Title: Magnetic Field Evolution and Superconductivity of Pulsars

Speakers: Ashley Bransgrove

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

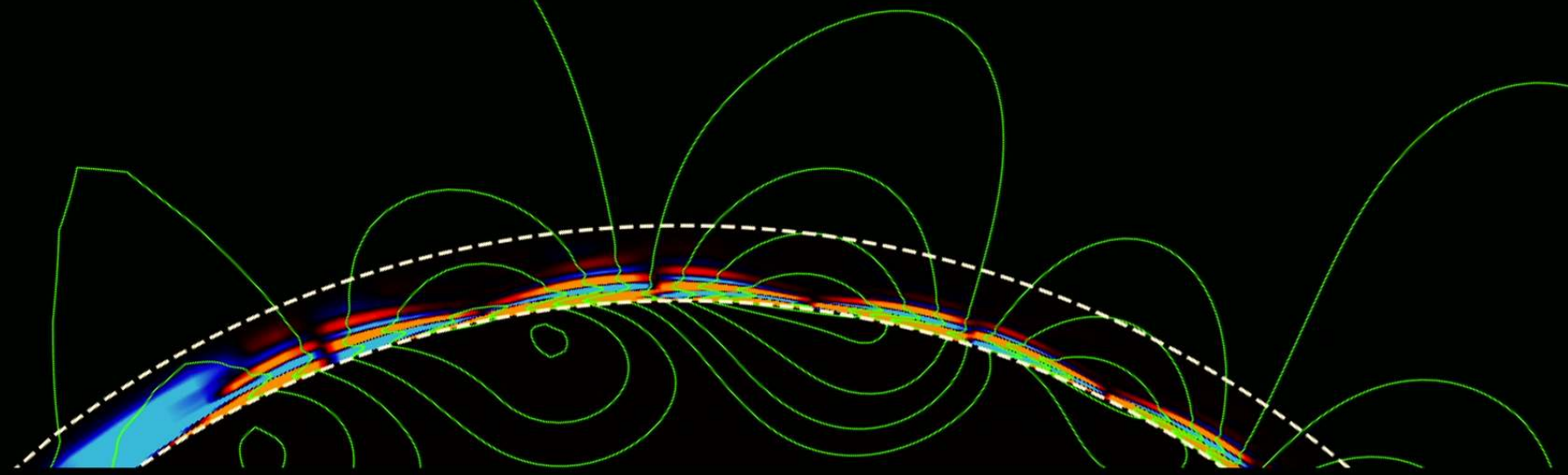
Date: March 28, 2025 - 10:15 AM

URL: https://pirsa.org/25030148

Abstract:

Radio pulsars display a range of puzzling long-term variability in their magnetospheric emission and spin-down. In this talk I will discuss the mechanisms for internal magnetic field evolution of pulsars, how it differs from the MHD of classical conducting fluids, and how the neutron star interior couples to the magnetosphere and its radiation.

Magnetic Field Evolution of Superconducting Pulsars



Ashley Bransgrove

Princeton University, PCTS

Thanks to Yuri Levin and Andrei Beloborodov

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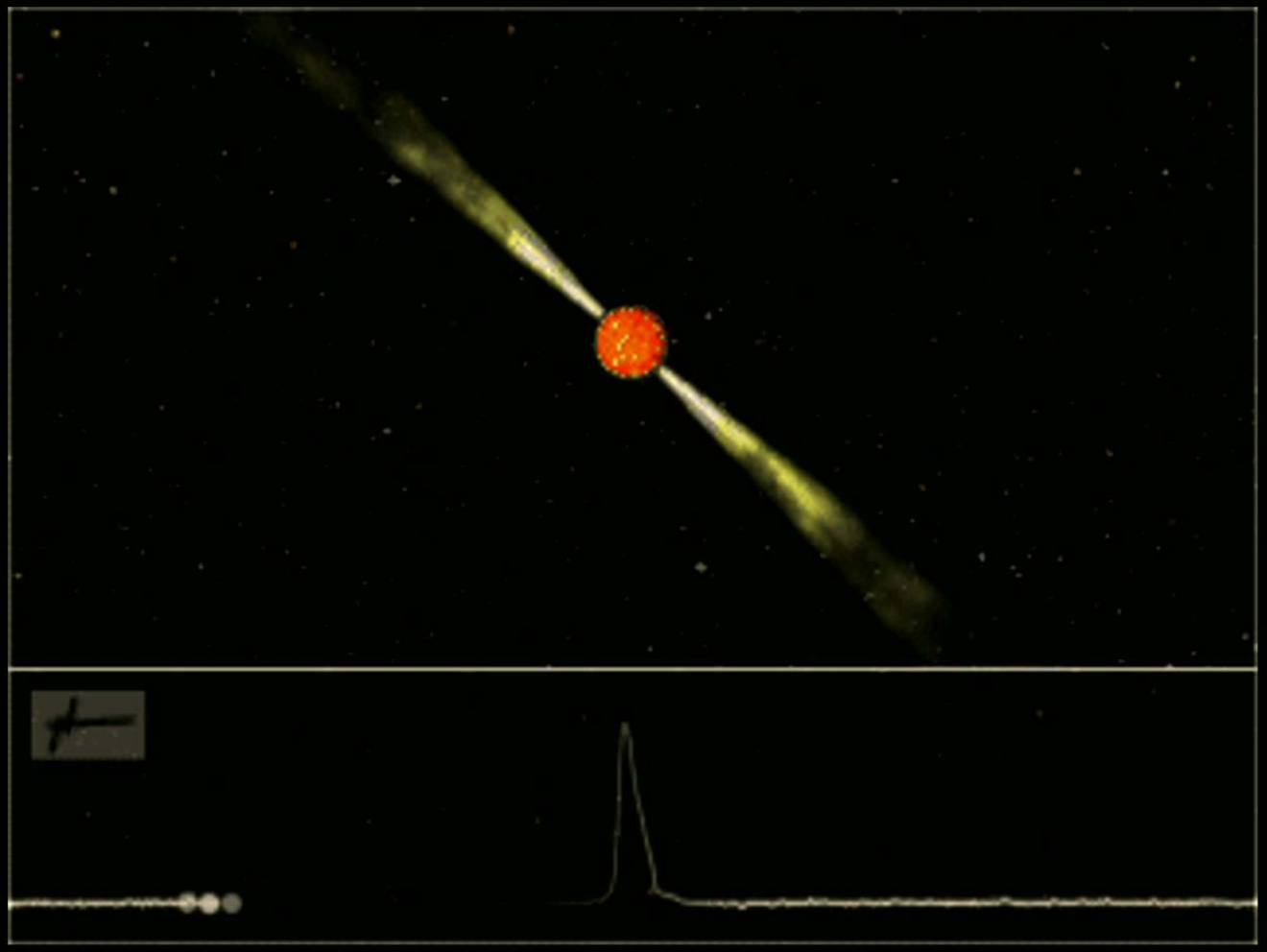
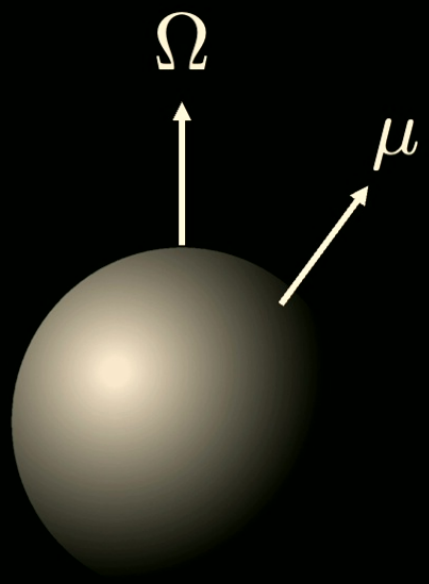


Joeri van Leeuwen, www.ligo.org/science/

Pulsar Spin-down



$$\dot{\Omega} = -k\Omega^n$$

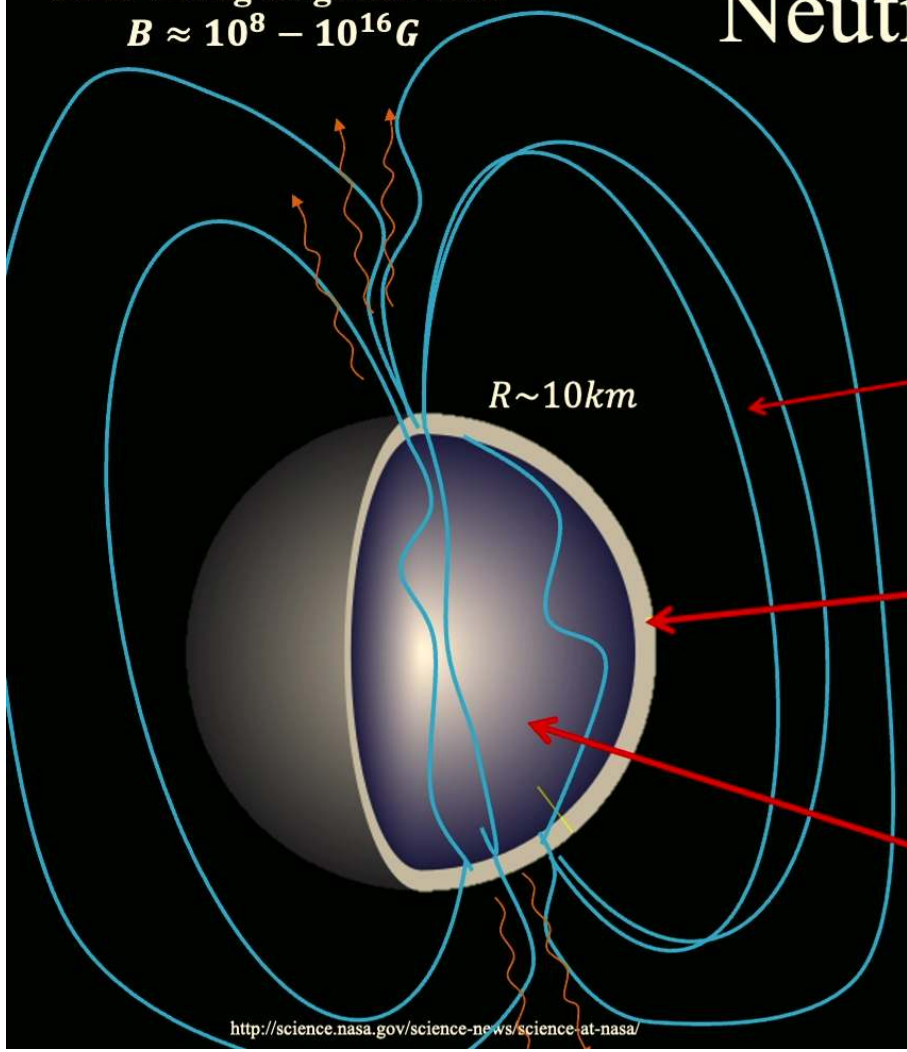
$$k = \frac{\mu^2\,\Omega^4}{Ic^3}, \qquad n = 3$$

Vacuum rotator: Pacini 68, Ostriker & Gunn 69
Force-free rotator: Goldreich & Julian 69, Spitkovsky 06
+ many more

Neutron Stars: Physics Playground

Ultra-strong magnetic fields
$B \approx 10^8 - 10^{16} G$

~ solar mass of baryons supported against gravitational collapse by strong nuclear forces, threaded by the ***strongest magnetic fields in the universe***
$B \approx 10^8 - 10^{16}$ G

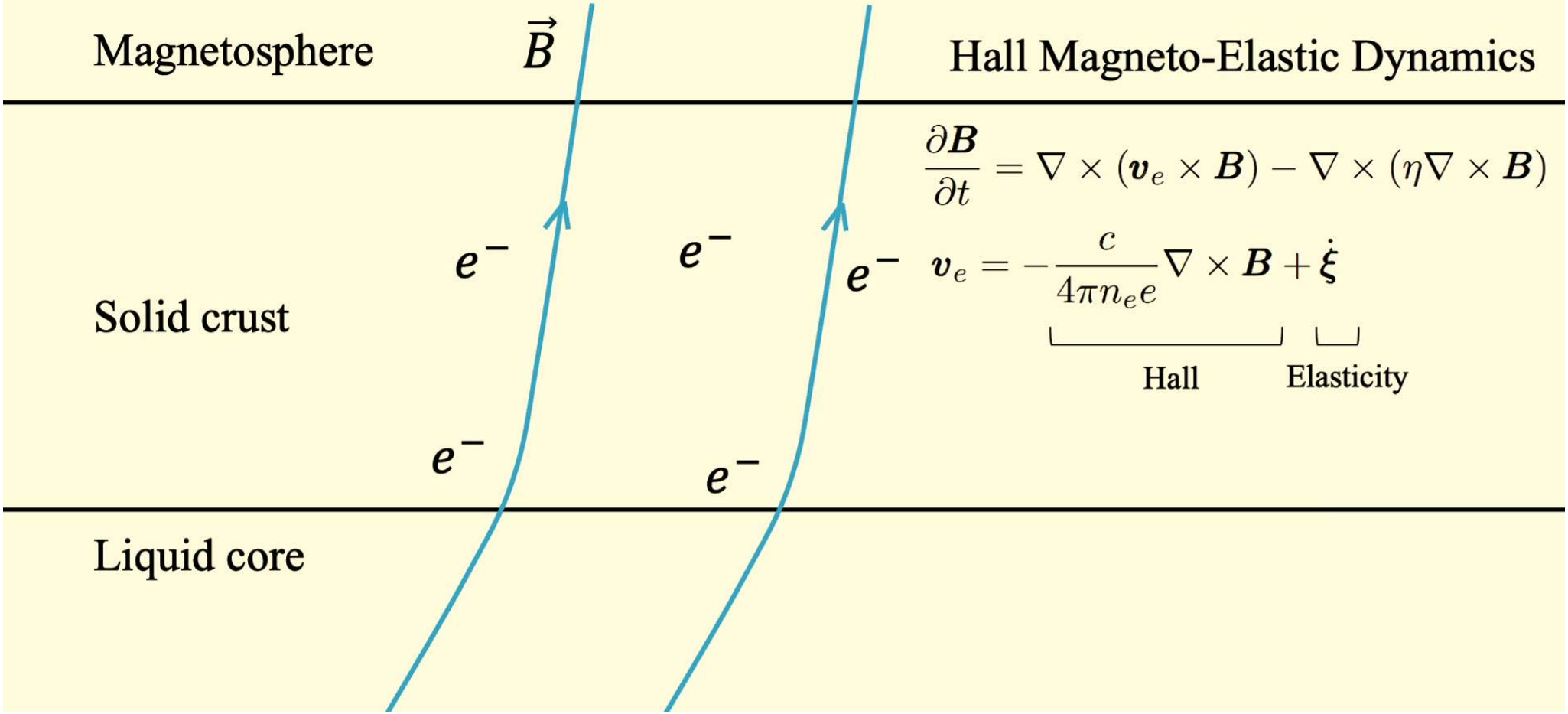


Magnetosphere: $e^{\pm}$ pair plasma

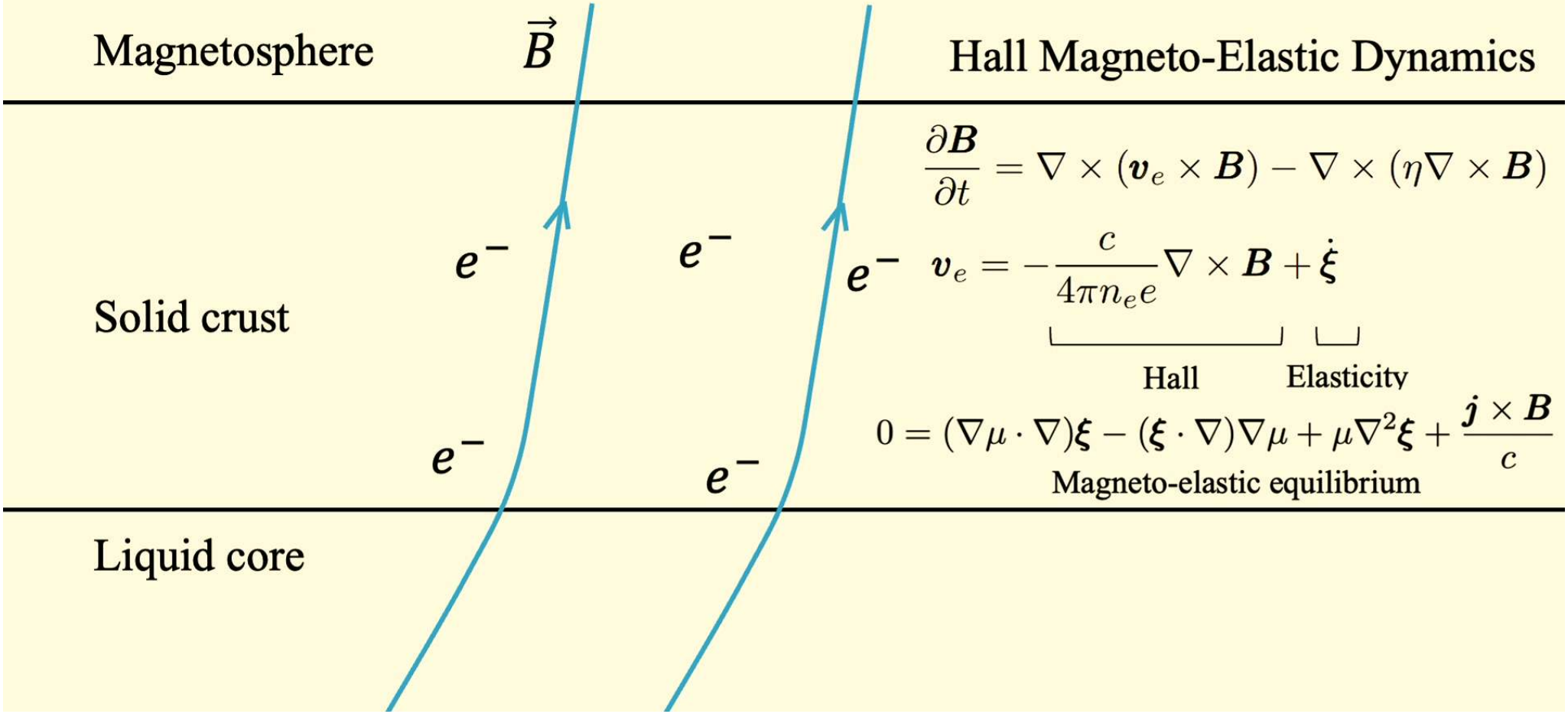
Solid crust, highly conducting

Liquid core – nuclear soup, superconducting protons, superfluid neutrons

Internal Magnetic Evolution of Pulsars



Internal Magnetic Evolution of Pulsars



Hall Magneto-Elastic Dynamics

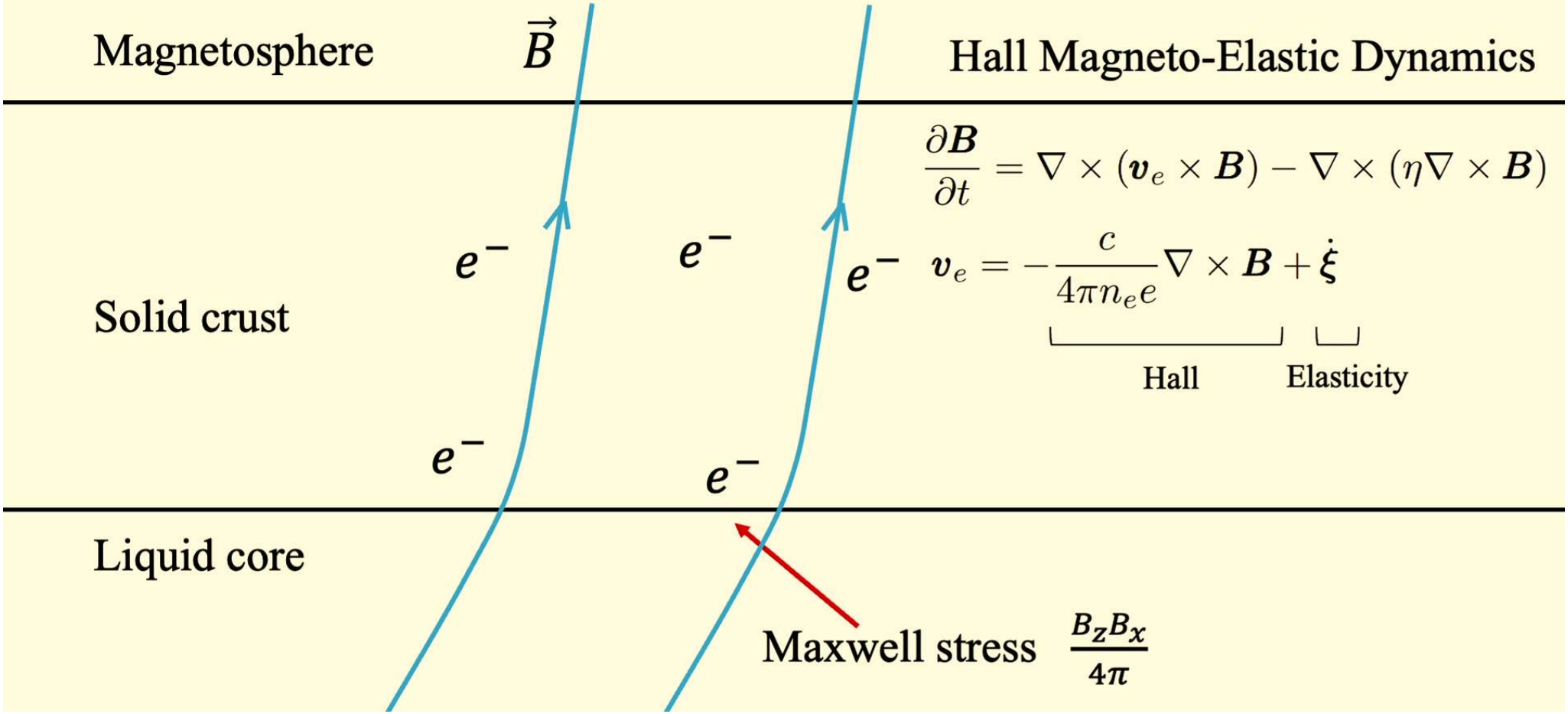
$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v}_e \times \boldsymbol{B}) - \nabla \times (\eta \nabla \times \boldsymbol{B})$$

$$\boldsymbol{v}_e = \underbrace{-\frac{c}{4\pi n_e e} \nabla \times \boldsymbol{B}}_{\text{Hall}} + \underbrace{\dot{\boldsymbol{\xi}}}_{\text{Elasticity}}$$

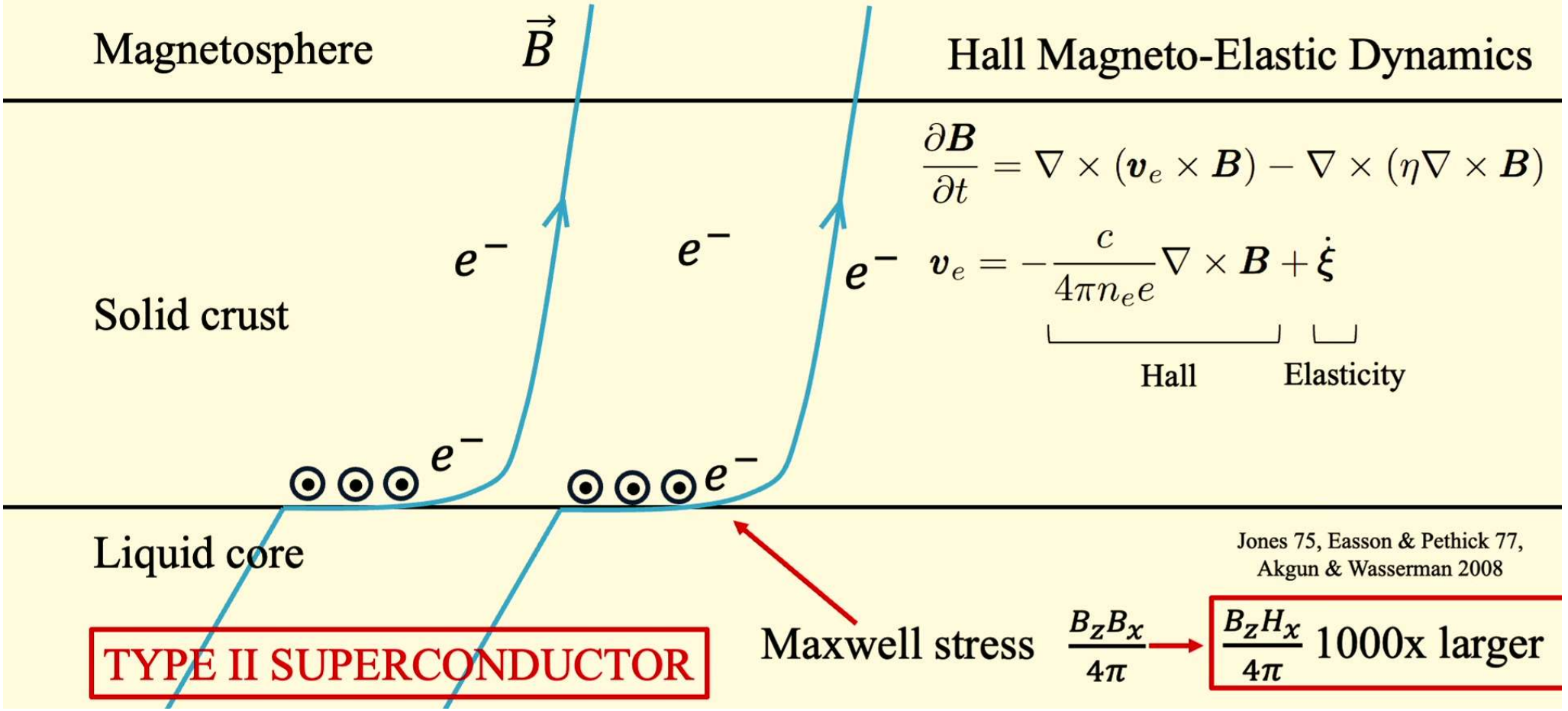
$$0 = (\nabla\mu \cdot \nabla)\boldsymbol{\xi} - (\boldsymbol{\xi} \cdot \nabla)\nabla\mu + \mu\nabla^2\boldsymbol{\xi} + \frac{\boldsymbol{j} \times \boldsymbol{B}}{c}$$

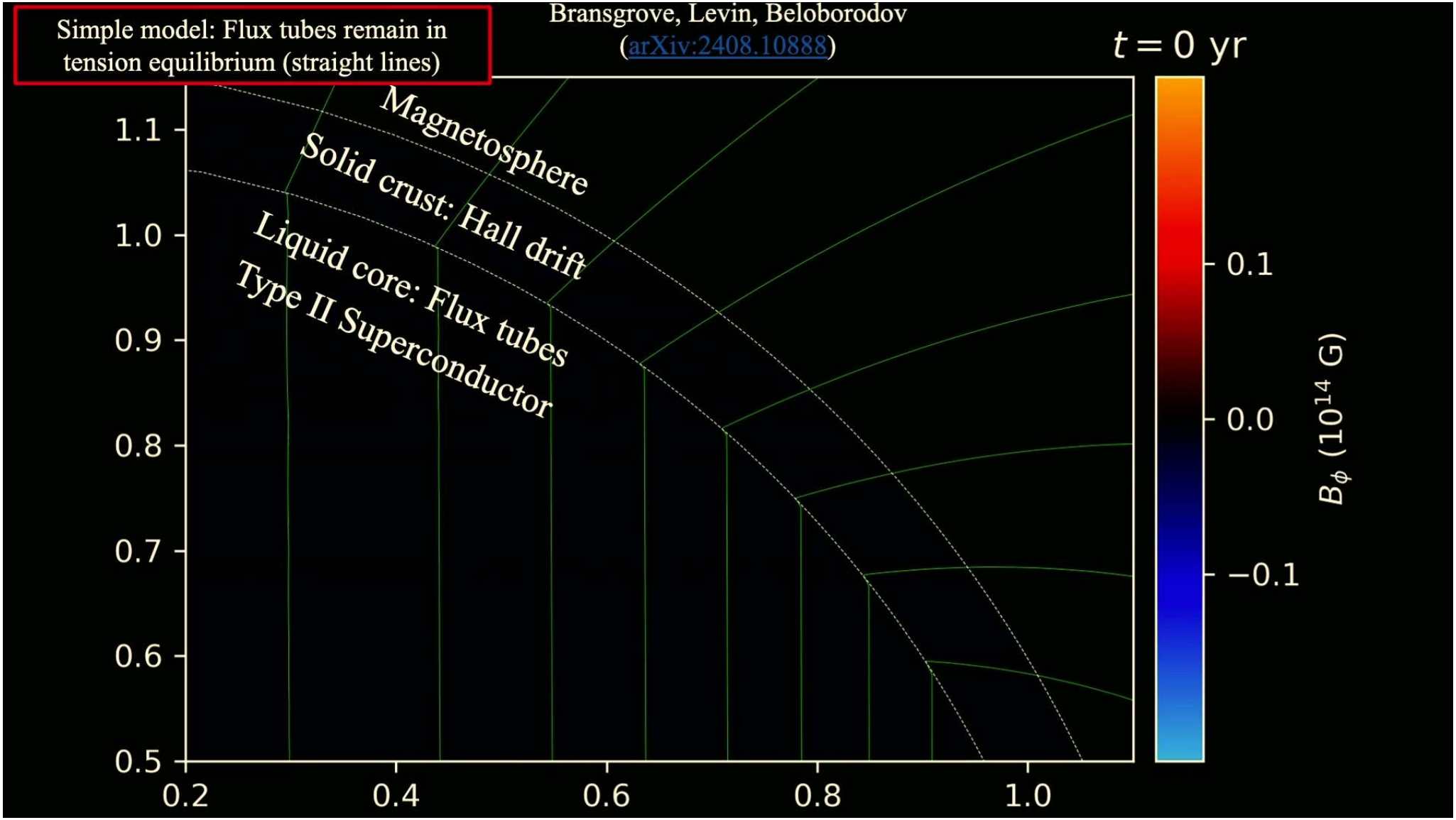
Magneto-elastic equilibrium

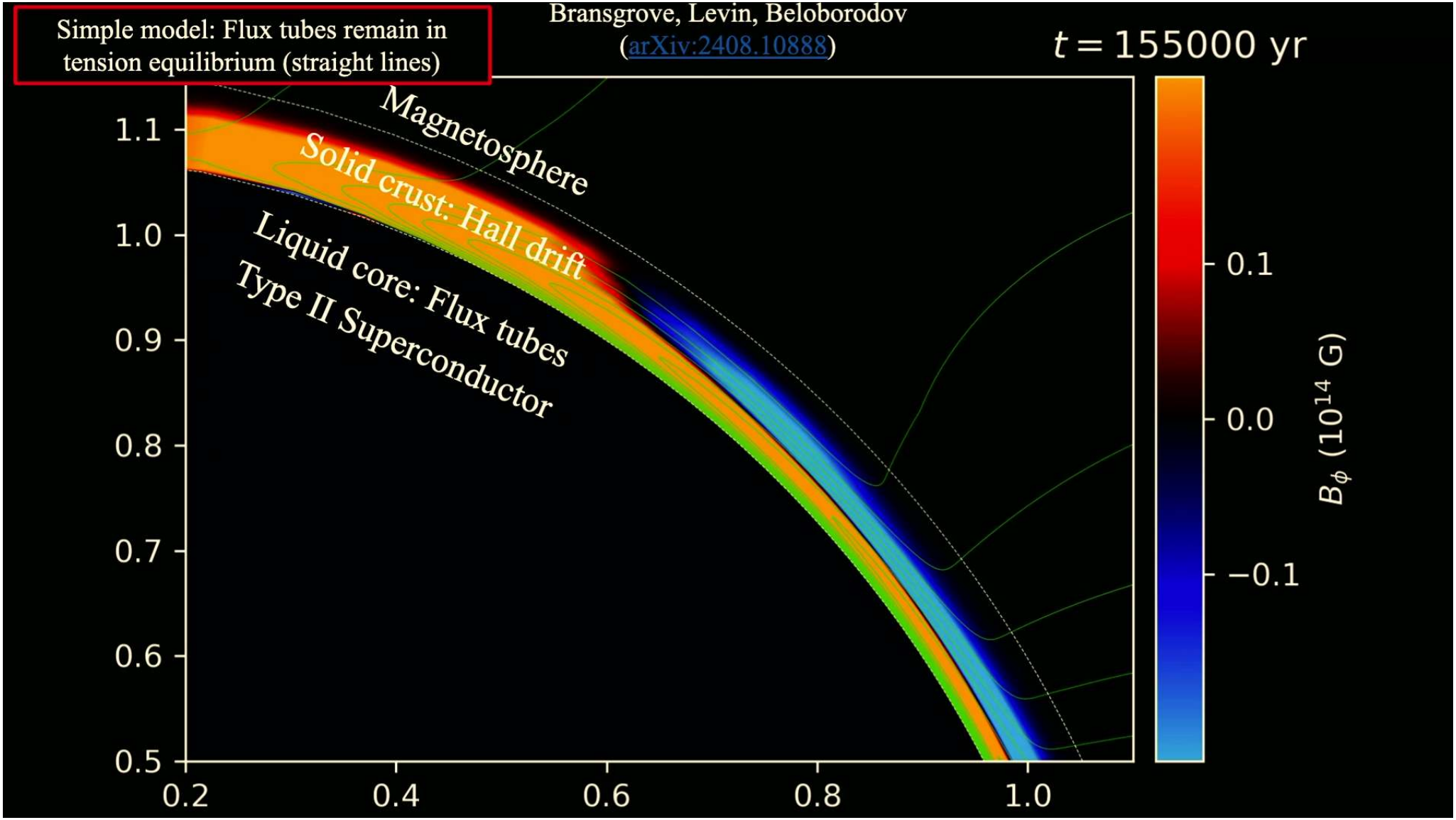
Internal Magnetic Evolution of Pulsars



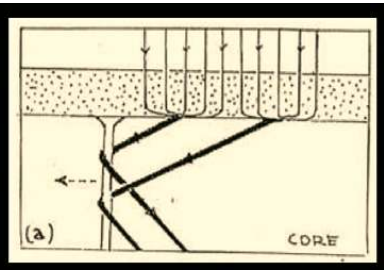
Internal Magnetic Evolution of Pulsars

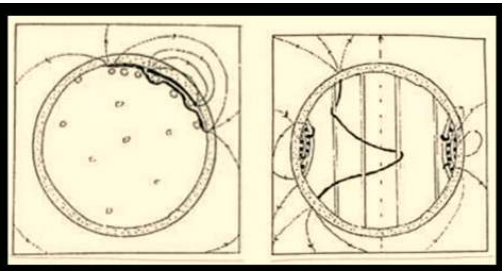


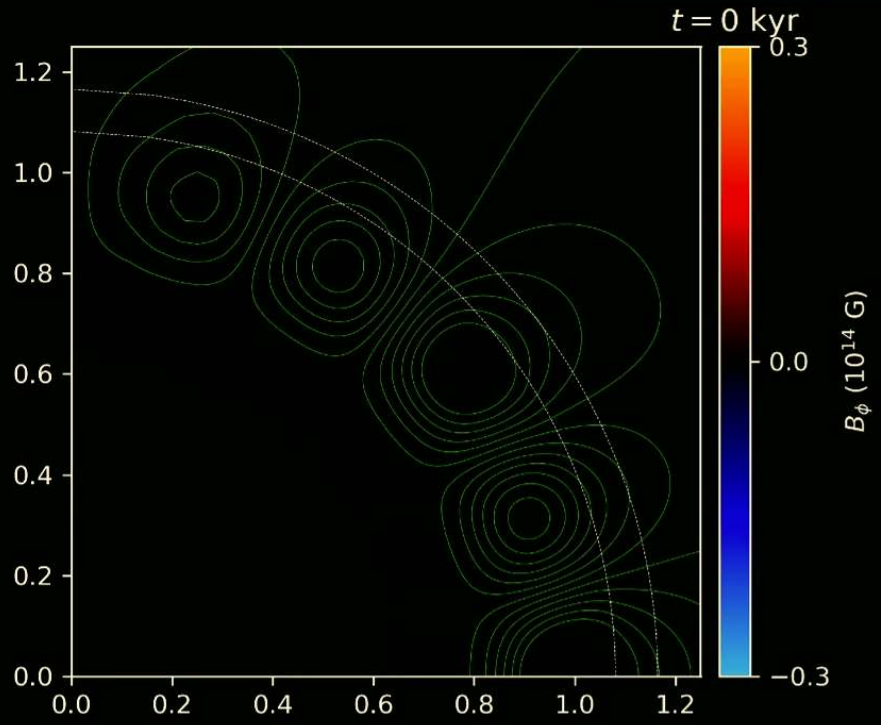

Simple model: Flux tubes remain in tension equilibrium (straight lines)
Bransgrove, Levin, Beloborodov
(arXiv:2408.10888)
$t = 0$ yr
Magnetosphere
Solid crust: Hall drift
Liquid core: Flux tubes
Type II Superconductor
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.2
0.4
0.6
0.8
1.0
0.1
0.0
−0.1
B_ϕ (10^{14} G)


Simple model: Flux tubes remain in tension equilibrium (straight lines)
Bransgrove, Levin, Beloborodov
(arXiv:2408.10888)
$t = 155000$ yr
Magnetosphere
Solid crust: Hall drift
Liquid core: Flux tubes
Type II Superconductor
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.2
0.4
0.6
0.8
1.0
0.1
0.0
−0.1
B_ϕ (10^{14} G)

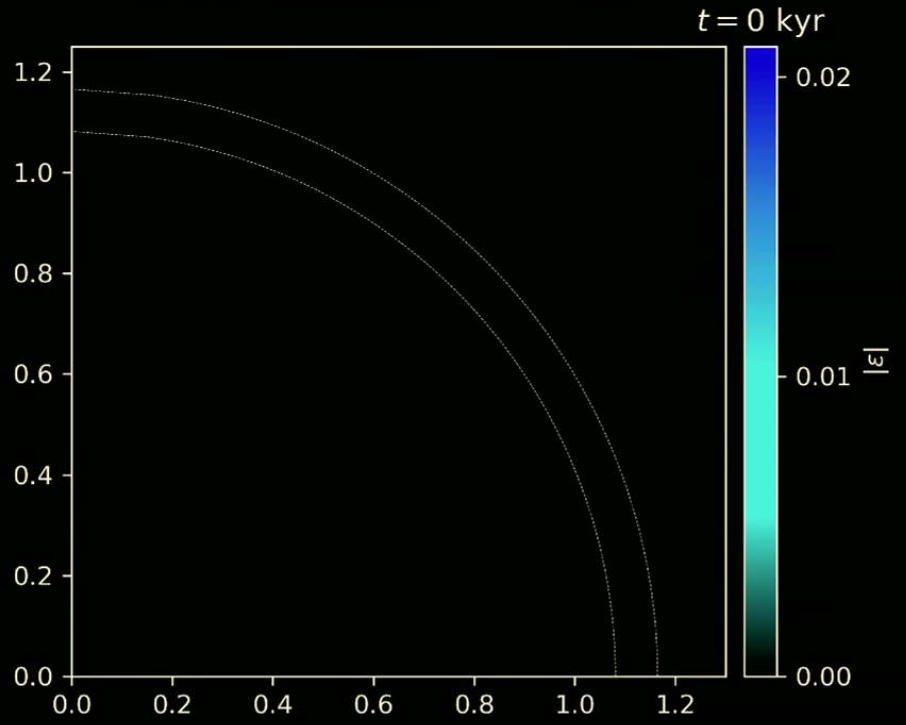
Ruderman-like model for vortex - flux tube interactions







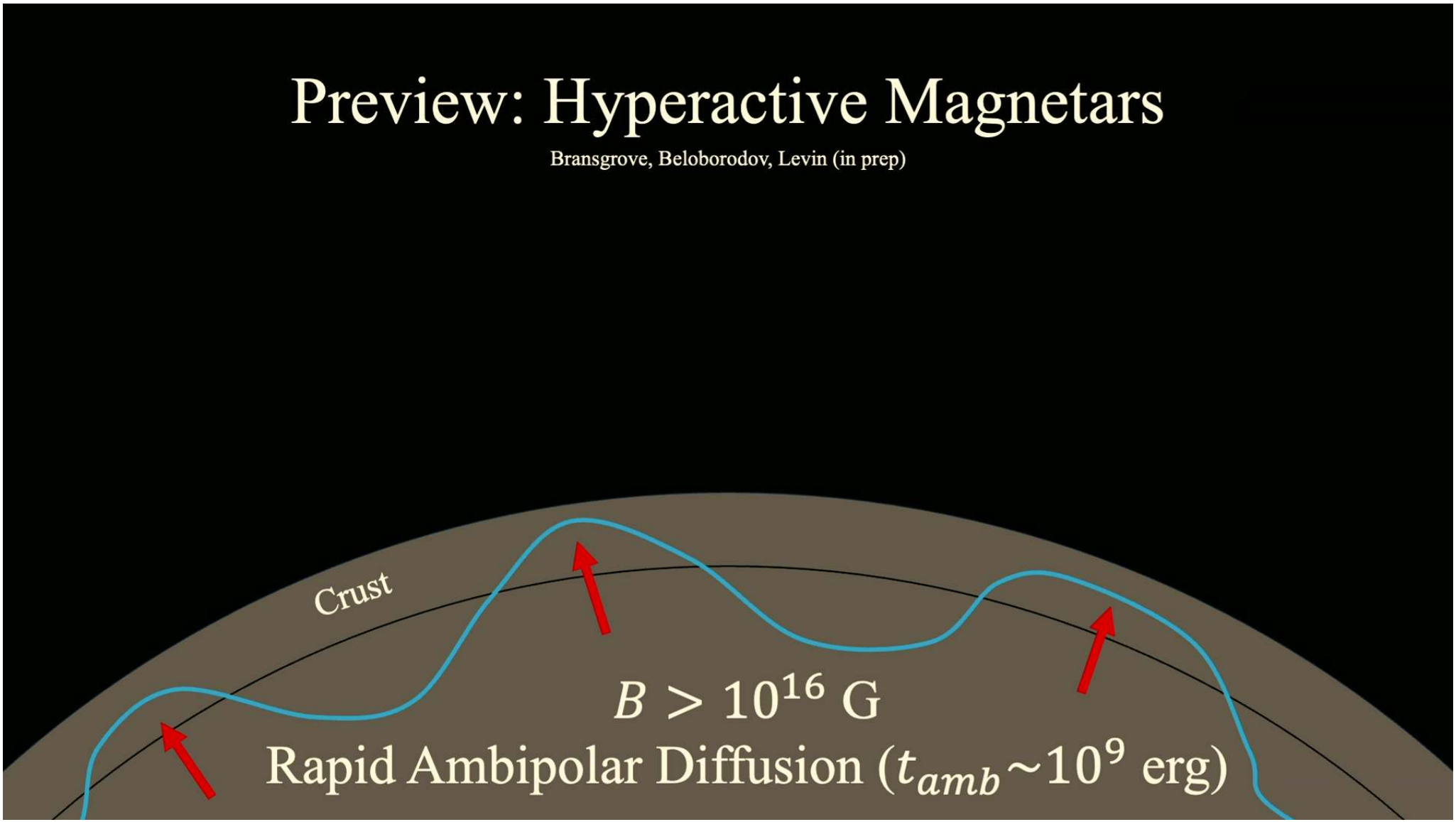
Magnetic Field

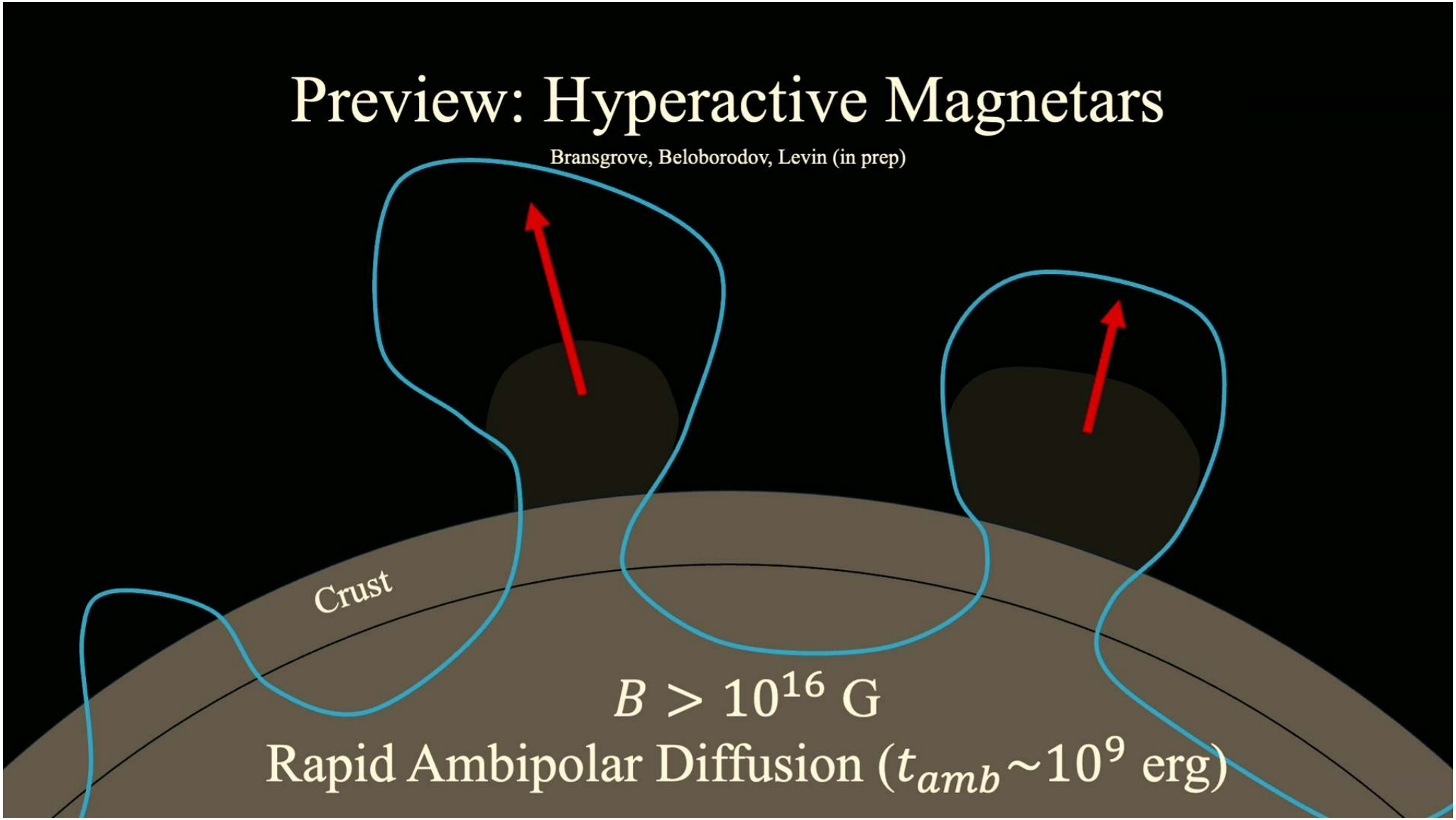


Elastic Strain

Preview: Hyperactive Magnetars

Bransgrove, Beloborodov, Levin (in prep)




Preview: Hyperactive Magnetars
Bransgrove, Beloborodov, Levin (in prep)
Crust
$B > 10^{16}$ G
Rapid Ambipolar Diffusion ($t_{amb} \sim 10^9$ erg)

Summary

- Superconductivity may be the dominant driver of magnetic field evolution in the first ~Myr of a pulsar's life.
- Pulsar variability may be related to evolution of their magnetic fields.
- Hyperactive magnetars powered by ambipolar diffusion.

Extreme Physics of Neutron Star Interiors

May 14-16, 2025
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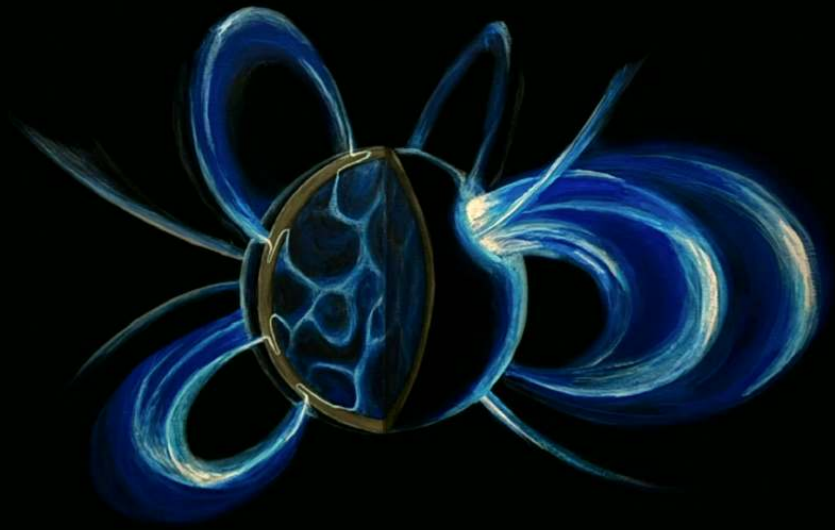
Pulsars

Magnetars

Fast Radio Bursts

Plasma Physics



Dense Matter

Nuclear Physics

Magnetic Fields

Quantum Fluids

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Organizers: Ashley Bransgrove, Anirudh Prabhu, Peter Rau, Anatoly Spitkovsky, Andrei Beloborodov

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