Neutron Stars as probe of Cosmic Neutrino Background

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Based on arXiv [hep-ph] : 2408.01489

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The Center for Neutrino Physics

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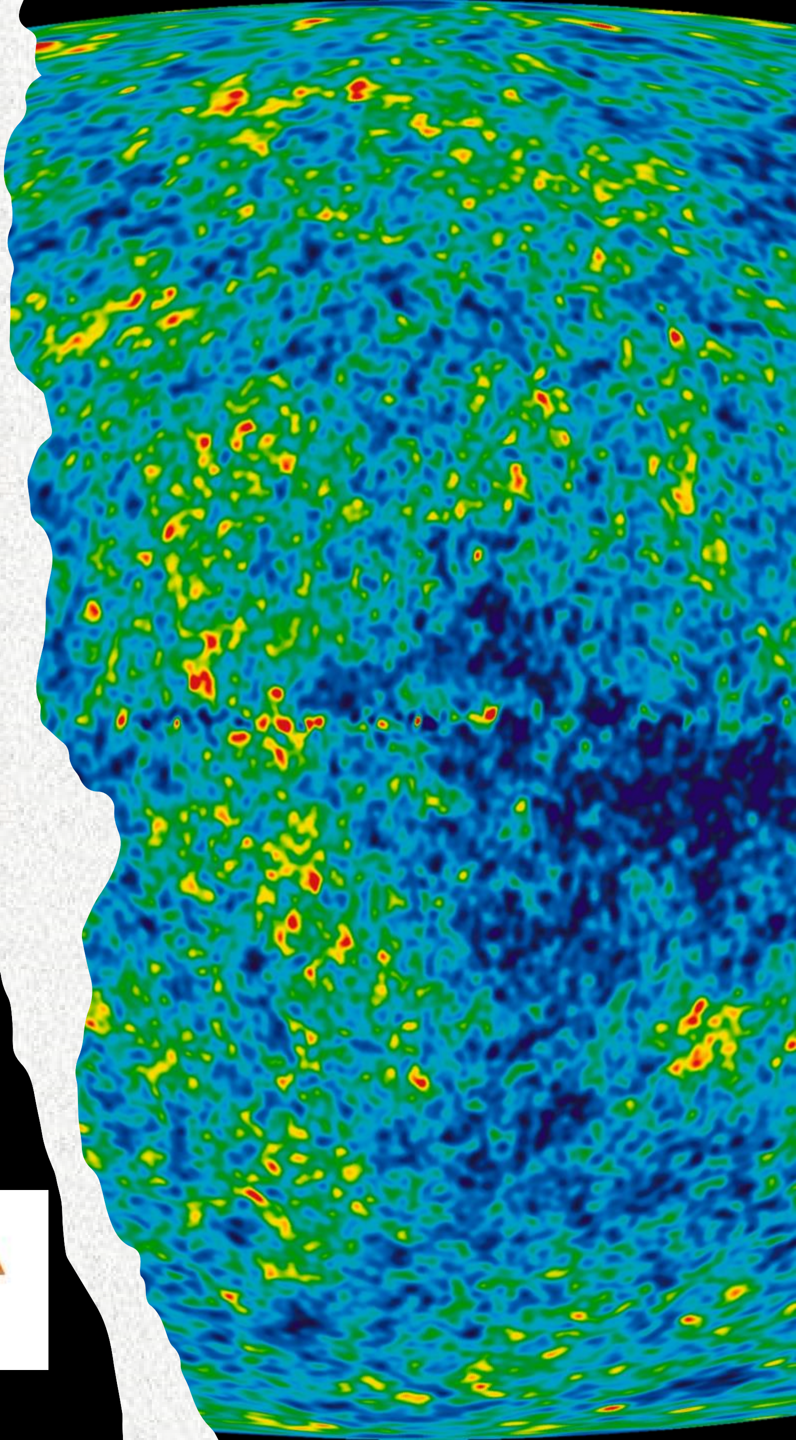
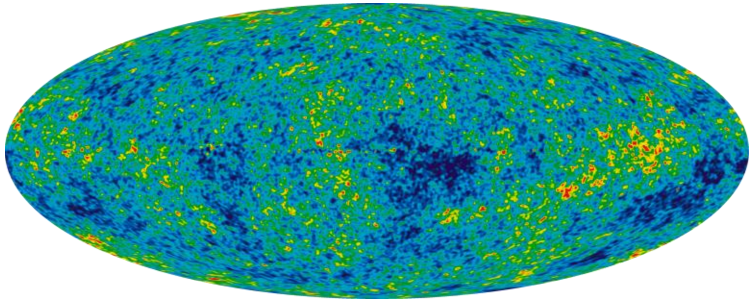
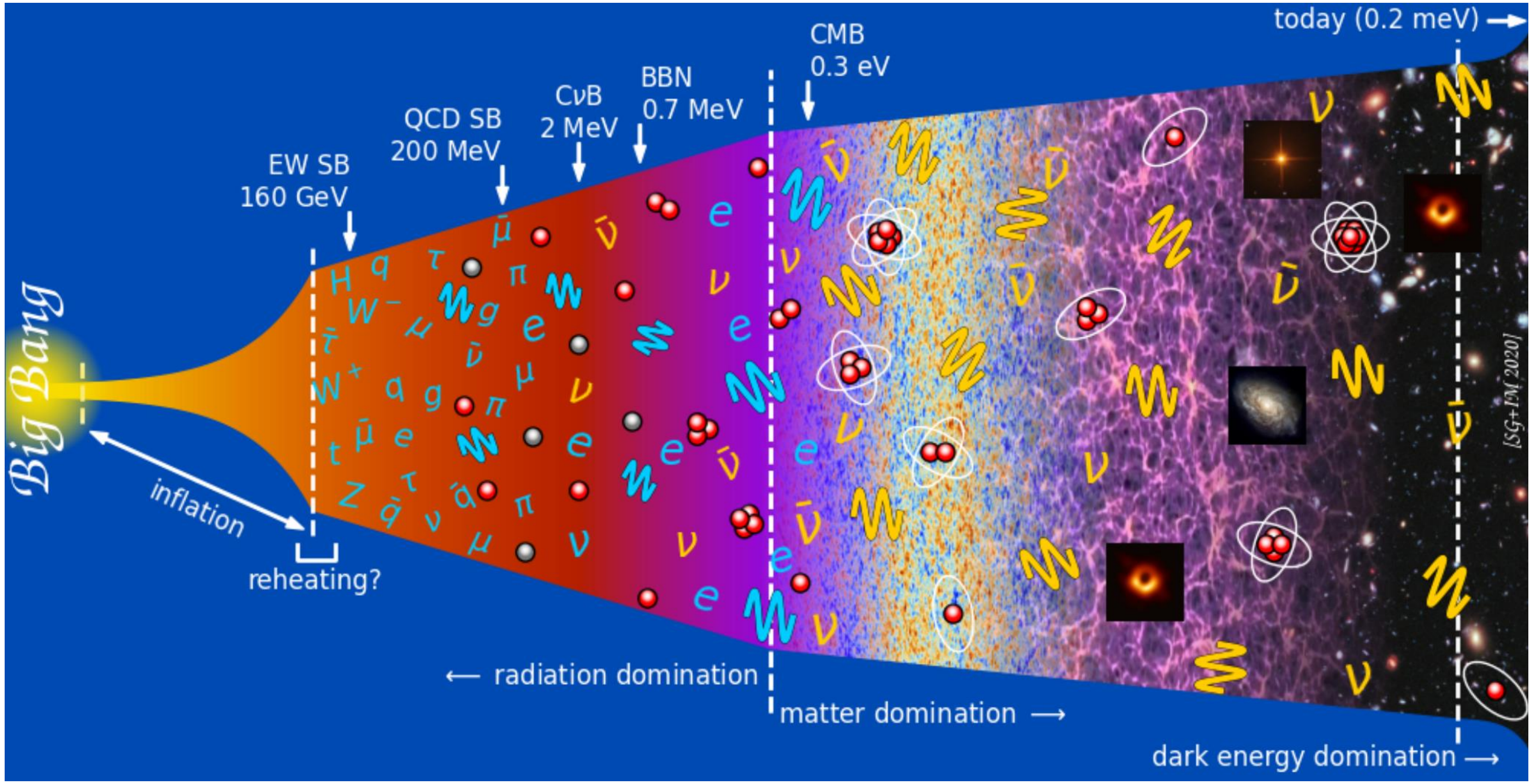
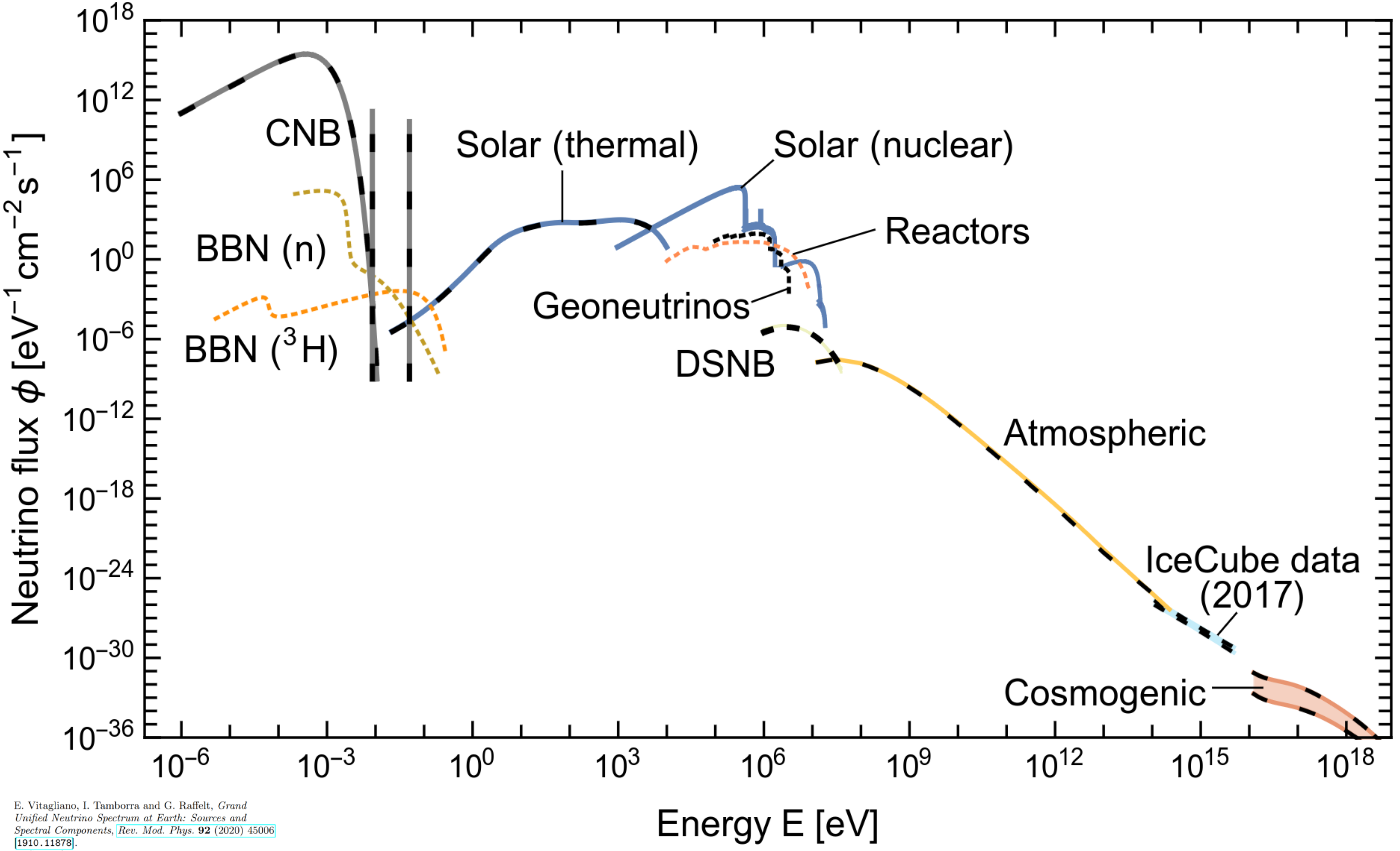


Cosmic Neutrino Background



- Relic neutrinos from $\tau \sim 1\ \mathrm{sec}$ after Big Bang.
- At time of free streaming, T_ν = 1 MeV but due to expansion of the universe, temperature dropped to 1.65×10^{-4} eV.
- $n_{\nu,\bar{\nu}} = 6 \times 56\ \mathrm{cm}^{-3}$
- Last observable prediction of standard cosmological model





E. Vitagliano, I. Tamborra and G. Raffelt, *Grand Unified Neutrino Spectrum at Earth: Sources and Spectral Components*, *Rev. Mod. Phys.* **92** (2020) 45006 [1910.11878].

Detection Proposals

PHYSICAL REVIEW VOLUME 128, NUMBER 3 NOVEMBER 1, 1962

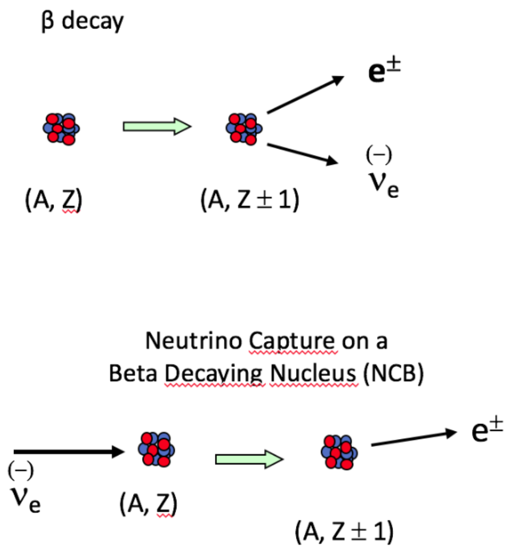
Universal Neutrino Degeneracy

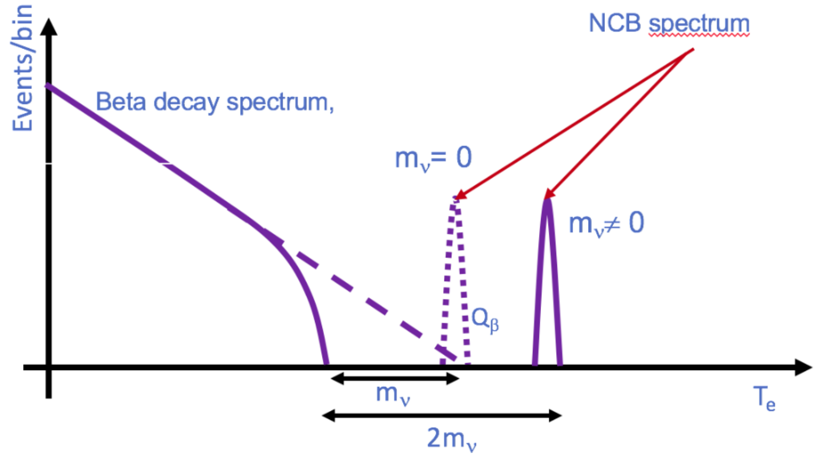
STEVEN WEINBERG*
Imperial College of Science and Technology, London, England
(Received March 22, 1962)

- Various detection proposals include neutrino capture, Stodolsky effect, coherent scattering e.t.c

- PTOLEMY is based on neutrino capture.

- In this work, we use the coherent nature of CNB neutrino scattering.





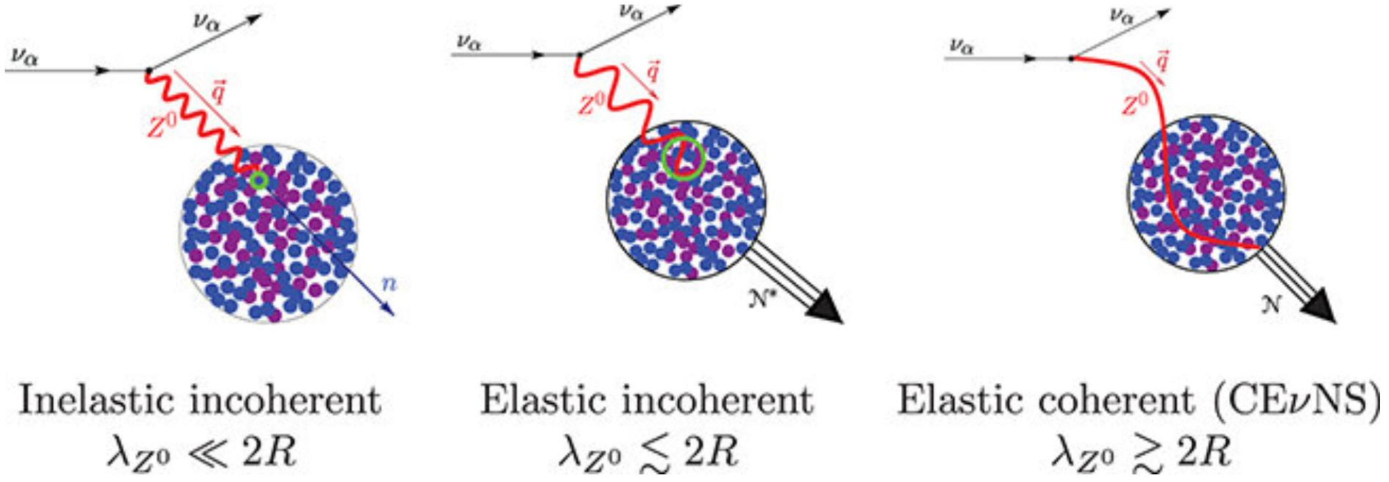
L. Stodolsky, *Speculations on Detection of the Neutrino Sea*, *Phys. Rev. Lett.* **34** (1975) 110.

R. Opher, *Coherent scattering of cosmic neutrinos*, *Astron. Astrophys.* **37** (1974) 135.

Coherent Scattering

- Occurs when incoming neutrino wavelength is larger than the target.

- The coherent cross section per nuclei scales $\sim \rho$ while the total cross-section scales as $\sim \rho^2$



$$\sigma_{\nu-N} \simeq \frac{G_F^2}{4\pi}(A-Z)^2 E_\nu^2,$$

$$N_c = \left(\frac{2\pi}{p_\nu}\right)^3 \frac{N_A}{A\, m_A}\rho,$$

COHERENT collaboration, *Observation of Coherent Elastic Neutrino-Nucleus Scattering*, *Science* **357** (2017) 1123 [1708.01294].

Coherent Scattering

- For maximum cross section, the densest object is a Neutron Star.
- This observation of large coherence in dense stars was first mentioned by Freedman (1973).
- Increases opacity for SN neutrinos as shown by Wilson (1974).
- One subtle difference for CNB : thermodynamics.
- CNB is a very cold fluid, with its interaction with a hot medium i.e. NS, will gain energy.

Coherent Neutrino-Nucleus Scattering as a Probe
of the Weak Neutral Current

October 1973

DANIEL Z. FREEDMAN
National Accelerator Laboratory, Batavia, Illinois 60439

and

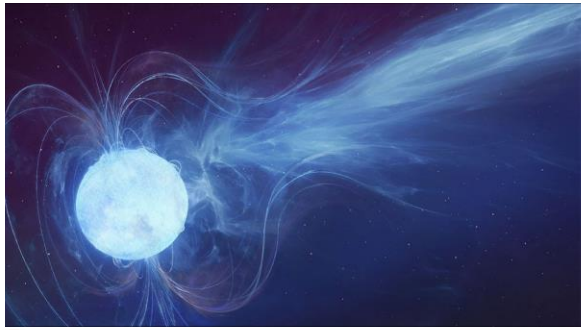
Institute for Theoretical Physics, SUNY
Stony Brook, NY 11790

VOLUME 32, NUMBER 15 PHYSICAL REVIEW LETTERS 15 APRIL 1974

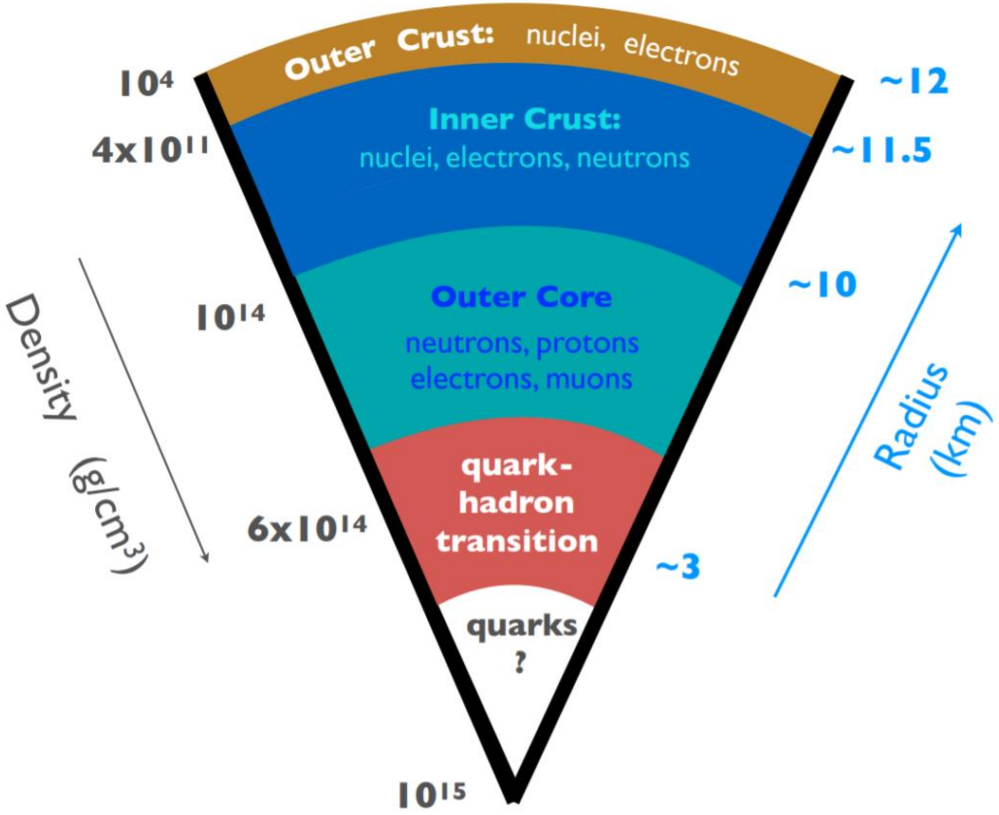
Coherent Neutrino Scattering and Stellar Collapse*

James R. Wilson
Lawrence Livermore Laboratory, University of California, Livermore, California 94550
(Received 24 January 1974)

Neutron Star : Overview

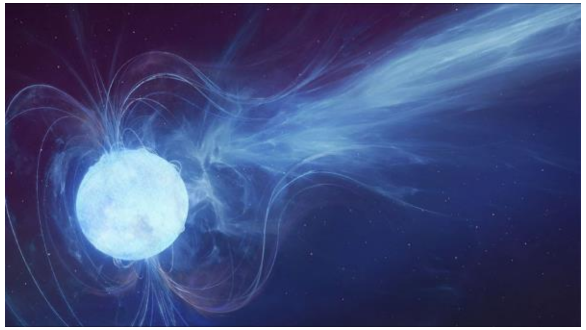


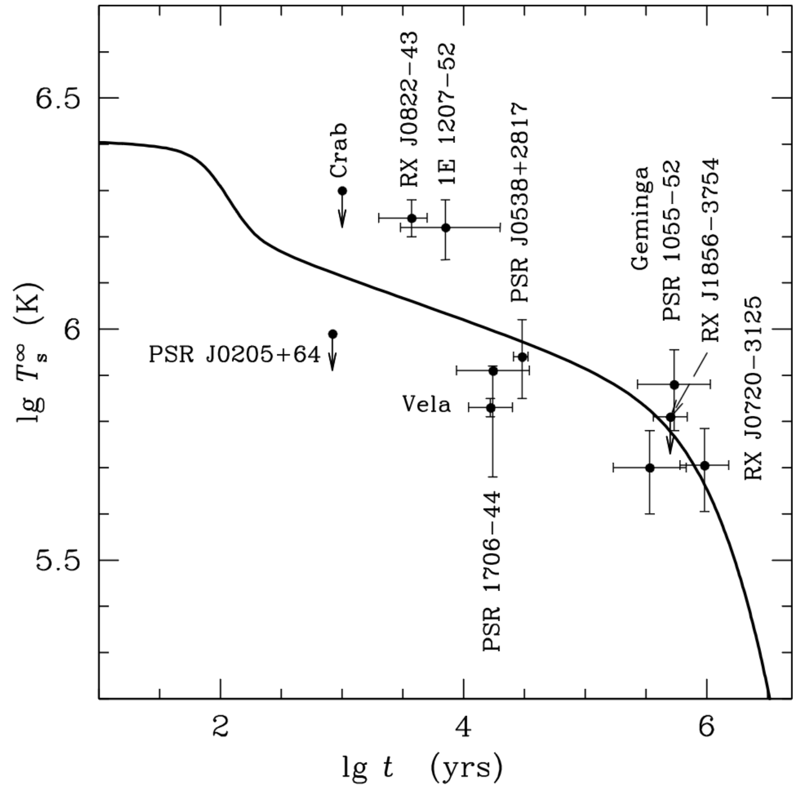
- Formed from stellar collapse
- Consists of different layers of increasing densities.
- While the internal temperature of newly born NSs is around several MeVs, the oldest observed neutron stars have cooled down to keV.

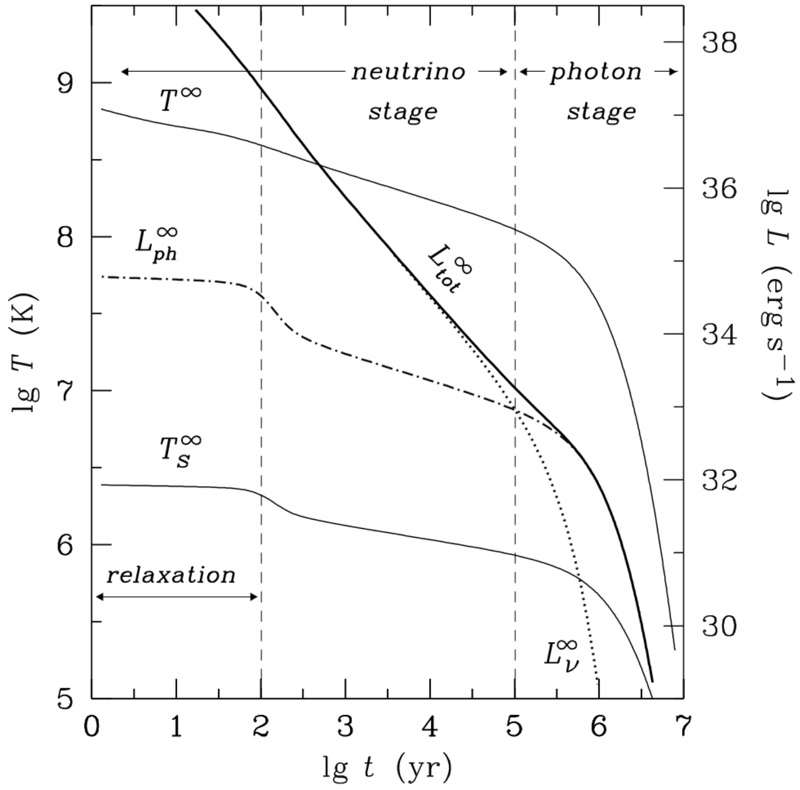


D. G. Yakovlev and C. J. Pethick, *Neutron star cooling*, *Ann. Rev. Astron. Astrophys.* **42** (2004) 169 [astro-ph/0402143].
D. G. Yakovlev, O. Y. Gnedin, M. E. Gusakov, A. D. Kaminker, K. P. Levenfish and A. Y. Potekhin, *Neutron star cooling*, *Nucl. Phys. A* **752** (2005) 590 [astro-ph/0409751].

Neutron Star : Cooling







Cross-section : Estimates

- Let's estimate the cross-section.
- It can be seen that elastic cross-section naively far exceeds the geometric cross-section!!
- This feature is only possible for long-ranged interactions such as gravity.
- We will hereby assume 100% of the CNB interacts with the NS.

$$\frac{1}{N}\frac{d\sigma(E_\nu)}{d\cos\theta} = \frac{G_F^2}{4\pi^2}(E_\nu)^2\left(C_V^2(1+\cos\theta)S_V(\mathbf{q})\right)$$

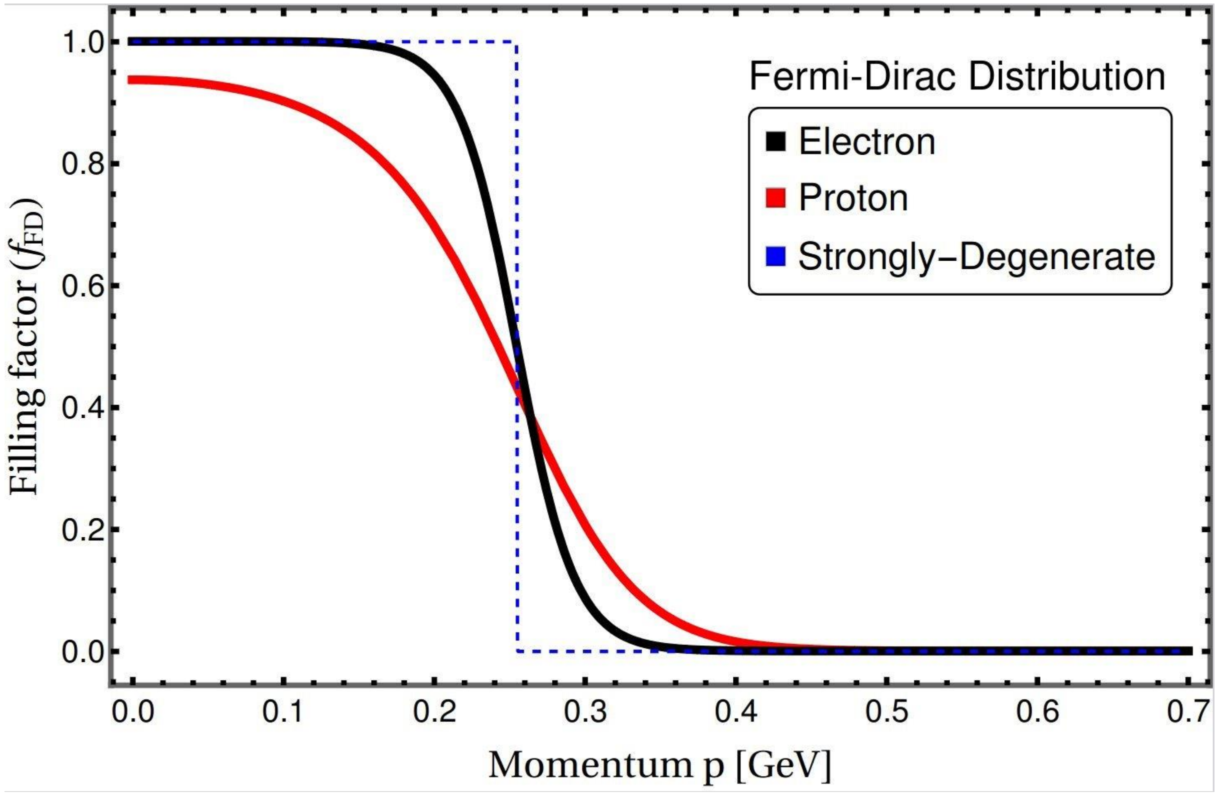
$$\sigma_{\nu-N} \simeq \frac{G_F^2}{4\pi}(A-Z)^2 E_\nu^2, \qquad N_c = \left(\frac{2\pi}{p_\nu}\right)^3 \frac{N_A}{A\, m_A}\rho,$$

$$\text{Elastic cross-section : } \sim 10^{-21}\ \text{cm}^2$$

$$\text{Geometric cross-section : } \sim 10^{-26}\ \text{cm}^2$$

How much energy transfer ?

- CNB will exchange energy with the NS core through scattering off nucleon medium.
- Neutrons forms a degenerate fermi gas.
- Naively, we might estimate no energy transfer is possible for highly degenerate gas.
- But this is exactly where the finite temperature comes in.
- Energy exhange of order T is possible, and we will assume this for rest of this talk.



How much energy transfer ?

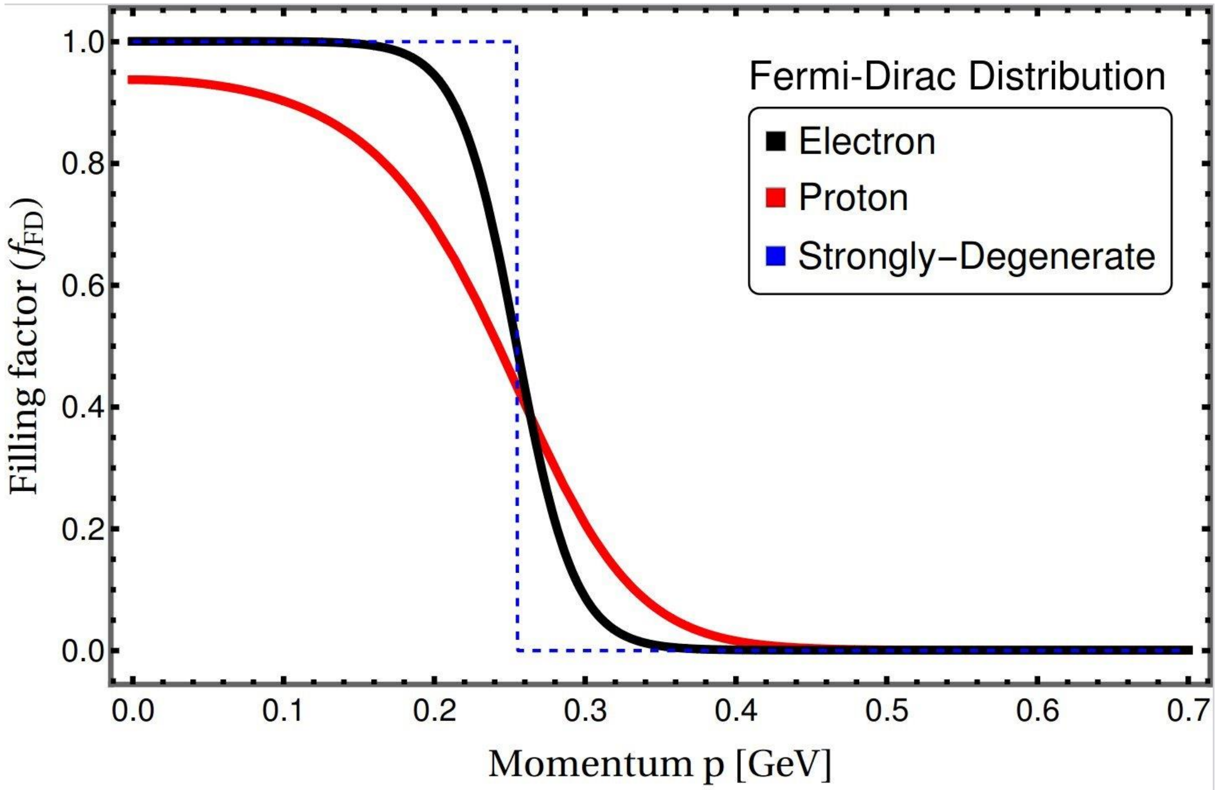
$$\eta_{\text{coh}} = \left(\frac{2\pi}{|\mathbf{q}|}\right)^3 \frac{g}{(2\pi)^3} \int_{\sqrt{\mu^2-m^2}-T}^{\sqrt{\mu^2-m^2}+T} dp \frac{4\pi p^2}{e^{\frac{\sqrt{p^2+m^2}-\mu}{T}}+1}$$

$$\sigma_{\nu-N} = \frac{G_F^2}{4\pi} E_\nu^2 \frac{g}{|\mathbf{q}|^3} \int_{\sqrt{\mu^2-m^2}-T}^{\sqrt{\mu^2-m^2}+T} dp \frac{4\pi p^2}{e^{\frac{\sqrt{p^2+m^2}-\mu}{T}}+1}$$

$$= \frac{G_F^2}{2\pi} \frac{1}{fT} \int_{\sqrt{\mu^2-m^2}-T}^{\sqrt{\mu^2-m^2}+T} dp \frac{4\pi p^2}{e^{\frac{\sqrt{p^2+m^2}-\mu}{T}}+1}$$

where we have used $E_\nu = \sqrt{m_\nu^2 + |\mathbf{q}|^2}$, $|\mathbf{q}| = fT$, where $f \in [p_0/T, 1]$ and yields the cross-sectional area

$\sigma_{\nu-N} \simeq 5\times10^{-41}\ \text{cm}^2 f^{-1}$, (for both $T = 1$ and 100 keV)



Neutron star cooling

- A similar work was first ever done in 1983 by Dixit and Lodenquai.
- This 2.5 page paper considers full thermalization of CNB by NS and argues along the same line for energy loss in neutron star.
- And as expected concludes in the negative for the detection prospects.

Home › Lettere al Nuovo Cimento (1971–1985) › Article

On neutron star cooling by relic neutrinos

Published: 07 January 2008

Volume 38, pages 174–176, (1983) Cite this article

V. V. Dixit & J. Lodenquai

Gravitational capture

- For slow-moving CNB neutrinos,
  the strong gravity of NS will pull them nearer.
- As pointed earlier, the capture cross section for gravity can exceed the geometric cross section.
- For mono-energetic particles, calculated simply by energy and angular momentum conservation.
- For a given spectrum, calculations done by Gould(1987) applies.

$$Cross\ Section = \pi b^2 = \pi R^2 \left(1 + \frac{2MG}{R{v_i}^2}\right)$$

Resonant Enhancements In WIMP Capture By The Earth

ANDREW GOULD*

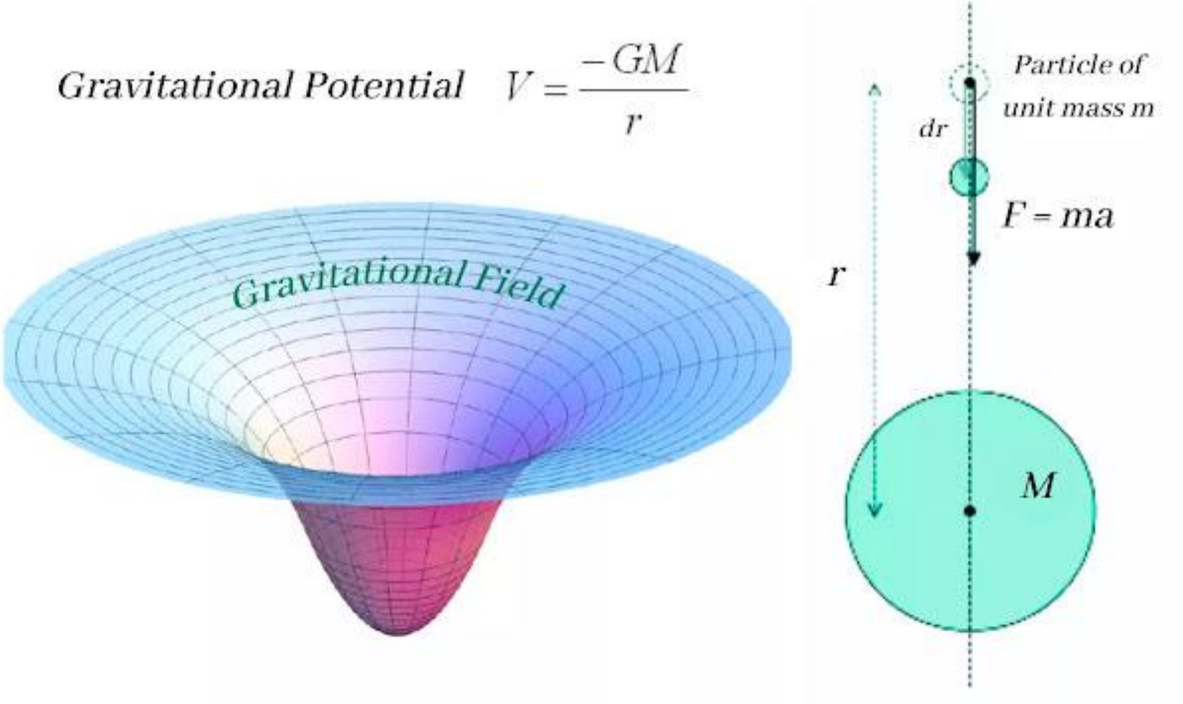
Stanford Linear Accelerator Center

Stanford University, Stanford, California, 94305

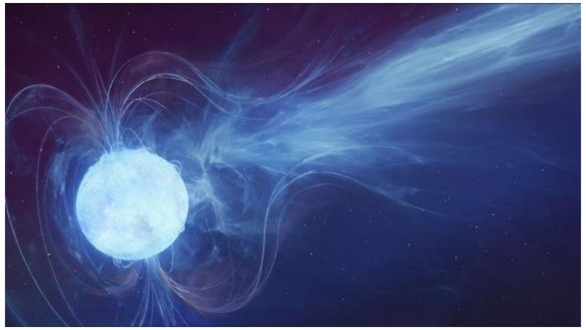
Gravitational boosting

- The infalling neutrino gains gravitational potential energy.
- Note it speeds up, but negligible change in energy due to tiny neutrino masses.

$$v_{\text{boost}} = \frac{1}{2}\left(v_{\text{avg}} + \sqrt{v_{\text{avg}}^2 + \frac{GM_{\text{NS}}}{R_{\text{NS}}}}\right) \simeq \frac{1}{2}\sqrt{\frac{GM_{\text{NS}}}{R_{\text{NS}}}}$$

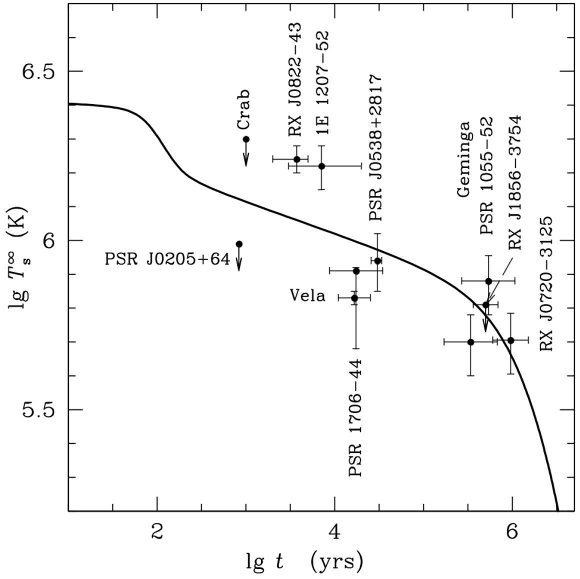


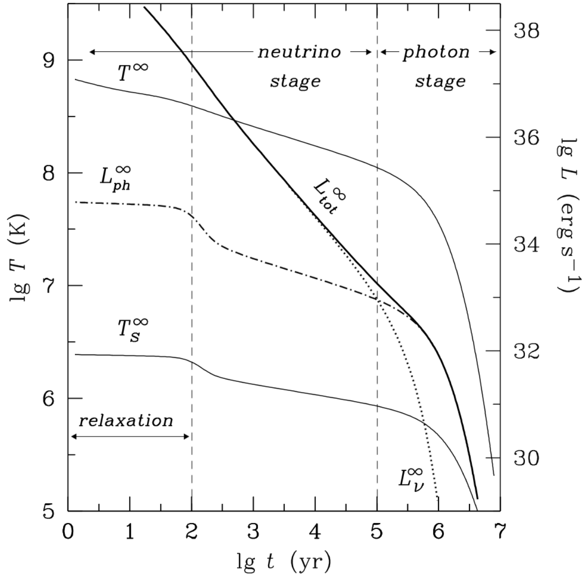
Neutron Star cooling



$$L_{C\nu B} = (4\pi R_{\rm cap}^2) \times (n_\nu v_{\rm boost}) \times \Delta E = 4\pi\, R_{\rm NS}^2 \left(1 + \frac{v_{\rm esc}^2}{v_{\rm avg}^2}\right) \times n_\nu v_{\rm boost} \times k_B\, T_{\rm core}$$

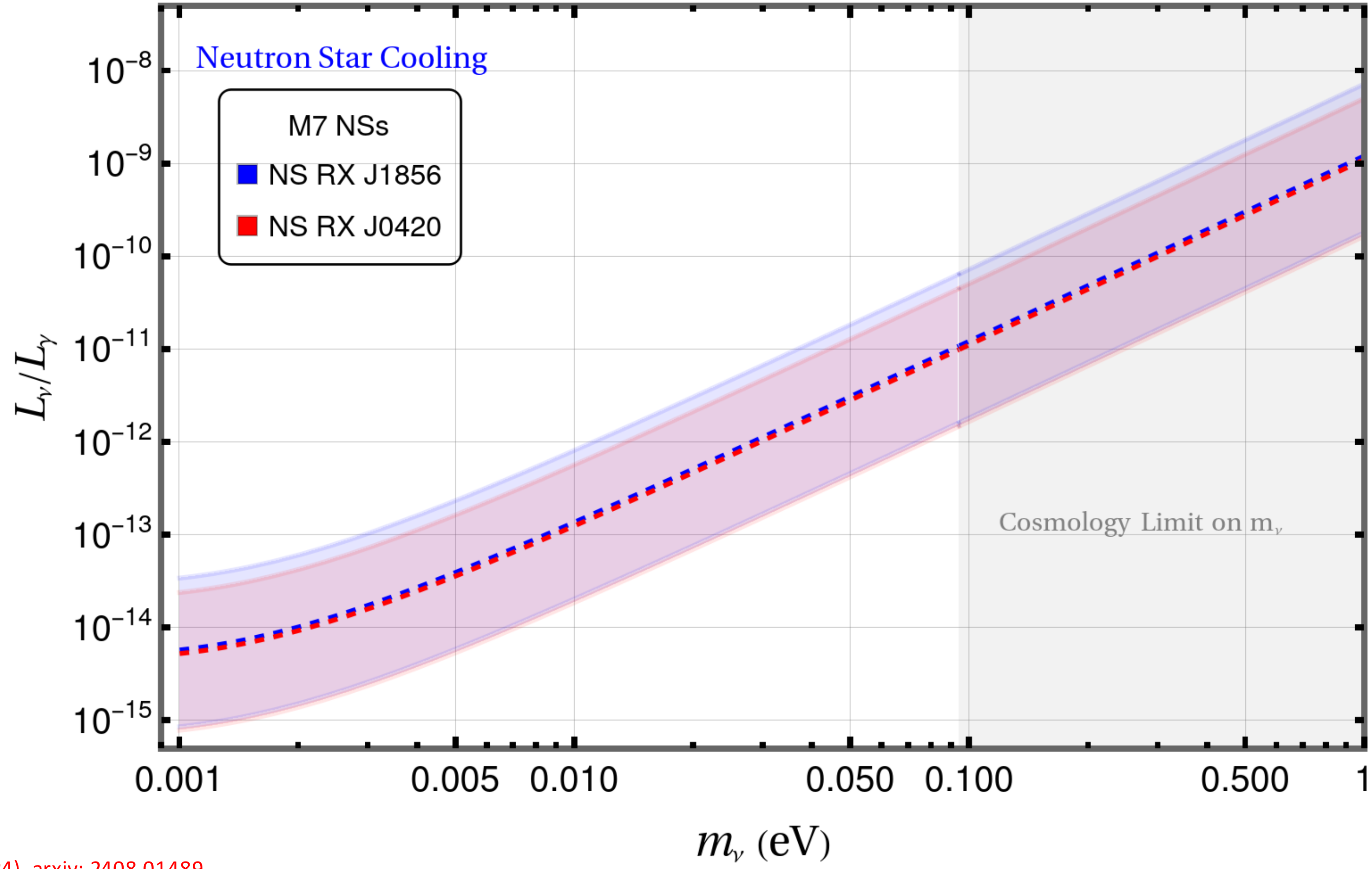
$$L_\gamma = 4\pi R_{NS}^2\, \sigma\, T_{sur}^4$$





Chauhan (2024), arxiv: 2408.01489

Neutron Star cooling



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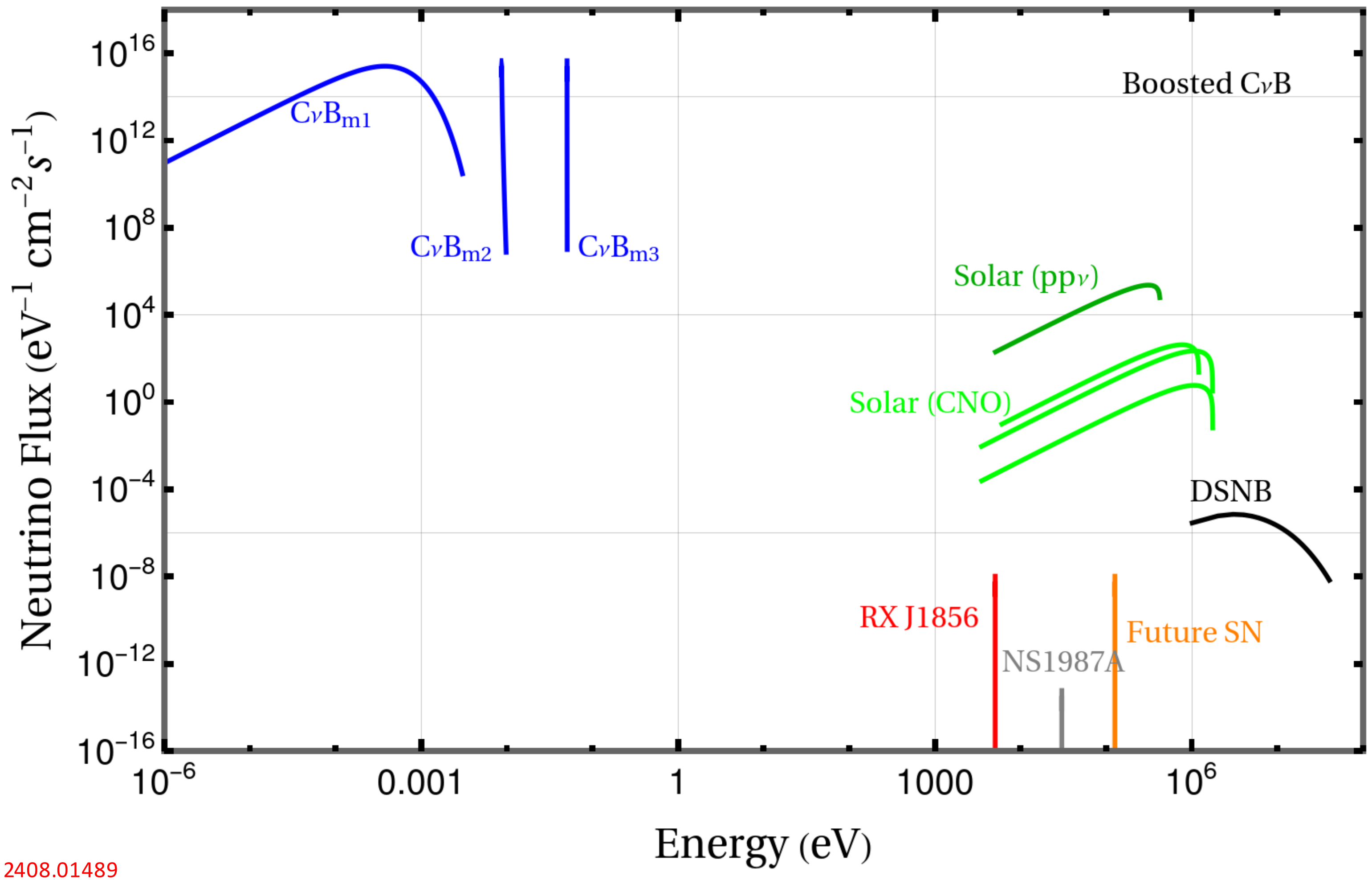
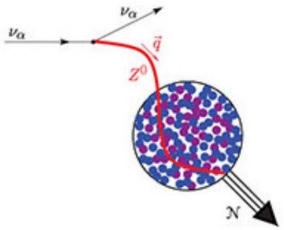
Boosted CNB : Future SN



Chauhan (2024), arxiv: 2408.01489

Cross-section : improving calculation



- Proper way is to use dynamic structure functions.
- In a medium, cross-section per nucleon for neutral current scattering of low-energy neutrinos on a gas of non-relativistic neutrons
- Computation of dynamic structure factors either require a fully time-dependent simulation or capability to resolve the full excitation spectrum of the system.

$$\frac{1}{N}\frac{d^2\sigma(E_\nu)}{d\cos\theta\, dq_0} = \frac{G_F^2}{4\pi^2}(E_\nu - q_0)^2\left(C_V^2(1+\cos\theta)S_V(\mathbf{q},q_0) + C_A^2(3-\cos\theta)S_A(\mathbf{q},q_0)\right)$$

$$|\mathbf{q}| = \sqrt{4E_\nu(E_\nu - q_0)\sin^2(\theta/2) + q_0^2}.$$

$$S_V(\mathbf{q},q_0) = \frac{1}{2\pi n}\int dt\, e^{iq_0 t}\langle\Phi_0|\hat\rho(\mathbf{q},t)\hat\rho(-\mathbf{q},t)|\Phi_0\rangle$$

$$S_A(\mathbf{q},q_0) = \frac{2}{3\pi n}\int dt\, e^{iq_0 t}\langle\Phi_0|\hat s(\mathbf{q},t)\hat s(-\mathbf{q},t)|\Phi_0\rangle$$

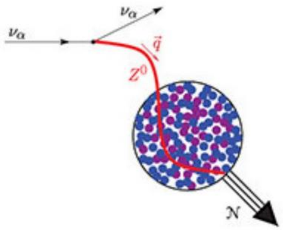
$$\hat\rho(\mathbf{q},t) = \frac{1}{V}\sum_{i=1}^{N} e^{i\mathbf{q}\mathbf{r}_i}, \quad \hat s(\mathbf{q},t) = \frac{1}{V}\sum_{i=1}^{N}\hat s_i e^{i\mathbf{q}\mathbf{r}_i}$$

P. F. Bedaque, S. Reddy, S. Sen and N. C. Warrington *Neutrino-nucleon scattering in the neutrino-sphere*, *Phys. Rev. C* **98** (2018) 015802 [1801.07077].

B. Schuetrumpf, G. Martínez-Pinedo and P. G. Reinhard, *Survey of nuclear pasta in the intermediate-density regime: Structure functions for neutrino scattering*, *Phys. Rev. C* **101** (2020) 055804 [1912.10510].

C. J. Horowitz and A. Schwenk, *The Neutrino response of low-density neutron matter from the virial expansion*, *Phys. Lett. B* **642** (2006) 326 [nucl-th/0605013].

Cross-section : improving calculation



- For the case of non-interacting nucleons and usual assumption of elastic scattering, the cross-section can be defined in terms of static structure factors.

- First equality holds only if significant part of the response lies in the kinematically allowed region for q_0.

- Structure factors contains the contributions from coherence.

$$\int_{-|\mathbf{q}|}^{\min(2E_\nu - |\mathbf{q}|, |\mathbf{q}|)} dq_0 \, S_{V,A}(\mathbf{q}, q_0) \simeq \int_{-\infty}^{\infty} dq_0 \, S_{V,A}(\mathbf{q}, q_0) = S_{V,A}(\mathbf{q})$$

$$\frac{1}{N} \frac{d\sigma(E_\nu)}{d\cos\theta} = \frac{G_F^2}{4\pi^2} (E_\nu)^2 \left(C_V^2 (1 + \cos\theta) S_V(\mathbf{q})\right)$$

Conclusion

- Cosmic neutrino background can thermalize with neutron stars, due to large coherent enhancement.
- We calculated this energy loss for old neutron stars and set an upper bound on CNB overdensities.
- This thermalized boosted background MIGHT potentially be discovered after a future nearby galactic supernova, with low-threshold highly sensitive detectors in (far-)future.
- There are various potential directions to pursue such as proper calculation of the structure functions, effect of Bragg-scattering with nuclear pasta phases, redshift dependence, NS evolution with CNB cooling and effect of BSM physics e.g. long-range forces.
- Neutron star cooling could be an excellent probe of CNB overdensities on the shortest scales in the universe.

Thank you !