Astrophysical jet formation from a magnetized *npe*-gas

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Quantum magnetic collapse

For a gas under the action of an uniform and constant magentic field B in z direction[1]

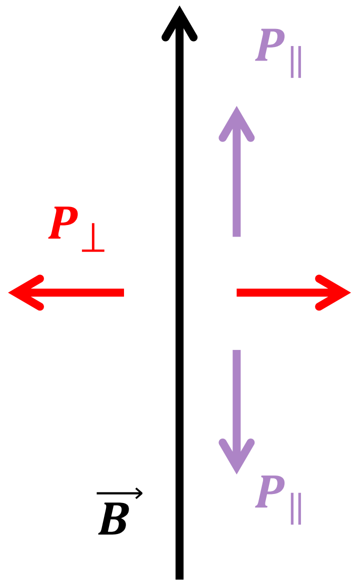
$$T^{\alpha\beta} = (-E, P_\perp, P_\perp, P_\parallel), \qquad \alpha, \beta = 0,1,2,3$$

$$E = \Omega + TS + \mu N + B^2/8\pi$$

$$P_\parallel = -\Omega - B^2/8\pi$$

$$P_\perp = -\Omega - MB + B^2/8\pi$$

Pressures of a magnetized quantum gas



$\Omega = \Omega(T, \mu, B)$ – thermodynamic potential

T – temprature　　S – entropy　　M – magnetization

μ – chemical potential　　N – particle number density

[1]Ferrer *et al.*, Phys. Rev. C **82**, 065802, 2010

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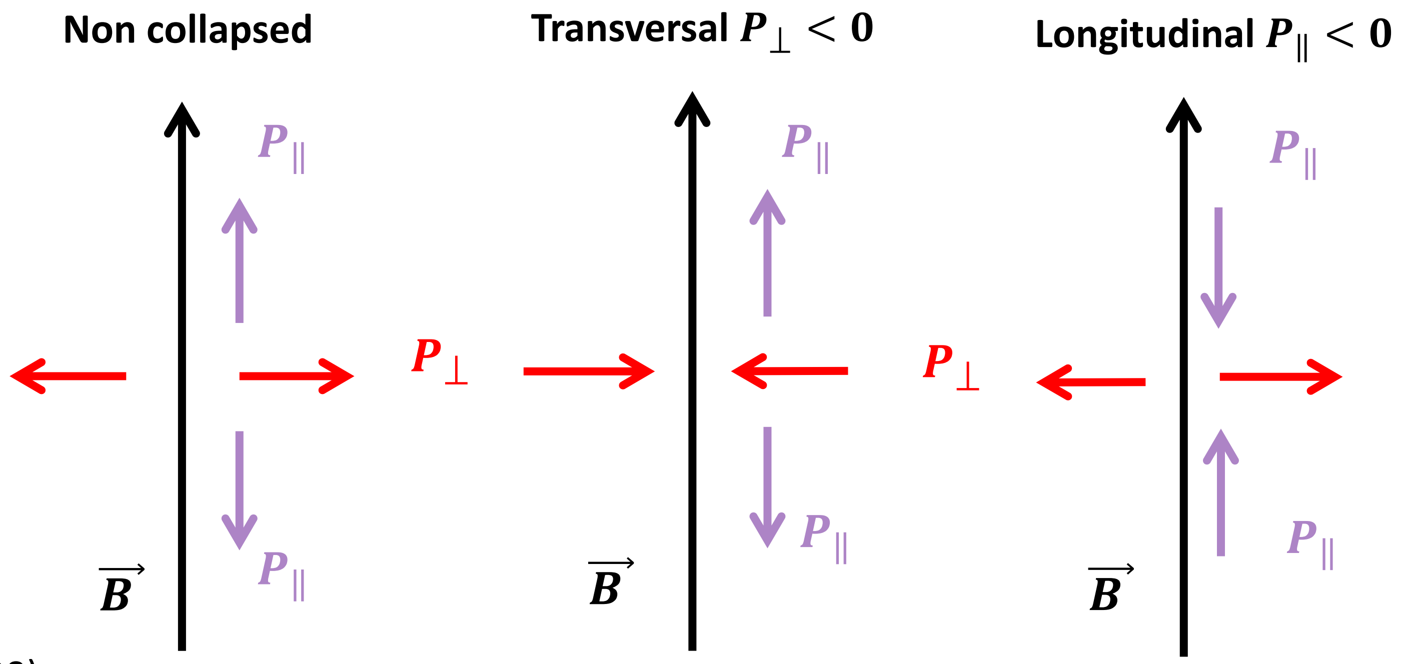
<u>Quantum magnetic collapse</u>

$P_\perp \leq 0$ or $P_\parallel \leq 0$

for certains values of

T, N, B

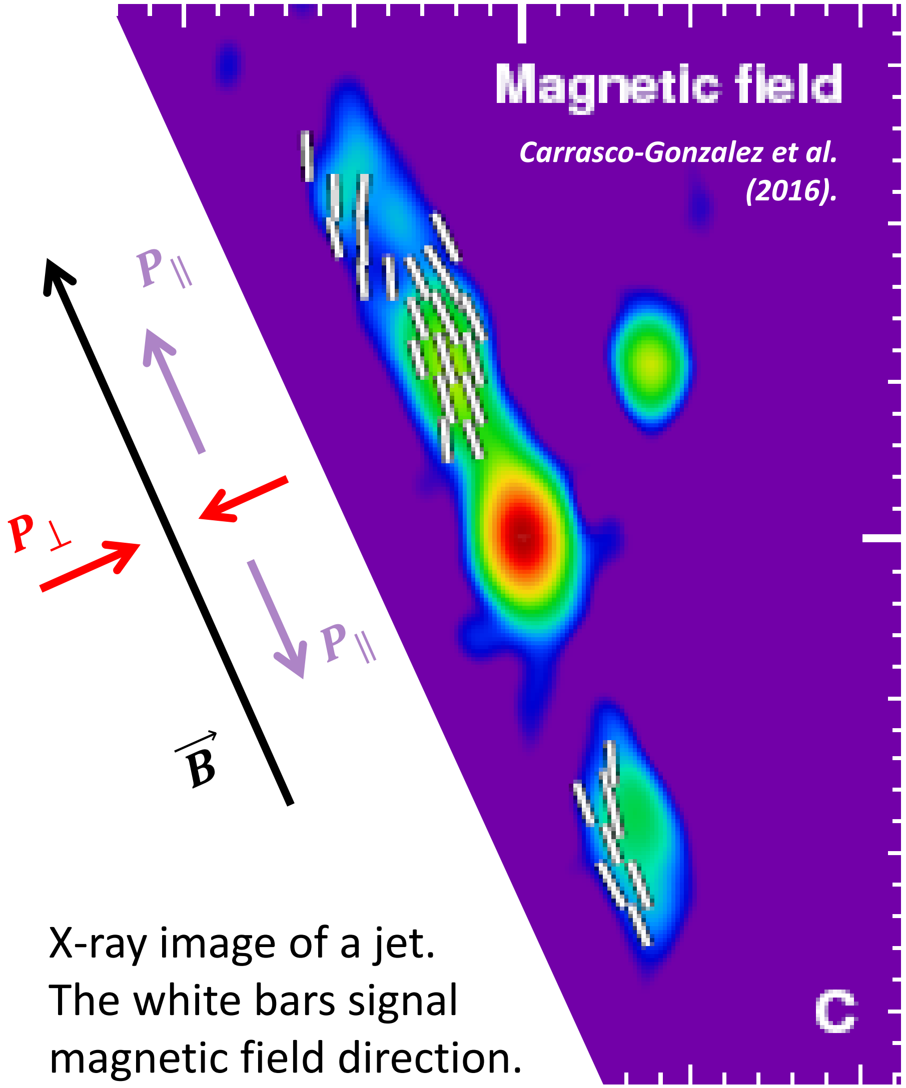


M. Chaichian *et.al,* Phys. Rev. Lett. **84**, 5261 (2000).

Astrophysical jets

Streams of collimated matter ejected by several astronomical objects:

stars, protostars, protoplanetary nebulae, compact objects, galaxies...



X-ray image of a jet.
The white bars signal magnetic field direction.

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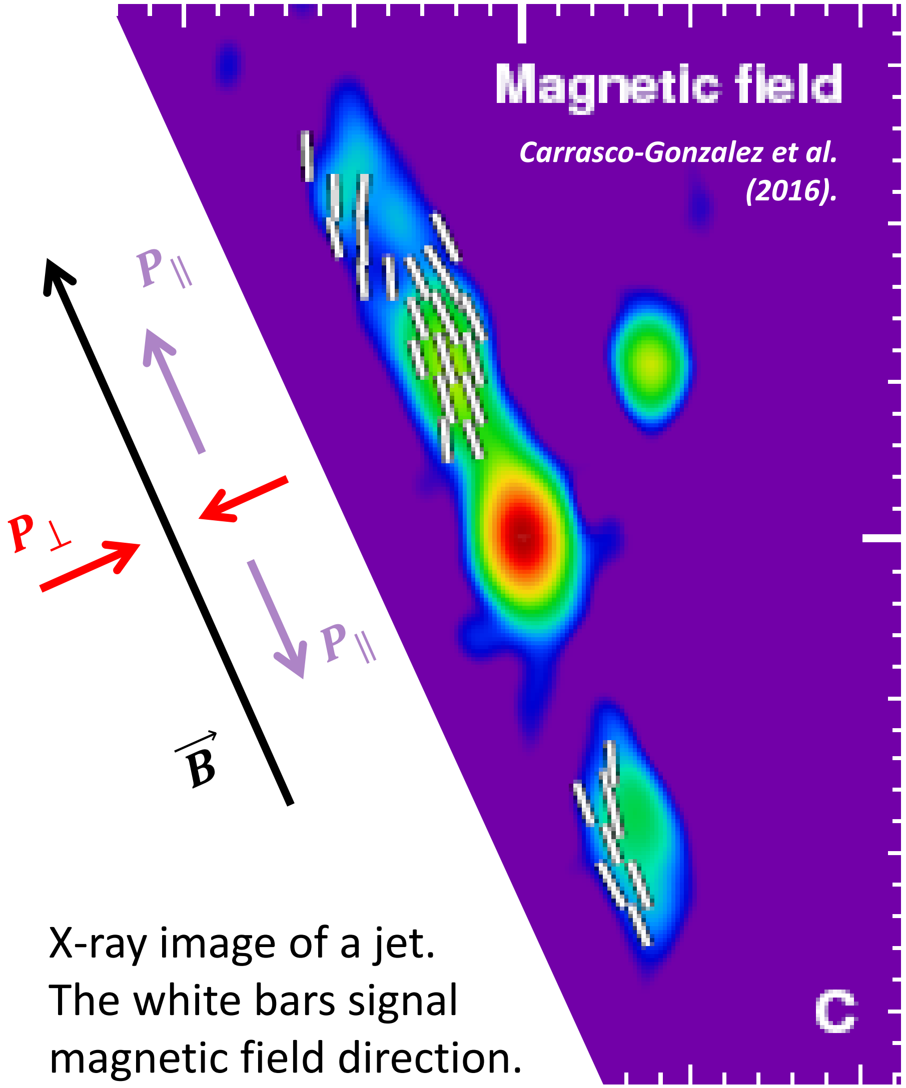
- it is believed that all jets are produced and maintained by the same mechanisms,



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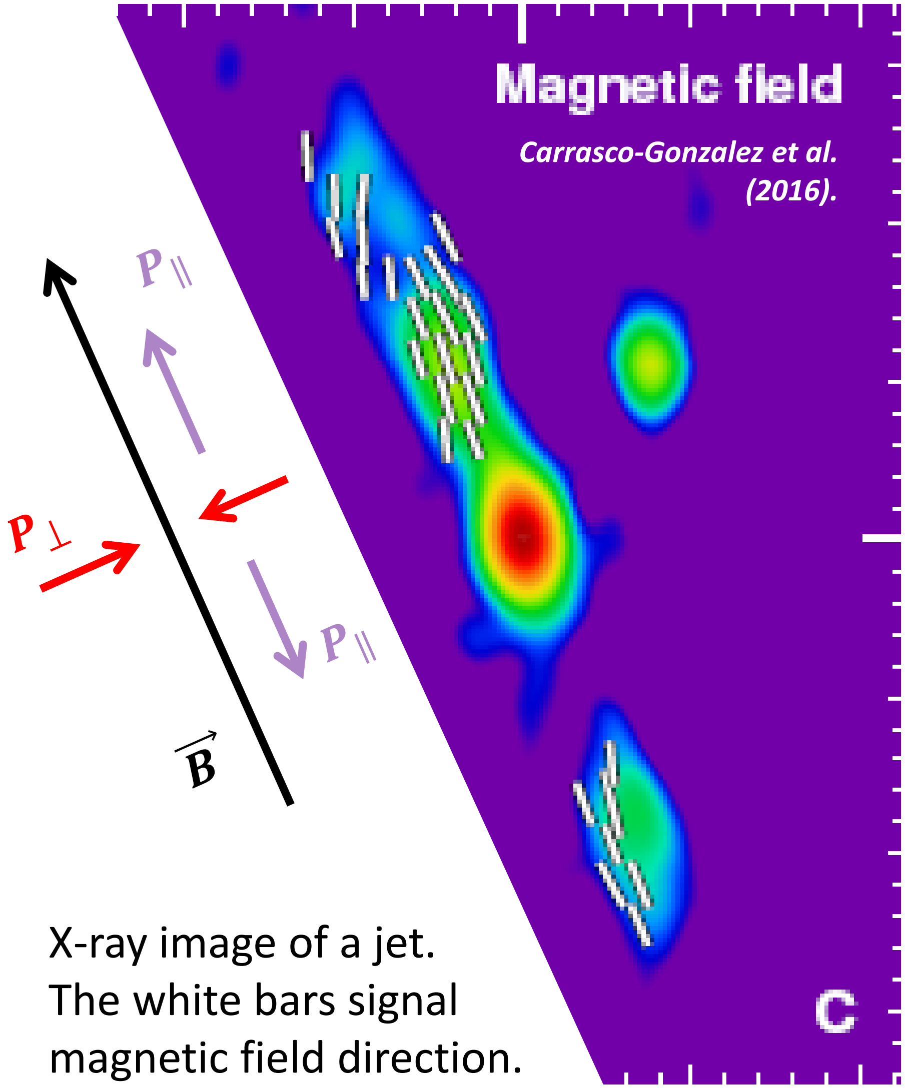

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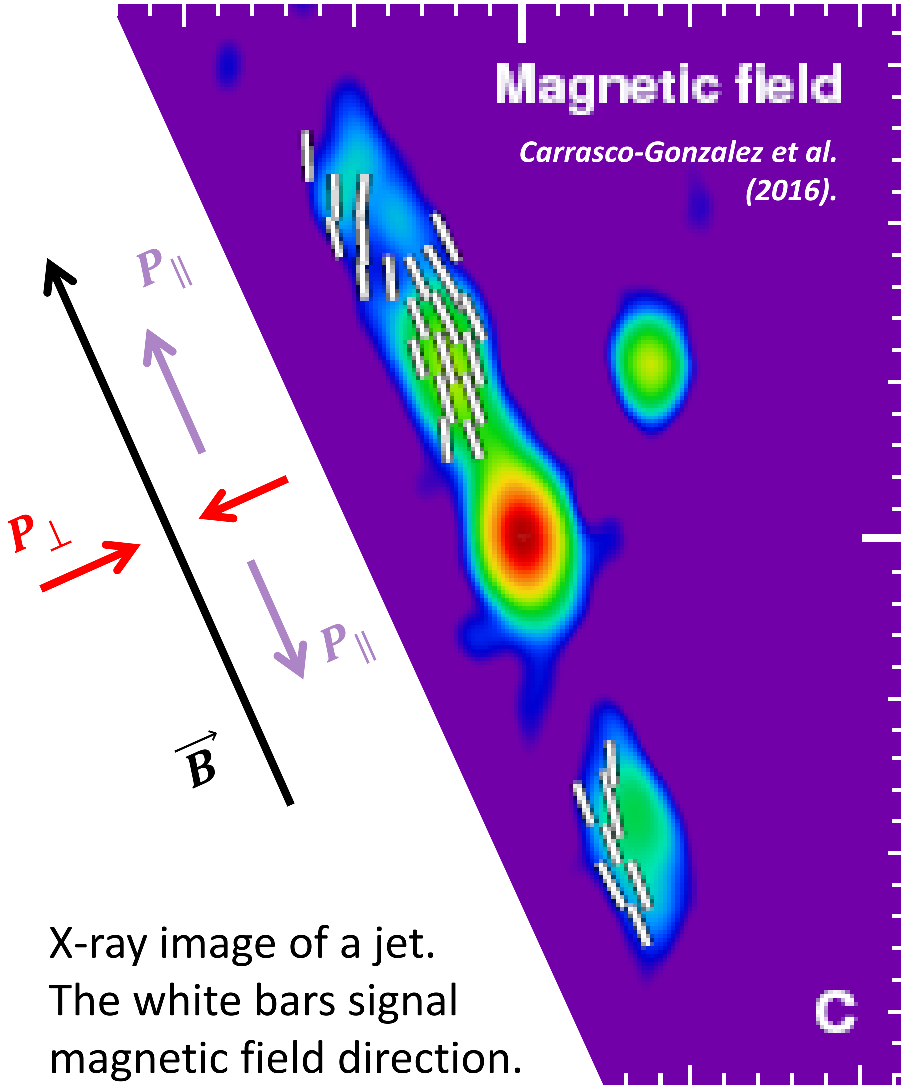
Our proposal is that this role is played through the quantum magnetic collapse with $P_\perp \leq 0$.



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Partially bosonized *npe*-gas

- A simple neutron star-type configuration composed by a mixture of free neutrons *n*, protons *p*, electrons *e* (*npe*-gas), and paired (bosonized) neutrons *nn* and protons *pp*.

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The ideal gas supposition is acceptable for electrons, but not so for nucleons, however, as a first approach to the problem, we keep the nucleon gases as ideal without attaching to any particular model for interactions, and focusing on magnetic field effects.

- The particles are under the action of a locally uniform and constant magnetic field directed along the *z* axis.

Partially bosonized *npe*-gas

- The total thermodynamic quantities of the gas mixture are calculated as:

$$E^{T} = \sum_i E_i + B^2/8\pi$$

$$P_{\parallel}{}^{T} = \sum_i P_{i\parallel} - B^2/8\pi$$

$$P_{\perp}{}^{T} = \sum_i P_{i\perp} + B^2/8\pi$$

$$M^{T} = \sum_i M_i$$

$i = n, p, e, nn, pp$
$T = 0$ for fermions

Mathematical details in arXiv:1911.09147 [astro-ph.HE].

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- The gases in the mixture are in stellar equilibrium, i.e. we impose:
  - baryon number conservation
  - charge neutrality
  - β equilibrium

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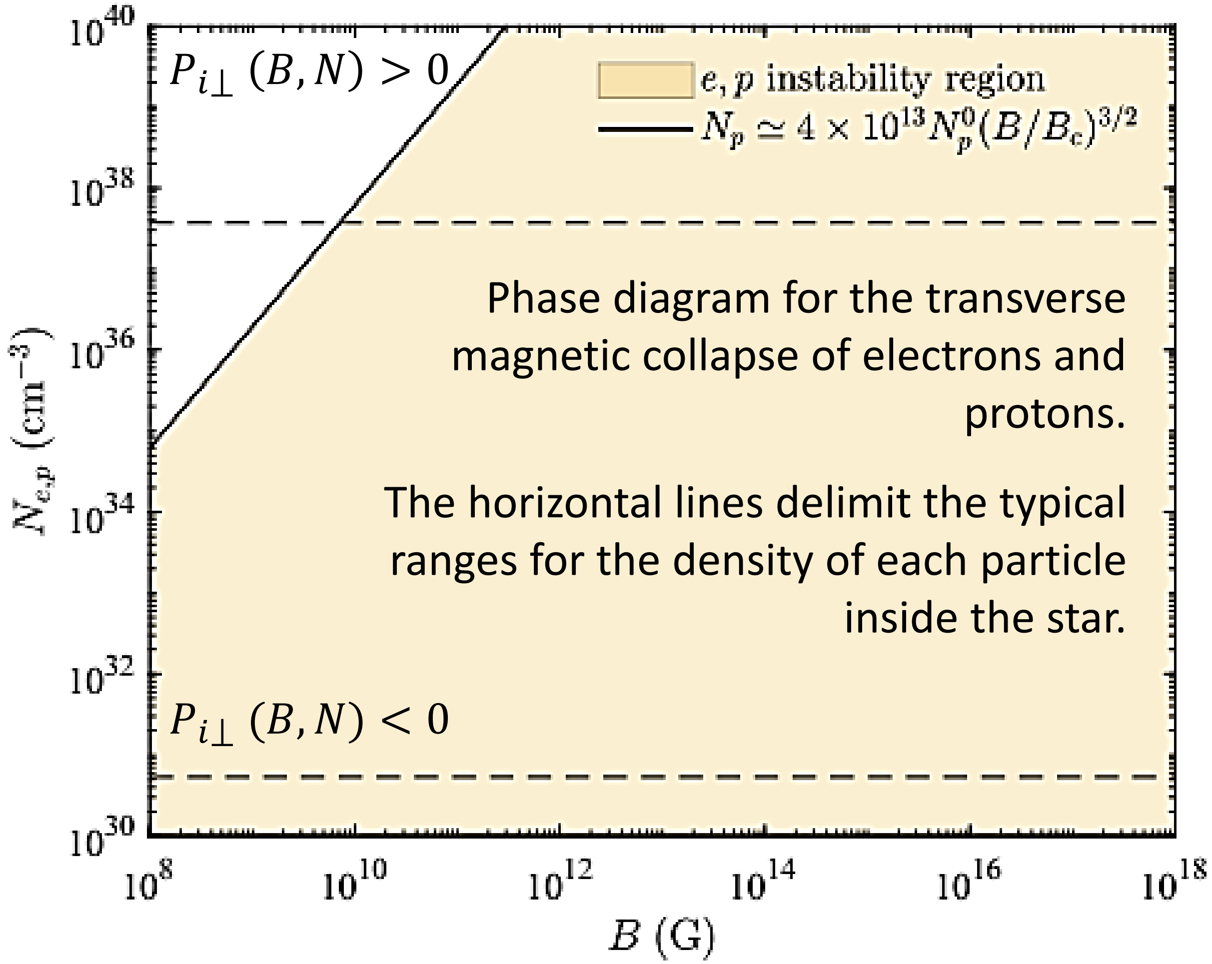
3. Once the matter leaves the star, is the magnetic field strong enough to keep it collimated?

Can the transverse magnetic collapse occur in astrophysical conditions?

To answer this question we draw the phase diagrams for the transverse magnetic collapse in the particle density (N) vs magnetic field plane (B) and found that:



Phase diagram for the transverse magnetic collapse of electrons and protons.

The horizontal lines delimit the typical ranges for the density of each particle inside the star.

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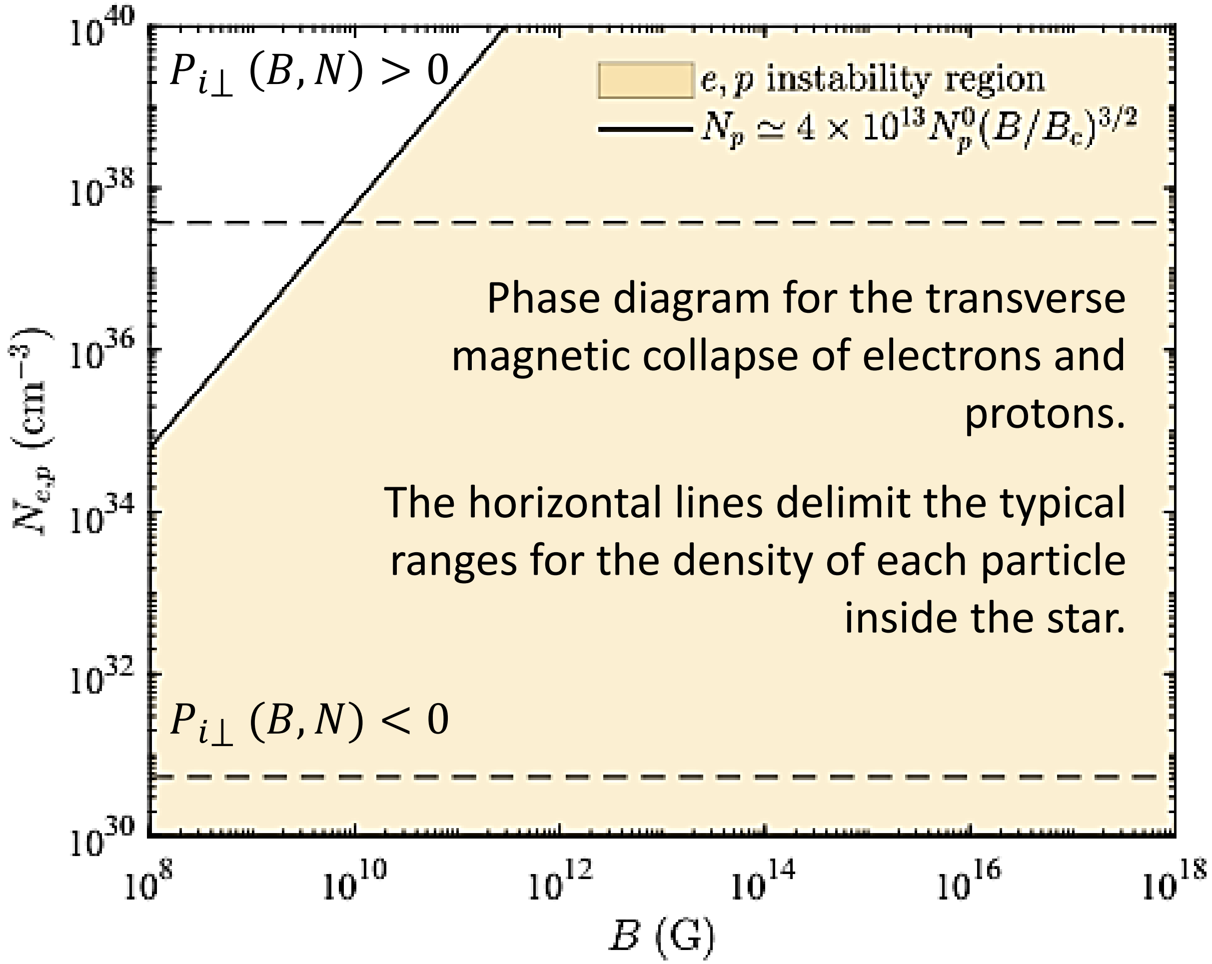
$$P_{\perp} = P_{\parallel} - MB, \text{ and } M > 0;$$



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- the gas of paired protons is always stable:

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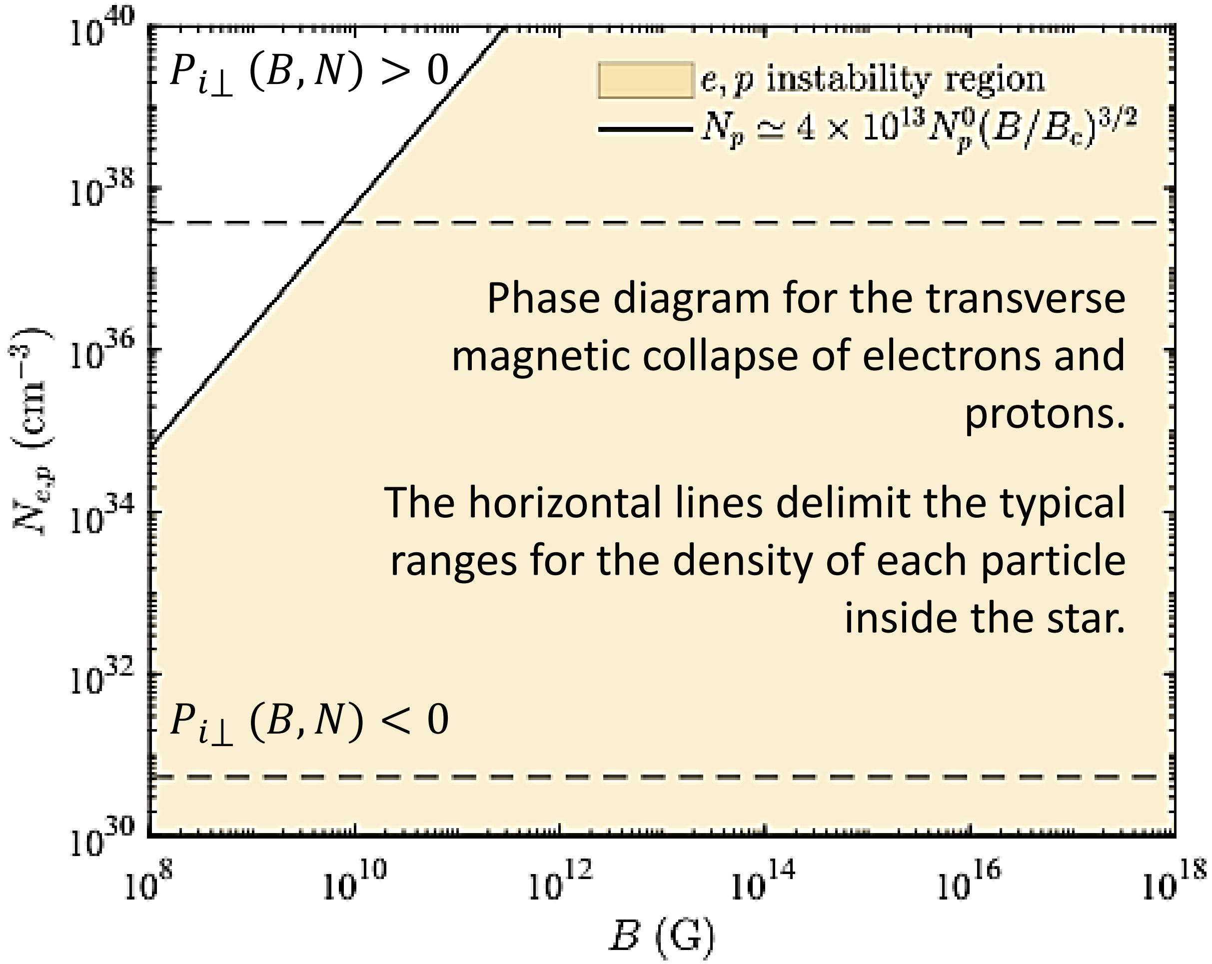

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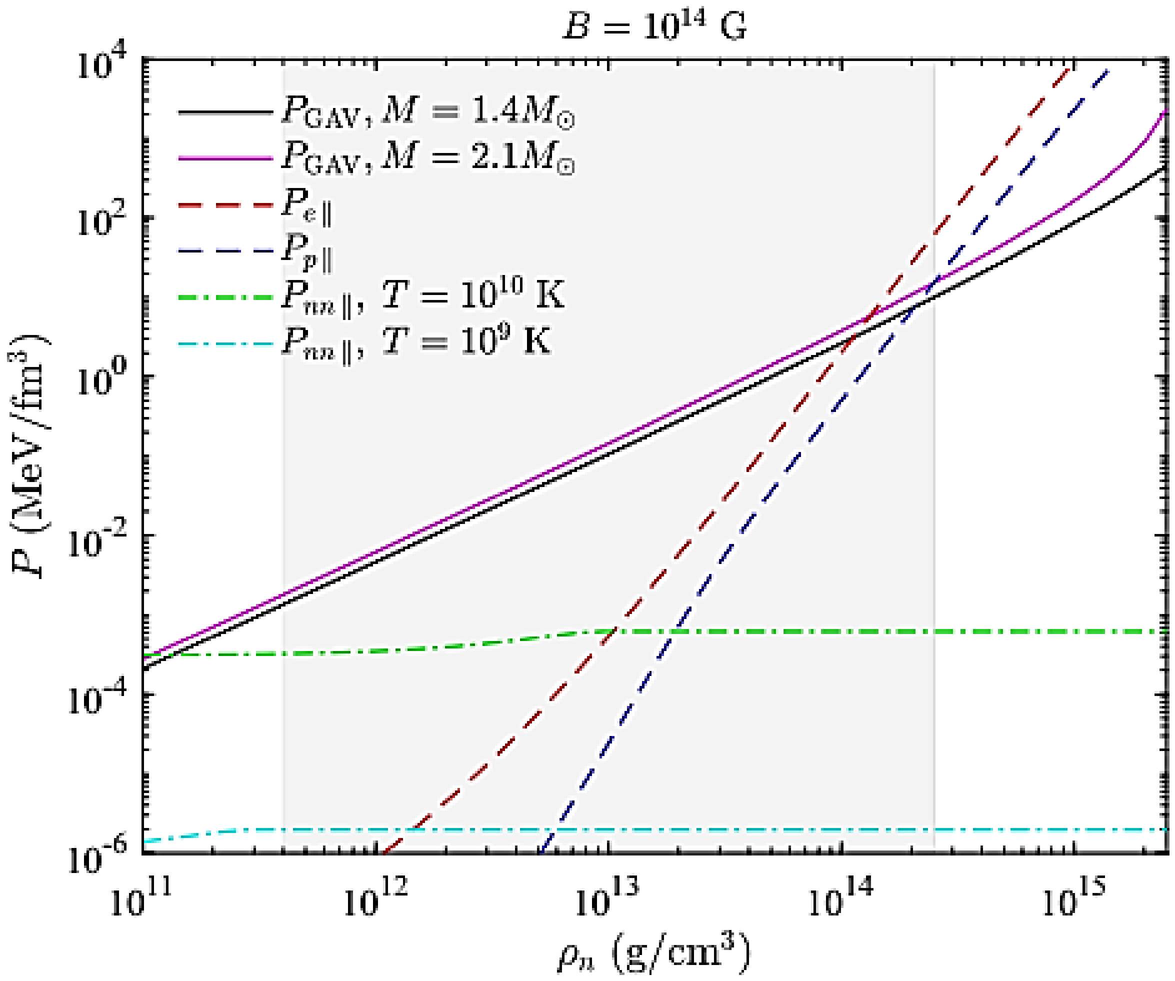

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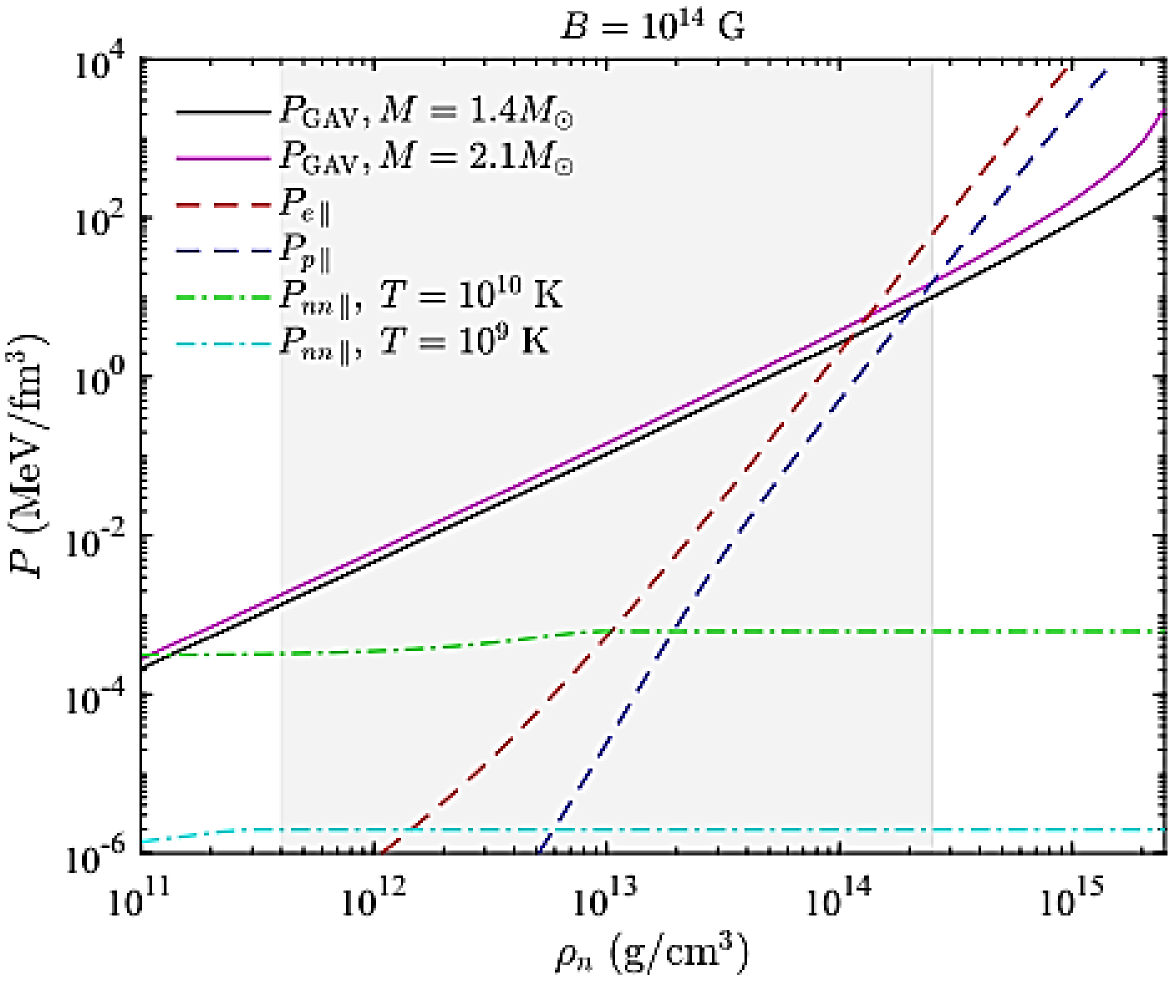

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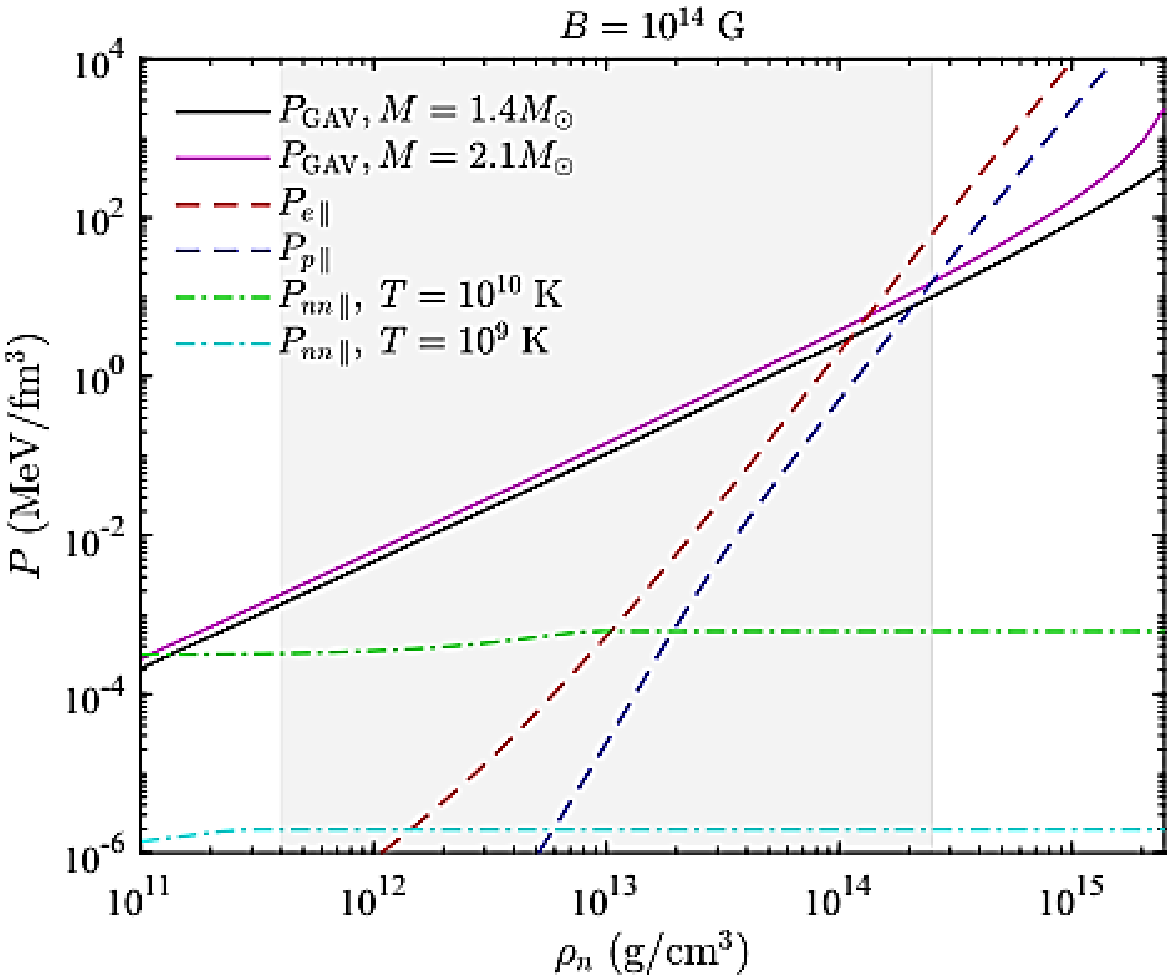

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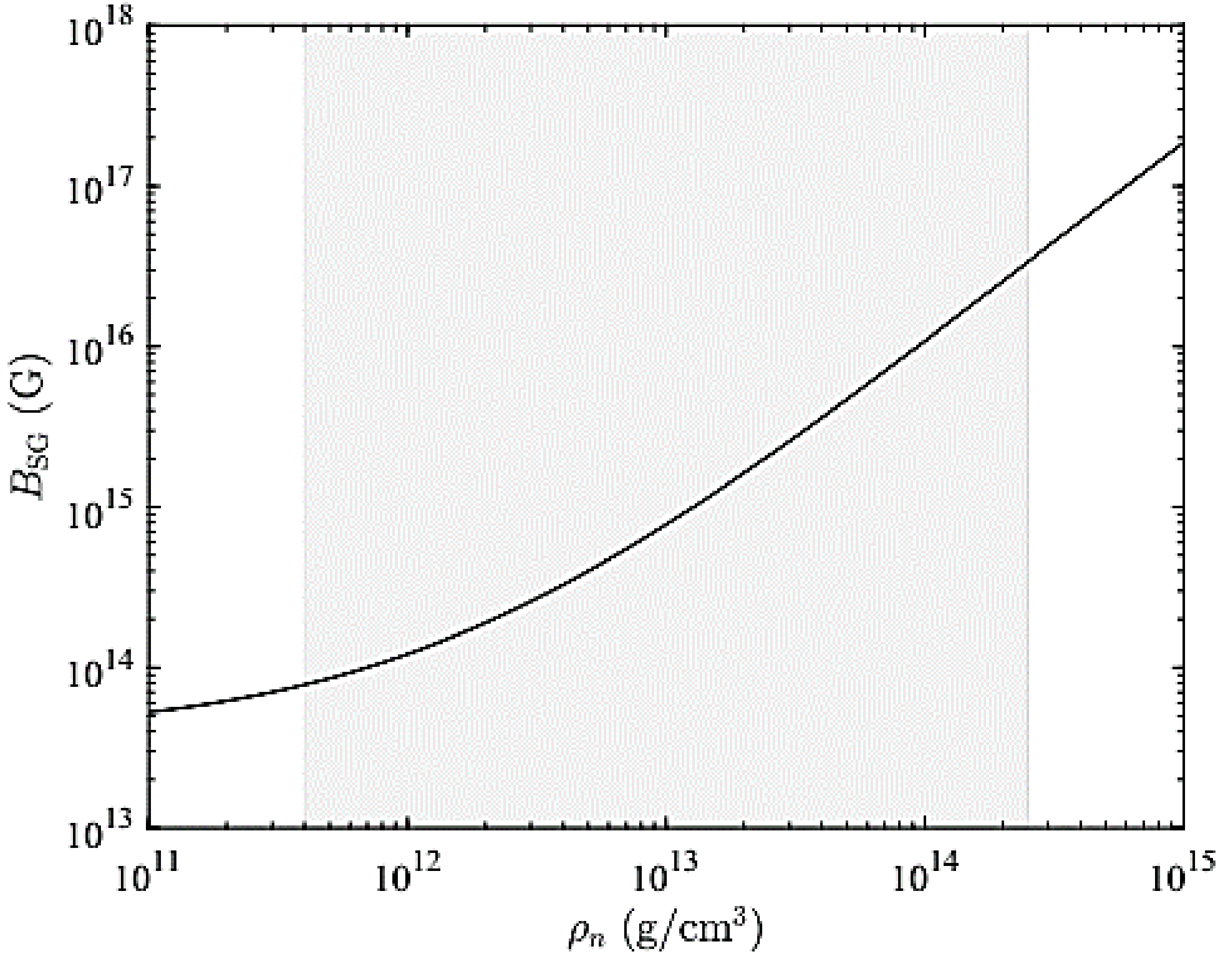
- the gravitational pressure of the star can be overcome by the parallel pressure of the collapsed electron and proton gases;
- the collapsed gases can trigger the ejection of matter!!!

Once the matter leaves the star, is the magnetic field strong enough to keep it collimated?

To address this we look for a self-generation of the magnetic field, i.e., for the existence of a solution of the equation

$$B_{SG} = 4\,\pi\, M^T$$



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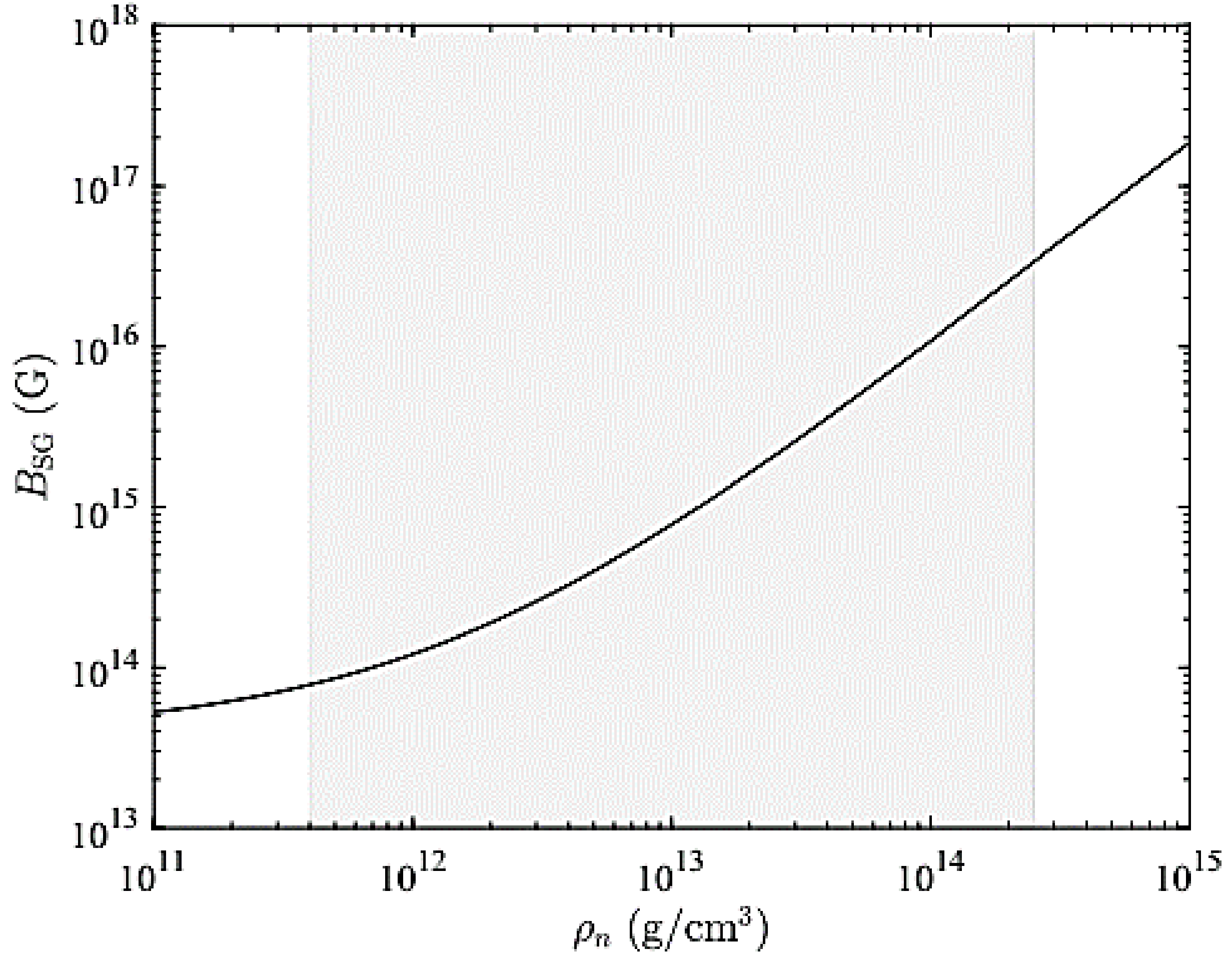
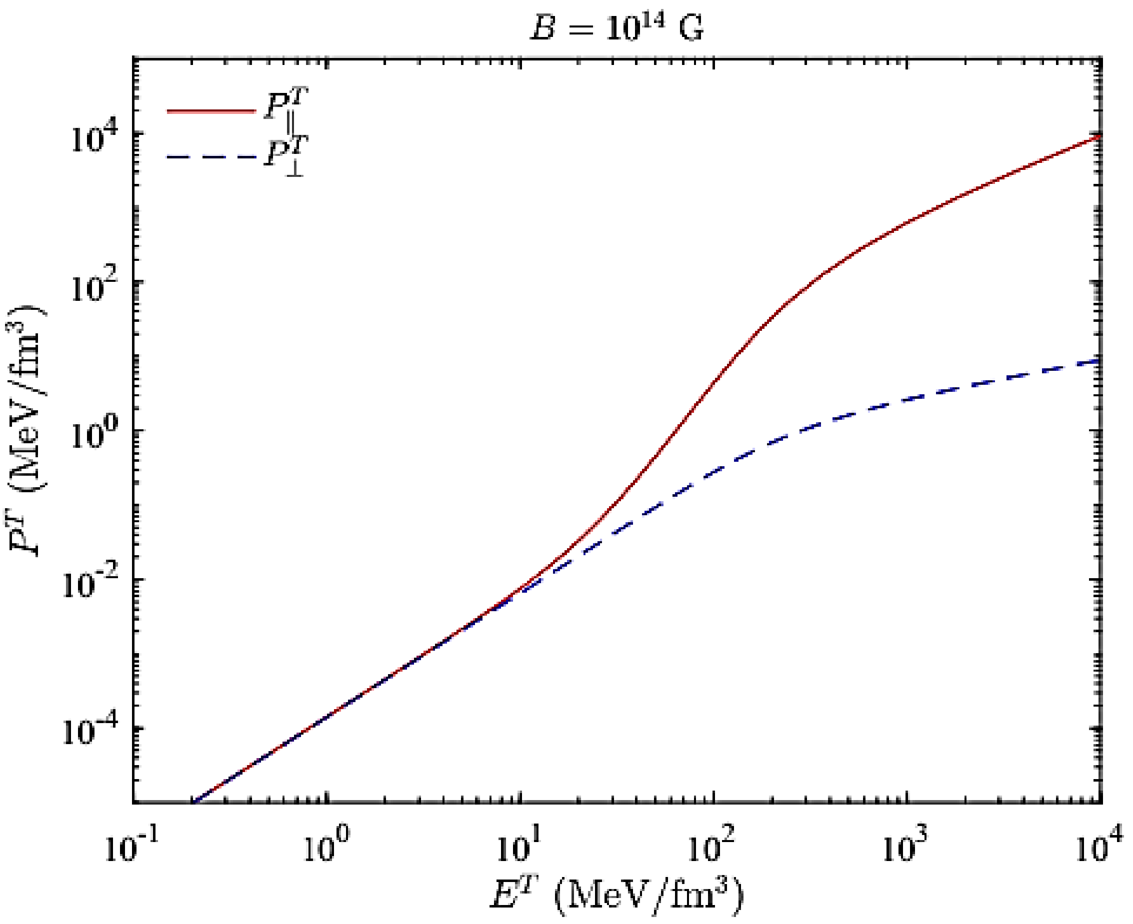
- depending on the density, the values of the self-generated magnetic field can be high enough ($B_{SG} > 10^{13}$G) to keep the gases in the collapsed regime.



Collapsed matter Equations of State



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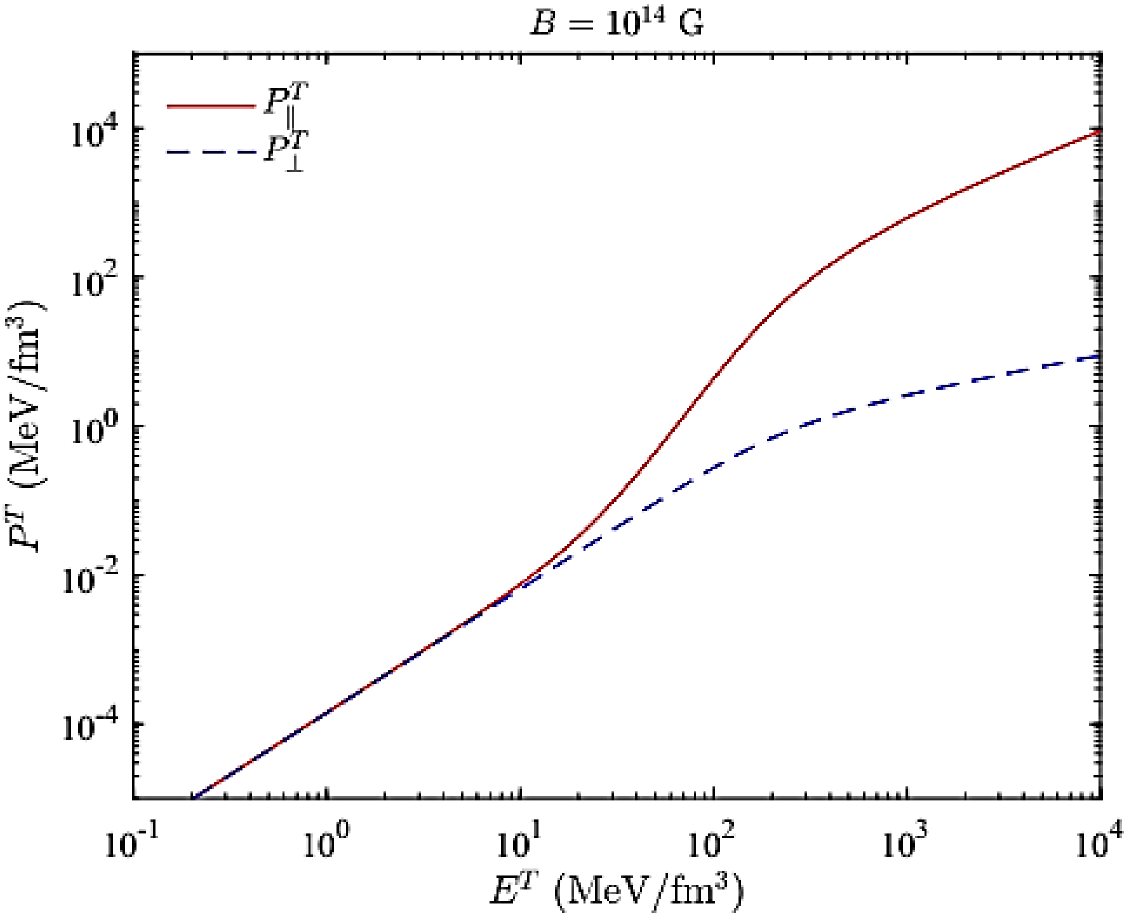

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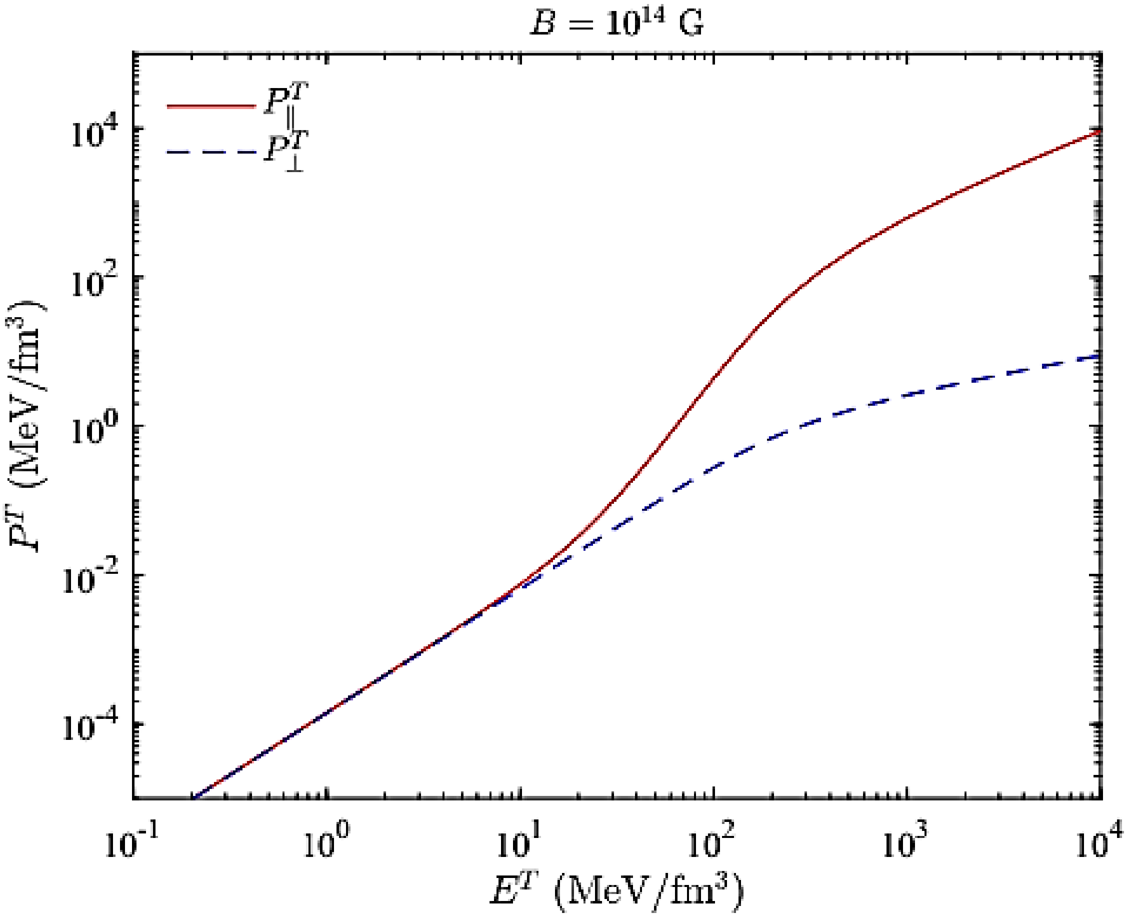

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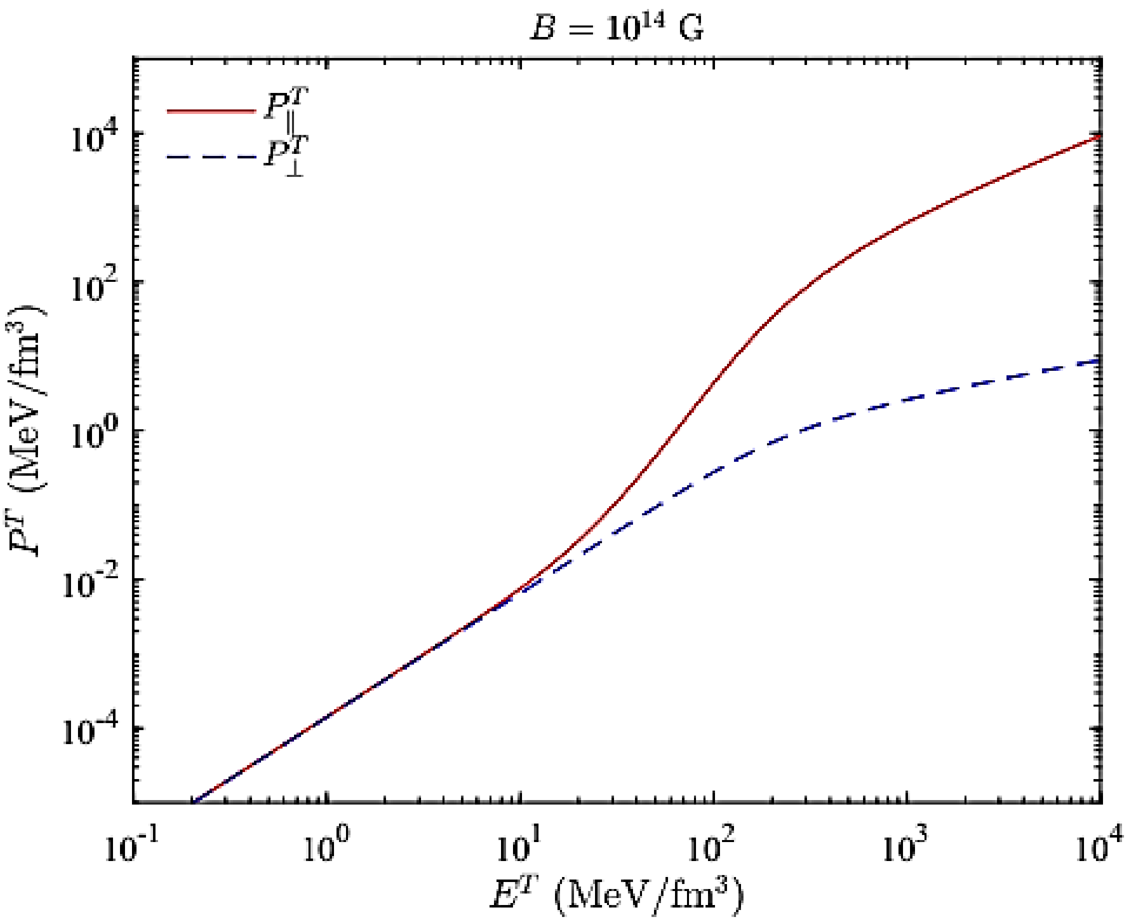

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From the viewpoint of gravitational equilibrium, the difference in the pressures is related to a difference in the object dimensions, which might account for the elongated form of jets!!!

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Next steps

- To consider more realistic matter models.
- To study the gravitational stability of the collapsed matter.