X-ray emission from isolated pulsars

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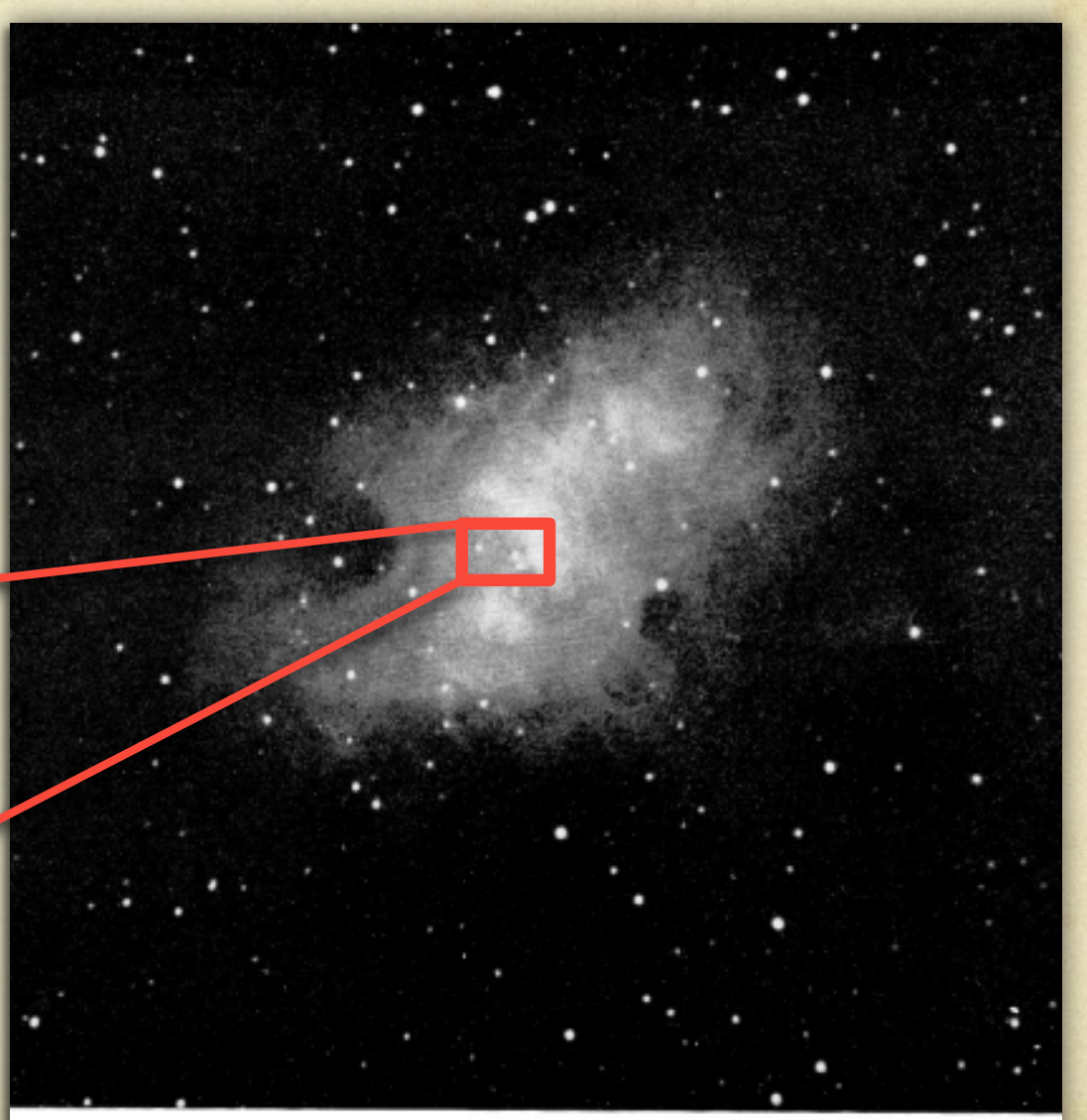
First seen neutron stars...

- OPTICAL

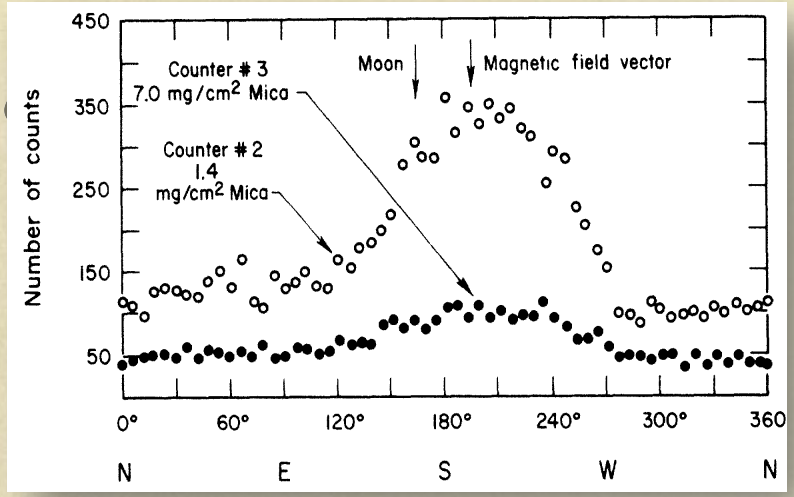
1942: Crab pulsar

The "south, preceding star" V≈16 at the center of the Crab Nebula (Baade 1942, Minkowsi 1942)



PHOTOGRAPH OF THE CRAB NEBULA: λ 7200–λ 8400

First seen neutron stars...



- X-RAYS

1962: Sco X-1 (Giacconi+ 1962)

1964: Tau X-1 (Bowyer+ 1964)

1967 June: Crab PSR at > 20 keV
(Fishman+ 1969)

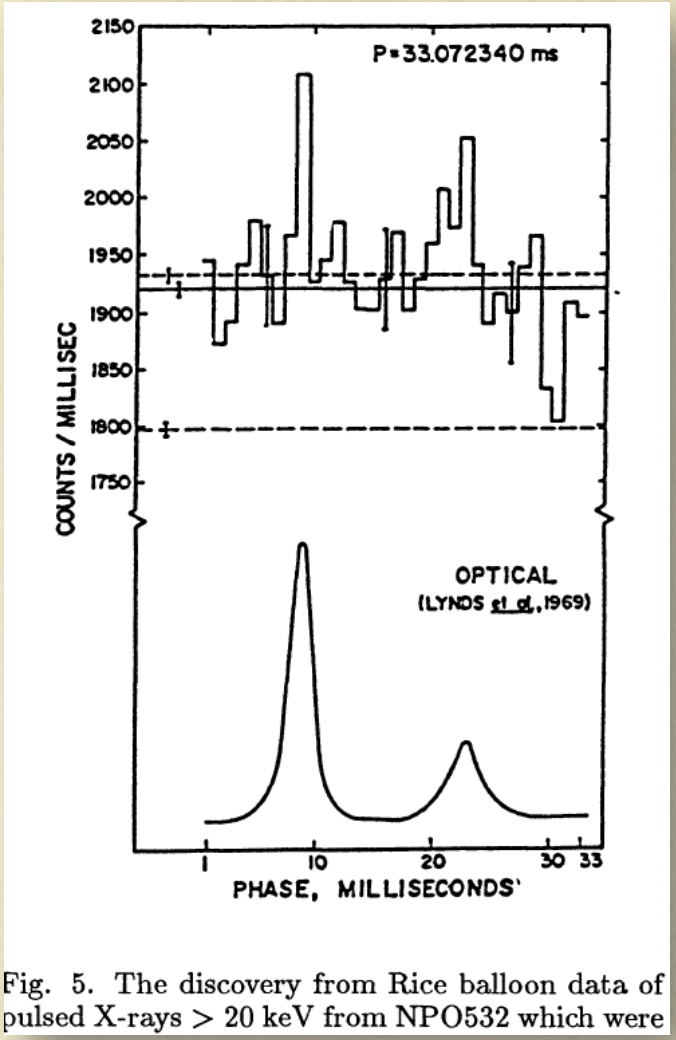


Fig. 5. The discovery from Rice balloon data of pulsed X-rays > 20 keV from NPO532 which were

... before the discovery of radio pulsars

Outline

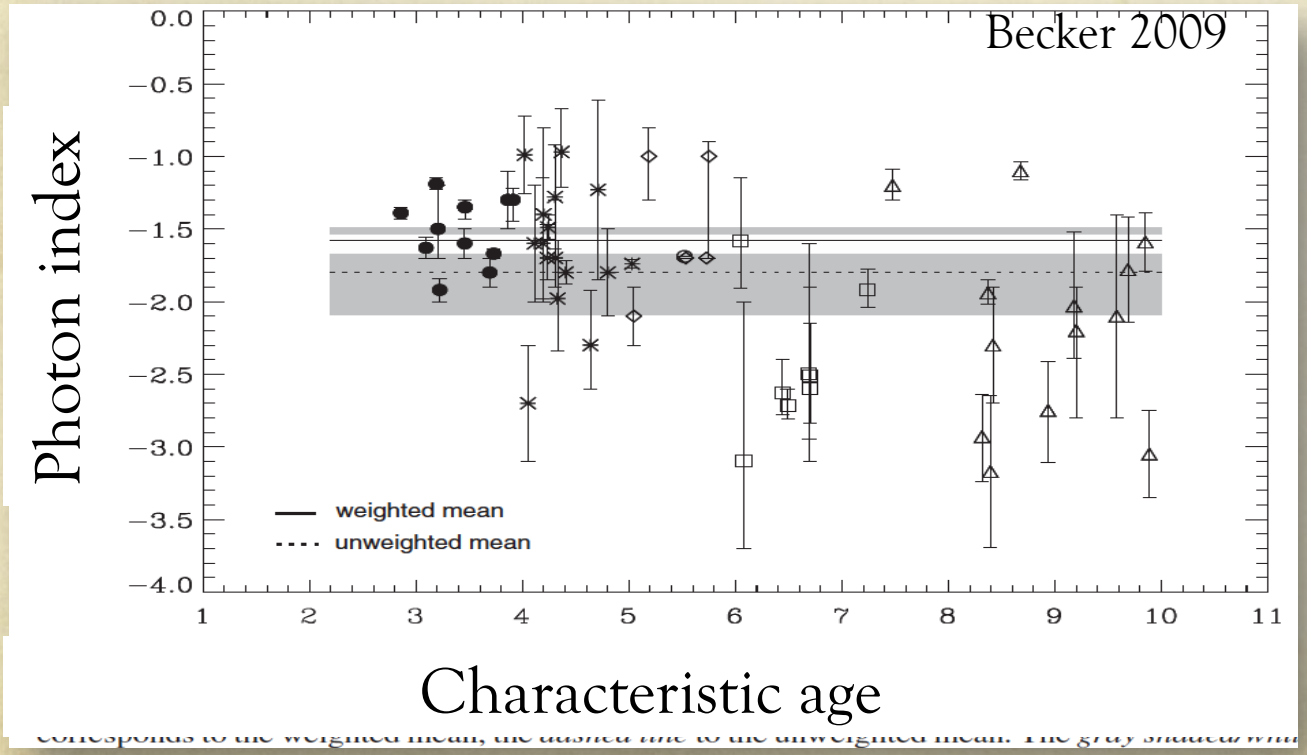
1. NON - THERMAL EMISSION
2. THERMAL EMISSION
3. LINES
4. VARIABILITY

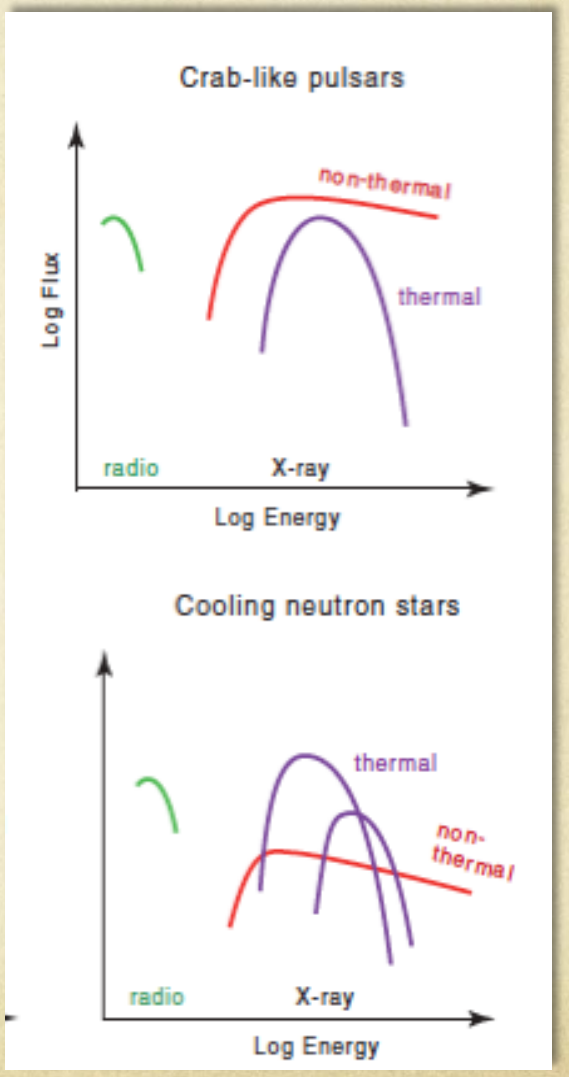
Mainly on results since PNS 2011

My apologies for incompleteness....

Non-thermal emission: basic facts

- Dominates in youngest/most energetic NS
  ...but present in (almost) all NS classes
- Pulsations – Power-law spectra





Non-thermal emission: basic facts

- Dominates in youngest / most energetic NS
  ...but present in (almost) all NS classes
- Pulsations – Power-law spectra
- Charges accelerated in magnetosphere at the expense of rotational energy
  $L_X \approx 10^{-3}\ \dot{E}_{ROT}$ (large scatter)
- Synchr. /Curvature radiation + Inv. Compton

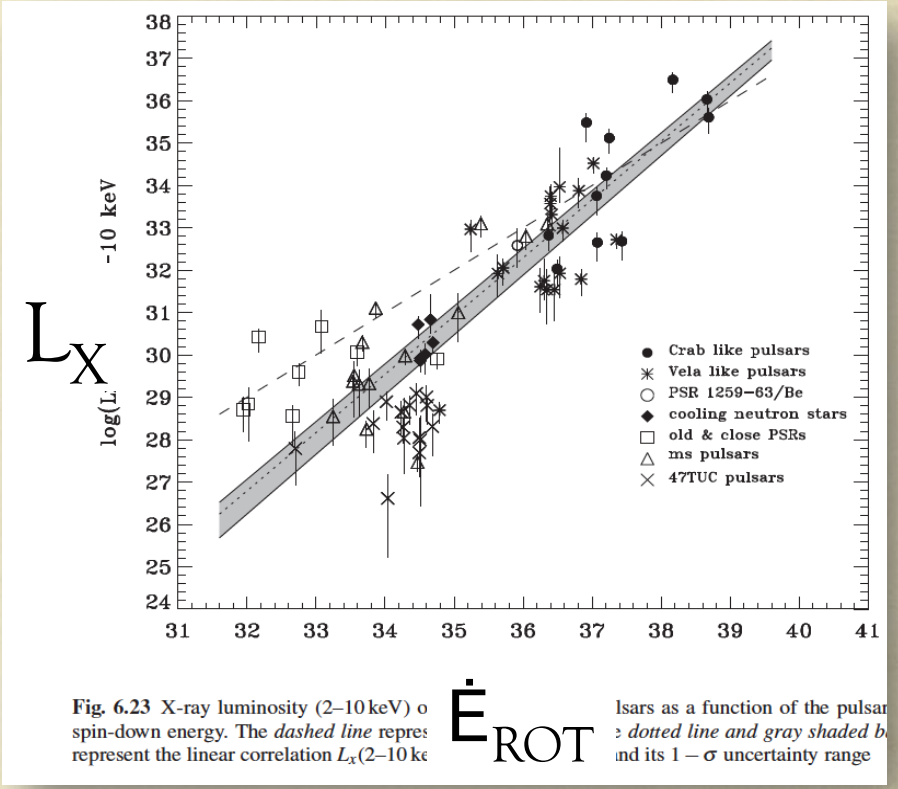


Fig. 6.23 X-ray luminosity (2–10 keV) o lsars as a function of the pulsar spin-down energy. The *dashed line* repres *e dotted line and gray shaded b* represent the linear correlation L_x(2–10 ke nd its $1-\sigma$ uncertainty range

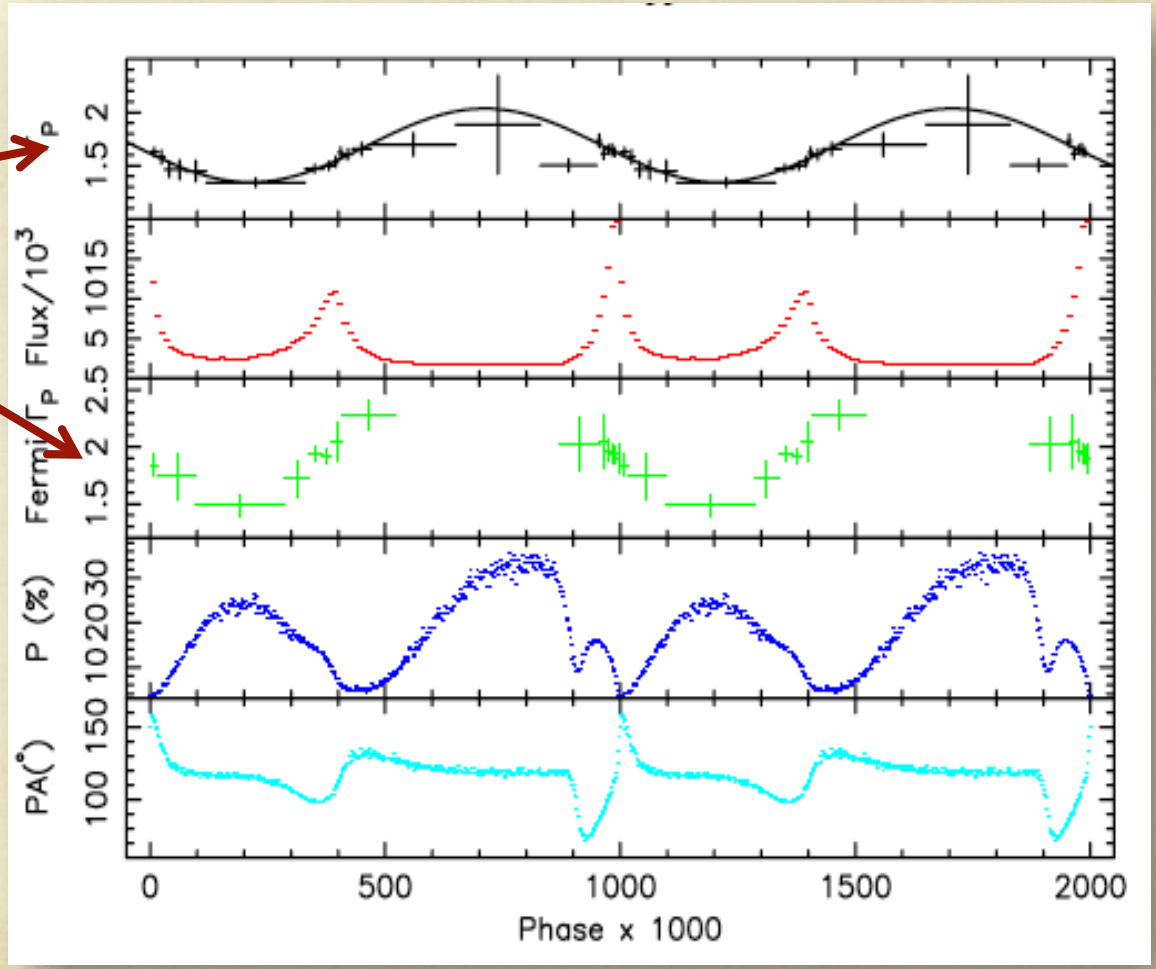
Crab PSR: phase-resolved spectroscopy

Chandra

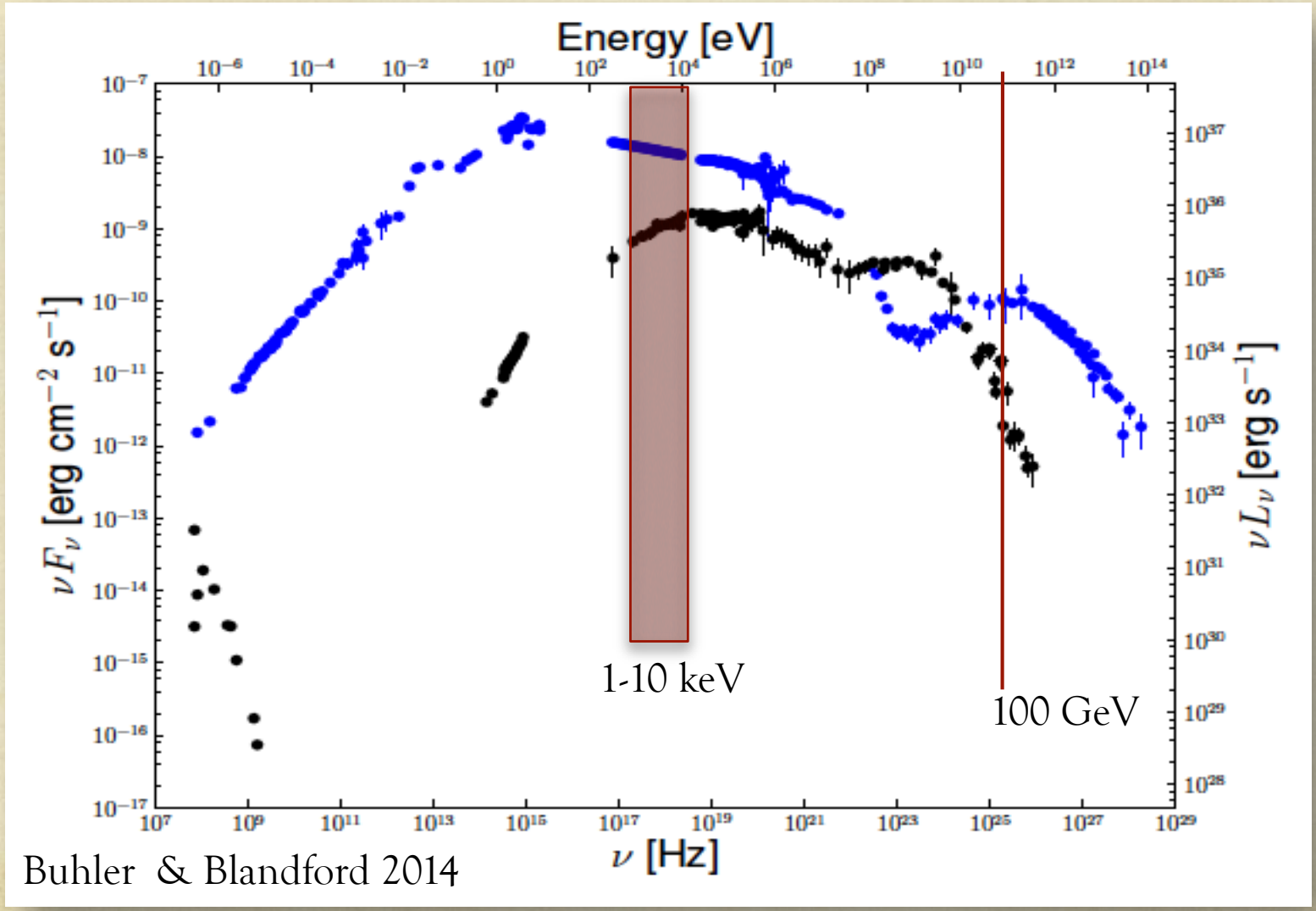
Weisskopf+ 2011

Same behavior of X-ray and γ-ray photon index

Subtle correlations with polarization properties



Crab SED: nebula and pulsar

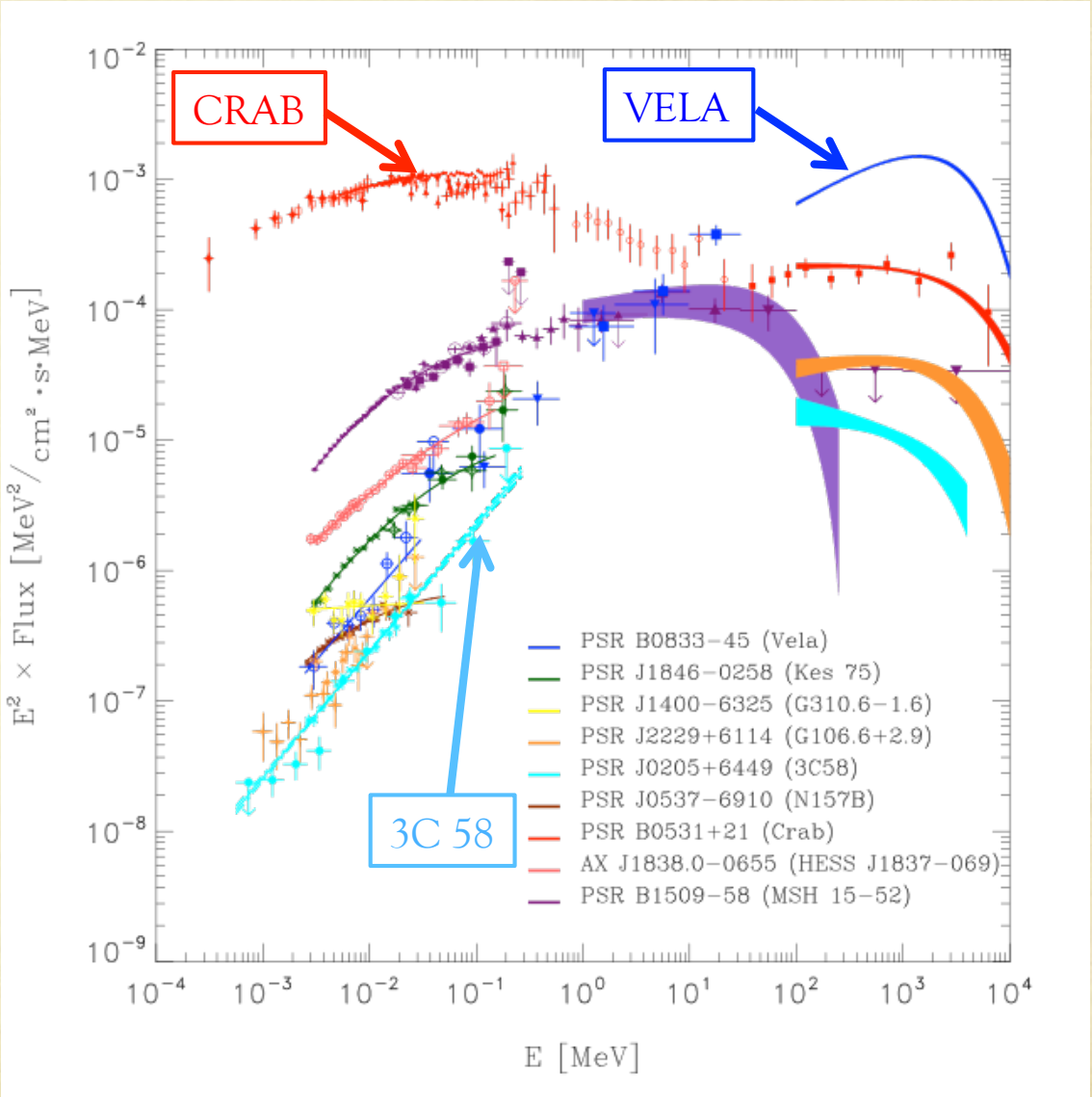


Buhler & Blandford 2014

The Crab is the best studied PSR...

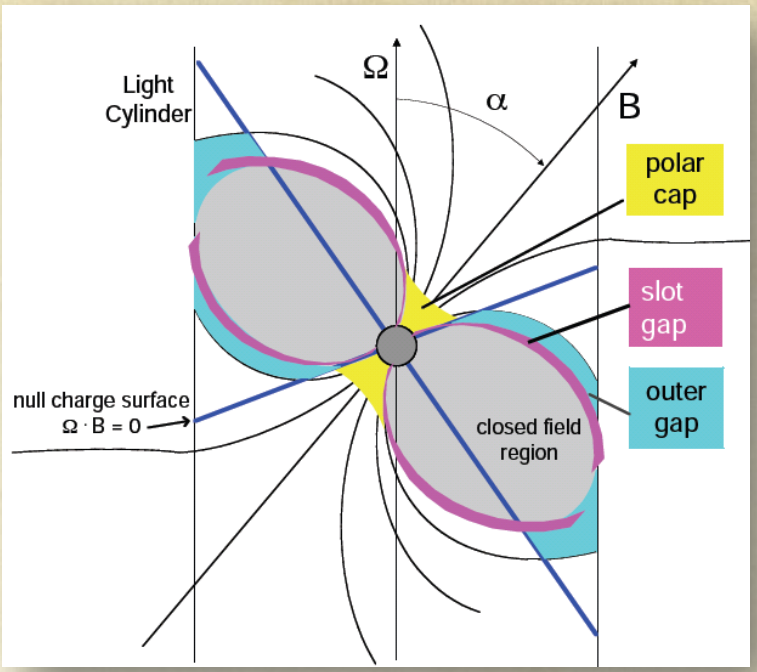
...but it is not representative of the whole population of X-ray and γ-ray pulsars !

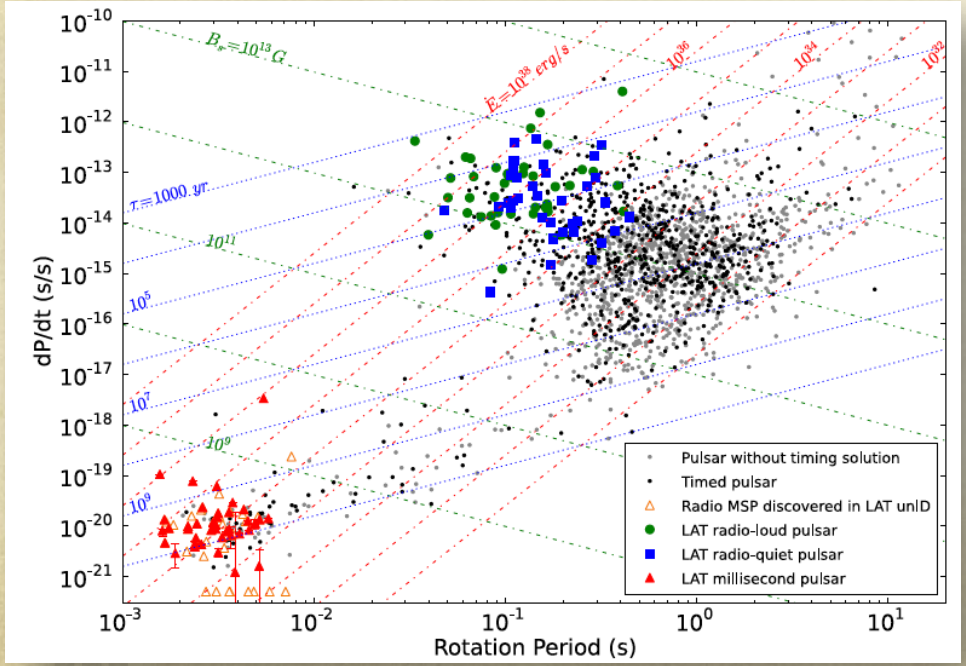
Kuiper & Hermsen 2013



See L. Kuiper talk

- Emission in outer magnetosphere favored:
  - Lack of super-exponential cut - off expected for magnetic pair production in γ-ray spectra
  - Large number of gamma PSR not seen in radio





2° Fermi PSR Catalog
Abdo+ 2013

See Pierbattista and Timokhin talks

2. Thermal emission

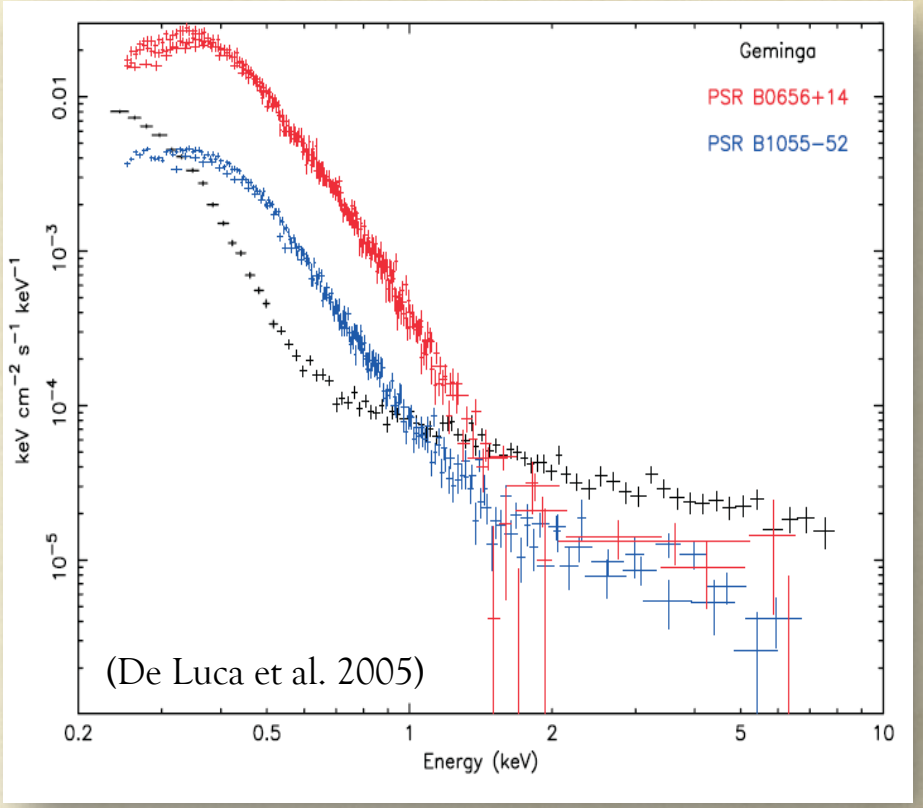
Thermal emission

- Best observed, e.g., in middle-aged NS and XDINS

- About 40 "coolers" (Vigano'+ 2014):

  11 RPP 7 XDINS

  4 CCOs 17-18 AXPs/SGRs

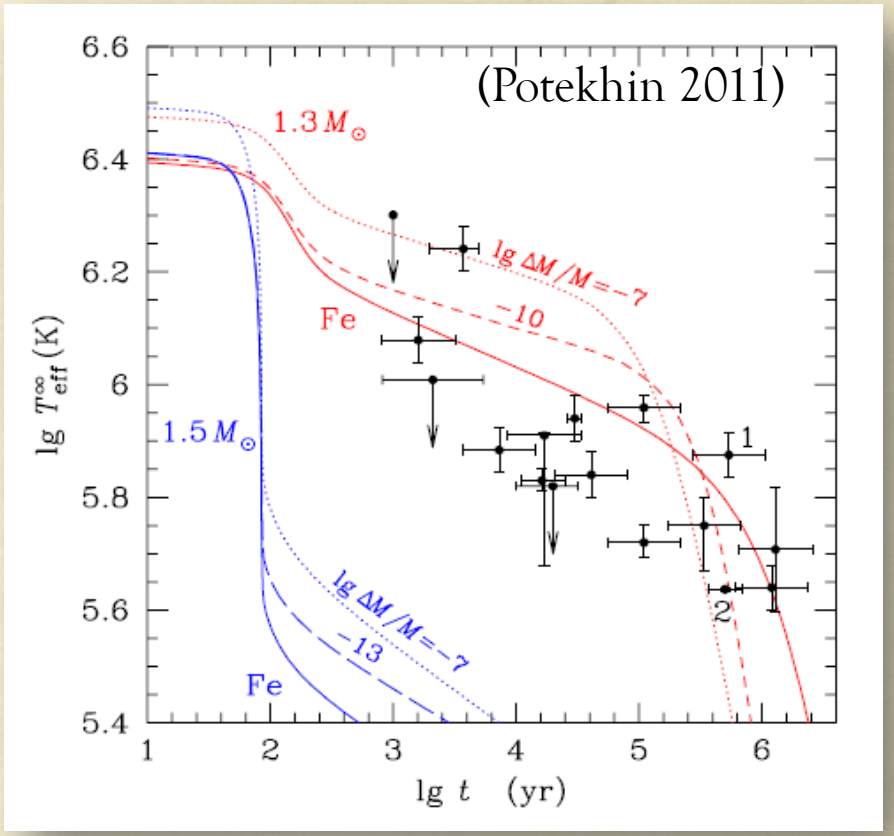


Thermal emission

- Best observed, e.g., in middle-aged NS and XDINS
- About 40 "coolers" (Vigano'+ 2014):

  11 RPP 7 XDINS

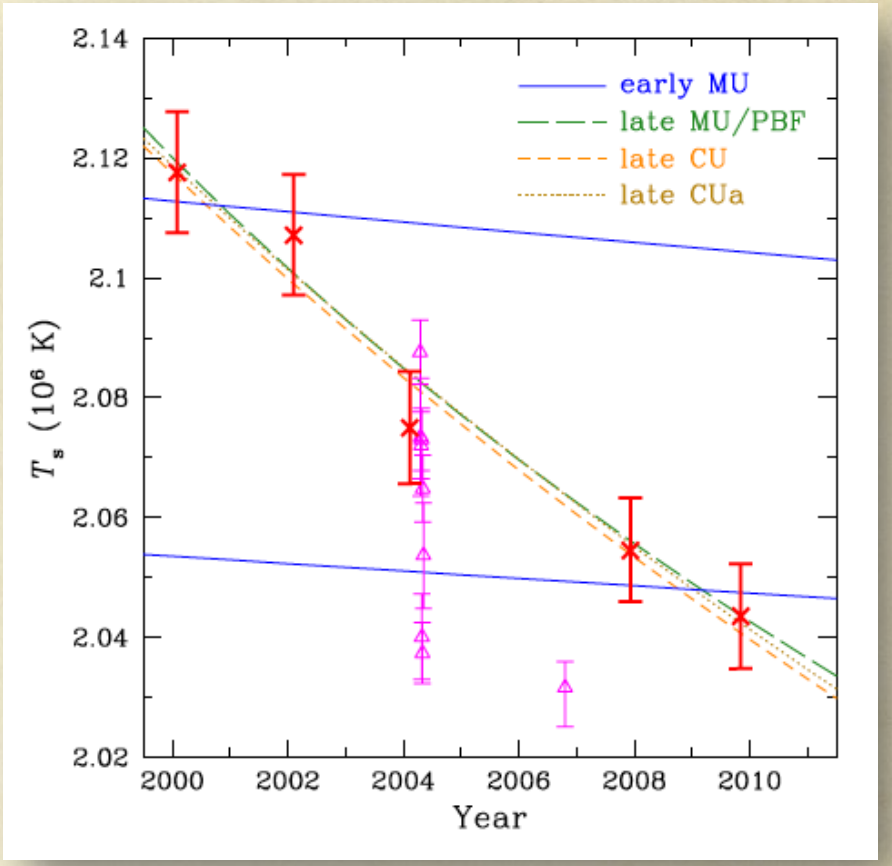
  4 CCOs 17-18 AXPs/SGRs
- Uncertainties / caveats:
  - Ages
  - Distances
  - Atmosphere composition and magnetization
  - Non-uniform sample
- No evidence for fast cooling, ...but data do not exclude it



See Page / Reisenegger talks

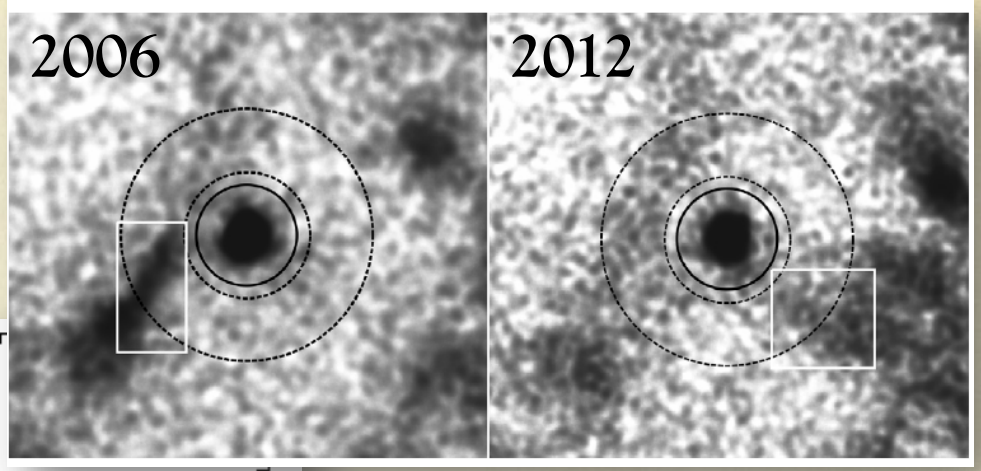
Fast (?) cooling of NS in Cas A

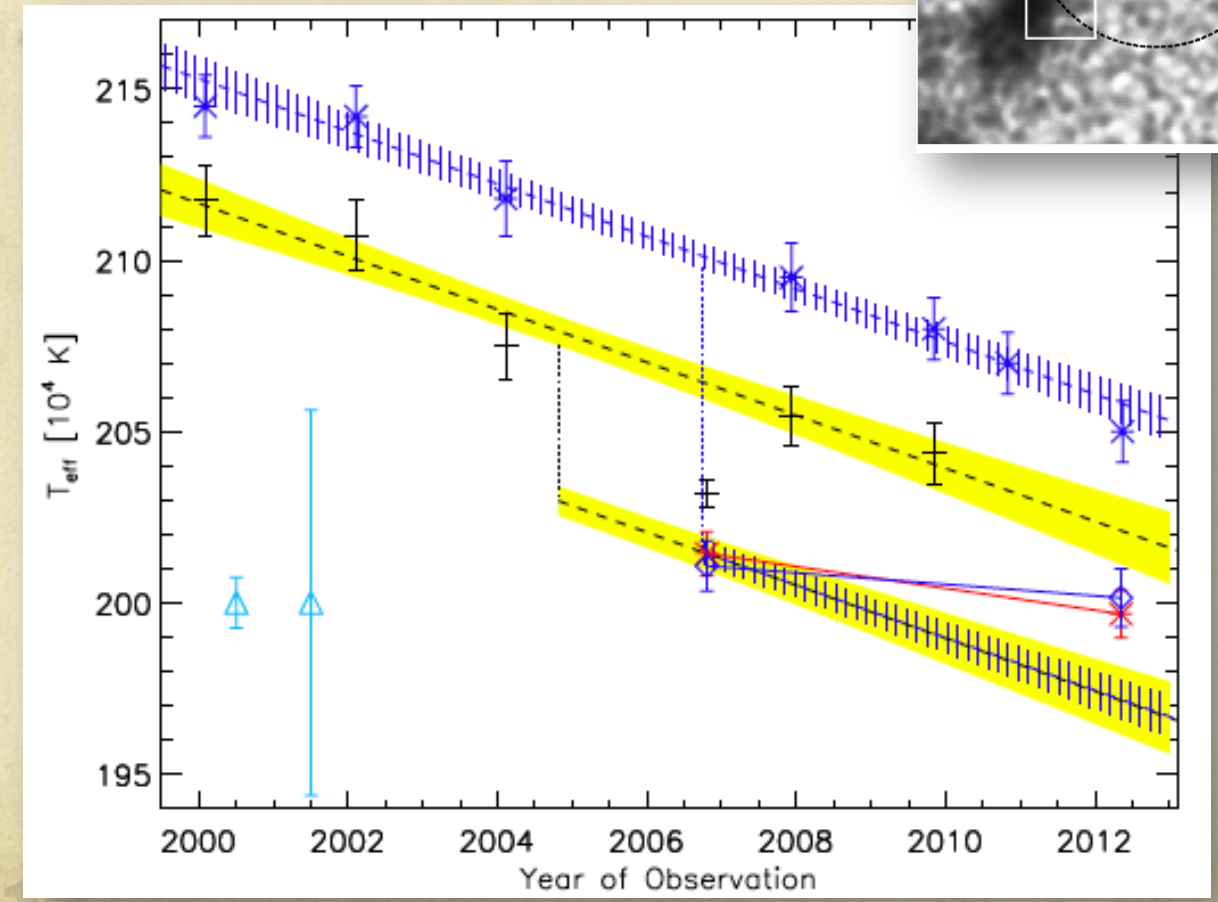
- No pulsations
  (<12% PF for P > 10 ms)
- C atmosphere, R≈12-15 km → NS
  (Ho & Heinke 2009)
- decrease 4% in T over 10 yrs
  (21% in observed flux)
  delayed thermal relaxation
  (Heinke & Ho 2010)
- triplet-state N superfluid in core
  steep T drop caused by ν emission
  from CPF
  (Shternin+ 2011, Page+ 2011)
- cooling significant only in ACIS-S
  graded mode (which suffers pile-up
  and CTI)
  (Elshamouty+ 2013)



Fast (?) cooling of NS in Cas A

- ACIS-S faint mode in 2006 and 2012 (Posselt+ 2013)

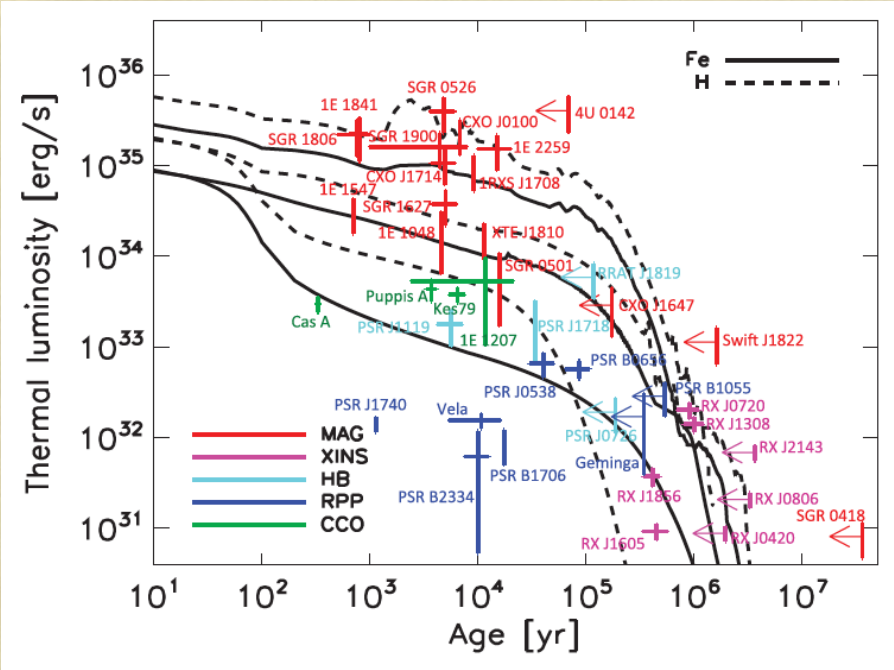




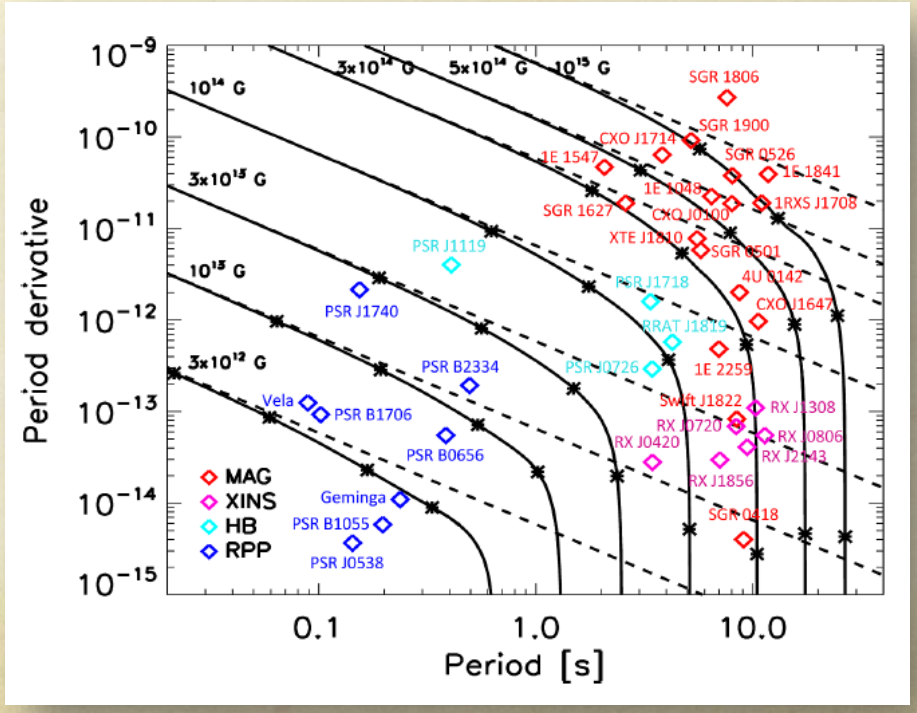
- With C model $\Delta T<1\%$ with significance $< 3\ \sigma$
- No change with H model

Magneto-thermal evolution of INS

See Pons and Reisenegger talks



Aguilera+ 2008, Pons & Geppert 2007, Pons+ 2009,2013, Vigano'+2012, 2014, ...



Explain variety of INS (timing and radiative properties) by coupled evolution of T and B

Variety of initial B, M and envelope composition

Evolutionary links between different classes

3. X-ray spectral lines

X-ray lines in INS

- A formidable diagnostic tool... (in principle!)

  See, e.g., accreting NS, where lines are well established and interpreted as cyclotron resonance features from electrons in $B \approx 10^{12}$-10^{13} G (→ e.g. Mushtukov talk)

- Lines reported in different classes of isolated NS: (CCOs, XDINSs, AXPs/SGRs, RRAT, RPPs)

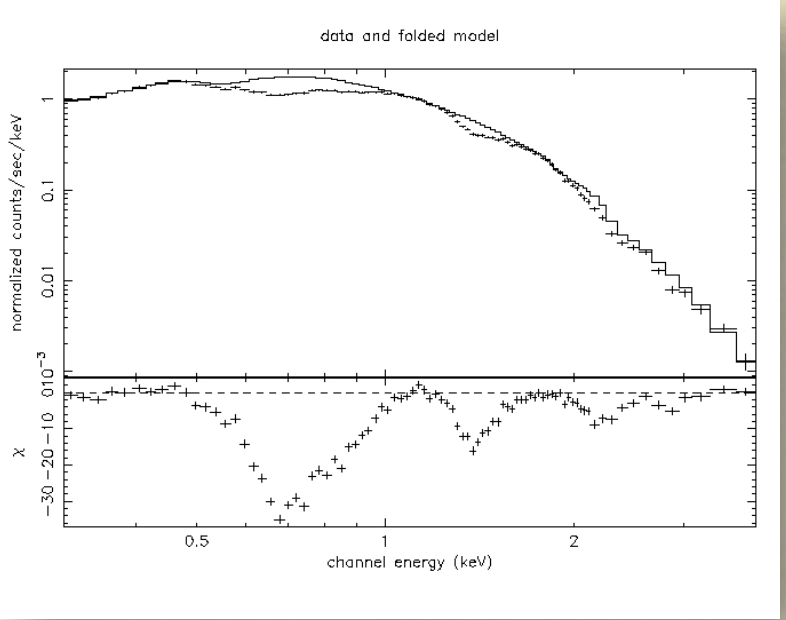
→ a variety of different situations and complex (sometimes unclear/controversial) results - no unique interpretation

X-ray lines in INS

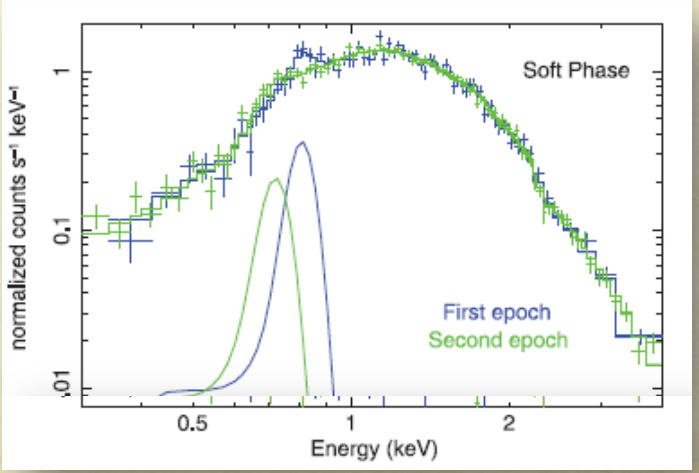
- CCOs:
  - Harmonically-spaced absorption lines in 1E 1207
    (Sanwal+2002, Mereghetti+2002, Bignami+2003, De Luca+ 2004, Mori+ 2005)

    P=0.4 s, Pdot=2 10^{-17} s/s
    (Gotthelf+ 2013)

    → electron cyclotr. line in B≈10^{11} G



  - time-variable phase-dependent feature in PSR J0821 (in Pup A)
    emiss. at 0.75 keV or abs. 0.45 keV ?
    (Gotthelf & Halpern 2009, De Luca+2012, Gotthelf+ 2013)



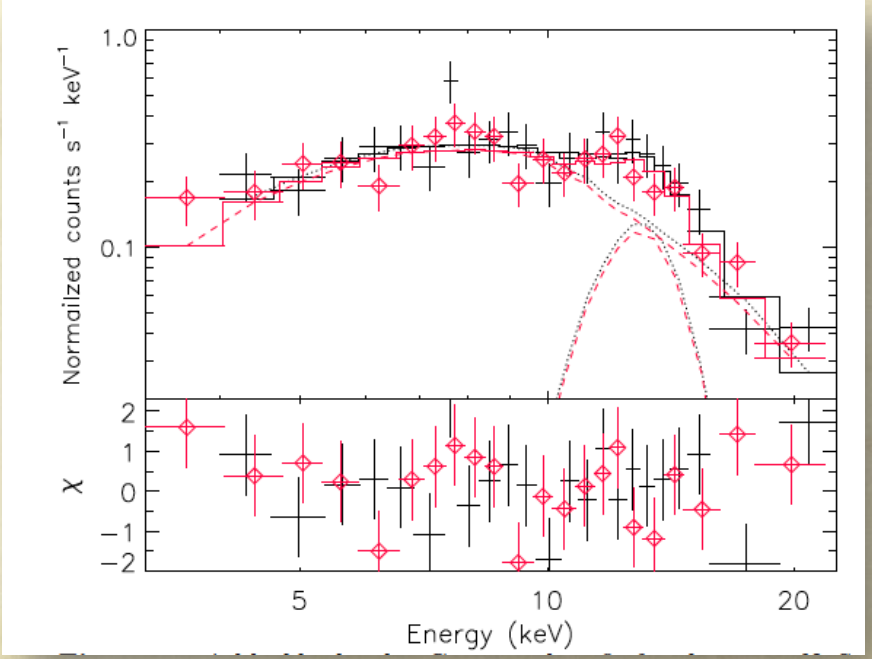
X-ray lines in INS

- XDINS:
  - Most have broad absorption lines
  - Proton cyclotron lines or atomic transitions in B ≈10^{13} G
  - No lines in RX J1856

See Kaplan talk

- Magnetars
  - A few unconfirmed claims in phase-resolved spectra of persistent emission
  - Transient features during (some) bursts (E ≈14 keV)
    Recently confirmed with NuSTAR
  - Strong phase-dependent line in SGR 0418 ("low Pdot magnetar")

1E 1048 NuSTAR An+2014

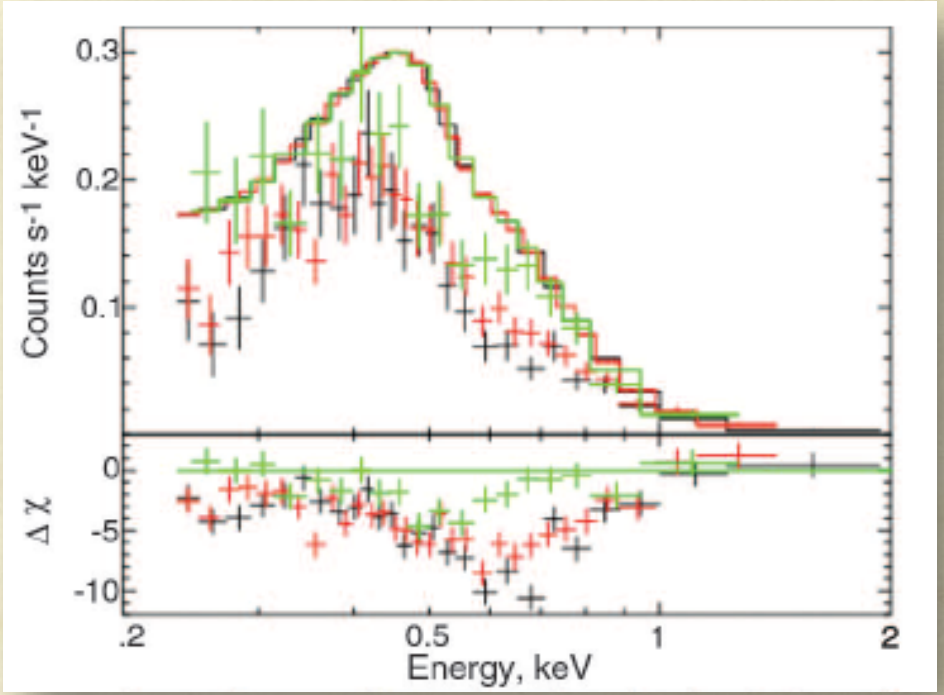


X-ray lines in INS

- RRAT PSR J1819 - absorption line at 1 keV
  (McLaughlin+ 2005, Rea+ 2009, Camero-Arranz+ 2013)

- Normal RPP:
  - PSR J1740+1000
    phase-dependent line at 0.5-07 keV
    (Kargaltsev+ 2012)

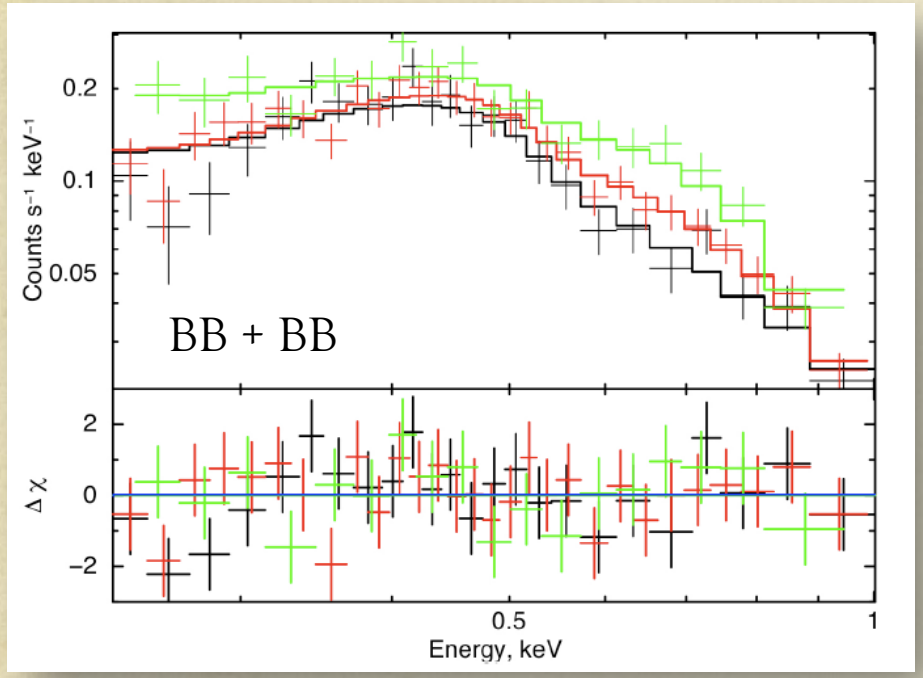
PSR J1740+1000 (Kargaltsev+ 2012)

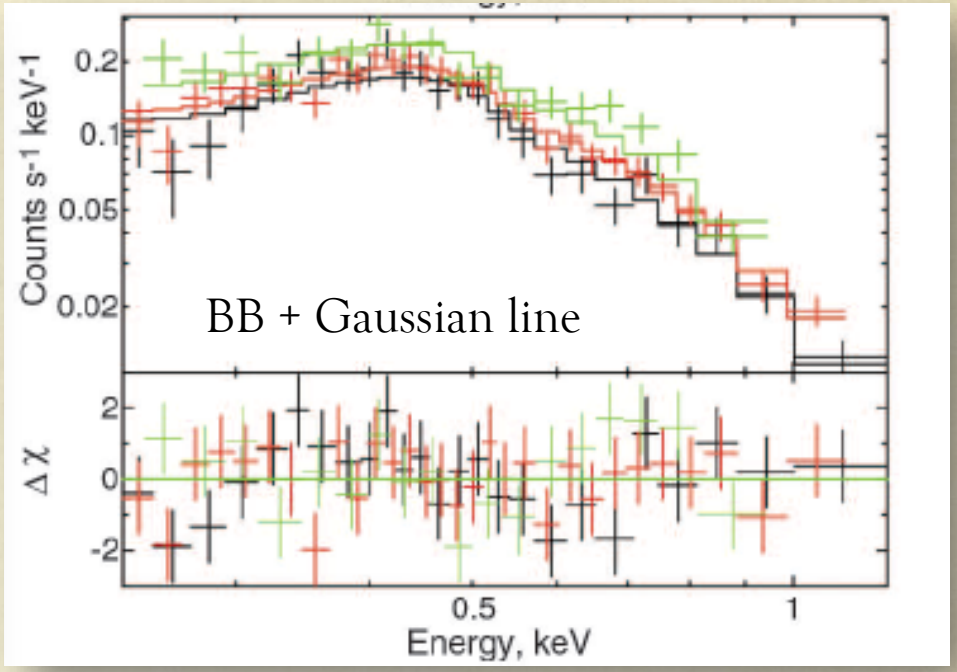


  - Fermi pulsar PSR J0633+0632
    (→ Danilenko talk)
  - Double pulsar PSR J0737-3039
    (→ Egron talk)

PSR J1740+1000

(Kargaltsev+ 2012)





P=154 ms Pdot =2 10^{-14} s/s 2BB+PL spectrum

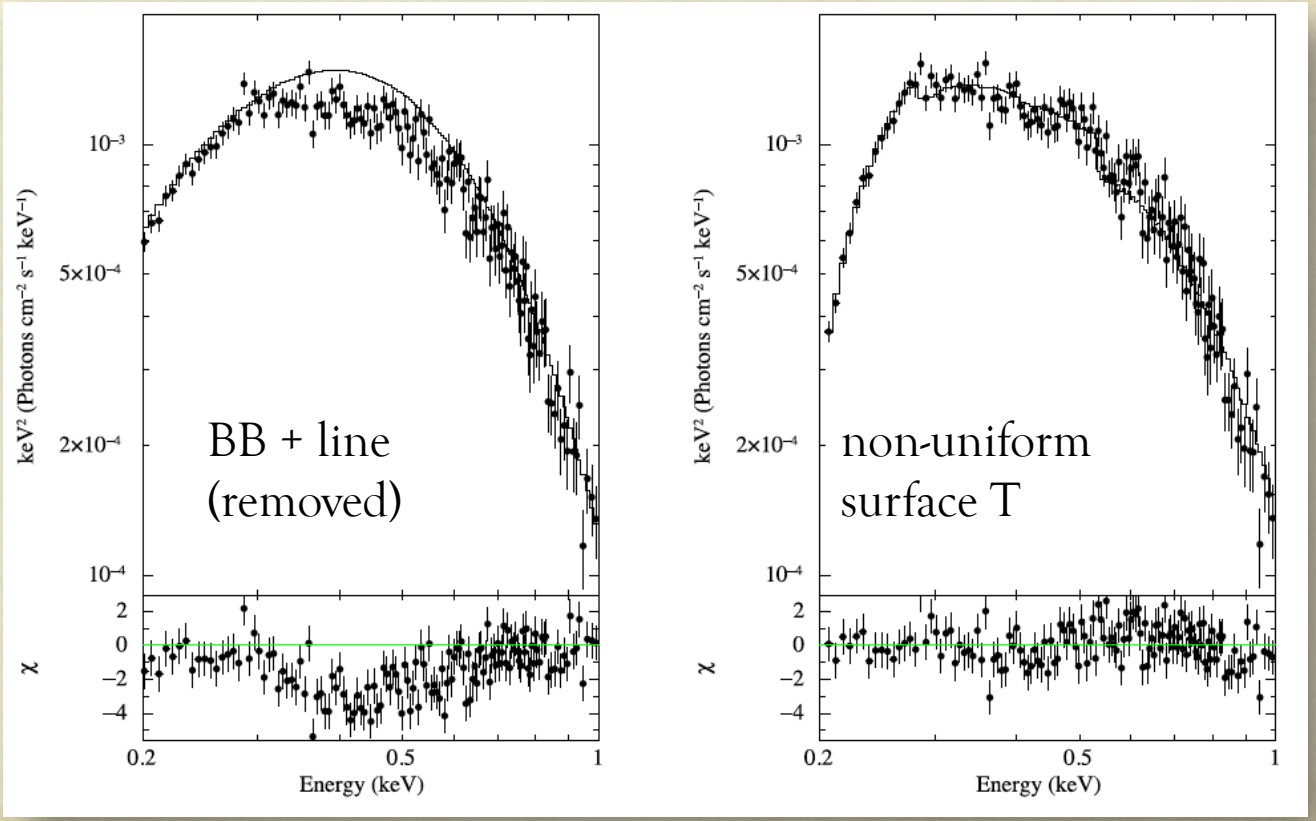
τ =10^5 yrs B=1.8 10^{12} G $\dot{E}_{ROT}$ = 2.3 10^{35} erg/s

Atomic transitions in Z>2 elements or cyclotron line from electrons at few R_{NS} in magnetosphere

Caveat for broad lines in thermal spectra

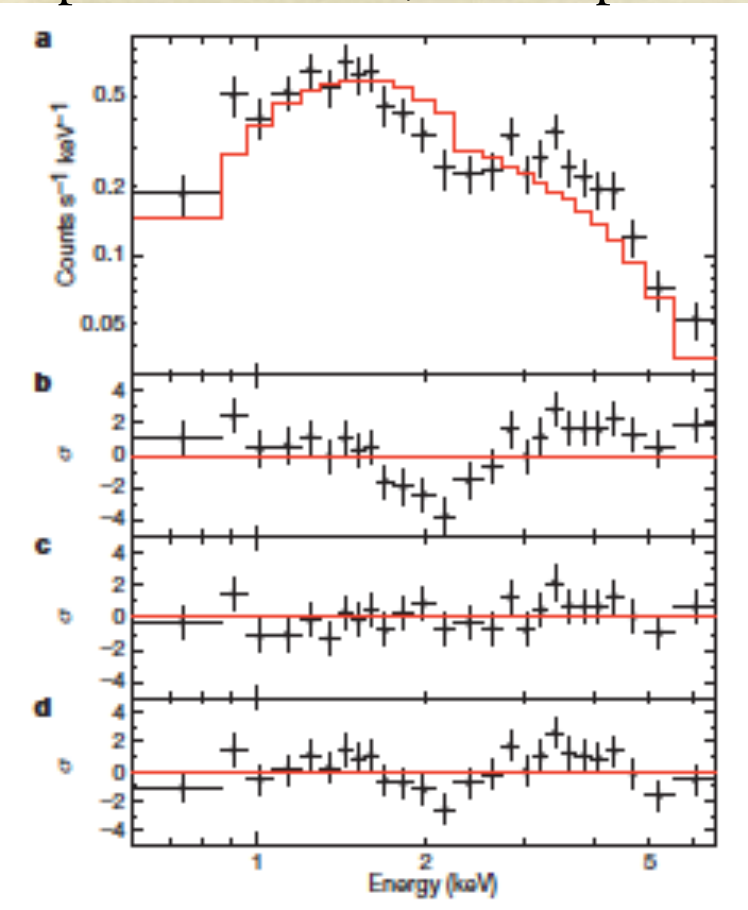
- Vigano'+ 2014 → Inhomogeneous surface temperature distributions can produce spectra which mimic broad absorption lines

XDIN RXJ 0806

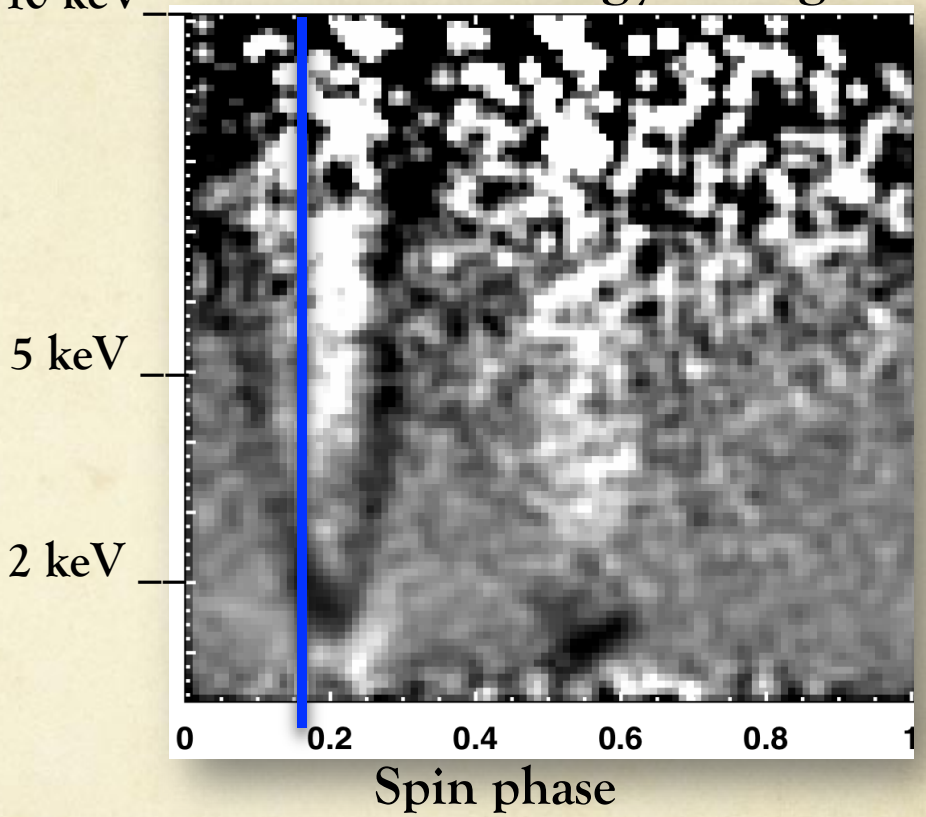


Absorption line at strongly phase-dependent energy in low-Pdot magnetar SGR 0418 (Tiengo+ 2013)

Spectrum of 1/50 of phase

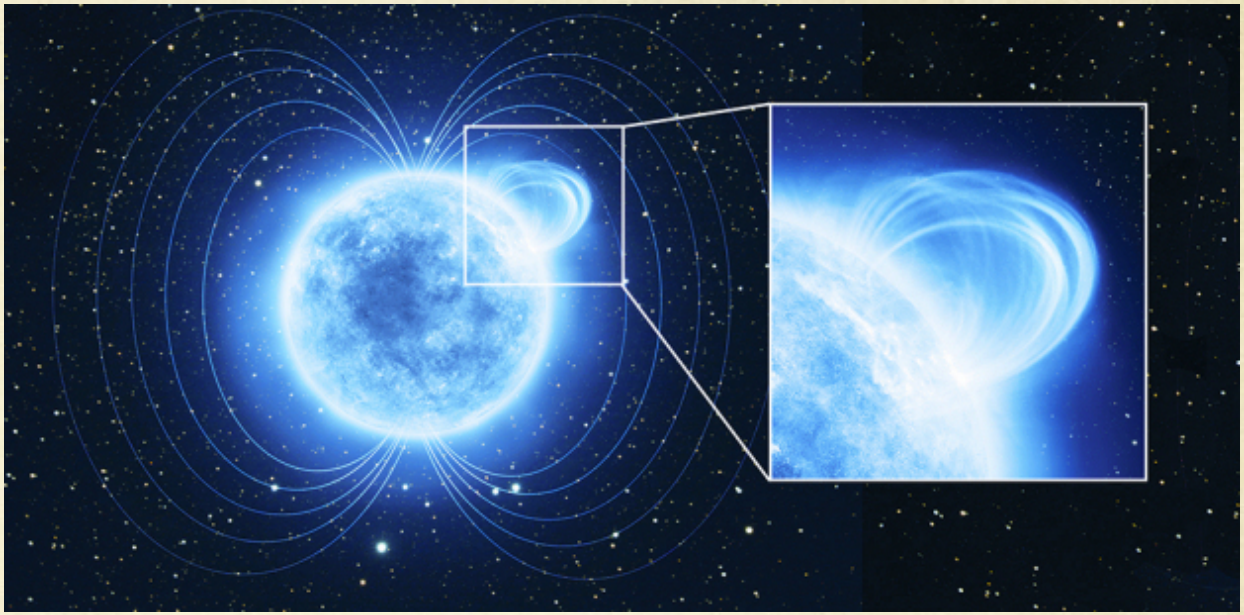


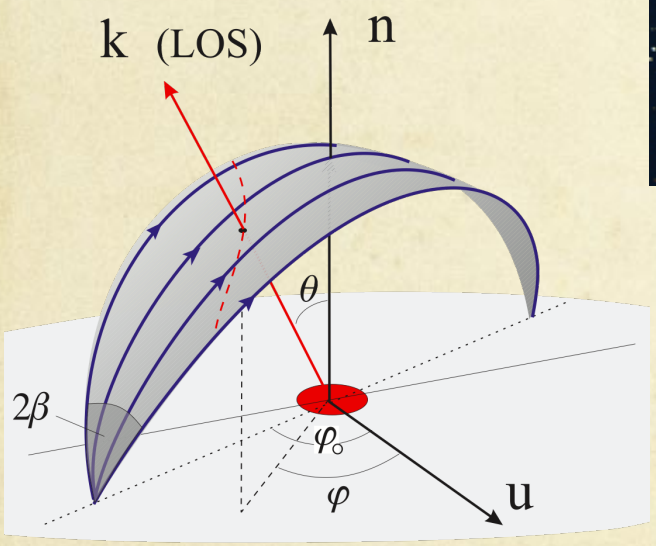
Phase-Energy Image



Line center varies from 1 to 10 keV in $\Delta\phi \approx 0.1$

Absorption line at strongly phase-dependent energy in low-Pdot magnetar SGR 0418 (Tiengo+ 2013)





- cyclotron line from protons in small-scale loop with B from ≈2 10^{14} to ≈2 10^{15} G

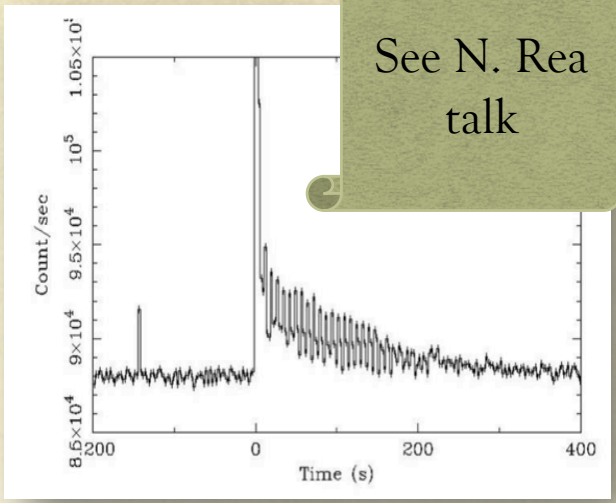
  wrt dipolar field B≈6 10^{12} G (Rea+ 2013)

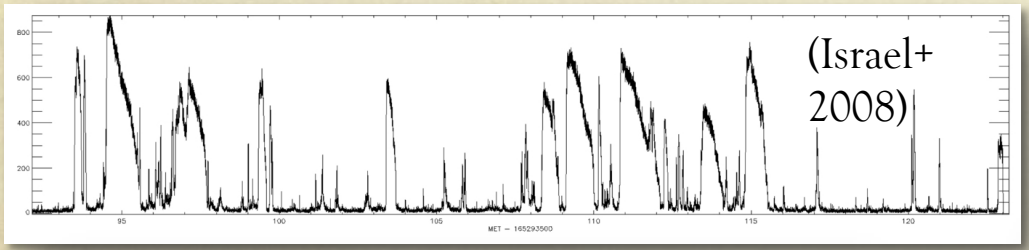
4. Variability

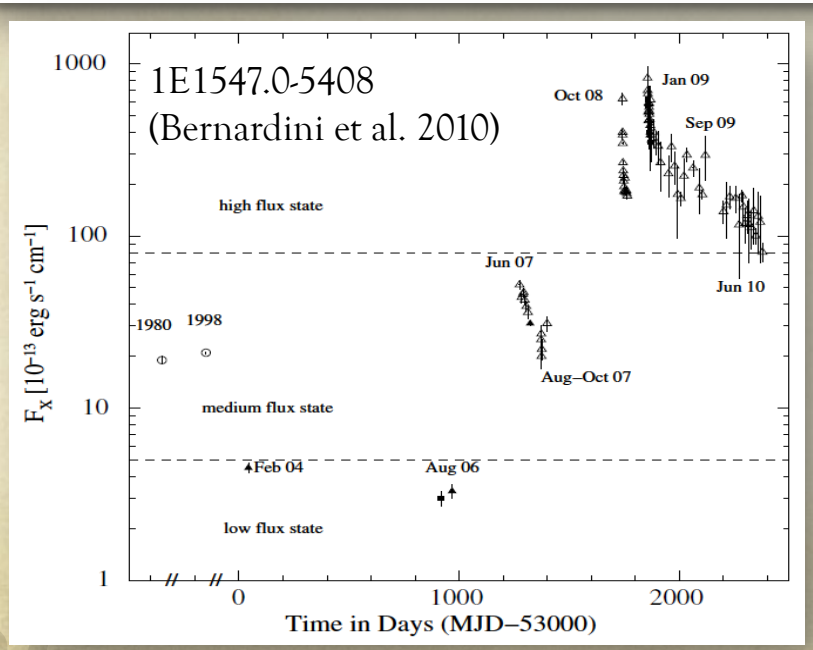
X-ray variability in INS

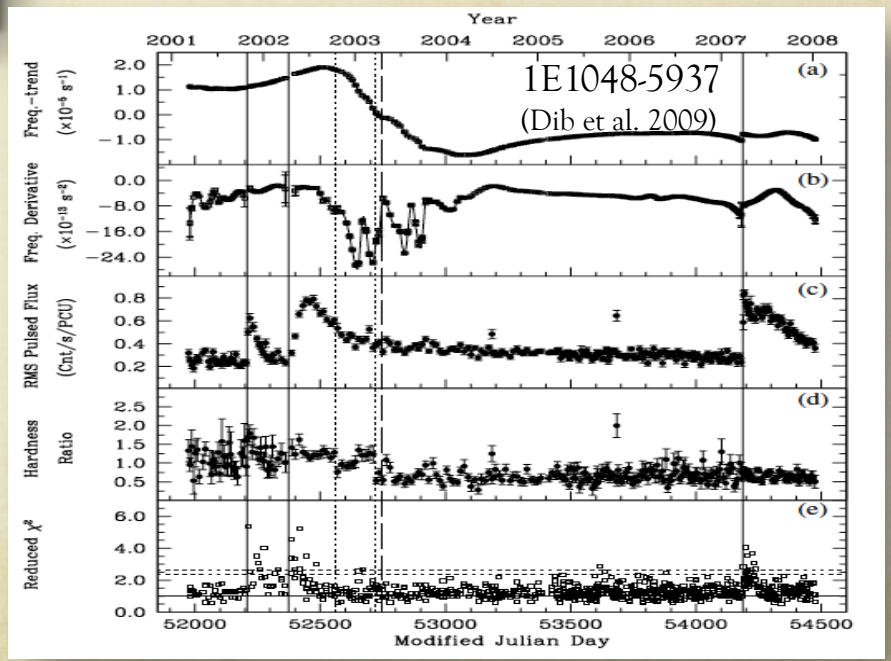
- Distinctive property of magnetars
  - bursts / flares
  - Transients / variable "persistent"

See N. Rea talk







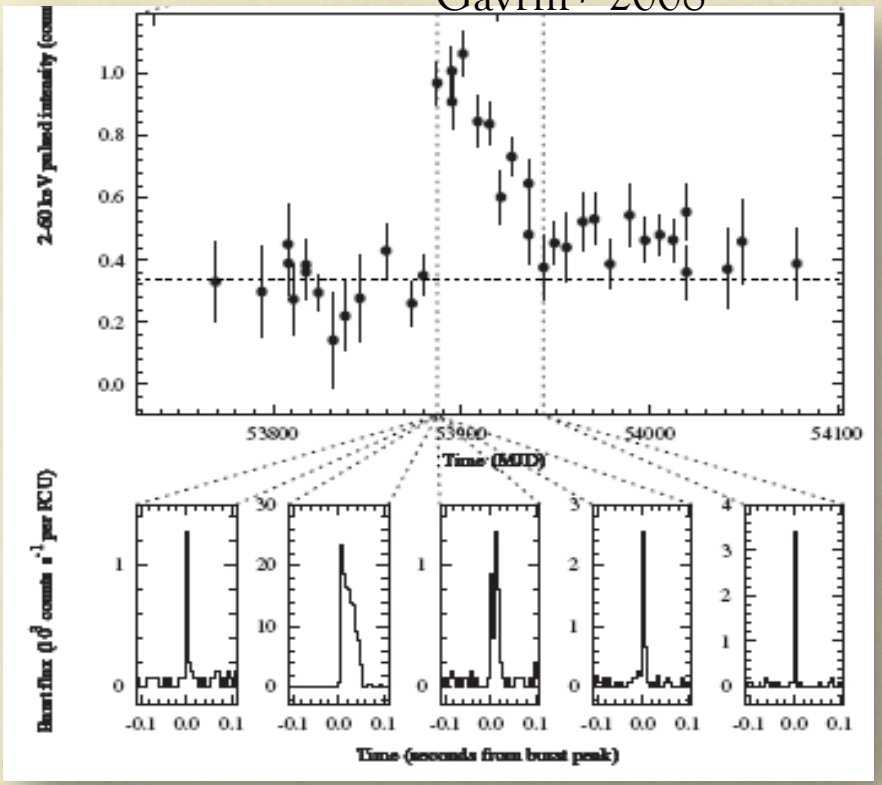


X-ray variability in INS

- Distinctive property of magnetars
  - bursts / flares
  - Transients / variable "persistent"
- Seen also in other NS of different classes, e.g.:
  - PSR J1846 (RPP)


Kes 75 (Kumar & Safi-Harb 2008)

Gavriil+ 2008



X-ray variability in INS

Hohle+ 2009, 2012

- Distinctive property of magnetars
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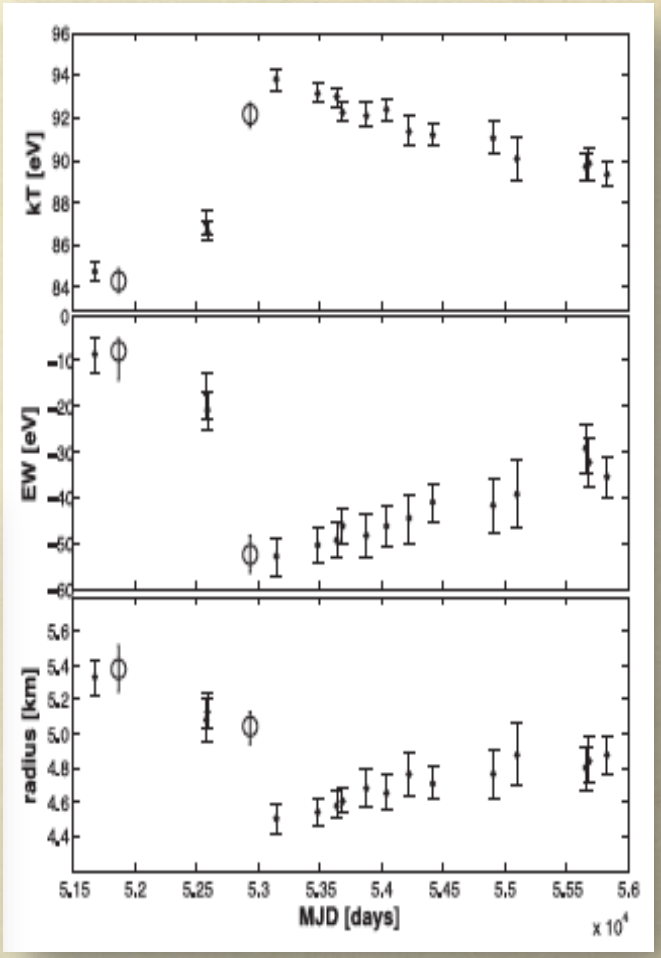
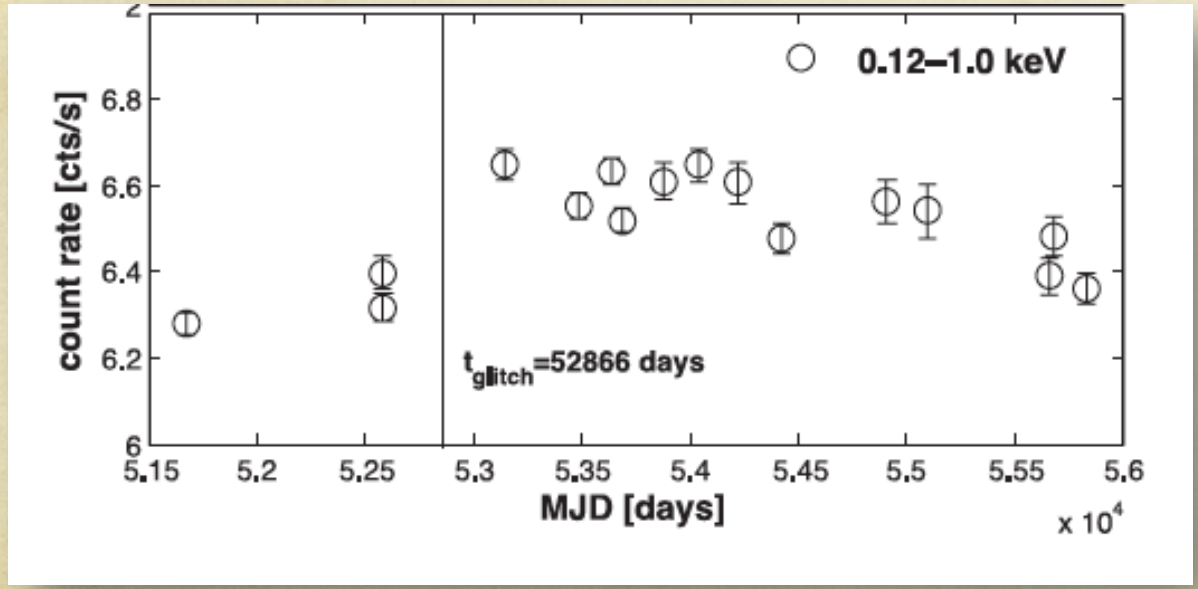
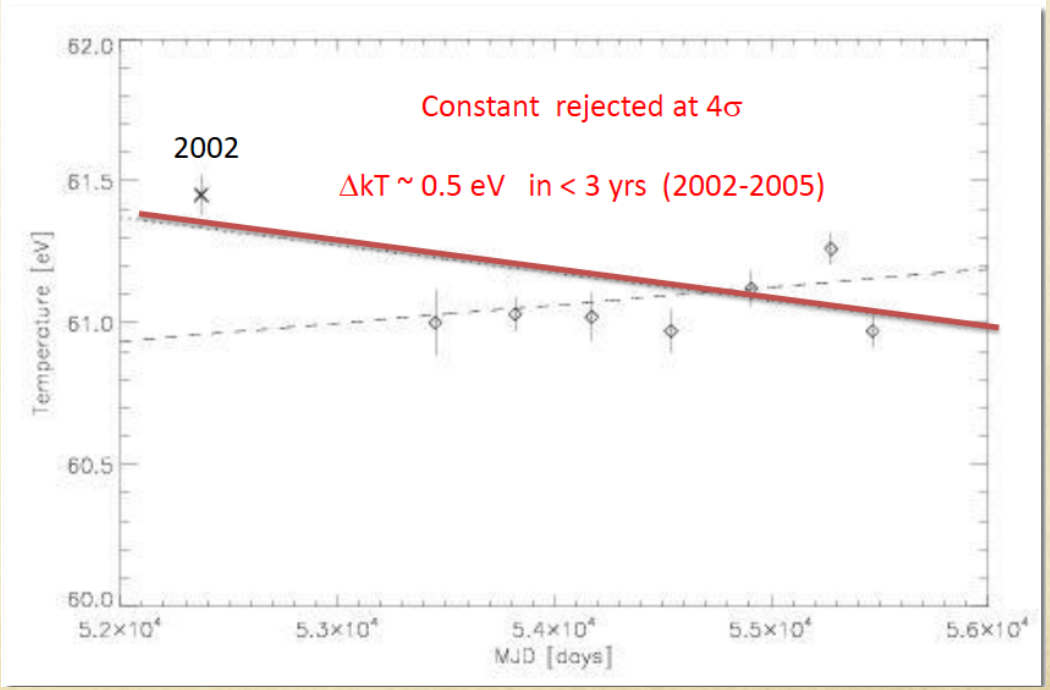
- Seen also in other NS of different classes, e.g.:
  - RXJ 0720 (XDINS)





X-ray variability in INS

- RXJ 0720 is the only XDINS with confirmed variability
- Most other XDINS are fainter and/or less observed
- Except RX J1856 in which small temperature variations could be caused by calibration issues (Sartore+ 2012)



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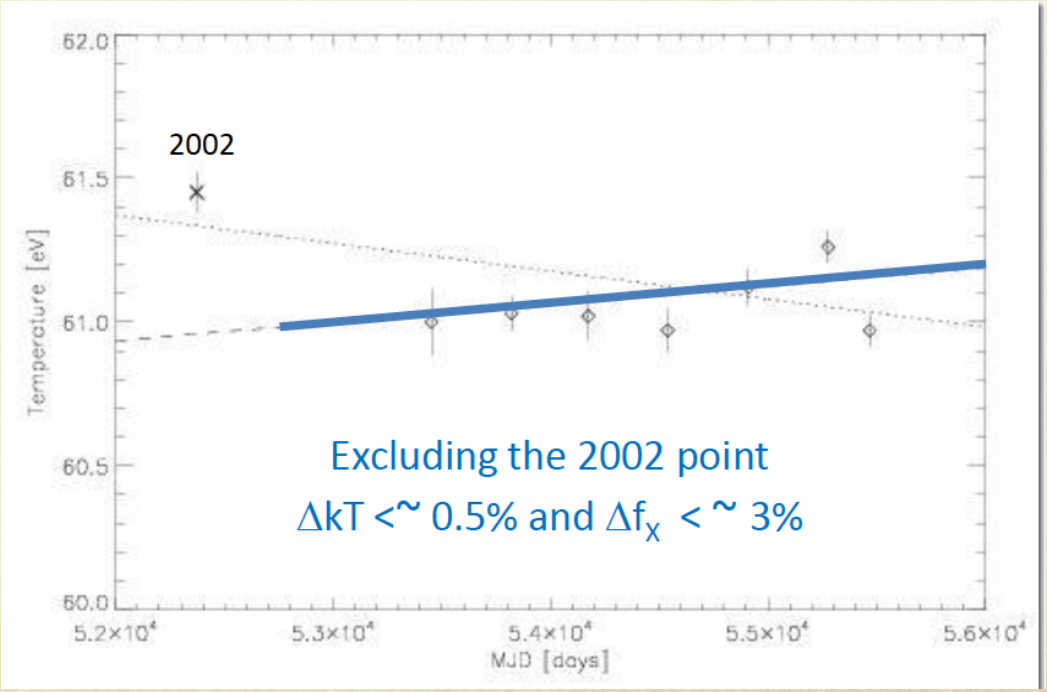
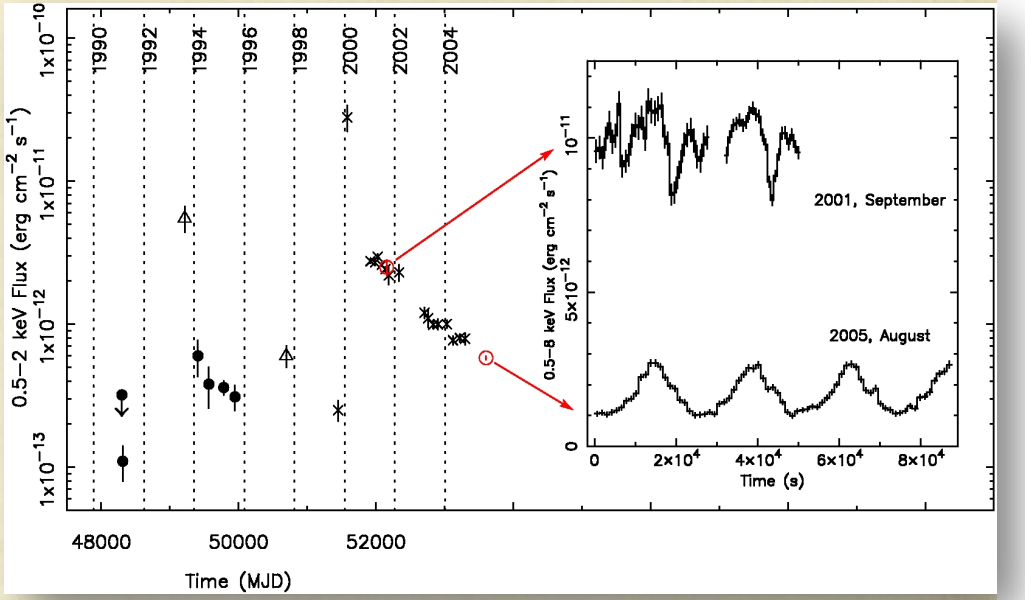


X-ray variability in INS

- Distinctive property of magnetars
  - bursts / flares
  - Transients / variable "persistent"
- Variability seen also in NS of other different classes, e.g.:
  - PSR J1846 (RPP)
  - RXJ 0720 (XDINS)
  - RCW 103
- **Possibly all related to dynamic manifestations of magnetic fields**

Central source in RCW 103



De Luca+ 2006, 2008, Pizzolato+ 2008

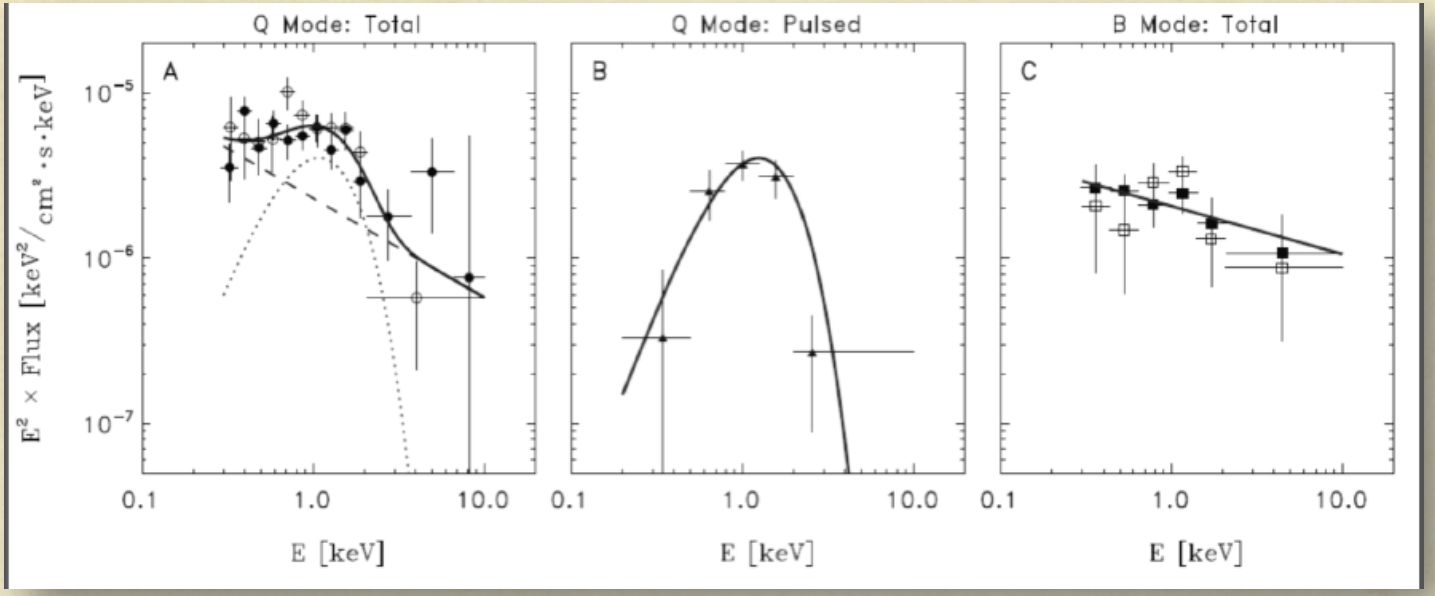
X-ray variability in INS

Mode-switching radio PSR B0943+10

Brigth mode: regularly drifting sub-pulses

Quiescent mode: sparse and caothic pulses

Hermsen+ 2013

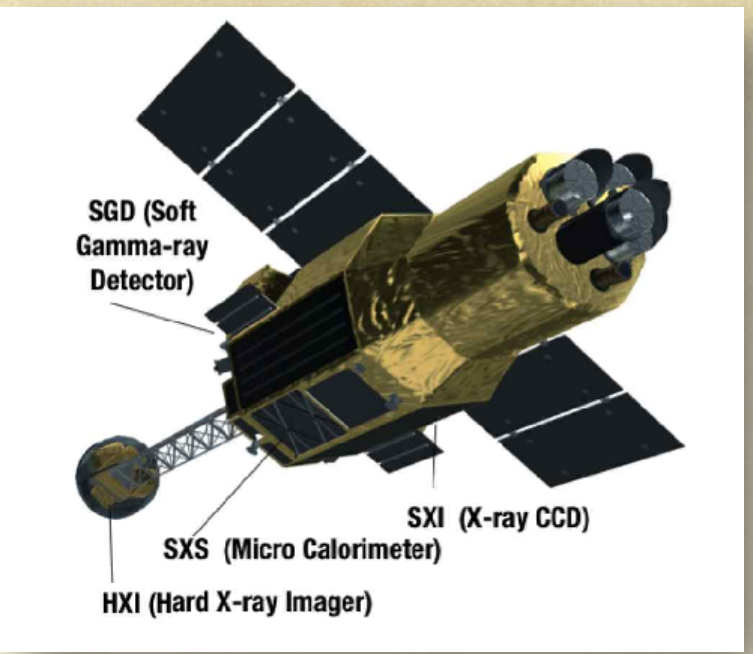


X-ray properties change with radio mode suggesting global magnetospheric variations (Hermsen+ 2013)

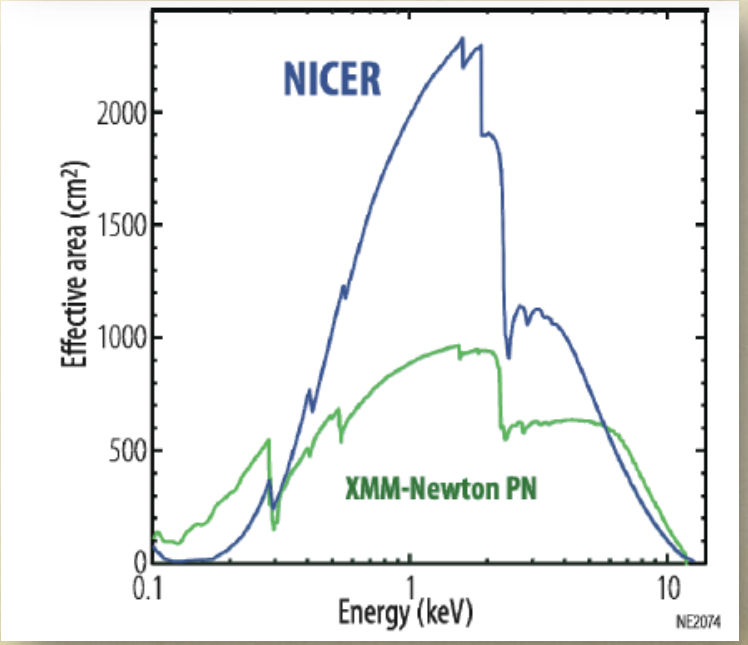
...but see Mereghetti+ 2013 for a different interpretation

See talks by Hermsen and Turolla

- ASTRO-H:
  - launch in 2015
  - soft and hard X-ray telescopes + different detectors to provide wide band coverage
  - Calorimeter:
    $\Delta E \approx 5$ eV in 0.3-10 keV band



- NICER:
  Neutron star **I**nterior **C**omposition **Explore**r
  - on ISS in 2017
  - Mission devoted to NS timing +spectroscopy



A few final remarks

1. **NON - THERMAL EMISSION**
   - *broad-band multi-λ approach fundamental,*
   - *impressive progress in γ-ray band (models geometry, population)*

2. **THERMAL EMISSION**
   - *observations-starved theoreticians...*

3. **LINES**
   - *mostly elusive results, but things are changing*

4. **VARIABILITY**
   - *magnetic activity not limited to magnetars*
   - *new great diagnostic tool also for RPP*

5. **(NEAR) FUTURE**
   - *try to get more time on XMM/Chandra...*
   - *Astro-H 2015 ? - NICER 2017 ?*