Neutron star magnetospheres

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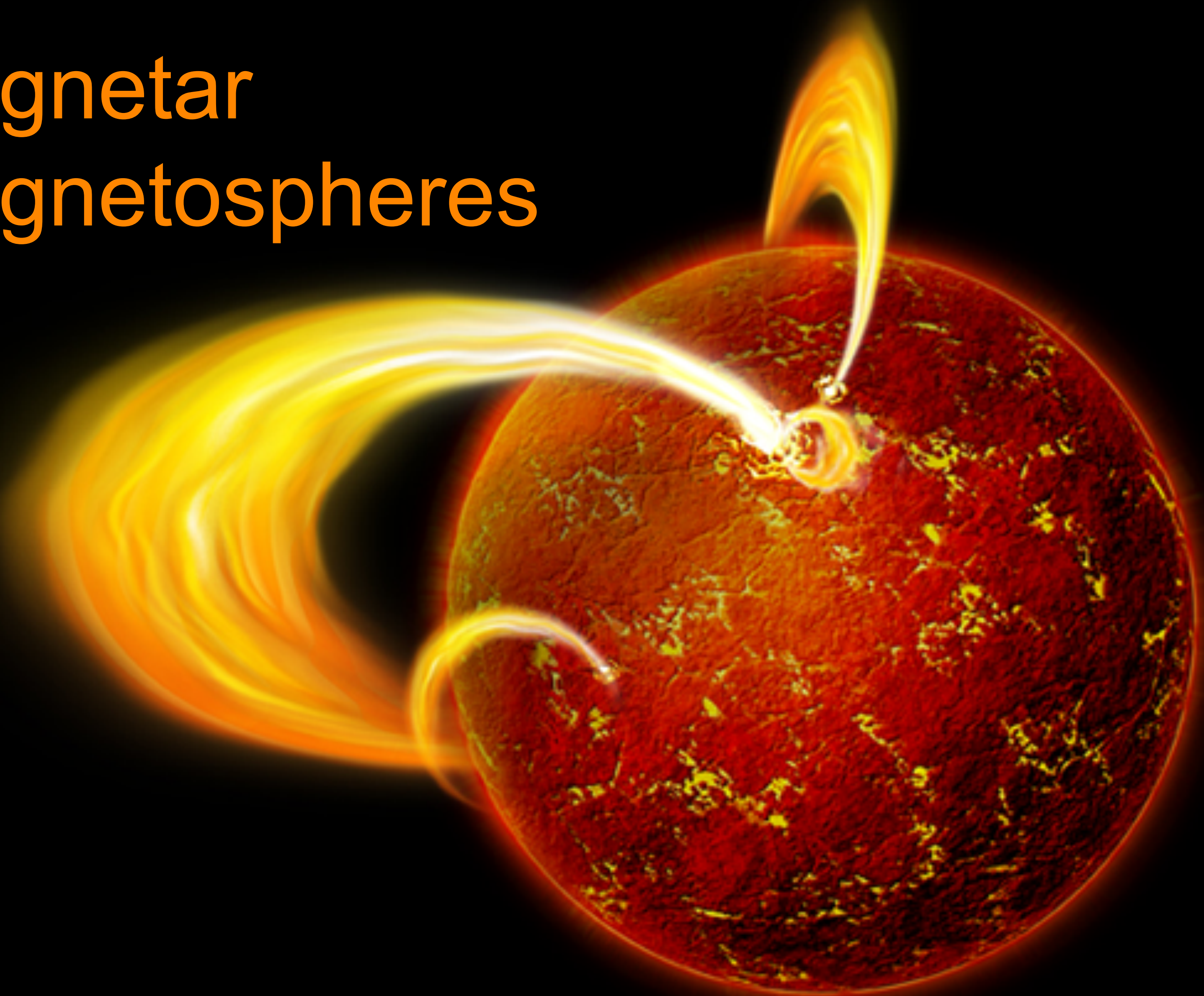
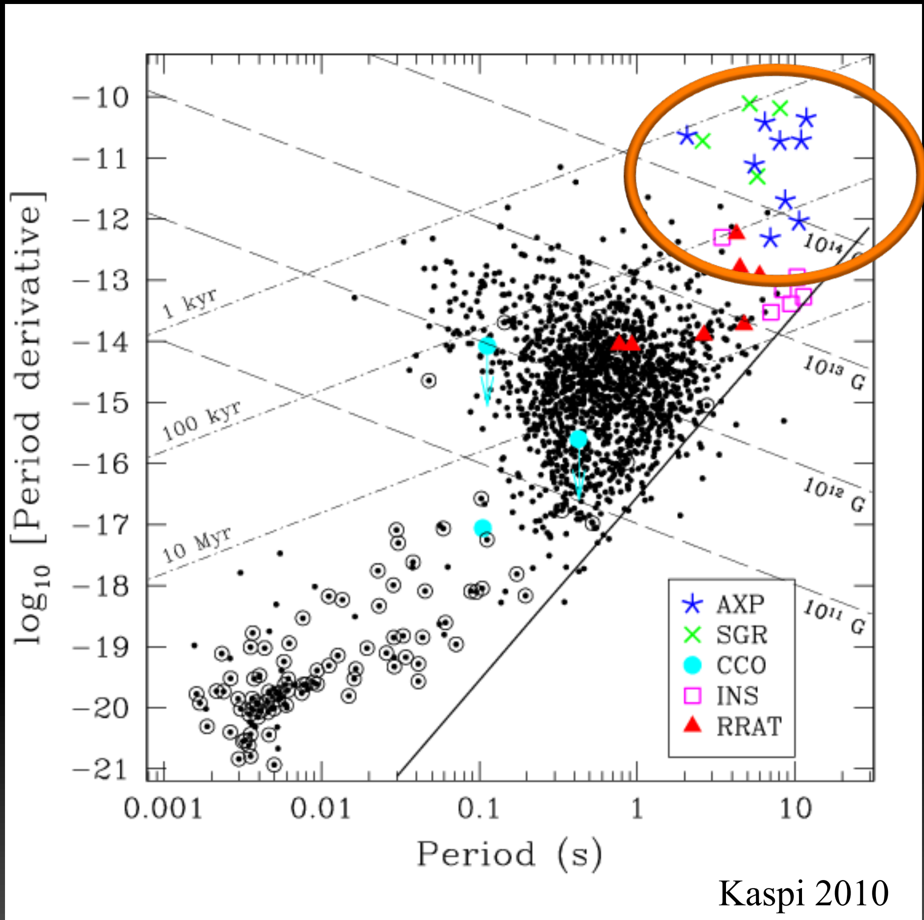
Outline

- Magnetar magnetospheres
    - Observations and models
    - Force-free twisted magnetospheres
    - Magnetosphere dynamics
- Supernova fallback and magnetic field burial

Magnetar magnetospheres



What are magnetars?

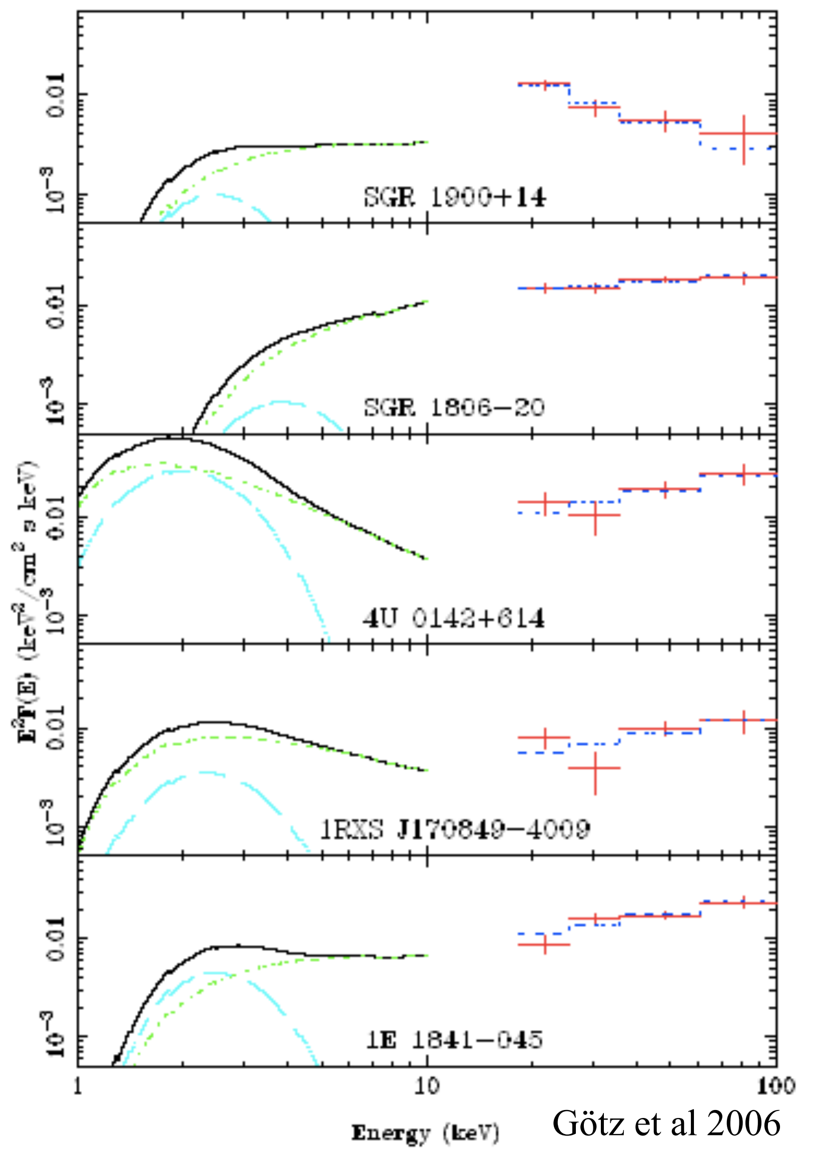


X-ray pulsars (no radio emission):

- Long rotation period: 2-12 s
- Rapid spin-down (10^3-10^5 y)

- Large inferred magnetic field 10^{14}-10^{15} G

Quiescence spectrum



Götz et al 2006

- X-ray luminosity ~10^{34}-10^{36} erg/s
- Thermal black body (~0.5 keV)
- Soft X-ray tail (2-10 keV)
- Hard X-ray component (15-100 keV)

- Magnetically powered emission
- Part of the emission comes from the magnetosphere

Magnetar magnetosphere

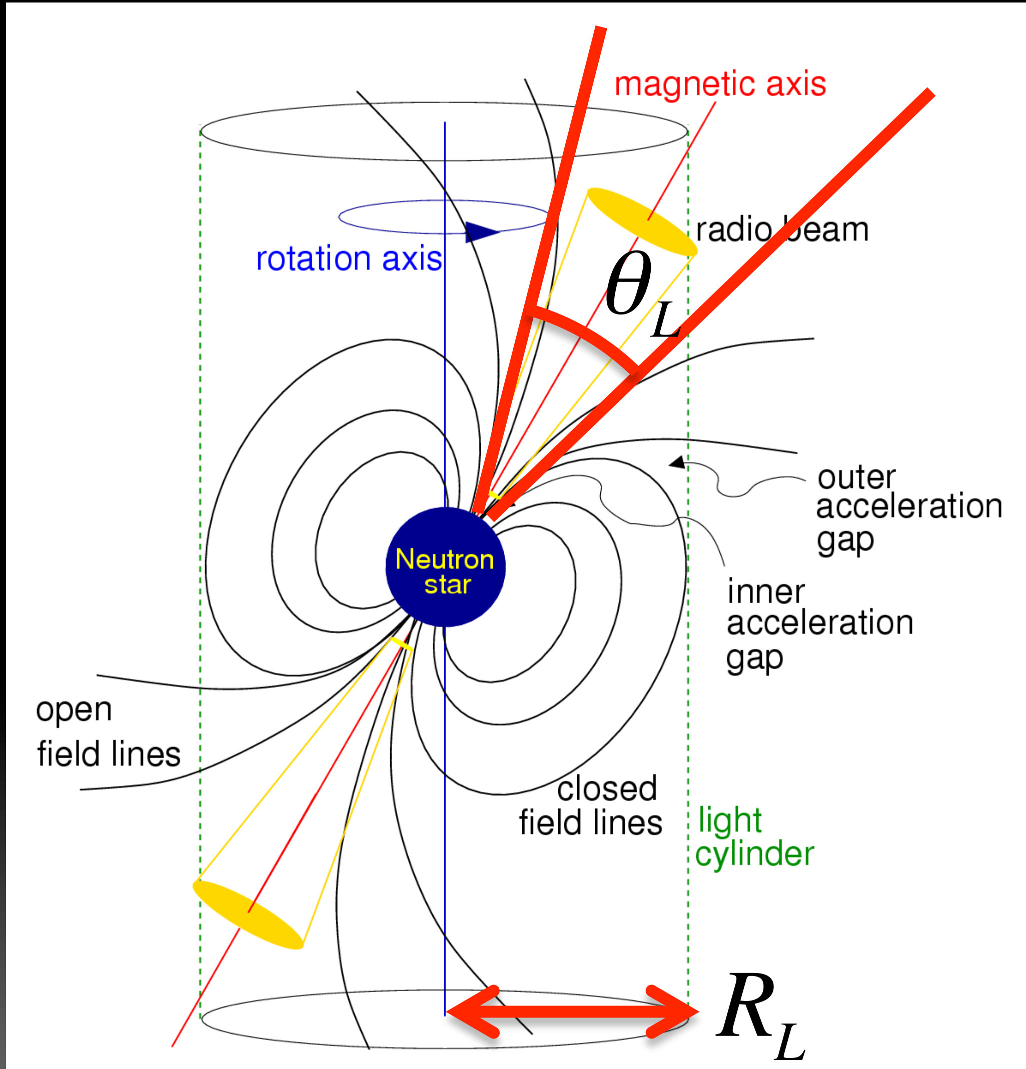
- Light cylinder:

$$R_L \approx 10^5 \left(\frac{P}{2s}\right) km$$

- Outside the light cylinder:
  - "open" field lines
  - Small bundle at the polar cap

$$\theta_L \approx \sqrt{R_* / R_L} \approx 0.5^\circ$$

- Inside the light cylinder:
  - Closed field lines
  - Force-free magnetosphere
    Currents sustained by $e^- e^+$ pair creation (Beloborodov & Thompson 2007)

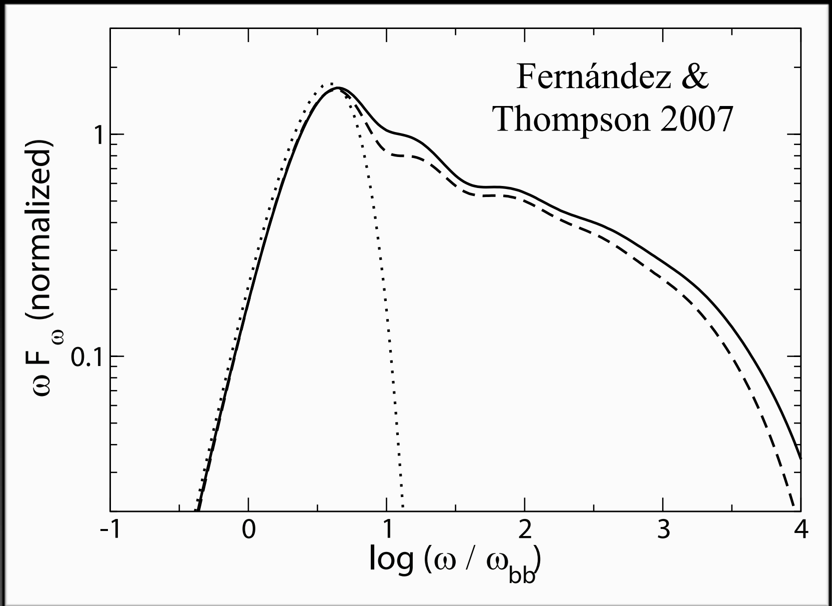


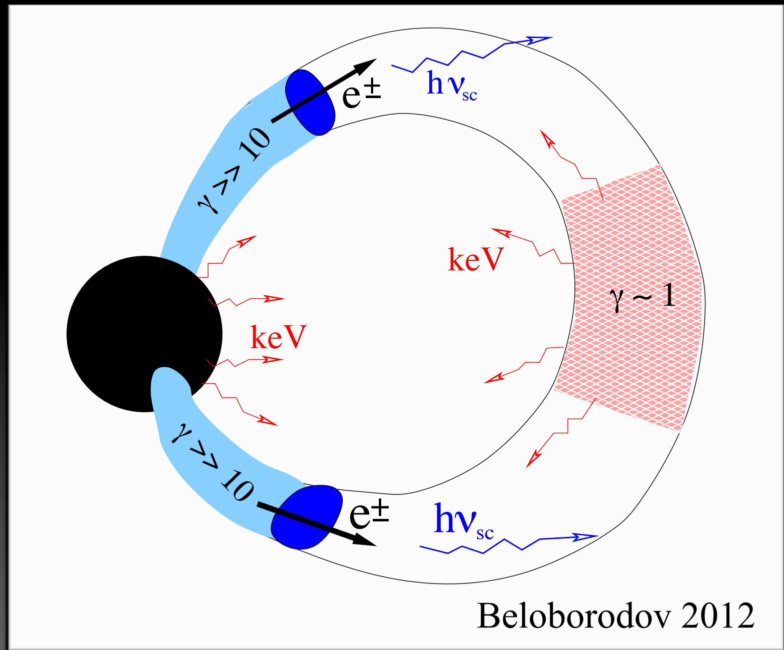
Lorimer & Kramer

Emission mechanism

Resonant cyclotron scattering (RCS) model

- Black body photons from the surface of the star
- Photons upscattered by currents in the magnetosphere (Lyutikov & Gavriil 2006, Fernández & Thompson 2007, Nobili et al 2008, Taverna et al 2015) → soft X-ray tail
- Accelerated pairs produce hard X-ray at ~100 km (Thompson & Beloborodov 2005, Belobodorov & Thompson 2007, Belobodorov 2013, Chen & Beloboborov et al 2016)





Origin of magnetospheric currents

$$f = \rho_q E + J \times B$$ Lorentz force density

Stationary solution: $4\pi J = \nabla \times B$ (Ampère's law)

Force-free: $f = 0$

Charge neutrality: $\rho_q = 0$

$J \times B = 0$: Currents flow along field lines

Origin of magnetospheric currents

Axisymmetric force-free solutions

$$B = \nabla P \times e_\phi + T\, e_\phi$$

- P : poloidal function
- T : toroidal function

$$\nabla P \times \nabla T = 0 \quad \rightarrow \quad T(P)$$

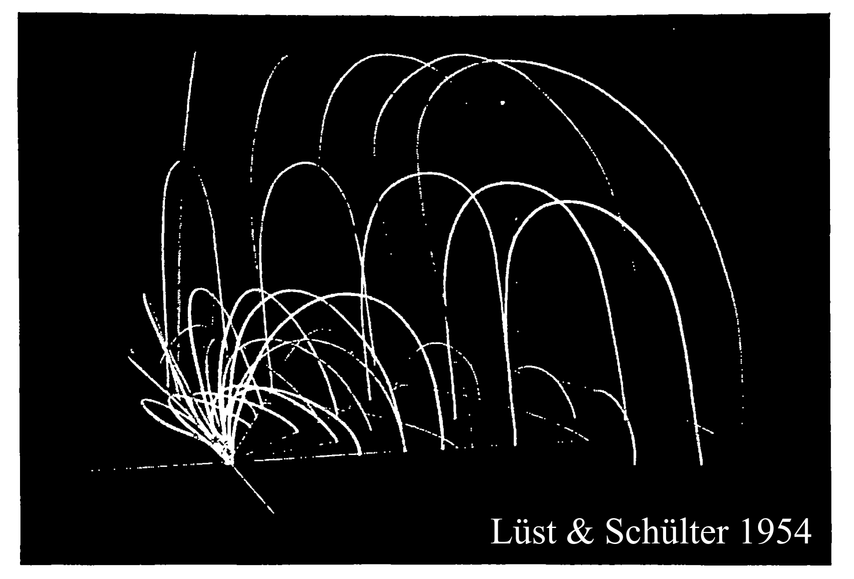
$$\Delta_{GS} P = -T(P)T'(P)$$: Grad-Shafranov equation

$$4\pi J = T'(P)B$$: Twist ←→ magnetospheric currents

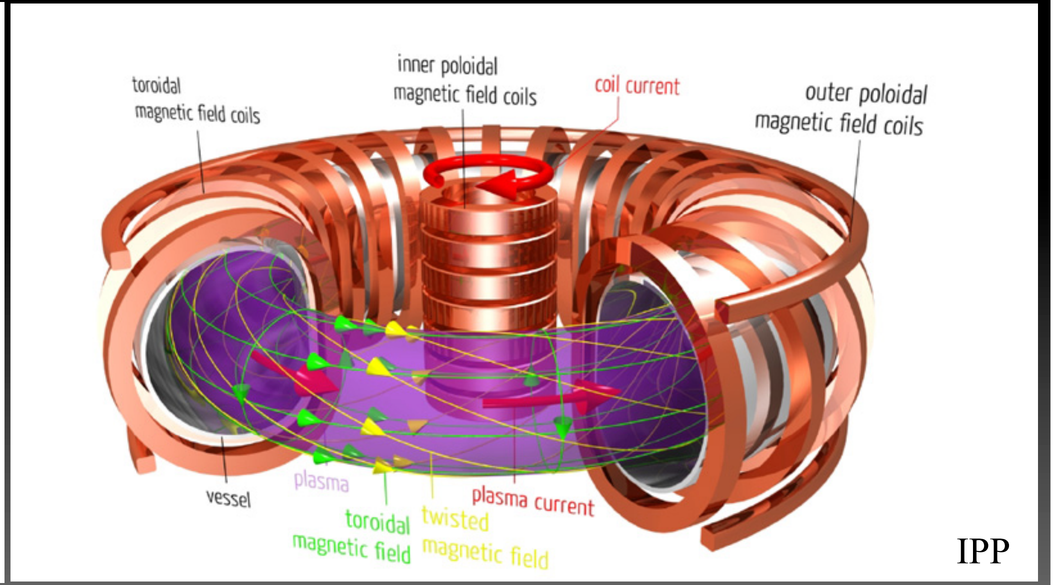
Grad-Shafranov equation

- Lüst & Schülter 1954 (astrophysical context)
- Grad & Rubin 1958; Shafranov 1966 (plasma confinement)

Early force-free solution
Of a twisted dipolar field

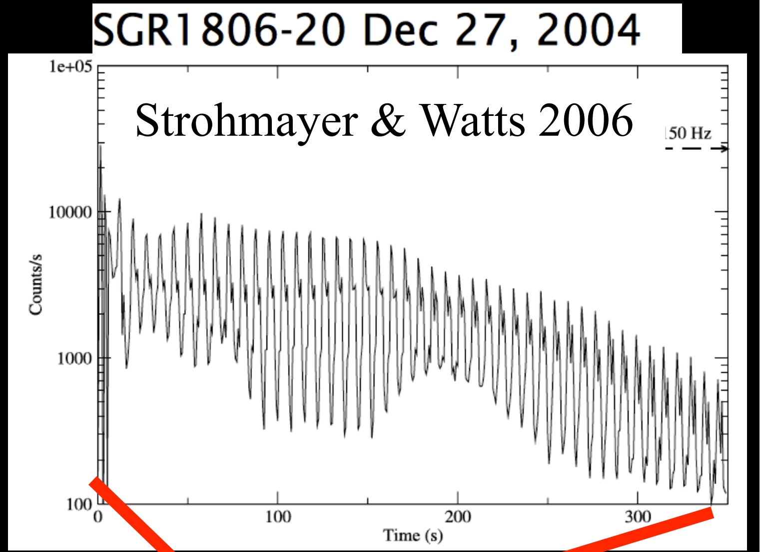


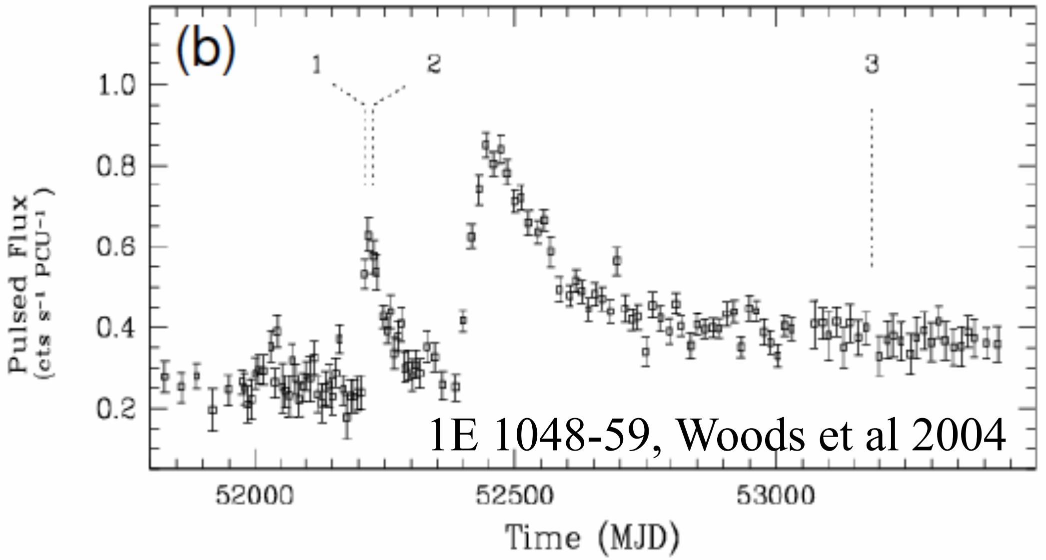
Tokamak fusion reactor

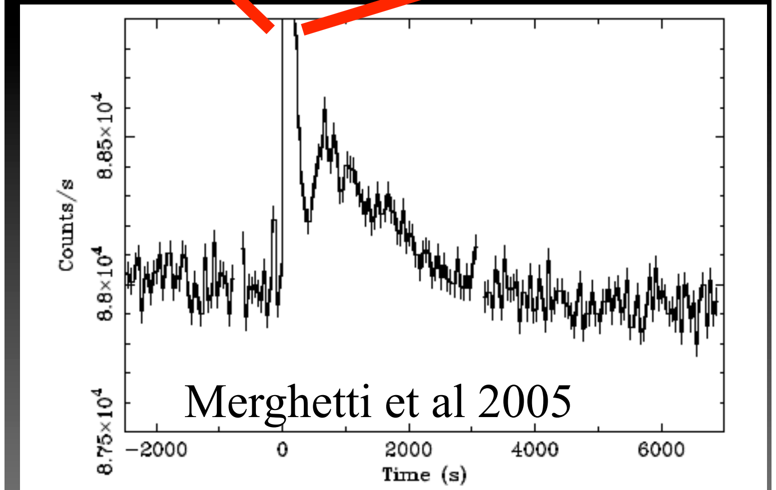


Variability

- Repeated burst activity: 10^{42} erg/s in 0.01-1 s
- Giant flares (3):
  - Initial spike: 10^{44} – 10^{47} erg/s in 0.25-0.5 s
  - Pulsating tail: 10^{44} erg/s in 200-400 s
- Long term variability: hours to years







Untwisting magnetospheres

- Twisted magnetospheres are not static → energy loses by radiation
- Magnetospheres untwist in secular time-scales (Beloborodov 2009, 2012, Chen & Beloborodov 2016)
- Pair plasma flowing along twisted field lines→ hot spot at the surface
- Twisted field at ~100km → magnetar corona → hard X-ray component

Model ingredients:

- Thermal emission from the surface
- Current distribution at the magnetosphere
  - **Force-free magnetic field configuration**
  - e^- and e^+ momentum/spatial distribution: multiplicity?
- Back-reaction:
  - Photon flux ←→ e^- and e^+ distribution
  - Hot spots

Burst models

Magneto-thermal evolution of the crust (Perna & Pons 2011)

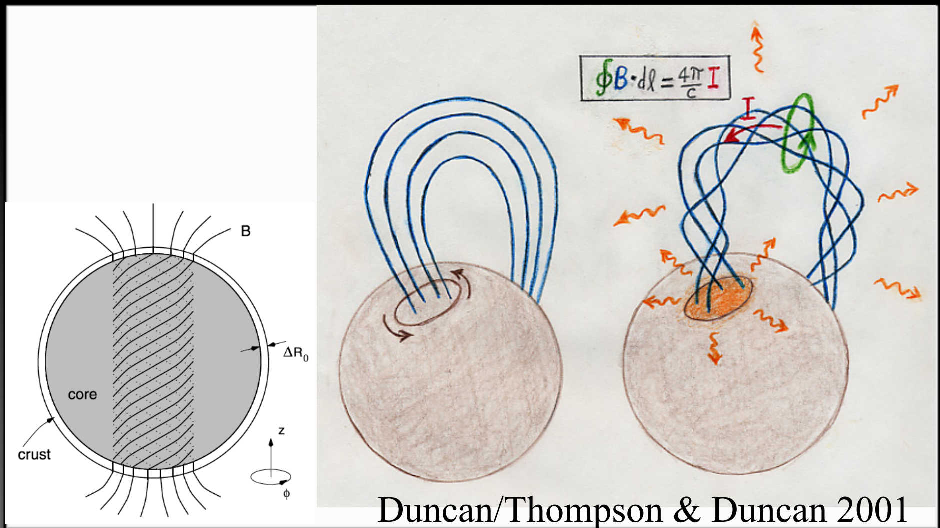
- Hall drift timescale ~ 10^3-10^4 yr
- Stress builds in the crust

Internal mechanism:

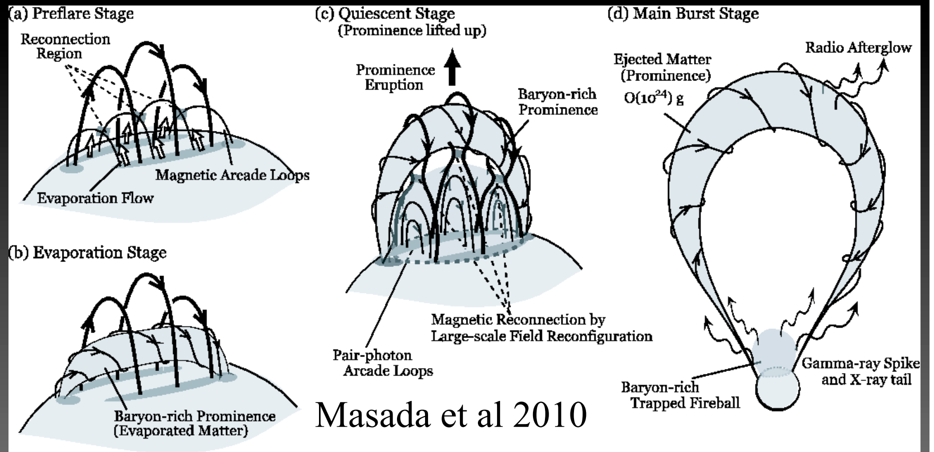
- Reach breaking strain ~0.1 (Horowitz & Kadau 2009)
- “Crustquake” (Thompson & Duncan 1996)
- Mechanical failure may propagates too slow (Levin & Lyutikov 2012, Belobodorov & Levin 2014, Li et al 2016)

External mechanism:

- Stress bulid-up limited by plastic deformations
- Highly twisted magnetosphere leads to magnetic reconnection event
- Solar-like flare (Lyutikov 2006, Masada et al 2010, Lyutikov 2014)



Duncan/Thompson & Duncan 2001



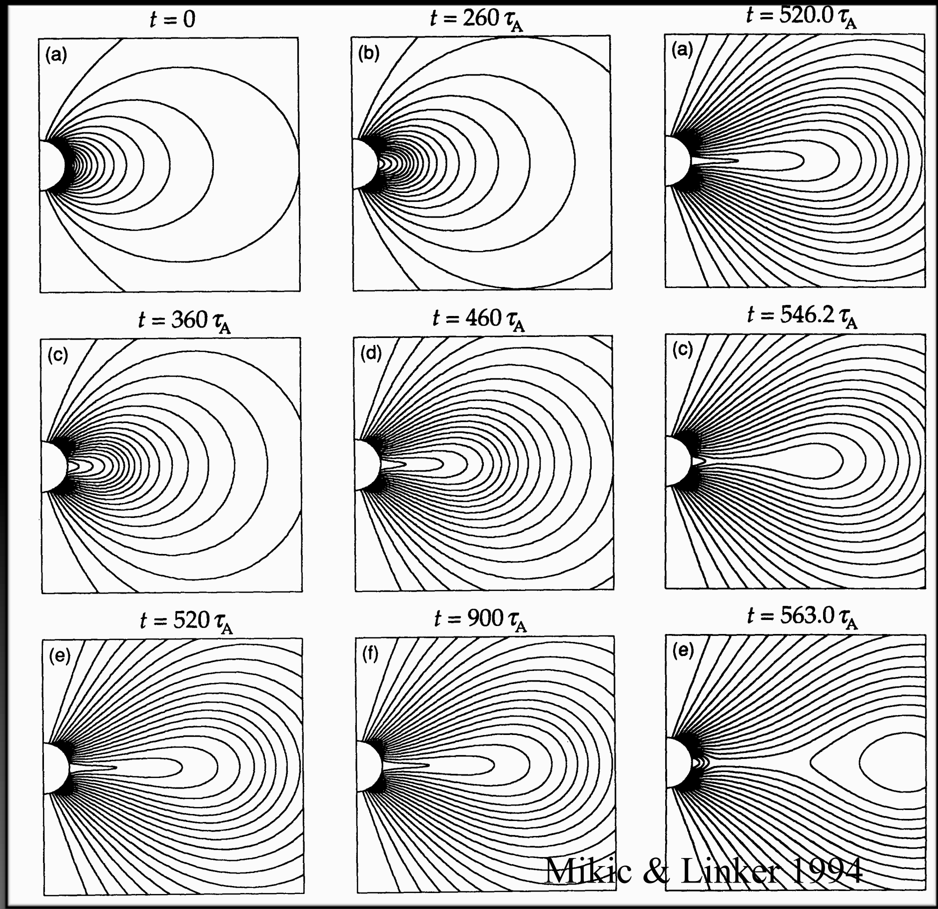
Masada et al 2010

Maximum magnetospheric twist

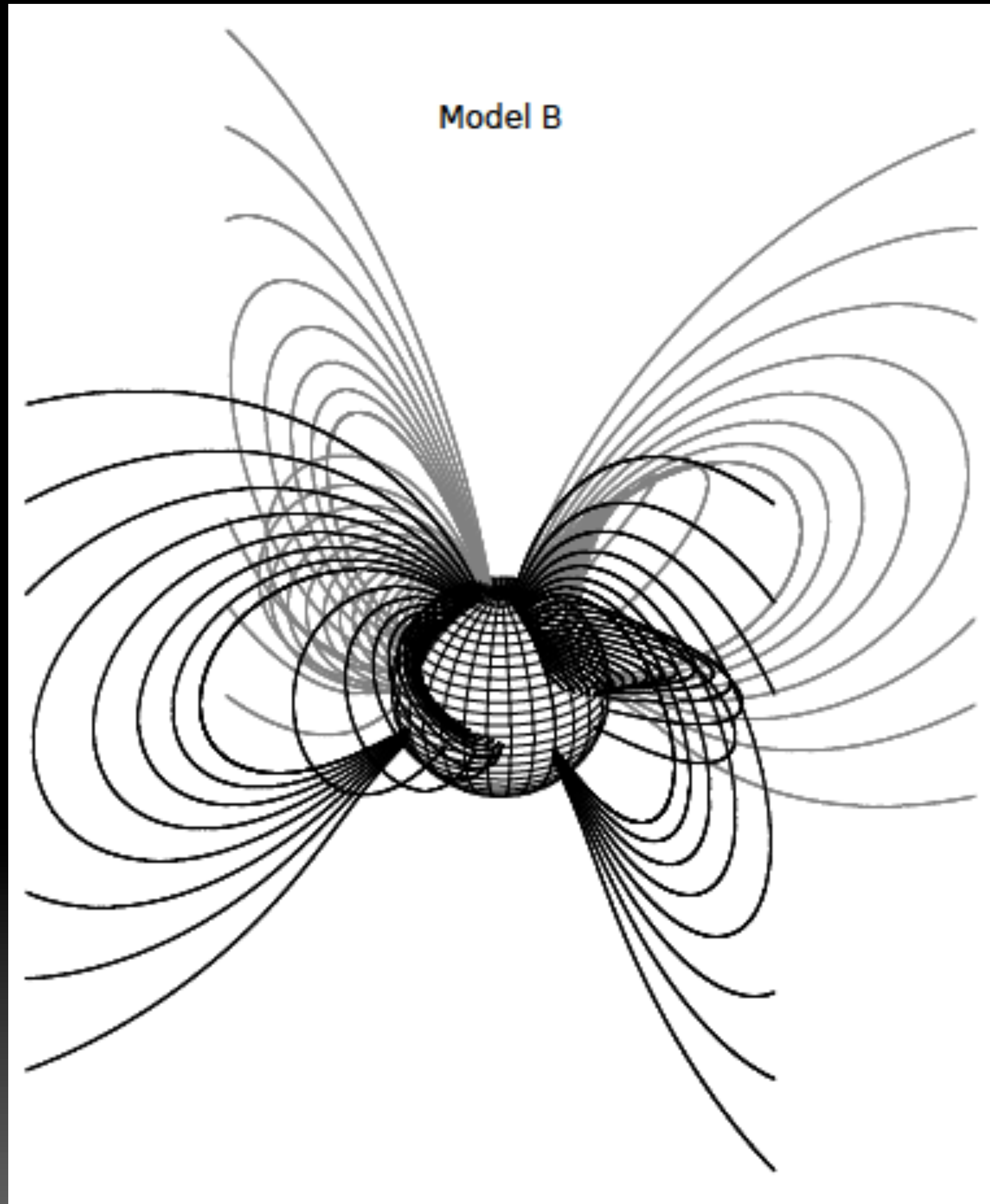
MHD dynamical calculations (Mikic & Linker 1994, Parfrey et al 2013)

- Maximum strain ~ maximum twist ~1 – 4 rad
- Results sensitive to:
  - How fast you twist the magnetosphere
  - Resistivity
  - Magnetic field configurarion
  - Twist profile

Can we learn something from force-free equilibrium models?



Force-free twisted magnetospheres



Force-free magnetospheres

Akgün, Miralles, Pons & CD, MNRAS, 462, 1894 (2016)

$$\Delta_{GS} P = -T(P)T'(P)$$: Grad-Shafranov equation

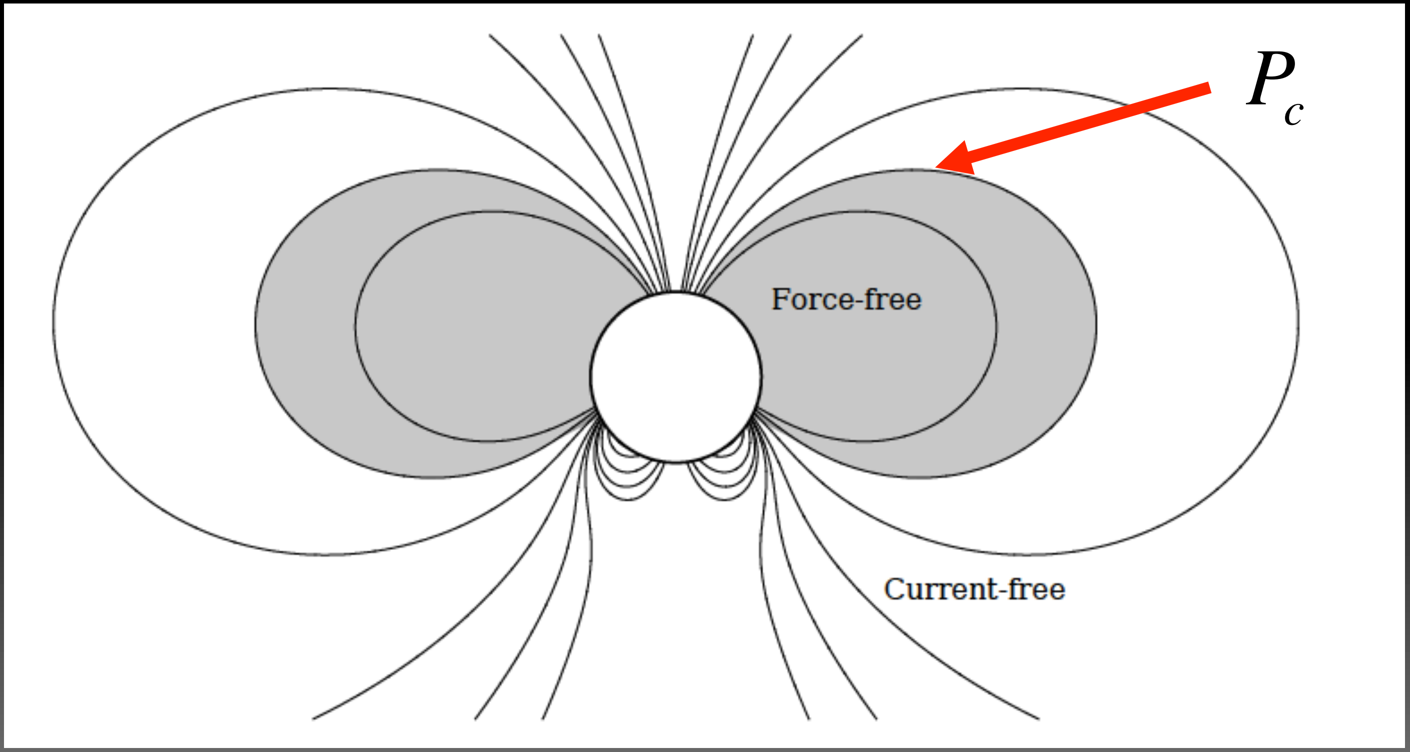
$$4\pi J = T'(P)B$$: Twist ←→ magnetospheric currents

$T(P)$: Toroidal function → fixed by the field at the NS surface

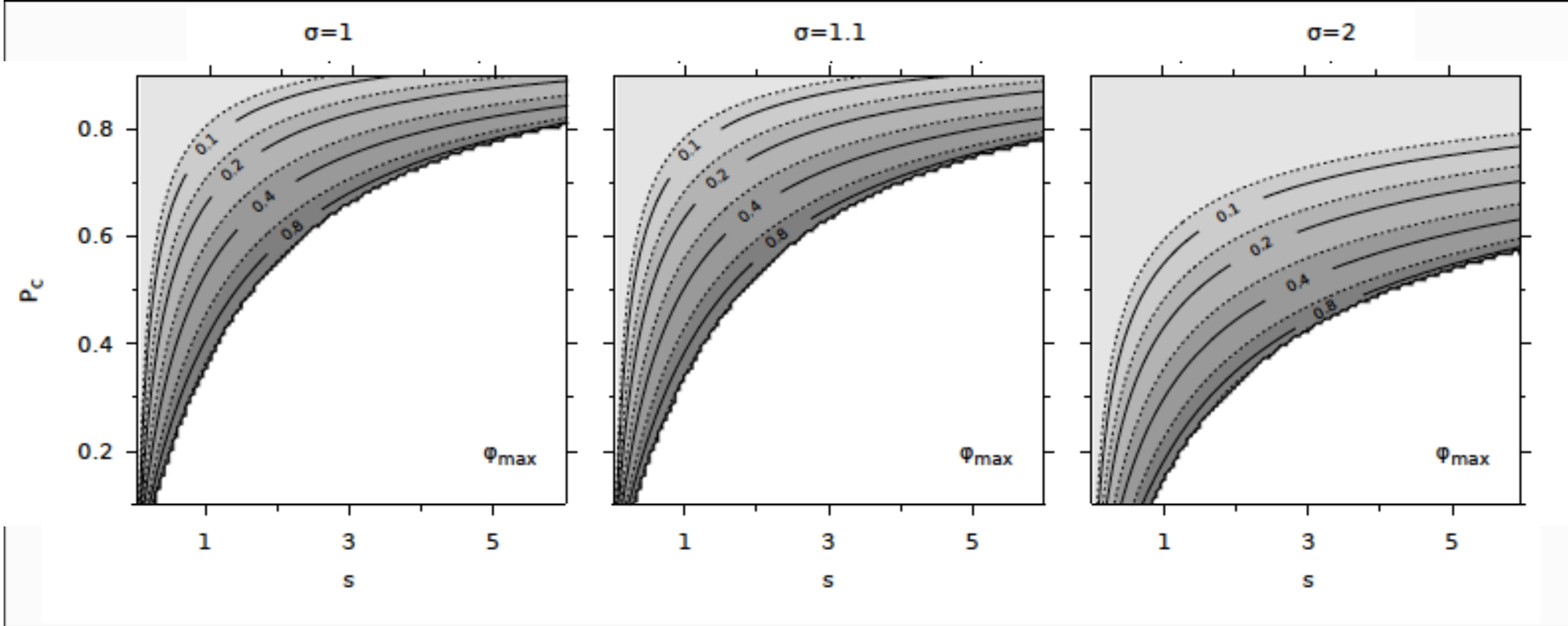
Non-linear elliptic equation → iterative numerical method (needs initial guess)

Toroidal function

$$T(P) = \begin{cases} s(P - P_c)^{\sigma} & \text{for} \quad P \geqslant P_c \,, \\ 0 & \text{for} \quad P < P_c \,. \end{cases}$$

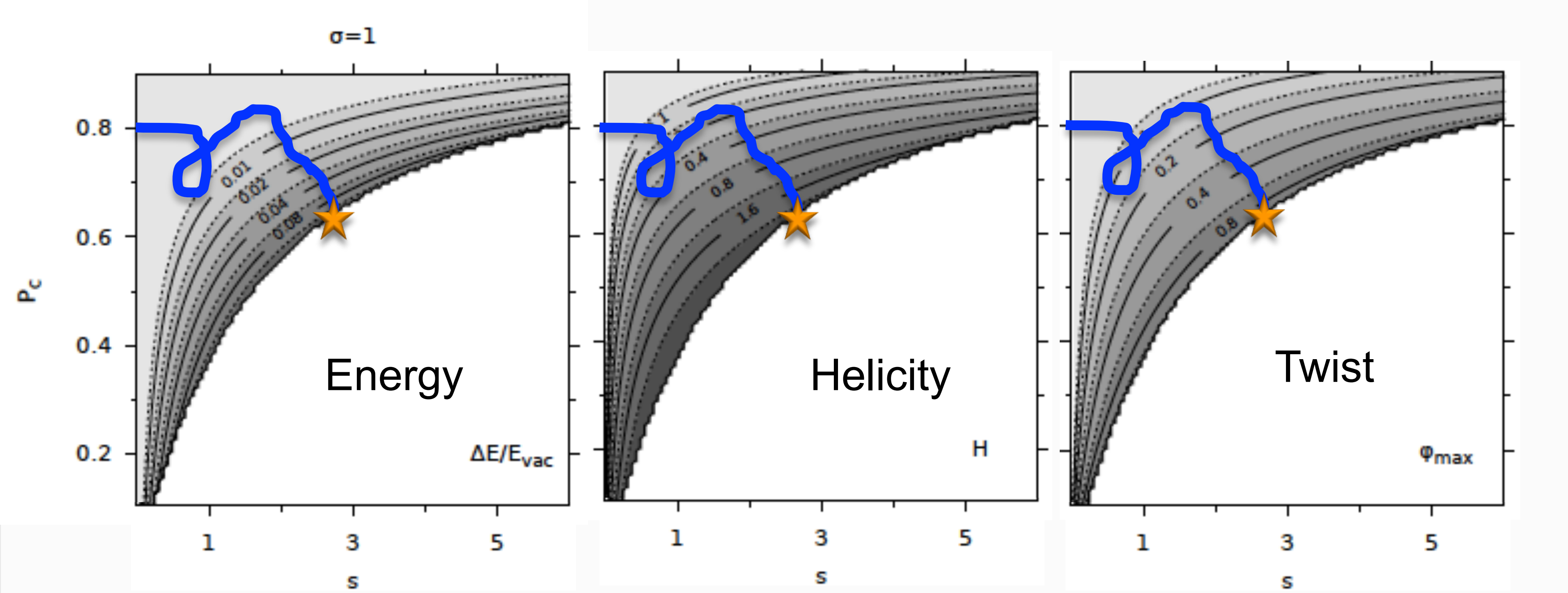


Twist



- Solutions of the GS equation with twist larger than ~1 cannot be found
- This limit is similar to dynamical simulations.
- **Is this limit related to the stability of the solution?**

Applications



- More realistic magnetospheres to compute emission
- If we can reliably estimate maximum twist with this method…
  - Force-free configurations can be computed within seconds.
  - Can be coupled to magnetothermal evolutions.

Uniqueness of the solution

$$\Delta_{GS} P = -T(P)T'(P)$$: Grad-Shafranov equation

- Current free (potential solutions):

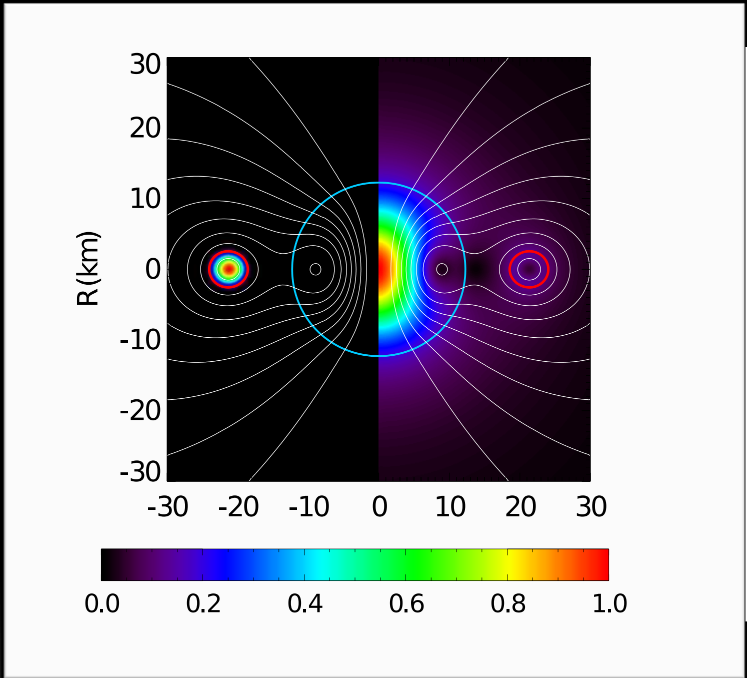
  $$\Delta_{GS} P = 0$$ + boundary conditions →Unique solution

- Linear perturbations in $T(P)$ → Unique solution (see e.g. Gabler et al 2014): potential solution + $T(P)$
- Bineau 1972 proved uniqueness for sufficiently small twist
- General case: it is not possible to use a maximum principle to prove uniqueness of the solution.

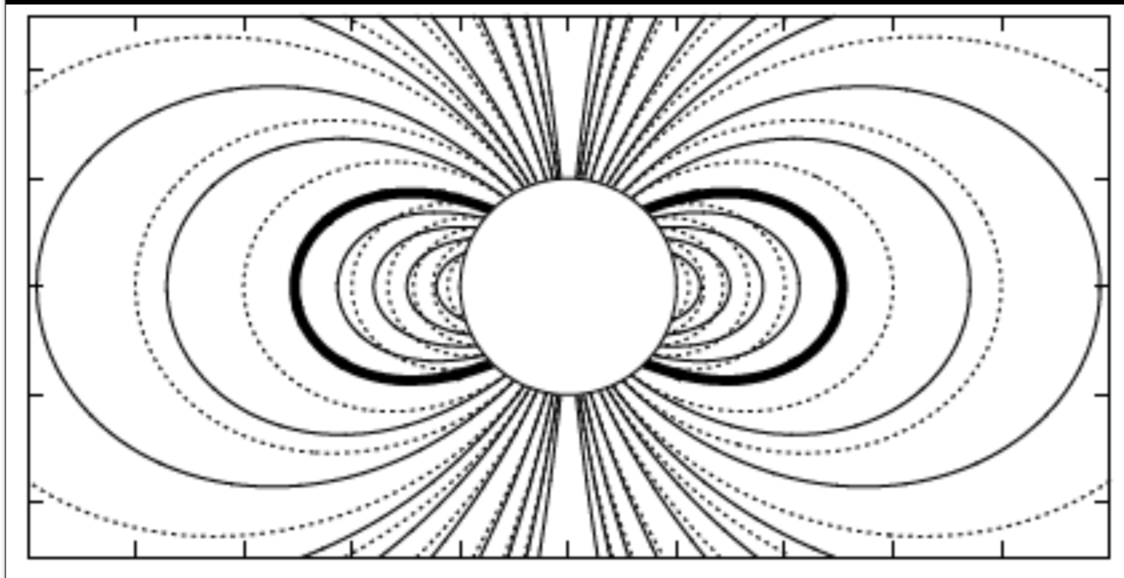
Solution may not be unique above certain threshold twist

Uniqueness of the solution?

Pili et al 2015



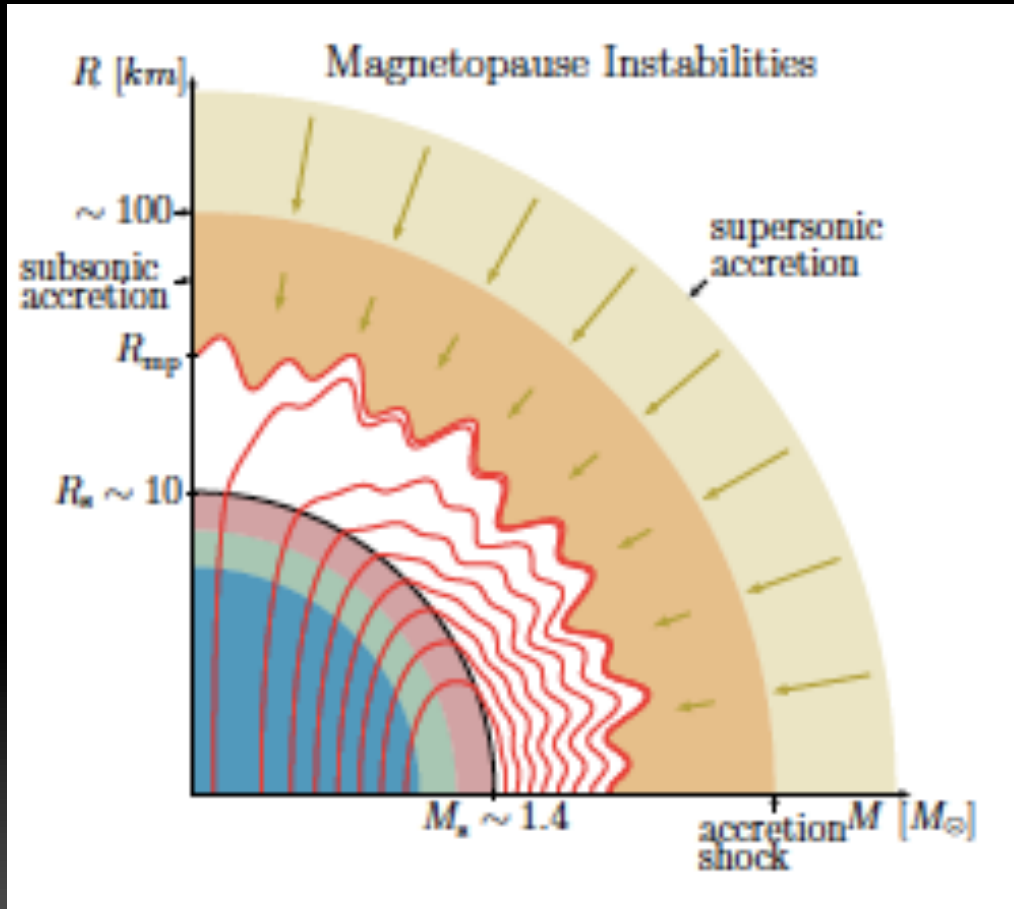
Akgün et al 2015



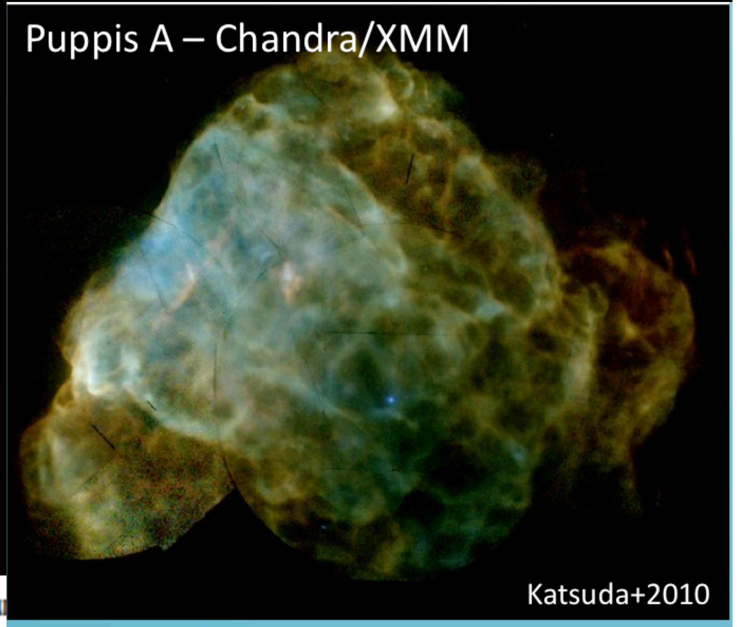
Discrepancy in force-free configurations for similar boundary conditions:

- Pili et al 2015 found different topologies of the magnetic field
- **Are we facing a problem with non-unique solution?**

Fallback and magnetic field burial



Central compact objects (CCOs)



- Isolated NS with no radio emission
- Associated to supernova remnants
- Inferred magnetic field smaller than typical radio-pulsars
- Spind-down age >> real age → CCOs were born with present spin

Table 1. Central Compact Objects in Supernova Remnants. From left to right the colu age, the distance d, the period P, the inferred surface magnetic field, B_s, the bolometric luminosity in X-rays, $L_{x,bol}$, the name of the remnant, the characteristic age, and bibliographical references.

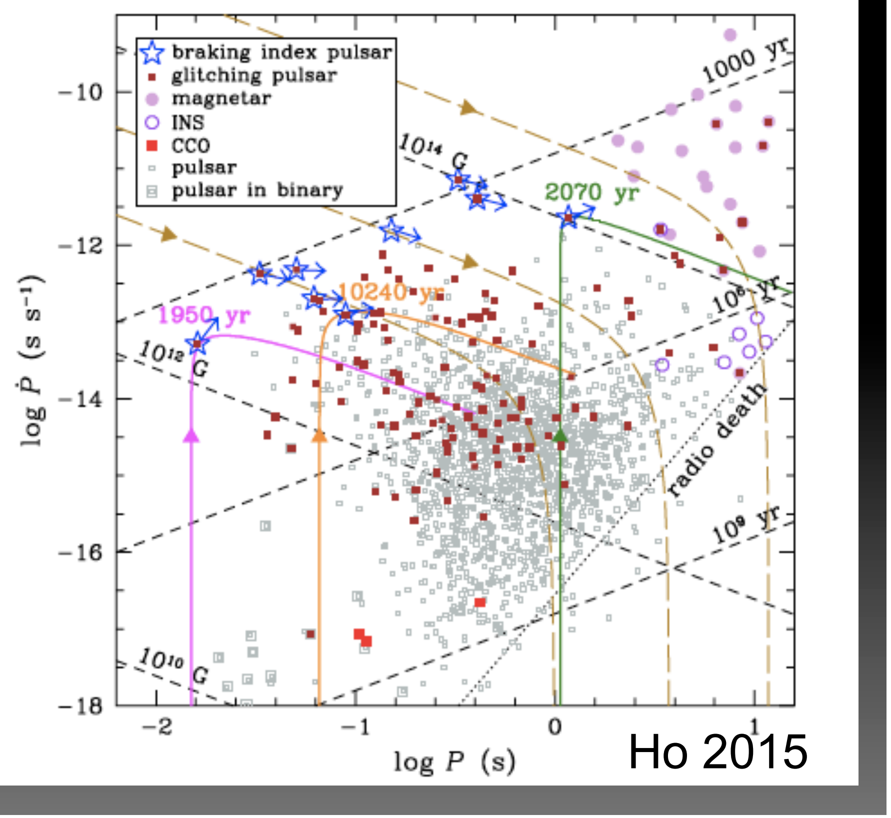
CCO	Age (kyr)	d (kpc)	P (s)	B_s 10^{11}G	$L_{x,bol}$ (erg s^{-1})	SNR	τ_c (Myr)	References
J0822.0-4300	3.7	2.2	0.112	0.65	6.5×10^{33}	Puppis A	190	1, 2
1E 1207.4-5209	7	2.2	0.424	2	2.5×10^{33}	PKS 1209-51/52	310	2, 3, 4, 5, 6, 7
J185238.6 + 004020	7	7	0.105	0.61	5.3×10^{33}	Kes 79	190	8, 9, 10, 11

References: (1) Hui & Becker (2006), (2) Gotthelf & Halpern (2013), (3) Zavlin et al. (2000), (4) Mereghetti et al. (2002), (5) Bignami et al. (2003), (6) De Luca et al. (2004), (7) Gotthelf & Halpern (2007), (8) Seward et al. (2003), (9) Gotthelf et al. (2005), (10) Halpern et al. (2003), (11) Halpern & Gotthelf (2010)

CCO models

Hidden magnetic field model

- Magnetic field buried by SN fallback
- Re-emergence of the magnetic field in 1-10^7 kyr
  (Young & Chanmugan 1995, Muslimov & Page 1995, Geppert et al. 1999, Shabaltas & Lai 2012, Ho 2011, Viganò & Pons 2012, Ho 2015).
- CCOs could be evolutionary linked to braking index pulsars (Ho 2015)



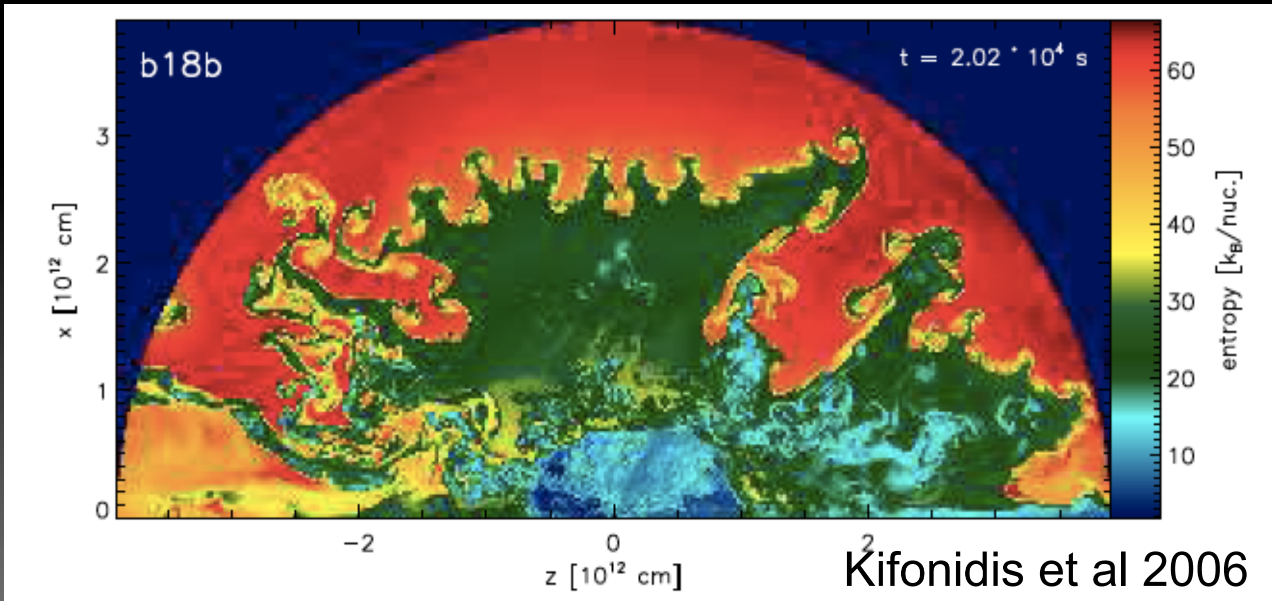
Ho 2015

"Anti-magnetar" model
(Halpern et al 2007)

- Born with low magnetic field
- Slowly rotating progenitors
- Numerical simulations show non-rotating progenitors can produce pulsar-like magnetic fields (Endeve et al 2012, Obergaulinger et al 2014)

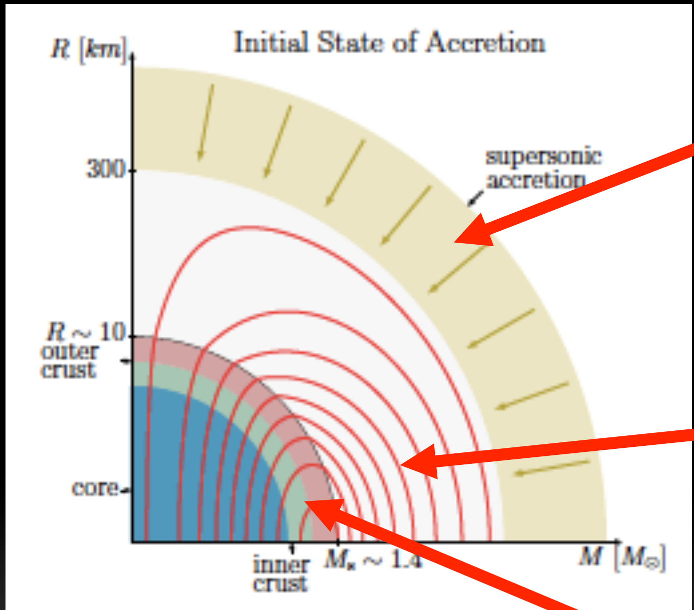
Supernova fallback

- SN shock produces reverse shock at composition discontinuities (e.g. H-He transition)
- Some material falls back into the NS (Colgate 1971, Chevalier 1989)
- Amount of fallback material ~10^{-4} – 1 M_{sun}
  (Woosley et al. 1995; Zhang et al. 2008; Ugliano et al. 2012, Ertl et al 2016)
- Accretion rate ~$t^{-5/3}$ → most of the matter accretes in 10^3 - 10^4 s



Kifonidis et al 2006

Fallback into neutron star



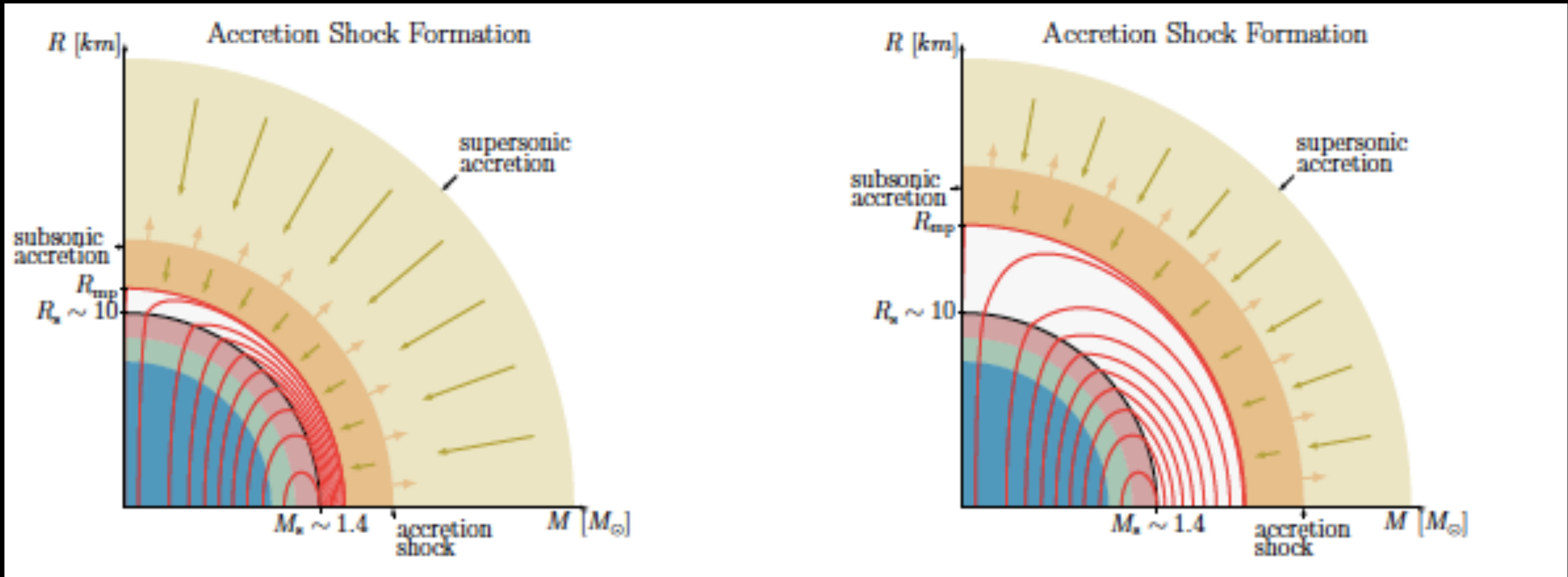
Fallback material
- Supersonic accretion
- Super-Eddington (>10^6)
- Adiabatic compression (no cooling)
- s~1-100 k_N/nuc
- Basically unmagnetized

Magnetically dominated magnetosphere

NS ~1 hour after onset of explosion
- Cold NS
- Inner crust crystalized

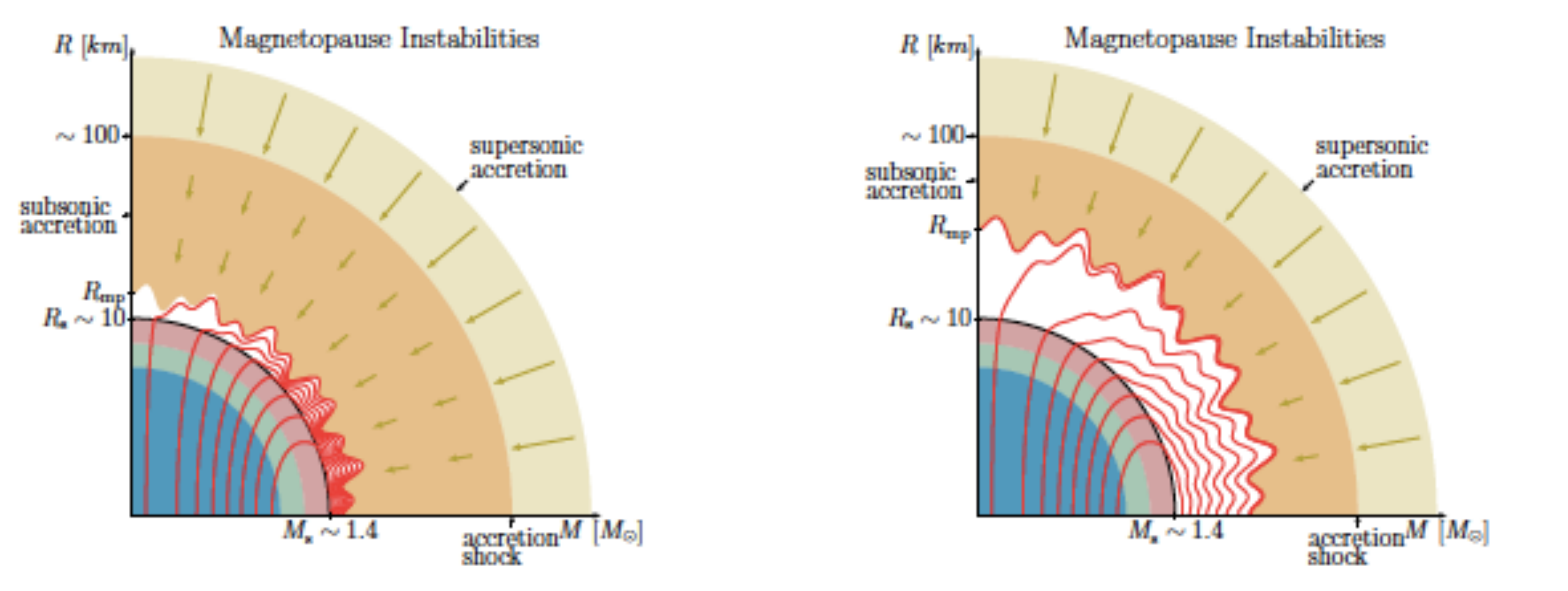
(Page et al 2004, Aguilera et al 2008)

Accretion shock formation



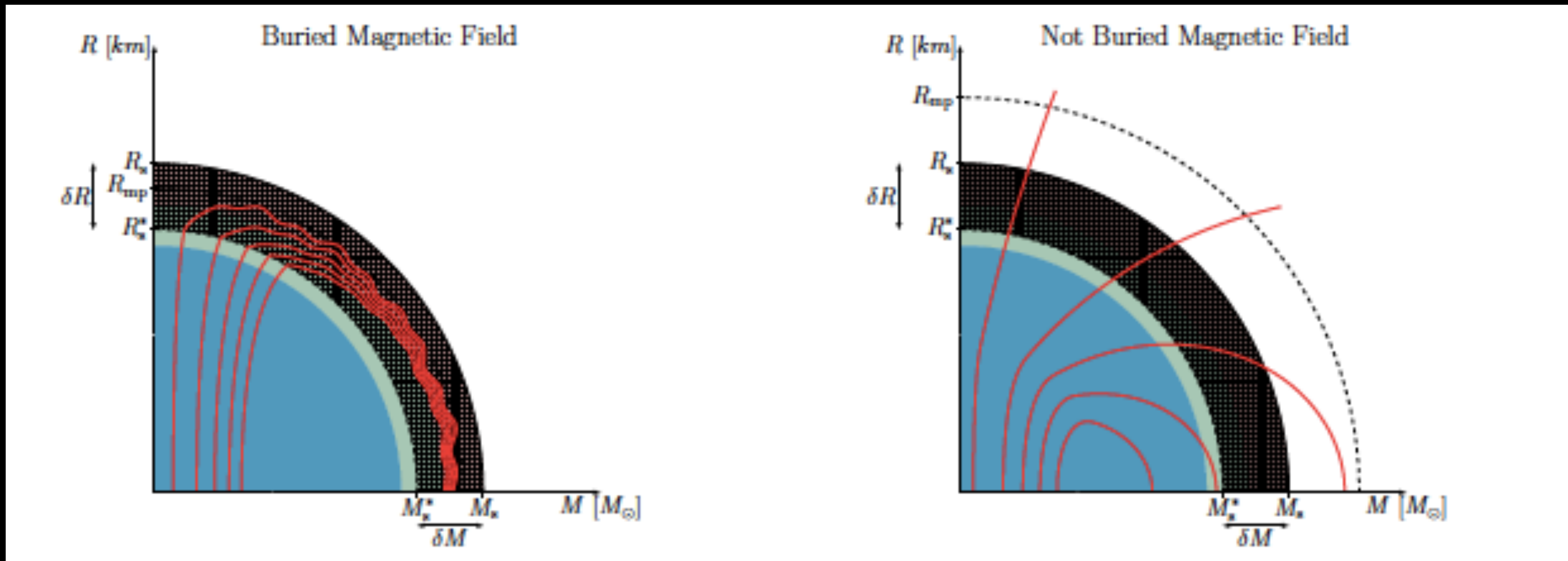
- Accretion shock is formed as the shock is slowed down by the NS surface or the compressed magnetosphere (Chevalier 1989)
- The shock stalls at about 10^7-10^8 km (Houck et al 1991)

Development of instabilities



- The compressed magnetosphere is supporting the fluid
- Magnetopause subject to interchange instabilities (Kruskal & Schwarzschild 1954, Arons & Lea 1976, Michel 1977)
- Mixing may allow accretion onto NS surface and dynamical reemergence of the magnetic field

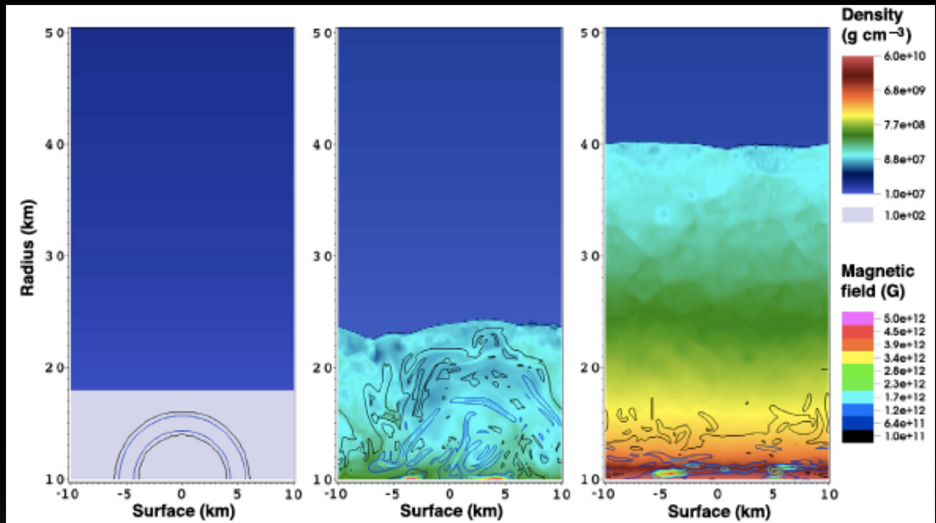
End of the accretion phase



- High accretion / low B field
  - instability vertical scale << burial depth
  - Buried field
- Low accretion / high B field
  - Instability vertical scale >> burial depth
  - Dynamical reemergence → non buried field?

Previous works

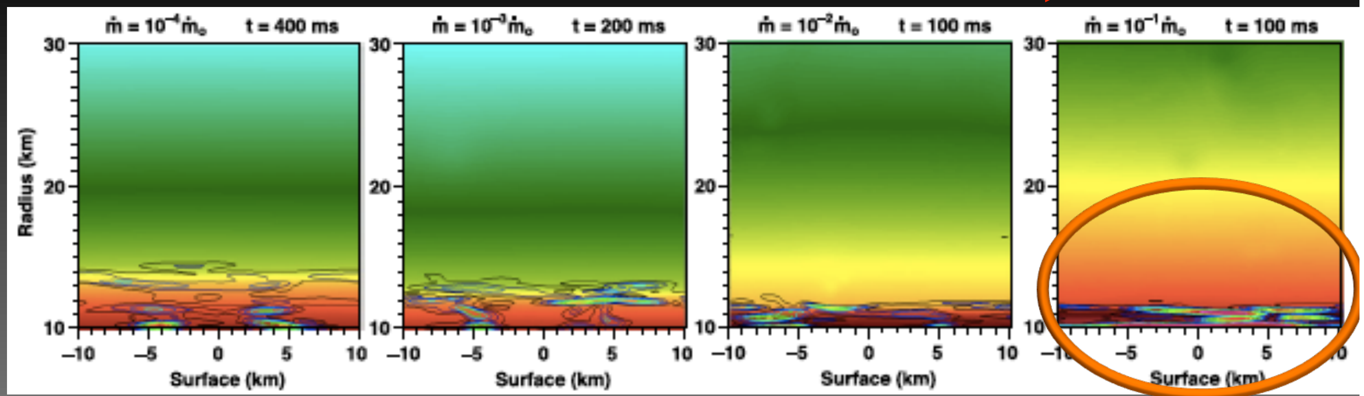
- Local MHD simulations
- Simplified geometries
- Difficult to resolve numerically all relevant regimes



- Payne & Melatos (2004, 2007)
- Bernal et al. (2010, 2013);
- Mukherjee et al (2013a,b)

Increasing accretion rate

Bernal et al 2013

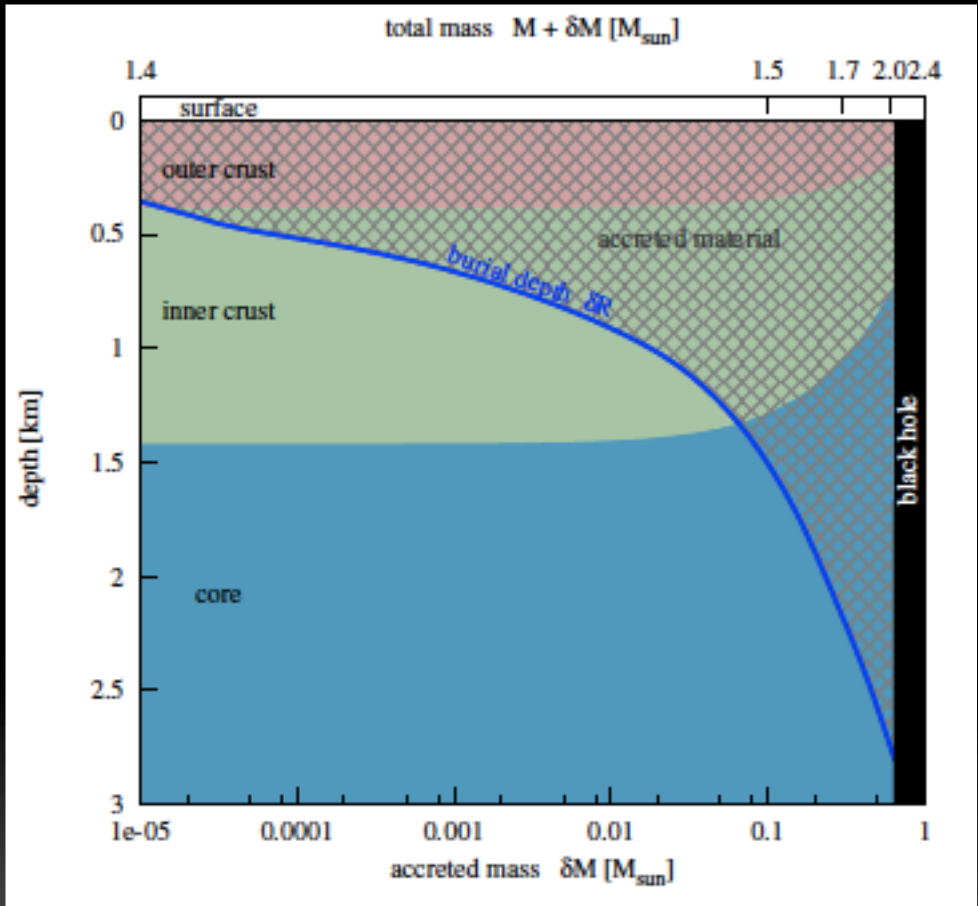


Our work (Torres-Forné et al 2016)

instability vertical scale vs burial depth

- Simple model: easy to explore parameter space
- Covers different regimes with similar accuracy
- Burial condition do not depend on details of the instabilities
- Non-buried case may depend on details of the inestabilities

Burial depth

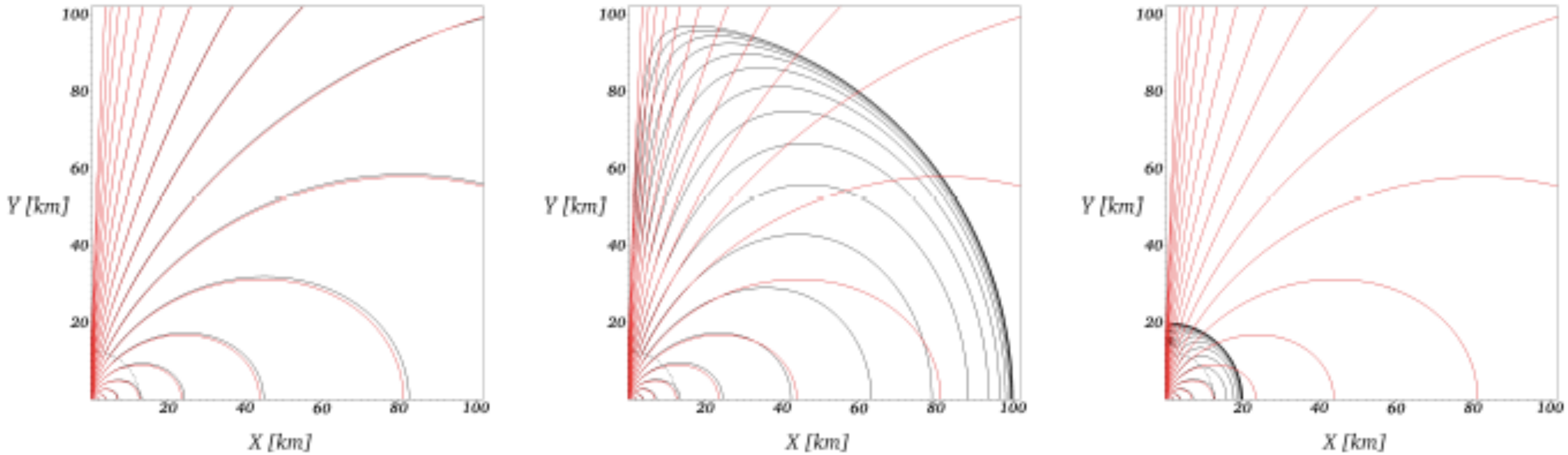


Depends on:

- Total accreted mass
- Equation of state
- Initial NS mass

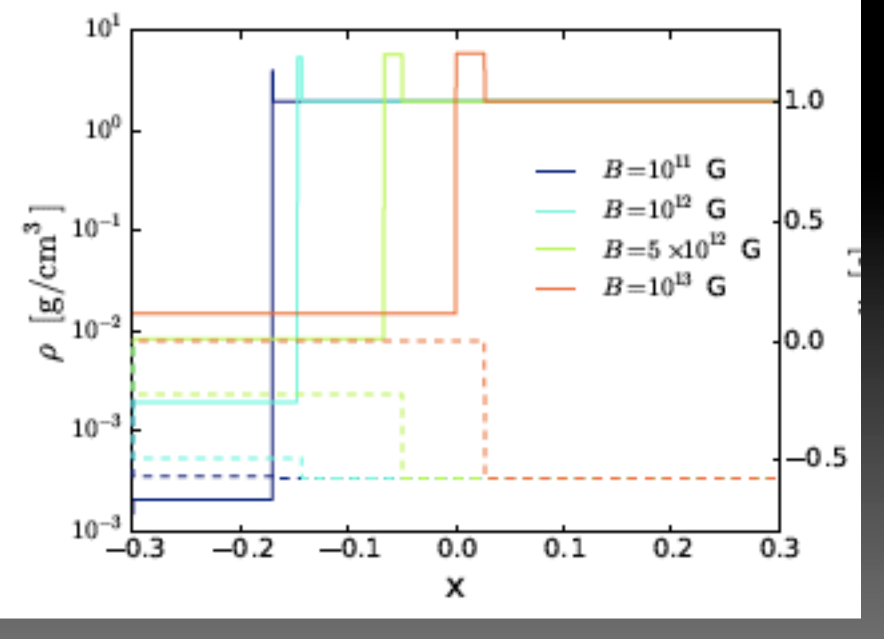
Compressed magnetosphere

- Force-free magnetosphere (potential solution) compressed by spherically accreting matter (non-dynamic)
- We use different configurations for the NS field
- Magnetic pressure increases as magnetosphere is compressed
- Magnetic pressure is highest at the equator



Magnetopause location

- Equilibrium point between ram pressure of infalling material and magnetic pressure
- We solve the MHD Riemann problem (Romero et al 2005) to find the equiibrium point (zero velocity contact discontinuity)
- Iteratively computed with magnetosphere
- Depends on: composition, entropy per baryon, accretion rate
- Helmholtz EoS

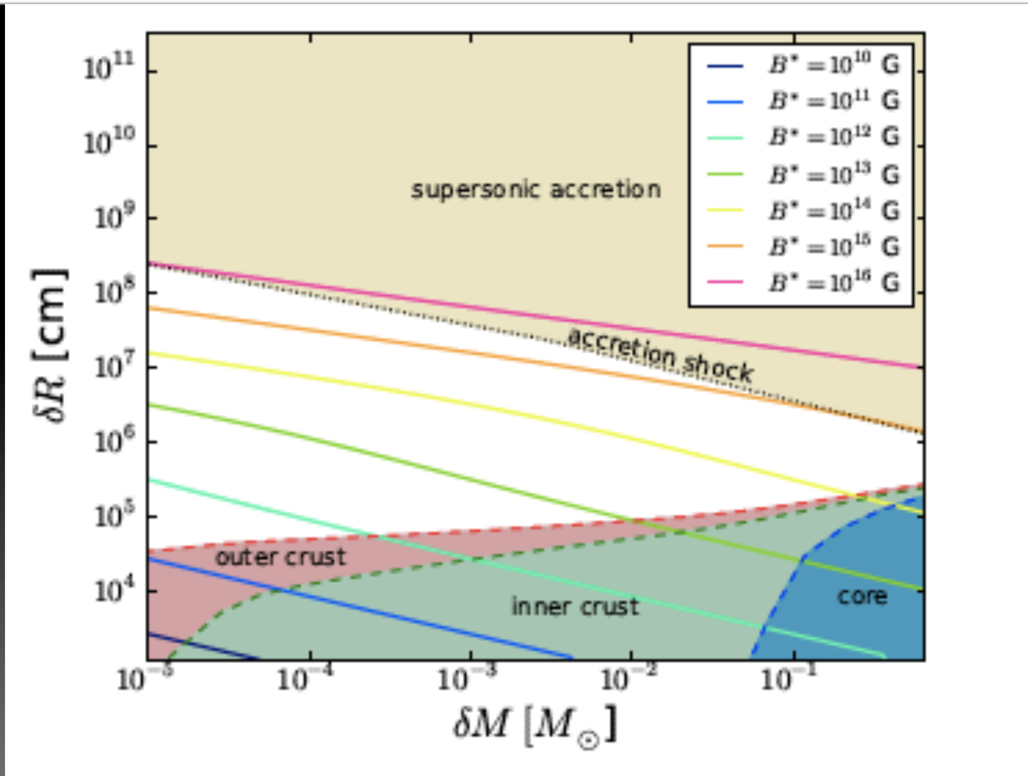


Instability vertical scale

Interchange instability (Kruskal & Schwarzschild 1954):

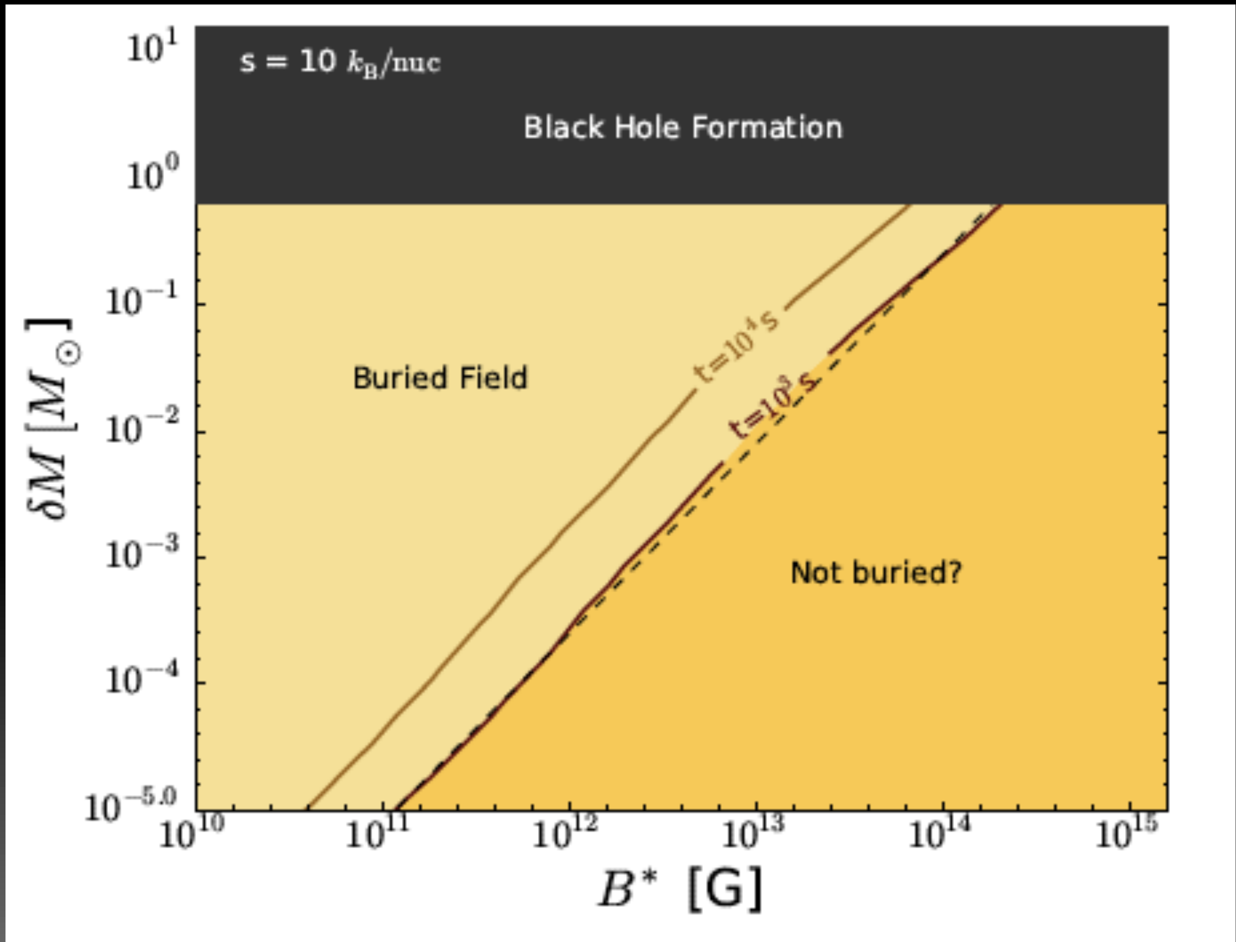
- All wavelengths are unstable
- Instability limited by the height of the magnetosphere

Magnetopause height over NS ~ instability vertical scale



Exploring the parameter space

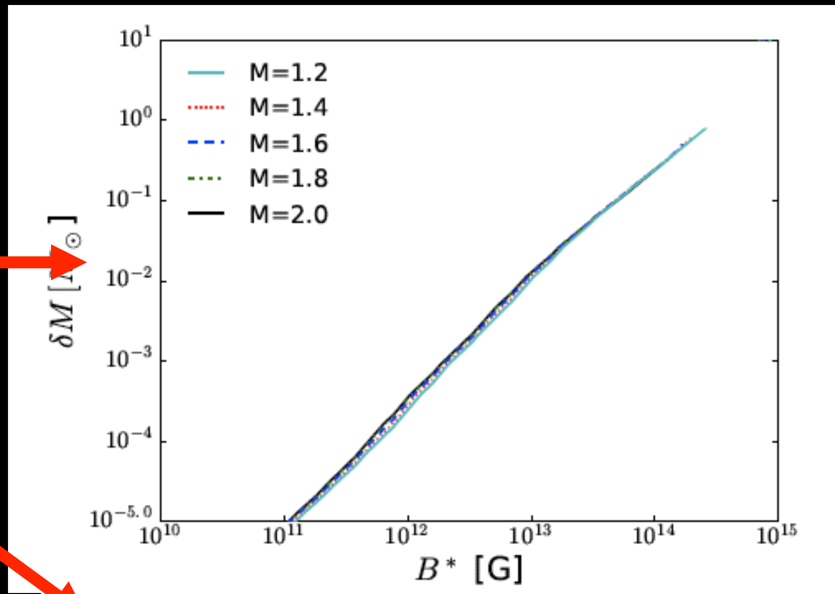
- Typical pulsar is easily buried by falback
- Very difficult to bury magnetar fields

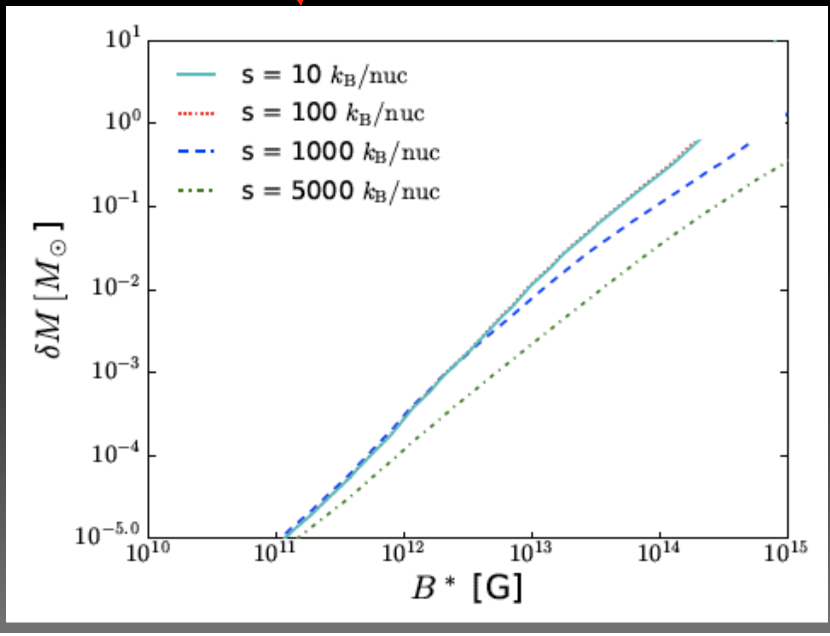


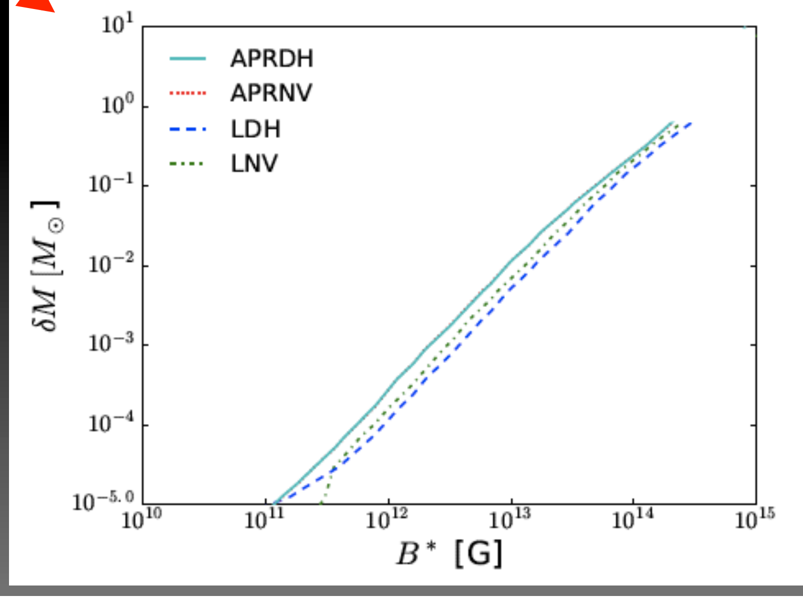
Exploring the parameter space

Results not very sensitive to different parameters

- Mass
- NS EoS
- Entropy per baryon







Conclusions

- Force-free magnetosphere models matching NS interior fields
  → emission mechanism
  → Magnetothermal evolution
  → Possible estimation of reconnection events
- Internal magnetar oscillations couple to the magnetosphere
  → QPO modulation mechanism
  → 1:3:5 frequencies ←→ odd/even symmetry
- CCOs: Buried magnetic field scenario is plausible