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Magnetic fields in neutron stars
(review talk)

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in MIAPP program
«Stellar Magnetic Fields from Protostars to Supernovae»
and beyond...
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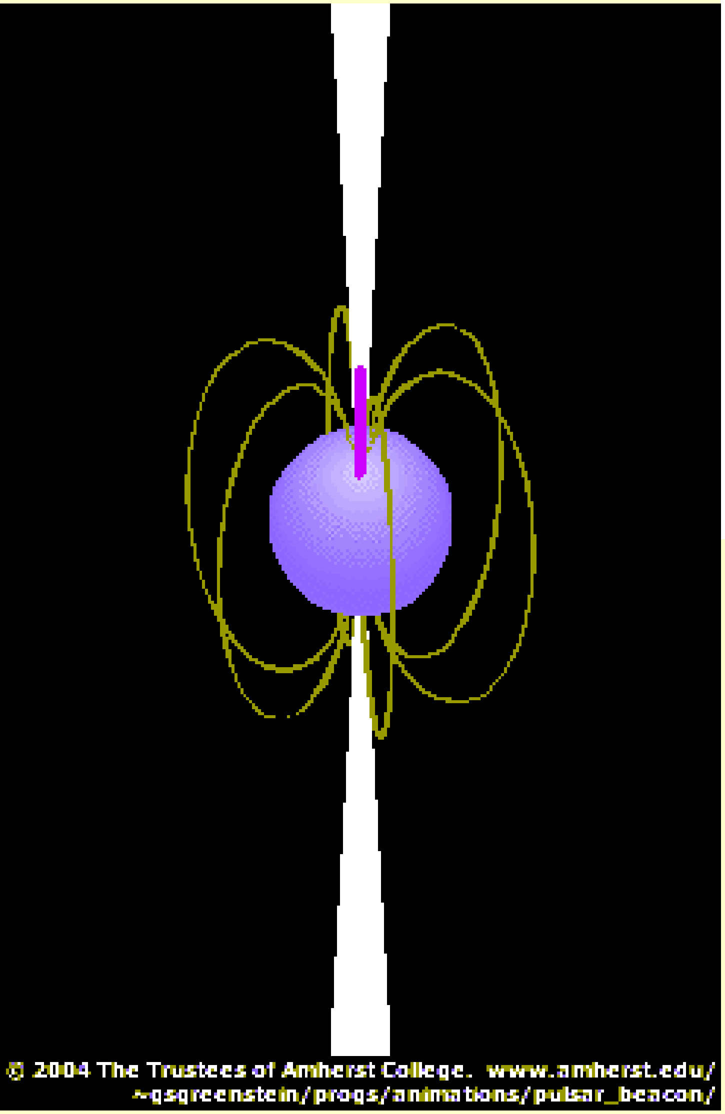
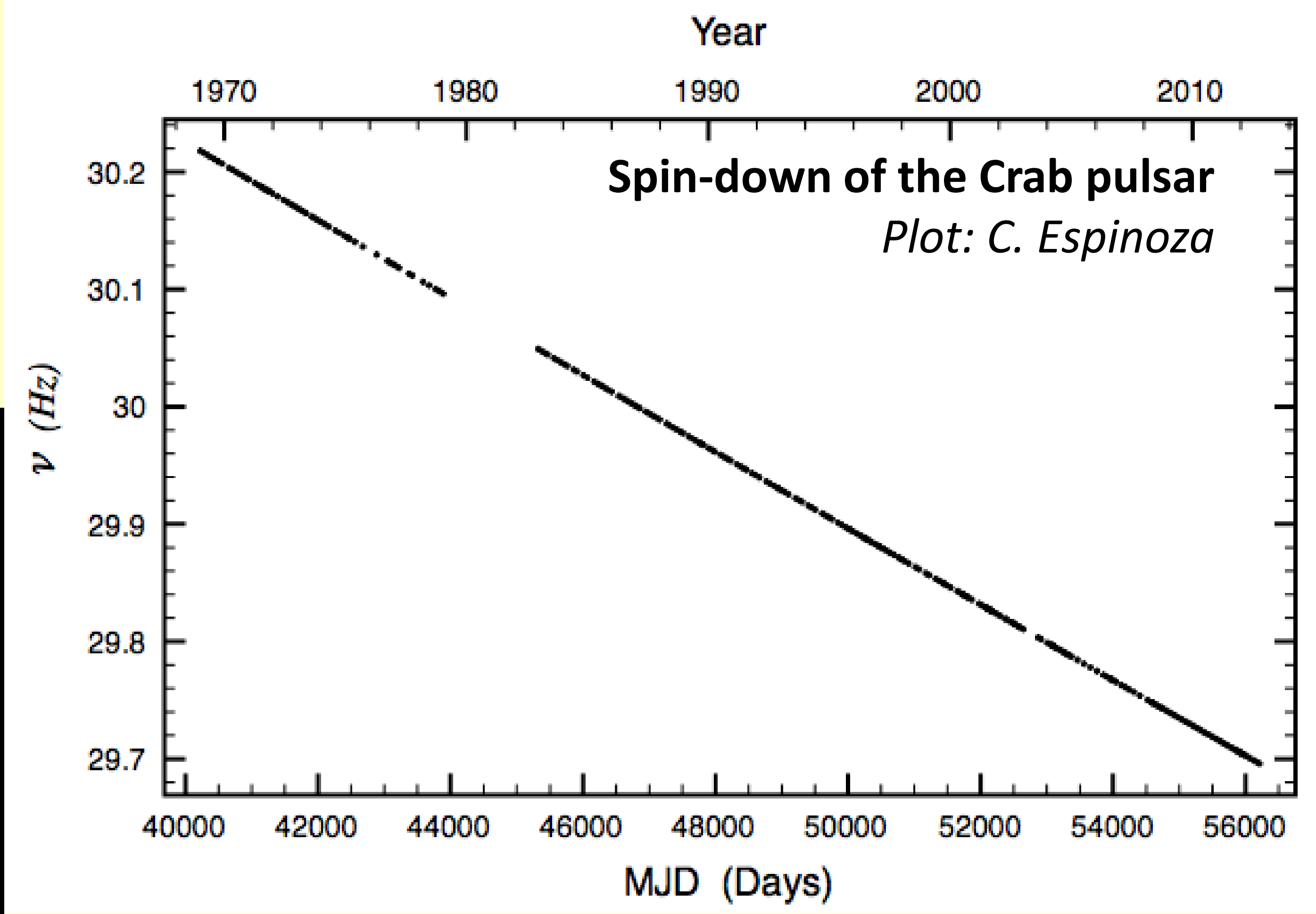
Outline

- What do we know from observations?
  - NS spin-down, *P*-*P*dot diagram, NS classes
  - Cyclotron lines
  - Field structure from pulse profiles
  - Fast radio bursts
  - Evidence for *B* evolution
- Internal structure of NSs
- Mechanisms for *B* evolution
  - Solid NS crust: Hall drift + Ohmic dissipation
  - Liquid NS core: stable stratification, ambipolar diffusion

Spin-down

(magnetic dipole model)





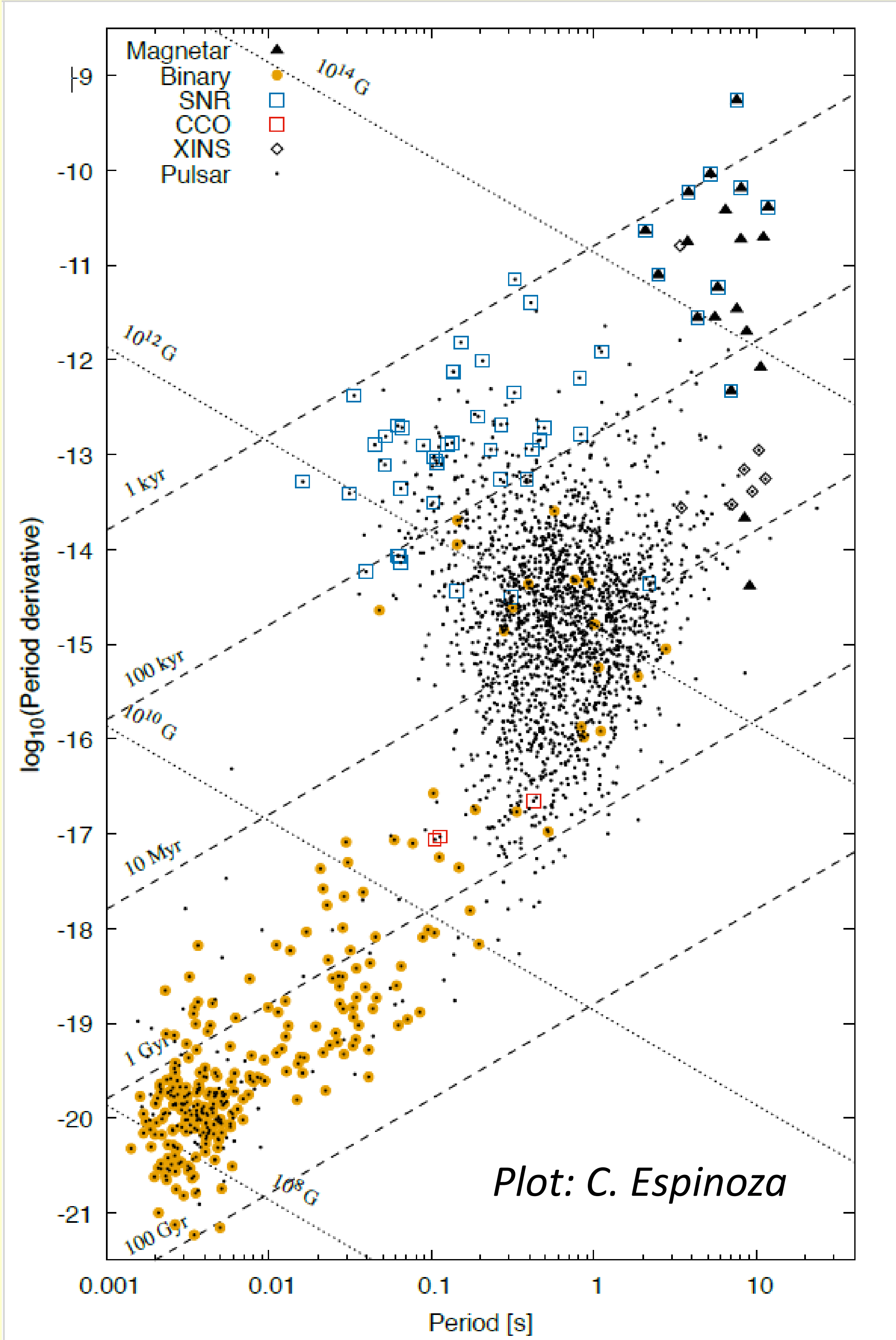
$$-I\Omega\dot{\Omega} = \frac{2}{3c^3}\left|\frac{d^2\vec{\mu}}{dt^2}\right|^2 \propto B^2\Omega^4 \quad \Rightarrow$$

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

Dipole in vacuum – not realistic in principle, but roughly confirmed by magnetosphere simulations (e.g. Spitkovsky 2006)

Pulsars: *P*-*P*dot diagram

- Includes only non-accreting NSs
- >3000 pulsars known
- Several classes of NSs
- Young NSs in supernova remnants may or may not have strong *B*
- *B* strengths >> anywhere else in the Universe, but dynamically unimportant
- Millisecond pulsars “recycled” through accretion spin-up



Caveat:
Braking index

Dipole braking ***model***:

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

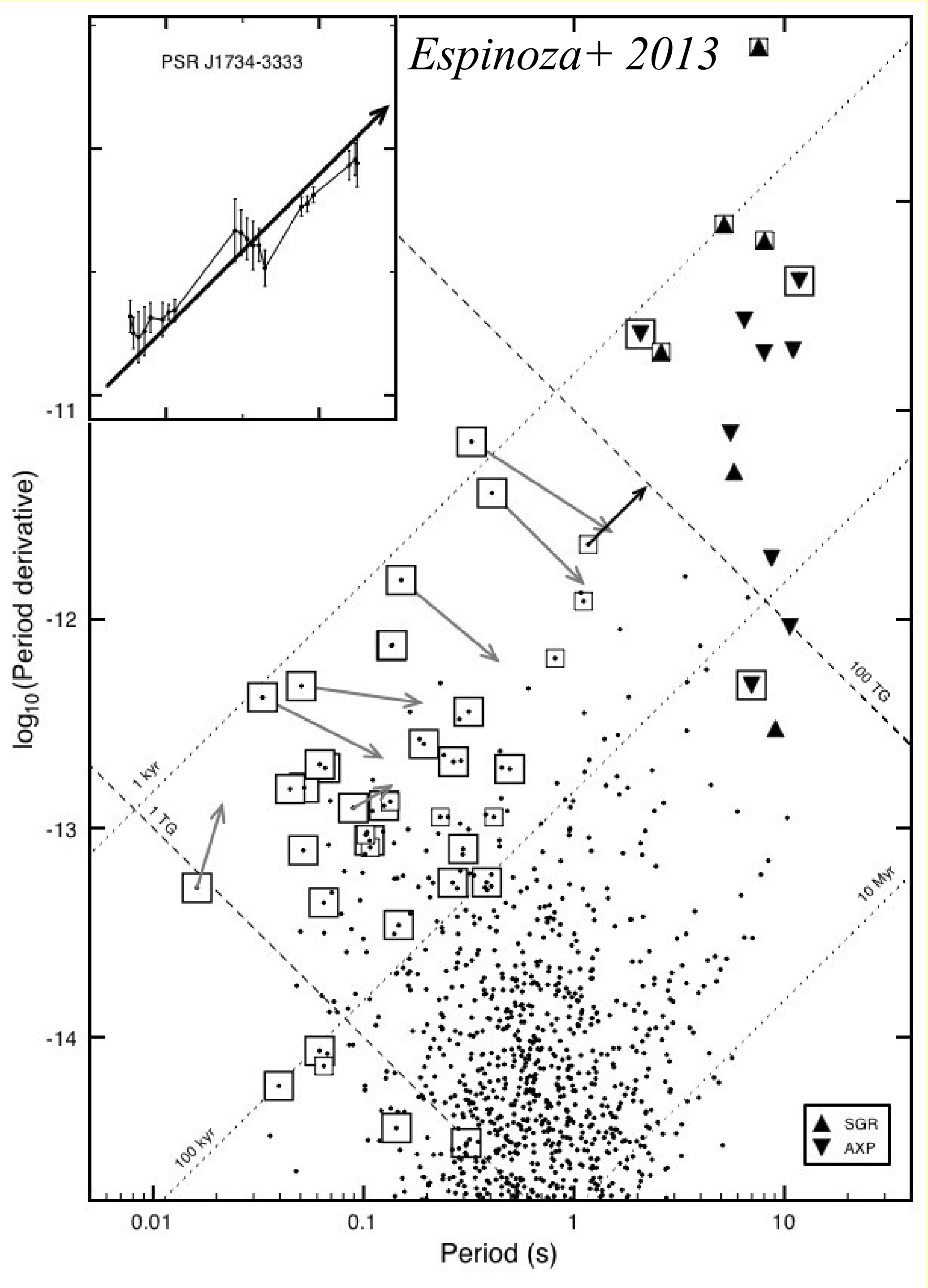
$$n \equiv \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2} = 3 \quad \text{if } K = \text{const.}$$

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

•Model is wrong,

or

•Orthogonal dipole moment **increasing**



NEW: Extremely slow pulsars

- Radio pulsars (challenge to emission models):
  - PSR J0901-4046: $\boldsymbol{P = 75.88}$ **s** (Caleb+ 2022)
  - GLEAM-X J1627-52: $\boldsymbol{P = 1091}$ **s** (Hurley-Walker+ 2022)
  - GPM J1839-10: $\boldsymbol{P = 1318.2}$ **s** (Hurley-Walker+ 2023)
- Magnetar in supernova remnant RCW103:
  - 1E161348-5055: $\boldsymbol{P = 6.67}$ **hours** (de Luca+ 2008; Rea+ 2016; D'Ai+ 2016)

X-ray cyclotron lines

$$E_{\rm cyc} = \frac{n}{(1+z)}\frac{\hbar e B}{m_{\rm e} c} \approx \frac{n}{(1+z)} 11.6\,[\mathrm{keV}] \times B_{12},$$

Pottschmidt+ 2005:

RXTE DISCOVERY OF MULTIPLE CYCLOTRON LINES DURING THE 2004 DECEMBER OUTBURST OF V0332+53

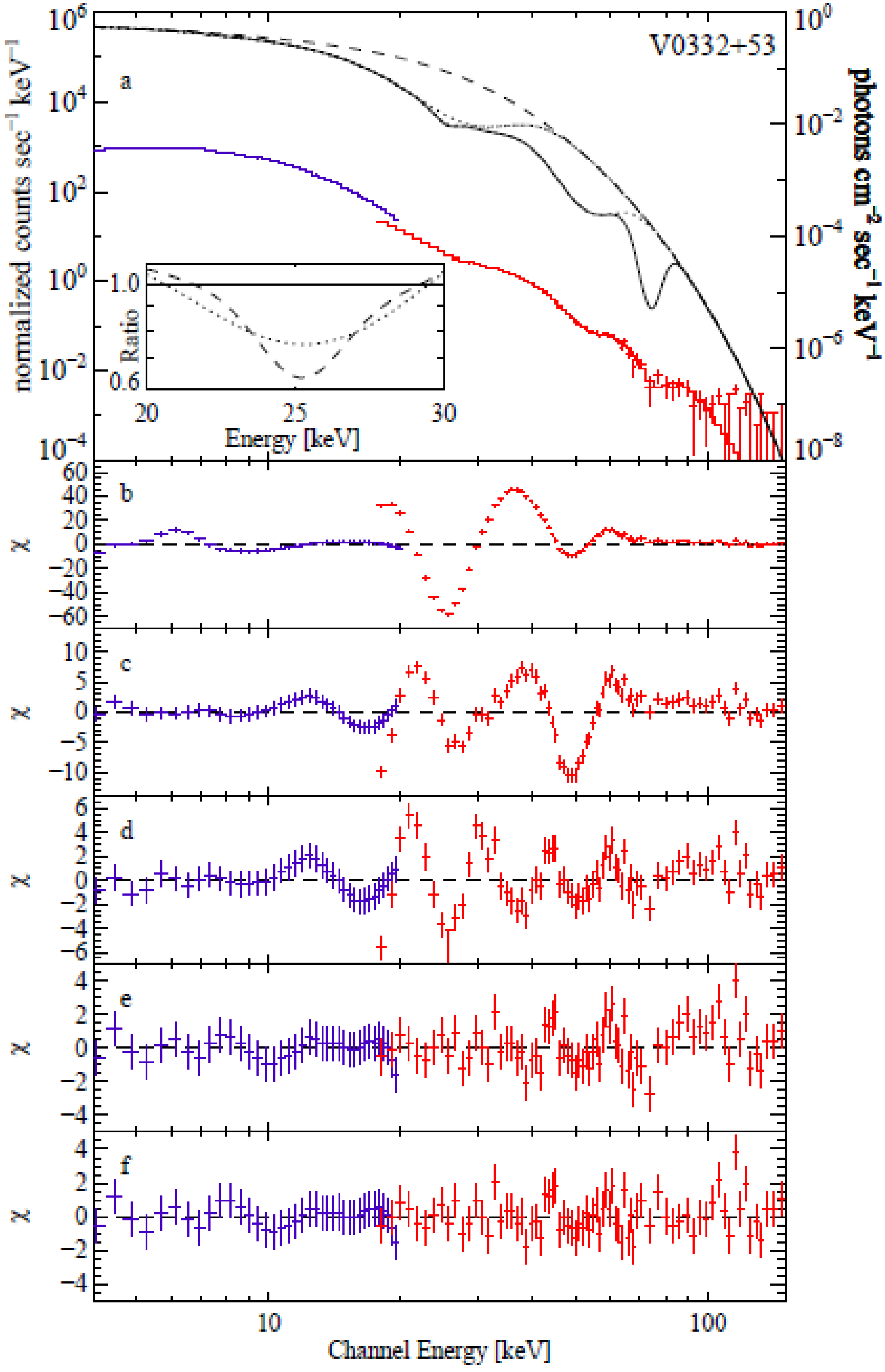


FIG. 2.—Cyclotron line modeling of the phase-averaged PCA/HEXTE spectrum of V0332+53. (*a*) Combined PCA/HEXTE spectrum (*crosses*), best-fit model (*histogram*), and unfolded spectrum (*dotted and solid lines, right y-axis label*), illustrating the cumulative effect of the CRSFs on the continuum (see text for a description of the continuum model). Note that the lines are already visible in the raw count spectrum. The inset shows the best-fit spectra with one (*dotted line*) and two (*dashed line*) line components for the fundamental line relative to the best-fit continuum with no lines (*solid line*). Panels *b–f* show residuals for models taking different numbers of CRSFs into account (see Table 1 for the best-fit values). (*b*) No line; (*c*) one line at 25.5 keV; (*d*) two lines, one at 26.6 keV and one at 50 keV; (*e*) two lines, a fundamental line that is best modeled with two Gaussian components at 25.2 and 26.6 keV and its harmonic at 49.9 keV; (*f*) three lines, the fundamental modeled by two components at ~25 and ~27 keV, and two lines at ~51 and ~74 keV. [*See the electronic edition of the Journal for a color version of this figure.*]

X-ray cyclotron lines

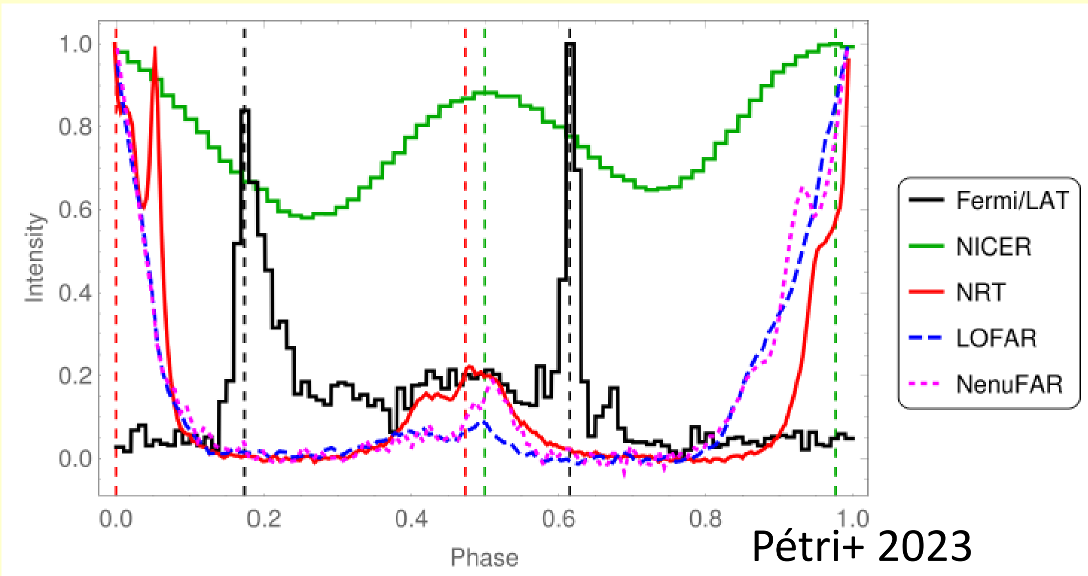
$$E_{\rm cyc} = \frac{n}{(1+z)}\frac{\hbar e B}{m_{\rm e} c} \approx \frac{n}{(1+z)} 11.6\,[\mathrm{keV}] \times B_{12}$$

Review: *Staubert+ 2019, A&A, 622, A61*

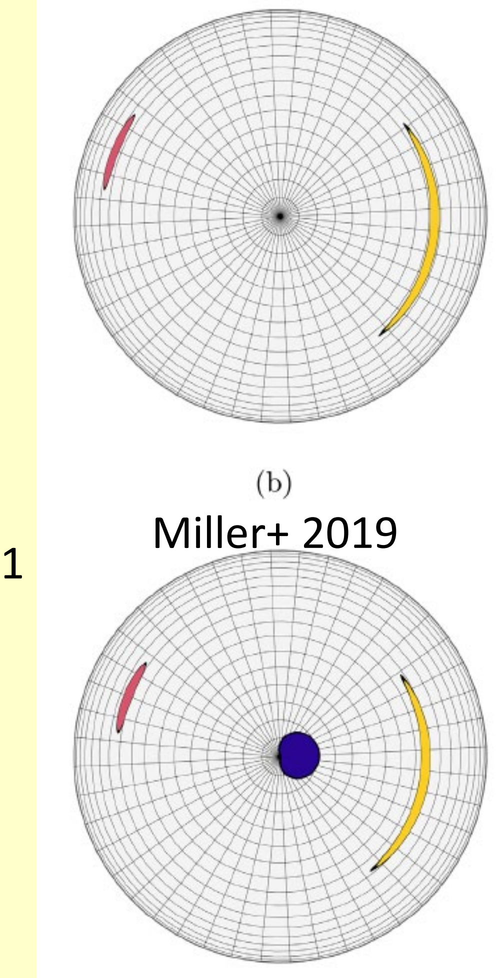
- Electron cyclotron lines in high-mass X-ray binaries (HMXBs):
  - ~35 sources, $B \sim 10^{12-13}$G (11 with ≥ 2 lines)
  - Energy varies with rotation pase, luminosity
- Possible proton cyclotron lines in X-ray-dim isolated NSs (XDINSs):
  - ~5 sources, $B \sim 10^{13-14}$G
  - Roughly consistent with dipole B from spin-down
- Perhaps also in magnetars

Strong selection effects

Field structure from pulse profiles



Millisecond pulsar PSR J0030+0451



- Radio & gamma: beamed non-thermal emission from magnetosphere, far from NS surface
- Thermal X-rays from NS surface (NICER!):
  - 2 or 3 hotspots at magnetic poles
  - Possibly off-centered dipole
  - Gravitational light bending constrains NS compactness

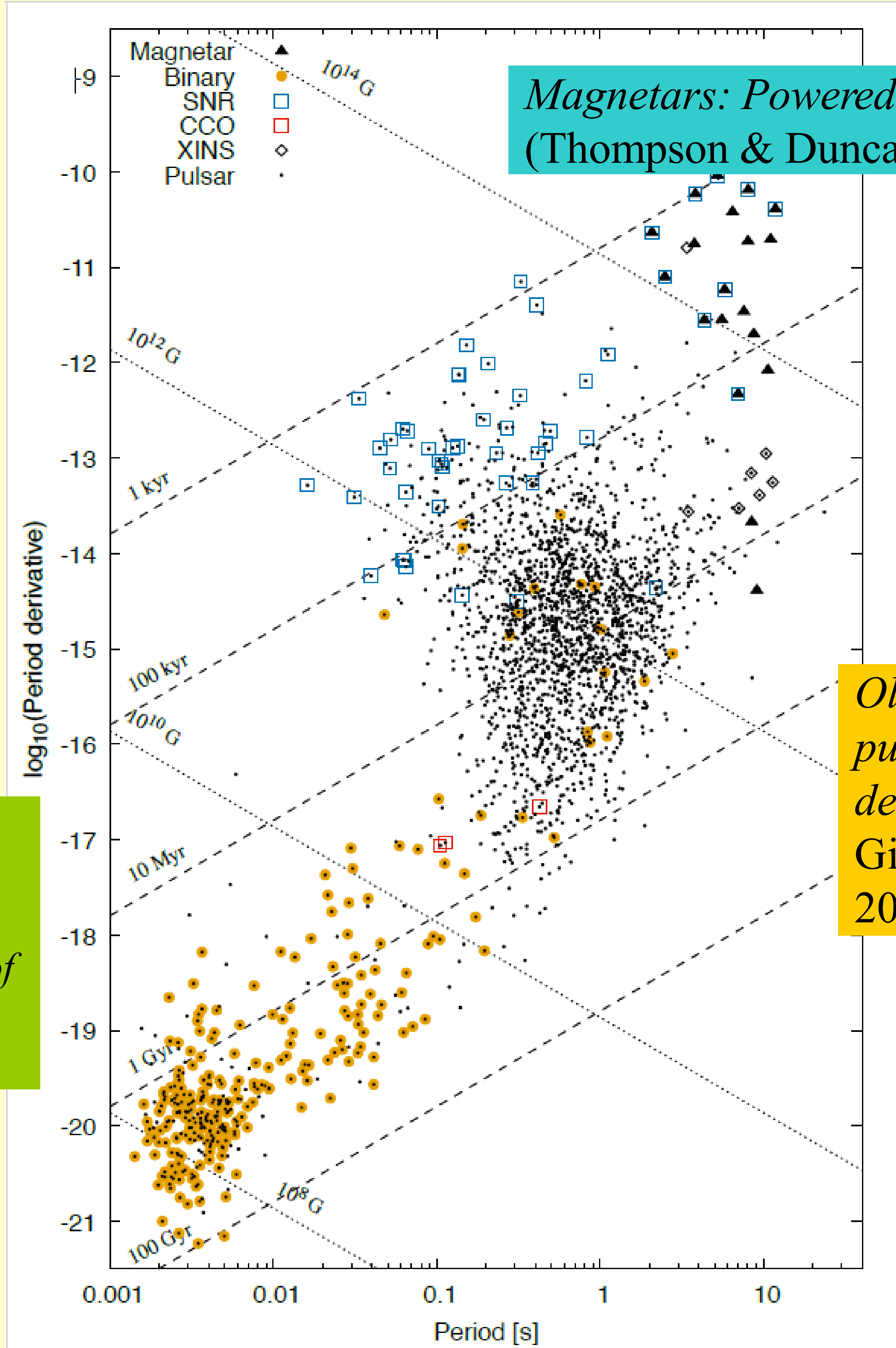
Fast radio bursts

- Very frequent millisecond-duration flashes in radio waves
- Nearly all extragalactic (large dispersion measures, some identifications with galaxies)
- Energy release ~ 10^{39}erg ~ magnetic energy in a NS magnetosphere with $B \sim 10^{11}$G
- Many (all?) FRB sources are "repeaters"
- 1 (much weaker) FRB associated with X-ray outburst from magnetar SGR 1935+2154 in the Galactic Center region

Evidence for *B* decay

Magnetars: Powered by B decay? (Thompson & Duncan 1995, 1996)

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



Millisecond pulsars (& LMXBs):
Very weak field @ old age
→ *Spontaneous or effect of accretion?*
(Cruces+ 2019)

Older classical pulsars: No field decay? (Faucher-Giguere & Kaspi 2006)

Plot:
C. Espinoza

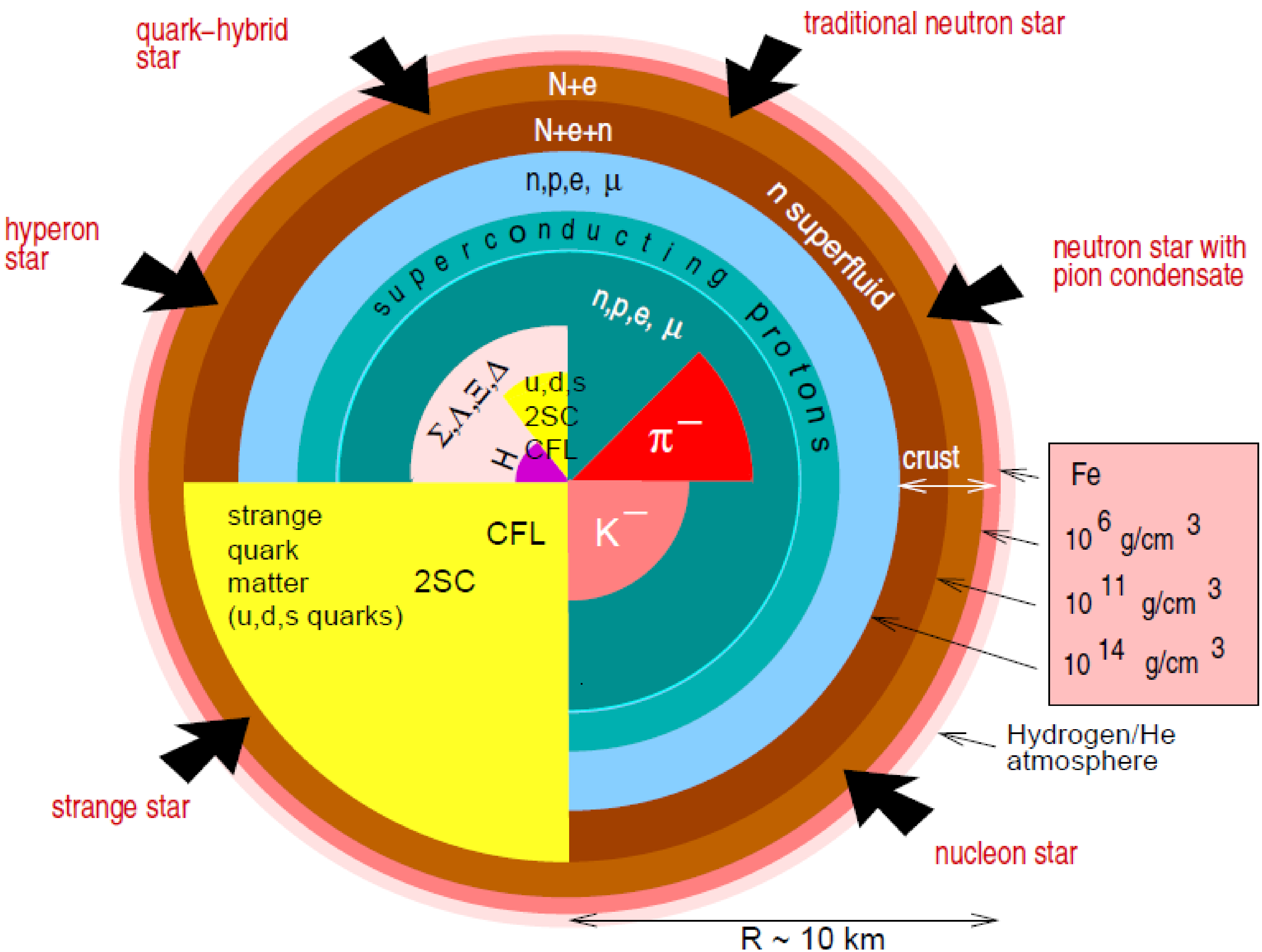
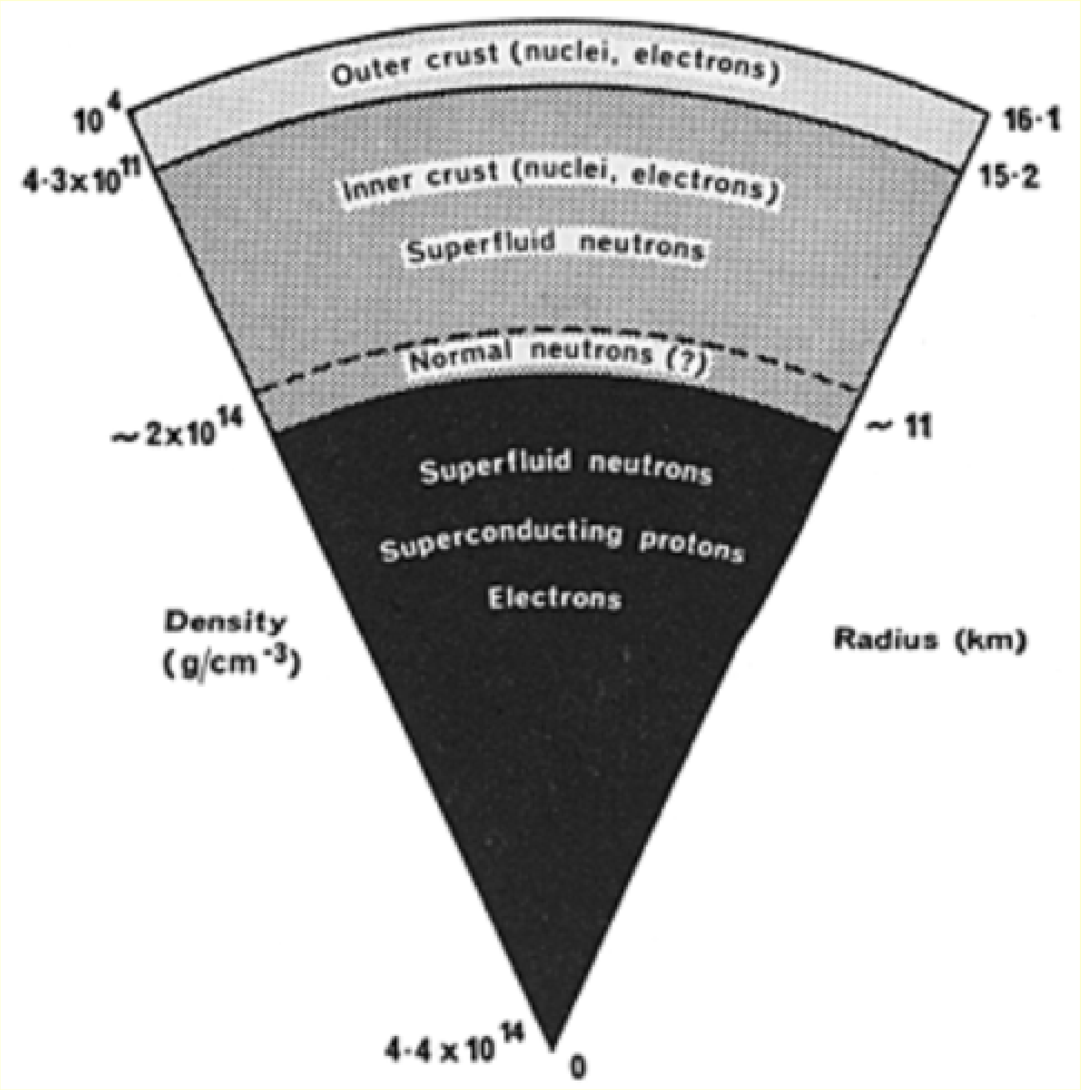


Fig. 1. Neutron star compositions predicted by theory.

Weber et al., arXiv/0705.2708

Internal structure of a «mature» (cool) NS
("conservative" model)



***__Solid crust__*:** magnetic flux carried only by electrons ("Hall drift")

***__Liquid core__*:** several mobile species: *n, p, e, μ*… likely superfluids & superconductors
→ more complex dynamics

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

Early evolution

- NSs are born in the collapse of a massive stellar core or accreting WD → hot → «Normal» conducting fluid → ideal MHD
- Differential rotation → MRI → Dynamo → Amplification & restructuring of the magnetic field (e.g., Spruit 2009; Barrère+ 2023)
- Eventually (~ few Alfvén times, possibly longer if quickly rotating) *B* settles into a **stable hydromagnetic equilibrium:** could be either
  - **axially symmetric** "twisted torus" (Prendergast 1956; Braithwaite & Spruit 2004, 2006; Becerra+ 2022b)
  - **very disorganized** (Braithwaite 2008; Becerra+ 2022a)
- Fast neutrino cooling → Crust freezing, superfluid/superconductor

NS crust: Hall drift + Ohmic diffusion

Electrons are the only (charged) mobile species
→ " Simple " dynamics: Hall drift + Ohmic diffusíon *(e.g., Goldreich & R. 1992)*

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \left(\frac{c}{4\pi n e} [\nabla \times \boldsymbol{B}] \times \boldsymbol{B} + \eta \nabla \times \boldsymbol{B} \right), \quad (1)$$

$$t_{Hall} \sim \frac{neL^2}{cB} \sim \frac{10^8}{B_{12}} \,\mathrm{yr} \qquad\qquad t_{Ohm} \sim \frac{L^2}{\eta} \sim \frac{10^7}{T_8^2 + Q} \,\mathrm{yr}$$

(e.g ., Cumming + 2004)

- Hall can be relevant only for high B → Magnetars, perhaps classical pulsars
- Impurity parameter *Q* very uncertain
  - (Constraints fron qLMXB cooling observations *(Brown & Cumming 2009)*
  - Theoretical predictions?
- Ohm is important if T or *Q* are large → Accreting NSs

Detailed magneto-thermal evolution calculations: *Viganò, Rea, Pons, et al. 2013*

NS crust: Hall drift + Ohmic diffusion

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \left(\frac{c}{4\pi n e} [\nabla \times \boldsymbol{B}] \times \boldsymbol{B} + \eta \nabla \times \boldsymbol{B} \right), \quad (1)$$

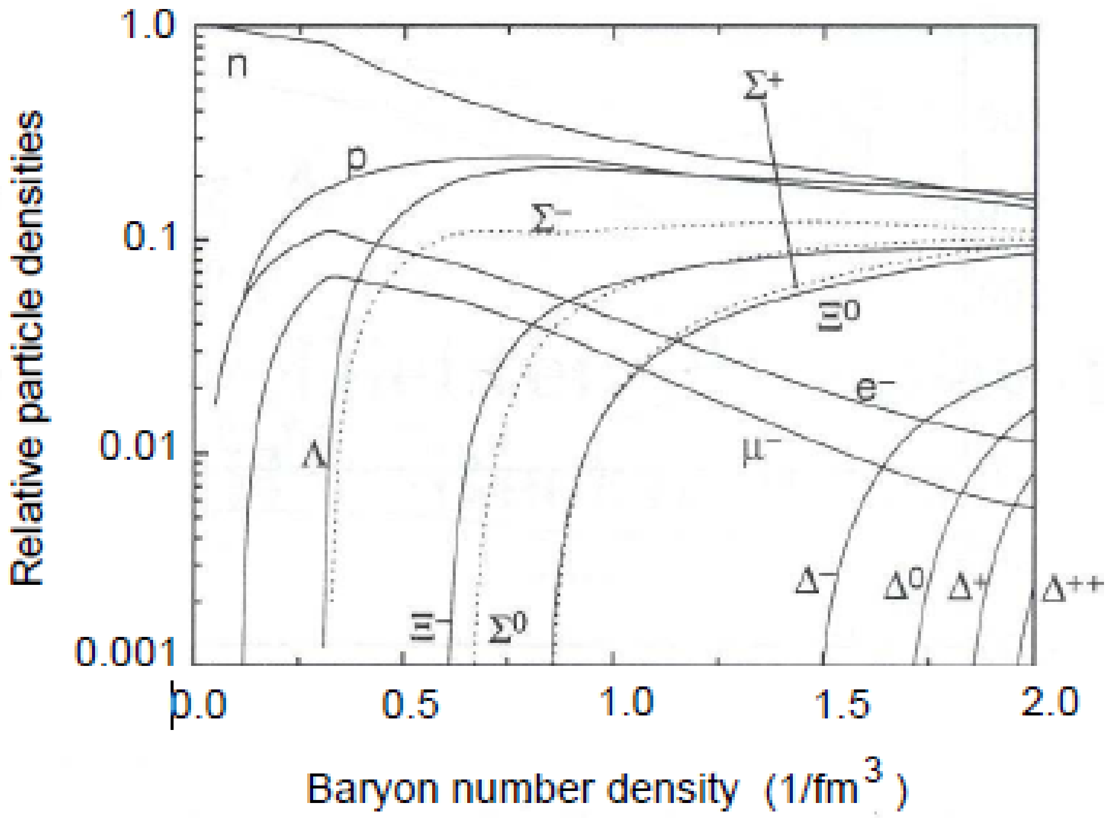
- Hall drift non-linear → "turbulent cascade" to small scales? (Goldreich & R. 1992)
- Analytic solutions:
  - Current sheets (Vainshtein et al. 2000; Reisenegger et al. 2007)
  - Large-scale Hall equilibria (Gourgouliatos et al. 2013)
- Numerical 2D (= axial symmetry):
  - **Stable Hall equilibria = "attractors"** (Gourgouliatos & Cumming 2014a,b; Marchant et al. 2014); braking indices $n < 3$ (Gourgouliatos & Cumming 2014c)
  - **Coupled thermo-magnetic evolution**: Viganò et al. 2013, 2021
- Numerical 3D: complex evolution (Dehman et al. 2023; Igoshev et al. 2023)
- Very strong B might cause (progressive or catastrophic) yielding of the crust → magnetar activity? (e.g., Gourgouliatos et al. 2022)

Models mostly assume that the magnetic flux goes only through the crust

→ Unlikely unless core superconductor can expel the flux

→ Either way, need to study processes in the core

NS core composition



Weber et al. arXiv:astro-ph/0612054

Figure 6: Composition of standard neutron star matter, i.e. $T = 0$ MeV and $Y_L = 0$ for the RMF approximation.

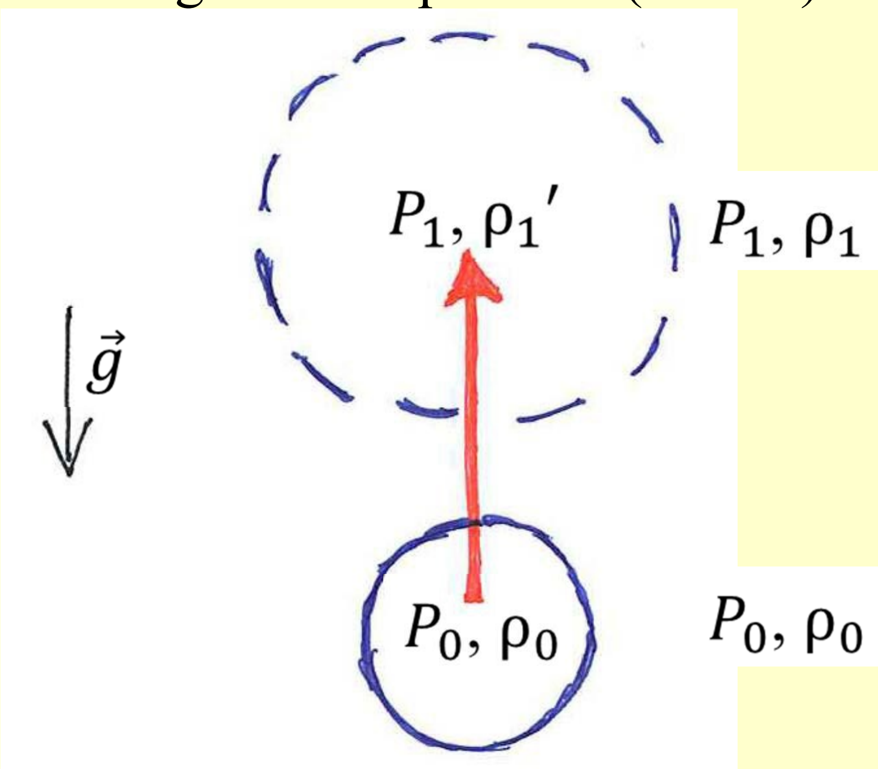
- Mix of particles set by local beta equilibrium
- Various charged particle species carry currents & interact with *B*
- Composition gradient

→ stable stratification
→ allows stable equilibrium *B*

Stratification & buoyancy

Non-barotropic fluid:

blob displaced from equilibrium "remembers" where it came from, through its composition (in NSs) or specific entropy (main sequence, WDs)



Brunt-Väisälä (buoyancy) frequency

$$N^2 = g^2 \left[\left(\frac{\partial \rho}{\partial P} \right)_{equil} - \left(\frac{\partial \rho}{\partial P} \right)_{adiab} \right]$$

\> 0: stable oscillations ("g-modes")

< 0: unstable → convection

= 0: neutrally stable ("barotropic")

"Ledoux criterion"

Stable stratification vs. *B*

In NS cores: $N^2 > 0$ → **stable** stratification

- $N \sim \frac{g}{c_s}\sqrt{\frac{n_p}{n_n}} \sim 10^3\ \mathrm{s}^{-1}$ (Reisenegger & Goldreich '92; Lai '94)

>> Alfvén frequency (~ growth rate of magnetic instabilities):

- $\omega_A \sim \frac{B}{R\sqrt{4\pi\rho}} \sim 10\ B_{15}\ \mathrm{s}^{-1}$

→ Magnetic forces can't overcome buoyancy unless $B \sim 10^{17}$G

→ Buoyancy helps stabilize magnetic equilibria

NS core: ambipolar diffusion

Strong coupling regime ($T_{core} > 5 \times 10^8$K):

Weak interactions ("Urca processes") convert particles into each other, allowing bulk flow → slower than NS cooling → very little evolution, even for magnetar-like B (Moraga+ 2023)

Weak coupling regime ($T_{core} < 5 \times 10^8$K): Charged particles & neutrons diffuse with respect to each other, B carried by charged particles (ambipolar diffusion)

→ eventually B only coupled to charged particles (Castillo+ 2020)

→ barotropic? → unstable? → field decay? (Cruces+ 2019)

Still to be done: Simulations combining core and crust evolution with correct physics, realistic (?) initial conditions, superconductivity (Gusakov+ 2020), superfluidity, stellar rotation (flux tubes + vortices; Thong+ 2023)

Low *B* in MSPs & LMXBs

Standard explanation: «Recycling» via **accretion** reduces not only *P*, but also *B*, through either:

1) Accretion heating → **enhanced crustal resistivity** (Shibazaki+ 1989): **requires *B* not to penetrate the core**

2) Diamagnetic **screening** by accreted material (Bisnovatyi-Kogan & Komberg 1974, many others): **strong instabilities** (Mukherjee+ 2013)

Possible alternative: **ambipolar diffusion of core field in cold, pre-accretion phase** (Cruces+ 2019)

- Time scale (Goldreich & R. 1992): $t_{ambip} = 3 \times 10^9 \frac{T_4^2 L_5^2}{B_8^2} yr$
- Requires also fast evolution in the crust (impurities)
- *B* should decrease with main-sequence lifetime of companion star
- Correlated with accretion time or accreted mass → not trivial to distinguish phenomenologically

Summary: 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 hydromagnetic equilibrium**
   - Magnetic energy << initial thermal energy << gravitational energy

3. Fast neutrino cooling → crust freezing, superfluidity, superconductivity

4. Secular *B* evolution:

   - Hall drift+Ohmic diffusion in the crust, ambipolar diffusion in the core make the field evolve and decay, possibly explaining weak fields of millisecond pulsars
   - Evolution of strong fields could break the crust, causing magnetar activity

Full, self-consistent models with all relevant ingredients yet to be constructed.