Magnetic field decay in (isolated) neutron stars

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CONICYT-DFG Collaboration Grant DFG-06 (Chile-Germany) ***Magnetic fields in massive stars & their compact remnants*** (with Langer, Spruit, Valdivia, Braithwaite – postdoc Joe Mitchell)

FONDECYT Regular Project 1110213 ***Thermal & magnetic evolution of neutron stars***

FONDECYT Postdoctoral Project 3130512 ***Physics under extreme conditions via observations of NSs*** (Cristóbal Espínoza):

PFB-06 (CATA) ***Center for Astronomy & Associated Technologies***

Chile: Not *just* great observatories

Present: ALMA, VLT, Magellan, Gemini-South, ….

Near future: LSST, CCAT, GMT, E-ELT

2020: Chile will host 70% of ground-based observing capacity

PUC Astrophysics staff

- 15 faculty
- 36 postdocs
- 15 PhD students
- 19 MS students
- >100 undergraduates

100 refereed papers/yr (2012)

NS/MHD group in Santiago

Pontificia Universidad Católica de Chile, *Institute of Astrophysics*

- Prof. **Andreas Reisenegger**
- Postdocs **Cristóbal Espinoza**, **Joe Mitchell**
- PhD student **Claudia Aguilera**
- MS students **Cristóbal Armaza, Ignacio Becker, Marilyn Cruces**
- Undergraduate students **Luis Rodríguez, Felipe Zepeda, José Rafael Fuentes**

Universidad de Chile, *Dept. of Physics*

- Prof. **Juan Alejandro Valdivia**
- PhD student **Francisco Castillo**

Pontificia Universidad Católica de Valparaíso, *Dept. of Physics*

- PhD student **Javier Arenas**

Opportunities to join – *ASK ME!*

- **National postdoc grants:** 1 application/yr (coming up soon!)
- **PhD program (fellowships, international exchange programs):** 2 appl./yr
- **For observers:** Chilean 10% of time on all telescopes

International collaborators

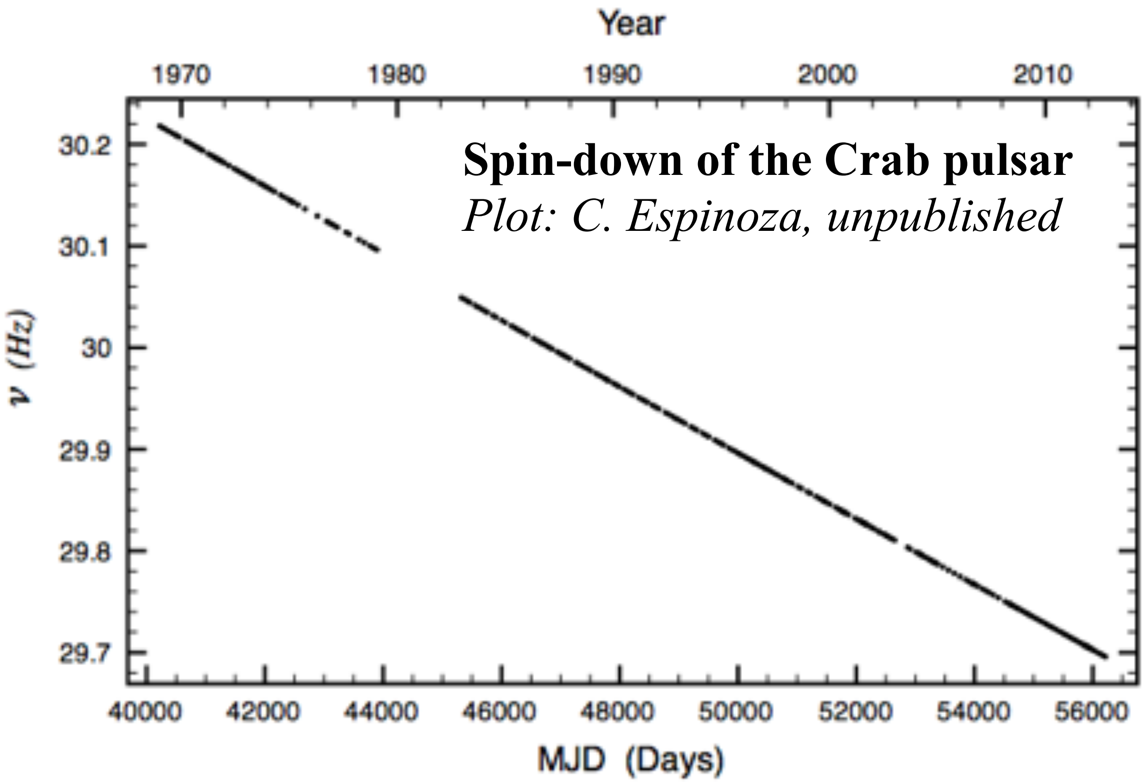
- **Bonn:** Norbert Langer, Jon Braithwaite, Pablo Marchant, Nicolás González
- **Garching (MPA):** Henk Spruit
- **Medellín:** Jaime Hoyos
- **Barcelona:** Taner Akgün
- **Montreal (McGill):** Kostas Gourgouliatos, Andrew Cumming
- **West Lafayette (Purdue):** Maxim Lyutikov
- **Melbourne:** Alpha Mastrano, Andrew Melatos

Outline

- Motivation: Measurement (?) of *B,* evidence for decay
- Structure and composition of NSs, stable stratification
- “Initial conditions”: ideal MHD equilibria with axial symmetry: poloidal & toroidal components
- Beyond ideal MHD: secular evolution processes in NS crust & core: Ohm, Hall, beta decays, ambipolar diffusion
- Conclusions & discussion

Spin-down

(magnetic dipole model)



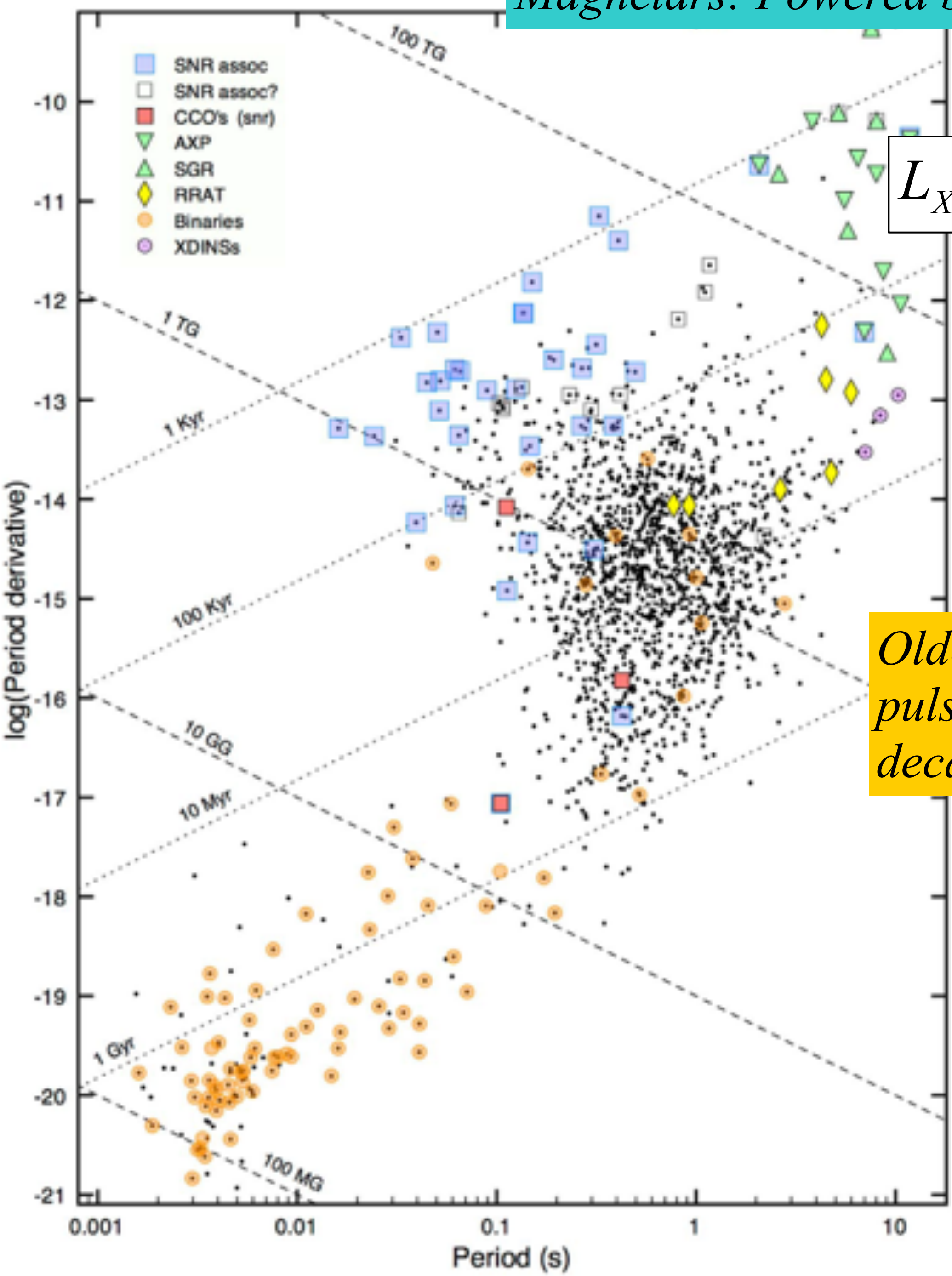
$$-I\Omega\dot{\Omega} = \frac{2}{3c^3}\left|\frac{d^2\vec{\mu}}{dt^2}\right|^2 \propto B^2\Omega^4 \quad \Rightarrow$$

$$B \propto \sqrt{\frac{|\dot{\Omega}|}{\Omega^3}} \propto \sqrt{P\dot{P}} \qquad \tau = \frac{\Omega}{2|\dot{\Omega}|} = \frac{P}{2\dot{P}}$$

Evidence for *B* decay

Magnetars: Powered by B decay?

$L_{X,\gamma} >> | I\Omega\dot{\Omega} |$



Older classical pulsars: Field decay?

Millisecond pulsars (& LMXBs): Very weak field @ old age Spontaneous or effect of accretion?

Plot: C. Espinoza, unpublished

Caveat: Braking index

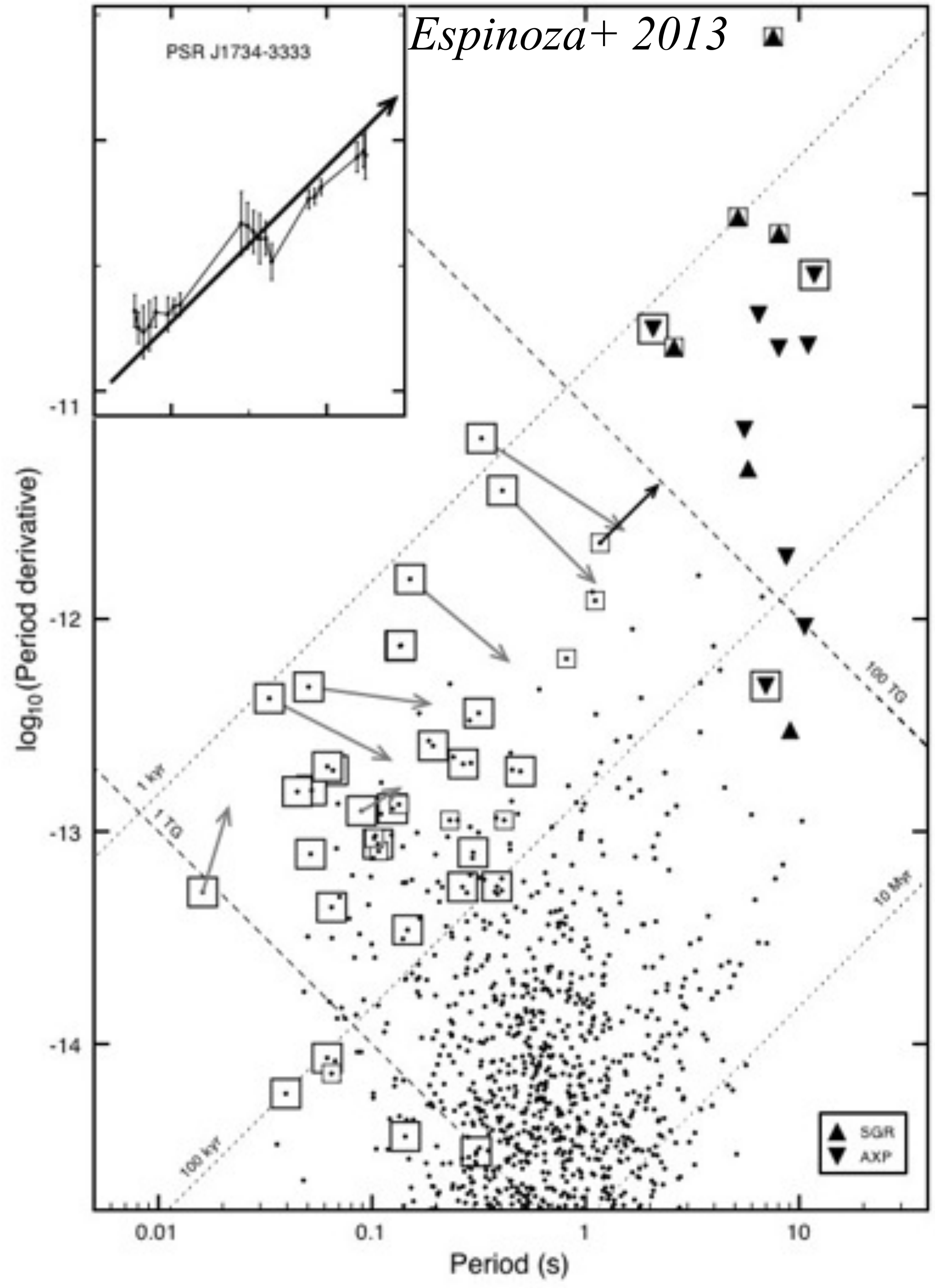
Dipole braking ***model***:

$$\dot{\Omega} = -K\Omega^3 \quad \Rightarrow \quad \ddot{\Omega} = -3K\Omega^2\dot{\Omega}$$

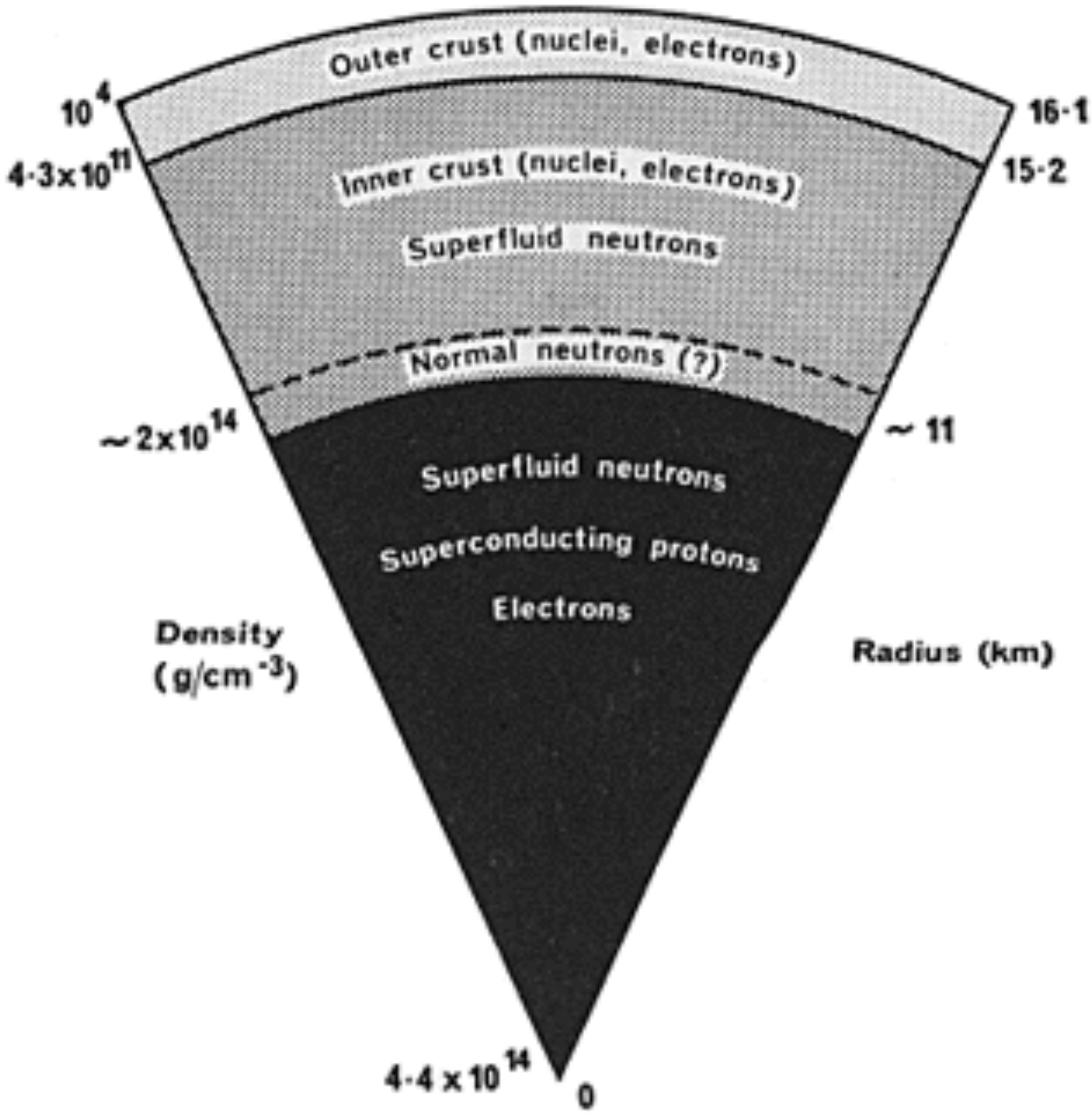
$$\therefore \quad n \equiv \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2} = 3 \quad \text{if } K = \text{constant}$$

***Measured*: *n* < 3**
(young radio pulsars):

- Dipole spin-down is wrong, *or*
- dipole moment **increasing**



Internal structure of a neutron star

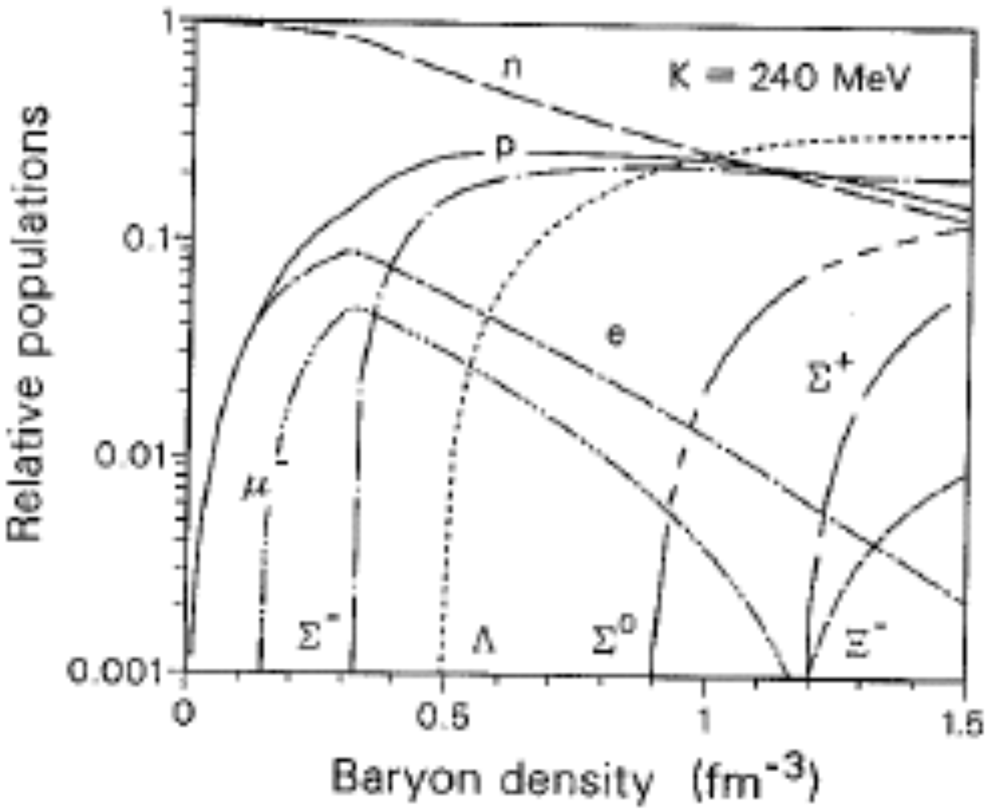


Solid crust

Exotic liquid core

http://heasarc.gsfc.nasa.gov/docs/objects/binaries/neutron_star_structure.html

Stable stratification in NS core



Equilibrium particle populations in very dense matter
Glendenning, *Compact Stars*, p. 239

Non-barotropic: $\rho(P, Y_j)$

→ **stably stratified**

(like water with salinity gradient):

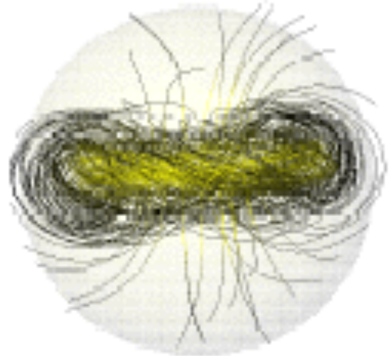
- Resists convection

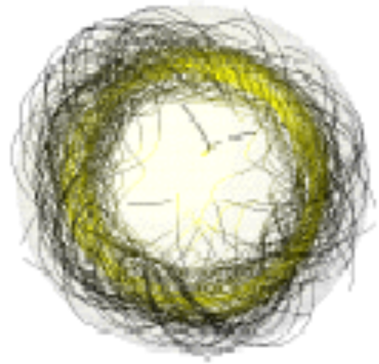
(Schwarzschild-Ledoux criterion)

- Radial fluid motions require strong forces
- Compositions adjust by beta decays & diffusion: long time scales

Reisenegger & Goldreich 1992;
Goldreich & Reisenegger 1992

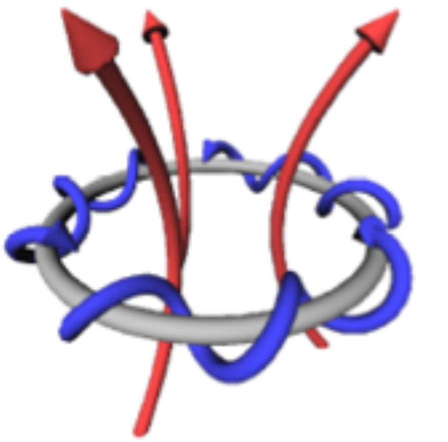
"Initial" conditions: Ideal MHD equilibria





- Gravitational collapse + +: "quick & dirty" setup
- **Ideal MHD: single fluid**, perfect conductor, interacts with *B* (fluid advects flux & reacts to Lorentz force)
- Could yield axisymmetric **stable equilibria** with
  - Linked **poloidal & toroidal** *B* ("twisted torus") **threading the whole star** (Braithwaite & Spruit '04, '06; Braithwaite & Nordlund '06)
  - **Stably stratified** fluid (Reisenegger '09; Mitchell+ in prep.)
- Tentative stability condition (Braithwaite '09; Marchant+ '11; Akgün+ '13)

$$0.25 < \frac{E_{tor}}{E_{pol}} < 0.5\left[\left(\frac{\Gamma}{\gamma}-1\right)\frac{|E_{grav}|}{E_{pol}}\right]^{1/2} \sim \frac{10^{17}G}{B_{pol}}$$



→ Possibly strong, hidden toroidal *B*

  → Energy reservoir for (low-*B*) magnetars (Rea+ '10, '12, '13)

  → Non-uniform surface temperature on CCOs

Non-ideal MHD:
B evolution mechanisms

Solid NS crust:

•**Resistivity**: currents damped: very slow for large-scale *B* (Baym et al. '69)

•**Hall drift:** Electron motion (current) carries *B*

•**Crust breaking:** If strong, unbalanced Lorentz forces (no MHD equilibrium)

Liquid core: all particles move → **include also:**

•**Ambipolar** diffusion: All charged particles drift w.r.t. neutrons, carrying *B*

•**Beta decays** change composition: $n \leftrightarrow p + e$

Goldreich & Reisenegger (1992); Hoyos, Reisenegger, & Valdivia 2008, 2010

Basis for Thompson & Duncan (1995, 1996) model of energy release in magnetars.

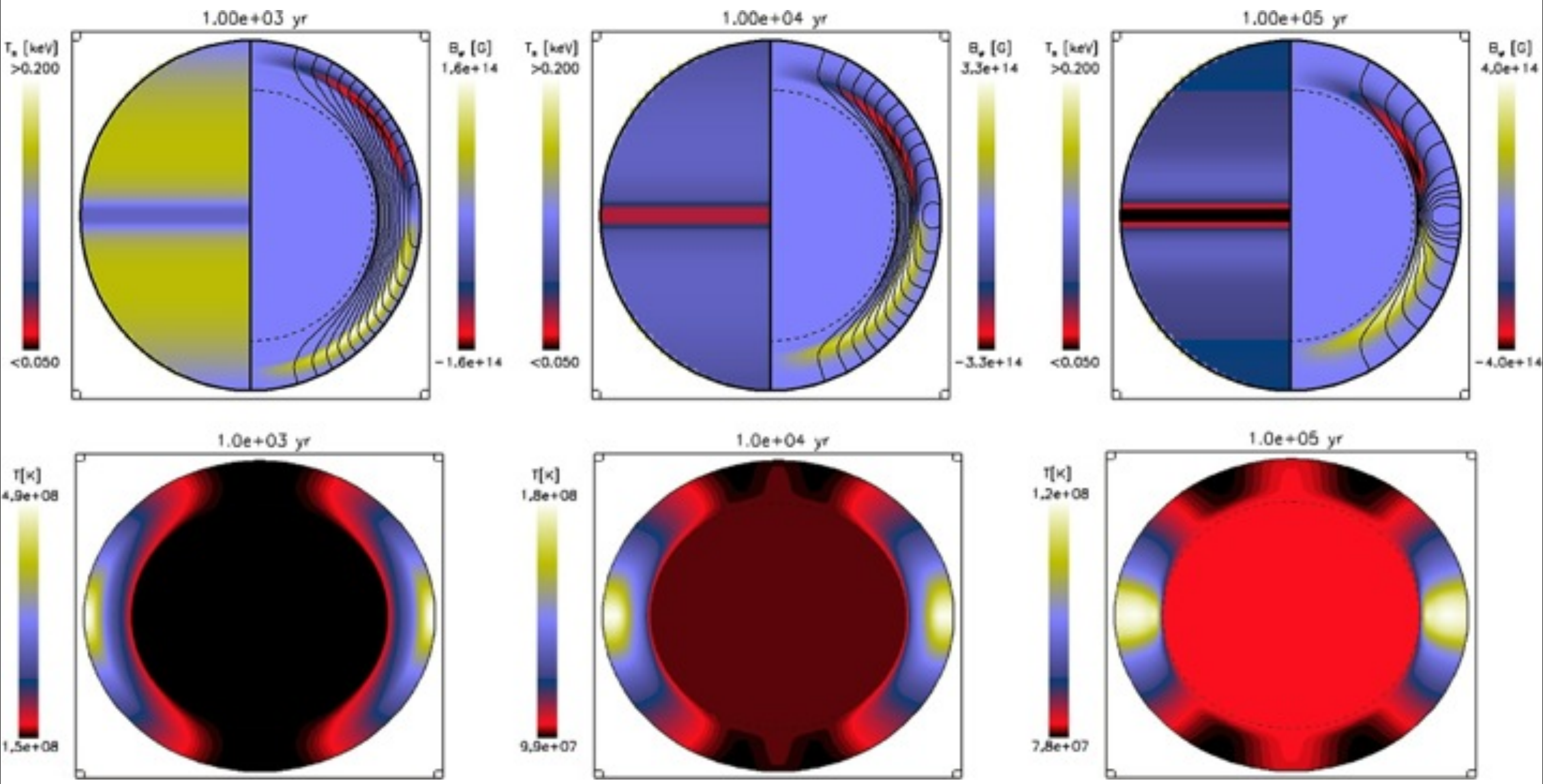
Plausible evolution of NSs (& their *B*!)

1. Violent birth: gravitational collapse, convection, differential rotation, possible dynamo
2. Done after < 1 hr:
   - *B* settles to a **stable equilibrium**
   - Magnetic energy << initial thermal energy << gravitational energy
3. Fast neutrino cooling: crust freezing, superfluidity, superconductivity
4. Secular *B* evolution:
   - Initially much slower than cooling
     - thermal energy becomes << magnetic energy
   - Eventually cooling balanced by magnetic dissipation (Pons & Geppert 07)
     - *B* evolution proceeds at roughly constant *T*

Simulations of *B* evolution

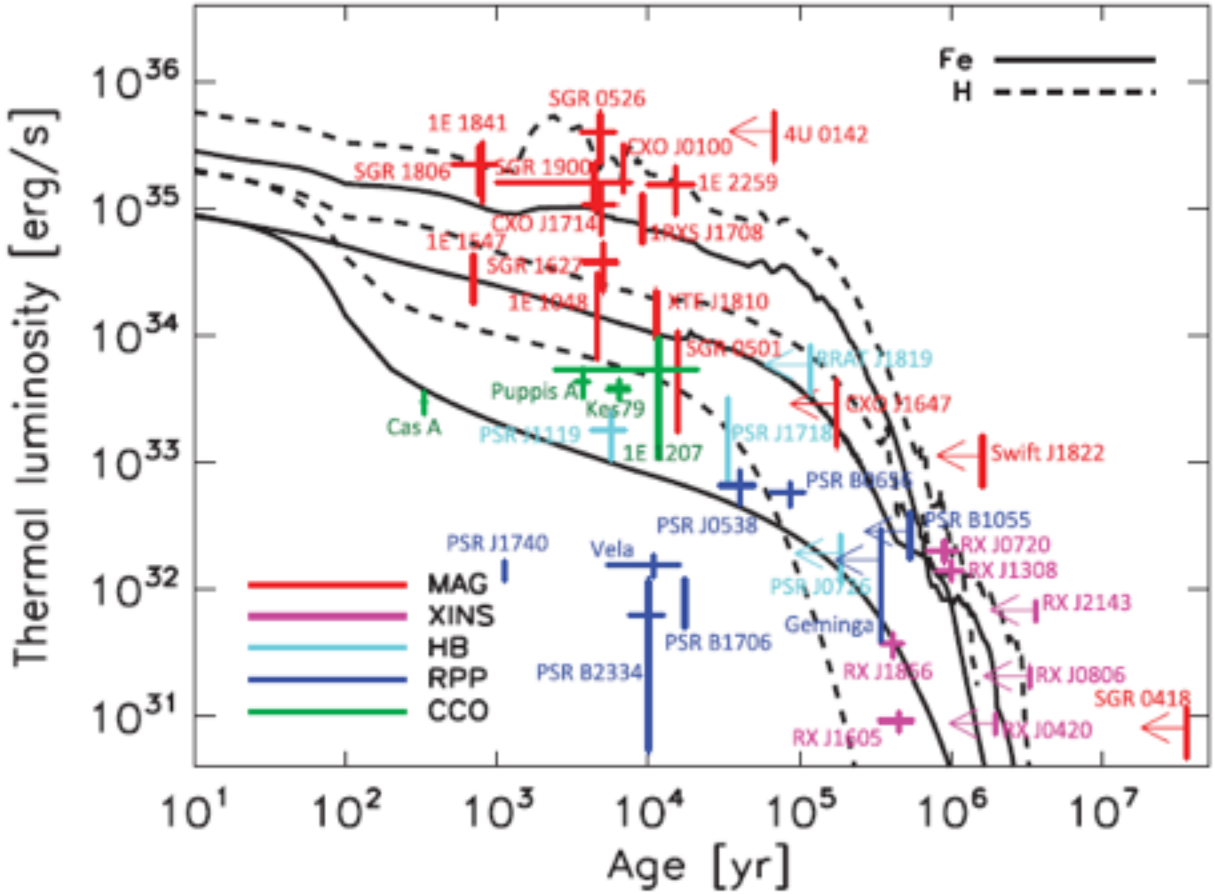
- Many efforts; progressively improving
- “State of the art”: **Viganò, Rea, Pons, et al. ‘13**
- Includes several interesting effects
  - Coupled thermo-magnetic evolution
  - Realistic neutron star structure & cooling mechanisms
  - Anisotropic heat conductivity due to *B*
  - Hall drift & Ohmic dissipation; Joule heating
- To be improved
  - “Fiducial” models have no *B* in NS core
  - Model with *B* in core has no realistic *B* evolution
  - Oversimplified model for crust breaking

Inhomogeneous temperature



Viganò et al. 2013

Simulation results



Viganò et al. 2013

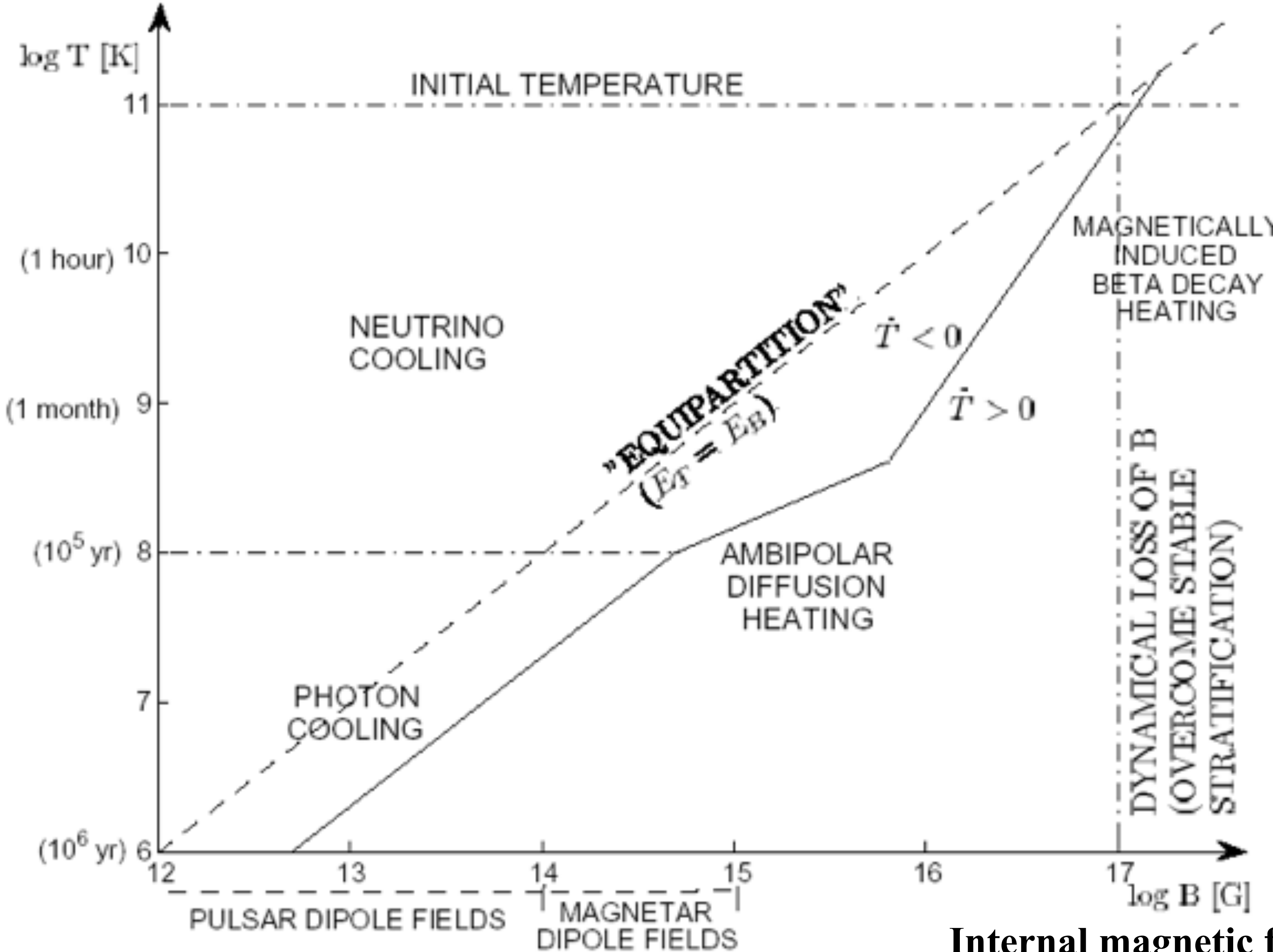
- High *T* for highly magnetized NSs, roughly as observed
- Non-uniform surface *T* → X-ray pulses
- Hall drift couples poloidal & toroidal components & accelerates decay

Gourgouliatos+ '13; Gourgouliatos & Cumming '13; Marchant+, in prep.:

- Stable Hall equilibria, “attractors” (at least in 2D)

B vs. *T* in NS core

Internal temperature



Internal magnetic field

Reisenegger 2009 - *Figure prepared by C. Petrovich*

Core *B* evolution

Two ways to **overcome stable stratification** → barotropic fluid

- **Direct & inverse beta decays**: $n \leftrightarrow p + e$
- **Ambipolar diffusion**: neutrons (most of mass) & charged particles (frozen to *B*) decouple → 2 fluids

(Goldreich & Reisenegger 1992; 1-D simulations: Hoyos+ 2008, 2010)

→ **Evolution on magnetar timescales** (Thompson & Duncan 1996)

→ **Plausible destabilization of MHD equilibria**

(Mitchell, Braithwaite, Reisenegger, et al., in preparation)

Conclusions & discussion

- Initial, ideal-MHD equilibrium fields probably depend on:
  - Linked poloidal & toroidal components
  - Stable stratification
  - → Allows for a strong, hidden toroidal component
- Secular evolution through non-ideal MHD processes:
  - Coupled thermo-magnetic evolution → non-uniform heating
  - Erosion of stable stratification in core → destabilization of equilibria?
  - Crust breaking if strong, unbalanced Lorentz forces appear
- Still no full simulations or understanding
- Might be further complicated by effects of superfluidity or superconductivity