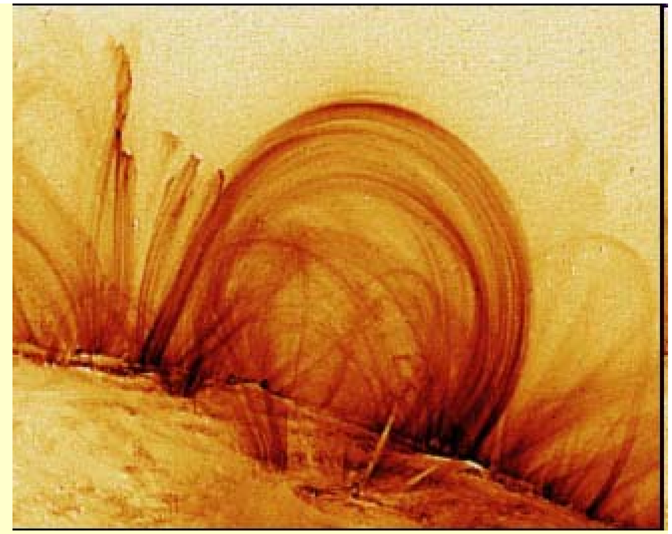
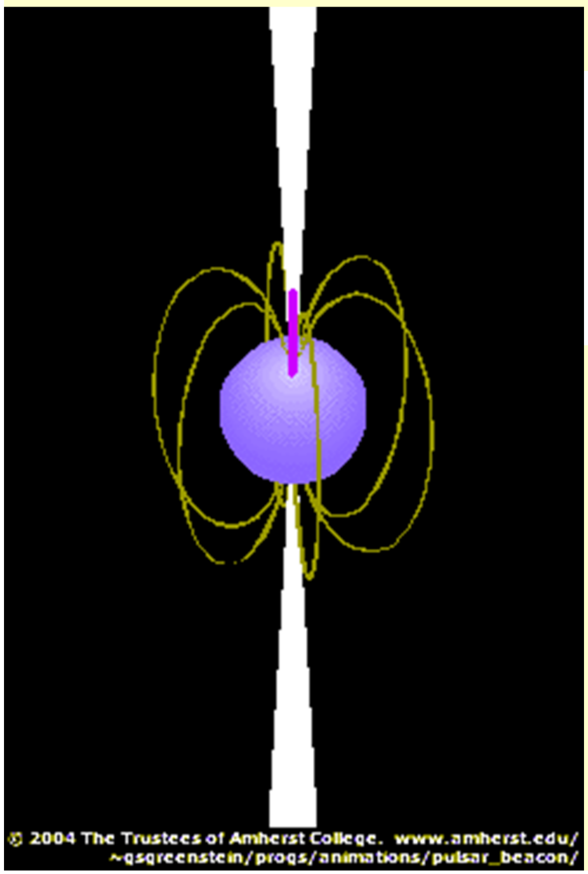
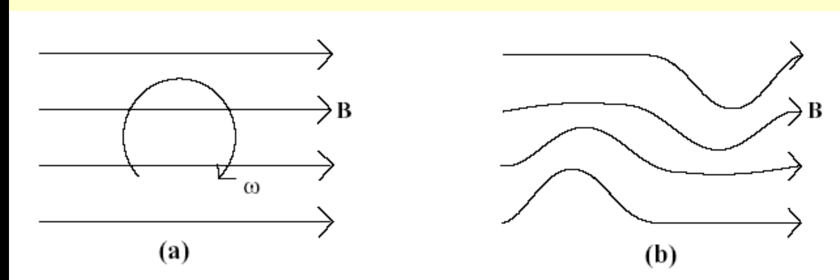
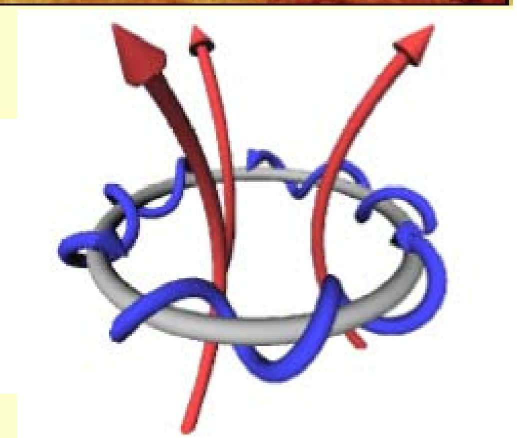
Magnetic fields of neutron stars









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Magnetic Fields in the Universe IV

Playa del Carmen, México, February 2013

Outline

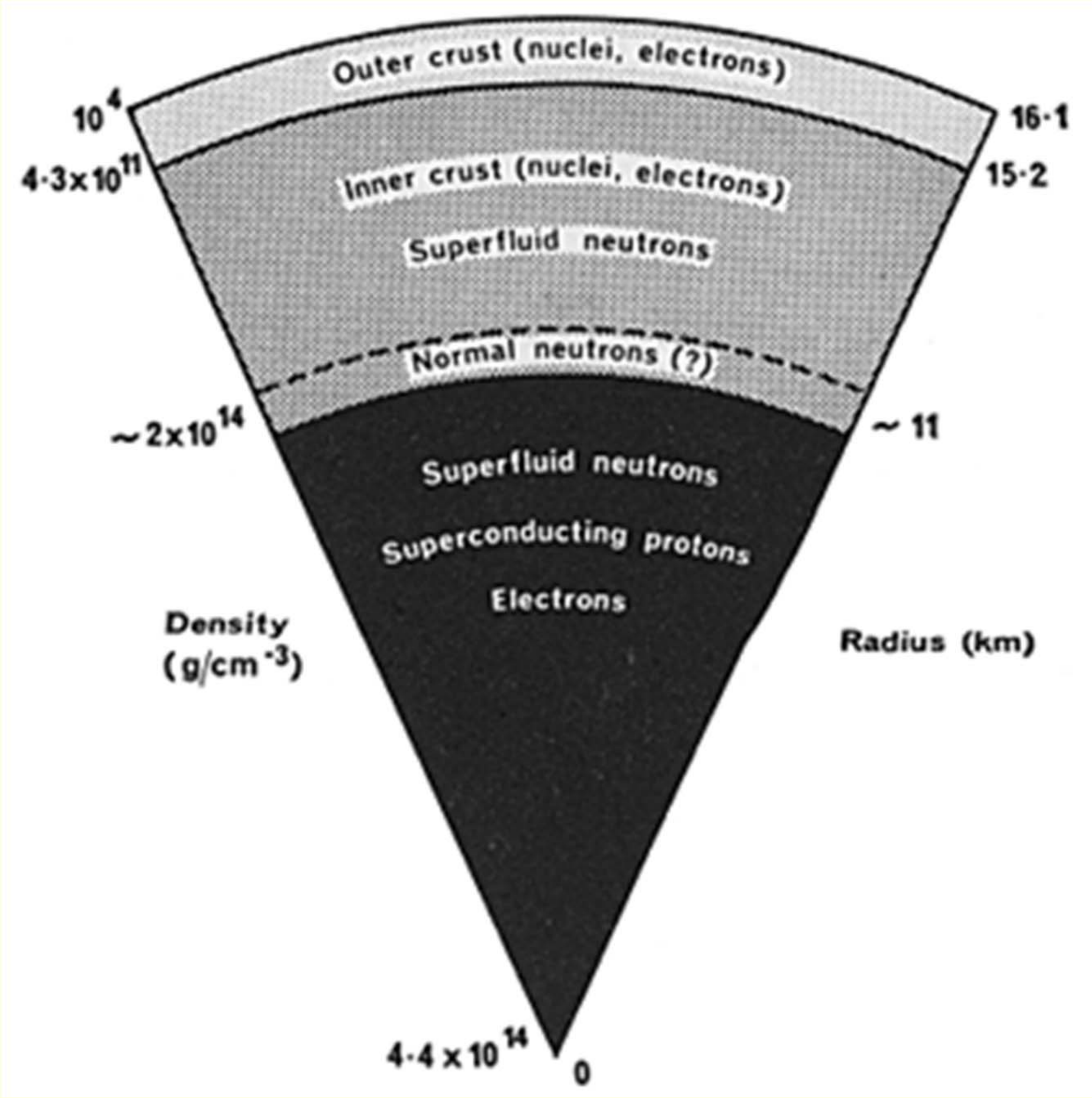
- Basic theory:
  - Internal structure and composition of neutron stars
  - Neutrons + charged particles, stable stratification
- Basic observations:
  - Spin-down and magnetic field measurement
  - Classes of neutron stars: pulsars, magnetars, etc.
- Field strength in context: very strong and very weak!
- MHD equilibria with axial symmetry
- Beyond ideal MHD: B evolution in neutron stars
- Our group & collaborators
- Conclusions

Internal structure of a neutron star (theoretical)

Very degenerate matter ($T \approx 0$)

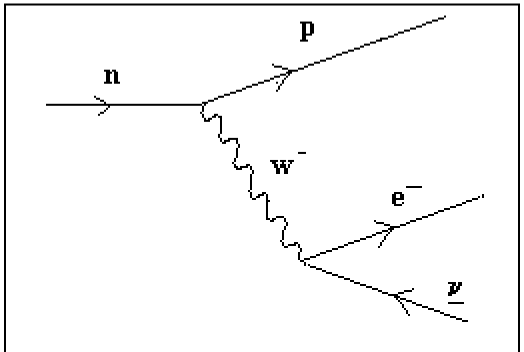
State of matter changes with increasing density:

1. "Ordinary" solid
2. Solid + neutrons
3. ***npe*** **liquid**
4. More exotic particles:
   - *muons* μ
   - *mesons* π, κ
   - *hyperons* Σ, Λ
   - Quark matter?



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

Why *neutron* stars?



Feynman Diagram for Beta Decay

- In vacuum (lab), neutrons decay with half-life ~ 15 min: $n \to p + e + \overline{\nu_e}$
- In dense matter, neutrons can decay only if proton and electron quantum states are available: Chemical potentials (Fermi energies) must satisfy

$$\mu_n > \mu_p + \mu_e$$

- In the opposite case, energetic protons & electrons combine:

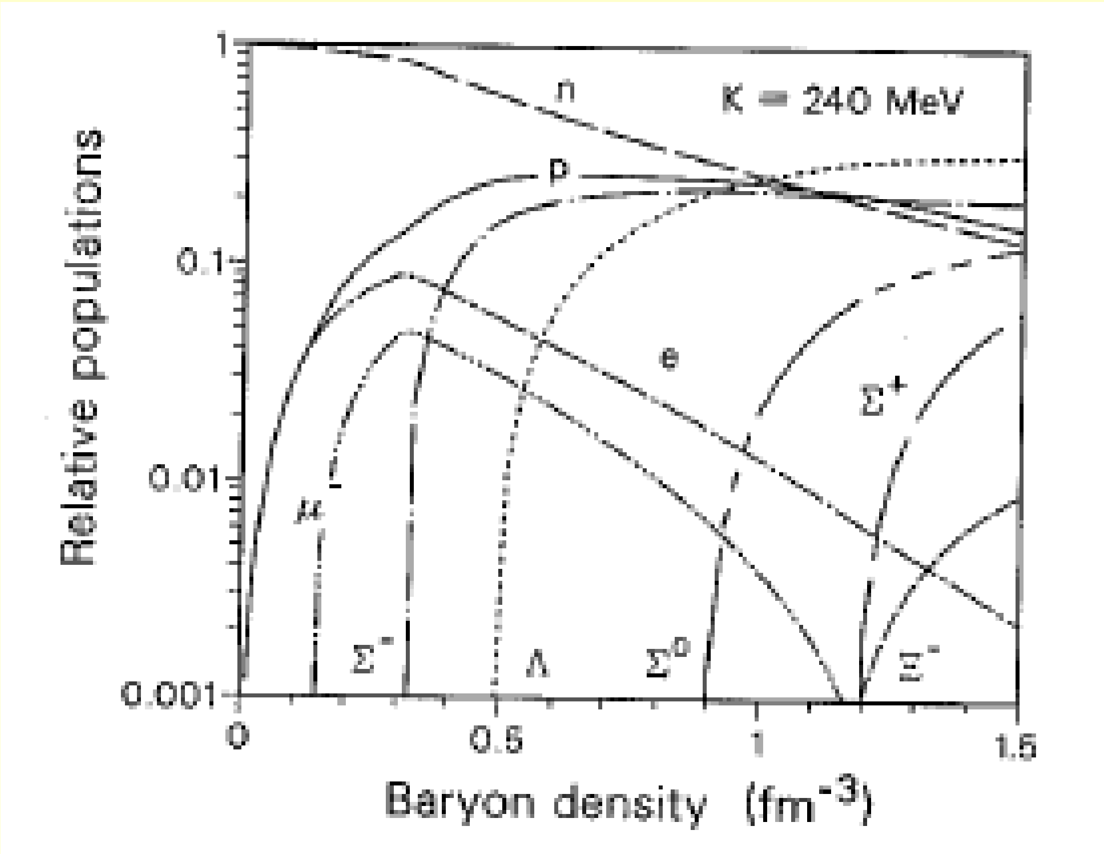
$$\mu_p + \mu_e > \mu_n \qquad \Rightarrow \quad p + e \to n + \nu_e$$

- "Chemical" (weak interaction) equilibrium: $\mu_n = \mu_p + \mu_e$

➔ **Around nuclear density, neutrons must coexist with some (few %) protons & electrons:**

- Charged & degenerate: **currents flow** with very little resistance
  → *B* "frozen in" for a long time (Baym et al. 1969)
- Fraction density-dependent: **stably stratified fluid**

Stable stratification in NS cores



(nuclear density ~ 0.15 fm^{-3})

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

Matter is stably stratified

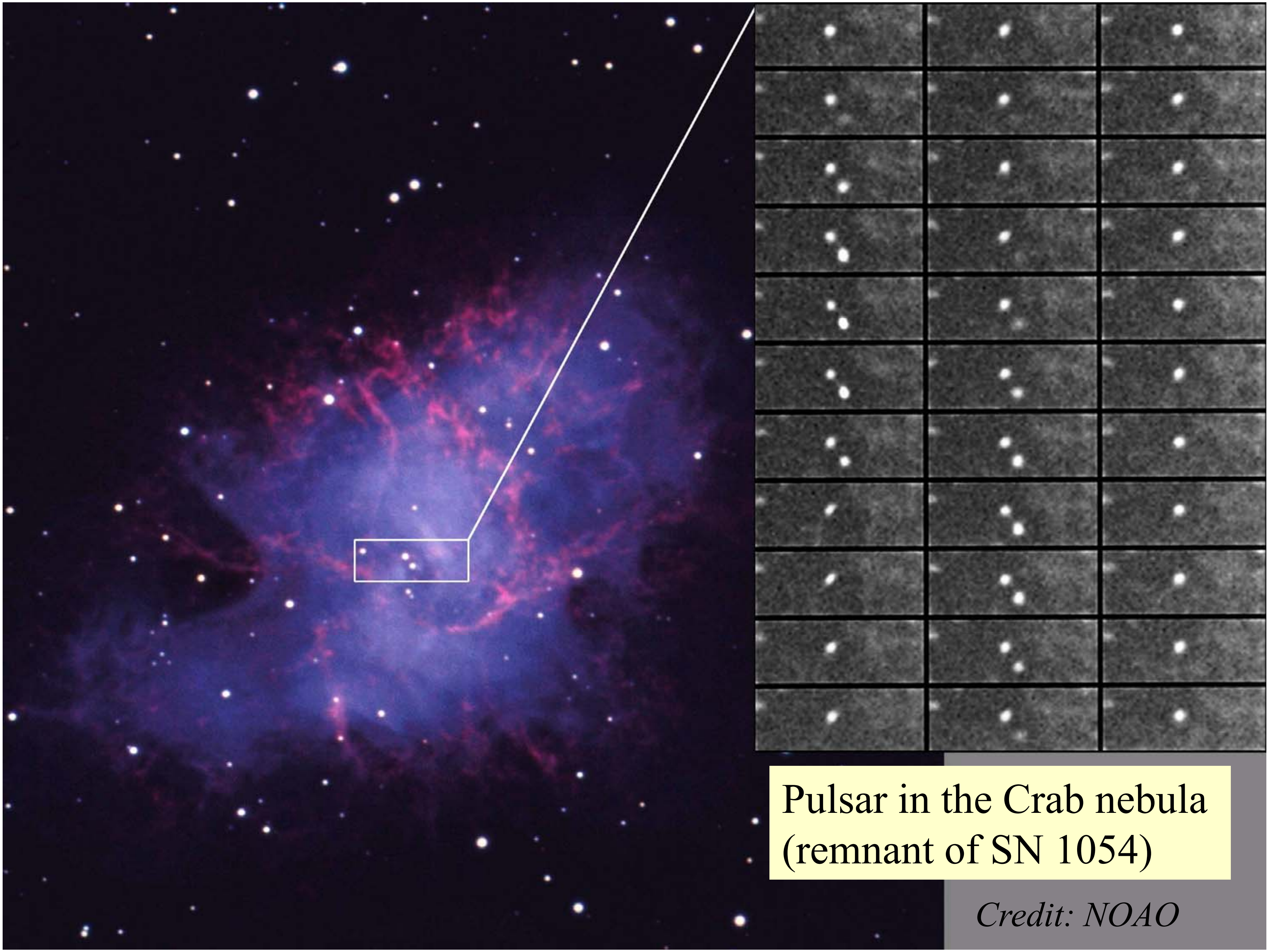
(like water with salinity gradient):

•Resists convection

(Schwarzschild-Ledoux criterion)

•Radial fluid motions require strong forces

(Reisenegger & Goldreich 1992)

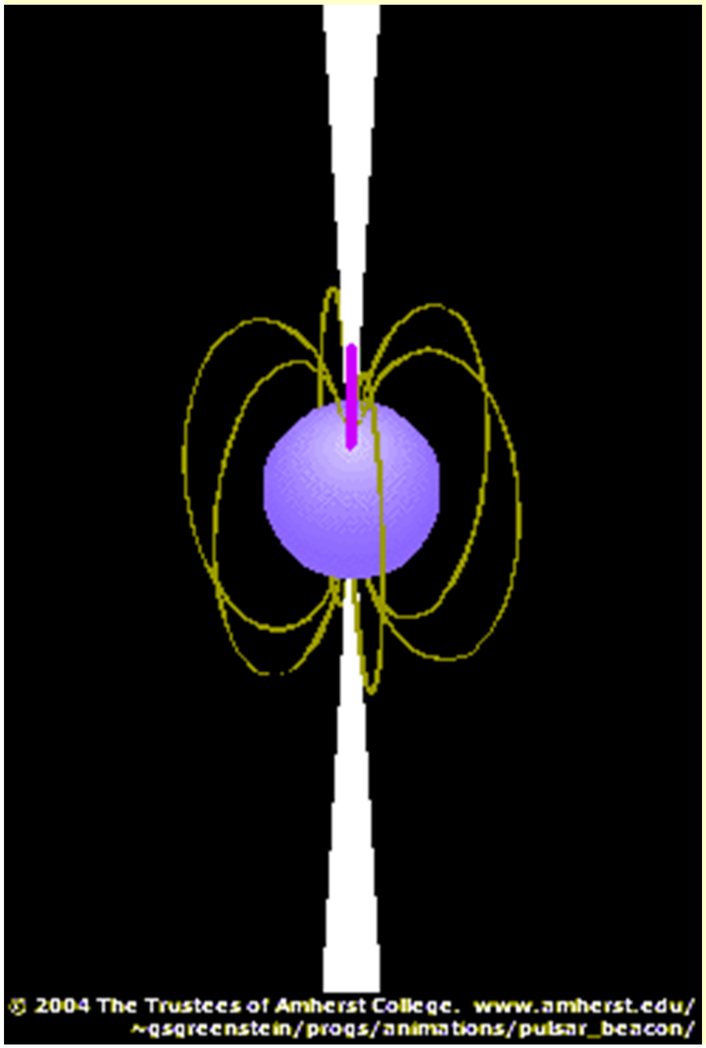

Pulsar in the Crab nebula
(remnant of SN 1054)
Credit: NOAO

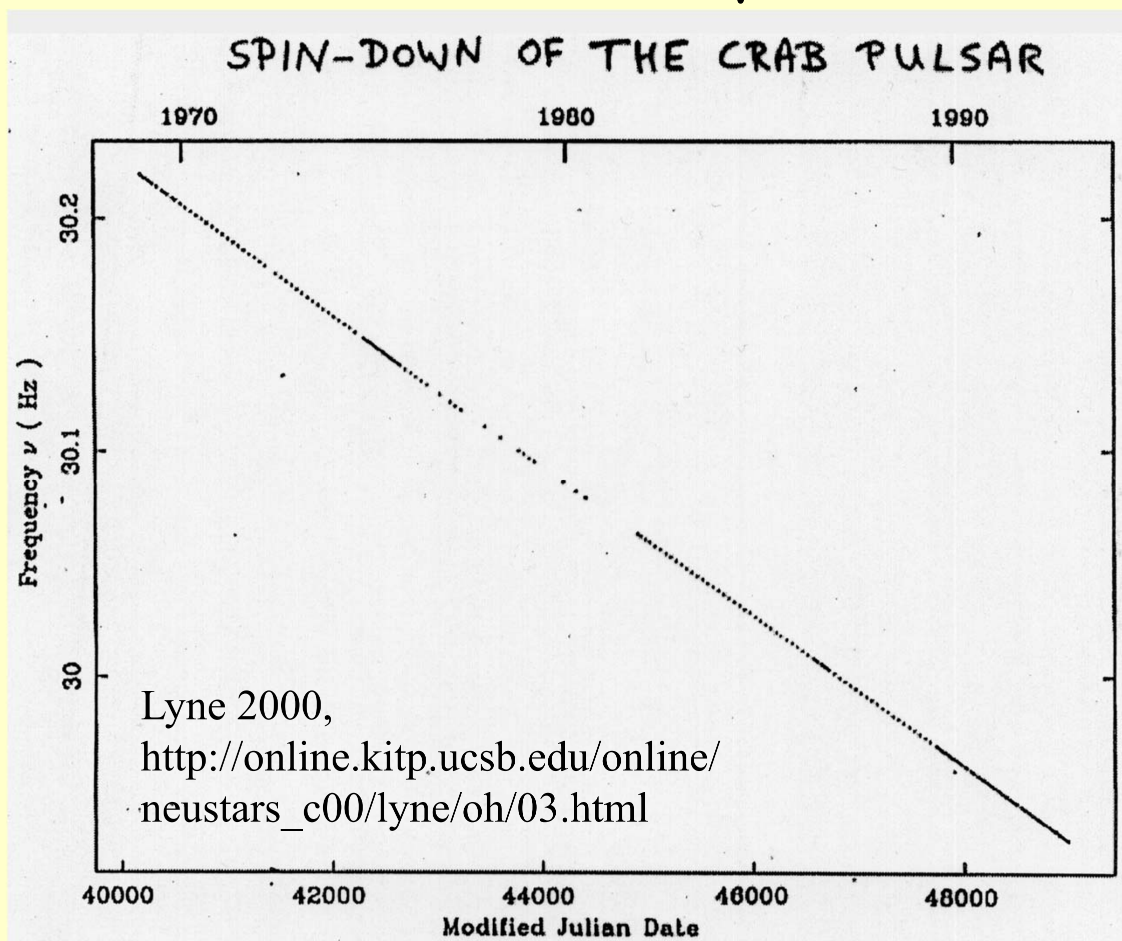
Spin-down

(magnetic dipole model)

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

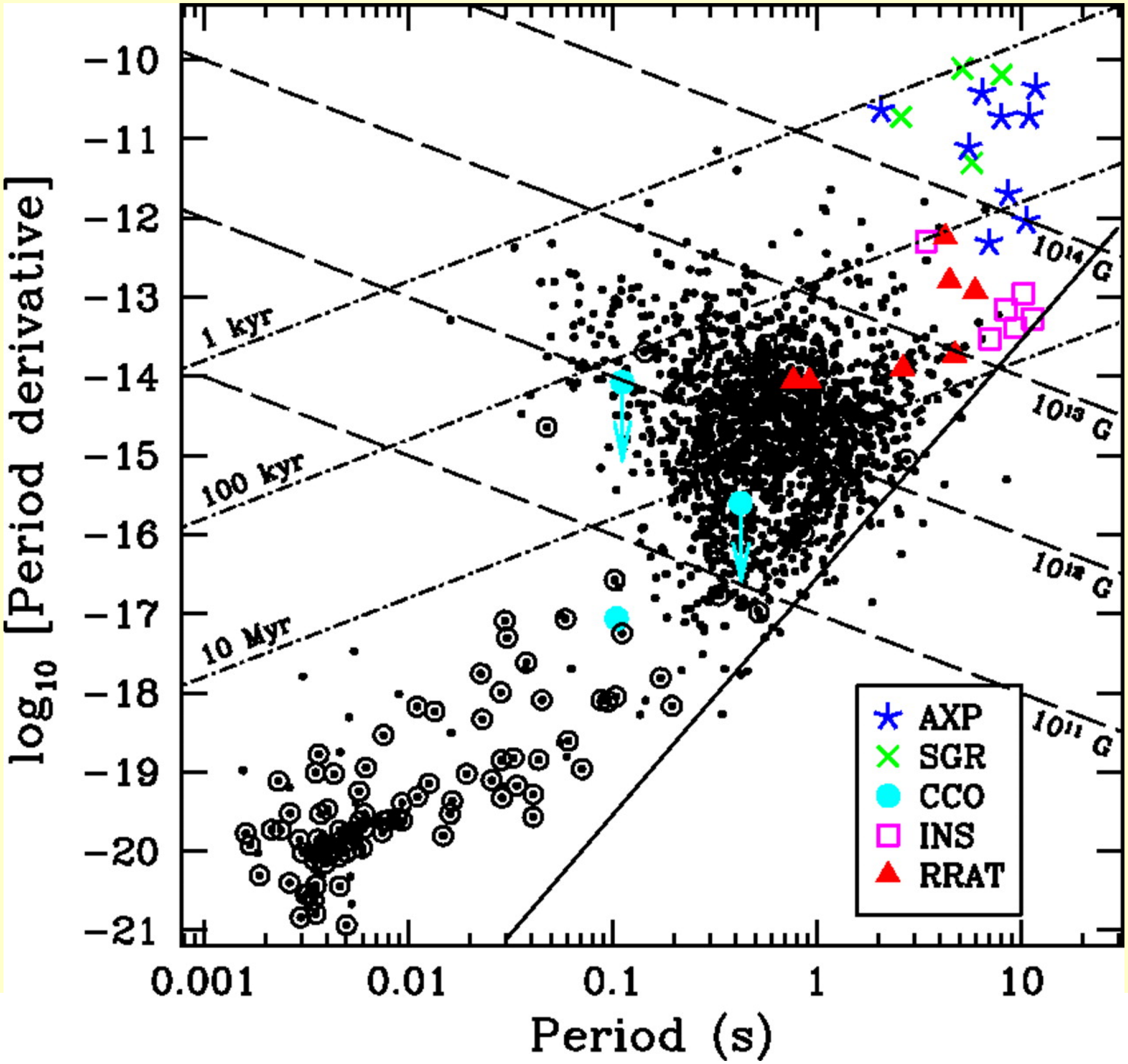
Magnetic dipole field: $B \propto \sqrt{\frac{|\dot{\Omega}|}{\Omega^3}} \propto \sqrt{P\dot{P}}$





Lyne 2000, http://online.kitp.ucsb.edu/online/neustars_c00/lyne/oh/03.html

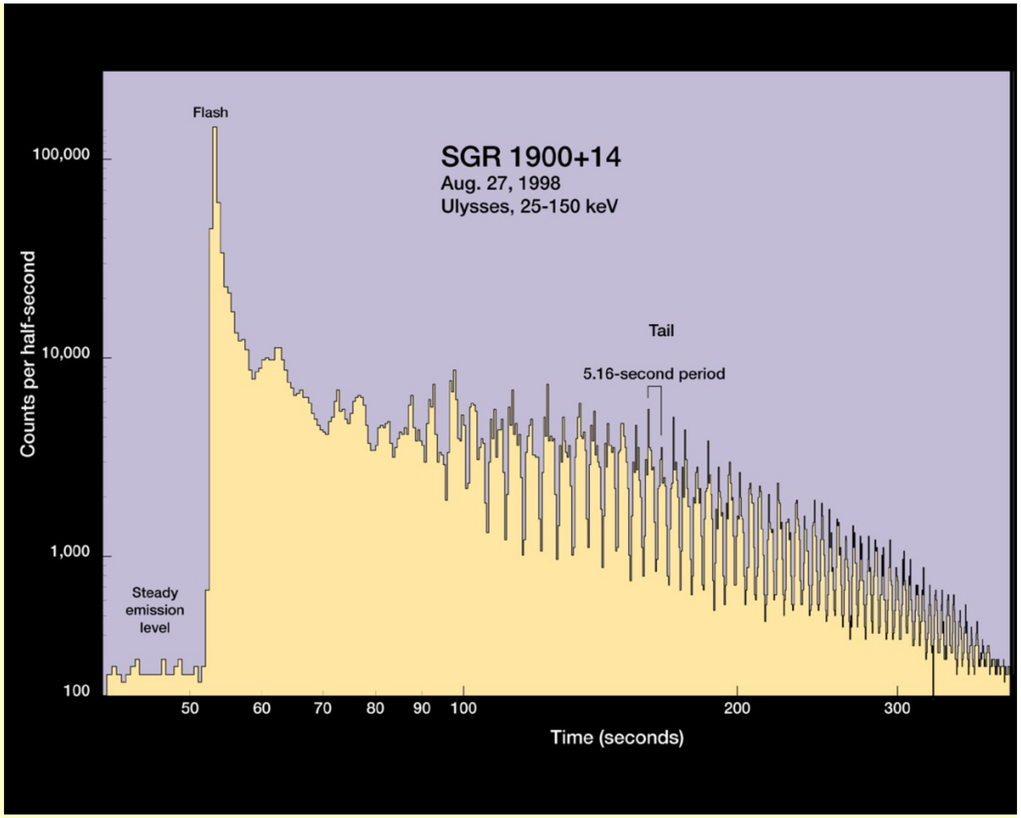
Spin parameters & classes of non-accreting NSs



Kaspi V M PNAS 2010;107:7147-7152

PNAS

Credit: Kevin Hurley, U. California Berkeley & NASA/Marshall.



Magnetars

- 2 groups of objects:
  - Soft gamma repeaters (SGR)
  - Anomalous X-ray pulsars (AXP)
- X/gamma radiation >> rotational energy loss
  - → *B* decay as plausible energy source (Thompson & Duncan 1996)
  - → Confirmed by strong dipole $B \sim 10^{14\text{-}15}$ G (Kouvelotou et al. 1998)
  - → Even so, need additional, hidden field component to account for total energy
- Quasi-periodic luminosity oscillations may be probing the structure of B inside (Israel et al. 2005)

Magnetic field strengths

mostly from R. Duncan, *http://solomon.as.utexas.edu/magnetar.html*

Source	B [G]
Earth	0.6
Refrigerator magnets	100
Strong sunspots	4000
Strongest steady field in lab	4×10^5
Strongest human-made field (explosive)	10^7
Strongest non-neutron star field (white dwarf)	10^9
Young radio pulsars	$10^{12\text{-}13}$
Quantum critical field $B_Q = m_e{}^2 c^3/e\hbar$	4×10^{13}
Magnetars (external dipole)	$10^{14\text{-}15}$

Magnetic field origin?

- **Fossil**: flux conservation during core collapse:
  - Woltjer (1964) predicted NSs with B up to $\sim 10^{15}$G.
- **Dynamo** in convective, rapidly (differentially) rotating proto-neutron star (~ minutes)
  - Scaling from solar dynamo led to prediction of "magnetars" with $B \sim 10^{16}$G (Thompson & Duncan 1993).
- **Both?:** Some memory of initial conditions, but strongly modified by differential rotation, etc.?

Stars with long-lived, ordered *B*-fields

	Radius R [km]	$\mathbf{B_{max}}$ [G]	**Maximum flux:** $\Phi_{max}=\pi R^2 B_{max}$ [G km^2]
Upper main sequence	$10^{6.5}$	$10^{4.5}$	10^{18}
White dwarfs	10^4	10^9	$10^{17.5}$
Neutron stars	10	10^{15}	$10^{17.5}$

- Similar fluxes: connected by **flux freezing**?
- Complex evolution expected: differential rotation, winding of *B*, angular momentum transfer, instabilities, dynamo…
- All are mostly **stably stratified** (entropy or composition gradient), not convective → **MHD equilibria**
- $\lambda^2 \sim G(M/\Phi)^2 \sim E_{grav}/E_{mag} > 10^6 \quad \Rightarrow$ **<u>Weak</u>** ***B***!!
  → small perturbations to stellar structure

Purely toroidal fields are unstable

Flux rings "repel" each other & tend to move apart, destroying the symmetry (Tayler 1973)

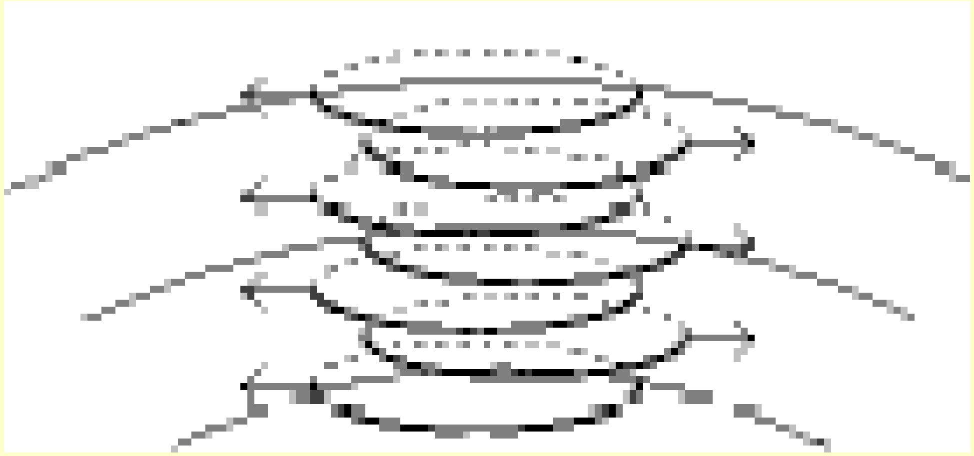


Figure from Spruit 1999

Purely poloidal fields are also unstable

Instability of poloidal fields

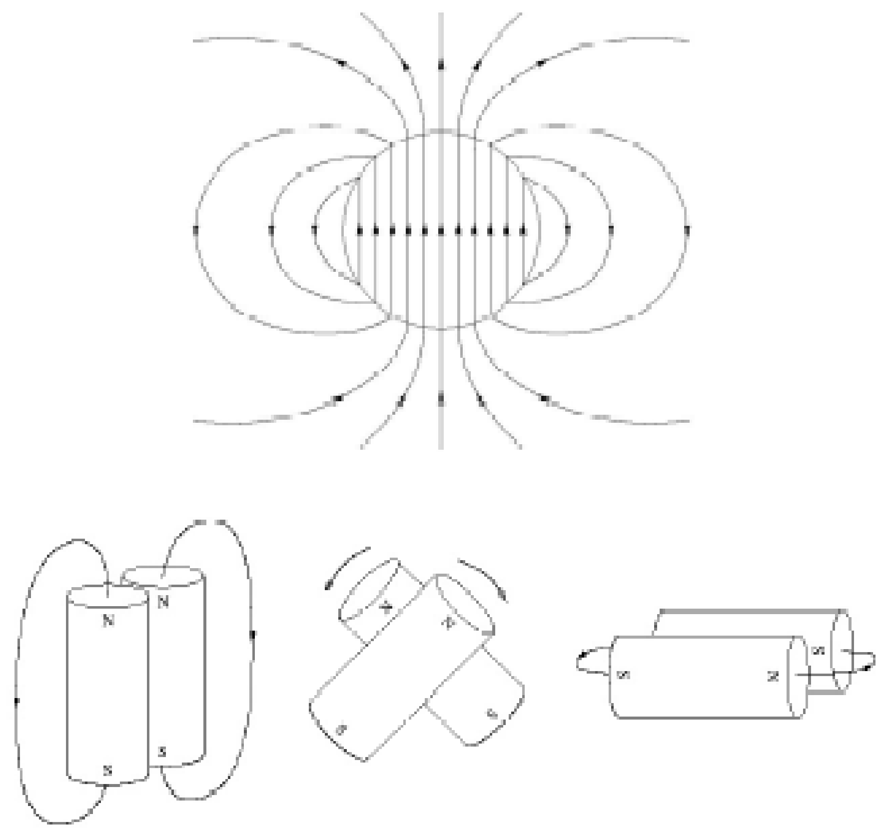


FIGURE 3. Instability of a poloidal field in a star. (From Flowers and Ruderman, 1977)

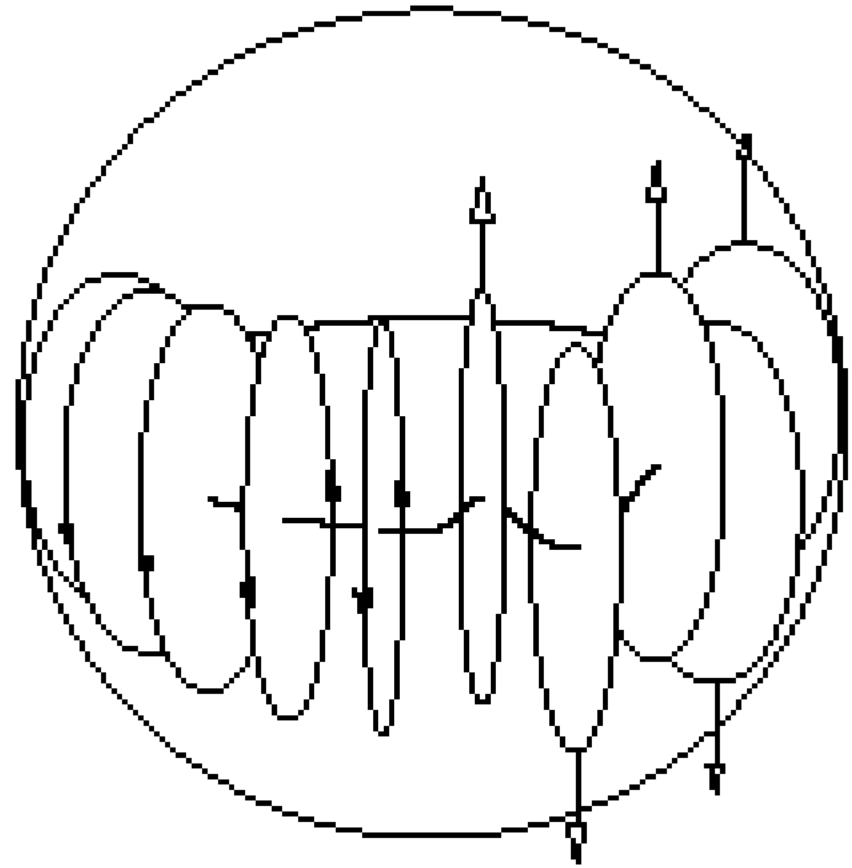


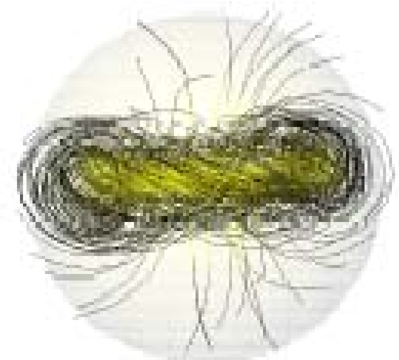
Figure 3. The form of the instability in a purely poloidal configuration. The left side shows the equilibrium and the right side the growth of a mode of particular azimuthal wavenumber.

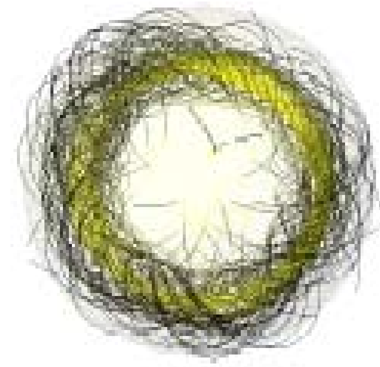
Braithwaite 2008

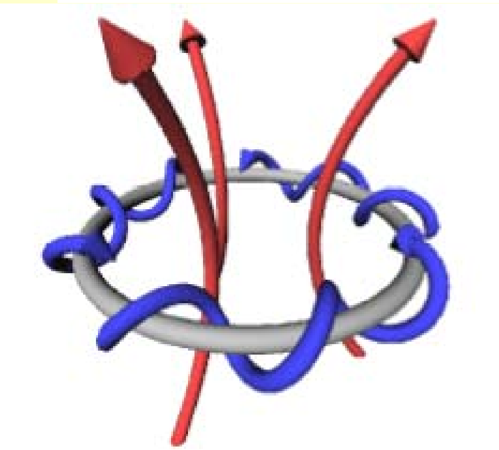
Stable MHD equilibria?

- **Need combination** of **poloidal+toroidal**
- Confirmed by MHD simulations
  - Braithwaite & Spruit 2004, 2006; Braithwaite 2009
- Our group: some analytical progress:
  - Marchant, Reisenegger, & Akgün 2011
    - Flowers-Ruderman instability of poloidal fields
  - Akgün, Reisenegger, Mastrano, & Marchant, arXiv:1302.0273
    - Tayler instability of toroidal fields
- **Toroidal component could contain substantially more energy than poloidal**

→ plausible energy reservoir for magnetars







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

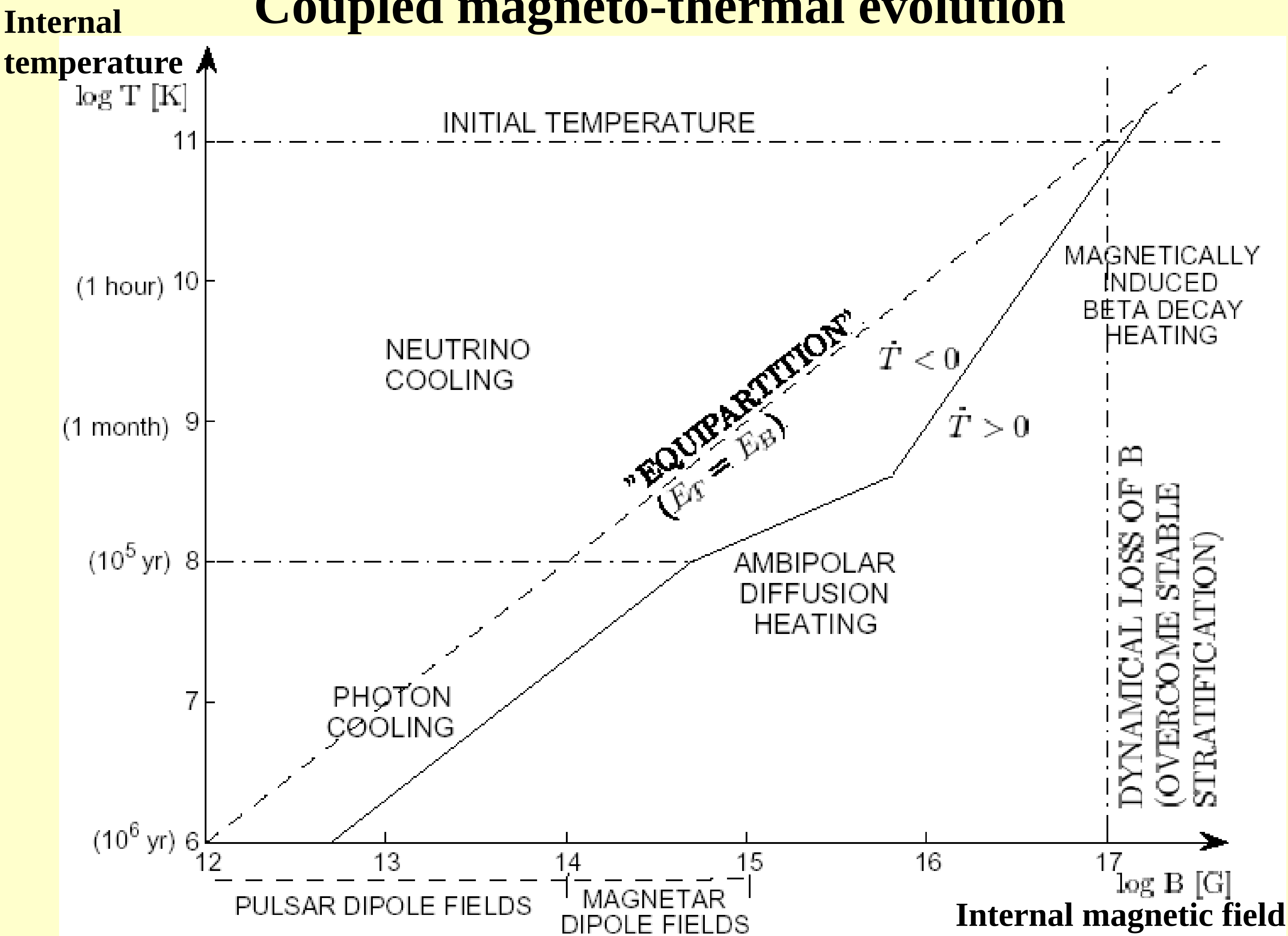
1. Violent birth: gravitational collapse, convection, differential rotation, possible dynamo

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*

Coupled magneto-thermal evolution



Reisenegger 2009 - *Figure prepared by C. Petrovich*

Evolution: beyond ideal MHD

Two ways to **overcome stable stratification:**

Direct & inverse beta decays: $n \leftrightarrow p+e$

Ambipolar diffusion: On long time scales (but ~ $1/B^2$), neutrons (most of mass) & charged particles (coupled to B) decouple & behave as 2 fluids (Goldreich & Reisenegger 1992).

1-D simulations: Hoyos et al. 2008, 2010; 2-D (axial symmetry) in prep.

→ **Plausible evolution on timescales required for magnetars** (Thompson & Duncan 1996)

Largely open issues (with substantial ongoing work by several groups):

- Effects of solid neutron star crust
- Effects of superconductivity & superfluidity

Our group

Pontificia Universidad Católica de Chile (PUC), Dept. Astronomy & Astrophysics

- **Andreas Reisenegger –** Prof.: NS theory, MHD
- **Joe Mitchell** – Chile-Germany postdoctoral fellow, PUC-Bonn: Simulations of *B* evolution in NSs – **see poster!**
- **Cristóbal Espinoza** – postdoctoral fellow: Pulsar timing observations
- **Claudia Aguilera** – PhD student: Breaking of NS crust
- **Cristóbal Armaza** – MS student: MHD equilibria in stars – **see poster!**
- **Ignacio Becker –** MS student: Thermal evolution of NSs
- **Antonio Henríquez, Luis Rodríguez** – undergraduate students

Universidad de Chile, Dept. of Physics

- **Juan Alejandro Valdivia –** Prof.: Space plasmas, non-linear physics, simulations
- **Francisco Castillo** – PhD student: Simulations of *B* evol. in NSs

Opportunities to join – *ASK ME!* areisene@astro.puc.cl - www.astro.puc.cl

- **Postdoc grants:** deadline ~ 1 April
- **PhD program (fellowships, international exchange programs):** appl. May & October
- **For observers:** 10% of time on ALMA, VLT, Magellan, Gemini-S, ACT …..

International collaborators

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

Conclusions

NS magnetic fields have:

- The largest strength observed anywhere in the Universe
- Tiny effects on NS structure
- Strong effects on NS appearance & evolution (pulsar braking, magnetars)
- Source currents due to moving *p, e,* or other charged particles
- Uncertain origin: fossil – dynamo – both ?
- Probably:
  - Stable equilibrium configurations with linked toroidal & poloidal components, thanks to stable stratification
  - Non-trivial evolution (ambipolar diffusion, weak interactions), providing energy source for magnetars
- **Many open questions, research to be done!**

Funding

- FONDECYT Regular Project 1110213: ***Thermal & magnetic evolution of neutron stars***
- CONICYT-DFG Collaboration Grant DFG-06 (Chile-Germany): ***Magnetic fields in massive stars & their compact remnants***
- PFB-06: ***Center for Astronomy and Associated Technologies*** (CATA)