Title: Challenge Talk 1 - The Cosmic Neutrino Background: Its distribution on the surface of the Earth and its manipulation on laboratory scales

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The Cosmic Neutrino Background

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

Savas Dimopoulos

in collaboration with Asimina Arvanitaki

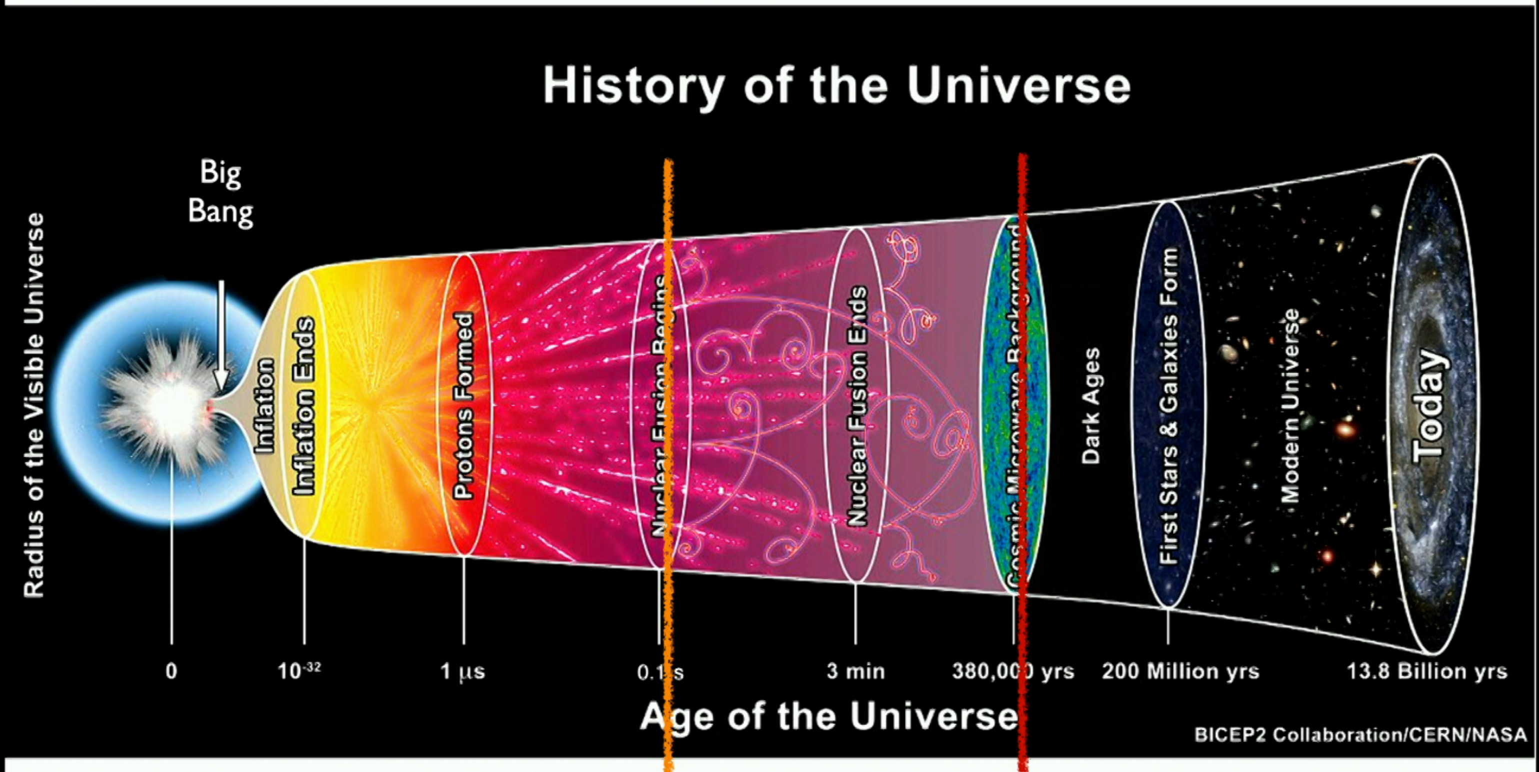
What is the Cosmic Neutrino Background (CνB)?

- 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)

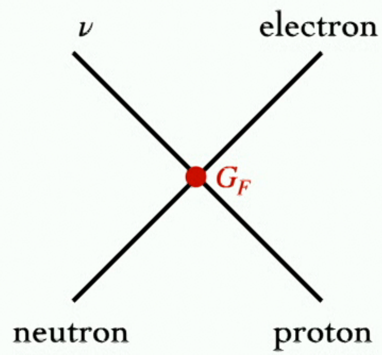
The CMB

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 $\propto G_F^2$

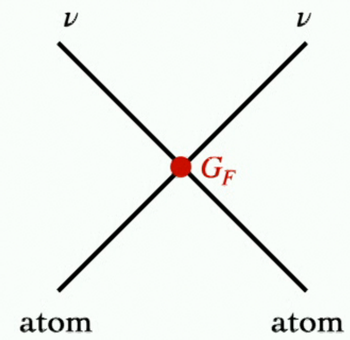


Effects linear in G_F for the CνB

- 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

CνB forces on macroscopic matter*

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



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

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

- $U_\nu \sim 10^{-14}$ 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)

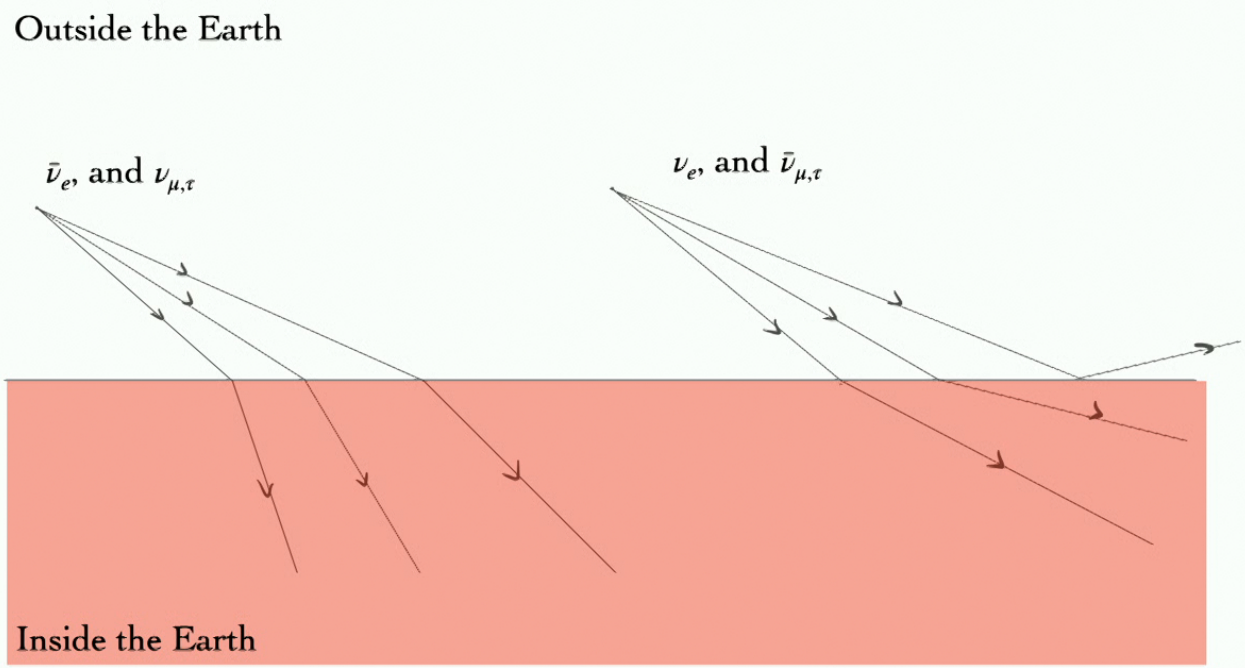
- Interaction energy U of neutrinos in matter determines the refractive index

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

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

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

Neutrinos vs Antineutrinos

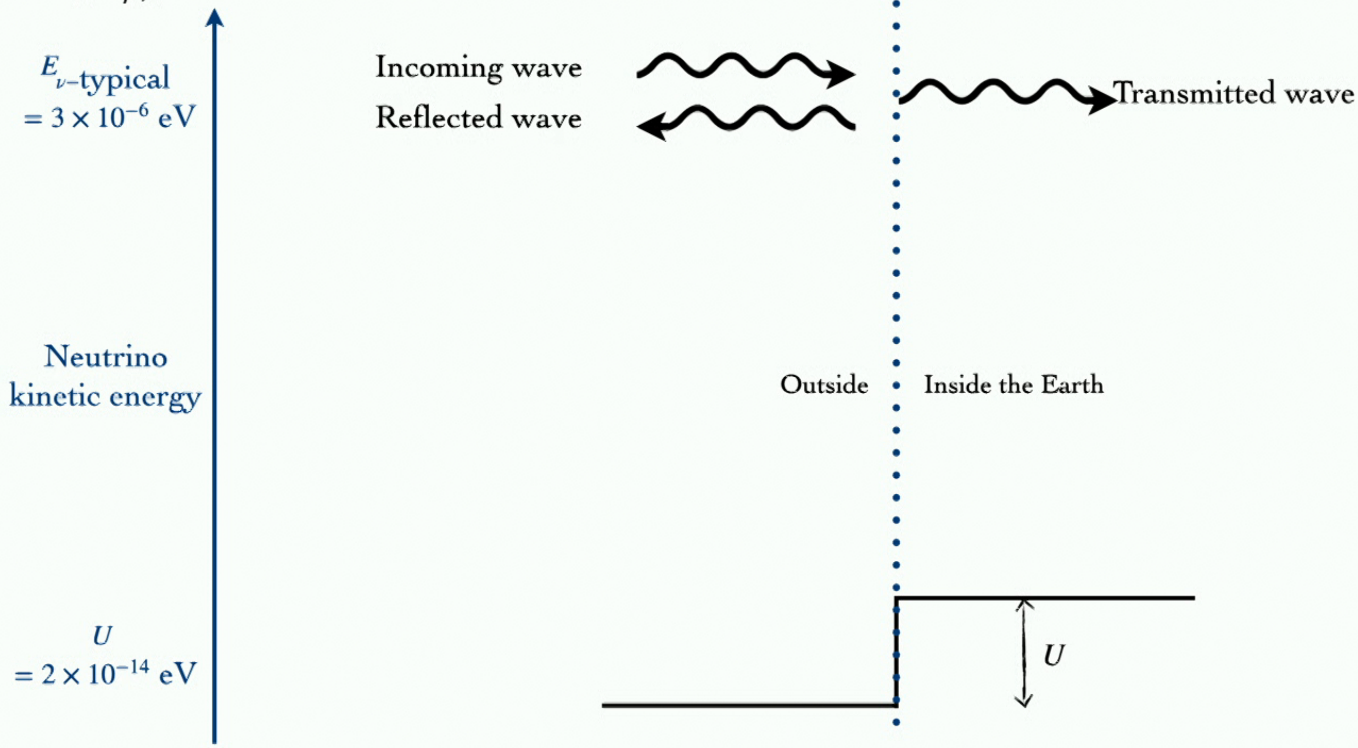


Traffic jam of neutrinos on the surface is responsible for the excess

CνB refraction and reflection on the Earth

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

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



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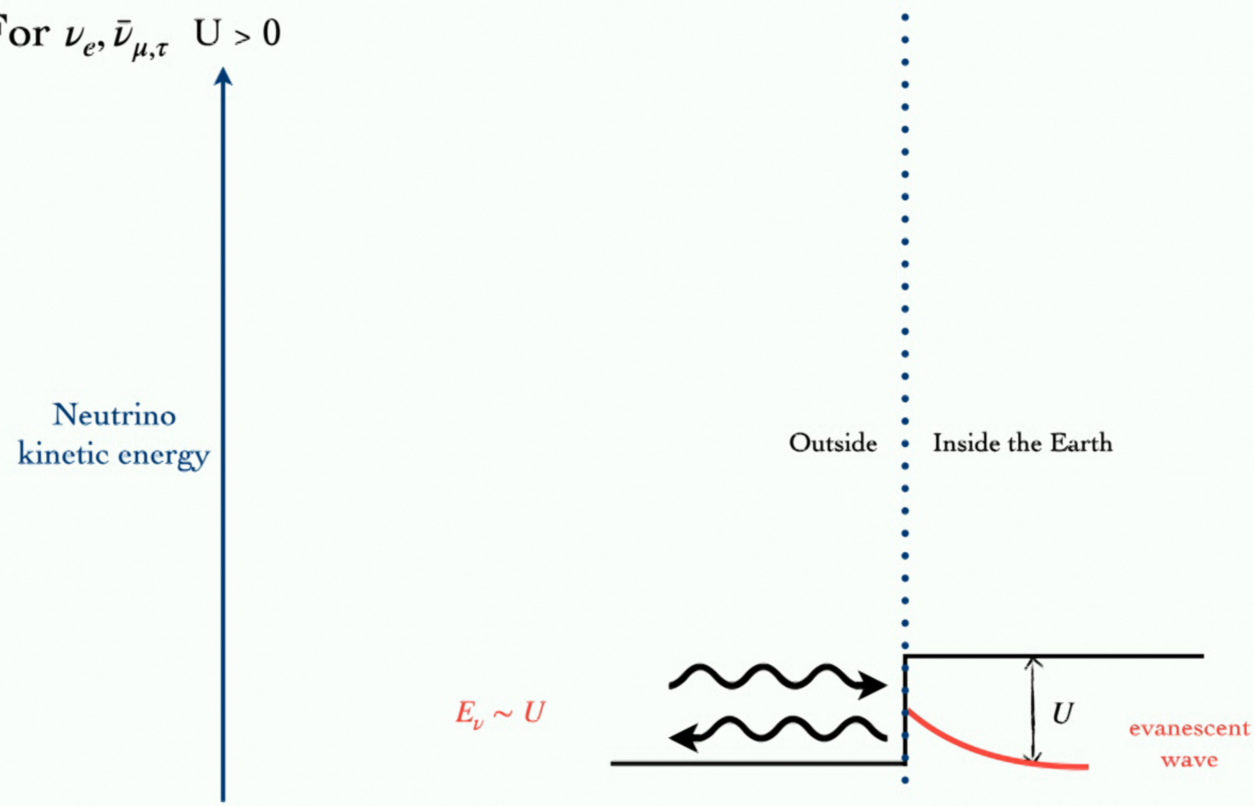

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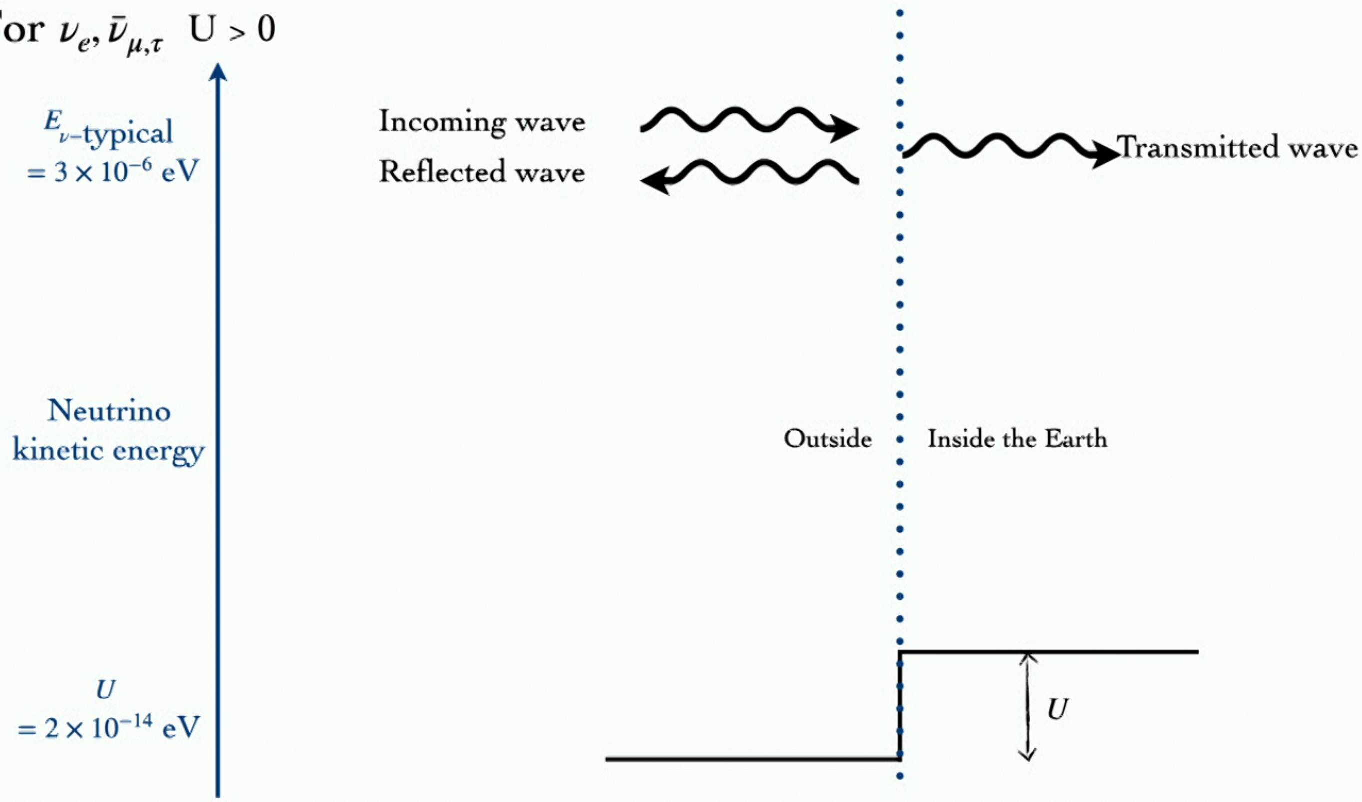
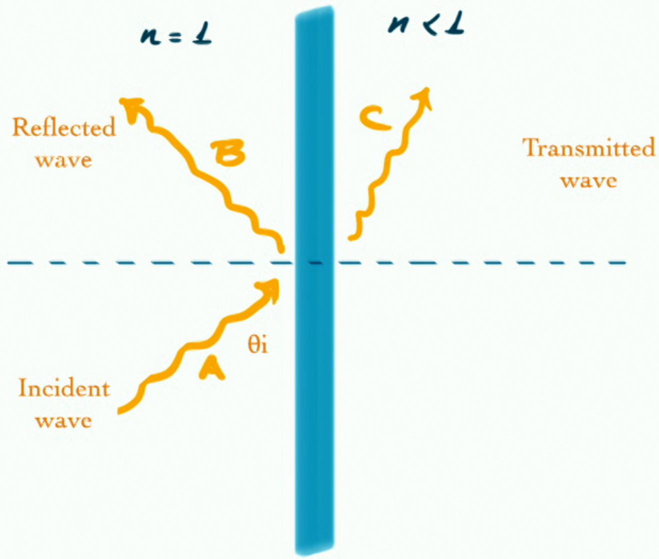


CνB refraction and reflection on the Earth



Translational symmetry along the boundary:

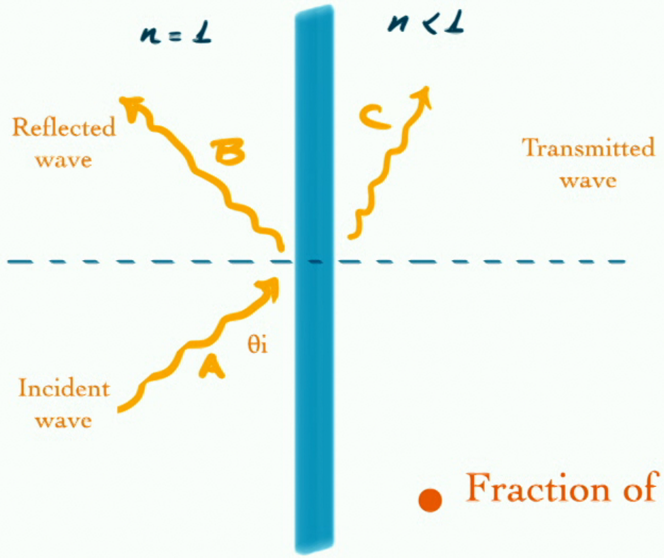
Only momentum perpendicular, $p_{\nu_\perp}$ to the boundary determines the dynamics

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

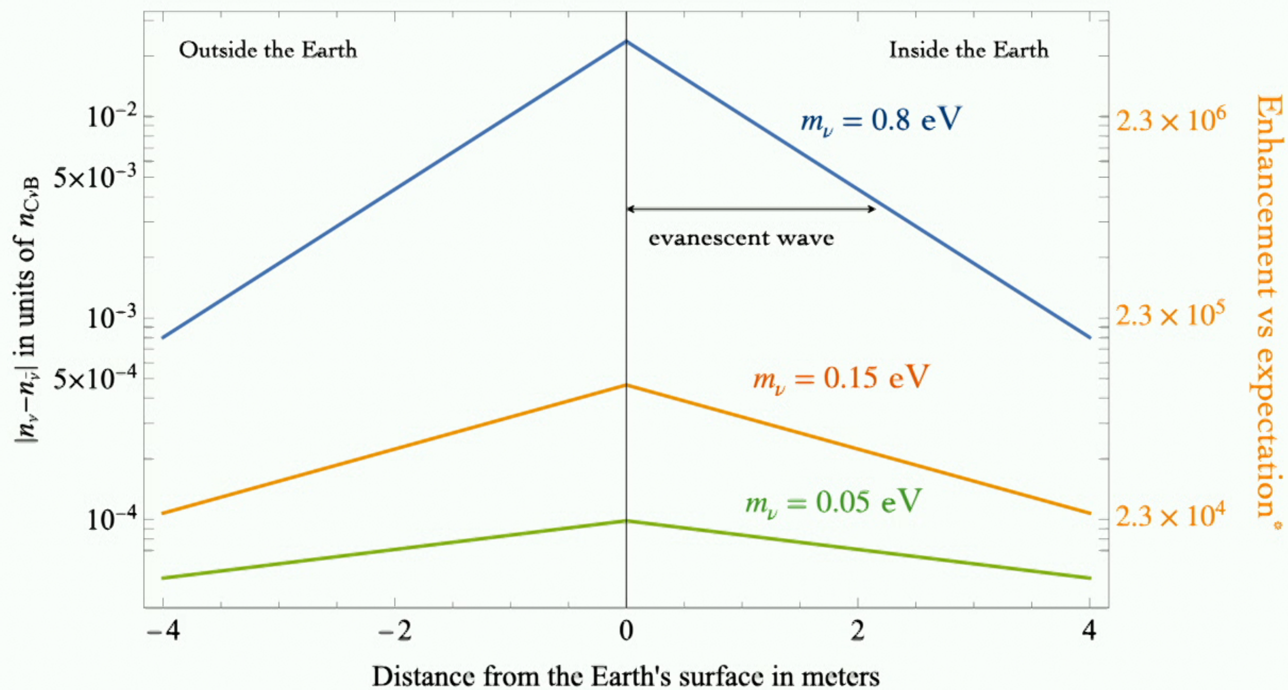


The incidence angle for which reflection occurs is: $\theta_i \sim \frac{p_{\nu_{\perp c}}}{p_\nu} \equiv \theta_c$

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

- 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

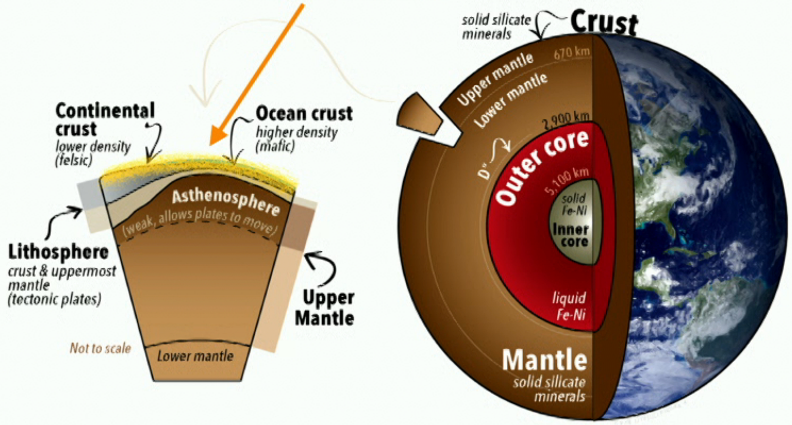
CνB distribution on the surface of the Earth



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

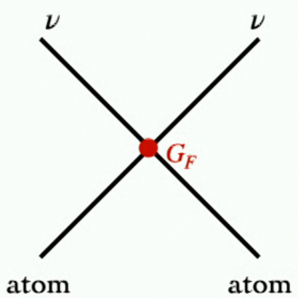


- Neutrino-antineutrino asymmetry larger by a factor of 100,000 in a roughly 3 meter zone above and below the Earth's surface

- This effect opens up new possibilities for Cosmic Neutrino detection

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

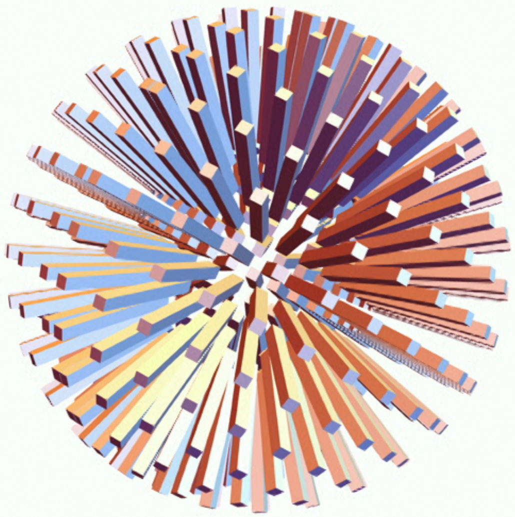
- The evanescent wave introduces a gradient of $(3 \text{ meters})^{-1}$
  - $F_{\text{induced}} = -\nabla U \sim 10^{-31}\, N \frac{V_{\text{Tungsten}}}{(10 \text{ cm})^3}$
- Force no longer zero but still pretty small

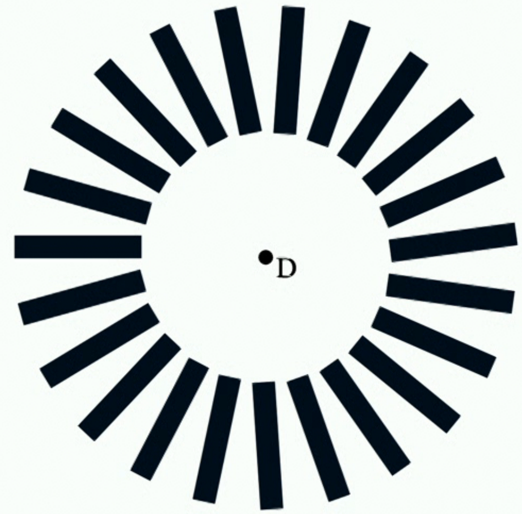


Can we get a bigger effect than the one we get for free?

A diffraction grating for the CνB

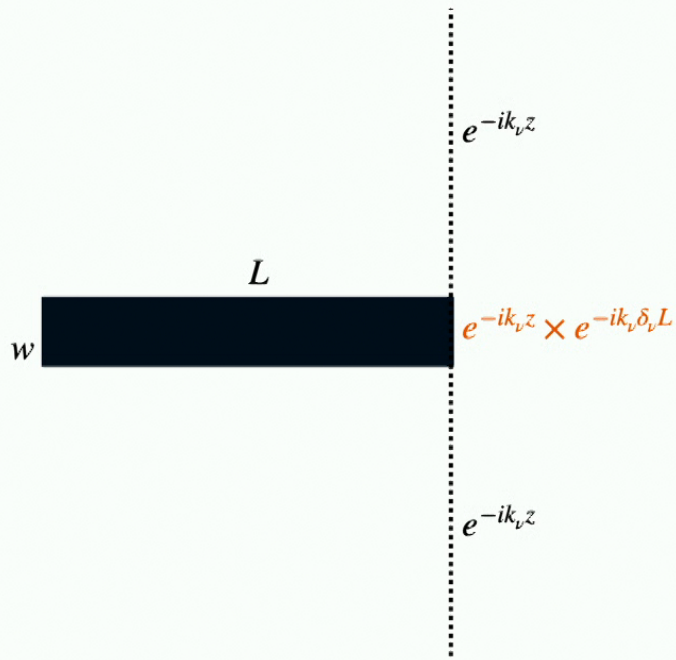
Arvanitaki, SD 2023

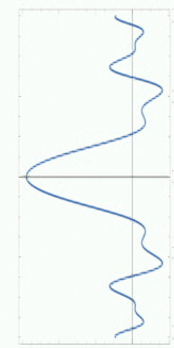




- Rods of width w and length L oriented along the surface of a sphere
- Takes advantage of the wave nature of neutrinos $\lambda_\nu \sim 2-4$ mm

A rod as a neutrino phase diffractor





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

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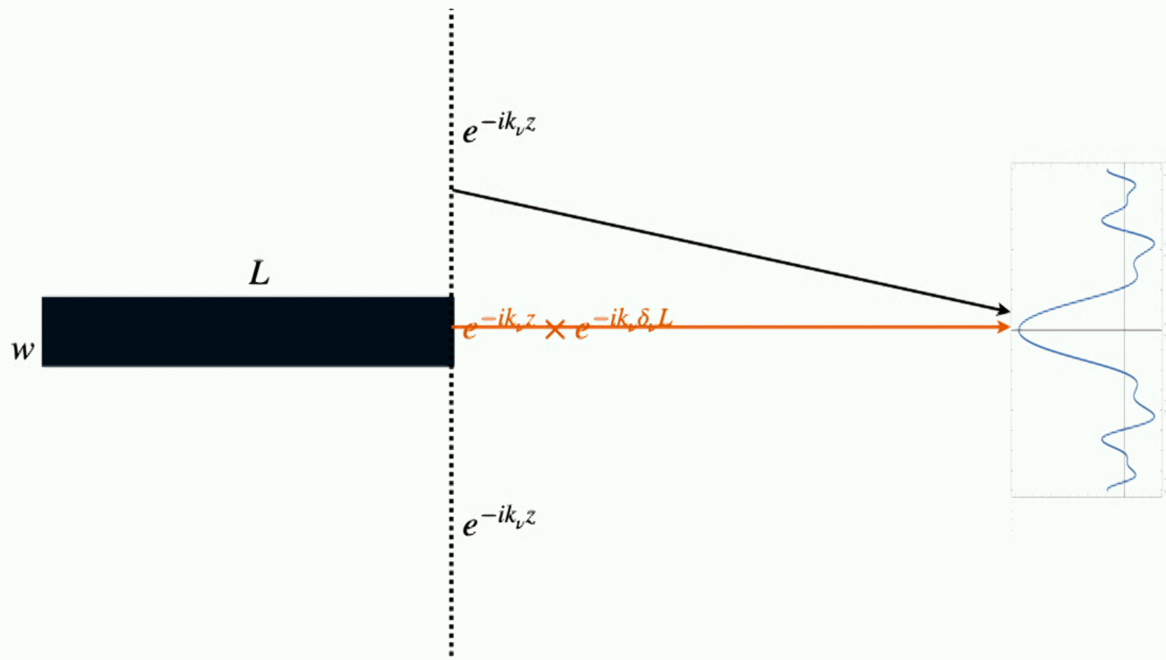

Asymmetry pattern of $\delta_\nu > 0 \; - \; \delta_\nu < 0$

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

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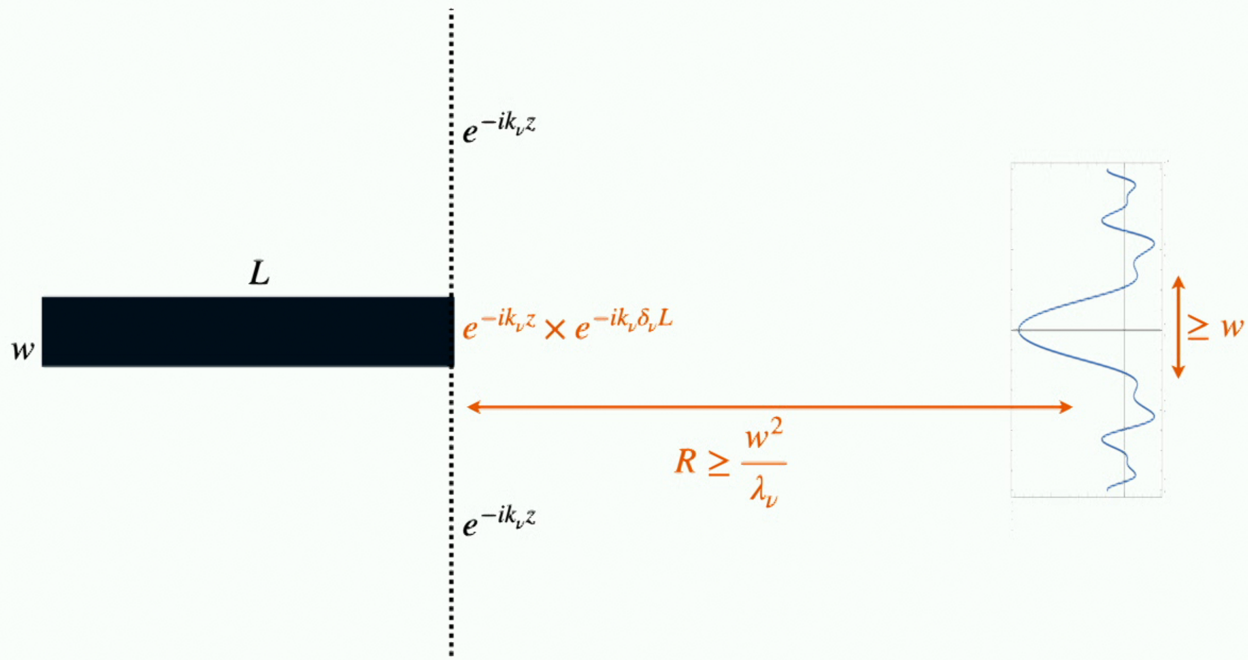

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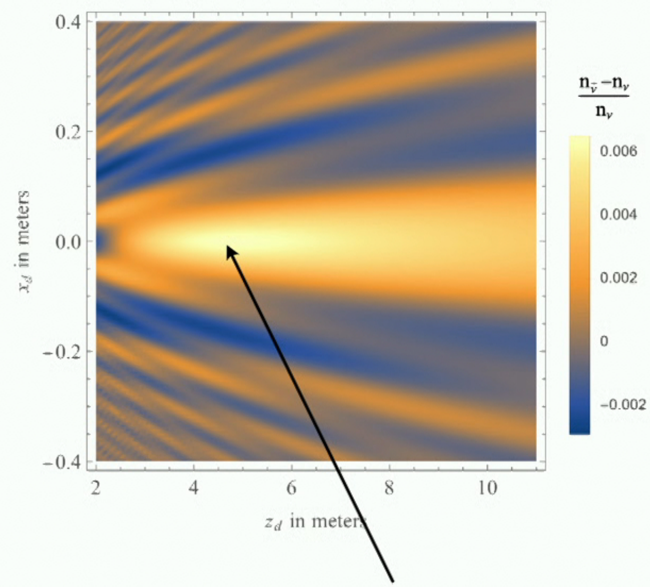
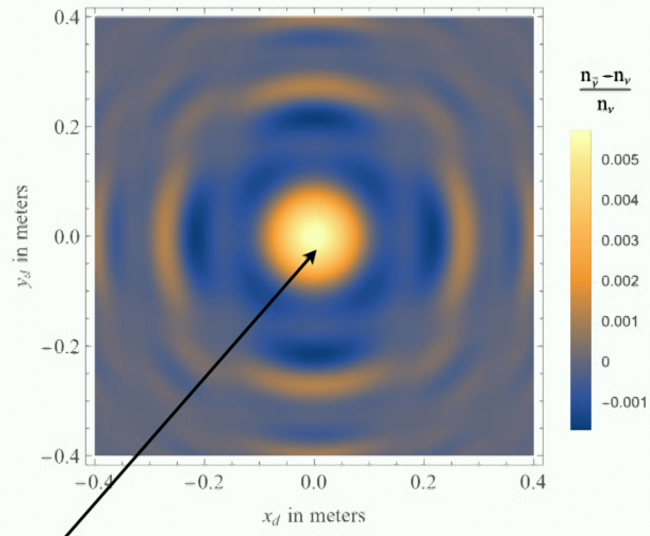
Neutrino wave as diffracted from a rod



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

Neutrino wave as diffracted from a rod



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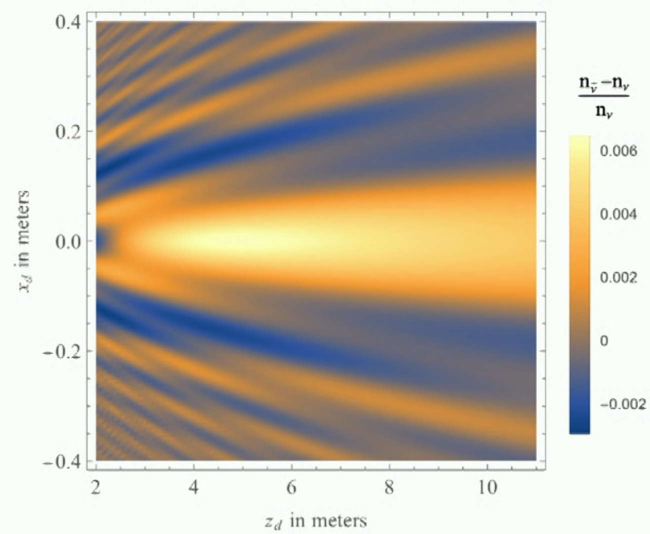

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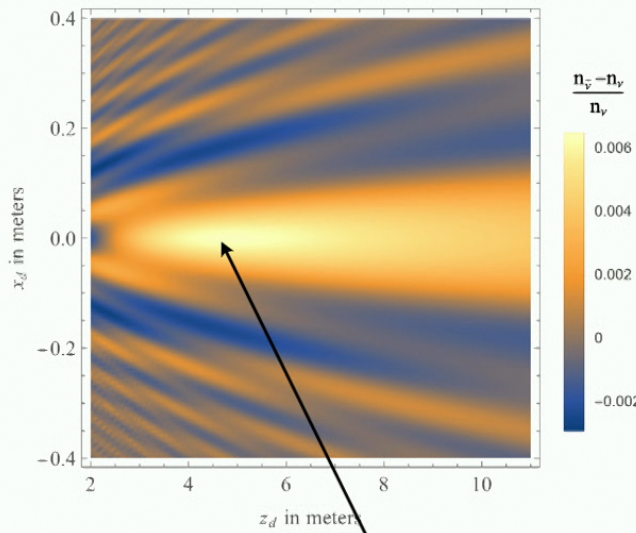

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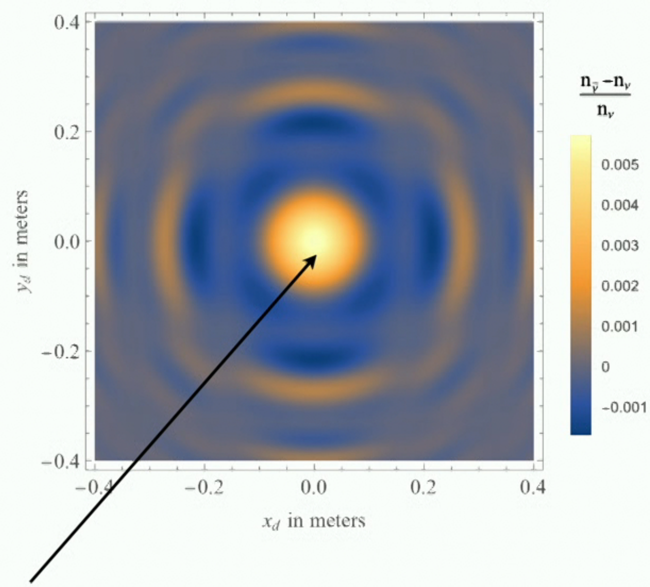

Excess of species for which $\delta_\nu > 0$
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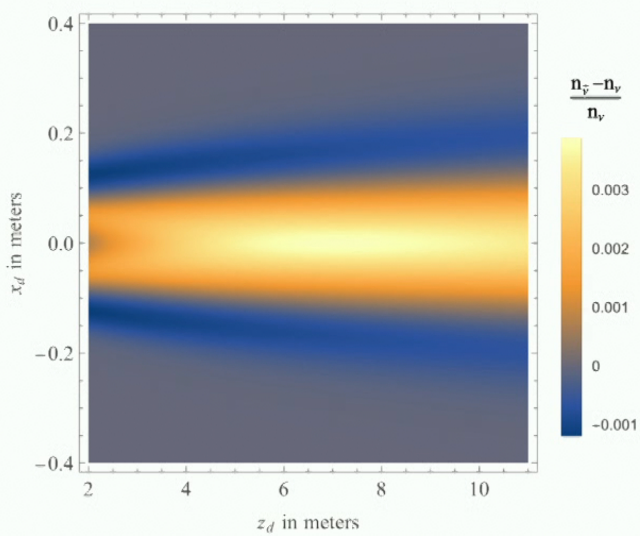
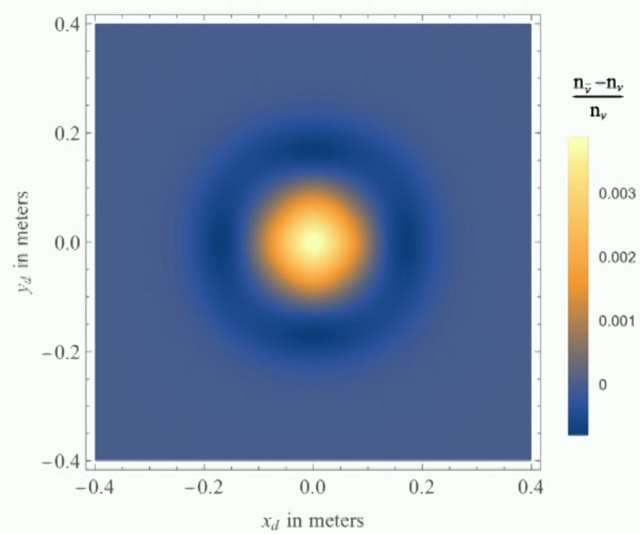
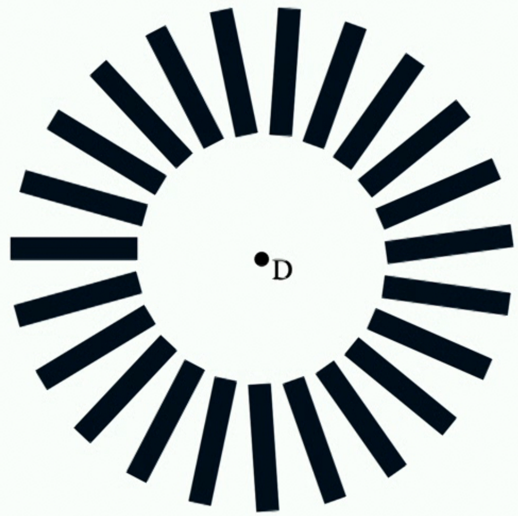
A rod as a diffractor of the CvB

- 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

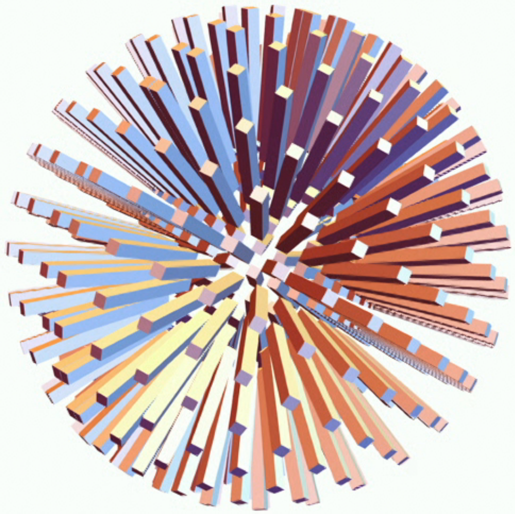
Index of refraction for different materials

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

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

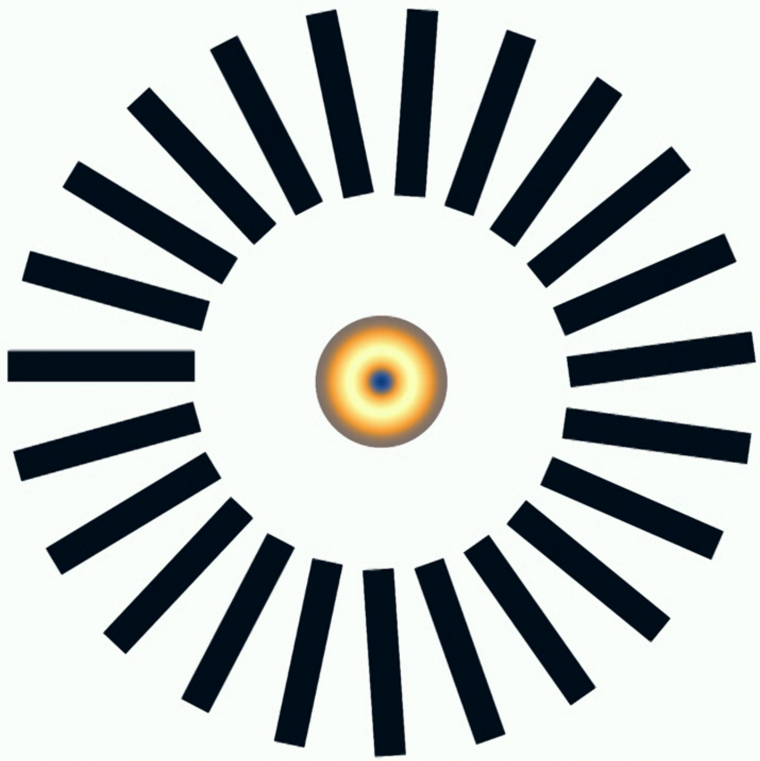
$\delta_\nu > 0$ for $\bar{\nu}_e$ and $\nu_{\mu,\tau}$

A compound diffraction grating

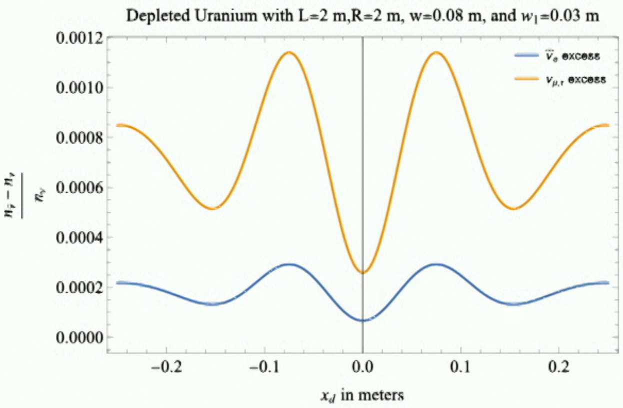


Set-up parameters	Grating 1	Grating 2	Grating 3
Rod Material	Depleted Uranium	Tungsten	Iron
Rod length L	2 meters	10 meters	100 meters
Rod width w	0.08 meters	0.17 meters	0.54 meters
Inter-rod gap w_1	0.03 meters	0.06 meters	0.18 meters
Grating radius R	2 meters	10 meters	72 meters

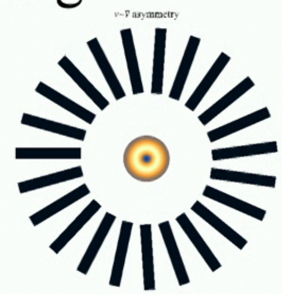
$\nu - \bar{\nu}$ asymmetry



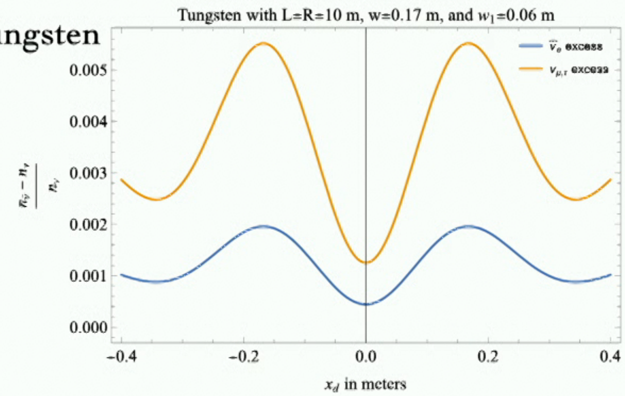
$\nu - \bar{\nu}$ asymmetry at the center of the grating

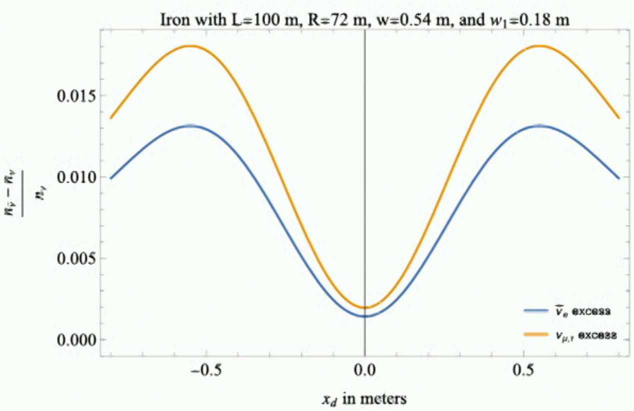


2 m Uranium



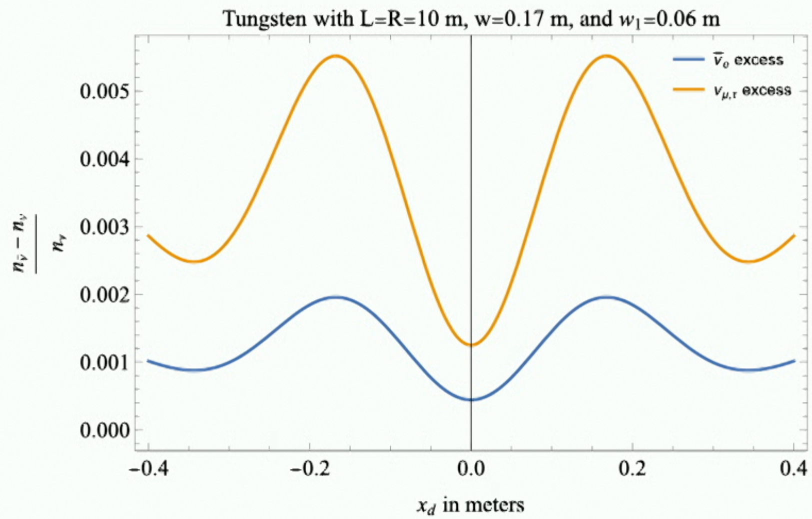
10 m Tungsten

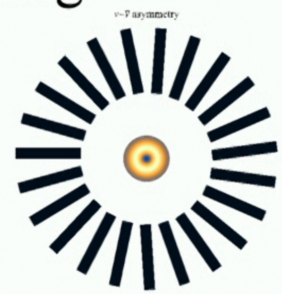




100 m Iron

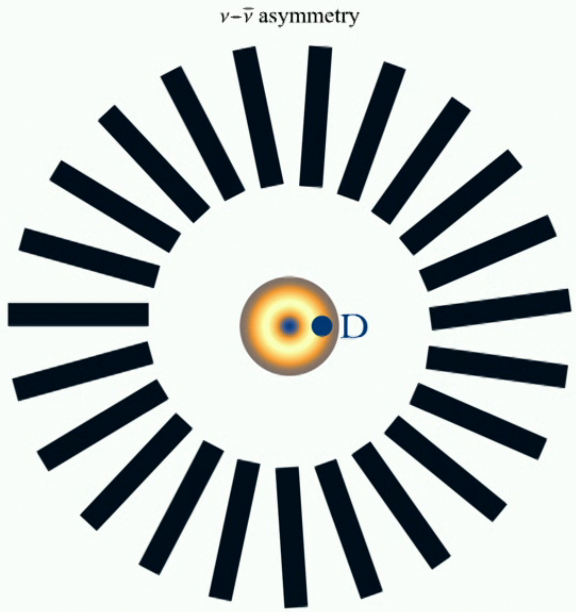
$\nu - \bar{\nu}$ asymmetry at the center of the grating





- 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 $R \sim \frac{w^2}{\lambda_\nu}$

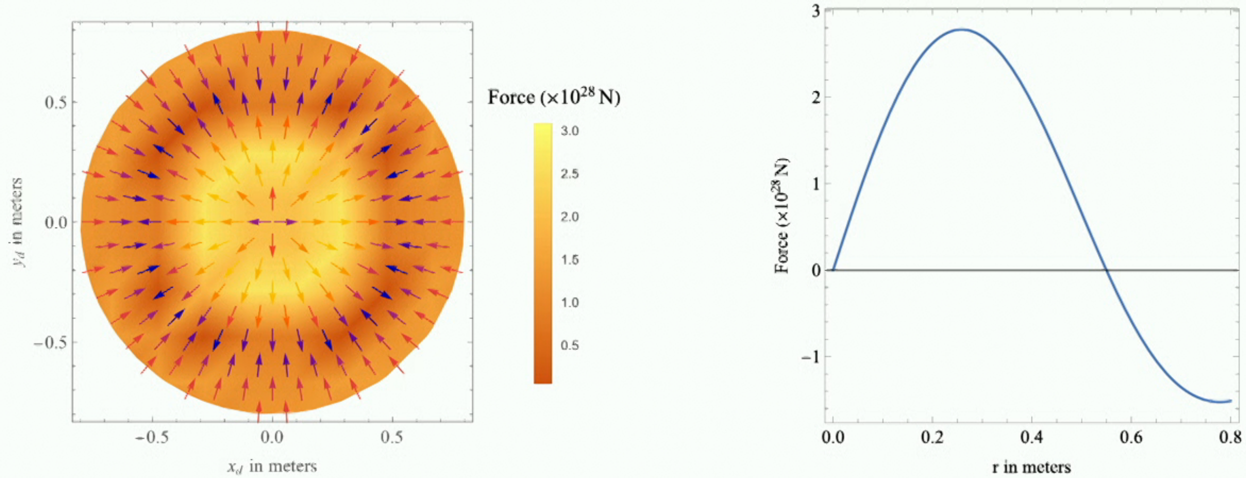
The force due to the induced $\nu - \bar{\nu}$ asymmetry gradient



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

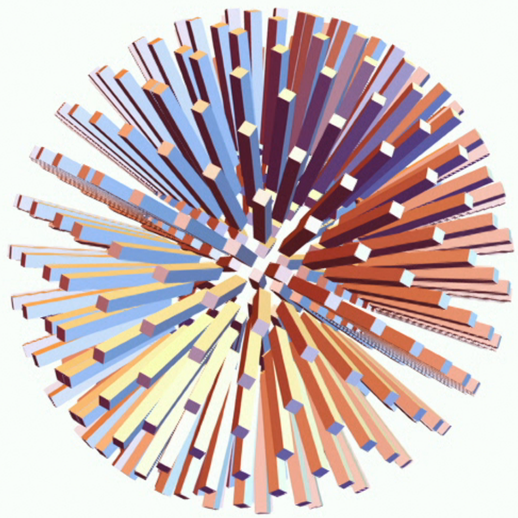
Force around the center of the compound diffractor

$m_\nu = 0.1$ eV

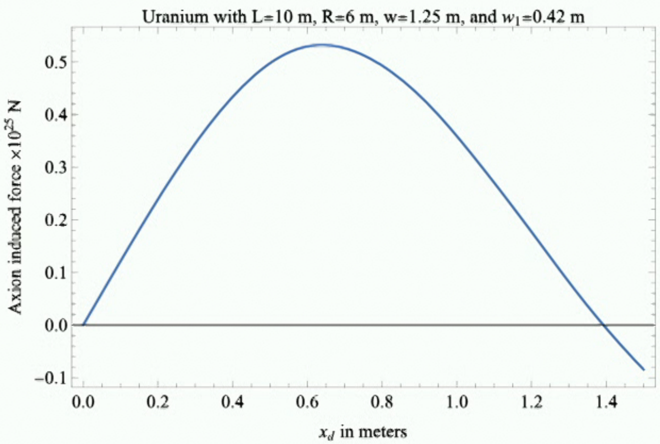


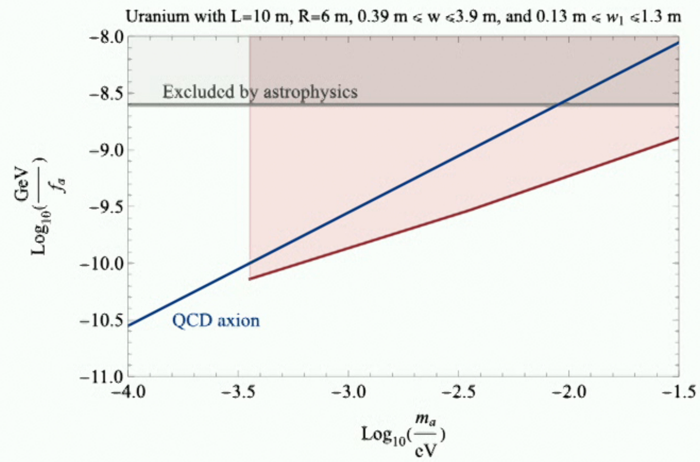
- Force on (10 cm)^3 Tungsten mass from ν_μ or ν_τ excess from 100 m iron structure
- Force is bigger by 5 orders of magnitude compared to that from coherent scattering and 3 orders of magnitude larger than the one from the Earth

A diffractor for Dark Matter



A diffractor for QCD Axion Dark Matter





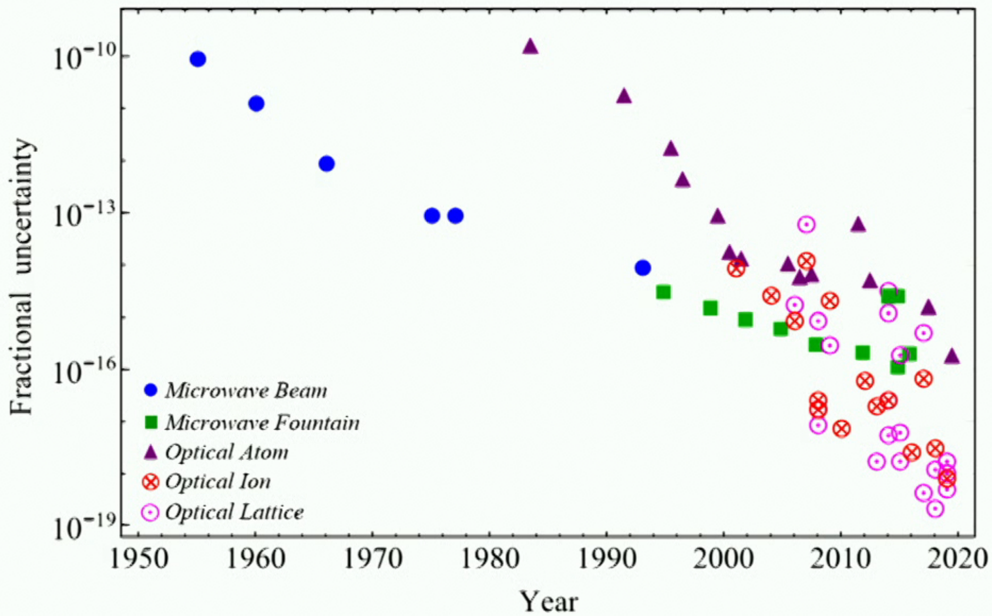
- Relevant for the QCD axion with decay constant $10^8 - 10^{10}$ GeV

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

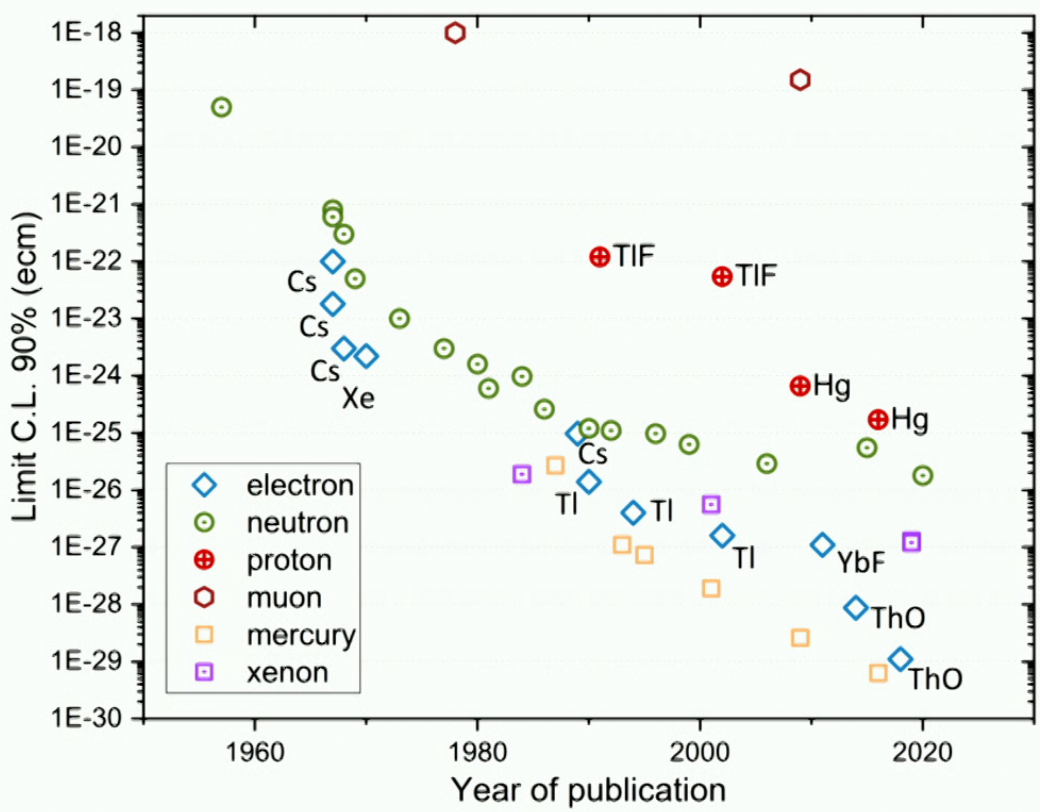
Conclusions

- 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.

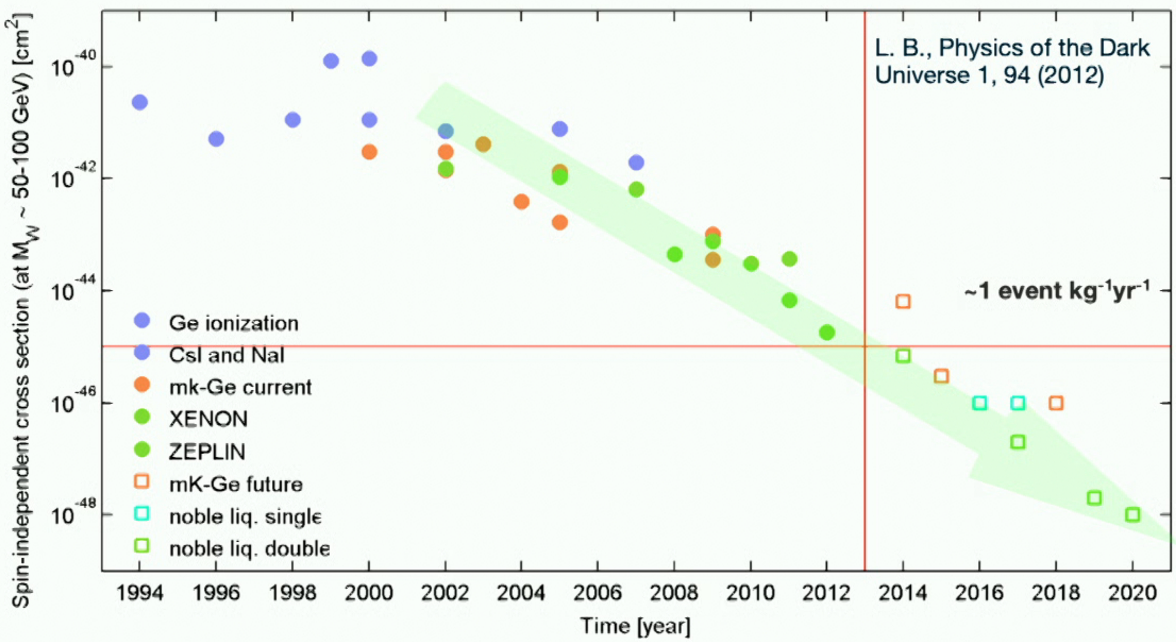
Evolution of atomic clock accuracy



Evolution of EDM measurements



Evolution of WIMP cross-section sensitivity



Why am I optimistic?

- Golden age of Small Scale Experiments

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- The CNB is part of the Standard Model and ΛCDM cosmology
  - Motivation for CNB searches is more akin to the CMB and GW detection than BSM searches

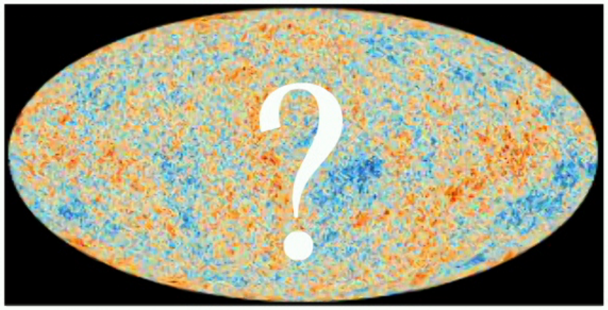
Why am I optimistic?

- Golden age of Small Scale Experiments

- The CNB is part of the Standard Model and ΛCDM cosmology.
  - Motivation for CNB searches is more akin to the CMB and GW detection than BSM searches

- 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?…