INSTITUTO DE ASTROFÍSICA
FACULTAD DE FÍSICA

ANSWERS

Magnetic field evolution in neutron star cores

Francisco Castillo, A. Reisenegger, J. A. Valdivia

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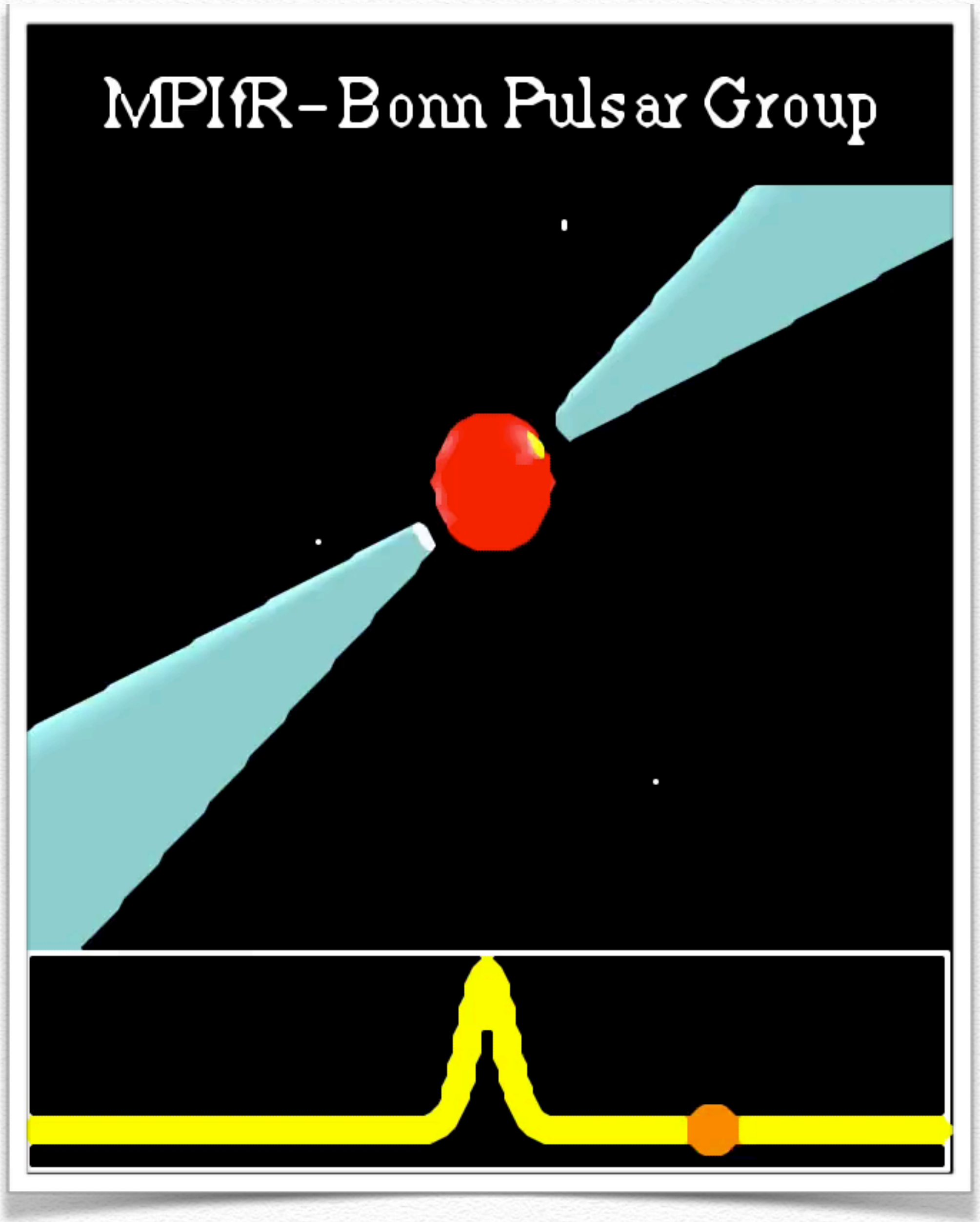
Center of Astrophysics
and Related Technologies

Evidence for evolution?

$$B = 3.2 \times 10^{19} \sqrt{P\dot{P}/\mathrm{s}}\ \mathrm{G}\,.$$

$$\tau = \frac{P}{2\dot{P}}\,.$$



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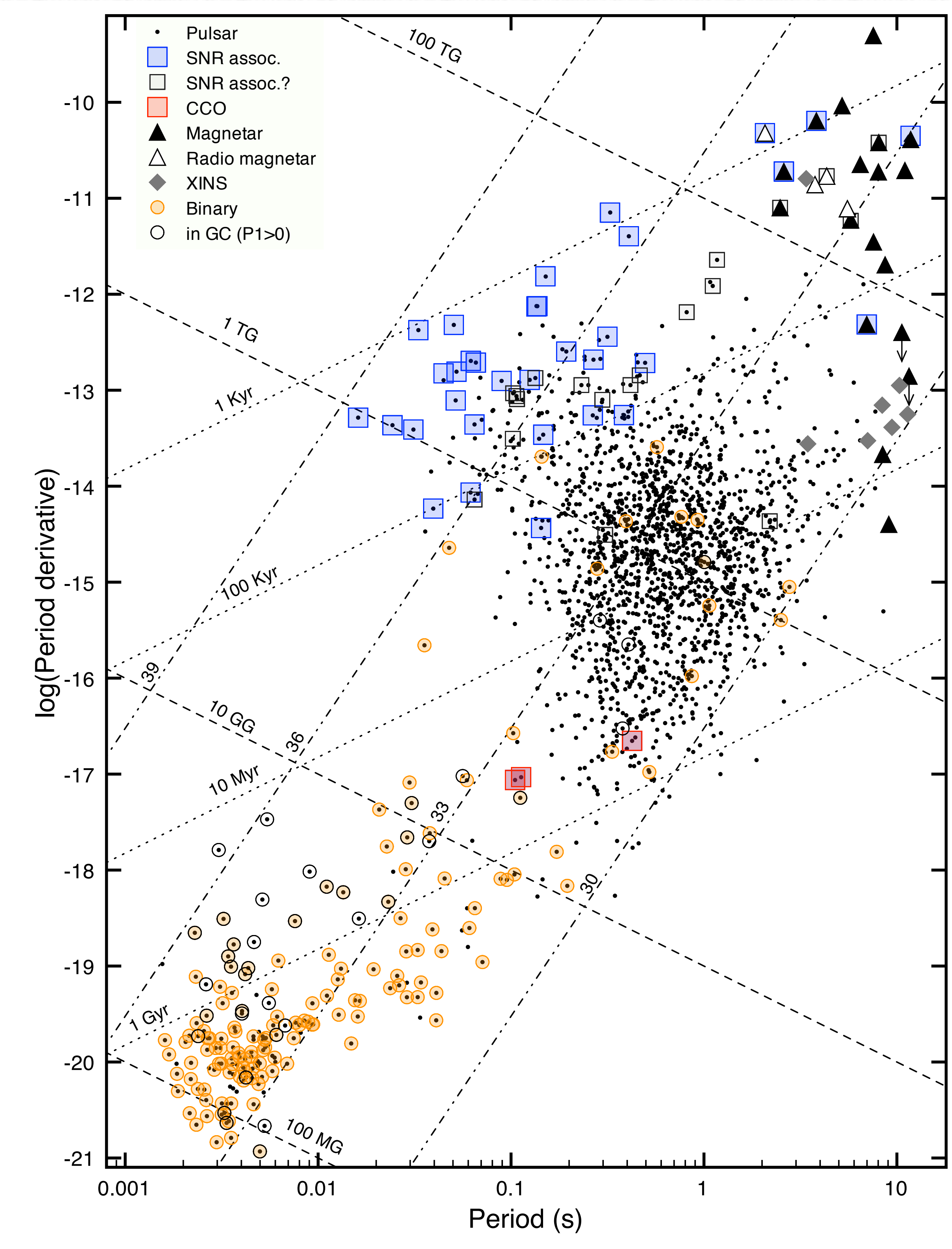


Figure: C. Espinoza.

How does B evolve?

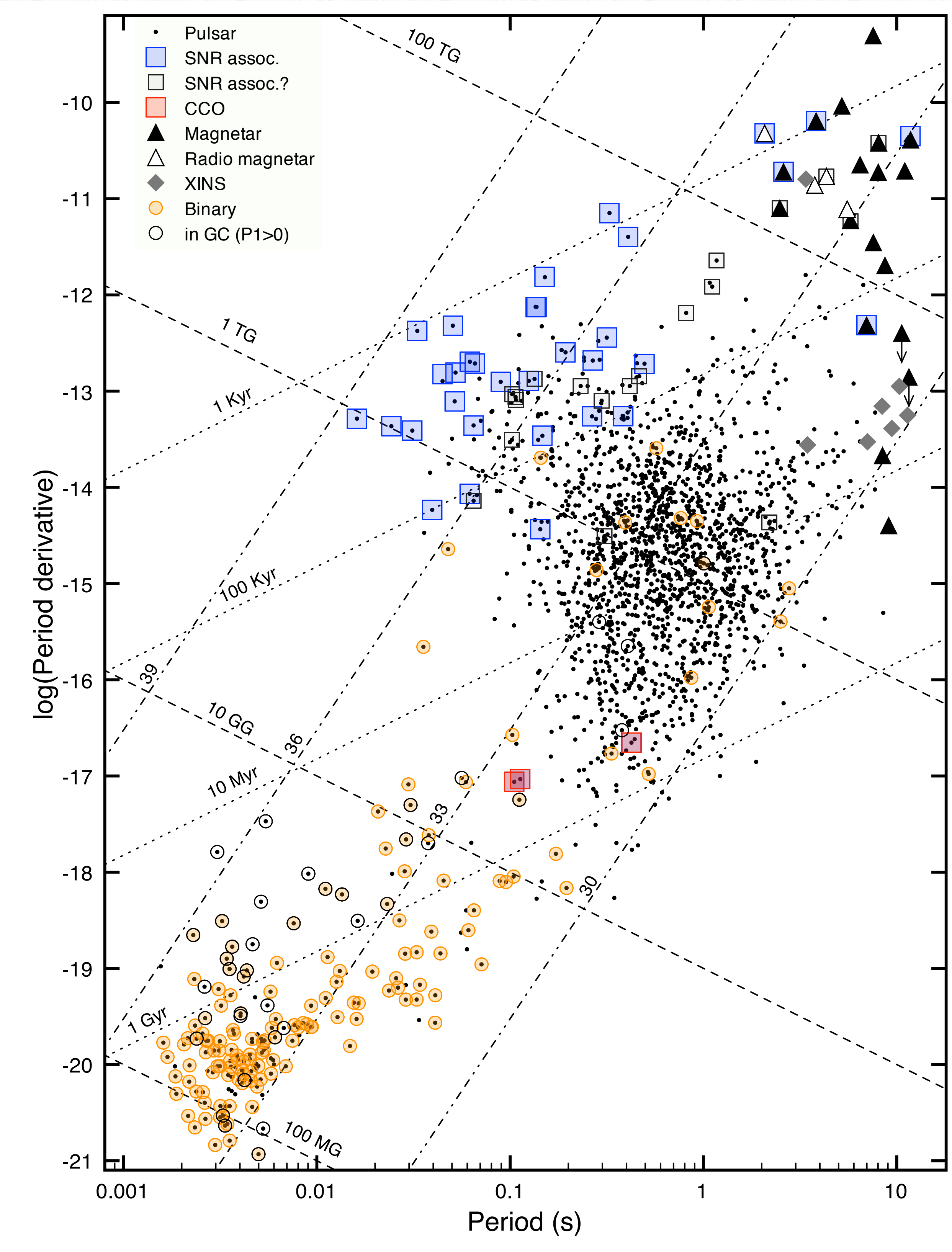
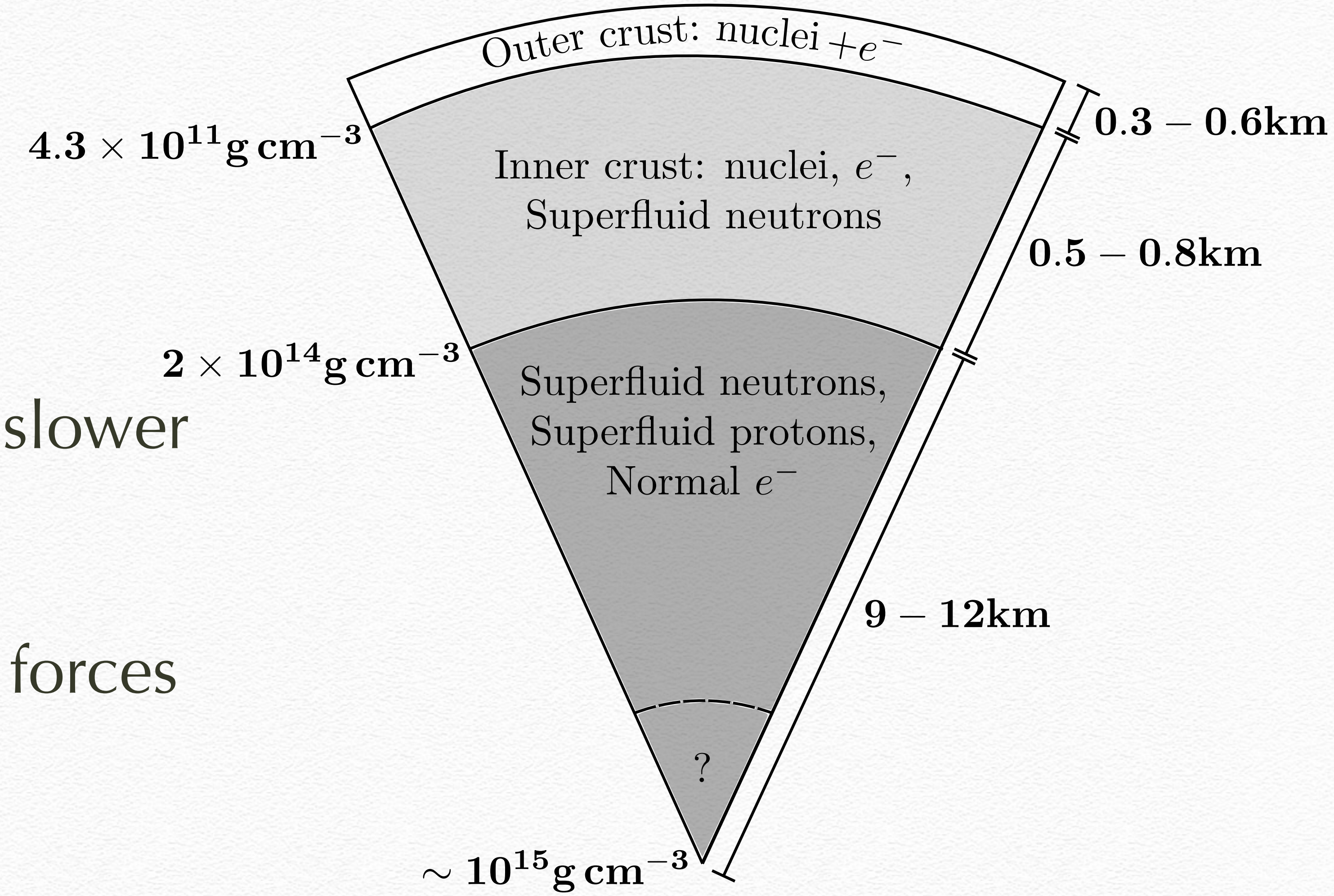


Figure: C. Espinoza.

Neutron star structure

- Crust
- Core
  - High conductivity: Hall+Ohm: Much slower
  - All particles can move: friction forces
  - Weak interactions



Outer crust: nuclei $+e^-$

$\mathbf{4.3\times10^{11}g\,cm^{-3}}$

$\mathbf{0.3-0.6km}$

Inner crust: nuclei, e^-, Superfluid neutrons

$\mathbf{0.5-0.8km}$

$\mathbf{2\times10^{14}g\,cm^{-3}}$

Superfluid neutrons, Superfluid protons, Normal e^-

$\mathbf{9-12km}$

?

$\mathbf{\sim10^{15}g\,cm^{-3}}$

B evolution: Core vs. Crust

$$t_{\mathrm{Ohm}} \sim \frac{5.7 \times 10^6}{Q}\,\mathrm{yr} \qquad t_{\mathrm{ambip}} \sim 3 \times 10^7 \frac{L_6^2 T_6^2}{B_{12}^2}\,\mathrm{yr}$$

We treat the crust as a vacuum

(whose magnetic field at any time is fully determined by the field in the core).

What happens in the core?

Formalism: Goldreich & Reisenegger (1992); Hoyos et al. (2008)

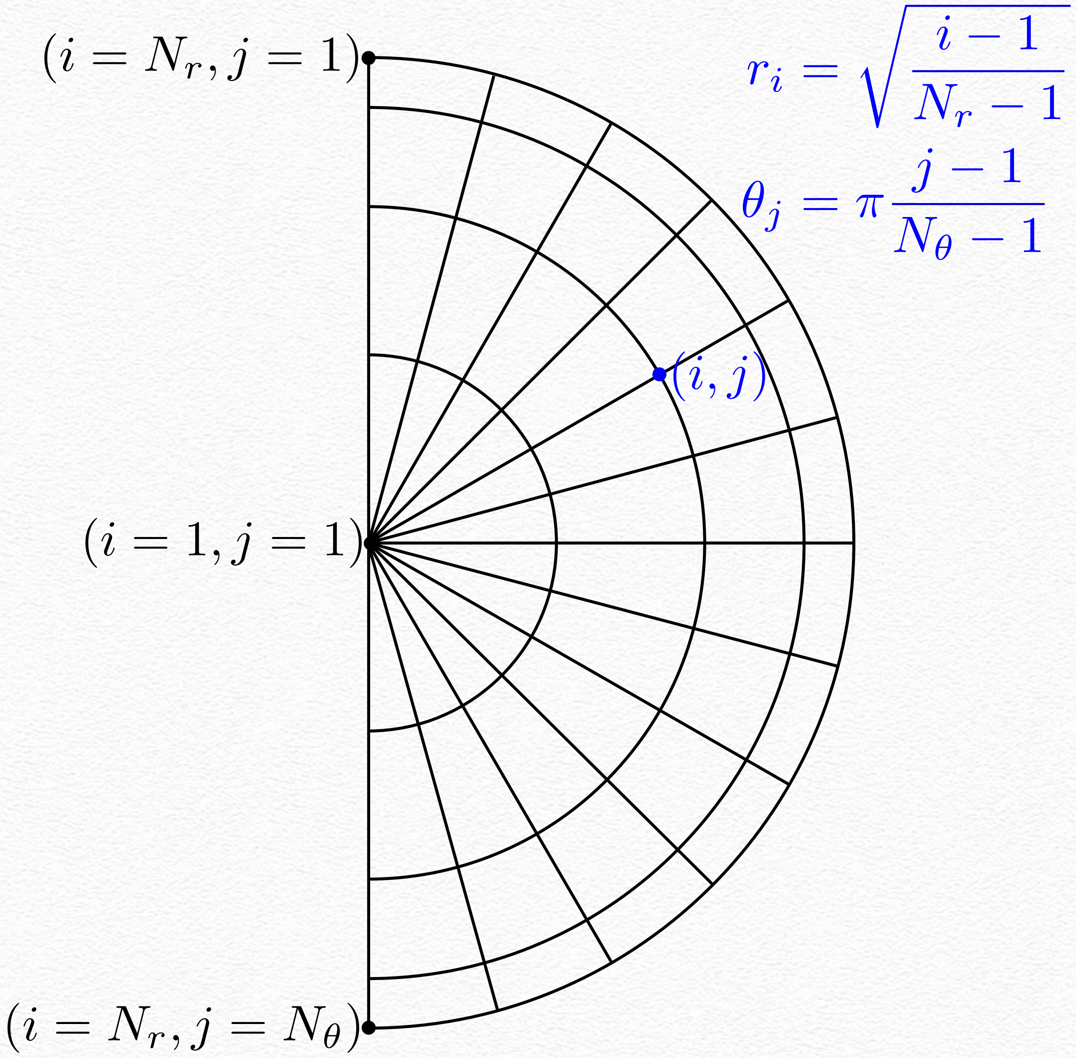
- *Charge neutrality.*
- *Uniform background in hydrostatic and chemical equilibrium*

$$\nabla\mu + \frac{\mu}{c^2}\nabla\Psi = 0\,.$$

- Ratio between the magnetic pressure and degeneracy pressure: $B^2/8\pi P \lesssim 10^{-6}$

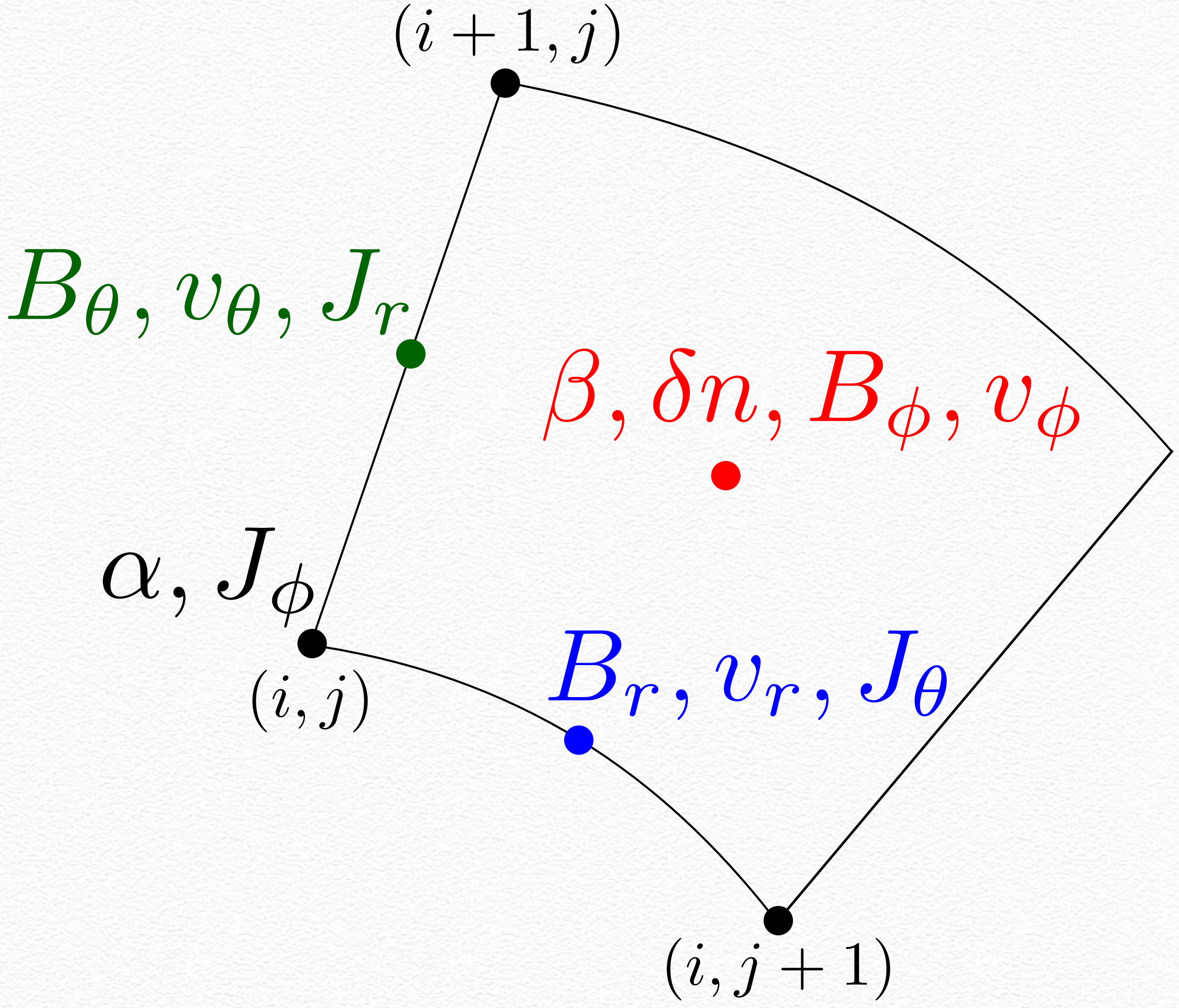
$$\begin{aligned} n_j(\vec{r},t) &\rightarrow n_j + \delta n_j(\vec{r},t) \quad j = n, c \\ \mu_j(\vec{r},t) &\rightarrow \mu + \delta\mu_j(\vec{r},t) \quad \mu = \mu_c = \mu_n \end{aligned}$$

We need numerical simulations

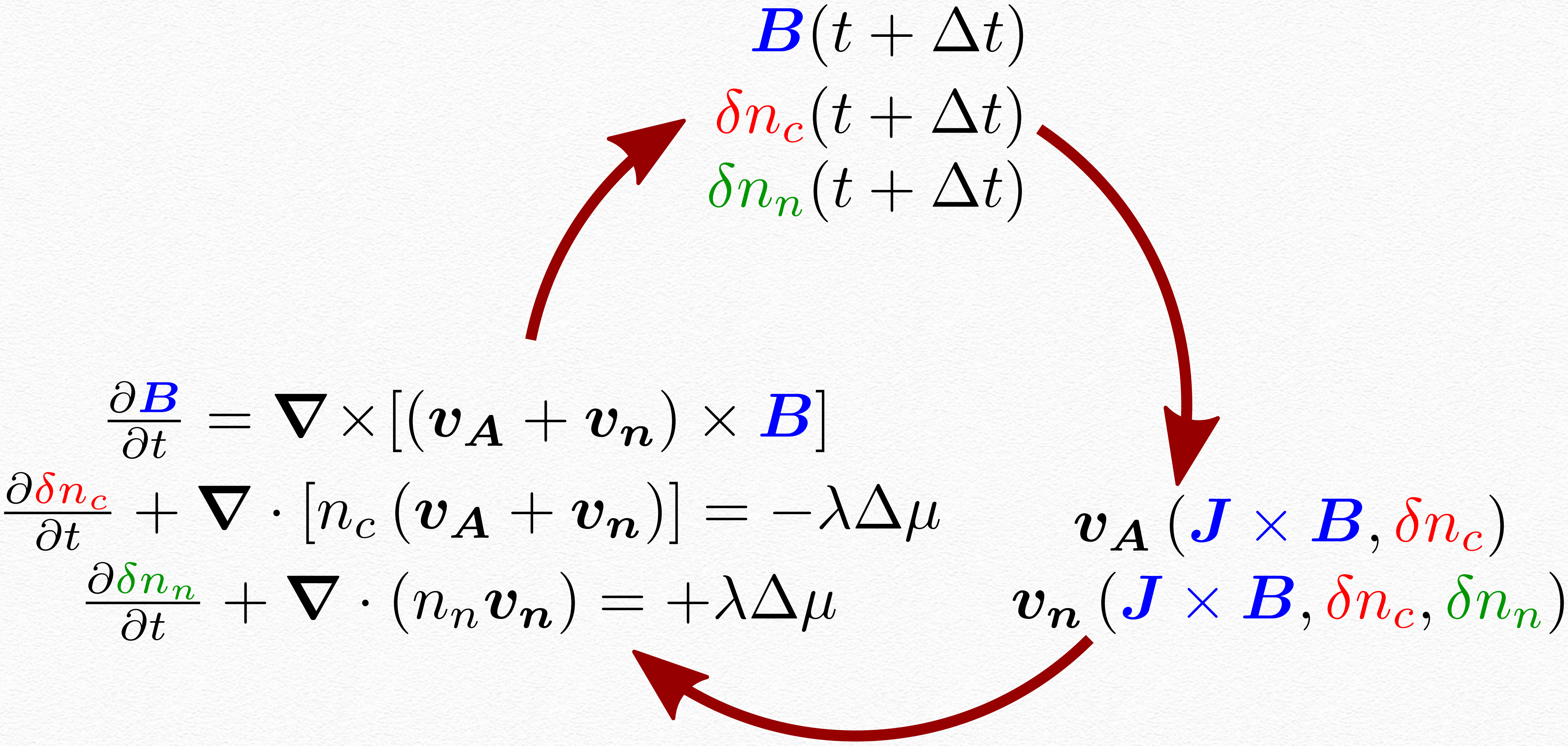


$$r_i = \sqrt{\frac{i-1}{N_r - 1}}$$

$$\theta_j = \pi \frac{j-1}{N_\theta - 1}$$



We need numerical simulations



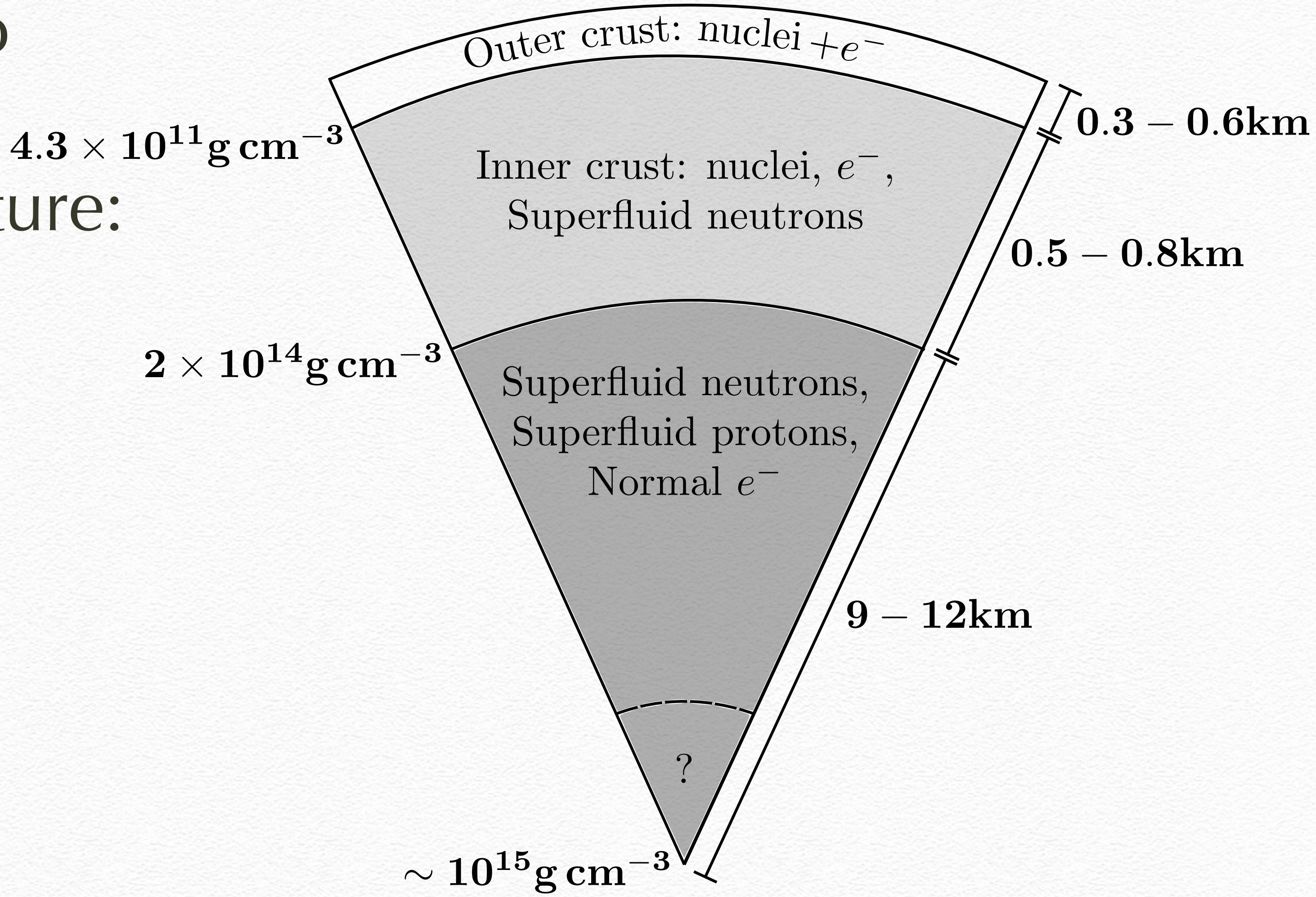
$$\boldsymbol{B}(t+\Delta t)$$
$$\delta n_c(t+\Delta t)$$
$$\delta n_n(t+\Delta t)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla}\times\left[\left(\boldsymbol{v_A}+\boldsymbol{v_n}\right)\times\boldsymbol{B}\right]$$
$$\frac{\partial \delta n_c}{\partial t} + \boldsymbol{\nabla}\cdot\left[n_c\left(\boldsymbol{v_A}+\boldsymbol{v_n}\right)\right] = -\lambda\Delta\mu$$
$$\frac{\partial \delta n_n}{\partial t} + \boldsymbol{\nabla}\cdot\left(n_n\boldsymbol{v_n}\right) = +\lambda\Delta\mu$$

$$\boldsymbol{v_A}\left(\boldsymbol{J}\times\boldsymbol{B},\delta n_c\right)$$
$$\boldsymbol{v_n}\left(\boldsymbol{J}\times\boldsymbol{B},\delta n_c,\delta n_n\right)$$

What happens in the core?

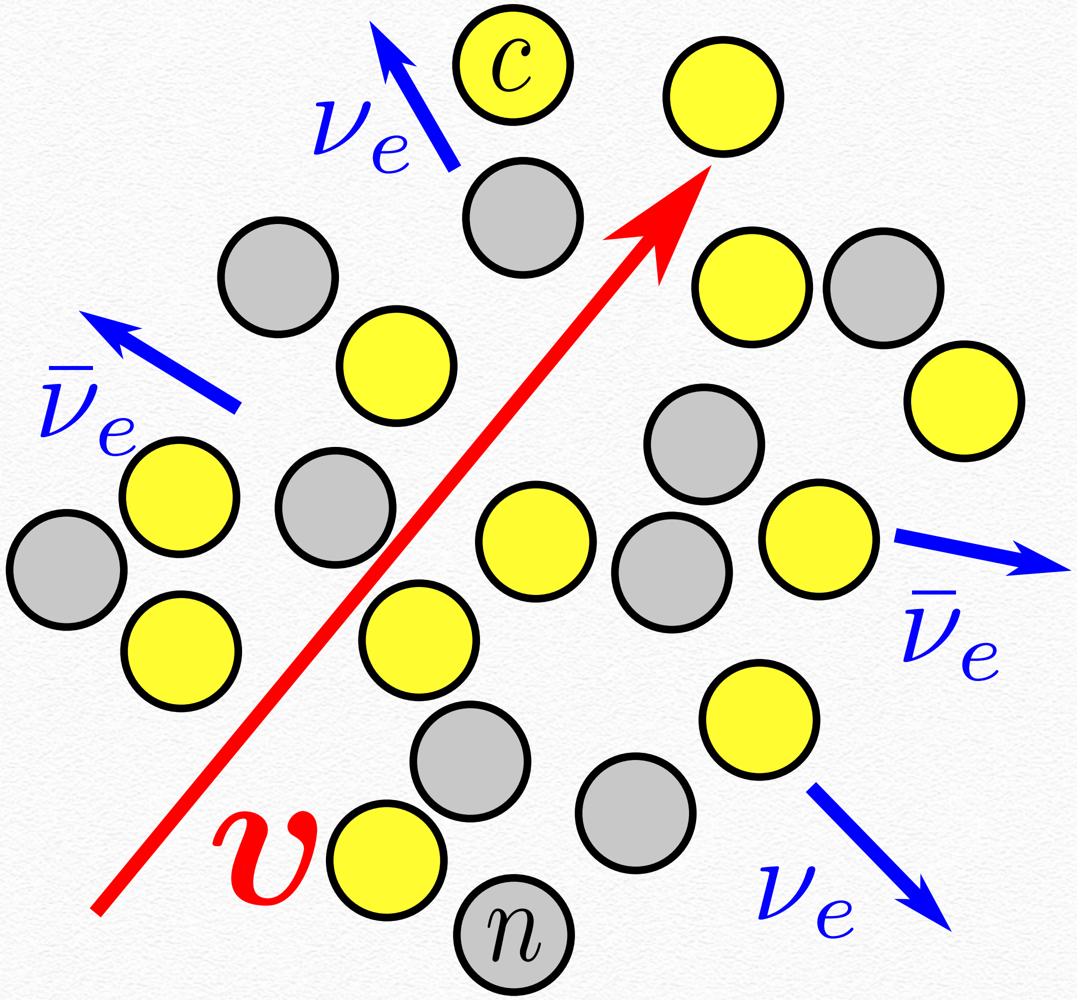
We can distinguish two different regimes depending on temperature:



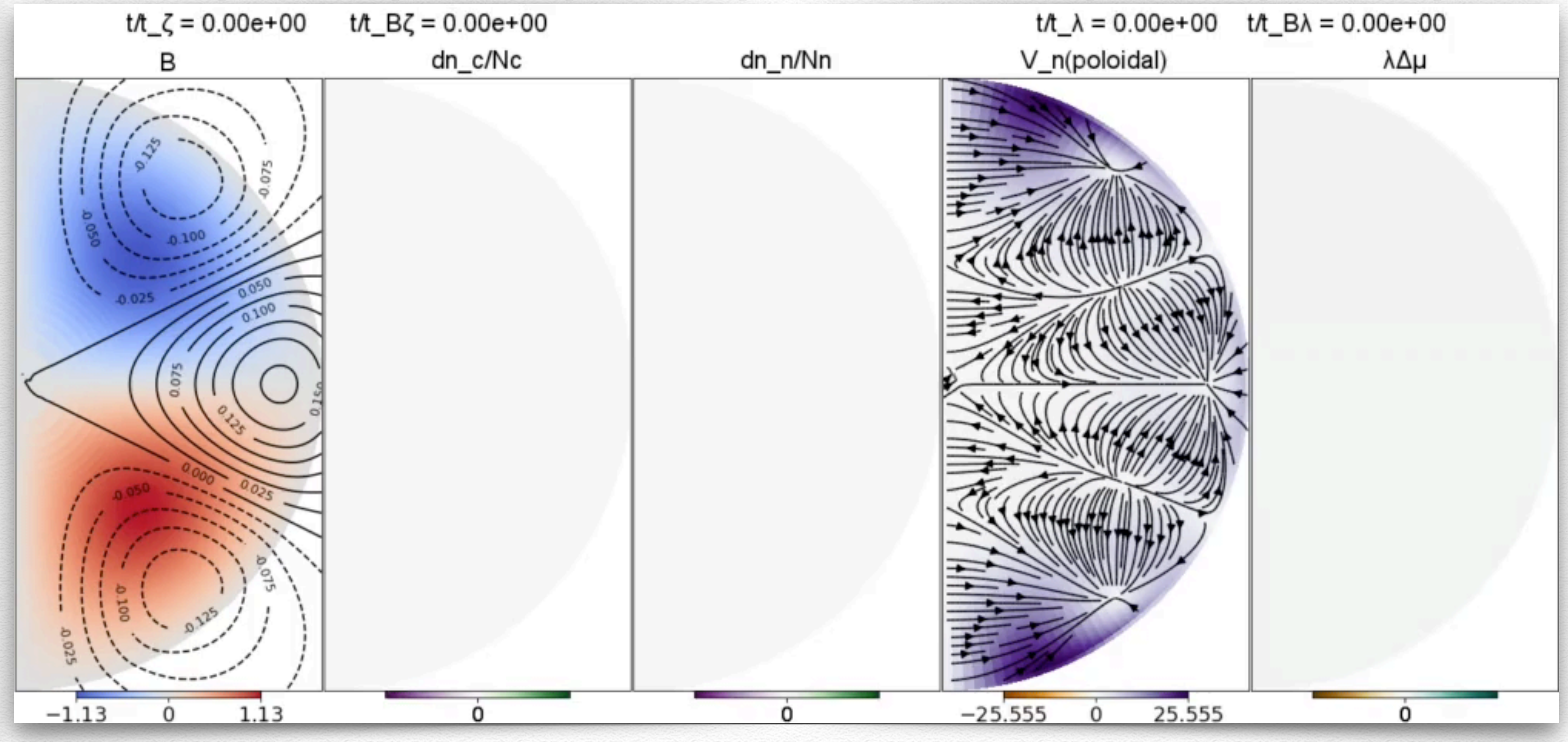
What happens in the core?

We can distinguish two different regimes depending on temperature:

- ***High* temperature**: strong coupling regime
- Joint radial motions:
  - Opposed by strong buoyancy forces
  - Feasible only during a very short time after the neutron star birth

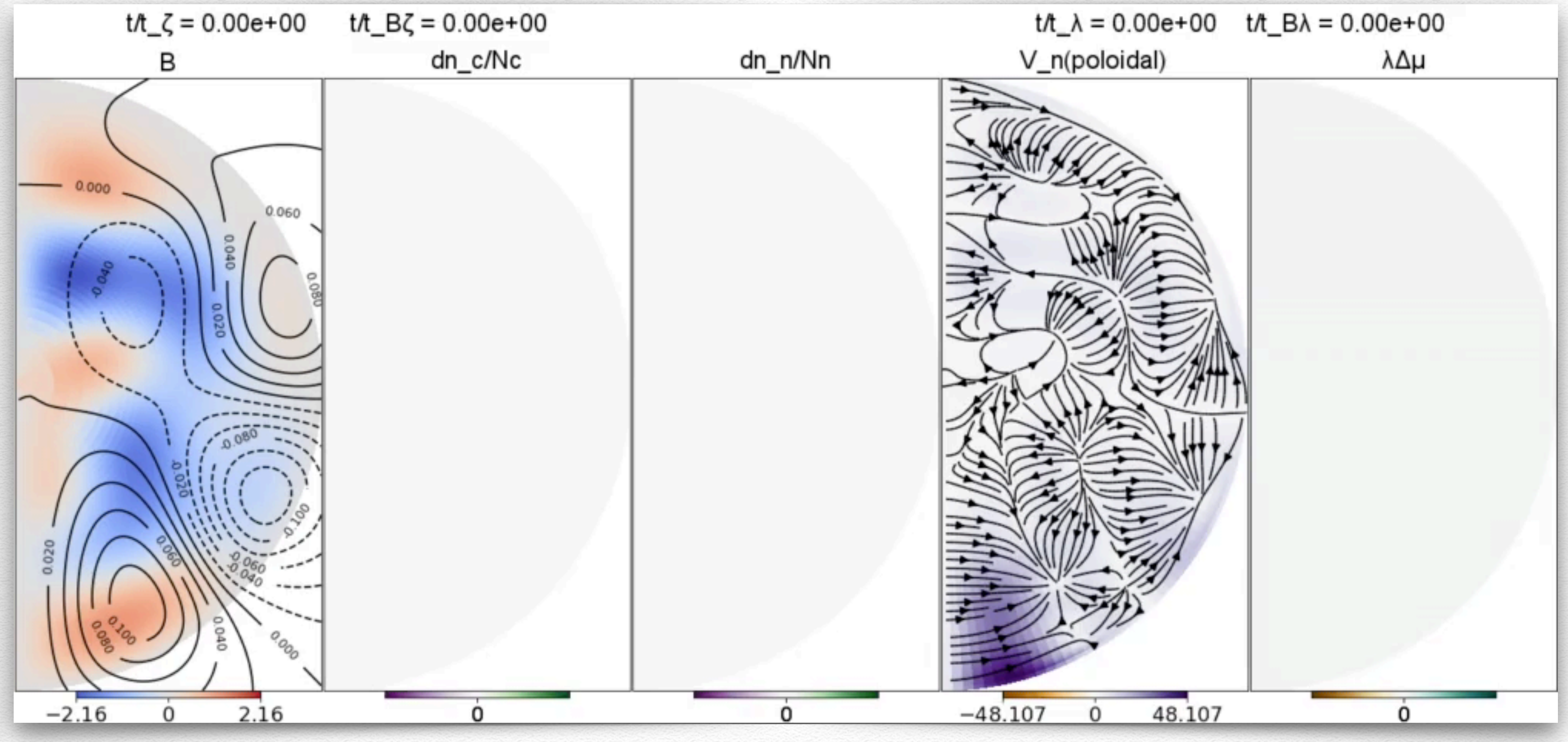


Strong coupling regime



Simulation performed taking $t_\zeta : t_{B\zeta} : t_\lambda : t_{B\lambda} = 1 : 100 : 640 : 64000$

Strong coupling regime

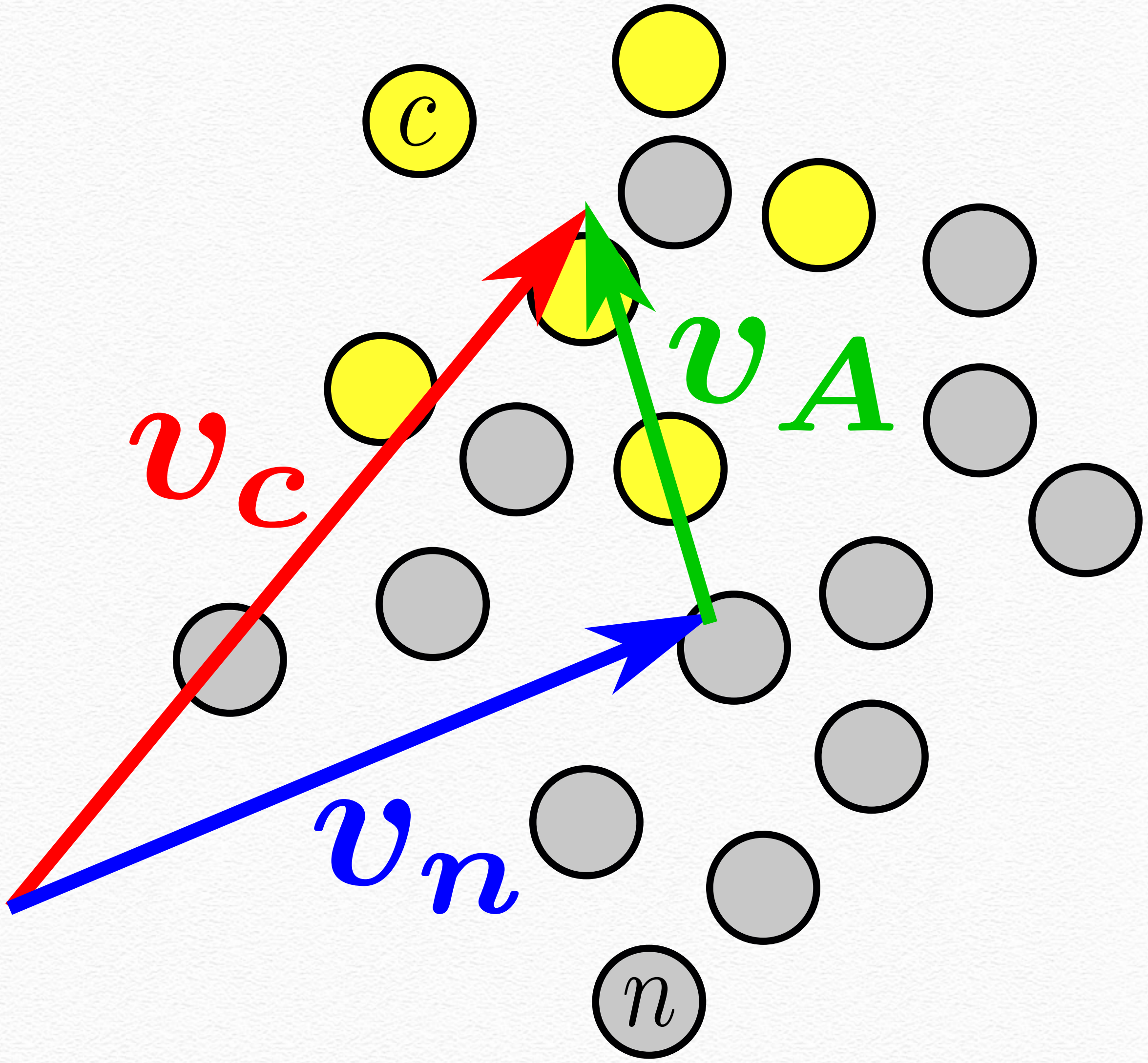


Simulation performed taking $t_\zeta : t_{B\zeta} : t_\lambda : t_{B\lambda} = 1 : 100 : 640 : 64000$

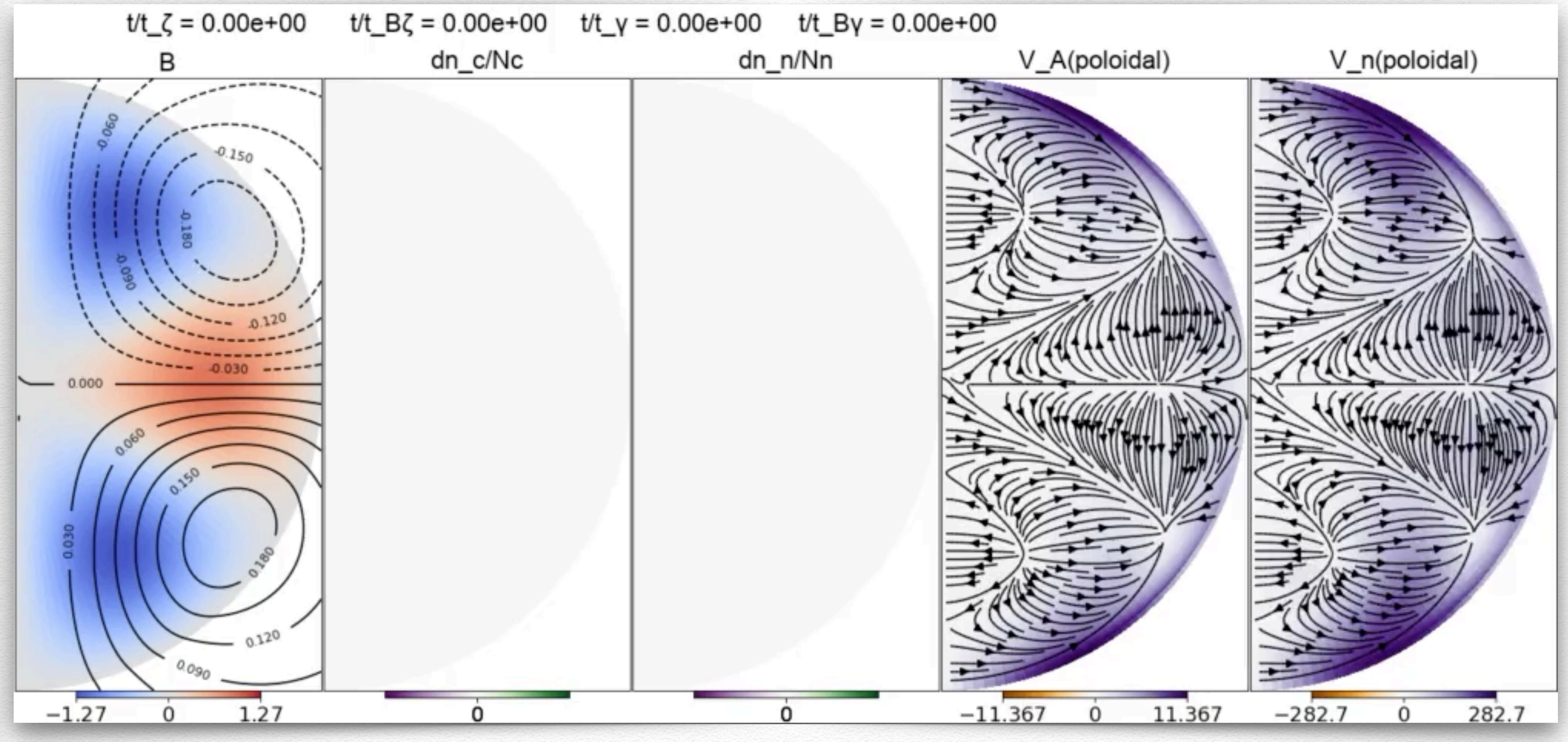
What happens in the core?

We can distinguish two different regimes depending on temperature:

- ***Lower* temperatures**:
  weak coupling regime
  - Weak interactions are strongly suppressed
  - Collisional coupling is reduced: Relative motions
  - Ambipolar diffusion



Weak coupling regime



Simulation performed taking $t_\zeta : t_{B\zeta} : t_\gamma : t_{B\gamma} = 1 : 500 : 2000 : 57290$

Summary and Conclusions

- Simulations that evolve simultaneously the magnetic field and the density perturbations it induces for neutrons and charged particles.
- Two regimes of magnetic field evolution:
  - Strong coupling
    - Urca reactions can adjust the composition “in real time”.
    - Matter behaves as a single fluid (with time-varying composition) which moves together with the magnetic field.
  - Weak coupling
    - Relative motion of neutrons and charged particles: Ambipolar diffusion
- The star evolves towards hydromagnetic equilibria

Summary and Conclusions

- Caveats:
    - Neglected the currents in the crust (assumed to have a very low conductivity.
    - Superfluidity/superconductivity.

Summary and Conclusions

- Previous work indicates that there are no stable hydromagnetic equilibria in barotropic stars:
    - Resulting equilibria are likely to become unstable if considered in full 3D.
    - **Currently:** I aim to develop a 3D code:
        - Challenge: Integration time
        - **Any input appreciated**