The Cosmic Neutrino Background

Its distribution on the surface of the Earth and its manipulation on laboratory scales

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in collaboration with Asimina Arvanitaki

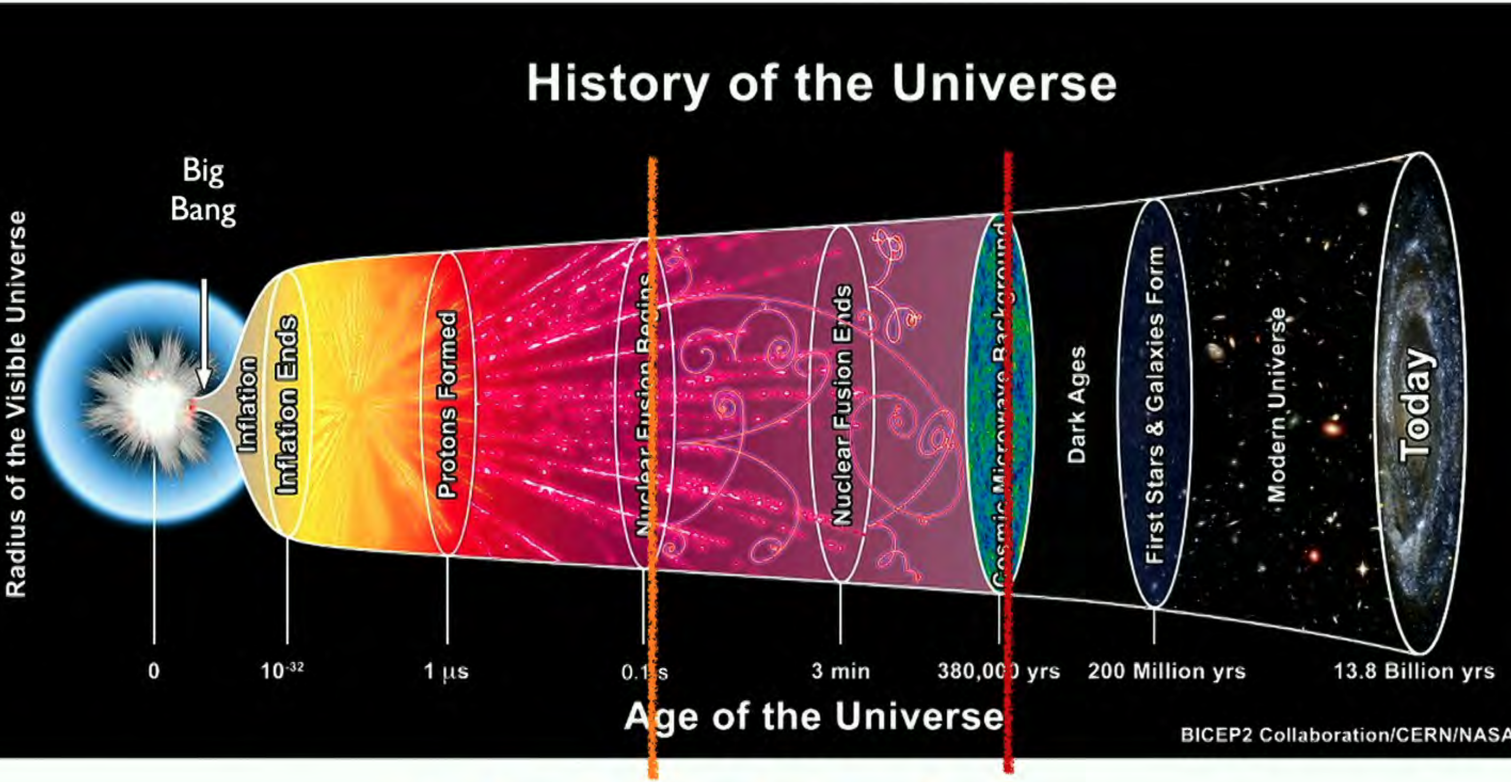
What is the Cosmic Neutrino Background (CνB)?

- Relic neutrinos from the pre-BBN era $\tau_{\text{universe}} \sim 0.1$ sec

- They follow a Fermi-Dirac distribution with:
  - $T_\nu = 1.65 \times 10^{-4}$ eV or 1.95 K
  - $\langle p_\nu \rangle = 6 \times 10^{-4}$ eV
  - $n_\nu = 56$ cm^{-3} per flavor, per helicity mode
  - m = 0.1 eV

- The SM expectation for the neutrino-antineutrino asymmetry is $\frac{n_\nu - n_{\bar{\nu}}}{n_\nu} = 4.4 \times 10^{-9}$

Why is the CνB important?



The Cosmic Neutrino Background (CνB)

The CMB

Why is the CνB important?

- Picture of the Universe when it was less than 1 second old

- An entire sector of the Standard Model: 3 flavors and 7+ parameters

- The most abundant SM species (~ photons)

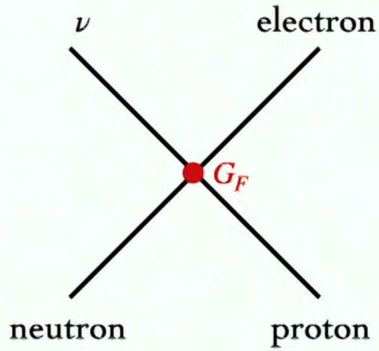
- The only non relativistic neutrinos (Dirac vs Majorana)

- The most abundant source of right-handed neutrinos

Why is the CνB hard to see?

- Ways with which the CνB can interact with matter:

    - Scattering $\propto G_F^2$



Effects linear in G_F for the CνB

- Only non-zero effect a torque on spins (Stodolsky 1975):
  - $\Delta E = G_F(n_\nu - n_{\bar{\nu}})\vec{v}_{\nu-rel} \cdot \vec{\sigma} \approx 10^{-47}$ eV
    vs smallest $\Delta E_{\text{measured}} \approx 10^{-25}$ eV
  - Suppression due to the small $n_\nu - n_{\bar{\nu}}$ asymmetry

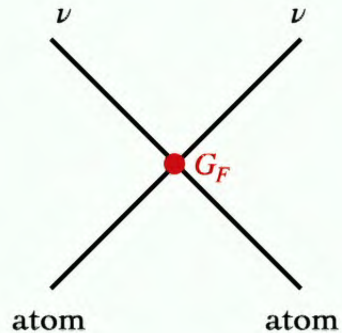
CvB forces on macroscopic matter*

- $\frac{U}{V} = \frac{G_F}{2\sqrt{2}} j_\nu^0 j_{0\text{matter}}$ vector interaction

- $U_{\text{atom}} = \frac{G_F}{2\sqrt{2}} Q_W j_\nu^0$

- $U_\nu = \frac{G_F}{2\sqrt{2}} \rho_{\text{matter}} \times \begin{cases} (-)(3Z - A) & \text{for } \nu_e\ (\bar{\nu}_e) \\ (-)(Z - A) & \text{for } \nu_{\mu,\tau}\ (\bar{\nu}_{\mu,\tau}) \end{cases}$

- $U_\nu \sim 10^{-14}$ eV vs characteristic kinetic energy of $E_\nu \sim 10^{-6}$ eV



*We assume neutrinos are Dirac and simultaneous mass/weak eigenstates

No-go theorem for CνB forces on matter

Langacker et. al. (1982)
Cabibbo and Maiani (1982)

$$\text{Since } U_{\text{atom}} = \frac{G_F}{2\sqrt{2}} Q_W j_\nu^0,$$

$$\vec{F}_{\text{atom}} = -\vec{\nabla} U_{\text{atom}} \propto \vec{\nabla} n_\nu = 0$$

The force on matter from a uniform neutrino density is zero

How to evade the no-go theorem: CνB refraction in the Earth

Arvanitaki, SD (2022)

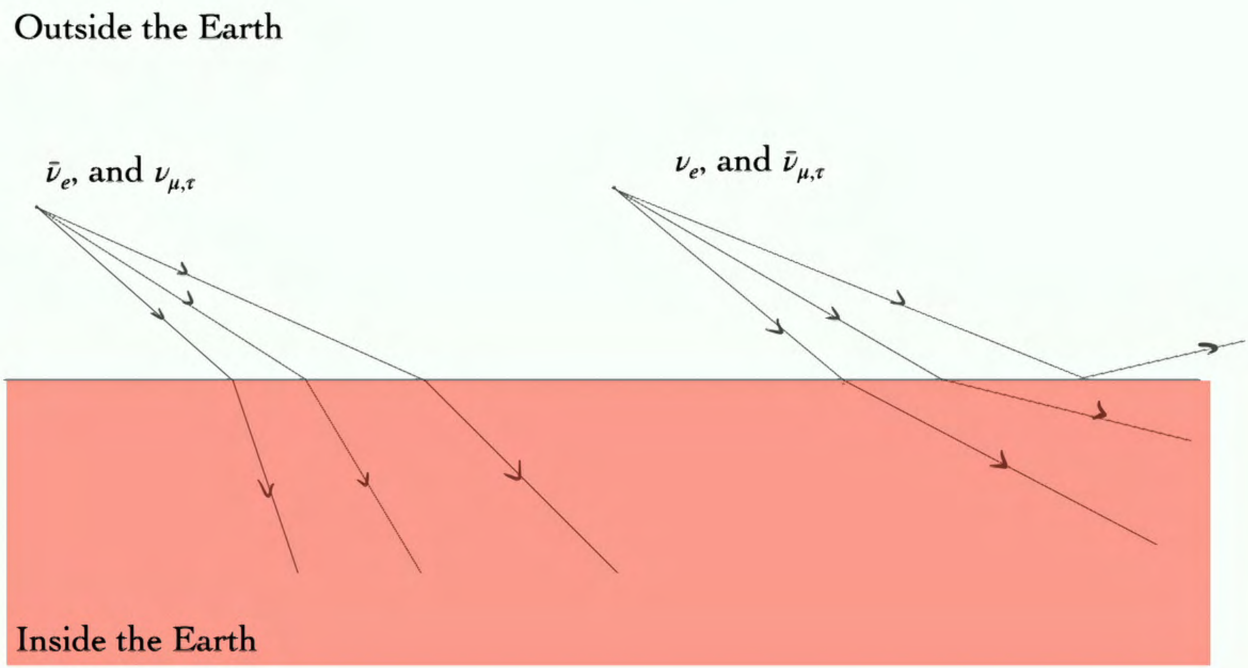
- Interaction energy U of neutrinos in matter determines the refractive index

$$\delta_\nu \equiv n - 1 = \frac{p_{\text{inside}} - p_{\text{outside}}}{p_{\text{outside}}} = -\frac{m_\nu}{p_\nu^2} U \sim 10^{-8} - 10^{-7}$$

- $U_\nu = \dfrac{G_F}{2\sqrt{2}} \rho_{\text{matter}} \times \begin{cases} (-)(3Z - A) & \text{for } \nu_e \ (\bar{\nu}_e) \\ (-)(Z - A) & \text{for } \nu_{\mu,\tau} \ (\bar{\nu}_{\mu,\tau}) \end{cases}$

- Interaction is repulsive(attractive) for $\nu_e(\bar{\nu}_e)$, and $\bar{\nu}_{\mu,\tau}(\nu_{\mu,\tau})$

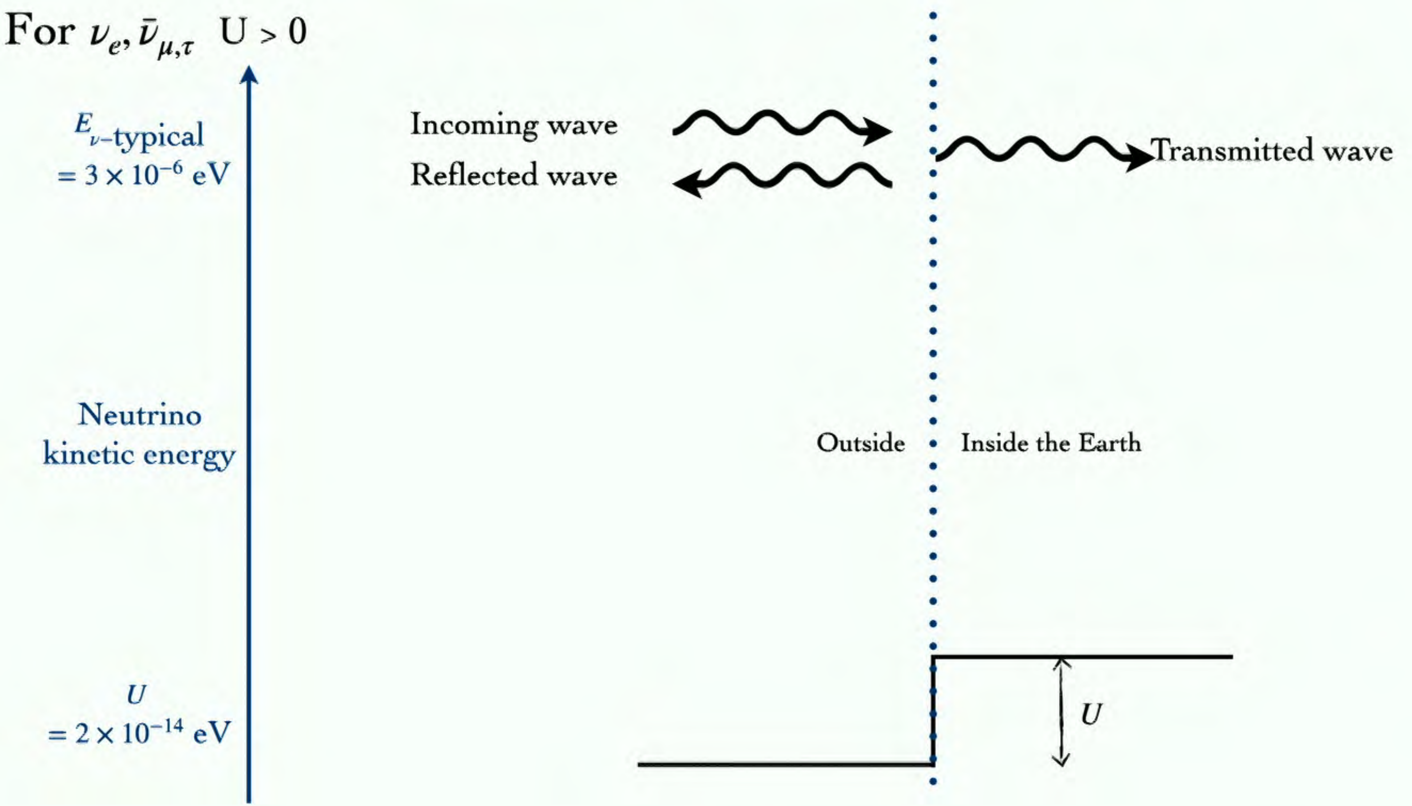
Neutrinos vs Antineutrinos



Traffic jam of neutrinos on the surface is responsible for the excess

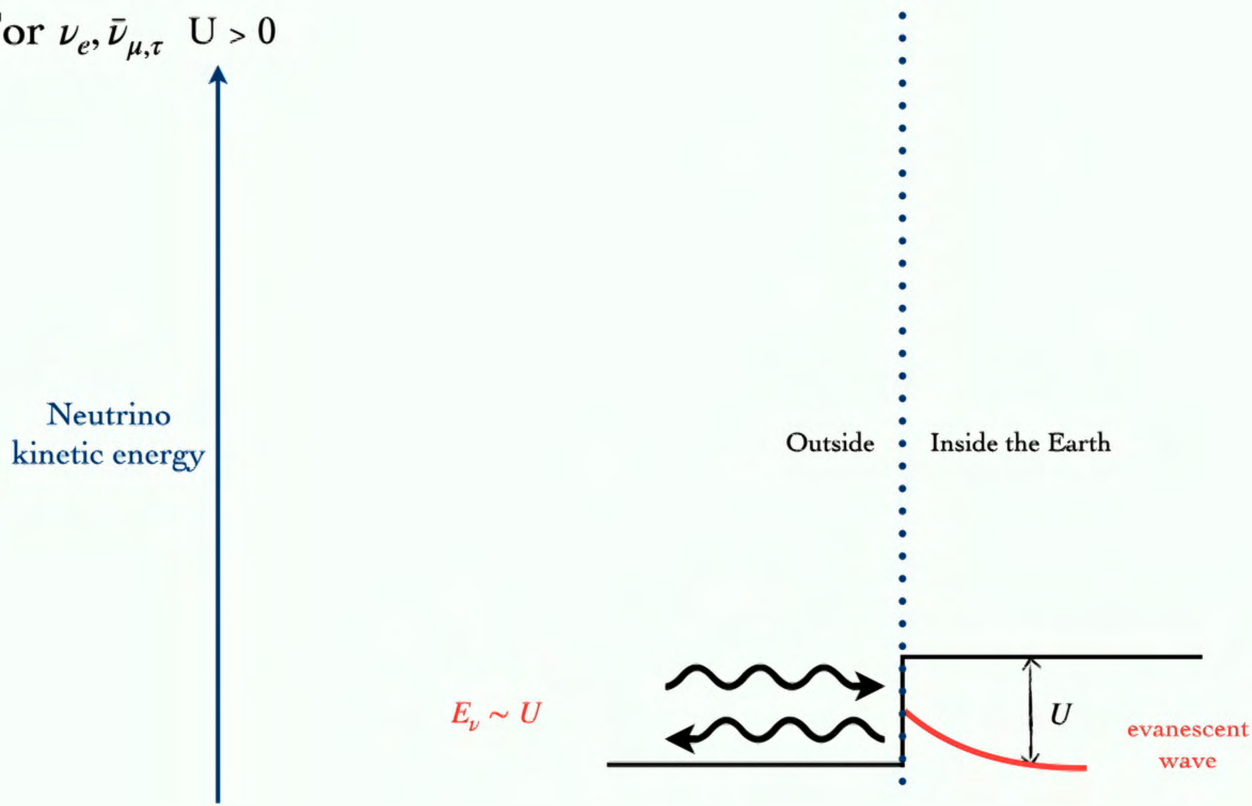
CνB refraction and reflection on the Earth

Refraction is reduced to neutrino waves incident on a potential well of size U



CνB refraction and reflection on the Earth

For $\nu_e, \bar{\nu}_{\mu,\tau}$ U > 0



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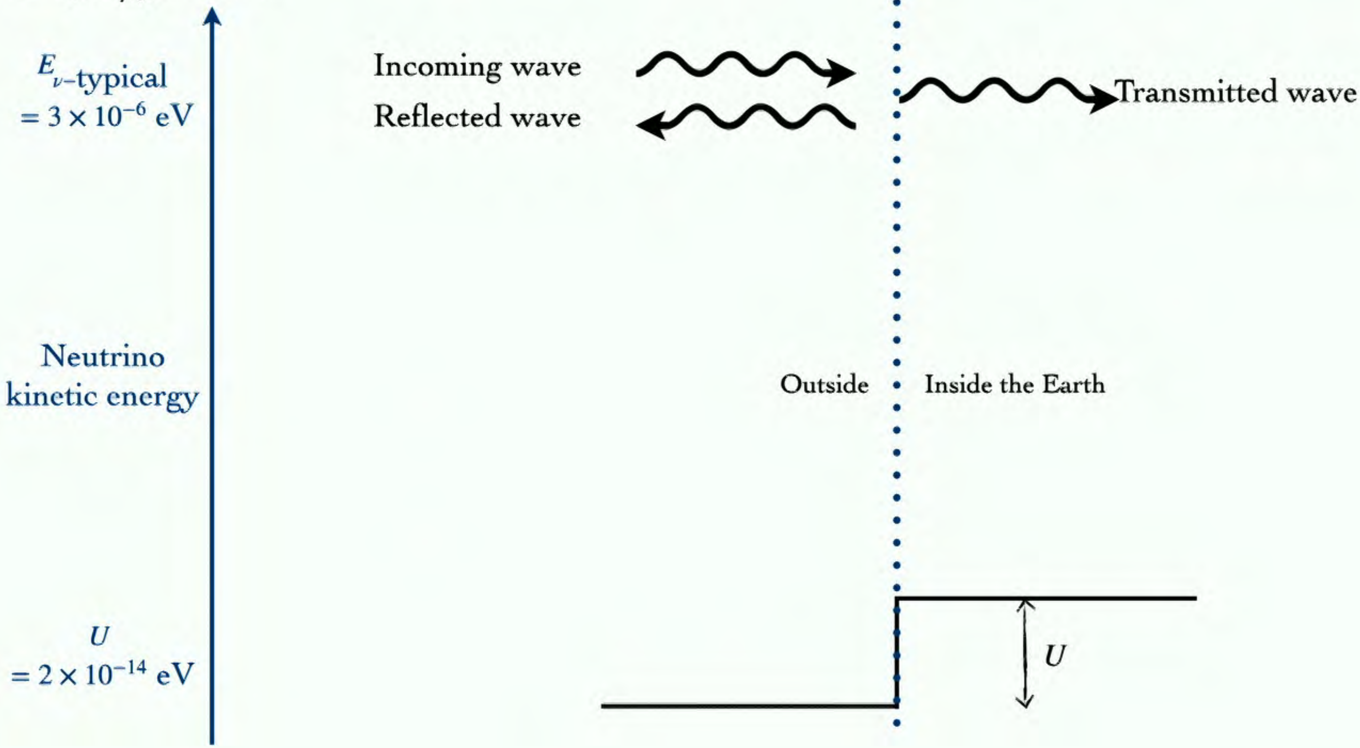

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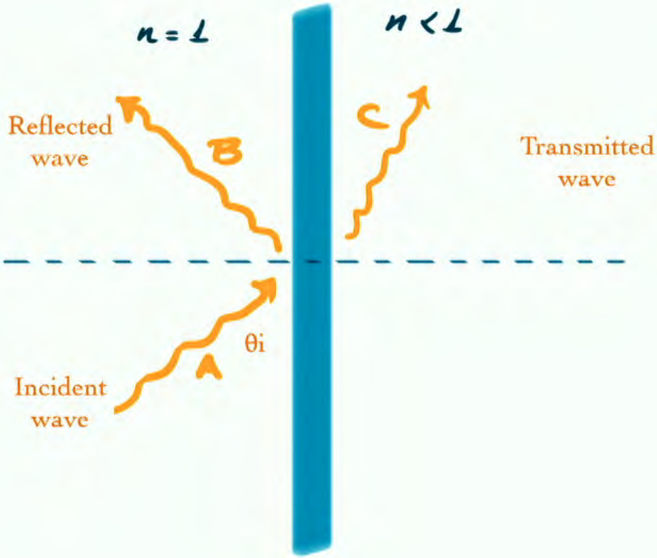


Translational symmetry along the boundary:

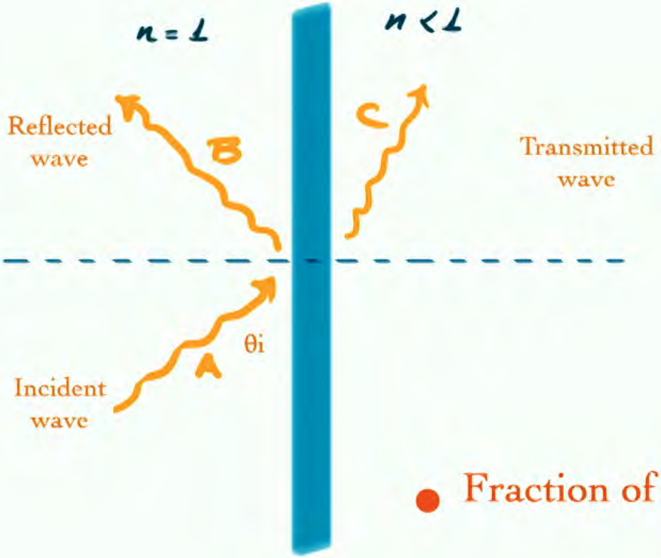
Only momentum perpendicular, $p_{\nu_\perp}$ to the boundary determines the dynamics

Total reflection occurs when:

$$\frac{p_{\nu_\perp}^2}{2m_\nu} \leq U$$

when $p_{\nu_\perp} \leq p_{\nu_{\perp c}} \equiv \sqrt{2m_\nu U} = \frac{1}{3 \text{ meters}} \propto \sqrt{G_F}$

CνB refraction and reflection on the Earth

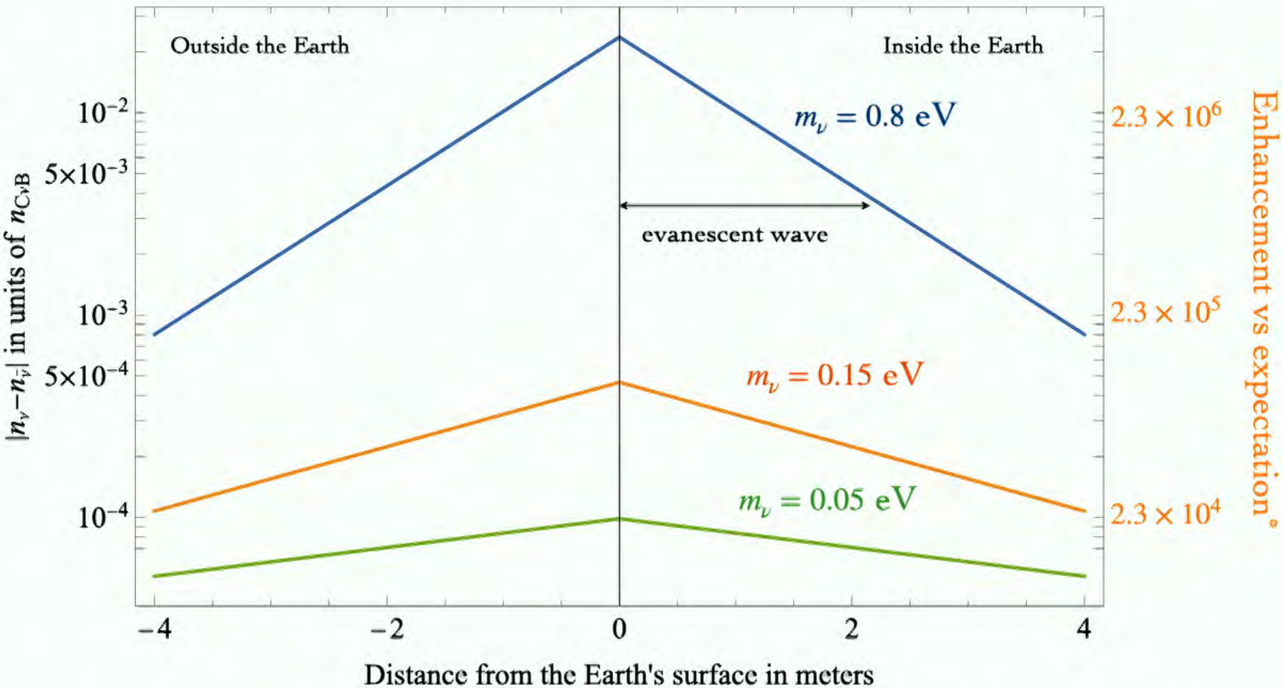


The incidence angle for which reflection occurs is: $\theta_i \sim \frac{p_{\nu_{\perp c}}}{p_\nu} \equiv \theta_c$

- Fraction of neutrinos affected is $\sim \theta_c \approx 10^{-4}\sqrt{\frac{m_\nu}{0.1\ \mathrm{eV}}}$

- The scale of the variation is set by the scale of $p_{\nu_{\perp c}} = (3\ \text{meters})^{-1}$ which is the evanescent wave scale

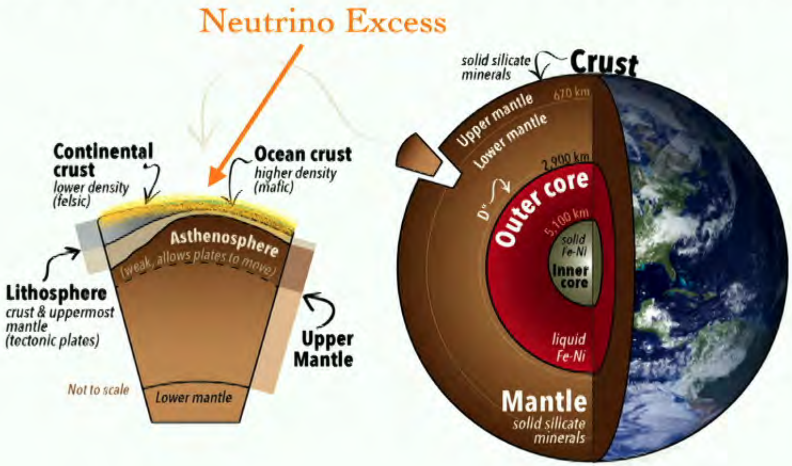
CνB distribution on the surface of the Earth



Gradient set by the evanescent wave scale $(\sqrt{2m_\nu U})^{-1} \approx 3\sqrt{\frac{0.1\ \text{eV}}{m_\nu}}$ meters

*This includes possible clustering effects for cosmic neutrinos, maximum of $\mathcal{O}(100)$ only for $m_\nu = 0.8$ eV

Cosmic Neutrino Background distribution on the Earth's surface

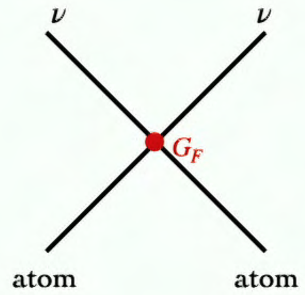


- Neutrino-antineutrino asymmetry larger by a factor of 100,000 in a roughly 3 meter zone above and below the Earth's surface

- This effect opens up new possibilities for Cosmic Neutrino detection

The force from the Earth-induced $\nu - \bar{\nu}$ asymmetry

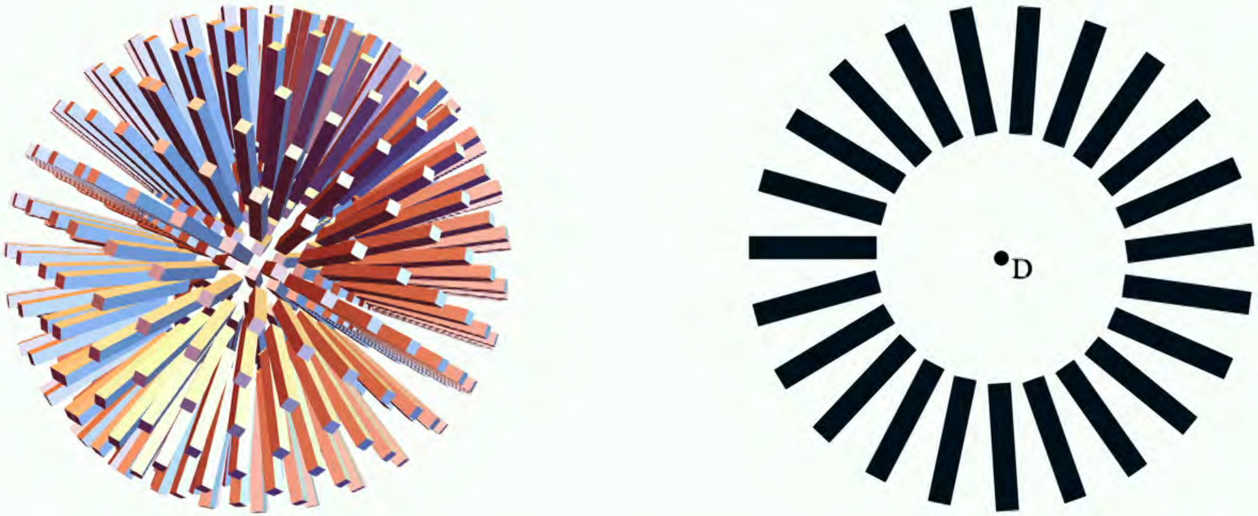
- The evanescent wave introduces a gradient of (3 meters)$^{-1}$
    - $F_{\text{induced}} = -\nabla U \sim 10^{-31}\, N \frac{V_{\text{Tungsten}}}{(10 \text{ cm})^3}$
- Force no longer zero but still pretty small



Can we get a bigger effect than the one we get for free?

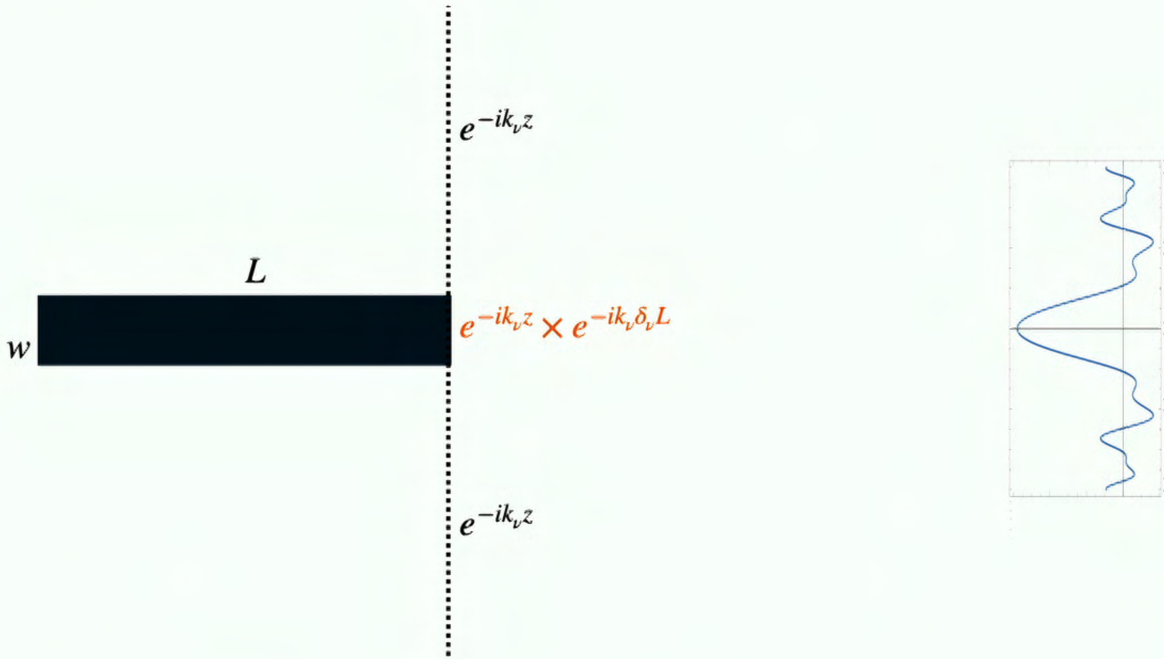
A diffraction grating for the CνB

Arvanitaki, SD 2023



- Rods of width w and length L oriented along the surface of a sphere
- Takes advantage of the wave nature of neutrinos $\lambda_\nu \sim 2 - 4$ mm

A rod as a neutrino phase diffractor



Asymmetry pattern of $\delta_\nu > 0 \; - \; \delta_\nu < 0$

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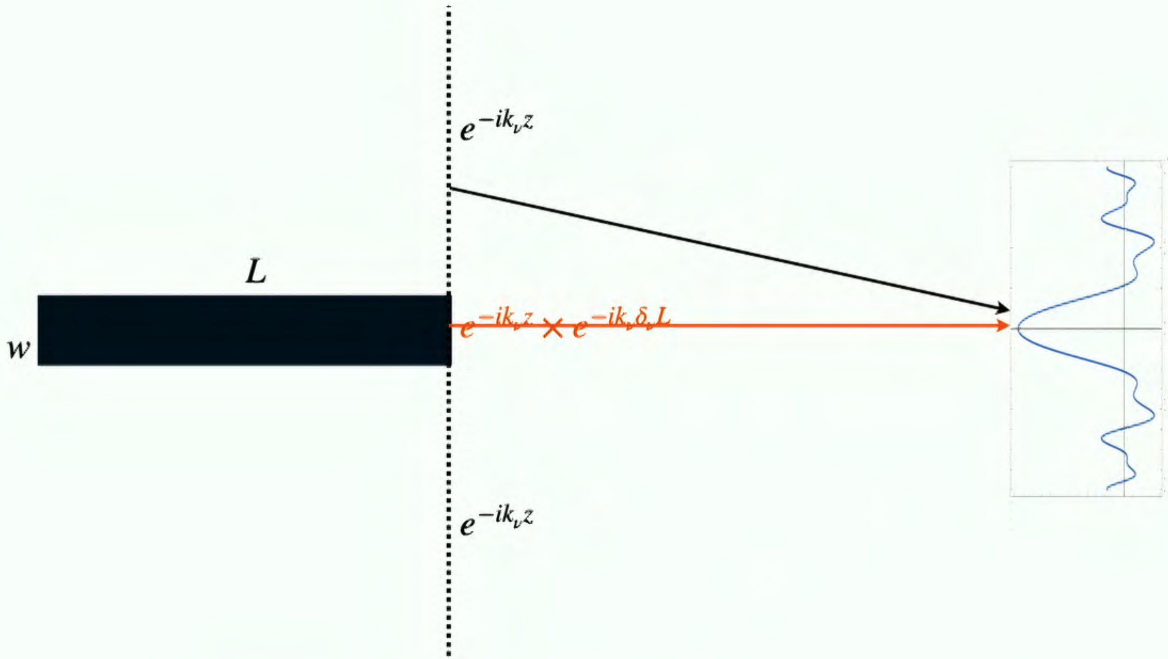

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Wave interferes with itself to produce a diffraction pattern a distance $R \geq \frac{w^2}{\lambda_\nu}$

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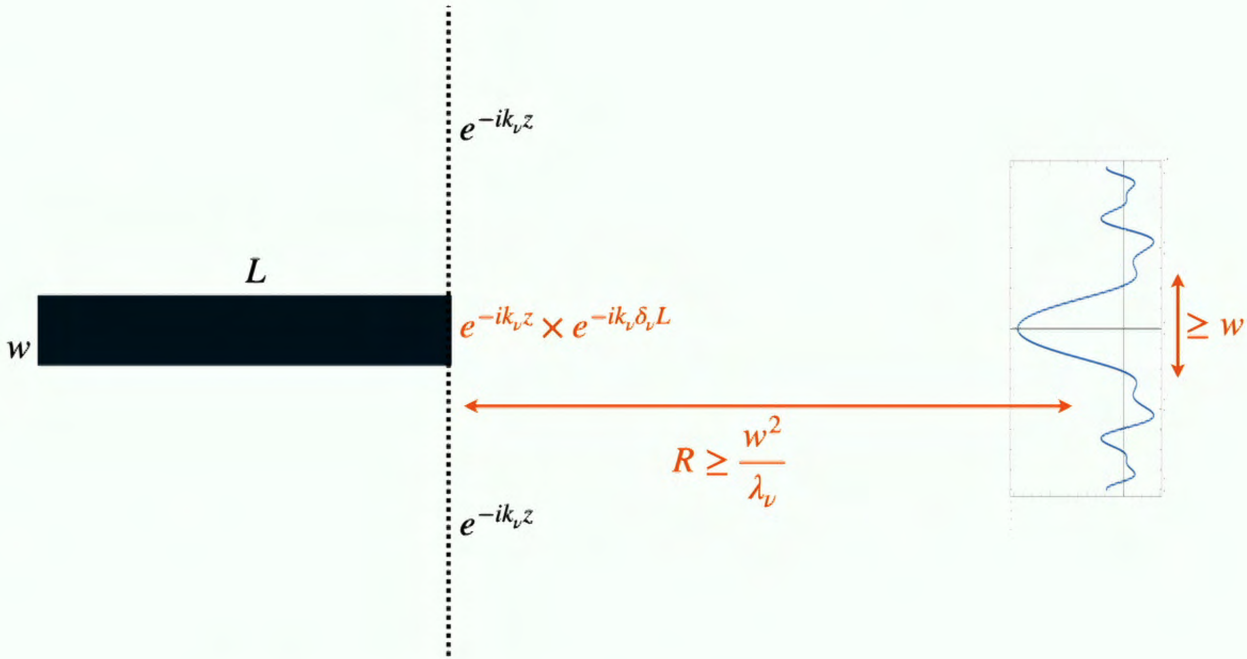

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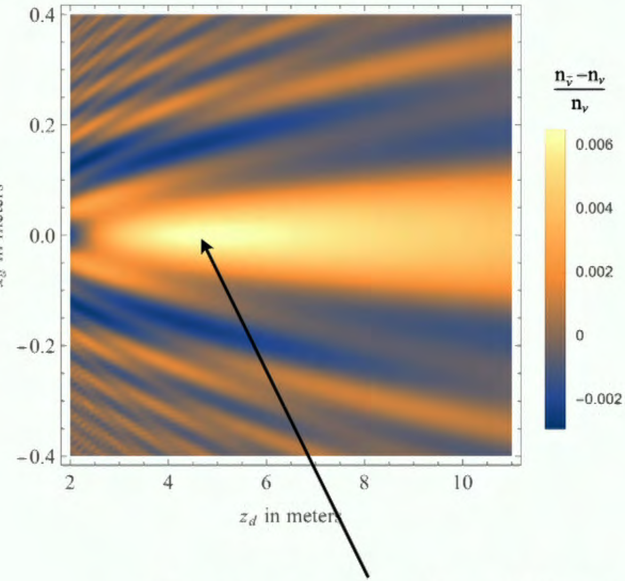
Neutrino wave as diffracted from a rod



Excess of species for which $\delta_\nu > 0$
at a distance $R \sim \dfrac{w^2}{\lambda}$

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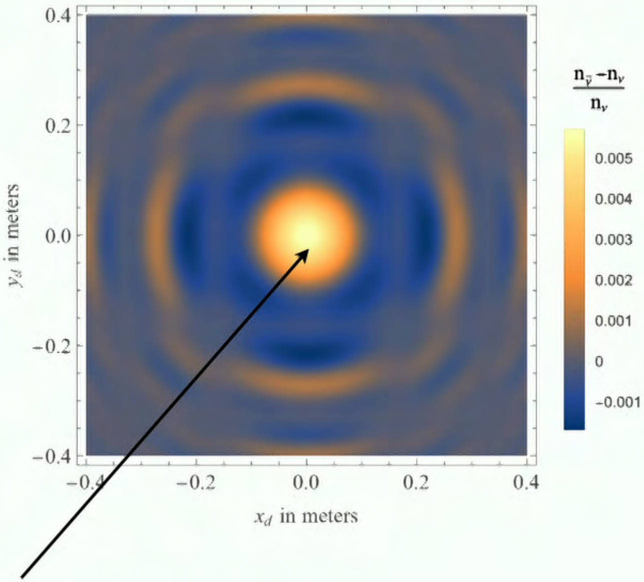

Excess of species for which $\delta_\nu > 0$
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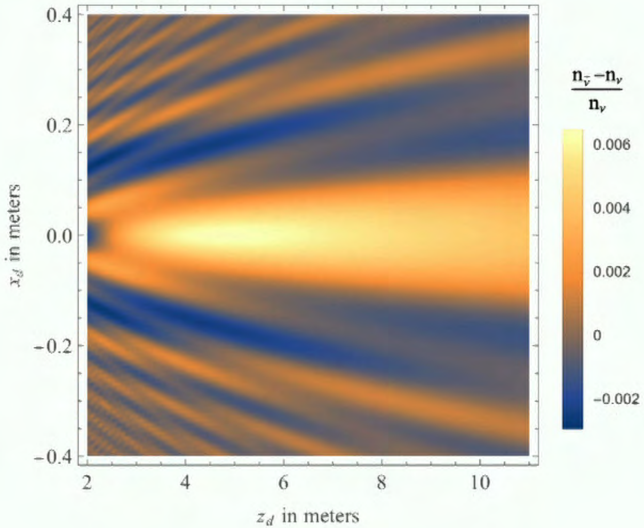

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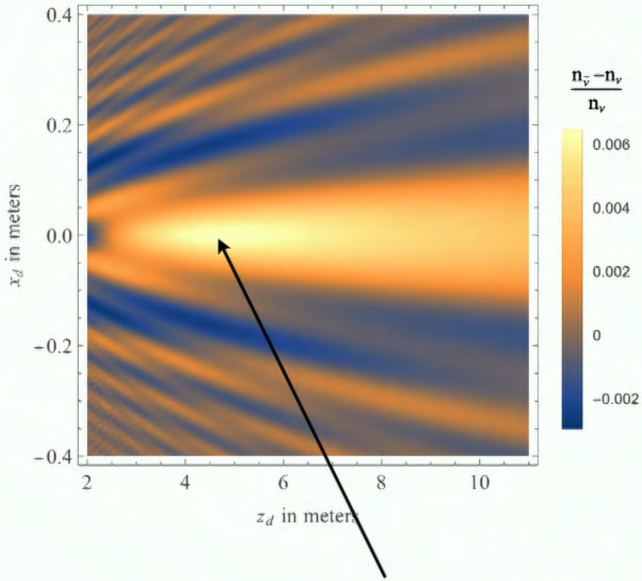

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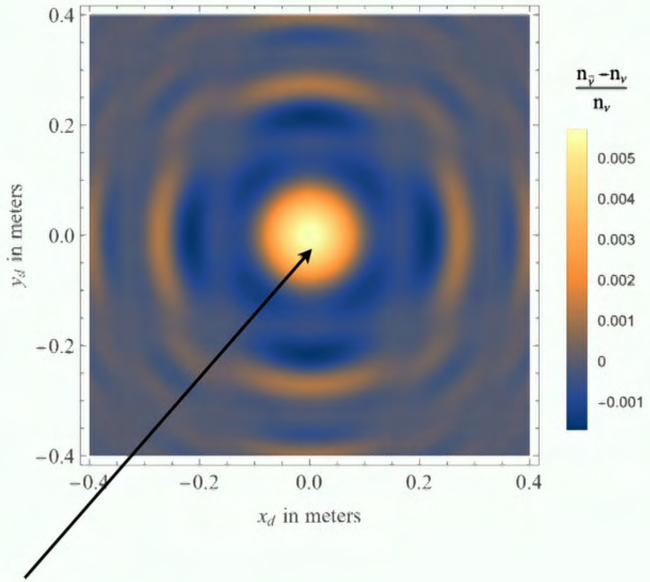
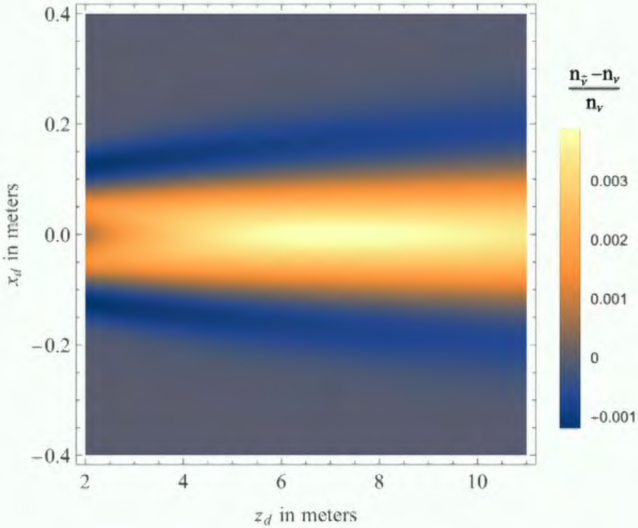
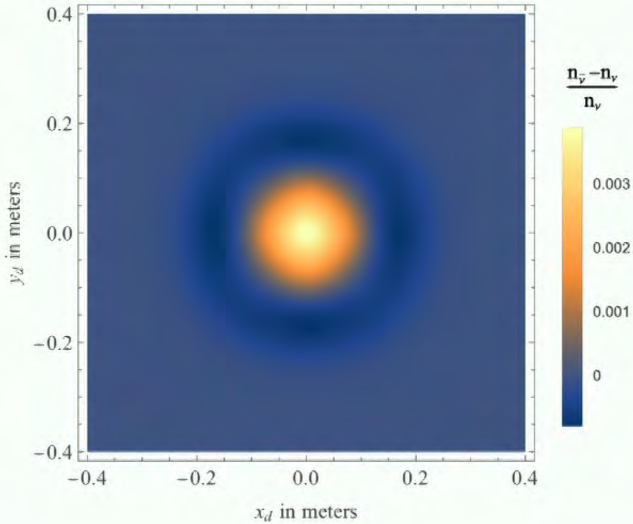


Excess of species for which $\delta_\nu > 0$
over a region of size w

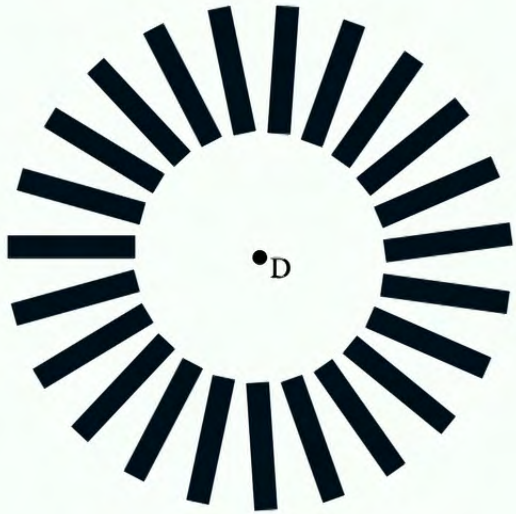
A rod as a diffractor of the CνB

- Neutrinos are not monochromatic
- Need to average over neutrino momenta
- The effect does not go away and it is of size $k_\nu |\delta_\nu| L$





A compound neutrino diffractor



- Need to account for neutrinos coming from all directions

- Place rods a distance of $\frac{w^2}{\lambda_{av}}$ from the center

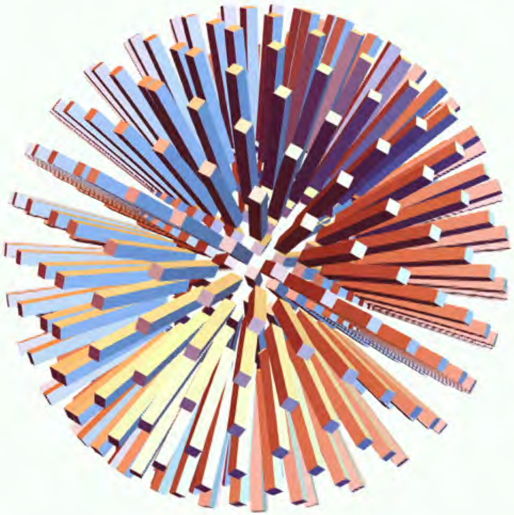
Index of refraction for different materials

$$\delta_\nu \equiv n - 1$$

	ν_e	$\nu_{\mu,\tau}$
$\lvert\delta_\nu\rvert$ in Water	2×10^{-8}	1.3×10^{-8}
$\lvert\delta_\nu\rvert$ in SiO_2 (rock)	2.5×10^{-8}	2.5×10^{-8}
$\lvert\delta_\nu\rvert$ in Iron	8×10^{-8}	1.1×10^{-7}
$\lvert\delta_\nu\rvert$ in Lead	5.6×10^{-8}	1.9×10^{-7}
$\lvert\delta_\nu\rvert$ in Mercury	7.1×10^{-8}	2.2×10^{-7}
$\lvert\delta_\nu\rvert$ in Gold	1.1×10^{-7}	3.2×10^{-7}
$\lvert\delta_\nu\rvert$ in Tungsten	1.1×10^{-7}	3.1×10^{-7}
$\lvert\delta_\nu\rvert$ in Depleted Uranium	8.2×10^{-8}	3.2×10^{-7}

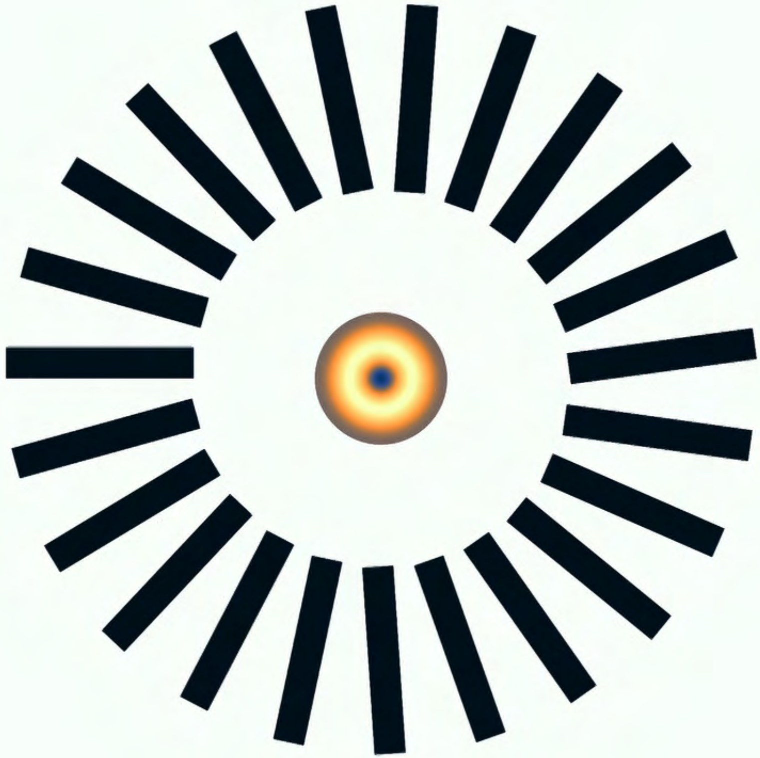
$\delta_\nu > 0$ for $\bar{\nu}_e$ and $\nu_{\mu,\tau}$

A compound diffraction grating

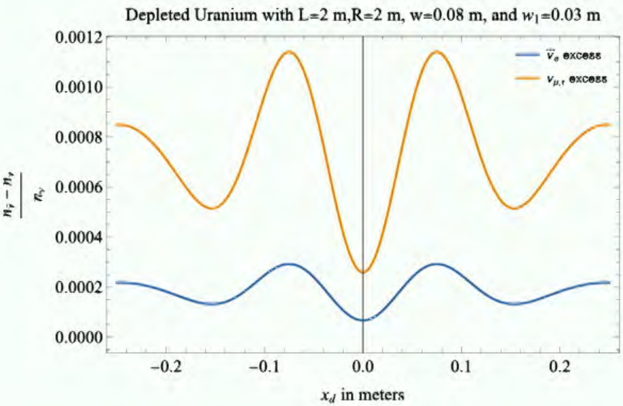


Set-up parameters	Grating 1	Grating 2	Grating 3
Rod Material	Depleted Uranium	Tungsten	Iron
Rod length L	2 meters	10 meters	100 meters
Rod width w	0.08 meters	0.17 meters	0.54 meters
Inter-rod gap w_1	0.03 meters	0.06 meters	0.18 meters
Grating radius R	2 meters	10 meters	72 meters

$\nu - \bar{\nu}$ asymmetry

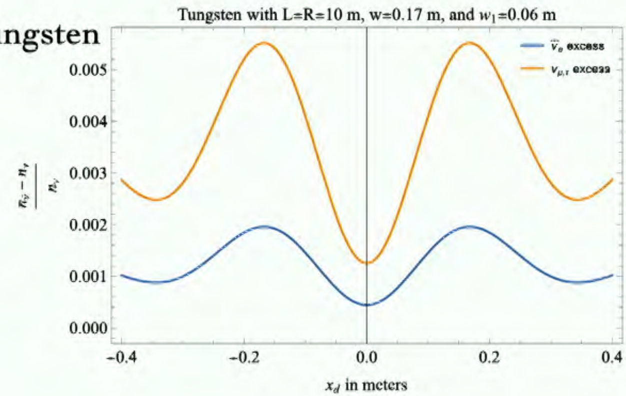


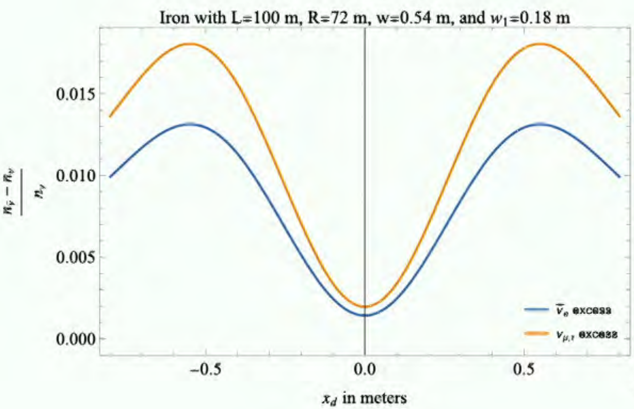
$\nu - \bar{\nu}$ asymmetry at the center of the grating



2 m Uranium

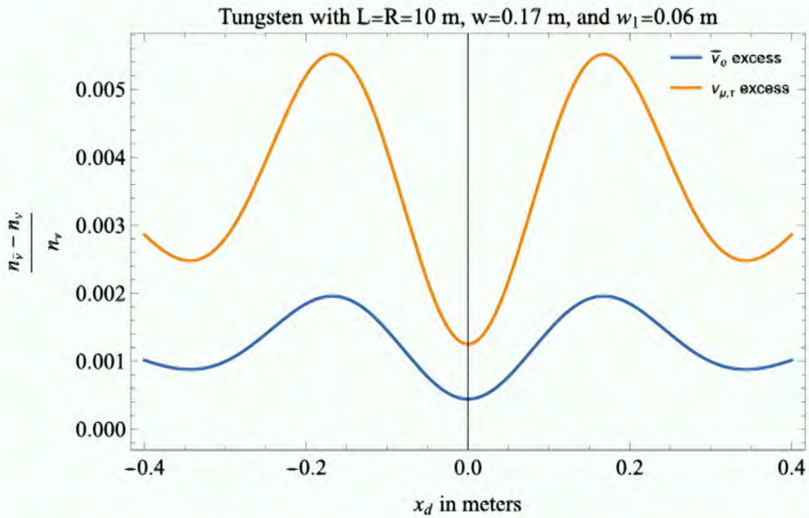
10 m Tungsten





100 m Iron

$\nu - \bar{\nu}$ asymmetry at the center of the grating



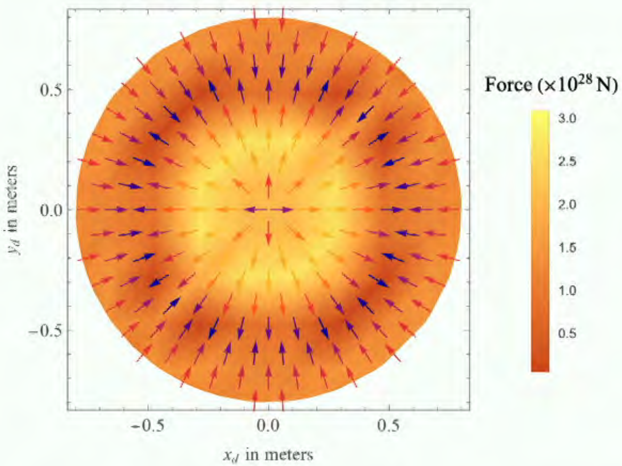
- Size of the asymmetry is roughly $k\delta_\nu L$ and grows with size L till the small phase approximation breaks down
- Size of the gradient set by chosen w
- Size of structure set by $R \sim \frac{w^2}{\lambda_\nu}$

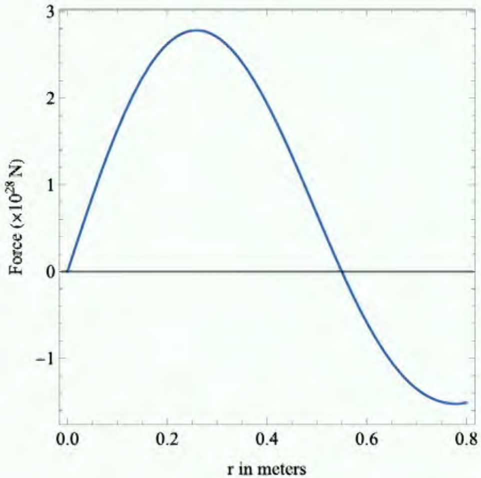
The force due to the induced $\nu - \bar{\nu}$ asymmetry gradient

- $\vec{F} = -\vec{\nabla} U \propto \vec{\nabla}(n_\nu - n_{\bar{\nu}})$
- Detector made out of Tungsten or Gold or… will feel a radial force
- Place different material on a torsion balance: Force turns to torque

Force around the center of the compound diffractor

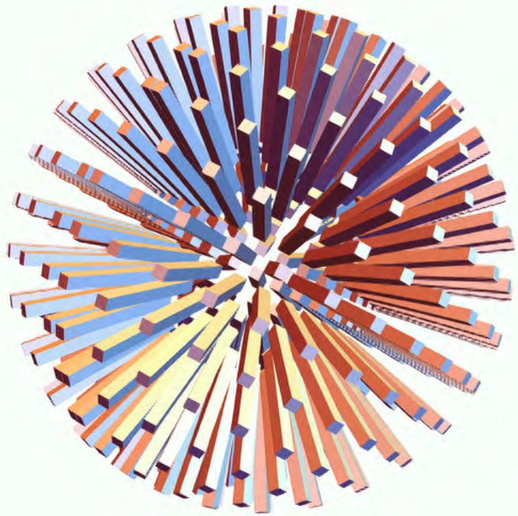
$m_\nu = 0.1$ eV



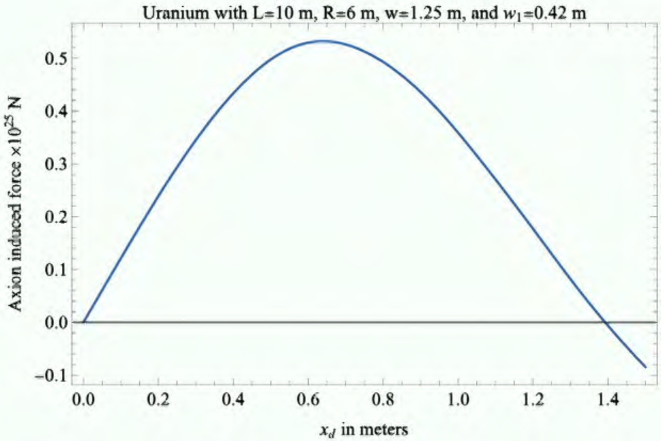


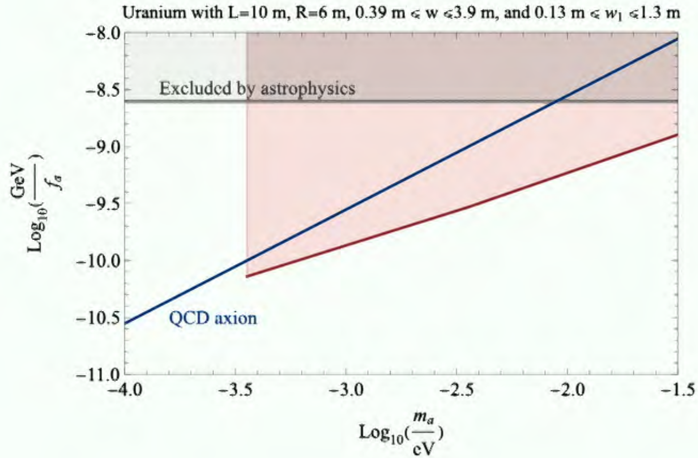
- Force on (10 cm)^3 Tungsten mass from ν_μ or ν_τ excess from 100 m iron structure
- Force is bigger by 5 orders of magnitude compared to that from coherent scattering and 3 orders of magnitude larger than the one from the Earth

A diffractor for Dark Matter



A diffractor for QCD Axion Dark Matter





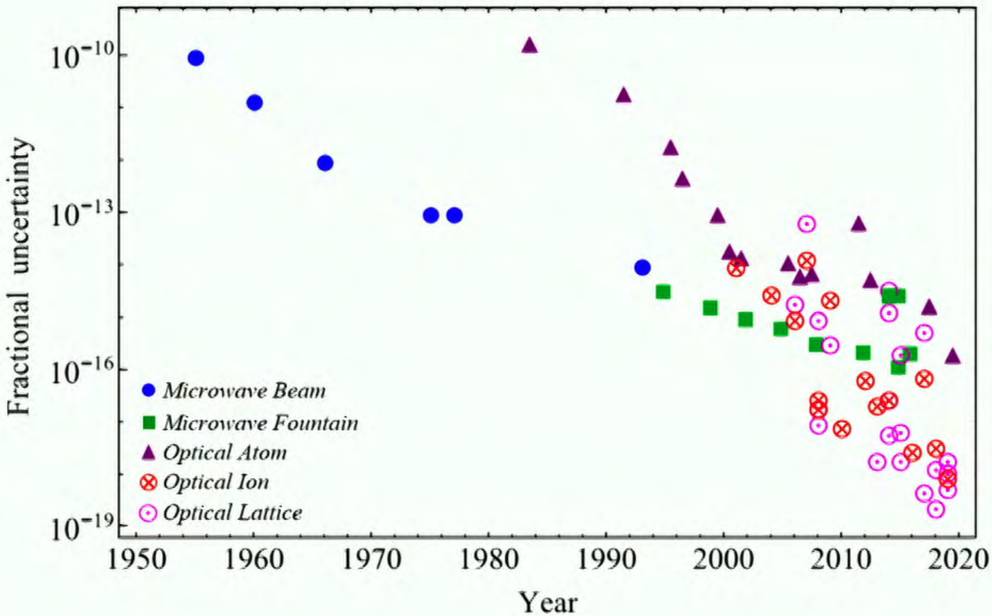
- Relevant for the QCD axion with decay constant $10^8 - 10^{10}$ GeV

- Signal can be up to 1000 times larger than that of the CνB

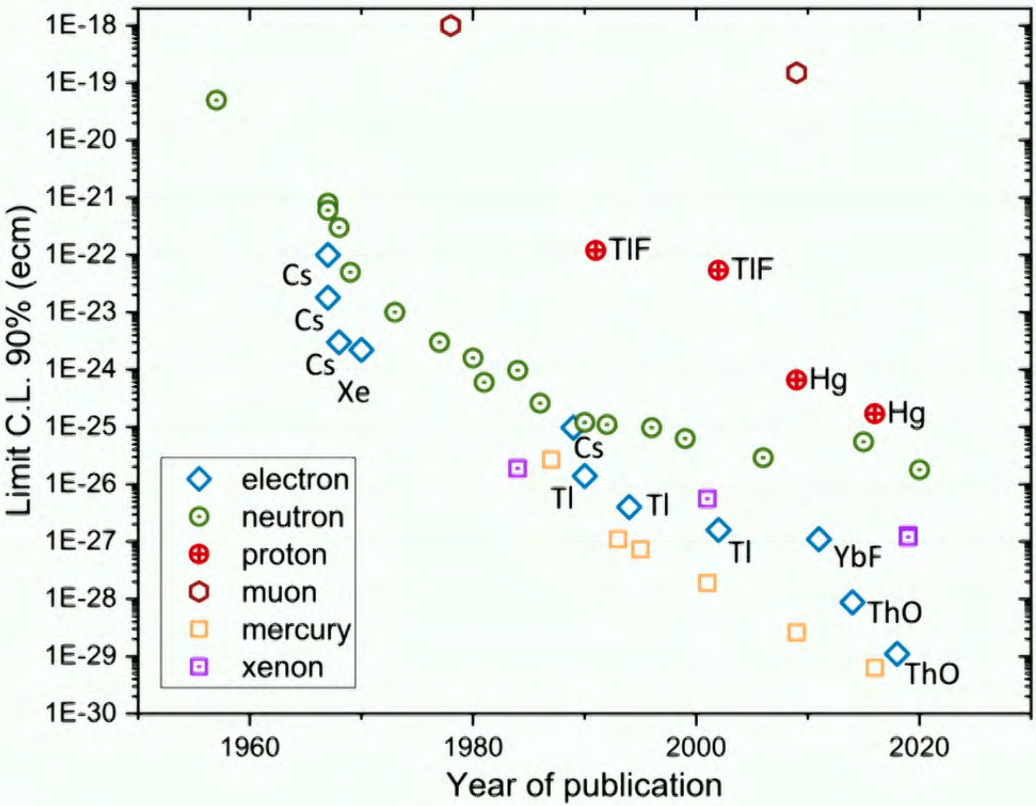
Conclusions

- The presence of the Earth is enough to significantly modify the local CνB distribution
- CνB and DM can be manipulated at laboratory scales
- Sets a challenging target for new experiments of direct detection of the CνB
- But we have been there before, several times.

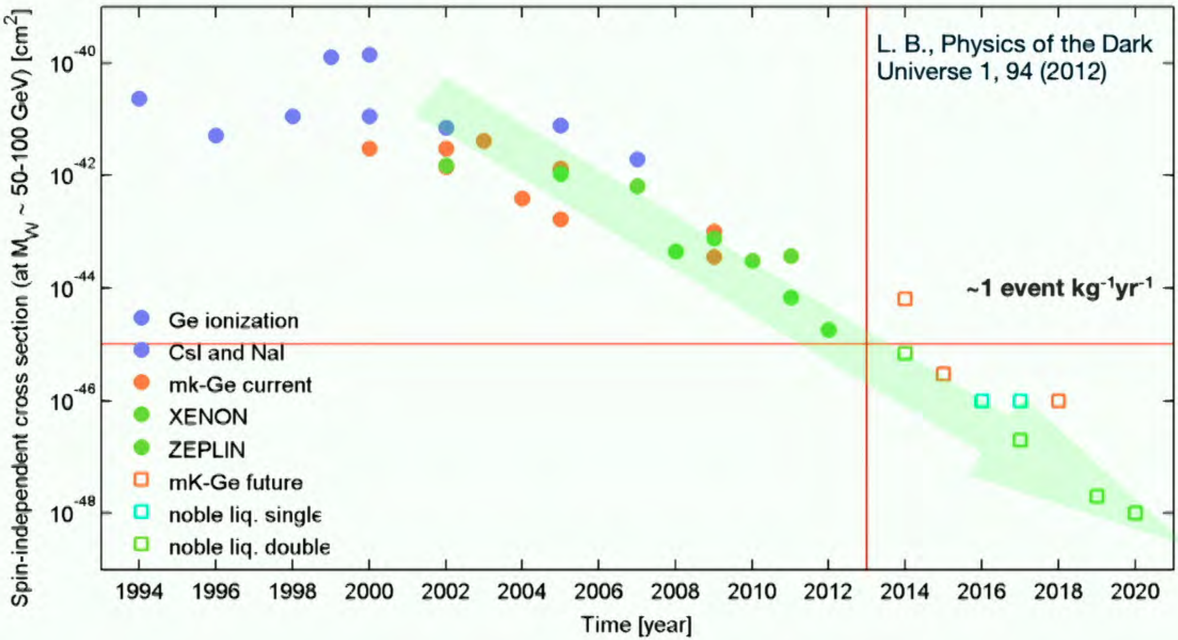
Evolution of atomic clock accuracy



Evolution of EDM measurements



Evolution of WIMP cross-section sensitivity



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- Golden age of Small Scale Experiments

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- Unlike BSM searches, finding nothing would be as important as finding something!

A Cosmic Neutrino Background Telescope?

What did the Universe look like when it was less than 1 second old?...