2025Aug@TDLI

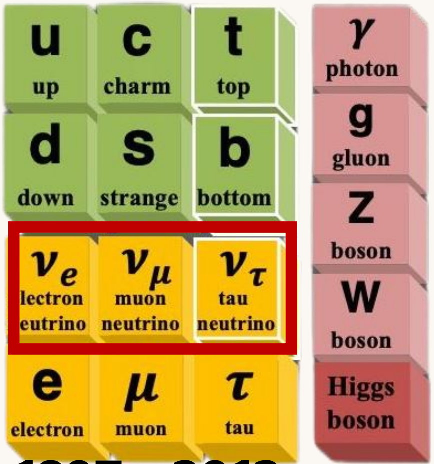
Coherent scatterings of relic neutrinos with material targets

Guo-yuan Huang (黄国远)

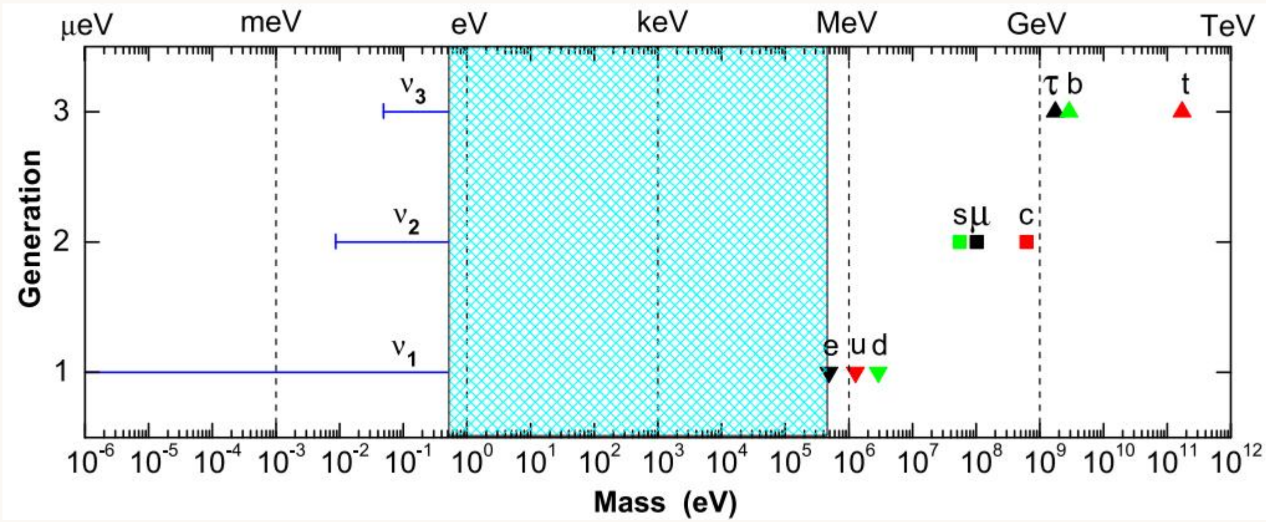
CHINA UNIVERSITY OF GEOSCIENCES
武汉 · WUHAN

Neutrinos

Y.-F. Li, Z.-z. Xing, PLB 695 (2011) 205
Z.-z. Xing, Physics Reports 854 (2020) 1



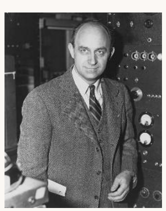
1897—2012 ©Fermilab



1930

1933

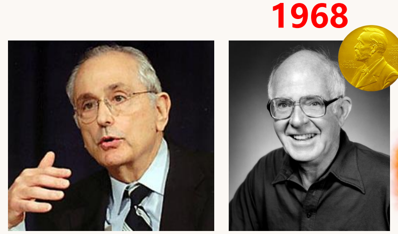
Fermi theory of beta decay



1956

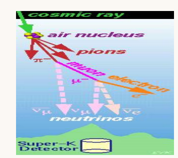
First discovery of neutrinos with the fission reactor

1968



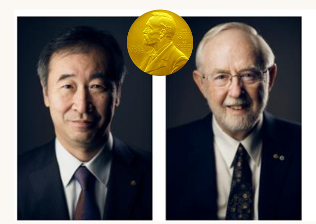
Solar nu. First clue of nu osci.

For discovery of nu osci.



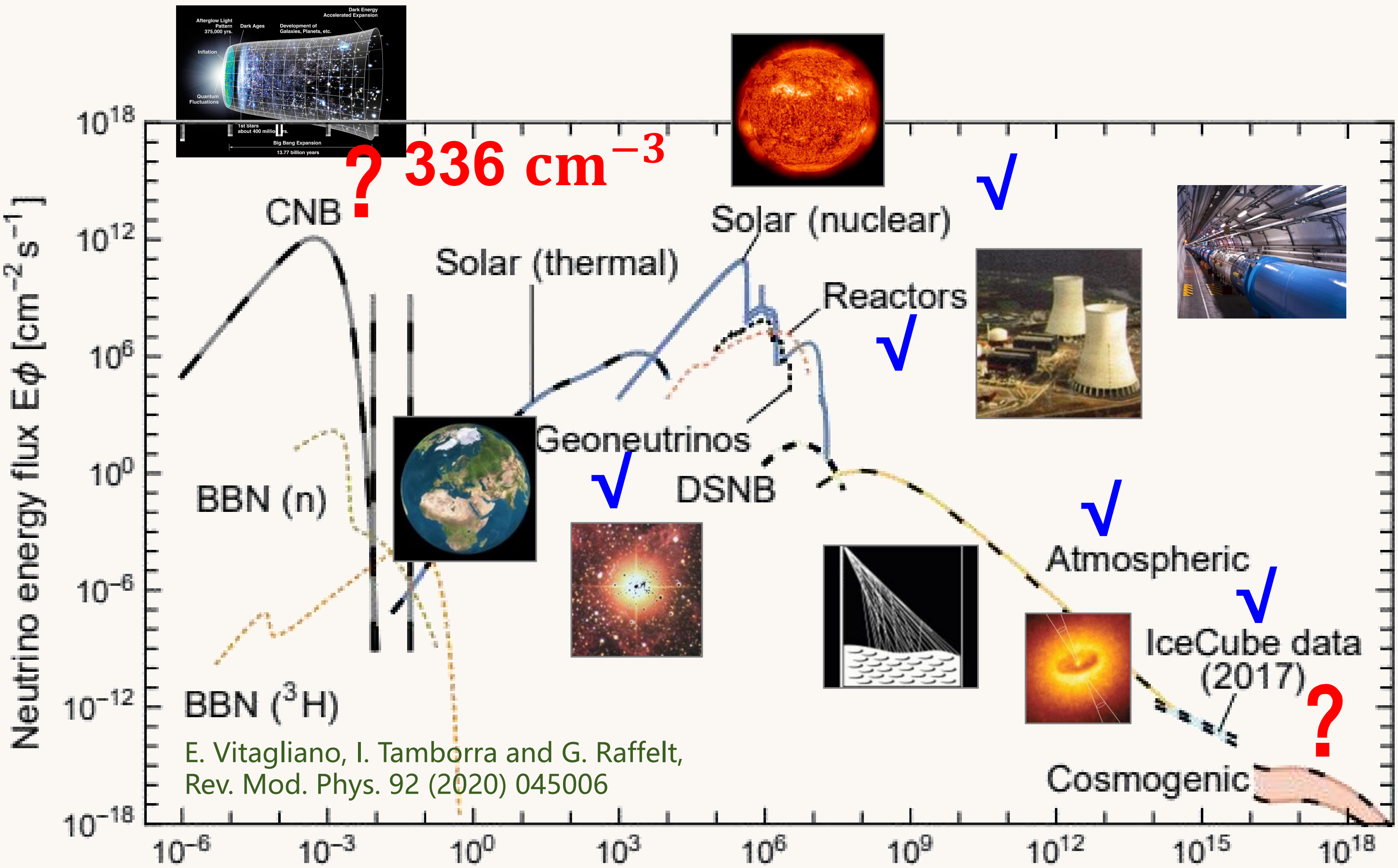
1987

Discovery of SN nu



2015

Neutrinos



Relic neutrinos

High flux

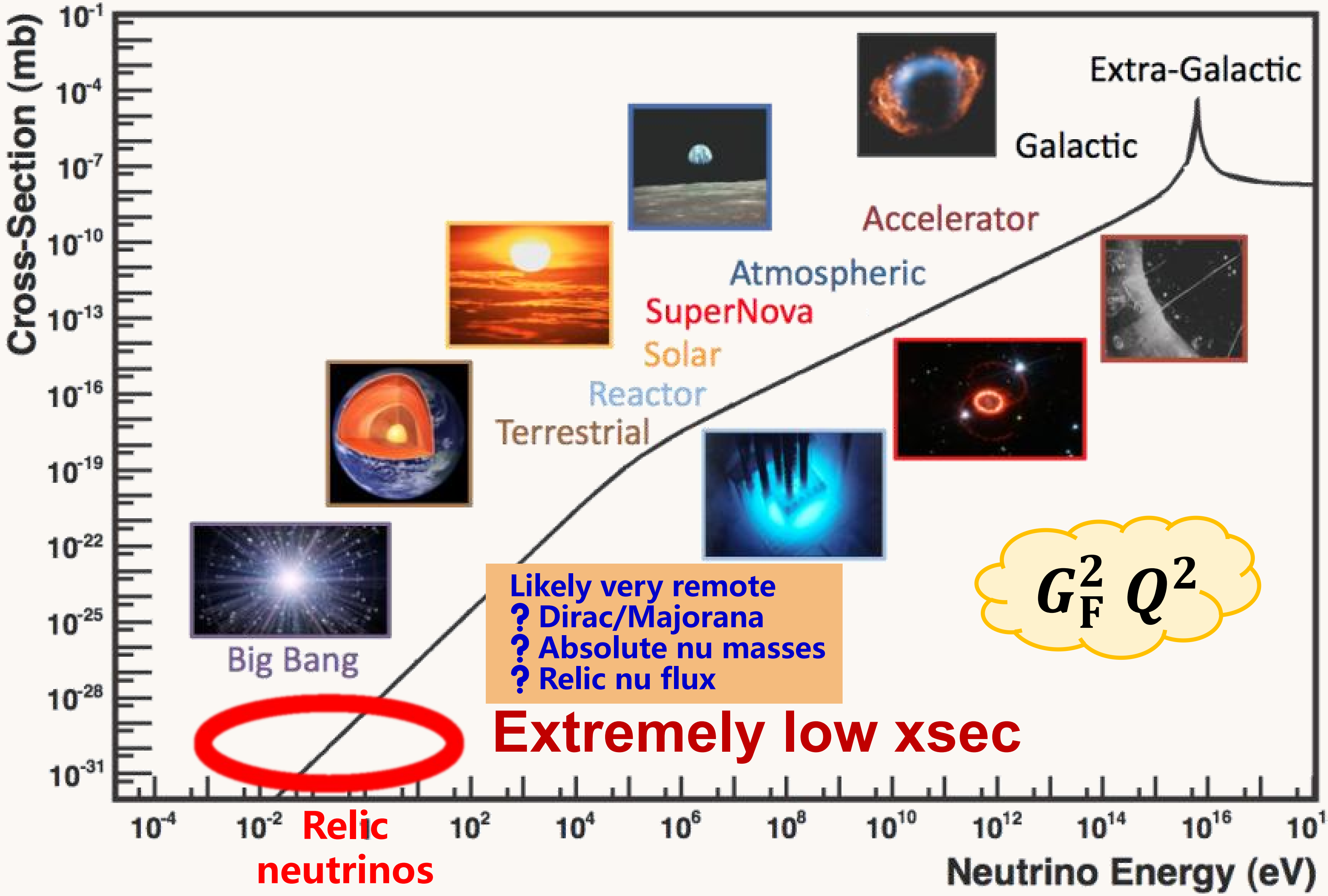
<-------------- Energy E [eV] -------------->

Cosmogenic neutrinos

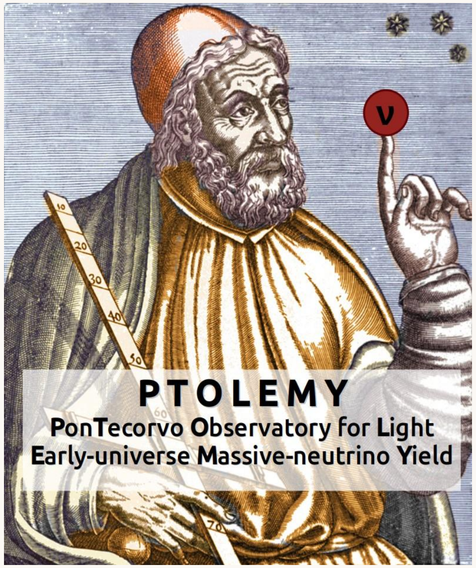
Low flux

Cosmic relics

Formaggio and Zeller, Rev. Mod. Phys. 84 (2012) 1307



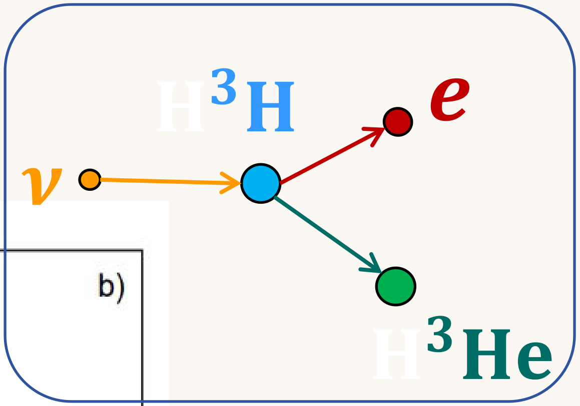
Triutium capture

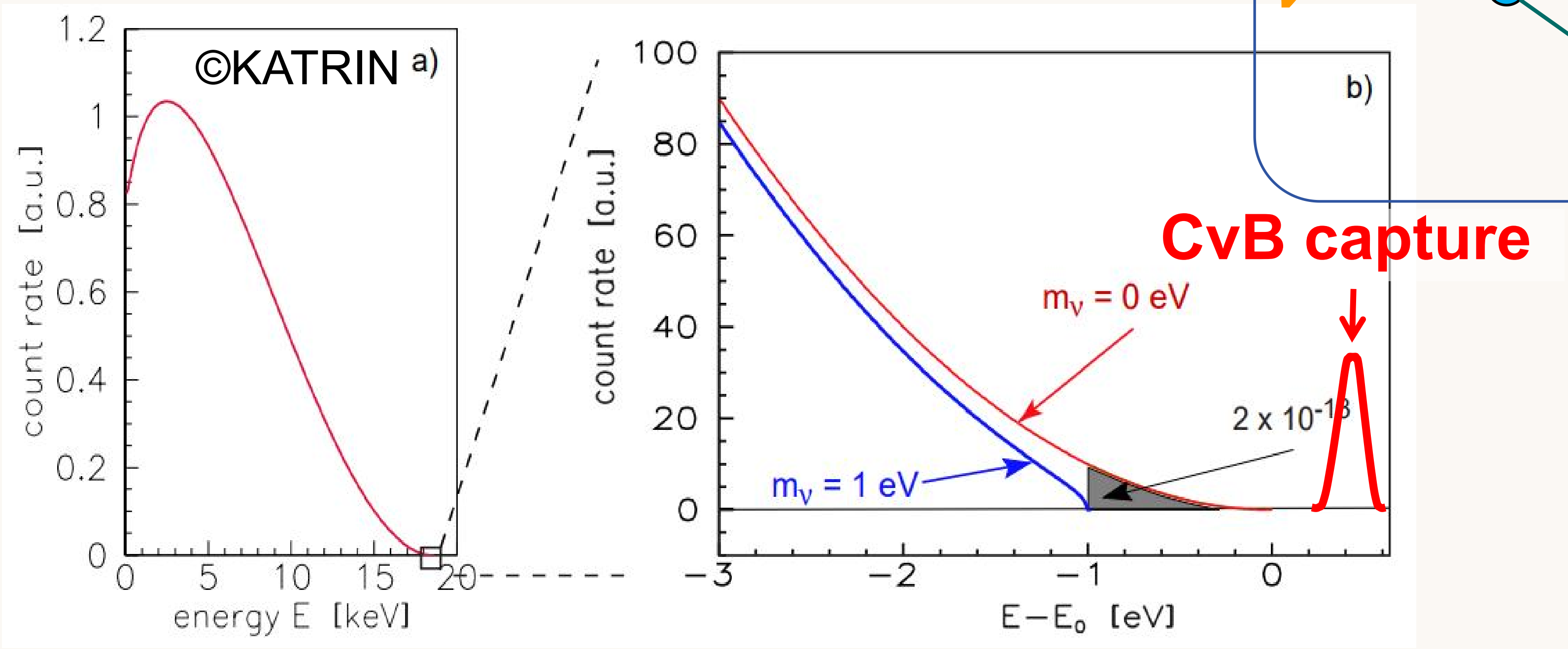


* Inverse β decay proposed by S. Weinberg.

* A direct evidence of the era when the Universe is one second old.

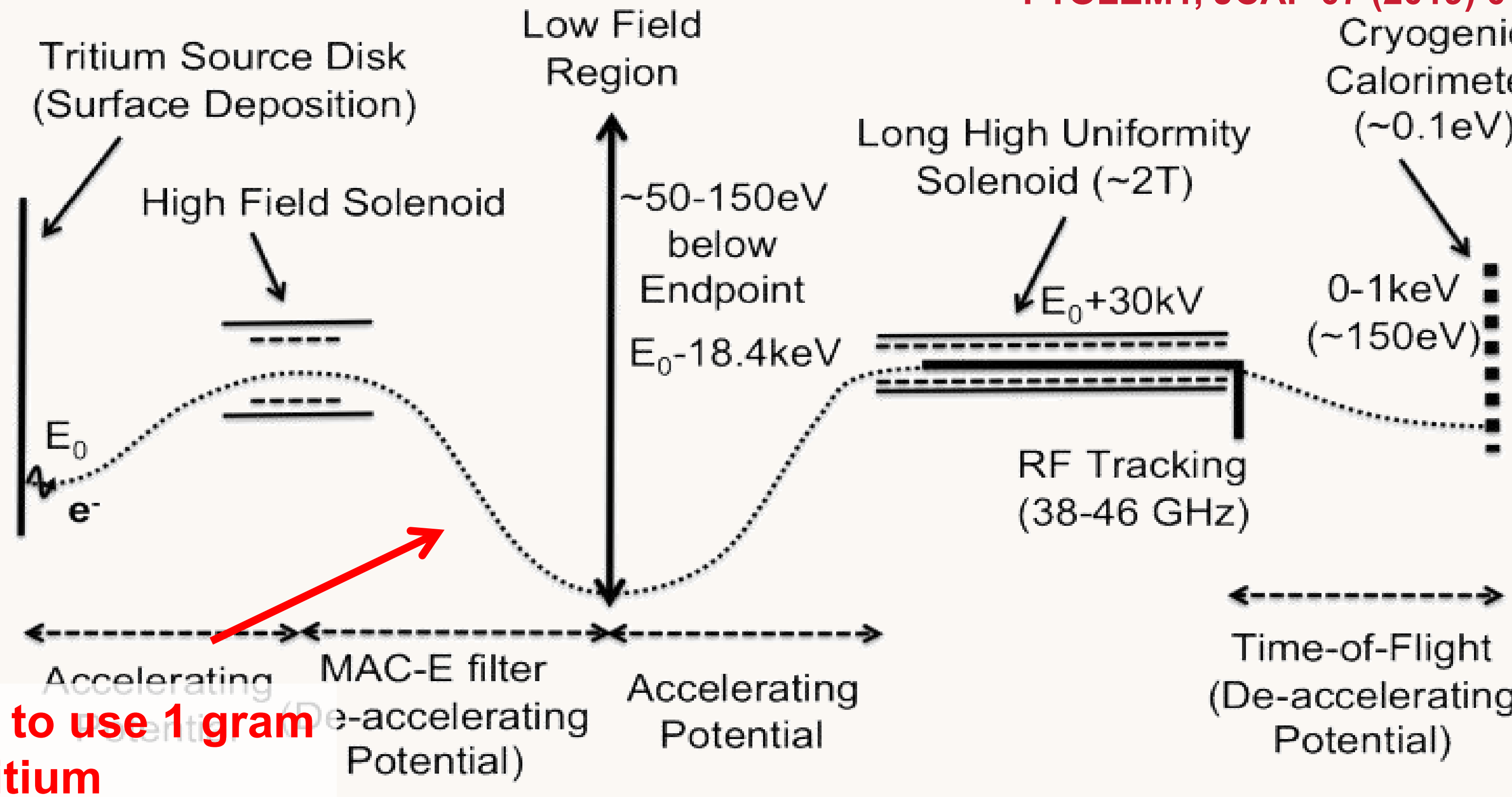
* The detection can also help to pin down neutrino's properties such as absolute mass and Dirac/Majorana nature.



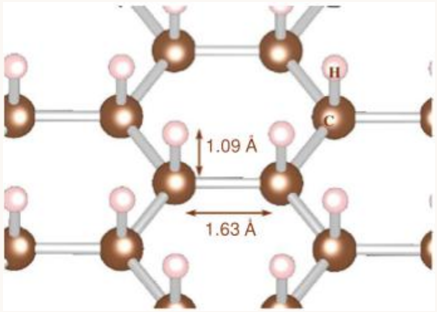


PTOLEMY Project

PTOLEMY, JCAP 07 (2019) 047



How to use 1 gram of tritium



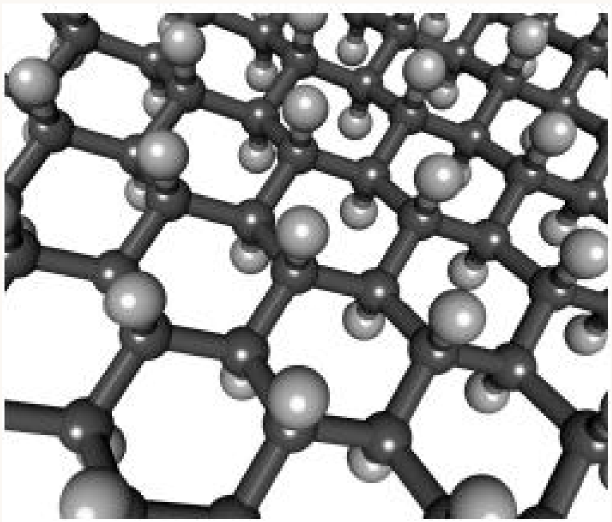
graphene

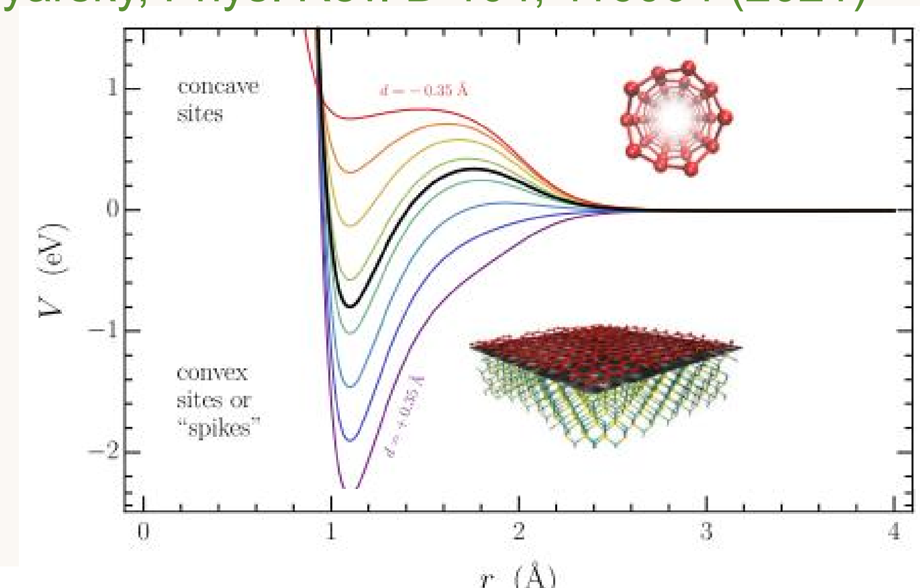
Neutrino mass as a byproduct

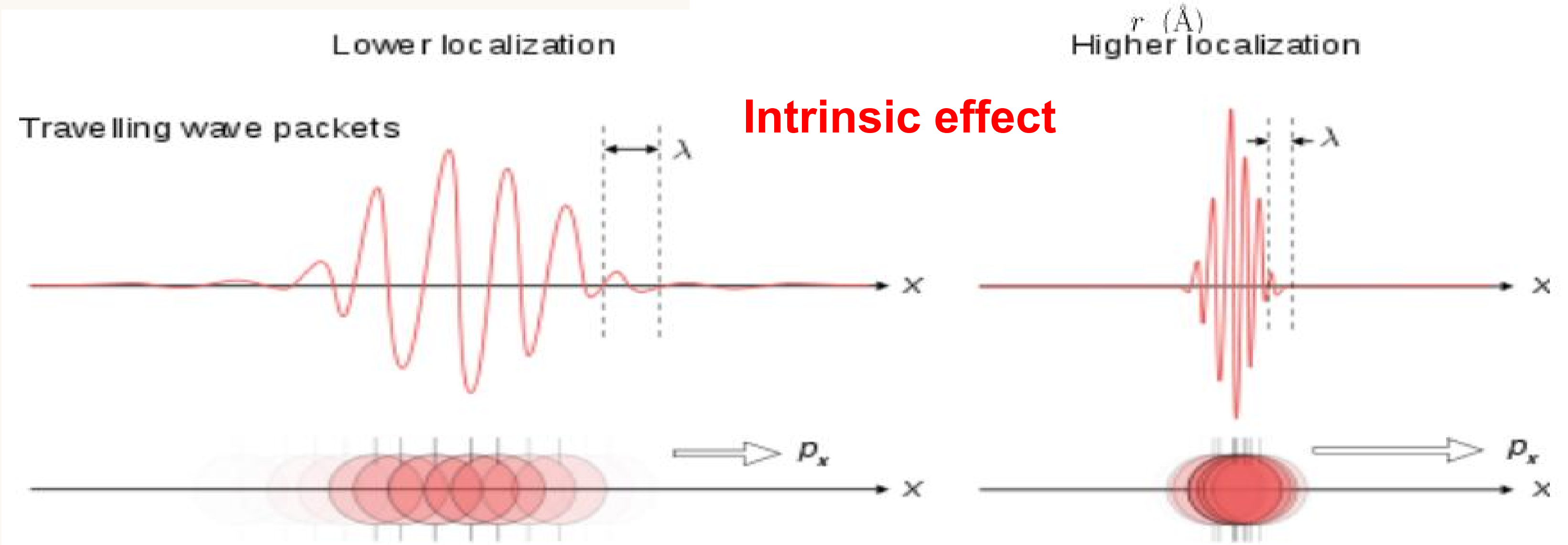
$$m_{\text{lightest}} > 0.01\ \text{eV}:$$
$$\sigma(m_{\text{lightest}})/m_{\text{lightest}} < 1\%$$

PTOLEMY: Quantum challenge

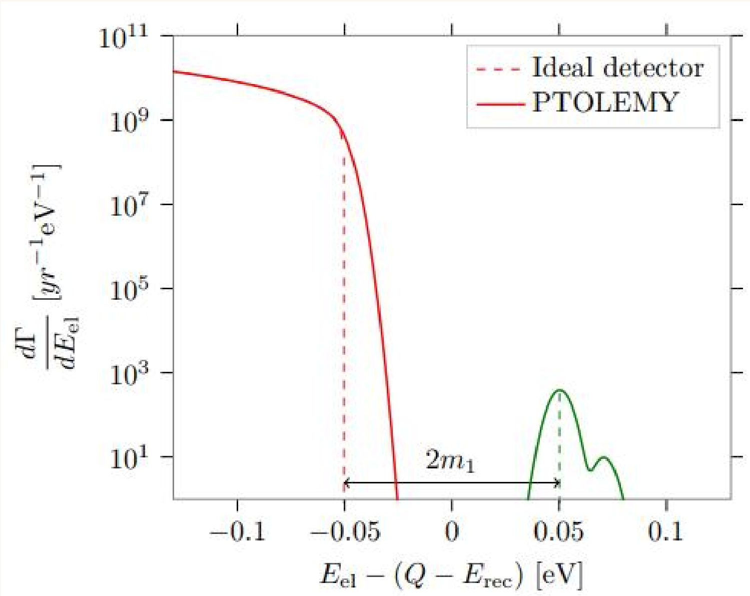
Cheipesh, V. Cheianov, and A. Boyarsky, Phys. Rev. D 104, 116004 (2021)



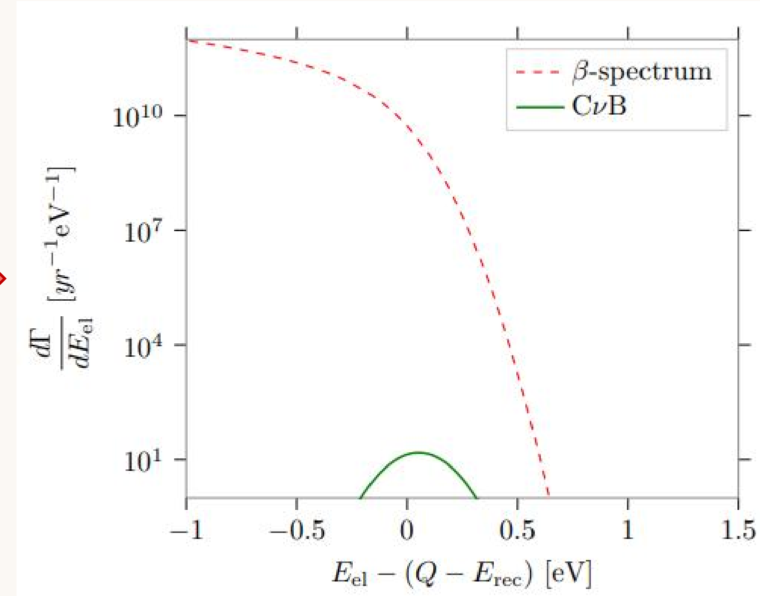




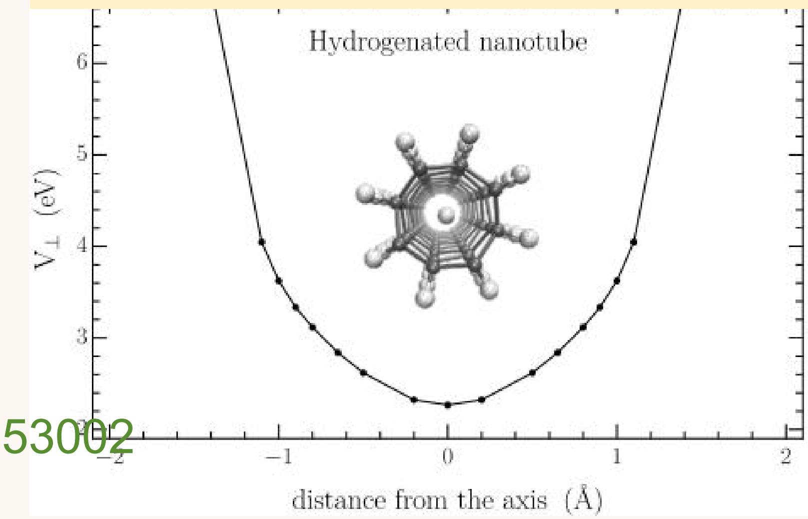
PTOLEMY: Quantum challenge



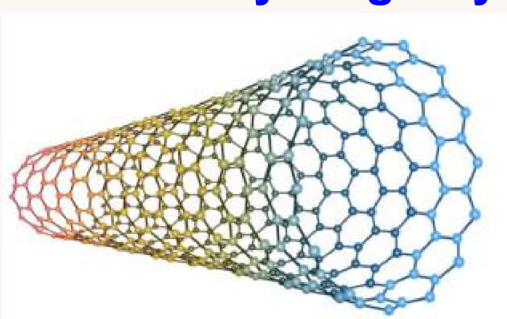
eV-scale smearing



Transverse potential to confine tritium



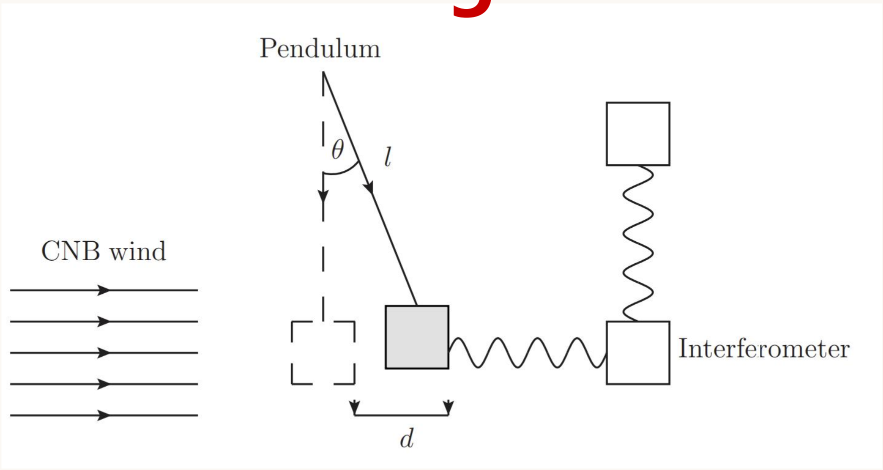
Carbon nanotube may rescue,
but still a very long way to go.



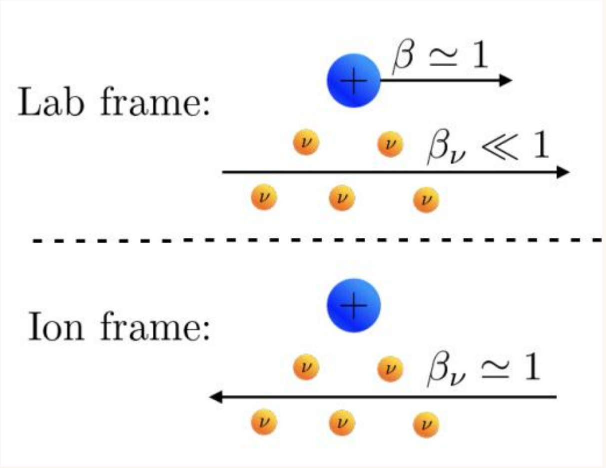
PTOLEMY, Phys.Rev.D 106 (2022) 5, 053002

Reconsider other methods?

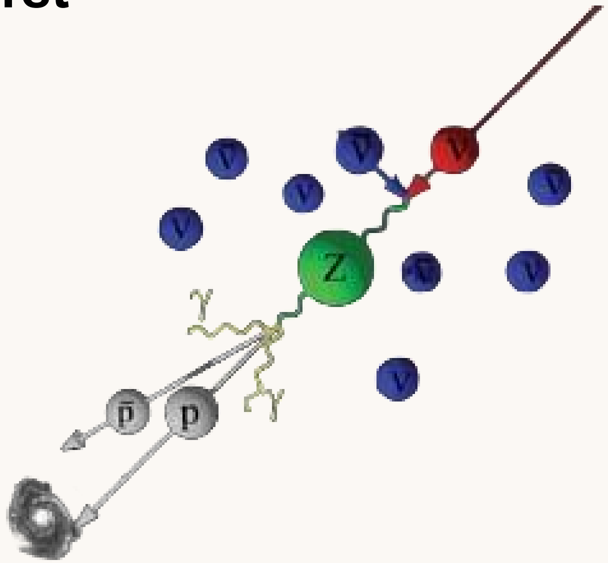
Coherent signals in lab



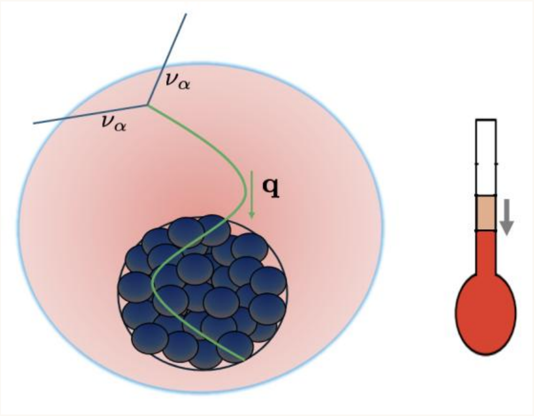
Ions in accelerators



Z-burst

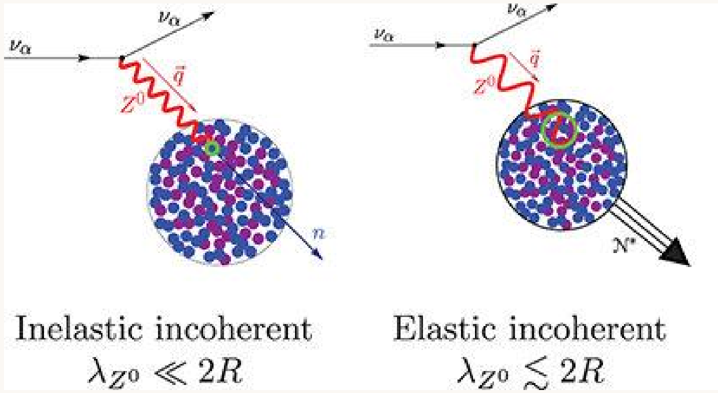


Neutron star cooling



Coherent enhancement

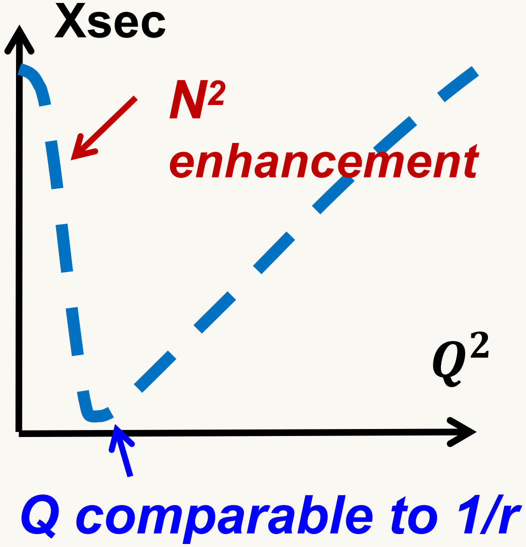
$$\Gamma \propto |\mathcal{M}_1|^2 + |\mathcal{M}_2|^2 + |\mathcal{M}_3|^2 + \cdots + |\mathcal{M}_N|^2 \propto N$$

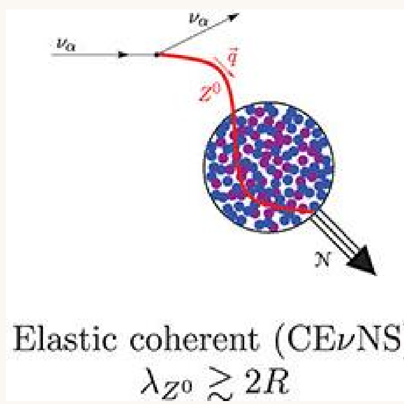


$$\mathcal{M}_{tot} = \sum_a \mathcal{M}(x_a) \bullet e^{i\sum_l k_l \cdot x_a}$$

Quantum phases are averaged out for lengthes beyond the De Broglie wavelength

$$\Gamma \propto |\mathcal{M}_1 + \mathcal{M}_2 + \mathcal{M}_3 + \cdots + \mathcal{M}_N|^2 \propto N^2$$





The extreme case is just the coherent forward scattering.

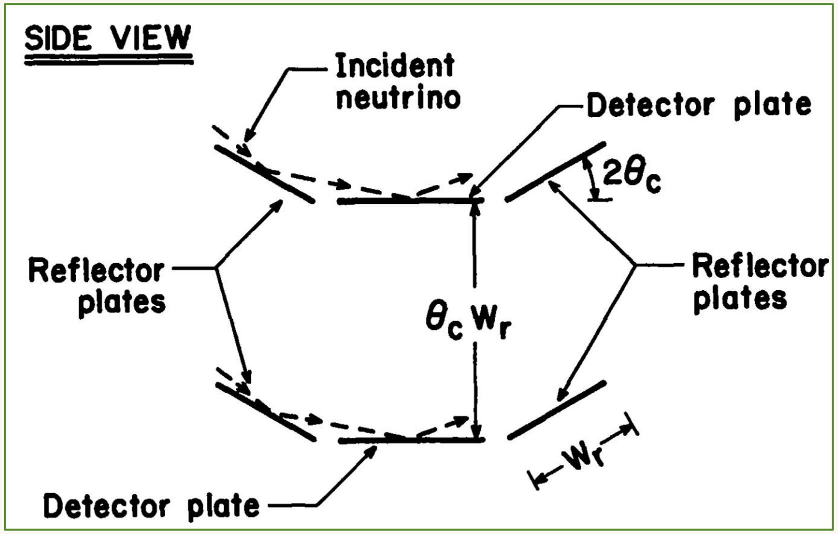
We are also clear here that coherence relies on momentum transfer *(!= absolute momentum)*

For CνB: $1/T_\nu \sim 0.1$ cm

Force of order G_F

Opher's proposal: Total reflection

Opher, Astron. Astrophys. 37 (1974) , 135-137



Matter potential

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

Refractive index

$$n_\nu - 1 \equiv \delta_\nu = -\langle \frac{m_\nu U}{k_\nu^2} \rangle \quad \sim 10^{-8}$$

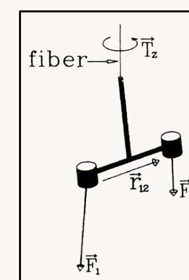
Critical angle

$$\theta_C = \sqrt{-2\delta_\nu} \propto G_F^{1/2} \quad \sim 10^{-4}$$

$\sim 0.01°$

2. Lewis's idea of refraction

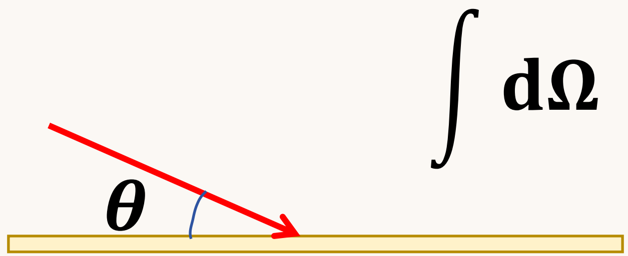
- Mechanical recoil
- Torque



Lewis, Phys. Rev. D 21 (1980) 663.

The recoil force here will be of order G_F

Vanishing of G_F force



N. Cabibbo and L. Maiani, Phys. Lett. B 114 (1982) 115–117

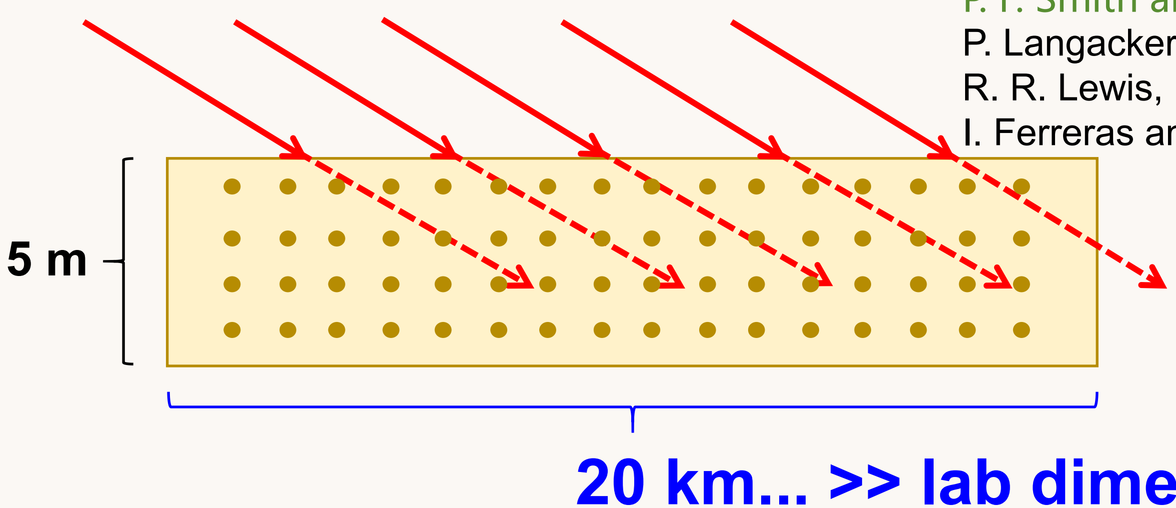
How many G_F's for the force?

- **reflection recoil ($\theta_c \propto G_F^{1/2}$)**
- **isotropic flux (θ_c)**
- **inclined surface (θ_c)**

By integrating over both sides, Cabibbo and Maiani find only G_F^2 force remains and claim G_F force holds only for collimated neutrino flux

However, this is not true even for collimated neutrinos...

P. F. Smith and J. D. Lewin, PLB 127 (1983) 185
P. Langacker et al., PRD 27 (1983) 1228.
R. R. Lewis, PRD 35 (1987) 2134.
I. Ferreras and I. Wasserman, PRD 52 (1995) 5459

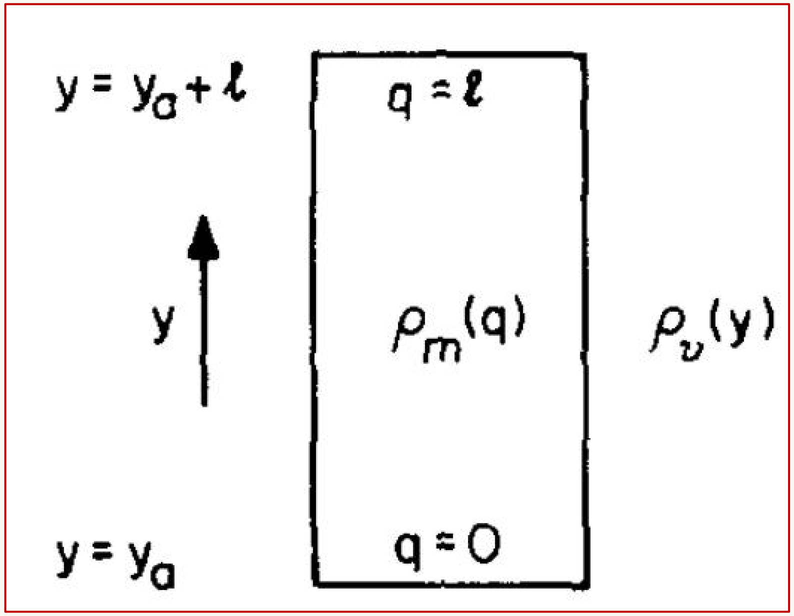


Total reflection is not a sudden reaction at the surface

Gradient force

Matter potential, but role reversed

$$\mathcal{H}_{\text{eff}}(x) = \frac{G_F}{\sqrt{2}} \overline{\nu}_e(x)\gamma^\mu(1-\gamma_5)\nu_e(x)\,\overline{e}(x)\gamma_\mu\left(g_V^e - g_A^e\gamma_5\right)e(x)$$



$$U(\mathbf{x}_d, t) = \frac{G_F}{\mu}\int_{\mathcal{V}} d^3x\,\rho(\mathbf{x})[n_\nu(\mathbf{x}_d+\mathbf{x},t) - n_{\bar{\nu}}(\mathbf{x}_d+\mathbf{x},t)]\ ,$$

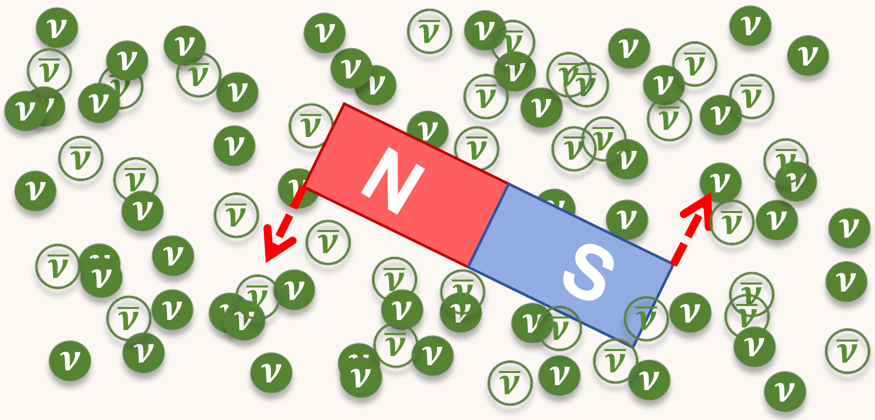
$$E = S\int_0^l U_1\,\rho_m(q)\,\rho_\nu(y_a+q)\,\mathrm{d}q$$

$$F_y = -\frac{V}{l}\int_0^l U_1\,\rho_m(q)\,\frac{\partial}{\partial y_a}\rho_\nu(y_a+q)\,\mathrm{d}q$$

"There is no known way to generate artificial density gradients large enough to result in easily measurable steady forces O(G_F)"

Ferreras & Wasserman, 1995

Stodolsky effect



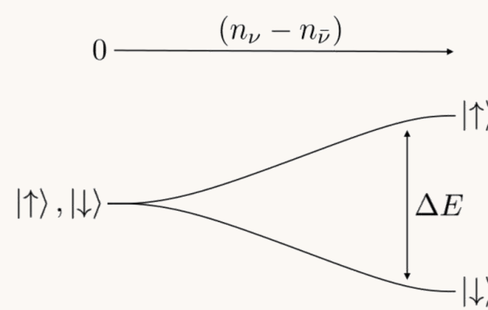
Stodolsky has discussed two effects in his original paper:

- **Electron spin rotation in vacuum**
- **Torque of ferromagnet**

Stodolsky, Phys. Rev. Lett. 34 (1975) 110

Energy spliting between two spin/helicity states (relativistic nu)

$$E \approx -2\sqrt{2}G_F g_A \vec{s}_e \bullet \vec{\beta}_{earth}(n_\nu - n_{\bar{\nu}})$$



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Torque acceleration for a magnet

$$a^R_{G_F} \approx 4 \cdot 10^{-29} \frac{n_{\bar{\nu}_\mu} - n_{\nu_\mu}}{2\,\bar{n}_\nu}\ \mathrm{cm/s^2}$$

Unfortunately, the suppresion of neutrino-antineutrino asymmetry will worsen the situation

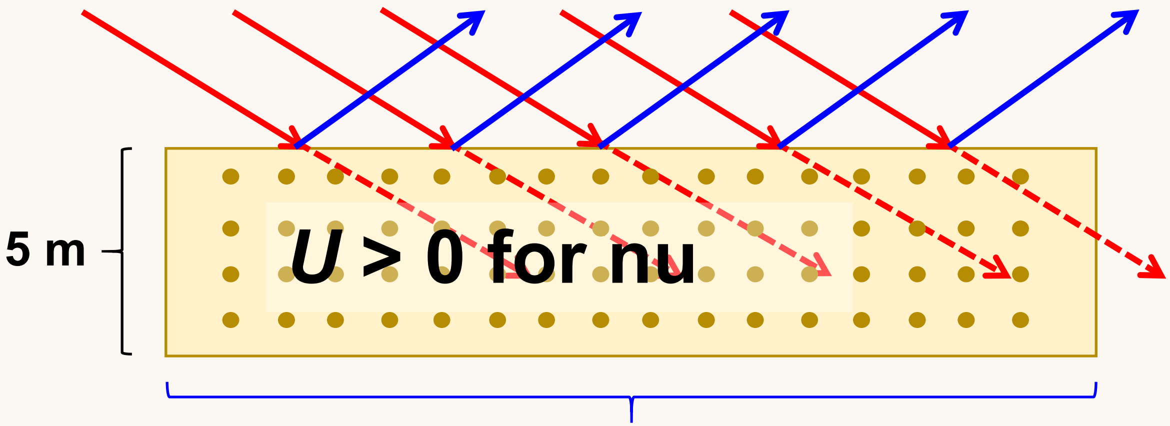
Evade no-go?

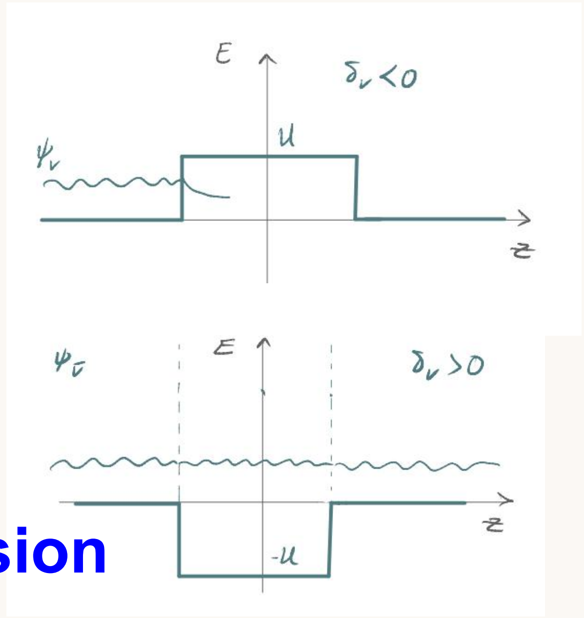
Two bottlenecks

1. Negligible neutrino-antineutrino asymmetry in SM

2. Relic neutrino flux is believed to be uniform (i.e., no gradient term)

Total reflection by the Earth





20 km... << Earth dimension

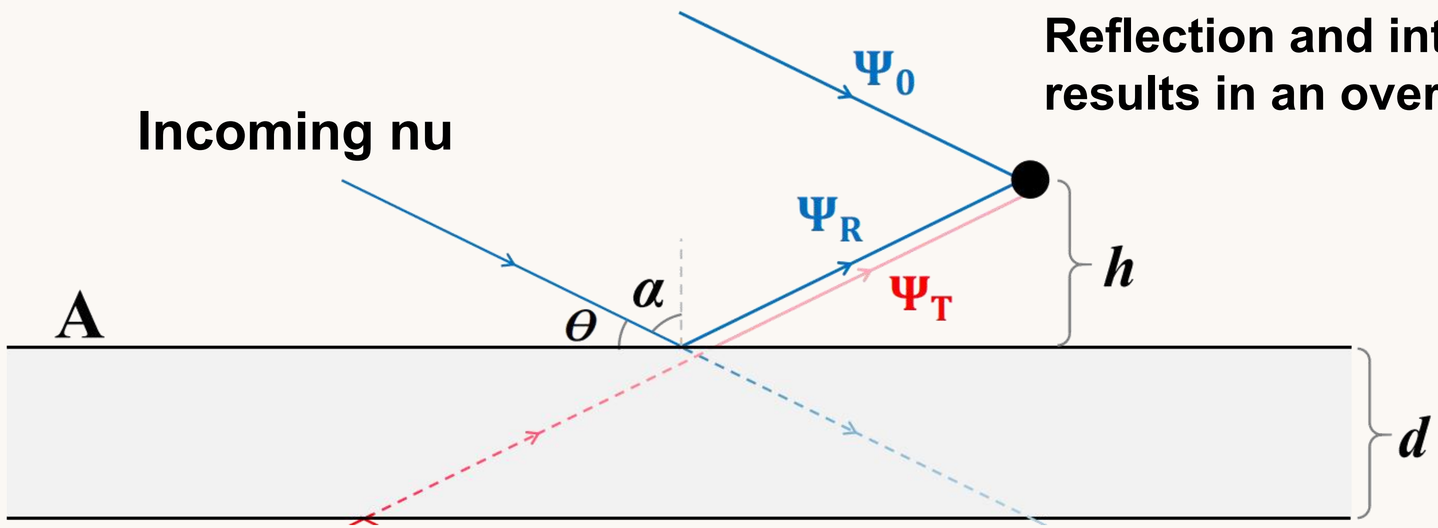
$$P \approx |C_Z^A|^2\, G_F^2 n^2 L^2 \left(\frac{E}{p}\right)^2 \sim |C_Z^A|^2 \left(\frac{n}{N_A \bullet \mathrm{cm}^{-3}}\right)^2 \left(\frac{L}{10\,\mathrm{km}}\right)^2$$

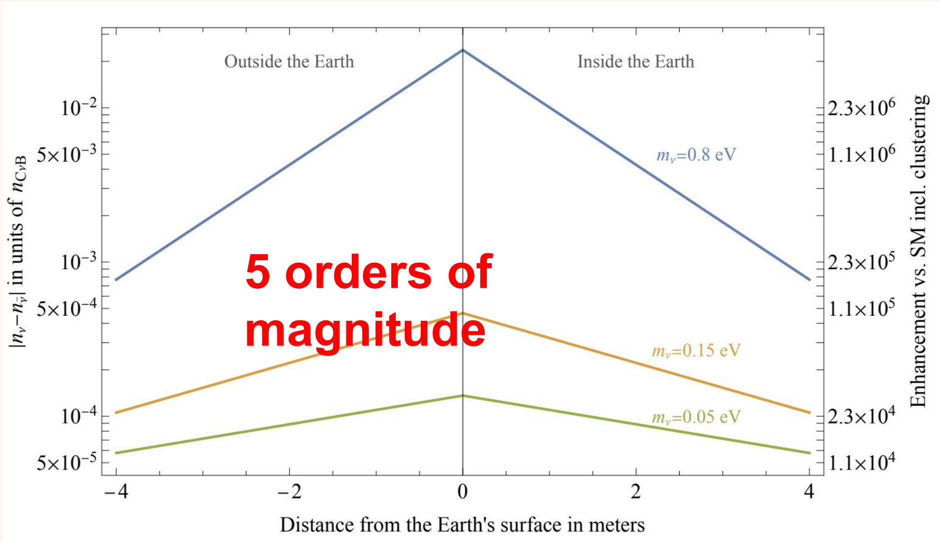
(Dirac neutrinos)

A. Arvanitaki and S. Dimopoulos, Phys. Rev. D 108 (2023) 043517

"total reflection of cosmic neutrinos from the surface of the Earth results in a local ν−νbar asymmetry"

Enhanced asymmetry and gradient





An asymmetry peaked at the surface and decreasing away the surface

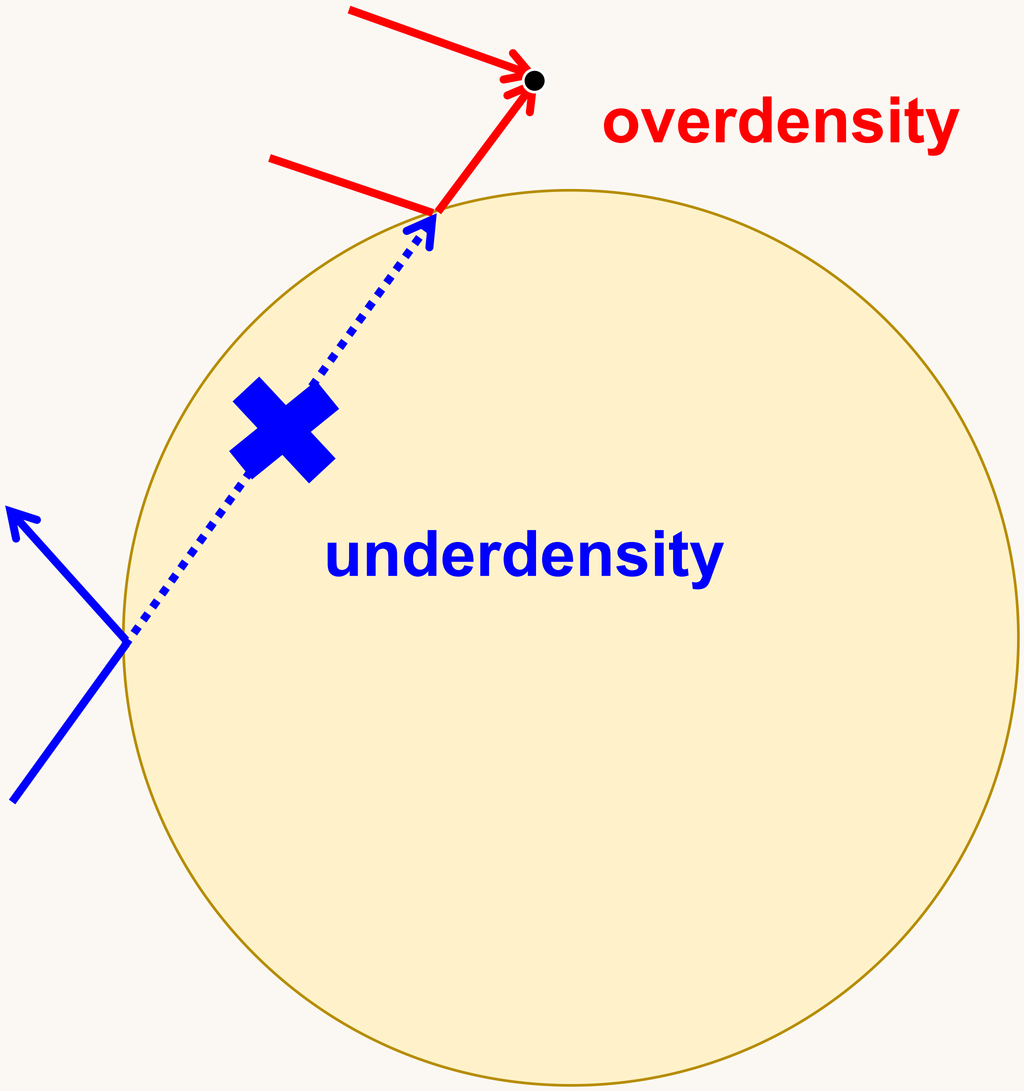
$$\frac{n_\nu - \bar{n}_\nu}{n_\nu}(z) = \frac{2}{15}\sqrt{2|\delta_\nu|}\left(3 + 5e^{-\frac{|z|}{\lambda_{\rm cr}}}\right)$$

Asymmetry ✓

Gradient ✓

an acceleration of order 10^{-30} cm/s^2

But Earth is round

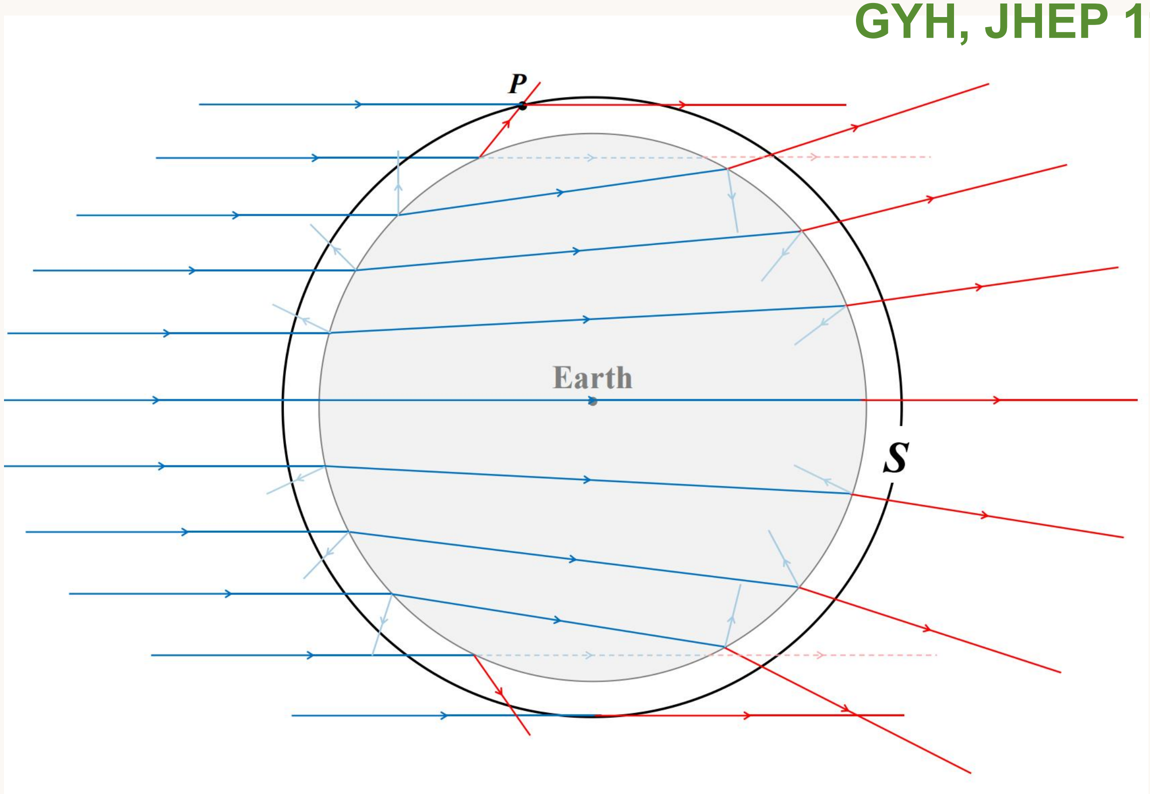


Roundness conserves things, just a simple observation:

overdensity + underdensity ~ 0

Semiclassical treatment

GYH, JHEP 11 (2024) 153



Three conservation laws

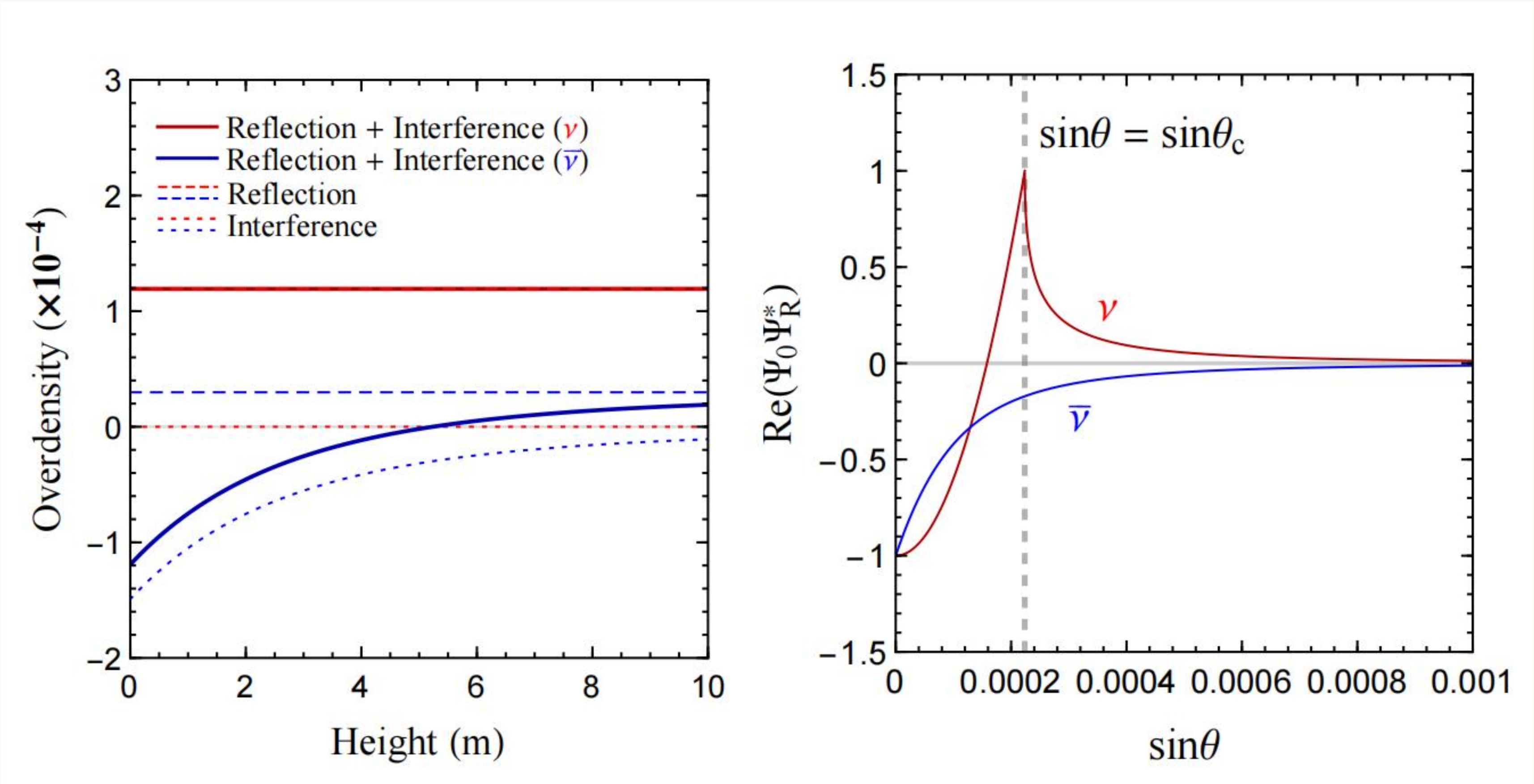
- **Particle number**
- **Kinetical energy**
- **Angular momentum**

$$n_\nu(r) = n_0$$

$$n_{\nu(\overline{\nu})}(r) = \frac{n_0}{4\pi} \int |\Psi(\boldsymbol{x})|^2 \, \mathrm{d}\Omega = \frac{n_0}{4\pi r^2} \oiint |\Psi(\boldsymbol{x})|^2 \, \mathrm{d}S$$

in the semiclassical limit (ignoring interference)

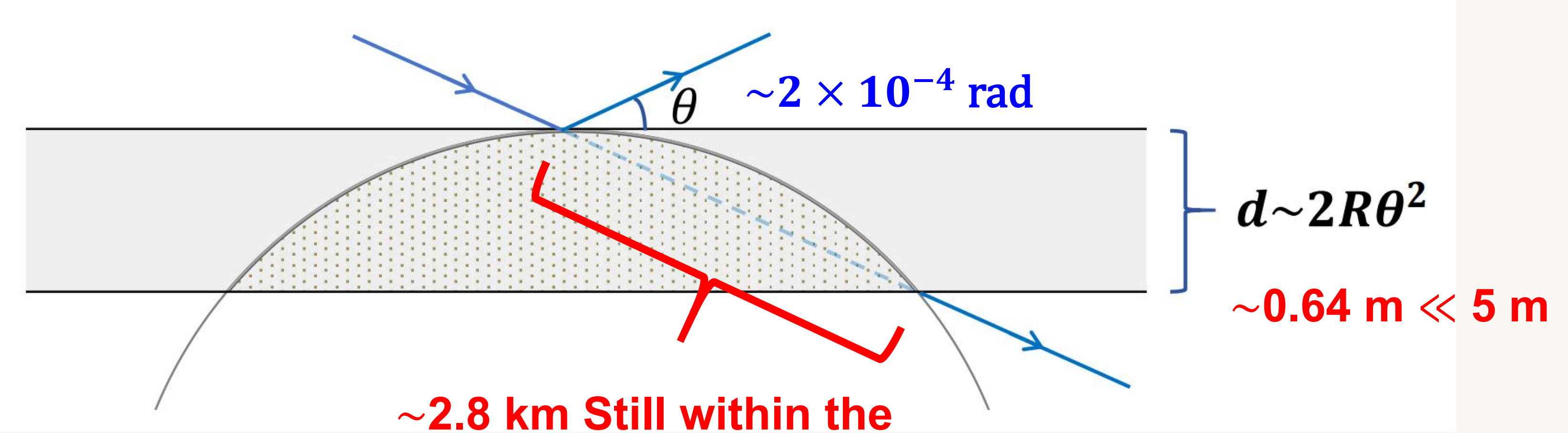
Looking closer



Interference matters for antineutrinos

The overdensity for neutrinos is solely due to reflected waves, while the underdensity of antineutrinos receives two contributions.

Semiclassical treatment

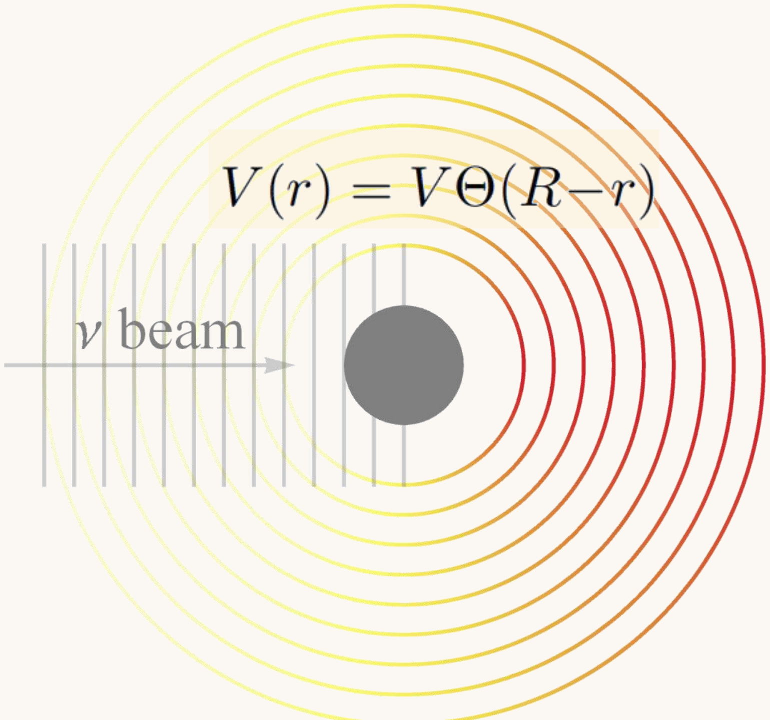


~2.8 km Still within the perturbative regime

Neutrinos can already feel the curvature of the Earth spanning over 20 km, corresponding to an arc of 0.003 rad.

Slab approximation ✖

The scattering problem



Lippmann-Schwinger equation

$$|\Psi\rangle = |\phi\rangle + \frac{1}{E - \widehat{H}_0 + \mathrm{i}\epsilon}\widehat{V}\,|\Psi\rangle$$

Partial-wave expansion

$$\Psi(r,\theta) = \sum_l \mathrm{i}^l(2l+1)A_l(r)P_l(\cos\theta)$$

Radial wavefunction

$$\frac{\mathrm{d}^2(rA_l)}{\mathrm{d}r^2} + \left[k_\nu^2 - 2mV(r) - \frac{l(l+1)}{r^2}\right]rA_l = 0$$

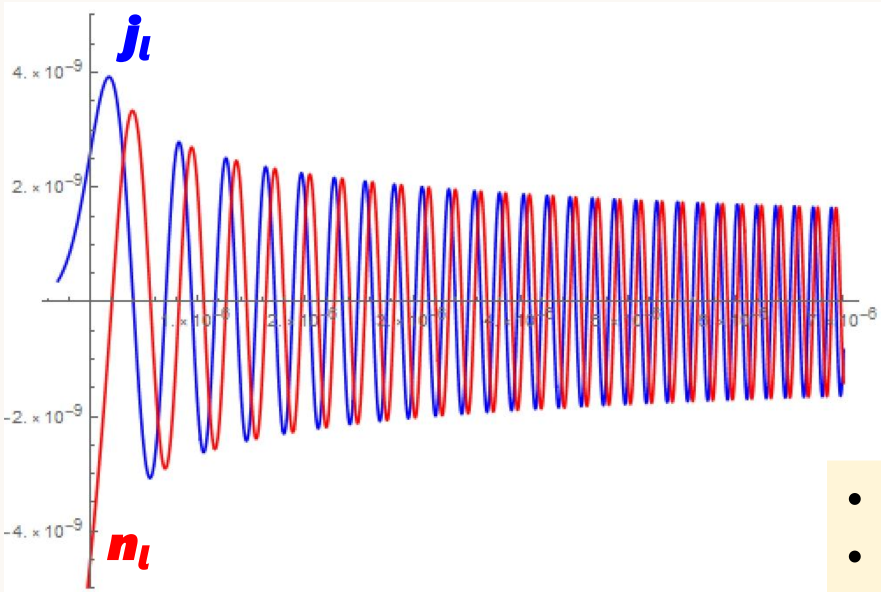
$$A_l(r) = \mathrm{e}^{\mathrm{i}\delta_l}\left[\cos\delta_l j_l(k_\nu r) - \sin\delta_l n_l(k_\nu r)\right]$$

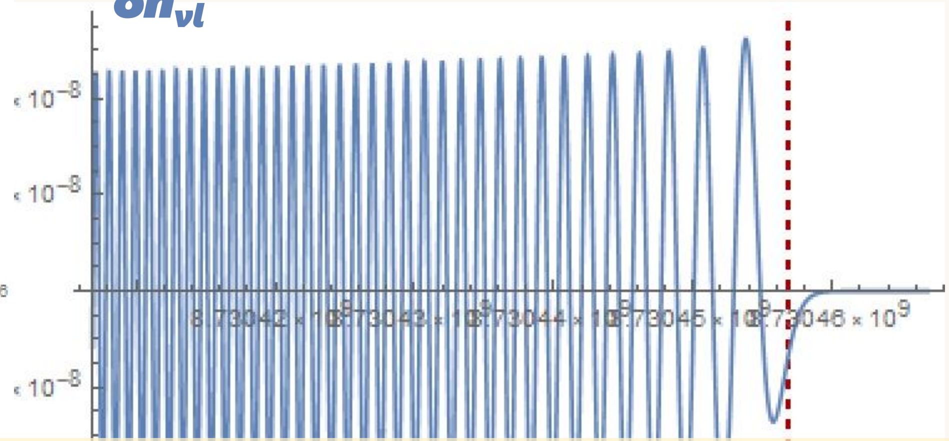
A typical scattering problem in quantum mechanics

- **Uniform spherical potential**
- Monoenergetic and isotropic neutrino flux

Key is to pin down the phase shift δ_l

Bessel modes





- **Highly oscillatory, i.e., high stiffness**
- **One has to directly sum over the angular modes from *l = 0* to *$l \sim 10^{10}$*...**

By requiring the continuity of wavefunction and its derivative

$$\tan\delta_l = \frac{k_\nu\, j_l(k'_\nu R)\, j_{l+1}(k_\nu R) - k'_\nu\, j_l(kR)\, j_{l+1}(k'_\nu R)}{k_\nu\, j_l(k'_\nu R)\, n_{l+1}(k_\nu R) - k'_\nu\, j_{l+1}(k'_\nu R)\, n_l(k_\nu R)}$$

$$\delta n_{\nu(\bar{\nu})}(r) = n_0 \sum_{l=0}^{\infty} (2l+1)\left[\sin^2\delta_l\,(n_l^2(kr) - j_l^2(kr)) - \sin 2\delta_l\, j_l(kr) n_l(kr)\right]$$

Bessel evaluation precision

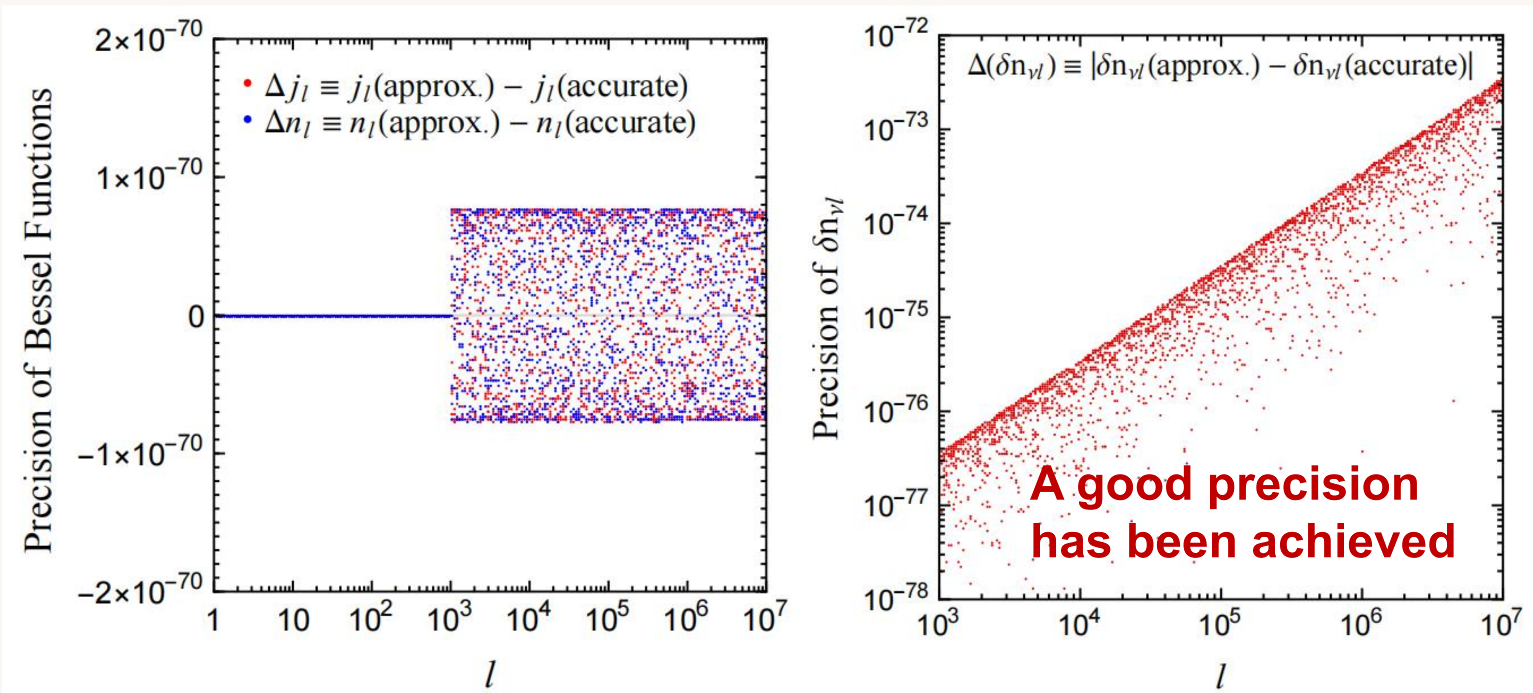
Asymptotic approximation (https://dlmf.nist.gov/10.20)

$$J_\nu(\nu z) \sim \left(\frac{4\zeta}{1-z^2}\right)^{\frac14}\left(\frac{\mathrm{Ai}\left(\nu^{\frac23}\zeta\right)}{\nu^{\frac13}}\sum_{k=0}^{\infty}\frac{A_k(\zeta)}{\nu^{2k}} + \frac{\mathrm{Ai}'\left(\nu^{\frac23}\zeta\right)}{\nu^{\frac53}}\sum_{k=0}^{\infty}\frac{B_k(\zeta)}{\nu^{2k}}\right),$$

$$Y_\nu(\nu z) \sim -\left(\frac{4\zeta}{1-z^2}\right)^{\frac14}\left(\frac{\mathrm{Bi}\left(\nu^{\frac23}\zeta\right)}{\nu^{\frac13}}\sum_{k=0}^{\infty}\frac{A_k(\zeta)}{\nu^{2k}} + \frac{\mathrm{Bi}'\left(\nu^{\frac23}\zeta\right)}{\nu^{\frac53}}\sum_{k=0}^{\infty}\frac{B_k(\zeta)}{\nu^{2k}}\right),$$

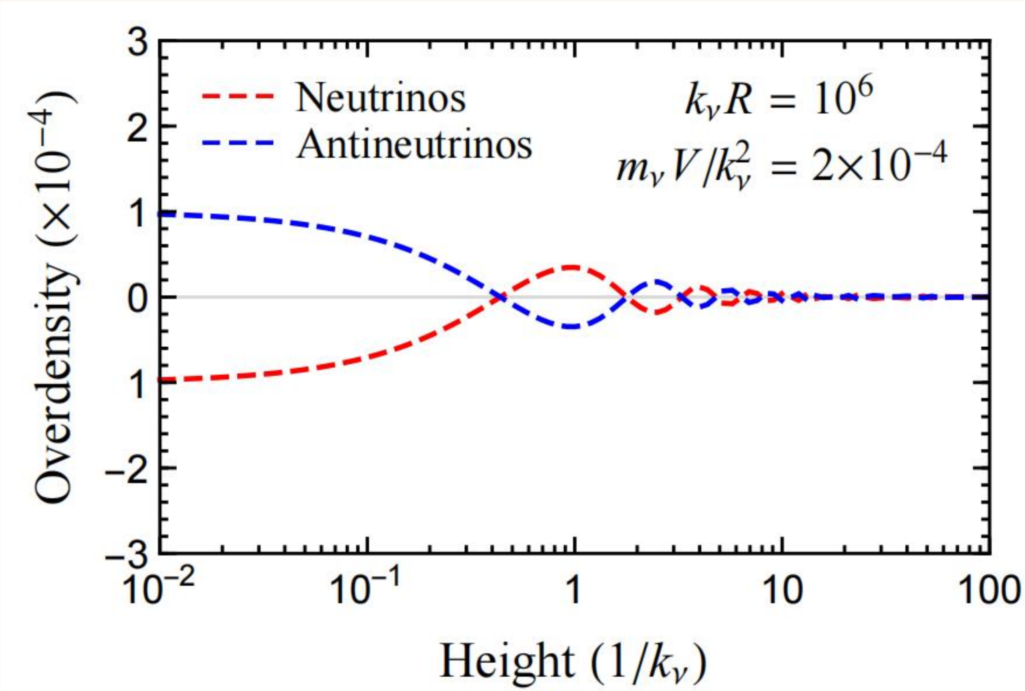
$$J_\nu\left(\nu + a\nu^{\frac13}\right) \sim \frac{2^{\frac13}}{\nu^{\frac13}}\mathrm{Ai}\left(-2^{\frac13}a\right)\sum_{k=0}^{\infty}\frac{P_k(a)}{\nu^{2k/3}} + \frac{2^{\frac23}}{\nu}\mathrm{Ai}'\left(-2^{\frac13}a\right)\sum_{k=0}^{\infty}\frac{Q_k(a)}{\nu^{2k/3}},$$

$$Y_\nu\left(\nu + a\nu^{\frac13}\right) \sim -\frac{2^{\frac13}}{\nu^{\frac13}}\mathrm{Bi}\left(-2^{\frac13}a\right)\sum_{k=0}^{\infty}\frac{P_k(a)}{\nu^{2k/3}} - \frac{2^{\frac23}}{\nu}\mathrm{Bi}'\left(-2^{\frac13}a\right)\sum_{k=0}^{\infty}\frac{Q_k(a)}{\nu^{2k/3}},$$



Sum up to the second order

Overdensity



- The overdensity gradually decreases away from the surface due to the decoherence effect.
- The overdensities for neutrinos and antineutrinos are opposite.
- The results are proportional to delta

The numerical evaluation for the actual Earth takes about two days on a laptop, giving

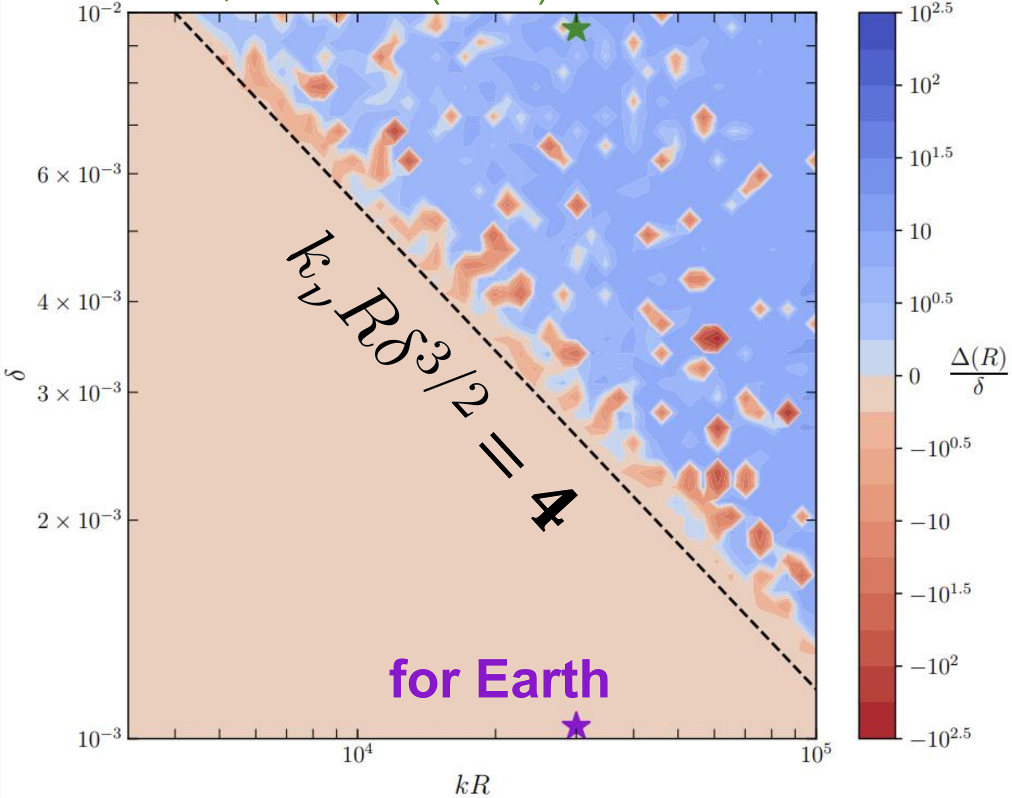
$$-\delta n_\nu \approx \delta n_{\overline{\nu}} \approx 1.25 \times 10^{-8}$$

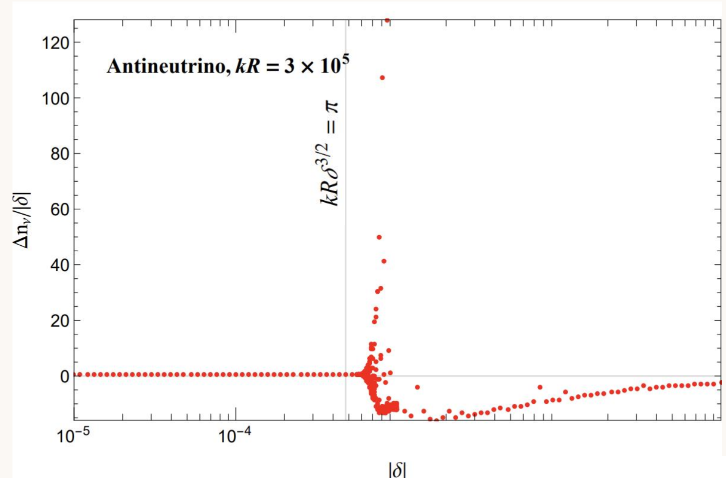
← $\frac{\delta_\nu}{2}$

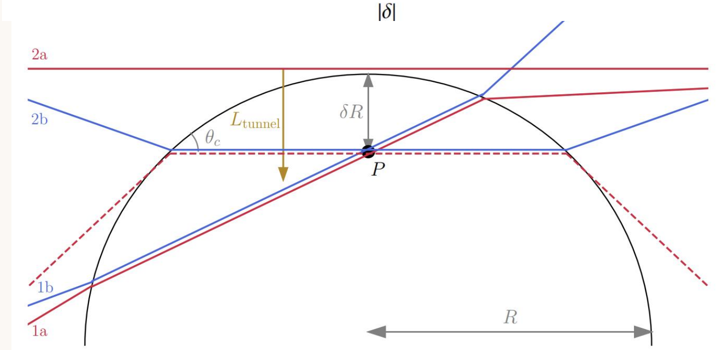
This result is not a surprise for neutrino, but things for antineutrino are expected to be different because of the interference

There is a criterion

Kalia, PRD 110 (2024) 053001





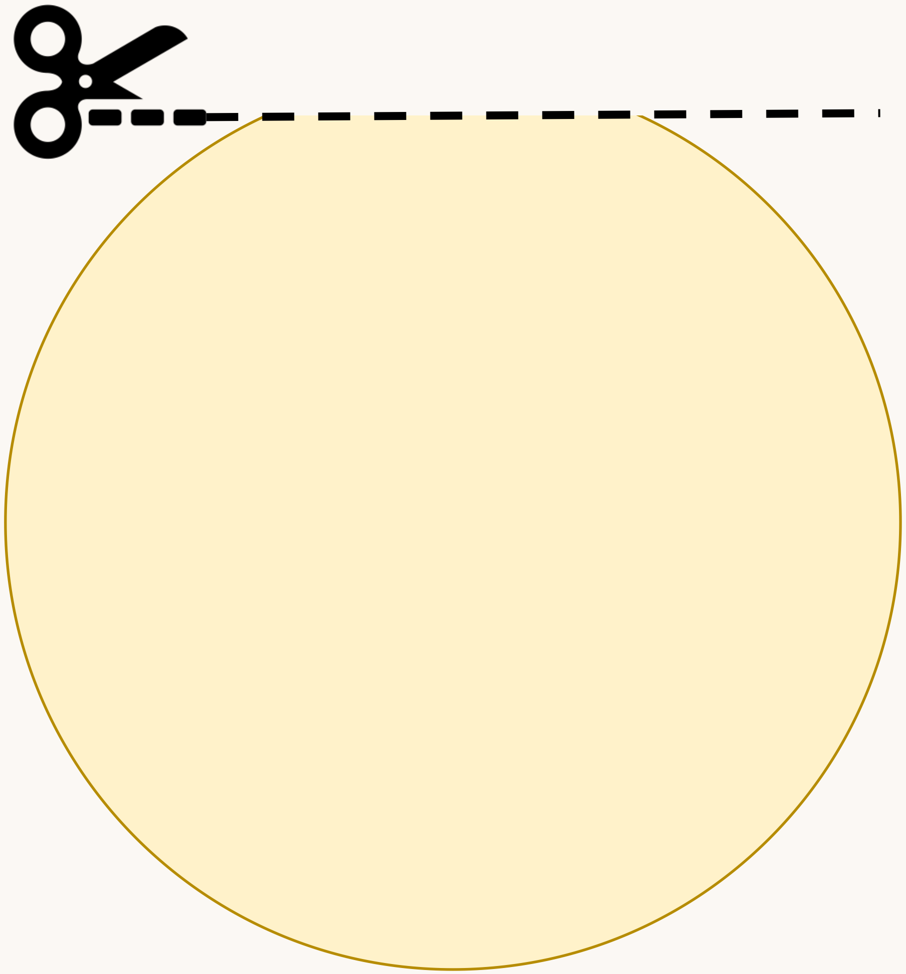


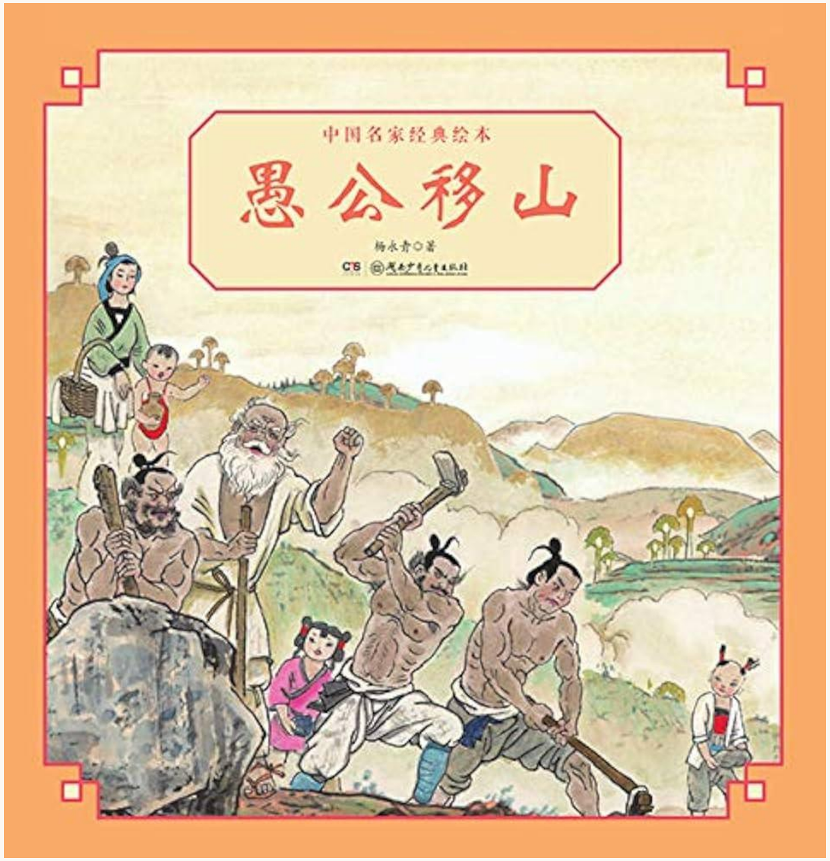
$$k_\nu R\delta^{3/2} \ll 1$$

It's about the Earth curvature

- **The scattering near the critical angle should be perturbative**
- **Focal effect, which can eliminate the underdensity for antinu**
- **Tunneling effect of waves**

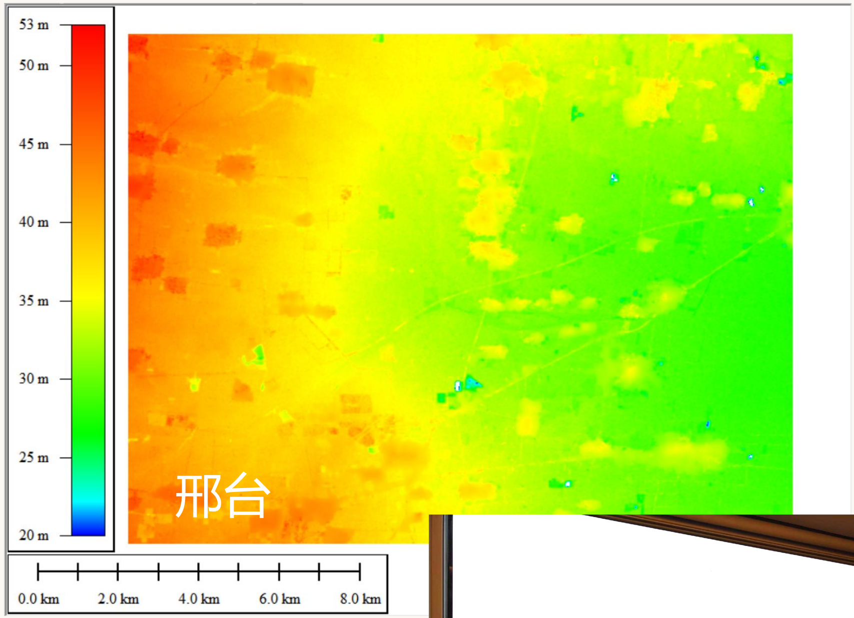
Flatten the Earth

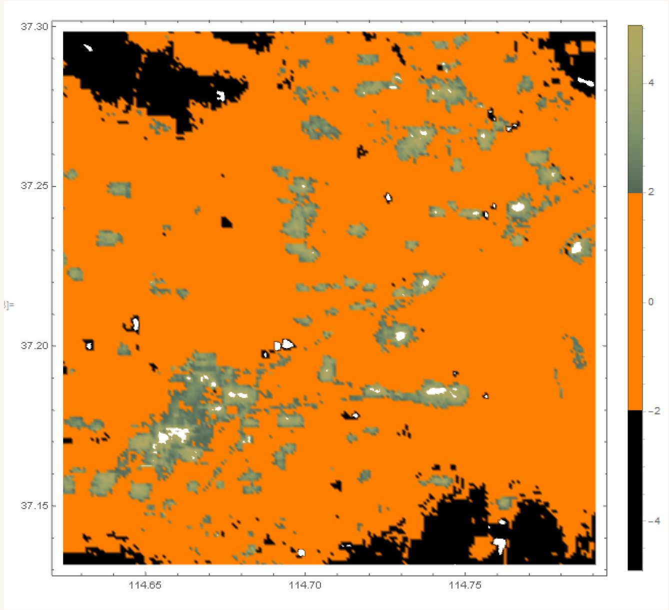


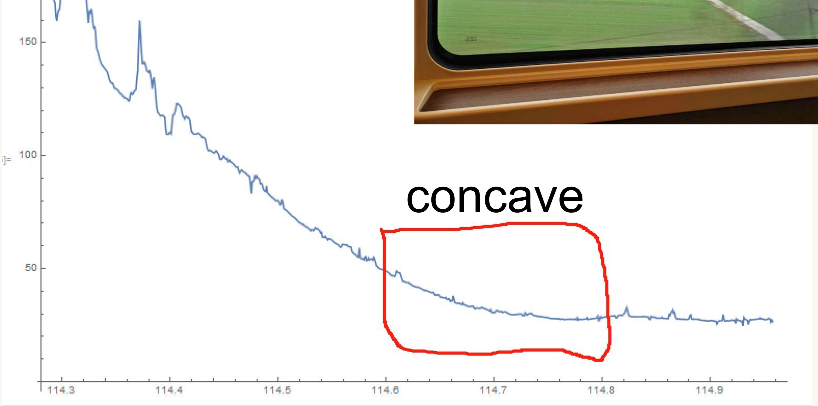


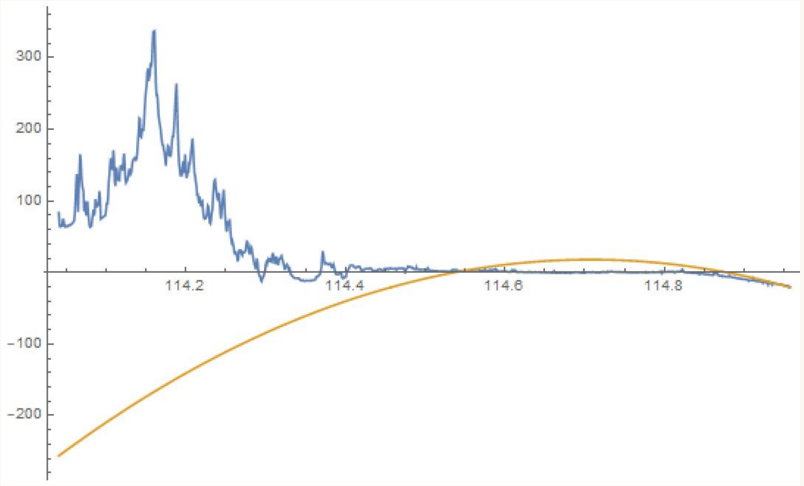
Flatten the Earth

20 km * 20 km

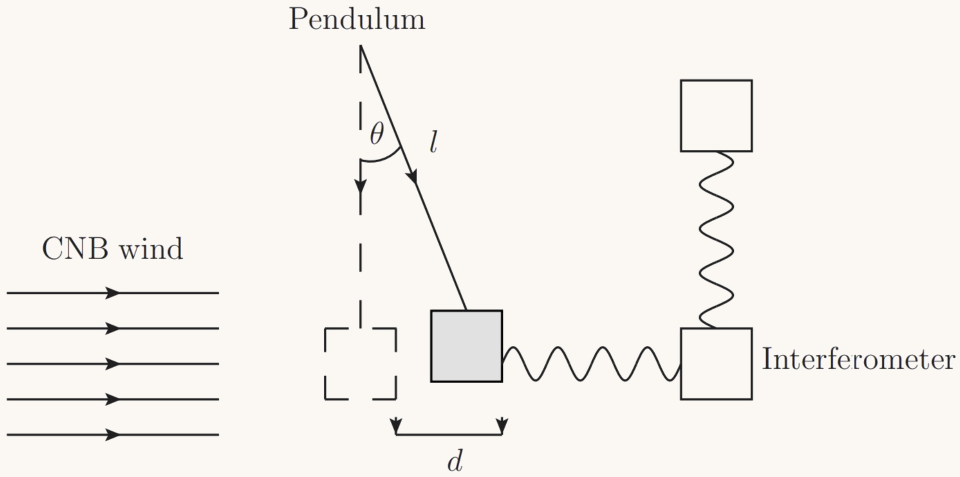


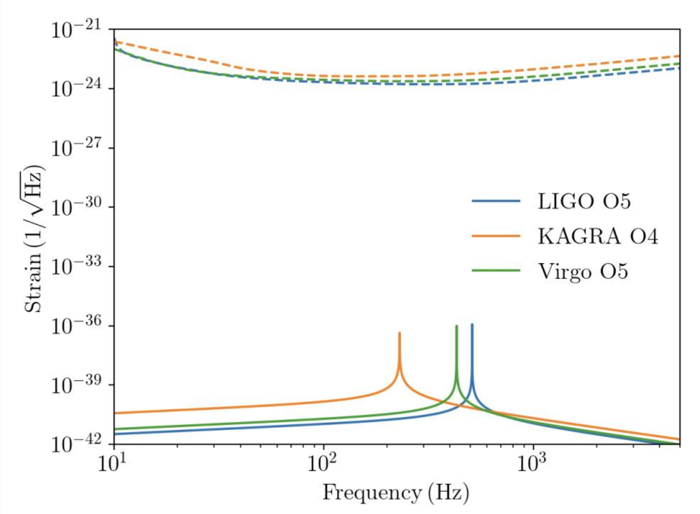






Sensitivity for acceleration





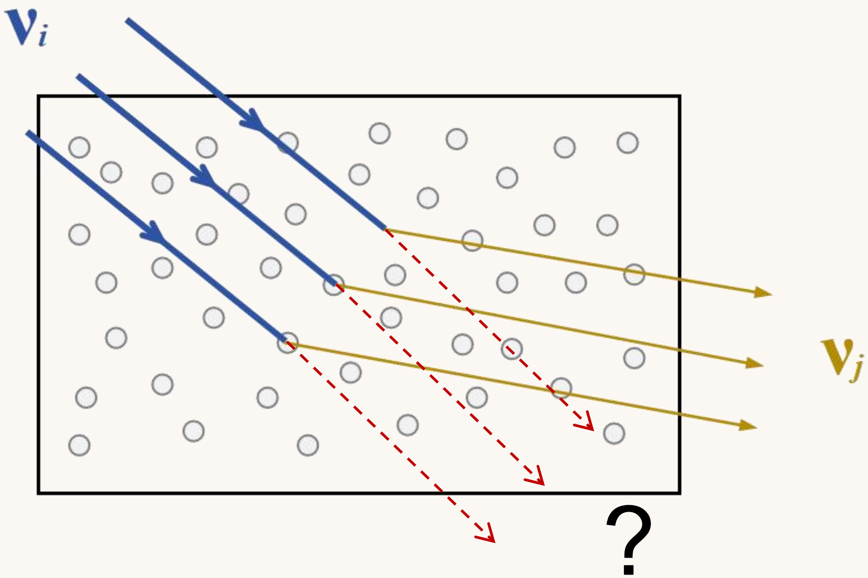
Torsion-balance gives

$$a < 10^{-15}\ \mathrm{cm} \bullet \mathrm{s}^{-2}$$

It seems not working even with the Earth enhancement

V. Domcke and M. Spinrath, JCAP 06 (2017) 055
J. D. Shergold, JCAP 11 (2021) 052

Coherent scattering rate



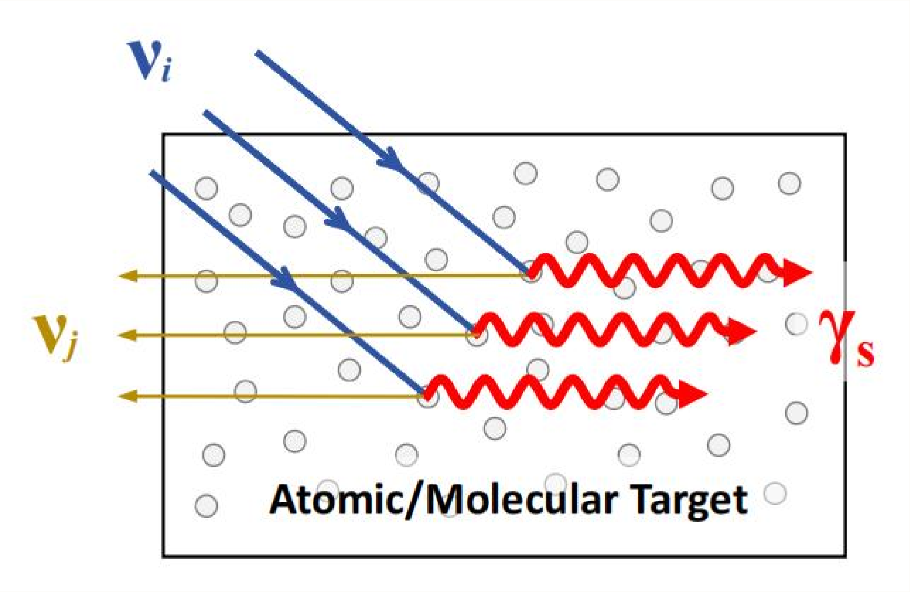
* Superconducting current
* Softphoton emission
* Phonon emission
... But effects are all negligible

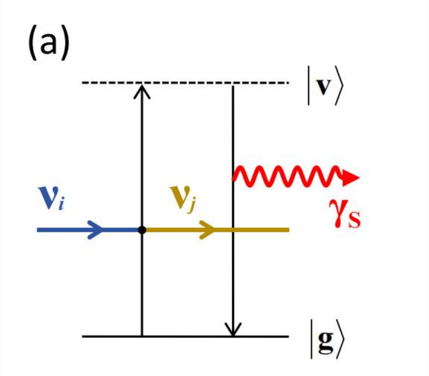
✦ The scattering rate for a meter-scale target can reach 0.01 Hz, quite significant!

✦ However, **the mechanical effect is averaged across all atoms.** the resultant acceleration per strike is barely observable.

✦ **Whatelse observable effects can an acceleration have, but not averaged over N_A ??**

Coherent photon emission





GYH and Shun Zhou, 2507.10868

☆ **Medium-induced neutrino decay**

☆ **This is inelastic. Why this is coherent?**

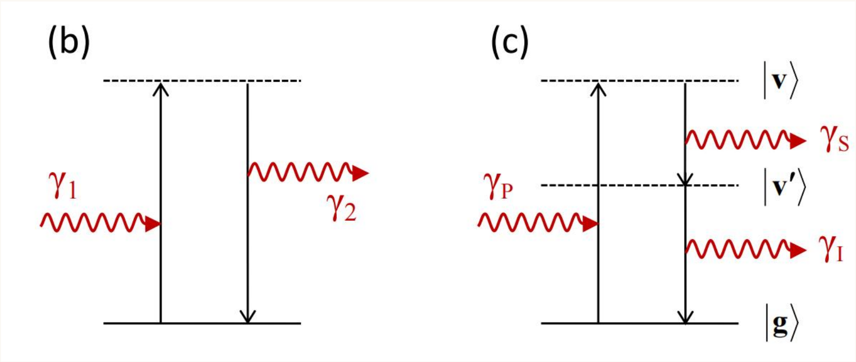
From first principles, the key for coherence may be summarized as:

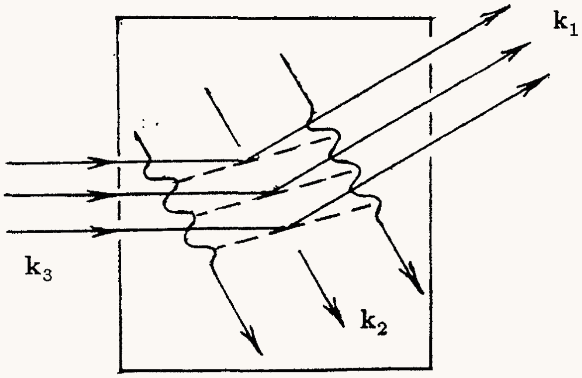
1. Radiants in the medium is not altered by the scattering.

2. The quantum phases of different radiants are not averaged out.

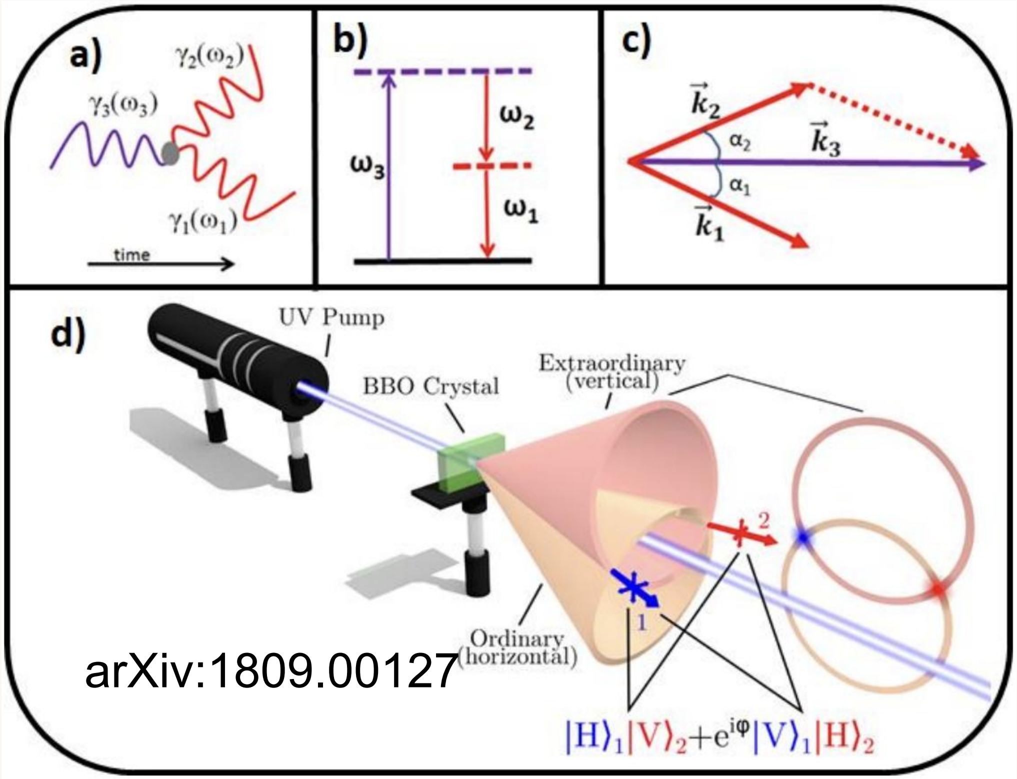
$$\mathcal{M}_{\rm tot} = \sum_{r=1}^{N} \mathcal{M}_r \cdot e^{i(\boldsymbol{p}_i - \boldsymbol{p}'_j - \boldsymbol{k}) \cdot \boldsymbol{x}_r}$$

Nonlinear optics





SPDC process/parametric fluorescence

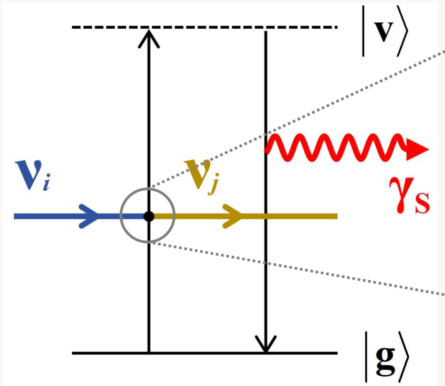


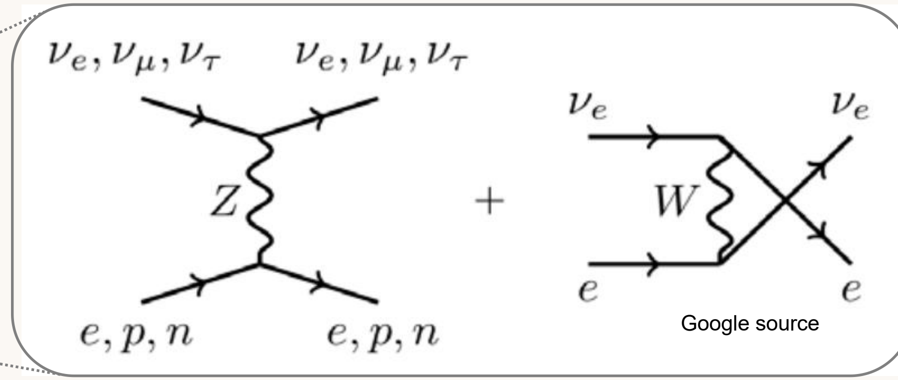
☆ The generated two photons are highly entangled at the intersection points.

☆ A phase-matching condition should be satisfied.

$$\mathcal{M}_{\text{tot}} = \sum_{r=1}^{N} \mathcal{M}_r \cdot e^{i(\boldsymbol{p}_i - \boldsymbol{p}_j' - \boldsymbol{k})\cdot \boldsymbol{x}_r}$$

Fluorescence of relic neutrinos





$$-\mathcal{L} \supset \sum_{i,j=1}^{3} \frac{G_{\rm F} C_{ij}}{\sqrt{2}} \overline{\nu}_j \gamma^\mu \left(1-\gamma_5\right) \nu_i \cdot \overline{e} \gamma_\mu \left(1-\gamma_5\right) e$$

Note: Only CC contributes to non-diagonal transitions

$\overline{e}\gamma_0 e$ ⇨ the E1 transition

$\overline{e}\gamma_\alpha\gamma_5 e$ ⇨ the M1 transition

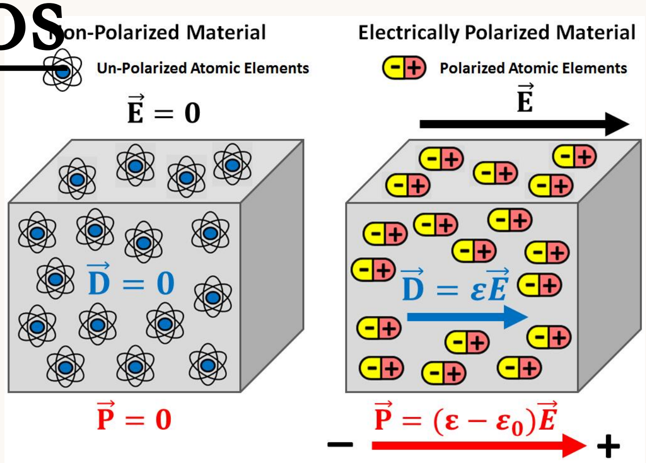
$$-H_{\rm I}^{\rm E1}(t, \boldsymbol{x_d}) = \frac{G_{\rm F} C_{ij}}{\sqrt{2}{\rm i}} \hat{j}_{ij}^0(\boldsymbol{p}_i, \boldsymbol{p}_j') \, \boldsymbol{x}_{\rm vg} \cdot (\boldsymbol{p}_i - \boldsymbol{p}_j') \, {\rm e}^{{\rm i}(E_{\rm vg} + E_j' - E_i)t} \left|{\rm v}\right\rangle \left\langle {\rm g}\right| + \boldsymbol{d}_{\rm vg} \cdot \boldsymbol{\mathcal{E}}(\boldsymbol{k}) \, {\rm e}^{{\rm i}(-E_{\rm vg} + \omega)t} \left|{\rm g}\right\rangle \left\langle {\rm v}\right| + {\rm h.c.} \, ,$$

$$-H_{\rm I}^{\rm M1}(t, \boldsymbol{x_d}) = \frac{G_{\rm F} C_{ij}}{\sqrt{2}} \hat{\boldsymbol{j}}_{ij}(\boldsymbol{p}_i, \boldsymbol{p}_j') \cdot \boldsymbol{\sigma}_{\rm vg} \, {\rm e}^{{\rm i}(E_{\rm vg} + E_j' - E_i)t} \left|{\rm v}\right\rangle \left\langle {\rm g}\right| + \boldsymbol{d}_{\rm vg} \cdot \boldsymbol{\mathcal{B}}(\boldsymbol{k}) \, {\rm e}^{{\rm i}(-E_{\rm vg} + \omega)t} \left|{\rm g}\right\rangle \left\langle {\rm v}\right| + {\rm h.c.} \, ,$$

Fluorescence of relic neutrinos

The key is to calculate the polarization *P*.

Hamiltonian follows $\mathcal{H}_{\rm eff} = -\boldsymbol{P}\cdot\boldsymbol{\mathcal{E}}$

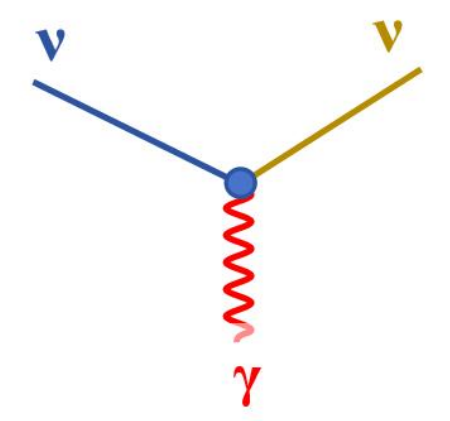


$$|\Psi(t)\rangle = C_{\rm g}(t)\,|{\rm g}\rangle + \sum_{\rm v} C_{\rm v}(t)\,|{\rm v}\rangle$$

$$C_{\rm v}^{(1)}(t) = \frac{G_{\rm F} C_{ij}}{\sqrt{2}{\rm i}} \frac{\hat{j}^0_{ij}\, \boldsymbol{x}_{\rm vg}\cdot(\boldsymbol{p}_i - \boldsymbol{p}'_j)}{E_{\rm vg} + E'_j - E_i} {\rm e}^{{\rm i}(E_{\rm vg}+E'_j-E_i)t}$$

$$\mathcal{H}^{\rm E1}_{\nu\nu\gamma} = \frac{G_{\rm F} C_{ij}}{-\sqrt{2}{\rm i}} \frac{n_{\boldsymbol{d}}\,[\hat{j}^0_{ij}\, \boldsymbol{x}_{\rm vg}\cdot(\boldsymbol{p}_i - \boldsymbol{p}'_j)]\,[\boldsymbol{d}_{\rm gv}\cdot\boldsymbol{\mathcal{E}}(\boldsymbol{k})]}{E_{\rm vg} + E'_j - E_i} \times {\rm e}^{{\rm i}(\omega+E'_j-E_i)t} + {\rm h.c.}$$

$$\mathcal{H}^{\rm M1}_{\nu\nu\gamma} = -\frac{G_{\rm F} C_{ij}}{\sqrt{2}} \frac{n_{\boldsymbol{d}}\,[\hat{\boldsymbol{j}}_{ij}\cdot\boldsymbol{\sigma}_{\rm vg}]\,[\boldsymbol{d}_{\rm gv}\cdot\boldsymbol{\mathcal{B}}(\boldsymbol{k})]}{E_{\rm vg} + E'_j - E_i} \times {\rm e}^{{\rm i}(\omega+E'_j-E_i)t} + {\rm h.c.}$$



Effectively, we end up with a ννγ coupling

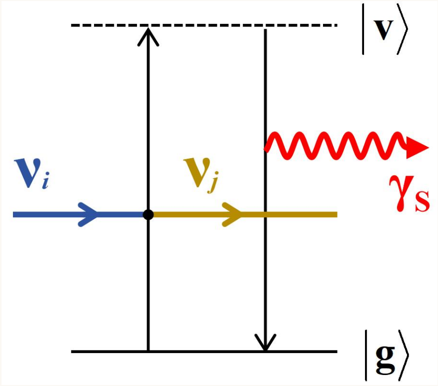
Fluorescence of relic neutrinos

The E1 transition rate

$$\Gamma \approx \frac{G_F^2 |U_{ei}^* U_{ej}|^2}{2\pi e^2} \frac{f_\theta^{E1}\, n_{\boldsymbol{d}}^2 |\boldsymbol{d}_{vg}|^4 D_k\, \omega |\boldsymbol{k}|^4}{(E_{vg} + E_j' - E_i)^2 + \Gamma_v^2/4}$$

$$R_{\nu_3 \to \nu_1}^{NO} \sim 4 \times 10^{-8}\ \mathrm{yr}^{-1}\,,$$
$$R_{\nu_2 \to \nu_1}^{IO} \sim 7 \times 10^{-15}\ \mathrm{yr}^{-1}\,,$$

For a cubic target of dimension of 3 meter.



Transition can be resonant when $E_{vg} = E_i - E_j$!

The M1 rate

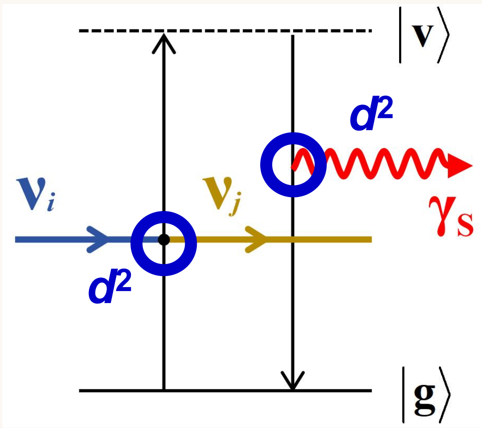
$$\Gamma \approx \frac{G_F^2 |U_{ei}^* U_{ej}|^2}{2\pi} \frac{f_\theta^{M1}\, n_{\boldsymbol{d}}^2 |\boldsymbol{d}_{vg}|^2 D_k}{(E_{vg} + E_j' - E_i)^2 + \Gamma_v^2/4} \frac{|\boldsymbol{k}|^4}{\omega}$$

$$R_{\nu_3 \to \nu_1}^{NO} \sim 5\ \mathrm{yr}^{-1}\,,$$
$$R_{\nu_2 \to \nu_1}^{IO} \sim 9 \times 10^{-4}\ \mathrm{yr}^{-1}\,,$$

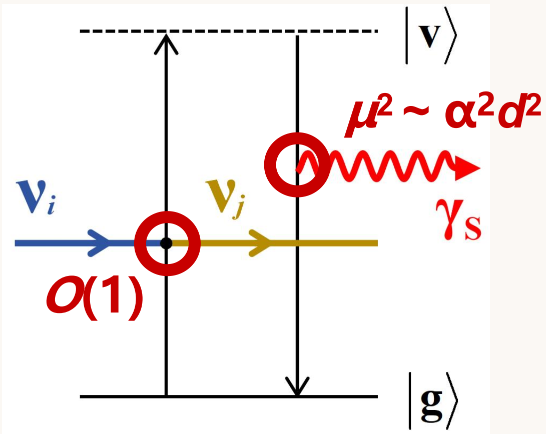
- ✦ The rates for IO are small because the corresponding photon energy is tiny.
- ✦ The M1 transition is much larger because E1 is further suppressed by the atomic size.
- ✦ Estimation assumes full resonance.

Further enhancement

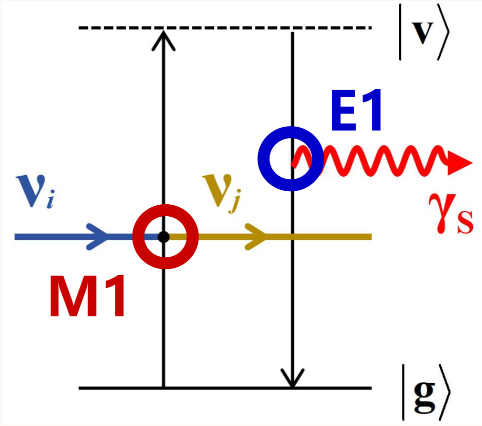
For E1 transition



For M1 transition

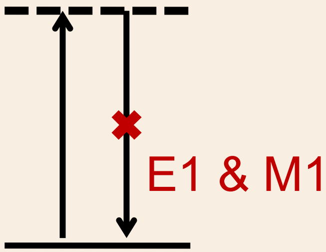


?



Further enhancement

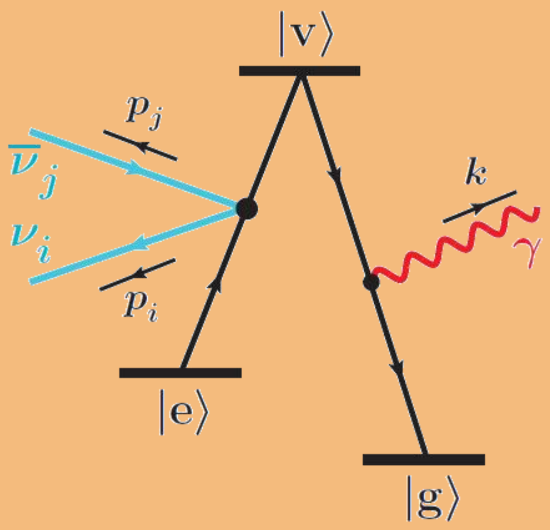
Parity mixing

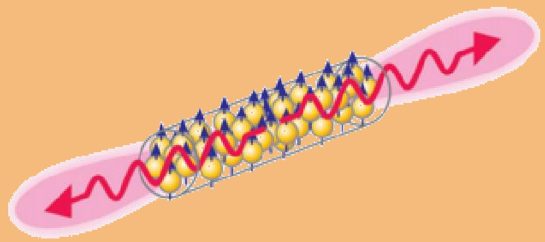


We know that this is not allowed from our atomic physics textbook: parity violation as well as selection rules

In modern AMO, we can use techniques such as the Stark effect to make it happen.

Superradiance





The time cycle for maintaining the coherence is of nano second scale, but we need year long collection time.

The system is not in ground state. Overwhelming QED background.

Summary and prospects

- As the community becomes skeptical about the feasibility of PTOLEMY project, the coherent way of CvB detection has been reconsidered. Attempts have been made to evade the no-go theorem.

- The parametric fluorescence of cosmic neutrino background provides a possible way to detect those elusive relics.

- A thorough study should be made to find suitable material candidates for the resonance enhancement.

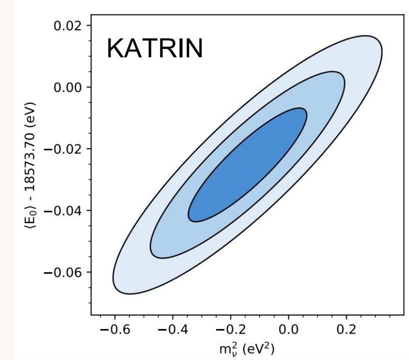
谢谢!!!
Thanks!!!

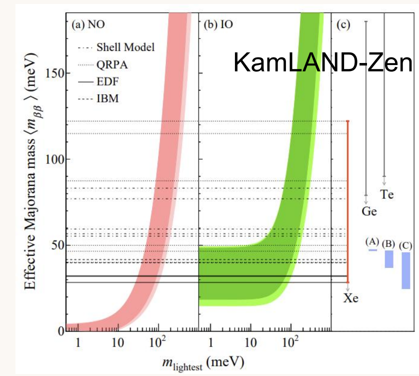
BACKUPS

Challenges

I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, et al.,

Accuracy (1σ/bf)		Normal Ordering (best fit) ?		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
2% √	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
	$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \to 0.585$	$0.550^{+0.012}_{-0.015}$	$0.440 \to 0.584$
2% √	$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \to 49.9$	$47.9^{+0.7}_{-0.9}$	$41.5 \to 49.8$
	$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \to 0.02388$	$0.02231^{+0.00056}_{-0.00056}$	$0.02060 \to 0.02409$
1% √	$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.59^{+0.11}_{-0.11}$	$8.25 \to 8.93$
16% ?	$\delta_{CP}/^\circ$	212^{+26}_{-41}	$124 \to 364$	274^{+22}_{-25}	$201 \to 335$
3% √	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
1% √	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \to -2.421$

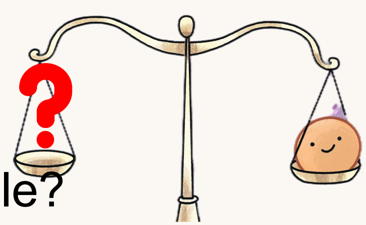




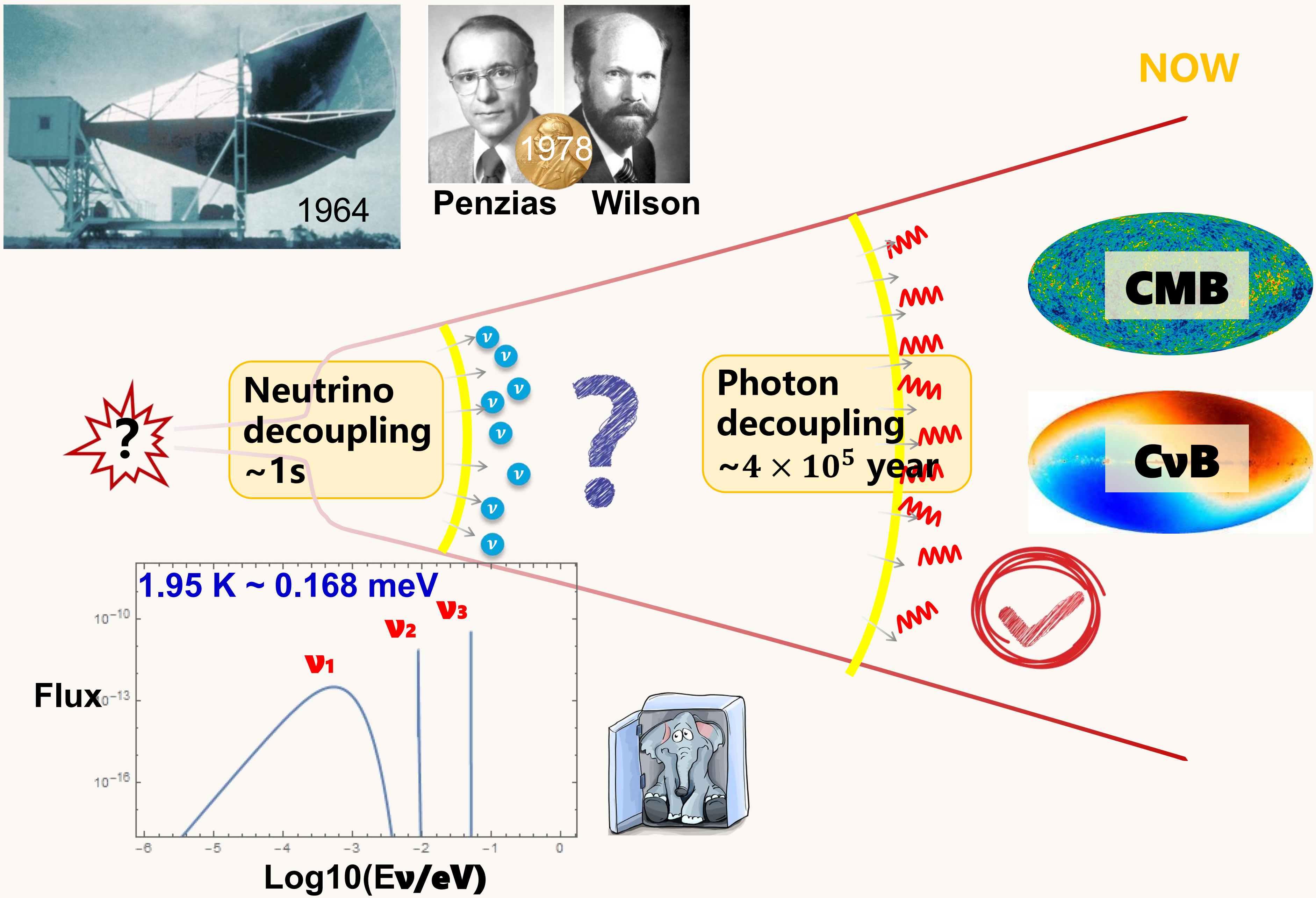
Achievements made
- ✔ Oscll. paras
- ✔ Solar flux
- ✔ Atm. flux
- ✔ Reactor flux
- ✔ Geo. flux
- ✔ SN flux
- ✔ Accel. flux
- ✔ UHE flux

Near future
- ➽ Nu mass ordering
- ➽ Dirac CP violating phase
- ➽ Cosmogenic nu flux

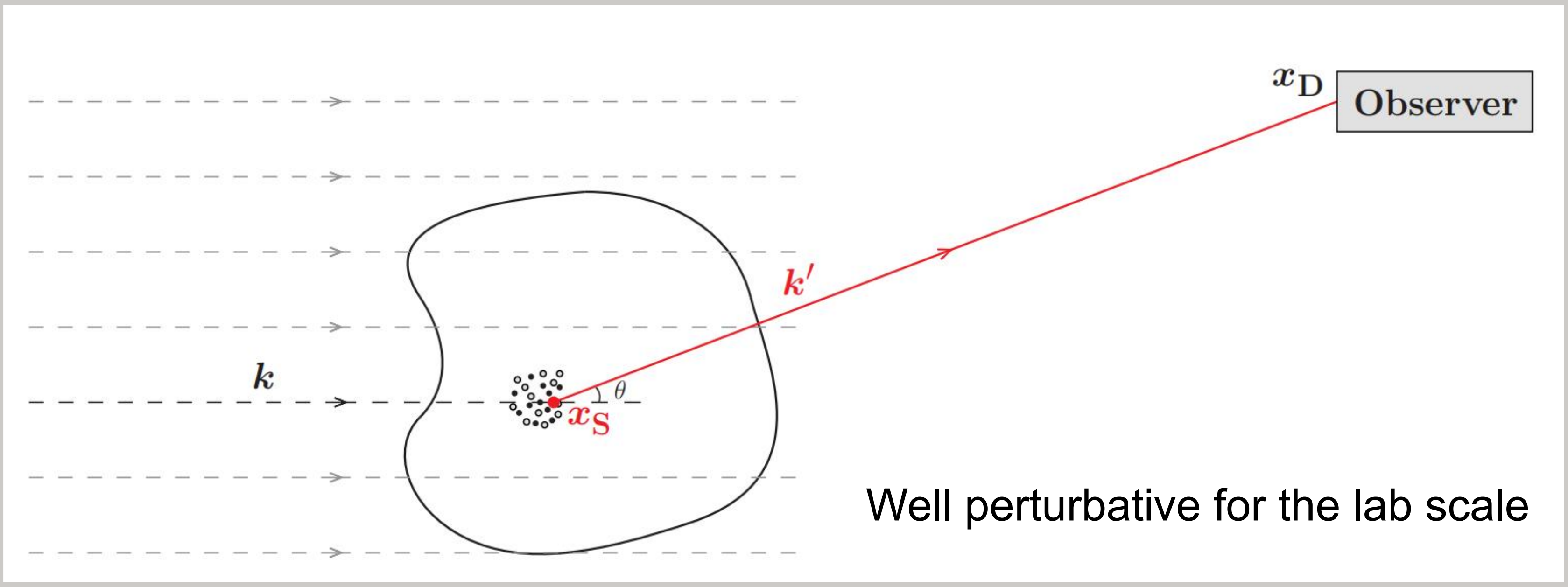
Likely very remote
- ? Dirac/Majorana
- ? Absolute nu masses
- ? Relic nu flux → Mission npossible?



Cosmic relics



A no-go theorem



The probability for a coherent scattering of NR nu follows

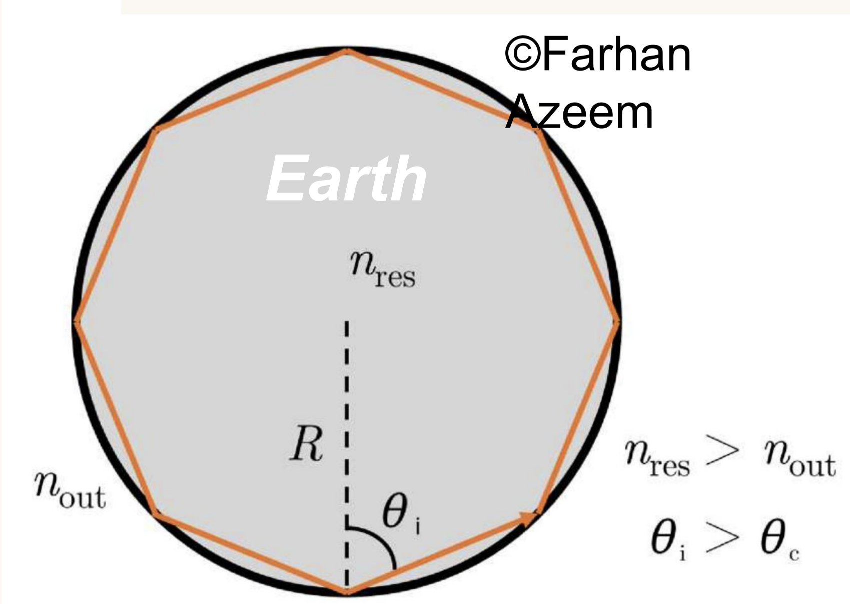
$$P \approx 2|C_Z^A|^2 G_F^2 n^2 L^2 \sim |C_Z^A|^2 \left(\frac{n}{N_A \bullet \mathrm{cm}^{-3}}\right)^2 \left(\frac{L}{2500\,\mathrm{km}}\right)^2$$ **(Majorana neutrinos)**

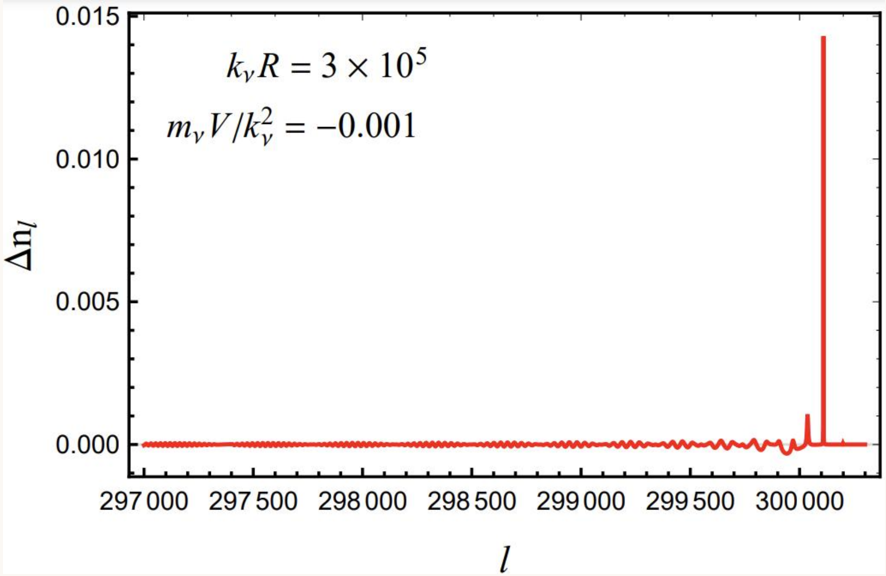
$$P \approx |C_Z^A|^2 G_F^2 n^2 L^2 \left(\frac{E}{p}\right)^2 \sim |C_Z^A|^2 \left(\frac{n}{N_A \bullet \mathrm{cm}^{-3}}\right)^2 \left(\frac{L}{10\,\mathrm{km}}\right)^2$$ **(Dirac neutrinos)**

GYH, working in progress
P. Langacker et al., PRD 27 (1983) 1228.
R. R. Lewis, PRD 35 (1987) 2134.
I. Ferreras and I. Wasserman, PRD 52 (1995) 5459

Any mechanical forces of this kind should be of G_F^2

Whispering gallery mode

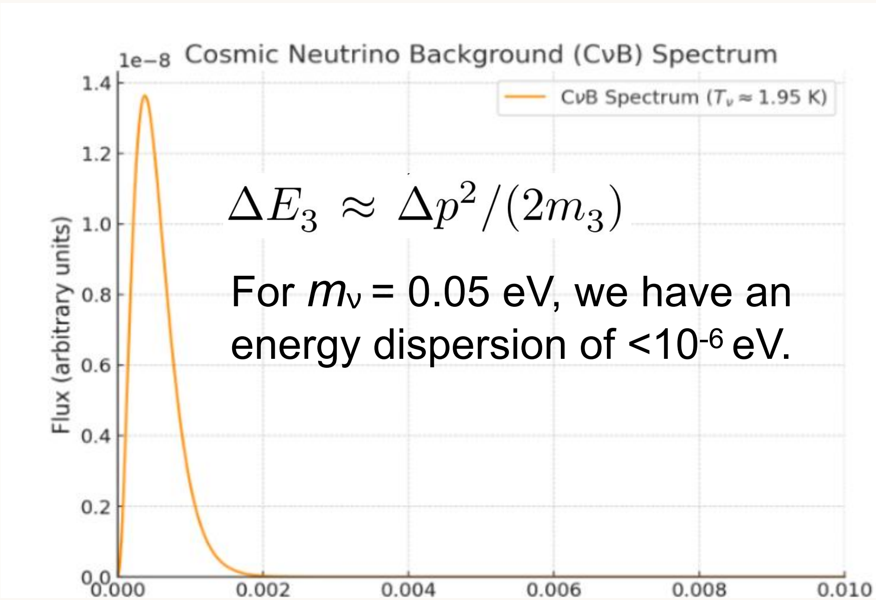




Monoenergetic requirement

A momentum dispersion of order 10^{-3} - 10^{-4} eV

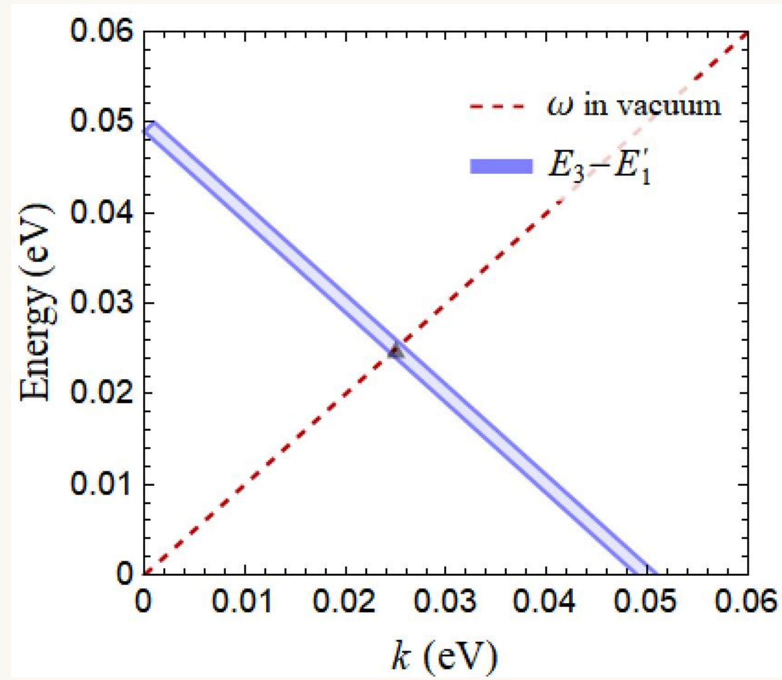
The uncertainty of $E_3 - E_1'$ follows the momentum....



$$\Delta E_3 \approx \Delta p^2/(2m_3)$$

For m_ν = 0.05 eV, we have an energy dispersion of <10^{-6} eV.

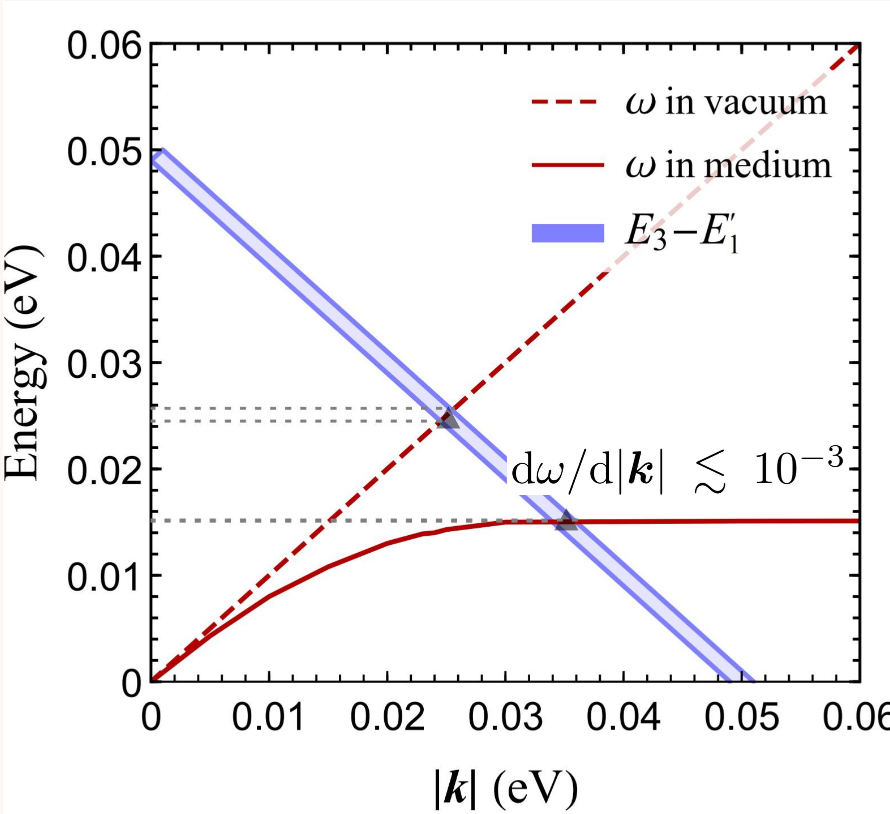
P



$$R \sim 2 \times 10^{-6}\ \text{yr}^{-1}$$

Maximal rate?

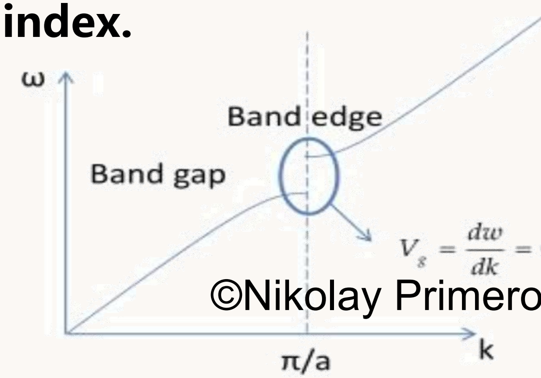
Monoenergetic requirement

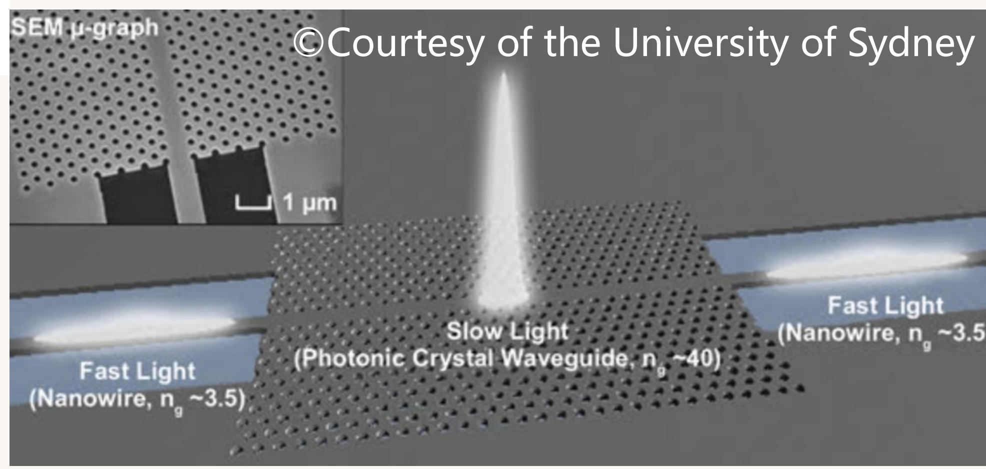


The group velocity is just

$$v_g = d\omega/dk$$

Slow-light phenomenon is very common in quantum optics by properly adjusting the rafractive index.





The flattening of the dispersion relation of photon can rescue our rates.