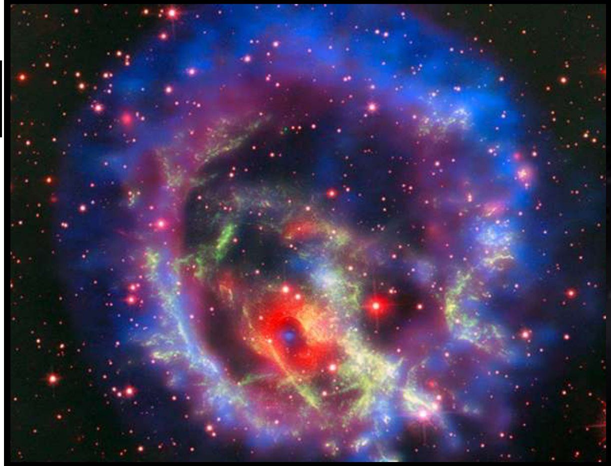
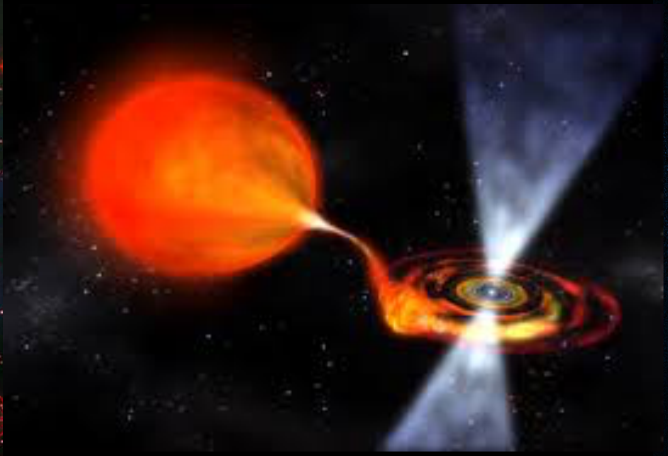
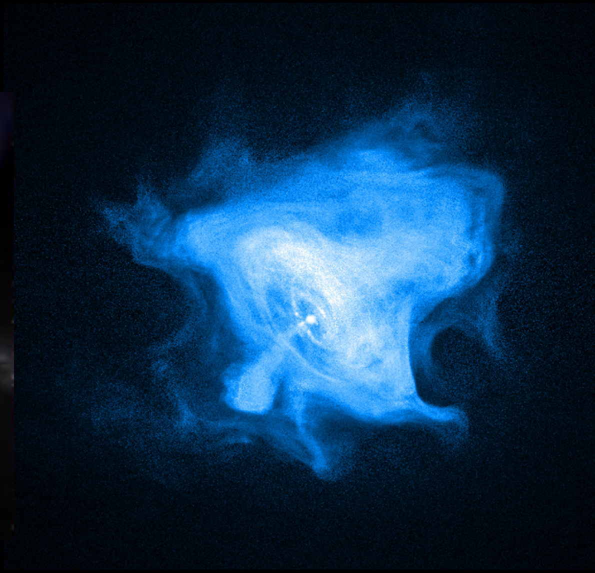
  

Vicky Kaspi, McGill University, Montreal, Canada

CHANDRA & NEUTRON STARS

DEC 3, 2019
CHANDRA 20TH ANNIVERSARY
BOSTON, MA

Census of Non-Accretion Neutron Stars

Isolated Neutron Stars
(formerly Dim Isolated Neutron Stars – DINs)

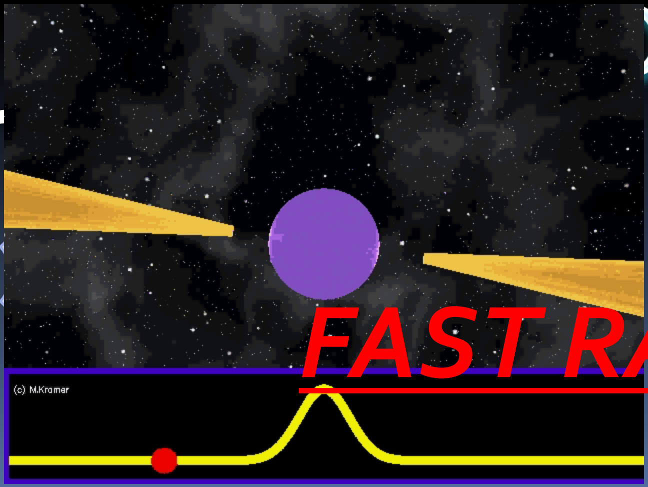
CCOs
(Central Compact Objects)

RRATs
(Rotating Radio Transients)

RADIO PULSARS
(aka Rotation-Powered Pulsars)

ND PULSARS

Magnetar
(AXPs and SGRs)



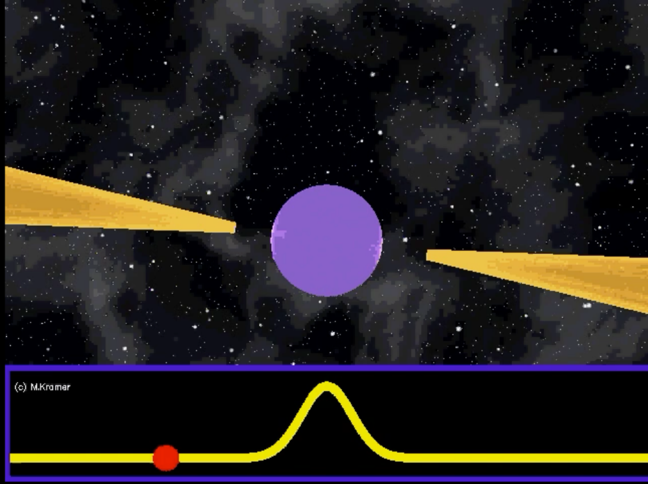
FAST RADIO BURSTS


NEUTRON STAR
THE ZOO

Broad Overview: Why Chandra Observations of Neutron Stars?

- Help understand
  - The neutron star "zoo"
  - Formation & evolution of isolated & binary compact objects
  - Neutron star magnetospheric physics
  - Neutron star interior structure & EoS
  - Pulsar wind and interaction with environment (see posters by Kargaltsev, Klingler, de Vries)

Radio Pulsars



- Rapidly rotating (1.6 ms – 23 s), highly magnetized (10^8 – 10^{14} G) neutron stars
- $B = 3.2 \times 10^{19}$ G (P Pdot)$^{1/2}$
- Powered by loss of rotational kinetic energy
  - L_{sd} = "spin-down" luminosity
- Most readily observed in radio waves: ~2800 known (ATNF pulsar catalog)
- In X-rays, no catalog; 100-150 X-ray detected

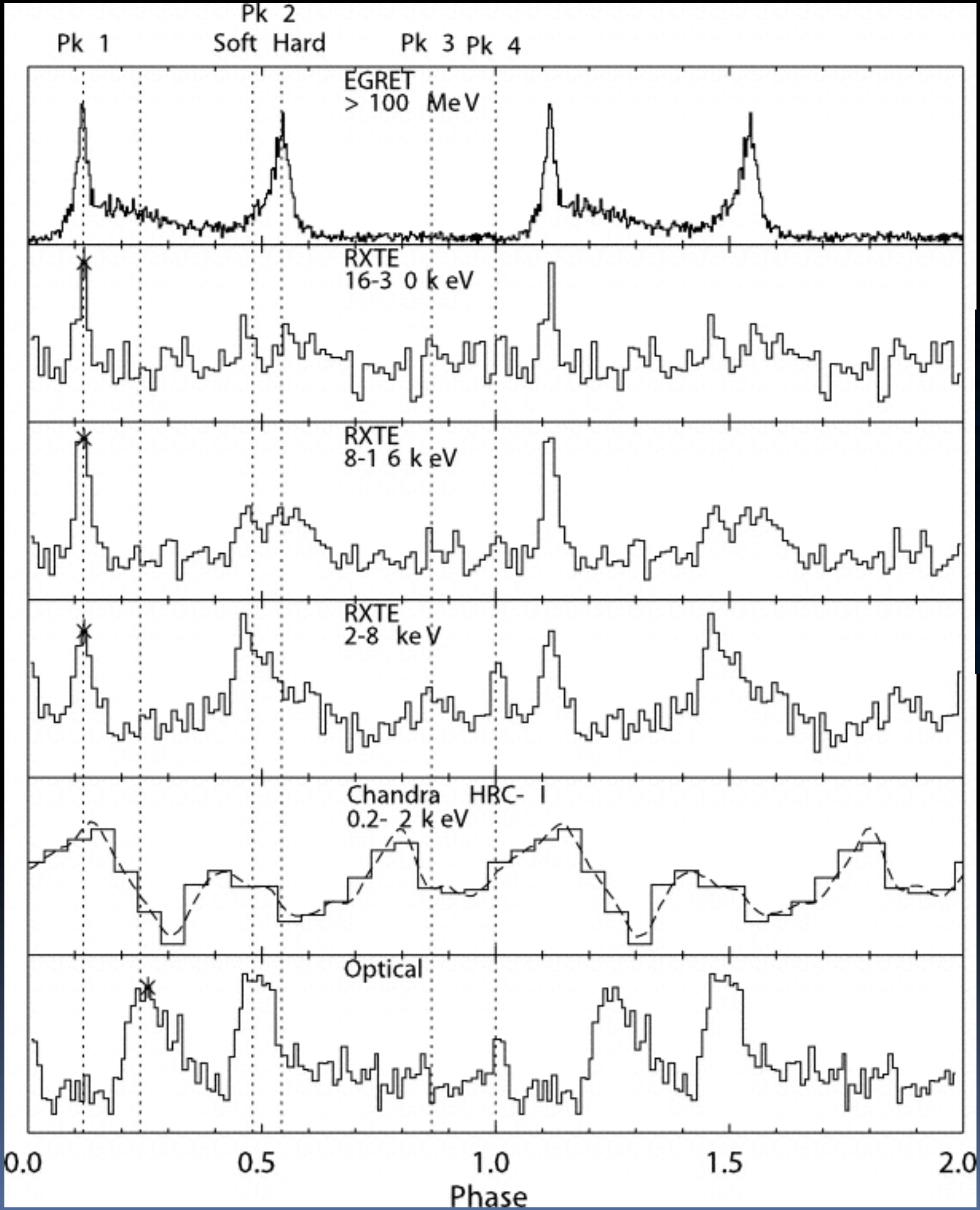
Radio Pulsars II

- <u>4 main emission mechanisms:</u>
  - Non-thermal (from magnetosphere): powered by L_{sd}
  - Thermal (from polar caps): powered by L_{sd}
  - Thermal (from surface): residual heat
  - Thermal & non-thermal: from decaying B (in high-B sources)
  - All "contaminated" by surrounding nebular wind emission (powered by Lsd)
    - Beauty of Chandra for pulsar observations!

Vela Pulsar

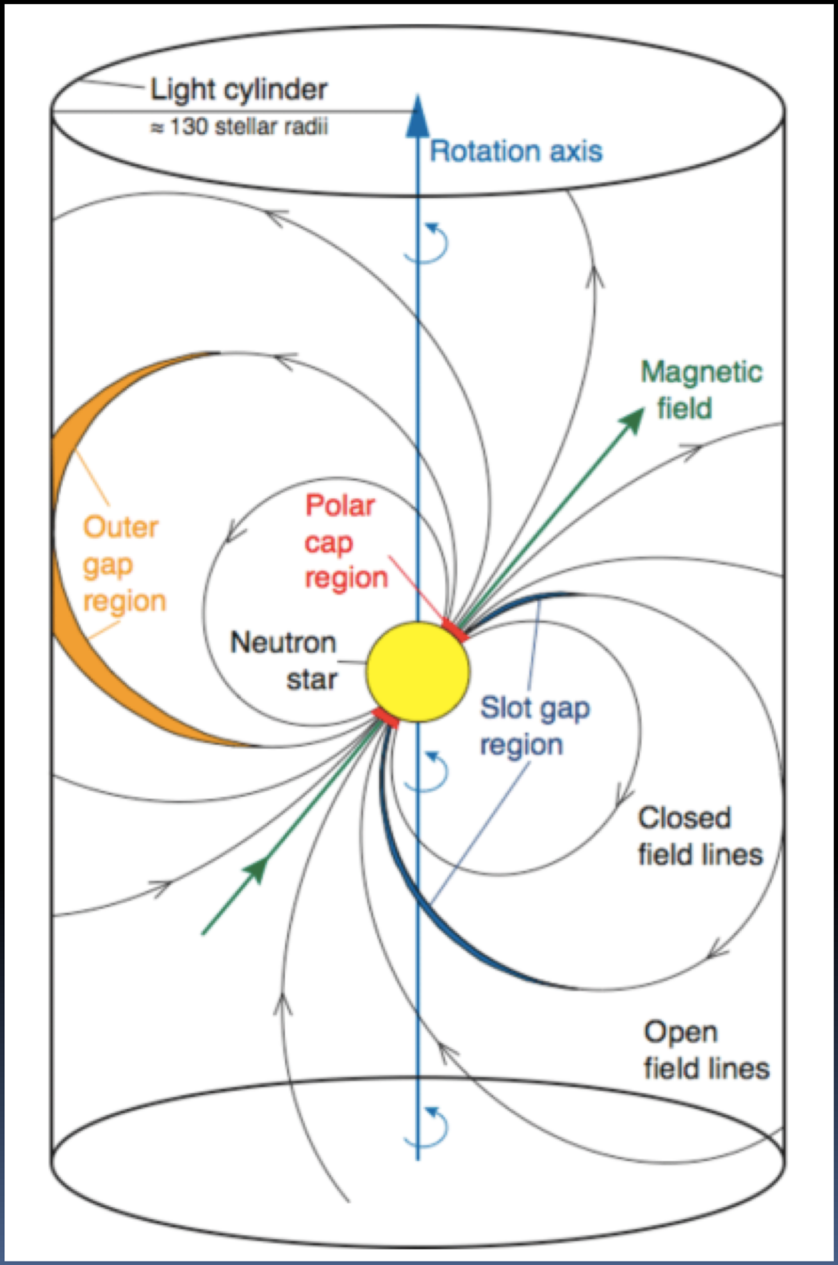
Non-thermal emission

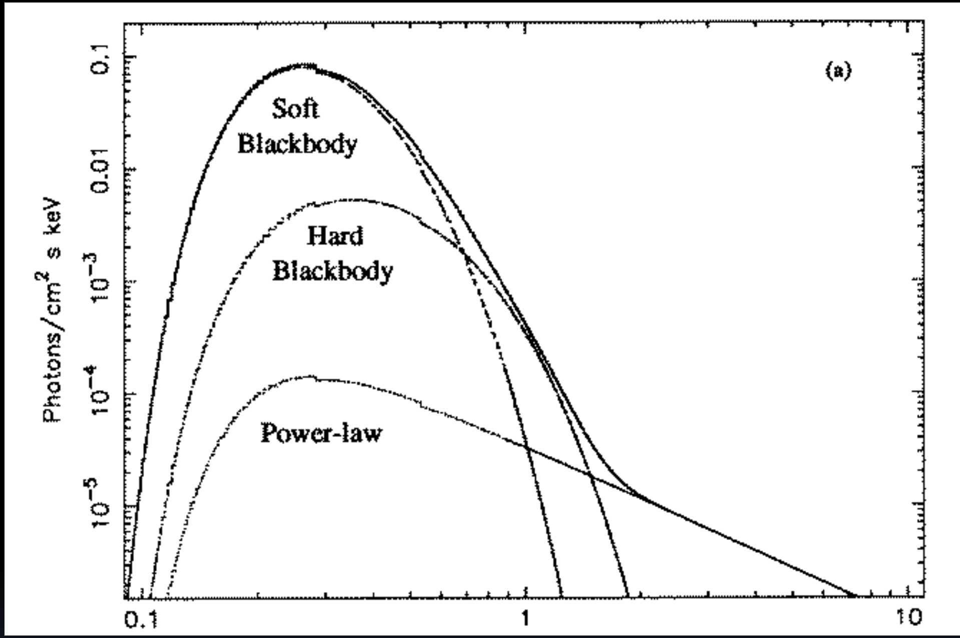
Thermal emission



Harding et al. 2002

Typical Pulsar X-ray Spectrum

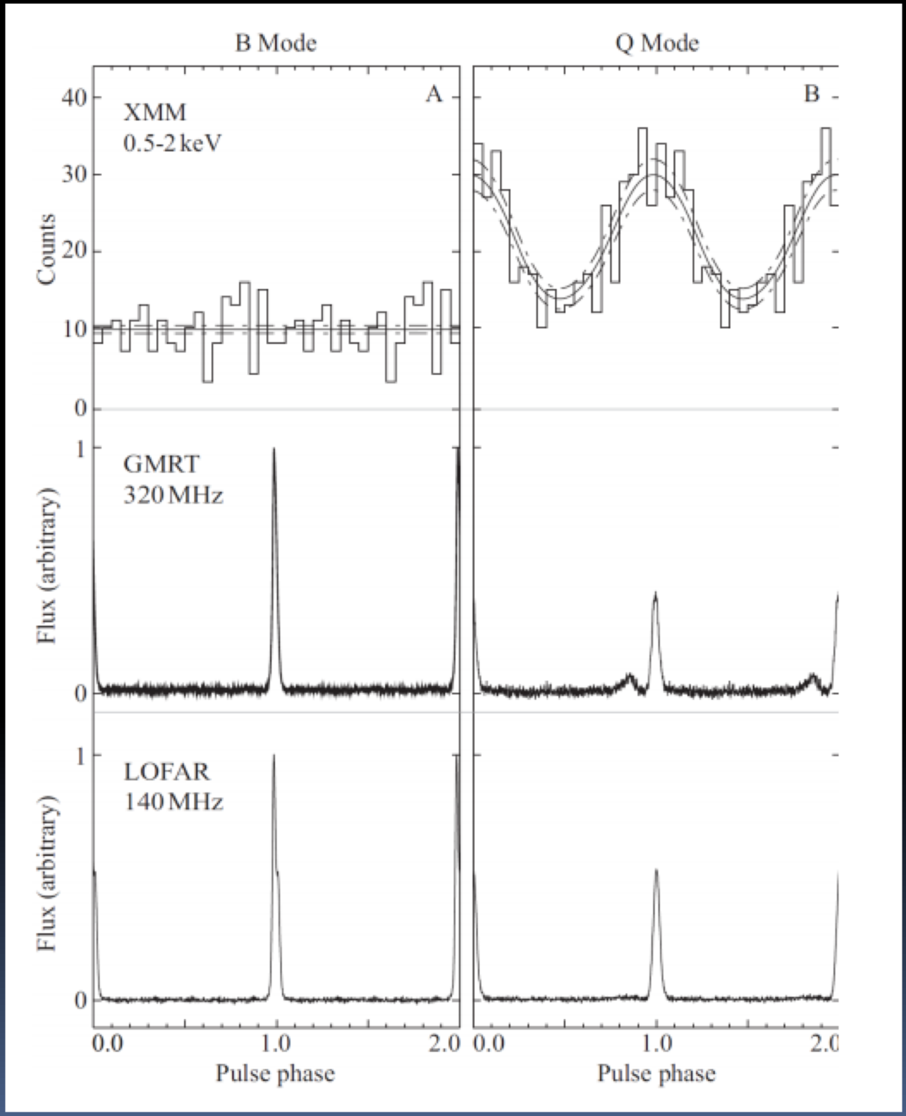




Chandra has done foundational work on many pulsars

Radio Pulsars: Key Question I

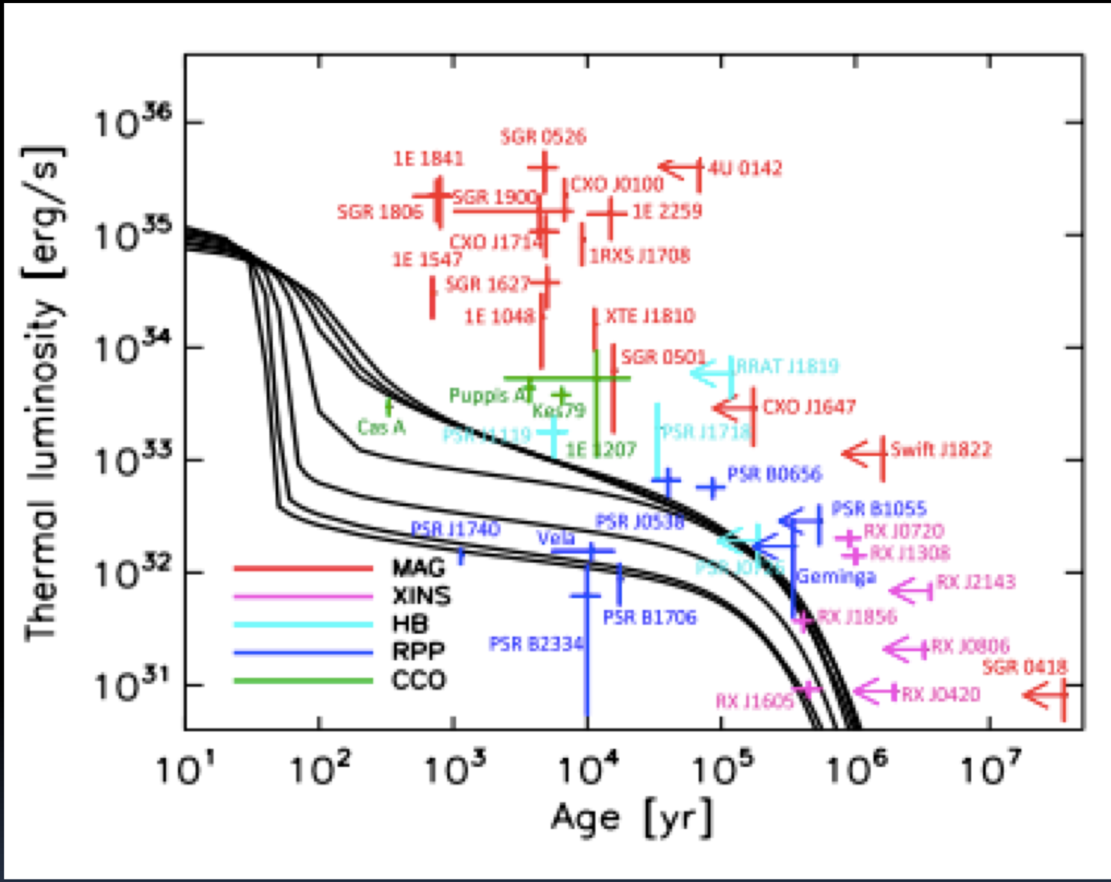
- Do we understand physics of the magnetosphere?
- Mode-changing PSR B0943+10 (Hermsen et al. 2013; Mereghetti et al 2016) suggests maybe no!
  - Strong coupling between radio and X-ray emission: Unexpected
  - Chandra: No X-ray nebula



Hermsen et al. 2013

Radio Pulsars: Key Questions II

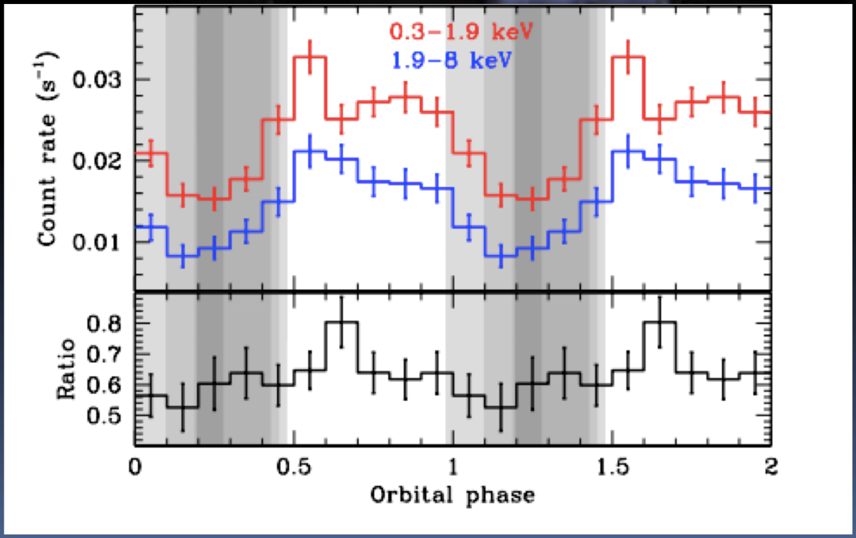
- Thermal emission: constrain EoS of NS via cooling?
  - Beautiful theory!
- Chandra legacy:
  - High angular resolution enables separation of nebular emission
  - See talk by P. Slane
  - Hint at rapid cooling from Chandra obs of 3C 58 Slane et al. (2002, 2004)
- Challenges:
  - “contamination” from
    - age uncertainties
    - mass uncertainties
    - spin-powered thermal emission



Potekhin, Pons & Page 2015

Millisecond Pulsars: Key Question

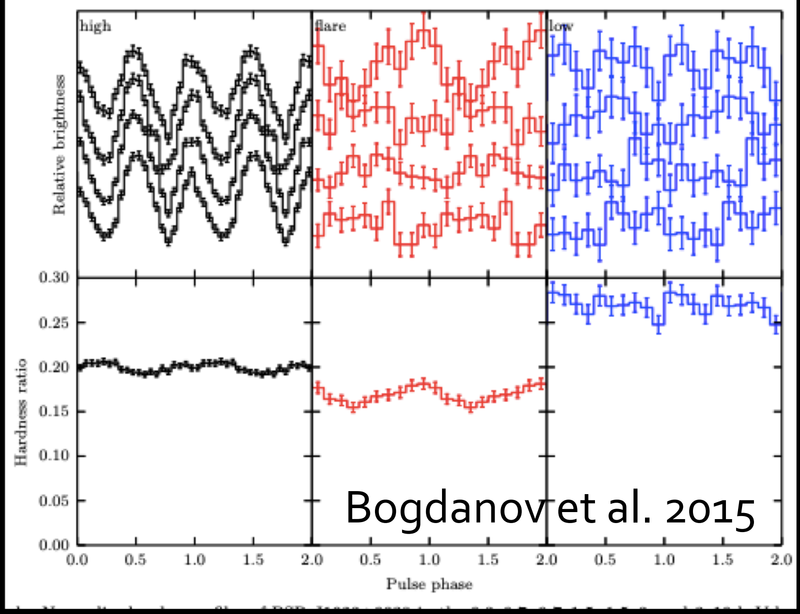
- Radio pulsars that were "recycled" by accretion of material from binary companion
- Rapid rotation, low B-field
- If "recycling" correct, are there "transitional" MSPs that sometimes accrete, sometimes are radio pulsars?
- Yes! e.g. PSR J1023+0038:
  - 1.7 ms (part-time) radio pulsar in 4.75 hr orbit around bloated 0.2 solar mass MS star (Archibald et al. 2009)
- See also Papitto et al. 2013, de Martino et al. 2015…

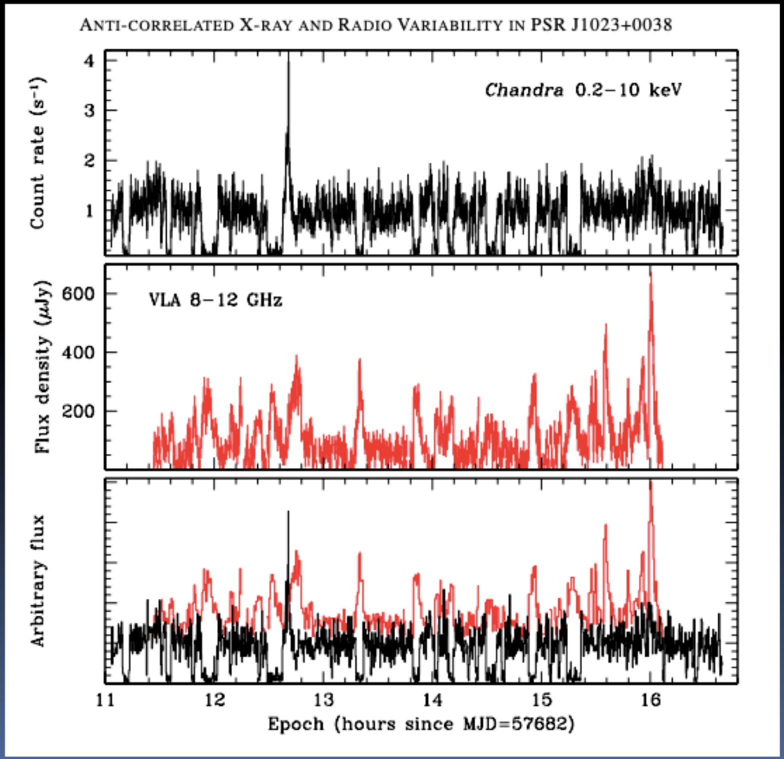


Bogdanov et al. 2011

Transitional MSPs: Surprising Phenomenology

- Surprising "3-level" X-ray emission seen (Tendulkar et al. 2014; Bogdanov et al. 2015,18; Archibald et al. 2015)
- Anti-correlation with radio variability
- Unclear if NS accreting during flares
- Radio pulsar active??



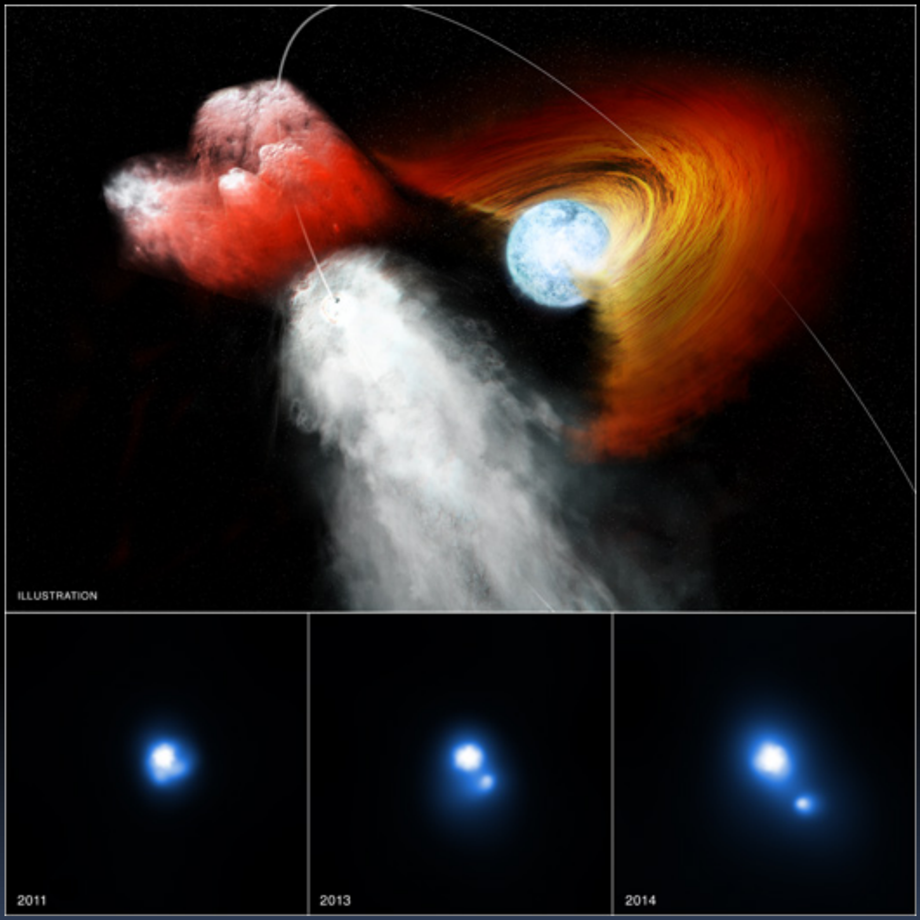


Bogdanov et al. 2018

Binary Radio Pulsars

Talk by G. Pavlov yesterday!!

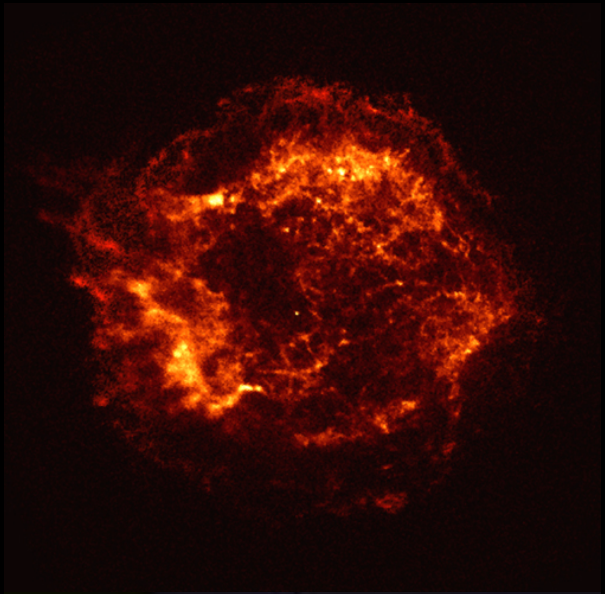
- Pulsars in binaries can interact with companion stellar wind (for MS companions)
- Regular controlled experiment…pulsar moves predictably through highly variable environment
  - or not!!
- Similar system recently found, studied by Chandra (Ho et al. 2017)



PSR B1259-63: Be Star binary
Pavlov et al. 2015

Central Compact Objects

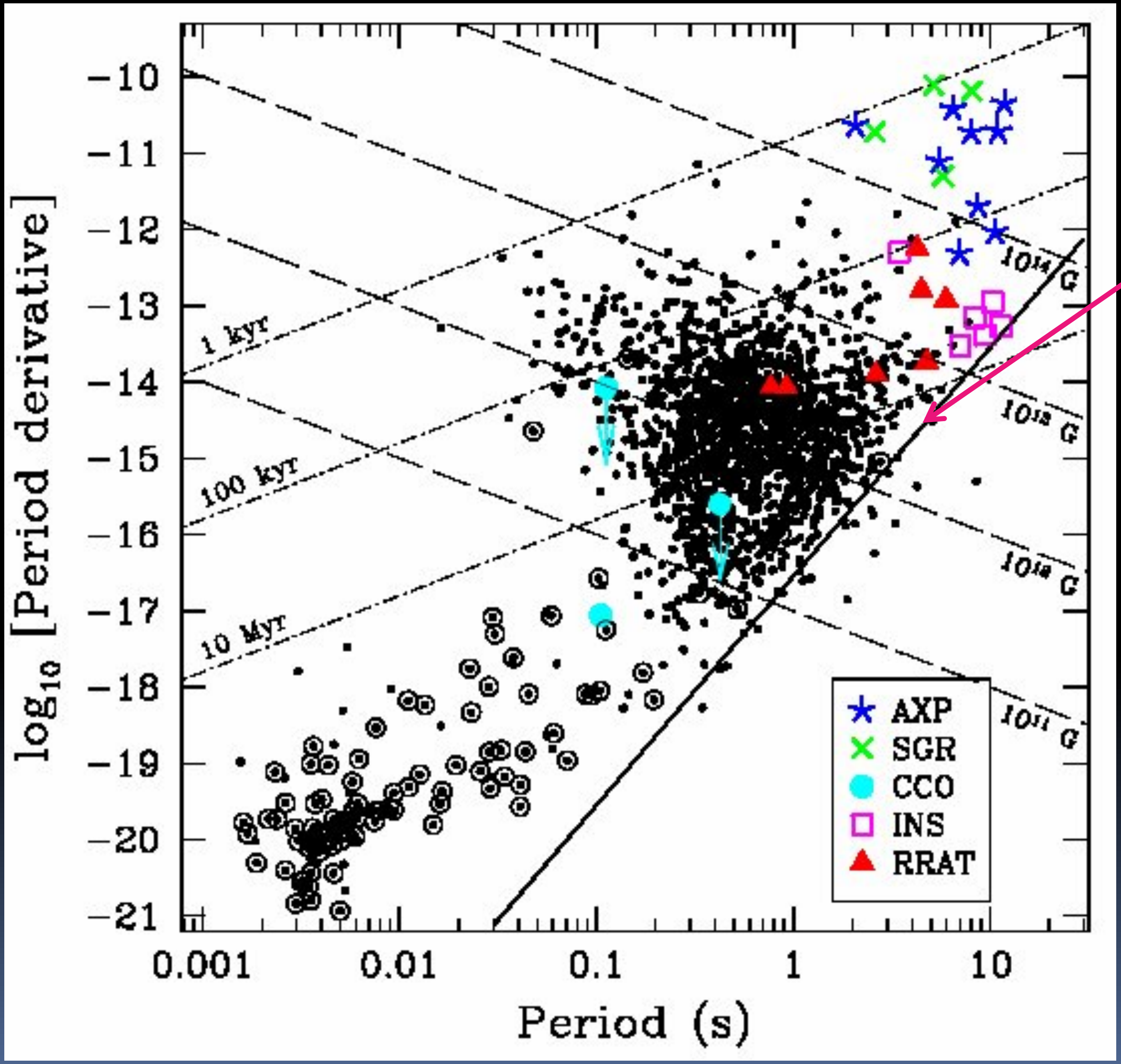
- X-ray point sources in centers of SNRs
- Major Chandra legacy!
- Unclear nature of central sources…mixed bag
  - Some have P, Pdot measured
    e.g Kes 79 CCO
    B= 3 x 10^{10} G
    (Halpern & Gotthelf 2010)



Cas A

Kes 79

P-Pdot Diagram: CCO Puzzle



Death Line

Kes 79 CCO will take ~3 Gyr to reach death line

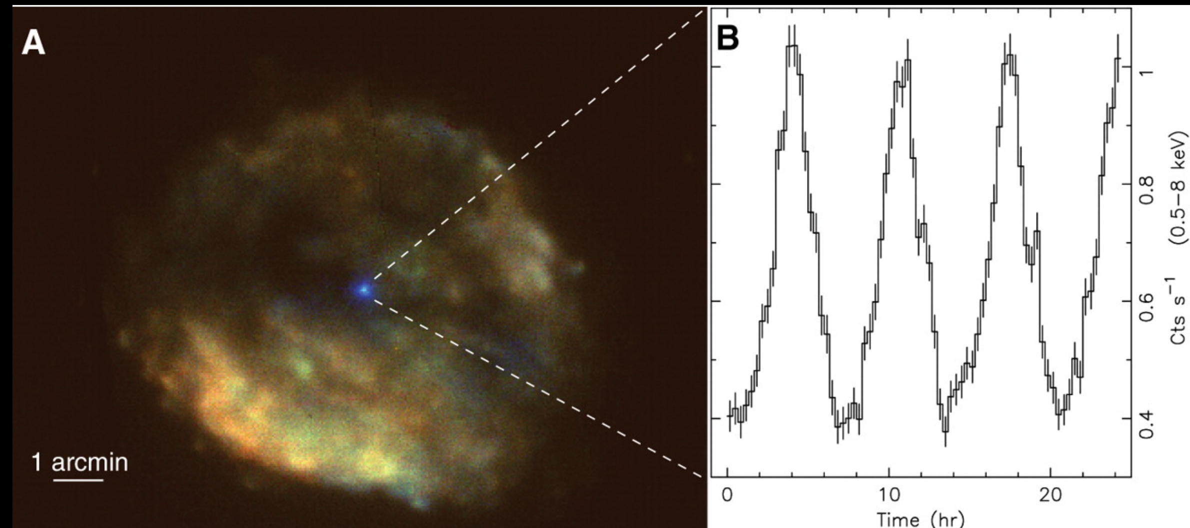
If BR~ 3/7 kyr, should be 1,000,000 in Galaxy!!

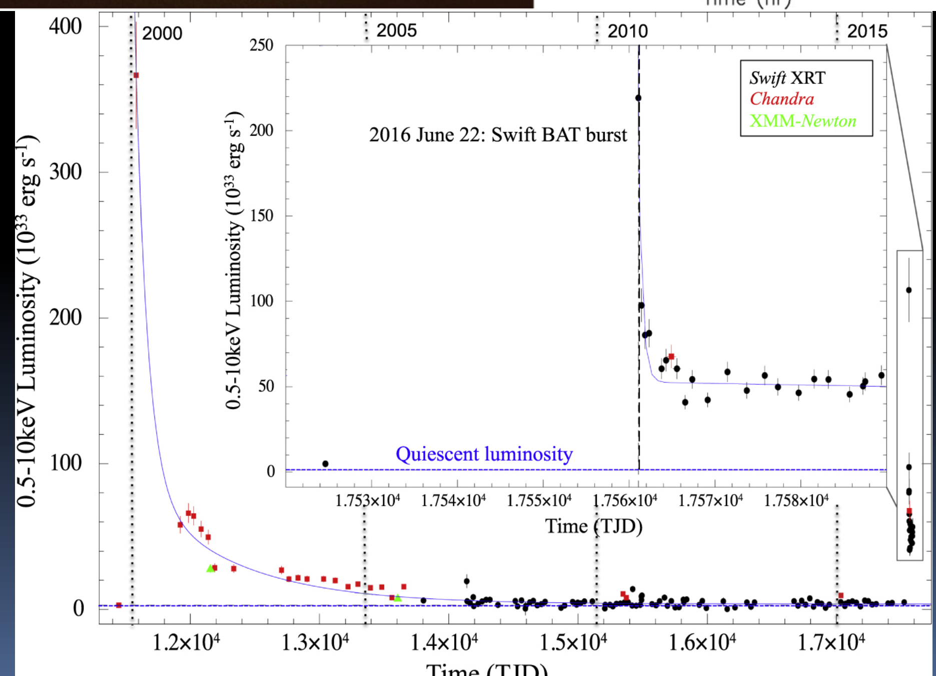
B-field growth?? (Halpern & Gotthelf 2015)

CCO in RCW 103

- 6.67 hour X-ray pulsar found by XMM
- No companion observed (Tendulkar et al. 17)
- Magnetar-like burst observed (D'Ai et al. 2016; Rea et al. 2016)
- Unclear how produce so slow a magnetar
- **Fall-back disk?** (e.g. Ho & Andersson 2017; Xu & Li 2019)

De Luca et al. 2006

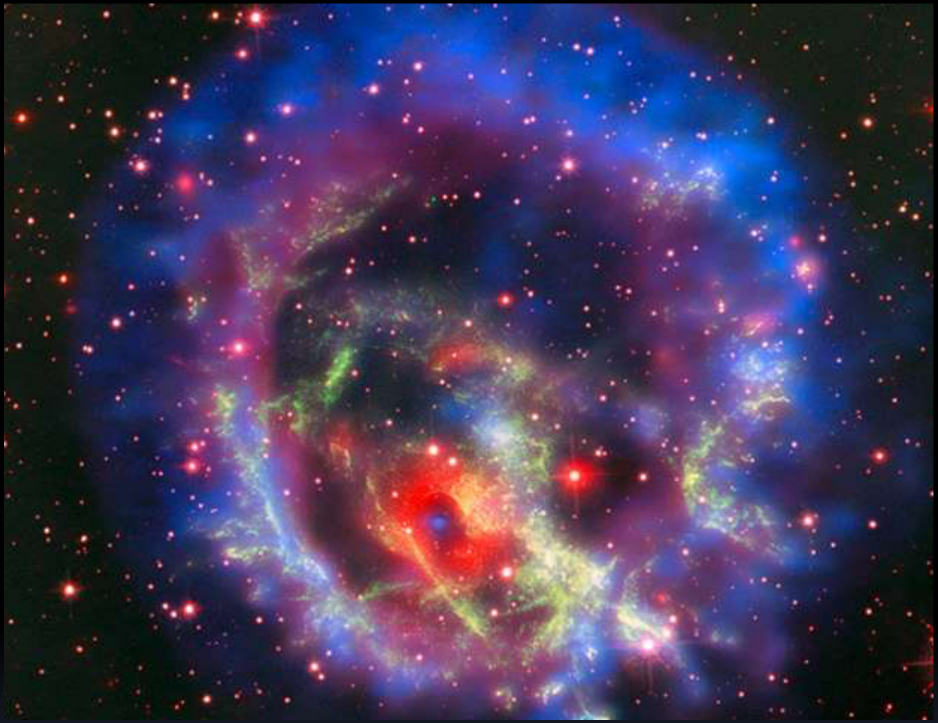




Rea et al 2016

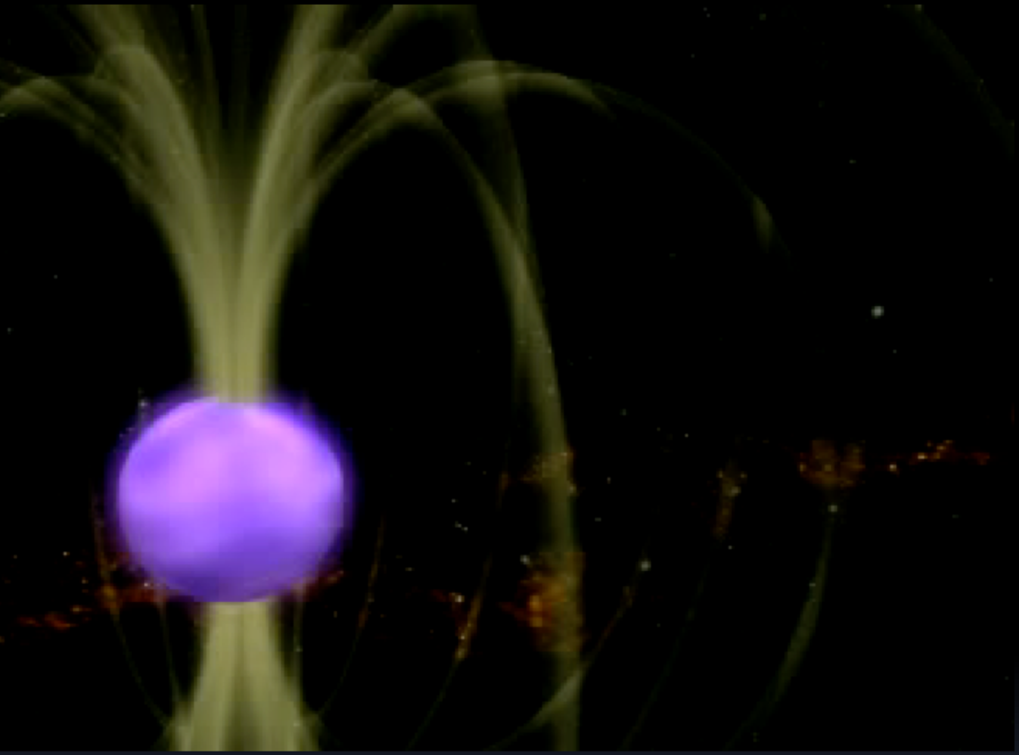
New Chandra CCO in 1E 0102.2-7219

1E 0102.2-7219



- SMC O-rich supernova remnant
- Vogt et al. 2018
  note optical "ring" structure, and
  report compact object
  $L_x = 1.4 \times 10^{33}$ erg/s
- Hebbar et al. 2020
  find bb+pl, but high kT
  - High B young NS?
- Lynx!

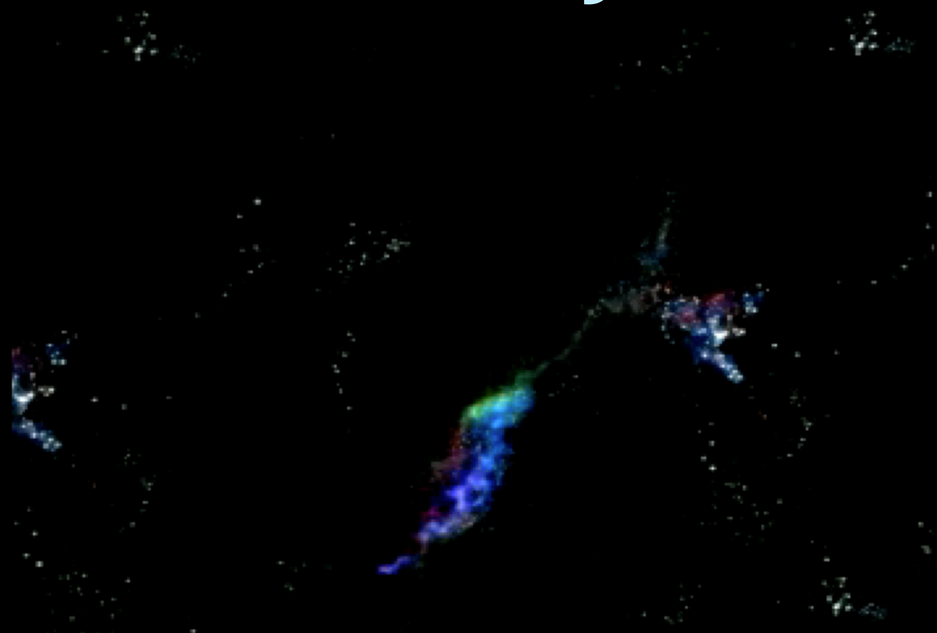
Magnetars



Recent review by VK & Beloborodov, 2017, ARAA

- 23(28) known today
- Volatile NSs: X-ray/soft g-ray bursts
- Young (<~ 10 kyr)
- X-ray pulsations
- Periods 2-12 s, spin-down
- Luminosities exceed spin-down flux
- Emission powered by decay of 10^{14}-10^{15} G B field: "magnetars"

Magnetar Radiative Activity



- 3 broad categories:
  - Giant flares
    - Outshine all cosmic X-ray sources combined
    - 3 seen so far
  - Outbursts
    - Long-lived flux enhancements
    - Rise suddenly (< hrs) and decay over months
  - Bursts
    - Short duration: few ms to 1 sec
    - Common during outbursts but seen alone

Chandra has done key work on practically all these topics

Unification?

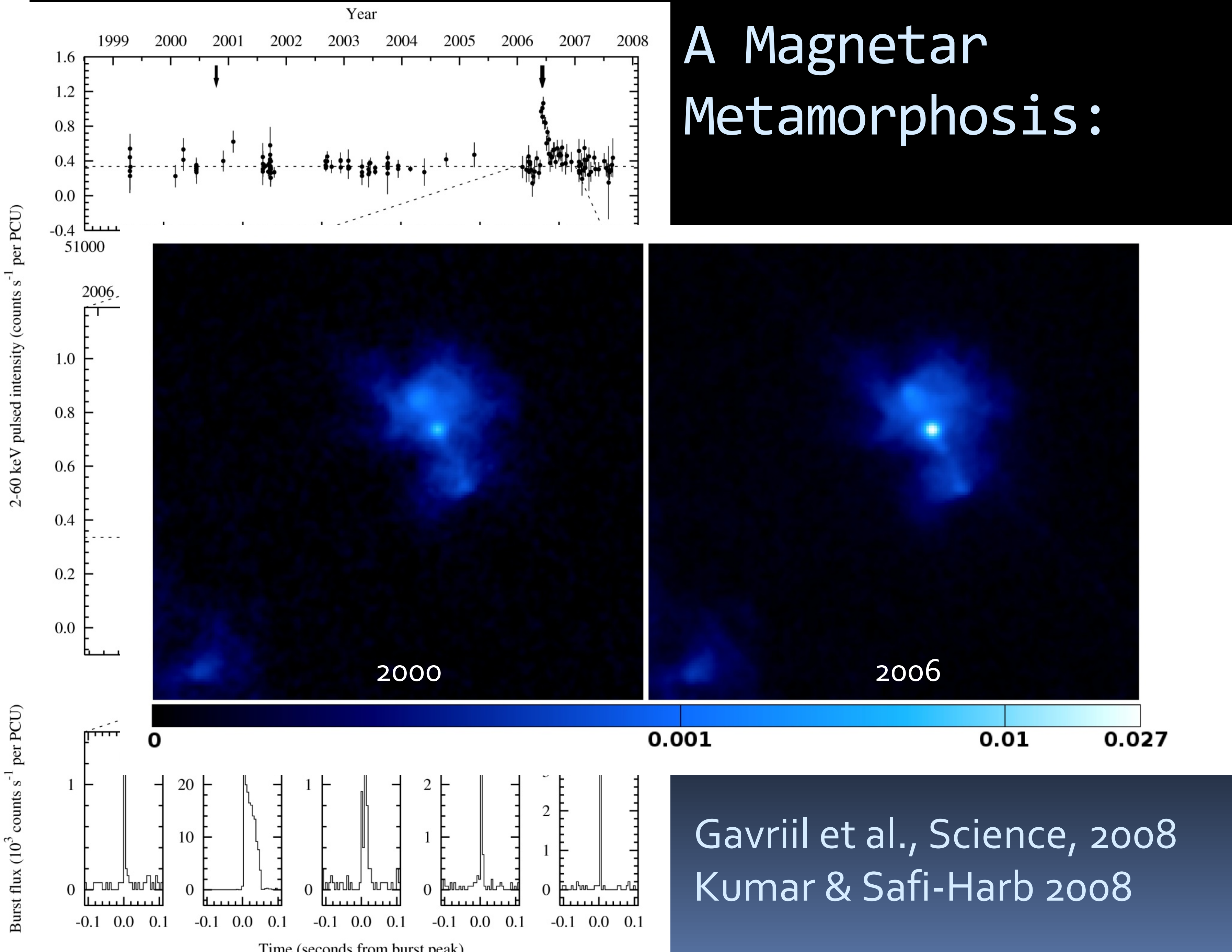
B

Radio pulsars → Magnetars

Suggests other transition objects should exist!

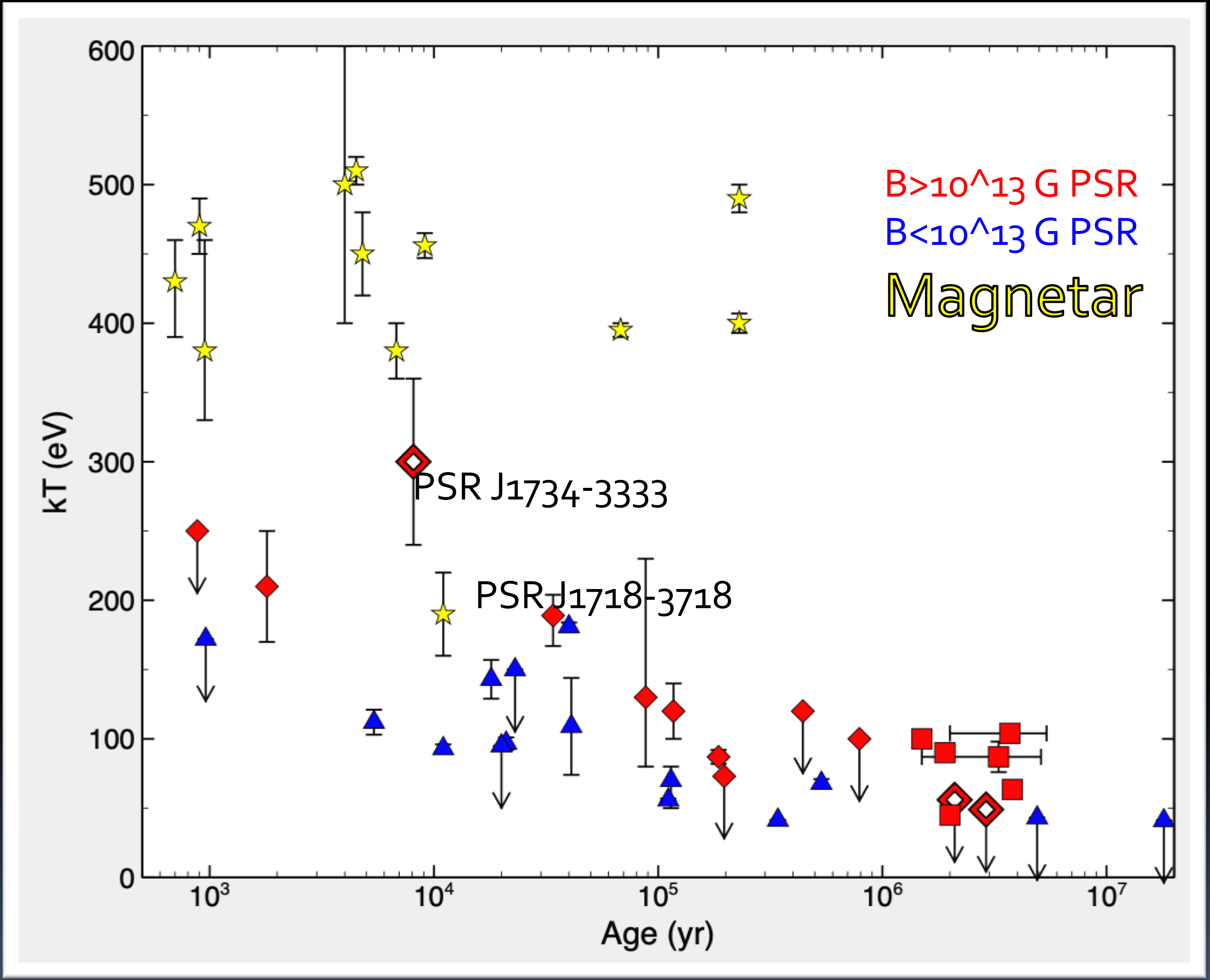
Pons & Perna (2012); Vigano et al. (2013); Gourgouliatos & Cumming (2014)

A Magnetar Metamorphosis:



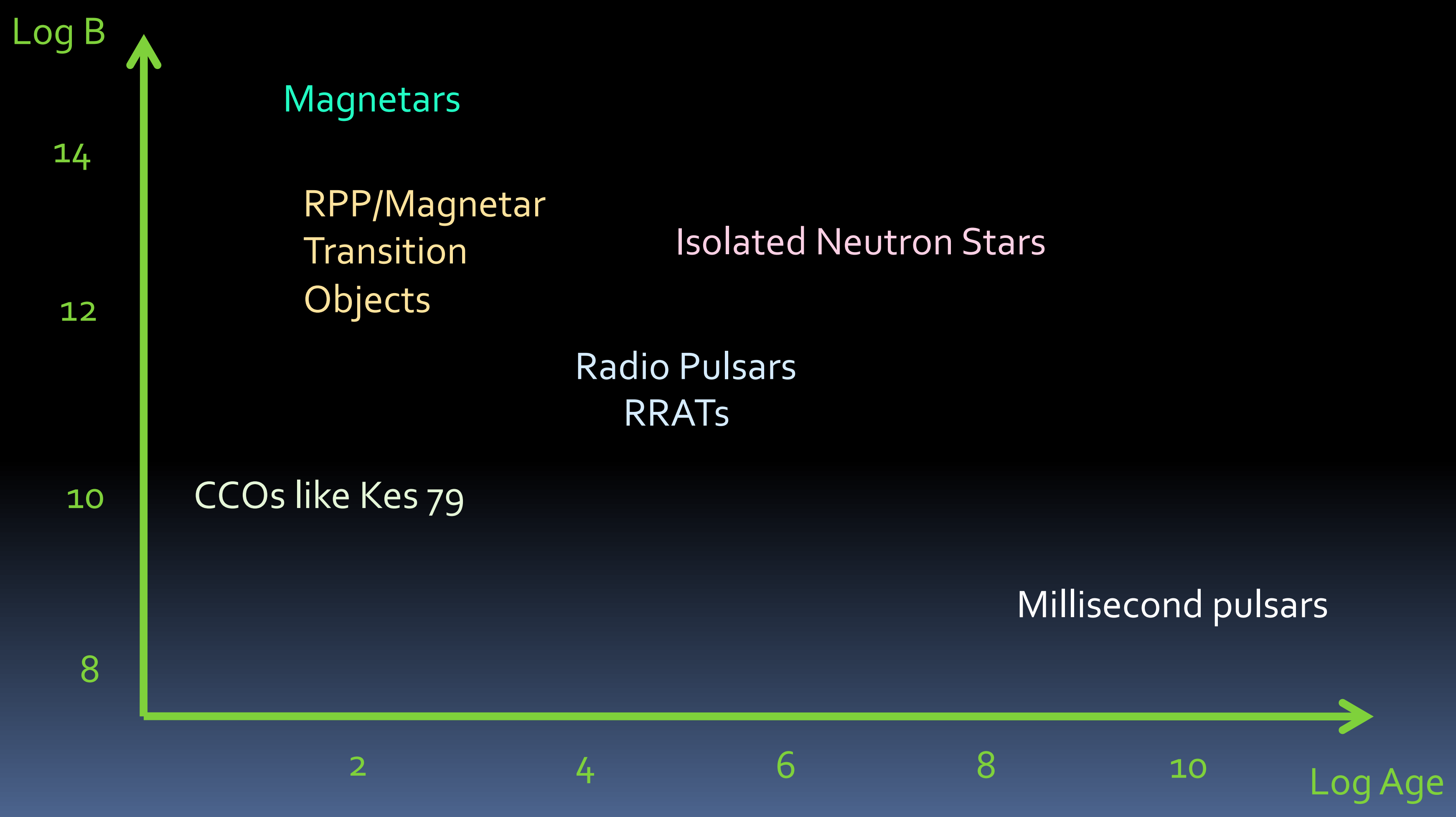
Gavriil et al., Science, 2008
Kumar & Safi-Harb 2008

Other Evidence of Unification?



Olausen et al. 2013

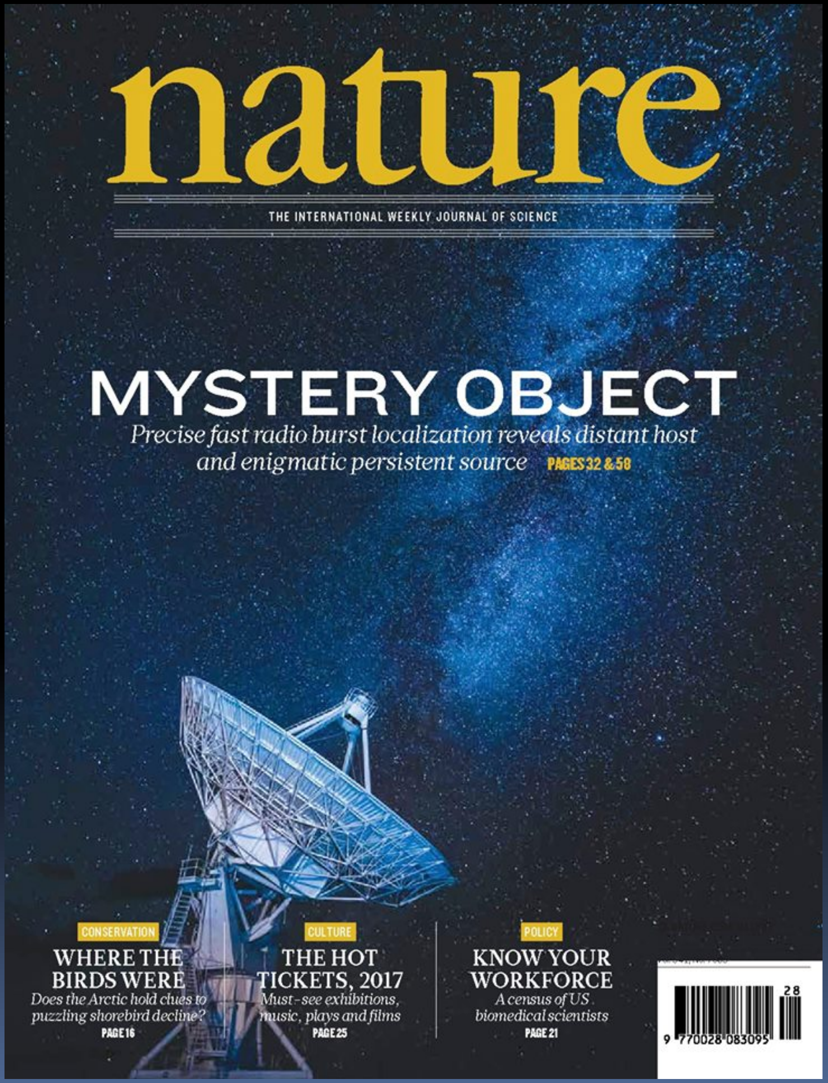
Neutron Star Unification??



Fast Radio Bursts

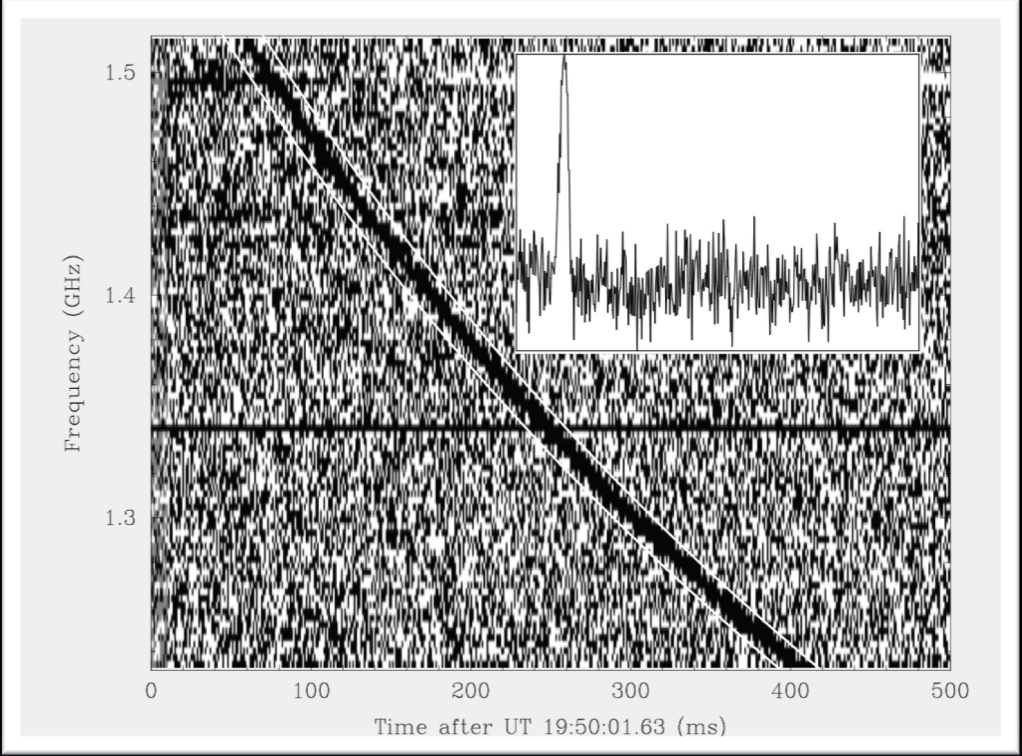
- Most highly cited "Chandra & pulsar" paper since 2012: "The Repeating Fast Radio Burst FRB 121102: Multi-wavelength Observations and Additional Bursts"   Scholz et al. 2016 ApJ

And it's a non-detection paper!!



Fast Radio Bursts

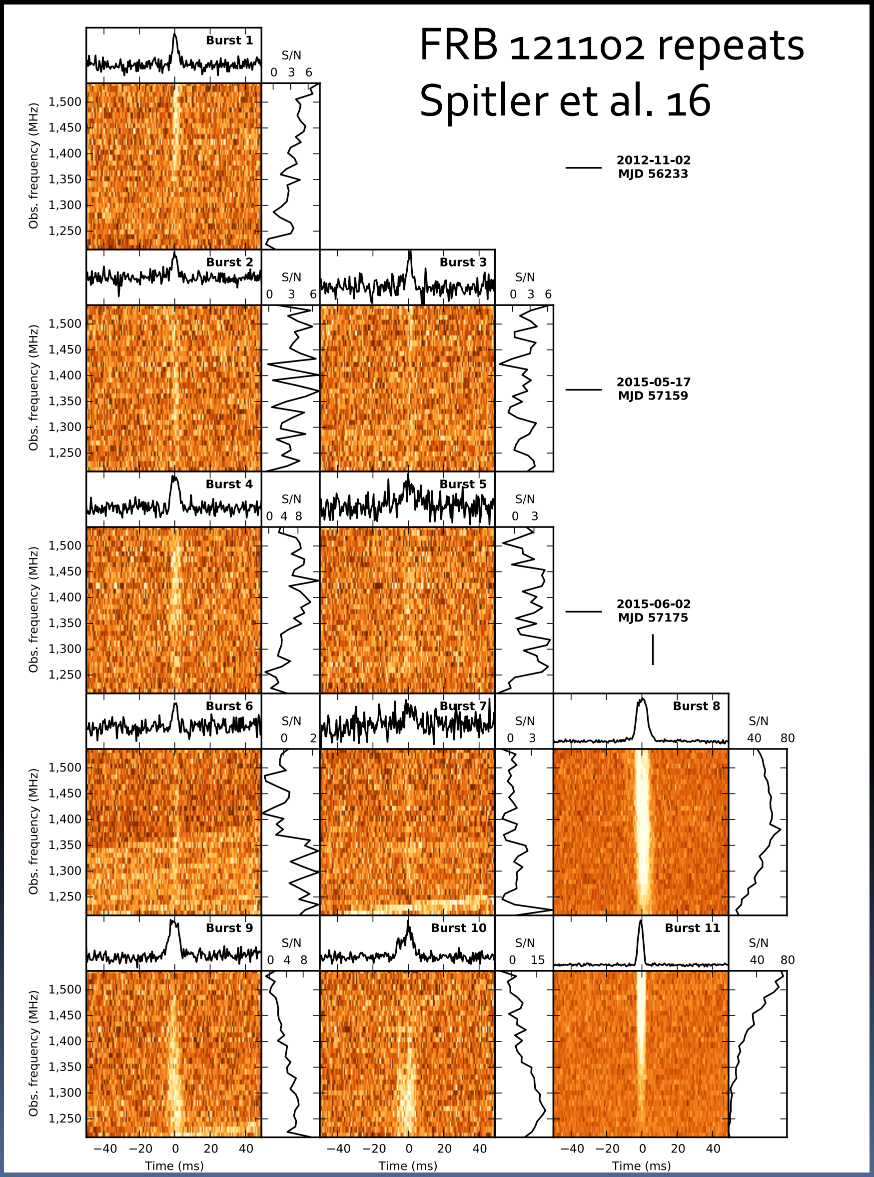
- Brief (~ms) radio bursts
- 1st : Lorimer et al. 2007 using Parkes @ 1.4 GHz
- Today: ~70 published
- Estimated rate: ~1,000 /sky/day @ 1.4 GHz
- Extragalactic, probably cosmological
- ORIGIN UNKNOWN!



$DM >> DM_{MW}$

Some FRBs Repeat!

- First found repeater FRB 121102 (Spitler et al. 16)
  - Ruled out cataclysmic models… for this source
  - Enabled localization with VLA, VLBA, EVN
  - z=0.2, d~1 Gpc
  - Energy scale: ~10^{43} erg/s
- Now there are 11 known rFRBs … and more to come!
- Leading model: young magnetar?
  (Lyubarsky 2014; Beloborodov 2017; Margalit & etzger 2018; Metzger et al. 2019)



Chandra and FRB 121102

- Upper limits for Chandra & XMM are unconstraining of models as source is at 1 Gpc

Scholz et al. 2017

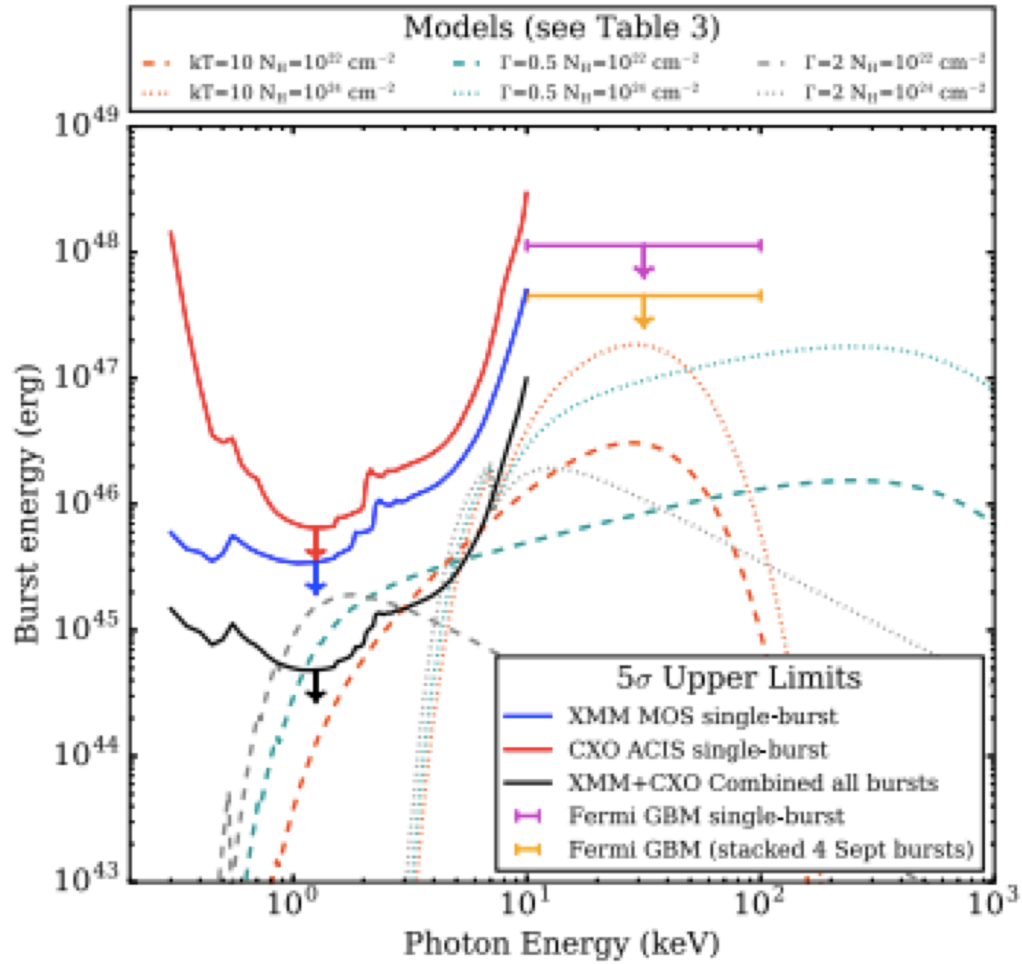
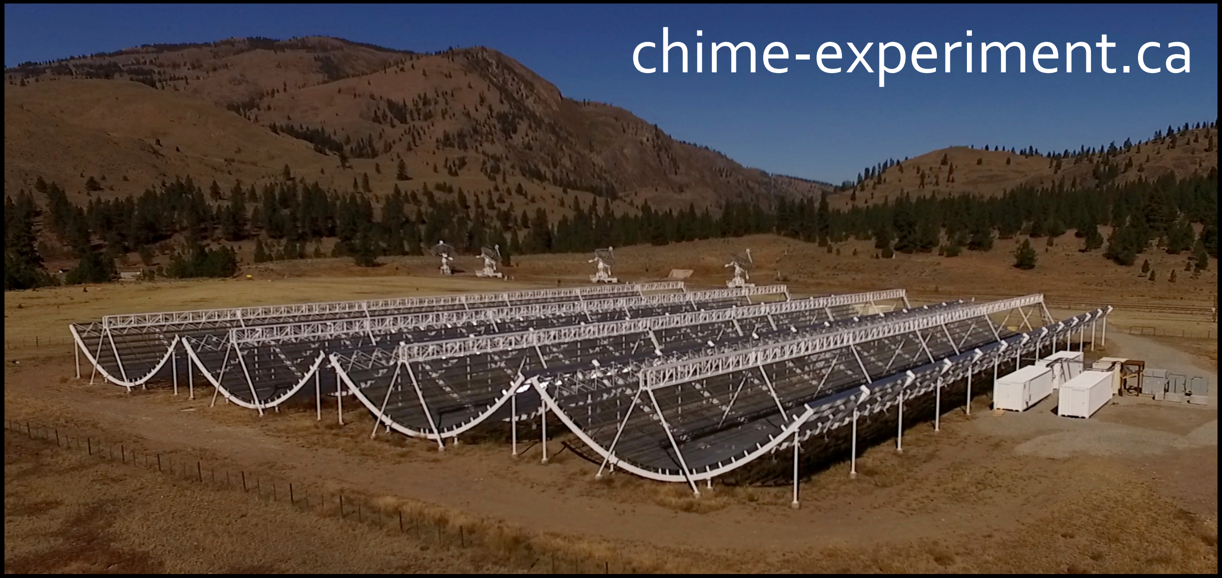
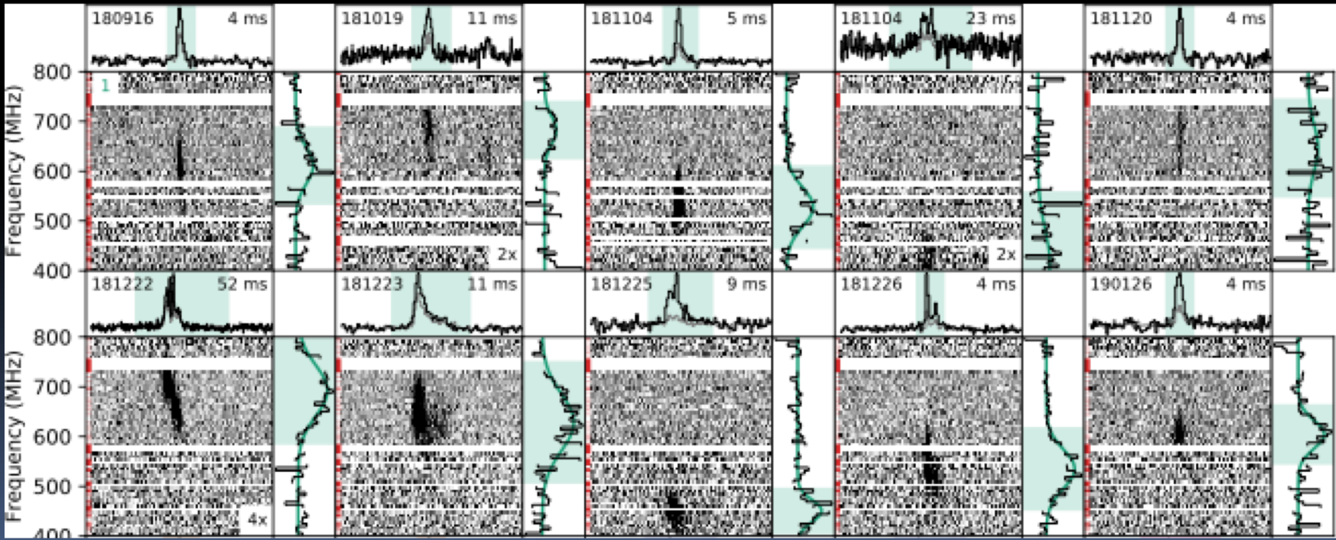


Figure 5. Limits on energy of X-ray bursts at the time of radio bursts from FRB 121102. Solid lines show the 5σ upper limits as a function of X-ray photon energy. The dashed lines show different burst spectra that are photoelectrically absorbed by an $N_H = 10^{22}\,\mathrm{cm}^{-2}$ plotted at their 0.5–10 keV fluence limits that result from a stacked search of the times of the radio bursts. The dotted lines show the same spectral models but with $N_H = 10^{24}\,\mathrm{cm}^{-2}$ to show the effects of absorption. Orange lines represent a blackbody model with $kT = 10$ keV, cyan curves show a cutoff power-law model with $\Gamma = 0.5$ and $E_{cut} = 500$ keV, and the gray curves show a soft power-law with $\Gamma = 2$ in order to illustrate the effect of different spectral models.

New! CHIME/FRB 180916…nearby!

- New nearby repeater found among 8 new repeaters by CHIME/FRB
- DM consistent with Galactic halo or max 500 Mpc
  - Likely much closer than 500 Mpc
- Chandra obs planned Dec 3(!!) & 18





CHIME/FRB Collaboration 2019, ApJ

Summary

- Chandra already has a legacy of many landmark NS results
- Many still open and new questions for *Chandra* to tackle in next decade!
  - Grand Unification…magnetars, transition objects, high-B radio pulsars… CCOs??
  - How does NS recycling take place? tMSP phenomenology: early days!
  - **What are FRBs?**

Chandra and FRB 121102

- Scholz et al. 2016, 2017
  - 40 ks ACIS-S full-frame obs of FRB 121102 during radio bursts in Nov 2015 simultaneous with GBT obs…
    no bursts seen ☹
  - 40 ks ACIS-I in Nov 2016, Jan 2017 (also 28 ks with XMM in Sept 2016) all simultaneous with GBT… many radio bursts seen ☺ but no X-ray bursts ☹

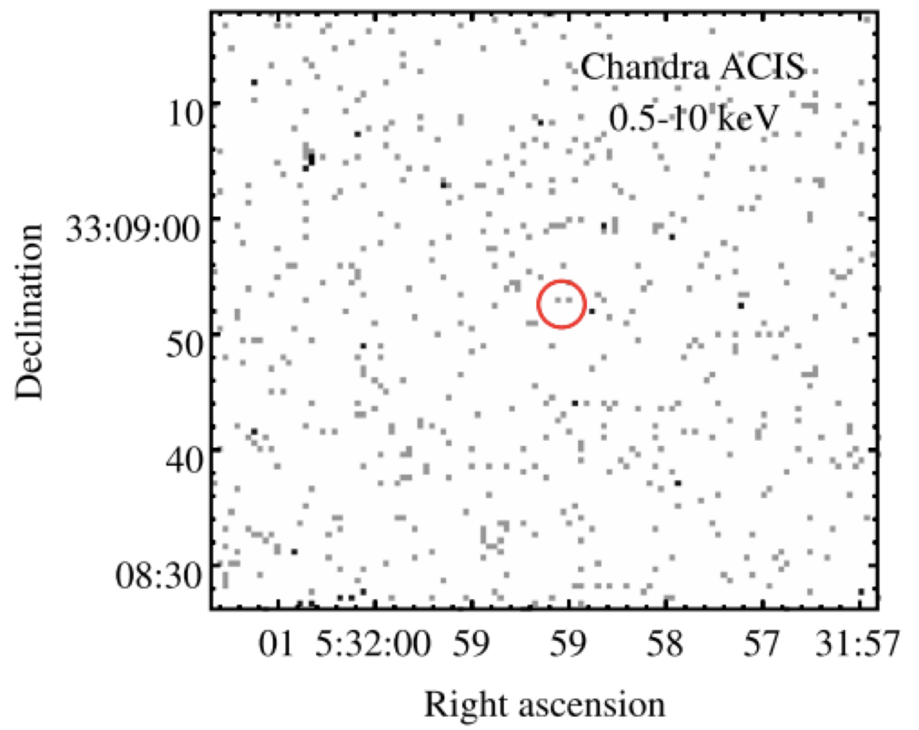
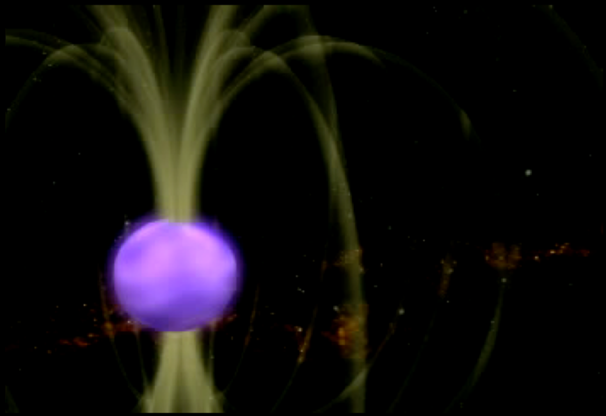


Figure 4. Co-added image of all *Chandra* observations of the FRB 121102 field in the 0.5–10 keV range. The red circle of radius 2″ is centered on the position from Marcote et al. (2017).

Pros of FRBs as Magnetars



- Magnetar Giant Flares have few ms peaks in X-rays
- 3 since 1979 → ~0.1 /MW/yr but FRBs ~10^{-3} /galaxy/yr
  - We must be sensitivity limited for FRBs
- Magnetars have sufficient energy: ~$10^{47\text{-}49}$ erg
  - Even for repeating FRB? Depends on activity life time
  - Cannot be for more than ~100 yr