Magnetic field amplification in proto- neutron stars

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Which mechanism can justify the magnetic field observed in neutron stars?

Mean field dynamo (operating during the PNS phase)

1. In what fraction of stars will the mean field dynamo be active?
2. What range of magnetic field can be produced ?

Constraint:
Can amplify the field in less than 1 minute (duration of the instabilities)?

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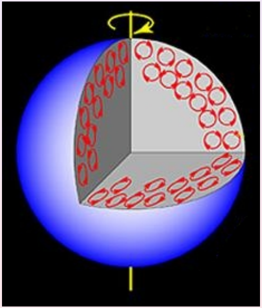

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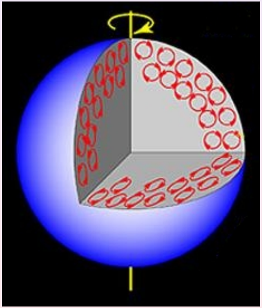

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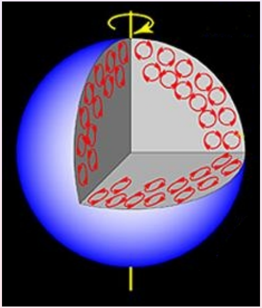

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Turbulence in PNSs

Two kinds of instabilities are active in two different zones:

1. Convective Instability
   Schwarzchild criterion
   - Small turn-over times $\tau \sim 0.1 - 1$ ms
   - Influence of rotation on turbulence is weak $\rightarrow$ local field
2. Neutron Finger Instability (double diffusive)
   temperature gradient + leptonic number gradient
   - Large turn-over times $\tau \sim 30 - 100$ ms
   - Small Rossby number $R_O = \frac{P}{\tau} \sim 1$
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Equations

- Induction equation:

$$\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

- Induction equation for mean fields:

$$\partial_t \bar{\mathbf{B}} = \nabla \times (\bar{\mathbf{v}} \times \bar{\mathbf{B}} - \alpha \bar{\mathbf{B}} - \eta_T \nabla \times \bar{\mathbf{B}})$$

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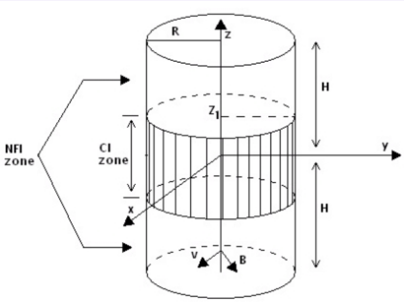
Analysis - Model

- 1D slab model with a vertical structure
- thin layer between NFI and CI



Final equations:

$$\partial_t \mathcal{A} = C_\alpha \, \alpha \, \psi_\alpha \, \mathcal{B} + \eta \, \psi_\eta \, \partial_z^2 \mathcal{A} \qquad \text{(poloidal)}$$

$$\partial_t \mathcal{B} = -C_\alpha \, [\alpha \, \psi_\alpha \, \partial_z \mathcal{A}] - C_\Omega \, \partial_z \mathcal{A} + \partial_z \, [\eta \, \psi_\eta \, \partial_z \mathcal{B}] \qquad \text{(toroidal)}$$

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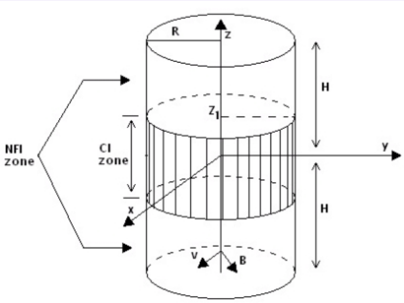

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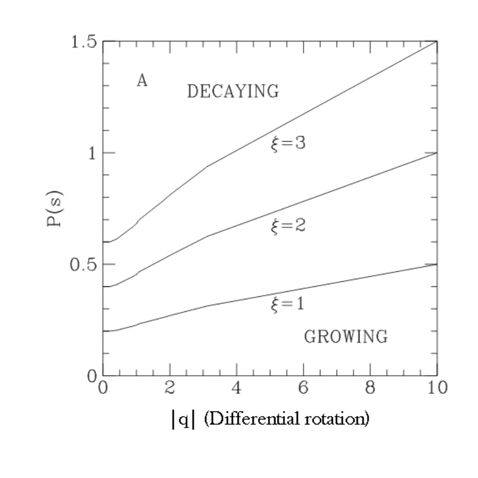
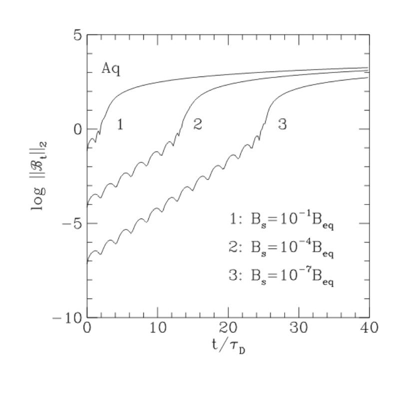
Critical period



For $P < P_c$ the dynamo is active (regardless of the differential rotation)

$P_C \sim 33 - 600$ [ms]

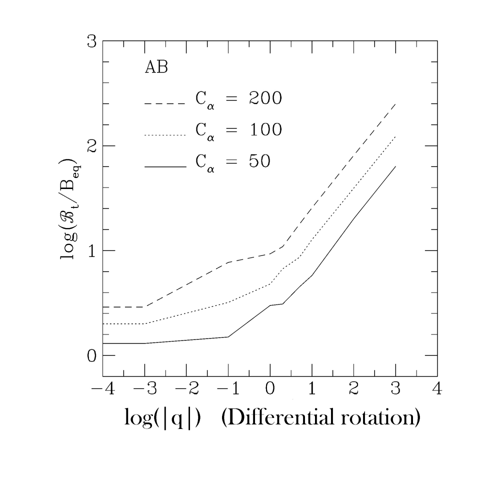
Time evolution



- Two phases: amplification and saturation
- Growth-rate is independent of the seed magnetic field:

$$B(t) = B_0\, e^{t/\tau}$$

Differential rotation



$$B_{fin} \propto |q|^\gamma$$

$$\gamma = 0.52 \pm 0.03$$

Conclusions

Plausibility of the mean field dynamo scenario:

1. In which fraction of stars?
   Active in stars with $P < P_c \sim 30 - 600$ ms
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   Amplification factors up to 10^{13}

New results:

- Growth rates and saturation field independent of initial magnetic seed
- Power-law between final field and differential rotation (with universal exponent)

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