Introduction to the Astrophysics of Neutron Stars

INT Workshop “Astro-solids, Dense Matter, and Gravitational Waves” Introductory lecture, April 16, 2018

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This talk

Aim is to cover (at least some of) the astrophysics background relevant for continuous gravitational wave sources

Want to understand:

- population of sources that may produce continuous GWs
- spins
- (internal) magnetic fields, crust properties (composition, yielding)
- core temperatures and composition
- particularly accreting neutron stars

Outline:

- neutron star census
- neutron star magnetism
- accreting neutron stars

The Neutron Star Census

Back of the envelope:

supernova rate ~ 0.01 yr^{-1}, lifetime of the Galaxy ~ 10^{10} yrs

=> ~ 10^8 neutron stars in the Galaxy

About 3000 known:

		energy source
Radio pulsars	2635	rotation
Accreting neutron stars	~200	accretion
Thermally-emitting neutron stars	~10	thermal (cooling)
Magnetars	29	magnetic field decay

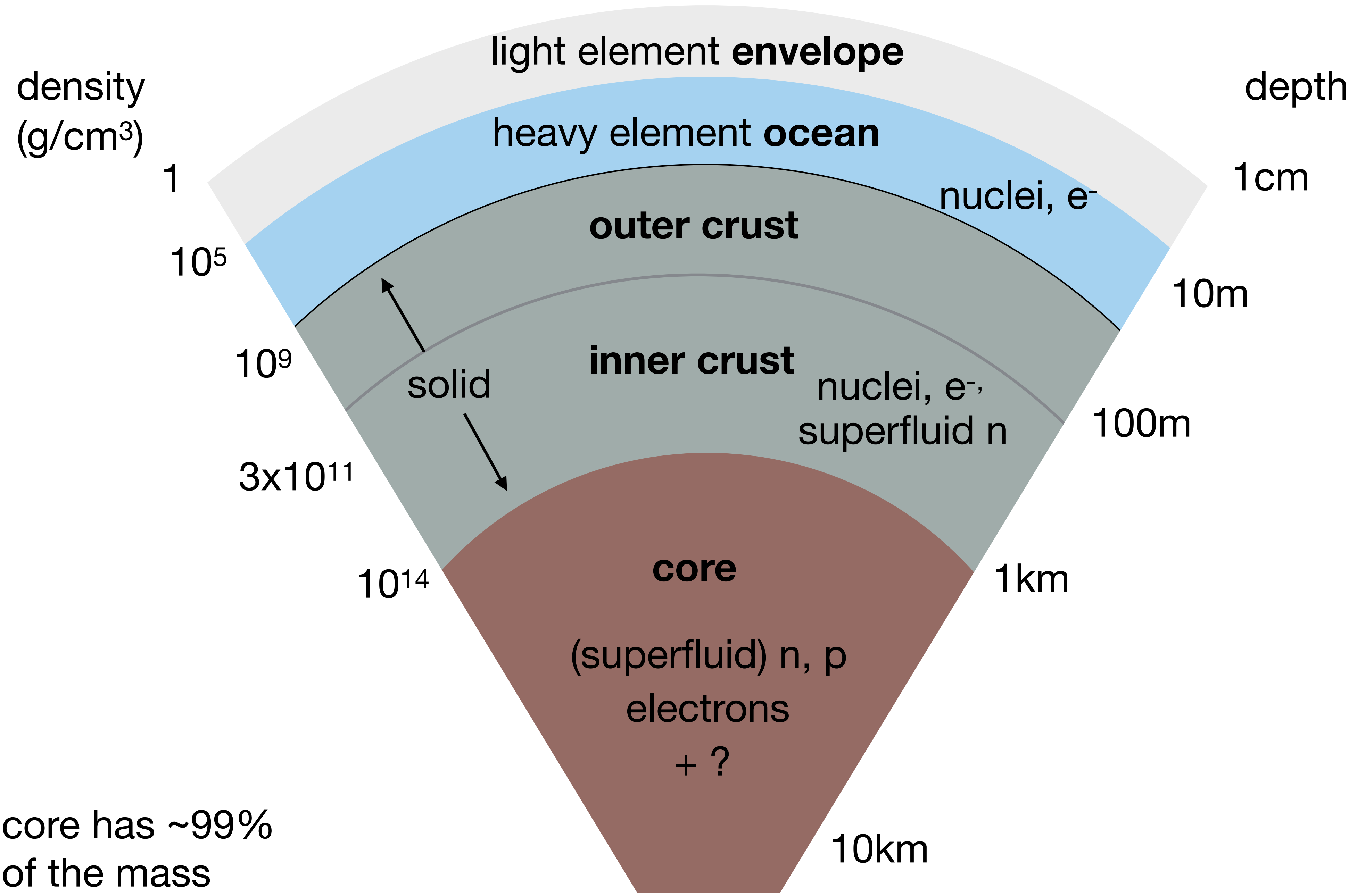
partly selection effects, but also they are not visible for very long:

~10^6 yrs in thermal emission (X-rays)

~10^8 yrs in radio

longer in accreting binaries

Neutron star internals



density (g/cm^3)

1

10^5

10^9

3×10^{11}

10^{14}

light element **envelope**

heavy element **ocean**

nuclei, e$^-$

outer crust

solid

inner crust

nuclei, e$^-$,
superfluid n

core

(superfluid) n, p
electrons
+ ?

depth

1cm

10m

100m

1km

10km

core has ~99%
of the mass

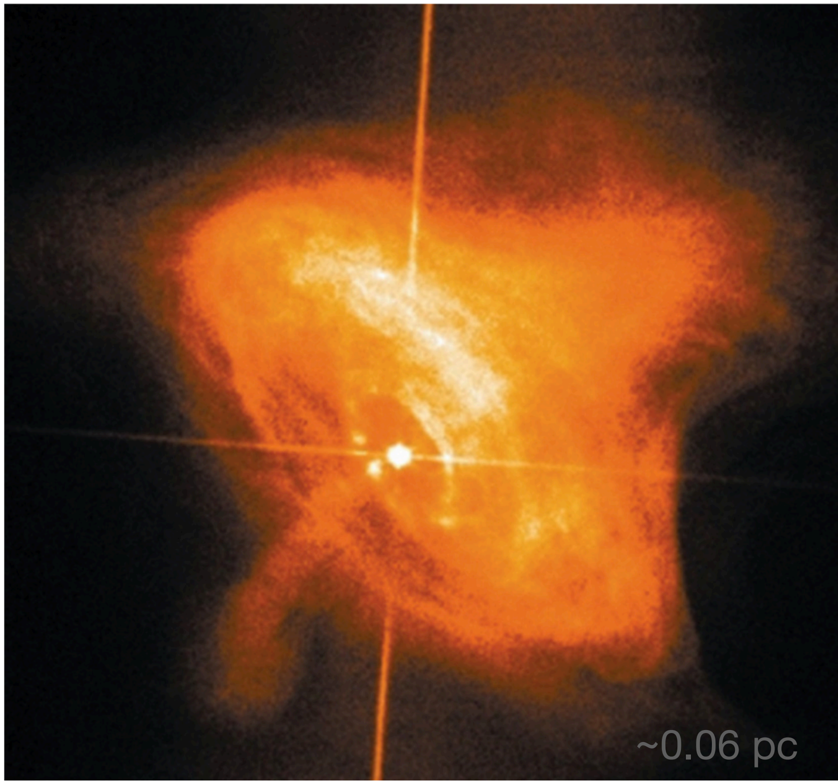
Diversity of observed neutron stars

1. radio pulsars

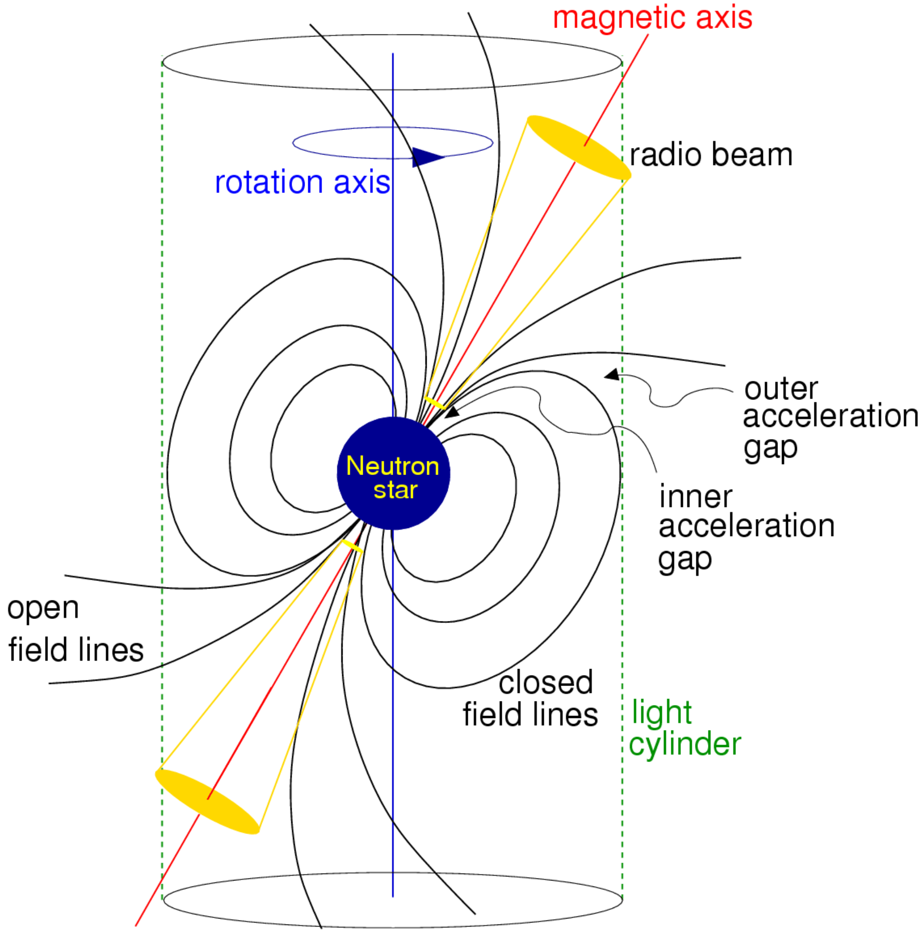
    - show radio pulses at the neutron star spin period (“lighthouse”)
    - powered by rotational energy as the star spins down
    - wide range of periods from ~2 ms to ~10 s, and magnetic fields 10^8—10^{13} G
    - young pulsars generally have “pulsar wind nebulae” and/or are in supernova remnants
    - young pulsars show glitches

ATNF pulsar catalog:

http://www.atnf.csiro.au/people/pulsar/psrcat/



Radio pulsar spin and magnetism



Lorimer & Kramer, Handbook of Pulsar Astronomy

- vacuum spin down:

$$\frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = -\frac{2}{3c^3}\mu^2\sin^2\theta\,\Omega^4$$

gives

$$B \approx 3.2\times10^{19}\,\mathrm{G}\,\left(P\dot{P}\right)^{1/2}$$

- dependence on magnetic inclination in this formula is wrong - when plasma is included an aligned rotator *does* spin down

- force-free magnetosphere gives similar prefactor and scalings (<factor of 2)

Contopolous et al. (1999), Spitkovsky (2006)

- braking index $n = \frac{\ddot{P}P}{\dot{P}^2}$ $\dot{\Omega} \propto \Omega^n$ only a handful of observed values: all are n<3

Diversity of observed neutron stars

1. radio pulsars

2. gamma-ray pulsars

- The most energetic radio pulsars can be detected in gamma-rays, with L ~ 10^{-3} Edot
- Emission from accelerated particles in the magnetosphere
- Fermi dramatically increased the number of known gamma-ray pulsars to >200

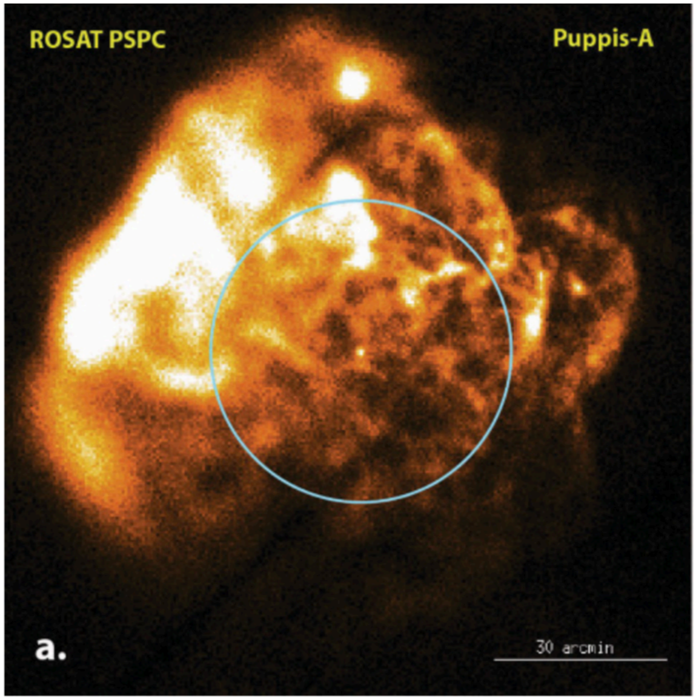
https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

Diversity of observed neutron stars

1. radio pulsars
2. gamma-ray pulsars
3. isolated neutron stars

- ROSAT all-sky survey found 7 isolated neutron stars in soft X-rays (kT ~ 100 eV ~ 10^6 K)
- they are not radio pulsars, and have high X-ray to optical ratio
- consistent with being isolated, cooling, neutron stars
- often referred to as XDINS
- six of the seven have measured spin periods, ranging from 3–12s
- eROSITA (launching 2018?) should find more

Diversity of observed neutr



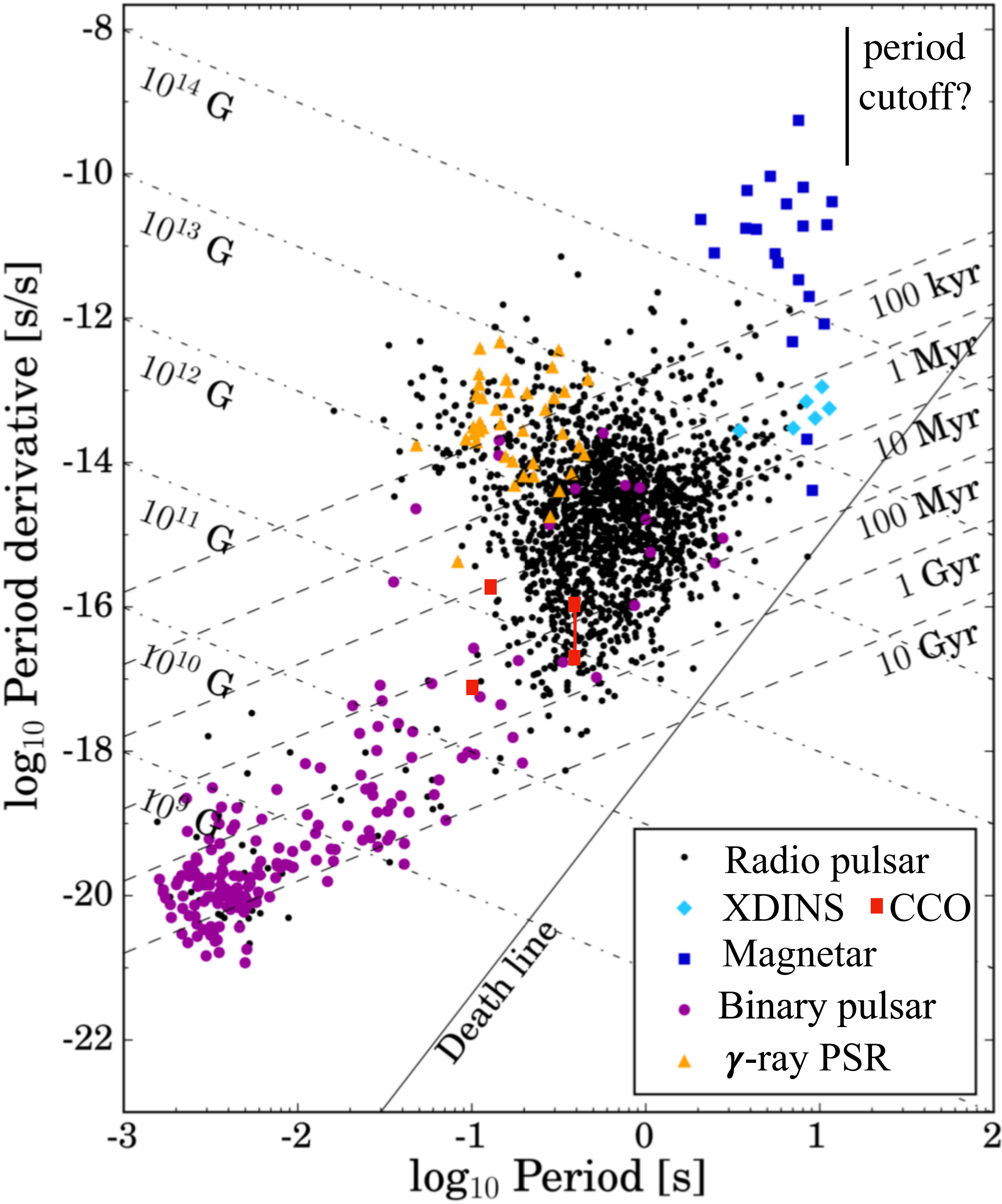
1. radio pulsars
2. gamma-ray pulsars
3. isolated neutron stars
4. central compact objects
    - X-ray sources found in supernova remnants
    - constant luminosity consistent with young NS, small blackbody emitting area
    - association with SNRs => young age $<10^4$ yrs
    - no pulsar wind nebula, not radio pulsars
    - 3 have measured spins in the range P=0.1-0.4 s, one has a 6.7h periodicity

Diversity of observed neutron stars

1. radio pulsars
2. gamma-ray pulsars
3. isolated neutron stars
4. central compact objects
5. magnetars
   - show gamma-ray and X-ray enhancements on a range of timescales — short (<1s) gamma-ray bursts to months long X-ray outbursts
   - luminosity >> rotational energy loss, instead powered by magnetic field decay
   - spin periods 2-12s, dipole fields ~ 10^{14} G
   - 29 magnetars known << number of radio pulsars, but the magnetar birth rate appears to be a significant fraction (~0.1) of pulsar birth rate.

http://www.physics.mcgill.ca/~pulsar/magnetar/main.html

P-Ṗ diagram



- magnetic field strength

$$B \approx 3.2 \times 10^{19}\,\mathrm{G}\,\left(P\dot{P}\right)^{1/2}$$

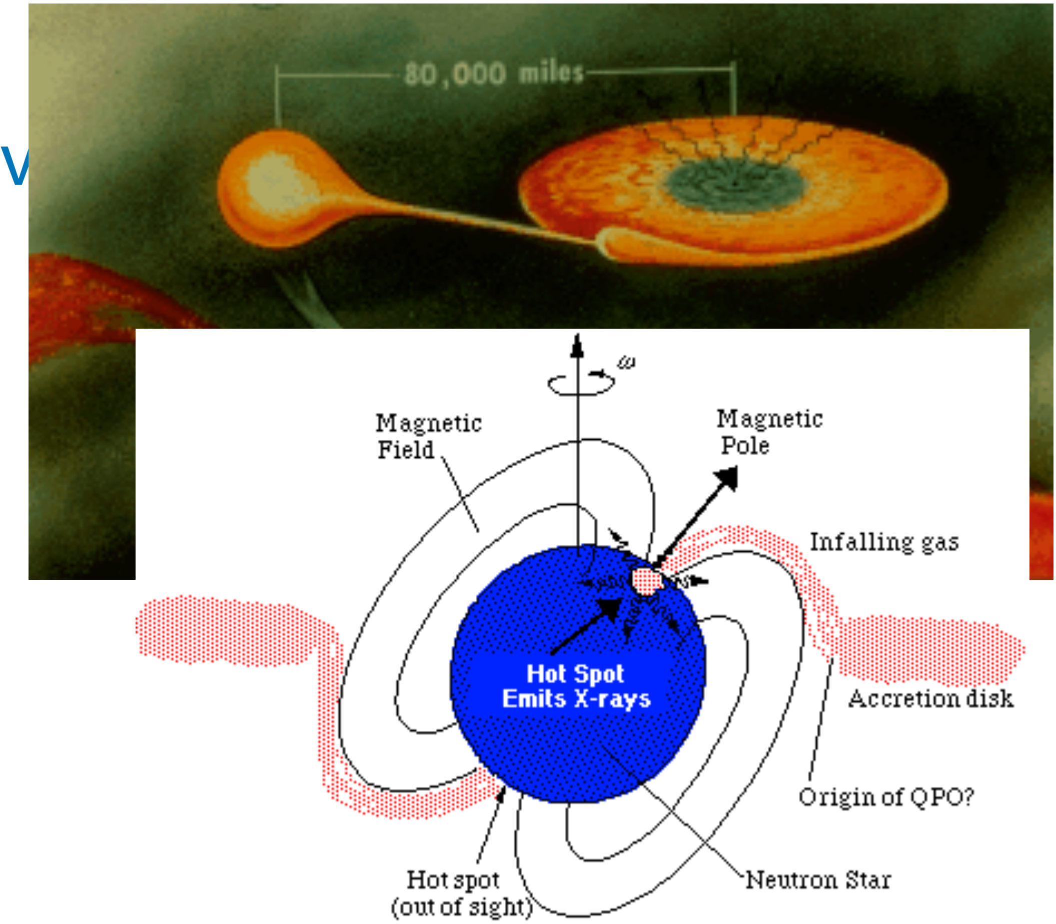
- spin down age

$$\tau = \frac{P}{2\dot{P}}$$

Figure from Graber (2016); data from ATNF catalog

Diversity of observ

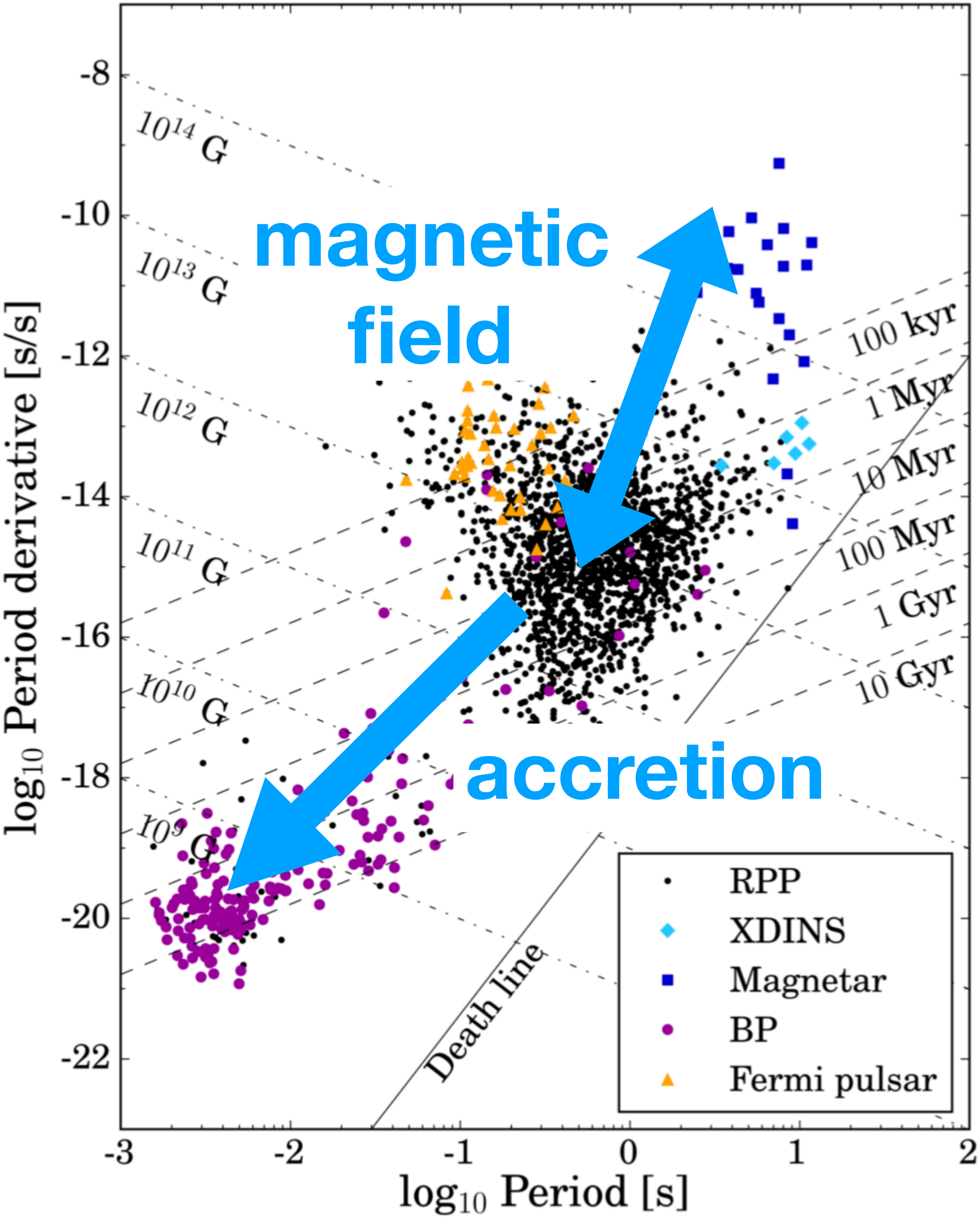
1. radio pulsars
2. gamma-ray pulsars
3. isolated neutron stars
4. central compact objects
5. magnetars
6. X-ray binary neutron stars



	HMXB	LMXB
companion mass	> solar mass	< solar mass
NS magnetic field	~10^{12} G	10^{8}-10^{9} G
age	~10^{7} yr	~10^{8}—10^{9} yr
NS spin	seconds — hours	typically 2-3 ms
B	~10^{11}-10^{13} G	~10^{8}-10^{9} G

https://heasarc.gsfc.nasa.gov/W3Browse/star-catalog/lmxbcat.html (hmxbcat.html)

Sources of diversity



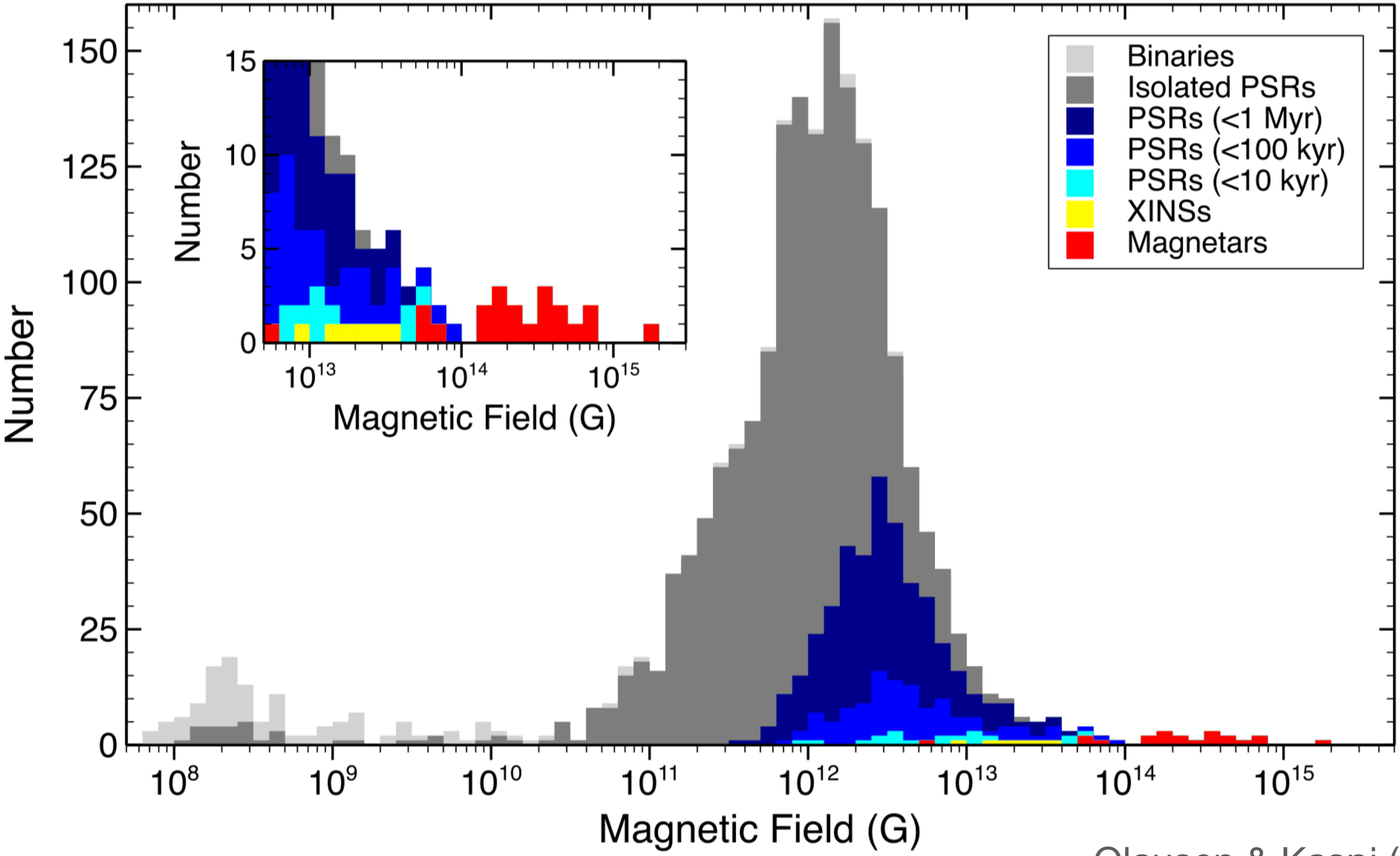
magnetic field

accretion

- B: probably internal toroidal field, certainly the dipole field does not give the whole picture
- accretion: spins up the star, leads to decay of B (?), changes crust composition

Figure from Graber (2016); data from ATNF catalog

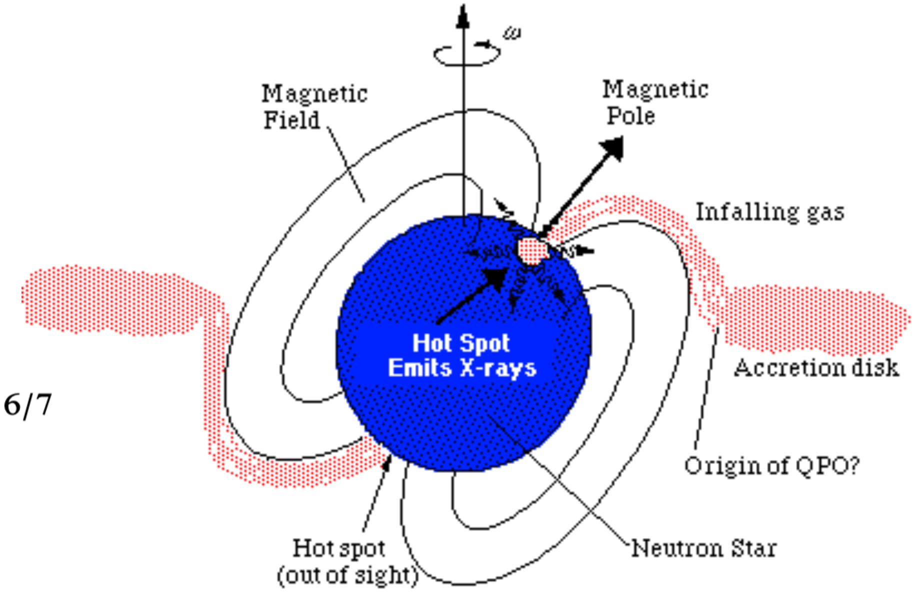
Inferred dipole magnetic field strengths: isolated NSs



Olausen & Kaspi (2014)

Magnetic fields of accreting neutron stars

- for accreting neutron stars in HMXBs, there are independent methods that provide a cross-check:



1. the size of the magnetosphere depends on the dipole field strength

$$P_{\mathbf{spin,eq}} \approx 8\ \mathrm{s}\left(\frac{10^{-10}\ M_{\odot}\ \mathrm{yr}^{-1}}{\langle \dot{M} \rangle}\right)^{3/7}\left(\frac{\mu}{10^{30}\ \mathrm{G\ cm}^3}\right)^{6/7}$$

2. cyclotron lines are seen in the X-ray spectrum of several HMXBs

$$\hbar\omega_c \approx 10\ \mathrm{keV}\ \left(\frac{B}{10^{12}\ \mathrm{G}}\right)$$

- generally $B \sim 10^{12}$G for HMXB neutron stars, although some suggestions of more strongly magnetized cases (e.g. Ho et al. 2014)

Evidence for non-dipolar fields

- two magnetars with relatively weak dipole magnetic fields

SGR 0418 has B = 7.5 x 10^{12} G Rea et al. (2010)
Swift J1822 has B = 1.3 x 10^{13} G Scholz et al. (2014)

- other types of neutron stars with weaker B have shown magnetar activity

high B radio pulsars:
PSR J1846–0258 (B = 5 x 10^{13} G) Gavriil et al. (2008)
and PSR J1119–6127 (B = 4 x 10^{13} G) Younes et al. (2016)

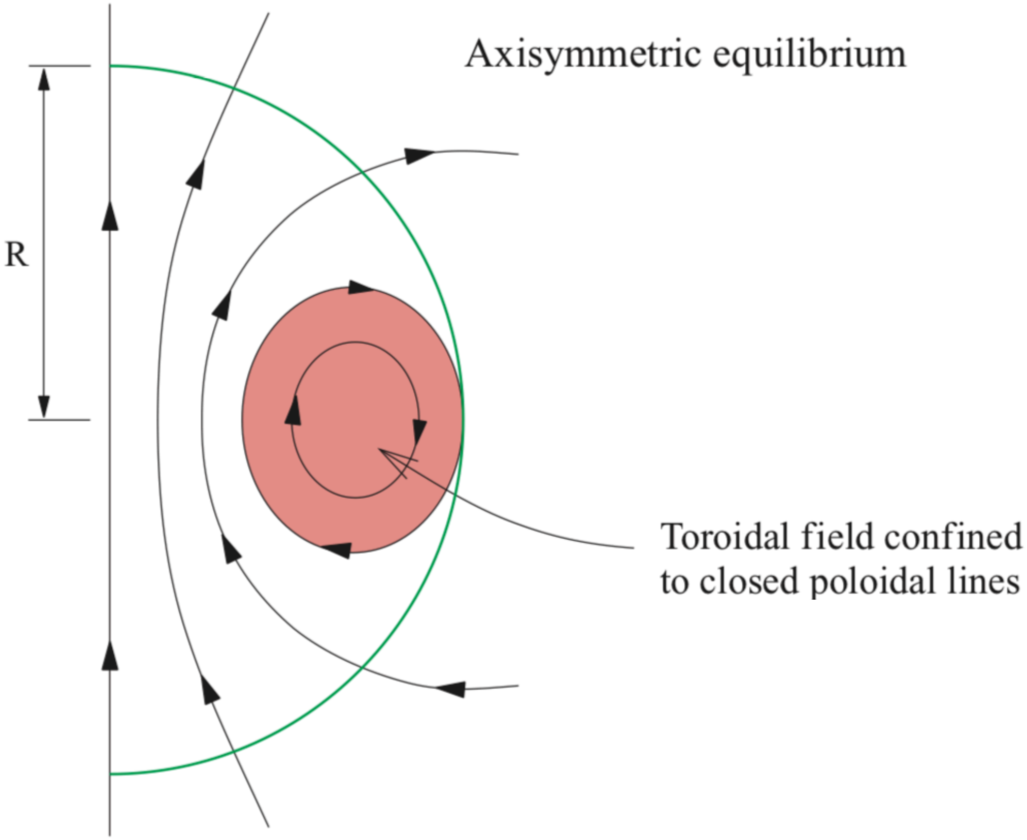
CCO in RCW 103 Rea et al. (2016)

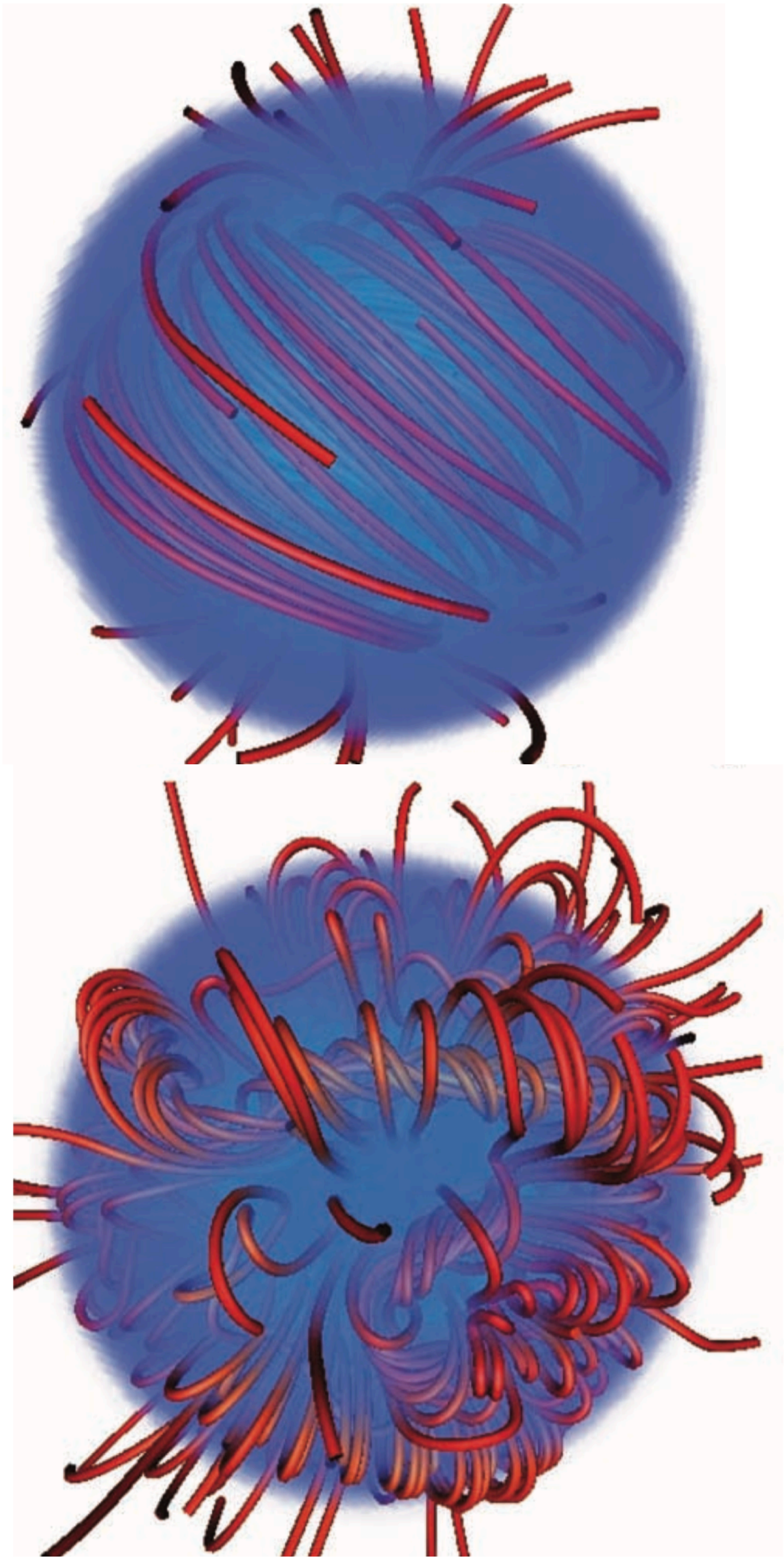
- pulse profile modelling: e.g. high pulse fraction in Kes 79 CCO => peaked temperature distribution => subsurface 10^{14}G toroidal field to prevent heat flow except at the poles Shabaltas & Lai (2013)

Similar argument for dim isolated NSs Geppert et al. (2006)

Initial conditions for B?

- before the crust solidifies the field will be in MHD equilibrium





Braithwaite & Spruit (2004), Braithwaite (2008)

The crust plays an important role in the observed magnetic activity

- the observed magnetic activity is perhaps surprising given the high conductivity of the interior

$$\tau_D = \frac{4\pi\sigma}{c^2}\left(\frac{R}{\pi}\right)^2 \sim 10^{13}\ \mathrm{yr}.$$

Baym, Pethick, Pines (1969)

evolution timescales also very long for superconducting core

- but you can get short timescales in the crust. Because the ions are fixed in the solid lattice, the magnetic field is frozen into the electron fluid (Hall-MHD). The timescale is

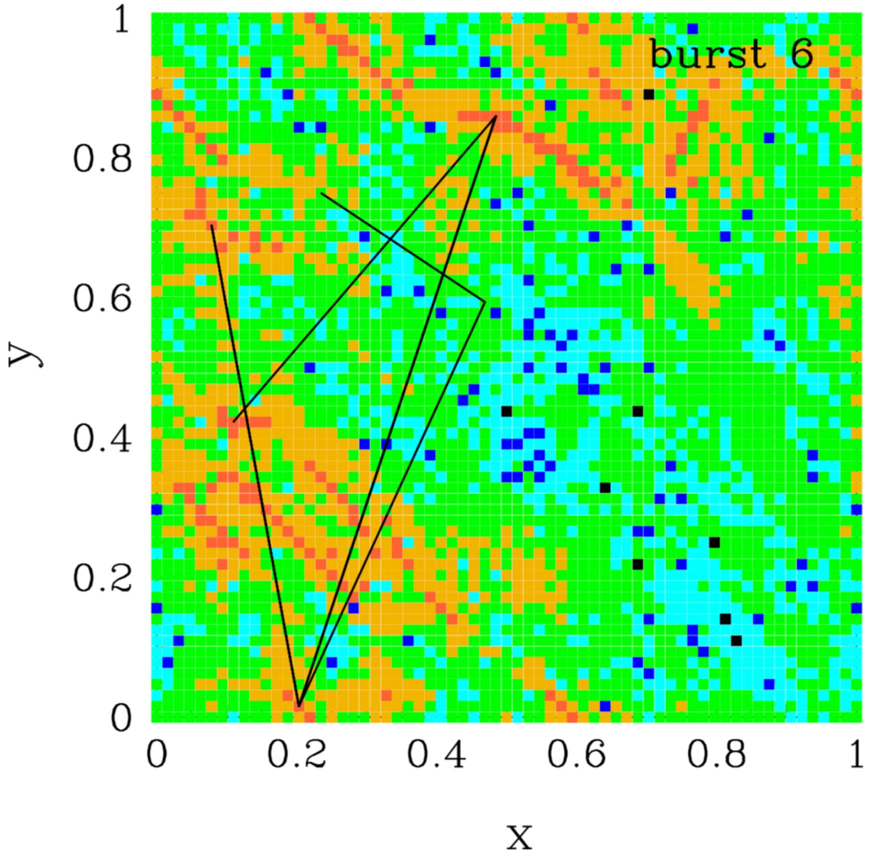
$$t_{\mathrm{Hall}} \approx 5 \times 10^8 \frac{L_5^2}{B_{12}}\left(\frac{\rho}{\rho_{\mathrm{nuc}}}\right) \mathrm{yr}$$

Goldreich & Reisenegger (1992)

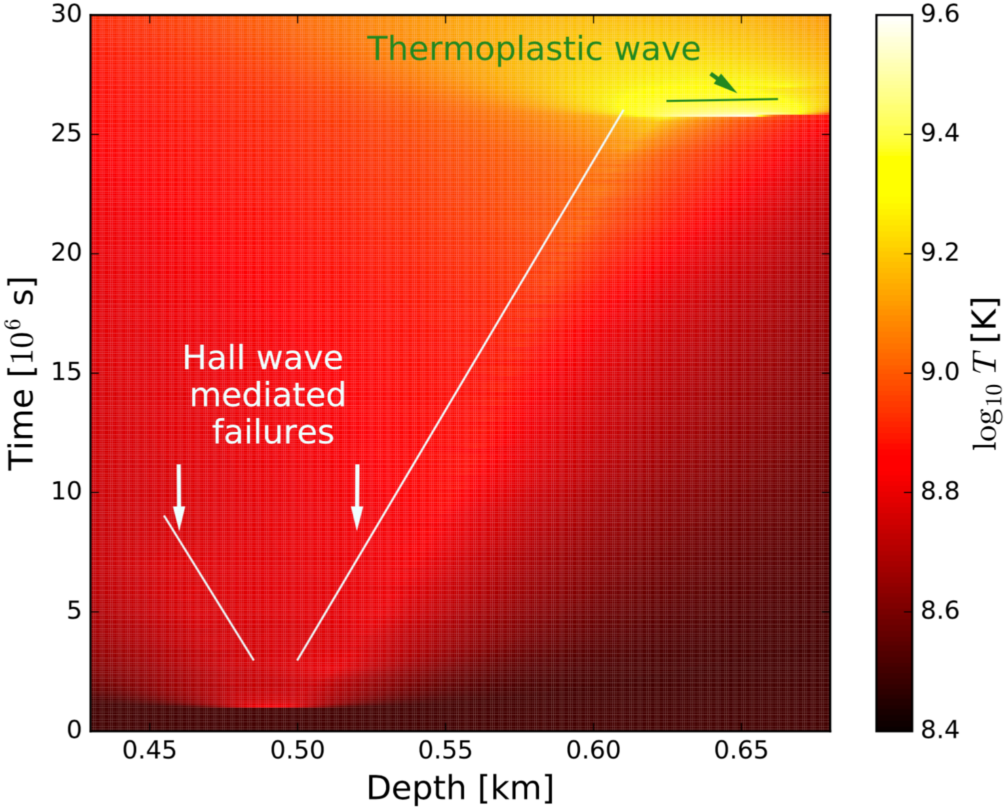
- Crust yielding (breaking, plastic flow) likely plays a role in mediating the transfer of magnetic twist from the interior into the magnetosphere.

Role of crust yielding

- in magnetars, the crust can yield in response to the applied magnetic stress
- crust creep rate is sensitive to the applied stress and temperature
- temperature dependence —> rapid release of stress “thermoplastic wave”
- stress dependence —> non-local yielding



Thompson et al (2018)



Li, Levin, Beloborodov (2018)

Neutron star binaries

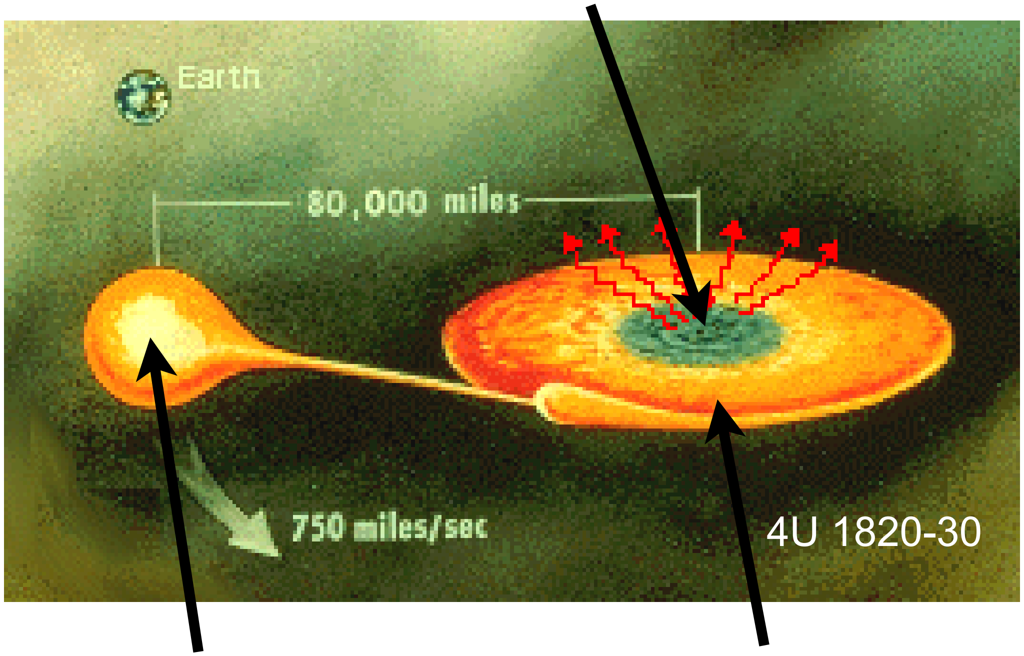
Not easy to make:

- need kick to prevent binary becoming unbound after supernova
- to accrete, the companion has to be brought into contact — angular momentum loss from the binary or common envelope drives the two stars together
- dynamical processes can play a role in GCs or dense environments

Pulsar binaries are important for mass measurements (+GR tests..)

For continuous GW sources, Low mass X-ray binaries LMXBs are interesting as long-lived systems that accrete a substantial amount of mass and could potentially sustain a mass quadrupole

Low mass X-ray binaries



neutron star

tidally-distorted companion
$M \lesssim 1 M_\odot$

accretion disk

typical mass transfer rates are

$$\dot{M} \sim 10^{-11} - 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$$
$$\sim 10^{15} - 10^{18}\ \mathrm{g\ s}^{-1}$$

giving an accretion luminosity

$$L_X \approx \dot{M}\frac{GM_{NS}}{R_{NS}}$$
$$\sim 10^{35} - 10^{38}\ \mathrm{erg\ s}^{-1}$$

(in outburst) these are
bright X-ray sources

orbital periods range from 10 mins to >days, depending on the type of companion star

binary separation:

$$\left(\frac{2\pi}{P_{\mathrm{orb}}}\right)^2 = \frac{GM_{\mathrm{tot}}}{a^3} \quad => a = 9\times 10^{10}\ \mathrm{cm}\ \left(\frac{M_{\mathrm{tot}}}{1\ M_\odot}\right)^{1/3}\left(\frac{P_{\mathrm{orb}}}{4\ \mathrm{h}}\right)^{2/3}$$

or $a \approx R_\odot$!

an orbital period < 80 mins => a hydrogen poor companion “ultracompact binary”

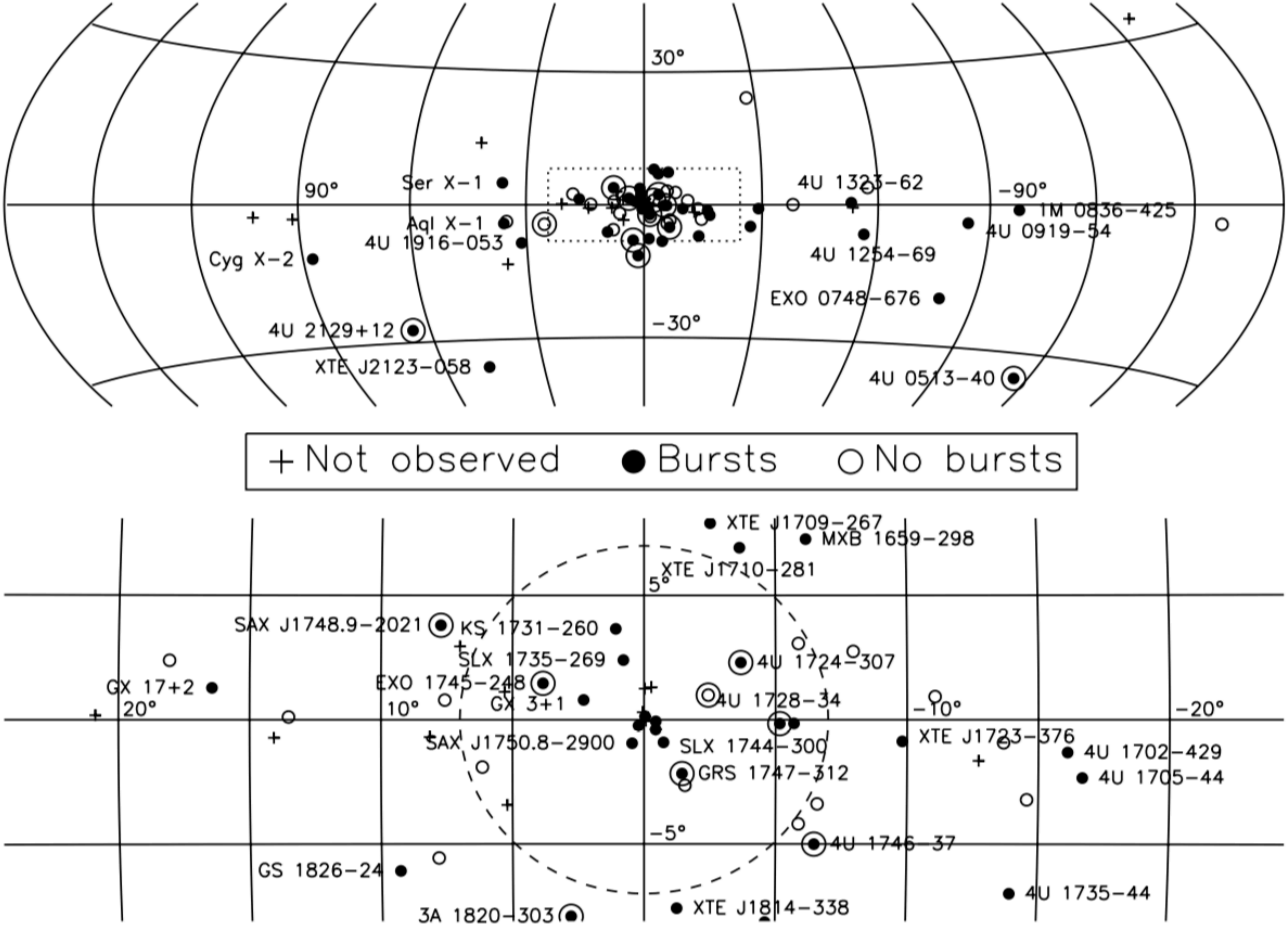


Fig. 7.—Sky distribution of bursters showing those observed by *RXTE*, as well as those from which bursts were detected. Sources within globular clusters are additionally indicated by a larger concentric circle. The bottom panel shows the region around the Galactic center. The four (unlabeled) sources closest to the Galactic origin are (clockwise from bottom left) SAX J1747.0−2853, GRS 1741.9−2853, KS 1741−293, and 2E 1742.9−2929. The dashed line shows the approximate projected radius of the Galactic bulge. Both panels are plotted in Galactic coordinates.

Galloway et al. RXTE burst catalog 2008

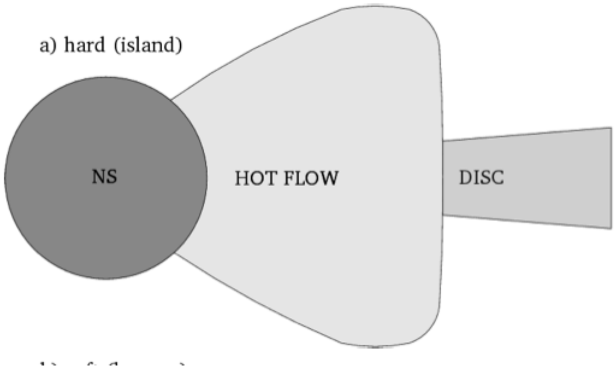
Low mass X-ray binaries have a rich phenomenology

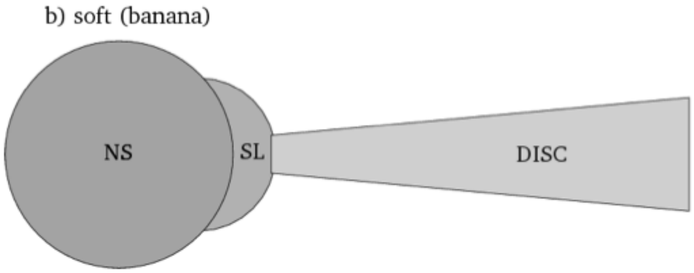
Pulsations

- Most do not show X-ray pulsations => the accretion disk extends almost to the stellar surface => weak B field ~ 10^8G
- There is a class of LMXBs with accretion-powered pulsations => somewhat stronger fields ~10^9-10^{10} G

Accretion state

- In a given source, the accretion rate can be extremely variable, including changes in accretion state / geometry

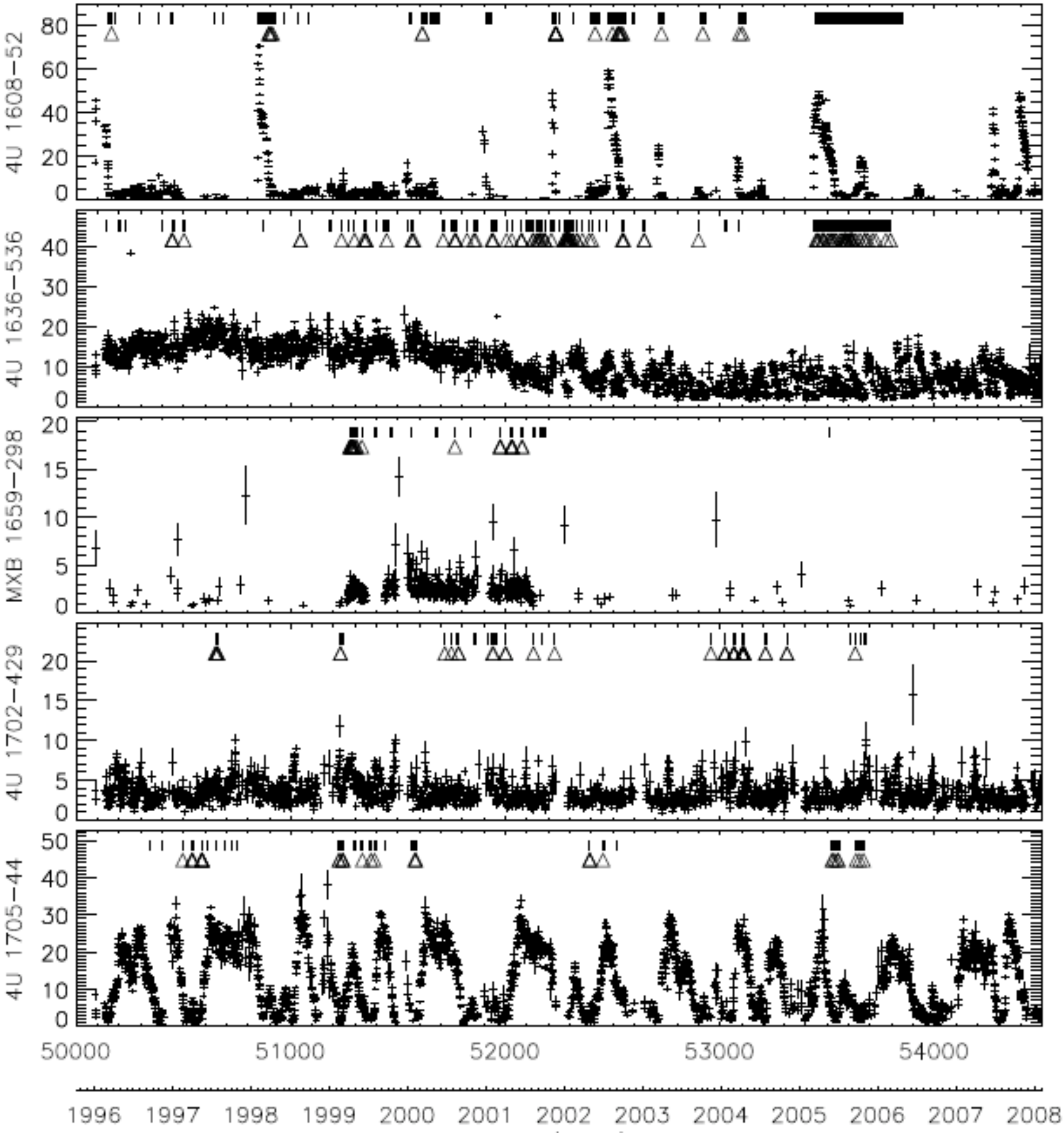




Accreted composition

- Depending on the orbital period / companion star can range from solar H/He to pure He or even CONe

Some lightcurves of LMXBs

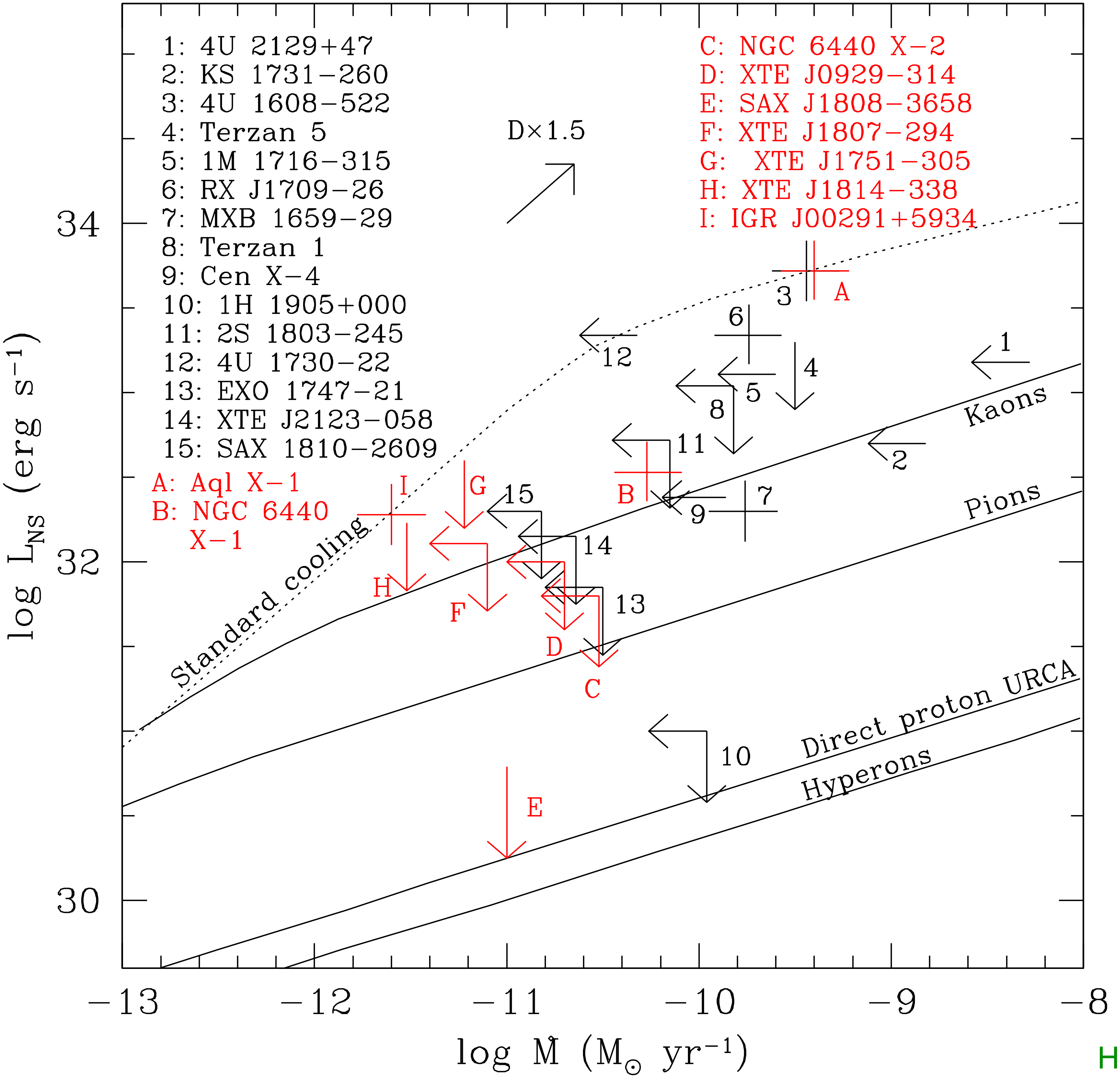


LMXBs show a range of transient behaviour

(even historically "persistent" sources can turn off after decades of accretion)

Galloway et al. (2008)

Quiescent luminosity of transiently accreting neutron stars

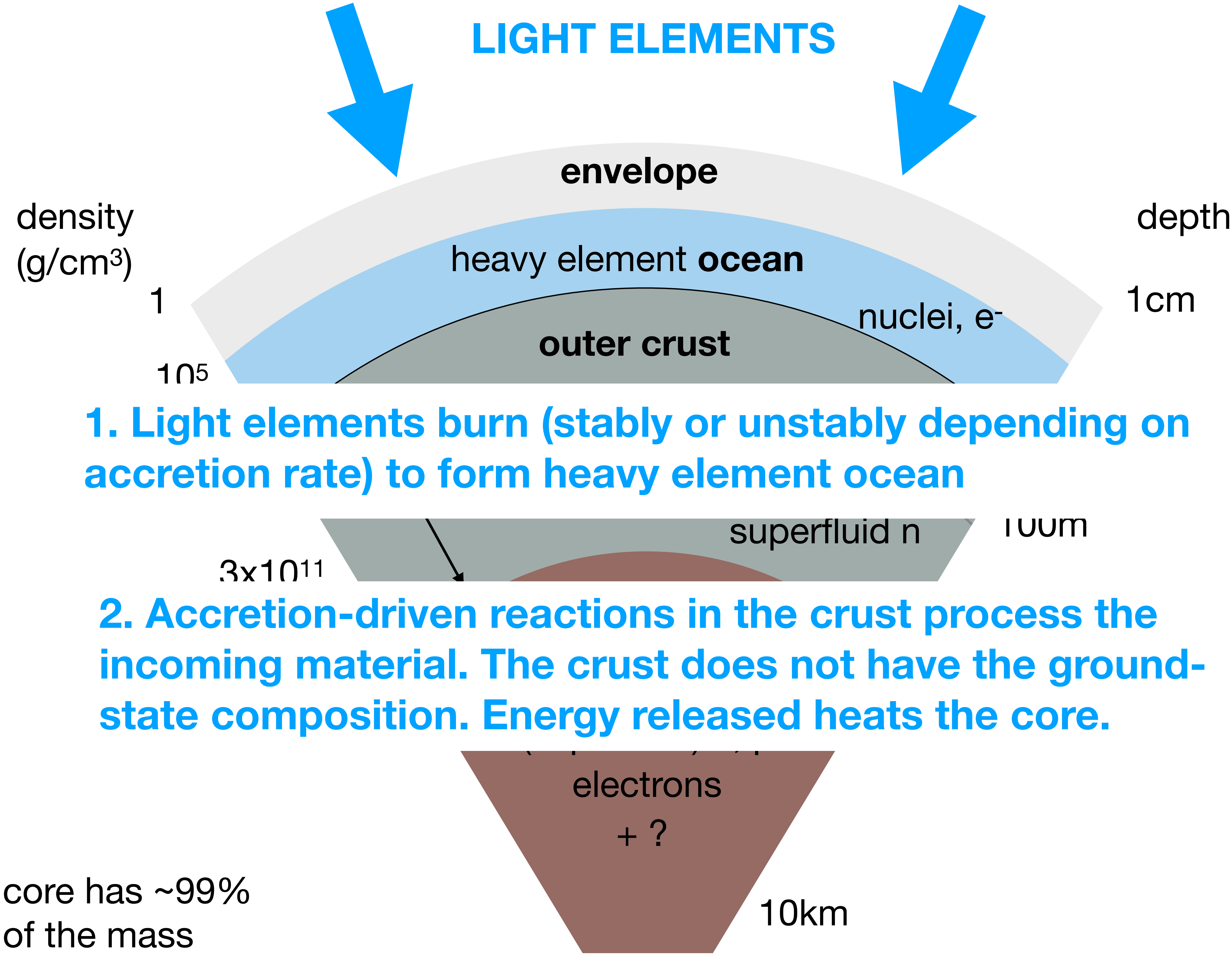


core temperatures can be determined in quiescence:

$T_c > 10^8$K

$T_c \sim 10^7$K

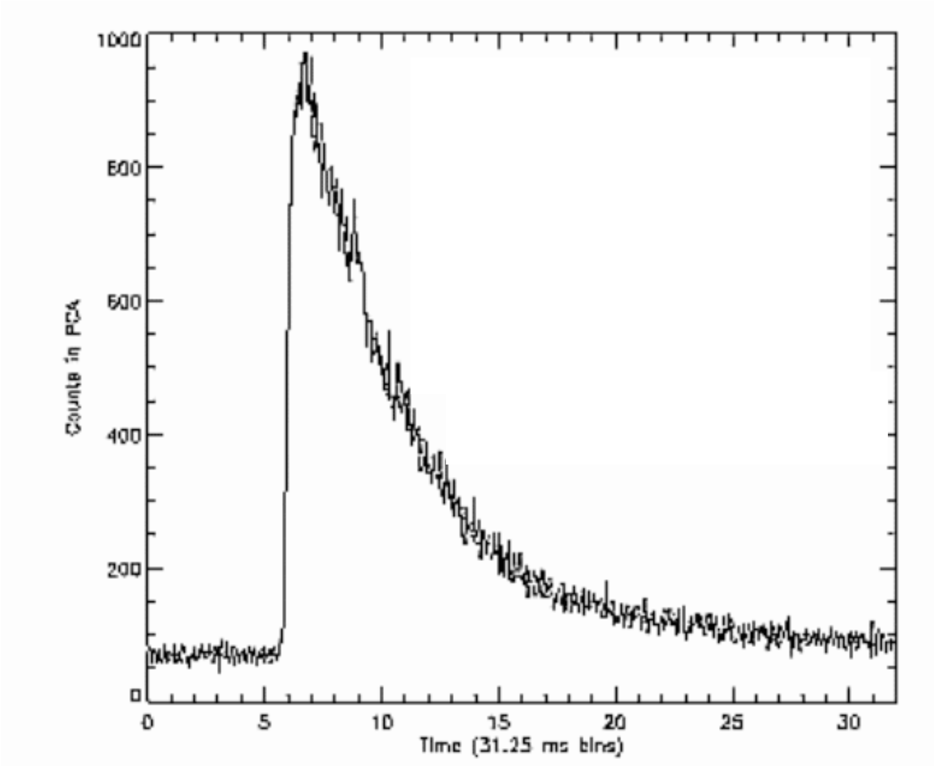
Heinke et al. (2010)

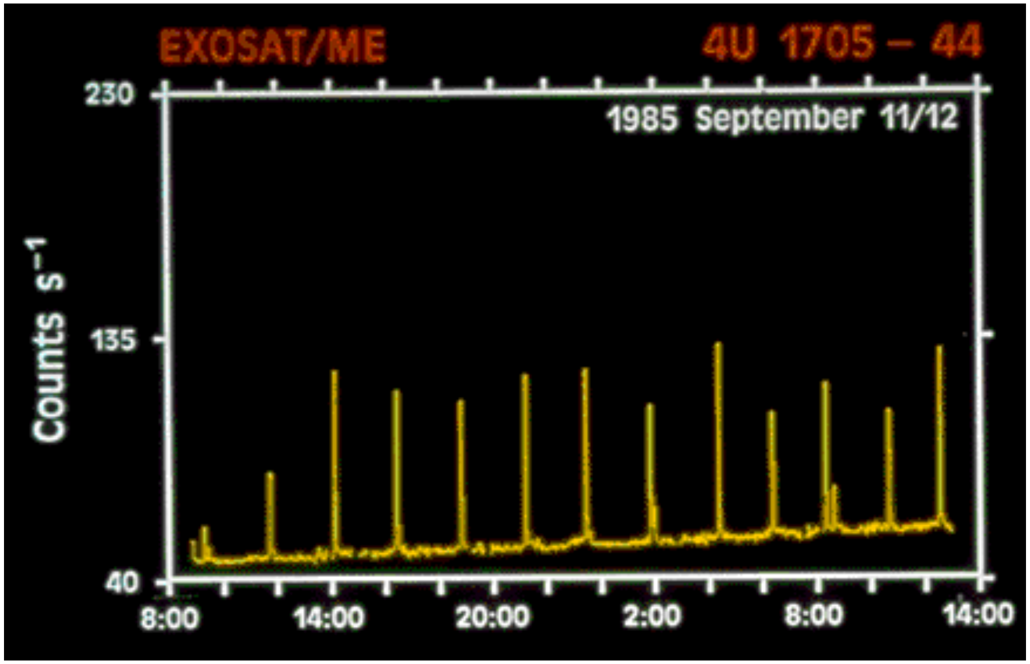


core has ~99%
of the mass

1. Light elements burn (stably or unstably depending on accretion rate) to form heavy element ocean

2. Accretion-driven reactions in the crust process the incoming material. The crust does not have the ground-state composition. Energy released heats the core.





https://personal.sron.nl/~jeanz/bursterlist.html

Type I X-ray bursts

- typical properties:

recurrence times ~ hours to days
durations ~ 10–100 seconds
energies ~ 10^{39}–10^{40} ergs
spectral softening during the tail

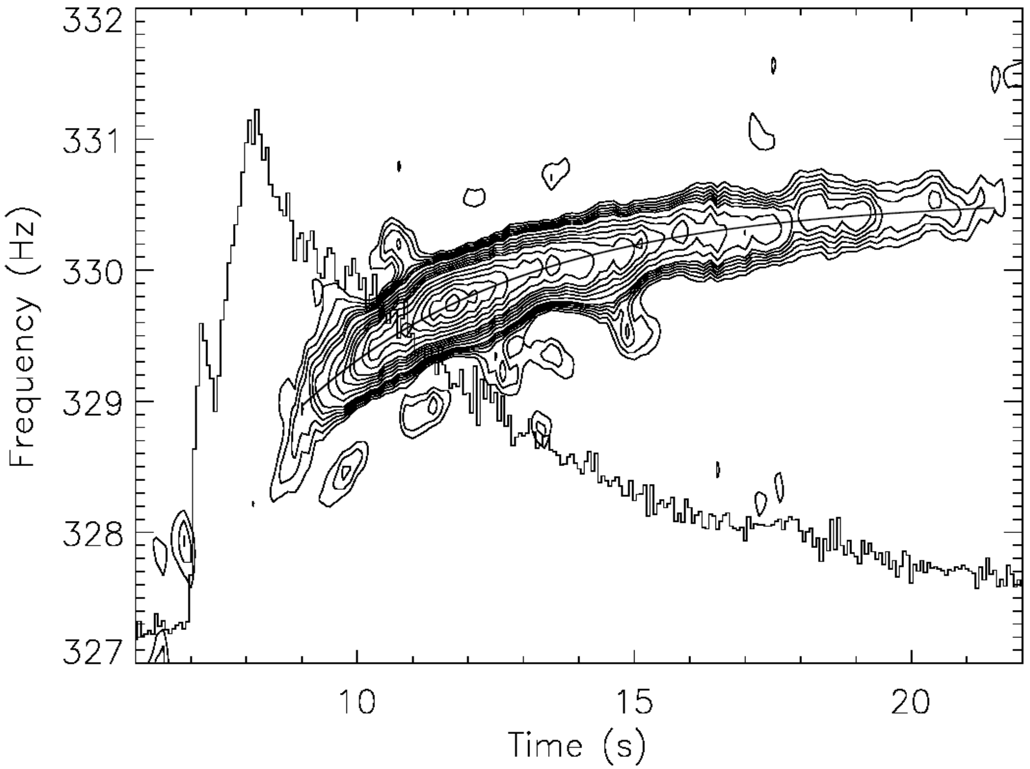
- tells us there is a neutron star in the system
- range of properties consistent with range of accreted compositions
- NS temporarily outshines the accretion disk => use to measure radii

- important because they make the heavy elements that later become crust

reviews: Lewin, van Paradijs, & Taam (1995); Bildsten & Strohmayer (2003)

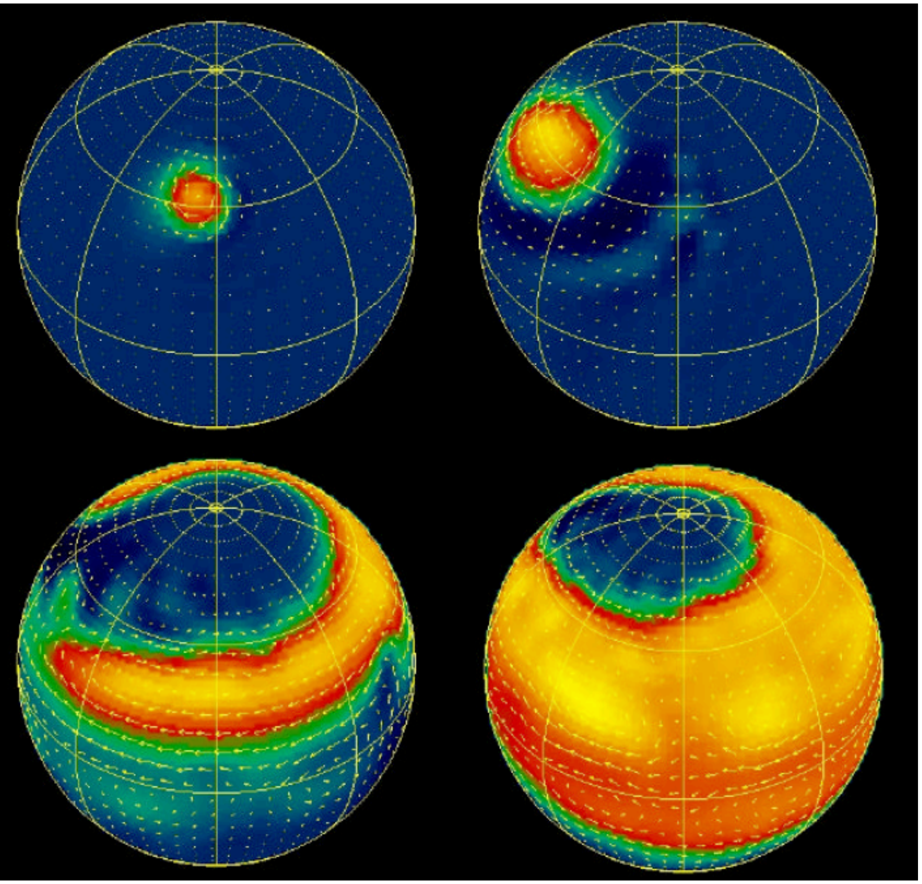
X-ray burst oscillations

- nuclear burning is not spherically-symmetric => rotational modulation at the spin frequency



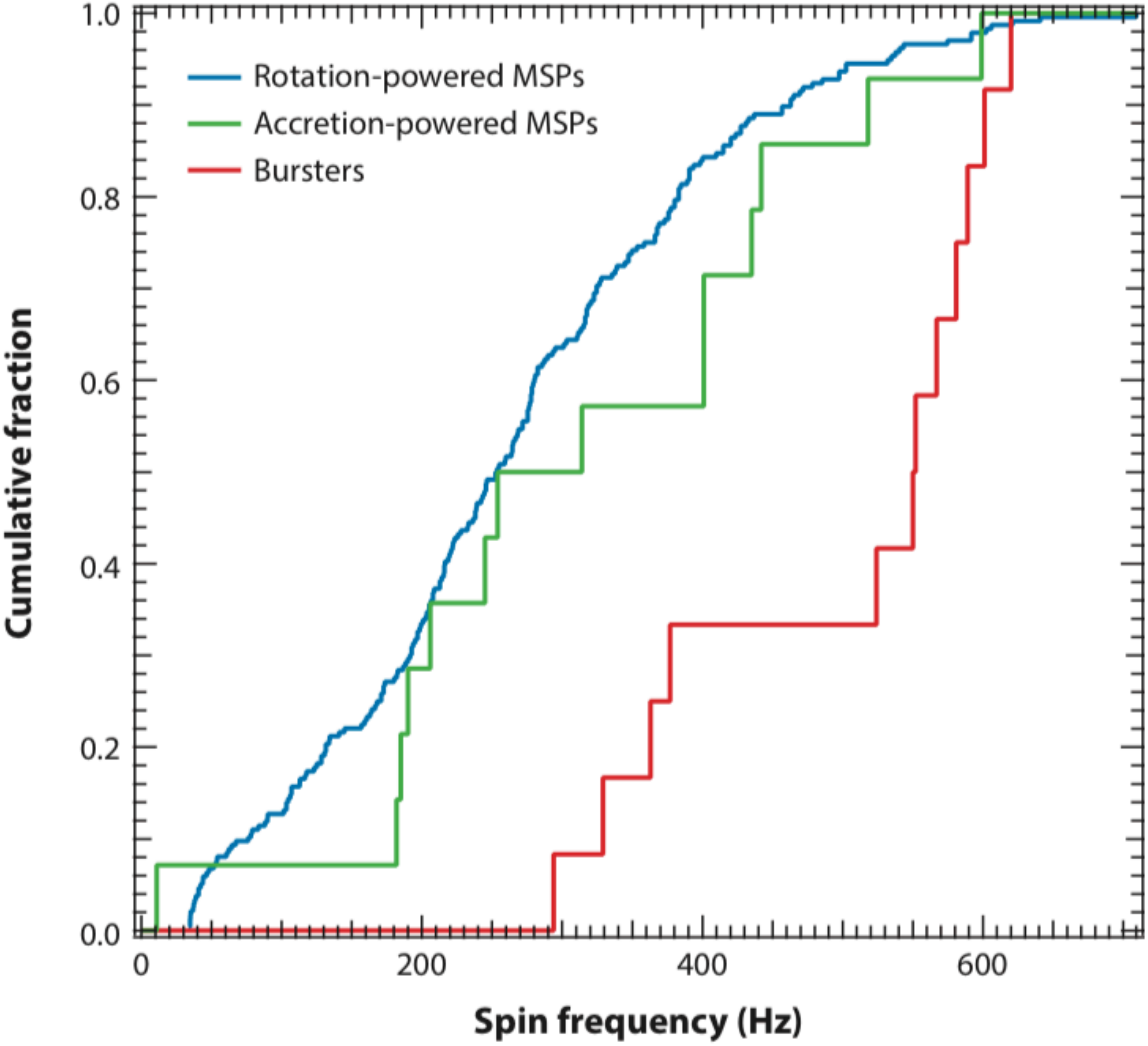
Strohmayer et al. (1997)

Spitkovsky, Ushomirsky & Levin (2002)



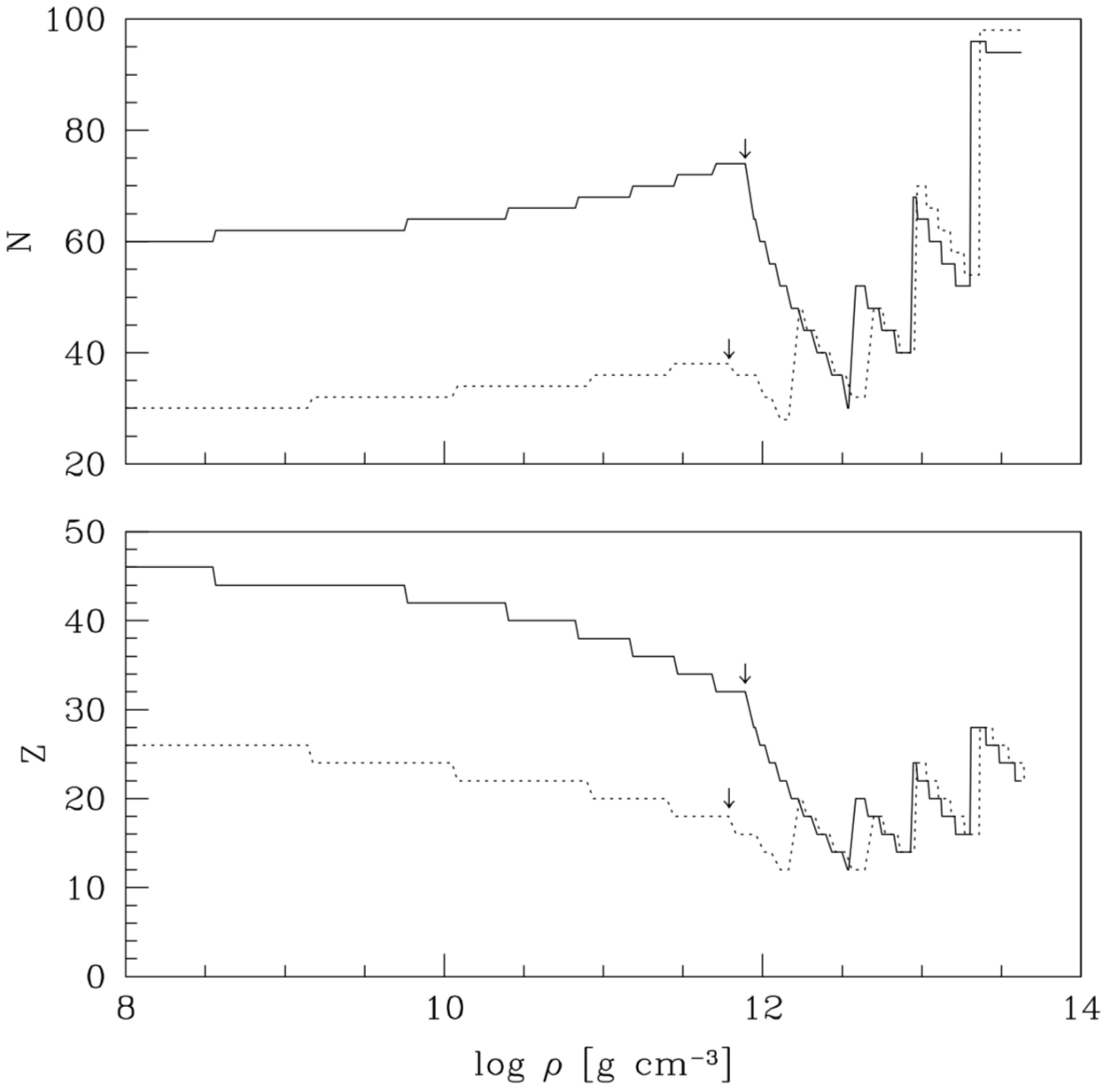
- rotationally-supported burning front during the rise makes sense
- but oscillations in the tail are a puzzle — r-modes (Rossby waves) in the ocean?
- magnetic field should have a significant effect on the dynamics

cutoff at ~700 Hz



Ozel & Freire (2016)

Accreted crust composition



Haensel & Zdunik (2003)

- Accreting crusts are not in the ground state: need to understand the history of accreted matter

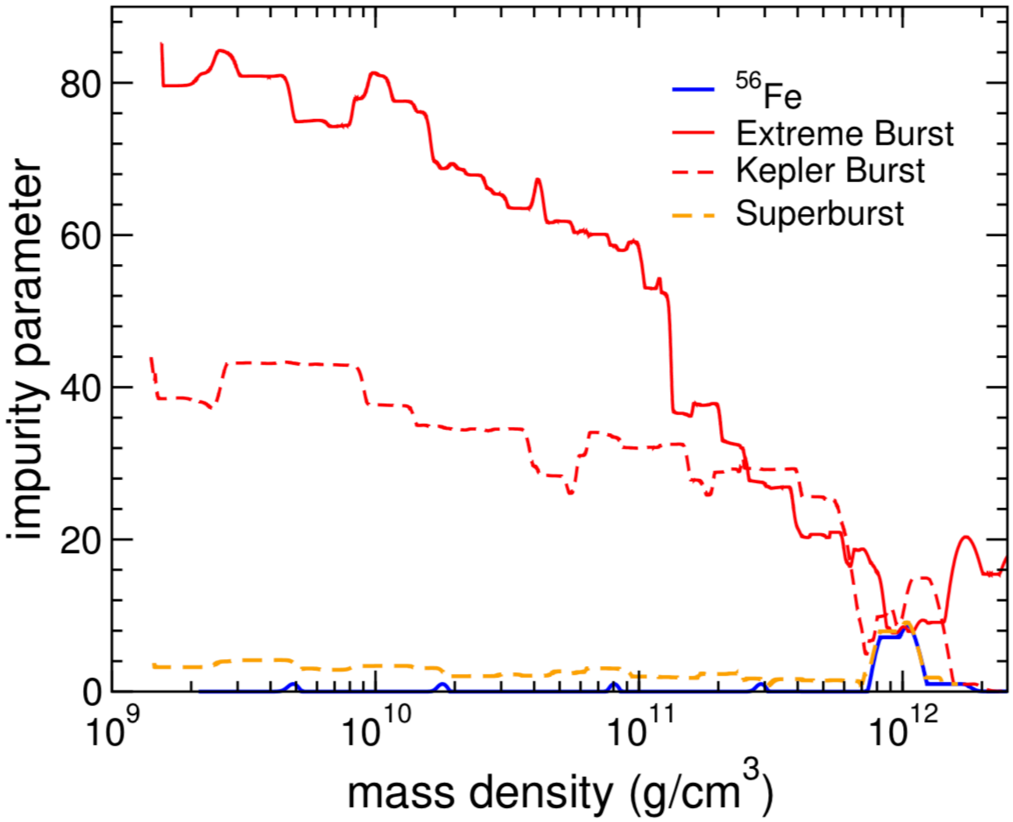
- accreted matter is processed in the solid phase in a sequence of electron capture, pycnonuclear and other reactions

- Use these captures layers to make a quadrupole

Bildsten (1998)

Multicomponent crusts

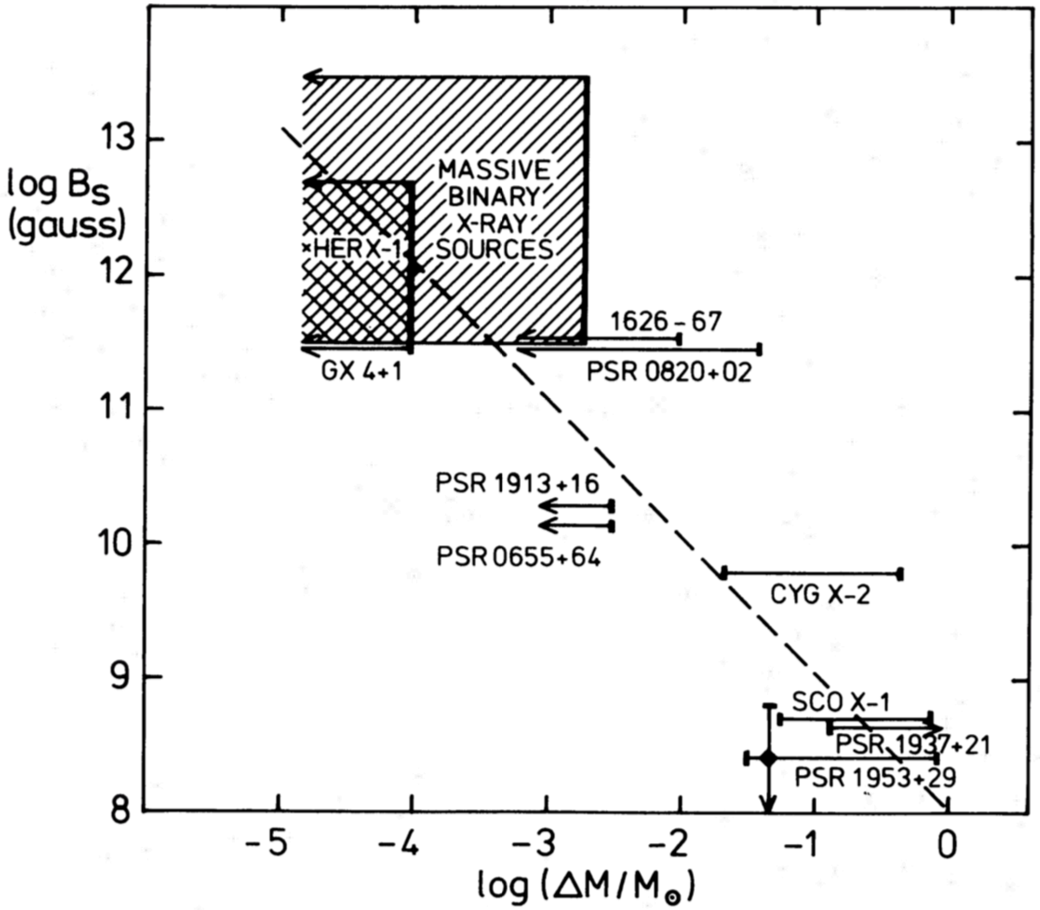
- H/He burning by the rp-process produces a complex mixture of heavy elements
- This mixture first undergoes chemical separation when freezing into new crust, likely forms multiple solid domains Caplan, Horowitz et al.
- The multicomponent composition in the crust opens up new reaction pathways



Lau et al. (2018), arXiv

How does accretion-induced magnetic field decay occur?

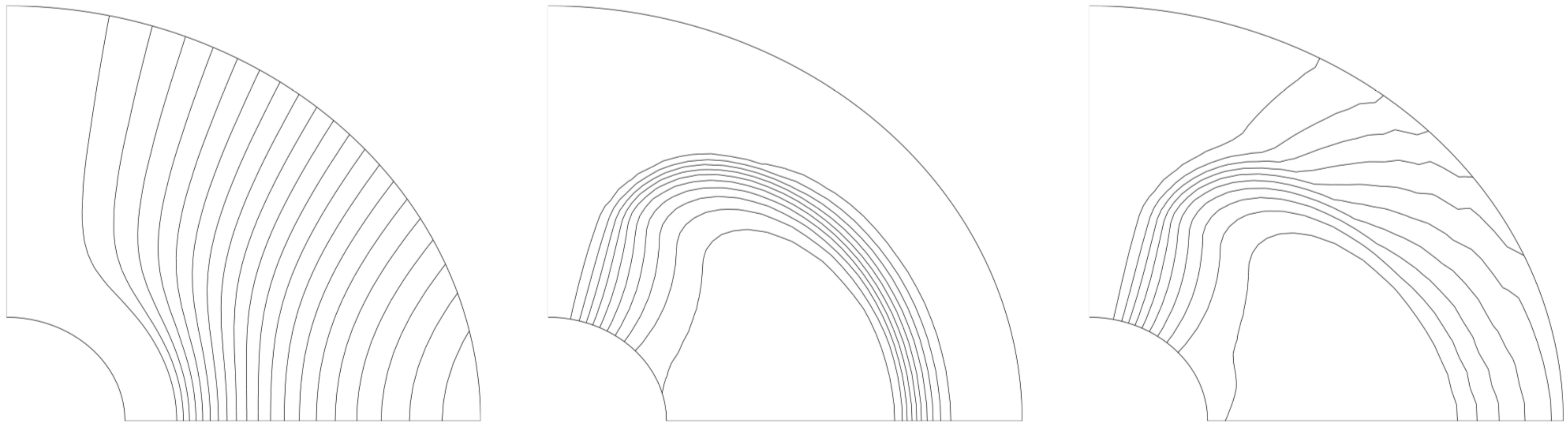
- Not understood, but several proposed mechanisms
  - use the crust to dissipate currents e.g. Urpin et al. 1997, Konar & Bhattacharya 1997, Srinivasan et al. 1990, Chen & Ruderman 1993
  - burial or screening e.g. Romani (1995)



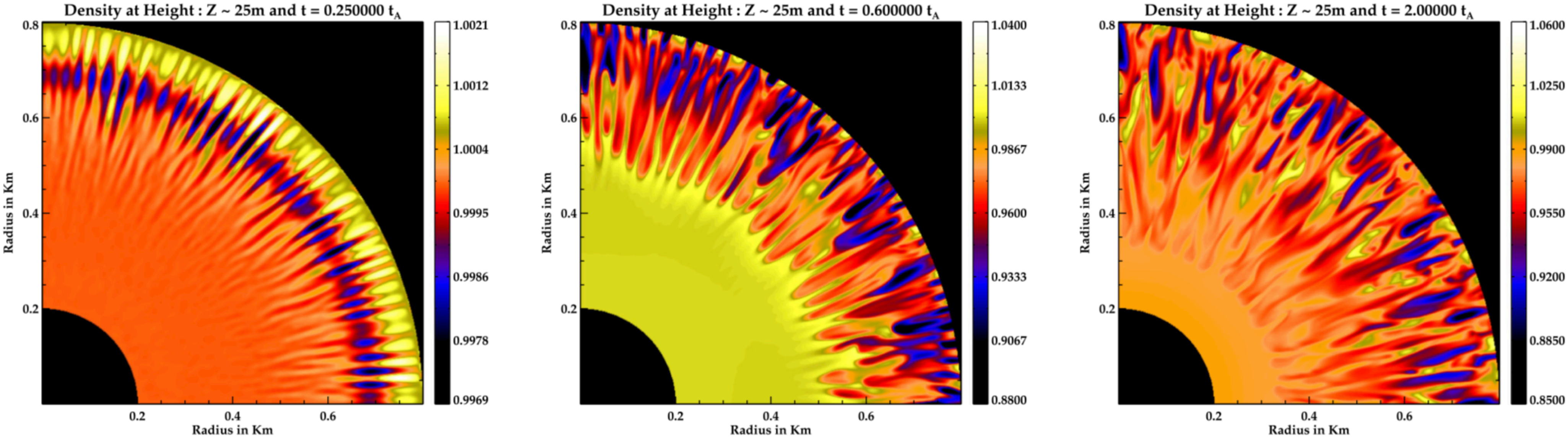
Taam & van den Heuvel (1986)

Magnetic field burial / screening in accreting NSs

Key question: how much is B distorted by accretion onto the magnetic polar cap?



Choudhuri & Konar (2002), many papers by Melatos and coauthors



Mukherjee et al. 2013

Summary/Open Issues

- Relation between different types of isolated neutron stars is still open
- Masses, spins and dipole magnetic fields are well-measured (not usually for the same star)

- Large range in dipole magnetic field strengths, increasing evidence that internal non-dipolar fields are there as well —> strong magnetar-like toroidal fields present in many NSs for ~10^4 yrs

- Neutron stars show magnetic activity. The multicomponent interior likely drives evolution, particularly in the crust for short timescales.
- Hall effect in the crust can give short timescales but need to balance magnetic stresses for thousands of years
- How the crust yields as a function of T and stress is important for magnetar outbursts

- LMXBs are a diverse population: many different orbits, accreted composition, time-dependence of accretion rate
- Most LMXB neutron stars have no spin measurement
- in a given source, accretion geometry changes between accretion states
- Crust is made of a mixture of many elements
- Buried fields? Need better understanding of spread of accreted matter