at a rate $\Gamma = \sigma v_\nu n_\nu N_H$

The capture rate Γ is determined by the neutrino density in our galaxy n_ν, the cross section σ for the process to occur and the number of target nuclei N_H

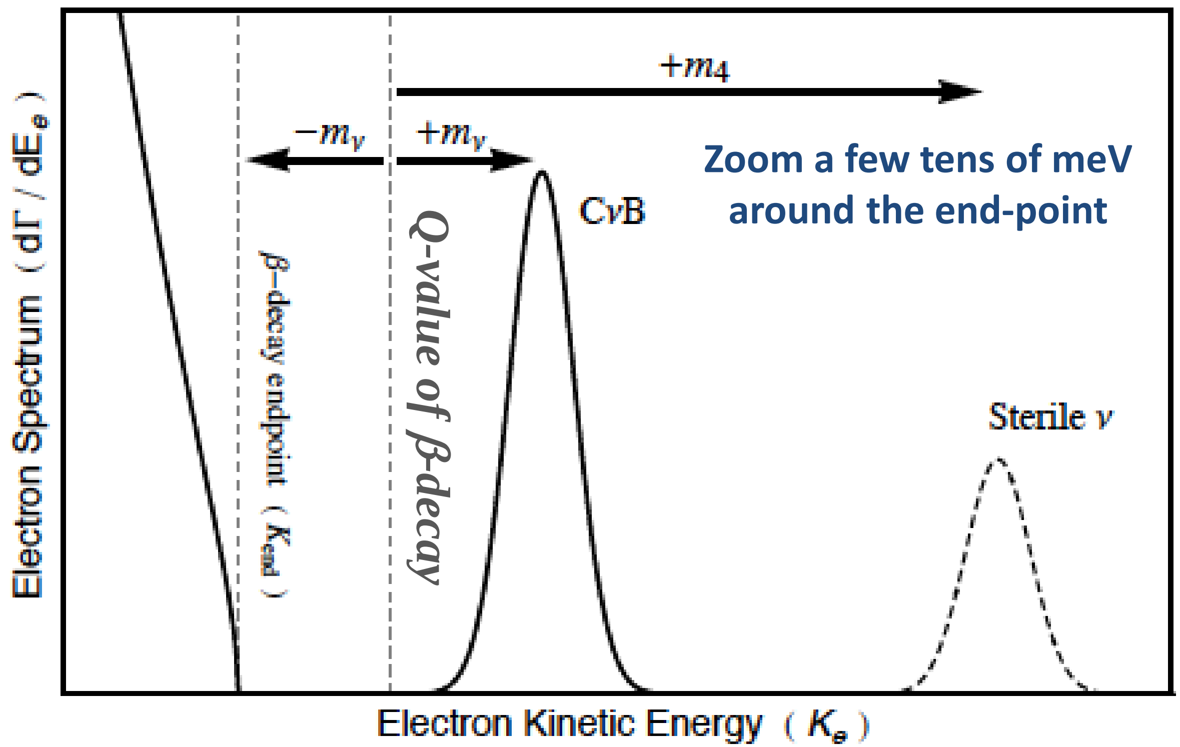
Cross section σ can be safely and exactly calculated from the ordinary β-decay matrix elements, which are experimentally known from the ordinary β-decay lifetime

As neutrino temperature is small (1.9 K), the energy distribution is also narrow and very small (**0.5 meV**) with respect to the neutrino masses indicated by oscillation experiments (**~50 meV**)

This results in a unique signature: **mono-energetic electrons** emitted by the target nucleus at an **energy given by the Q-value of the β-decay PLUS the neutrino mass**

Neutrino Capture on β-decaying nuclei (NCB)

Since **the by-far dominant ordinary β-decay coexists with the CνB capture**, the kinetik energy spectrum of the electrons emitted by the target nucleus is schematically:



(the three neutrino masses here are not resolved as detector energy resolution is not high enough – hyopthetical massive sterile neutrino is shown as well)

Neutrino Capture on β-decaying nuclei (NCB)

Esoenergetic nuclear reaction

Capture practically at rest (E_ν << Q-value)

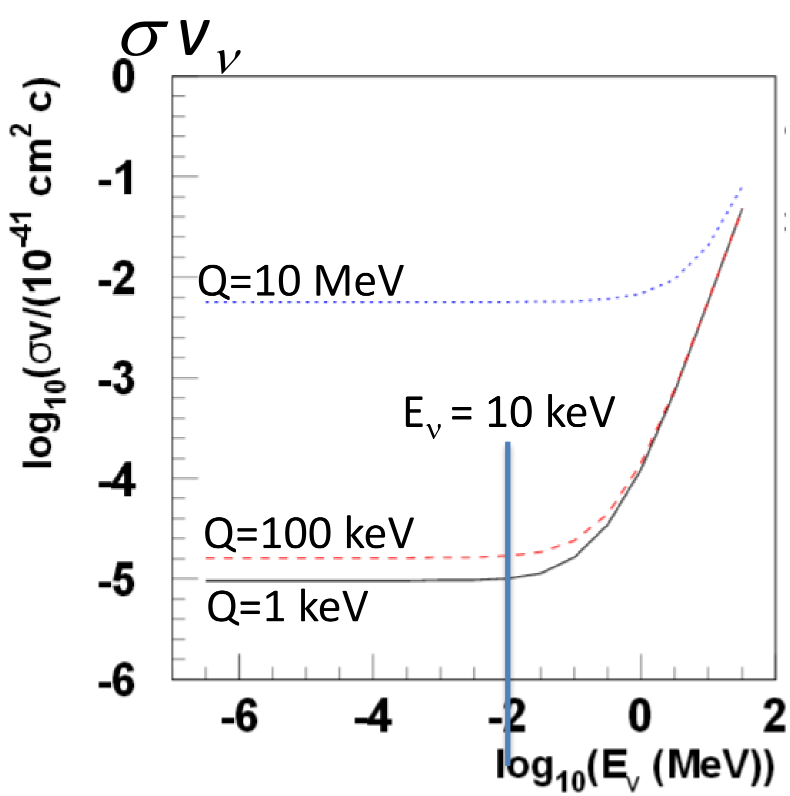
$$\sigma \propto 1/v_\nu$$

(see for example slow neutron capture cross section)

We get therefore $\sigma v_\nu = cost \equiv \sigma_0$

Crucial parameter

$$\Gamma = \sigma_0 \, n_\nu N_H$$



Neutrino Capture on β-decaying nuclei (NCB)

Criteria for the choice of the target nucleus

- Higher $\sigma_0 \tau_\beta$ product (determine lower ratio of capture to ordinary β-events)
- High σ_0 in order to have enough events for a reasonable target mass
- τ_β not too short (long exposure times are required)
- A detection technology well adapted to the target nucleus

Good compromise $\Rightarrow$ ^3H $\Rightarrow$

- **τ_β = 12.3 years**
- **σ_0/c = (7.84±0.03) x 10^{-45} cm^2**

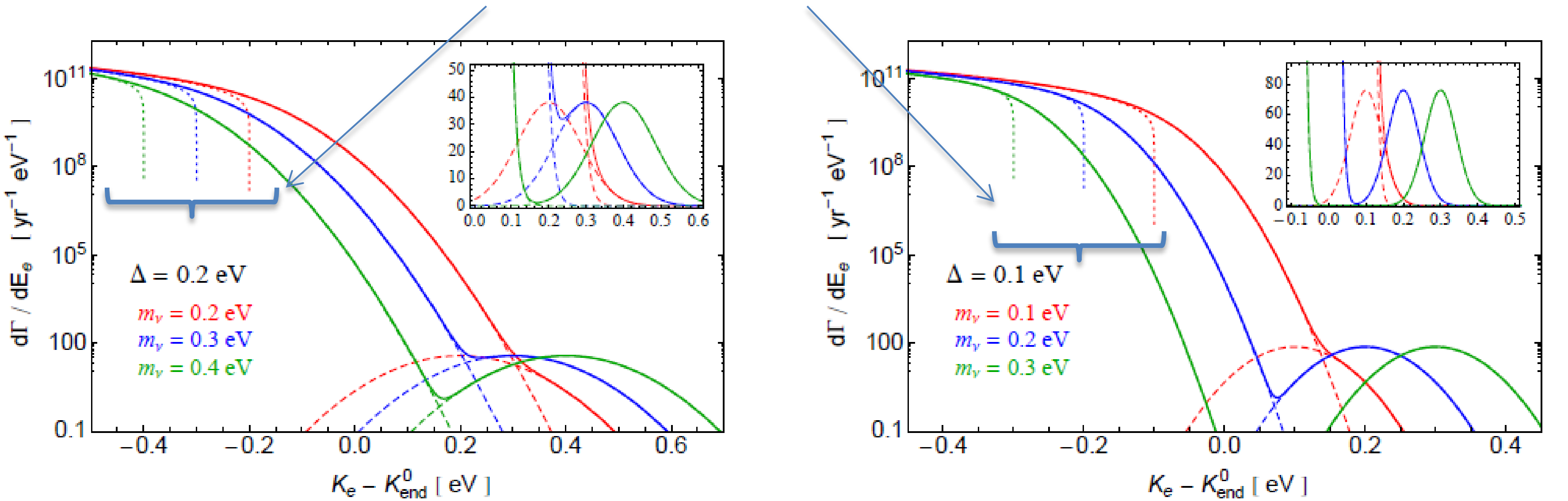
$$\Gamma \sim 5 \; \frac{\text{events}}{\text{year}} \; \frac{M_{target}}{100\text{ g}} \; \frac{n_\nu}{56\text{ cm}^{-3}}$$

Energy resolution: the most difficult challenge

We assume a single neutrinos mass (or three massive neutrinos with not-resolved masses)

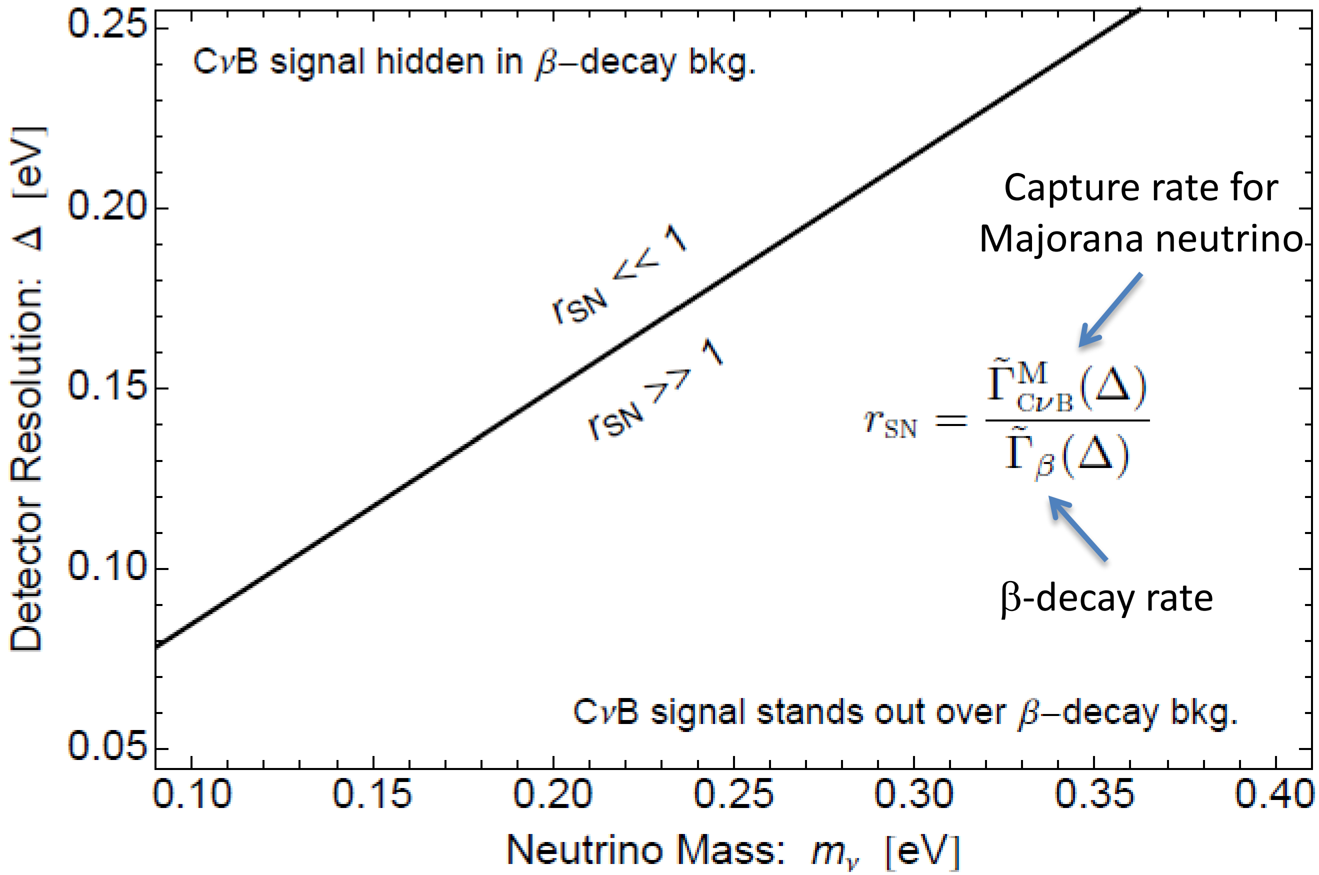
β-decay spectrum + neutrino capture

Infinite energy resolution



$\Delta \Rightarrow$ energy resolution

Energy resolution: the most difficult challenge

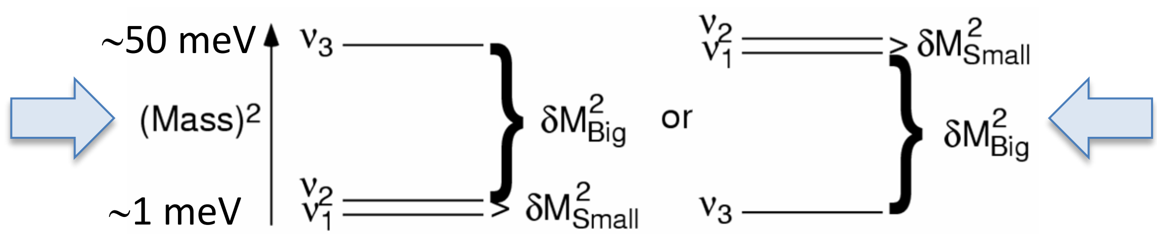


Rule of thumb $\Rightarrow$ $r_{SN} \gtrsim 1 \quad \text{for} \quad \Delta \lesssim 0.7 m_\nu$

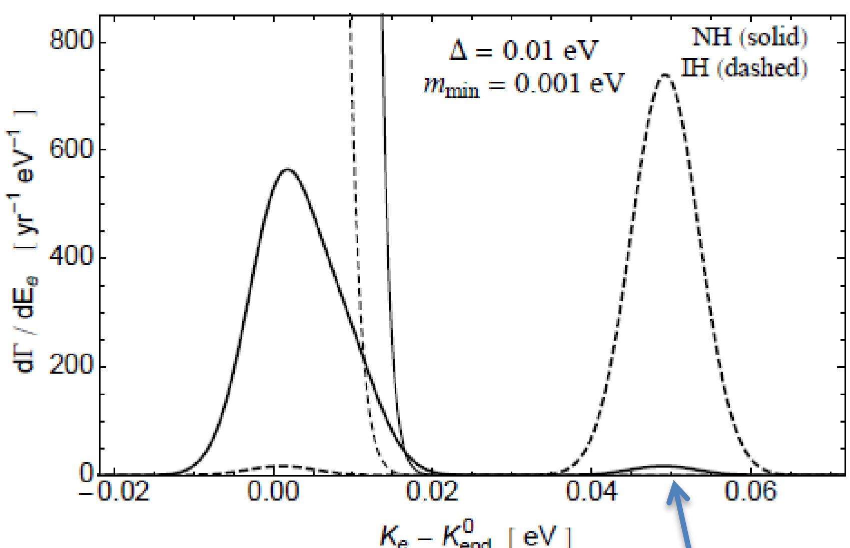
Energy resolution: the most difficult challenge

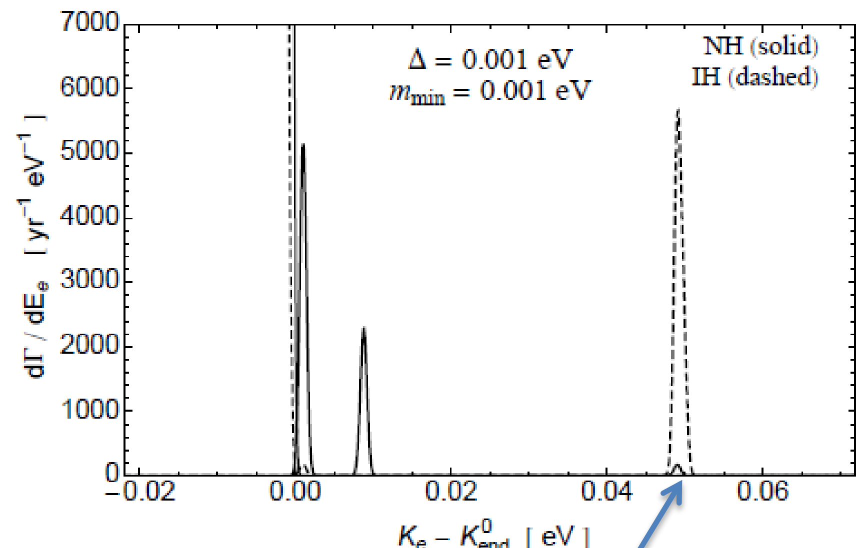
Masses strongly hierarchical (lightest neutrino mass ~ 1 meV or less)
Fantastic energy resolutions are required if the hierarchy is normal

Normal Hierarchy (NH)



Inverted Hierarchy (IH)





Note that the state ν_3 is weakly coupled with ν_e ($|U_{e3}|$ ~ 0.02)

The PTOLEMY[(*)] experiment in a nut-shell

[(*)] PTOLEMY = Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

- **100 g** of tritium (**1 MCi**) on 12-m diameter disk
  Surface deposition (tenuously held) on conductor (graphene) in vacuum
  Scalable mass/area of tritium source and detector (1g [sterile] → 100 g [CνB])
  Relic capture rate ~ 10/year without local clustering

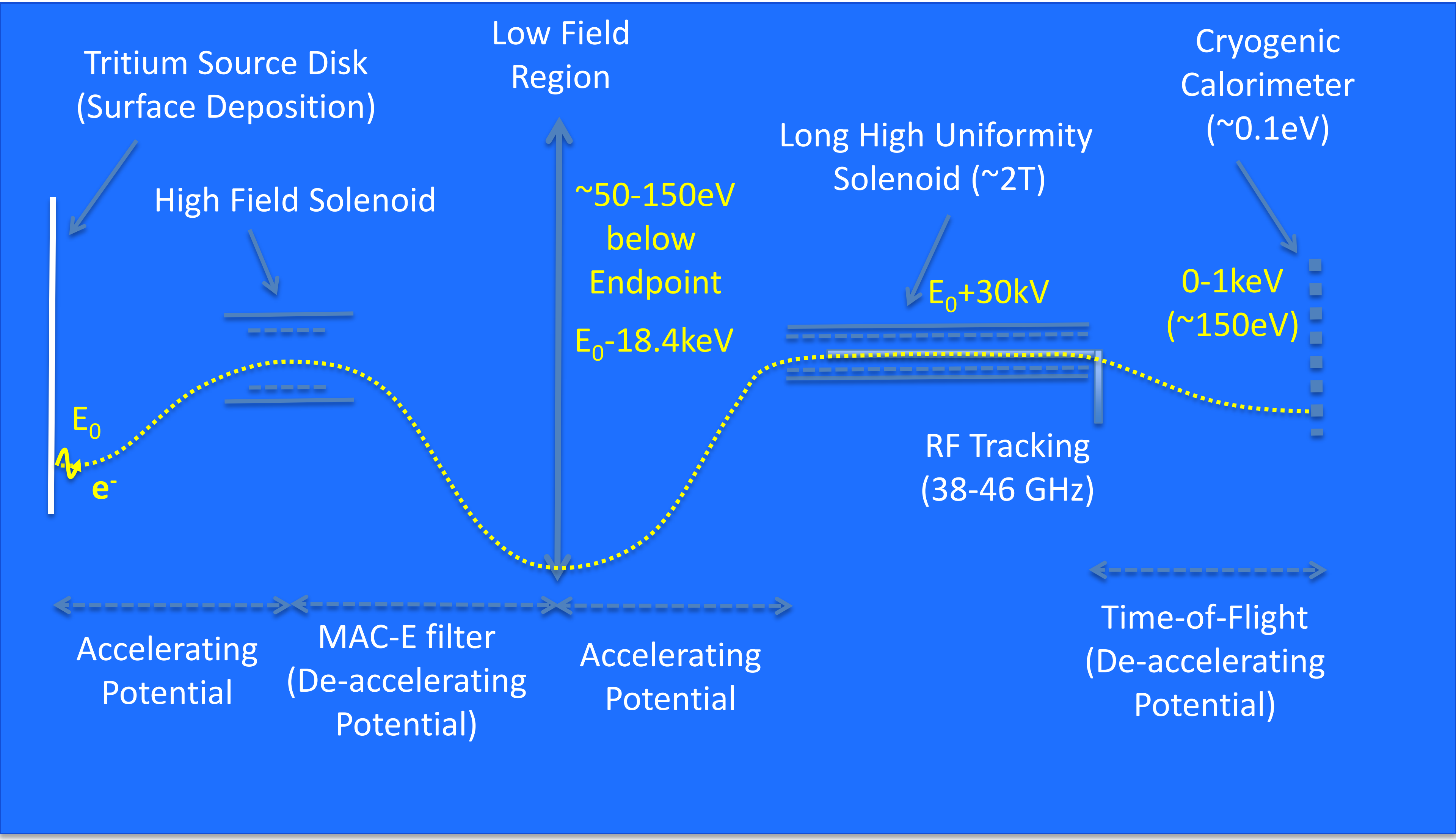
- Selection a of portion of the β-spectrum starting from **~100 eV** below the end point
  MAC-E filter magnetic collimation and electrostatic selection

- **~0.1-eV** energy resolution
  Transition-edge sensor array (extremely cryogenic detectors < 100 mK)

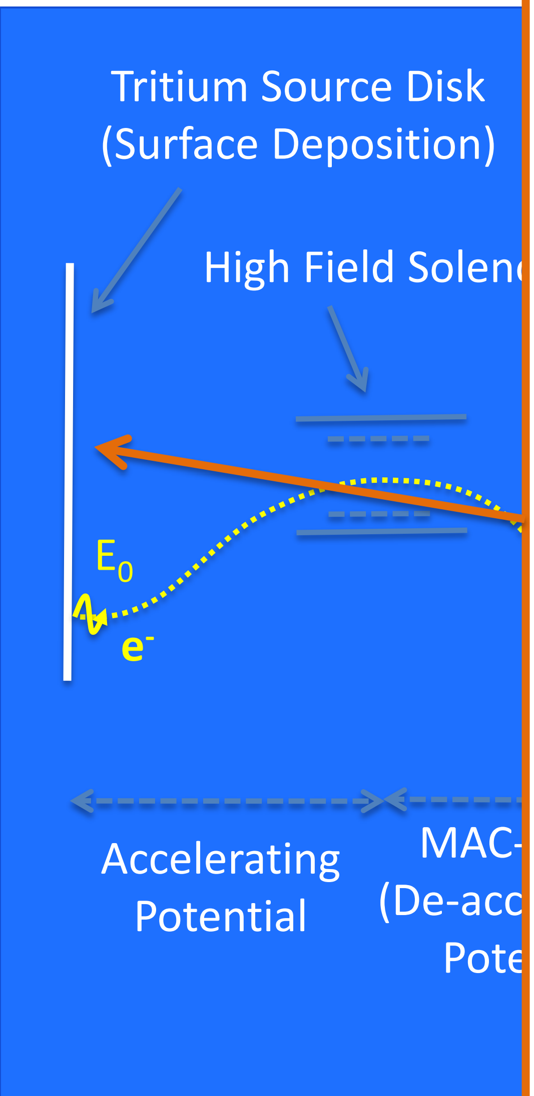
- Background abatement to **sub-μHertz rates** above endpoint
  Single electron tagging with RF cyclotron radiation (à la Project 8)
  Time-of-flight measurements

- Extreme challenges under any aspect
  (source technology, detector, cryogenics, RF measurement, B field features)

PTOLEMY Experimental Layout

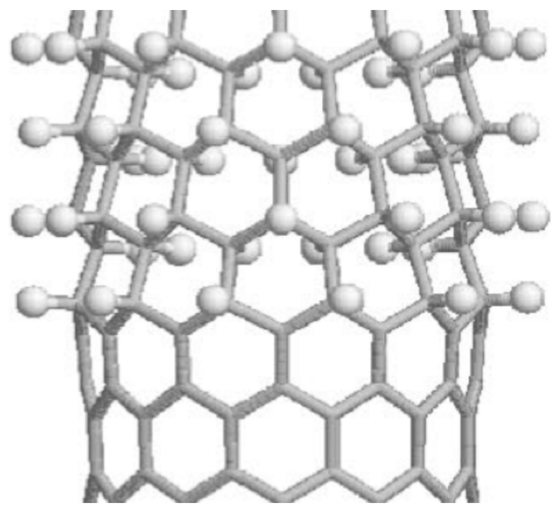


PTOLEMY Experimental Layout



SOURCE

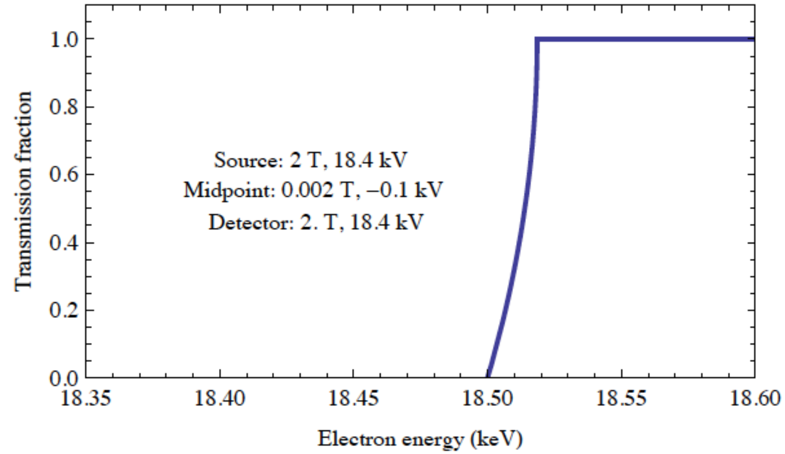
- **Monolayer of graphene** with one atomic tritium bound to each carbon atom (weak sub-eV binding energy) $\Rightarrow$ It needs to be cryogenic
- Titanium, gold, diamond are considered also
- 1 μg of tritium per cm^2 $\Rightarrow$ area of 100 m^2 for 100 g $\Rightarrow$ **12 m diameter source disk**

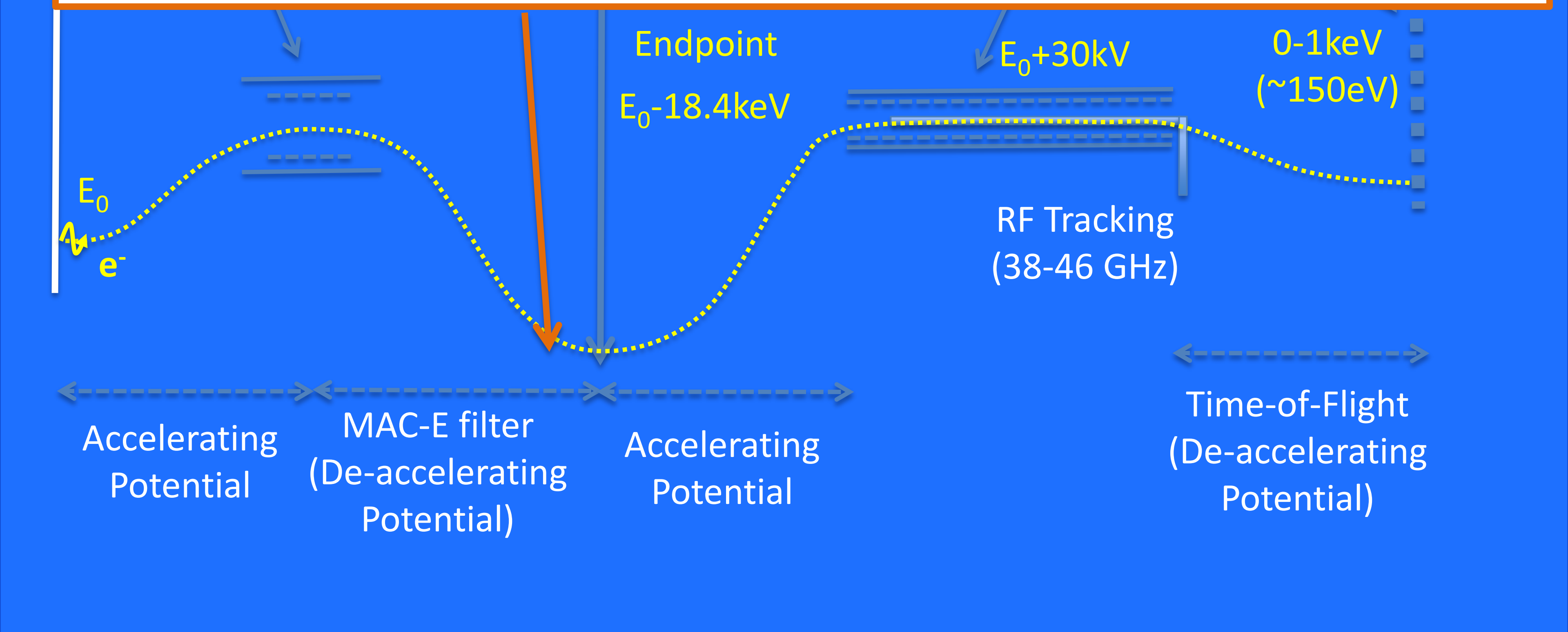


MAC-E FILTER

- Electrons from the source are guided
- by B field lines **(2π acceptance)**

- They move from a high field to low field region (transverse energy transformed into parallel energy)
  ⇒ electrostatic cut applied at **~18.4 keV** ($10^{-2} – 10^{-3}$ precision on electron energy)





nental Layout

RF TRACKING

- Electrons out of the MAC-E filter are re-accelerated and enter the RF tracking magnet (transit time < 1 μs)

- They undergo cyclotron motion

$$f_c = \frac{qB}{2\pi\gamma m_e c^2}$$

E=18.6 keV
B=1.9 T
f_c=46 GHz

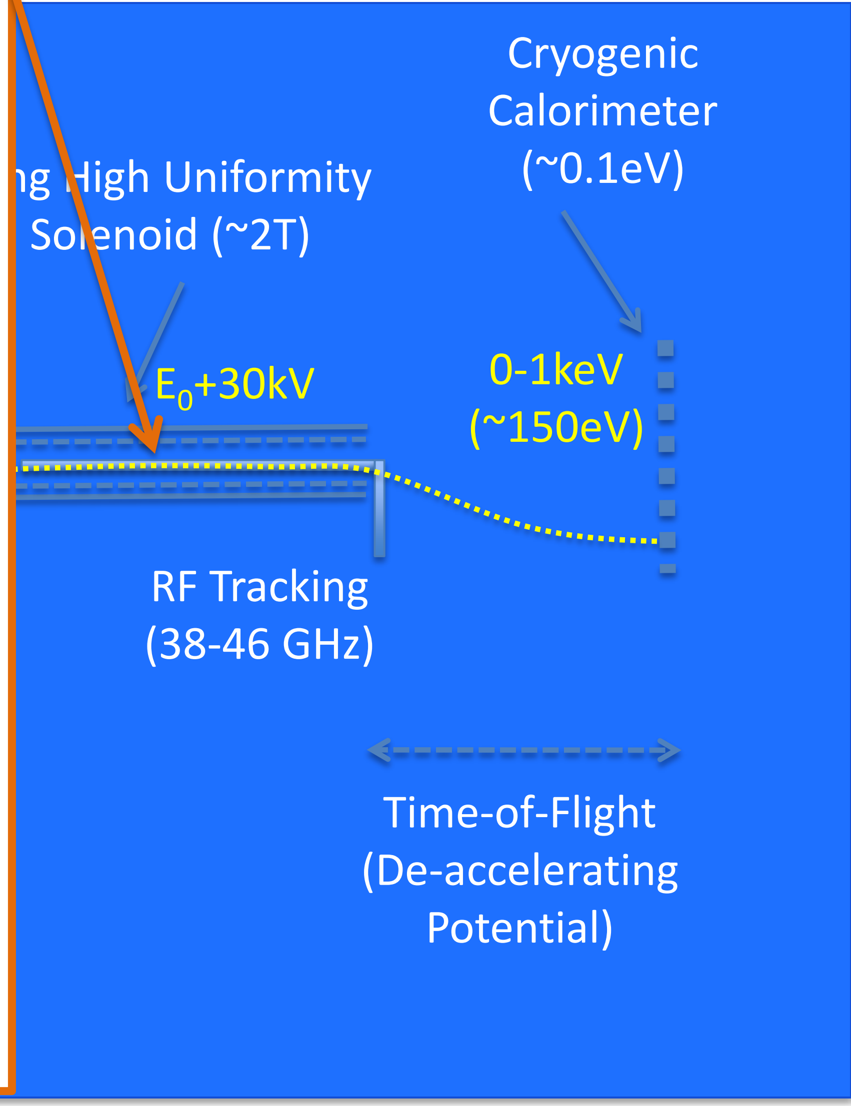
$\Rightarrow$ clear single electron tagging, put in coincidence with the detector signal

- Irradiated power depend on transverse velocity (which can be increased by re-acceleration)

$$P_{\rm tot} = \frac{1}{4\pi\epsilon_0}\frac{8\pi^2 q^2 f_c^2}{3c}\frac{\beta_\perp^2}{1-\beta^2}$$

E=18.6 keV $\beta_\perp \sim \beta$
P=3×10^{-14} W
P_{noise}=8×10^{-16} W

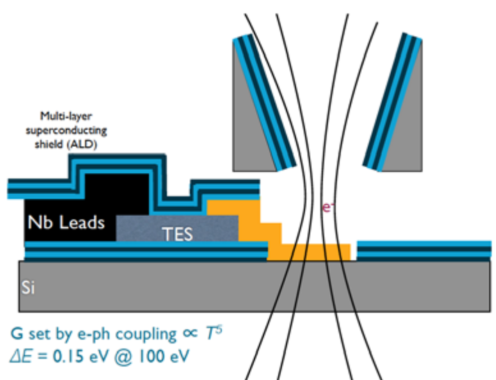
- Time of flight to the detector

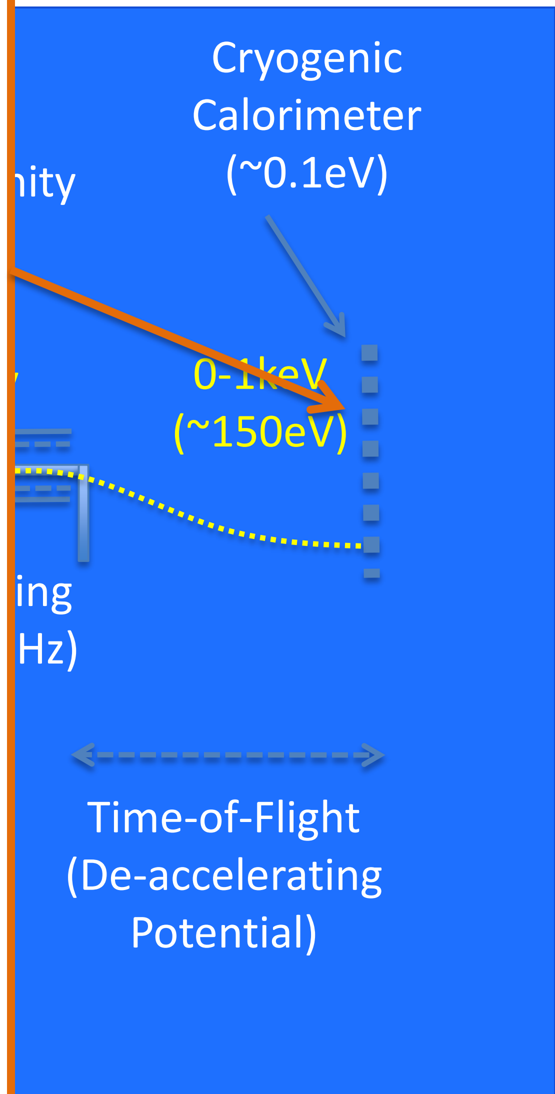


Layout

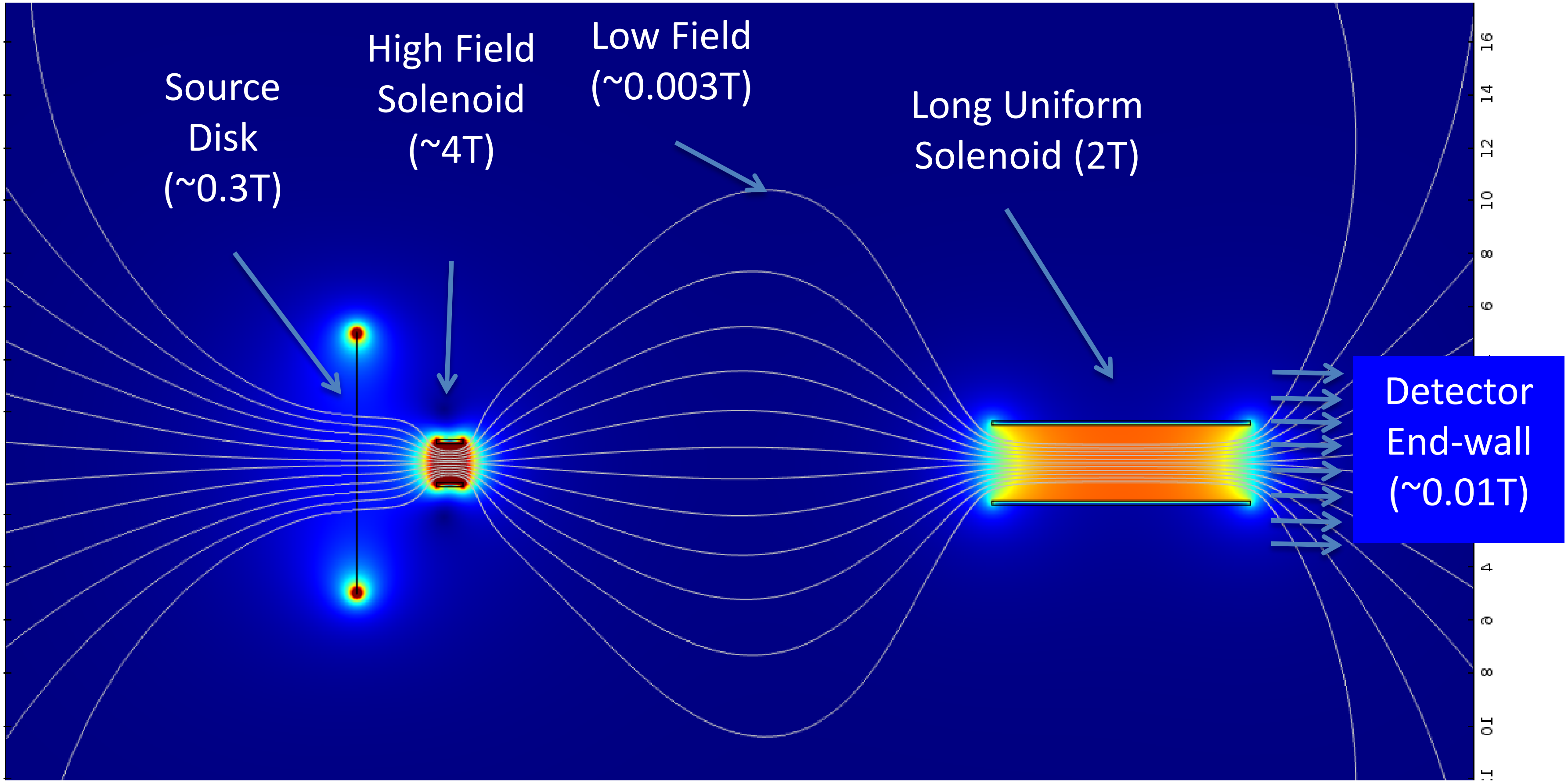
DETECTOR

- Electrons out of the RF tracking are decelerated to the detector location down to 100-200 eV energy range
- The magnetic flux will concentrate the electrons in the detector area
- The detector is an array of 10^5 TES (SQUID multiplexing for read-out) microcalorimeter with energy resolution of 0.1 eV at 150 eV
- Each detector pixel will have 40 – 400 μm size and will be operated at 70 mK
- The objective is to filter the electron so that the rate is 1 kHz/pixel – The « signal » rate (counts in the last 0.1 eV at the end-point) is 2 Hz

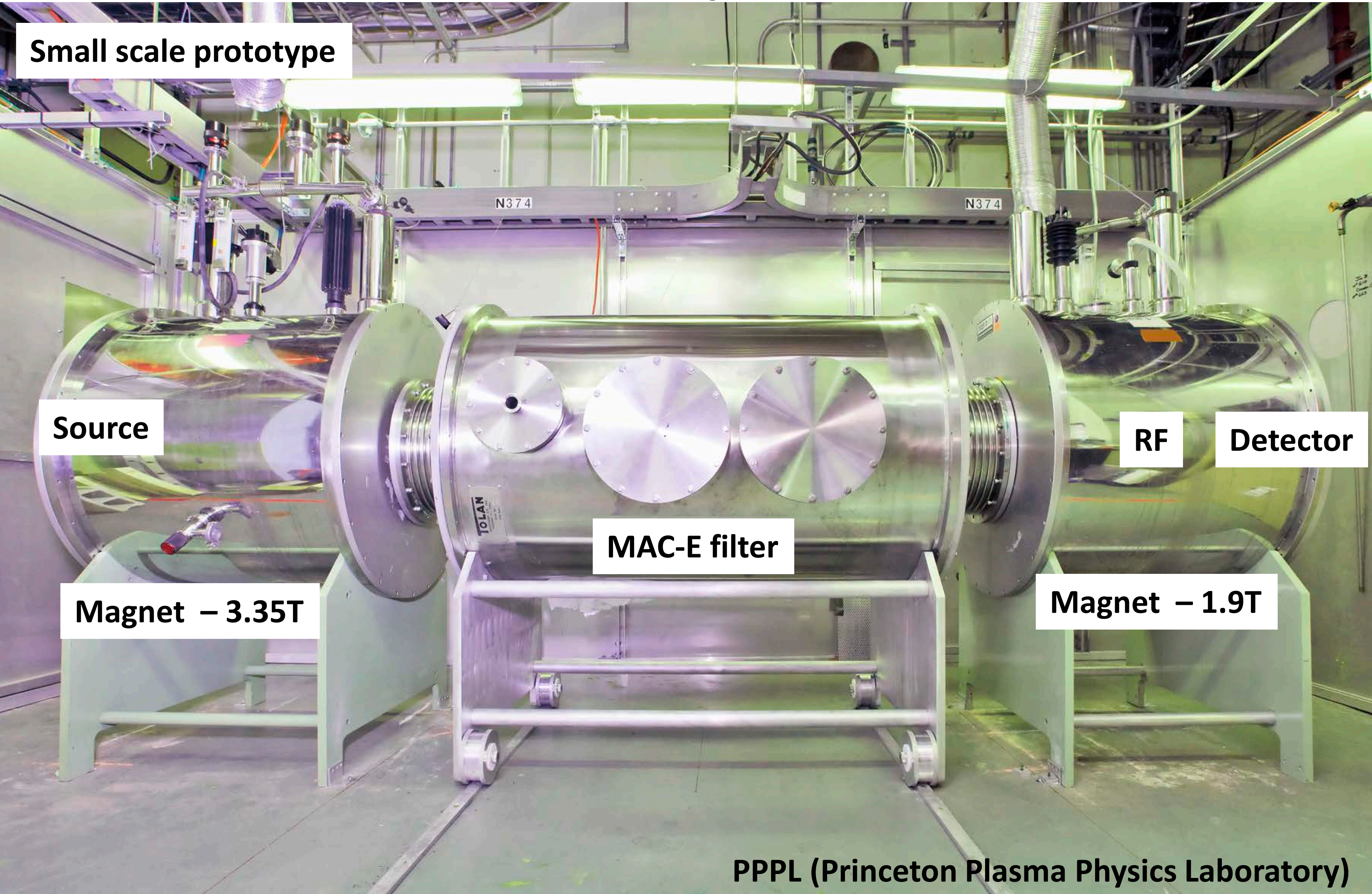




Example of B configuration



Proof of concept at Princeton



Annual modulation of CνB

B.R. Safdi, M. Lisanti, J. Spitz, and J.A. Formaggio, Phys. Rev. D 90, 043001 (2014)

Motion of the Sun and of the Earth in the CνB

The local ν density modulates annually
(effect of Gravitational Focusing by the Sun)

The detection rate modulates annually as well

Two extreme cases

Neutrinos bound to the galaxy

Unbound neutrinos

Different and peculiar amplitude/shape of modulations

Annual modulation of CνB

Let us recall that relic neutrinos are **extremely non-relativistic** today

T_0 = 0.168 meV → Present epoch CνB temperature

$\langle p_0 \rangle$ = 0.603 meV → Present epoch CνB root mean square momentum

To be compared with **m_ν > ~100 meV** relevant for CνB direct detection

$$\langle p_0 \rangle \ll m_\nu \quad \Rightarrow \quad E_\nu \sim m_\nu$$

Remember that we know that:

$\Sigma \; m_\nu < 660$ meV [Planck +WMAP + high-l data]
$\Sigma \; m_\nu < 230$ meV [Planck +WMAP + high-l data+BAO]
$\Sigma \; m_\nu > \sim 100$ meV [inverted hierarchy]
$\Sigma \; m_\nu > \sim 60$ meV [directed hierarchy]

} From ν flavor oscillations

Annual modulation of CνB

As a consequence of possible clustering, the local CνB phase-space distribution is more complicated than Fermi-Dirac statistics.

Both **velocity** and **space density** are affected today, depending on the neutrino mass

- **space density** → enhanced by a factor =
  - **~2** for $\mathbf{m_\nu}$ **= 150 meV**
  - **~20** for $\mathbf{m_\nu}$ **= 600 meV**
- **velocity** → **More high velocity neutrino** than expected from Fermi-Dirac distribution

(results of a simulated neutrino clustering in the Milky Way – *JCAP 0412 (2004) 005*)

Annual modulation of CνB

Important question: has the CνB a **peculiar velocity** with respect to the CMB?

The answer to this question is related to the **last scattering surface (LSS)** of relic neutrinos.

The LSS of CνB is much broader and, against expectations, much closer than that of the CMB, because relic neutrinos become non-relativistic at late times – *PRL 103(2009)171301*

Distance of LSS = { **2000 Mpc** for $\mathbf{m_\nu = 50}$ **meV** ; **500 Mpc** for $\mathbf{m_\nu = 1000}$ **meV** } (for CMB it is ~ 10000 Mpc)

↓

Distance of LSS remains anyway **much longer than size of largest superclusters** (~ 100 Mpc)

→ The CνB has no peculiar velocity with respect to the CMB.

↓

The motions of the Sun in the CνB and in the CMB have the same features.
Dipole anisotropy expected as in CMB.

Annual modulation of CνB

Uncertainties on local phase-space CνB distibution (which depends on the mass)

Two extreme cases

Relic neutrinos **unbound**

Relic neutrinos **bound to the Milky Way**

Likely, the local distribution is a mixture of bound and unbound neutrinos

Annual modulation of CνB

① **Unbound** relic neutrinos

Let's remind the capture rate formula

$$\Gamma = \sigma v_\nu n_\nu N_H \qquad \text{with } \sigma \propto 1/v_\nu \Rightarrow \sigma v_\nu = cost \equiv \sigma_0$$

Since relic neutrinos have a velocity distribution $f(v_\nu)$, we have to integrate over v_ν

$$\Gamma = N_H n_\nu \int dv_\nu \sigma v_\nu f(v_\nu) = N_T n_\nu \sigma_0 \int dv_\nu f(v_\nu)$$

normalized to 1

Consider Sun and Earth motion with respect to the CMB/CνB :

Replace: $v_\nu \rightarrow v_\nu' = v_\nu + v_{CMB} + v_{Earth}(t)$

Sun velocity wrt CMB

Earth velocity wrt Sun (annual modulation)

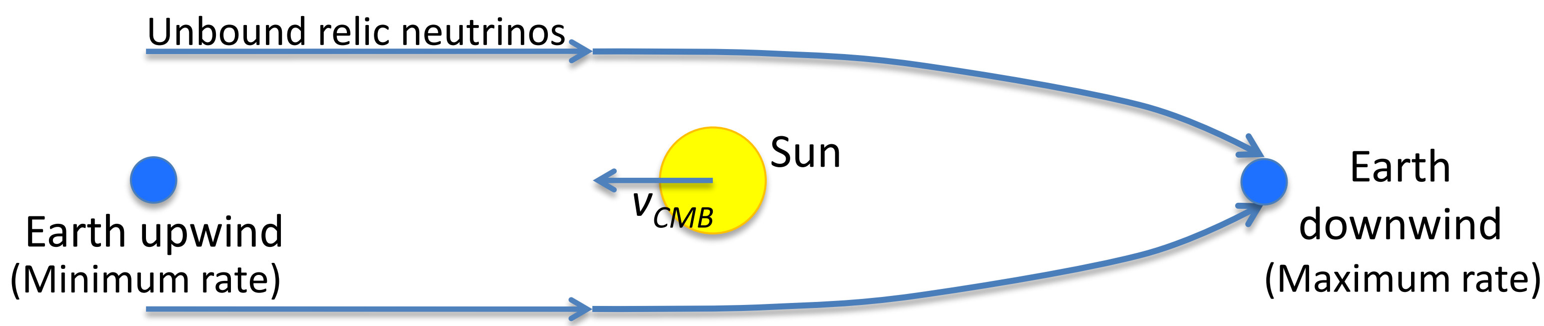
But $f(v_\nu')$ is also normalized to 1 $\Rightarrow$ no annual modulation?

Annual modulation of CνB

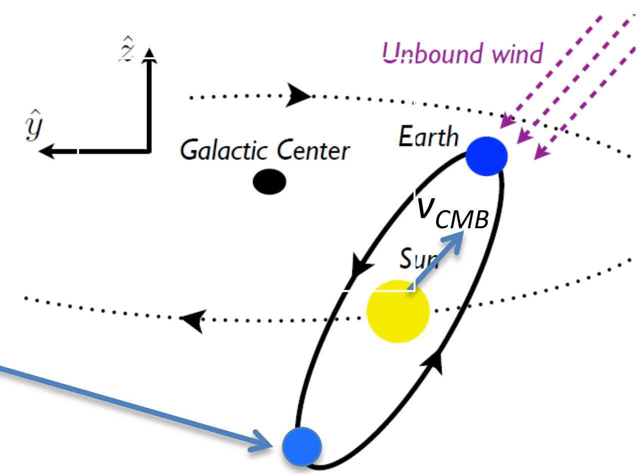
There is anyway annual modulation, since $\boldsymbol{n_\nu}$ **modulates**!

Effect of the **gravitational field** of the Sun

The neutrino wind due to Sun motion is focused on the Earth when it is downwind



Given the direction of the Sun motion and the orientation of the ecliptic, it turns out that the maximum is on **September 11** (not far from autumnal equinox)



Annual modulation of CνB

The amplitude and the shape of the distribution depend on the **neutrino mass** and on the **velocity distribution**

Effects more pronounced for **slow-moving particles** (more time close to the Sun)

Rough evaluation of the **modulation fraction** $\propto (v_{esc} / \langle v_{\nu} \rangle)^2$

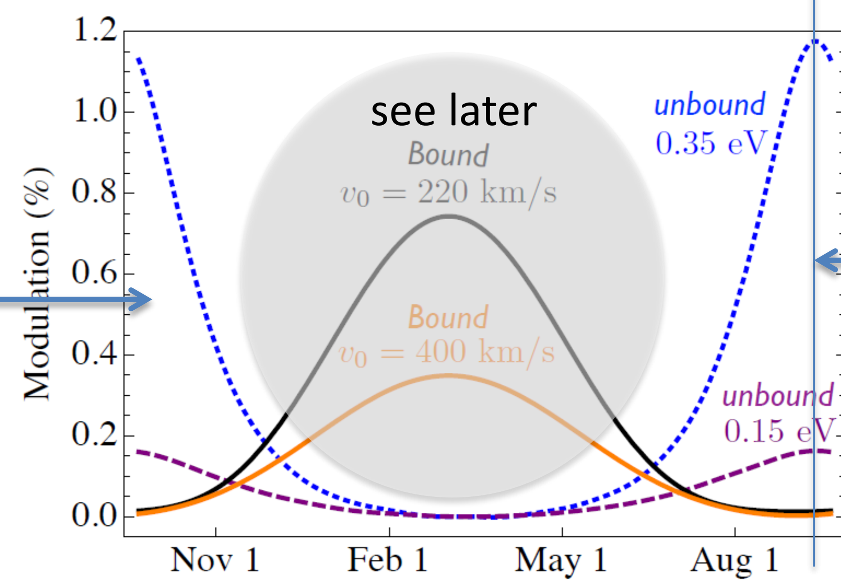
Mean neutrino speed

Escape velocity from Solar System at Earth location ~ 40 km/s

~ **0.13 %** for **m_ν = 0.15 eV**

~ **0.76 %** for **m_ν = 0.35 eV**

Precise calculations



September 11

0.1 – 1 % effect

Annual modulation of CνB

② **Bound to Milky Way** relic neutrinos

Repeat the same arguments as for unbound neutrinos, with these changes:

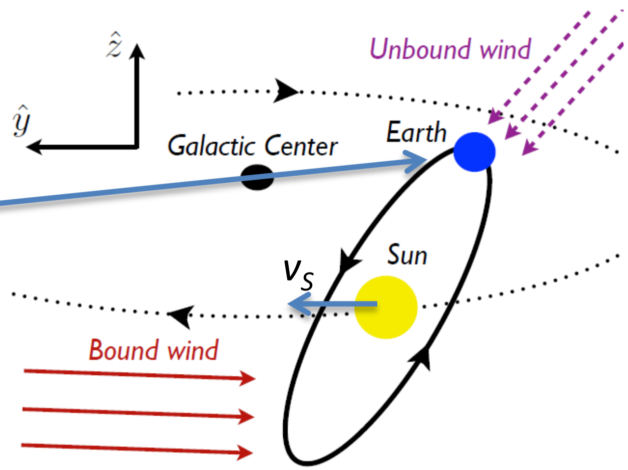
- Relic neutrinos had the time to virialize in the Milky Way
- Their $f(v_\nu)$ is isotropic in the Milky Way rest system
- $f(v_\nu)$ is the same as taken for WIMPs in the Standard Halo Model

$$\tilde{f}(\mathbf{v}_\nu) = \begin{cases} \frac{1}{N_{\rm esc}} \left(\frac{1}{\pi v_0^2}\right)^{3/2} e^{-\mathbf{v}_\nu{}^2/v_0^2} & |\mathbf{v}_\nu| < v_{\rm esc} \\ 0 & |\mathbf{v}_\nu| \geq v_{\rm esc} \end{cases}$$

- The relic neutrino wind is this time determined by $\boldsymbol{v_S}$ (**Sun velocity in the galactic frame**)

The maximum rate is shifted by about half year wrt unbound neutrinos

Given the direction of the Sun motion and the orientation of the ecliptic, it turns out that the maximum is on **March 1** (not far from the vernal equinox)



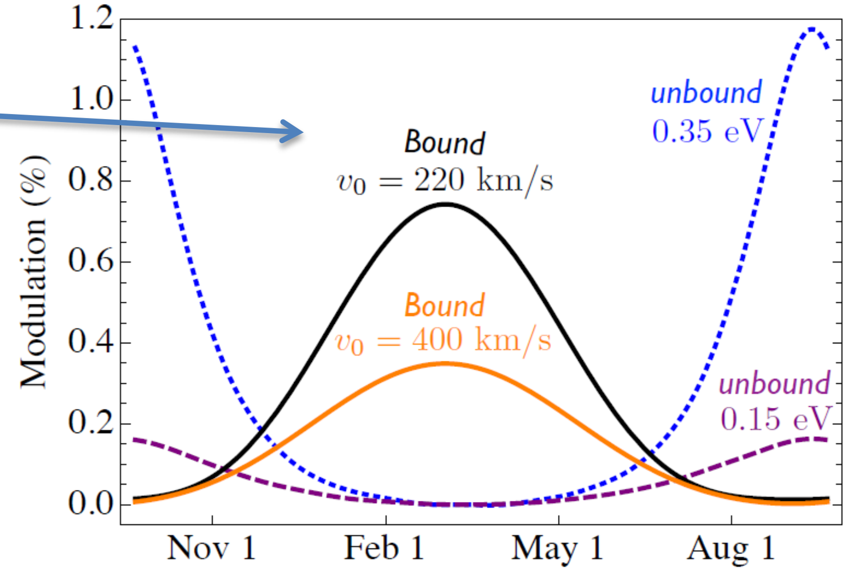
Annual modulation of CνB

Precise calculations determine the amplitude and the shape of the modulation

~ 0.75 % for **v_0= 220 km/s**

~ 0.35 % for **v_0 = 400 km/s**

The two scenarios have opposite phases
Easy to disentangle experimentally

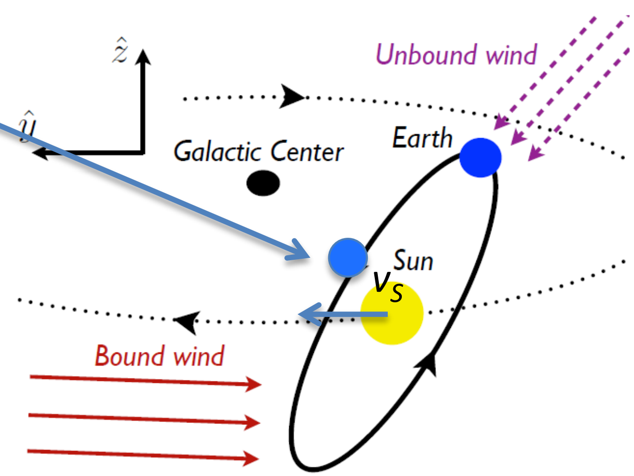


N.B. The maximum of the rate is about ¼ year shifted wrt that expected for WIMPs (**June 2**)

In the WIMP case, the highest maximum rate is related to velocity and not to density

It occurs when the Earth velocity is most parallel to the Sun velocity in the Milky Way

Sun gravitational focusing can anyway affect the amplitude and especially the phase of annually modulated WIMP interaction rates



Annual modulation of CνB

Is annual modulation of CνB capture rate detectable?

0.1 – 1 % effect $\Rightarrow$ $\sim 10^4 - 10^6$ events are needed for detection with 2σ statistical significance

The expected detection rate in PTOLEMY is $\sim$ 10 events/year (100 g tritium target)

⇒ **Modulation not detectable**

However:

- Using multilayers of graphene substrates it is in principle feasible to scale PTOLEMY target up to 10 kg
- Neutrino could cluster maximum by factor 10, but factors 10^3 are possible for exotic $\nu-\nu$ interactions (neutrino clouds) - *Int.J.Mod.Phys. A13(1998)2765*)

Measuring anisotropies in CνB

M. Lisanti, B.R. Safdi, Ch. Tully, arXiv:1407.0393 [astro-ph.CO]

Use NCB to detect relic neutrinos

↓

Use a polarized beta-decaying (^3H) target

↓

The capture rate is sensitive to direction of ν spin and velocity

↓

The rate is maximal when:

- Neutrino and ^3H spins are antiparallel
- Neutrino velocity is aligned with ^3H polarization axis

↓

A daily modulation of the rate is expected for anisotropies in CνB as seen from the lab frame

Measuring anisotropies in CνB

Calculation of the polarized scattering amplitude and differential cross section

Consider capture reaction

$\nu_j + n \to p + e^-$ *j* indicates **mass eigenstate** with overlap $\boldsymbol{U_{ej}}$ with ν_e **flavor state** (first row of U_{PMNS} matrix)

Matrix element in the Fermi theory

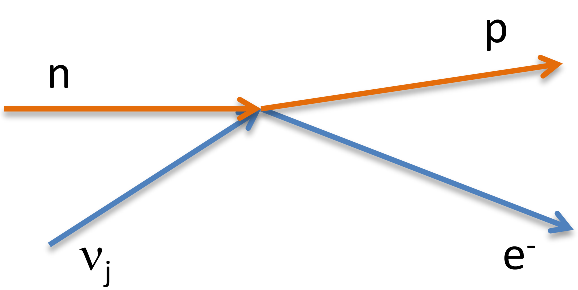
Fermi constant

Cabibbo angle

Axial-vector coupling

$$\mathcal{M} = \frac{G_F c_1 U^*_{ej}}{\sqrt{2}} \bar{u}_p \gamma_\mu (1 - g_A \gamma^5) u_n \bar{u}_e \gamma^\mu (1 - \gamma_5) u_\nu$$

Hadronic current Leptonic current



The generalization to $\nu_j + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$ is straight-forward as ^{3}H beta decay is superallowed and (p,n) – (^{3}He,^{3}H) are isospin doublets

$g_A = 1.27 \to g_A = 1.21$

Measuring anisotropies in CνB

From the above matrix element, the differential cross section (with respect to the outcoming electron direction) can be derived in the non-relativistic limit (first order in the neutrino velocity)

Asymmetry parameters (they depends only on g_A)

Constant fixing the scale

$B \approx 0.99$ $\quad A \approx -0.095$ $\quad a \approx -0.087$

$$\frac{d\sigma(\hat{\mathbf{s}}_\mathbf{H}, \hat{\mathbf{v}}_\mathbf{e})}{d\Omega_e} v_\nu \approx \frac{\bar{\sigma}}{4\pi} [1 - \hat{\mathbf{s}}_\nu \cdot \mathbf{v}_\nu + B\, \hat{\mathbf{s}}_\mathbf{H} \cdot (\mathbf{v}_\nu - \hat{\mathbf{s}}_\nu) + A\, \hat{\mathbf{s}}_\mathbf{H} \cdot \mathbf{v}_\mathbf{e}\, (1 - \hat{\mathbf{s}}_\nu \cdot \mathbf{v}_\nu) + a\, \mathbf{v}_\mathbf{e} \cdot (\mathbf{v}_\nu - \hat{\mathbf{s}}_\nu)]$$

Term independent of polarization
It contains neutrino helicity
It does not contain $\boldsymbol{S_H}$

Dominant asymmetry term
It favors: - neutrino velocity aligned with ^3H spin
- neutrino spin antiparallel to ^3H spin
(as anticipated)

Term containing electron velocity $\boldsymbol{v_e}$
It can be shown that terms with neutrino spin and velocity are negligible
Through $\hat{\mathbf{s}}_\mathbf{H} \cdot \mathbf{v}_\mathbf{e}$, it favours electrons emitted away from direction of polarization
Unfortunately, this is the same feature of beta-decay electrons
Experimentally, very difficult to measure (not impossible in principle)

Measuring anisotropies in CνB

In order to calculate the rate in the lab rest frame, we take the differential rate

$$\frac{d\Gamma(\hat{\mathbf{s}}_{\mathrm{H}}, \hat{\mathbf{v}}_{\mathrm{e}})}{d\Omega_e} = N_{\mathrm{H}} n_\nu \left\langle \frac{d\sigma(\hat{\mathbf{s}}_{\mathrm{H}}, \hat{\mathbf{v}}_{\mathrm{e}})}{d\Omega_e} v_\nu \right\rangle$$

The average indicates that velocity distribution $f(v_\nu)$ must be taken into account

***$f(v_\nu)$* is expected to be isotropic in the CνB rest frame** (both for unbound and bound cases)

In the lab rest frame, we get on the contrary

$$\langle \mathbf{v}_\nu \rangle = \int d^3 v_\nu \, f_{\mathrm{lab}}(\mathbf{v}_\nu) \, \mathbf{v}_\nu = -\mathbf{v}_{\mathrm{lab}}$$

where $\mathbf{v}_{lab}$ is the velocity of the detector wrt the CνB

$\mathbf{v}_{lab}$ =

- $\mathbf{v}_{CMB}$ ⇒ velocity of the Sun wrt CνB - $|v_{CMB}|$ = 369 km/s **- Unbound relic ν**
- $\mathbf{v}_{S}$ ⇒ velocity of the Sun wrt Milky Way - $|v_S|$ = 232 km/s **- Bound relic ν**

Measuring anisotropies in CνB

Integrating over the direction of emission of the electrons:

$$\Gamma(\hat{\mathbf{s}}_\mathbf{H}) = \int d\Omega_e \frac{d\Gamma(\hat{\mathbf{s}}_\mathbf{H}, \hat{\mathbf{v}}_\mathbf{e})}{d\Omega_e}$$
$$= N_\mathrm{H}\, n_\nu\, \bar{\sigma} \left(1 - B \frac{\mathbf{v}_\mathrm{lab}}{c} \cdot \hat{\mathbf{s}}_\mathbf{H}\right)$$

If the target is prepared with a given polarization, the angle between $\boldsymbol{v}_{lab}$ and $\boldsymbol{s}_H$ changes during the day

$$\mathcal{O}\left(B \frac{v_\mathrm{lab}}{c}\right) \sim 0.1\%$$

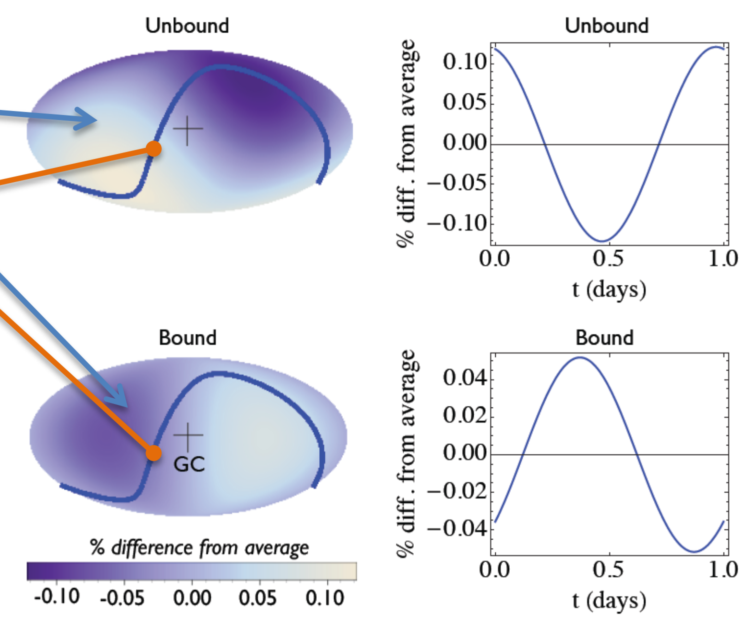
Diurnal modulation

Rate as a function of the direction in the sky

Daily trajectory of $\boldsymbol{s}_H$ in the sky ($\boldsymbol{s}_H \perp$ Earth axis)

Expectation: CνB nearly isotropic but small (0.1% - in principle detectable) dipole anisotropy due to lab motion (as for CMB)

If larger/different anisotropies observed, this would imply non-standard scenarios



Measuring anisotropies in CνB

Dirac vs Majorana neutrinos

4 degrees of freedom for generation **$n_0 \sim 56\ cm^{-3}$**

DIRAC

$n(\nu_{h_L}) = n_0$ ⇒ Active on ^3H

$n(\bar{\nu}_{h_R}) = n_0$ ⇒ Inactive on ^3H (they should produce e+ for L conservation)

$n(\nu_{h_R}) \approx 0$

$n(\bar{\nu}_{h_L}) \approx 0$

MAJORANA

$n(\nu_{h_L}) = n_0$ ⇒ Active on ^3H

$n(\nu_{h_R}) = n_0$ ⇒ Active on ^3H

$n(N_{h_R}) = 0$

$n(N_{h_L}) = 0$

Majorana case: density of active neutrinos = $2n_0 \sim 112\ cm^{-3}$

Dirac case: density of active neutrinos = $n_0 \sim 56\ cm^{-3}$

For PTOLEMY

$$\Gamma \approx 10\,\frac{\text{events}}{\text{year}} \cdot \frac{M_{\text{Det}}}{100\,\text{g}} \cdot \frac{n_0}{112\,\text{cm}^3}$$

$$\Gamma^{\text{M}}_{\text{C}\nu\text{B}} = 2\,\Gamma^{\text{D}}_{\text{C}\nu\text{B}}$$

Measuring anisotropies in CνB

Feasibility

First issue: polarize ^{3}H in a PTOLEMY-like experiment

- Apply external B and count on thermal polarization fraction: very inefficient
- Use advanced methods of dynamical polarization
- Exploit possible ferromagnetism of certain hydrogenations of graphene

Baseline PTOLEMY – with its detection rate of 10/y – cannot observe anisotropies.
0.1% effect requires 10^6 counts $\Rightarrow$ need detector upgrade to reach ^{3}H mass $\sim$ 10 kg

A lot of physics results can be obtained if detection is sensitive to 0.1% effects

Annual modulation + dipole anisotropy + known velocities of the lab frame in CνB

- Probe velocity dispersion and temperature of the CνB
- Disentangled bound from unbound components
- Determine local phase-space disitribution of the relic neutrinos
- Break degeneration between Dirac vs. Majorana and local CνB overdensity

Conclusions

- Standard cosmology predicts the existance of a **see of non-relativistic neutrinos** in which we are immersed and allows us to compute their main features (**spacial density** and **velocity distribution**)
- In spite of the low cross section and of the very small energy, there is a process which allows in principle the detection of these relic neutrinos, i.e. the **capture on beta-decaying nuclei**
- An experiment has been proposed, named **PTOLEMY**, which could detect, at a modest rate of **~10 events/year**, relic neutrino capture on ^{3}**H**
- PTOLEMY is **extremely challenging** under any aspect (source, detector, background) and its development poses formidable and fascinating experimental problems
- Detection of **time modulations** and **anisotropies** of the relic neutrino interactions (which requires an increase by at least a factor 100 of the baseline PTOLEMY target!) would provide detailed information, such as **neutrino phase space distribution**, **possible clustering** and nature (**Dirac / Majorana**)
- Detection of relic nautrino is a significant **test of standard cosmology**