Astronomical Diversity and Fundamental Physics of Neutron Stars Observed with NICER

Teruaki Enoto (RIKEN)
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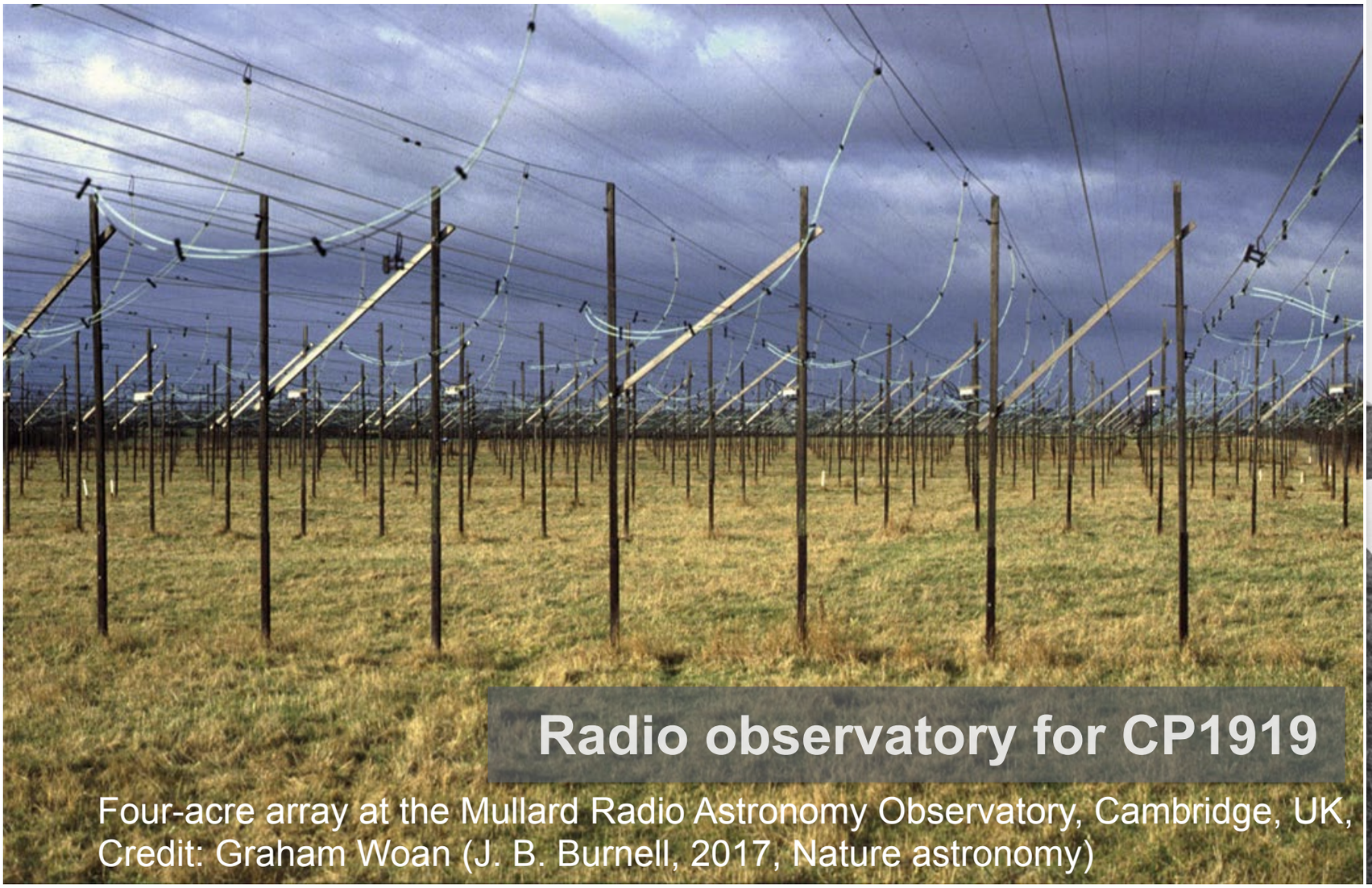
Zaven Arzoumanian (NASA/GSFC)
On behalf of the NICER Science Team



The Evolution of Massive Stars and Formation of Compact Stars: from the Cradle to the Grave”,
Waseda University, 2020/02/28 (Friday) 14:50-15:15

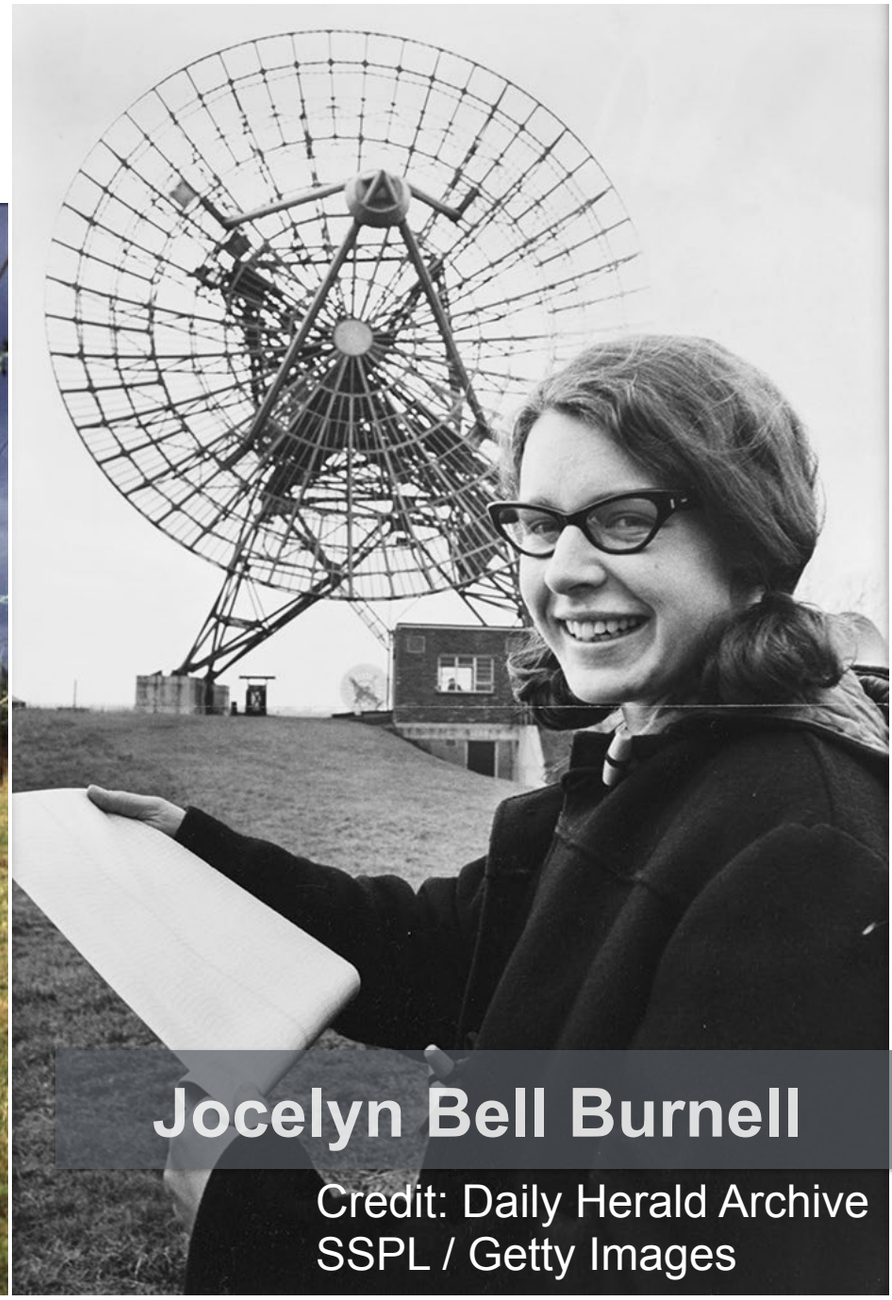
50th Anniversary of NSs

Discovery of the first polar CP1919 in 1967



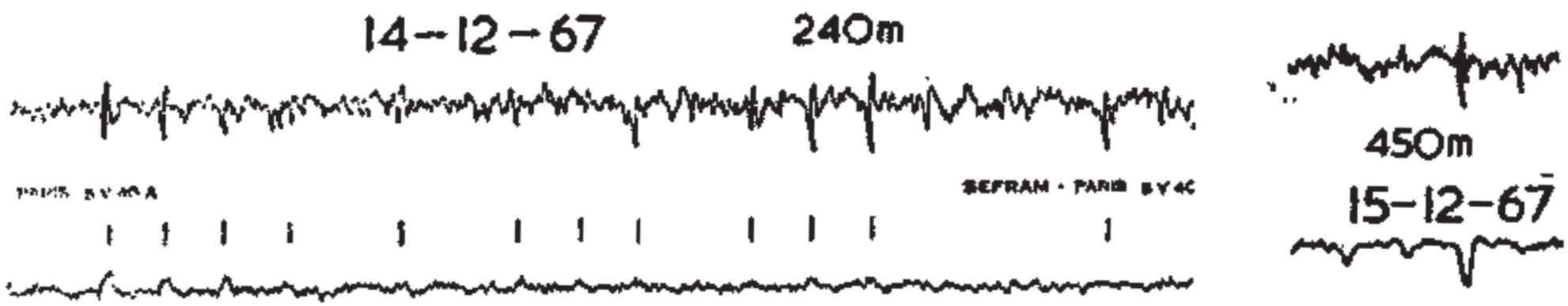
Radio observatory for CP1919

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



Jocelyn Bell Burnell

Credit: Daily Herald Archive
SSPL / Getty Images



Hewish & Bell et al.,1968, Nature

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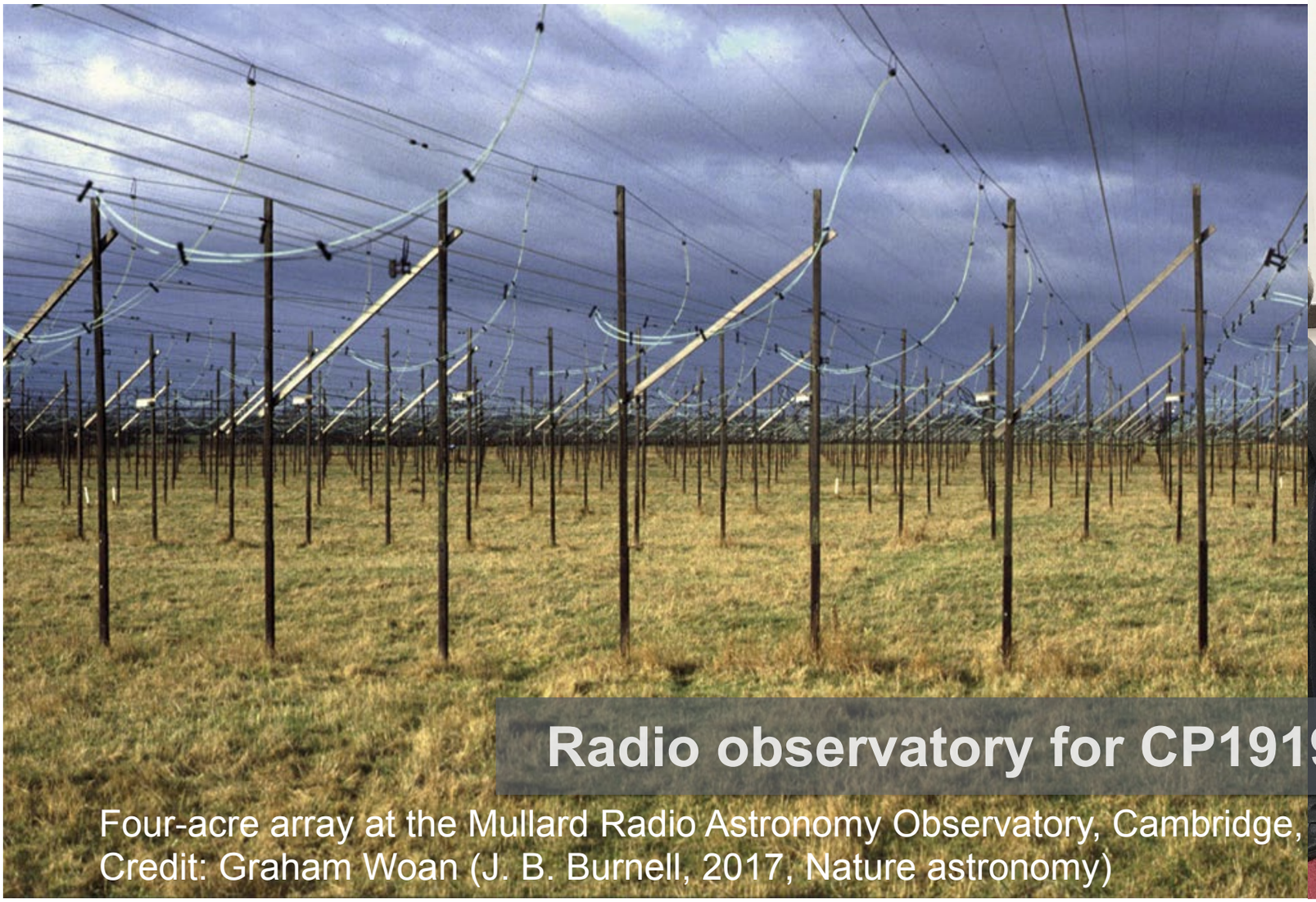

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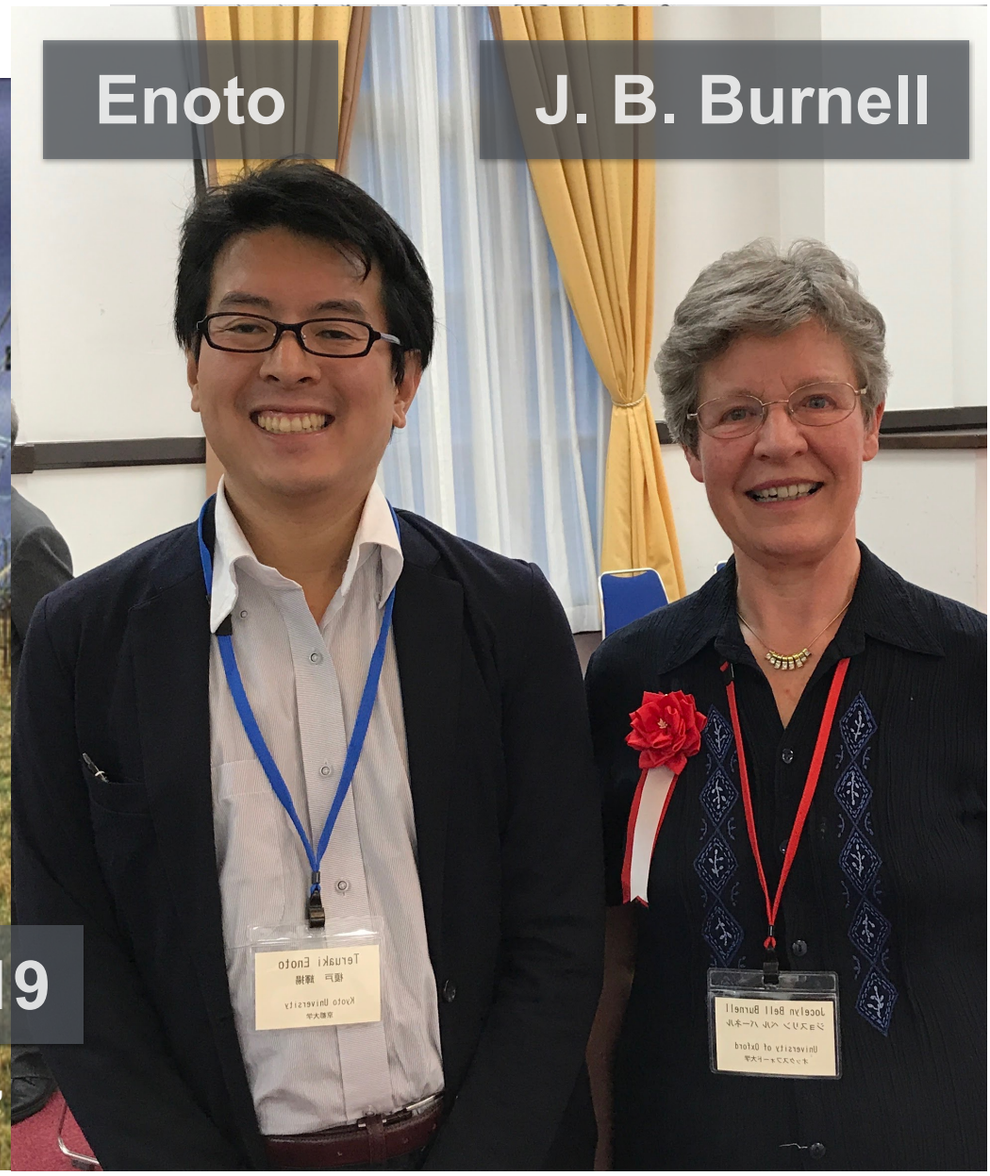
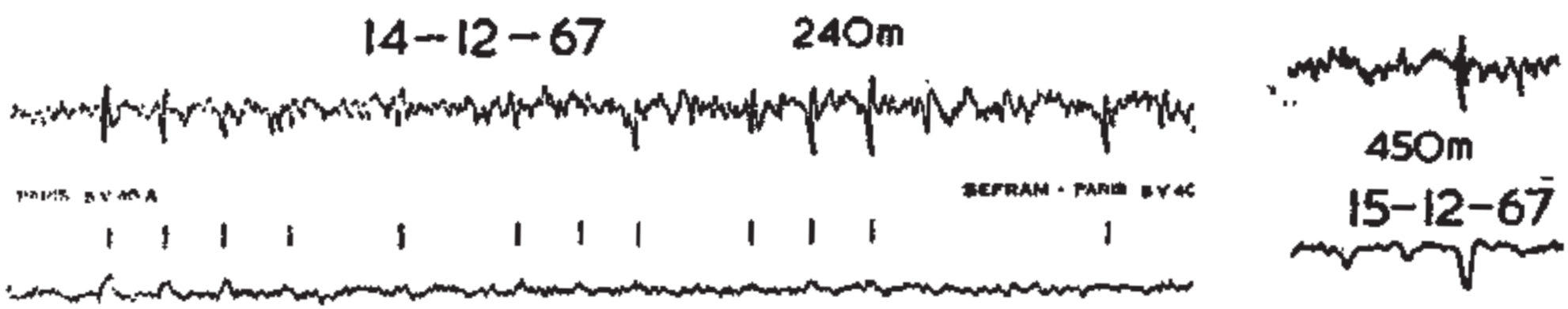
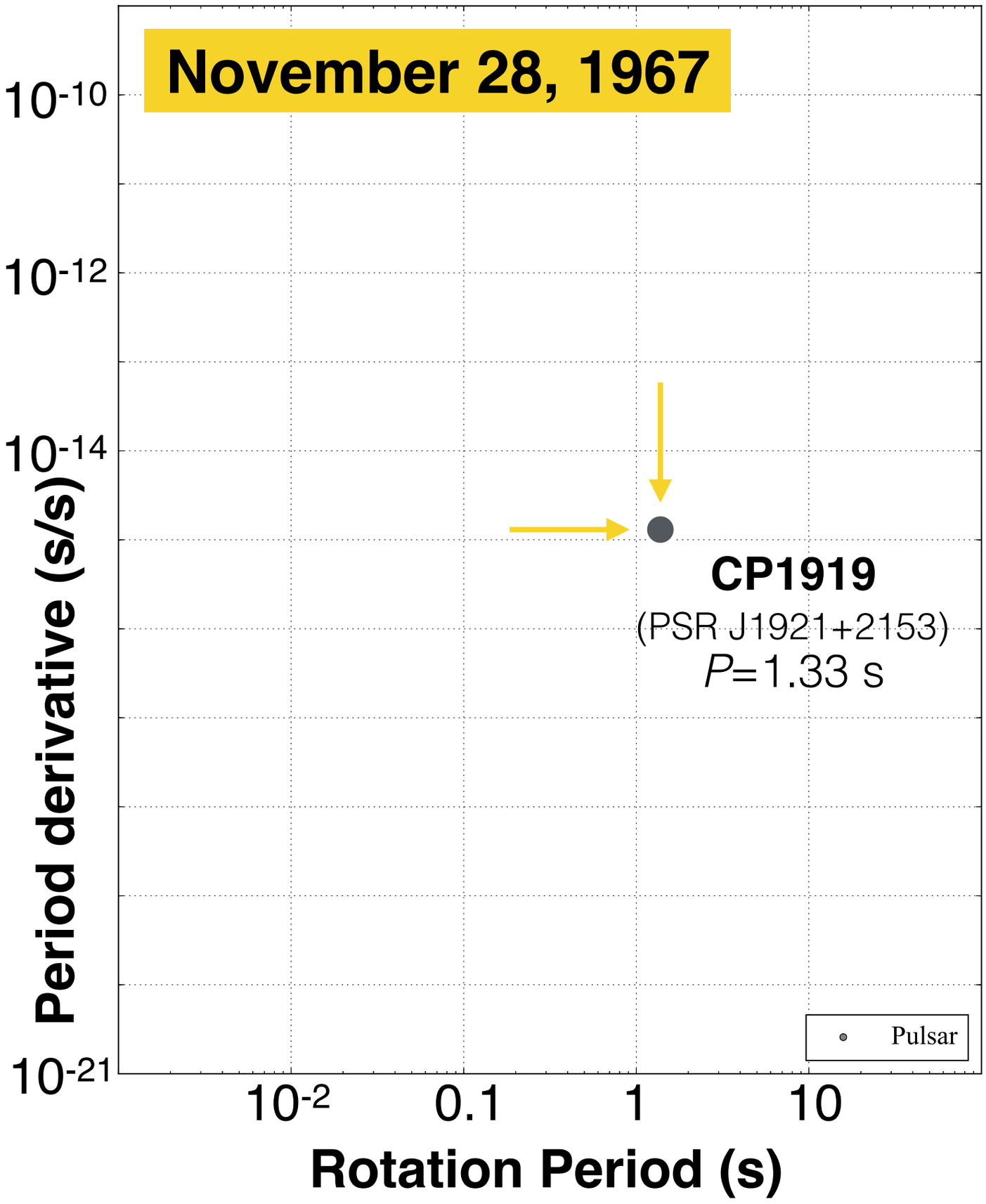
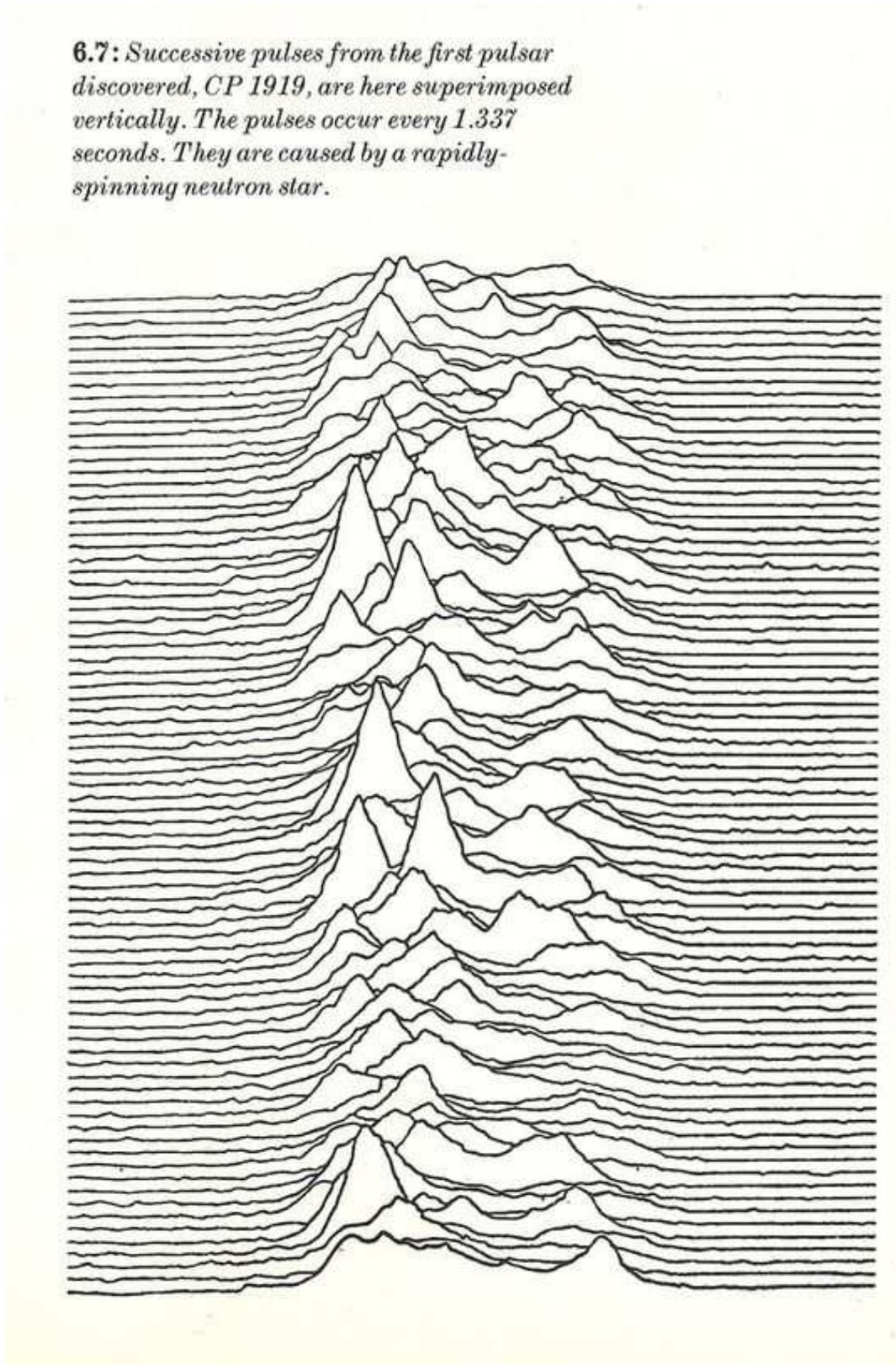




Hewish & Bell et al.,1968, Nature

Astronomical Diversity of Neutron Stars





Astronomical Diversity of Neutron Stars

1968

1 year later

Crab Pulsar
(PSR B0531+21)
P=0.033 s

CP1919

Pulsar

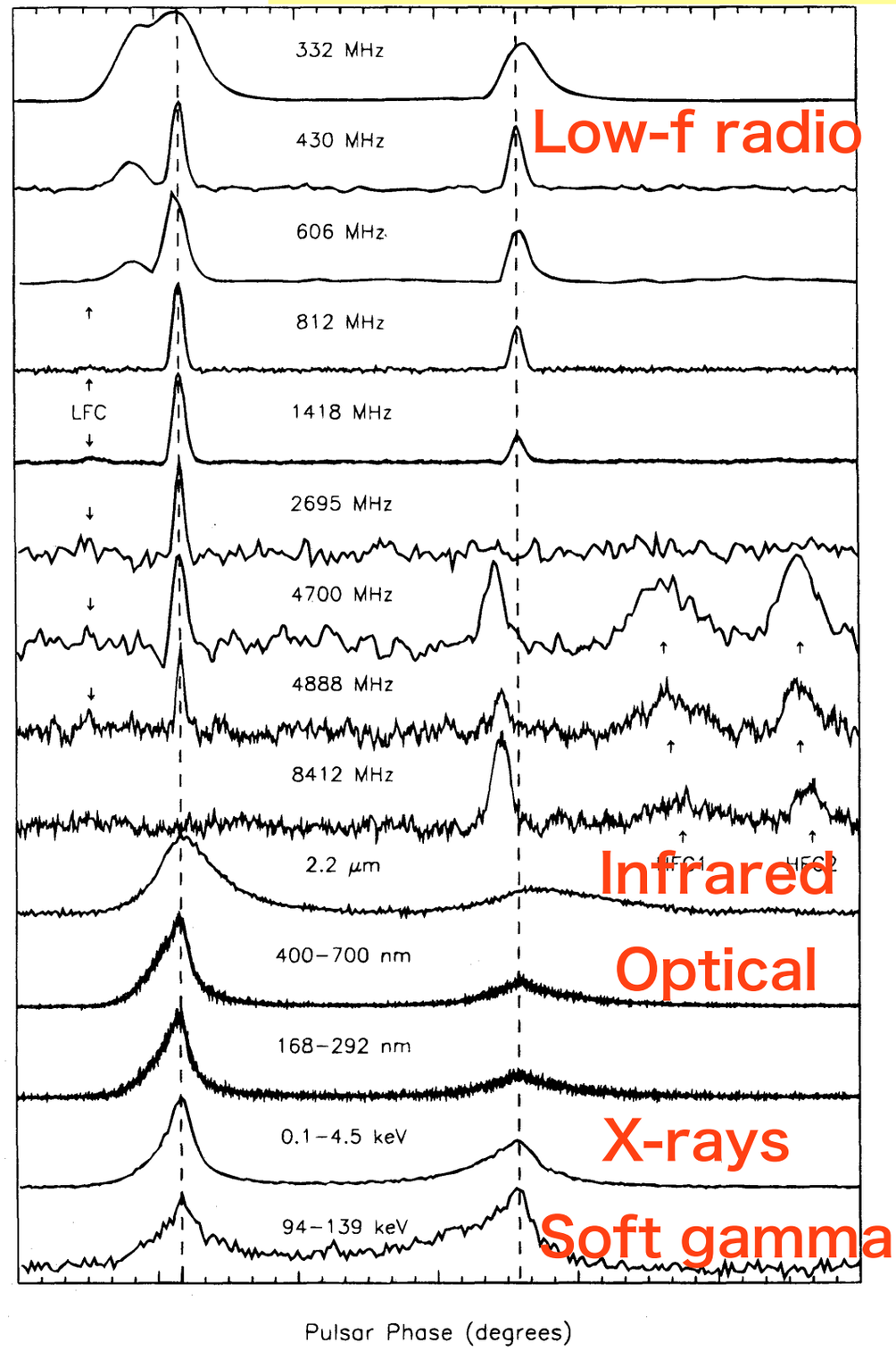
Period derivative (s/s)

10^{-10}
10^{-12}
10^{-14}
10^{-21}

10^{-2} 0.1 1 10

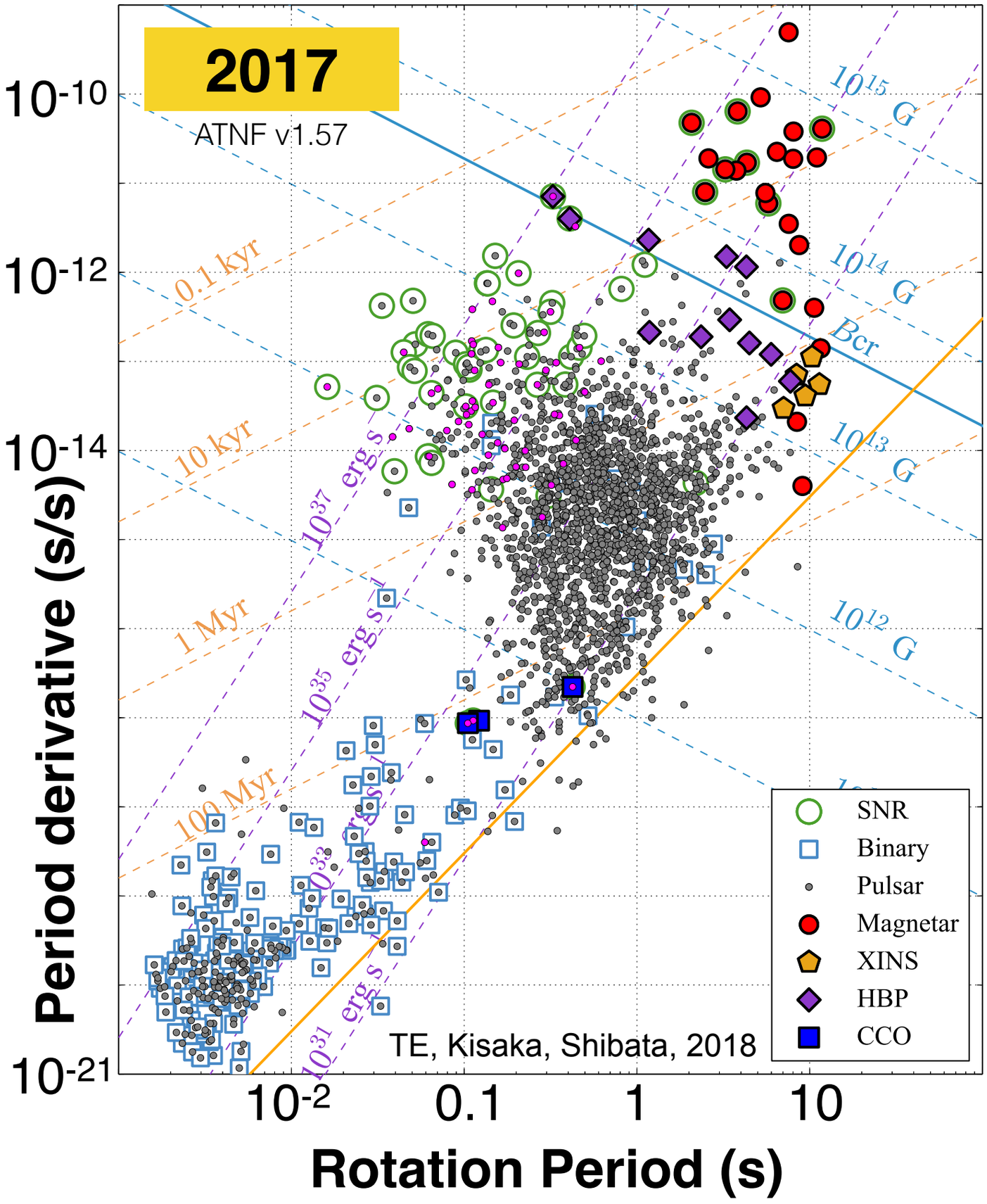
Rotation Period (s)

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



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

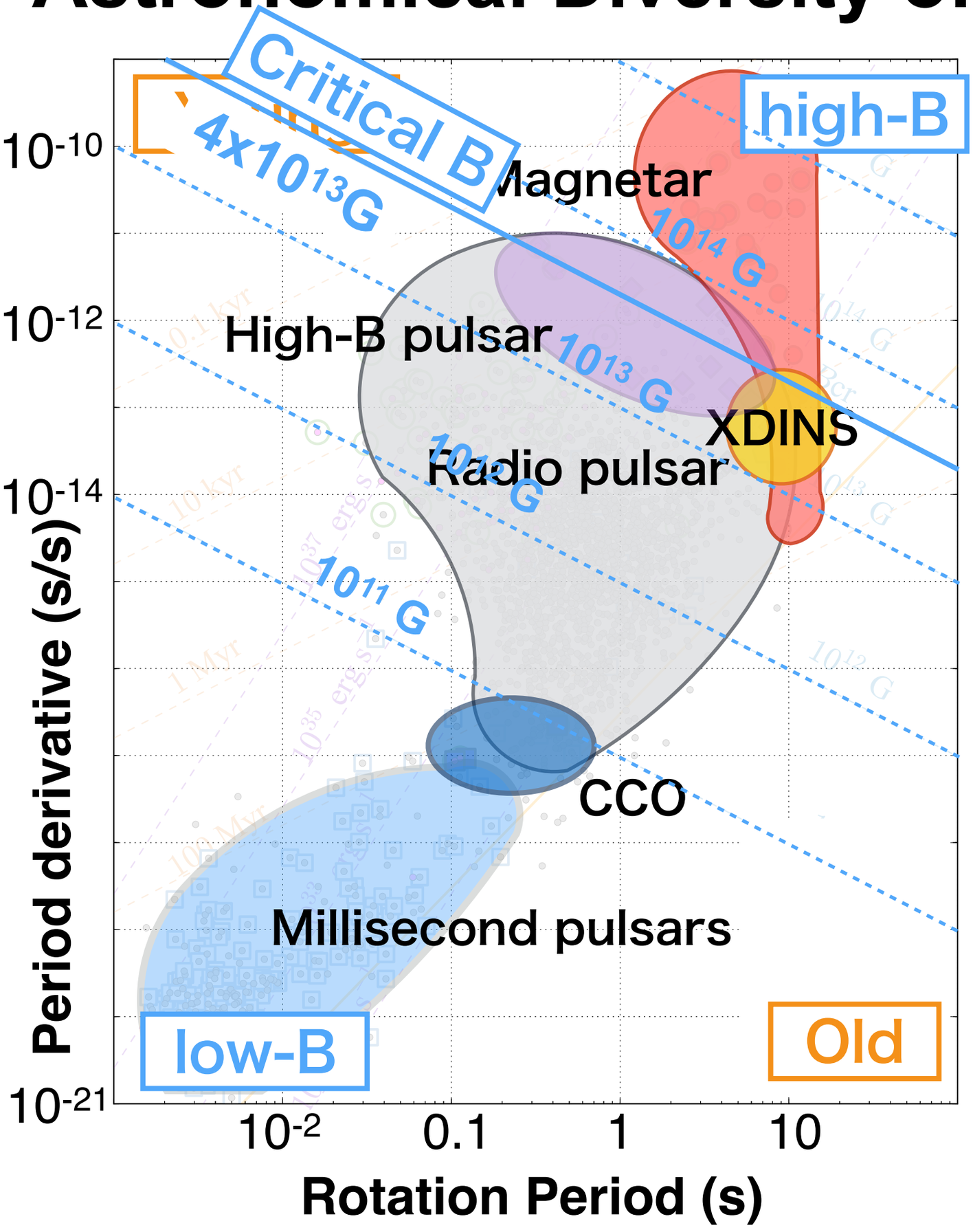
Astronomical Diversity of Neutron Stars



> 2500 known pulsars
(10^5 in Our Galaxy?)

- **Optical ~20**
- **X-ray ~100**
- **Gamma ~200**

Astronomical Diversity of Neutron Stars



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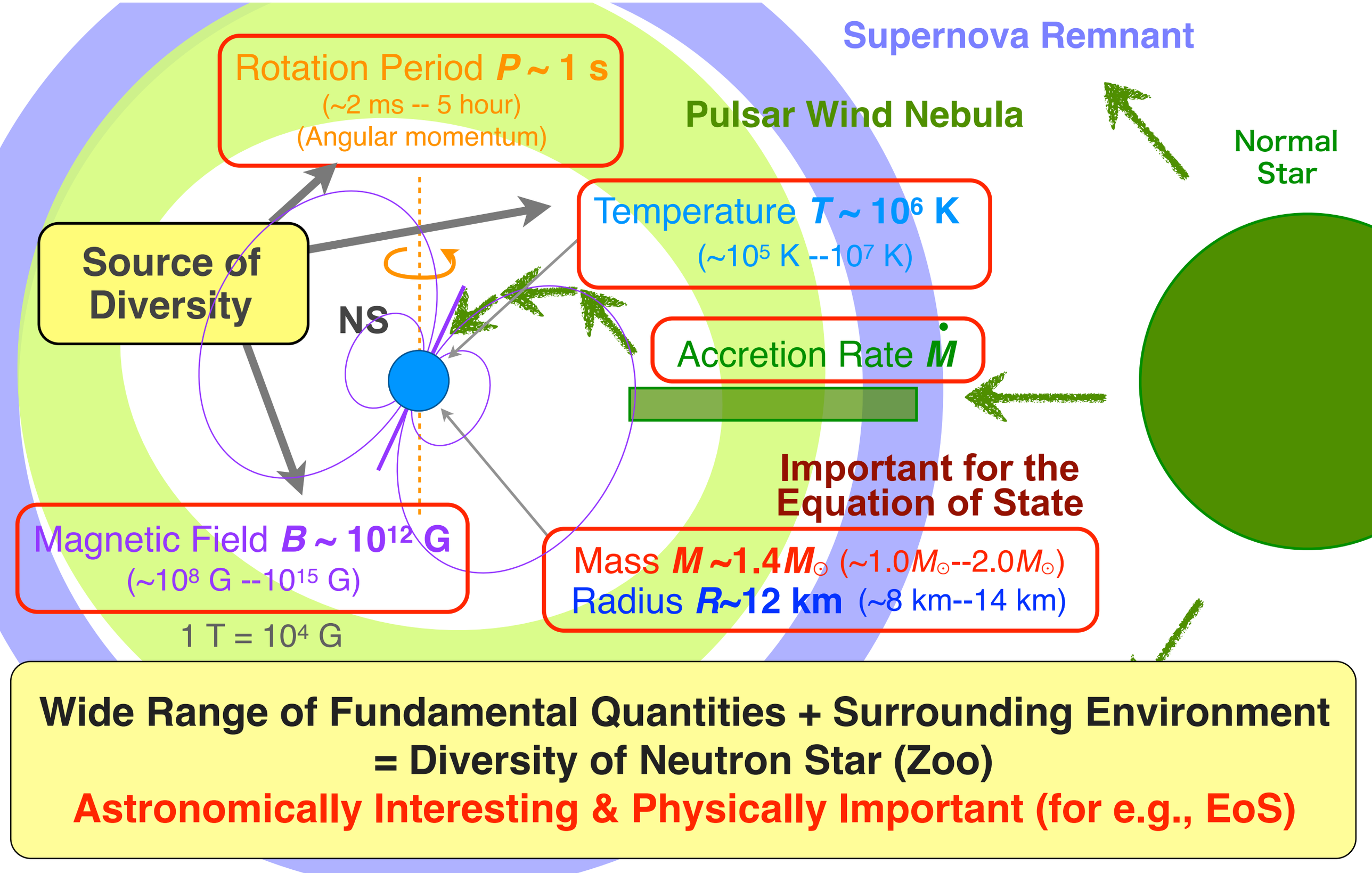
Observational diversity with various phenomena

Unified Theory of NS evolution?

Enoto, Kisaka, Shibata, ROPP (2019)

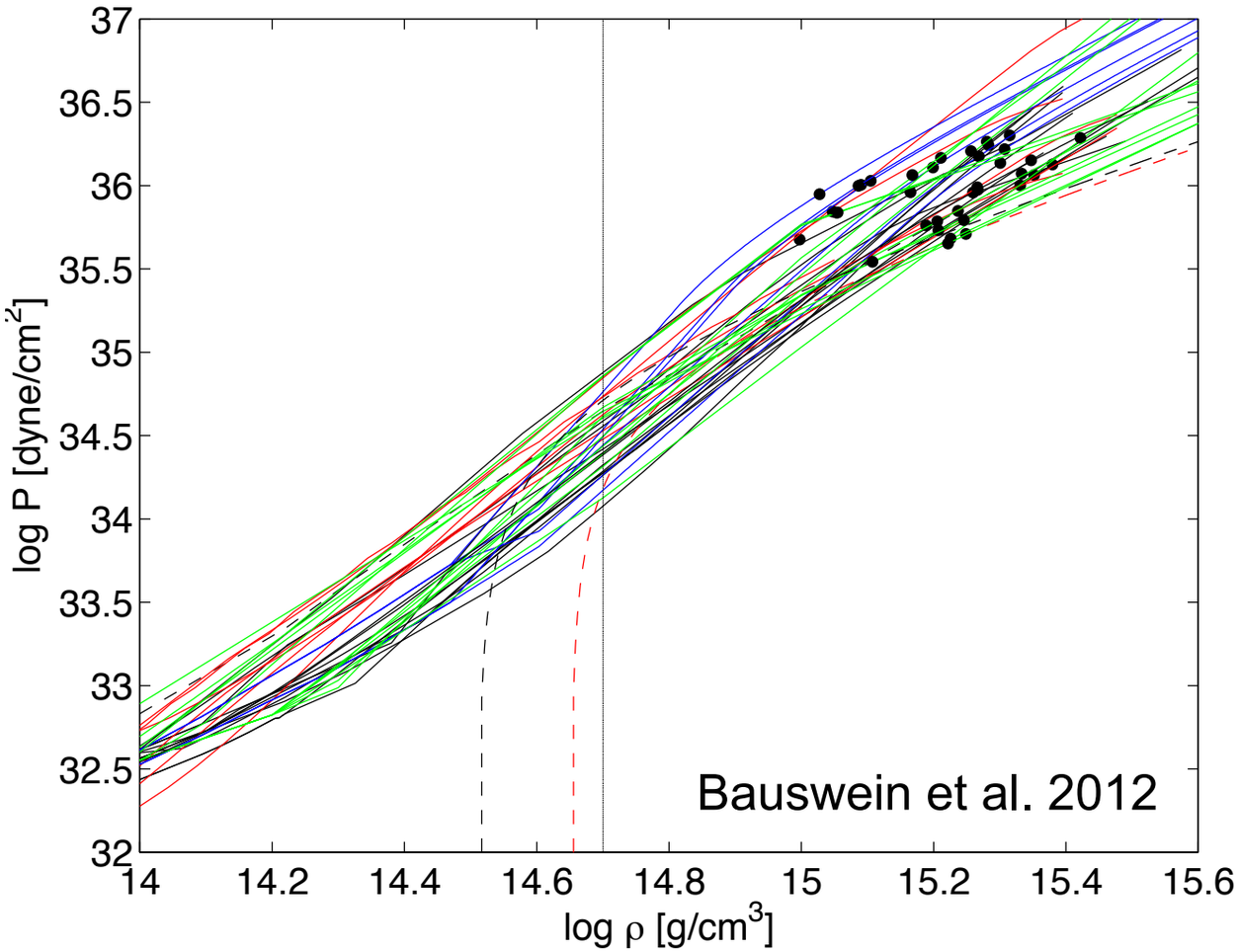
Fundamental Parameters of Neutron Stars

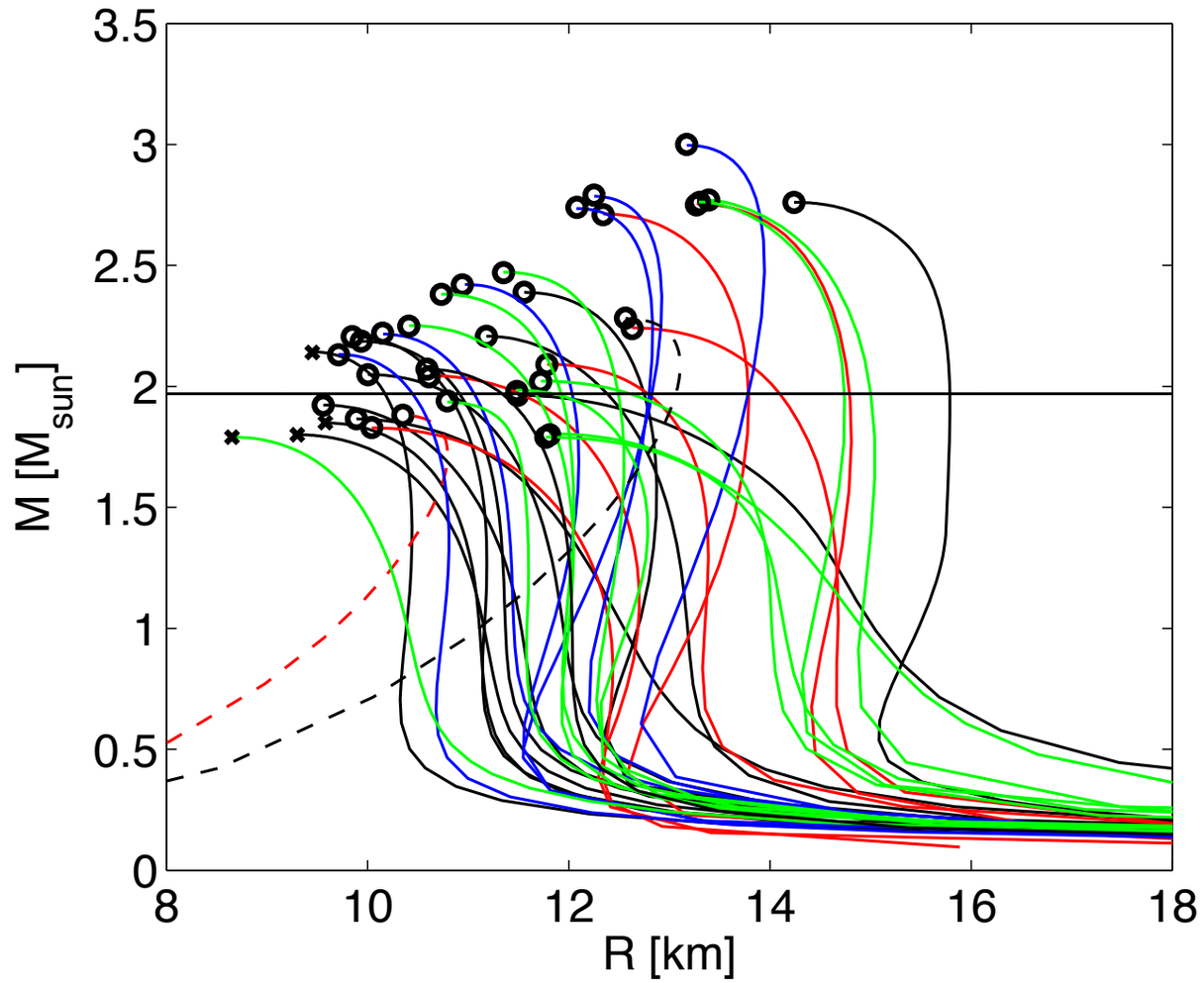
Dense nuclear matter, strong gravity, rapid rotation, and strong magnetic field



Wide Range of Fundamental Quantities + Surrounding Environment
= Diversity of Neutron Star (Zoo)
Astronomically Interesting & Physically Important (for e.g., EoS)

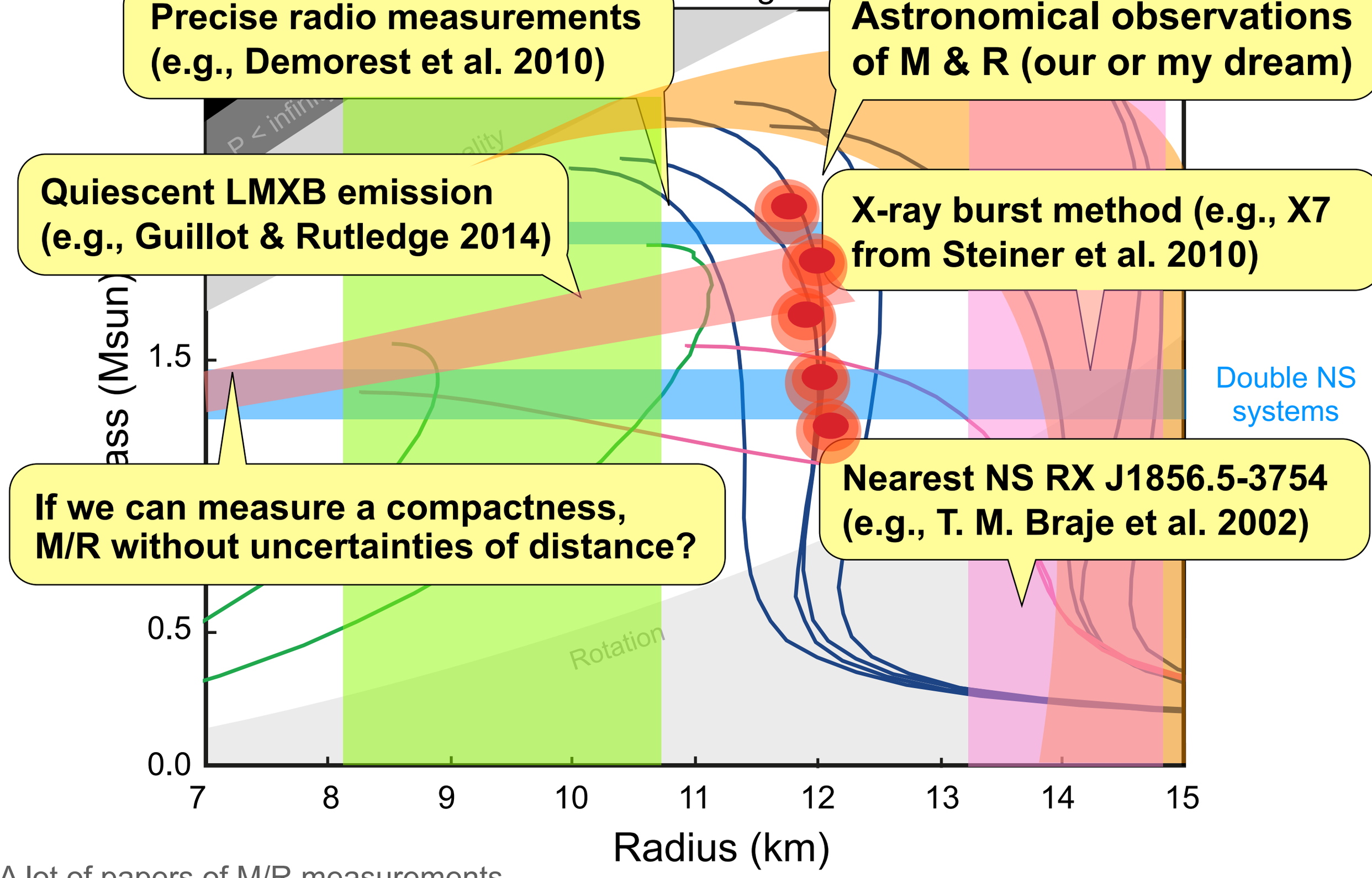
Equation of State of Dense Nuclear Matter





- Unsolved problem of equation of state inside neutron stars, of which density exceeds the nuclear density $\rho=3\times10^{14}$ g/cm^3
- (P, ρ) curves correspond with (M, R) ones
- Astronomical measurements are needed.
  - Precise mass determination via binary motions
  - Difficult radius estimation (distance, atmosphere, B-field)

Measurements of NS mass and radius (EoS)

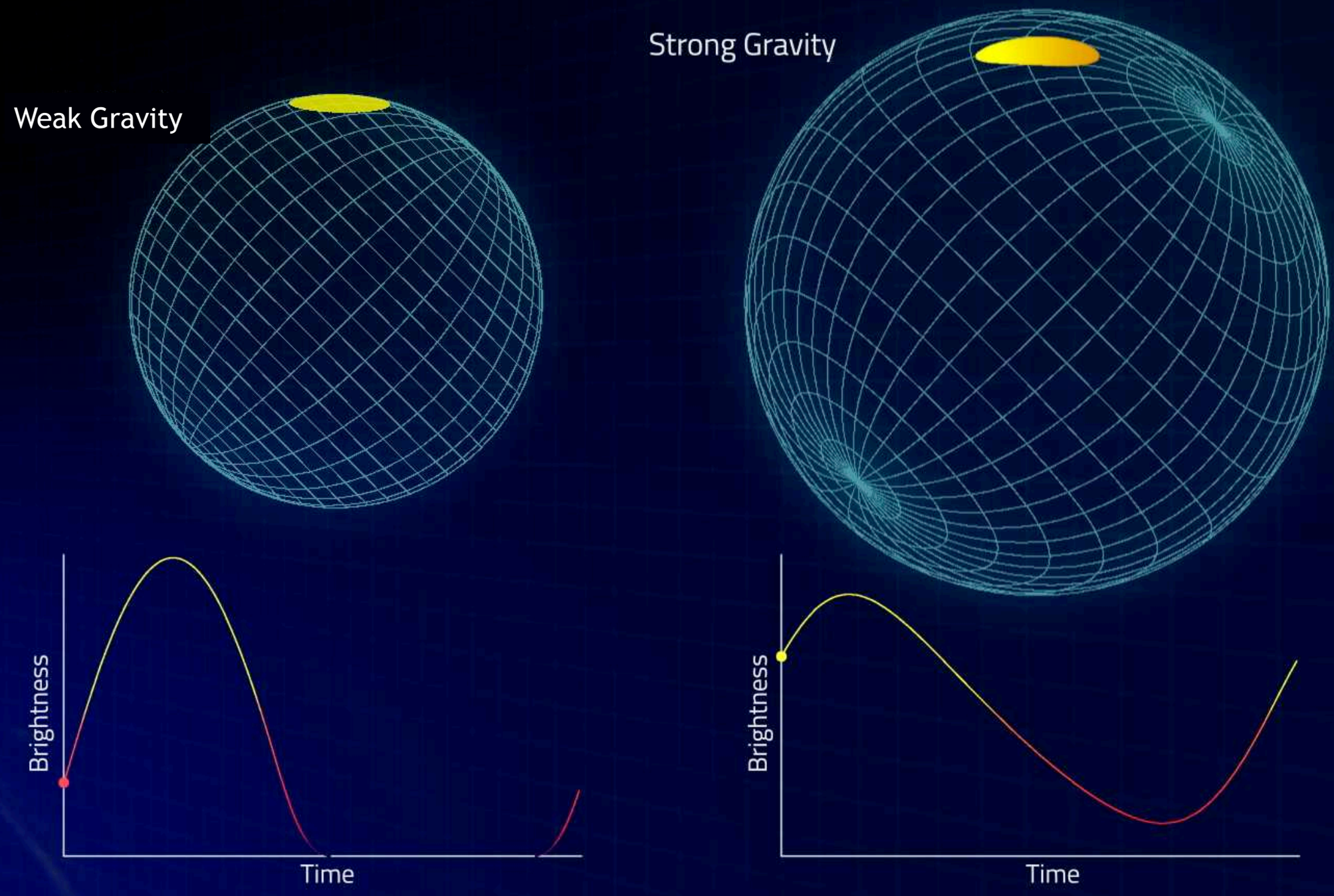


A lot of papers of M/R measurements
(see review in detail, Bhattacharyya 2010)

EoS Curves from Demorest et al. 2010

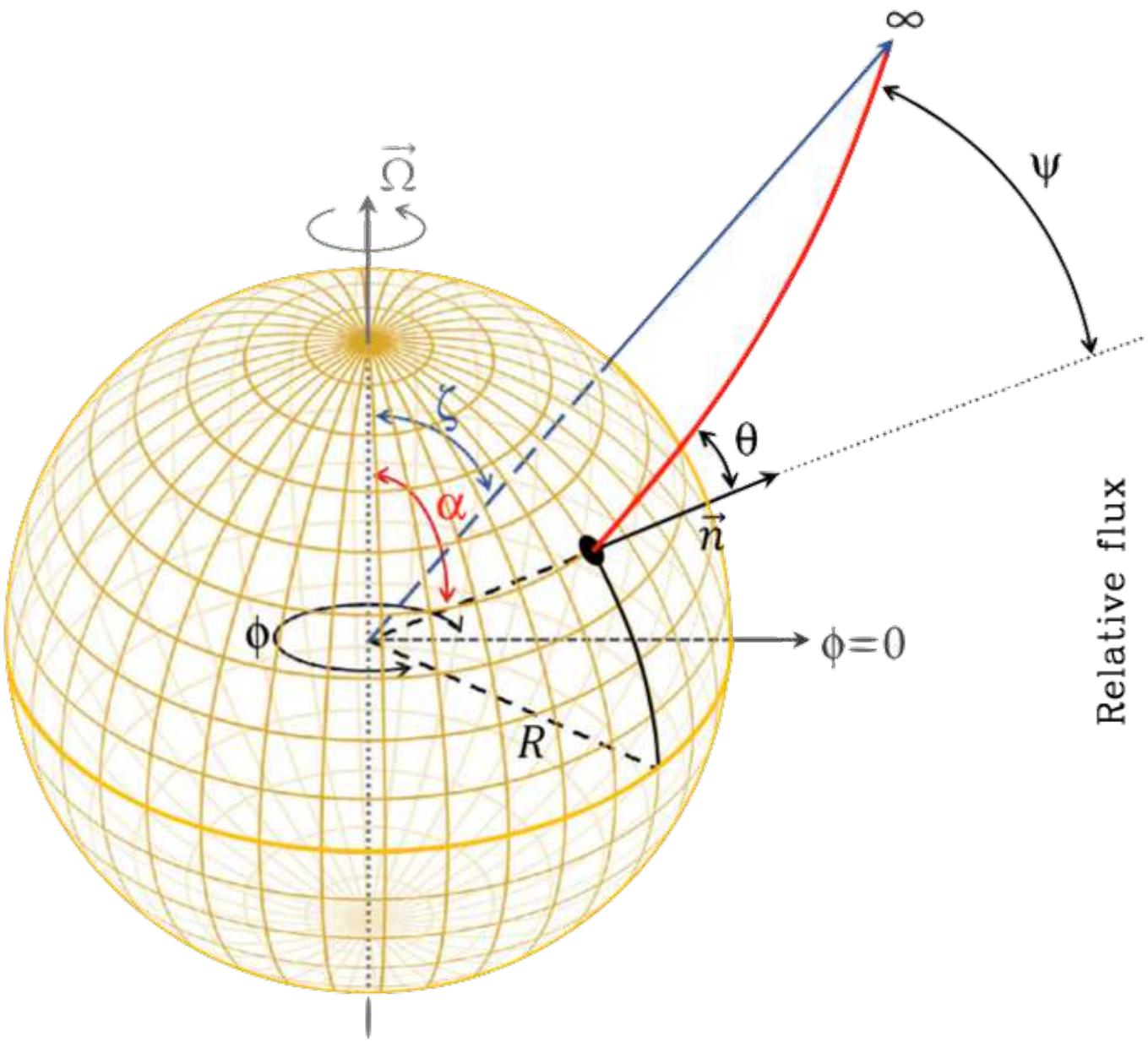
Modeling Surfacee X-ray Emission to Infer M-R

Lightcurve modeling of the gravitational light-bending constrains the compactness (M/R) and viewing geometry of a non-accreting millisecond pulsar through the depth of modulation and harmonic content of emission from rotating hot-spots.

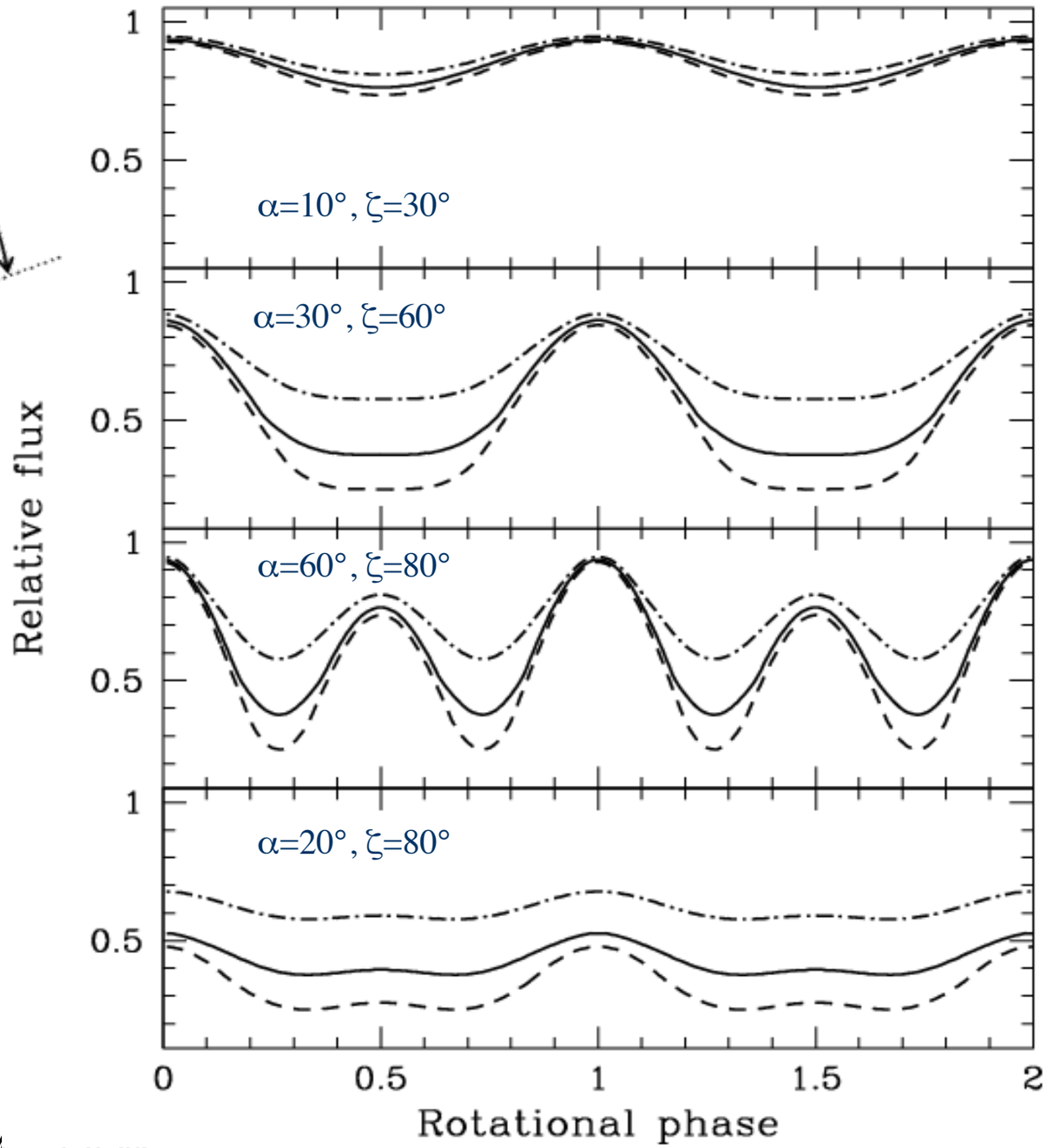


Credit: S. Morsink/NASA

Inferred NS radii through light curve modeling



Bogdanov, Rybicki, & Grindlay, *ApJ*, 670, 668 (2007)

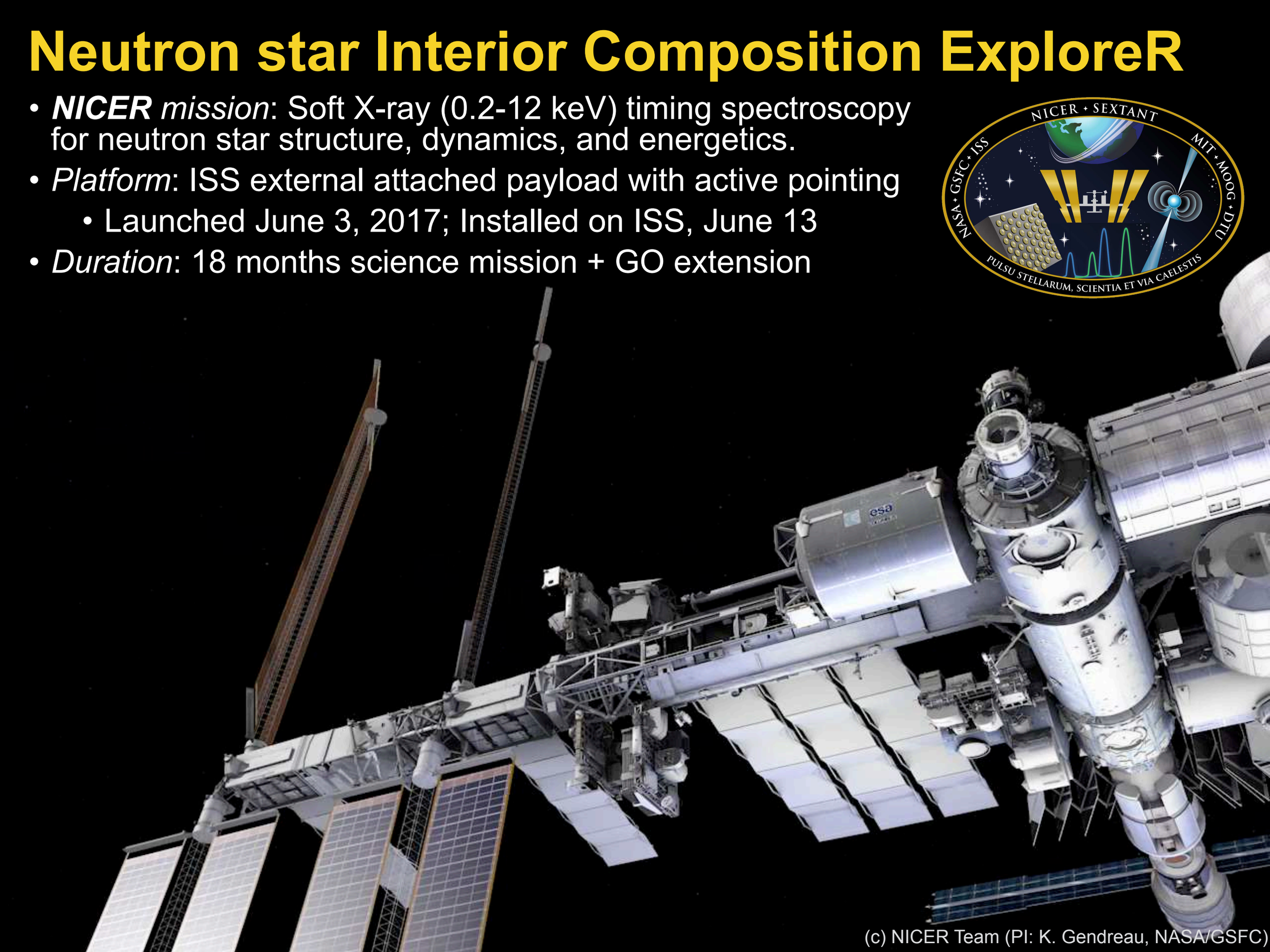


9 km
12 km
16 km
} for M = 1.4 $M_\odot$

(Gendreau, Arzoumanian, and NICER Collaboration)

Neutron star Interior Composition ExploreR

- ***NICER*** *mission*: Soft X-ray (0.2-12 keV) timing spectroscopy for neutron star structure, dynamics, and energetics.
- *Platform*: ISS external attached payload with active pointing
  - Launched June 3, 2017; Installed on ISS, June 13
- *Duration*: 18 months science mission + GO extension



(c) NICER Team (PI: K. Gendreau, NASA/GSFC)

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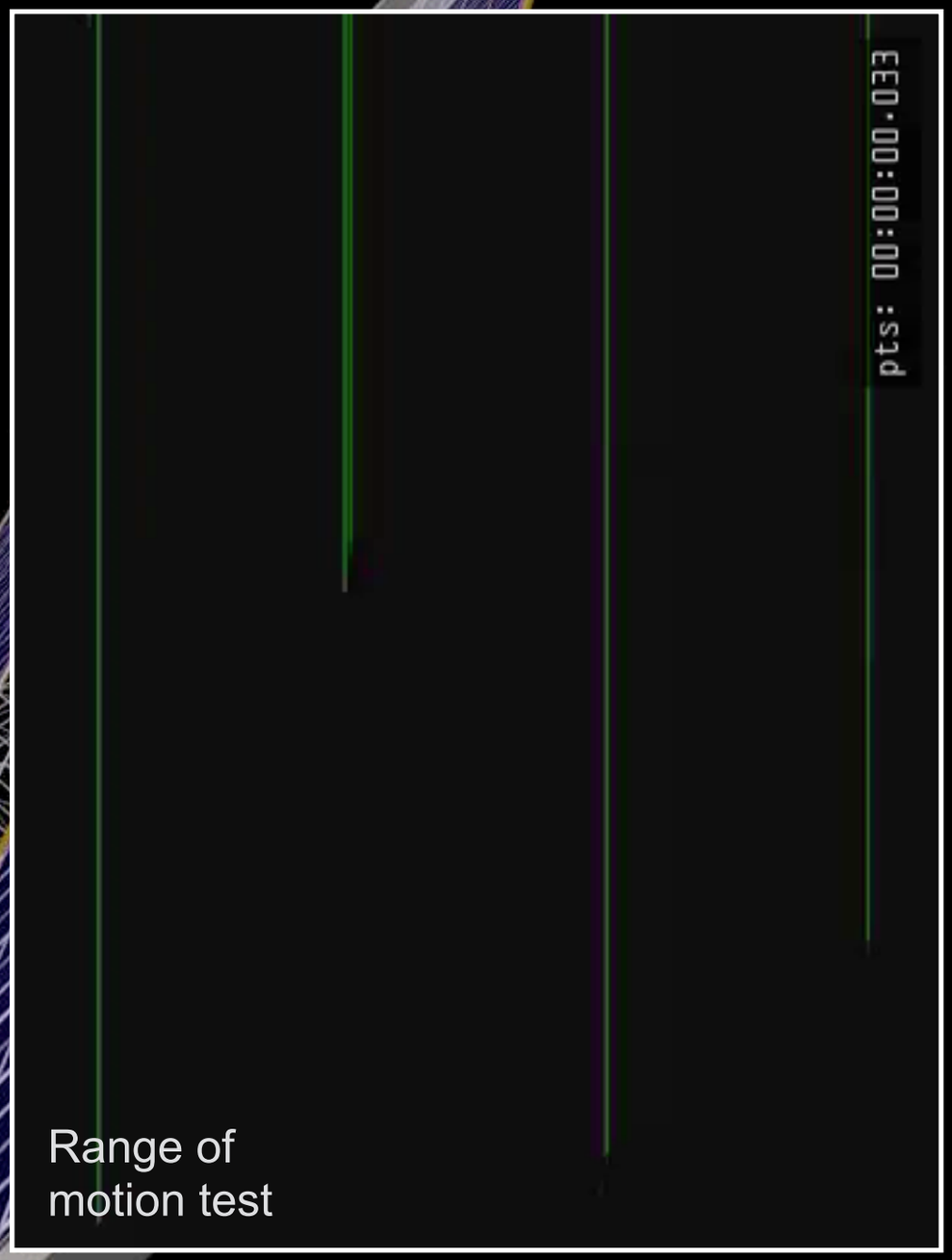
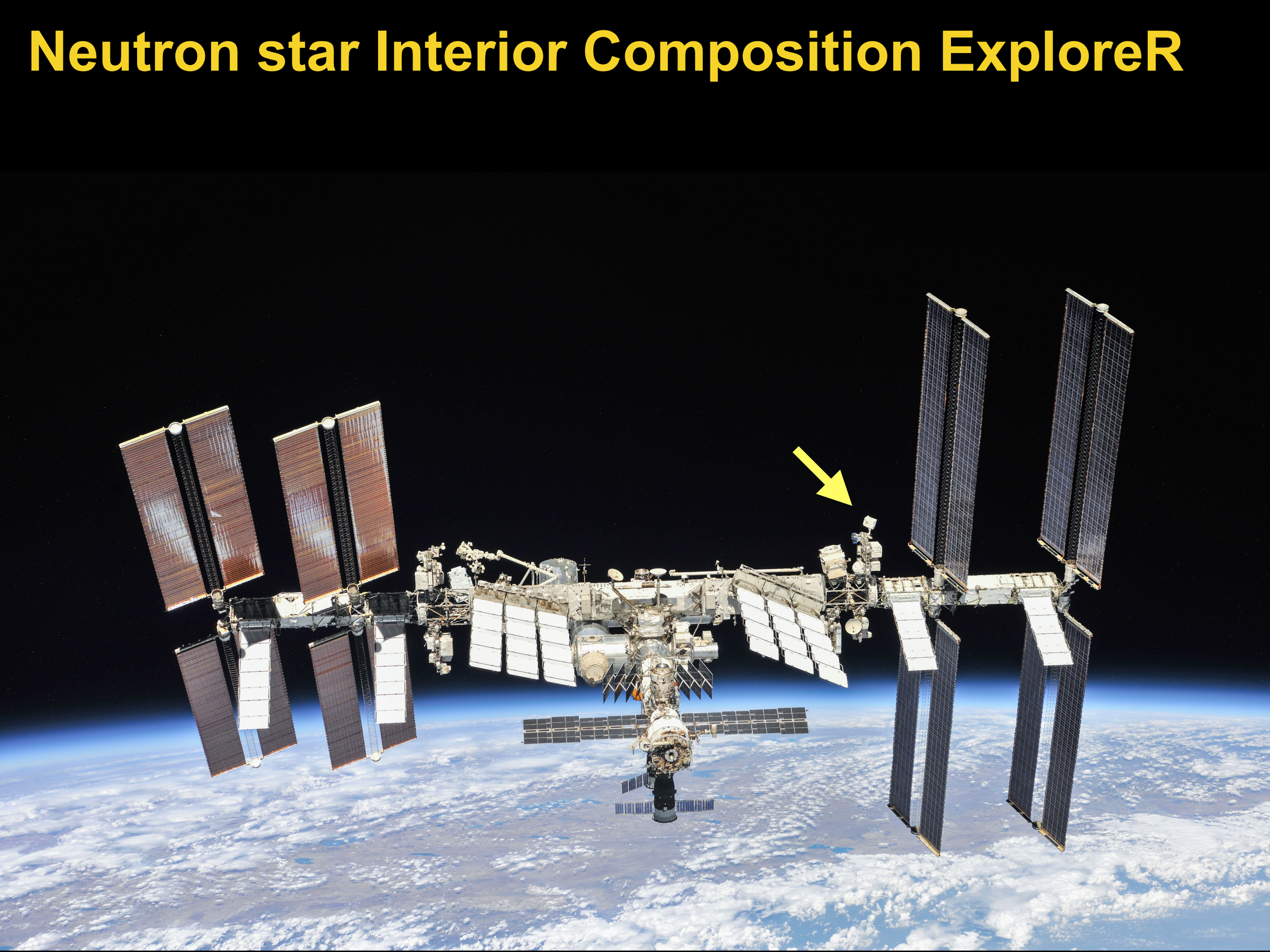


Range of motion test



(c) NICER Team (PI: K. Gendreau, NASA/GSFC)

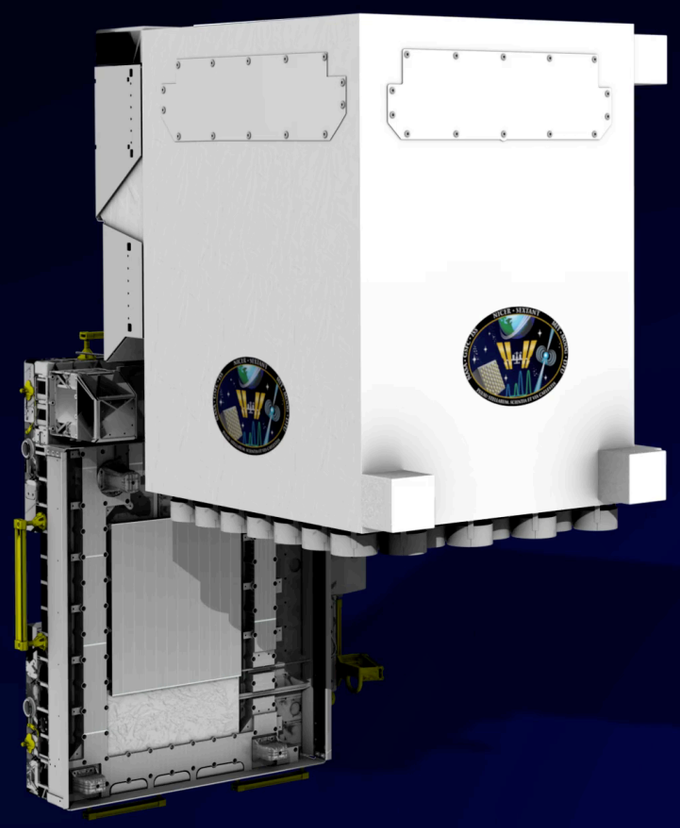
Neutron star Interior Composition ExploreR



NICER

Neutron Star Interior Composition Explorer

(c) NICER Team
(PI: K. Gendreau, NASA/GSFC)

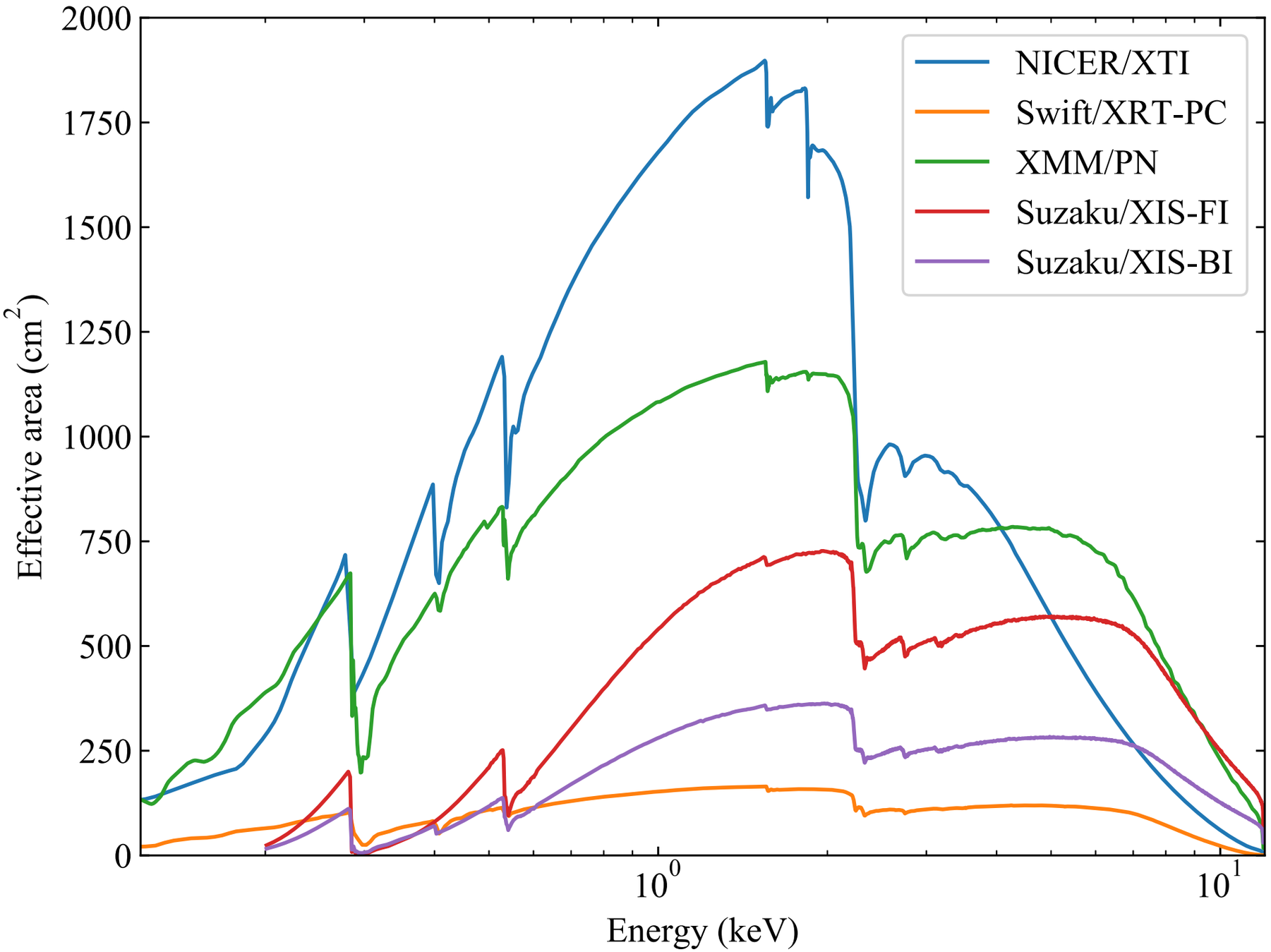


- Energy band : 0.2-12 keV (Resolution : 85 eV @ 1 keV, 140 eV @ 6 keV)
- Time resolution : <100 ns RMS (absolute)
- Non-imaging FOV 6 arcmin diameter
- Background : < 0.5 cps
- Sensitivity: 1×10^{-13} erg/s/cm^2 (5σ, 0.5-10 keV, 10 ksec exposure for Crab-like)
- Max rate: ~38,000 cps (3.5 Crab)

Gendreau et al., SPIE (2012), Arzoumanian et al., (2014)

Large Effective Area of NICER

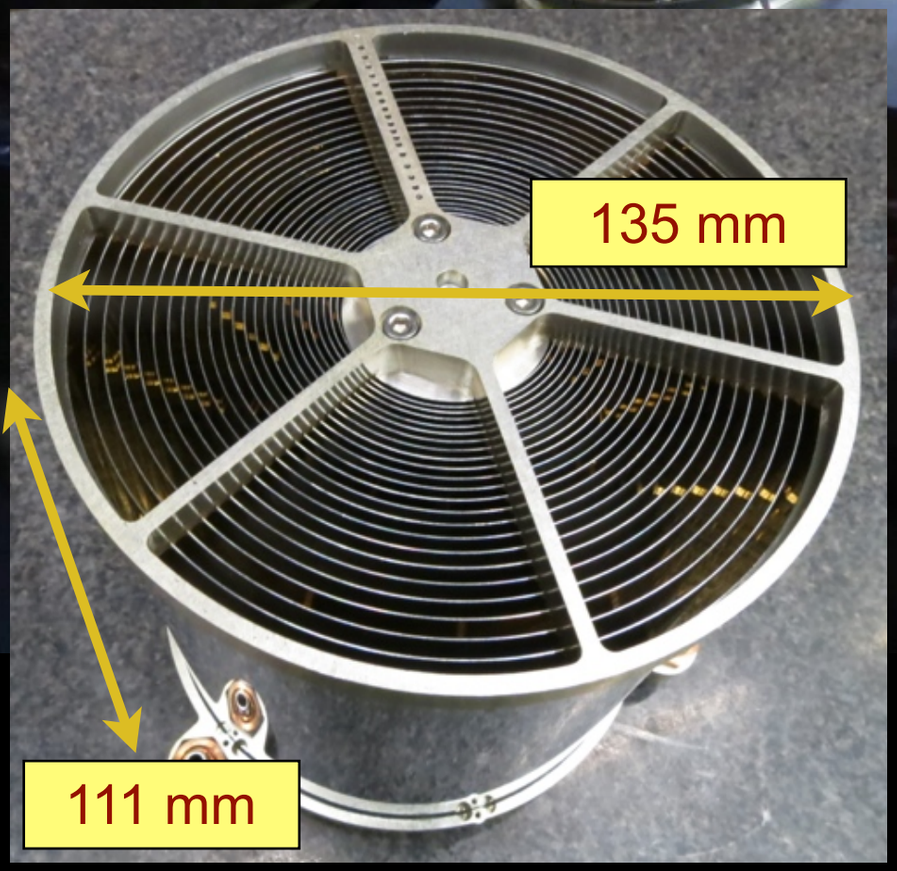
- 56 parallel X-ray Timing Instruments (XTIs)
- XTI = X-Ray Concentrator (XRC) + Sillicon Drift Detector (SDD)
- Large effective area (x2 of XMM at 1.5 keV), Dedicated to NS surface emission.



(K. Gendreau, et al., SPIE, 2012; Z. Arzoumanian, et al., SPIE, 2014)

X-Ray Concentrator optics (XRC)

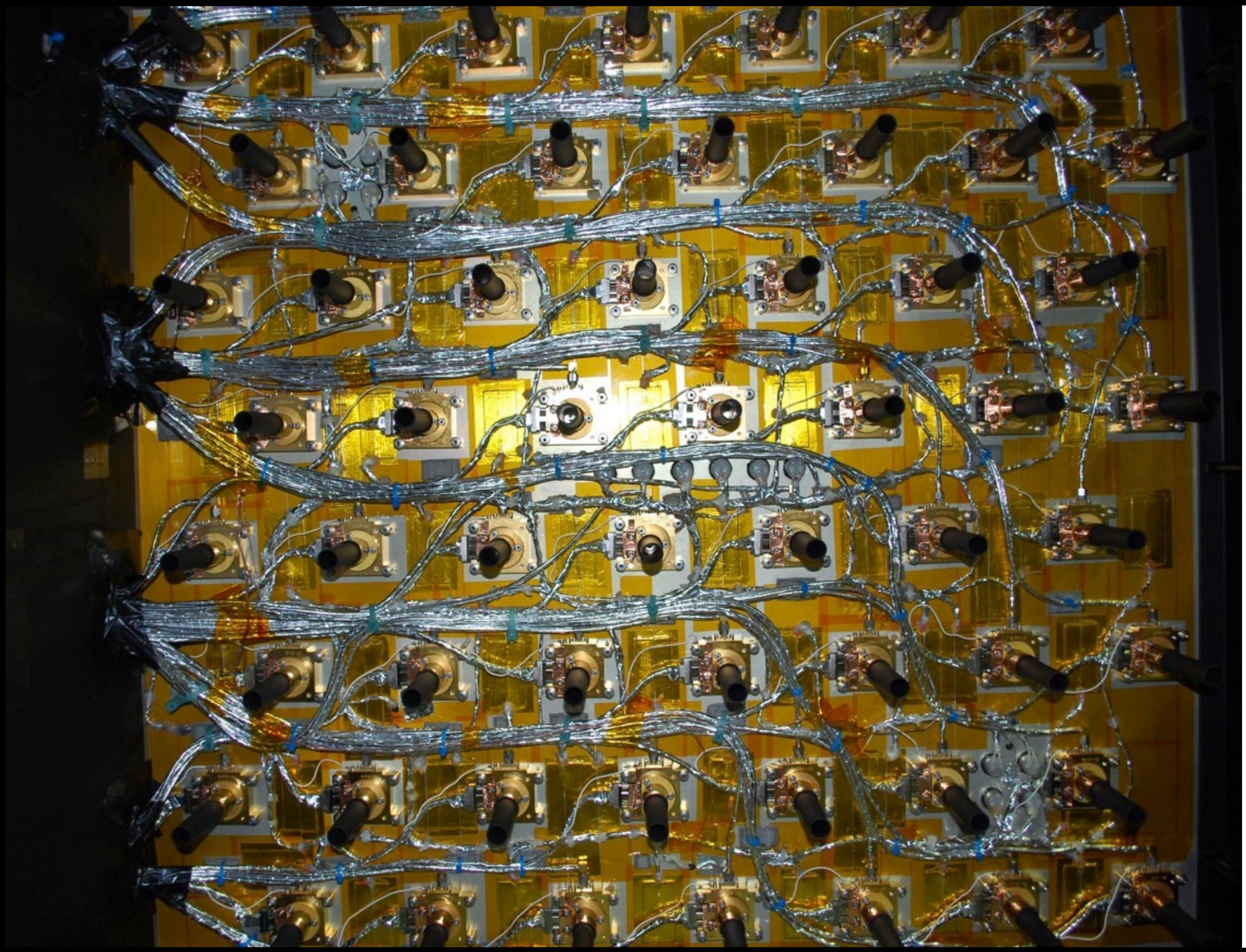
Single reflection, grazing-incidence nested gold-coated Al foils



- Multiple 24 shells are confocally nested to increase an effective area. (24x56=1344 foils)
- Grazing incidence optic of a parabolic gold surface to focus X-rays onto a detector (2 mm).
- Focal length = 1085 mm
- Total effective area > 1800 cm^2 @1.5 keV

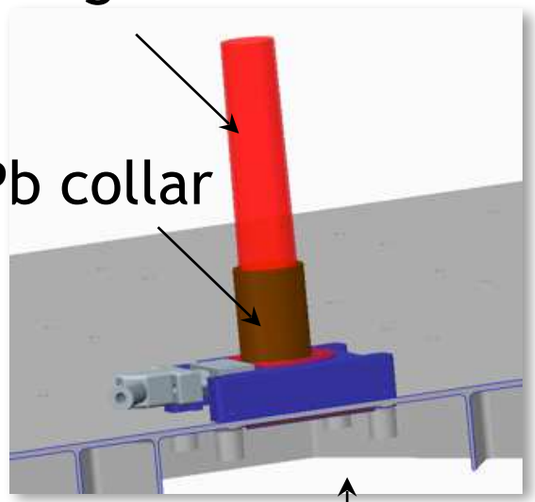
Sillicon Drift Detectors (SDDs)

Resolution : 140 eV @ 6 keV, Time resolution : <100 ns RMS (absolute)

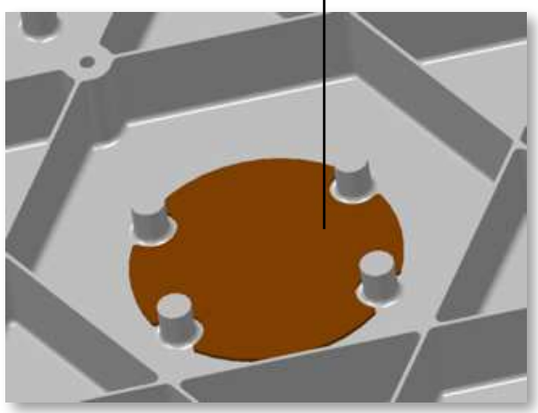


Radiation shielding

Au/Ag “traffic cone”



Pb disk



Launch by SpaceX-11 resupply, June 3, 2017

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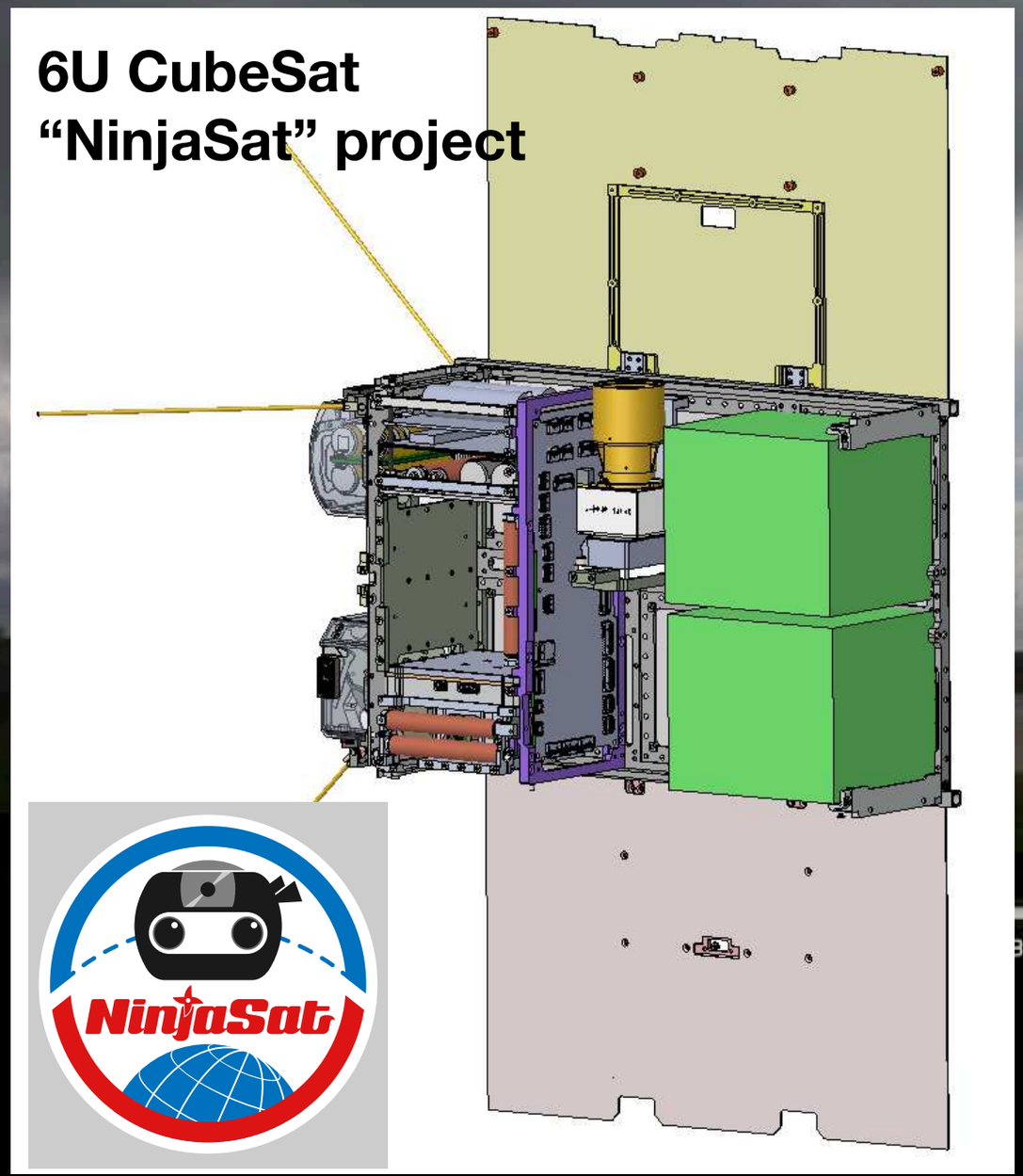
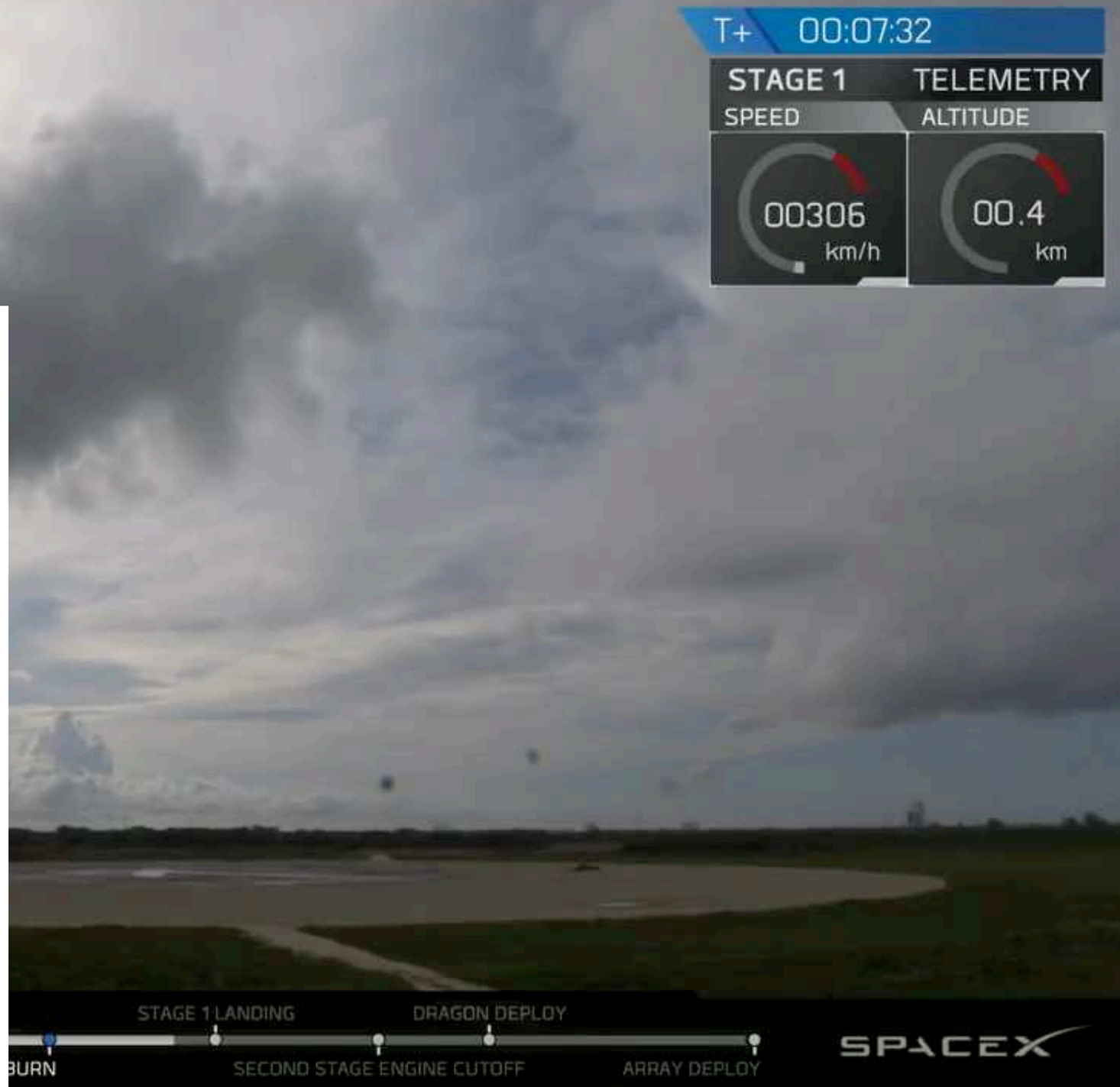
Falcon 9 rocket, Kennedy Flight Center

SpaceX “CRS-11 Hosted Webcast” YouTube: https://www.youtube.com/watch?v=JuZBOUMsYws

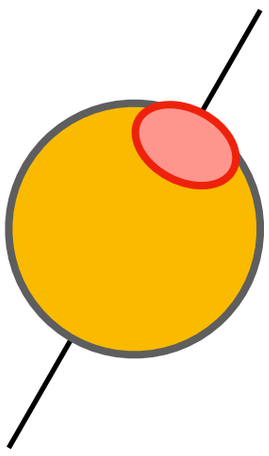
Launch by SpaceX-11 resupply, June 3, 2017





SpaceX “CRS-11 Hosted Webcast” YouTube
https://www.youtube.com/watch?v=JuZBOUMsYws

Rotation-Powered Millisecond Pulsars



- *Good targets for the M-R measurements via light curve modelings because …*

- soft X-rays are produced by thermal emission from hotter regions around their magnetic poles.

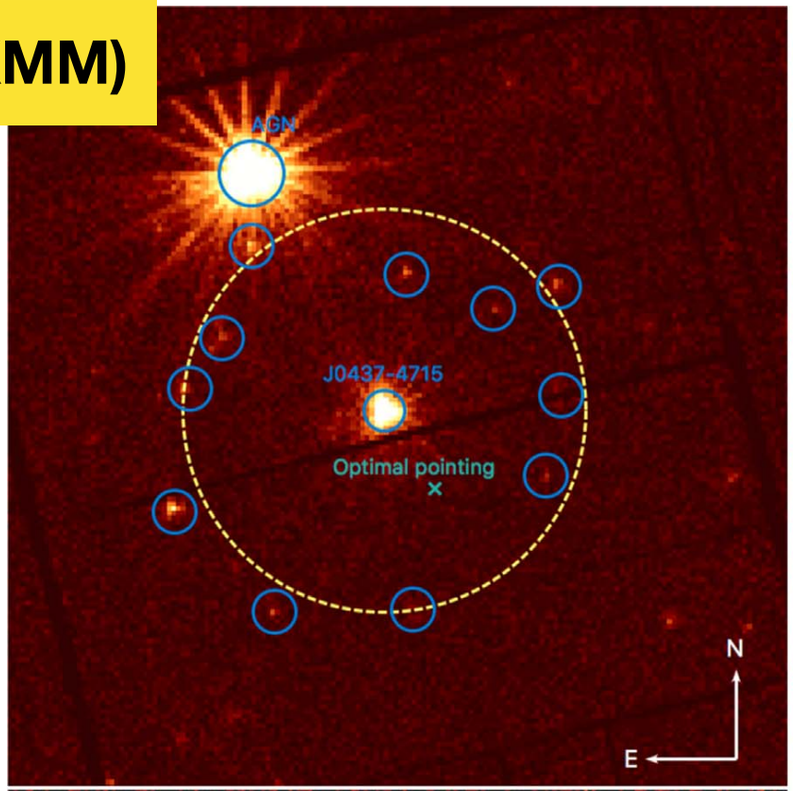
- Pulsations are always present, of which beaming pattern and spectrum are relatively well understood.

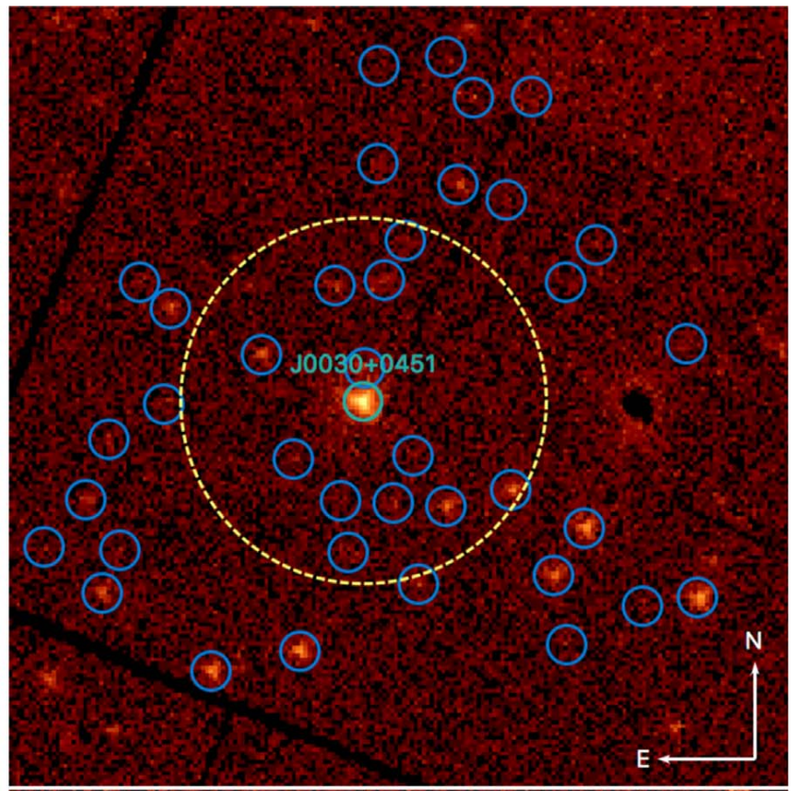
- Stellar rotation is rapid and exceptionally stable in a long time scale.

Four Nearby Rotation-Powered msec PSRs

X-ray image (XMM)

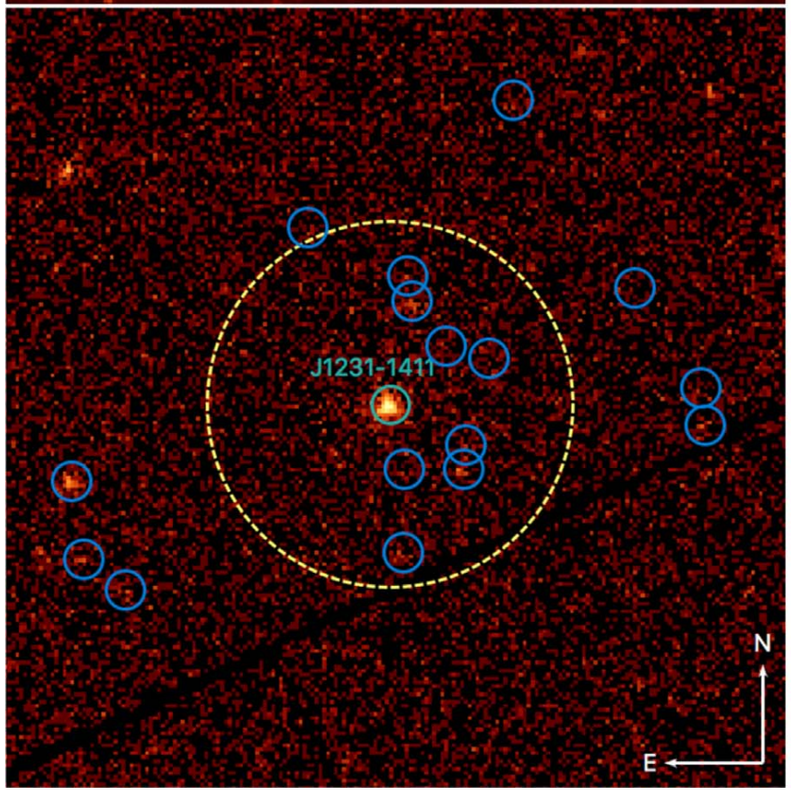
J0437-4715
P=5.76 ms
d=157 pc

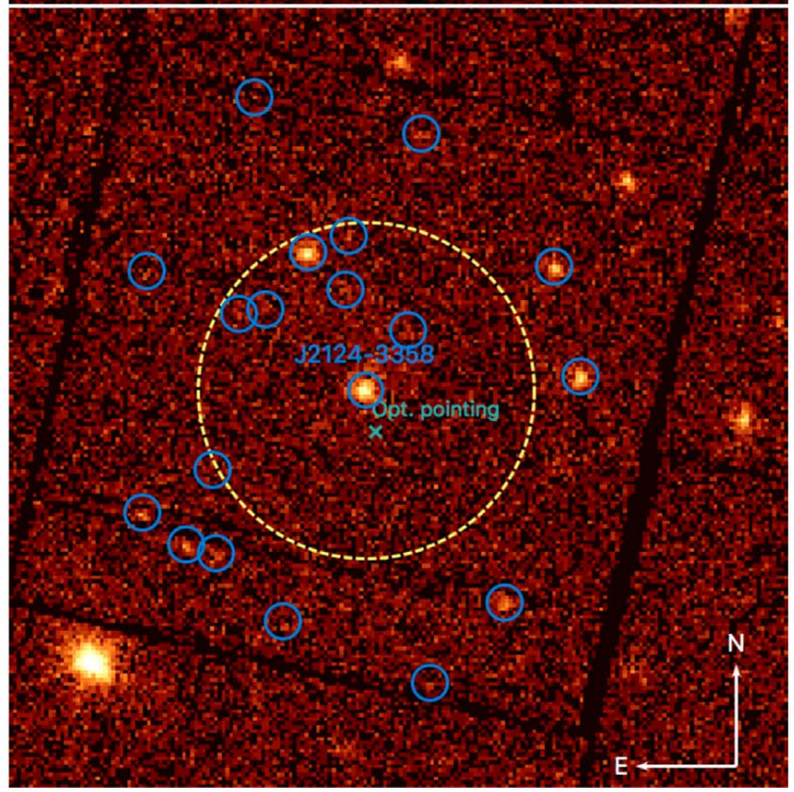




J0030+0451
P=4.87 ms
d=325 pc

J1231-1411
P=3.68 ms
d=420 pc





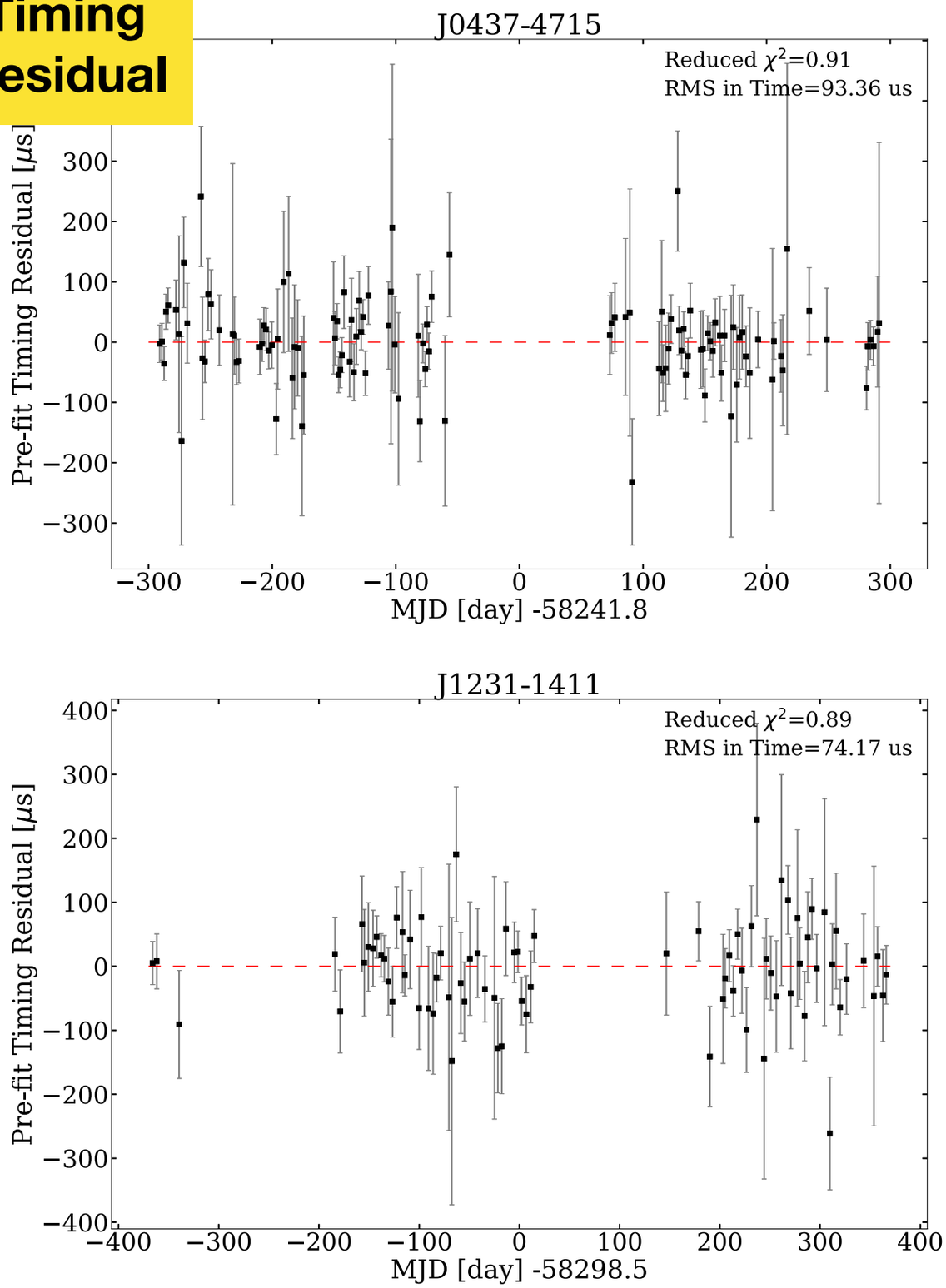
J2124-3358
P=4.93 ms
d=410 pc

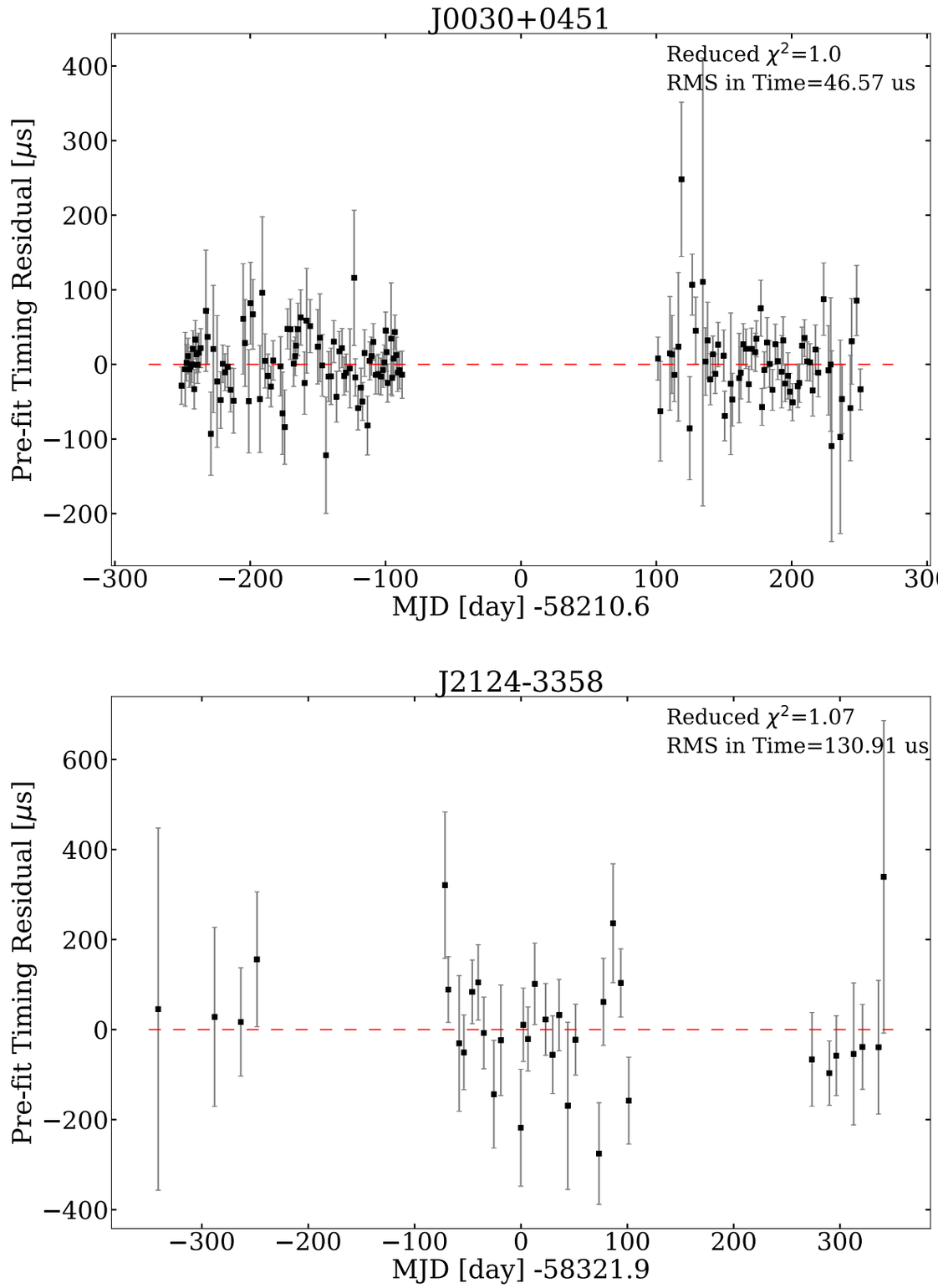
Bogdanov et al., ApJL, 2019a

Circle: NICER PSF of 6’2 (HPD)

Four Nearby Rotation-Powered msec PSRs

Timing Residual





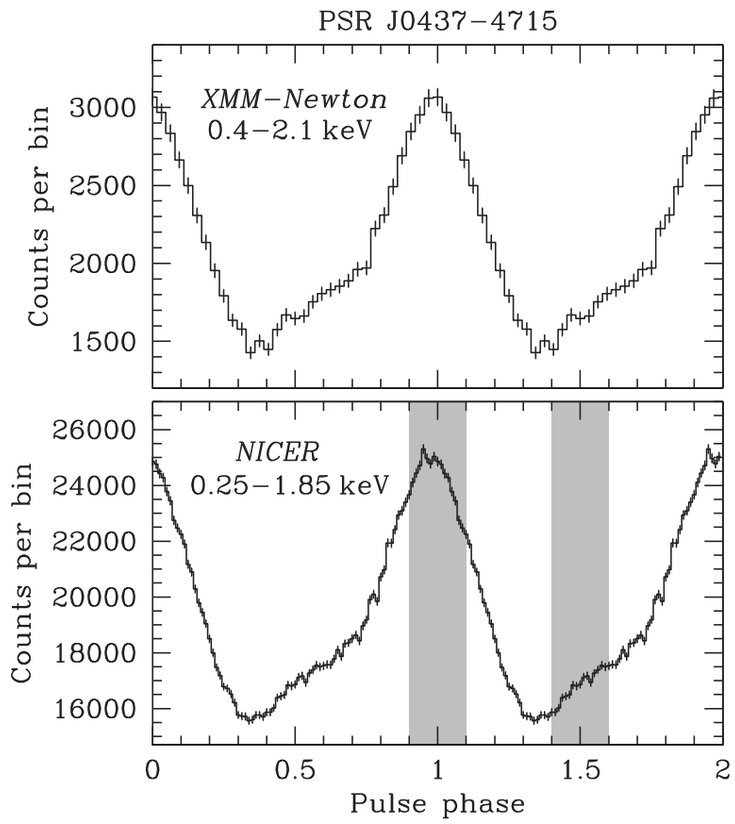
Bogdanov et al., ApJL, 2019a

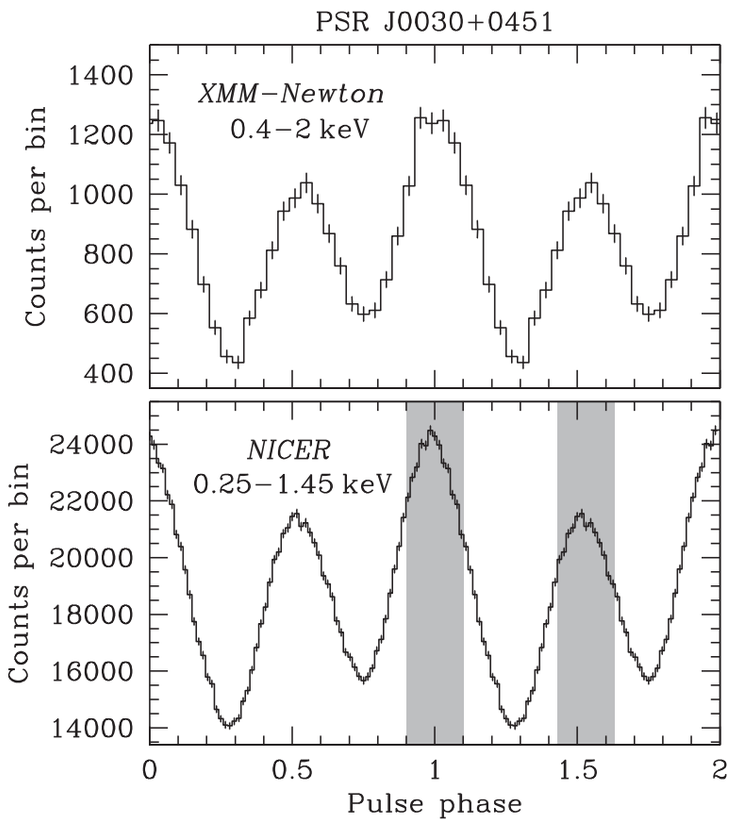
Long-term stability without any anomalies!

Four Nearby Rotation-Powered msec PSRs

X-ray Profiles

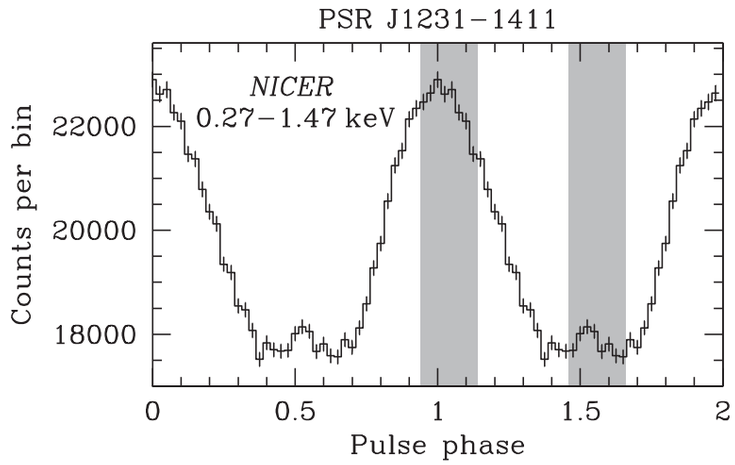
J0437-4715
P=5.76 ms
1.43 cps
(NICER rate)

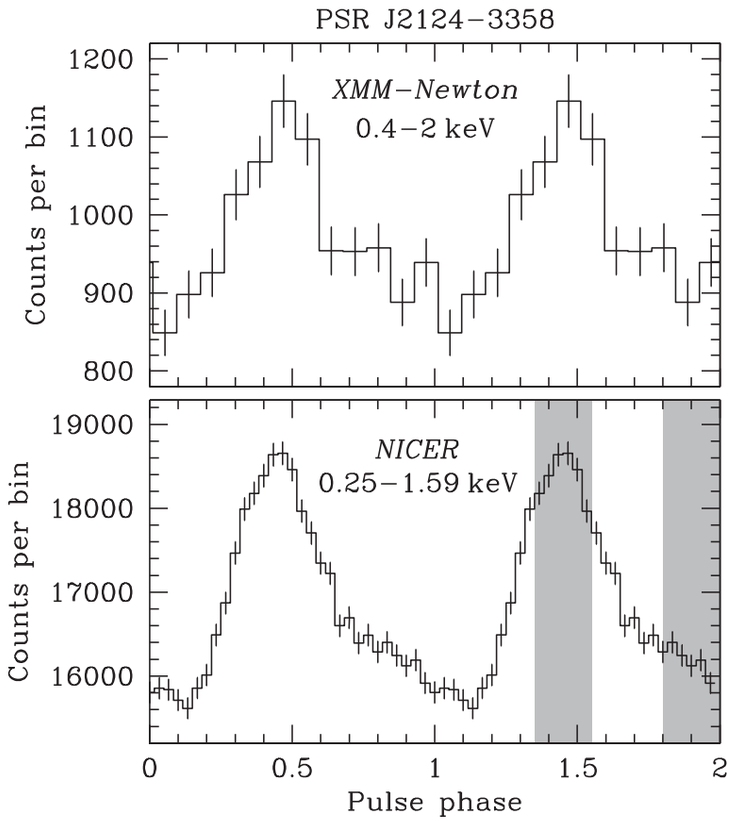




J0030+0451
P=4.87 ms
0.314 cps

J1231-1411
P=3.68 ms
0.210 cps



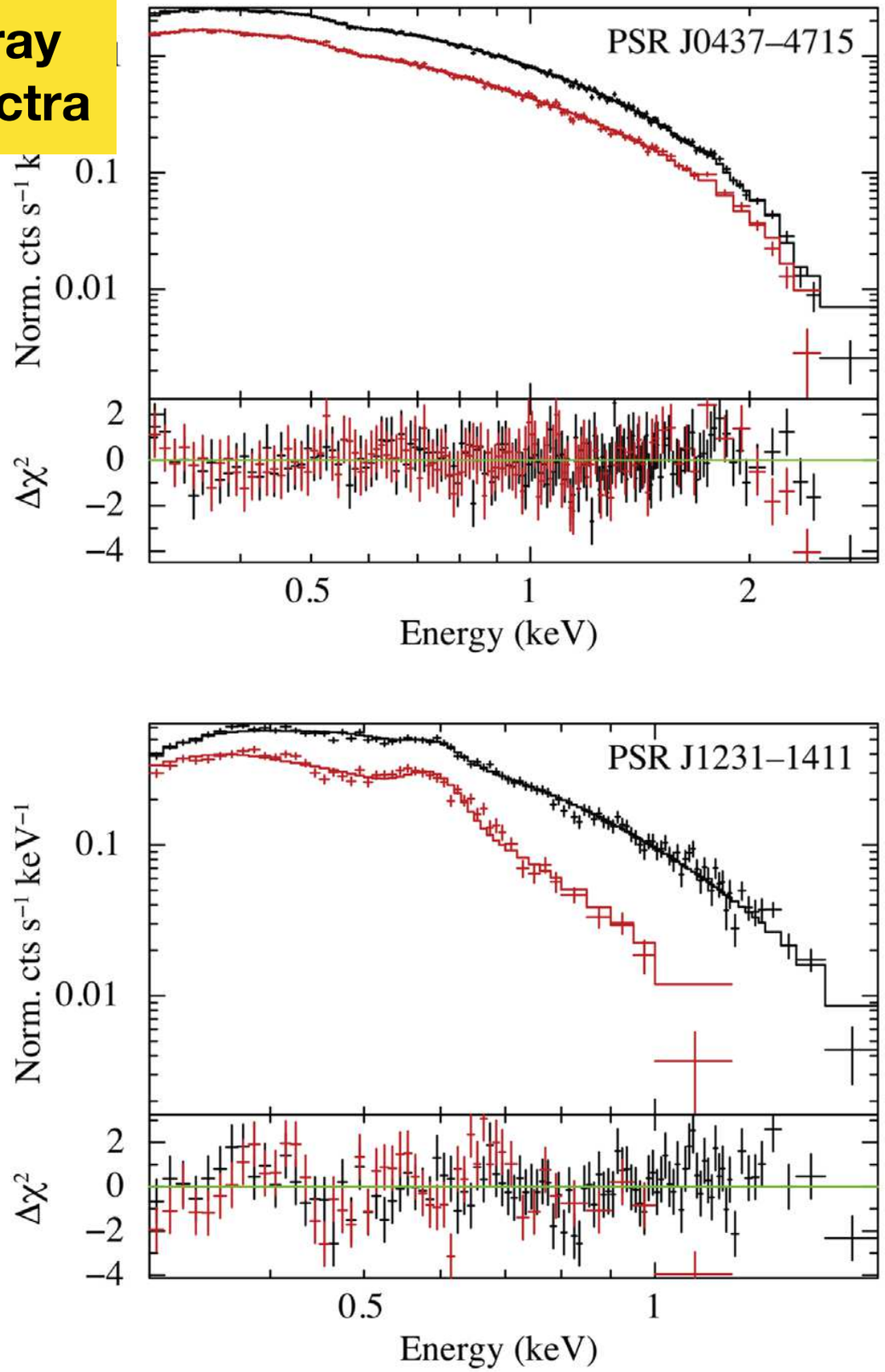


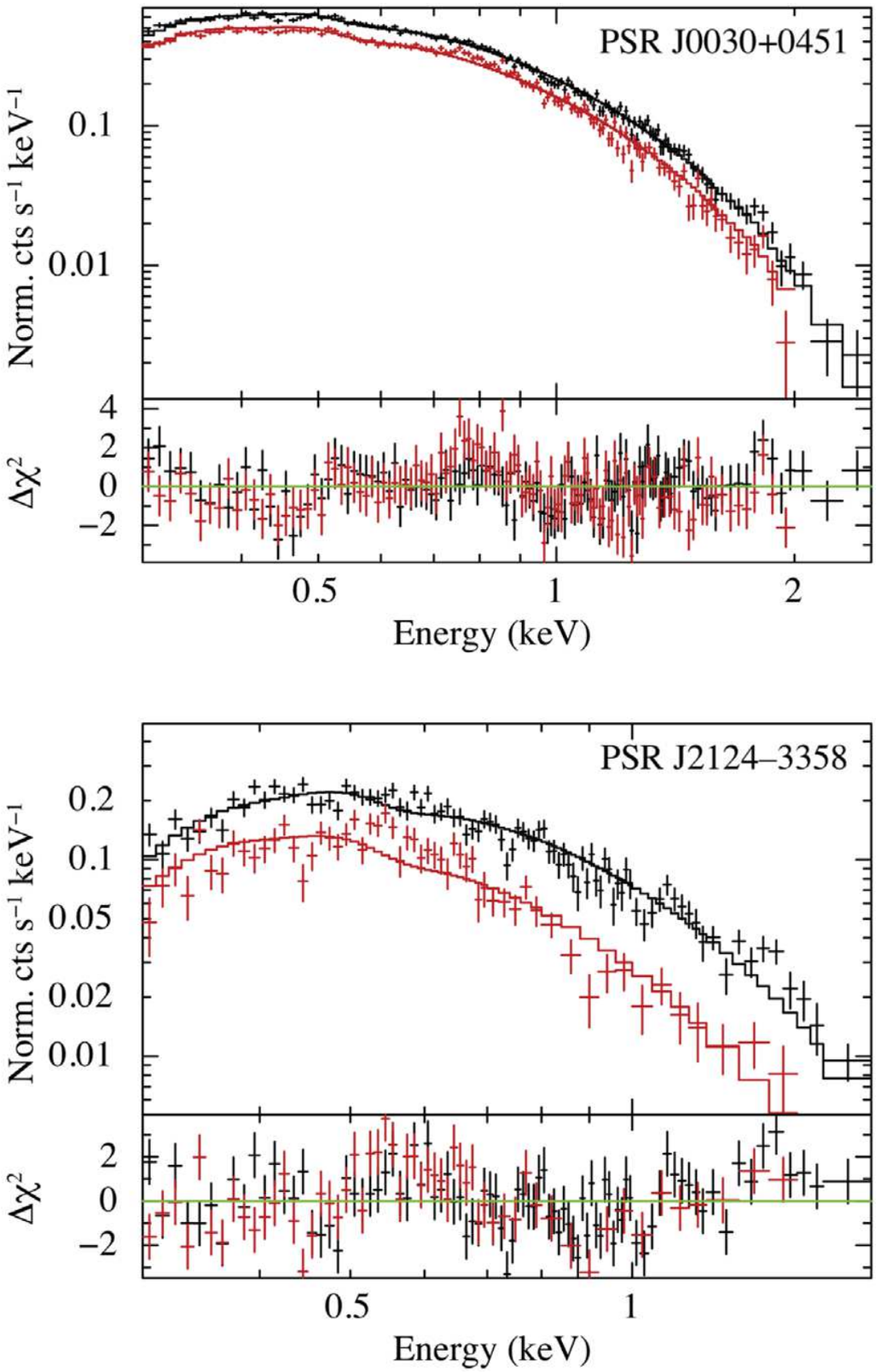
J2124-3358
P=4.93 ms
0.110 cps

Bogdanov et al., ApJL, 2019a

Four Nearby Rotation-Powered msec PSRs

X-ray Spectra





Bogdanov et al., ApJL, 2019a

Black: 1st peak, Red: 2nd (sub) peak

A Millisecond Pulsar : PSR J0030+0451

- *P*=4.87 msec pulsar (*f* = 205 Hz) with a long timing stability.

- NICER observed this target in 2017-2018 with a total 1.94 sec exposure without any timing and flux anomalies.

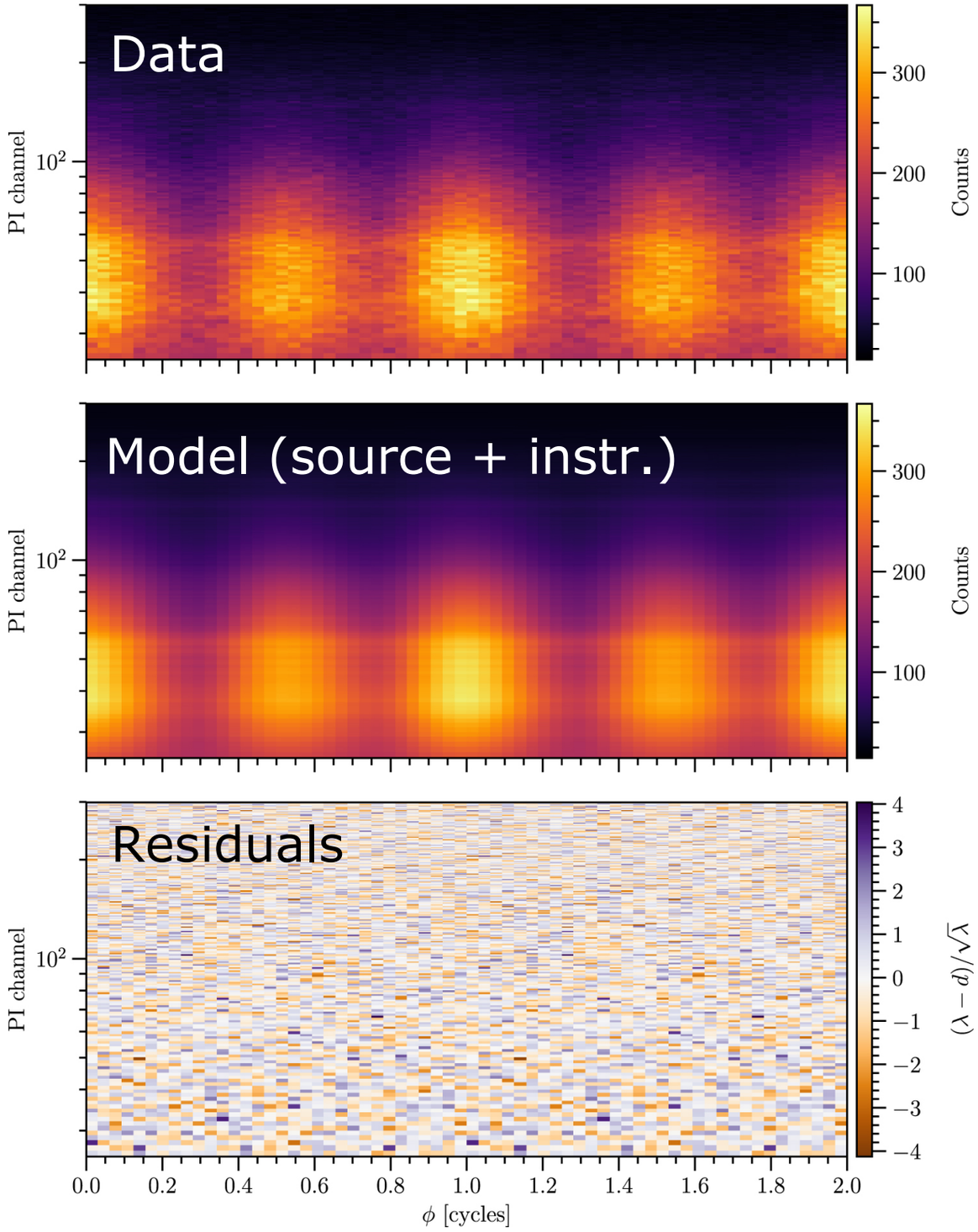
- Emission from individual pulse peaks (hot spots) is well described by a single-temperature hydrogen atmosphere model.

- NICER team developed numerical codes of surface emission from a rapidly rotation neutron star.

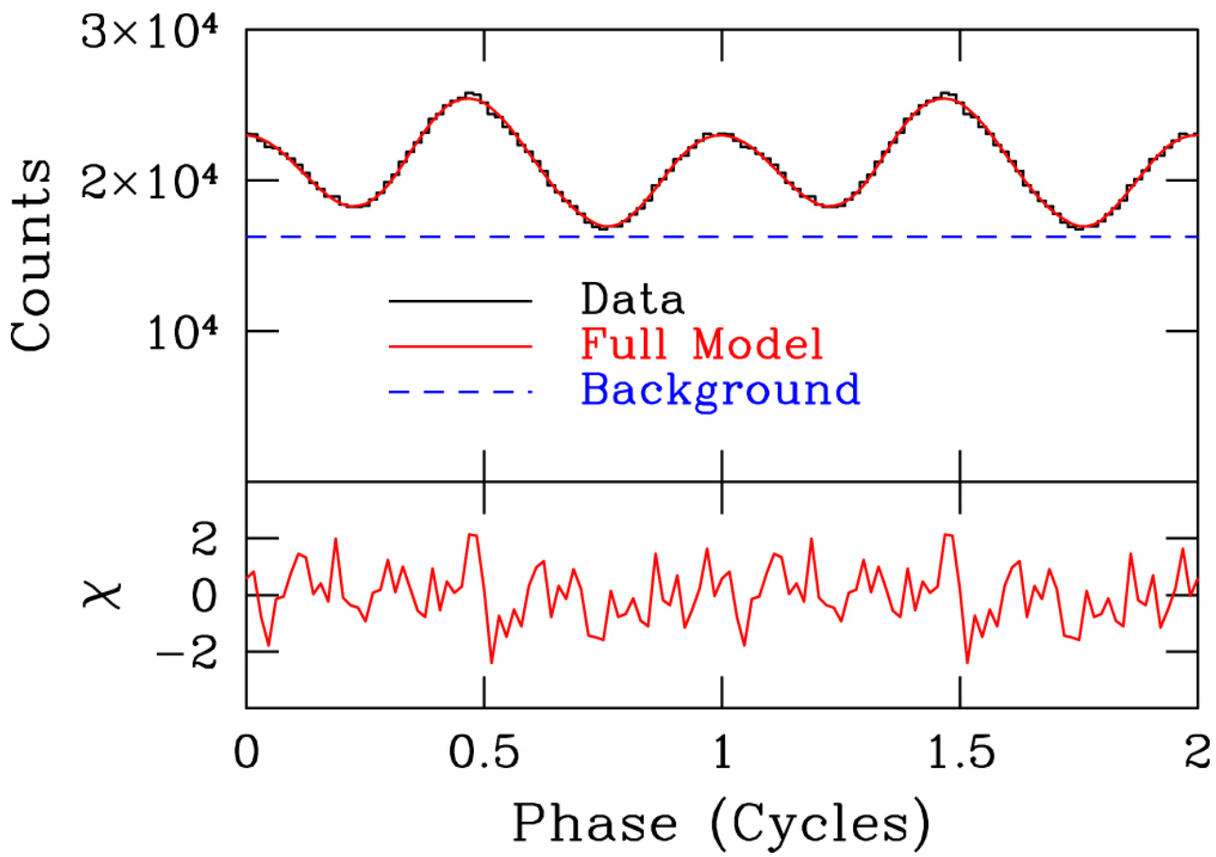
- Inferences drawn from Bayesian modeling of the pulsar pulse-profile provide estimation of the pulsar mass and radius.

NICER Measurements of PSR J0030+0451

Two independent methods showed identical results for mass and radius!



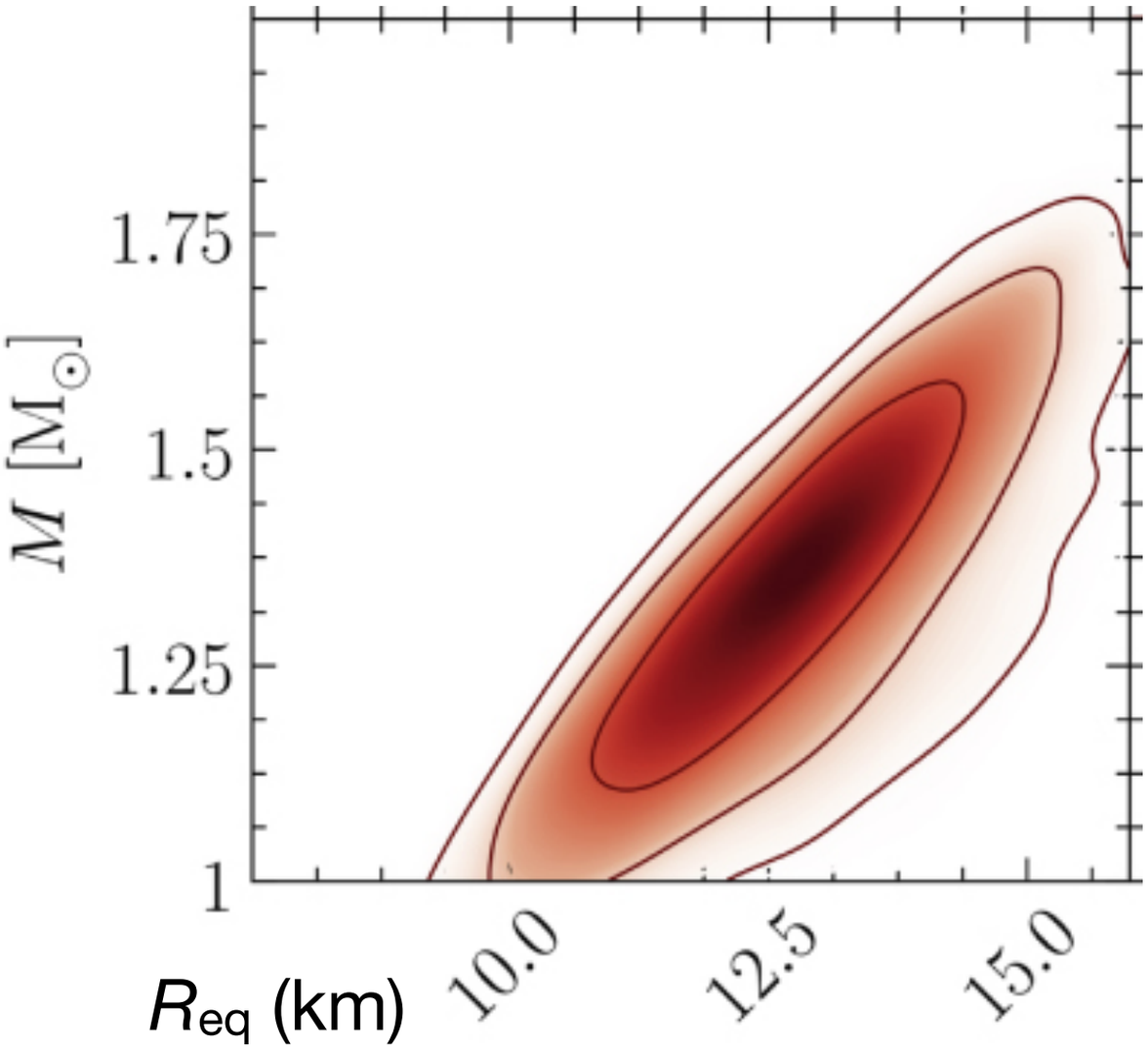
Riley et al. ApJL (2019), Univ. of Amsterdam

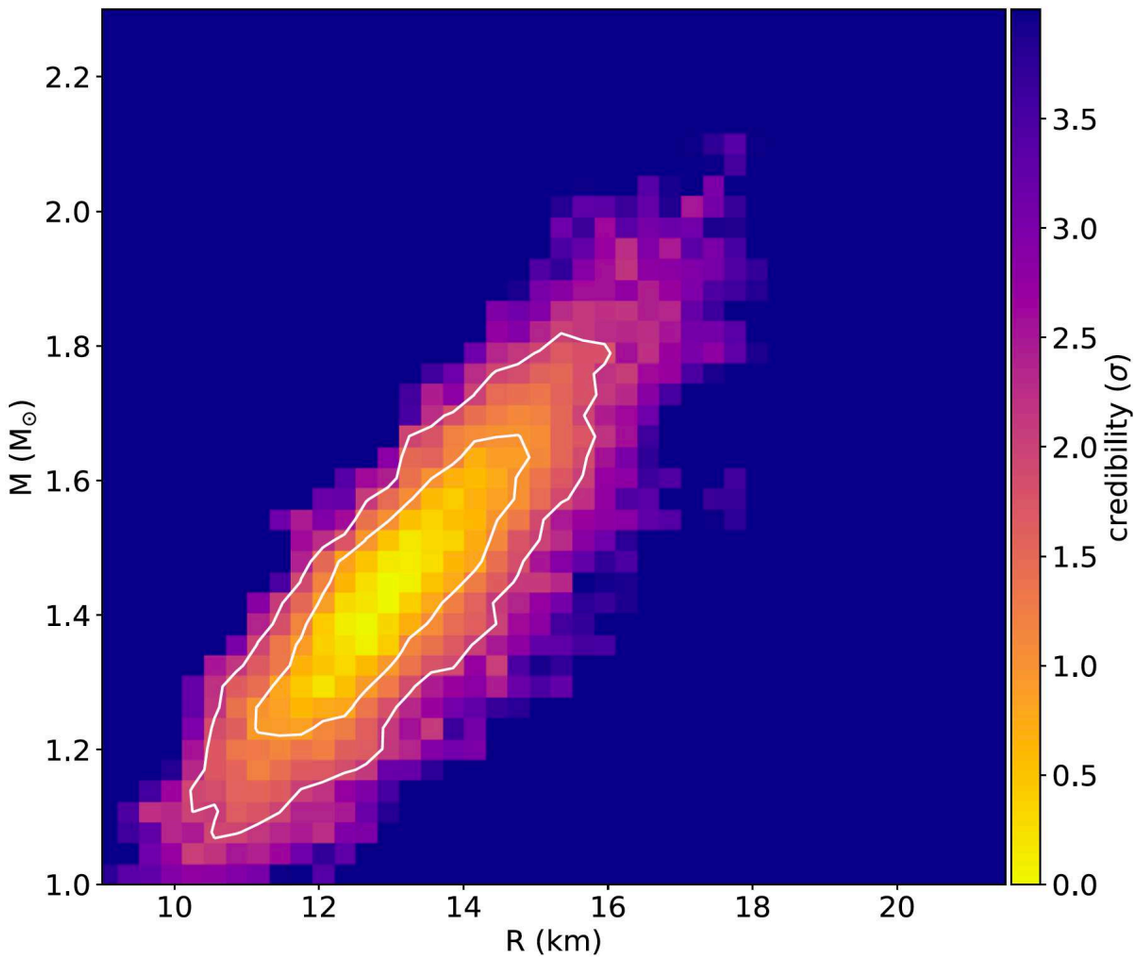


Miller et al. ApJL (2019), Univ. of Maryland

NICER Measurements of PSR J0030+0451

Two independent methods showed identical results for mass and radius!





$M = 1.34 \pm 0.15\ M_{sun}$
$R = 12.71 \pm 1.17$ km

Riley et al. ApJL (2019), Univ. of Amsterdam

$M = 1.44 \pm 0.15\ M_{sun}$
$R = 13.02 \pm 1.15$ km

Miller et al. ApJL (2019), Univ. of Maryland

NICER Measurements of PSR J0030+0451

Two independent methods showed identical results for mass and radius!

NICER Press Release Webpage
https://iopscience.iop.org/journal/2041-8205/page/Focus_on_NICER_Constraints_on_the_Dense_Matter_Equation_of_State



two hot spots — one small and circular, the other long and crescent-shaped

Riley et al. ApJL (2019), Univ. of Amsterdam



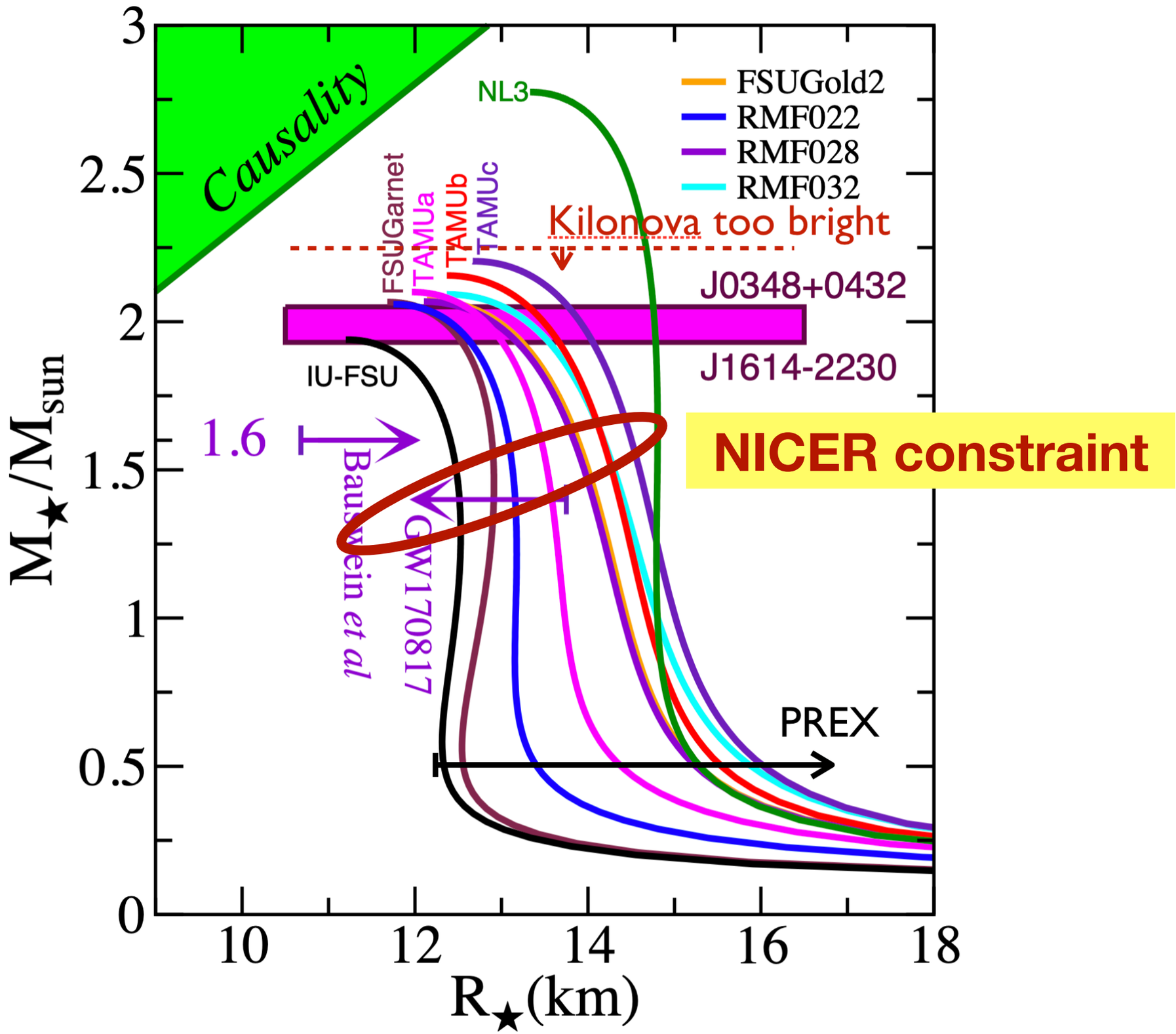
two or three oval-shaped hot spots

Miller et al. ApJL (2019), Univ. of Maryland

Implication from the PSR J0030+0451 Data

- **First precise (±10%) mass and radius measurements for the same star**
  - First mass of an isolated (i.e., non-binary) pulsar
- **First map of surface "hot spot" locations, shapes, sizes, and temperatures**
  - Robust demonstration of non-dipolar magnetic field
- **New constraint on the equation of state of ultra-dense matter**
  - Tightened pressure-density range by 30%

NICER Constrain on the M-R Relation

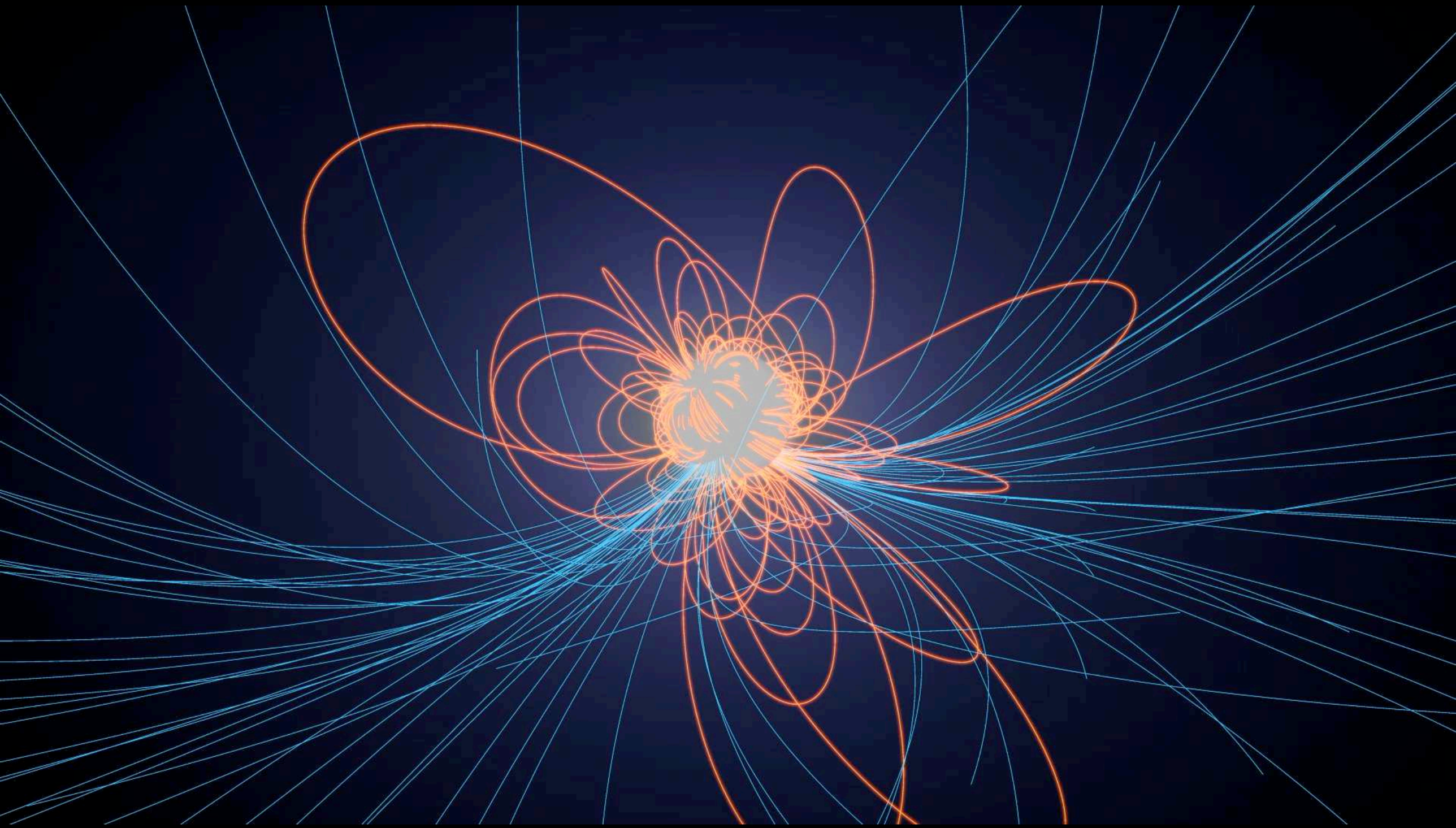


Another three sources will be in the future publications.

Horowitz, arXiv1911.00411v1

Redrawing Pulsar Magnetic Field

More complex than a single dipole.



https://svs.gsfc.nasa.gov/13240

Redrawing Pulsar Magnetic Field

More complex than a single dipole.



Hubble Tracks Bright Auroras on Jupiter
https://hubblesite.org/contents/media/videos/2016/24/866-Video.html?keyword=Planetary%20Atmospheres/Weather

References

1. Bogdanov, et al., “Constraining the Neutron Star Mass–Radius Relation and Dense Matter Equation of State with NICER. I. The Millisecond Pulsar X-Ray Data Set”, *ApJL*, 887, 1, L25 (2019). [link]

2. Bogdanov, et al., “Constraining the Neutron Star Mass–Radius Relation and Dense Matter Equation of State with NICER. II. Emission from Hot Spots on a Rapidly Rotating Neutron Star”, *ApJL*, 887, 1, L26 (2019). [link]

3. Miller et al., “PSR J0030+0451 Mass and Radius from NICER Data and Implications for the Properties of Neutron Star Matter”, *ApJL*, 887, 1, L24 (2019). [link]

4. Riley, et al., “A NICER View of PSR J0030+0451: Millisecond Pulsar Parameter Estimation”, *ApJL*, 887, 1, L21 (2019). [link]

5. Raaijmakers, et al., “A NICER View of PSR J0030+0451: Implications for the Dense Matter Equation of State”, *ApJL*, 887, 1, L22 (2019). [link]

6. Bilous, et al., “A NICER View of PSR J0030+0451: Evidence for a Global-scale Multipolar Magnetic Field”, ApJL, 887, 1, L23 (2019). [link]

NASA Press Release

(link is included in the bullet)

1. NASA news story “NASA’s NICER Delivers Best-ever Pulsar Measurements, 1st Surface Map”

2. NASA/GSFC news story “NASA’s NICER Sizes Up a Pulsar, Reveals First-ever Surface Map”

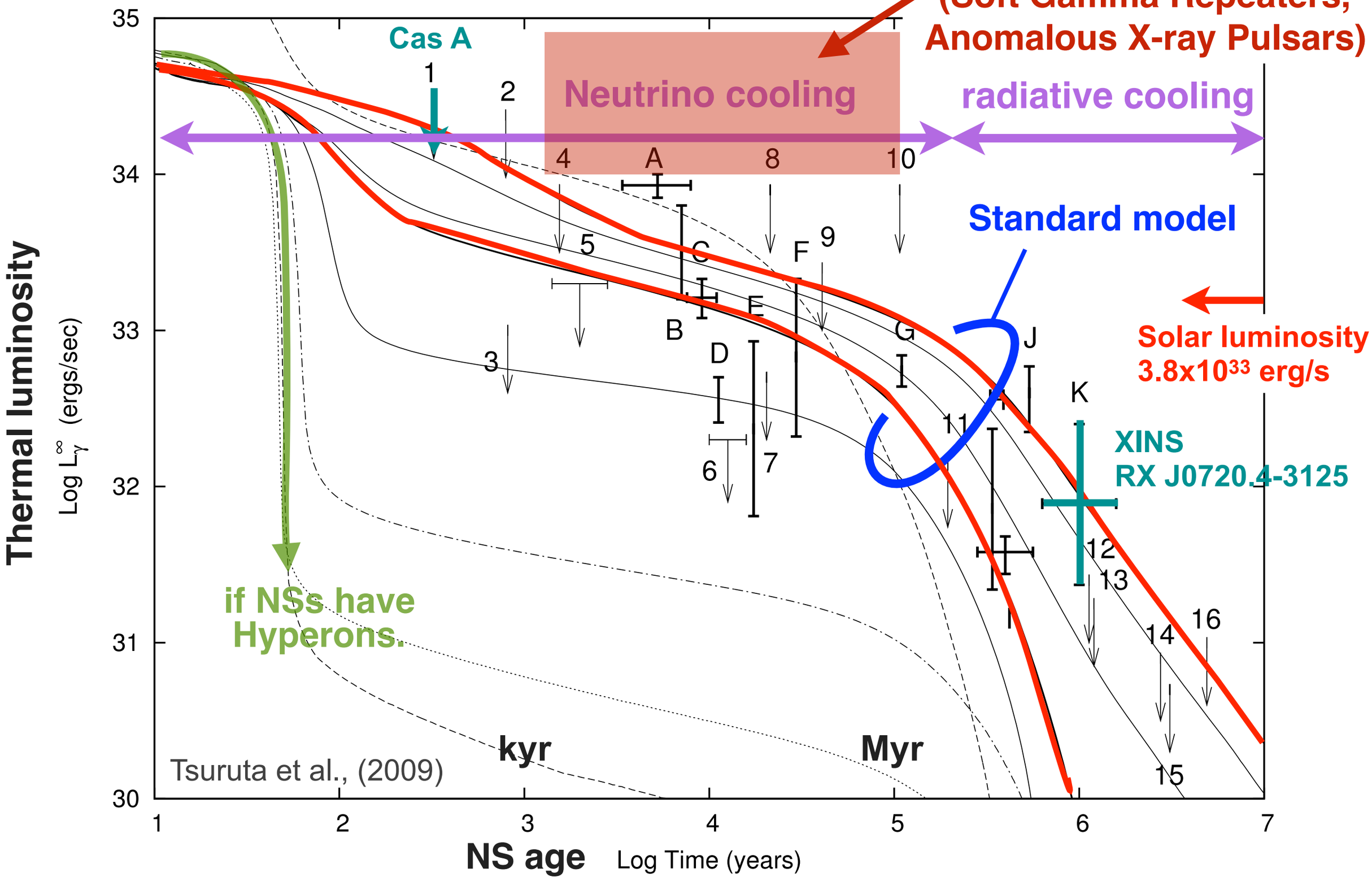
3. Video on YouTube “NASA’s NICER Reveals 1st-ever Pulsar Surface Map”

4. ApJ Letters focus issue, “Focus on NICER Constraints on the Dense Matter Equation of State”

Beyond the Determination of M-R Relation

- "*If the equation of state is well constrained, what we can do?*"
  - X-ray outbursts of magnetars (or thermal enhancements of canonical pulsars after a glitch) will provide us showcase of thermal response of the NS interior.
- *"Does the non-dipolar magnetic field play a role in NSs?"*
  - Yes! Understanding of non-dipole magnetic field configuration will be a key for the long-term evolution of NSs. This will affect systematic uncertainty to determine the NS equation of state.

Evolution of NSs: Cooling curves

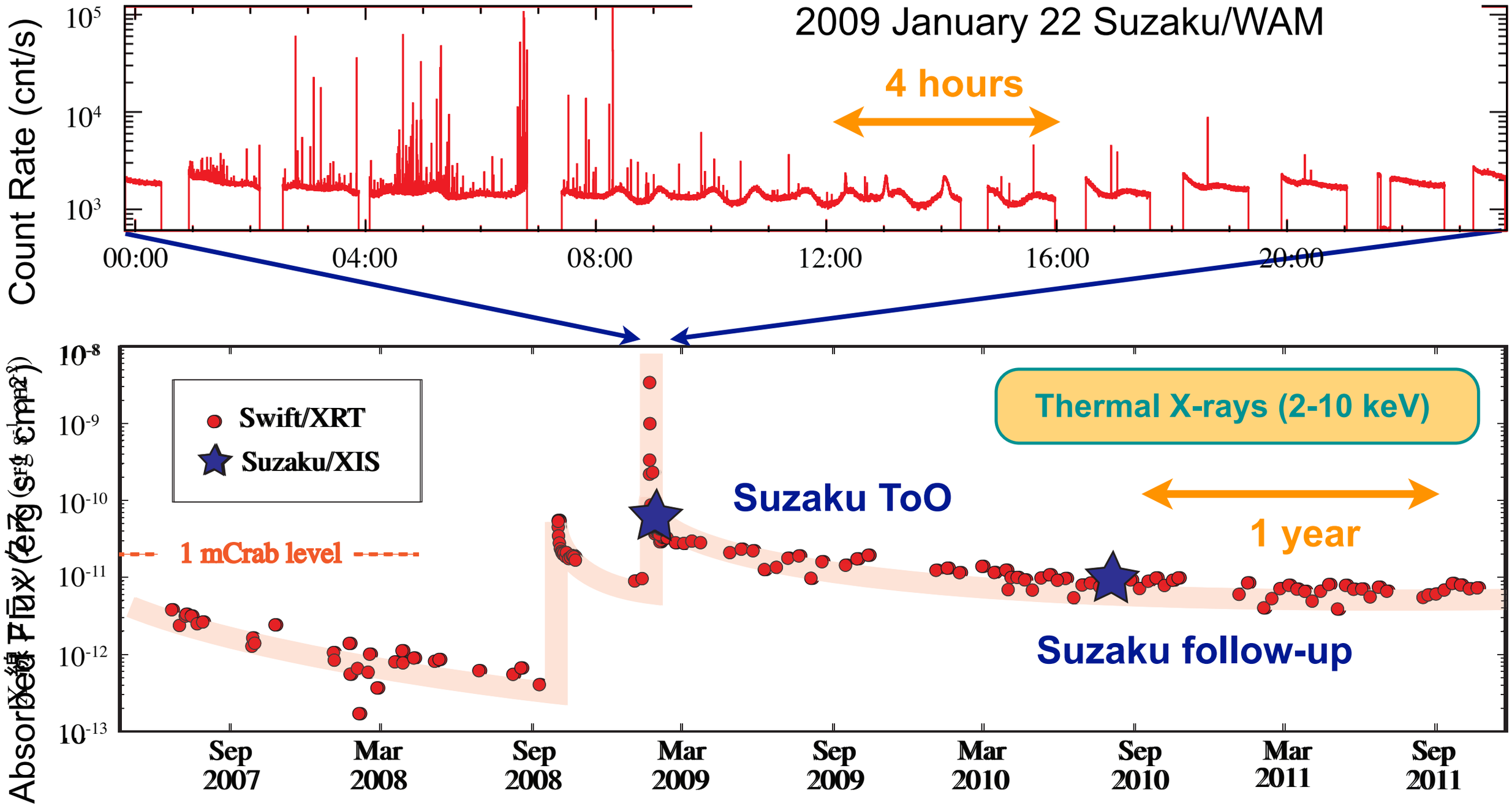


NS cooling is sensitive to states inside the stellar interior.

Magnetar Outburst Example: 1E 1547.0-5408

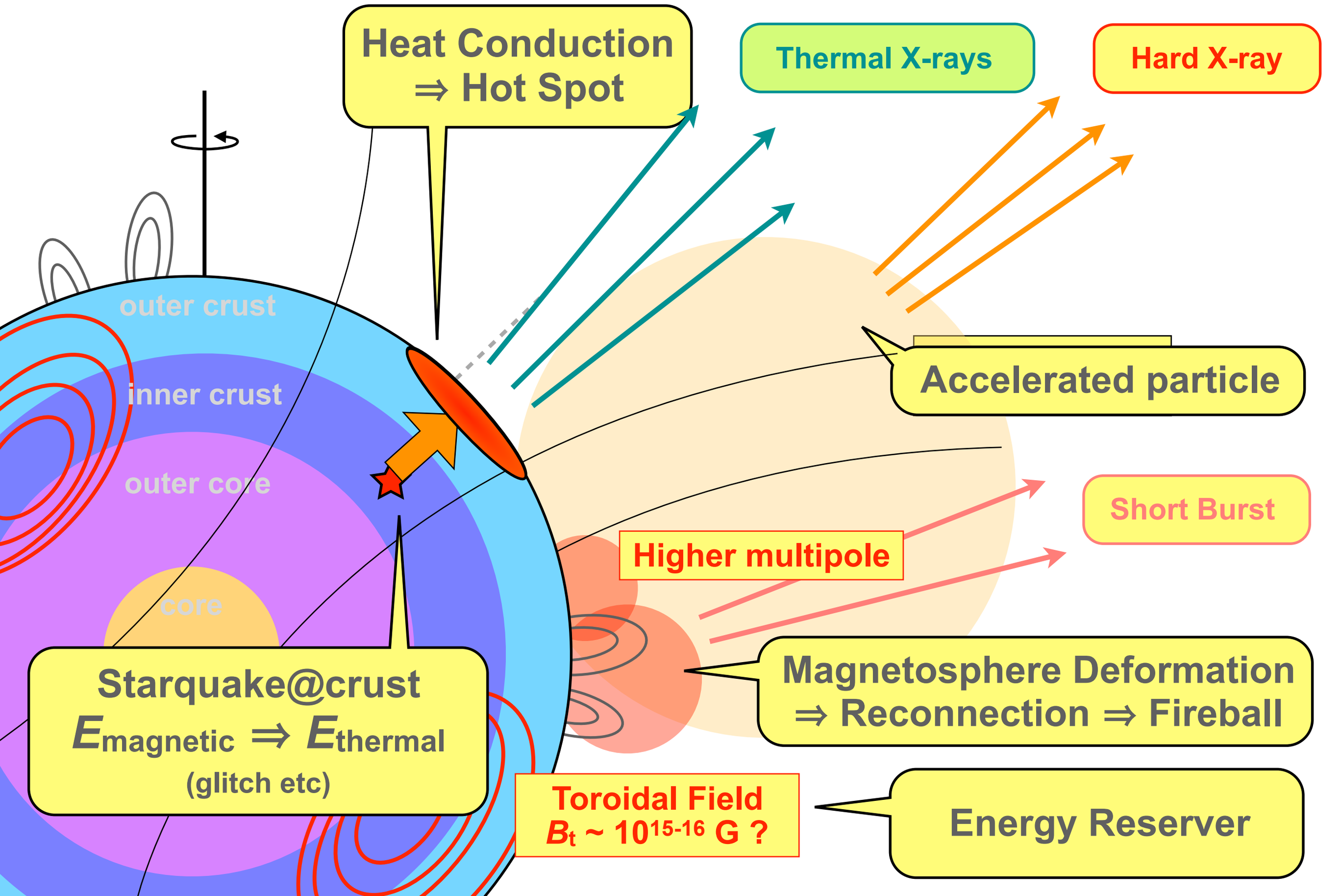
Known as a fast rotation faint AXP (P~2 sec)

Enoto+10 PASJ;
Enoto+12 MNRAS

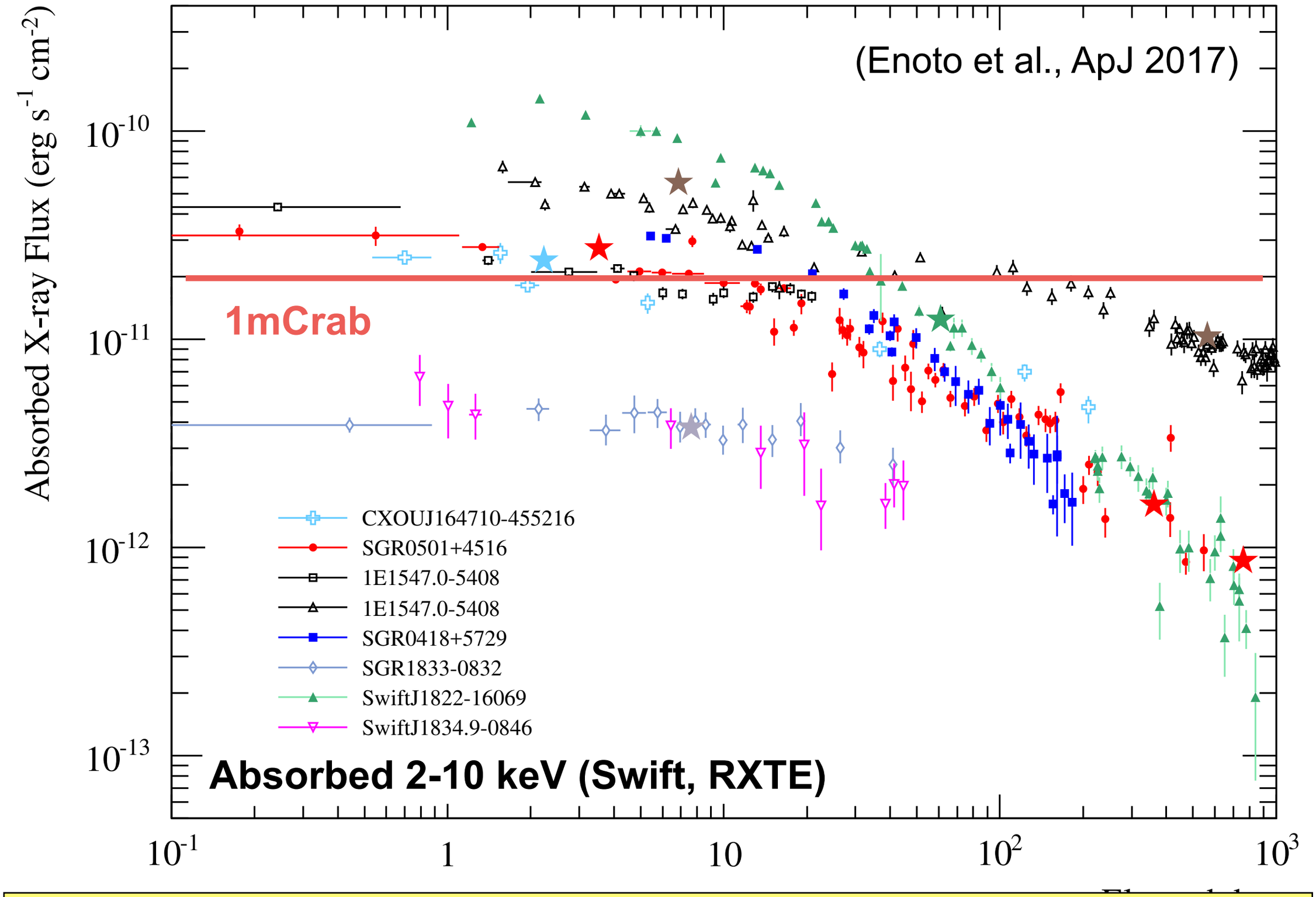


Transient magnetars sometimes go to the "outburst" state, characterized by frequent short bursts and enhanced persistent X-rays.

Magnetar X-ray Outbursts



Magnetar Outburst Examples



Thermal response of an energy injection in NS interior!?

Beyond the Determination of M-R Relation

- "*If the equation of state is well constrained, what we can do?*"

  - X-ray outbursts of magnetars (or expected thermal enhancements of canonical pulsars after a glitch) will provide us showcases of thermal response in the NS interior.

- *"Does the non-dipolar magnetic field play a role in NSs?"*

  - Yes! Understanding of non-dipole magnetic field configuration will be a key for the long-term evolution of NSs. This will affect systematic uncertainty to determine the NS equation of state.

Summary

- The NICER X-ray observatory was attached to the ISS in 2017, and characterized by its large effective area and high time resolution.
- NICER provided the first precise (±10%) mass and radius measurements of a millisecond and isolated PSR J0030+0451.
- This also provides robust demonstration of non-dipolar magnetic field, and new constraint on the equation of state, tightened pressure-density range by 30%.
- X-ray outbursts of neutron stars will give us another information of thermal response of its stellar interior.