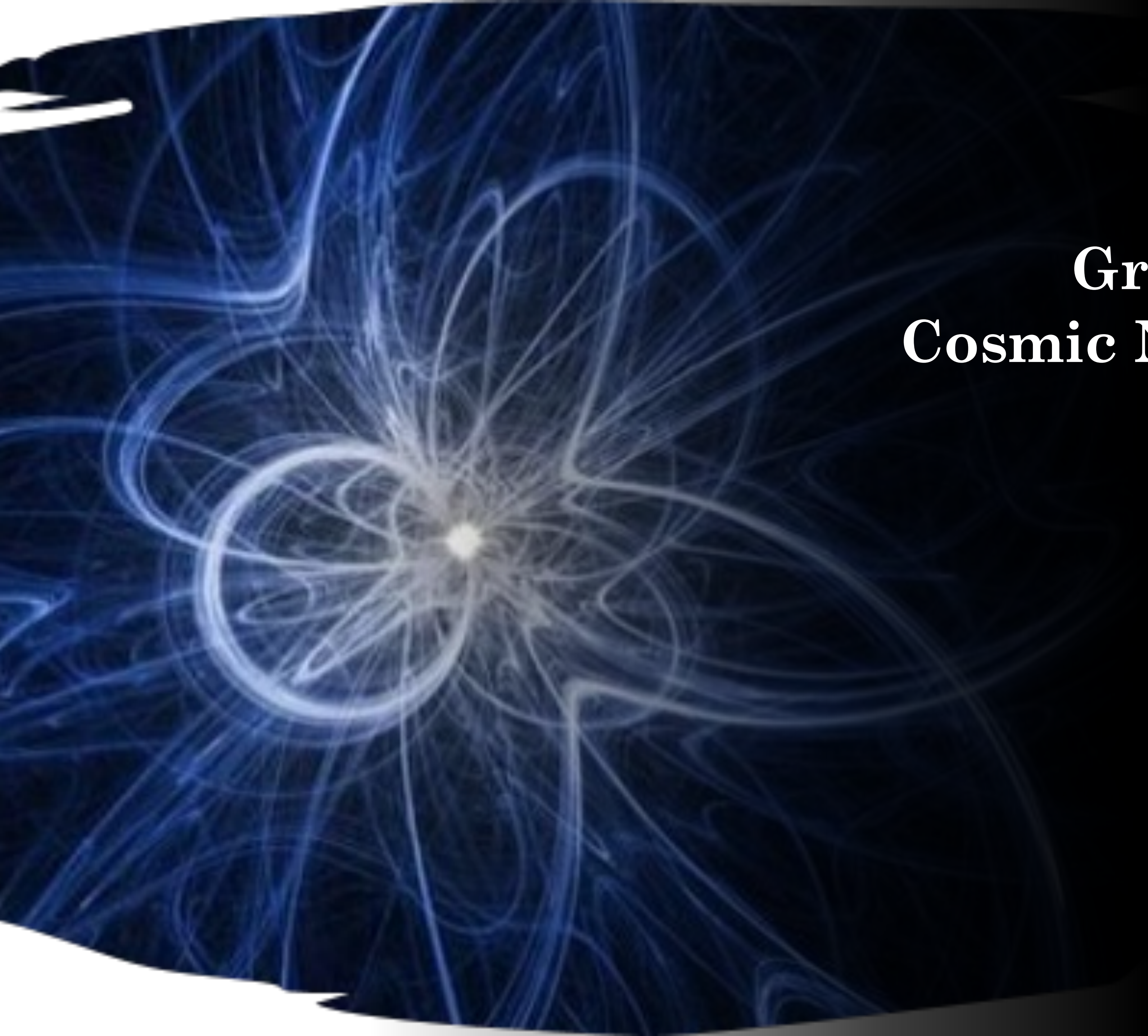

TRISEP 2024
Group Problem #6
Cosmic Neutrino Background

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What is cosmic microwave background?

- **Definition and Theoretical Origin:**

The Cosmic Microwave Background (CMB) is the (approximately) uniform radiation detected across all of space.
It is predicted by the Big Bang theory as the remnant photons from recombination as they decoupled from the hydrogen gas.

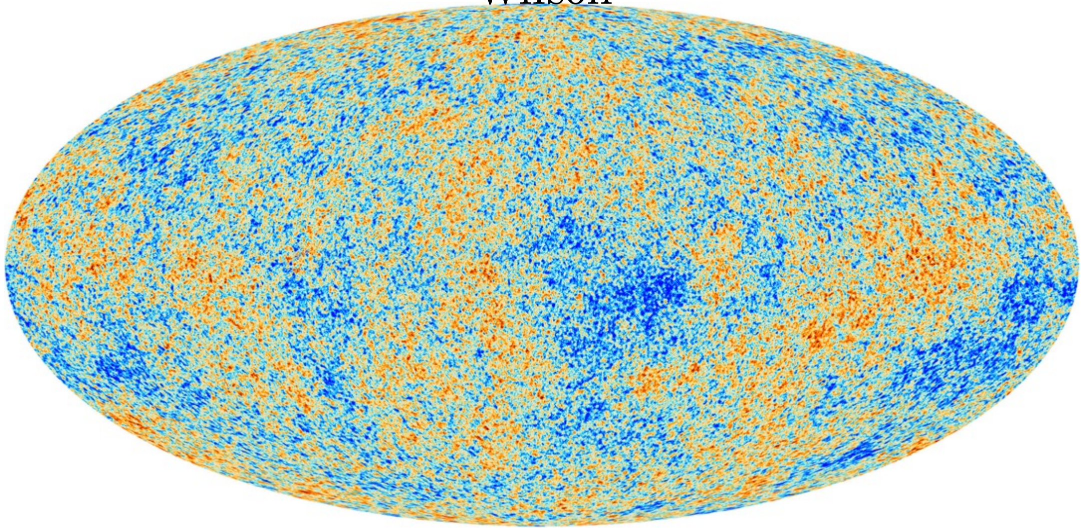
- **Discovery:**

Discovered in 1965 by Arno Penzias and Robert Wilson, who were awarded the Nobel Prize in Physics of 1978.

- **Characteristics:**

Uniform radiation profile with small fluctuation that fills the entire universe.
Detected in the microwave region of the electromagnetic spectrum.

Arno Penzias and Robert Wilson



What is cosmic microwave background?

・**Significance in Cosmology:**
Provides strong evidence for the Big Bang theory.
Strongly constraints the initial conditions of the universe, such as the abundance of matter, dark matter and dark energy.
・**Temperature and Spectrum:**
The CMB has a nearly uniform temperature of about 2.725 Kelvin.
The best blackbody spectrum observed, peaking in the microwave range.
・**Anisotropies:**
There are slight fluctuations in the temperature of the CMB at the order of 10^{-5} Kelvin.
These anisotropies are seeds of all current structures: galaxies, clusters of galaxies, and voids.

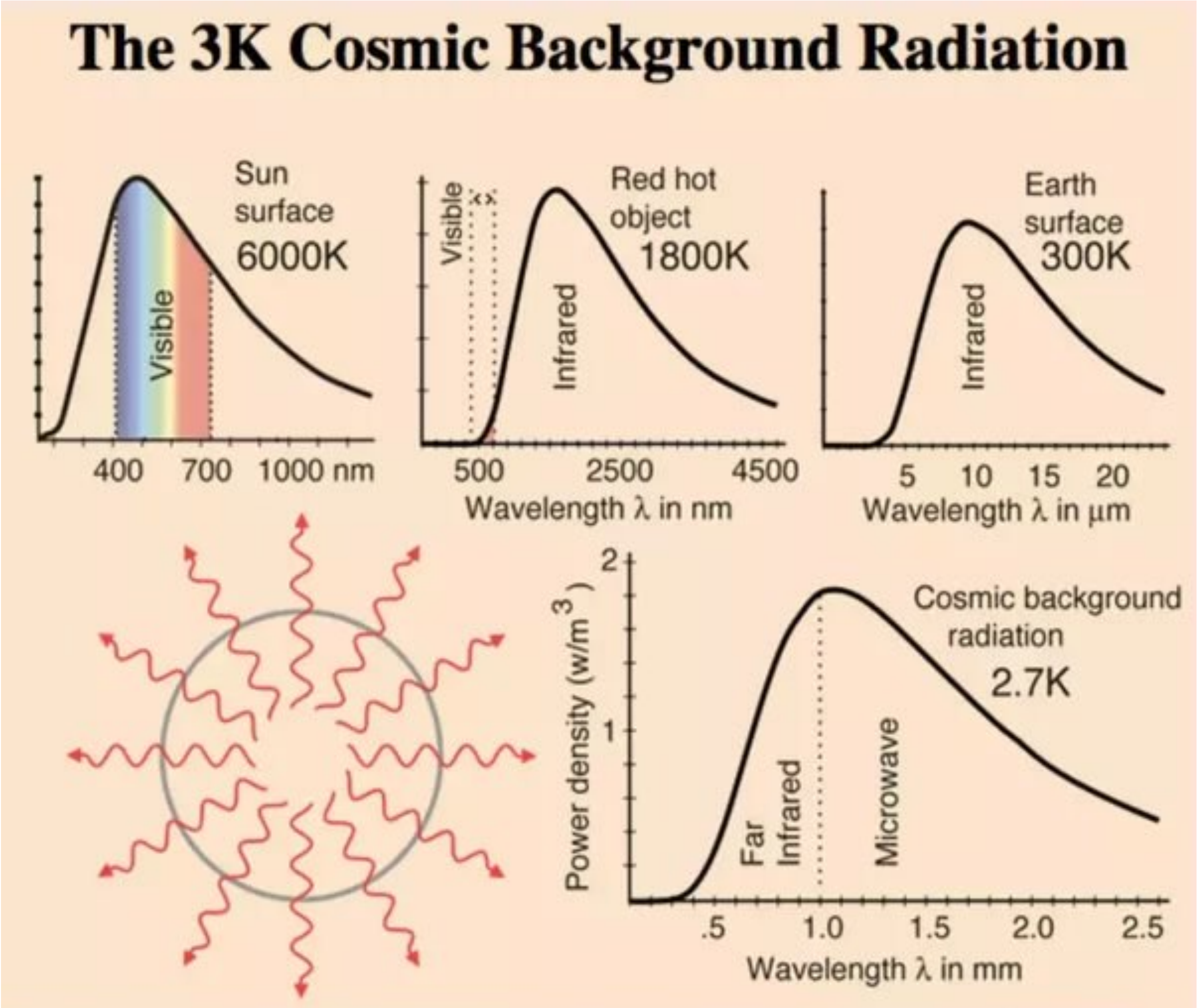


Figure LIUF6. Black-Body radiation applies along the whole spectrum. From [19].

What is the cosmic neutrino background?

- **Definition and Origin:**

The Cosmic Neutrino Background (CNB/CνB) consists of relic neutrinos from the early universe.

Formed about one second after the Big Bang, when the rate of weak interaction becomes smaller than the Hubble parameter.

- **Properties:**

Extremely low-energy neutrinos (~ 0.2 meV / ~ 1.95 K)

$T_\nu = 1.95, K = 0.16$ meV

$\sum m_\nu \lesssim 0.11 - 0.68$ eV

$n_\nu \approx 340$ cm^{-3} (all flavours, including anti-neutrinos)

$\lambda_\nu \sim O(0.1\text{cm})$

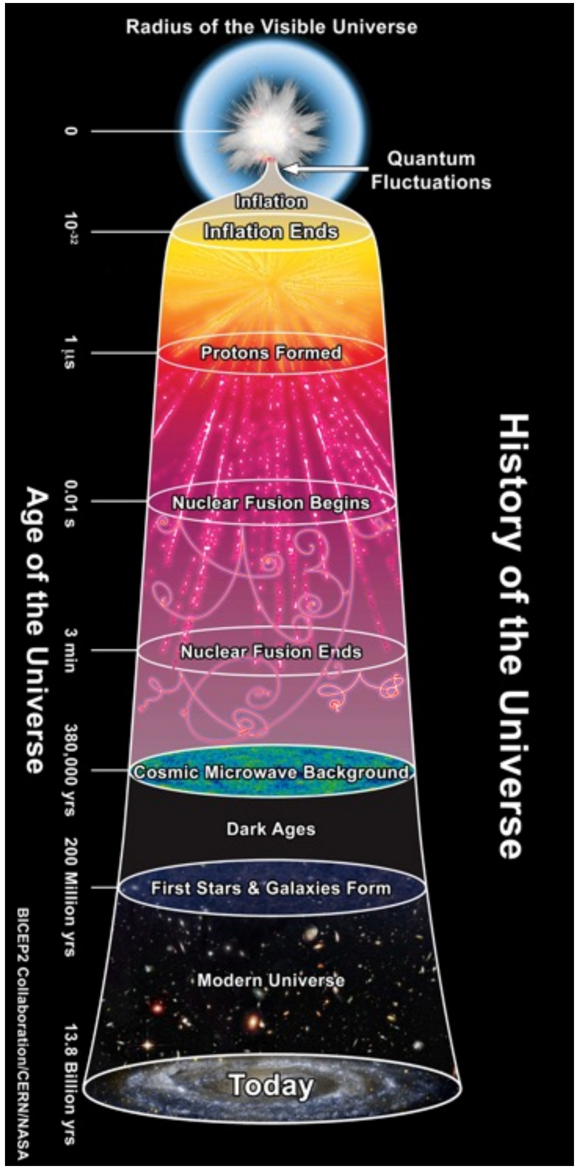
One of the few sources of nonrelativistic neutrinos

- **Insights from the Cosmic Neutrino Background:**

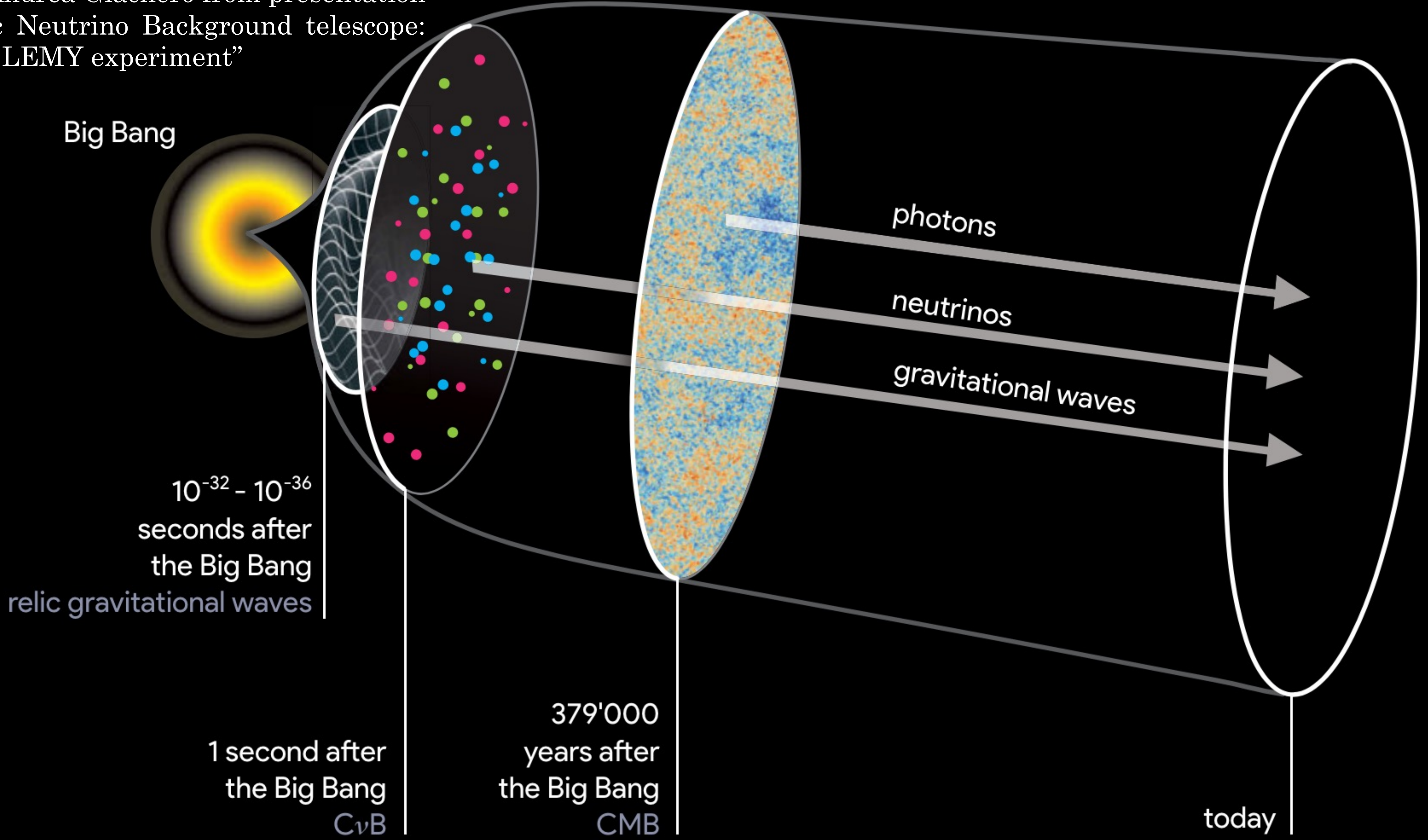
Allows probing into the period before recombination.

Complements the information from the CMB.

Influences the formation and evolution of large-scale structures in the universe.



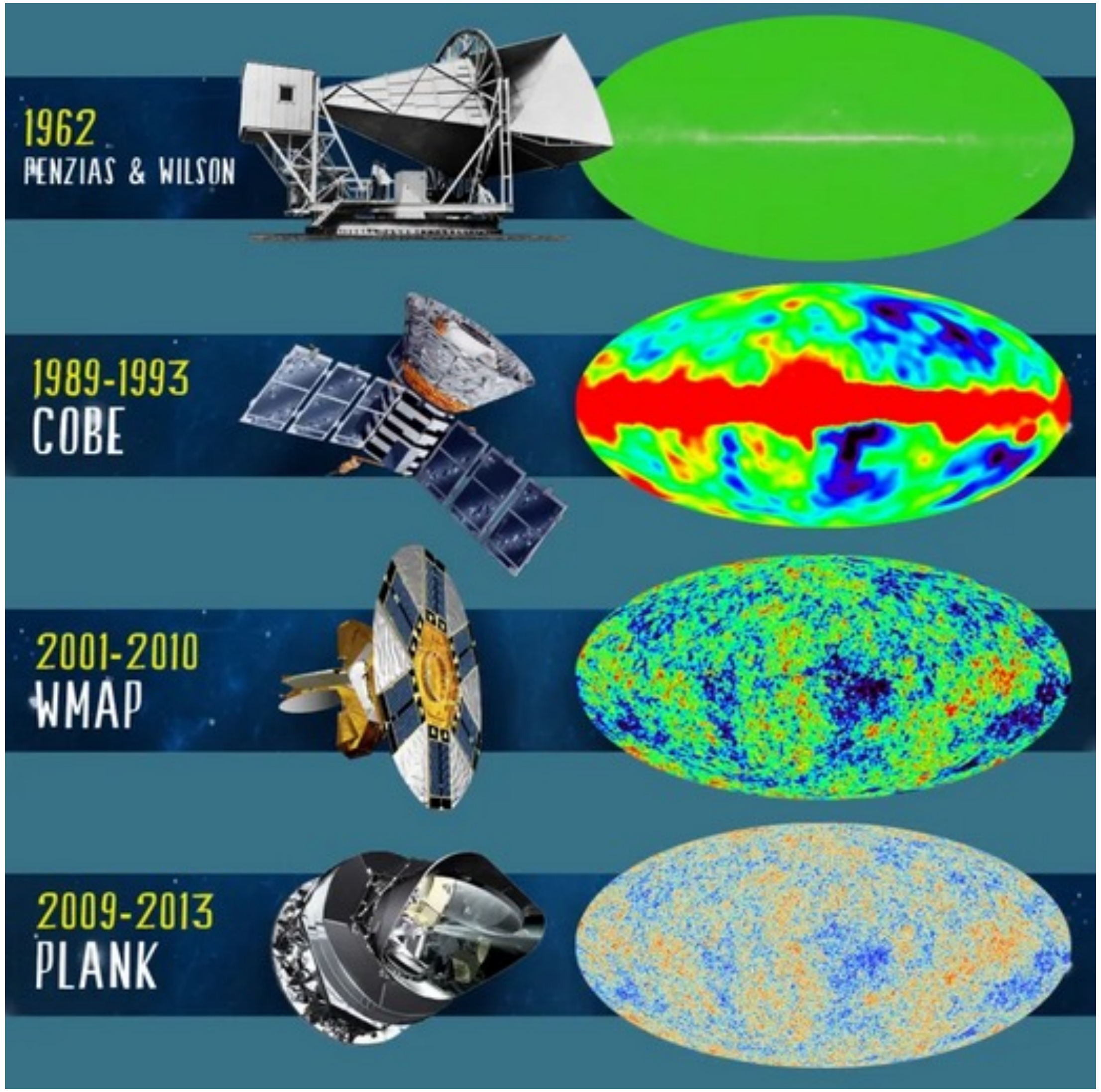
Credit: Andrea Giachero from presentation "Cosmic Neutrino Background telescope: The PTOLEMY experiment"



Indirect Observations

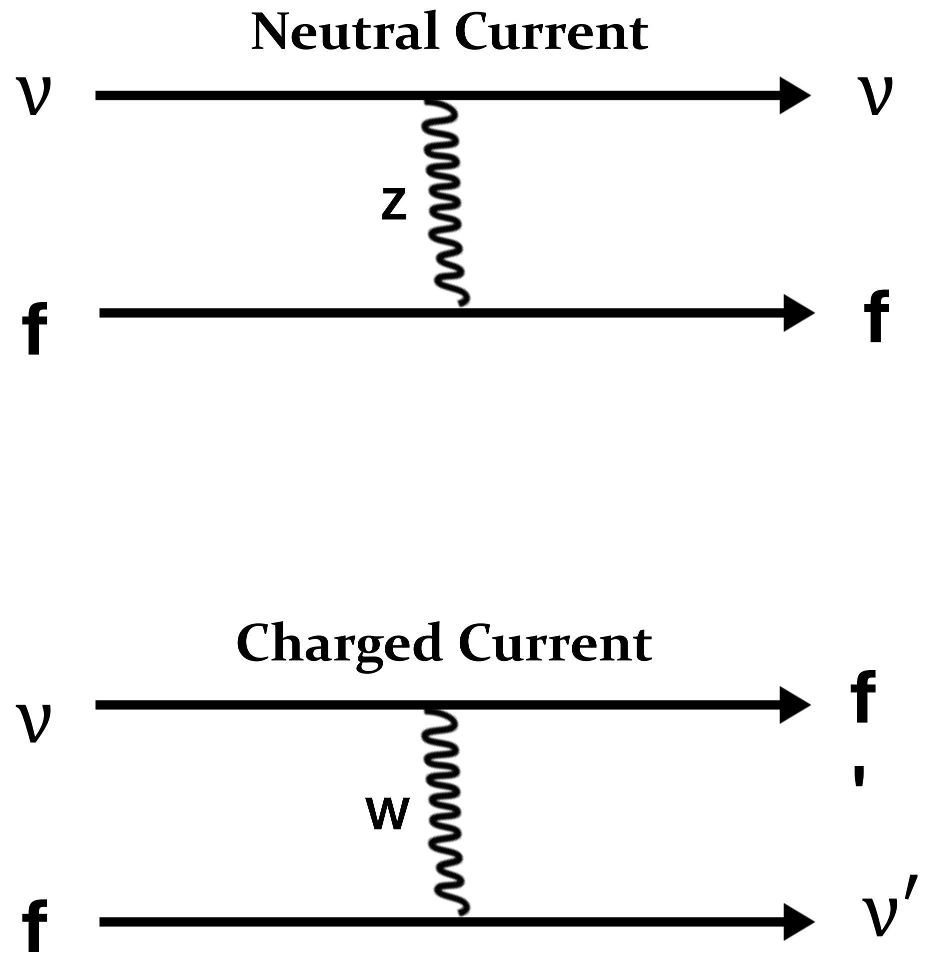
Measurements of the CMB done by the Planck collaboration indirectly detect the CNB.

- The existence of a neutrino background at recombination would affect the scale of baryonic acoustic oscillation
  - Effective neutrino degree of freedom measured at 2.99±0.17, consistent with SM prediction of 3.046 (Planck Collaboration, A&A 641, A6 (2020)).
- The CNB would also cause phase shifts in the BAOs
  - Analysis of the Planck data by Follin et al. in 2015 claims detection of such phase shifts at 4.5σ (Phys. Rev. Lett. 115, 091301) .



Experimental Challenges

- Only weakly interacting



See K. Zuber, "Neutrino Physics", 2020

Experimental Challenges

- Only weakly interacting
- Tiny cross-section

$$\frac{d\sigma}{d\cos\theta} = \frac{G_F^2\left|V_{ud}\right|^2 F\left(Z_{\mathrm{f}}, E_e\right)}{2\pi\beta_\nu} E_e p_e f_V^2(0)$$

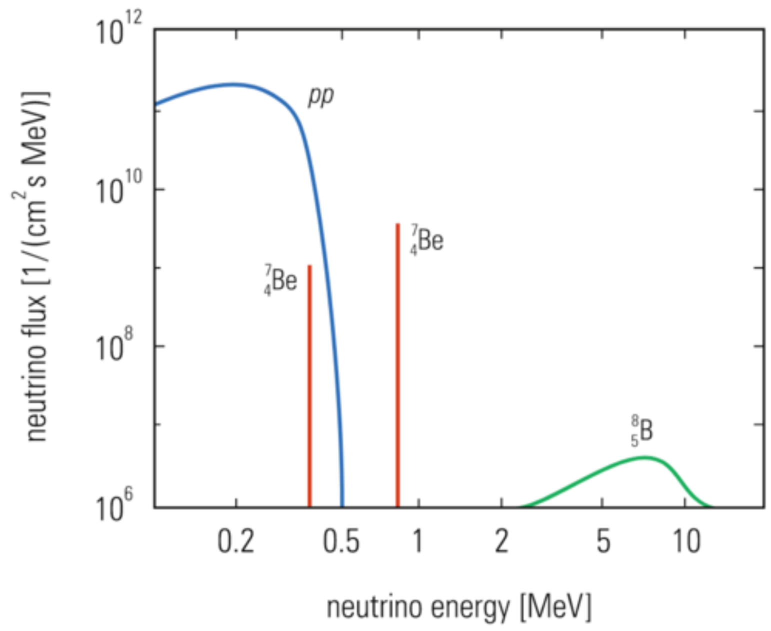
$$\times\left[\left(1+\beta_e\beta_\nu\cos\theta\right)+3\lambda^2\left(1-\frac{1}{3}\beta_e\beta_\nu\cos\theta\right)\right]$$

Neutrino-Capture on Nucleus

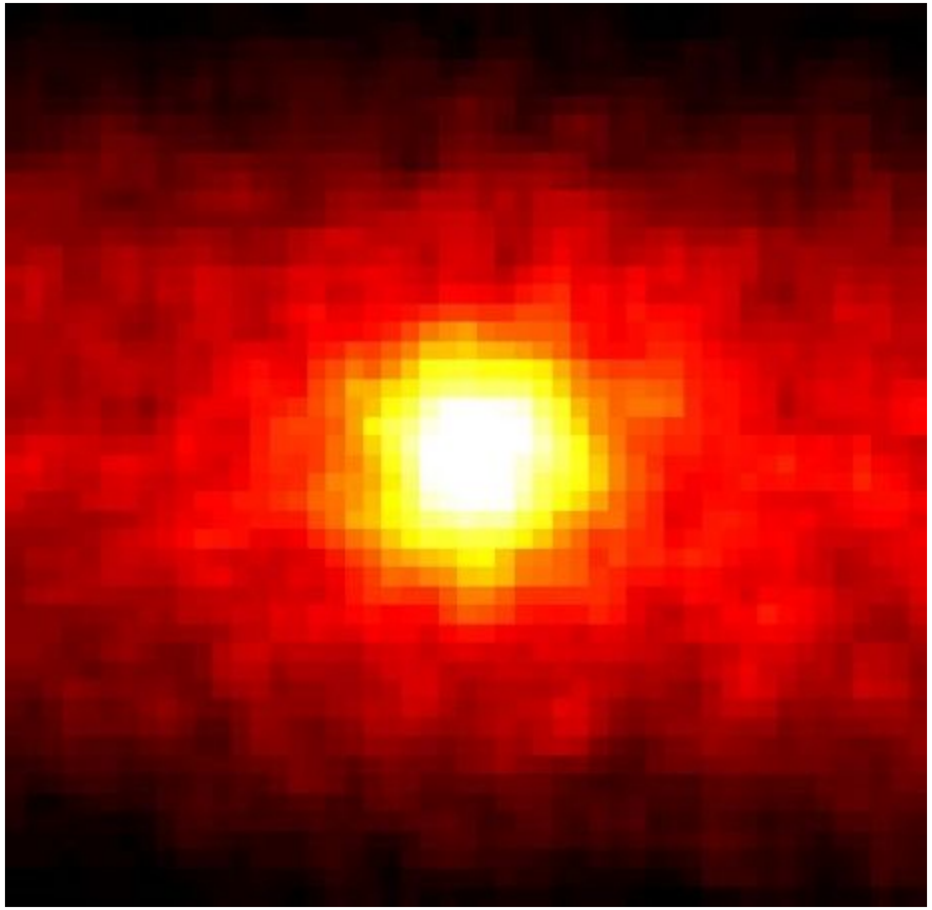
J. A. Formaggio and G. P. Zeller, *From eV to EeV: Neutrino Cross Sections across Energy Scales*, Rev. Mod. Phys. **84**, 1307 (2012).

Experimental Challenges

- Only weakly interacting
- Tiny cross-section
- Abundant potential backgrounds (all other ν's)
  - Solar pp-chain neutrinos in particular



See C. Grupen, *Astroparticle Physics*, 2010

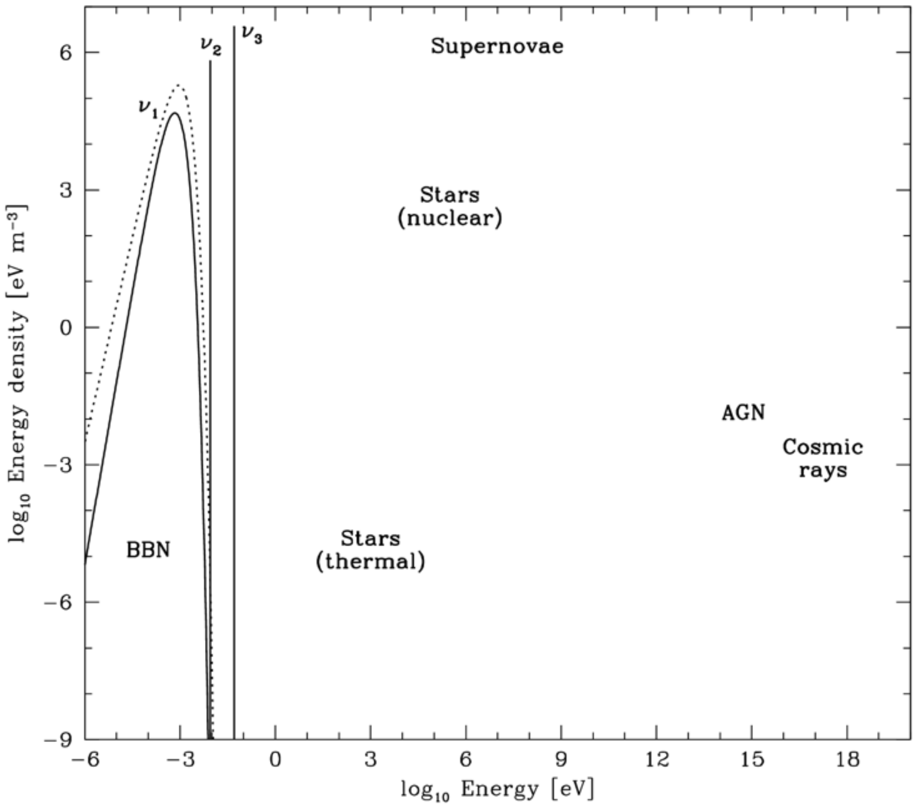


Super-Kamiokande Collab, c. 2007

Experimental Challenges

- Only weakly interacting
- Tiny cross-section
- Abundant potential backgrounds (all other ν’s)
  - Solar pp-chain neutrinos in particular
- Extremely low energy

D. Scott, The Cosmic Neutrino Background, arXiv:2402.16243.



See K. Zuber, "Neutrino Physics", 2020

Experimental Challenges

- Only weakly interacting (Judicious target choice)
- Tiny cross-section (As much target as possible)
- Abundant potential backgrounds (all other ν's) (Clever discrimination mechanisms)
  - Solar pp-chain neutrinos in particular
- Extremely low energy (E~0 thresholds)

Experimental Challenges & Potential Discrimination Methods

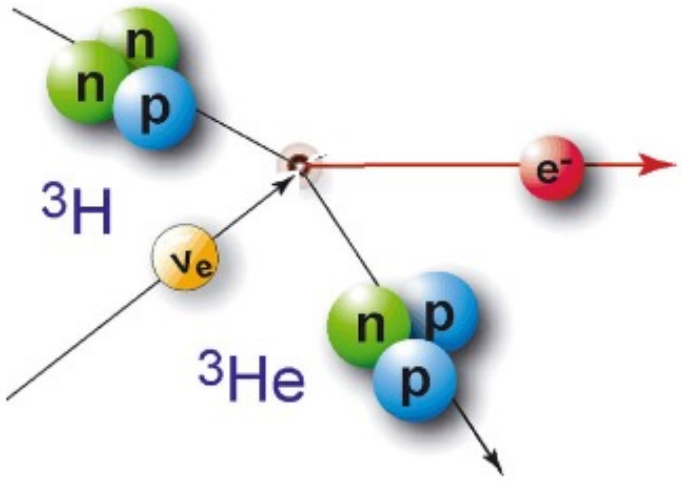
- Decohered into mass states
  - Differences in charged current
- CvB constitutes a slow Aether-like *wind*
  - Directional changes in flux
- Solar neutrino flux (will be) well characterized already
  - Easy background subtraction
- Uniquely low energy

B. Michelutti, *"Universe Self Awareness"*, c. 2020

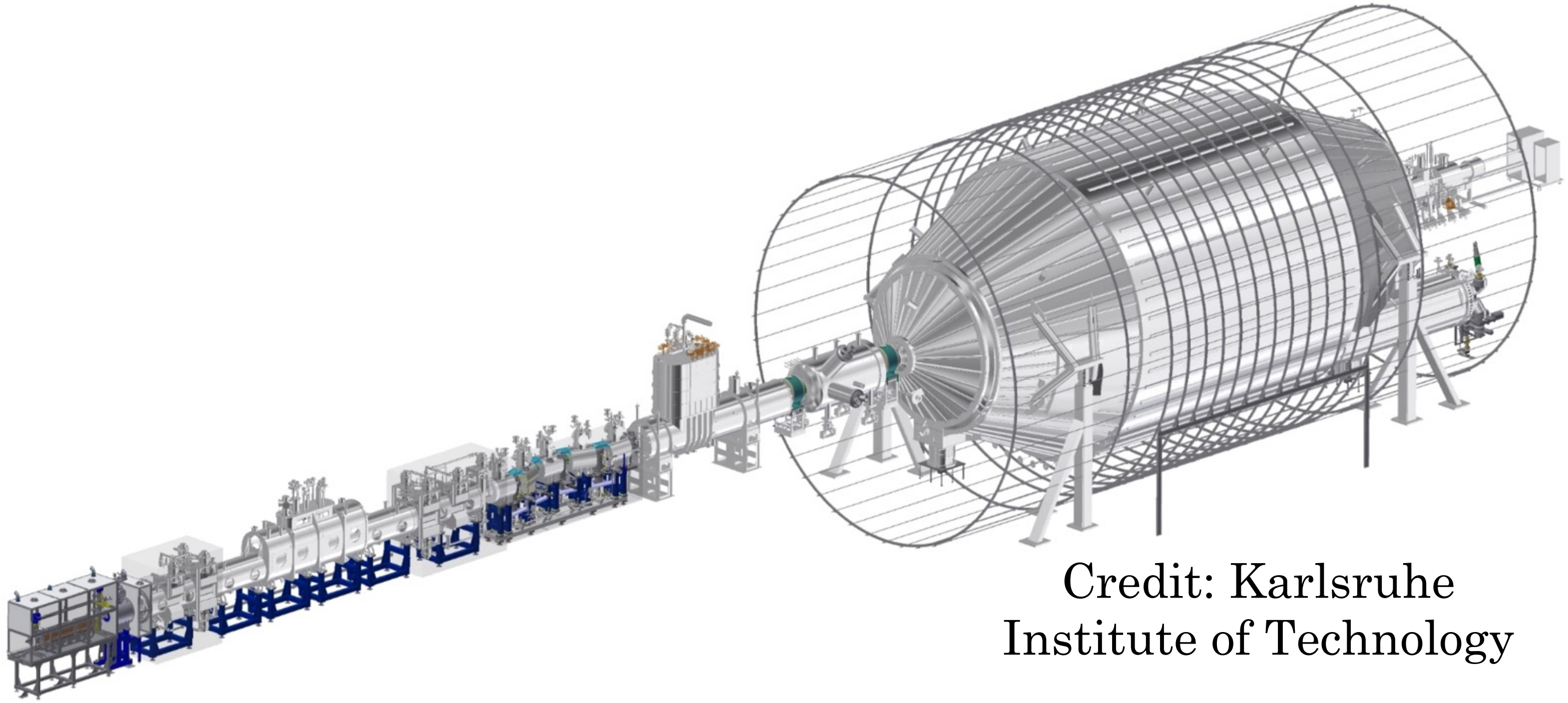
What kind of approach has the best chance of measuring CNB?

- **KATRIN**

Despite the challenges due to the neutrinos' weak interactions, the capture of relic neutrinos on tritium nuclei offers one of the highest potentials for directly observing the CNB.



Credit: Thomas Brunner, TRISEP 2024



Credit: Karlsruhe
Institute of Technology

The KATRIN experiment aims to measure the absolute mass of neutrinos and could potentially detect the elusive cosmic neutrino background.

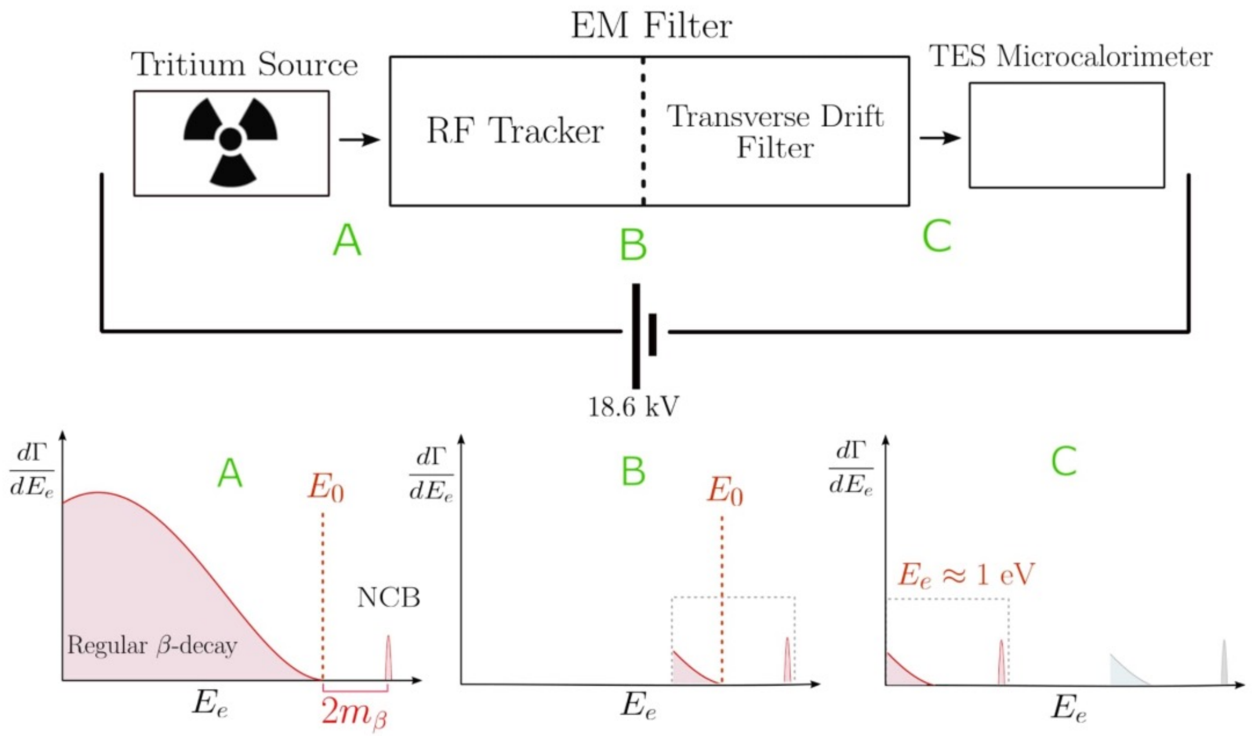
What kind of approach has the best chance of measuring CNB?

- **PonTecorvo Observatory for Light Early-Universe Massive-Neutrino Yield (PTOLEMY)**

The PTOLEMY experiment hopes to detect the CNB using 100 g of tritium embedded onto a graphene layer.

The PTOLEMY collaboration claims that by using the embedded graphene it can avoid energy being dumped into the vibrational modes of molecular gaseous tritium.

The experimental signal would be counts two neutrino masses beyond the end of the regular beta decay spectrum. (This would mean the detector doubles as a probe for neutrino mass)



Credit: Figure 1 from "Towards CRES-Based Non-destructive Electron Momentum Estimation for the PTOLEMY Relic Neutrino Detector" by PTOLEMY Collaboration; arXiv:2404.00817

What kind of approach has the best chance of measuring CNB?

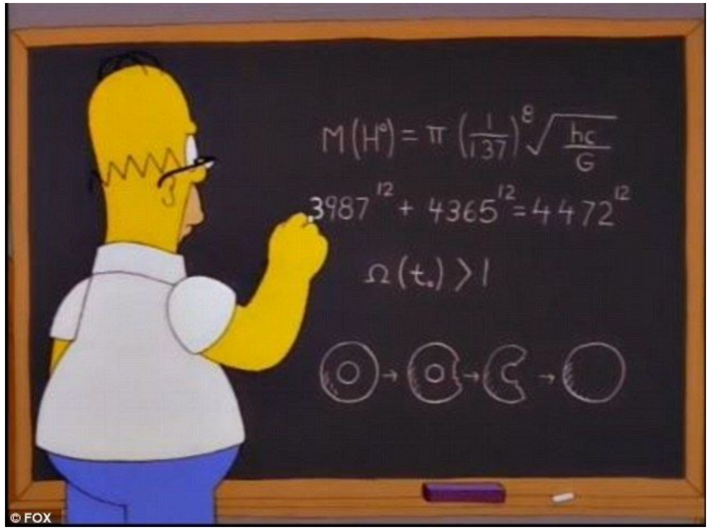
- **PTOLEMY Potential Drawbacks:**

In a paper titled "Navigating the pitfalls of relic neutrino detection", Cheipesh, Cheianov, and Boyarsky expressed concern for using ^3H as a detection medium, especially when bonded onto a substrate due to the position-momentum uncertainty principle. They suggest using a similarly stable but heavier β-emitter.

$\Delta x \Delta p \geq \frac{\hbar}{2}$ but Δx is small due to the localization of the initial tritium wave function so Δp which directly impacts the β energy spectrum.

In a follow up theory paper, PTOLEMY acknowledged these concerns and produced alternatives such gaseous tritium in carbon nanotubes such that tritium are in nearly free states with magnet fields to prevent dimerization.

Our Potential Ideas



- Quantum dots (would need wayy too many)
- Phonon detectors (no clue how it would work)
- Superconductors & TES Sensors (size VeRy big)
- Beam accelerator (super-duper LHC wouldn't hurt)
- Tune a splitting to CNB energies (not the *worst* idea)
- Neutrino capturing (discrimination hard)
- Use a pendulum in space to detect neutrino wind 🚀

Our Idea – CvB Heavy Element Magnet Observatory (CHEMO)

- **Zeeman effect**

Strong magnetic field (~1 T) splits an atomic spectral line into different states, with an energy difference of: $\Delta E \sim \mu_B B \sim 0.1$ meV $\lesssim T_\nu$

- **CνB neutrinos excite atoms via elastic scattering:**

<u>Neutrino-electron scattering:</u>

$\sigma_{e\nu_e} \approx \frac{7G_F^2}{4\pi} E_\nu^2, \sigma_{e\nu_{\mu,\tau}} = \frac{3}{7}\sigma_{e\nu_e} \quad (E_\nu \ll m_e)$

$\sigma_{\nu e} \sim \frac{7G_F^2}{4\pi} m_\nu^2 \sim 10^{-58}\text{cm}^2 \left(\frac{m_\nu}{50\text{ meV}}\right)^2$

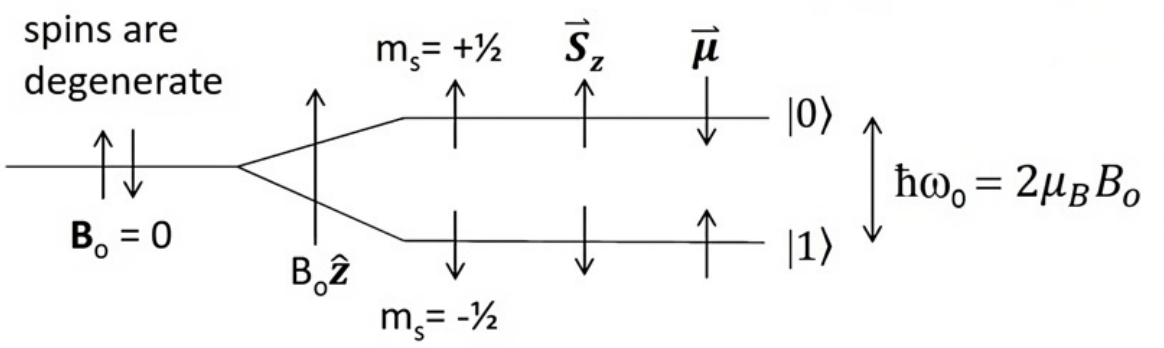
<u>Neutrino-nucleus scattering: (mass number A)</u>

$\sigma_{A\nu} \approx \frac{G_F^2}{4\pi}(A-Z)^2 E_\nu^2 \quad (E_\nu \ll m_e)$

$\sigma_{\nu A} \sim \frac{G_F^2}{16\pi} A^2 m_\nu^2 \sim 10^{-55}\text{cm}^2 \left(\frac{m_\nu}{50\text{ meV}}\right)^2 \left(\frac{A}{200}\right)^2$

Excited atoms emit soft photons (~meV)

Solar neutrinos are energetic (~keV–MeV), NO soft photon emission



Credit: Figure 14.3 from "Introduction to Quantum Computing (2021)" by Ray LaPierre

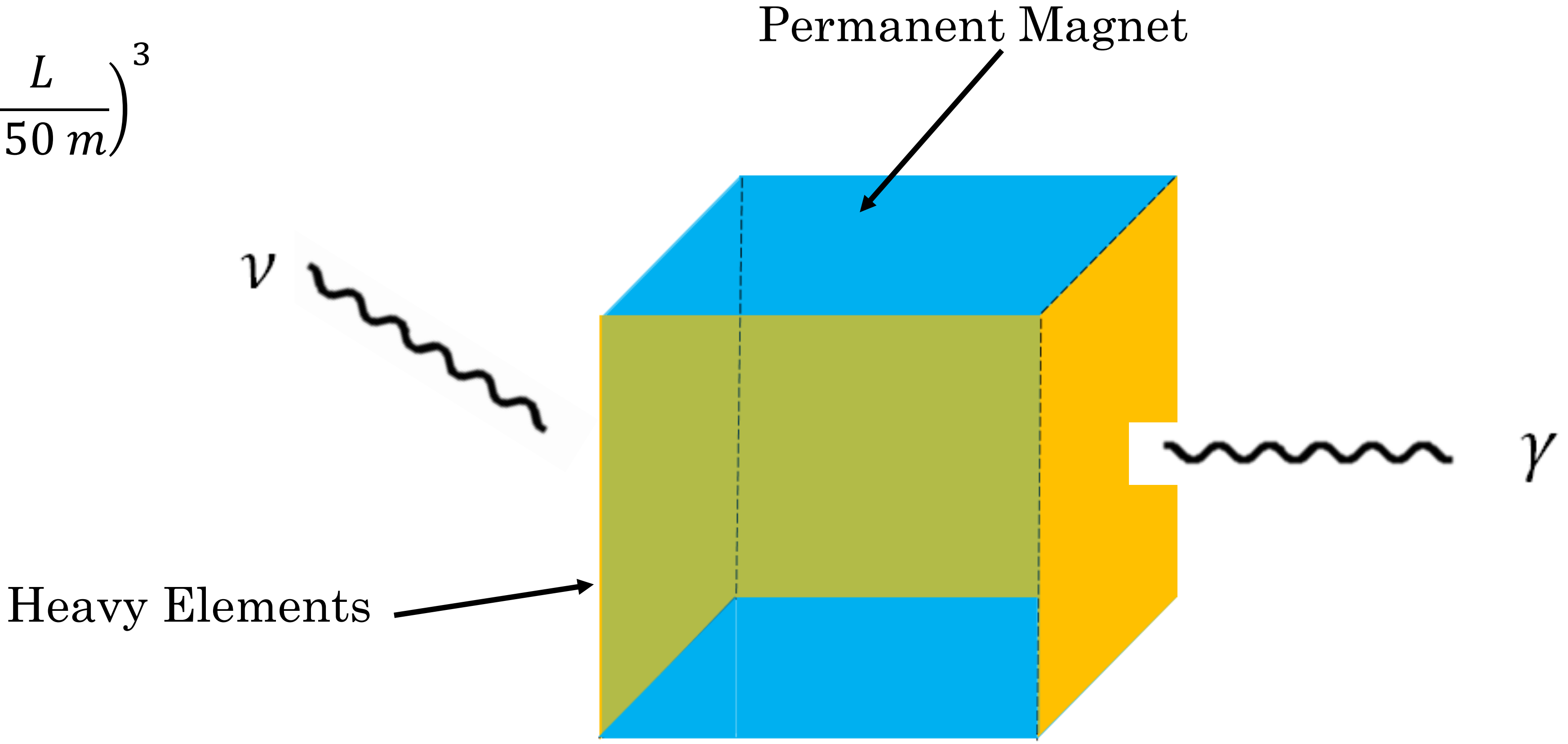
Our Idea – CvB Heavy Element Magnet Observatory (CHEMO)

- **Setup:**

heavy elements (e.g. Hg)
permanent magnet (~1 T)
cavity: L~150 m

- **Count rate:**

$$\Gamma \sim L^3 n_A n_\nu \sigma_\nu \langle v_\nu \rangle \sim 1\ yr^{-1} \left(\frac{L}{150\ m}\right)^3$$



EDI/DEI Project - Prompt

You are in a collaboration with about 120 people from 7 different counties and 17 different institutions. Your collaboration has a Code of Conduct and an EDI/DEI action plan that has been in place for a few years. In 3 of the countries it has become mandatory to describe an EDI/DEI plan in your collaboration funding application, which is part of the evaluation process. Provide 1-2 pages summarizing the achievements in the last 2 years and plans for the next 2.

EDI/DEI Project – Prior Achievements

Annual Climate Survey

- Aggregate demographic information
- Individual feedback on the members' feelings on the collaborations' equity, diversity, and inclusion

Colleague Pairing Program

- Manages a colleague pairing program twice a year, where students are paired with senior members from different institutions within the collaboration
- This program gives participants insights into activities at other institutions, familiarizes them with different aspects of the experiments, and increases their sense of belonging to the collaboration

Collaboration Meeting Accessibility

- Avoid major collaboration meetings during any religious festivals, major national holidays, etc. This includes times of fasting such as Ramadan.
- A hotel with good accessibility is suggested for those with physical accommodations

EDI/DEI Project – Future Plans

Parent Fund

- Support collaborators with young children to attend major collaboration meetings.
- Covers additional needs related to childcare during travel.

Cultural Night

- Celebrate the diversity of the collaboration by honoring the cultures of the collaborators.
- Potluck dinner followed by traditional dances or storytelling.

Language Accessibility

- Enhance inclusivity by making the collaboration's website accessible in multiple languages.
- Translate the website into the official languages of all countries involved in the collaboration.
- Involve young collaborators proficient in their native language and English.
- Facilitates easier access for new members and external individuals.

Questions

Please have mercy

Backup slides

CνB Basics

$$T_\nu = 1.95\ \mathrm{K} = 0.16\ \mathrm{meV}$$

$$\sum m_\nu \lesssim 0.11 - 0.68\ \mathrm{eV}$$

$n_\nu \approx 340\ \mathrm{cm}^{-3}$ (all flavours, including anti-neutrinos)

$$\lambda_\nu \sim \mathcal{O}(0.1\mathrm{cm})$$

$$\langle v_\nu \rangle \approx 150\ \mathrm{km\ s}^{-1}\left(\frac{\mathrm{eV}}{m_\nu}\right)$$

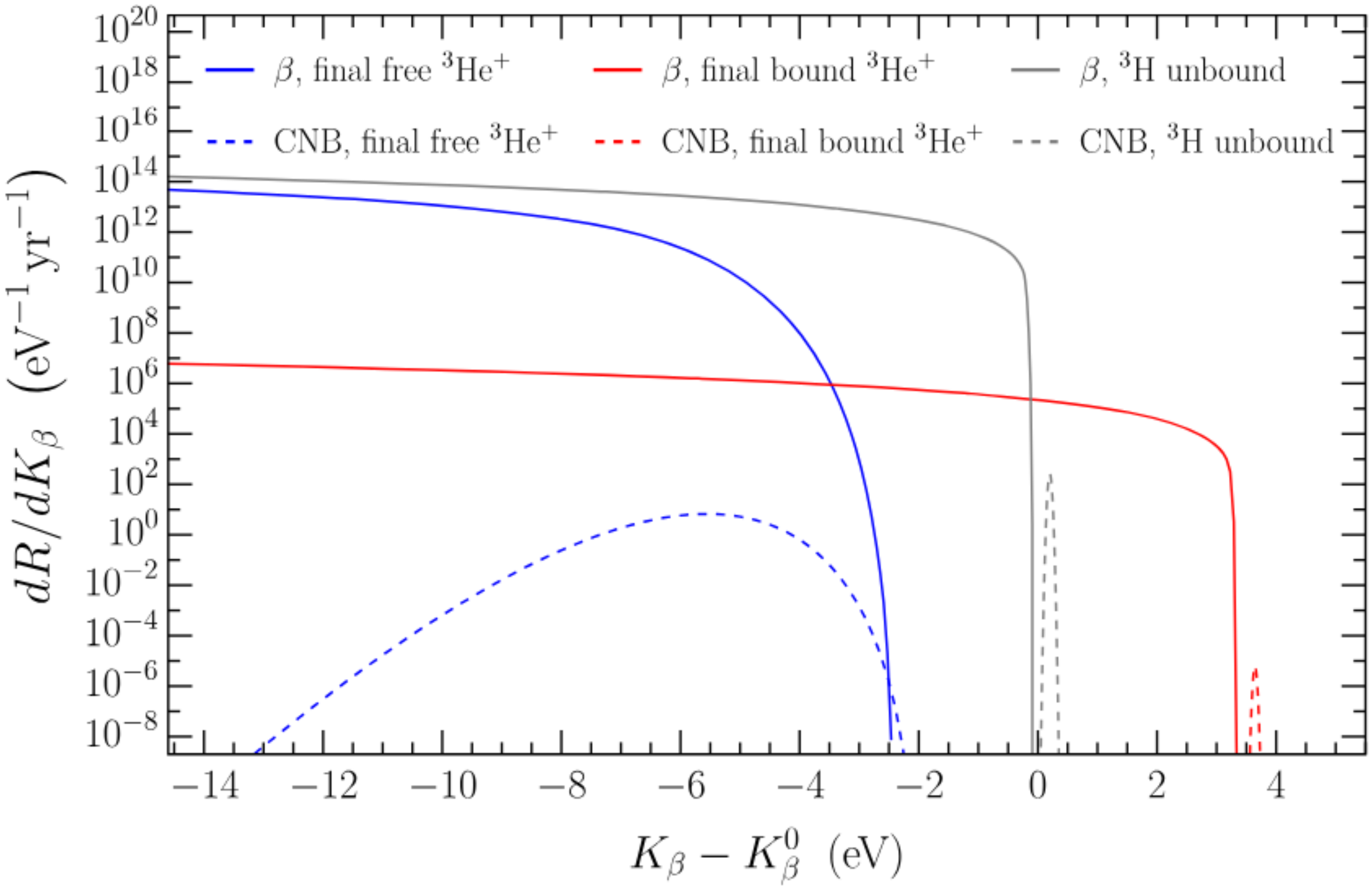
$$\sigma_{e\nu_e} \approx \frac{7G_F^2}{4\pi}E_\nu^2,\ \sigma_{e\nu_{\mu,\tau}} = \frac{3}{7}\sigma_{e\nu_e} \qquad (E_\nu \ll m_e)$$

$$\sigma_{A\nu} \approx \frac{G_F^2}{4\pi}(A-Z)^2 E_\nu^2 \qquad (E_\nu \ll m_e)$$

$$\sigma_{\nu,cap} \approx 3.84\times10^{-45}\ \mathrm{cm}^2 \qquad (E_\nu \ll keV,\ {}^3\mathrm{H} + \nu_e \to {}^3\mathrm{He} + e^-)$$

V. Domckea and M. Spinrath, JCAP 06 (2017) 055
M. Bauer and J. D. Shergold, JCAP 01 (2023) 003

PTOLEMY Supplemental Information



PTOLEMY Supplemental Information