Current Status of Astronomical Observations of Neutron Stars (especially magnetars!)

Teruaki Enoto (Kyoto University / RIKEN)

General overview of astronomical observations

@teru_enoto

Compact Stars in the QCD Phase Diagram (CSQCD2024),
Kyoto University, 2024 October 7, 9:00-9:50 (40+10)
https://indico.yukawa.kyoto-u.ac.jp/event/30/

Neutron stars (NSs) are ideal laboratory of physics

- Neutron stars (NSs) are compact objects with 1.4 Solar mass and ~10 km radius → Extreme physics
  - High density exceeding the atomic nucleus density
  - Strong gravitational field that bends light and causes spectral redshift
  - Strong photon field ranging from radio waves to gamma rays
  - Strong magnetic field close to the QED critical field

Crab Nebula
Multi-wavelength component

Credit: NASA/CXC/SAO/STScI

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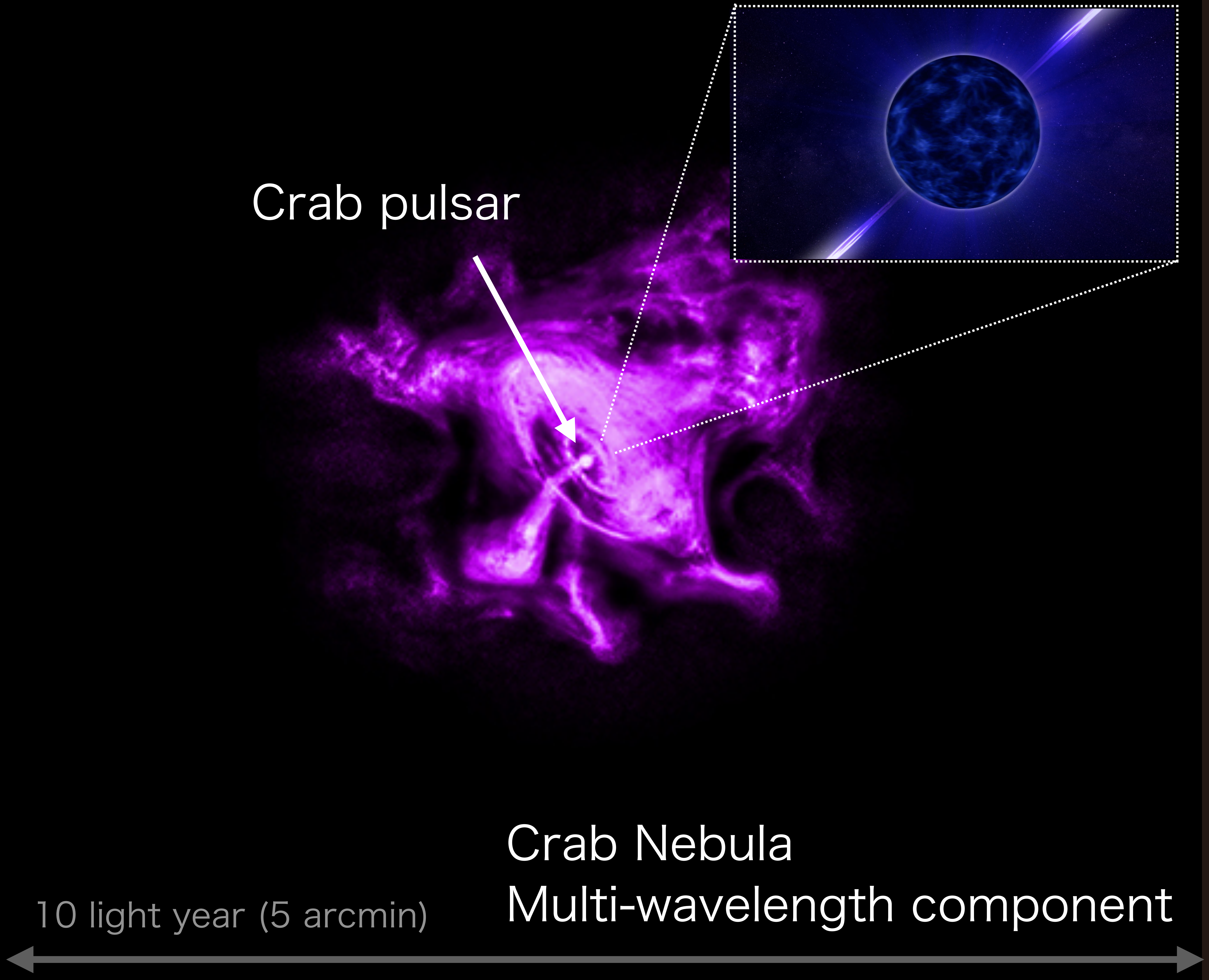

Credit: NASA/CXC/SAO/STScI

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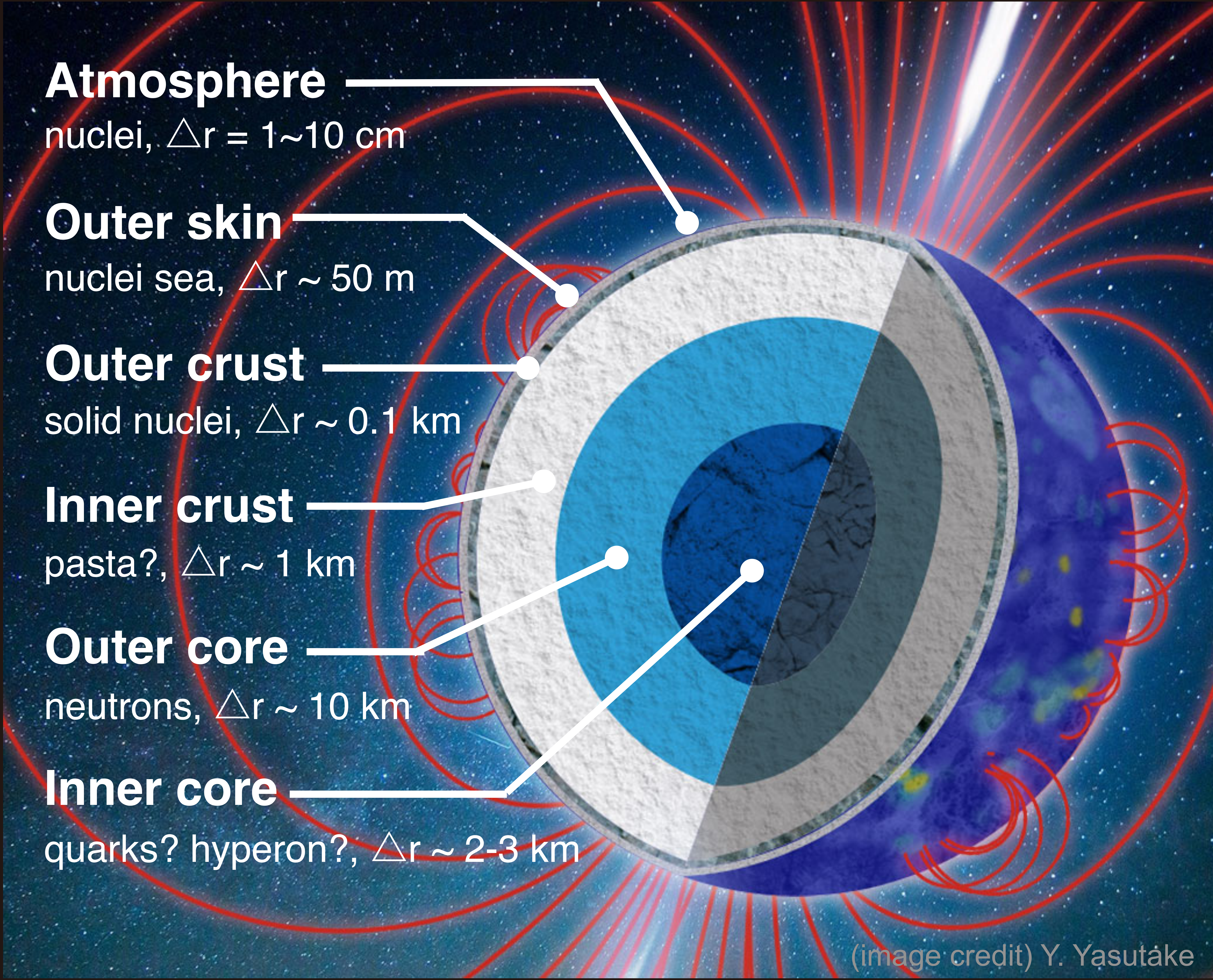


Atmosphere
nuclei, △r = 1~10 cm

Outer skin
nuclei sea, △r ~ 50 m

Outer crust
solid nuclei, △r ~ 0.1 km

Inner crust
pasta?, △r ~ 1 km

Outer core
neutrons, △r ~ 10 km

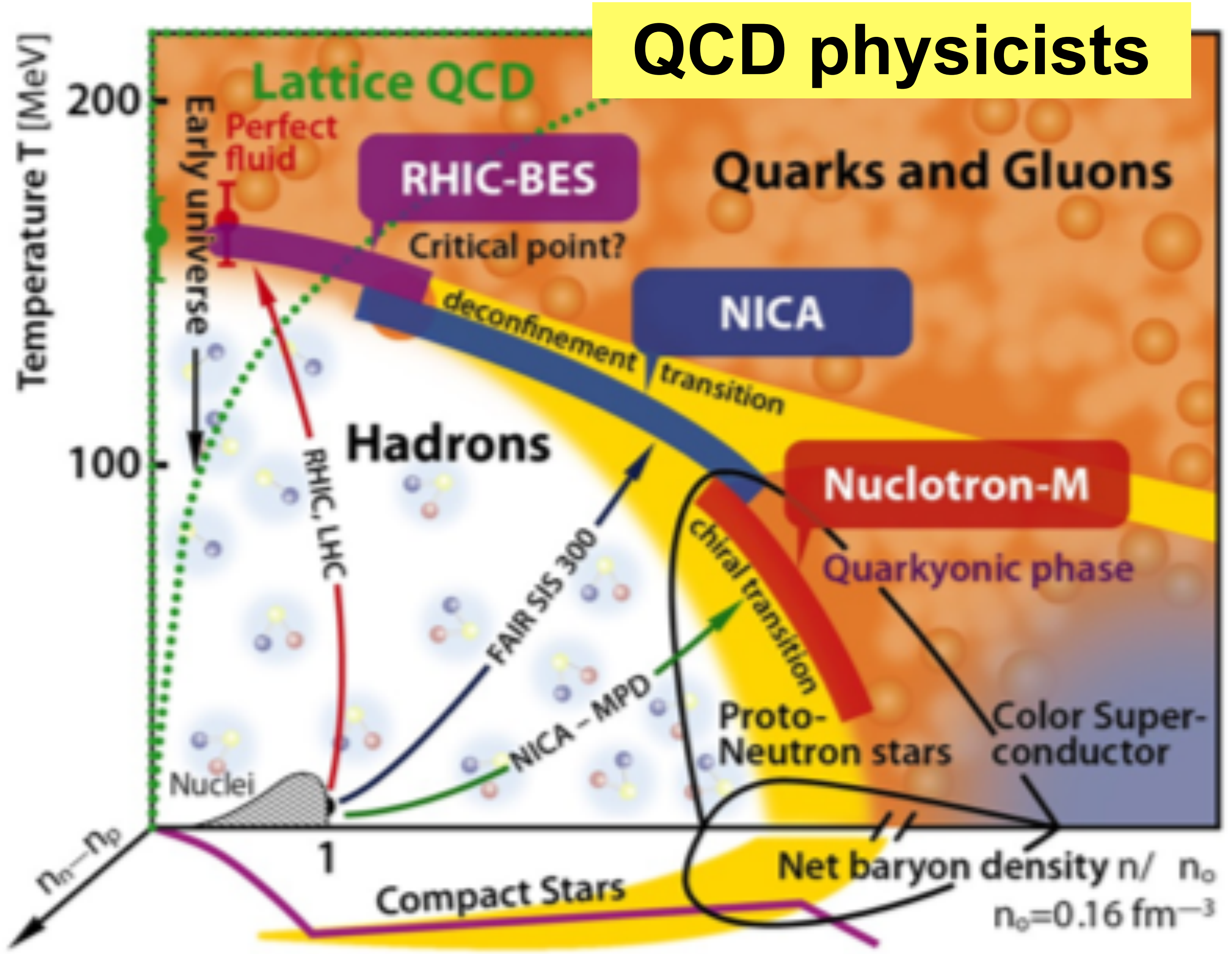
Inner core
quarks? hyperon?, △r ~ 2-3 km

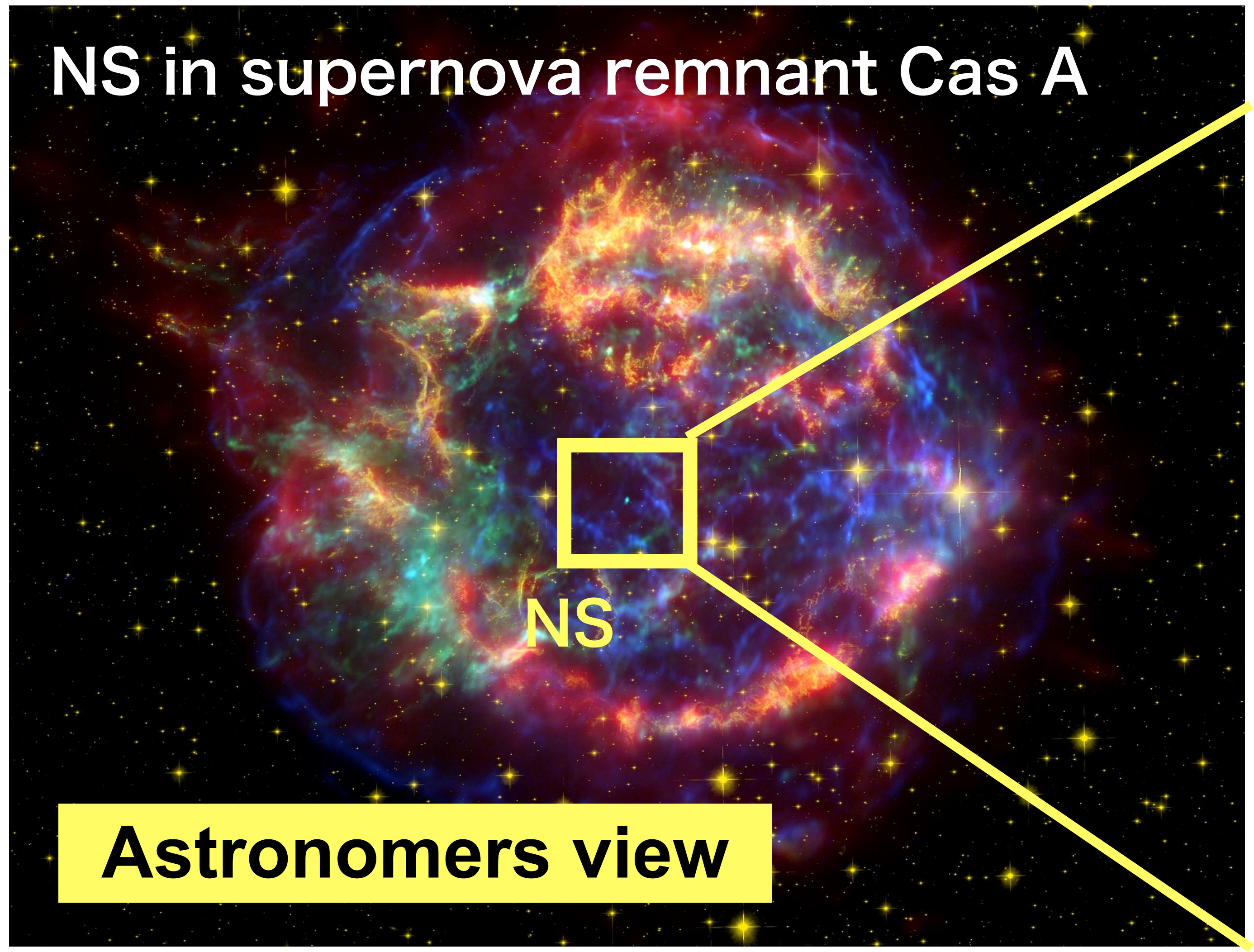
(image credit) Y. Yasutake

Observational quantities of neutron stars

- QCD physicists might want to know the mass, radius and interior of NSs…but

https://www.interactions.org/blog/our-experiment





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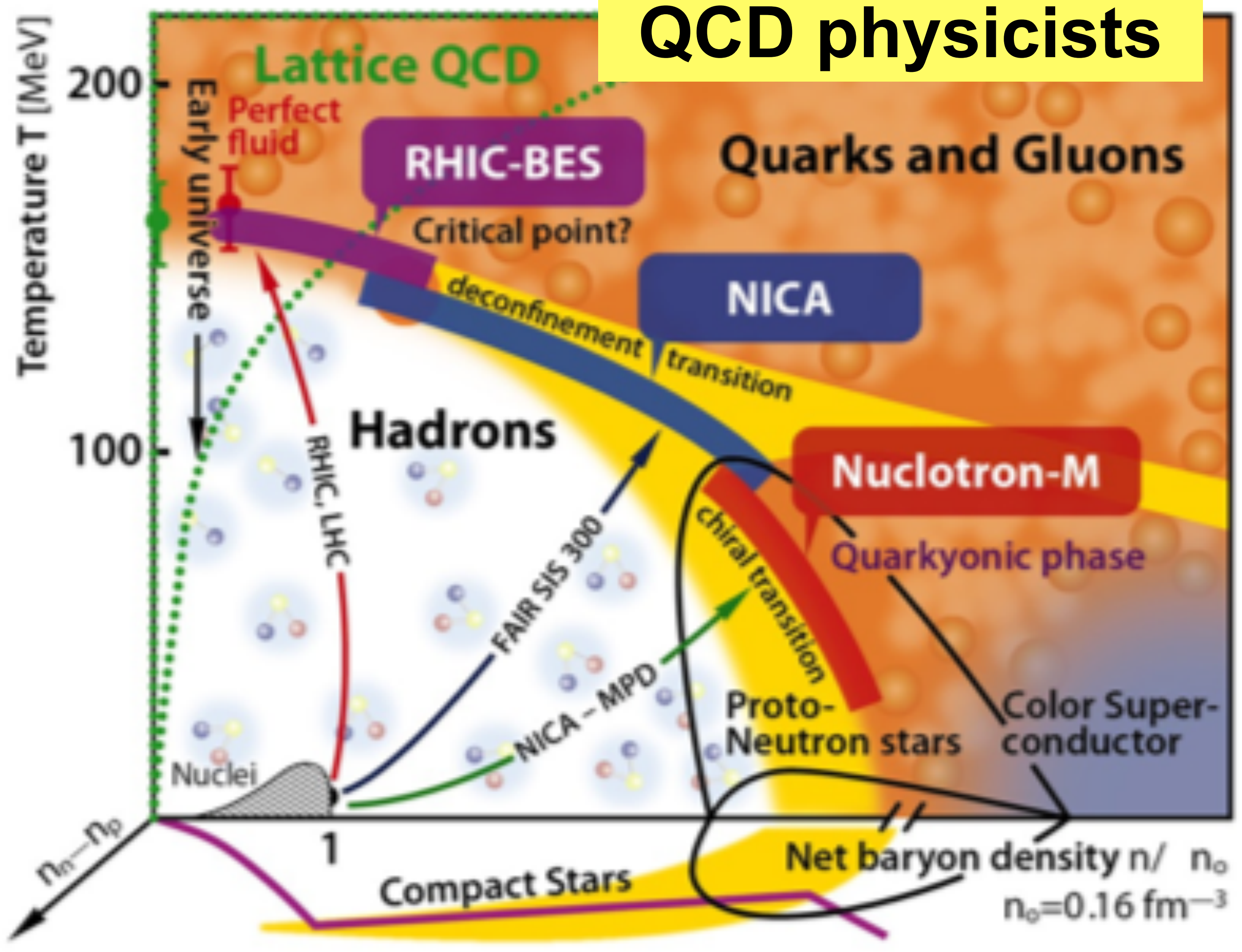
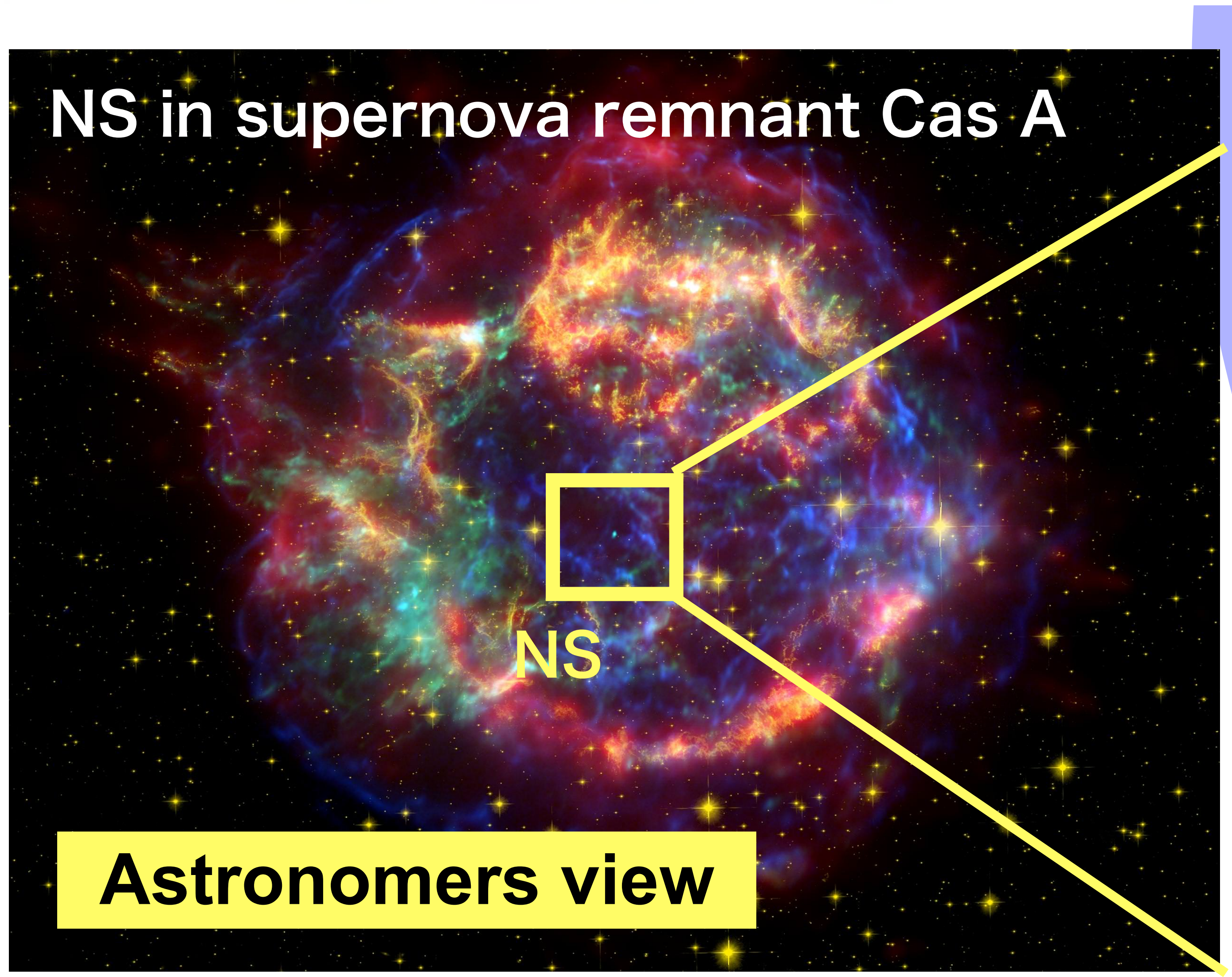
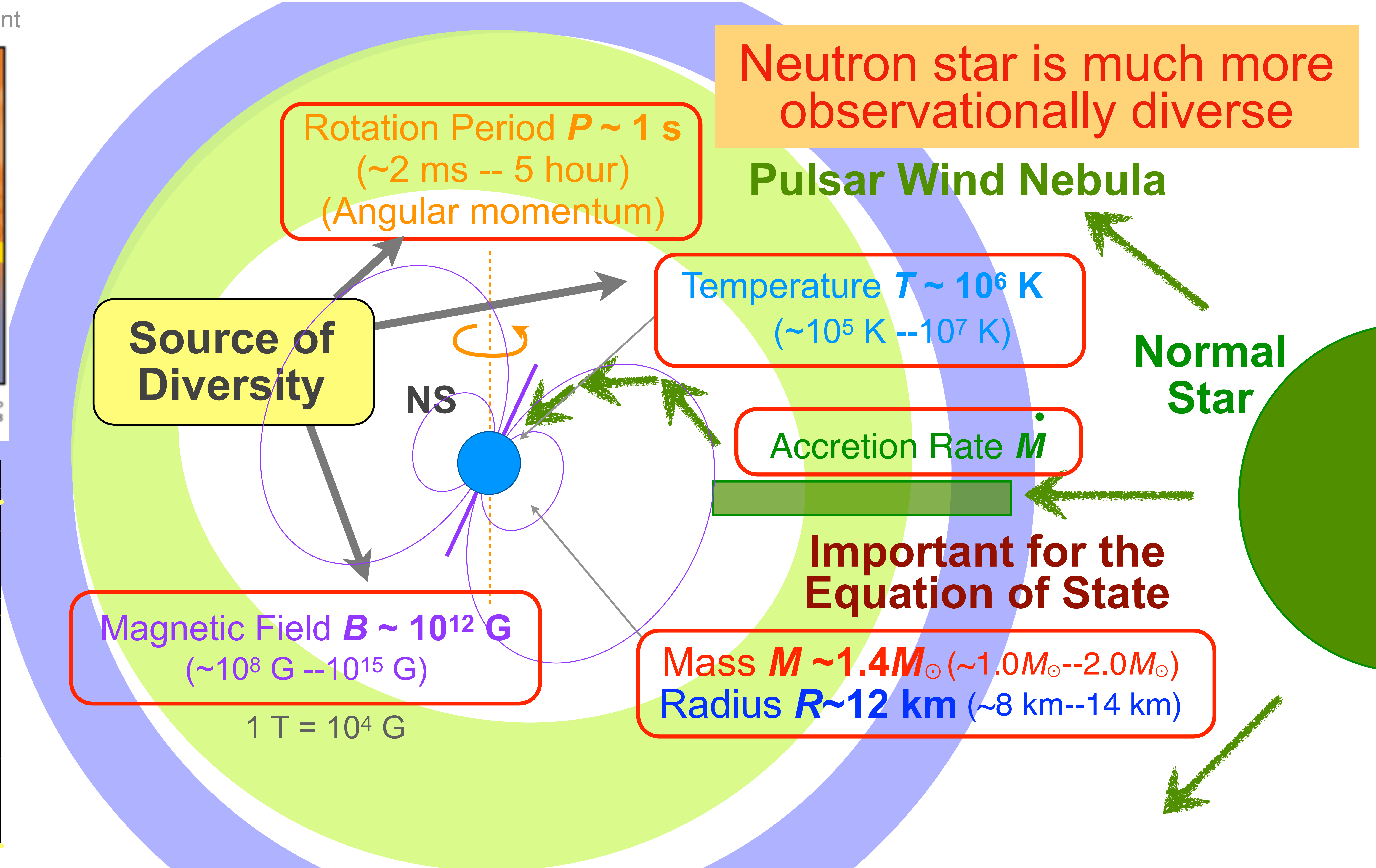

QCD physicists


NS in supernova remnant Cas A

Astronomers view



Neutron star is much more observationally diverse

Rotation Period ***P* ~ 1 s**
(~2 ms -- 5 hour)
(Angular momentum)

Pulsar Wind Nebula

Source of Diversity

Temperature ***T* ~ 10^6 K**
(~10^5 K --10^7 K)

NS

Normal Star

Accretion Rate $\dot{M}$

Important for the Equation of State

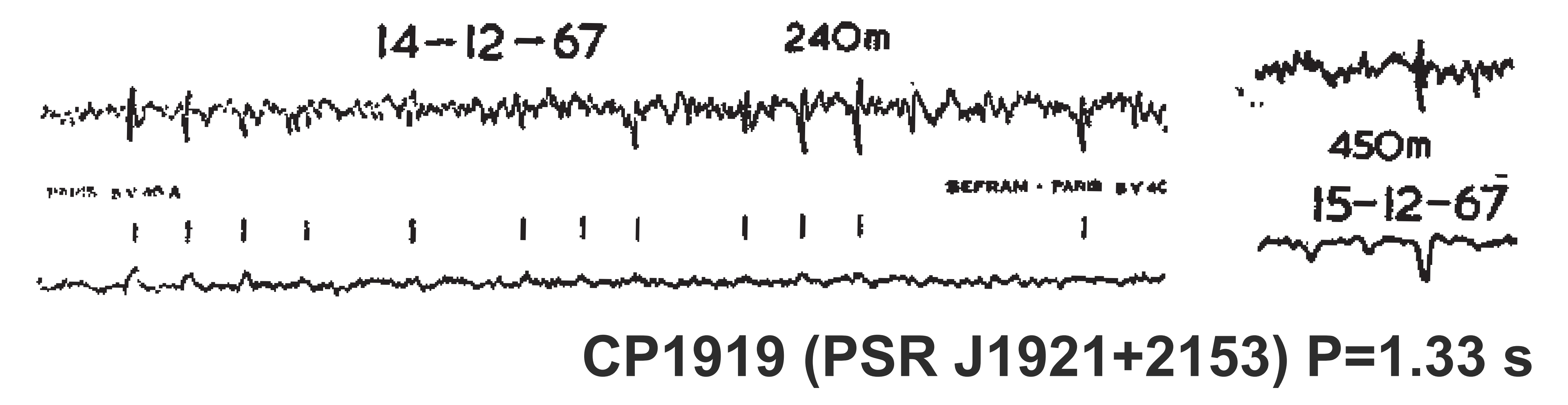
Magnetic Field ***B* ~ 10^{12} G**
(~10^8 G --10^{15} G)

1 T = 10^4 G

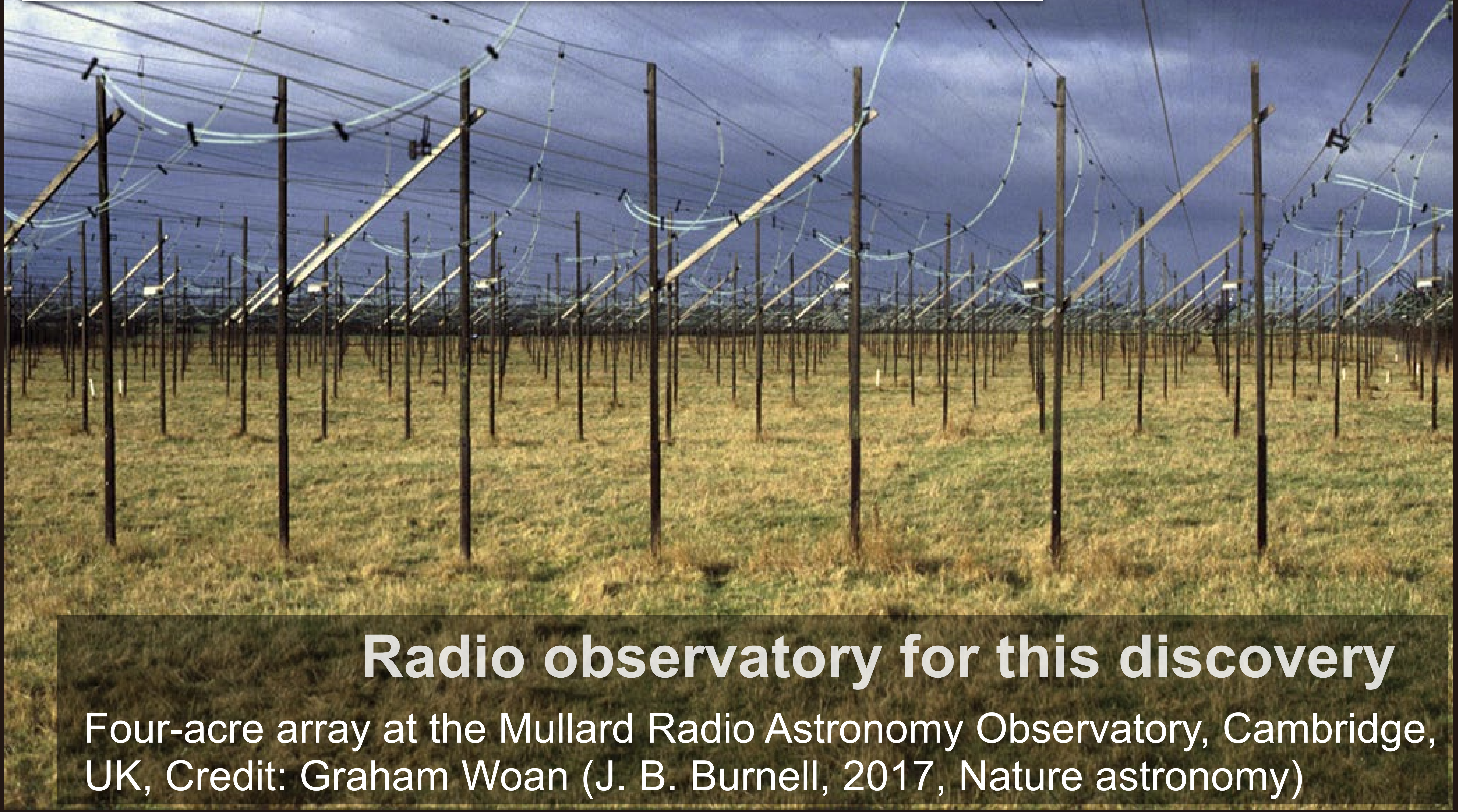
Mass ***M* ~1.4*M*$_\odot$** (~1.0$M_\odot$--2.0$M_\odot$)
Radius ***R*~12 km** (~8 km--14 km)

Discovery of neutron stars in 1967 (57 years ago)

Hewish, Bell, et al., Nature (1968)



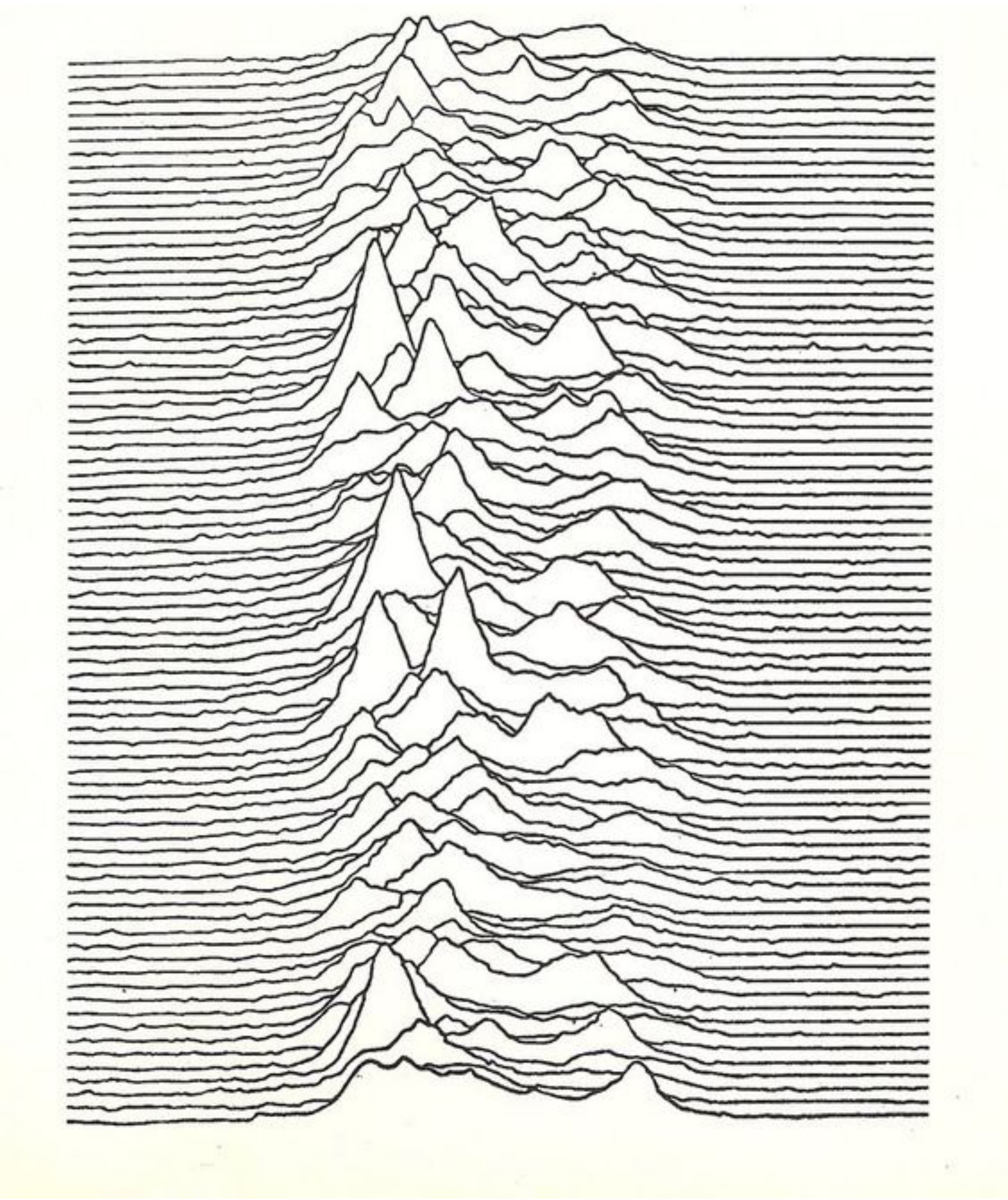
CP1919 (PSR J1921+2153) P=1.33 s

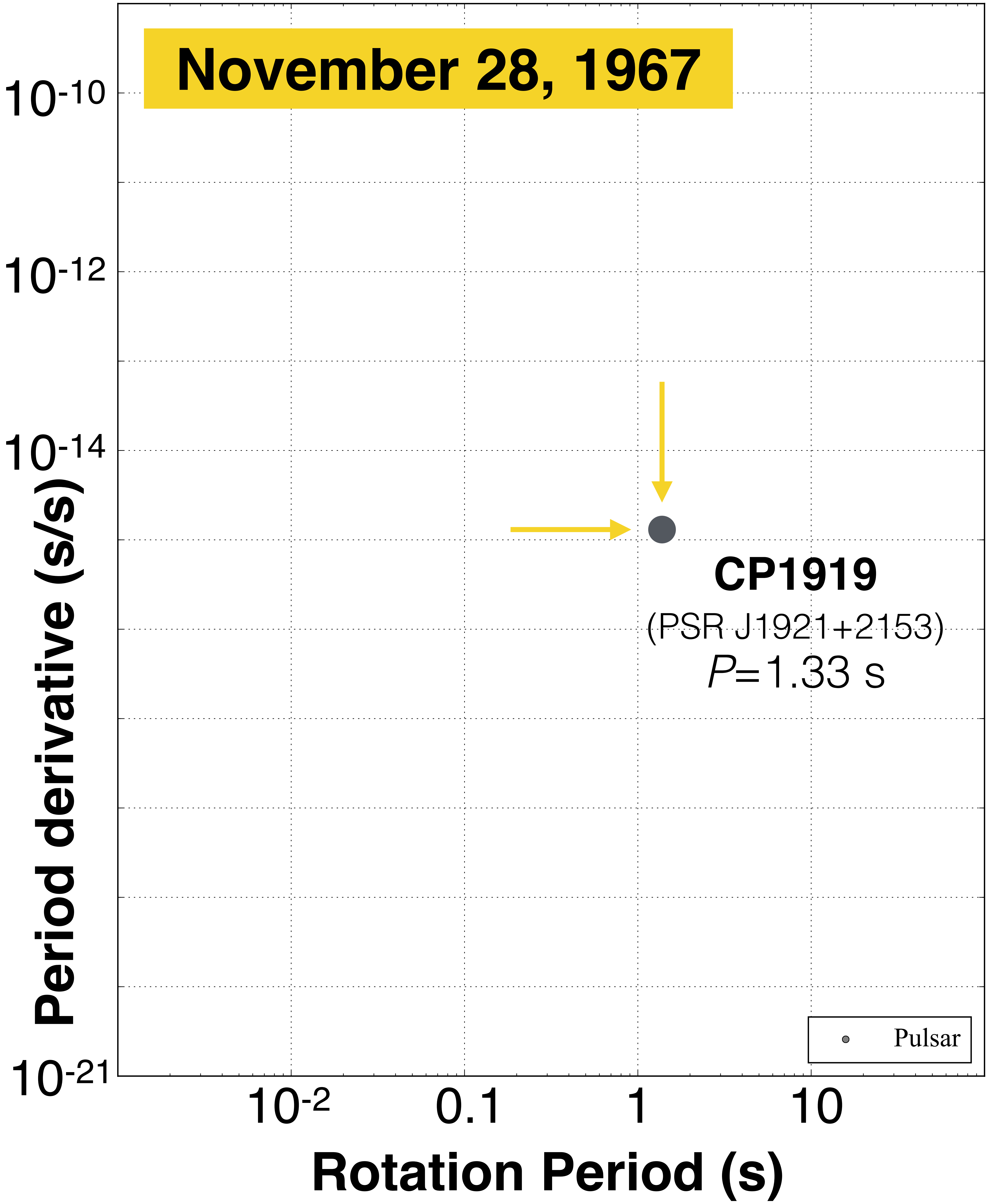


Radio observatory for this discovery

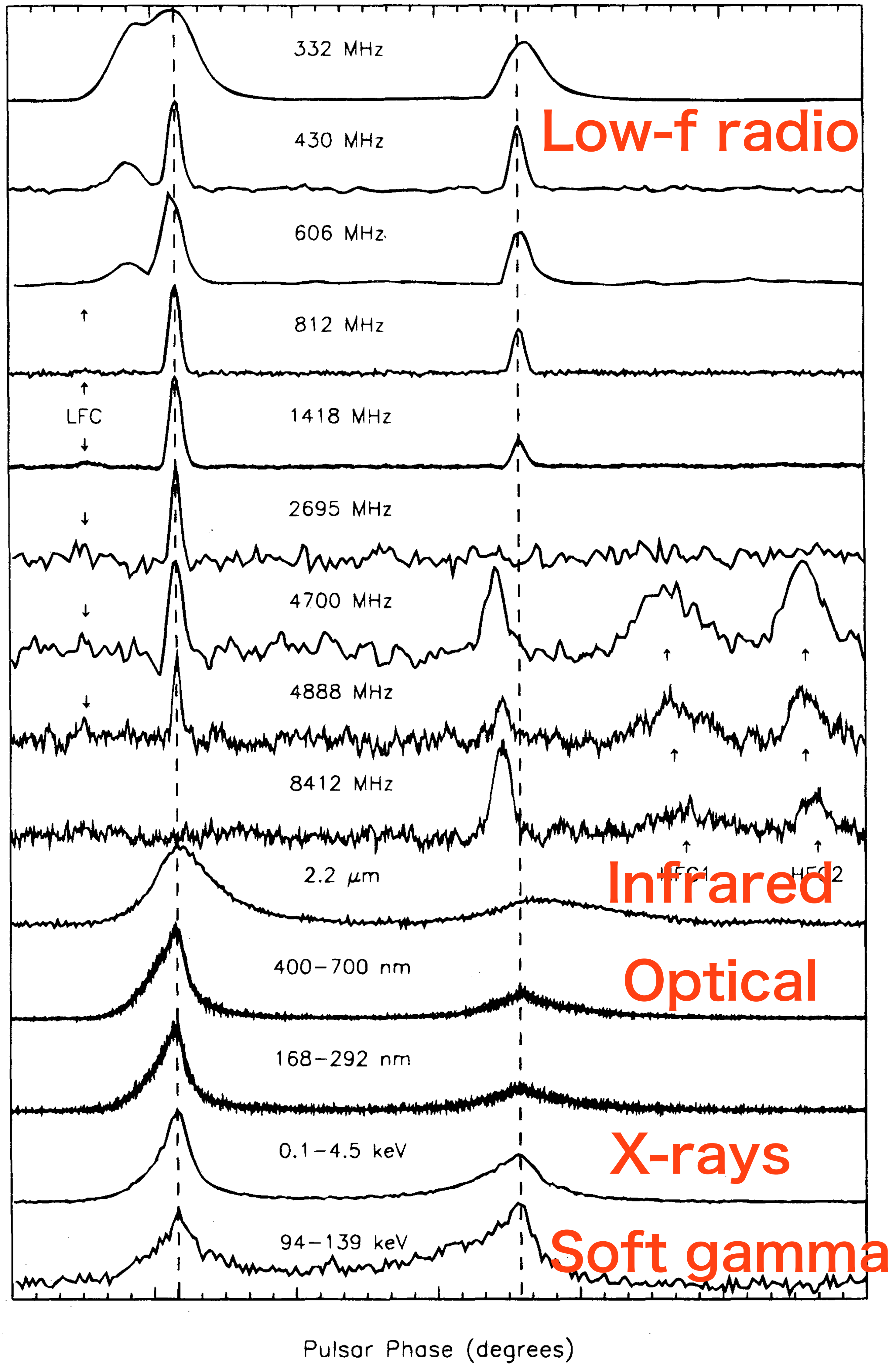
Four-acre array at the Mullard Radio Astronomy Observatory, Cambridge, UK, Credit: Graham Woan (J. B. Burnell, 2017, Nature astronomy)

Diversity of Neutron Stars

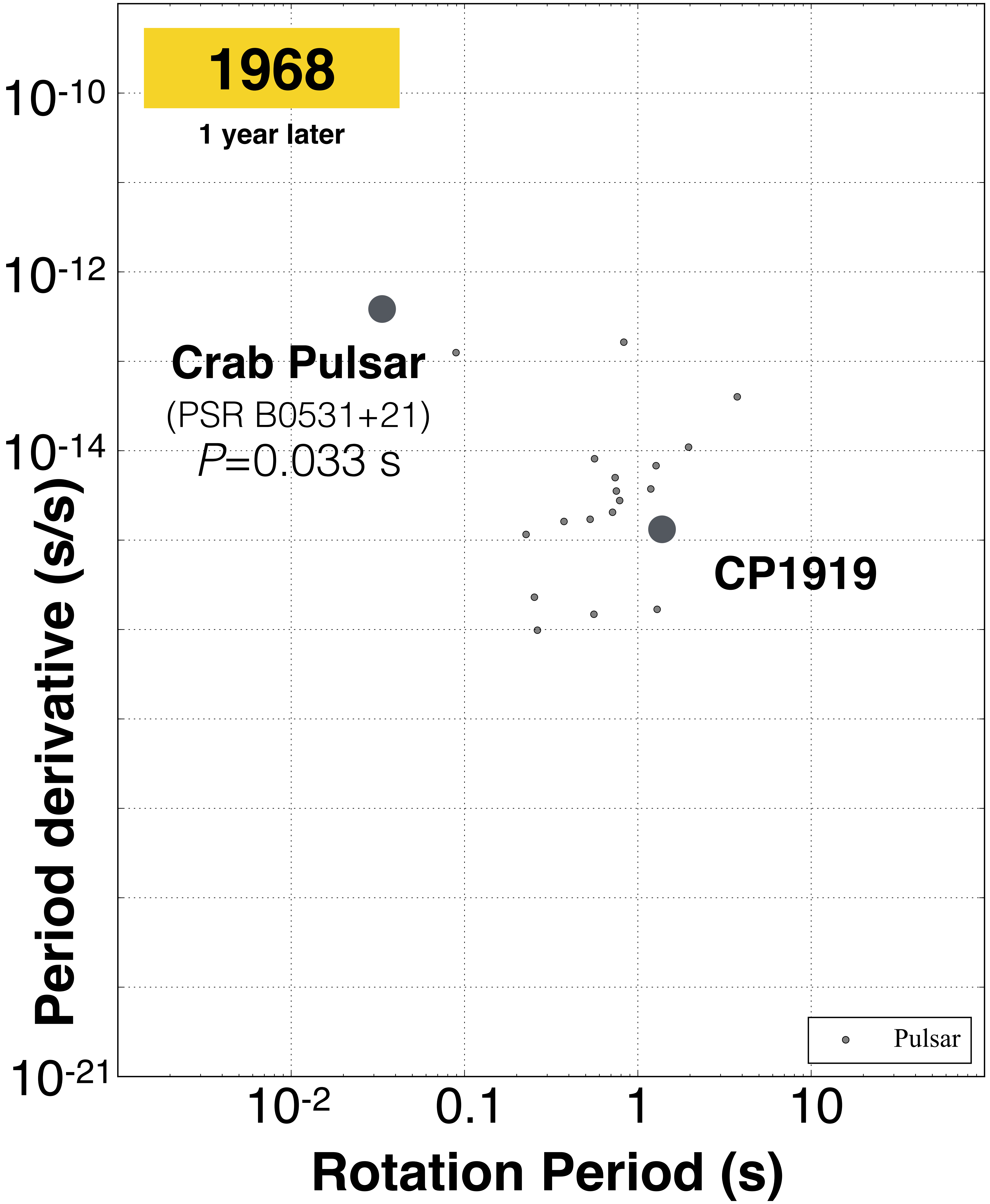




Diversity of Neutron Stars



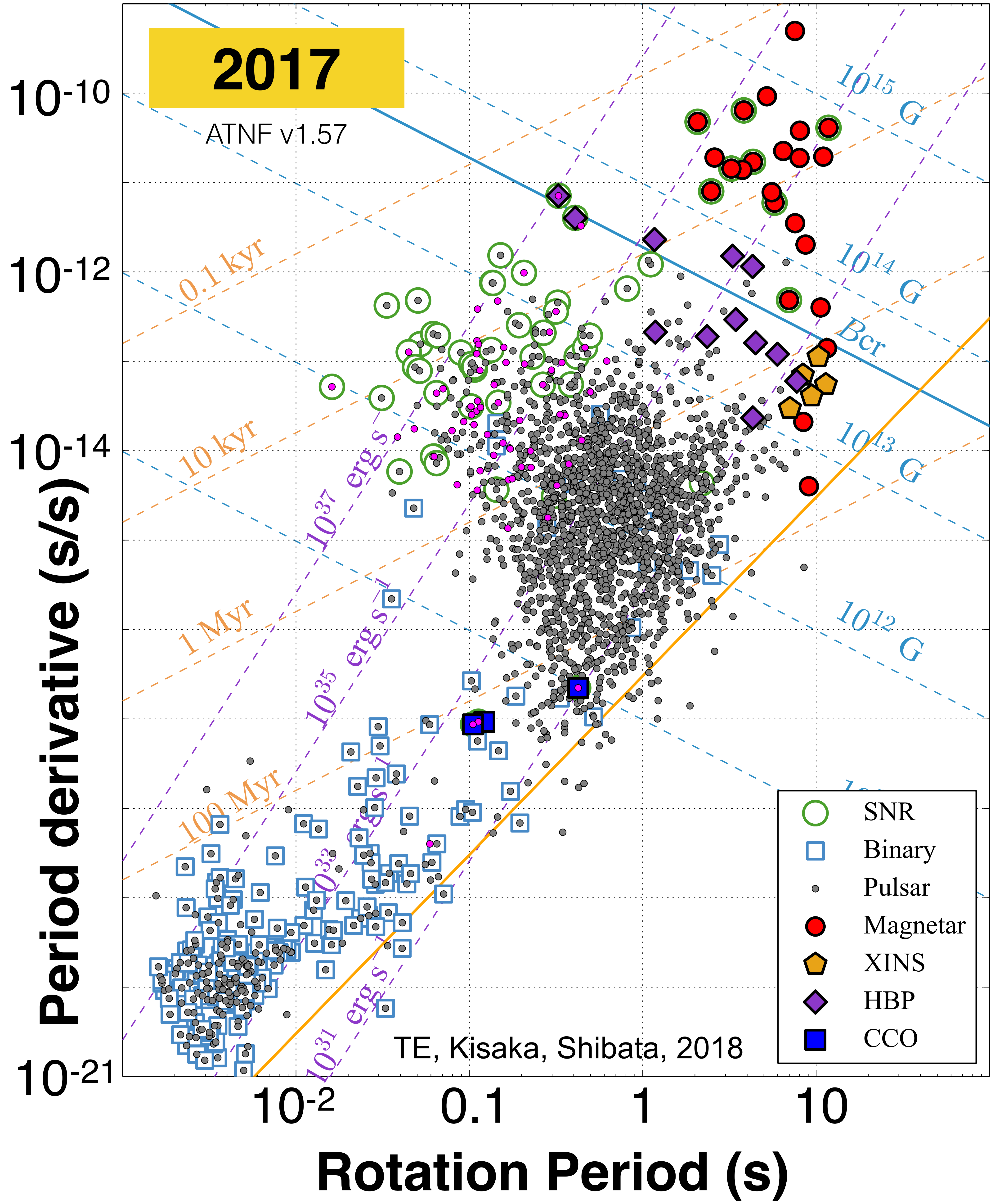
P = 33 ms
P_{dot} = 4.2x10^{-13} s/s



David A. Moffett et al., ApJ **468, 779-783** (1996)

Diversity of Neutron Stars

- >3,000 known pulsars (10^5 in our Galaxy?)
- Multi-wavelength observations from radio, optical, X-rays, and gamma rays.



TE, Kisaka, Shibata, 2018

Diversity of Neutron Stars

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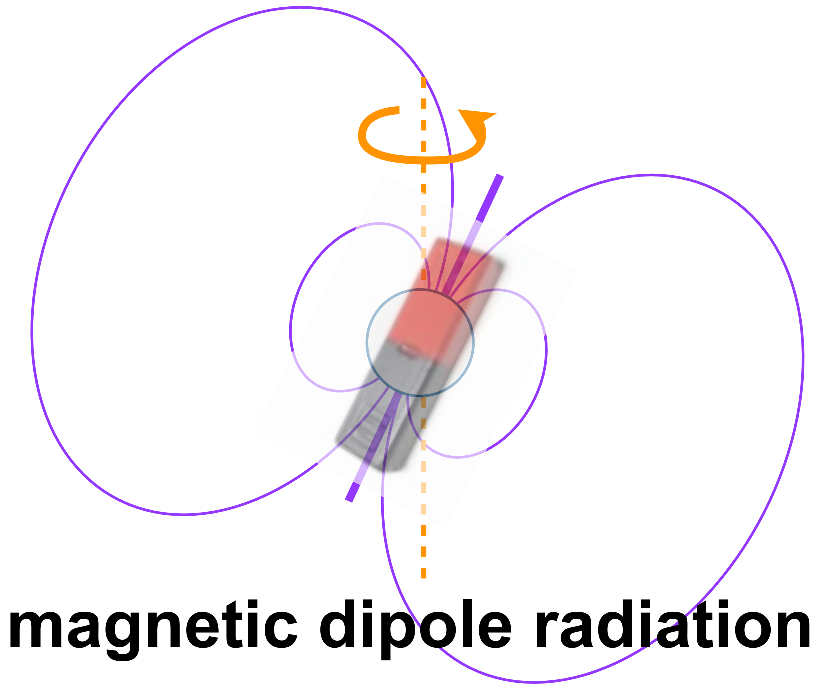
- Multi-wavelength observations from radio, optical, X-rays, and gamma rays.
- Magnetic field strength

$$L_{\rm rot} = \frac{dE_{\rm rot}}{dt} = -\frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right)$$
$$= 3.9\times 10^{46}\,\frac{\dot{P}}{P^3}\ {\rm erg/s}$$

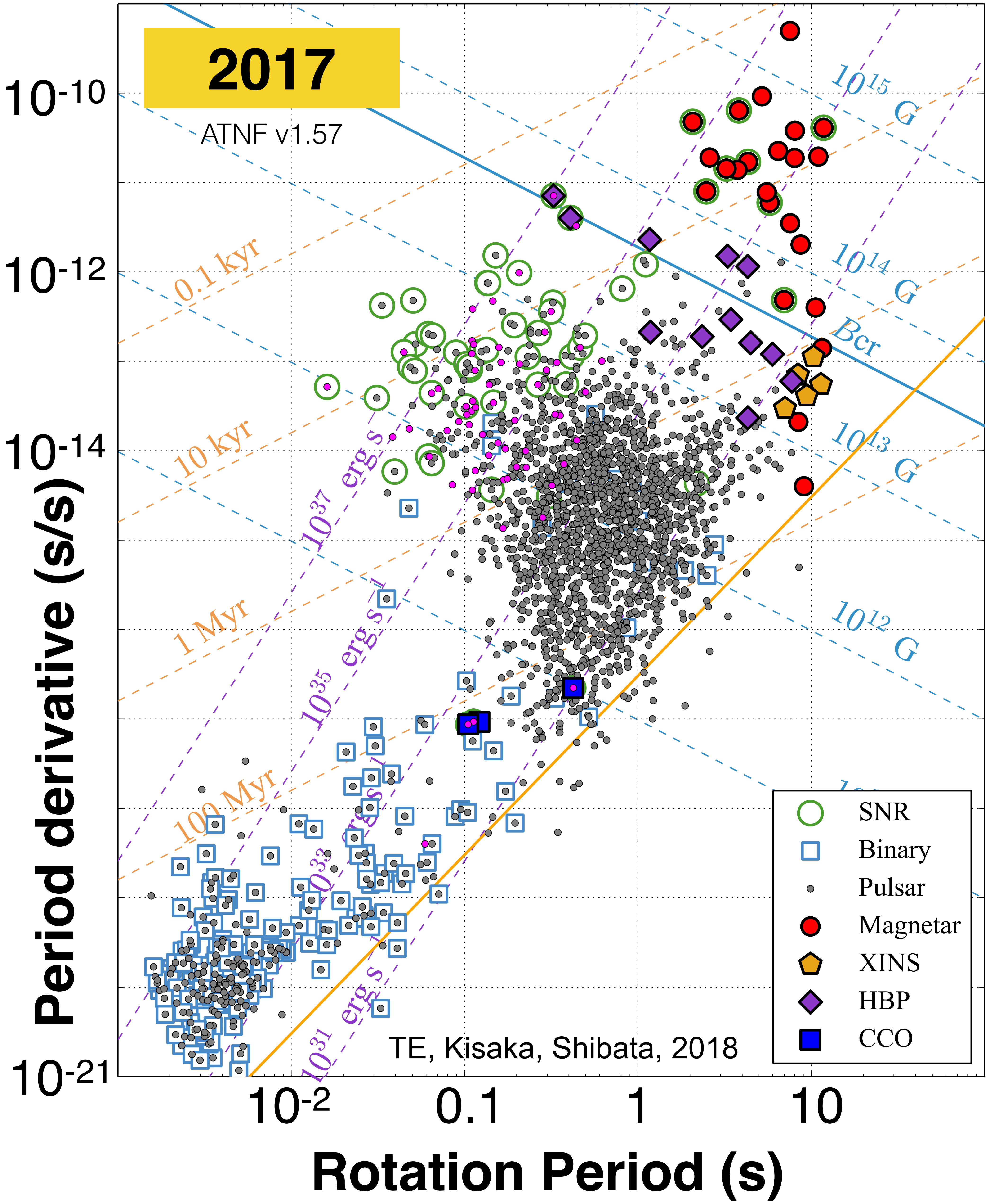


magnetic dipole radiation

$$L_{\rm mag} = \frac{2}{3c^3}|\ddot{\mu}|^2 = \frac{2}{3c^3}|\mu|^2\Omega^4\sin^2\theta \ \propto \frac{B^2}{P^4}$$

$$L_{\rm rot} \sim L_{\rm mag} \ \longrightarrow \ B = 1.0\times 10^{12}\sqrt{\left(\frac{P}{1\,{\rm s}}\right)\left(\frac{\dot{P}}{10^{-15}\,{\rm s/s}}\right)}\ {\rm G}$$

- Characteristic age $\tau_{\rm c} = \dfrac{P}{2\dot{P}}$



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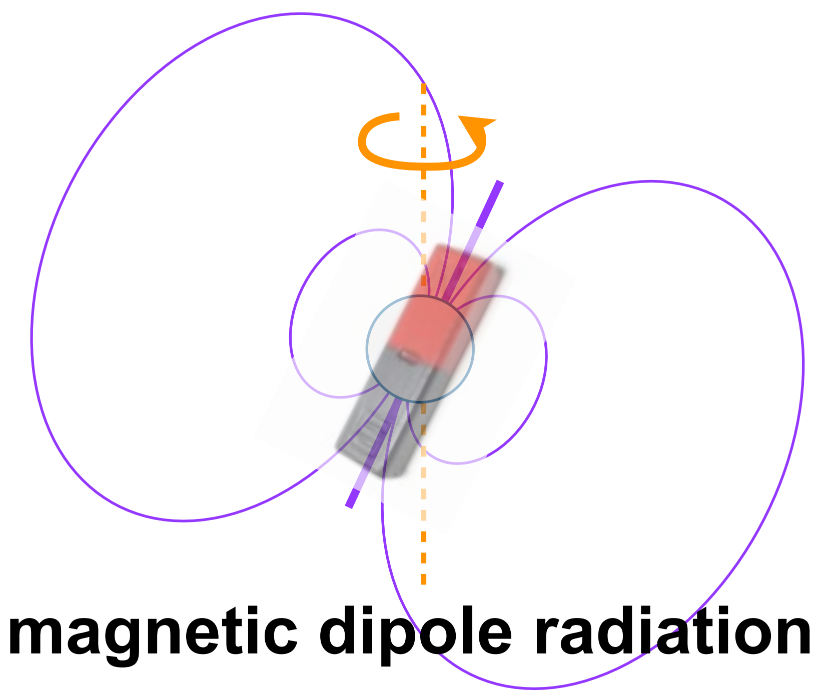

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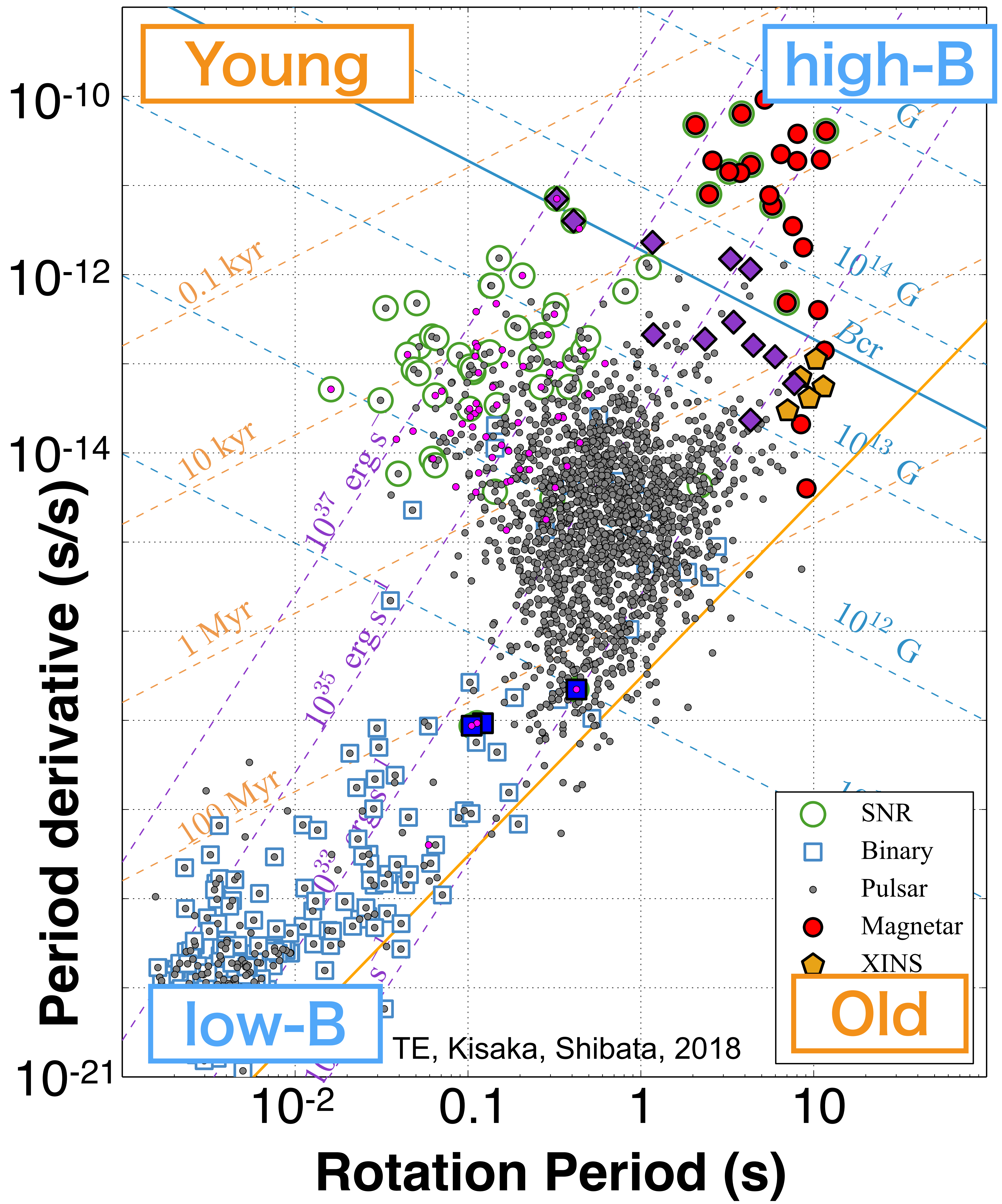

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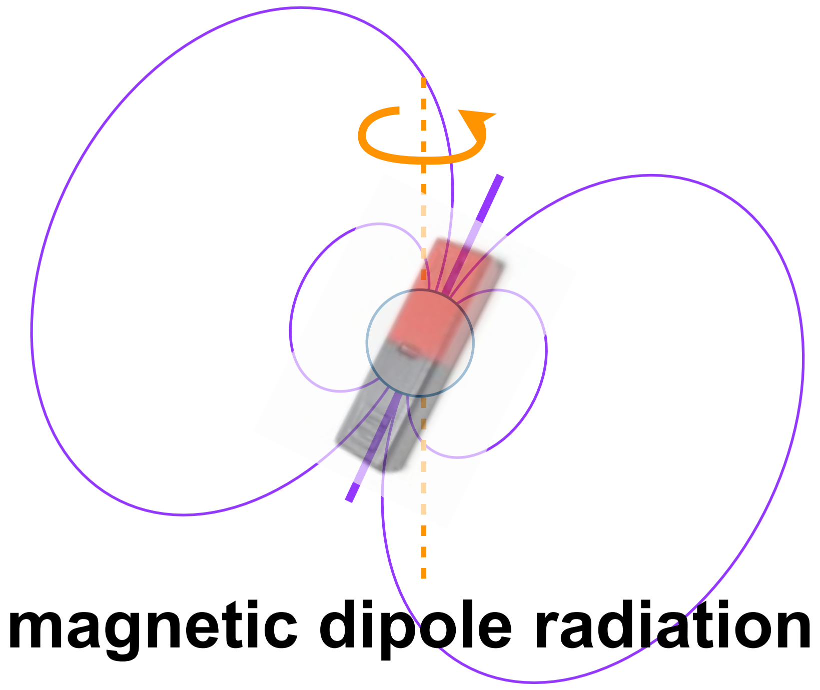
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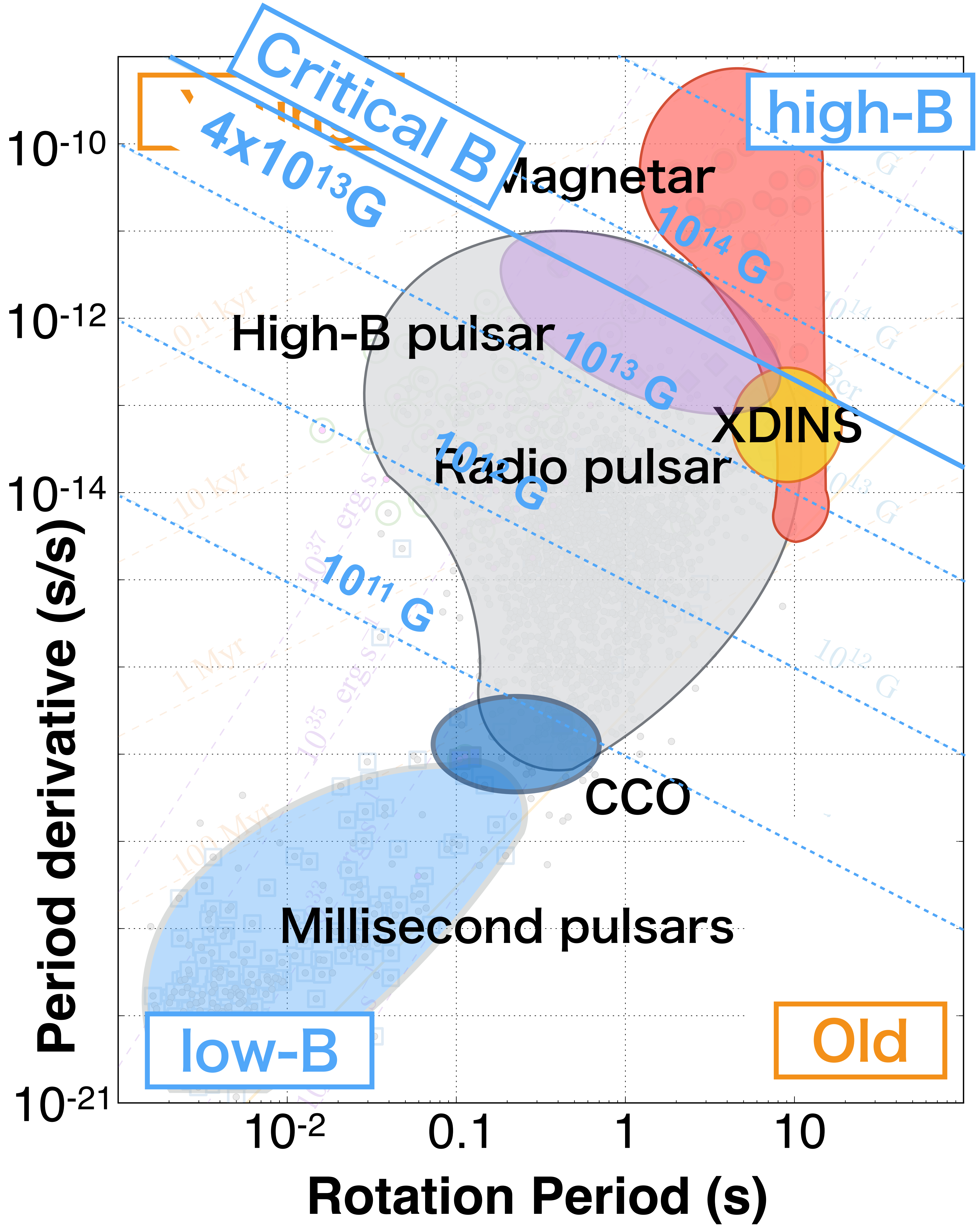
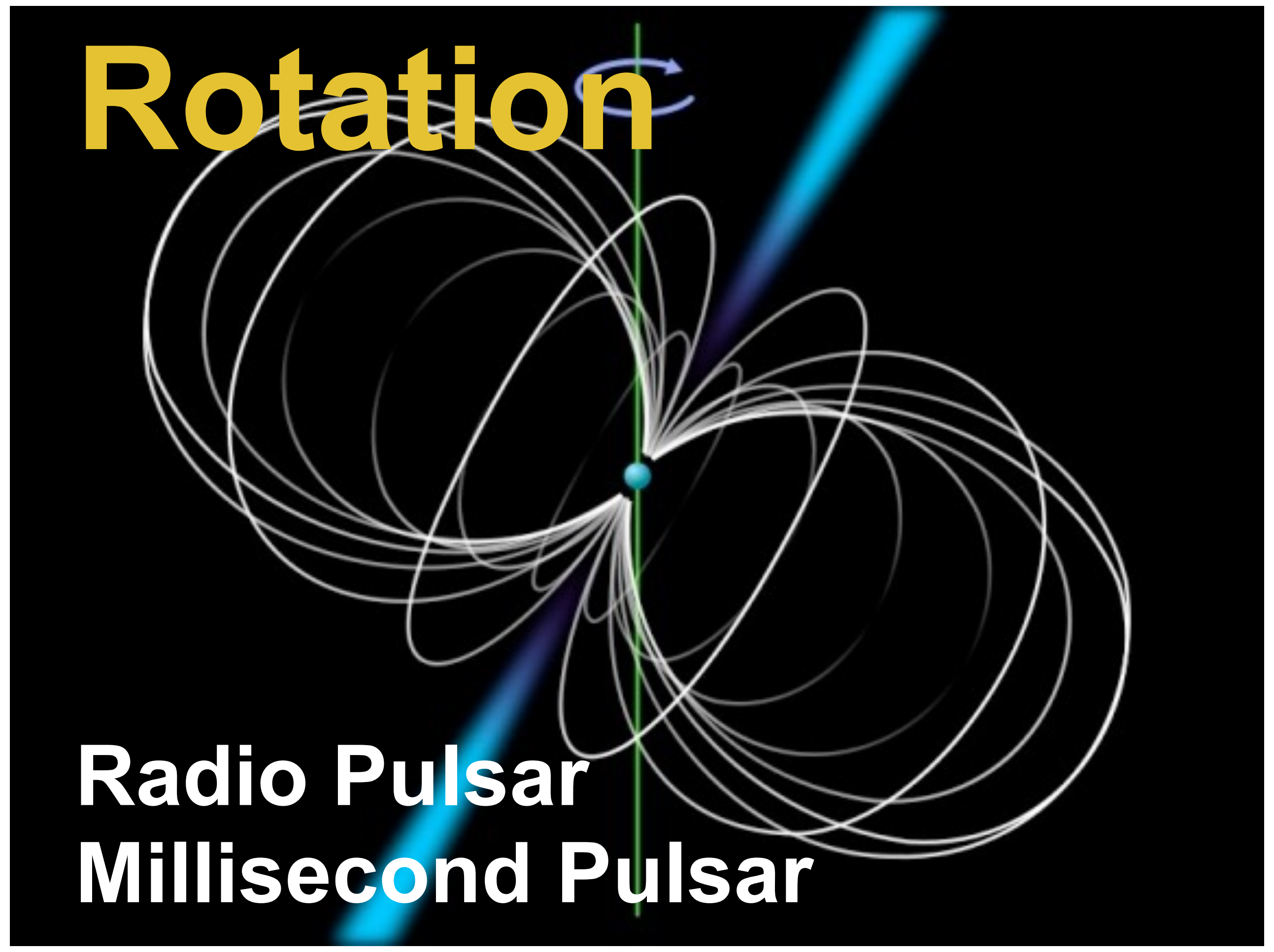


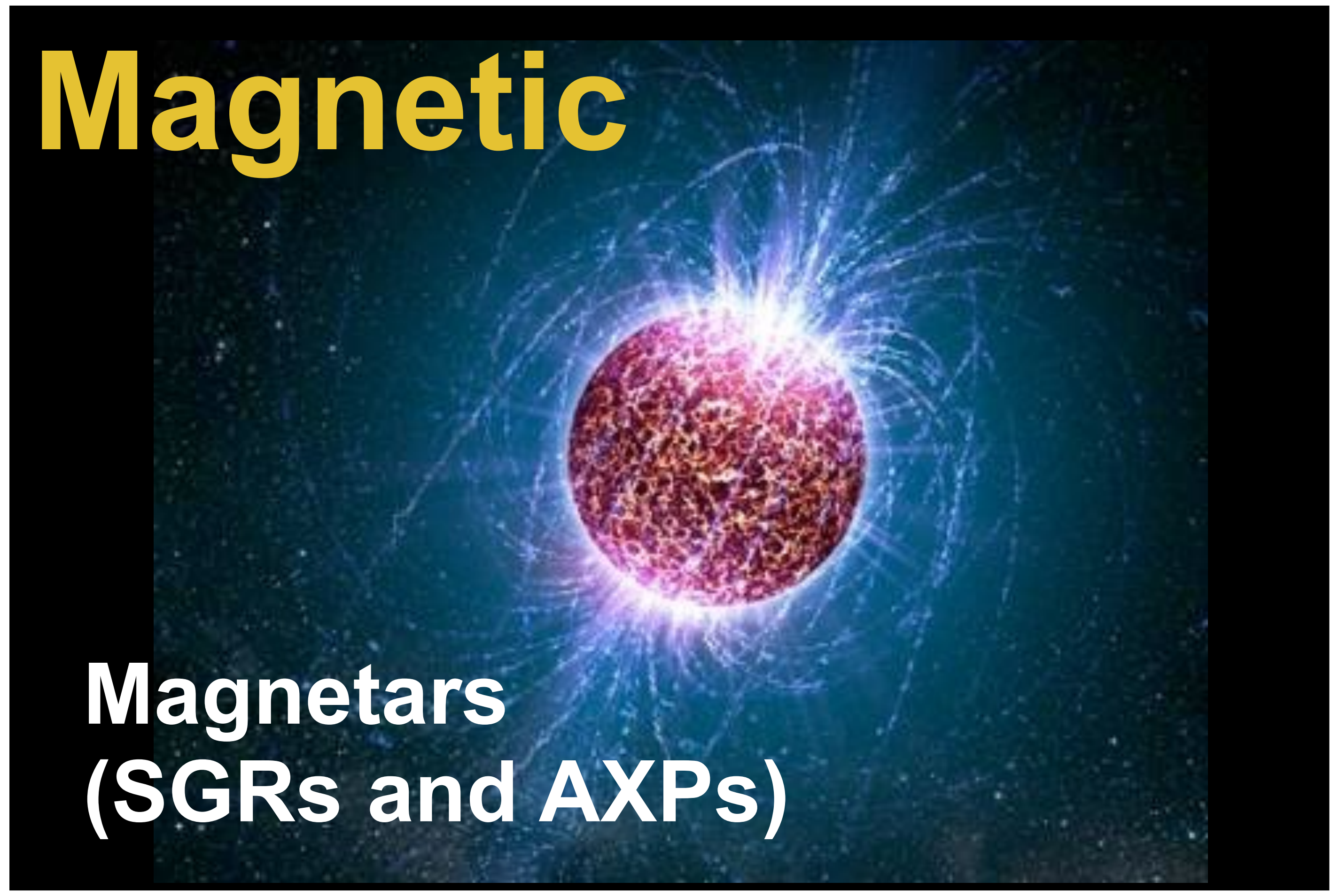
Diversity of Neutron Stars

Energy source of radiation & outflows



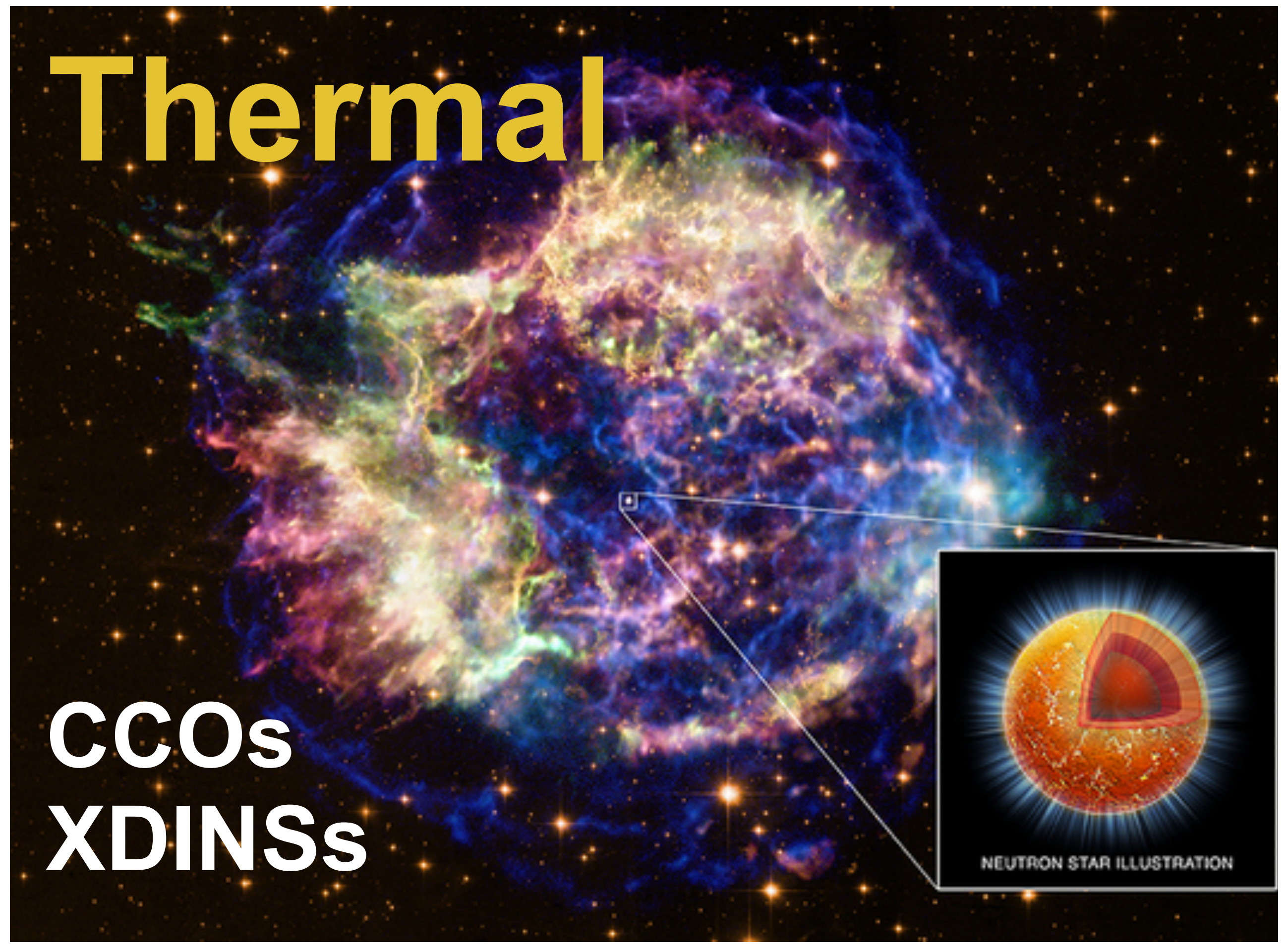
Rotation

Radio Pulsar
Millisecond Pulsar



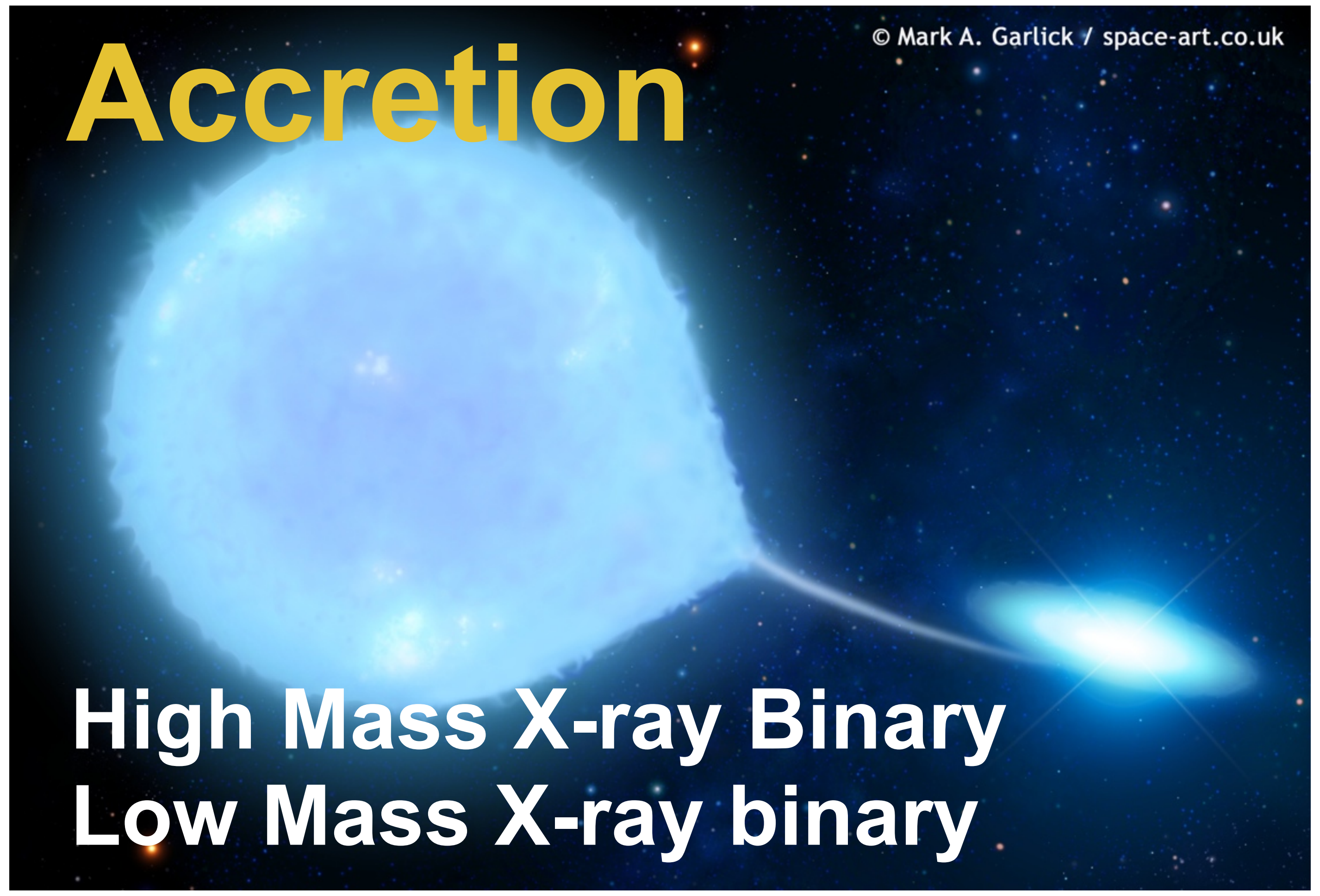
Magnetic

Magnetars
(SGRs and AXPs)



Thermal

CCOs
XDINSs



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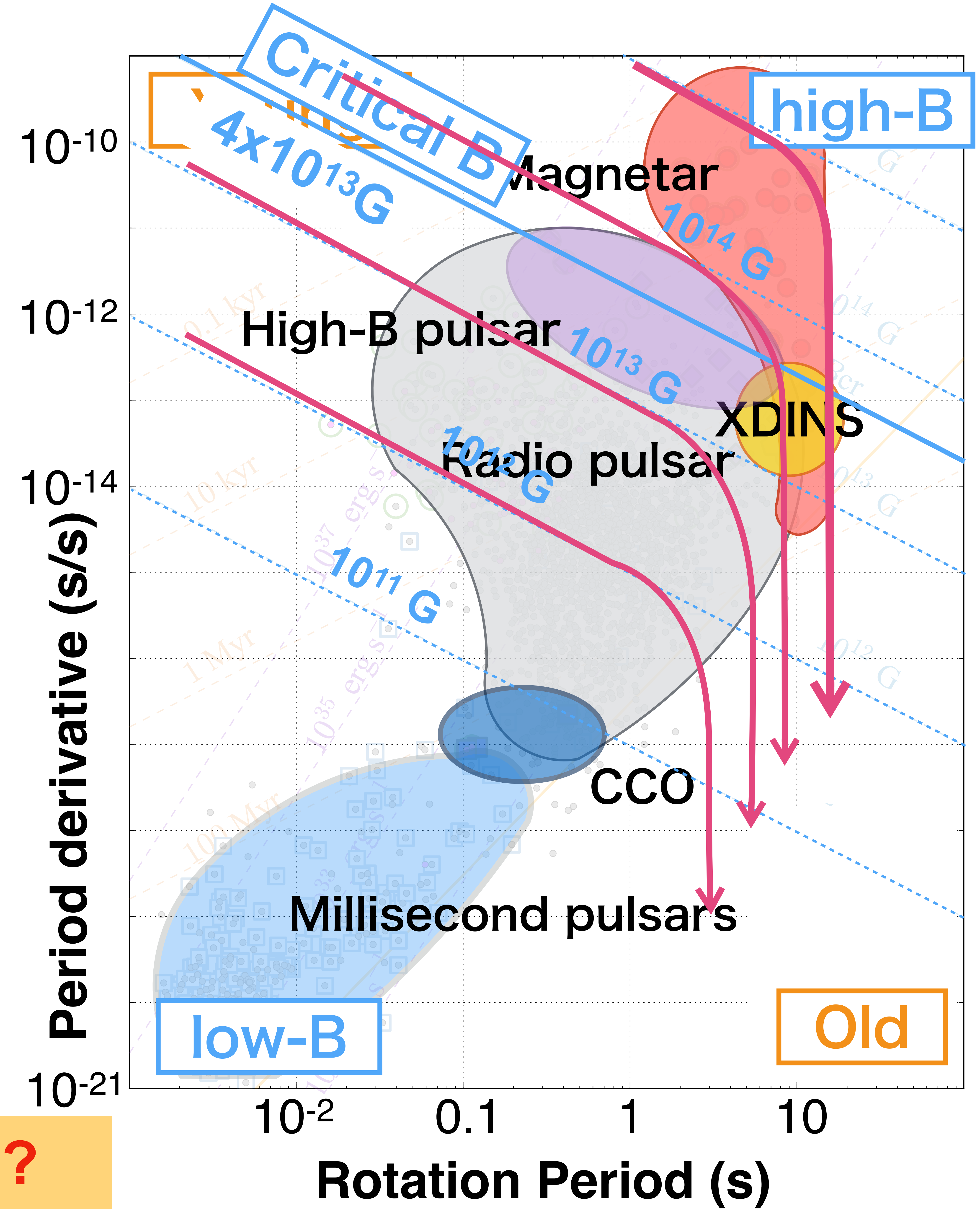
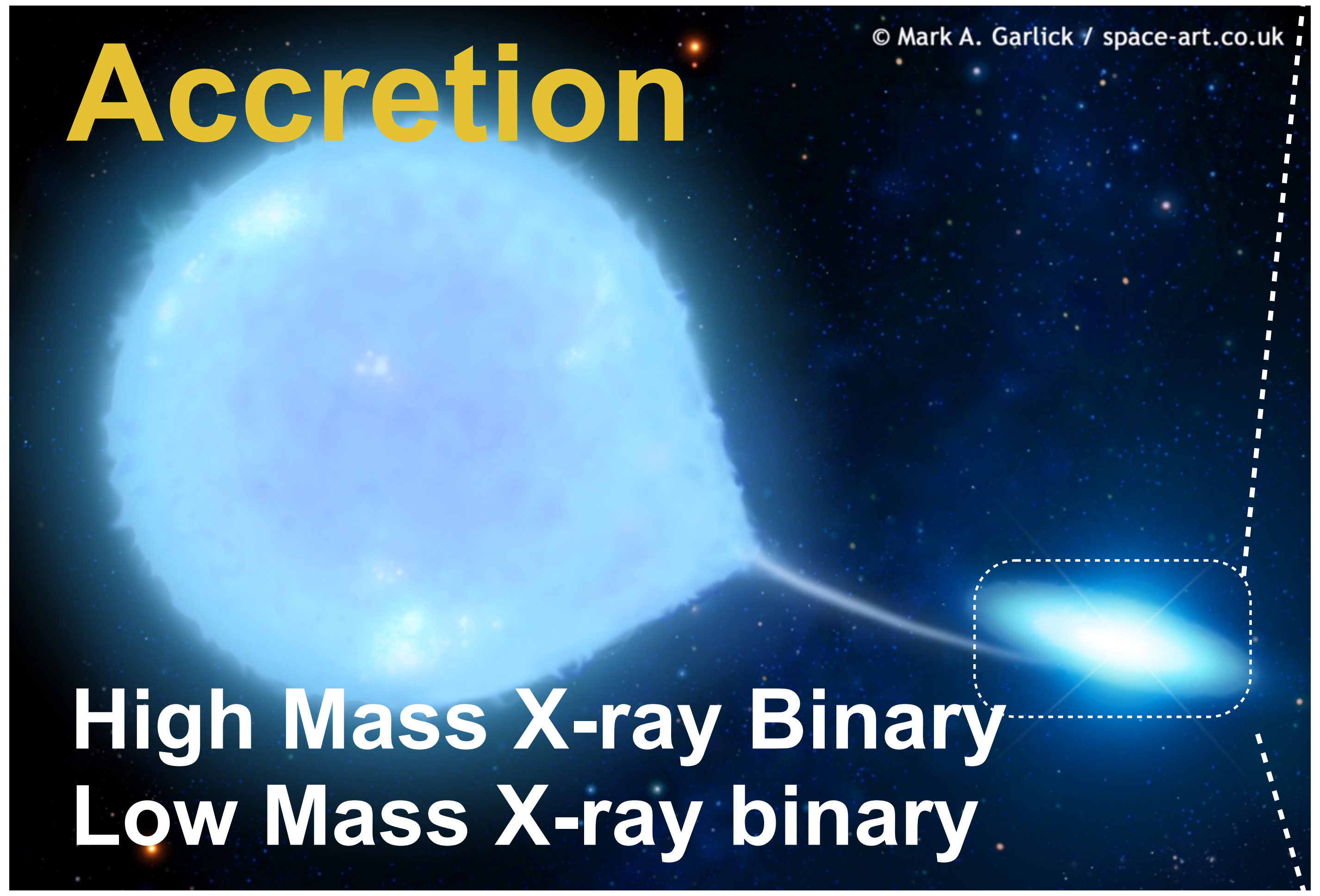
Accretion

High Mass X-ray Binary
Low Mass X-ray binary

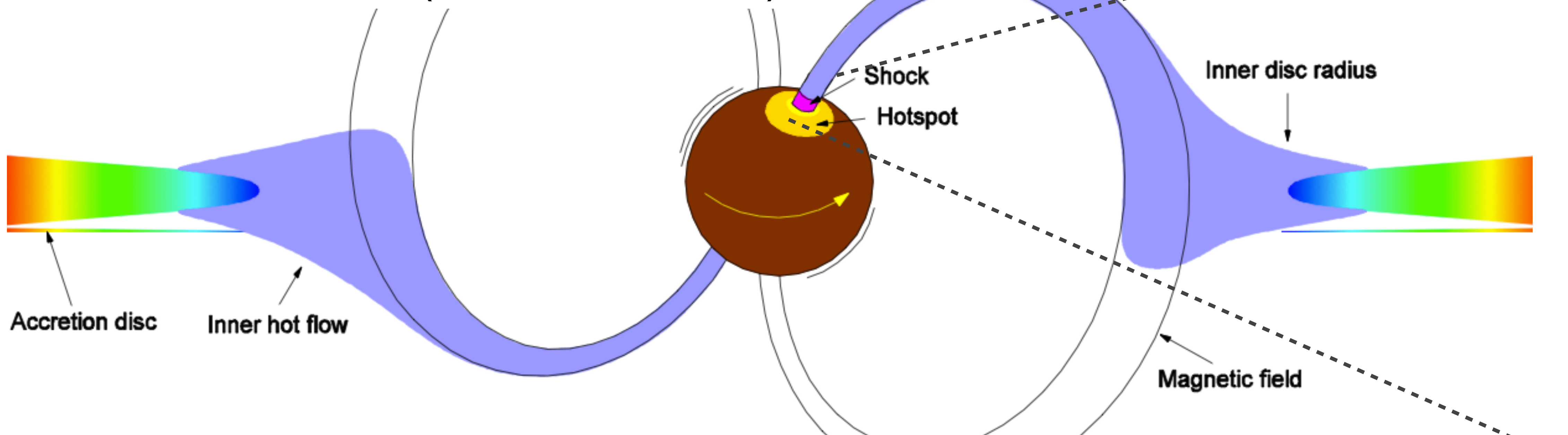


What is the unified evolution theory of NSs?

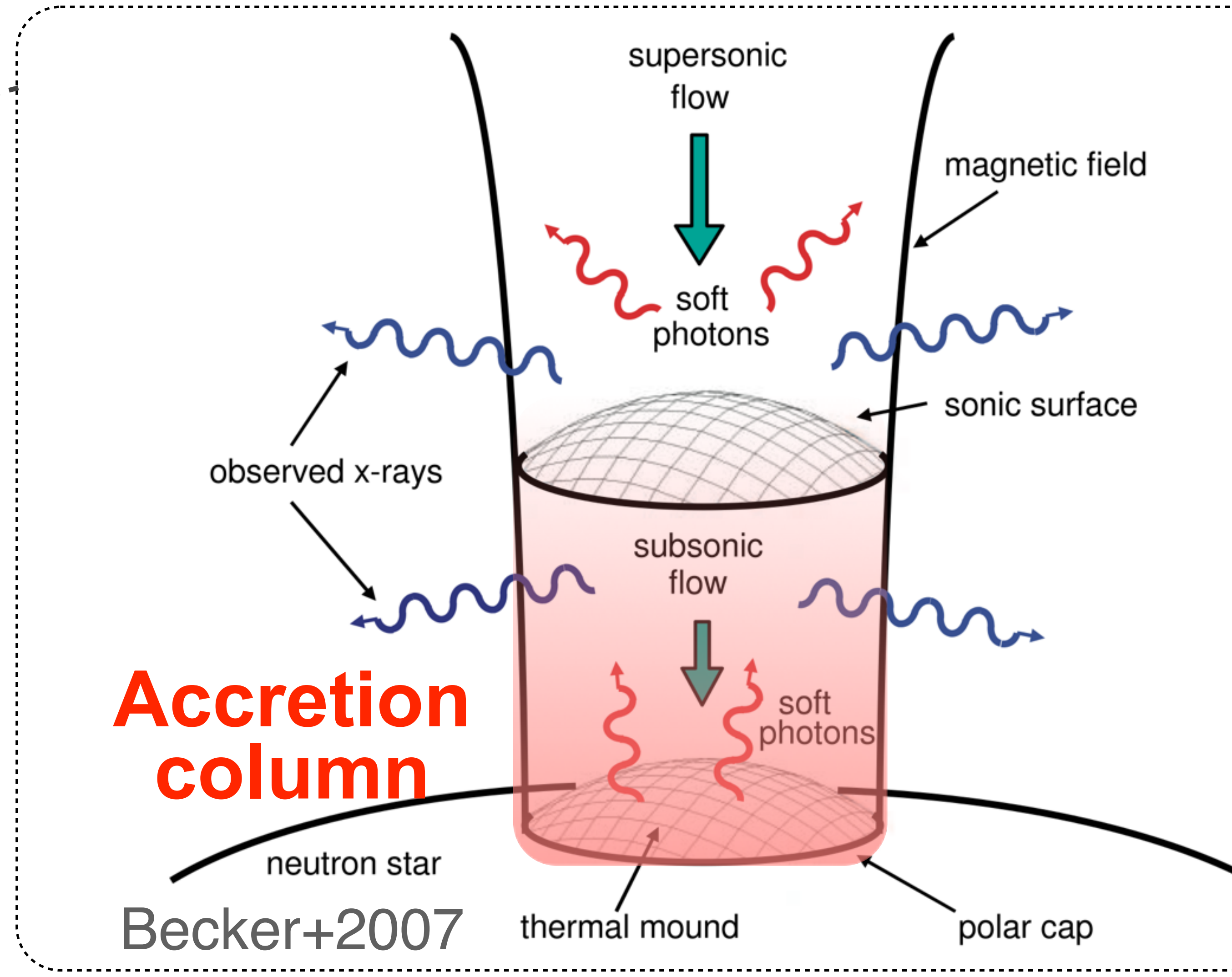
Magnetic field of accreting X-ray pulsars



Accretion flow from the Alfven radius
Release of the gravitational energy
Accretion column (kT ~ a few keV)



from Askar Ibragimov (Mark A. Garlick



Becker+2007

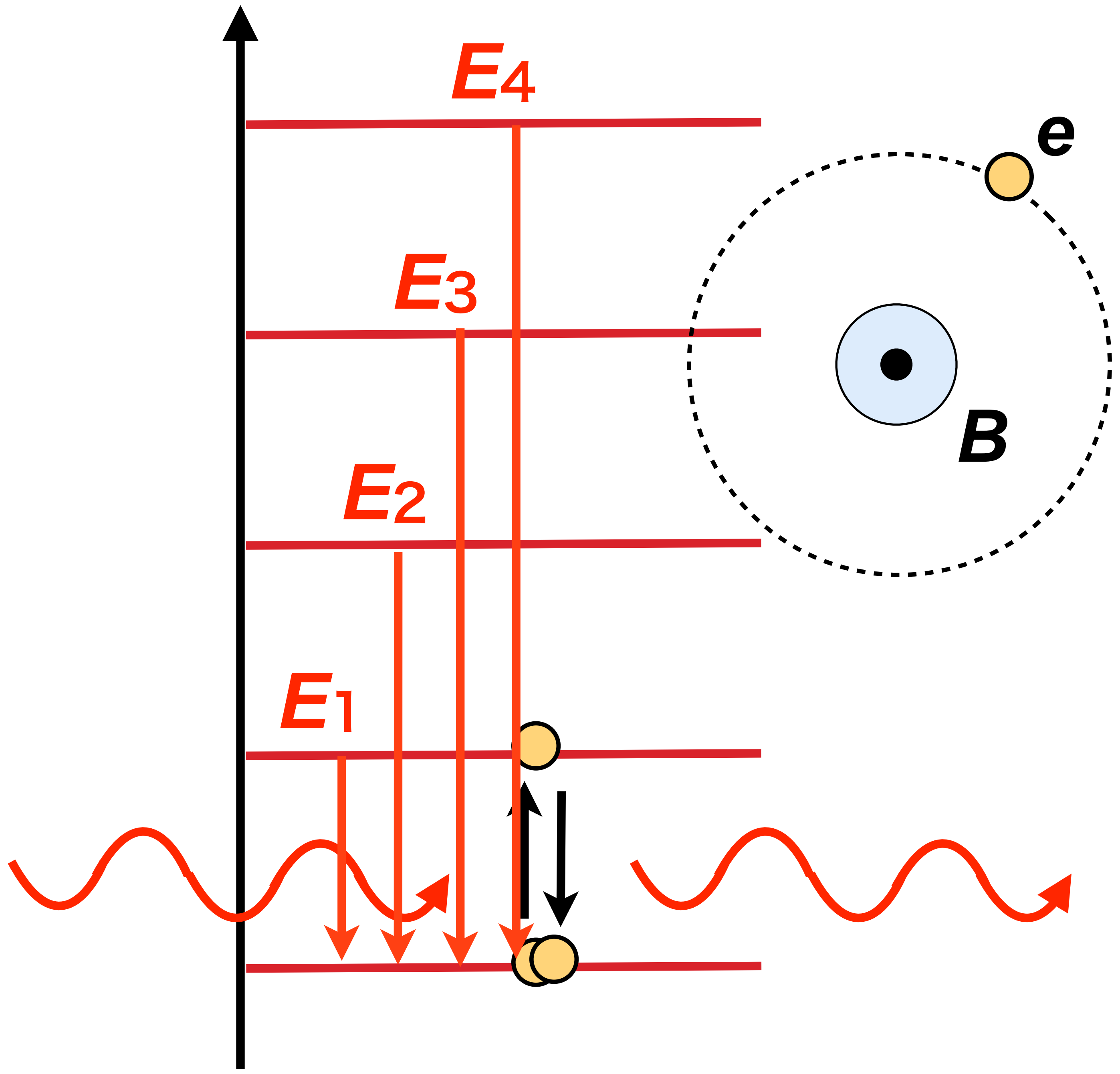
Cyclotron Resonance Scattering Feature (CRSF)

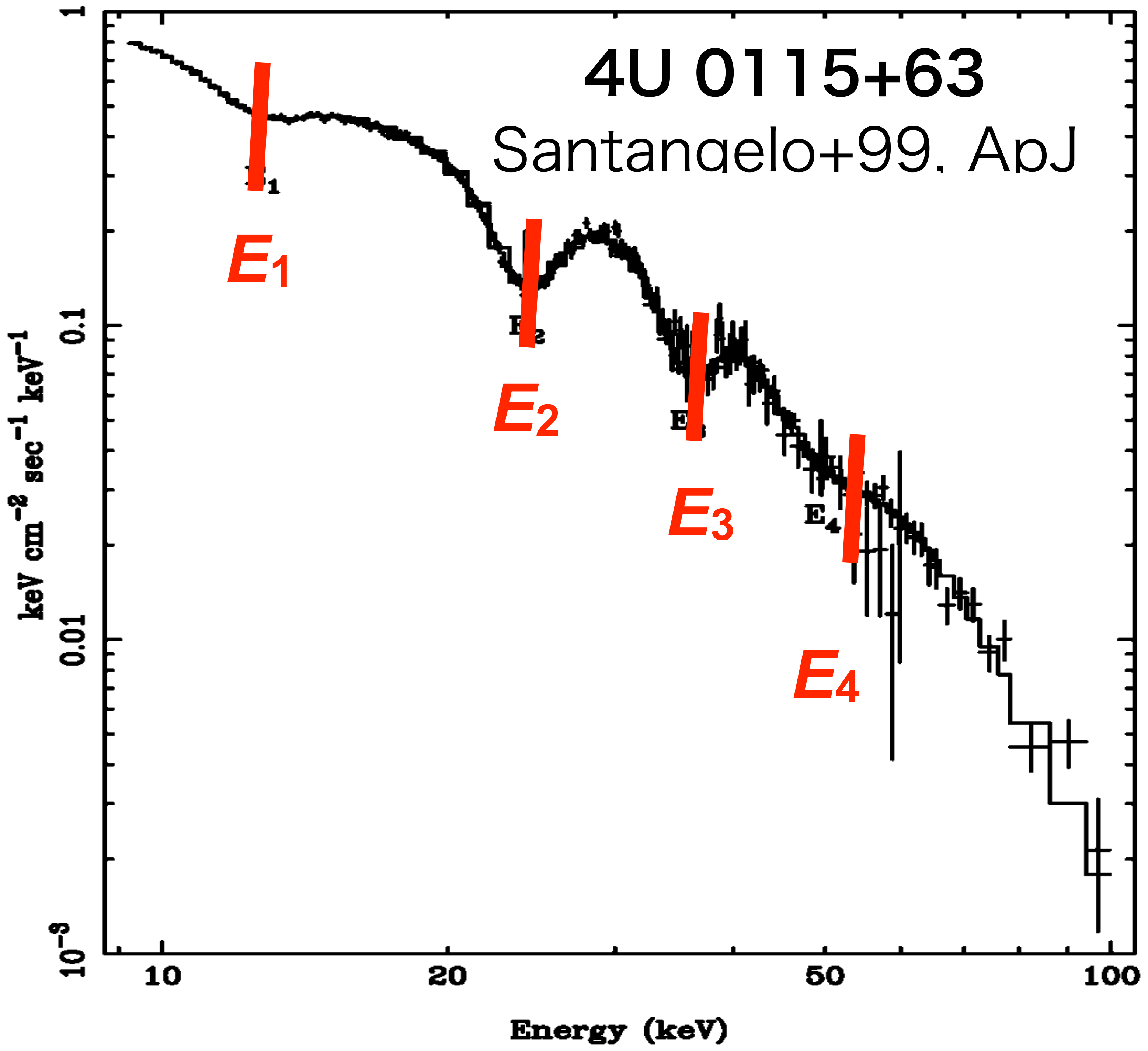
$$E_n = n\hbar\omega_c = m_e c^2 \frac{B}{B_c} \cdot n$$

$$B_{\rm cr} = \frac{m_e^2 c^3}{\hbar e} = 4.4 \times 10^9 \ \mathrm{T}$$

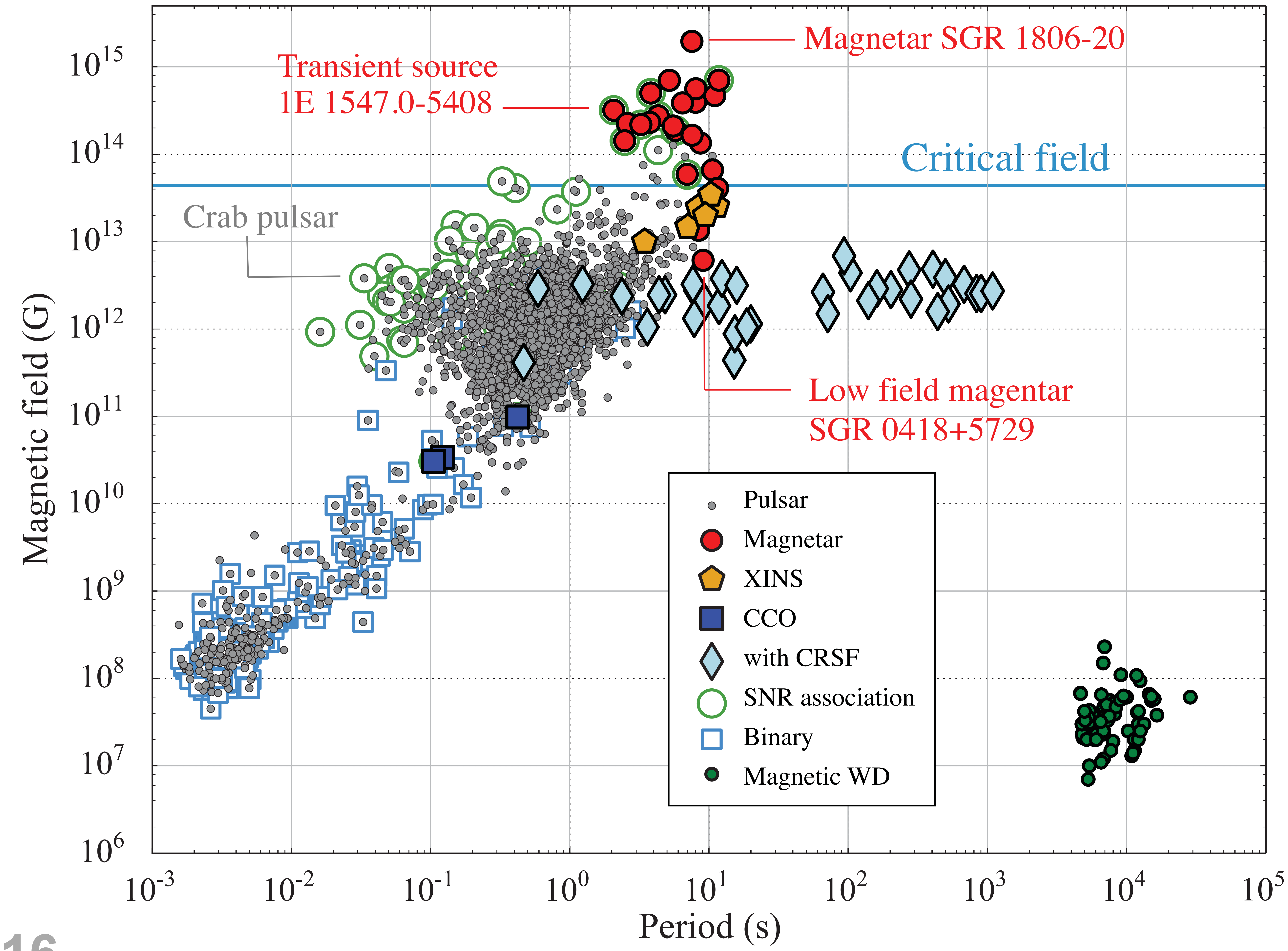
$E_n \sim 11$ keV for $B = 10^8$ T

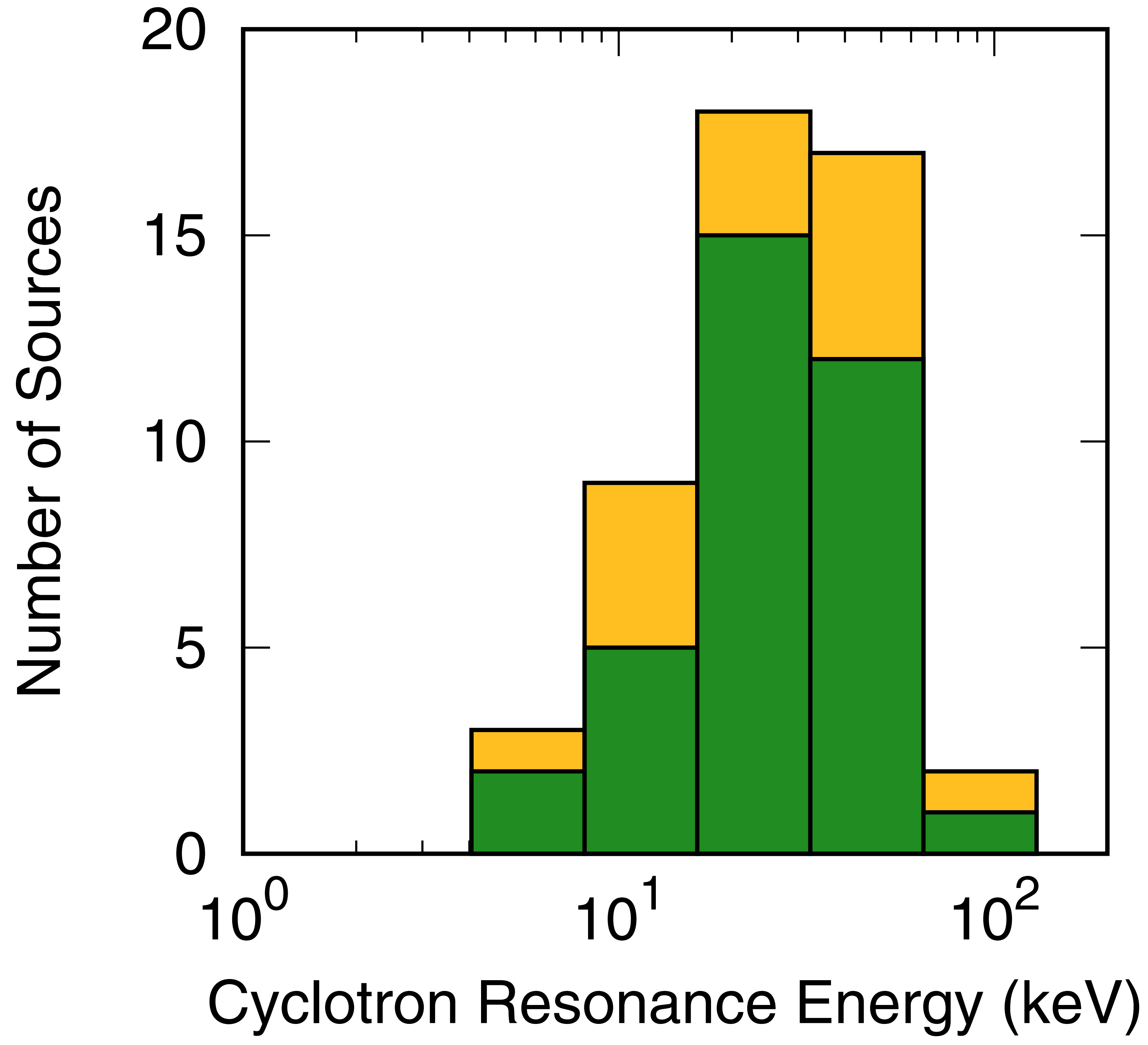
cf. atom $$E_n = -\frac{\alpha^2}{2} m_e c^2 \cdot \frac{Z^2}{n^2}$$





NS rotation period vs. magnetic field strength





- Canonical neutron stars: B ~ 10^{12} G (=10^{8} T)
- Magnetars B~$10^{14\text{-}15}$ G
- millisecond pulsars B~$10^{8\text{-}10}$ G

IOP Publishing
Reports on Progress in Physics
Rep. Prog. Phys. **82** (2019) 106901 (54pp)
https://doi.org/10.1088/1361-6633/ab3def

Review

Observational diversity of magnetized neutron stars

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Received 8 August 2018, revised 8 May 2019
Accepted for publication 22 August 2019
Published 24 September 2019

Corresponding Editor Professor Gordon Baym

https://iopscience.iop.org/article/10.1088/1361-6633/ab3def

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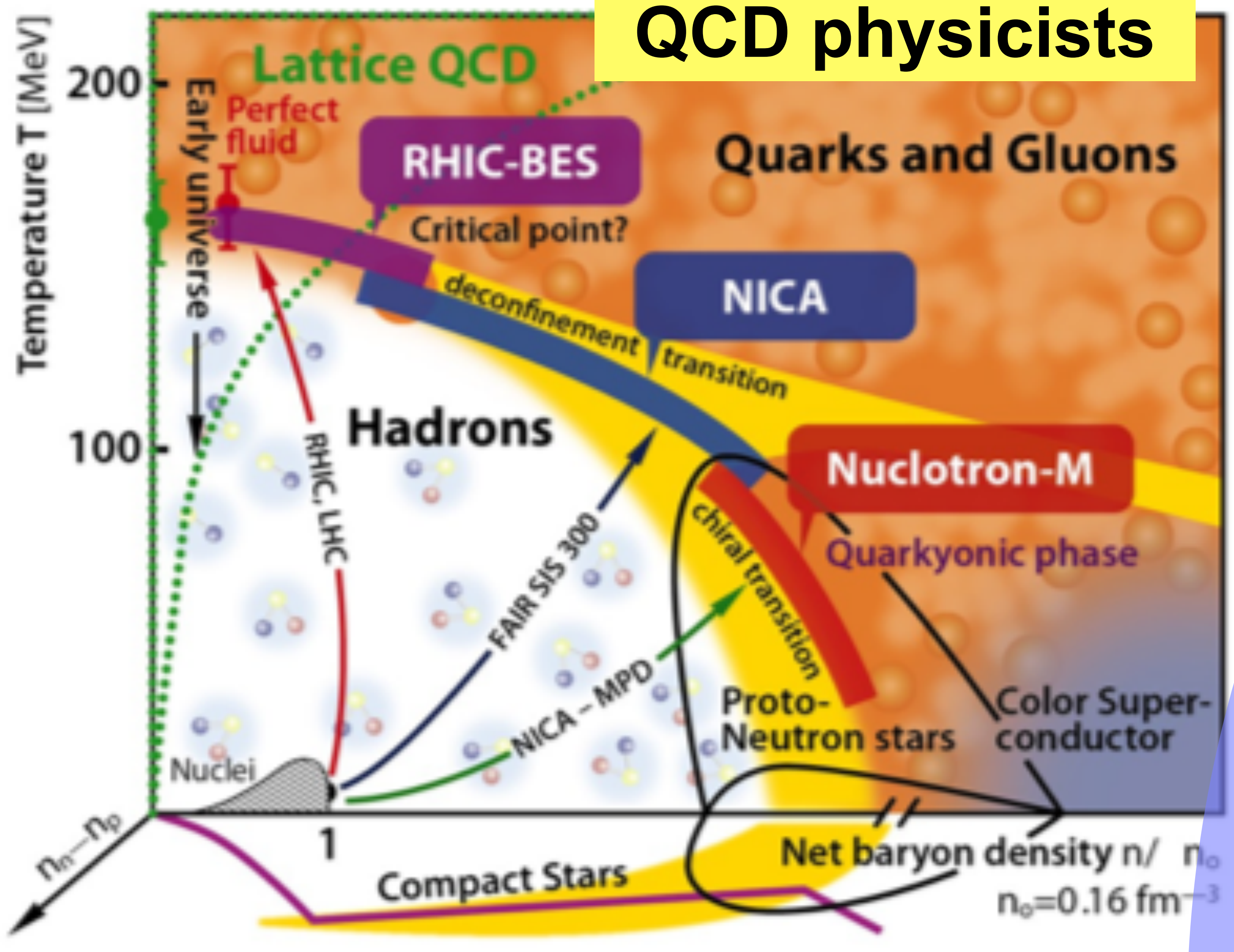
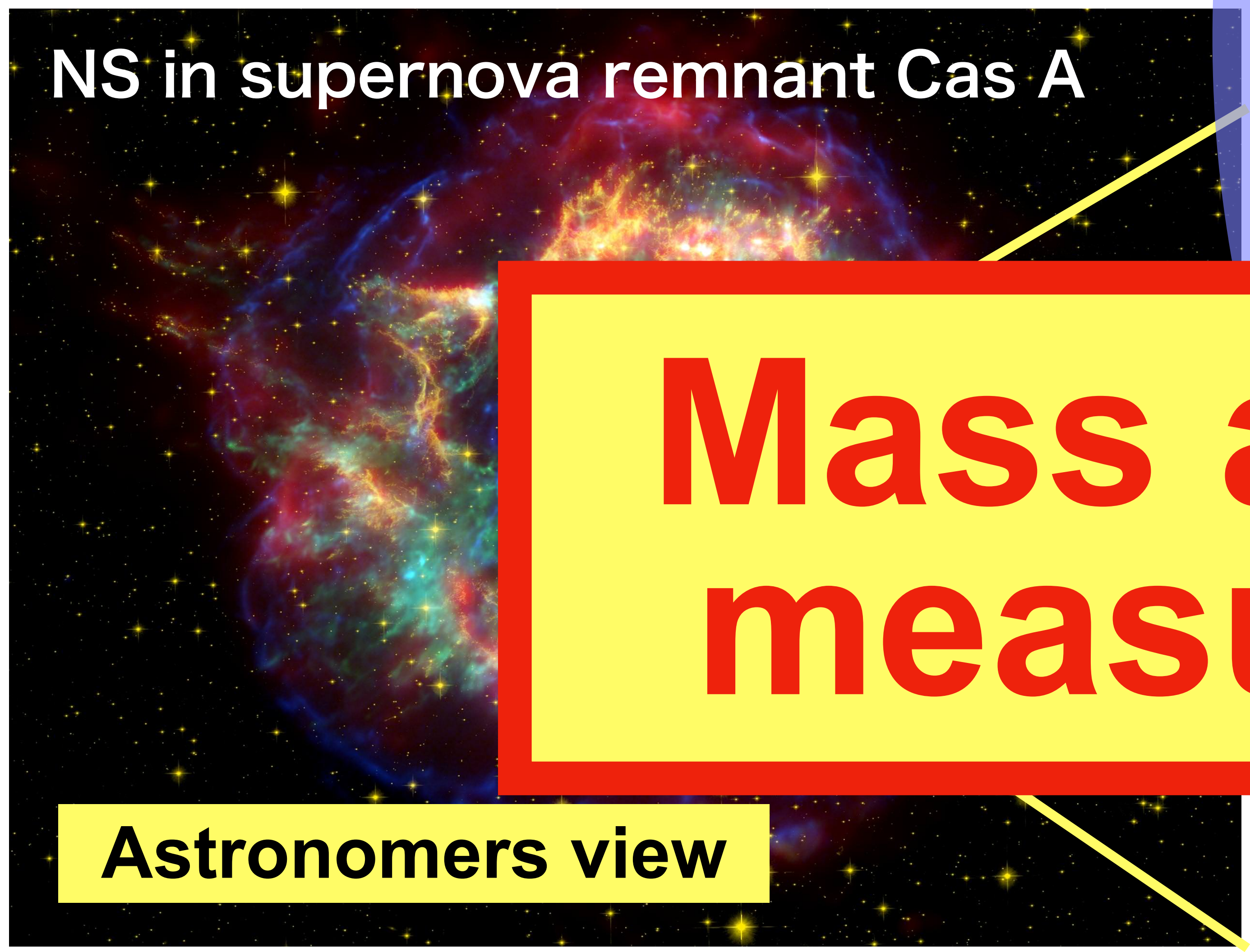
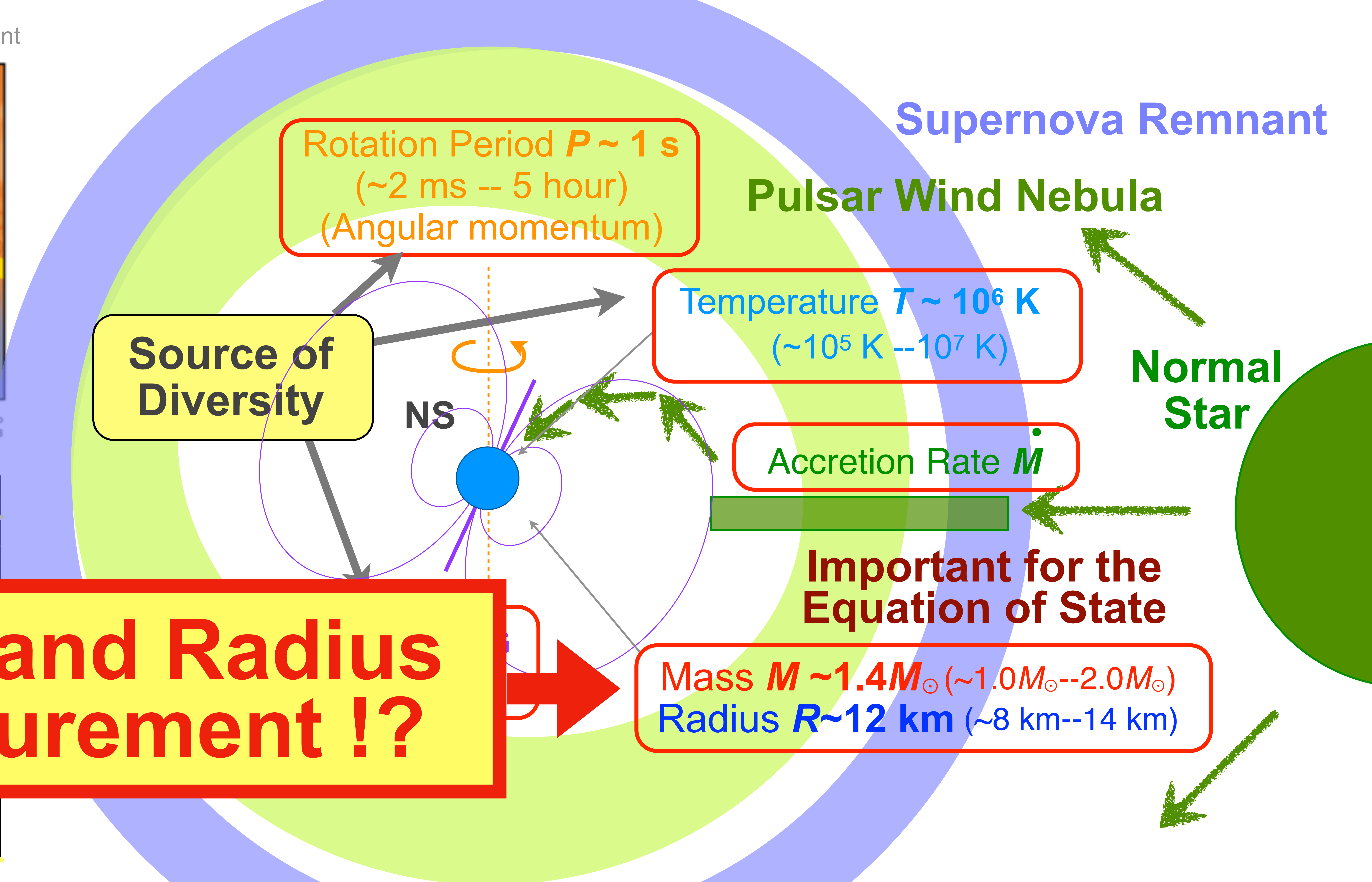
QCD physicists



NS in supernova remnant Cas A



Astronomers view



Supernova Remnant

Pulsar Wind Nebula

Normal Star

Source of Diversity

NS

Rotation Period $P \sim 1$ s
($\sim$2 ms -- 5 hour)
(Angular momentum)

Temperature $T \sim 10^6$ K
($\sim 10^5$ K -- 10^7 K)

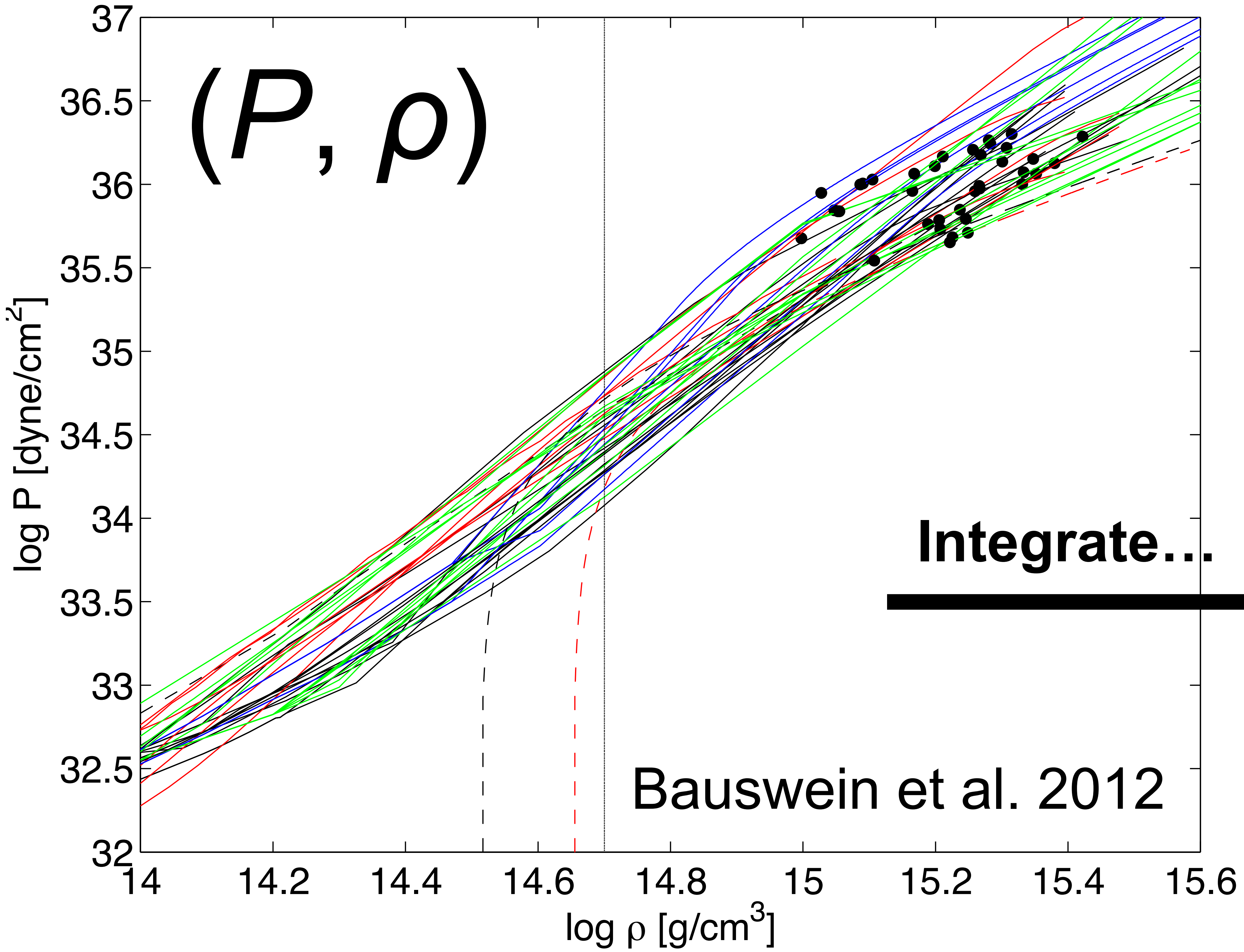
Accretion Rate $\dot{M}$

Important for the Equation of State

Mass $M \sim 1.4 M_\odot$ ($\sim 1.0 M_\odot$--$2.0 M_\odot$)
Radius $R \sim 12$ km ($\sim$8 km--14 km)

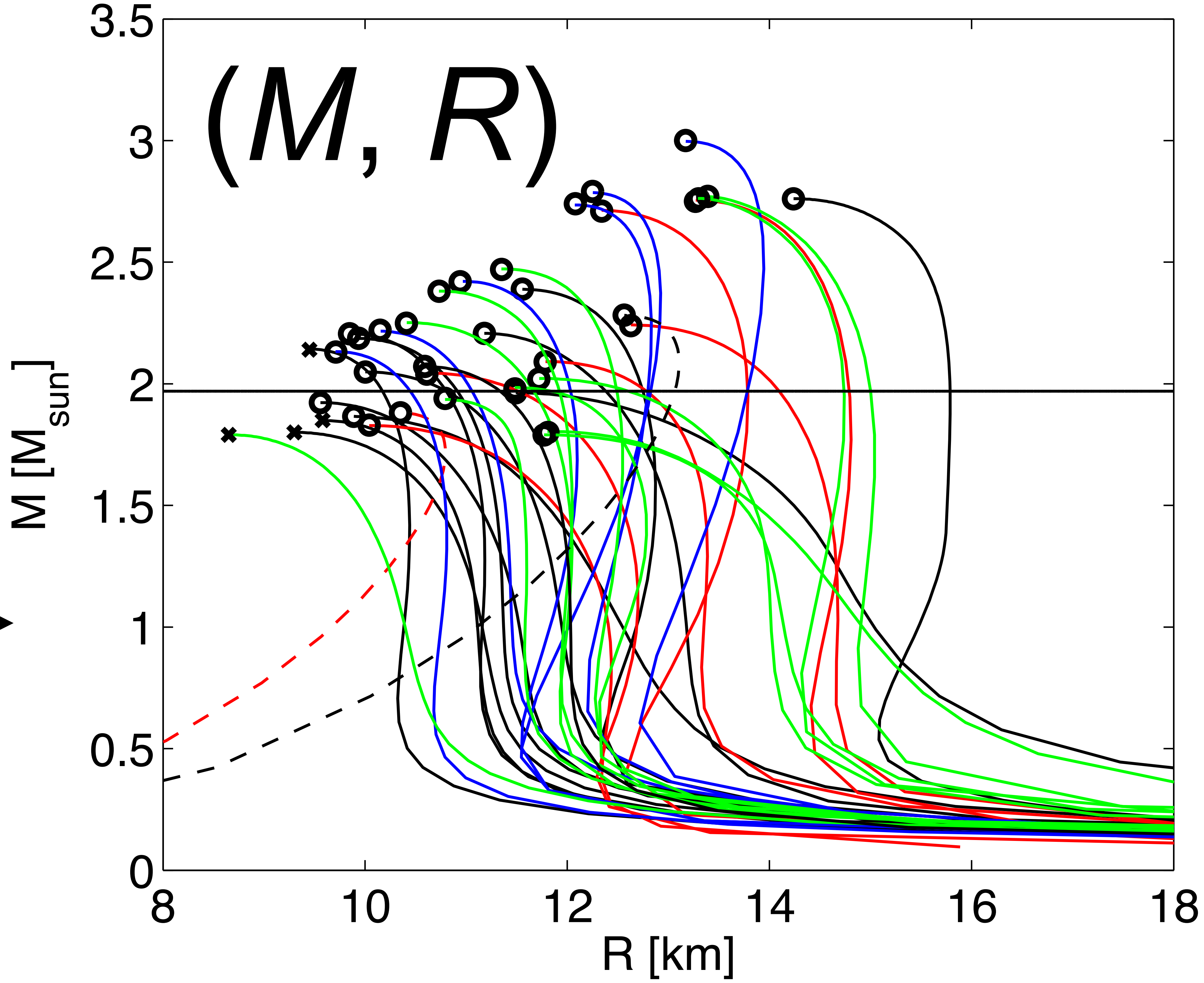
Mass and Radius measurement !?

Equation of state of neutron star nuclear matter



Bauswein et al. 2012

Integrate…



$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\rho\,\frac{GM(r)}{r^2}$$

Outward

Gravity

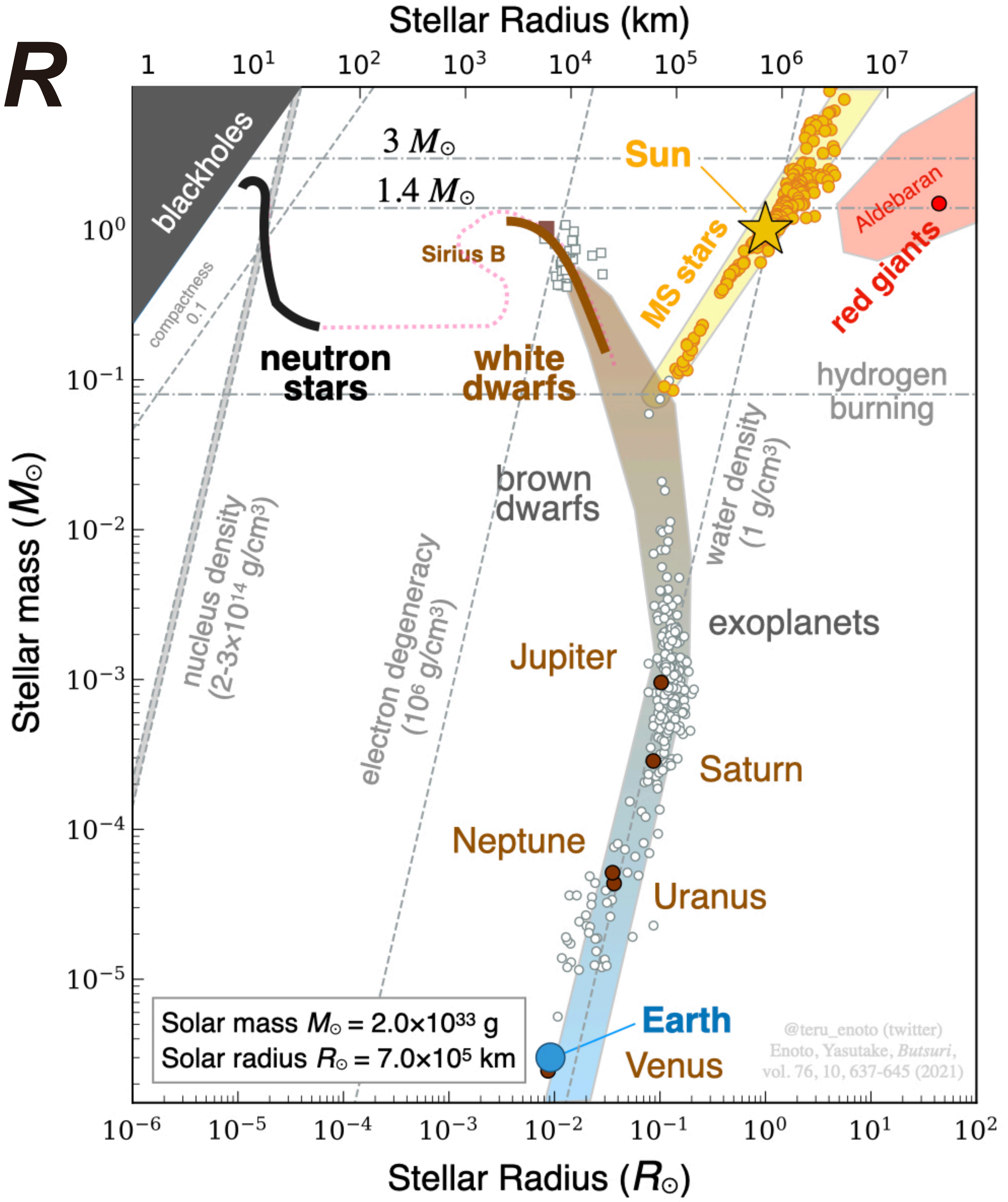
Pressure valance

(Non relativistic case,
Relativistic case is
the TOV equation)

- The state equation (P, ρ) corresponds to the curve of macroscopic mass and radius (M, R)
- and can be expected to be measured in astronomical observation.

Stellar mass M and radius R

- M and R of various celestial bodies (self-gravitational systems) are determined by the equation of state (including internal structure, composition, pressure…)
  - Planet: electrical repulsion $M \sim R^3$
  - Star: gas & radiation pressure $M \sim R$
  - White dwarf: e-degenerate pressure $M \sim R^{-1/3}$
  - Neutron stars: n-degenerate pressure $M \sim R^0$
- Observational data is scattered around the M-R relation with large uncertainties.
- Equation of state of neutron stars (and thus the M-R relation) requires precise astronomical observations in the upper left region.

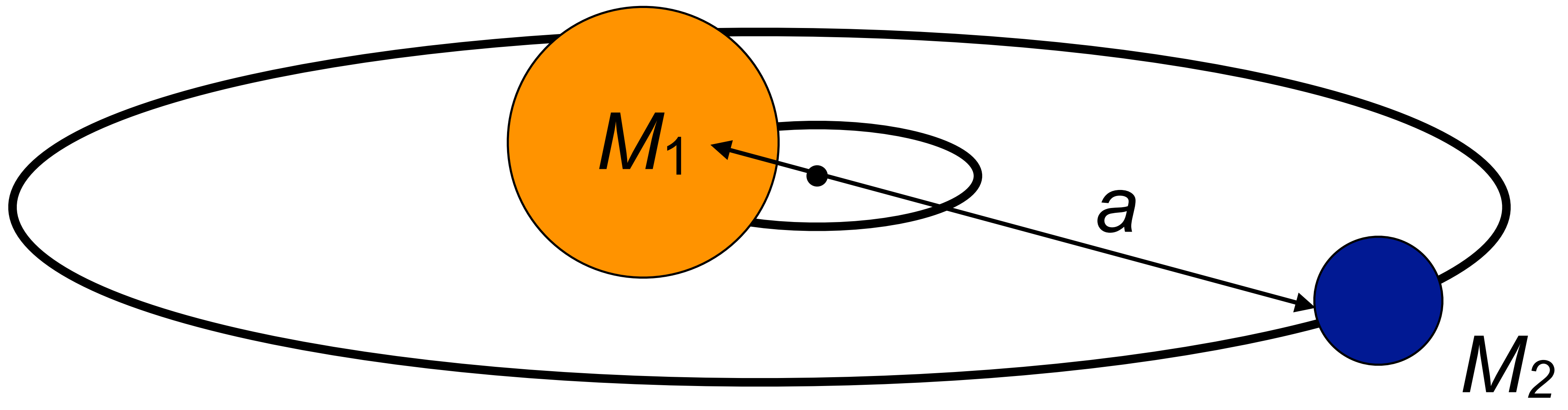


@teru_enoto (twitter)
Enoto, Yasutake, *Butsuri*, vol. 76, 10, 637-645 (2021)

Astronomical measurements of mass and radius

Mass

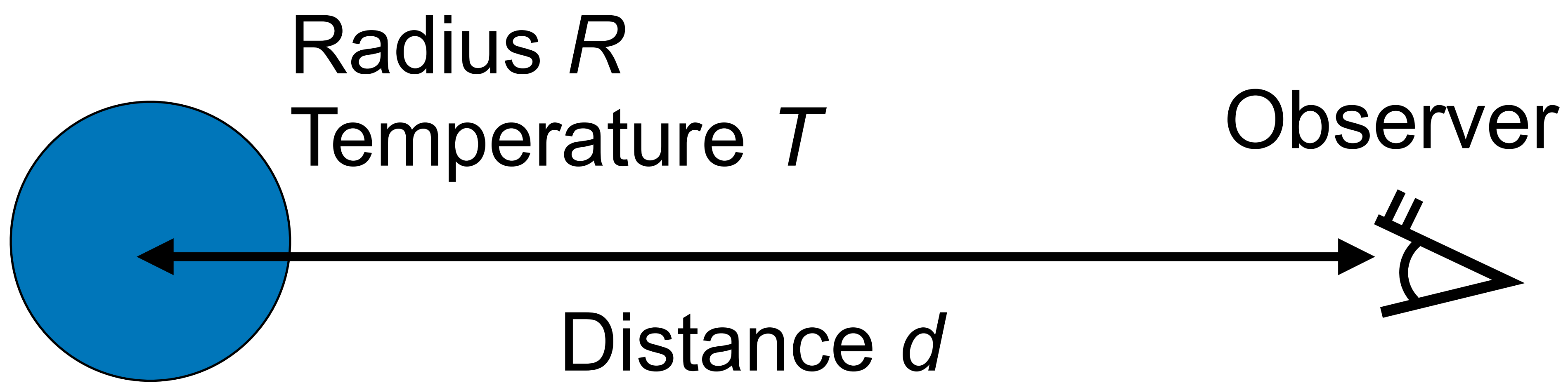
- Measurement using pulsation in radio, X-rays, gamma rays to measure the binary orbital motion
- Precise



$$G(M_1 + M_2) = a^3 \left(\frac{2\pi}{P}\right)^2$$

Radius

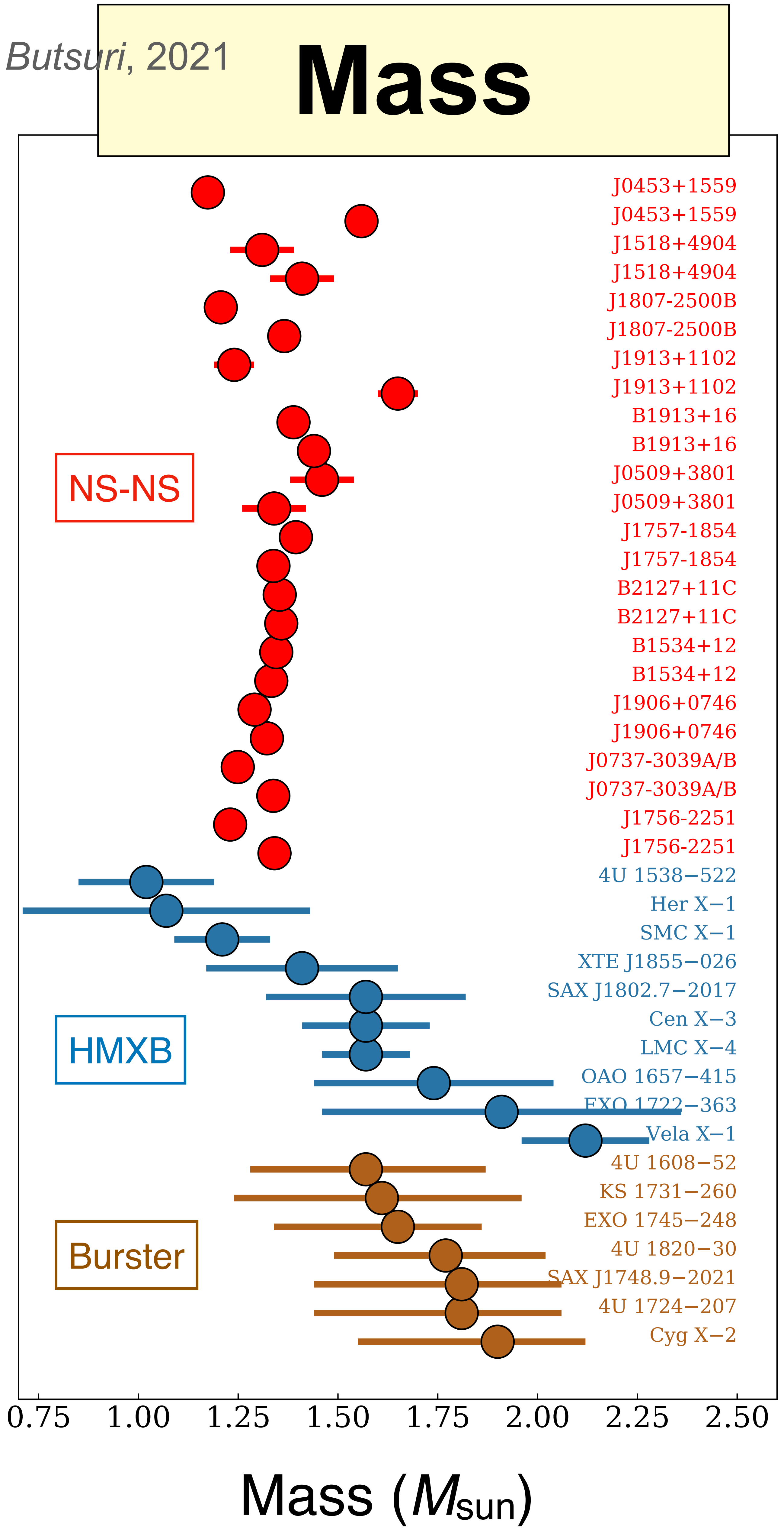
- Necessary to estimate the radius from the surface radiation in X-rays
- Large uncertainties, e.g., distance and atmospheric composition.

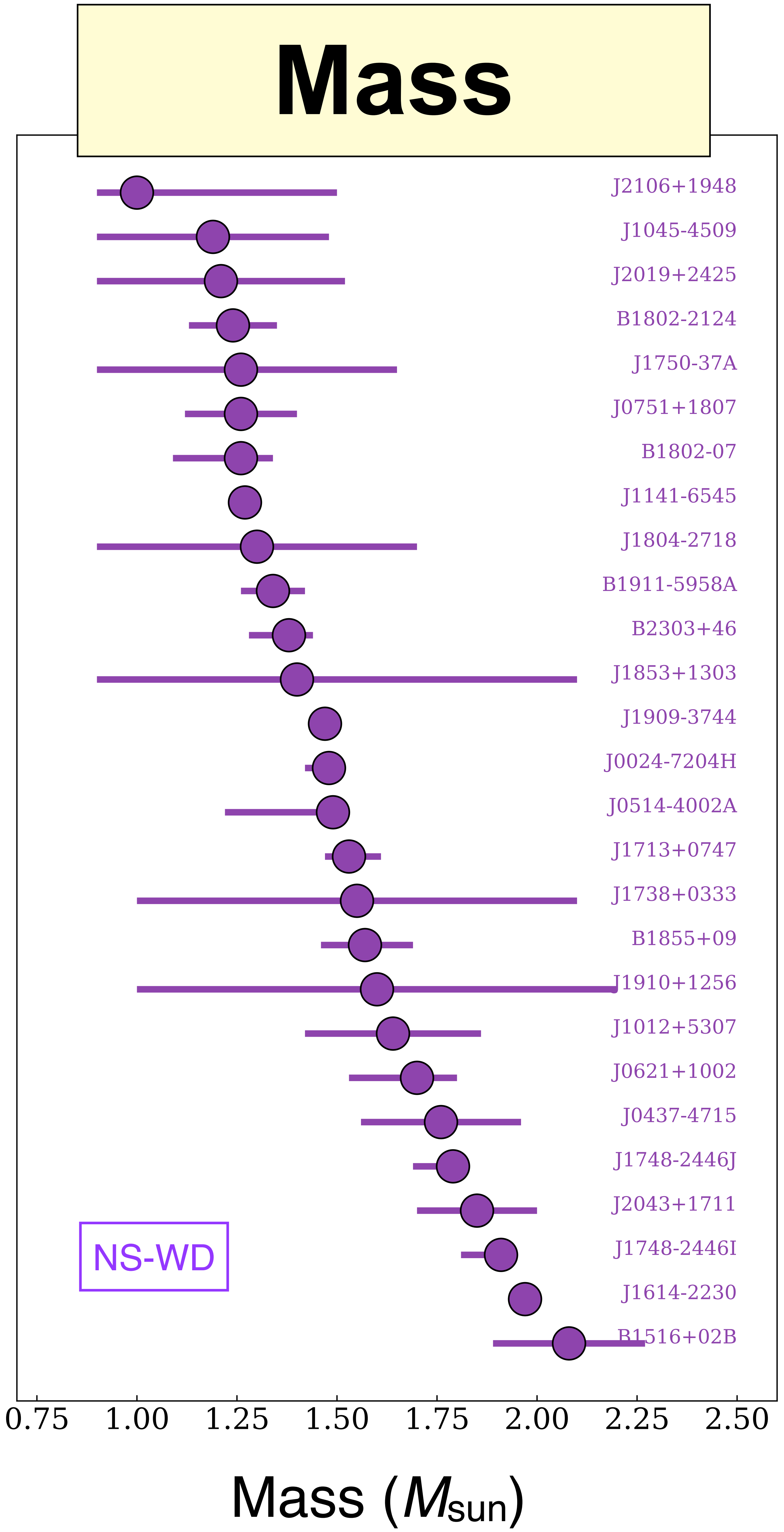


$$f = \frac{L}{4\pi d^2} = \frac{4\pi R^2 \sigma T^4}{4\pi d^2}$$

Astronomical measurements of mass and radius

Enoto, Yasutake, *Butsuri*, 2021


Mass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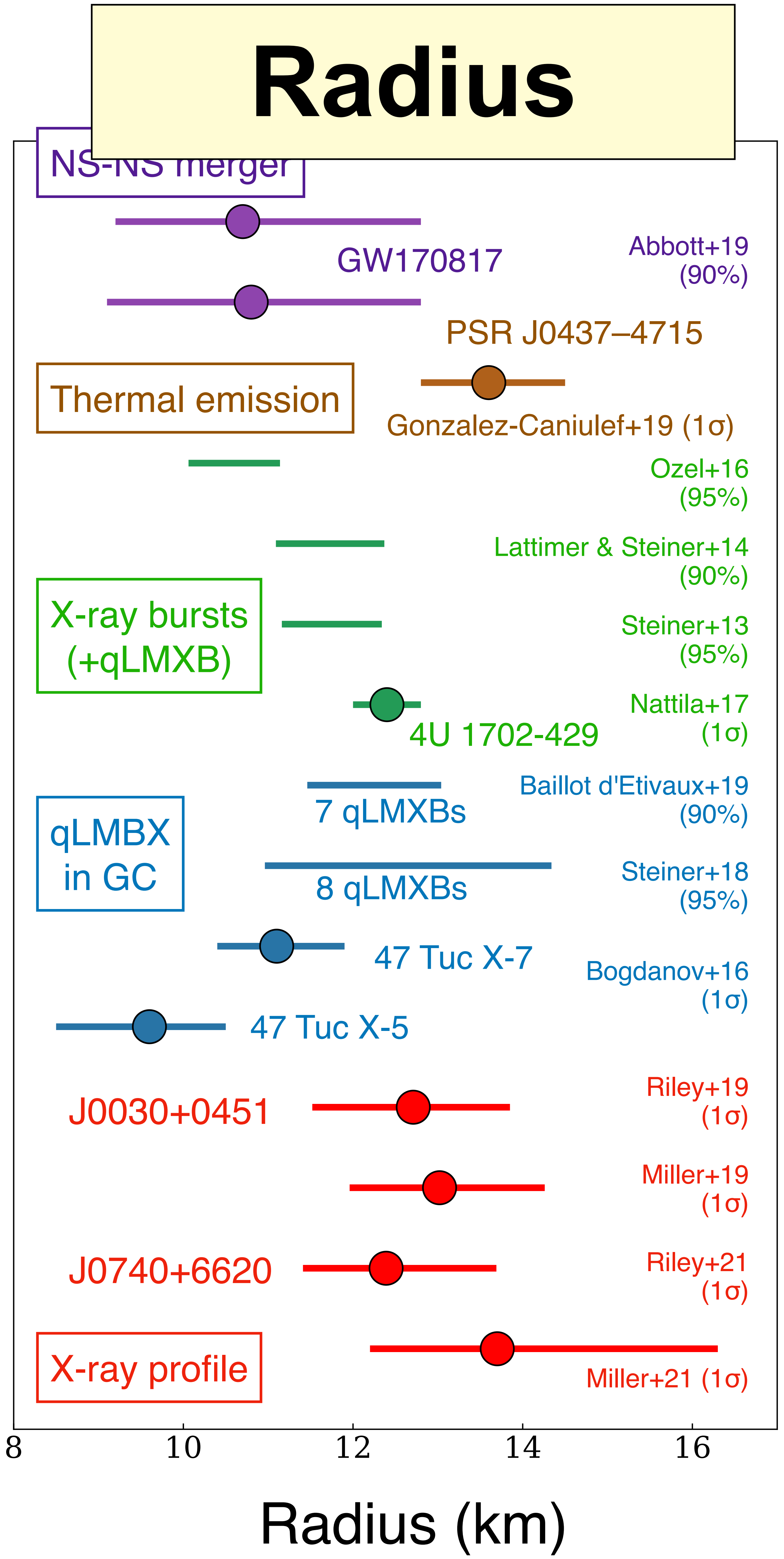
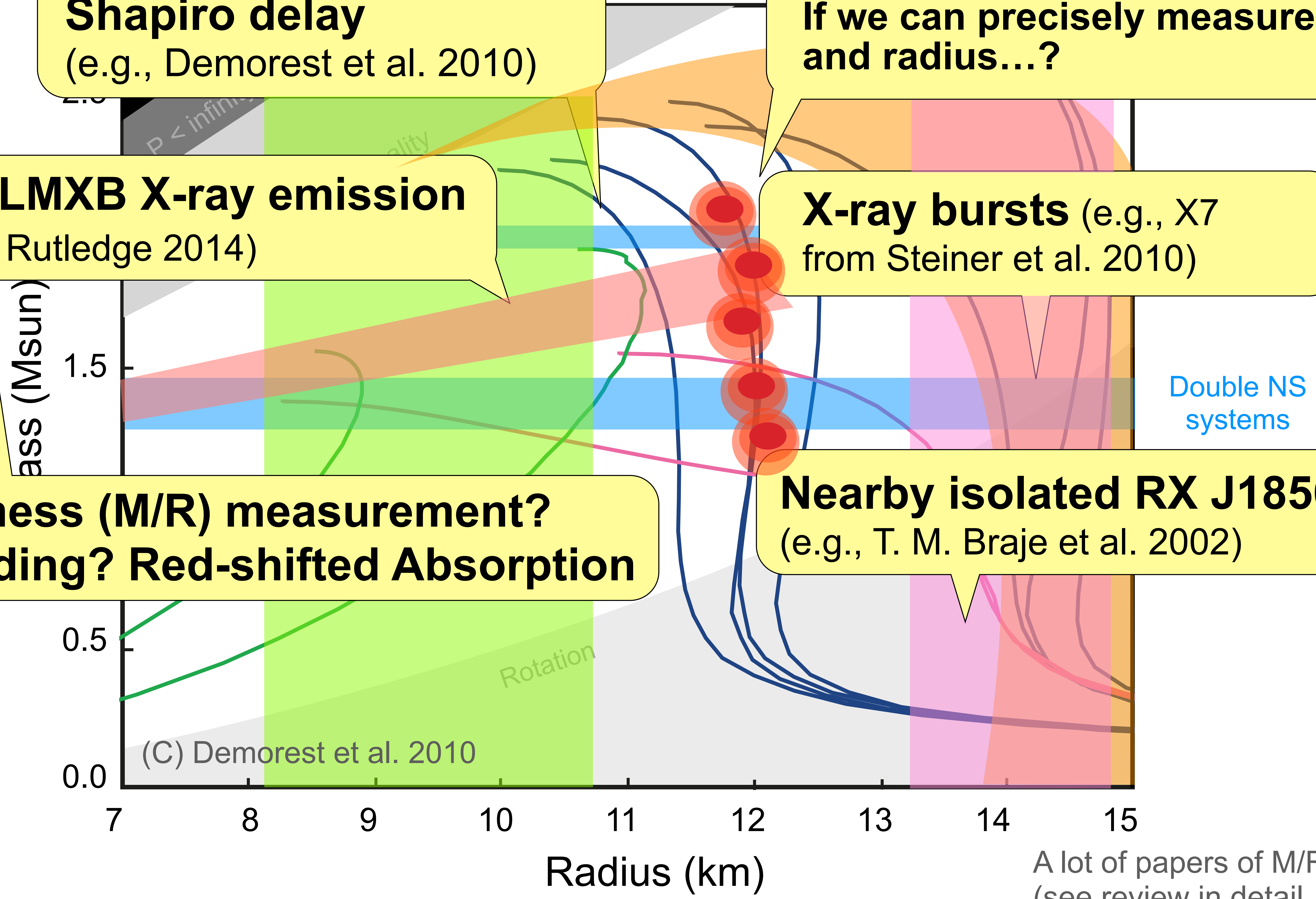

Radius

Astronomical measurements of mass and radius



Shapiro delay
(e.g., Demorest et al. 2010)

If we can precisely measure mass and radius…?

Quiescent LMXB X-ray emission
(e.g., Guillot & Rutledge 2014)

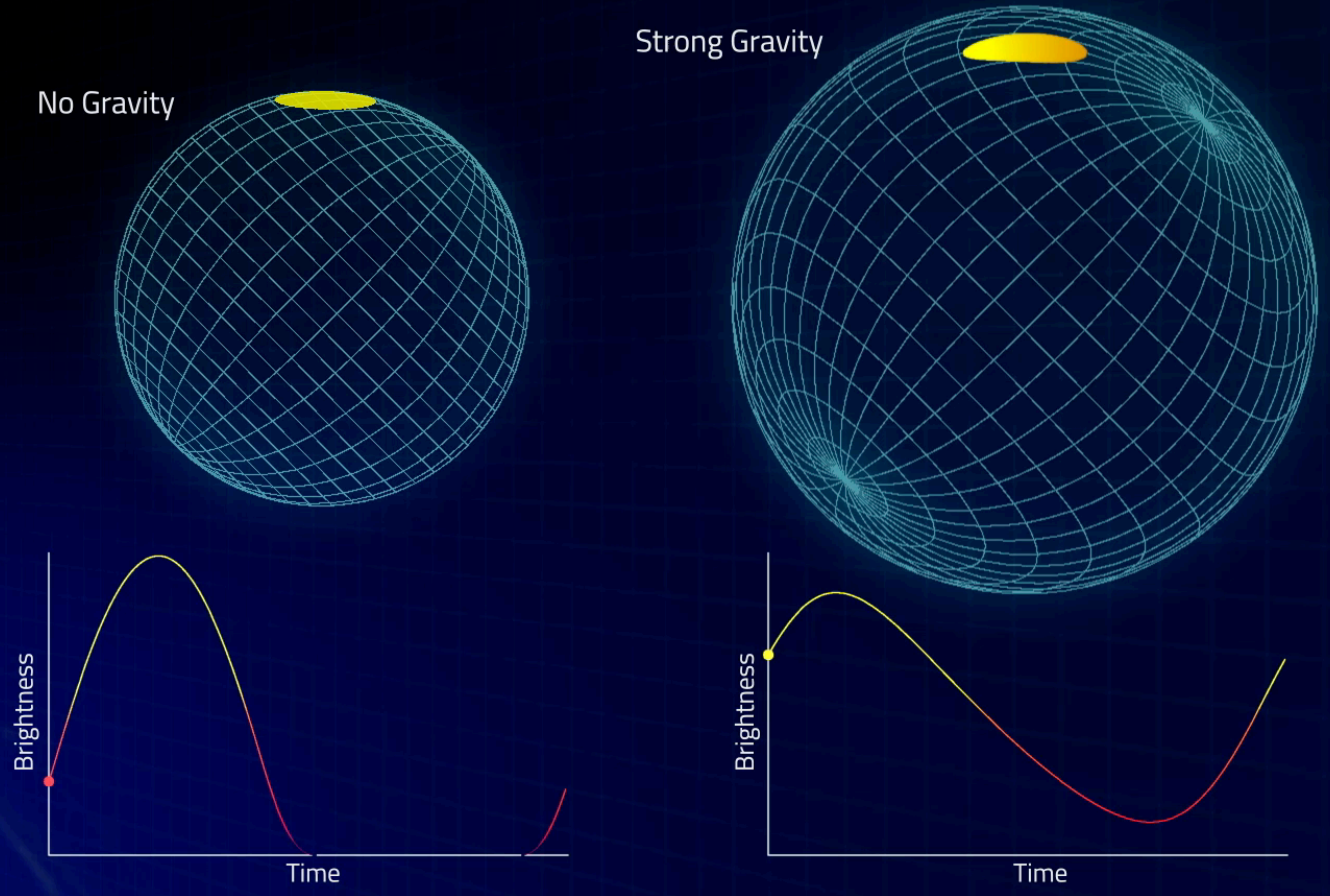
X-ray bursts (e.g., X7 from Steiner et al. 2010)

Compactness (M/R) measurement?
Light bending? Red-shifted Absorption

Nearby isolated RX J1856.5-3754
(e.g., T. M. Braje et al. 2002)

A lot of papers of M/R measurements
(see review in detail, Bhattacharyya 2010)

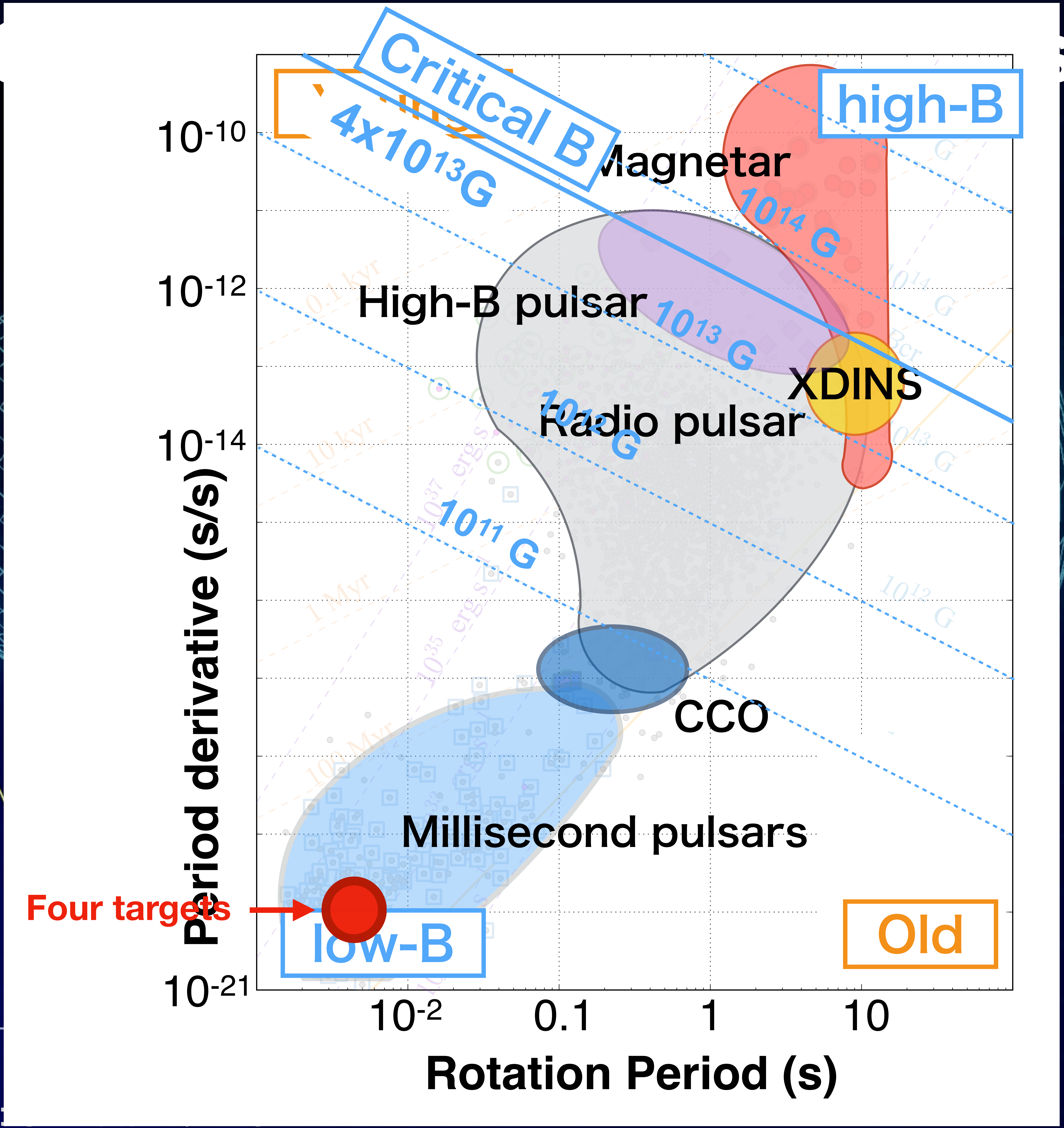
Light-bending for compactness measurements



Credit: S. Morsink/NASA

- X-ray pulse profile from a surface hot spot is affected by the gravitational light bending. Comparison between the observation and precise modeling gives the compactness (M/R)
- Target: Non-accretion stable millisecond pulsars with a high rotation speed and low magnetic field.

Light s measurements



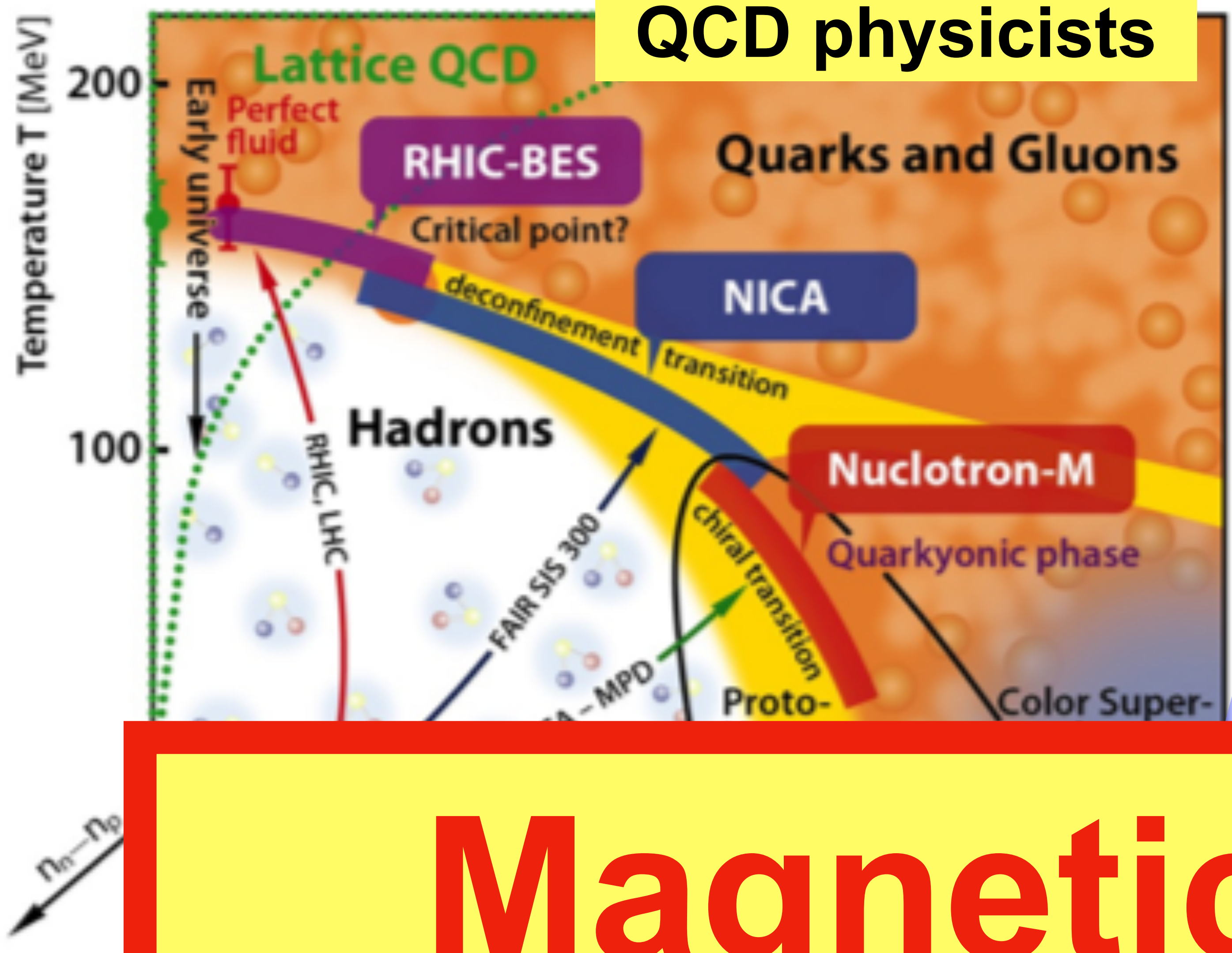
- X-ray pulse profile from a surface hot spot is affected by the gravitational light bending. Comparison between the observation and precise modeling gives the compactness (M/R)
- Target: Non-accretion stable millisecond pulsars with a high rotation speed and low magnetic field.

Credit

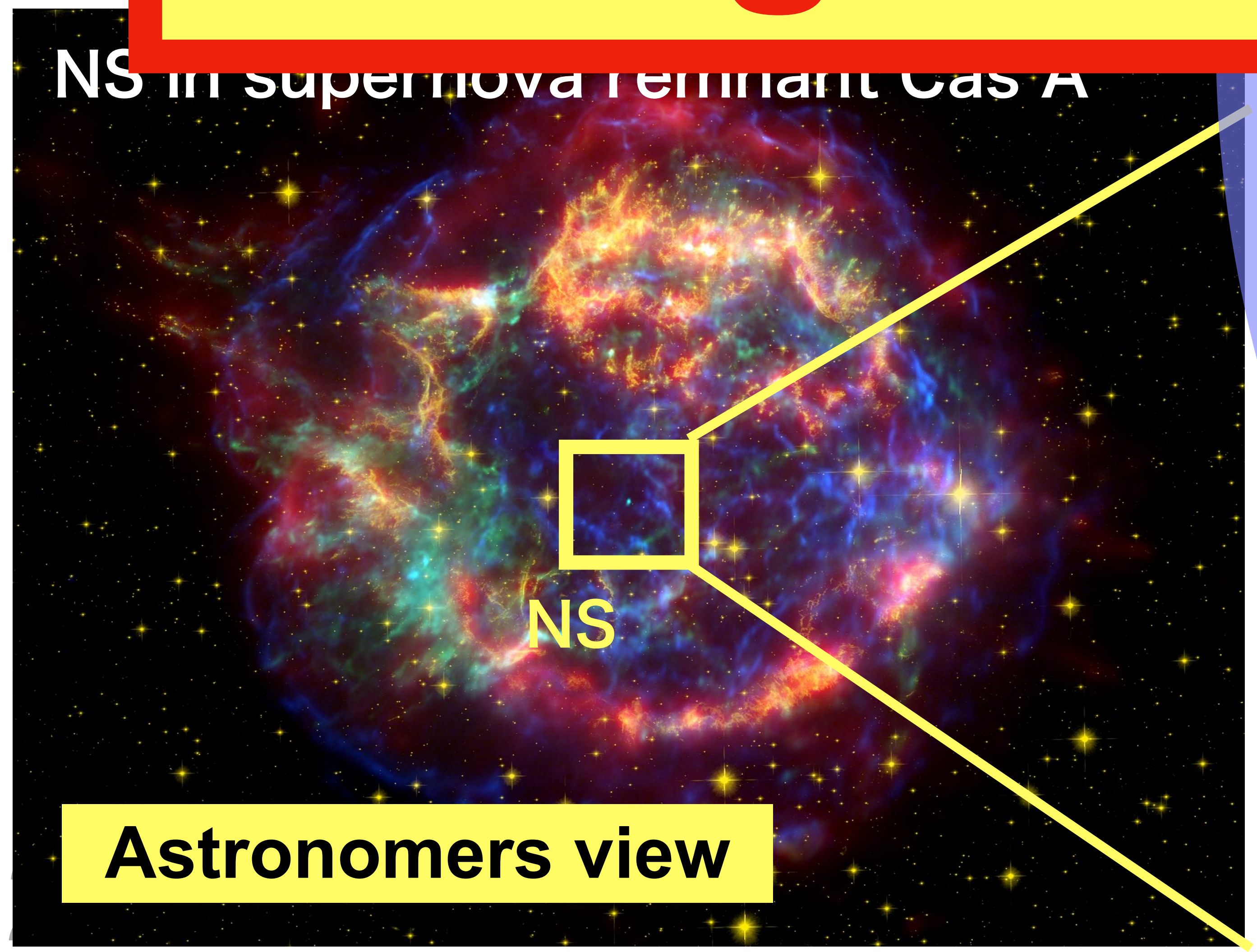
Observational quantities of neutron stars

- QCD physicists might want to know the mass, radius and interior of NSs…but

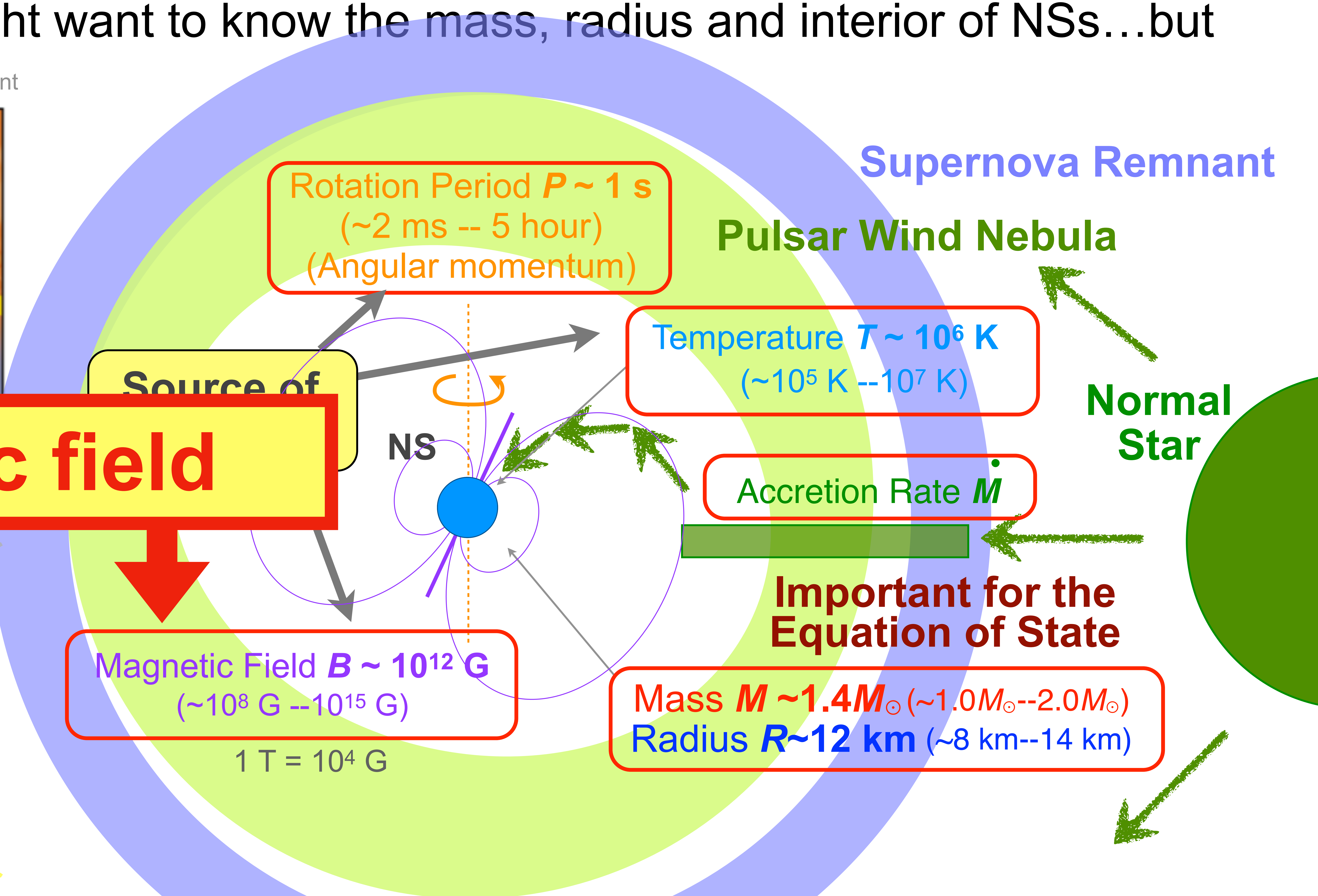
https://www.interactions.org/blog/our-experiment



Magnetic field



Astronomers view



Rotation Period $P \sim 1$ s
(~2 ms -- 5 hour)
(Angular momentum)

Temperature $T \sim 10^6$ K
($\sim 10^5$ K --10^7 K)

Accretion Rate $\dot{M}$

Important for the Equation of State

Magnetic Field $B \sim 10^{12}$ G
($\sim 10^8$ G --10^{15} G)

1 T = 10^4 G

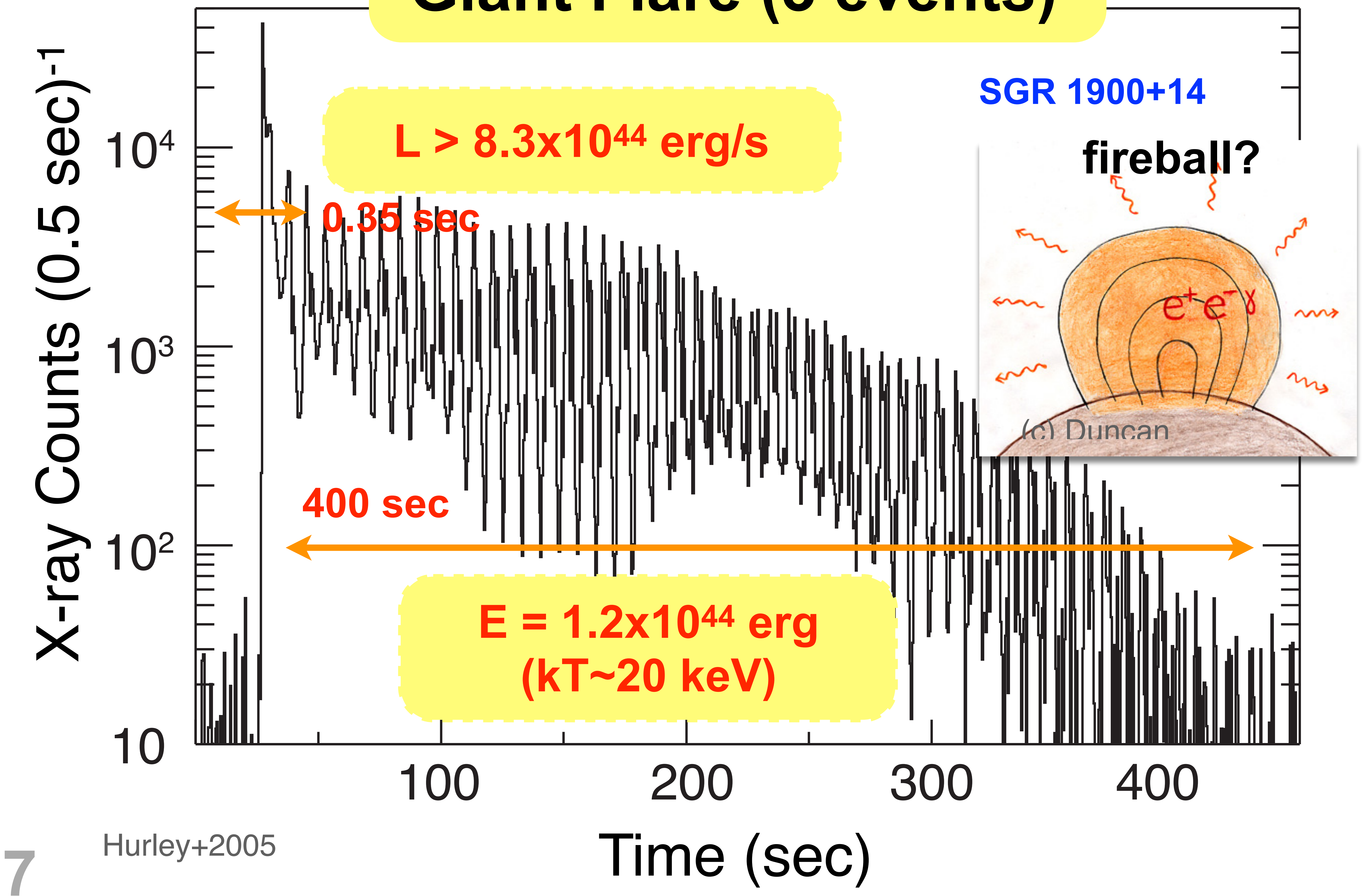
Mass $M \sim 1.4 M_\odot$ ($\sim 1.0 M_\odot$--$2.0 M_\odot$)
Radius $R \sim 12$ km (~8 km--14 km)

Magnetar: Soft Gamma Repeater (SGR)

Discovered by “Giant Flares” or recurrent burst activities. ~ 5 SGRs

- Exceeding the Eddington Luminosity (~10^{38} erg/s) by ~6 orders of magnitudes
- B > 10^{14} G is required to confine a few dozen keV plasma for ~400 sec

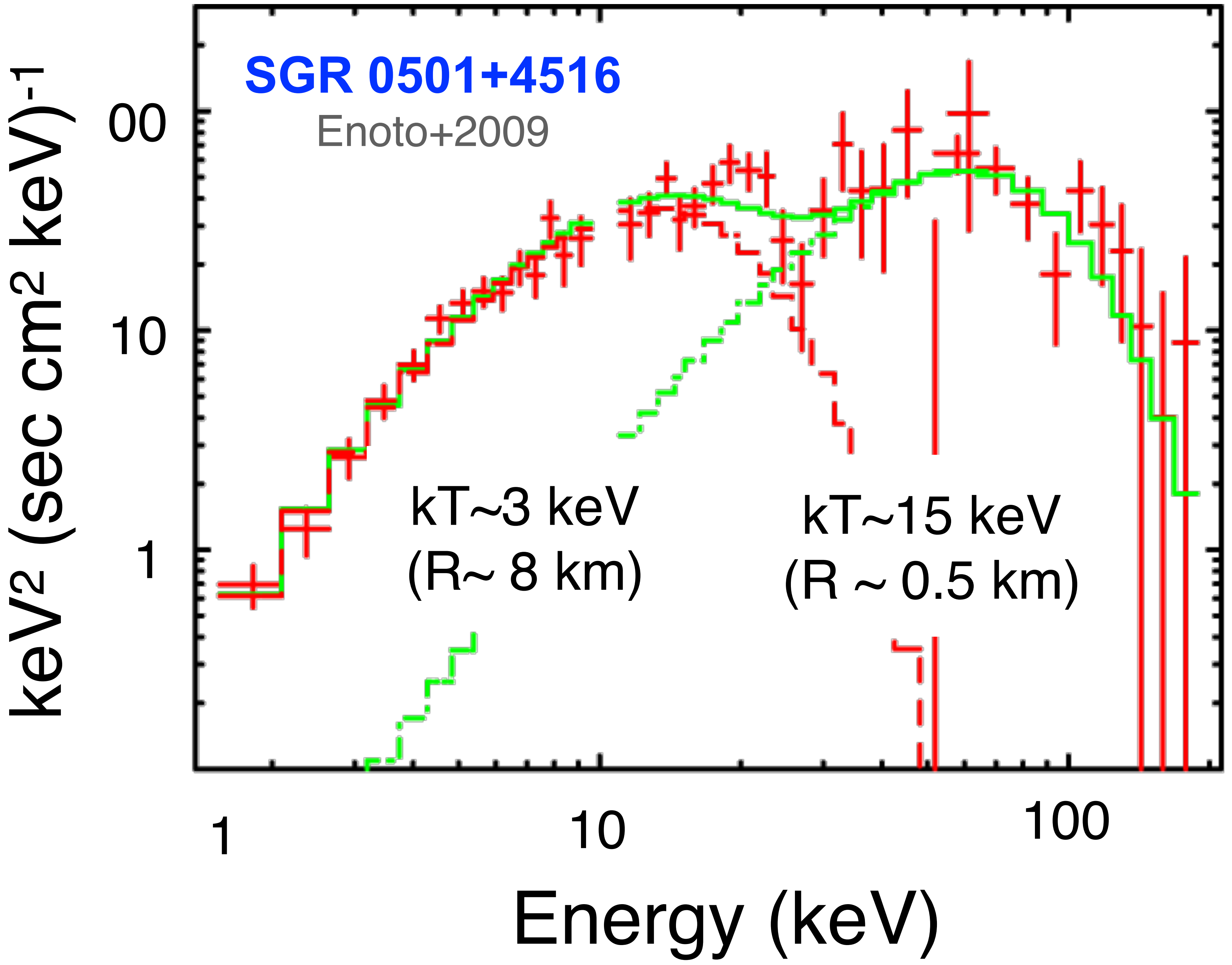
Giant Flare (3 events)



Hurley+2005

Short Bursts

a few hundred millisecond
empirically two Blackbody



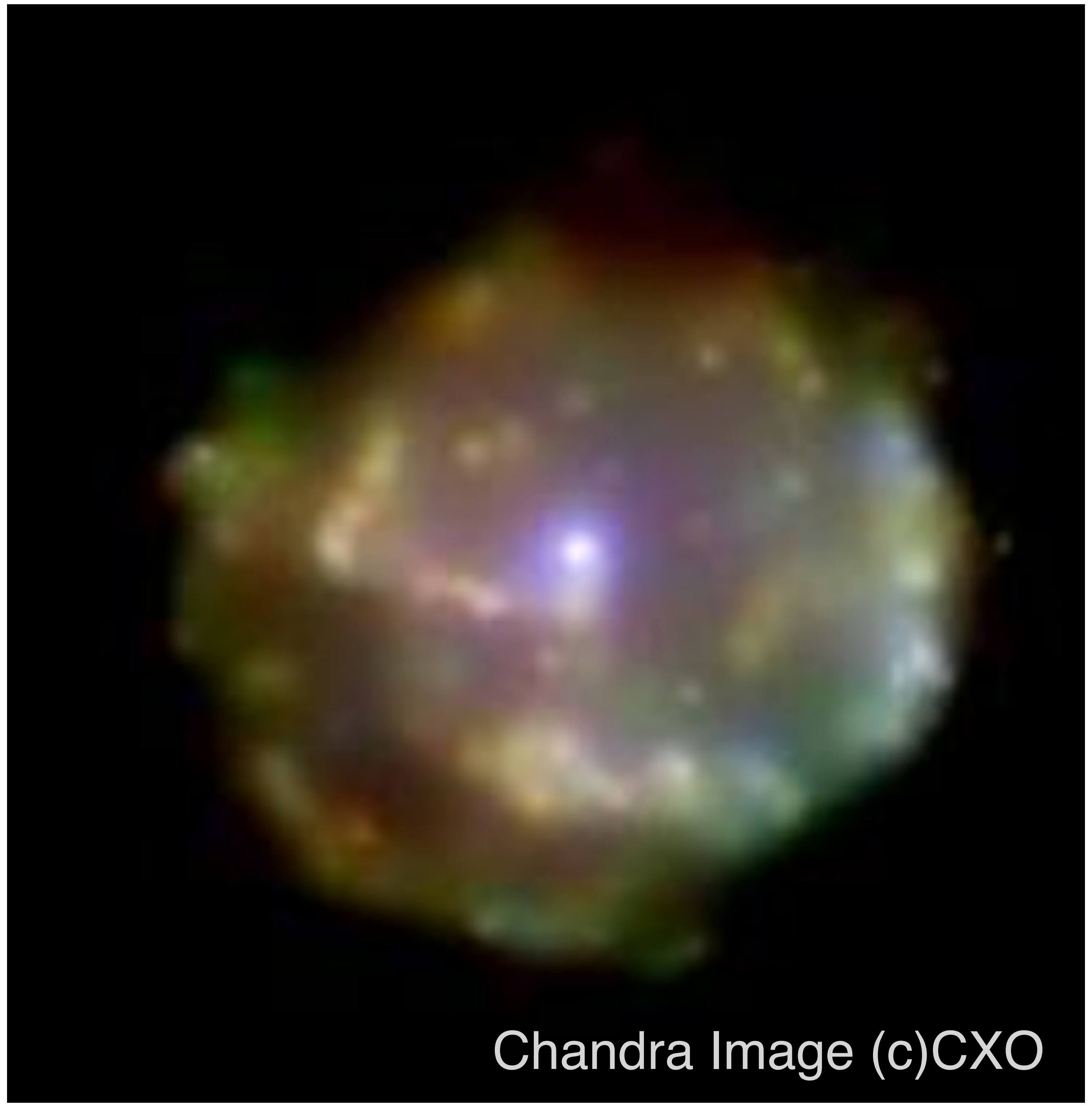
Magnetar: Anomalous X-ray Pulsar (AXP)

Discovered as pulsed bright persistent X-ray sources. ~15 AXPs

- Exceeding the spin-down luminosity by ~2 orders of magnitudes ($L_x >> L_{sd}$)

Associated with SNR

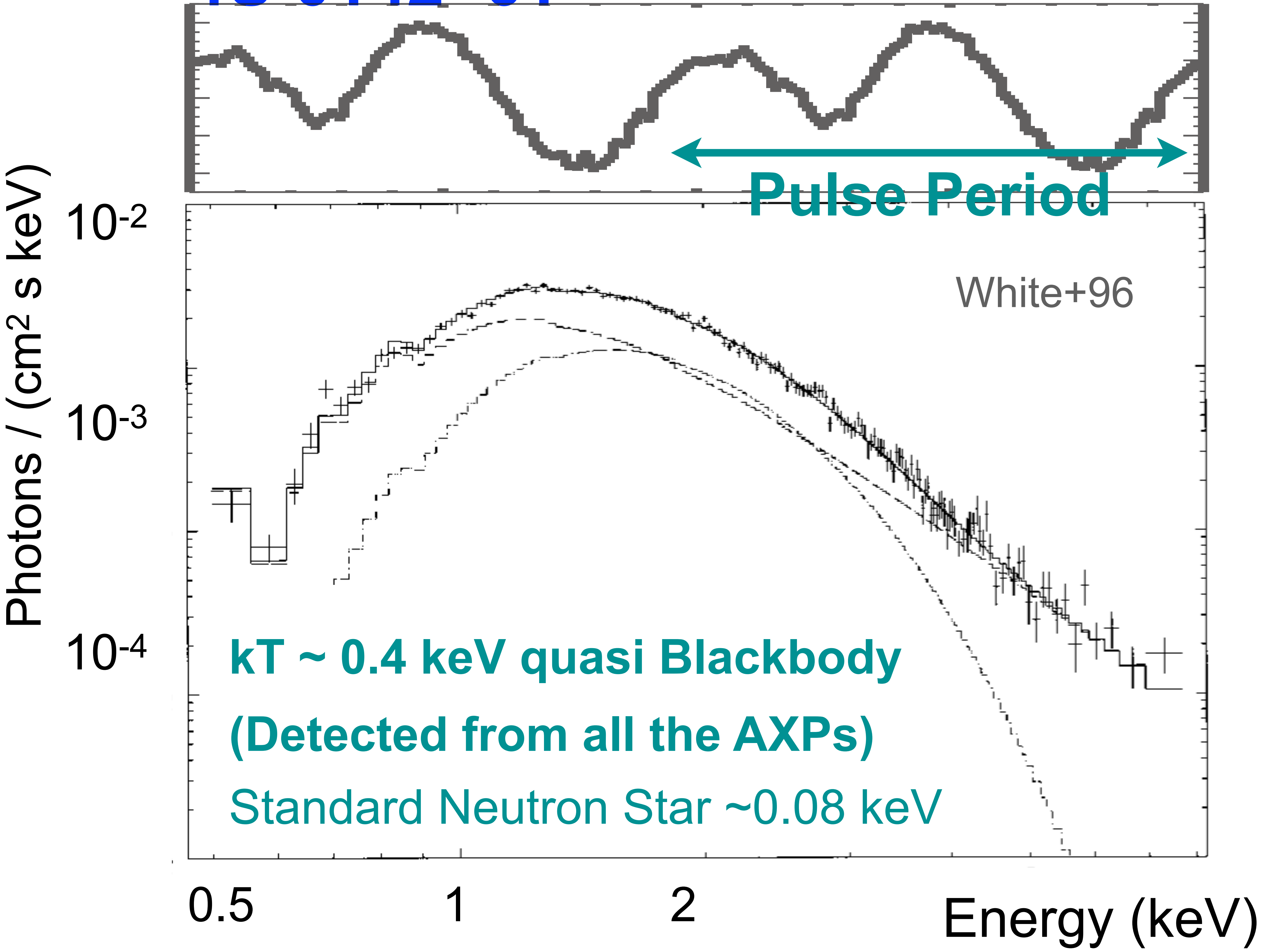
1E 1841-045 (SNR Kes73)



Chandra Image (c)CXO

Persistent X-ray Emission

4U 0142+61



kT ~ 0.4 keV quasi Blackbody

(Detected from all the AXPs)

Standard Neutron Star ~0.08 keV

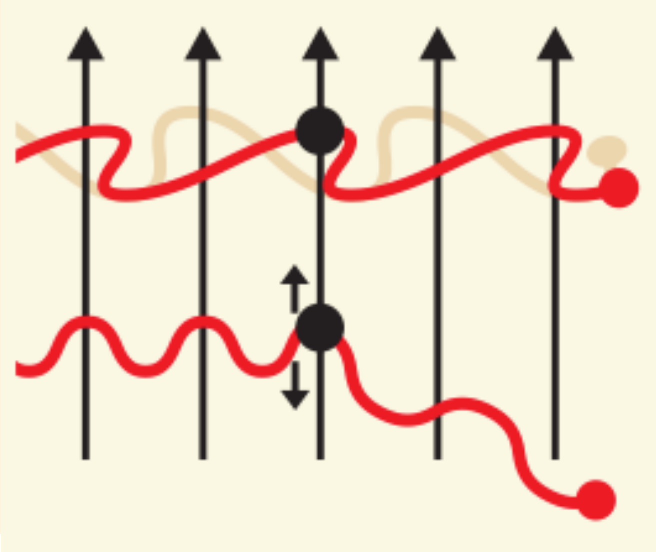
Magnetar hypothesis to the establishing model

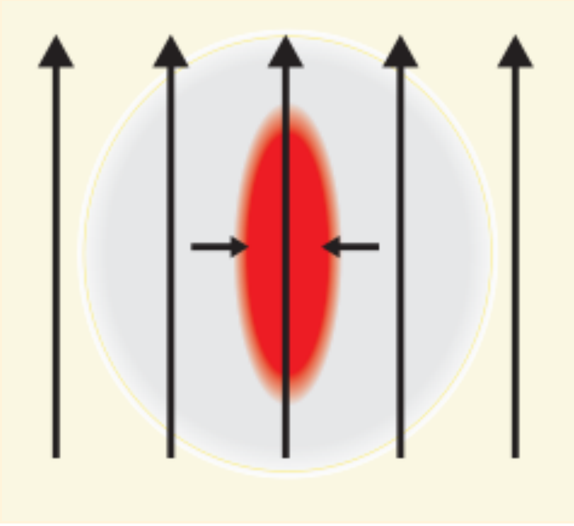
"SGRs and AXP are ultra-strongly magnetized NSs with B~$10^{14\text{-}15}$ G powered by their stored magnetic energy in the stellar interior." Thompson & Duncan+95, 96

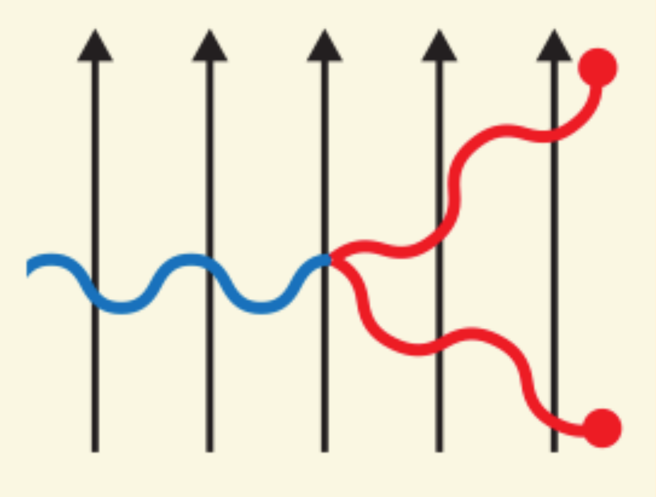
1. SNR association, slow P and large Pdot ⇒ Young (τ<100 kyr) & B~$10^{14\text{-}15}$ G
2. Lx >> Lsd by 2-3 orders of mag. ⇒ Not rotation-powered pulsars
3. No evidence of binary system ⇒ Not accretion-powered pulsars
4. Marginal "proton" cyclotron resonance ⇒ Suggests B > 10^{14} G
5. Peculiar burst activities ⇒ Magnetic dissipation (e.g., reconnections)??
6. Super-Eddington giant flares ⇒ B > 10^{14} G & suppression of σ

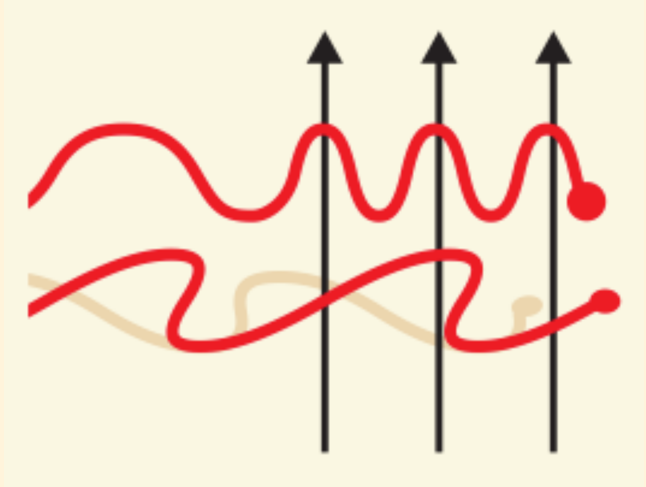
QED Critical Field

$$\hbar\frac{eB}{m_e c} = m_e c^2 \Rightarrow B_{QED} = 4.4 \times 10^{13}\ \mathrm{G}$$


Suppression of σ

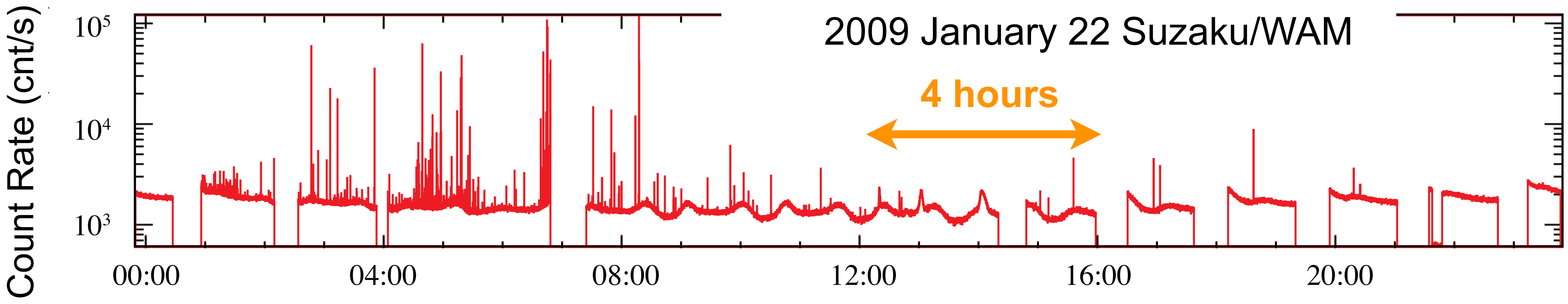

Distortion of atom


Photon Splitting

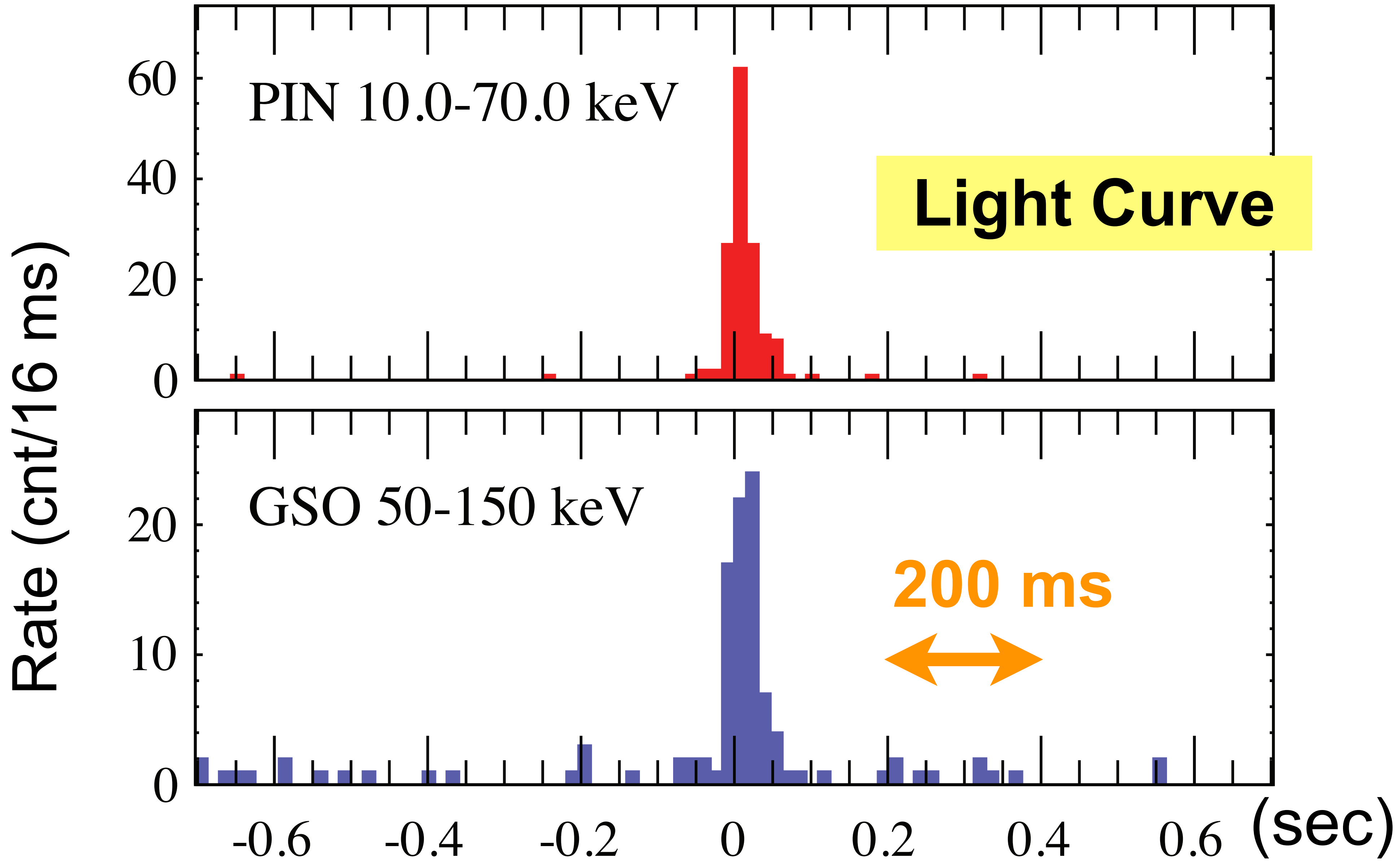

Birefringence

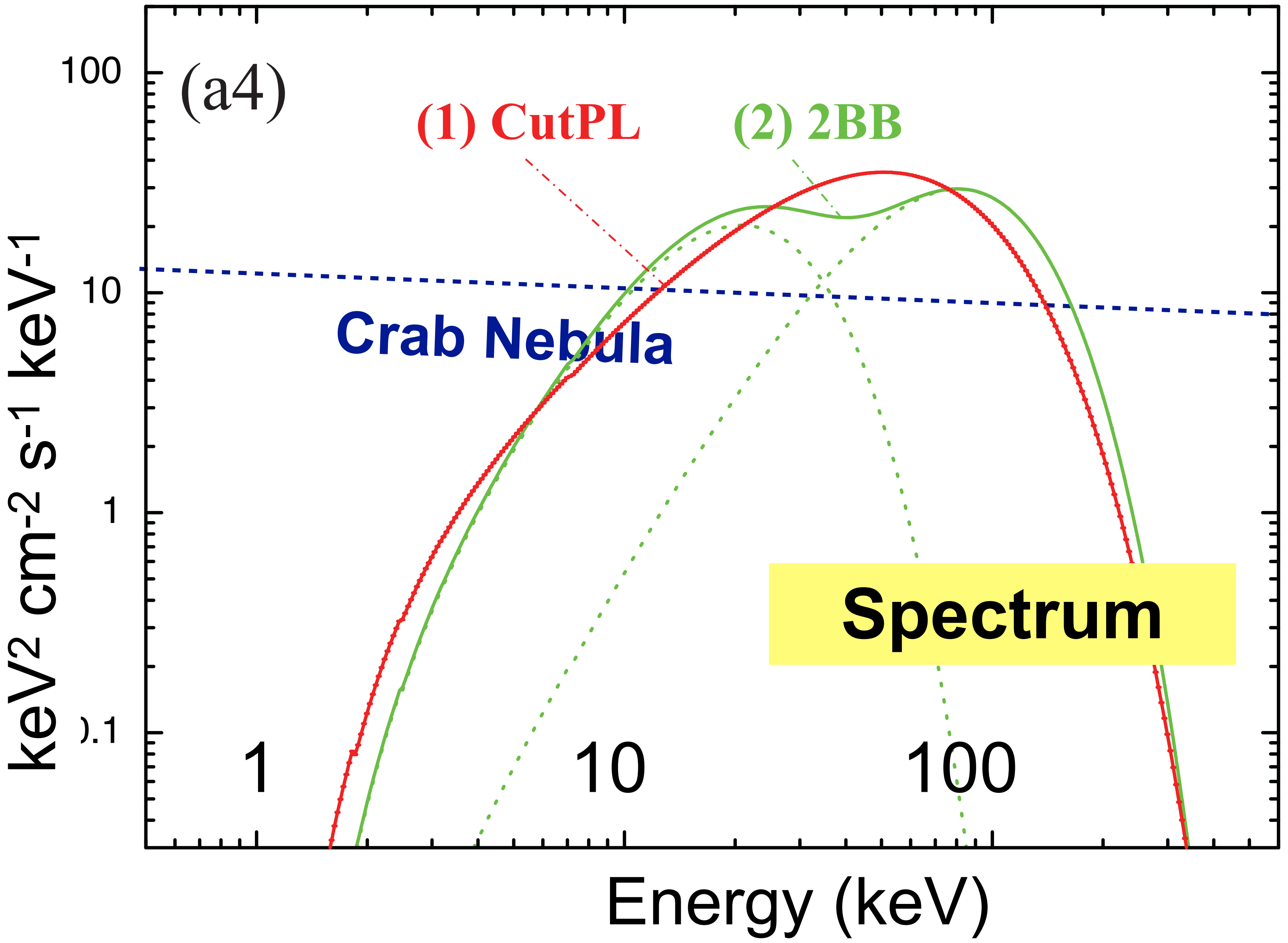
Magnetar outburst (example 1E 1547.0-5408)

Known as a fast rotation faint AXP (P~2 sec)



Enoto+10 PASJ;
Enoto+12 MNRAS



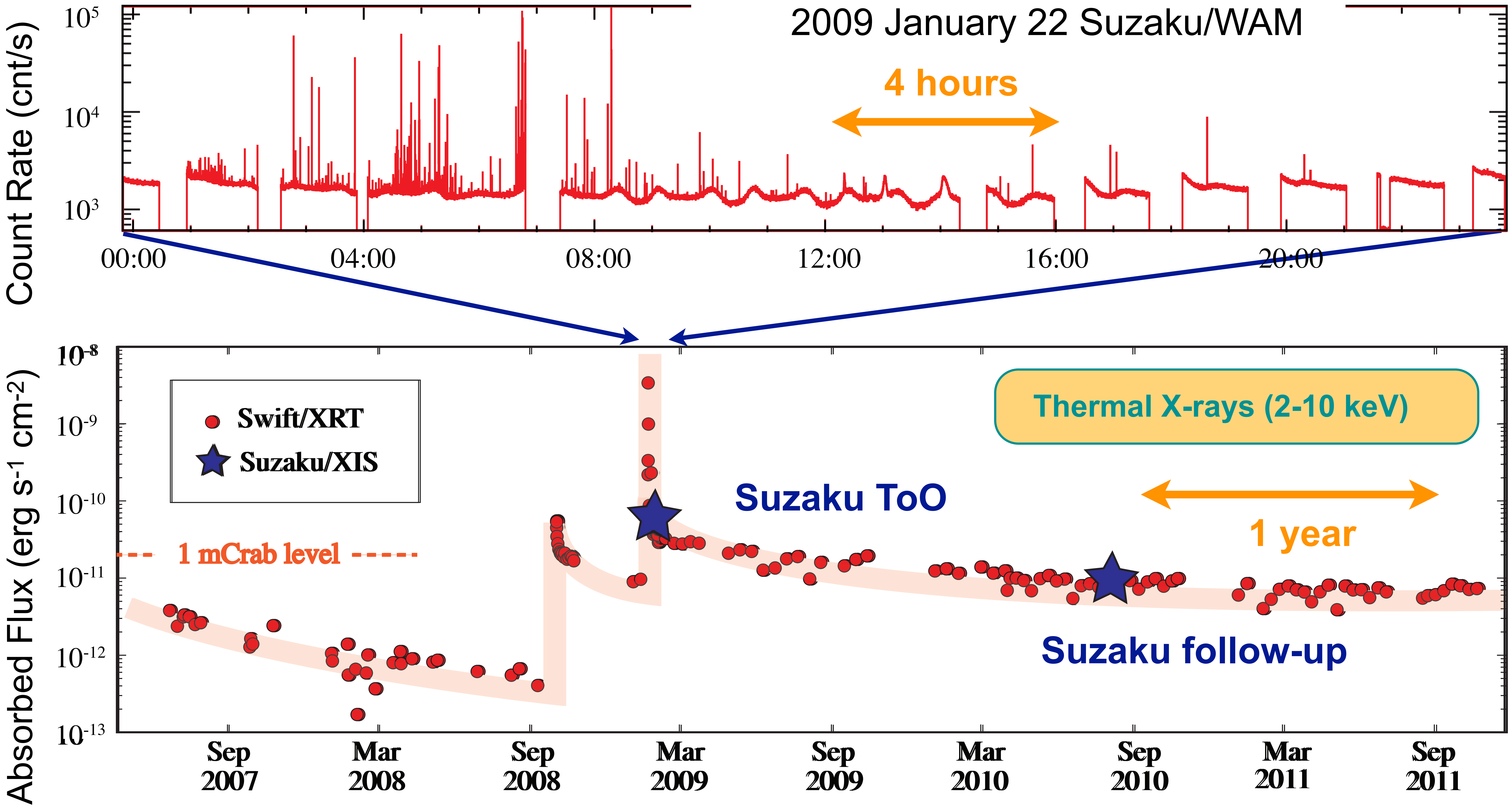


Feature1: Recurrent Bright “Short Burst”

Duration ~100-500 ms, (Empirically) Two blackbody spectrum (kT ~ 4, 11 keV)

Magnetar outburst (example 1E 1547.0-5408)

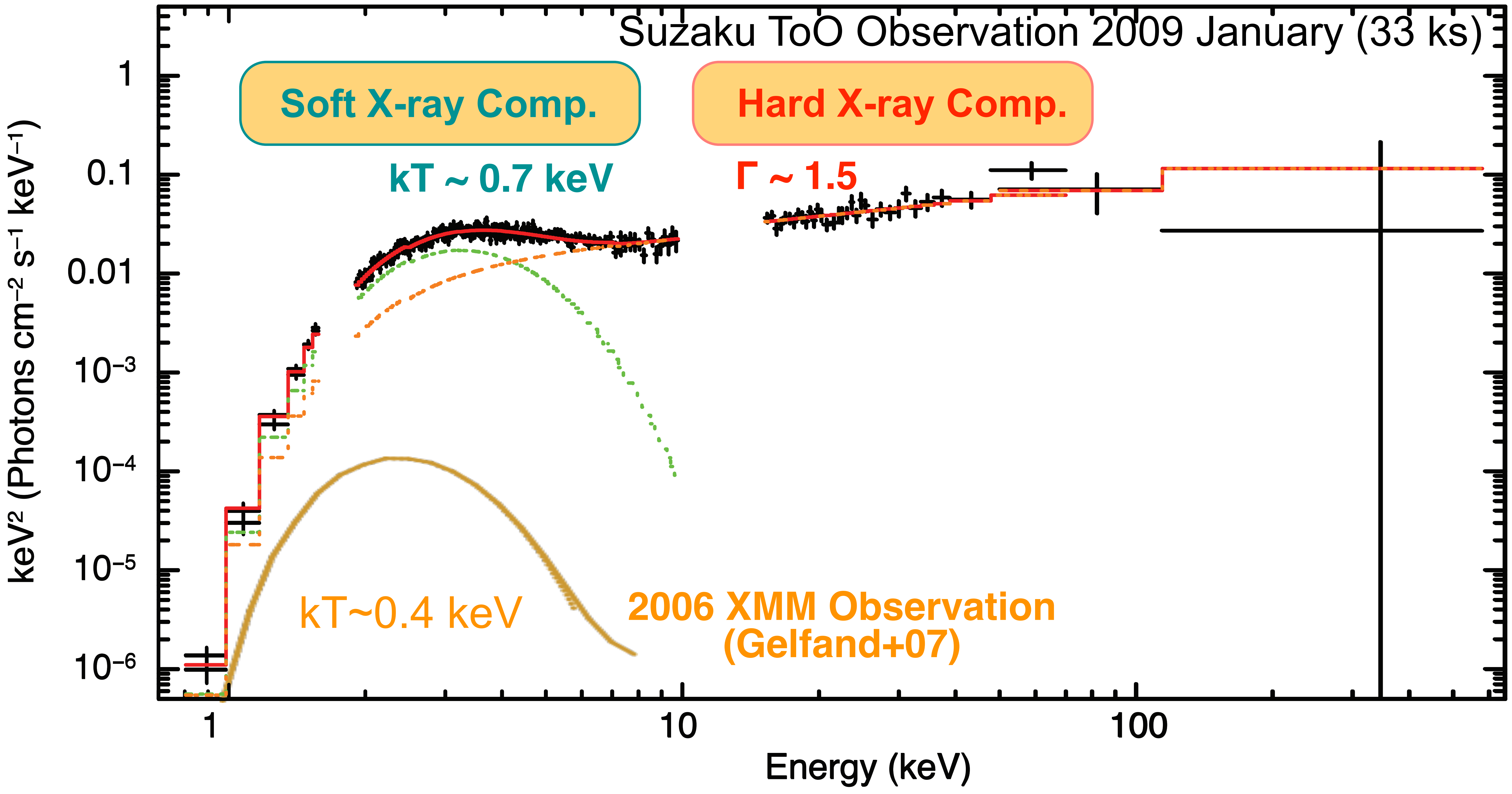
Known as a fast rotation faint AXP (P~2 sec)



Enoto+10 PASJ;
Enoto+12 MNRAS

Feature2: **Persistent X-ray becomes brighter by 2-3 orders of magnitude. (“Outburst”)**

Magnetar outburst (example 1E 1547.0-5408)



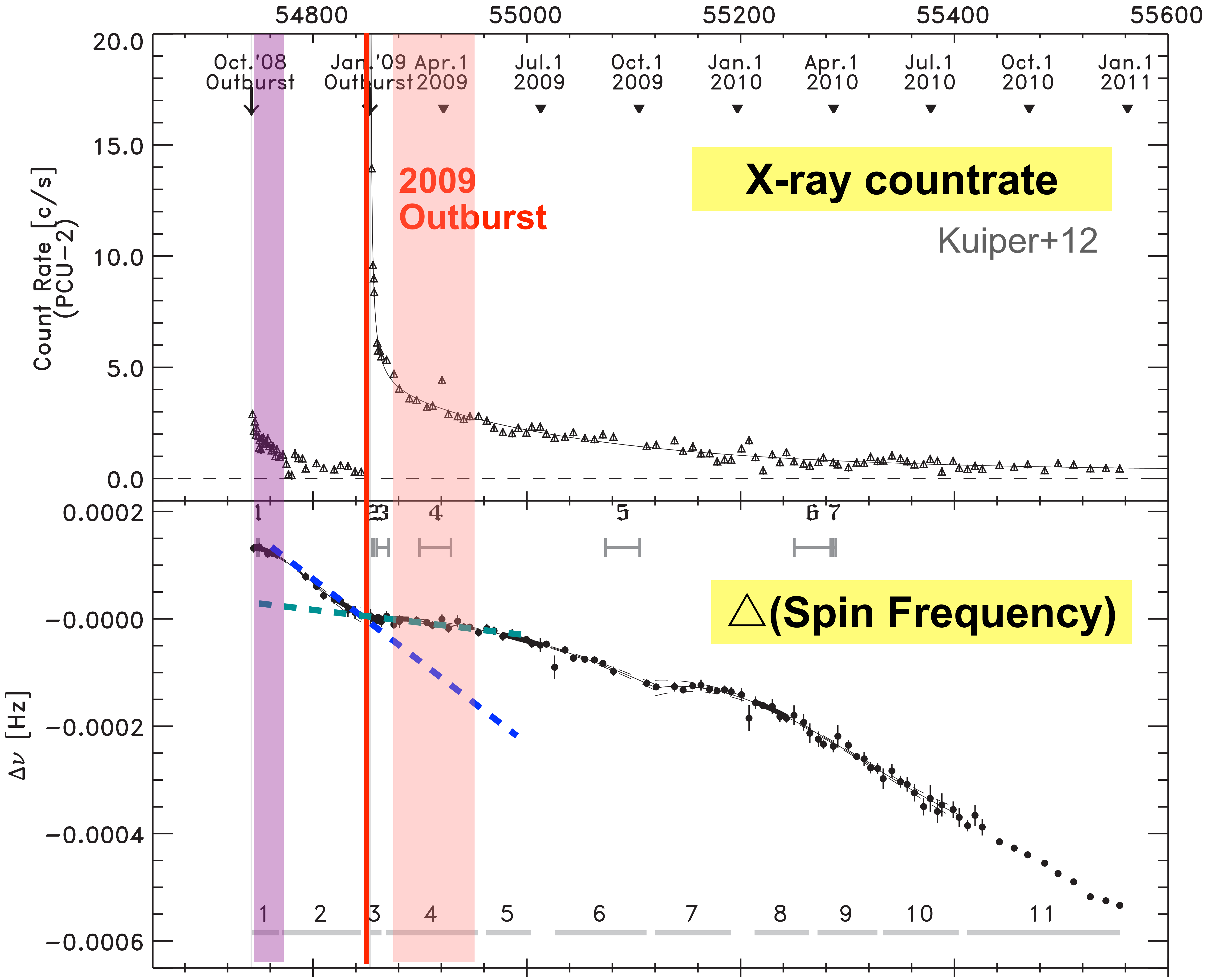
Enoto+10 PASJ;
Enoto+12 MNRAS

New hard X-ray components have been discovered from persistently bright famous magnetars (Kuiper et al., 2006) and some transients (Enoto et al., 2010).

Feature3: Two spectral components: distinctive soft and hard X-rays

Both becomes brighter during the outburst

Magnetar outburst (example 1E 1547.0-5408)

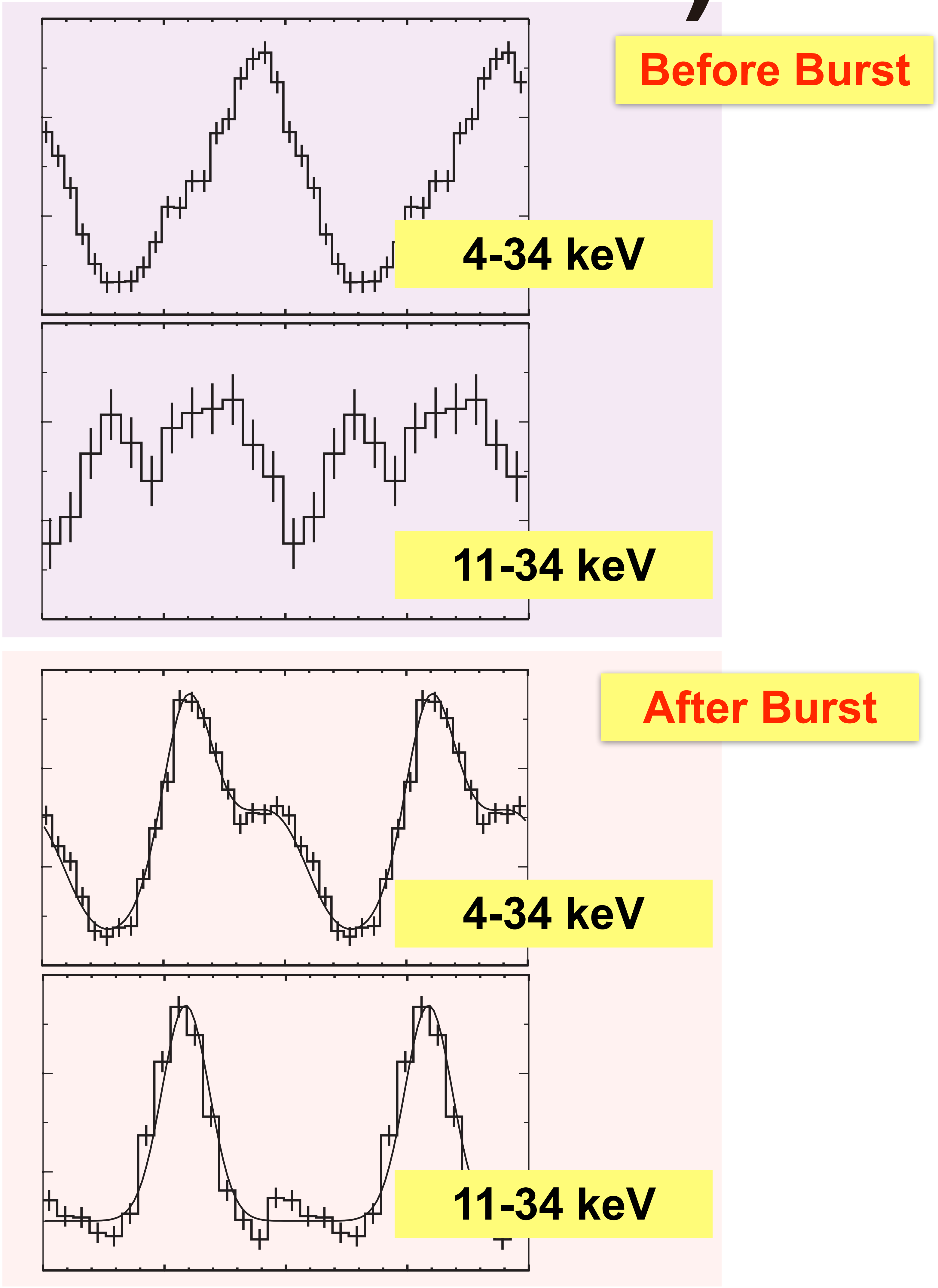


2009 Outburst

X-ray countrate

Kuiper+12

△(Spin Frequency)



Before Burst

4-34 keV

11-34 keV

After Burst

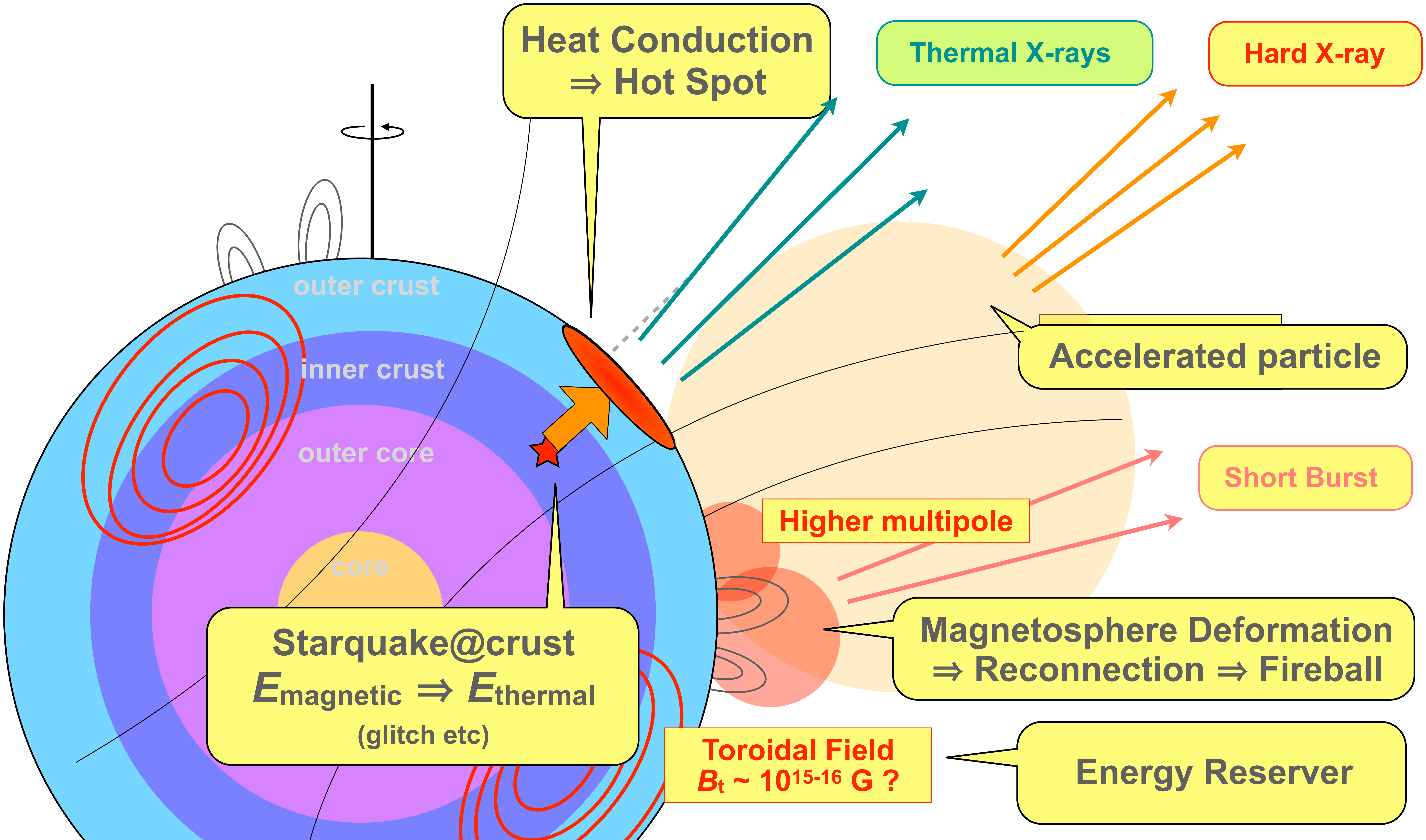
4-34 keV

11-34 keV

A frequency derivative jump at the outburst ($\triangle\dot{\nu}/\nu = -0.69 \pm 0.07$)

Pulse profile change around the onset of the burst ⇒ Hot spot?

Magnetar energy release and emission



Heat Conduction
⇒ Hot Spot

Thermal X-rays

Hard X-ray

Accelerated particle

Short Burst

Higher multipole

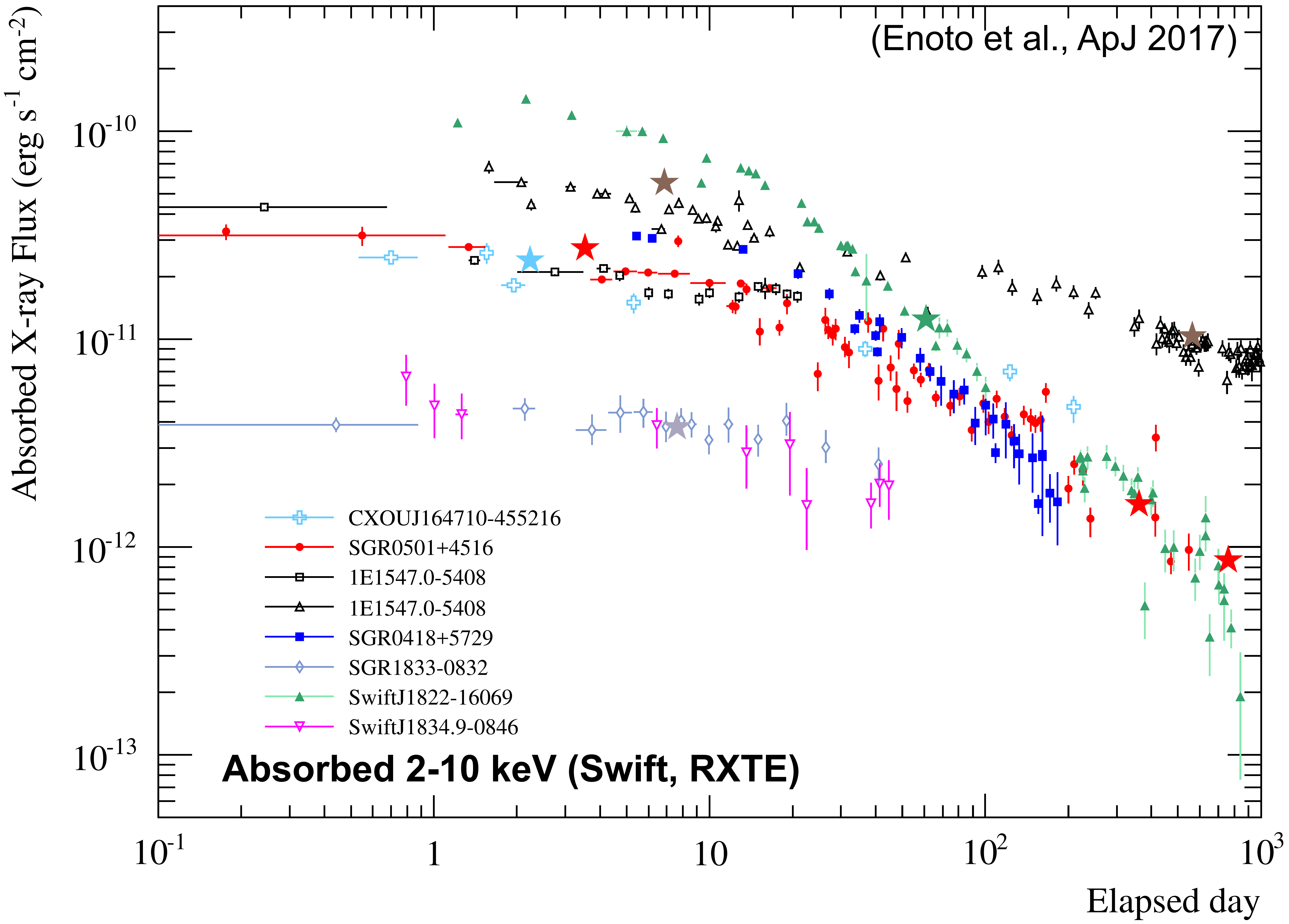
Starquake@crust
$E_{\text{magnetic}} \Rightarrow E_{\text{thermal}}$
(glitch etc)

Magnetosphere Deformation
⇒ Reconnection ⇒ Fireball

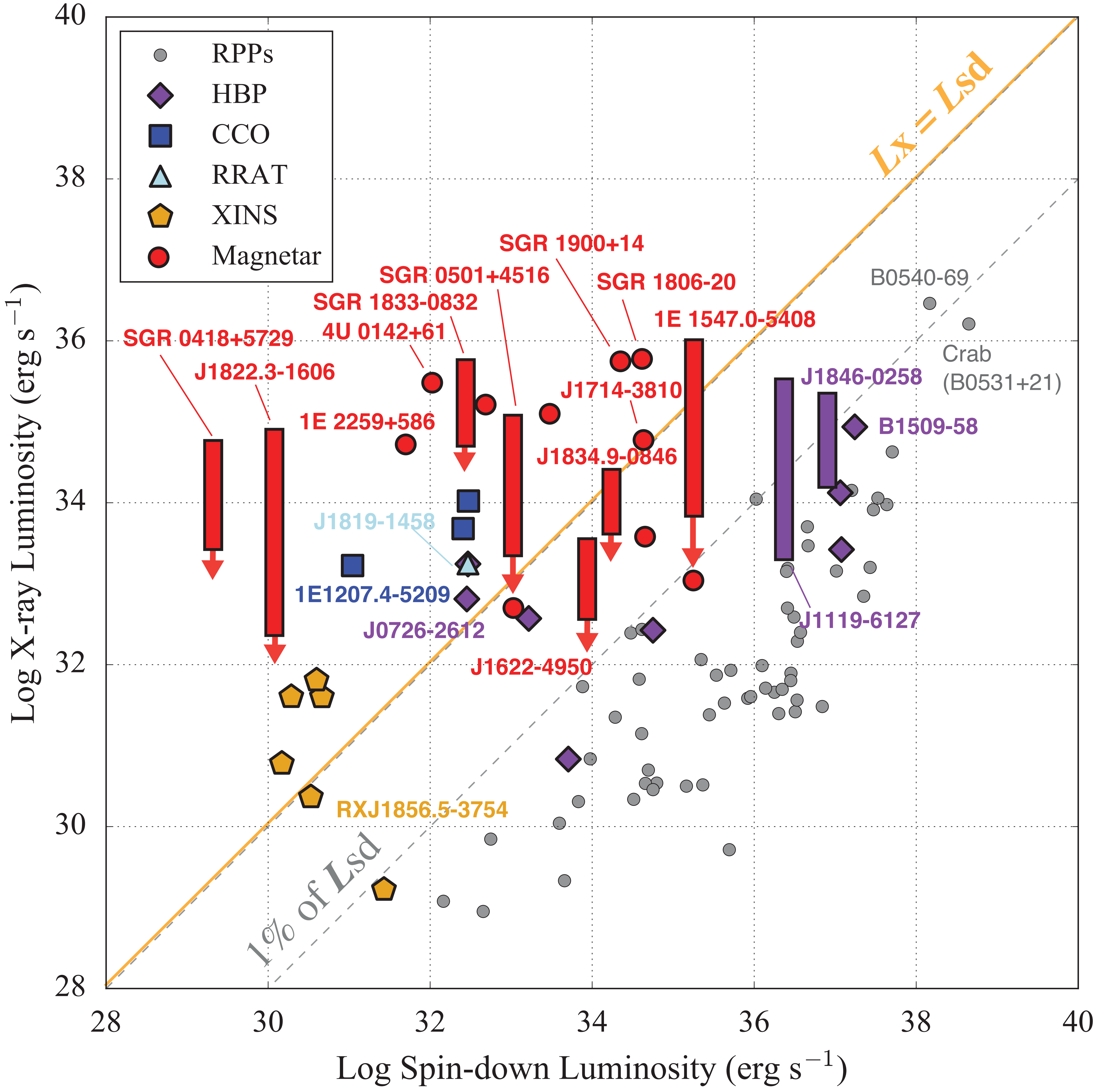
Toroidal Field
$B_t \sim 10^{15\text{-}16}$ G ?

Energy Reserver

X-ray flux decay of outbursts of transient magnetars



Spin-down luminosity L_{sd} vs. X-ray luminosity L_x



- Spin-down luminosity

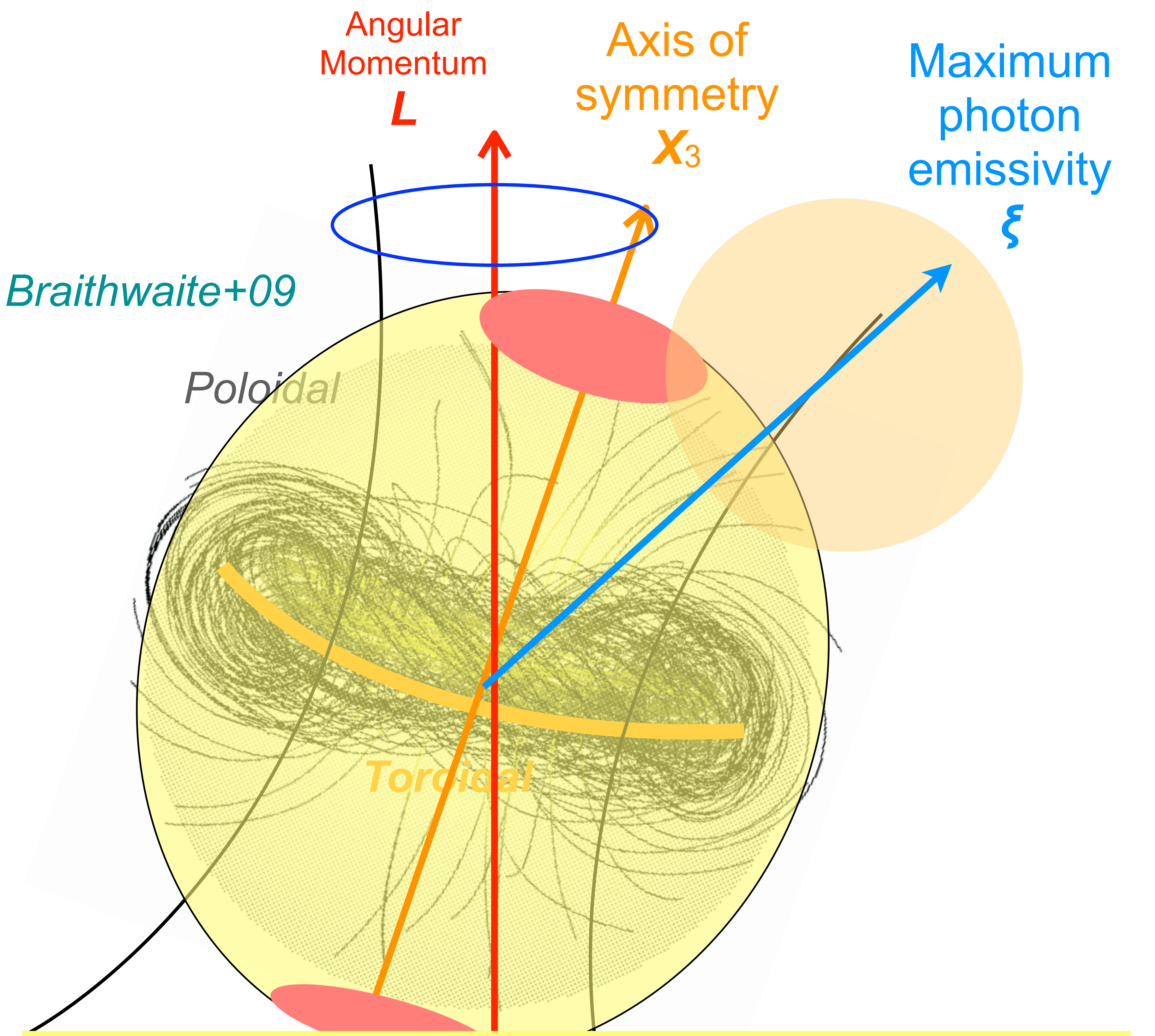
$$L_{\rm sd} \propto \dot{P}/P^3$$

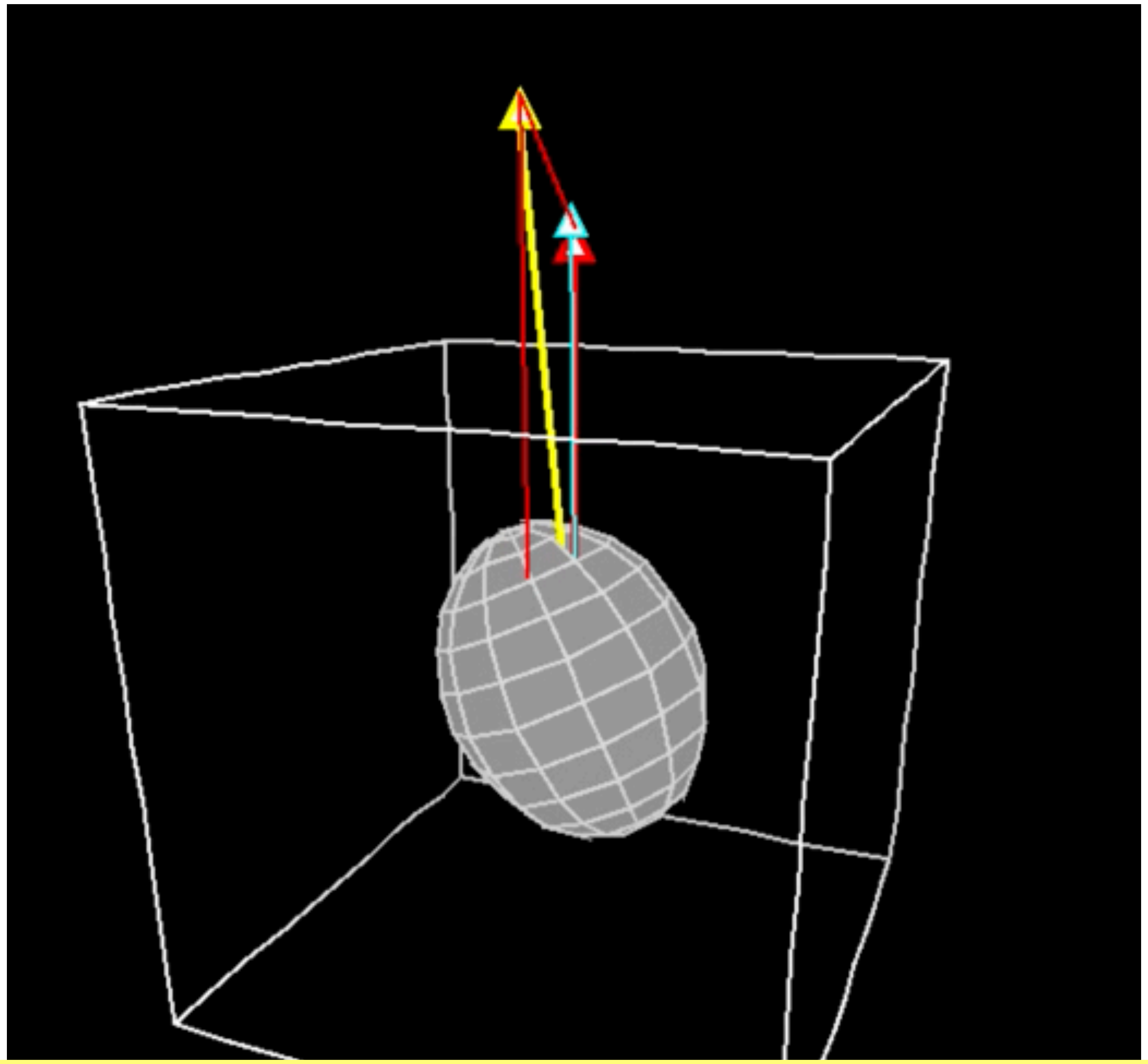
- Rotation powered pulsars: $L_x < L_{sd}$
  - c.f., Eddington luminosity ~10^{38} erg/s
- Persistent magnetars: $L_x >\sim L_{sd}$
- Transient magnetars: $L_x \rightarrow < L_{sd}$
- Possibility that many neutron stars can exhibit magnetar-like outbursts?

Toroidal magnetic field induced NS precession?

Huge energy reserver is needed inside the magnetars

⇒ Strong toroidal Field inside NSs? (can not be measured by *P*-P_{dot})





Toroidal B-field ⇒ Prolate shape

$$\epsilon = \frac{\Delta I}{I} \sim 10^{-4} \left(\frac{B_t}{10^{16}\,\mathrm{G}} \right)^2$$

$X_3 \neq \xi$

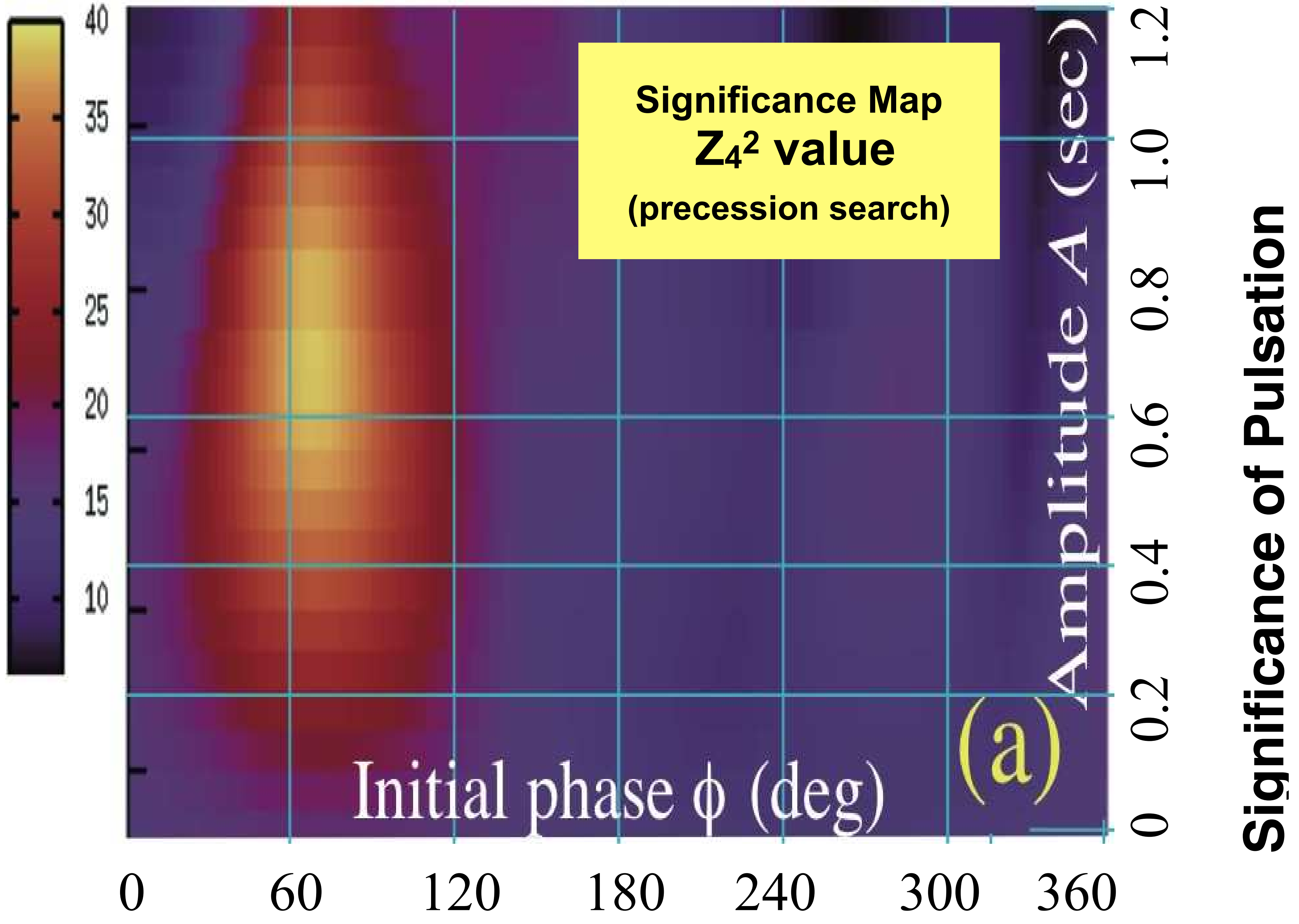
Free Precession with period *Q*

$$Q = \frac{P_{\mathrm{spin}}}{\epsilon}$$

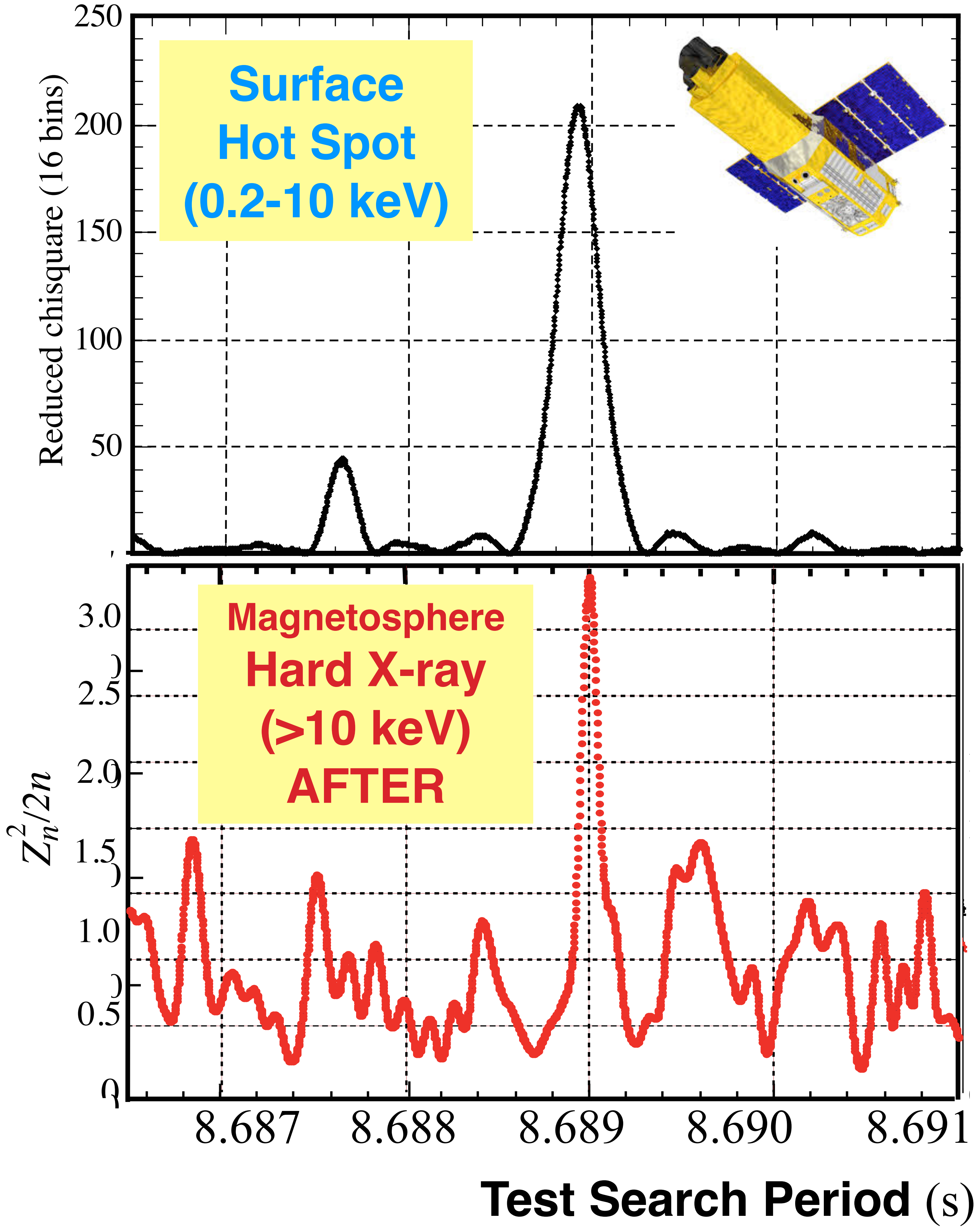
(see., e.g., Landau & Lifshitz textbook)

Evidence for NS precession?

Prototypical AXP 4U 0142+61 (P=8.69 s, Poloidal field B_d~1.3×10^{14} G)



Hard X-ray shows a sinusoidal, T=1.5 hour, phase modulation (amplitude 0.7 s)



Makishima, TE et al., PRL, 2014

$$\epsilon \sim \frac{8.69\,\mathrm{s}}{1.5\,\mathrm{h}} \sim 1.6\times10^{-4}$$

→

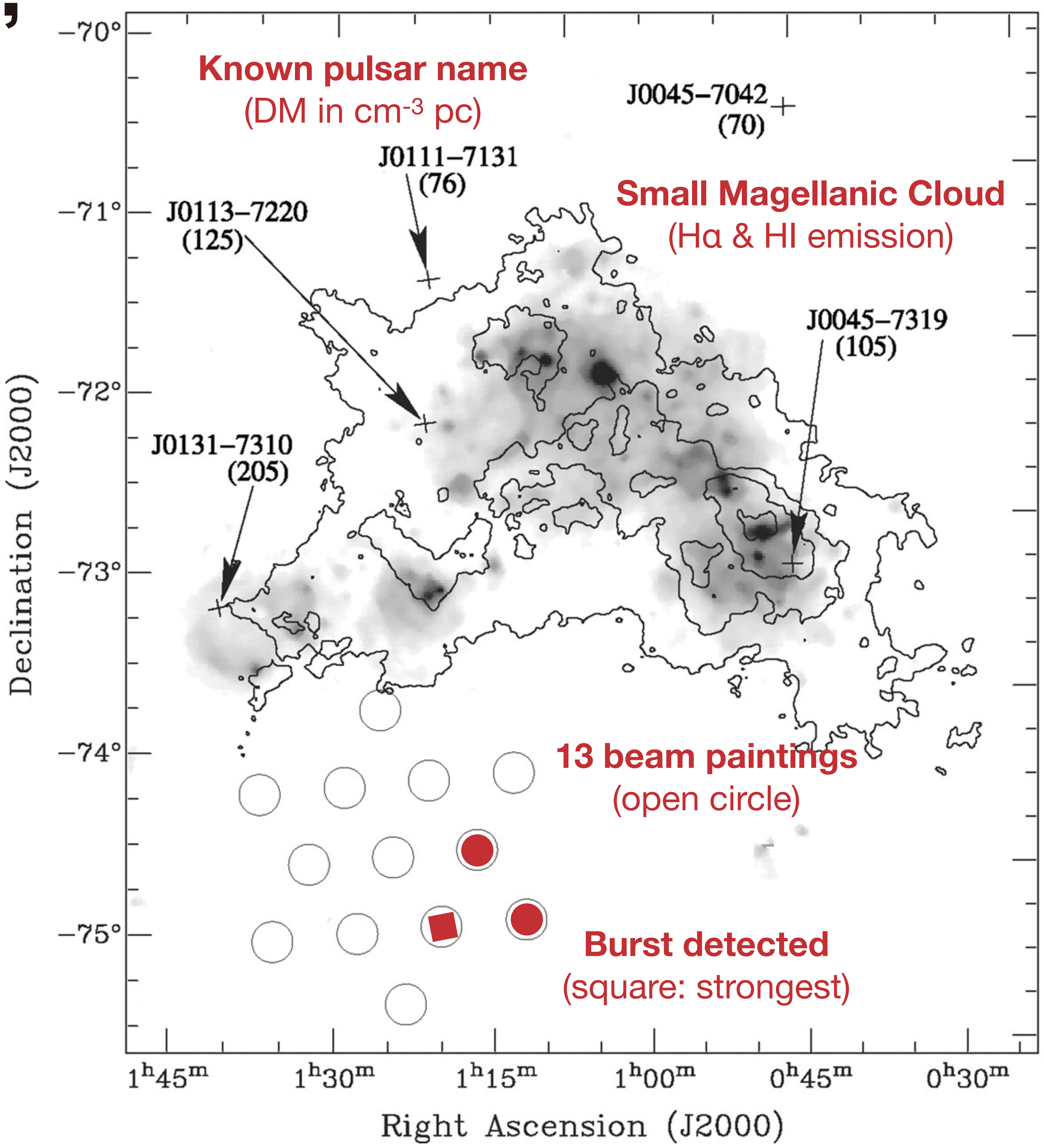
Toroidal B-field B_t ~ 10^{16} G

$$\epsilon \sim 10^{-4}(B/10^{16}\,\mathrm{G})^2$$

Confirmation with NuSTAR (Makishima+2019), Similar signature was detected from 1E 1547.0-5408 (Makishima+2020)

Mysterious “Lorimer burst”

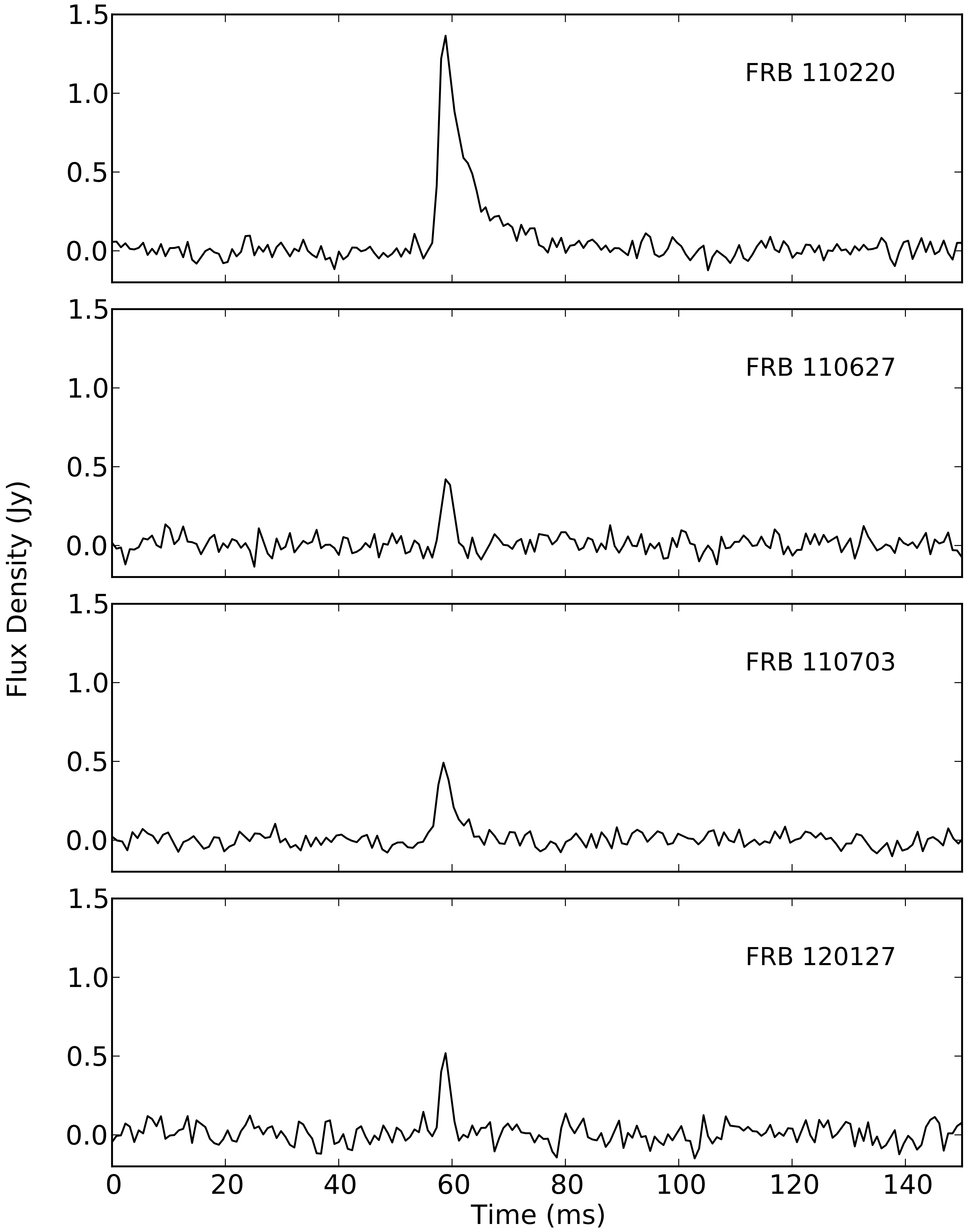
- Motivated by transient pulse of pulsars
- Archival data of 1.4 GHz survey of the Magellanic Cloud using the 64-m Parkes Radio Telescope in Australia
- Mysterious burst on 24 August, 2001
    - Located 3 degree from the SMC
    - Single event, not recursive
    - Bright 30 Jy (1 Jy = 10^{-26} W m^{-2} Hz^{-1})
    - Short duration < 5 msec
    - DM = 375 cm^{-3} pc (distant? <~ 1 Gpc)



Lorimer et al., Scence (2007)

Fast radio bursts (FRBs)

- Four FRBs were further reported in 2013.
- Short duration: ~a few ms or less
- Fluence *S* = 0.6-8.0 Jy ms @ 1.3 GHz
- High Galactic latitude $|b| > 41$ deg
- $R_{\mathrm{FRB}} \sim 10^{-3}$ / galaxy / year
  - $R_{GRB} \sim 10^{-6}$ / galaxy / year
  - $R_{ccSN} \sim 10^{-2}$ / galaxy / year
- DM = 553-1103 cm^{-3} pc
  - Cosmological distance: z = 0.45-0.81



Thronton et al., Science, 2013

Dispersion Measure (DM)

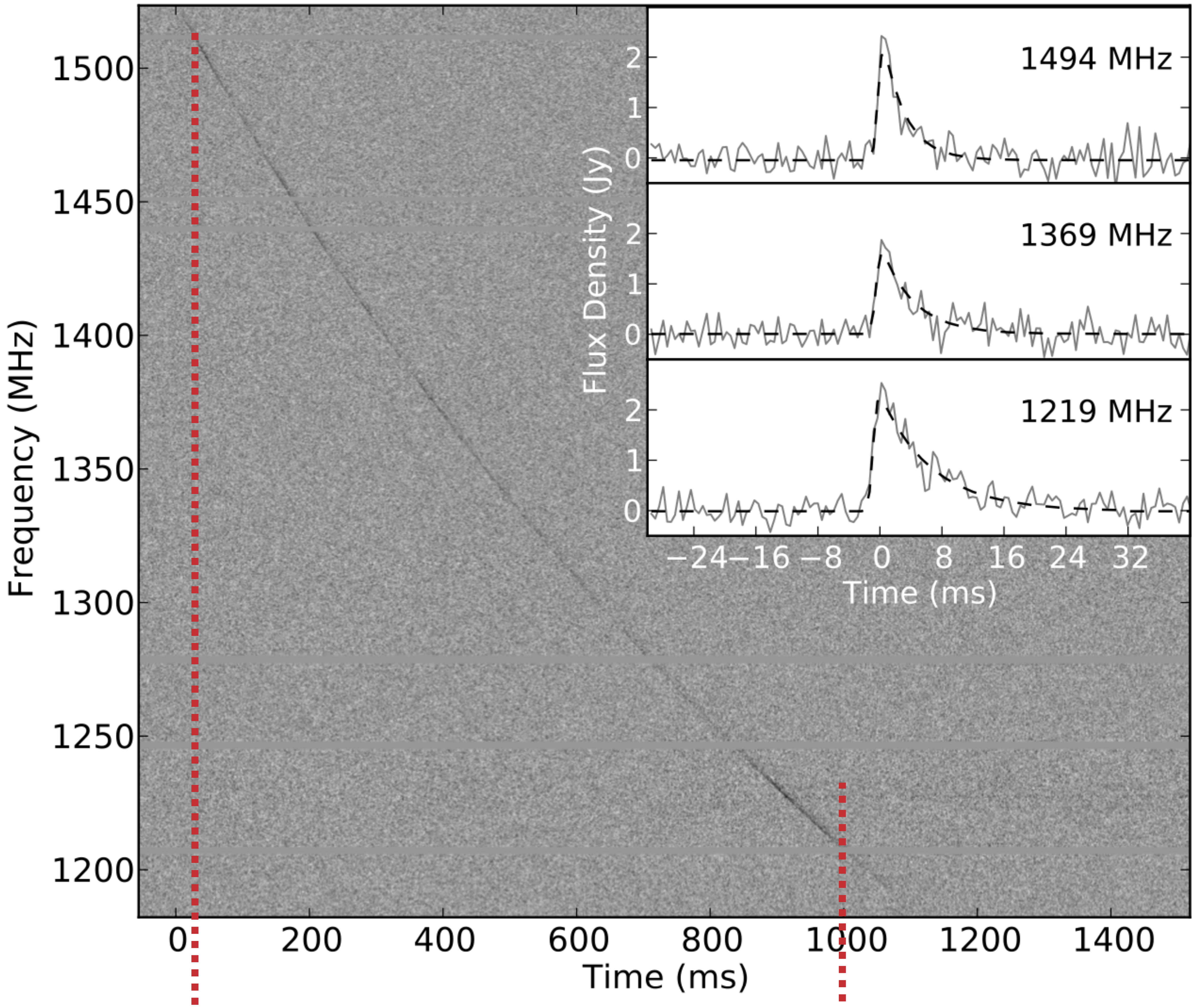
$$\mathrm{DM} = \int_0^d n_e dl \quad (\mathrm{cm}^{-3}\ \mathrm{pc})$$

- Integrated column density (n_e) of free electrons along the line of sight
- This makes a frequency-dependent dispersive delay Δt through a plasma

$$\Delta t = \frac{e^2}{2\pi m_e c} \frac{\mathrm{DM}}{\nu^2}$$

$$= 4.14{\times}10^3\ \mathrm{sec} \left(\frac{\mathrm{DM}}{\mathrm{cm}^{-3}\ \mathrm{pc}}\right) \left(\frac{\nu}{1\ \mathrm{MHz}}\right)^{-2}$$

Thronton et al., Science, 2013



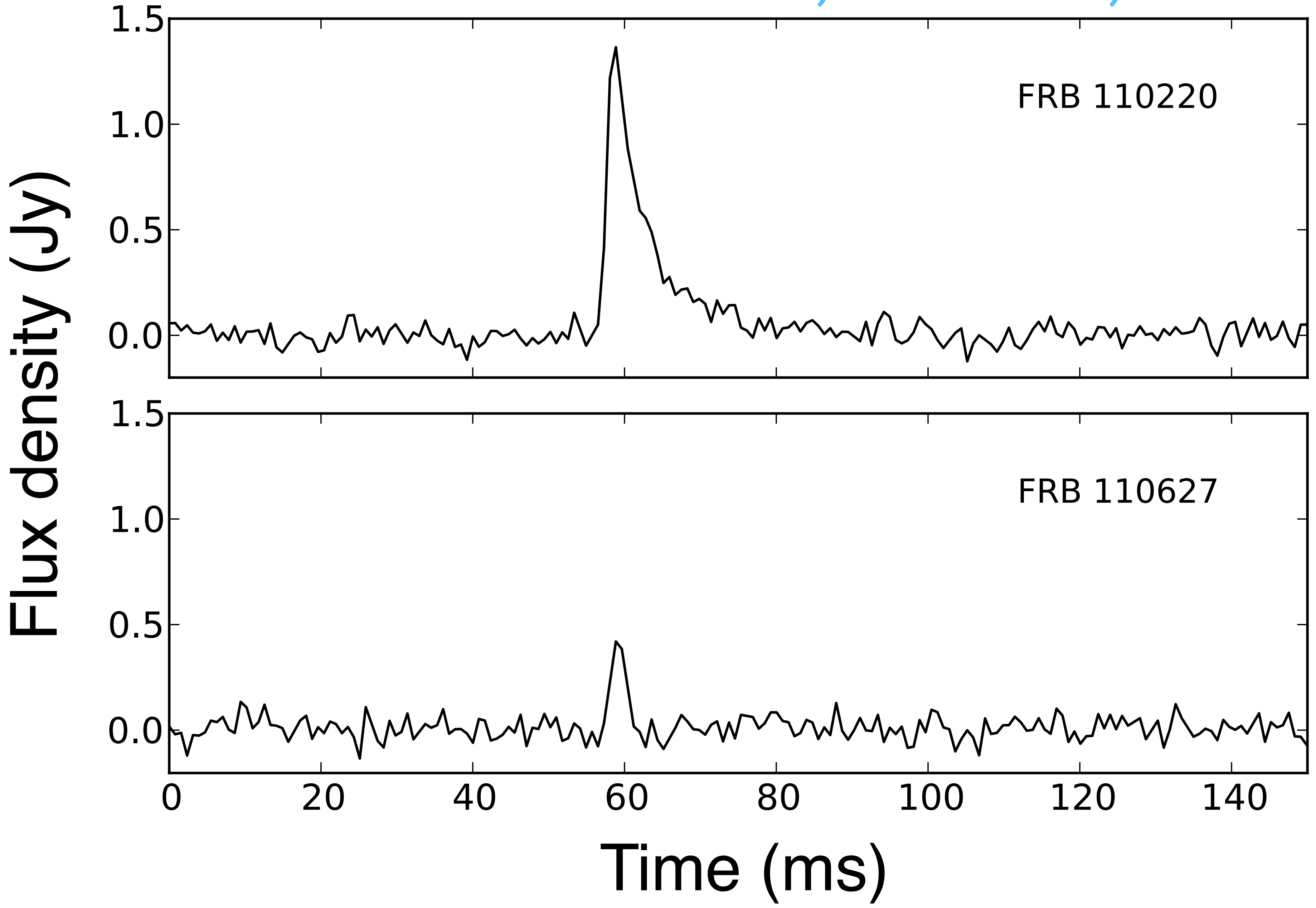
Delay Δ*t* ~ 1000 ms

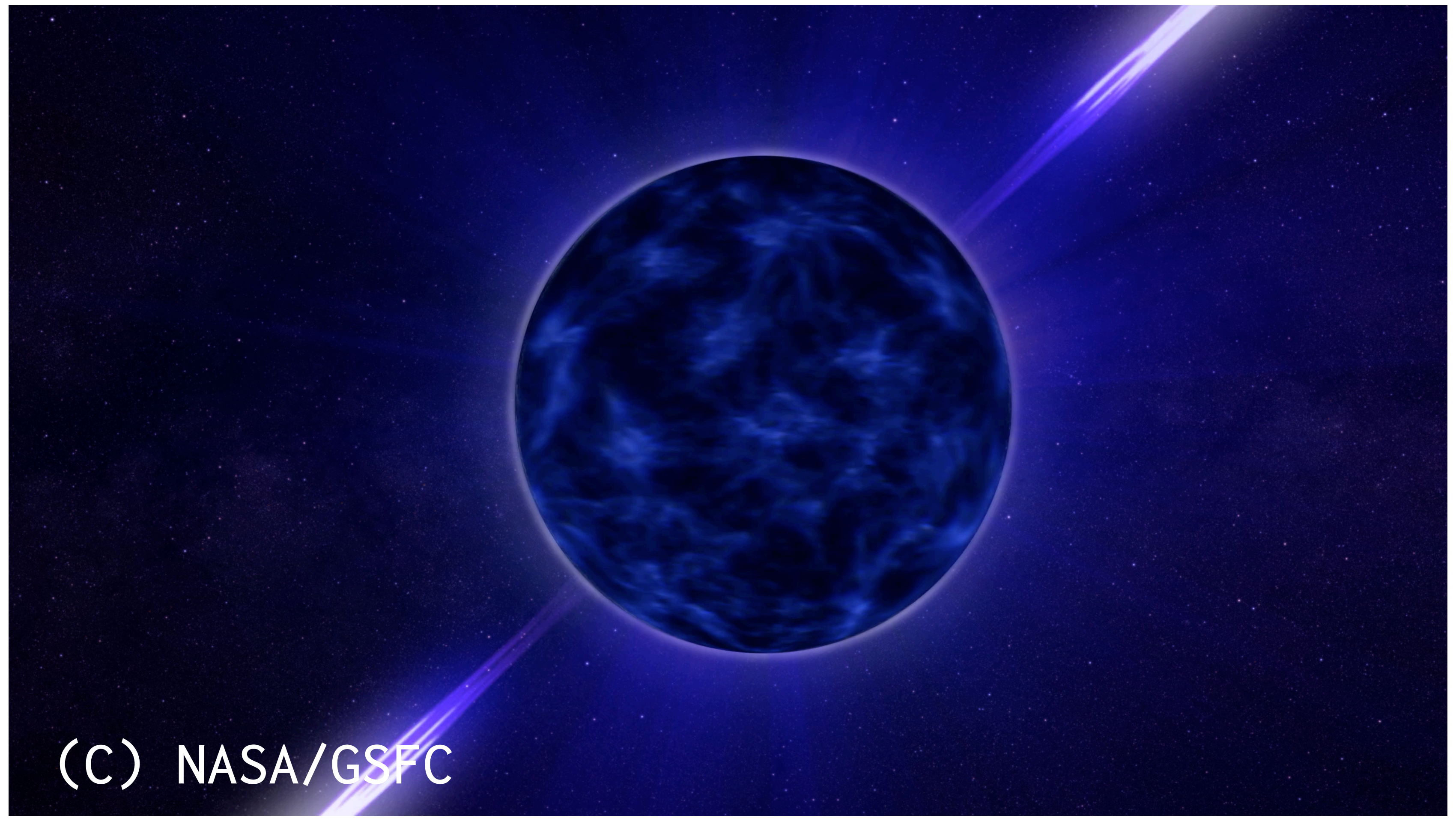
- DM (delay) is a good indicator of a source distance!

Unsolved origin(s) & emission mechanism of FRB

- Fast radio burst (FRB) characteristics:
  1. Bright radio emission F ~ 0.2-120 Jy @ ~1 GHz
  2. Large DM ~ 300-1600 $\mathrm{cm^{-3}}$ pc
     → Cosmological distance (z <~ 1)
  3. Brightness temperature $T_b = 10^{33\text{-}37}$ K
     → Coherent radio emission
  4. Short duration $\Delta t < 1$ ms
     → Compact origin? ($R \sim c\Delta t \sim 3\times10^2$ km~ $30 R_{\rm NS}$)
  5. Fluence $S = F\,\Delta t$ = 1-10 Jy ms
     → Energetics $E \sim 4\times10^{39}$ erg $(d / 1\ \mathrm{Gpc})^2$
  6. High event rate $R_{\rm FRB} \sim 10^4$ / sky / day
     → $R_{\rm FRB} \sim 0.1\ R_{\rm SN} \sim 10^4\ R_{\rm GRB}$ (Common star?)
- Neutron star (NS) related phenomena as the promising candidate of FRBs?

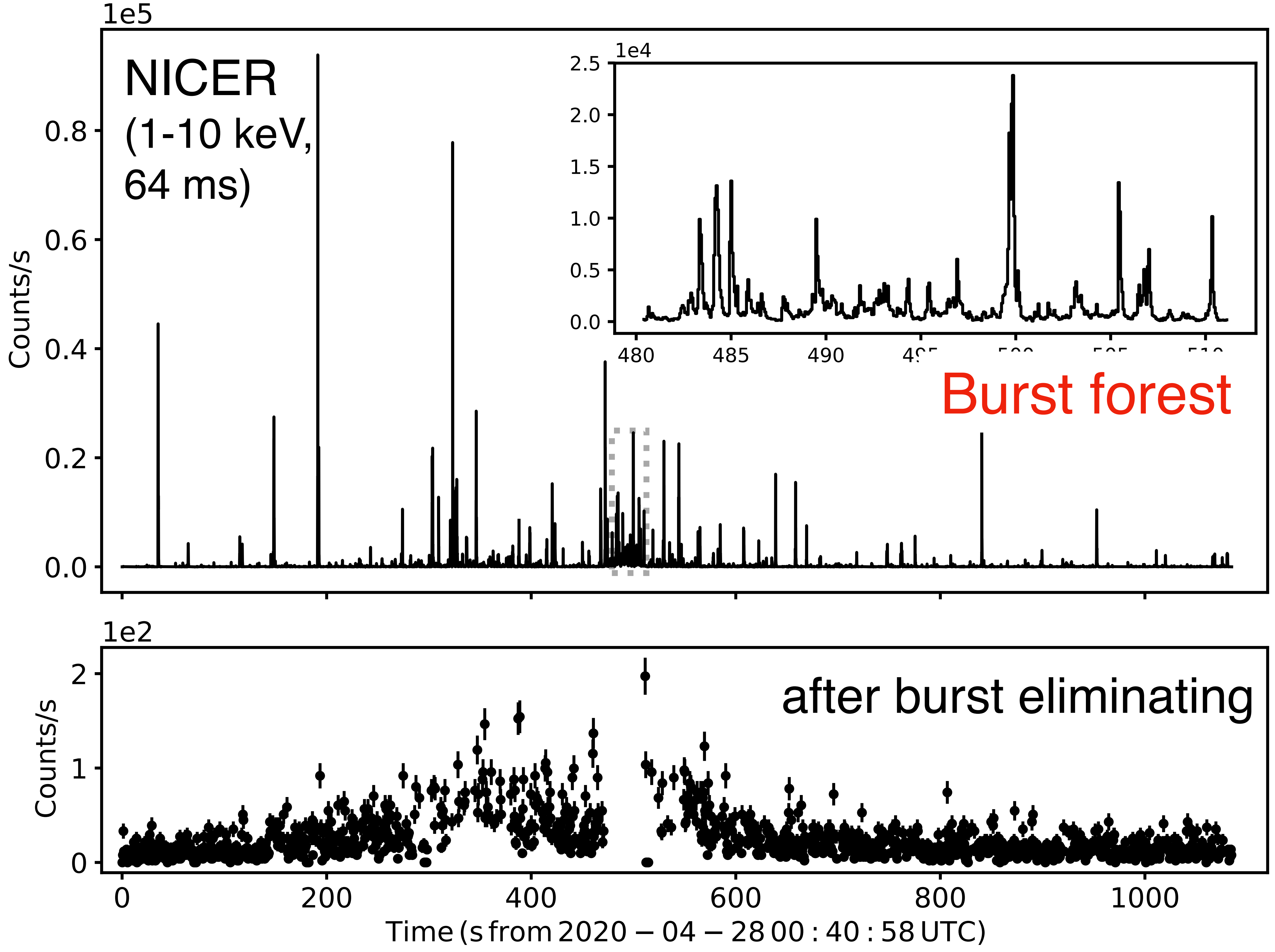
Thronton et al., Science, 2013



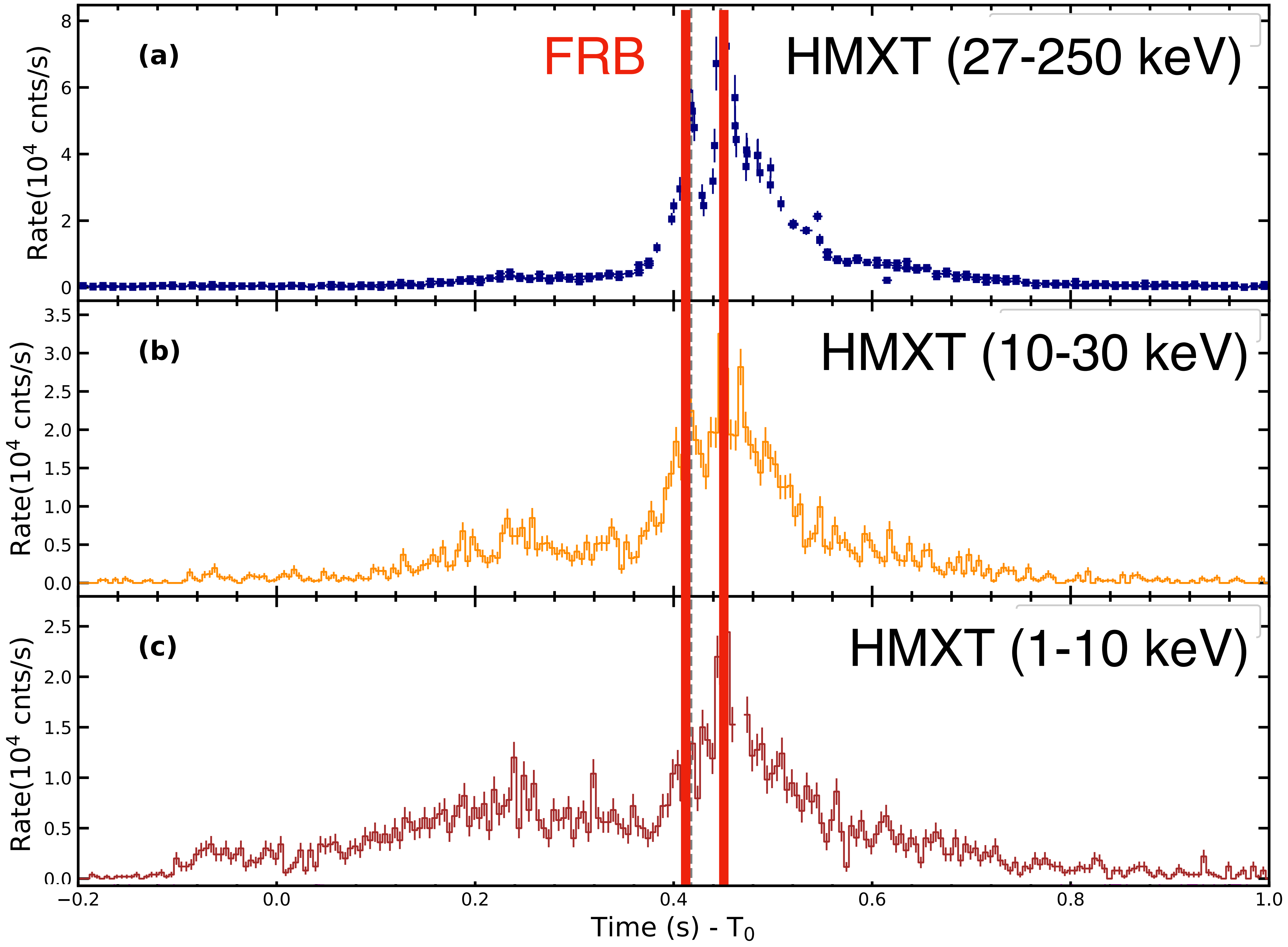

(C) NASA/GSFC

Galactic magnetar SGR 1935+2154 w/ a faint FRB

- SGR 1935+2154 (~9 kpc?) — P=3.24 s, P_{dot}=1.43e-11 s/s → B ~ 2.2e+14 G
- A burst detected with Swift/BAT on April 27, 2020. Magnetar outburst with an intense bursting activity for at least 7 hours, e.g., burst forest, 217+ bursts in 20 min. e.g., CHIME/FRB Collab. Nature, 2020
- Two-peak FRB coincided with a magnetar X-ray burst (HMXT, INTEGRAL, AGILE, and Konus-Wind)
- Cutoff energy of the FRB-associated burst is higher than others (Younes et al., Nature astronomy, 2021)



(Younes et al., ApJ, 2020)



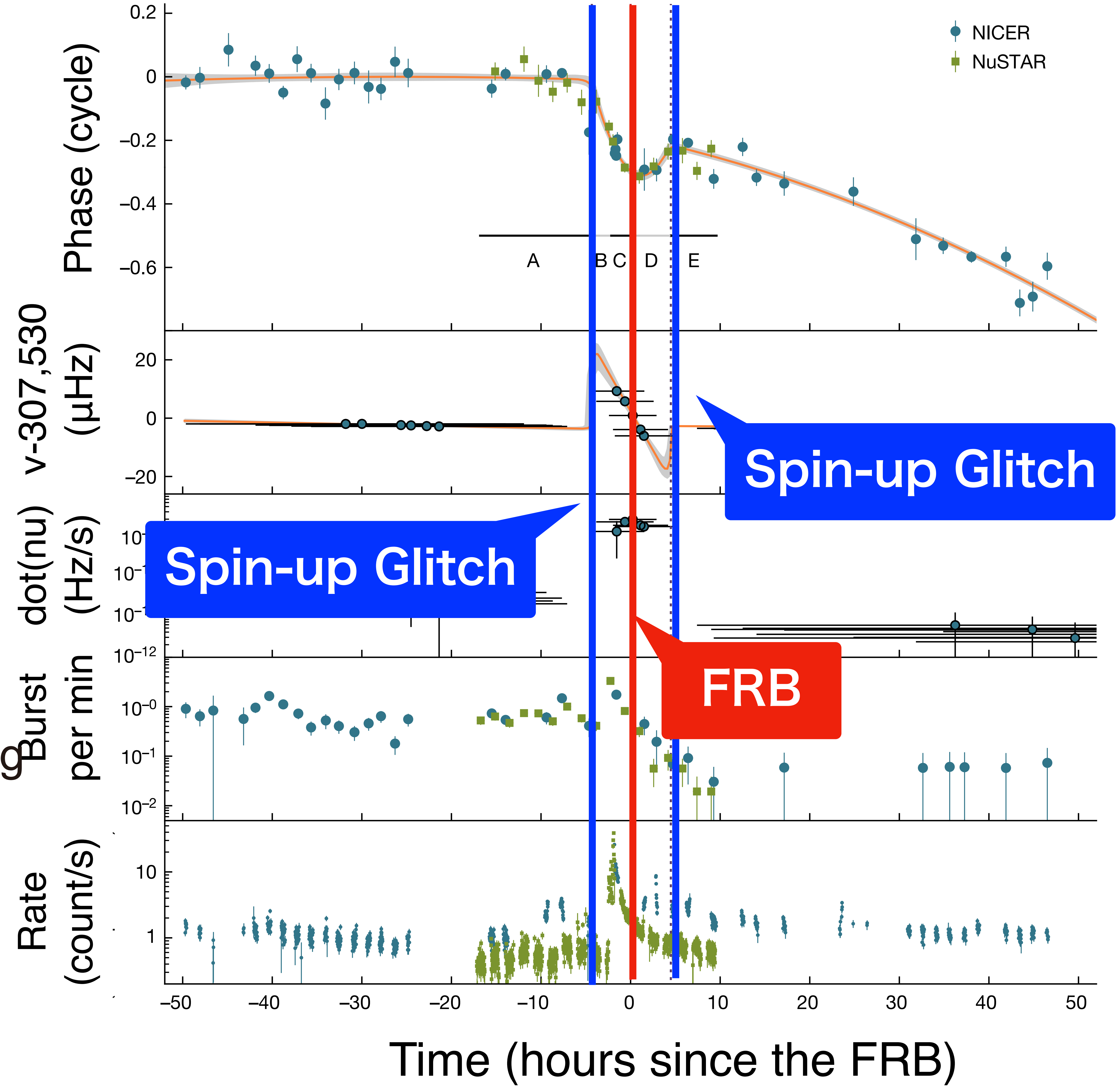
(Li et al., Nature Astronomy, 2021)

Double glitch around a FRB from SGR 1935+2154

- Another magnetar outburst in 2022 October.
- Our high-cadence ToO monitoring with NICER and NuSTAR serendipitously covered a FRB occurrence (e.g., ATel 15697).
- We detected two strong spin-up glitches and a rapid spin-down between them.
- Released rotational energies at the glitches, $E_{\mathrm{glitch}} = 4\pi^2 I\nu \triangle \nu$, are 3.9×10⁴¹ erg and 2.6×10⁴¹ erg (comparable), respectively!!
- Rotational energy loss between the glitches is

$$dE_{\mathrm{rot}} = \int L_{\mathrm{sd}} dt = \int (4\pi^2 I\nu\dot{\nu}) dt = 6.5 \times 0^{41}\ \mathrm{erg}$$

- Twin double glitches show almost the same intensity and energy release.



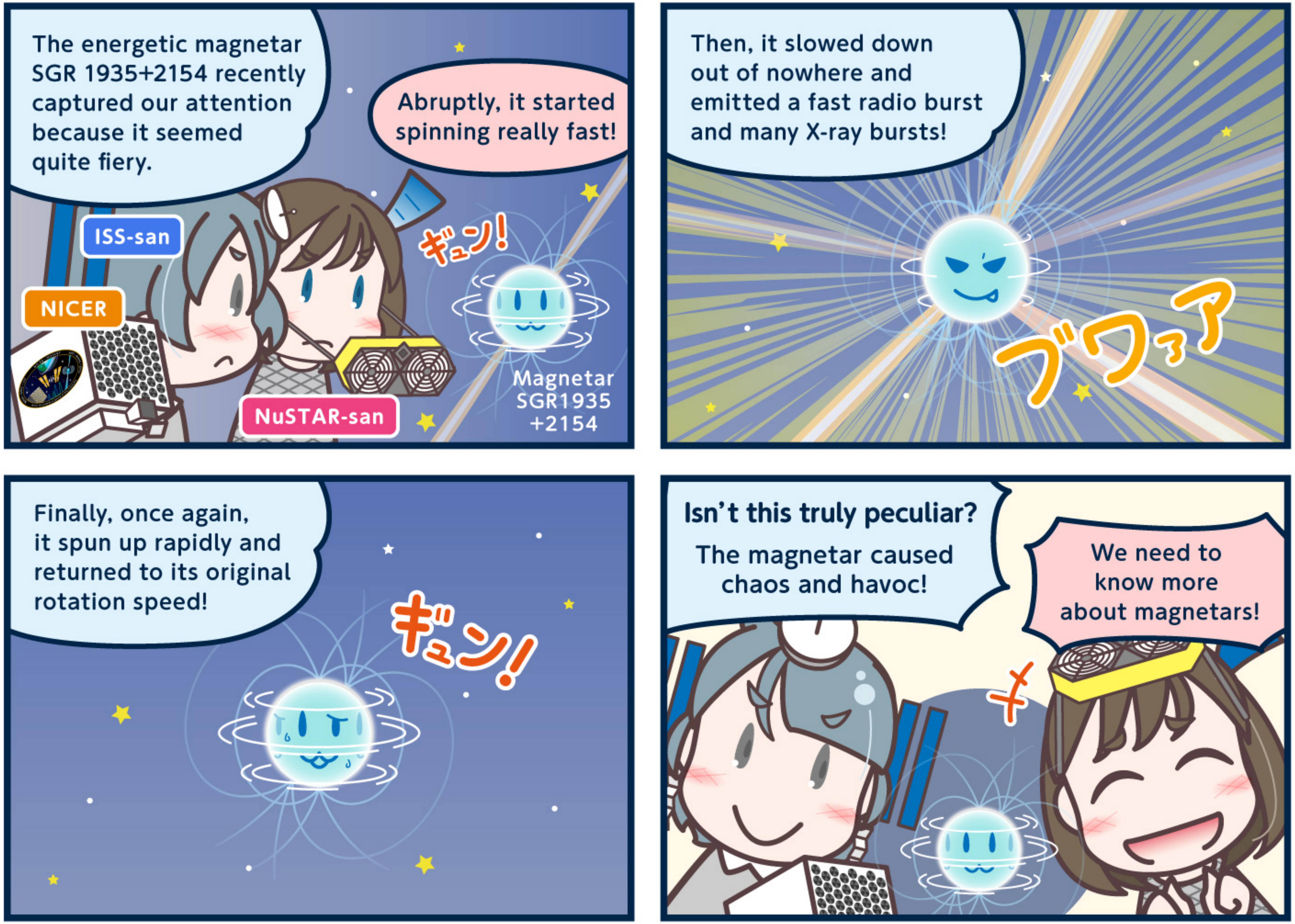
Spin-up Glitch

Spin-up Glitch

FRB

(Hu, Narita, Enoto, et al., Nature, 2024)

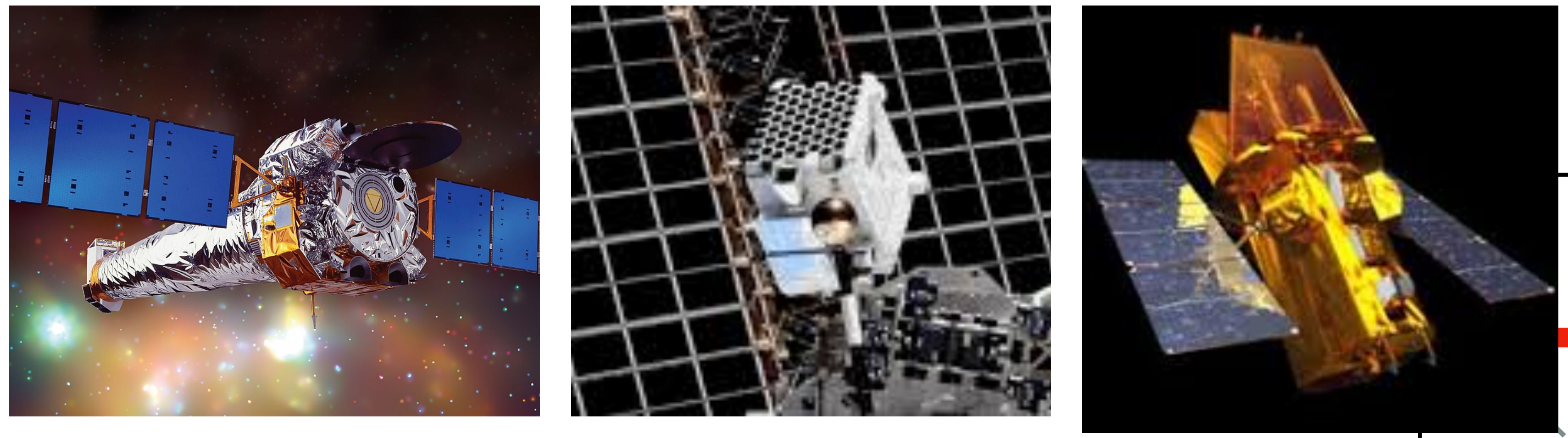
The Case of the Mysterious Magnetar SGR 1935+2154



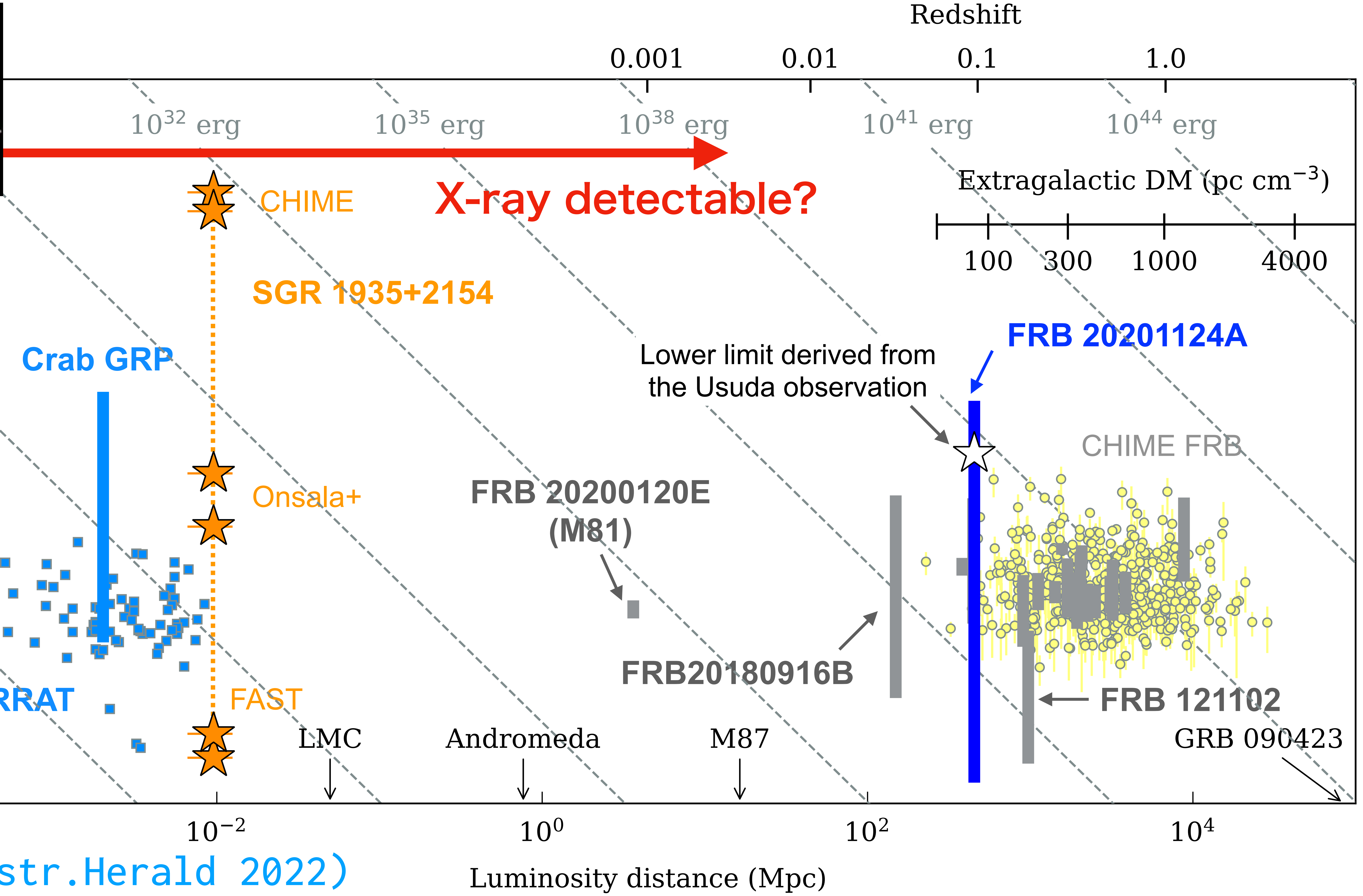
(Hu, Narita, Enoto, et al., Nature, 2024)

Waiting for nearby repeating FRB discoveries!

- X-ray follow-up observations become very important for nearby repeating FRBs closer than 50 Mpc. We are looking forward to receive alerts from the BURSTT!



[Back-of-envelope calculation]
Assuming persistent X-ray luminosity of L_x~10^{39} erg/s for FRB-related sources or phenomena, the Chandra/ACIS sensitivity, $F_x=4\times10^{-15}$ erg/s/cm^2 (0.4-6 keV) for a 10 ks exposure, corresponds with reachable distance up to 50 Mpc. For the Swift/XRT of $Fx=8\times10^{-14}$ erg/s/cm^2 (0.2-10 keV) for a 10-ks exposure, this becomes 10 Mpc. On the X-ray burst detection associated with we need systematic studies of background event properties.



(Enoto, Kisaka, Terasawa, Astr.Herald 2022)

Summary: message to theoreticians from an astronomer

- Neutron stars are observationally diverse. In order to determine the internal equation of state, it is necessary to deeply understand the uncertainty associated with this diversity. Furthermore, we should further consider to use other observational quantities (temperature, B-field, …) in the future.
- There are several methods for measuring the mass and radius of neutron stars, including measuring the motion of binary stars, X-ray bursts, gravitational redshifts due to absorption lines and light bending, and gravitational waves. NICER is updating the latest EoS measurements.
- Magnetars are a new target for observing the interior of neutron stars. X-ray outbursts from magnetars can be used to measure the response to the release of internal energy deposit. Glitches related to fast radio bursts can be used to learn about angular momentum transfer in the stellar interior.