Gluon propagation in cold quark matter: soft gluon self-energy at next-to-leading order

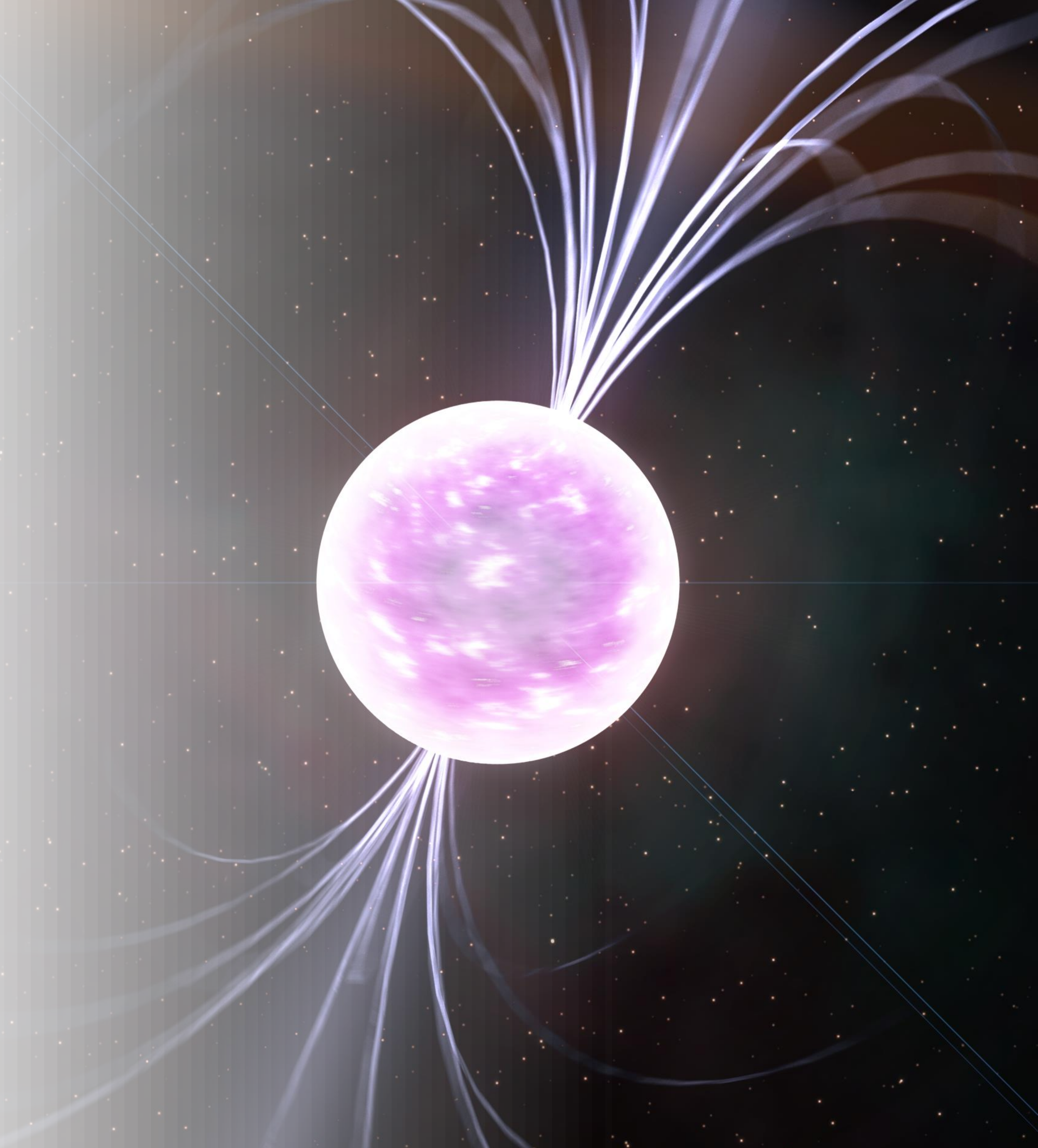
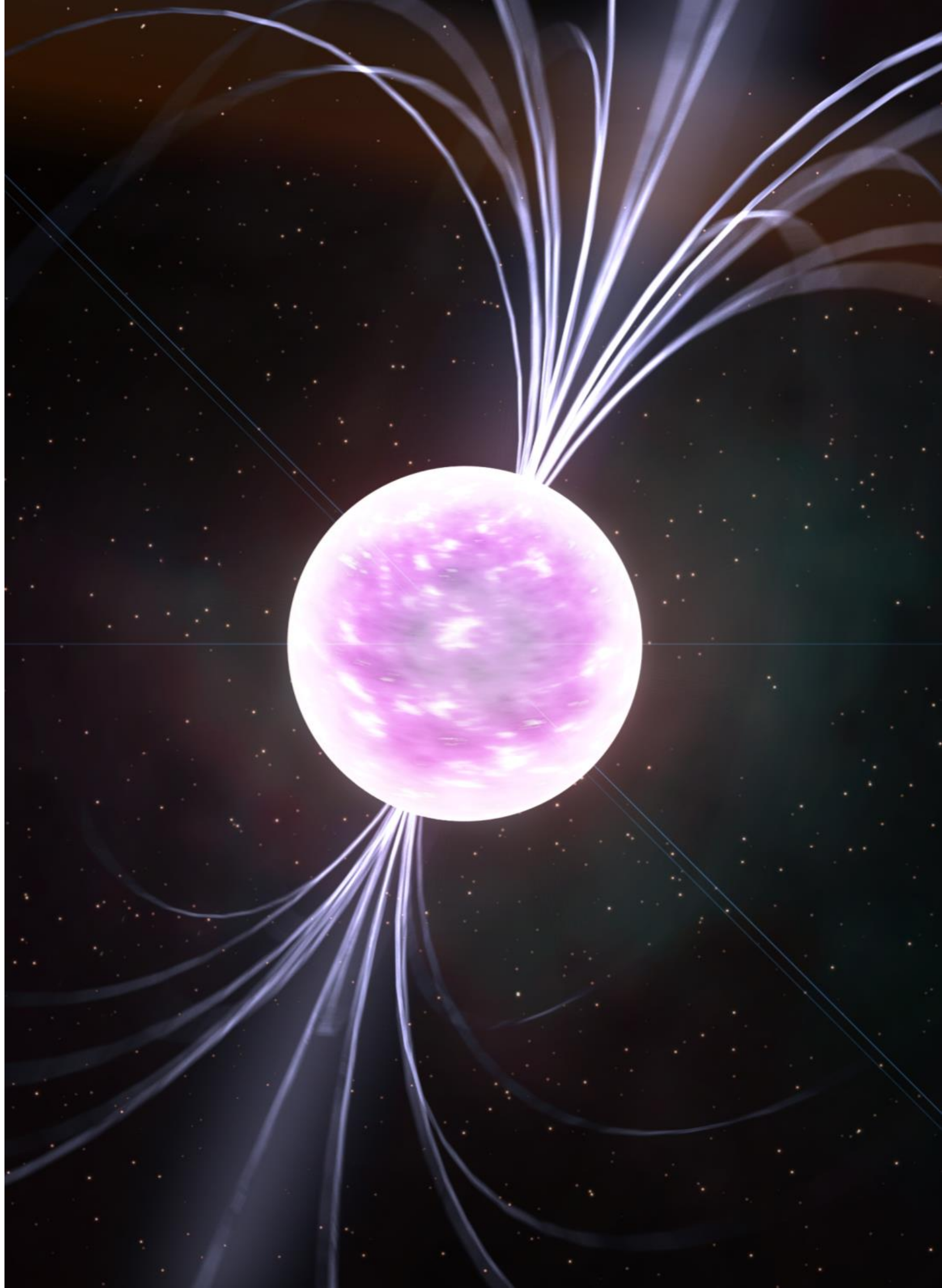


Image source: Kevin Gill / Flickr

Tomi Ruosteoja 23.1.2024

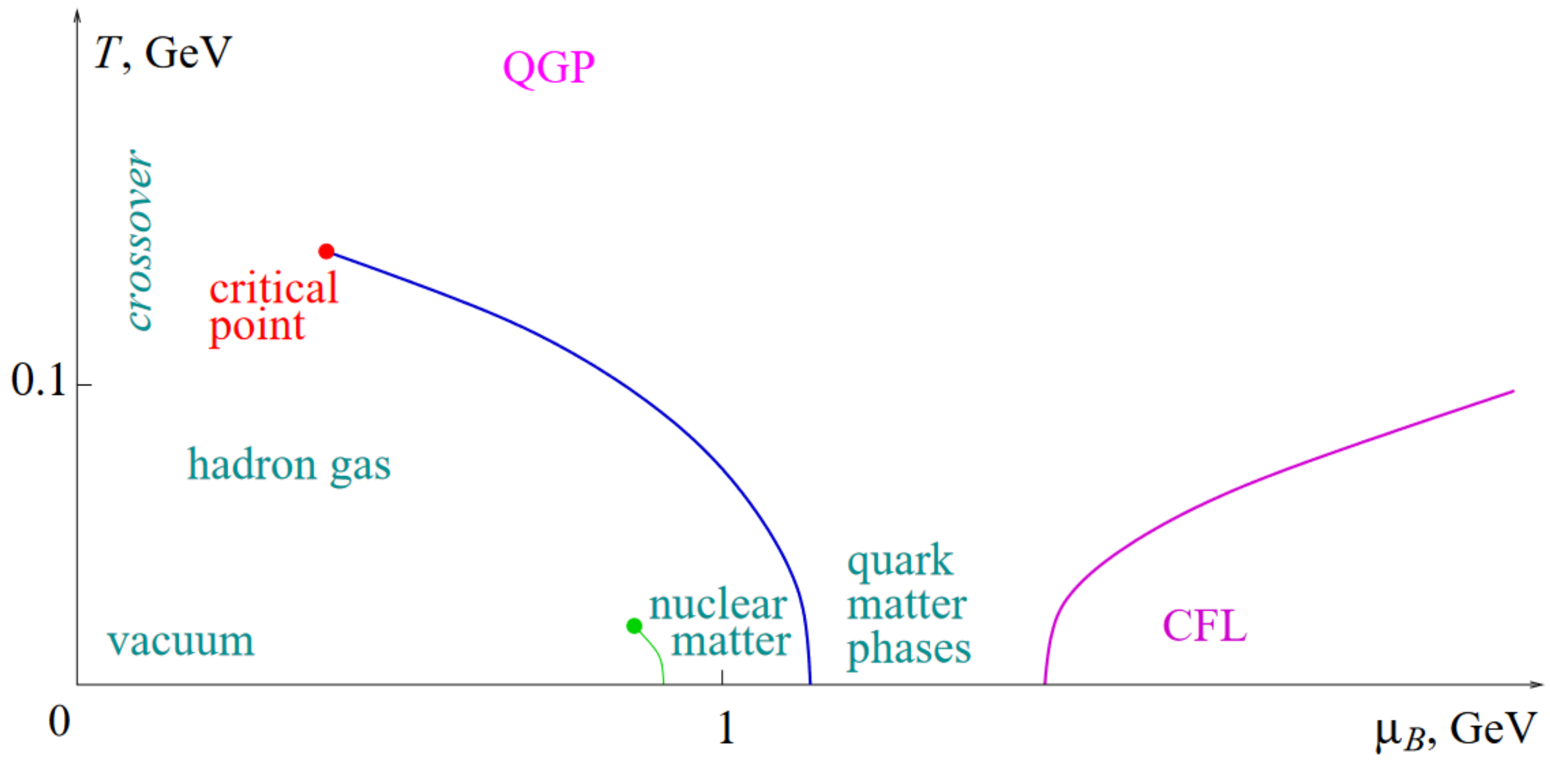
Outline

1. Neutron stars could contain quark matter
2. Thermal QCD
3. Propagation of gluons at finite density
4. Results and future research



Phase diagram of QCD

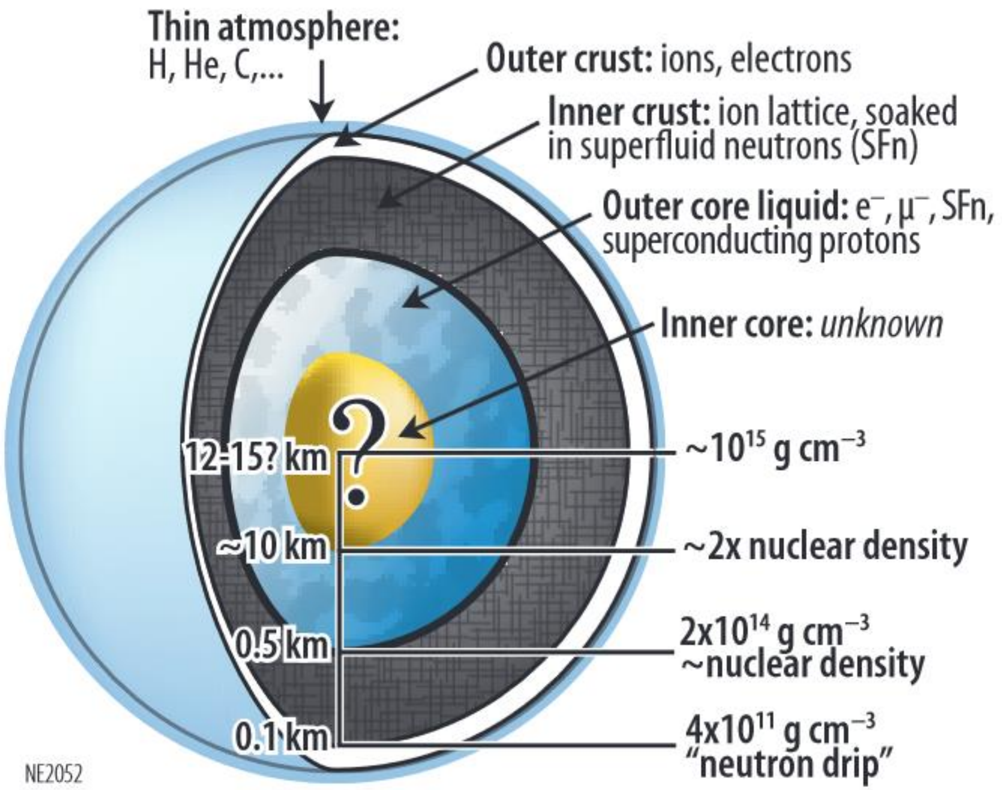
- Low energies
  - hadronic matter: protons, neutrons, etc.
- High energies
  - deconfined plasma of quarks and gluons



Phase of QCD-matter as a function of temperature (T) and baryon chemical potential (μ_B). [M. Stephanov, 2006]

Neutron stars are dense and cold

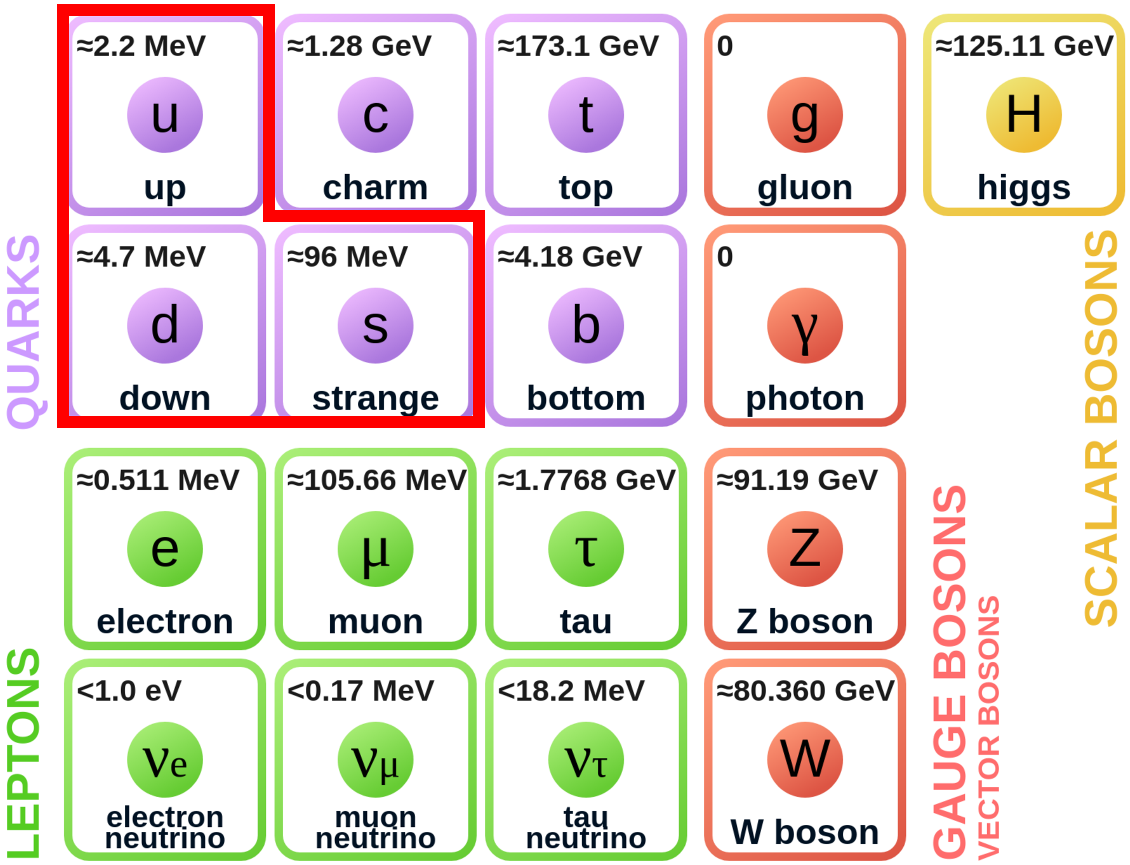
- Neutron stars cool rapidly after their formation. $\Rightarrow T \ll \mu_{\mathrm{B}}$
- Density in the cores of heaviest neutron stars is greater than $5\mathrm{n}_{\mathrm{o}}$.
- Analyses of neutron-star equations of state suggest existence of quark-matter cores.



[https://heasarc.gsfc.nasa.gov/docs/nicer/nicer_about.html]

Cold quark matter

- Three quark flavors (u, d, s) are present at densities relevant to neutron stars.
- The quarks can be approximated to be massless.
- Color-superconductivity can be ignored in some cases.



[https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg]

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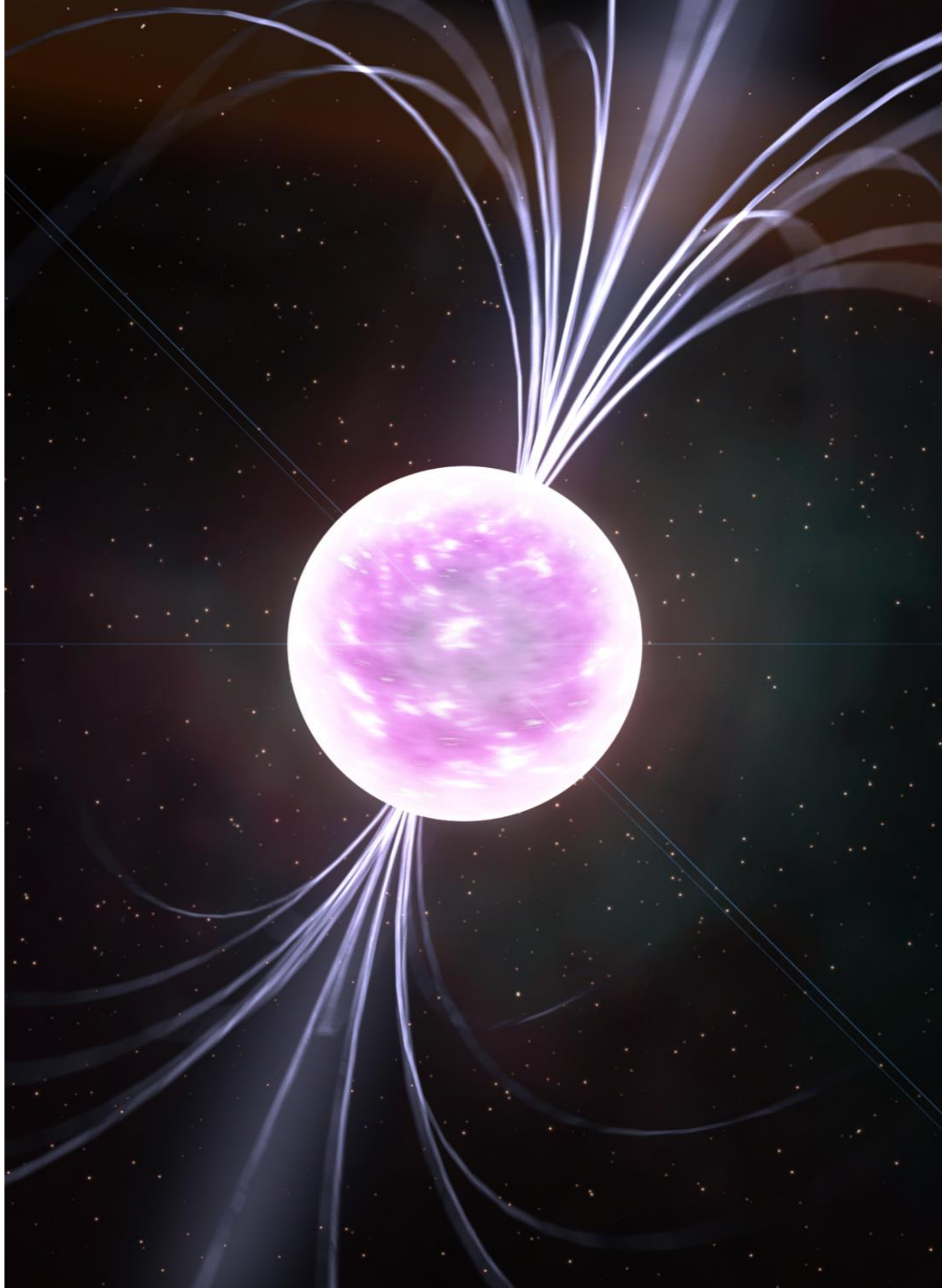
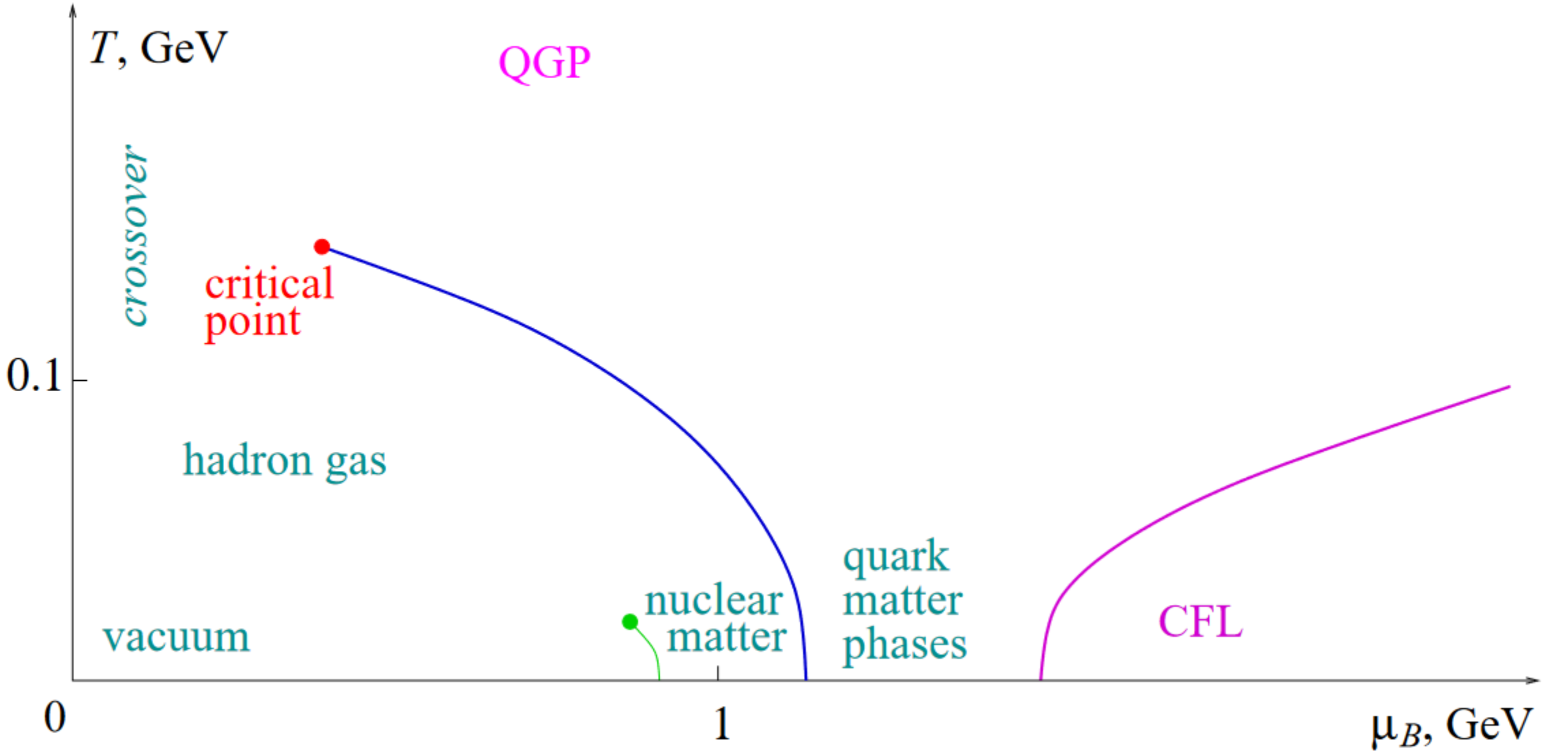


Thermal field theory

- Thermal field theory combines statistical mechanics with quantum field theory.
- Describes large systems where only macroscopic information is available.
- As in vacuum QFT, quantities are expressed as a path integral.

Perturbation theory is needed at high densities

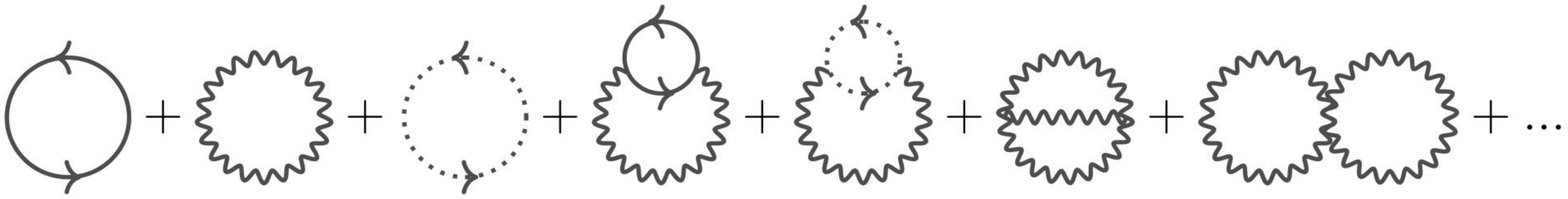
- Lattice QCD
  - low densities and high temperatures
- Perturbative QCD
  - high temperatures or high densities



Phase of QCD-matter as a function of temperature (T) and baryon chemical potential (μ_B) [M. Stephanov, 2006]

Observables

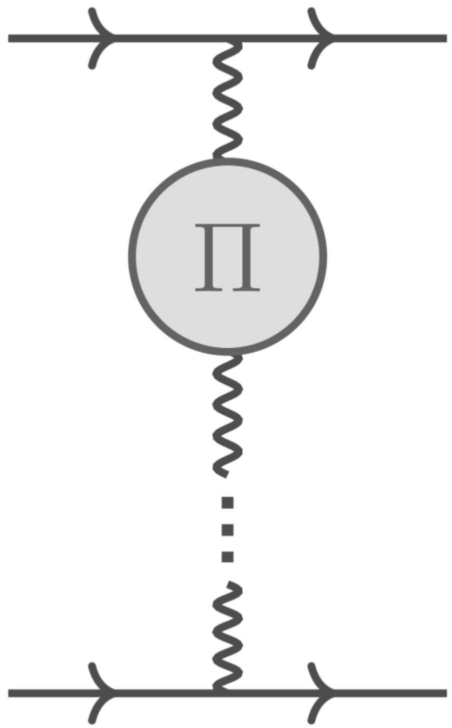
- Pressure (equation of state)
  - Mass-radius relation for neutron stars
- Transport coefficients
  - Viscosity
  - Thermal conductivity
- In perturbation theory, quantities can be written in terms of Feynman diagrams.



Diagrams contributing to the pressure of QCD

Gluon self-energy

- Self-energy describes how interactions affect particle propagation.
- Gluon self-energy contributes to many transport coefficients through the current-current correlator.



Diagrams contributing to the current-current correlator

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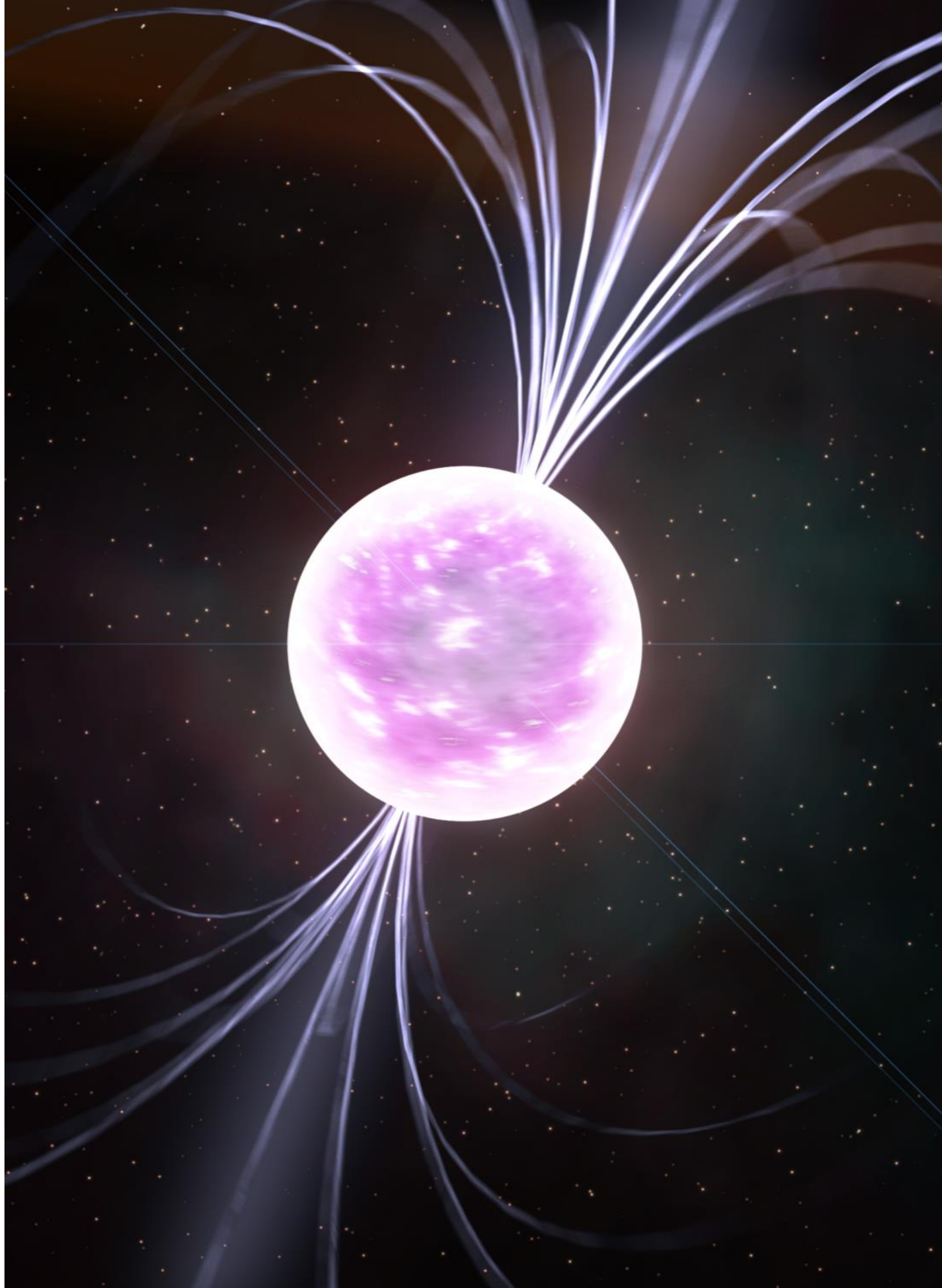
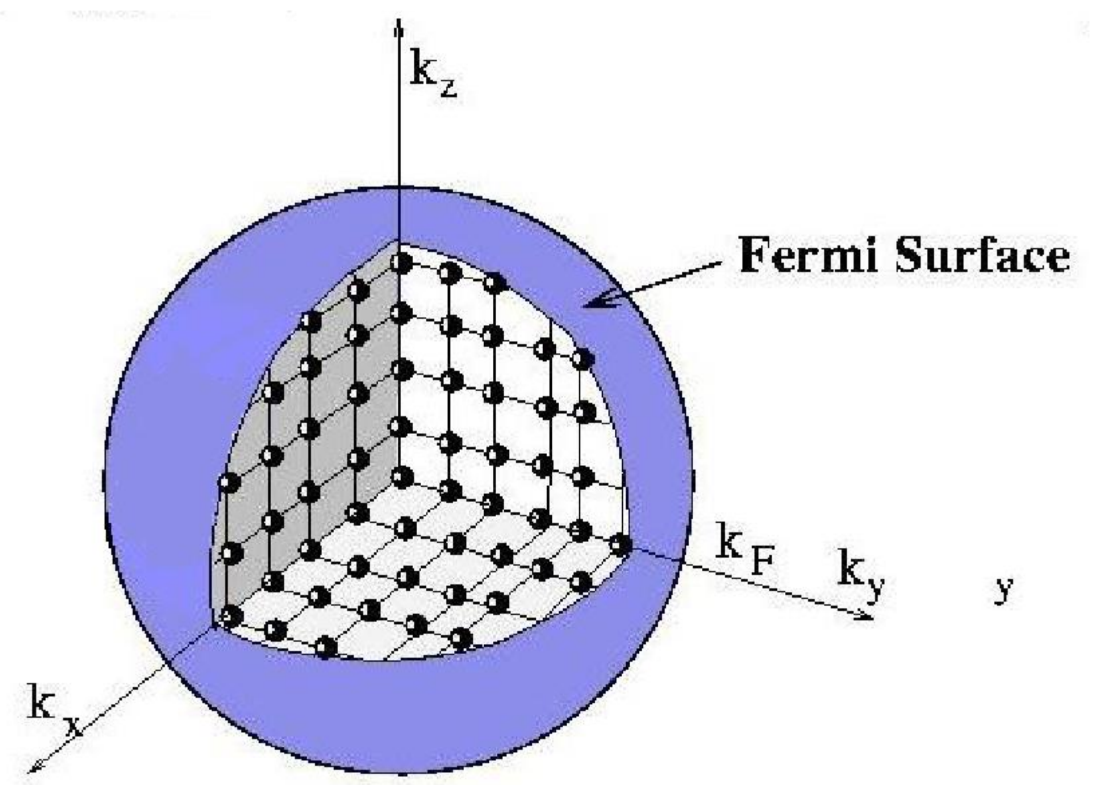


Propagation of quarks and gluons is modified at finite density

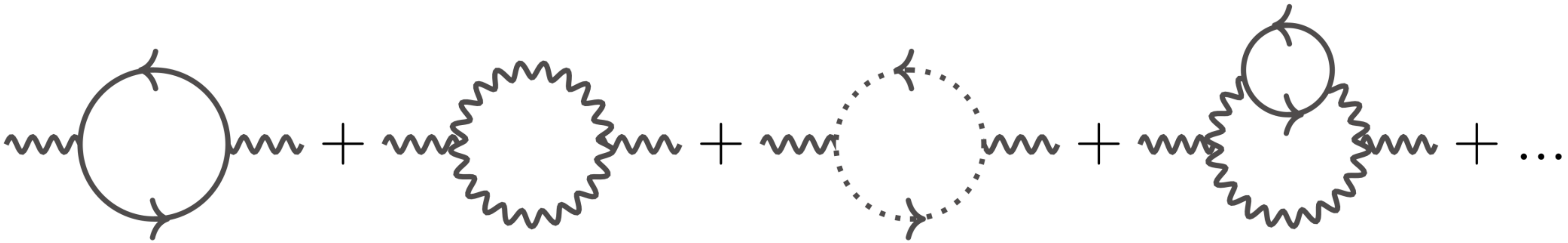
- Thermal medium introduces two energy scales.
  - Soft scale, $\alpha_s^{1/2}\mu$
  - Hard scale, μ
- Low-momentum quark states are occupied by the medium.
  - Only relevant scale for quarks is the hard scale.
- Gluons obtain an effective (thermal) mass, $m_E \sim \alpha_s^{1/2}\mu$.



[M. Baggioli, 2016]

Breakdown of the loop expansion

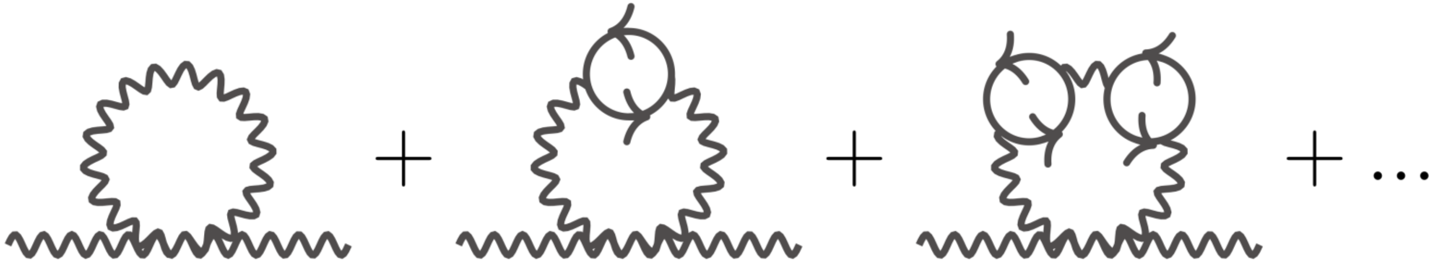
- In vacuum, Feynman diagrams with more loops are proportional to higher powers of α_s.
- At finite density, the naive loop expansion breaks down
  - Uncanceled IR divergences
  - All loop-orders contribute to a finite order in α_s.



Diagrams contributing to the gluon self-energy

Resummation

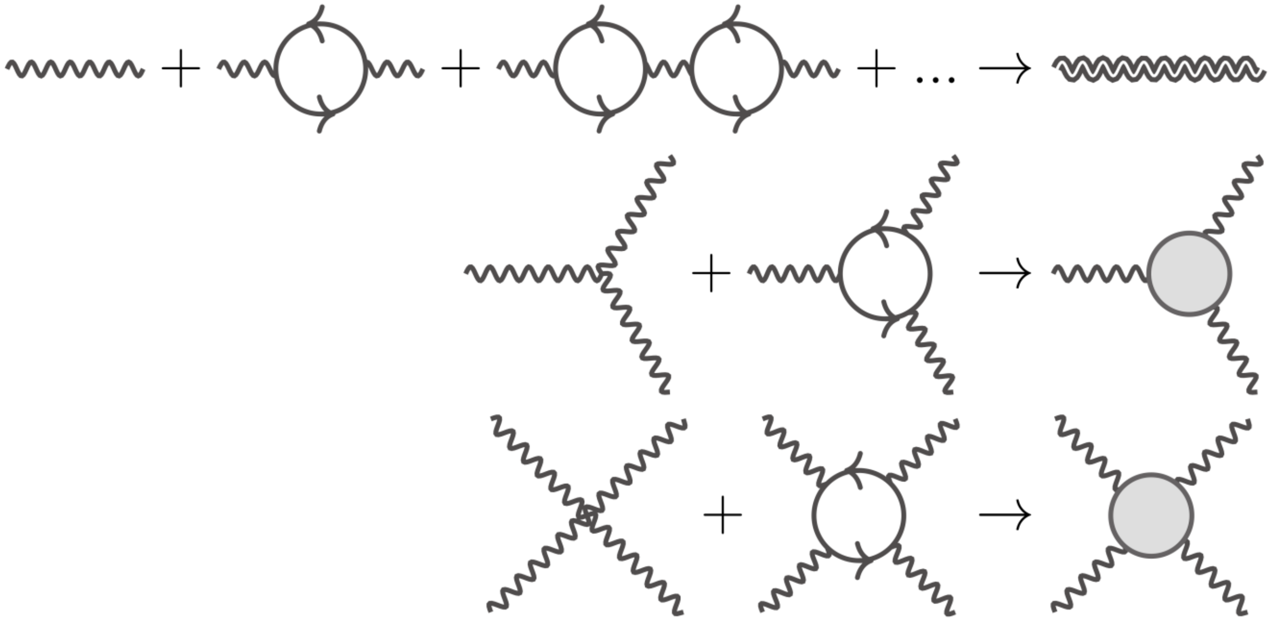
- Resummation is required to reach a finite order in α_s.
- Resummation of quark loops with full kinematics is not viable.
- Only soft gluons need resummation.



Example of diagrammatic quark-loop resummation

Hard thermal loops

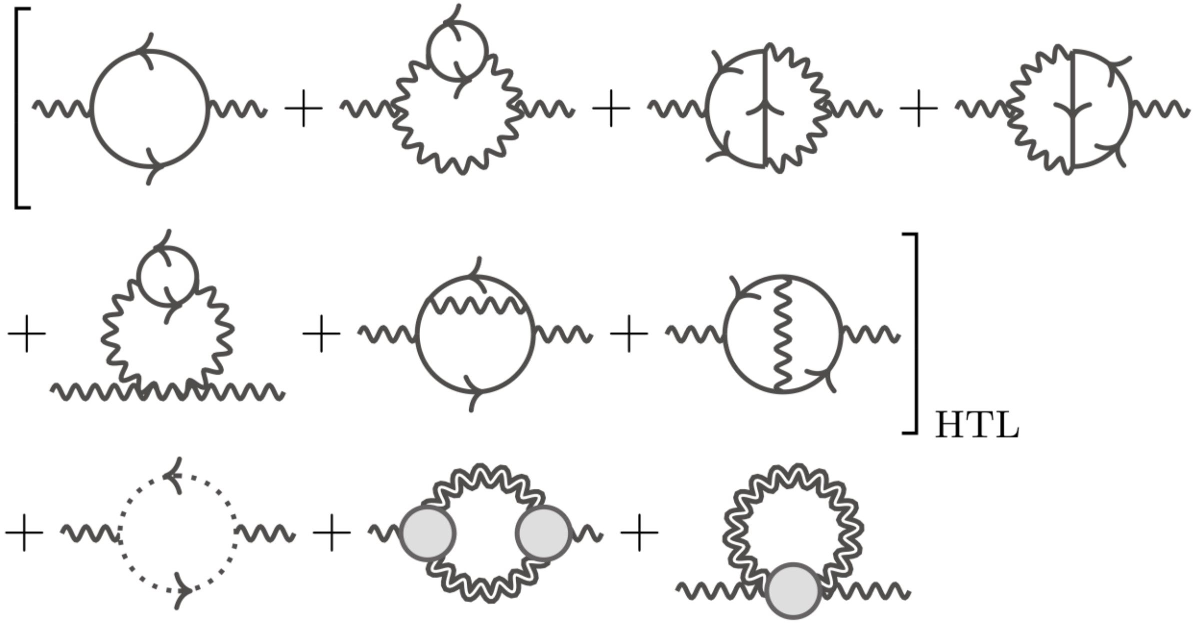
- Take all internal momenta to be hard ($P \gtrsim \mu$).
- Take all external momenta to be soft ($P \lesssim m_{\mathrm{E}}$).
- Leads to an effective theory for soft gluons
    - Effective propagators and vertices with a simple structure



Effective propagator and vertices defined as the zero-momentum limit of the corresponding n-point diagrams

Two contributions to the self-energy of soft gluons at NLO

- HTL self-energy
  - Naive loop expansion with HTL approximation
- HTL-resummed self-energy
  - Computed within HTL effective theory
- Only a finite number of diagrams



All diagrams contributing to the self-energy of soft gluons up to NLO at zero temperature.

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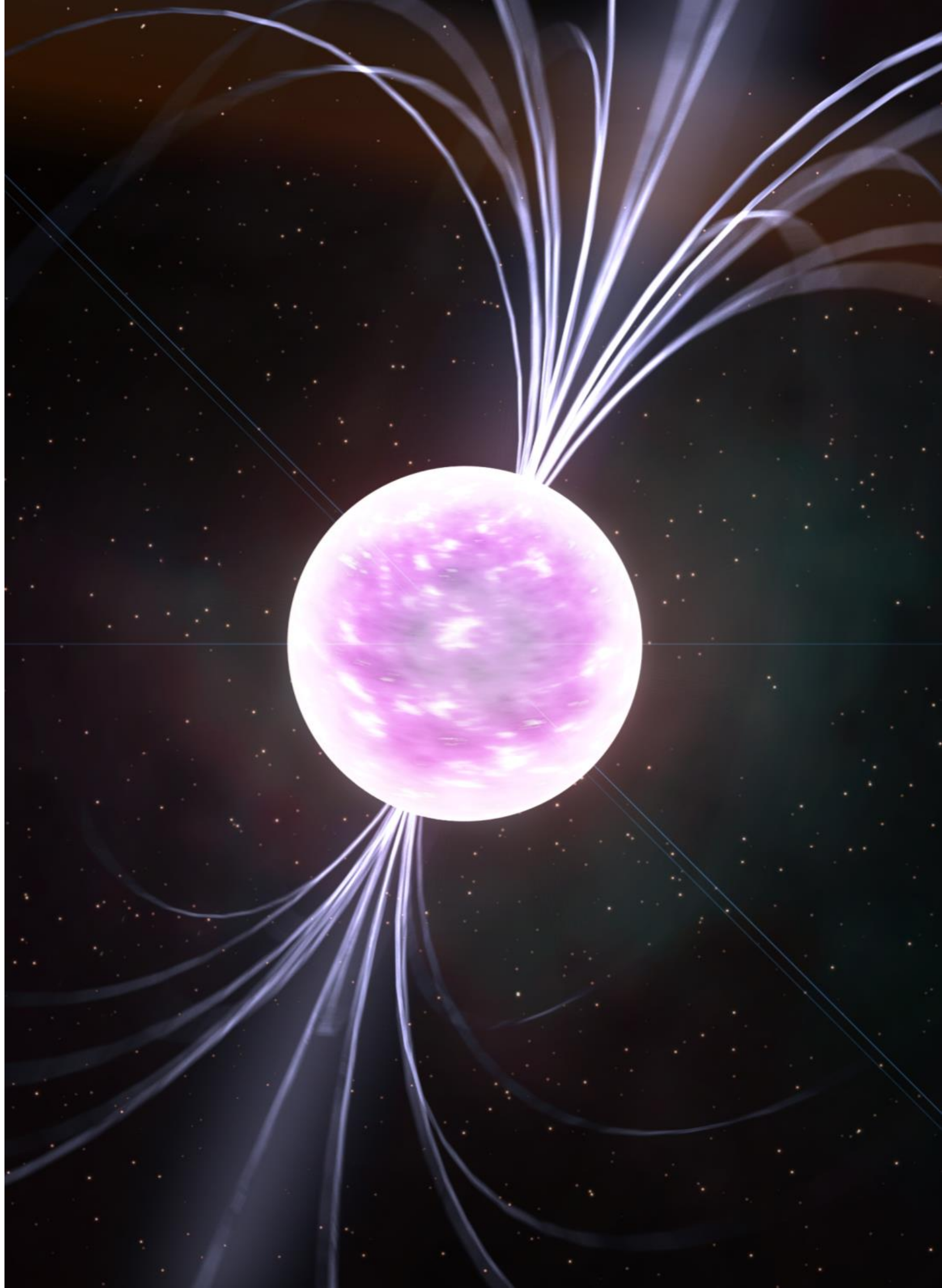
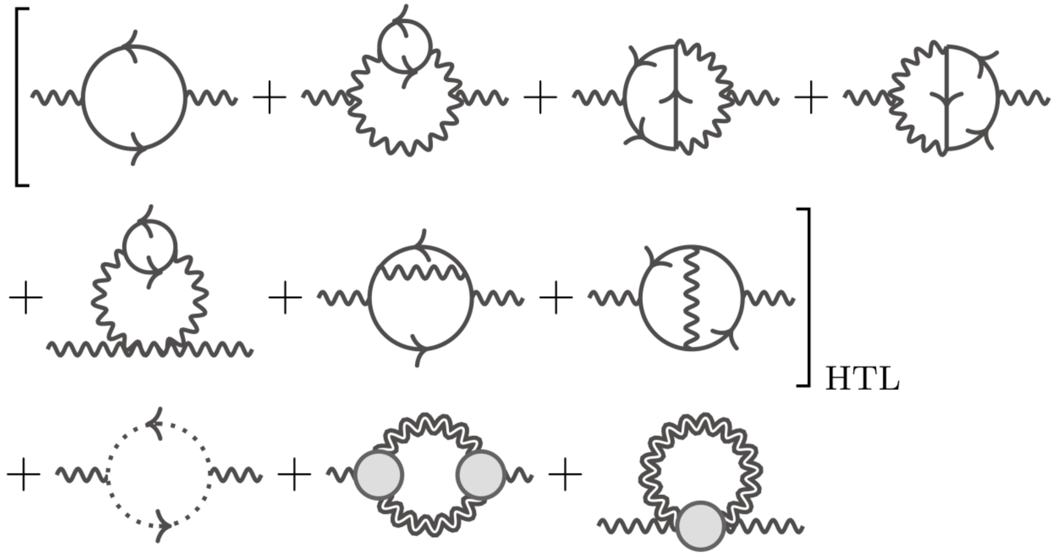


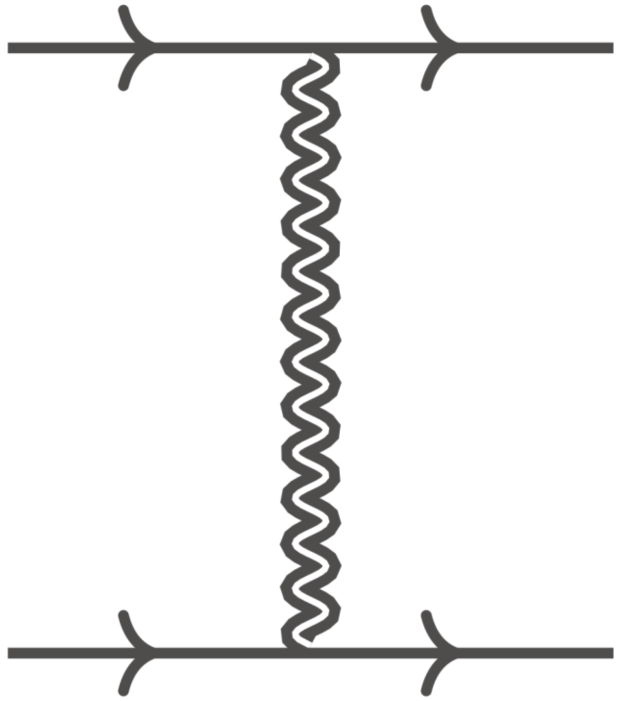
Gluon self-energy is finite and gauge-dependent

- Divergences cancel between the two contributions
  - o Self-energy is finite after renormalization
- The self-energy is gauge-dependent
  - o All observables computed from the self-energy must be gauge-independent
- Result can be presented as a finite numerical integral.



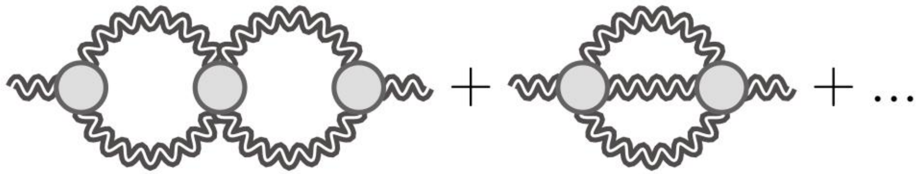
Future research (1/2)

- Corrections to transport coefficients in cold quark matter
- Gluon damping rate
- Generalization to non-zero temperatures
    - Requires a much more complicated computation



Future research (2/2)

- Two-loop HTL-resummed self-energy
  - Divergences can be related to non-analytic terms in the pressure of cold quark matter.
  - Allows resummation of logarithmic terms, which leads to better convergence.



$$P = P_{\mathrm{FD}}(1 + a_{1,0}\alpha_{\mathrm{s}} + a_{2,0}\alpha_{\mathrm{s}}^2 \ln \alpha_{\mathrm{s}} + a_{2,1}\alpha_{\mathrm{s}}^2 + a_{3,0}\alpha_{\mathrm{s}}^3 \ln^2 \alpha_{\mathrm{s}} + a_{3,0}\alpha_{\mathrm{s}}^3 \ln \alpha_{\mathrm{s}} + a_{3,0}\alpha_{\mathrm{s}}^3 + \ldots)$$

Summary

- Neutron stars provide phenomenological motivation for perturbative computations at high density.
- Thermal QCD requires resummation.
- Gluon self-energy is needed for computing corrections to transport coefficients in cold quark matter.