

Neutron Stars as probe of Cosmic Neutrino Background

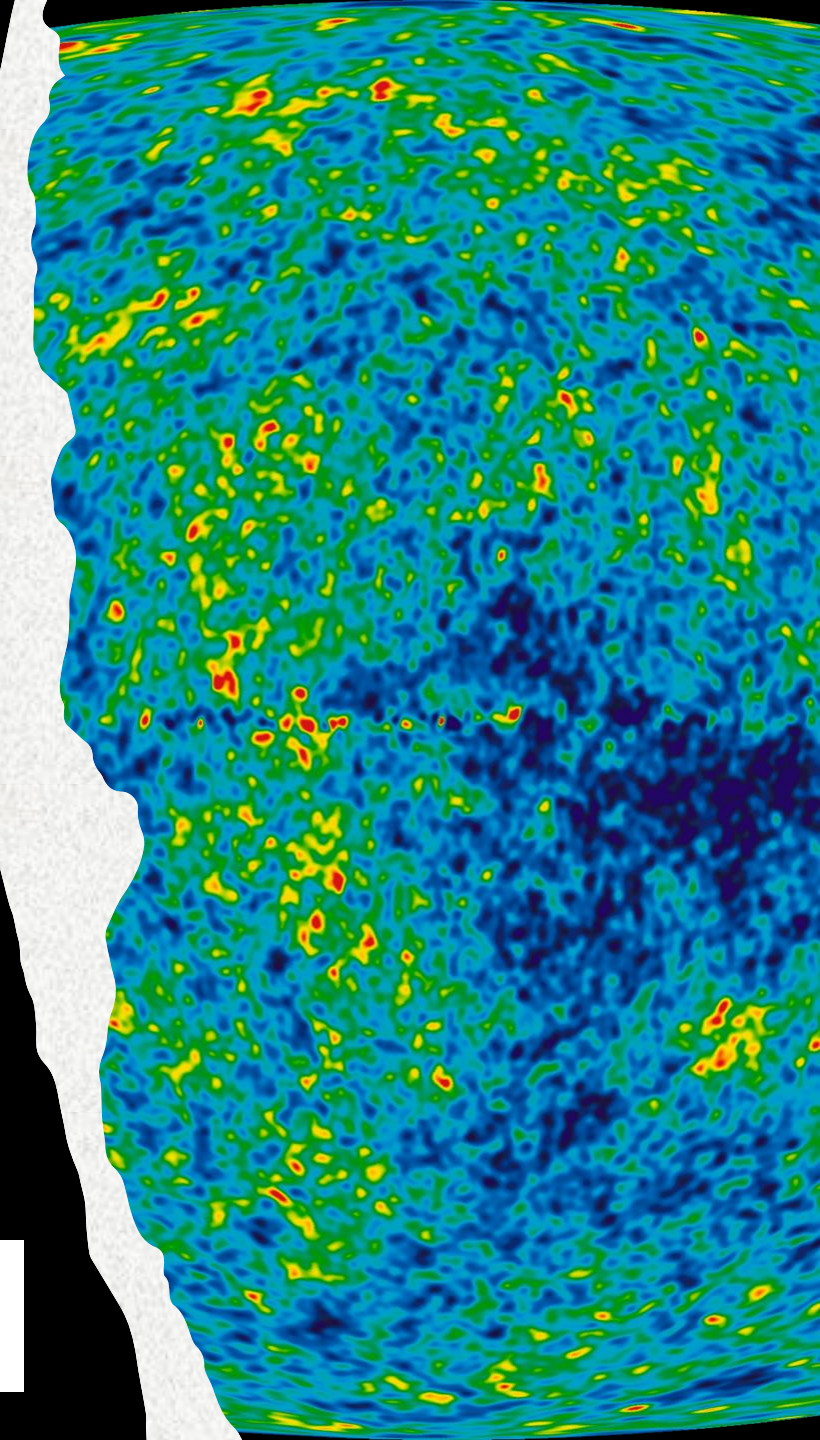
Garv Chauhan

*Center for Neutrino Physics,
Department of Physics,
Virginia Tech*

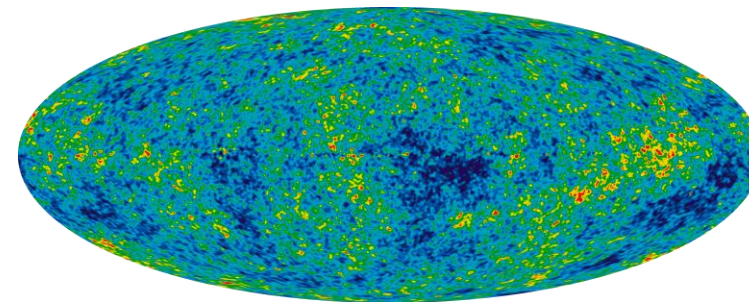
Based on arXiv [hep-ph] : 2407.abcde

CETUP* 2024

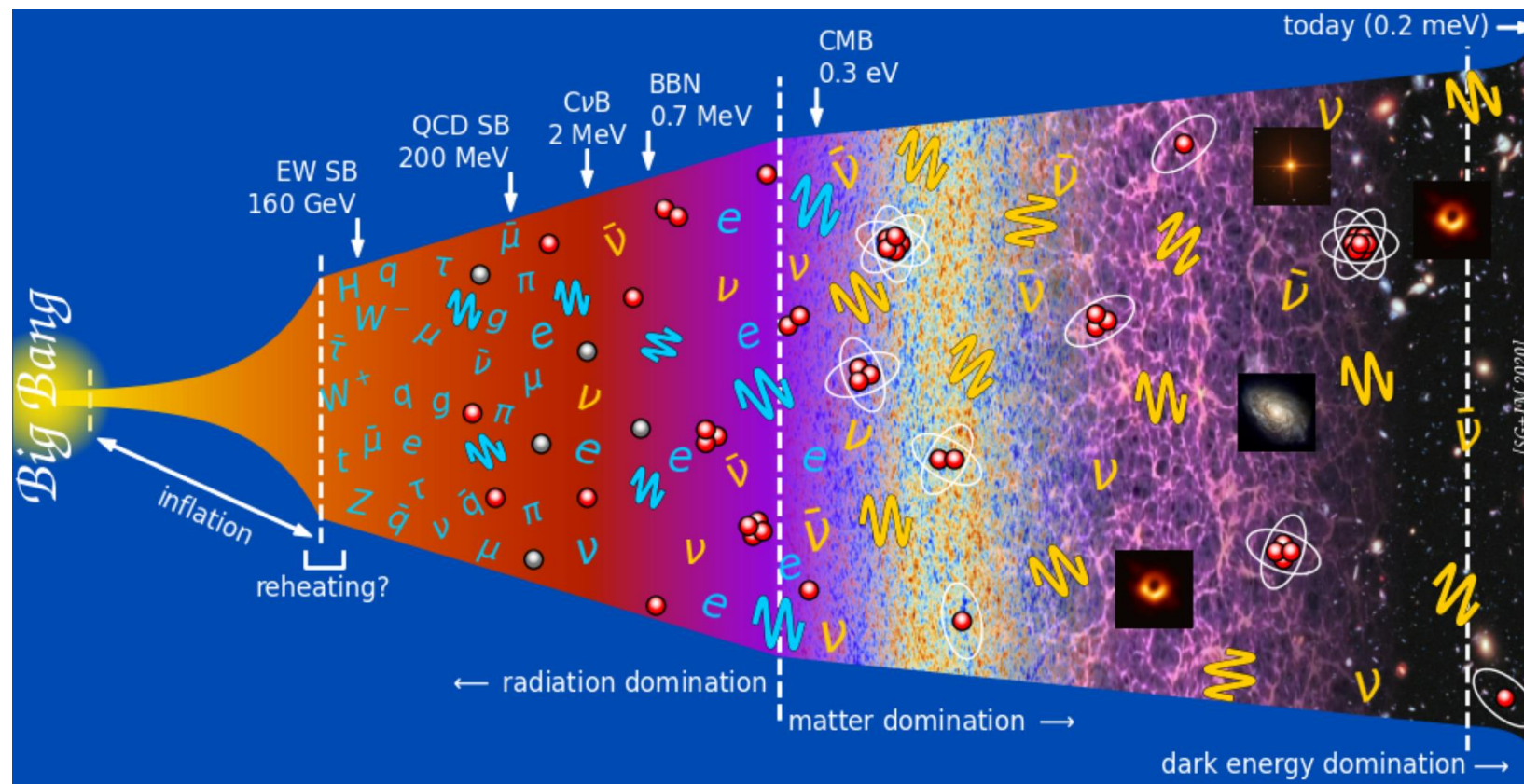
July 11

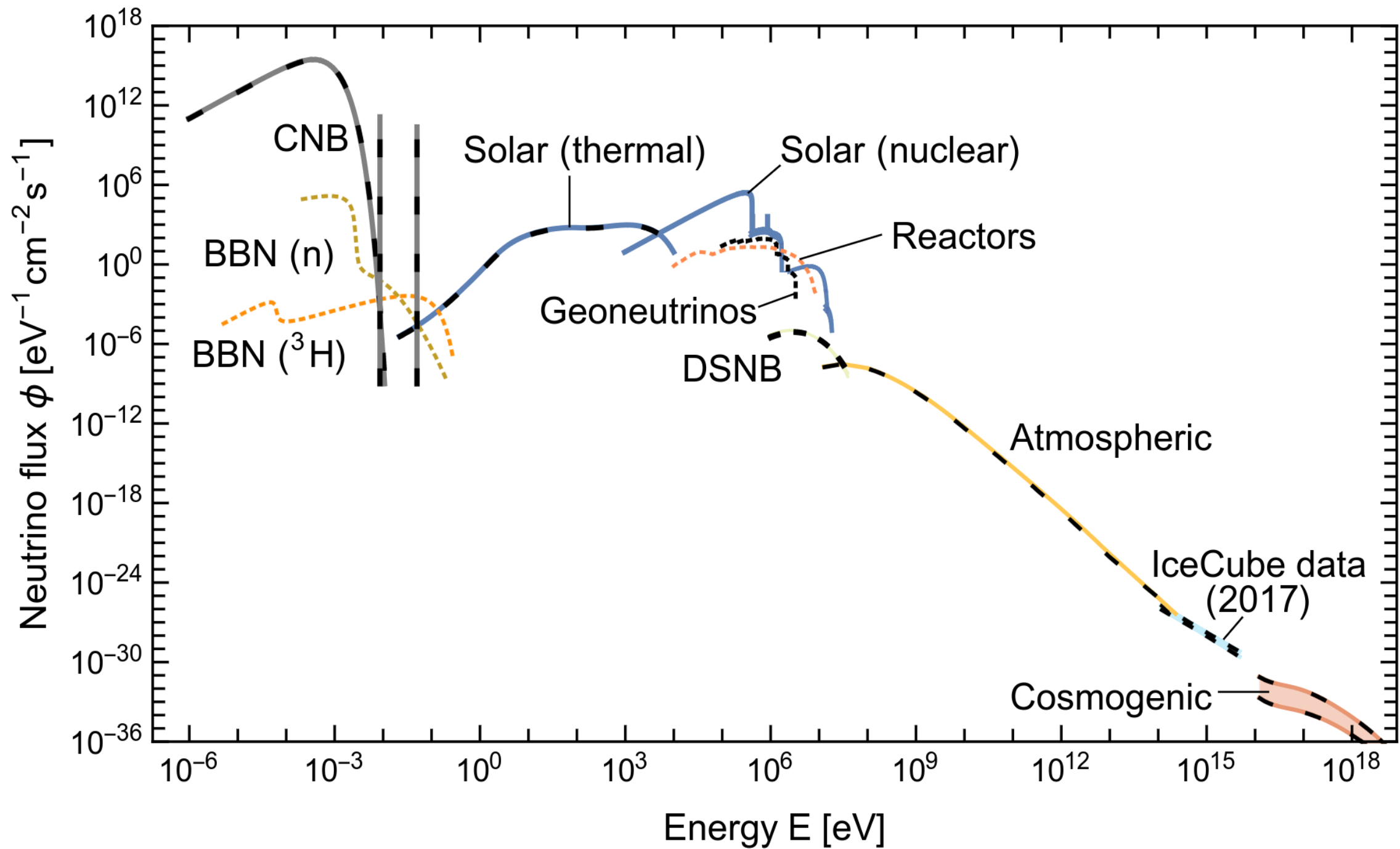


Cosmic Neutrino Background



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





Detection Proposals

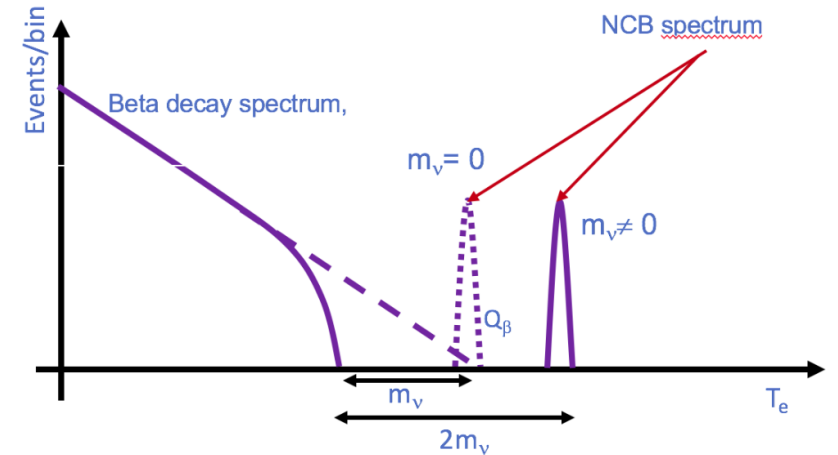
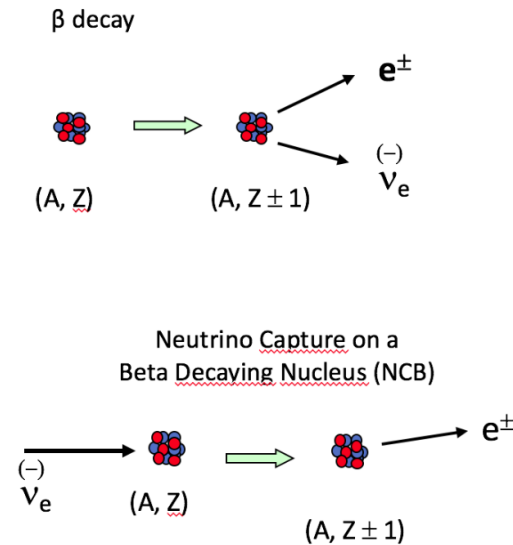
- Various detection proposals include neutrino capture, Stodolsky effect, coherent scattering e.t.c
- PTOLEMY is based on neutrino capture.
- In this work, we use the coherent nature of CNB neutrino scattering.

Universal Neutrino Degeneracy

STEVEN WEINBERG*

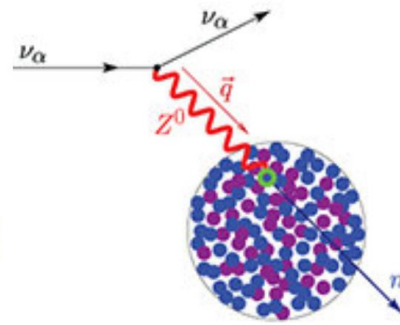
Imperial College of Science and Technology, London, England

(Received March 22, 1962)

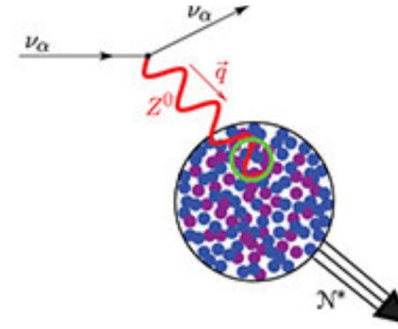


Coherent Scattering

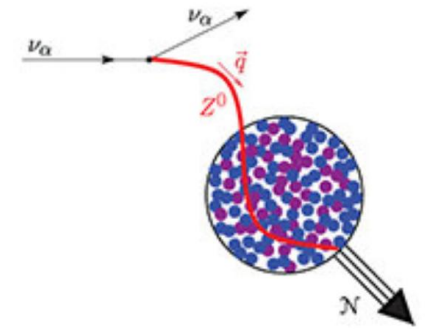
- Occurs when incoming neutrino wavelength is larger than the target.
- The coherent cross section per nuclei scales $\sim \rho$ while the total cross section scales as $\sim \rho^2$



Inelastic incoherent
 $\lambda_{Z^0} \ll 2R$



Elastic incoherent
 $\lambda_{Z^0} \lesssim 2R$



Elastic coherent (CEvNS)
 $\lambda_{Z^0} \gtrsim 2R$

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

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

Coherent 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

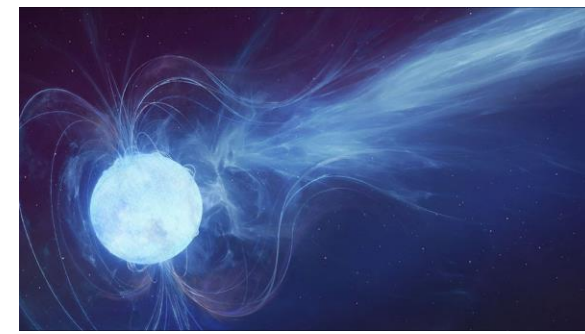
PHYSICAL REVIEW LETTERS

15 APRIL 1974

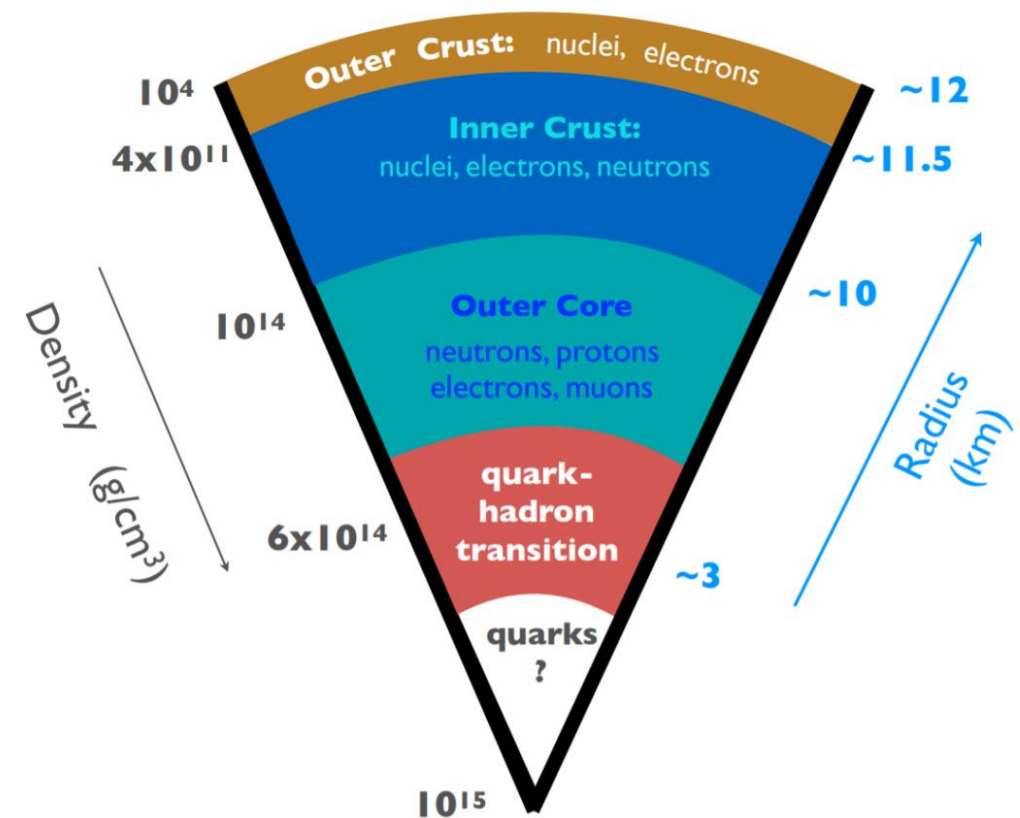
Coherent Neutrino Scattering and Stellar Collapse*

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

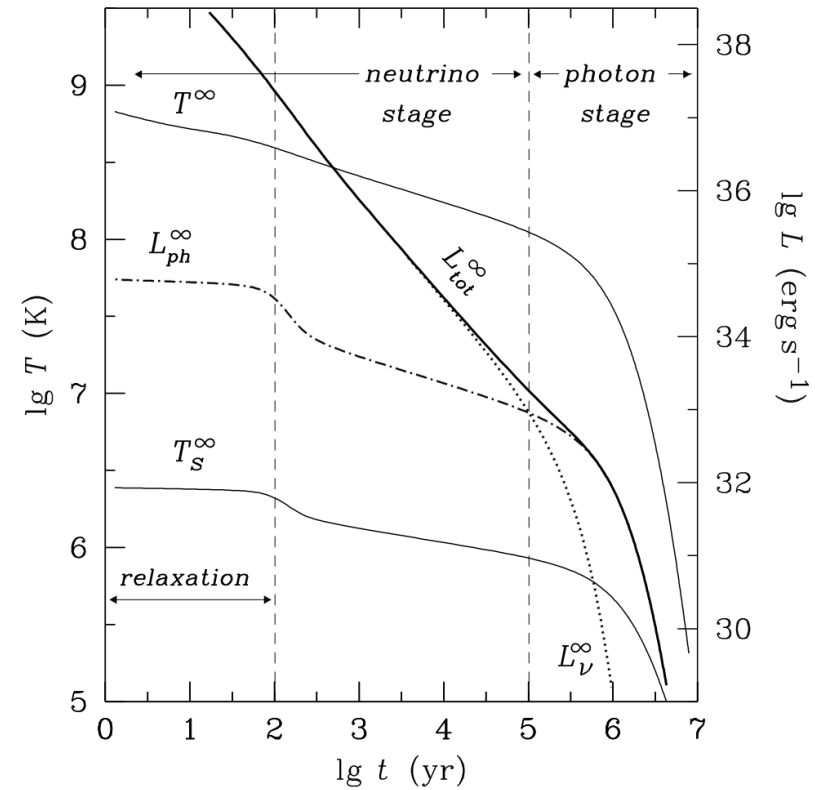
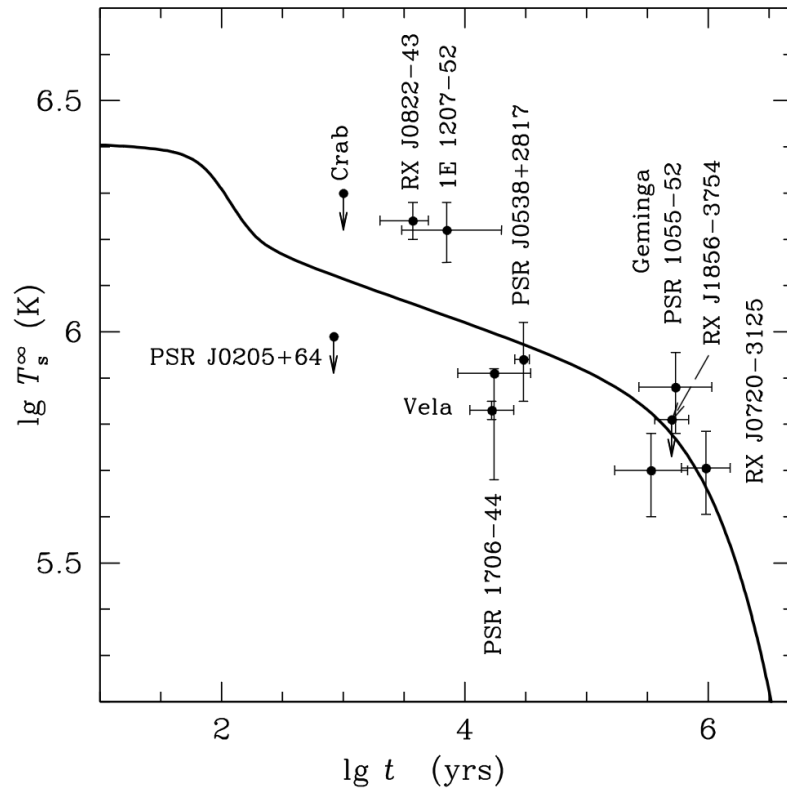
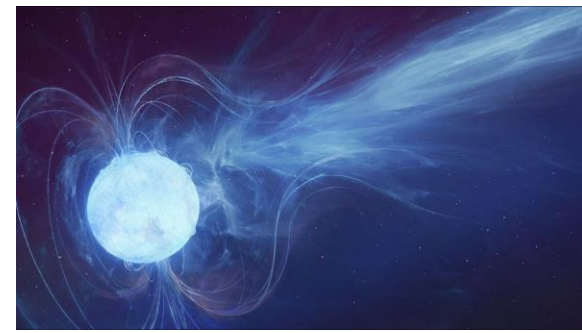
Neutron Star : Overview



- 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.



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.

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

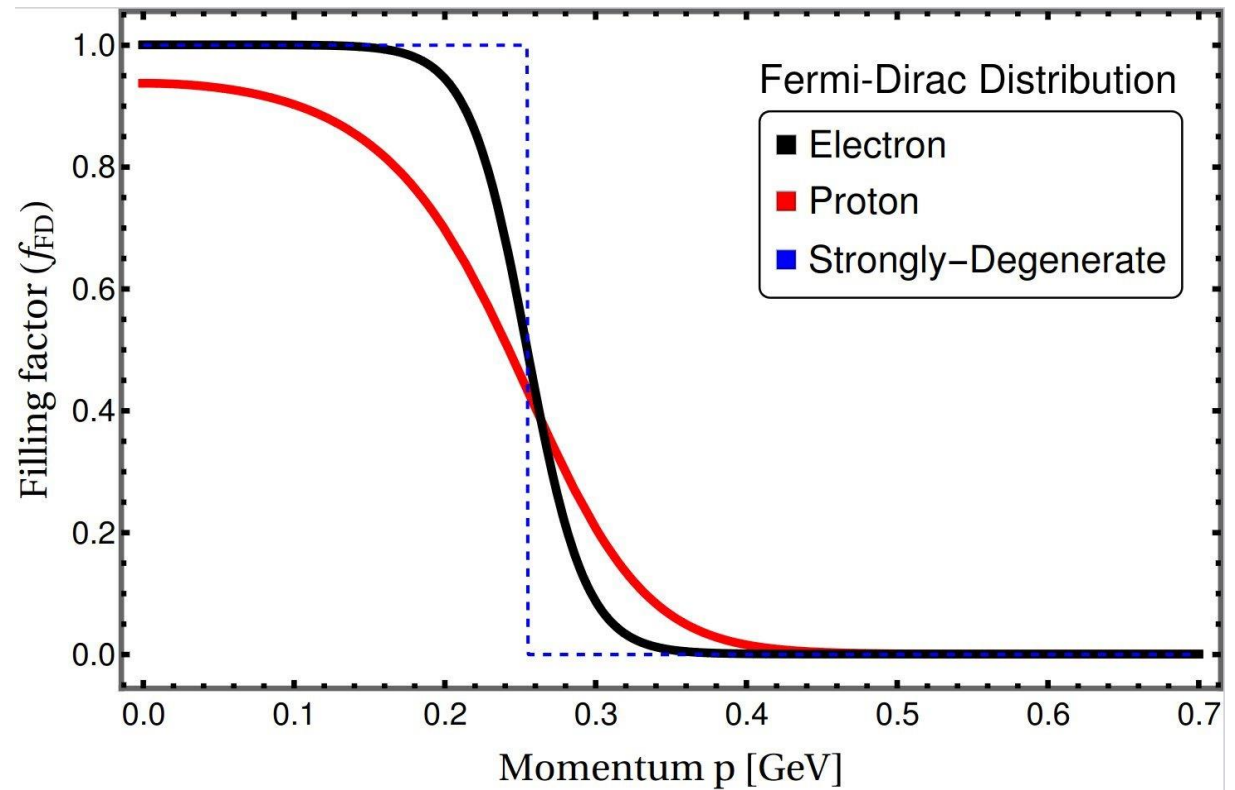
$$\sigma_{\nu-N} \simeq \frac{G_F^2}{4\pi} (A - Z)^2 E_\nu^2, \quad N_c = \left(\frac{2\pi}{p_\nu}\right)^3 \frac{N_A}{A m_A} \rho,$$

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

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 exchange of order T is possible, and we will assume this for rest of this talk.



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.

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

Resonant Enhancements In WIMP Capture By The Earth

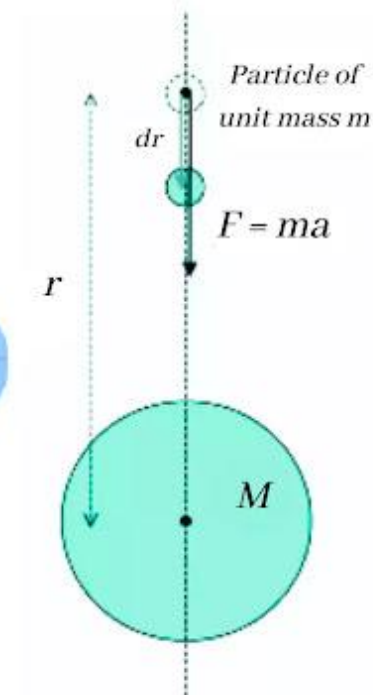
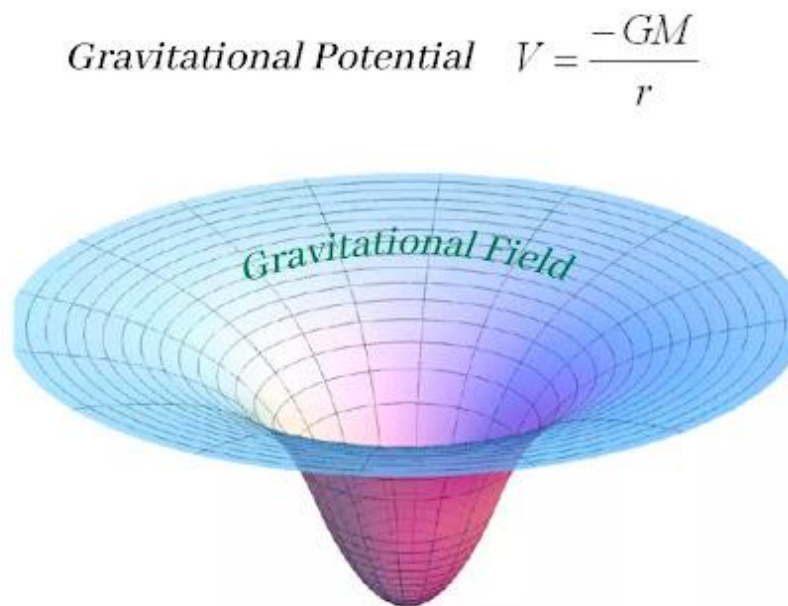
ANDREW GOULD*

*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.

$$v_{\text{boost}} = \sqrt{v_{\text{avg}}^2 + \frac{GM_{NS}}{R_{NS}}}$$

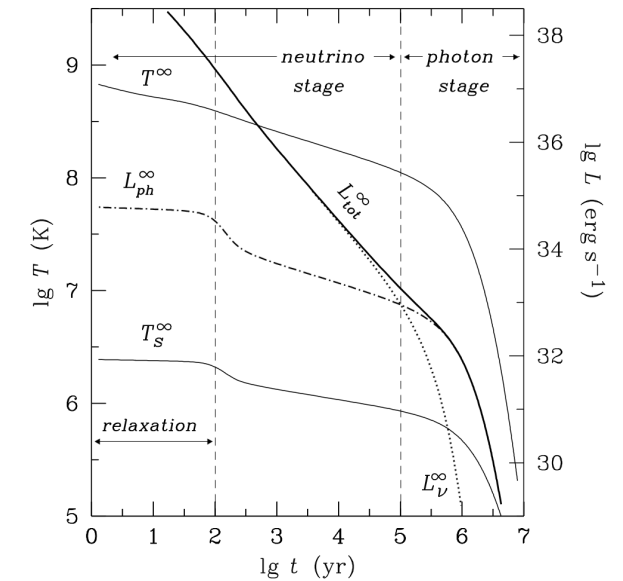
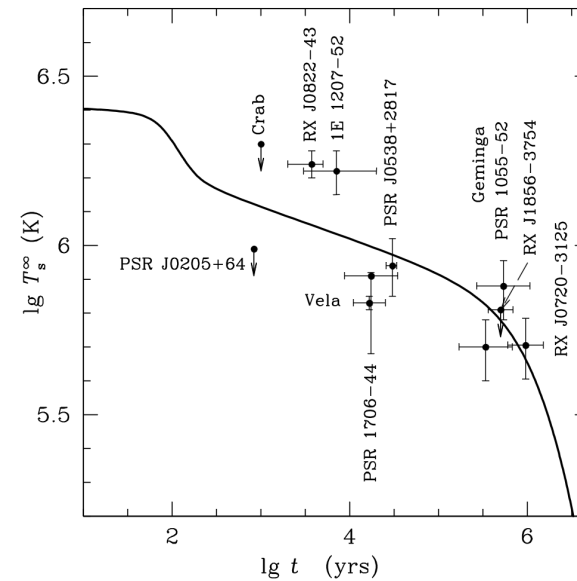


Neutron Star cooling

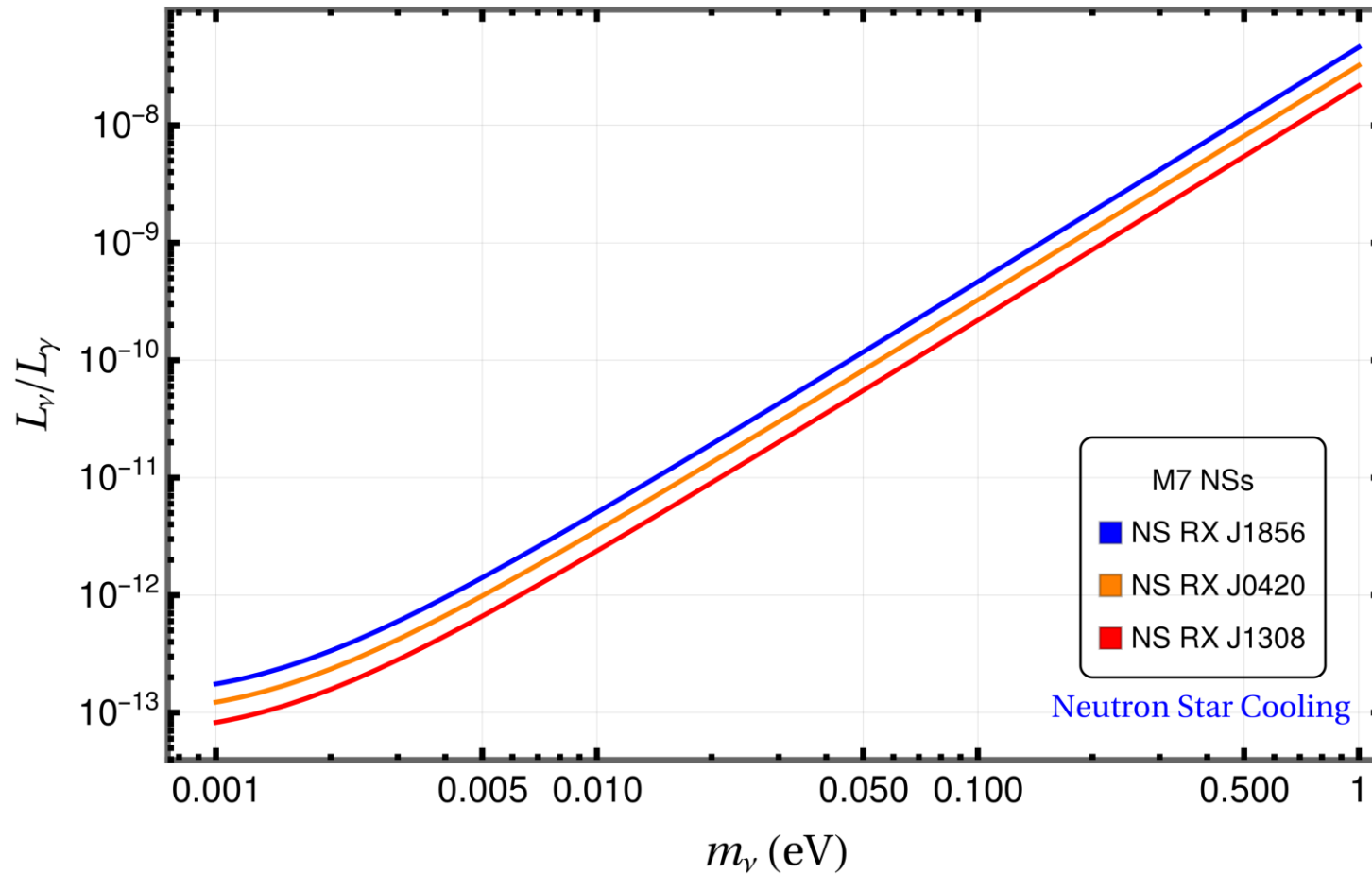


$$L_{\nu B} = 4\pi v_{\text{boost}} R_{NS}^2 \left(1 + \frac{v_{\text{esc}}^2}{v_{\text{avg}}^2}\right) n_{\nu} \frac{3}{2} k_B T_{\text{core}}$$

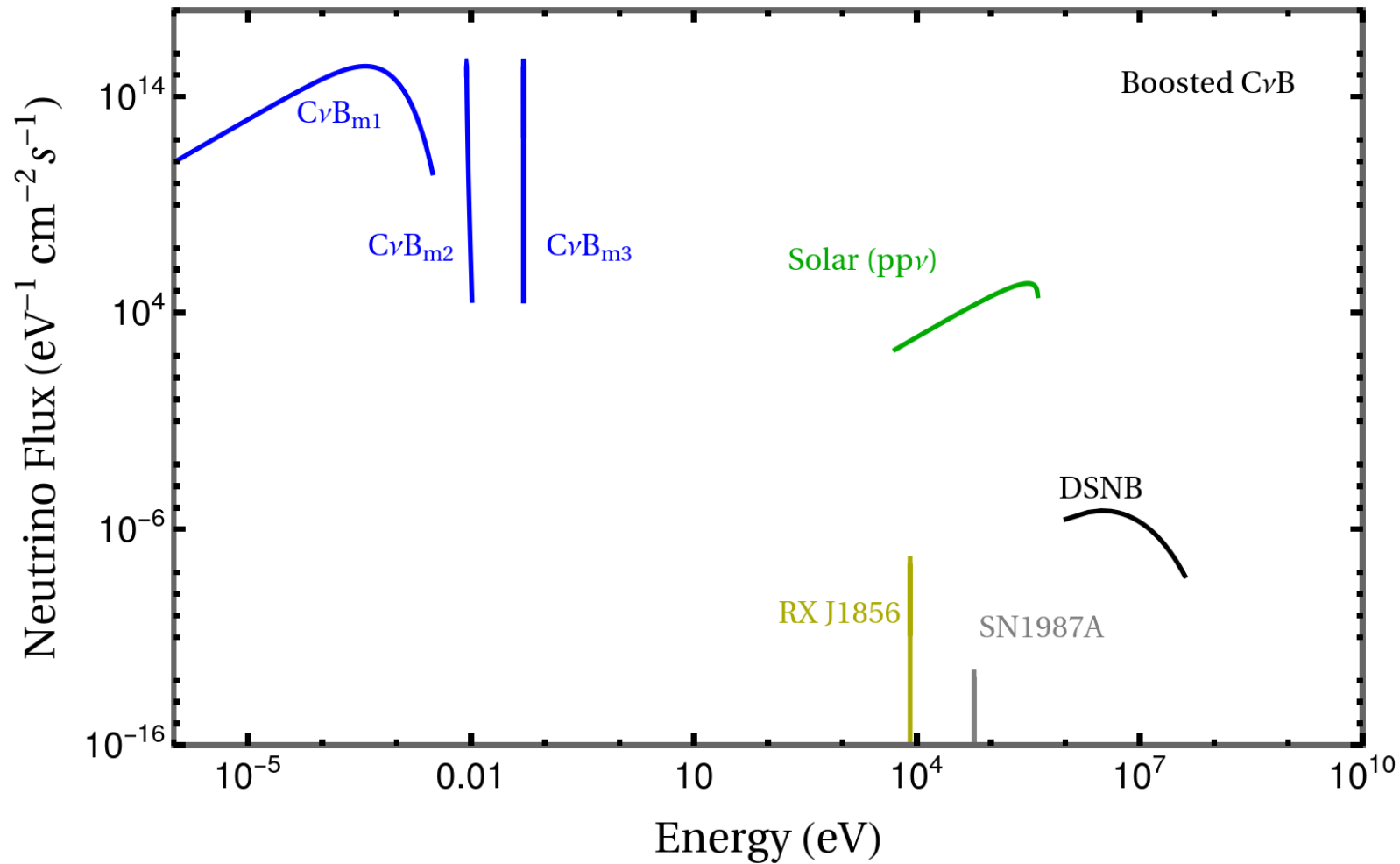
$$L_{\gamma} = 4\pi R_{NS}^2 \sigma T_{\text{sur}}^4$$



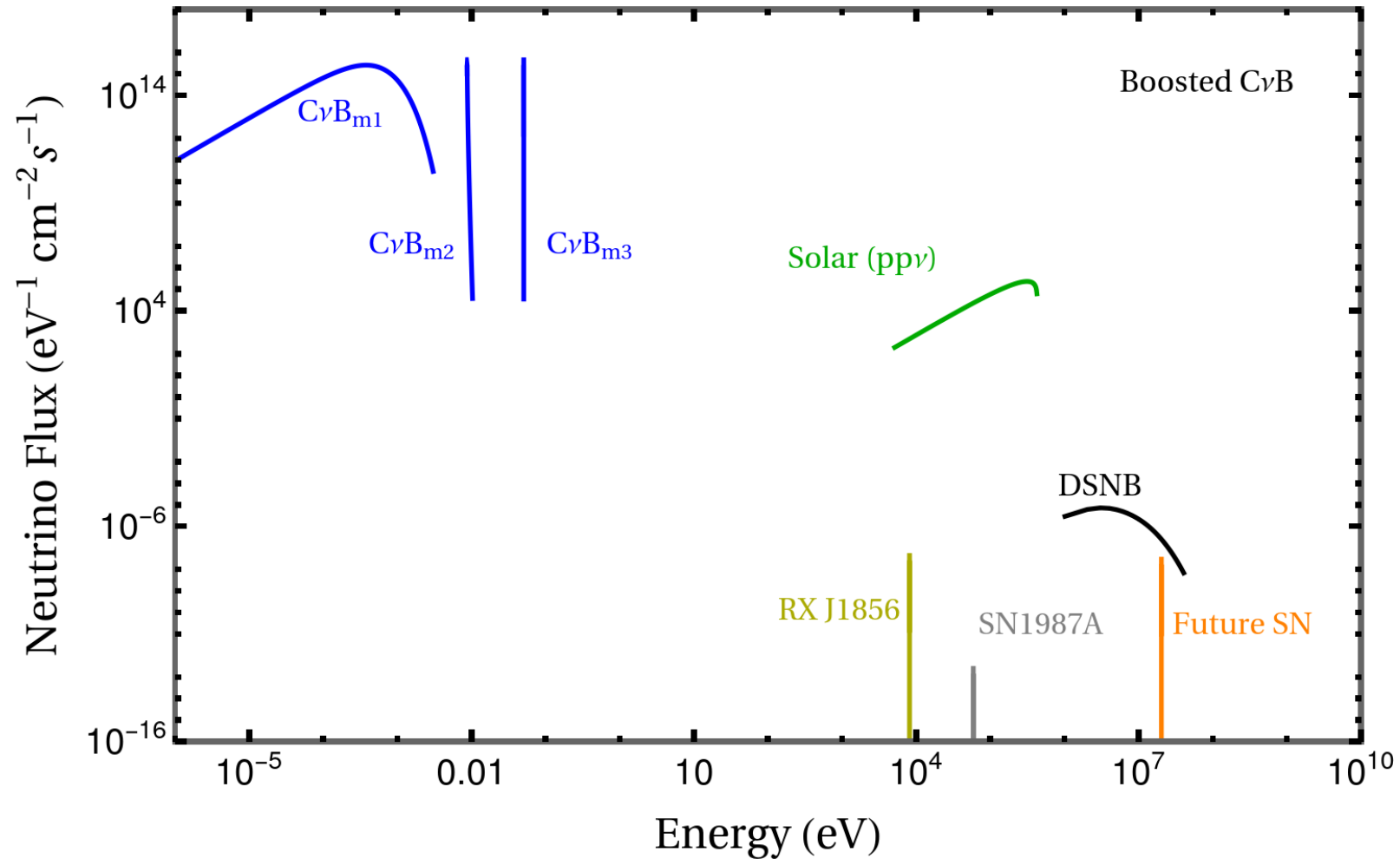
Neutron Star cooling



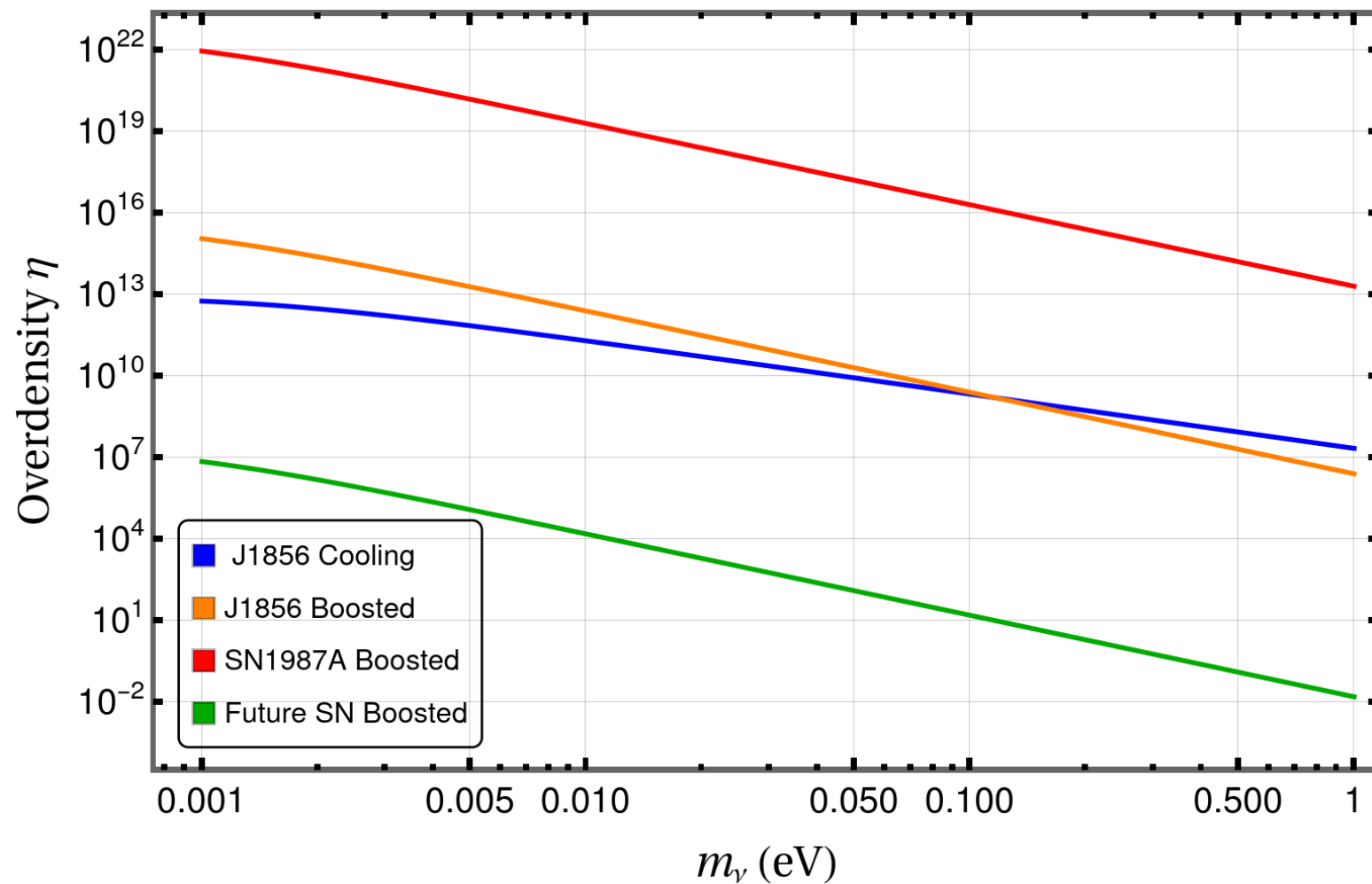
Boosted CNB : J1856 & NS1987A



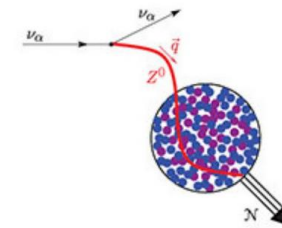
Boosted CNB : Future SN



Combined Bounds



Cross-section : improving calculation



- Proper way is to use dynamic structure functions.

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

- In a medium, cross-section per nucleon for neutral current scattering of low-energy neutrinos on a gas of non-relativistic neutrons

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

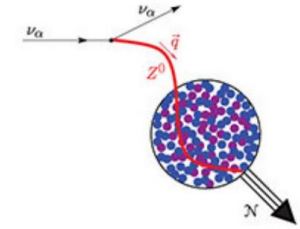
- Computation of dynamic structure factors either require a fully time-dependent simulation or capability to resolve the full excitation spectrum of the system.

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

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

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

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.

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

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

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

- structure factors contains the contributions from coherence.

I just need
the main ideas



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 can potentially be discovered after a future nearby galactic supernova.
- There are various potential directions to pursue such as proper calculation of the structure functions, 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 !