Enhancements to Neutrino Opacities in Hot Magnetized Matter

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Pronouns: she/her

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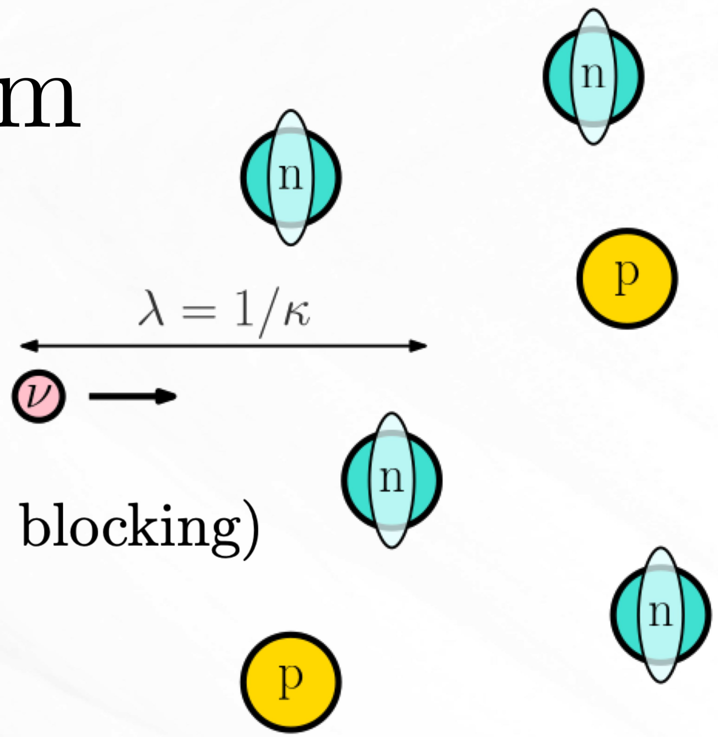
INSTITUTE for NUCLEAR THEORY

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

Statement of the Problem



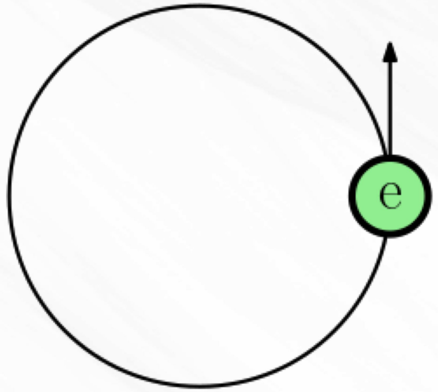
- How far can a neutrino travel before it is captured or scatters?

$$\kappa = \frac{\Gamma}{c} \sim n\sigma \, (+ \text{ Pauli blocking})$$

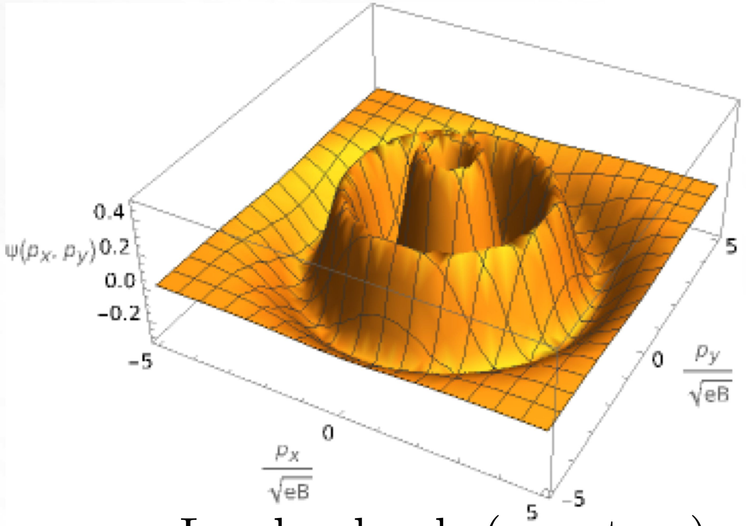
- What effects does the medium have beyond just the density of scatterers? (Pauli blocking, finite temperature, magnetic fields, stimulated absorption)

- When eB ~ k^2, charged particles have their tranverse momentum quantized.

- In a BNS merger, eB ~ 10 – 1000 MeV^2 in some regions of the remnant.



Cyclotron (classical)



Landau levels (quantum)

Why care about neutrino opacities?

- Long mean free path → Dominate transport
- Weak processes can change proton fraction, effects on r-process?
- Neutrinos will carry invaluable data in the next nearby CCSN
- Neutrinos are a (relatively) weakly constrained portal to BSM interactions.

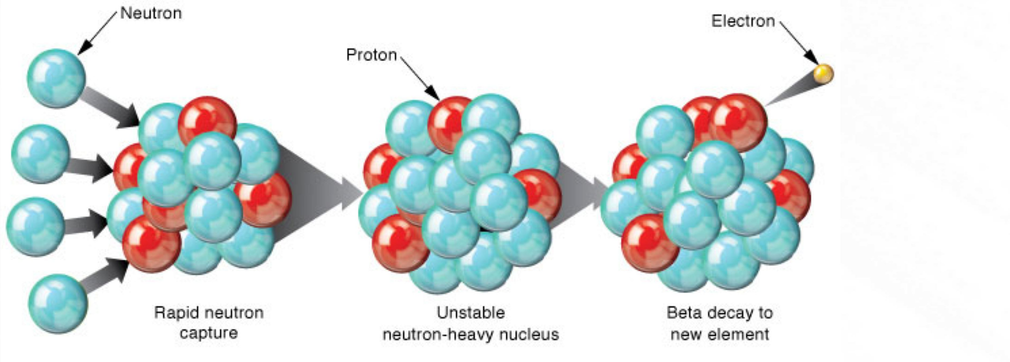


Image: LLNL

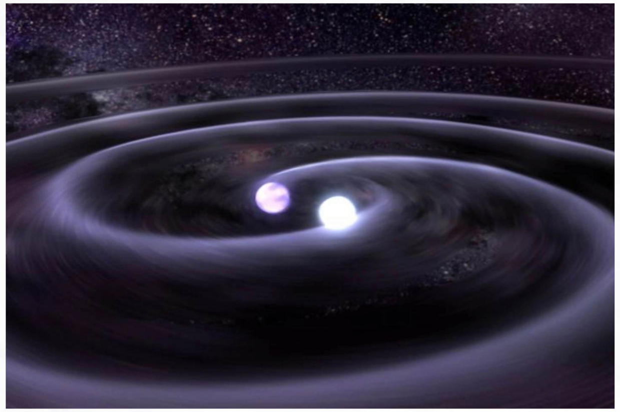


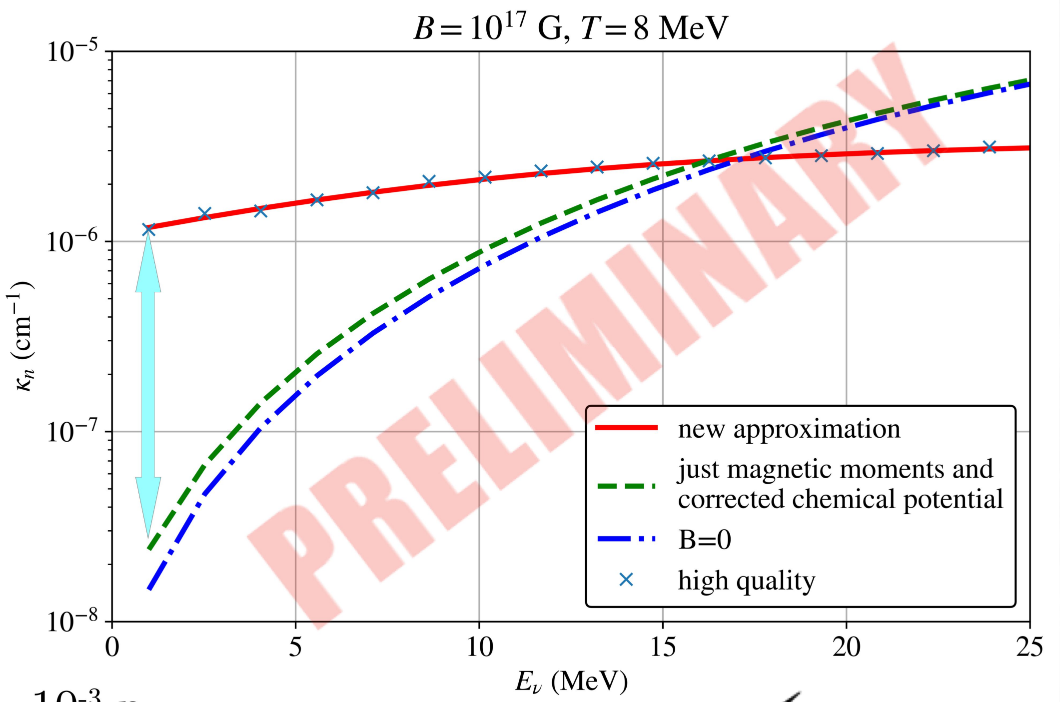
Image: NASA

Image: JWST NIRCam

This talk is an advertisement

So I'm going to give the punchline first

Early Conclusion



$n_B = 10^{-3}\ n_{sat}$
$Y_p = 0.25$

- Low energy neutrinos have their opacities strongly enhanced in magnetic fields. (MK + Welch 2025, PRD)
- Different mechanisms affect neutrinos and antineutrinos → Possible effect on Y_p
- Hard to precompute (6D parameter space) but ours is fast enough to calculate at run time for a simulation.

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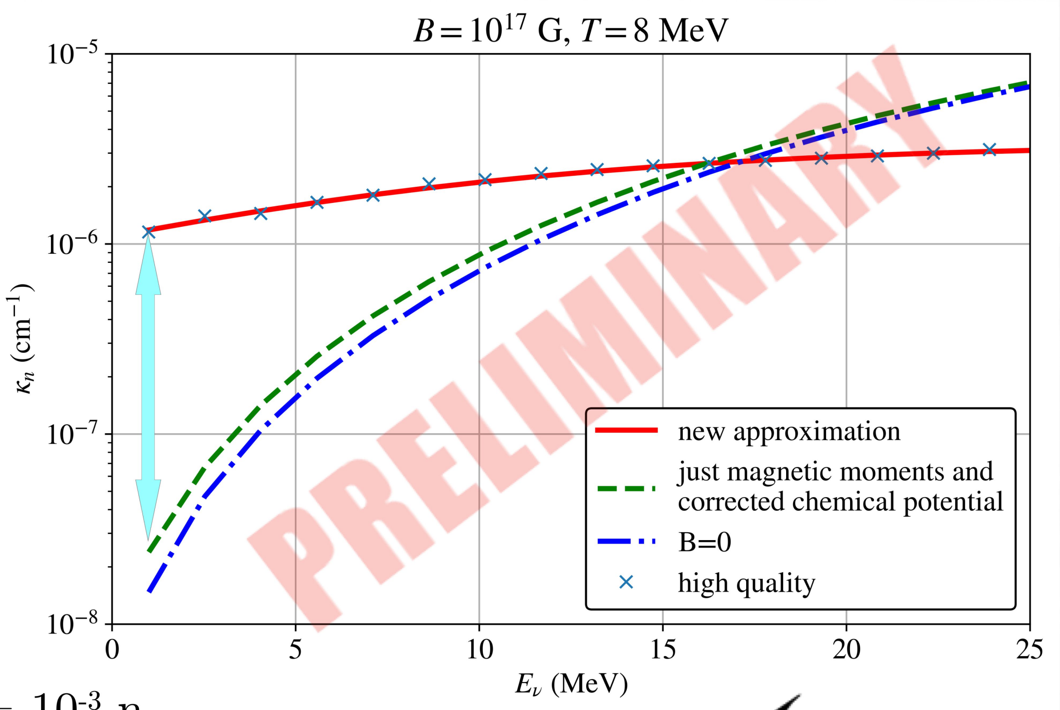

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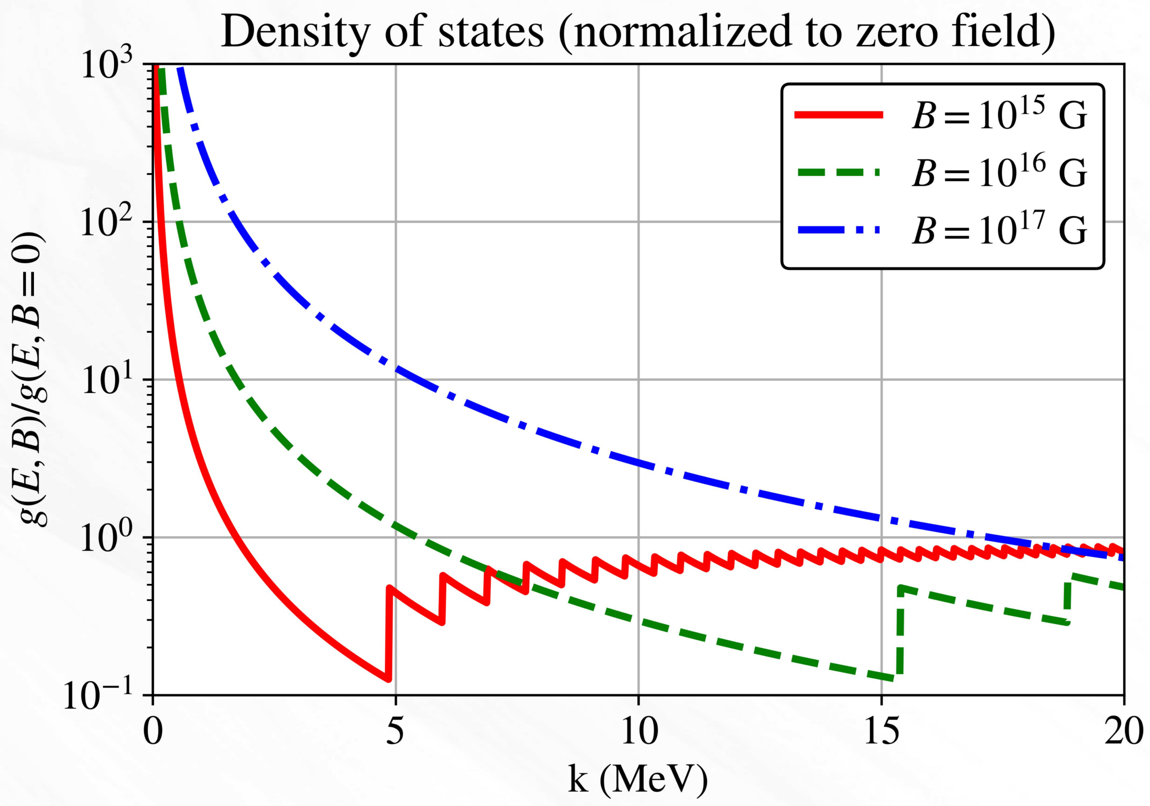
And now back to the start...

What is actually happening?

- Quantization modifies the density of states → Cannot take continuum limit
- Resonances when new levels become available. (Relevant at high density, Maruyama et al 2022, Tambe et al 2024, MK & Welch 2025)
- Many more states to scatter into and out of at low energy. (!)
- Large anomalous magnetic moments for nucleons.



There is just one problem

$$T \propto \sum_{n_e,n_p} \int \mathrm{d}^2 x_\perp e^{ik_\perp \cdot x_\perp} \psi^\dagger_{n_p} \psi_{n_e} \propto \sum_{n_e,n_p} \frac{n_e!}{n_p!} \left(\frac{k_\perp^2}{2eB} \right)^{n_p - n_e} \exp\left(- \frac{k_\perp^2}{2eB} \right) L_{n_e}^{n_p - n_e} \left(\frac{k_\perp^2}{2eB} \right)$$

These are Landau levels, not number density

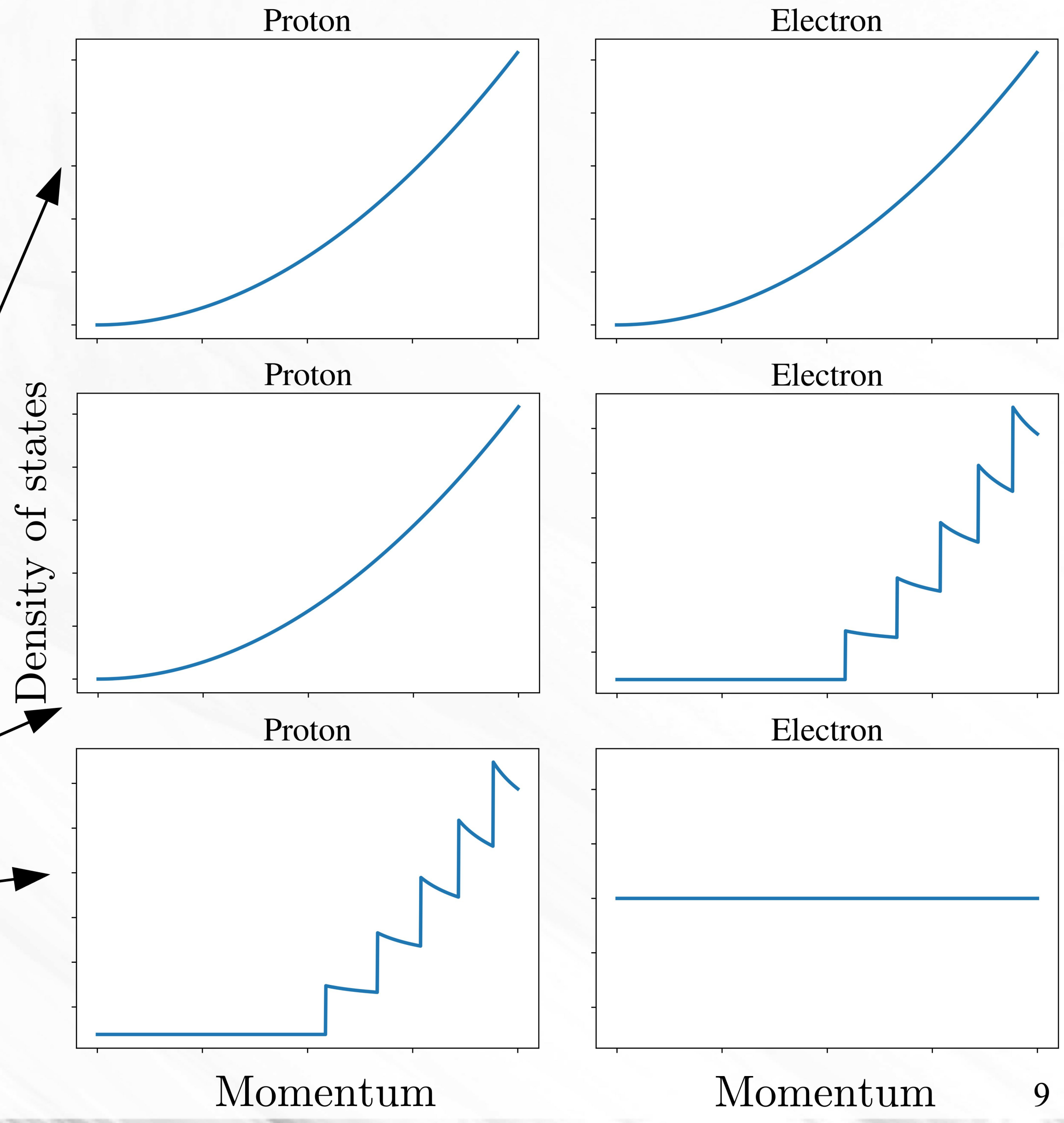
- Repeated calculation of modified Laguerre polynomials is inefficient.
- Precomputing for numerical integration takes too much memory (surmountable) and is still too slow.
- Numerically performing this sum has a computational cost that grows as $T^{3/2}$

Simplification from mass scales

- Observation: When T dominates, every particle species has the same average KE

- $M_N >> m_e$ so typical proton momentum is much larger than a typical electron.

- Three regimes of magnetic field:
  - Electron and proton both continuous
  - Electron quantized, proton continuous
  - Proton quantized, electron only in zeroth Landau level



What does this actually get you?

Electron quantized, proton continuous

- Scattering is strong when transverse momentum conservation is weakly broken.

$$\sqrt{n_p} - \sqrt{n_e} \lesssim \frac{(\vec{k}_{\perp n} - \vec{k}_{\perp \nu})^2}{2eB} \lesssim \sqrt{n_p} + \sqrt{n_e}$$

$$e^{ik_\perp \cdot x_\perp} \psi^\dagger_{n_p} \psi_{n_e} \Rightarrow \delta_{n_p, k_\perp^2/2eB}$$

- Kronecker delta for n_p when eB << $M_N T$

Even high quality calculations do not need costly Laguerre polynomial evaluations!

Proton quantized, electron LL = 0

- When either Landau level is zero, the zeroth Laguerre polynomial is just 1.

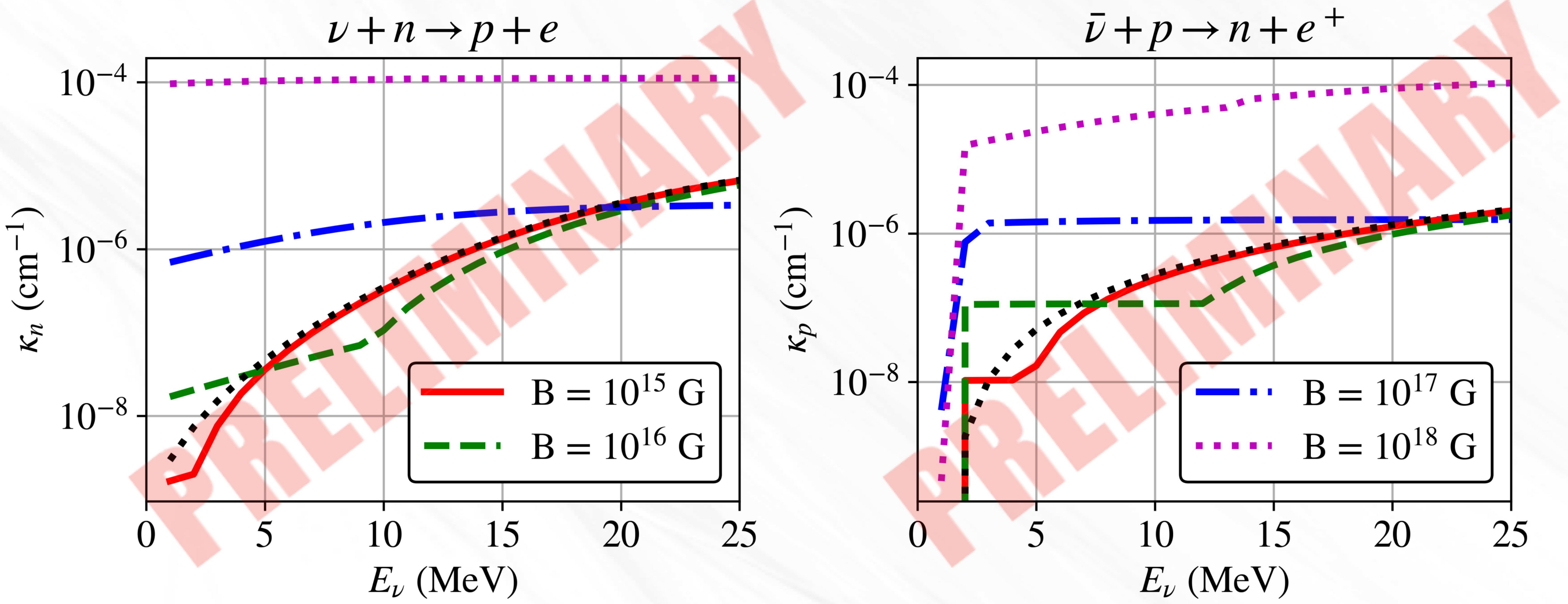
Edmond Laguerre
(Image: wikipedia)

- Wavefunction is a power law times an exponential, we can do that!

$$e^{ik_\perp \cdot x_\perp} \psi^\dagger_{n_p} \psi_{n_e=0} \Rightarrow \left(\frac{k_\perp^2}{2eB}\right)^{n_p} \exp\left(-\frac{k_\perp^2}{2eB}\right)$$

A few preliminary trends

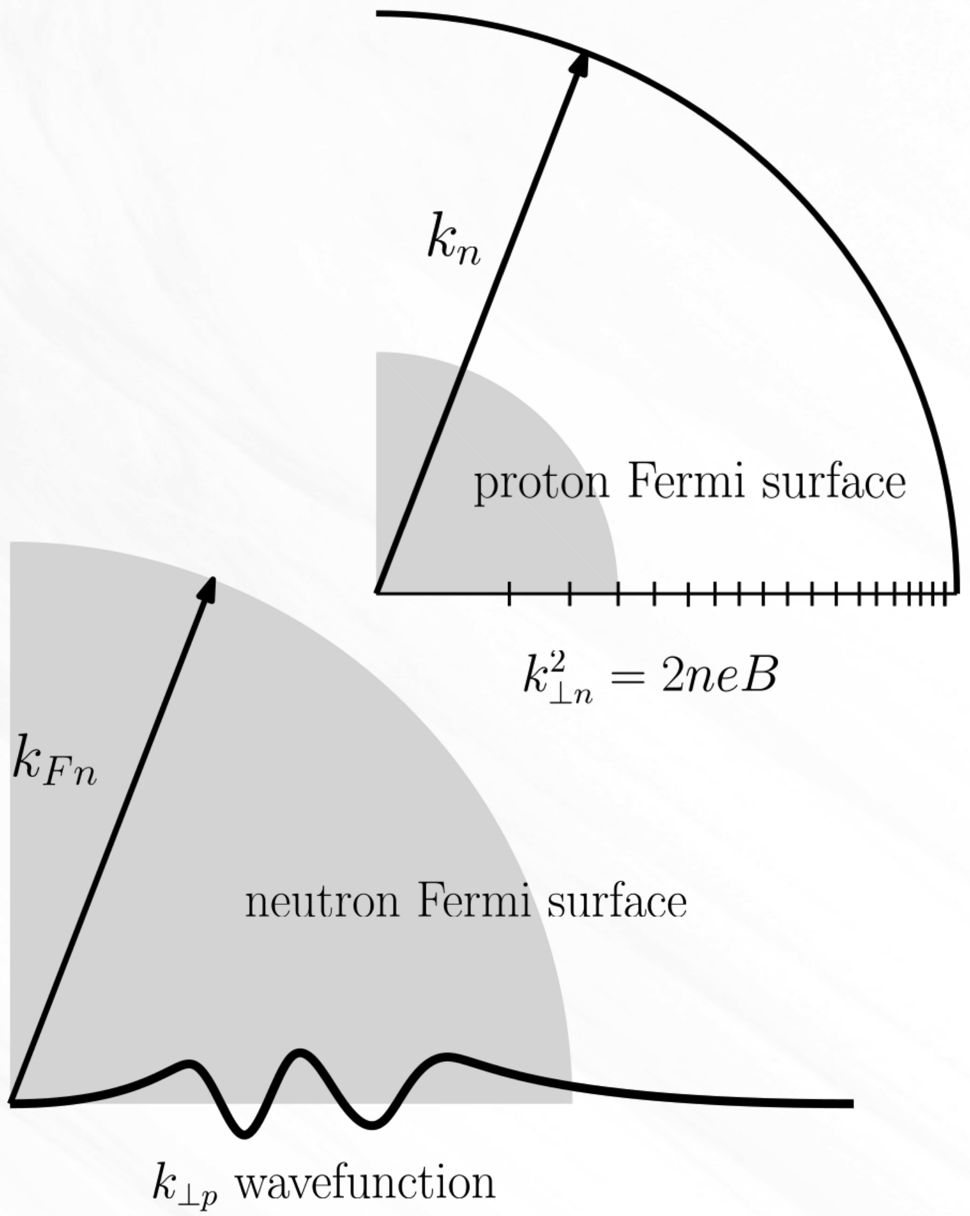
- Below 10^{16} G, effects are minimal at low density (as expected)
- Large field → weaker dependence on neutrino energy (flat density of states)
- Large field → more differentiation between neutron and proton branches



Differences for protons and neutrons

- Capture on neutrons:
  - Pauli blocking from electrons
  - Degenerate matter typically very isospin asymmetric, proton looks continuous

- Capture on protons:
  - Minimal Pauli blocking from positrons
  - Degenerate matter Pauli blocks neutrons for B=0, proton quantization is important
  - Nucleon mass difference suppresses capture for very low energies.



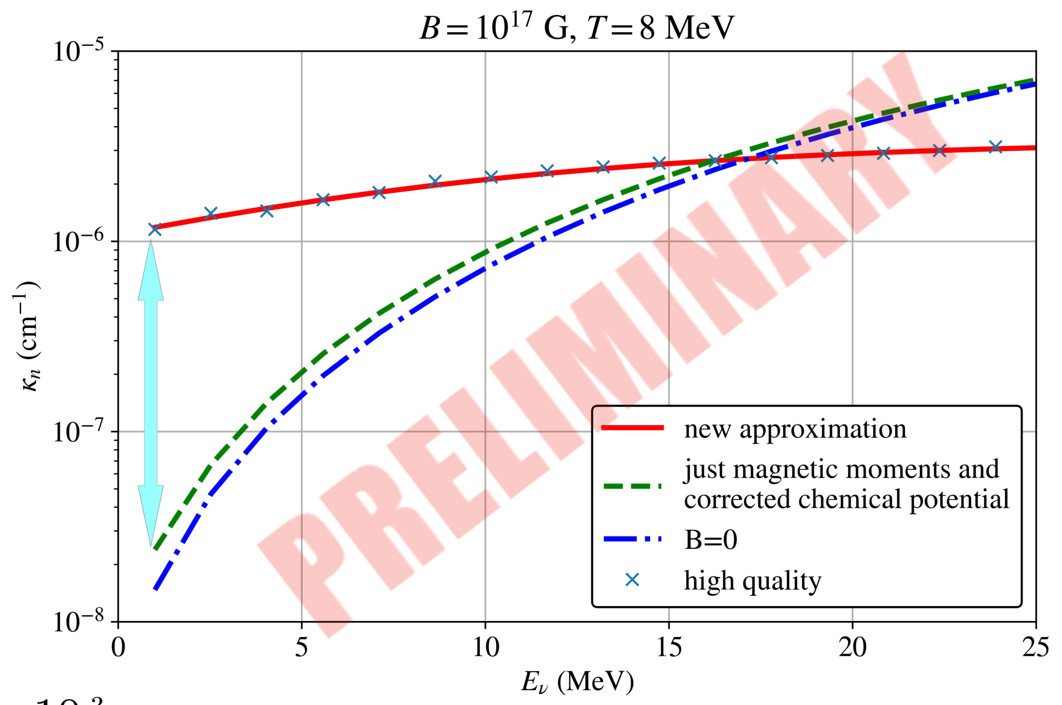
Conclusion 2: Electric Boogaloo

- Low energy neutrinos have their opacities strongly enhanced in magnetic fields. (MK + Welch 2025, PRD)

- Different mechanisms affect neutrinos and antineutrinos → Possible effect on Y_p

- Next: high accuracy (but slower) results for post-processing studies

- Publication soon with accompanying github repo (managed by a much better programmer than me)



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Catherine Welch

New grad student at UC Berkeley