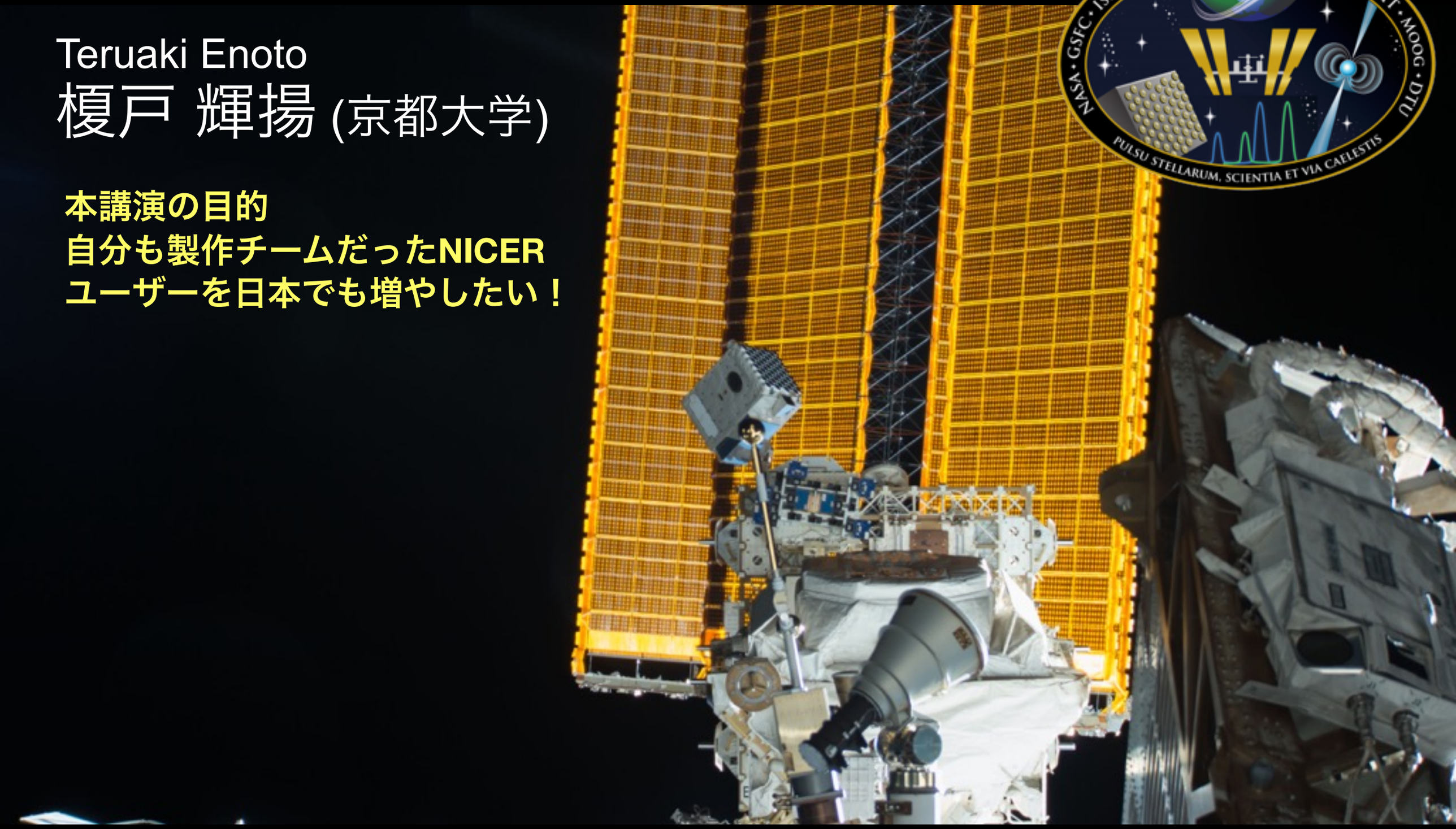
大面積X線望遠鏡 NICER の初期成果とデータ解析へのお誘い

Teruaki Enoto
榎戸 輝揚 (京都大学)

本講演の目的
自分も製作チームだったNICER
ユーザーを日本でも増やしたい！

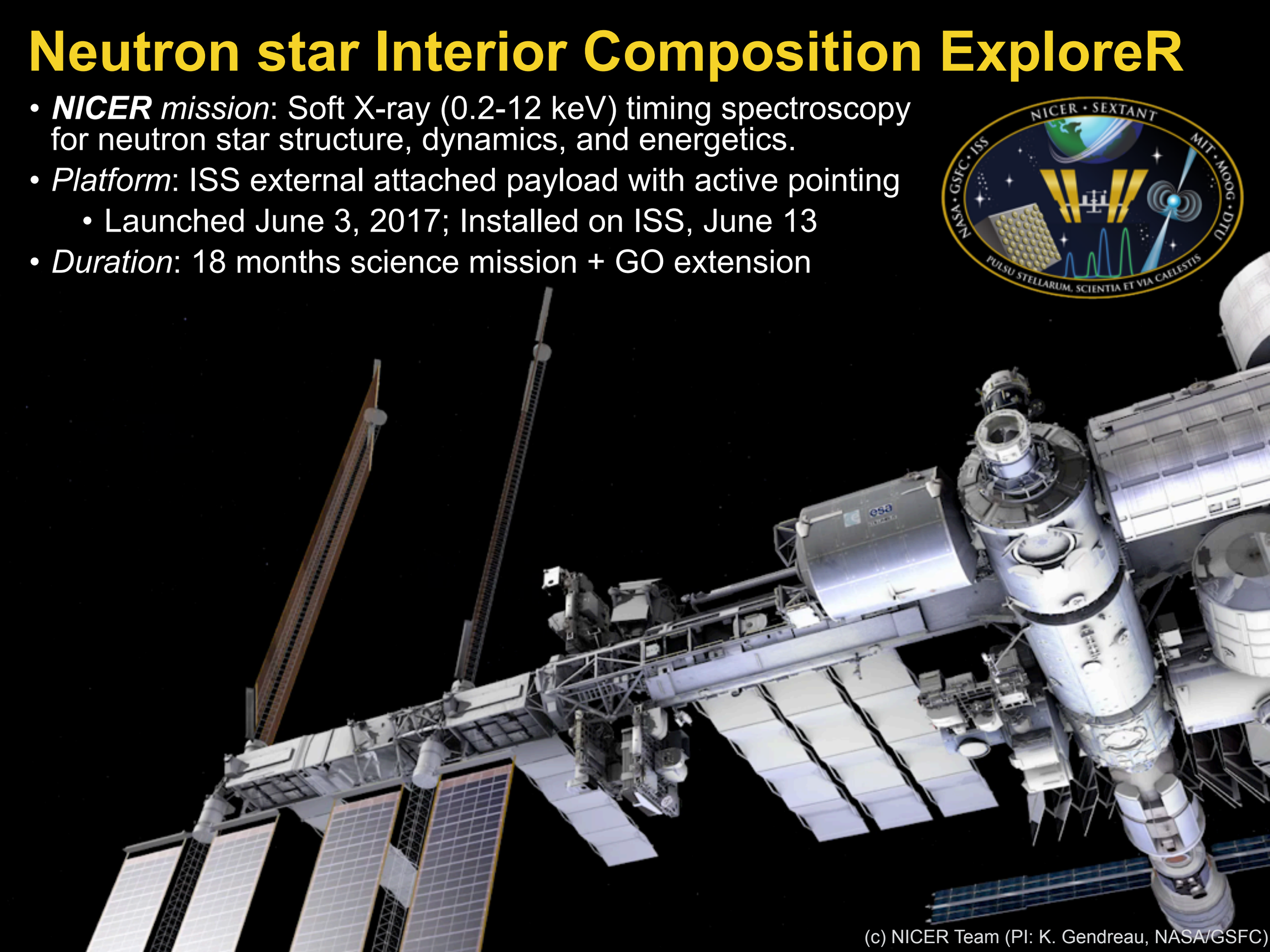


~中性子星の観測と理論~ 研究活性化ワークショップ 2019 https://indico2.riken.jp/event/2840/timetable/#20190218.detailed
2019年2月19日(火) 京都大学理学セミナーハウス 17:00-17:25 (20+5)

Launch by SpaceX-11 resupply, June 3, 2017

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



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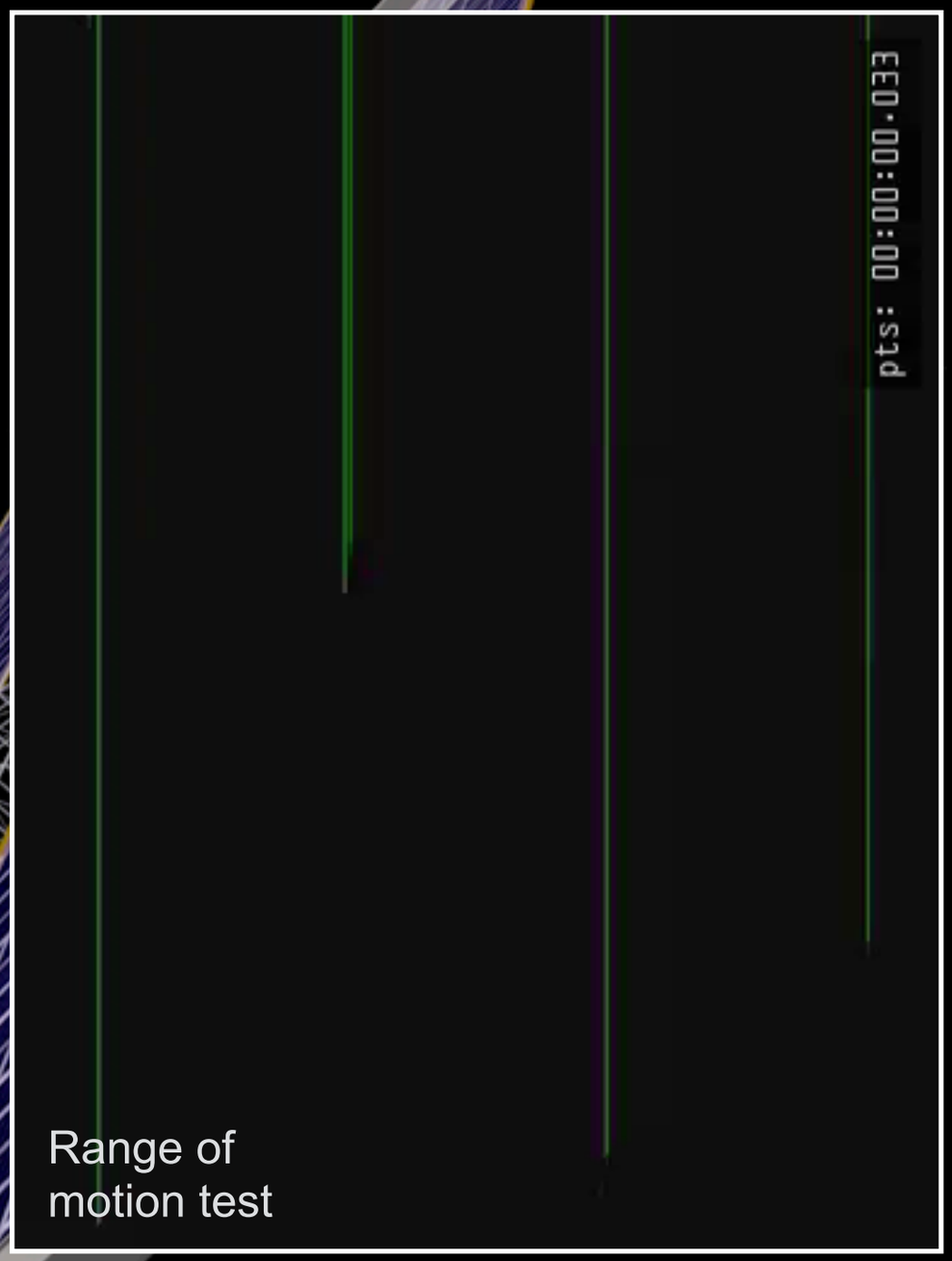
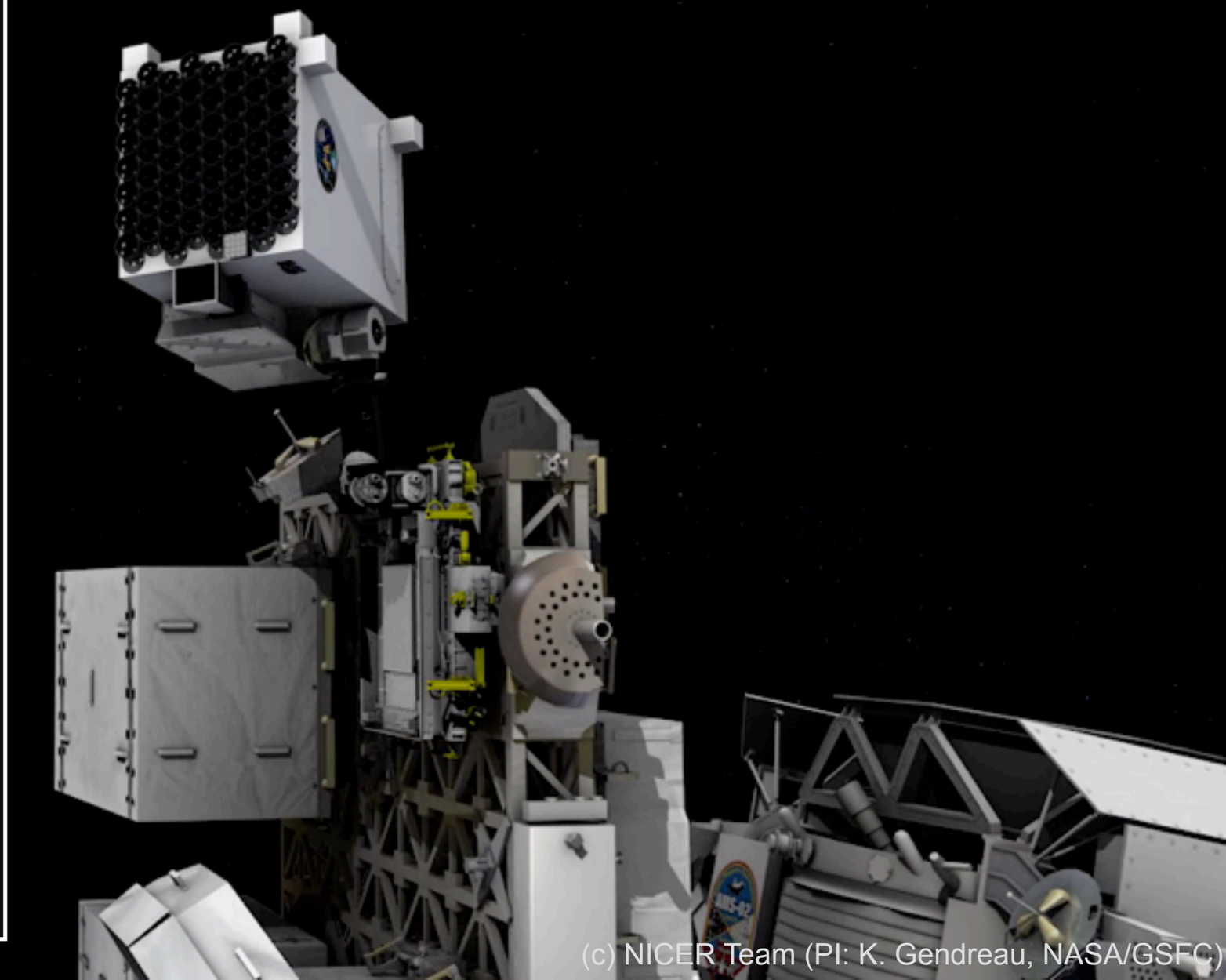


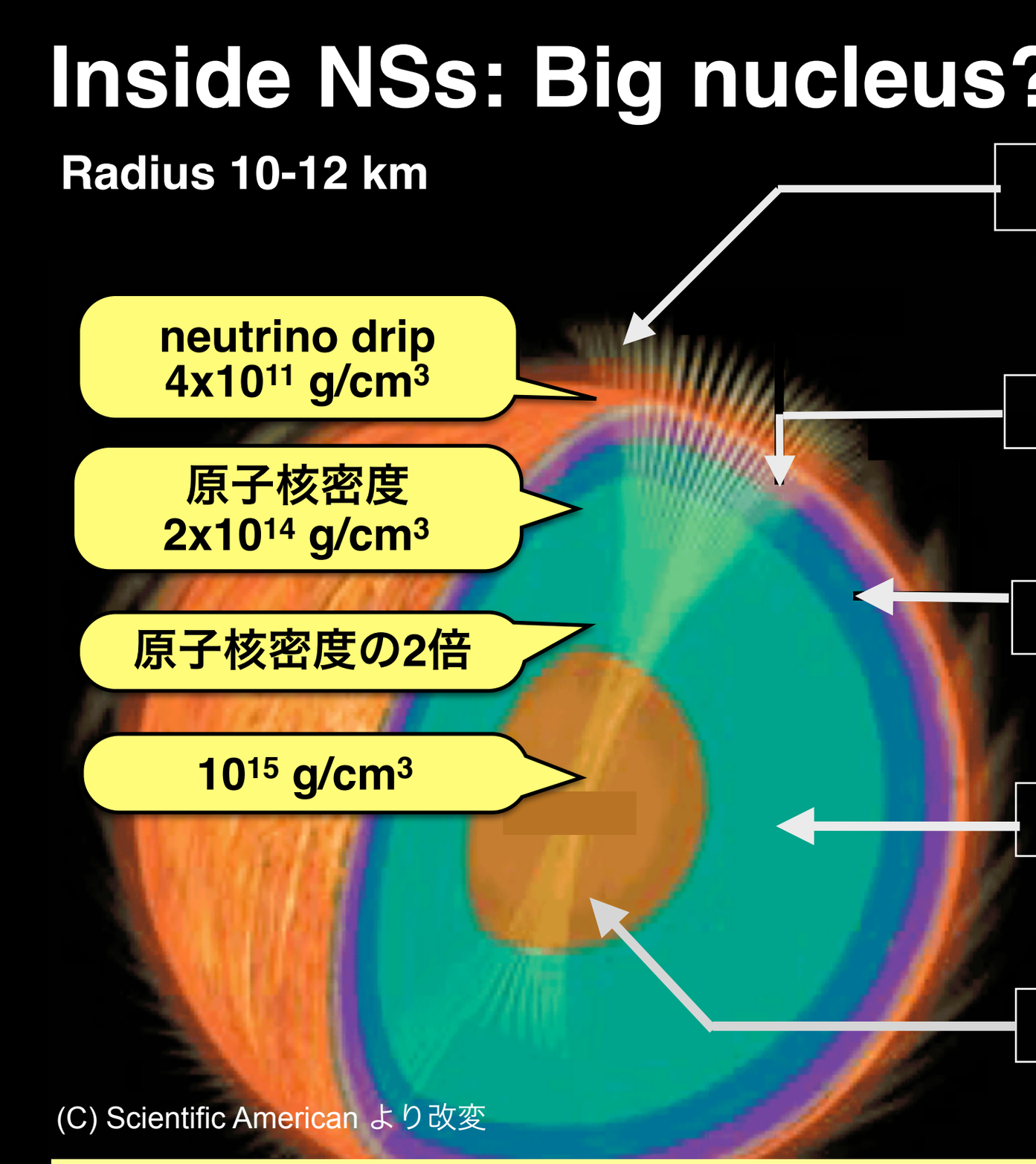
Range of motion test



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

Inside NSs: Big nucleus?

Radius 10-12 km



中性子星の大気 (とても薄い)

水素, ヘリウム, 炭素 (H, He, C)

アウタークラスト

原子核(鉄ほか)＋電子

インナークラスト

中性子過剰核＋電子＋(超流動)中性子

アウターコア

(超流動)中性子＋電子＋(超伝導)陽子

インナーコア

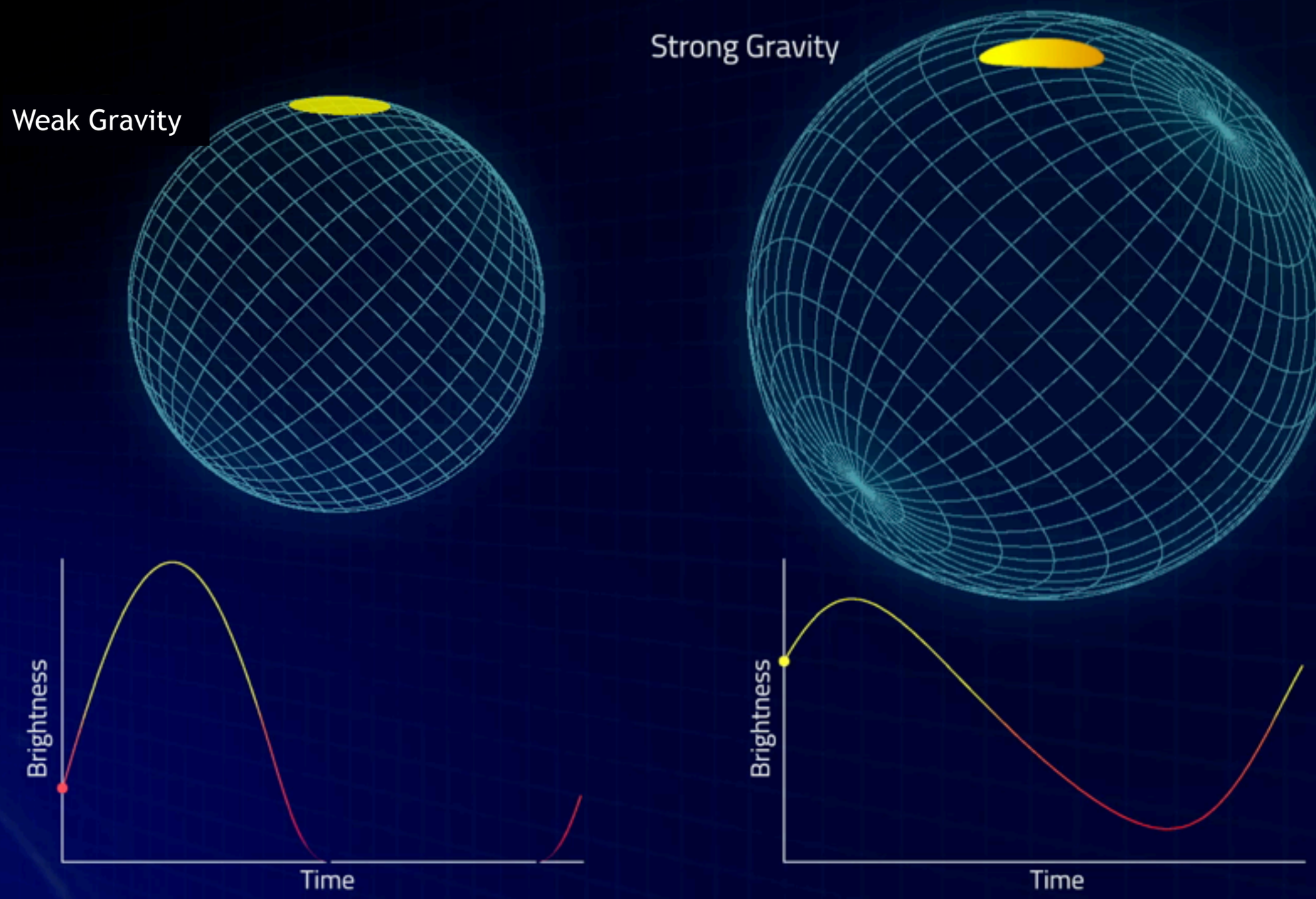
なんかやばい。ハイペロン？

(C) Scientific American より改変

Equation of State (EoS) inside neutron stars is still a big question in the fundamental physics

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.

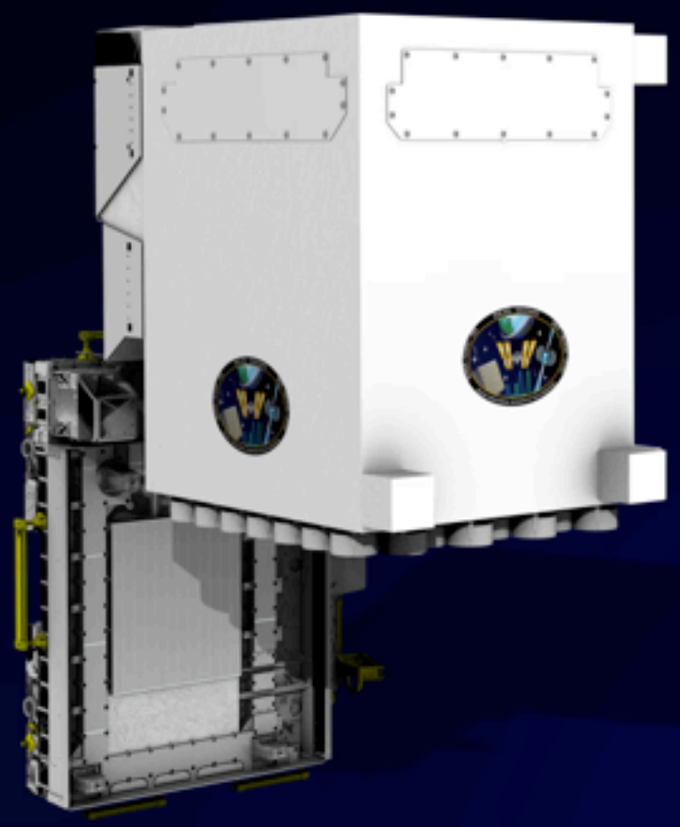


(Gendreau, Arzoumanian, and NICER Collaboration)

NICER

Neutron Star Interior Composition Explorer

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

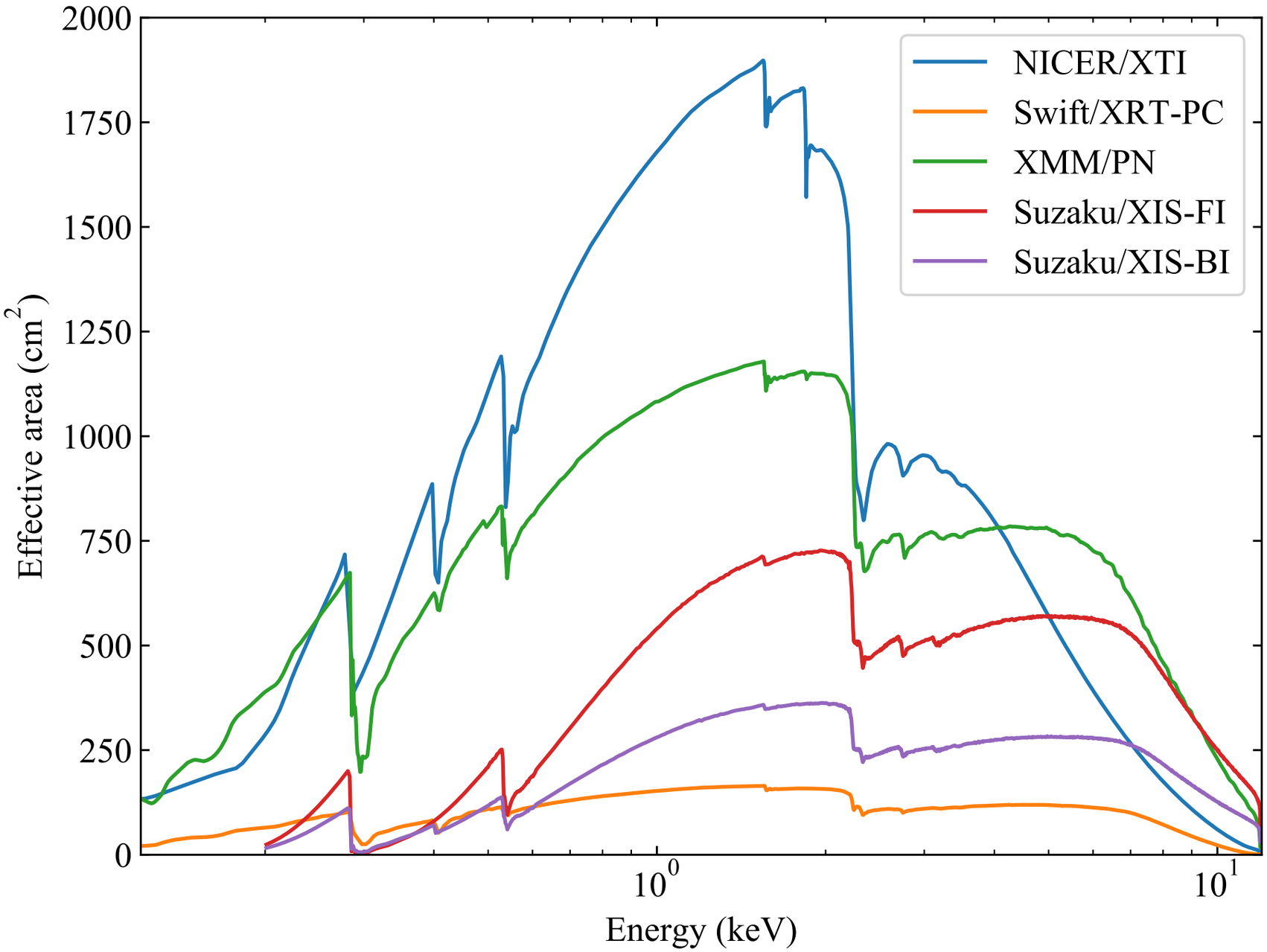


- Energy band : 0.2-12 keV (Resolution : 85 eV @ 1 keV, 140 eV @ 6 keV)
- Time resolution : <100 ns RMS (absolute)
- Non-imaging FOV 6 arcmin diameter
- Background : < 0.5 cps
- Sensitivity: 1×10^{-13} erg/s/cm^2 (5σ, 0.5-10 keV, 10 ksec exposure for Crab-like)
- Max rate: ~38,000 cps (3.5 Crab)

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

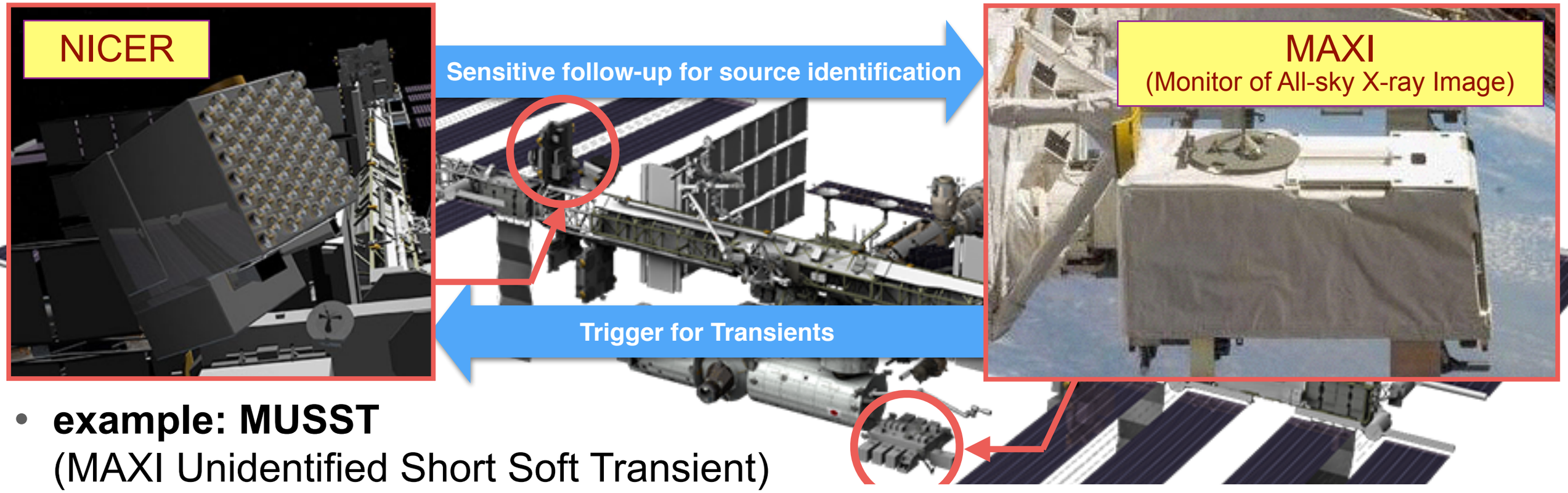
Large Effective Area of NICER

- 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.

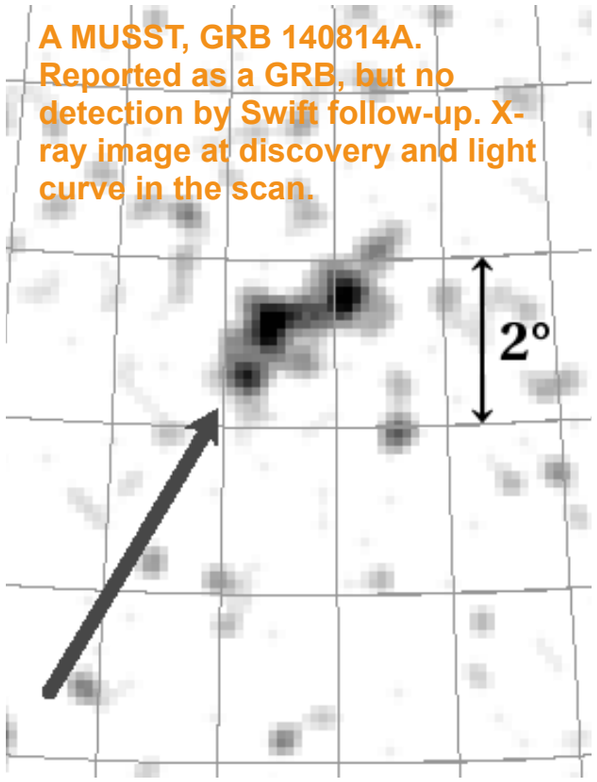


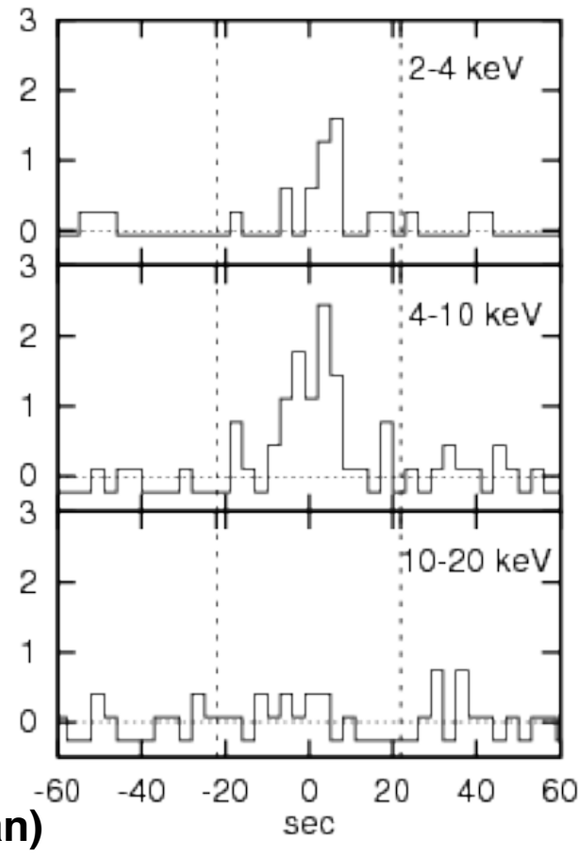
(K. Gendreau, et al., SPIE, 2012; Z. Arzoumanian, et al., SPIE, 2014)

Future NICER-MAXI Collaboration on the ISS



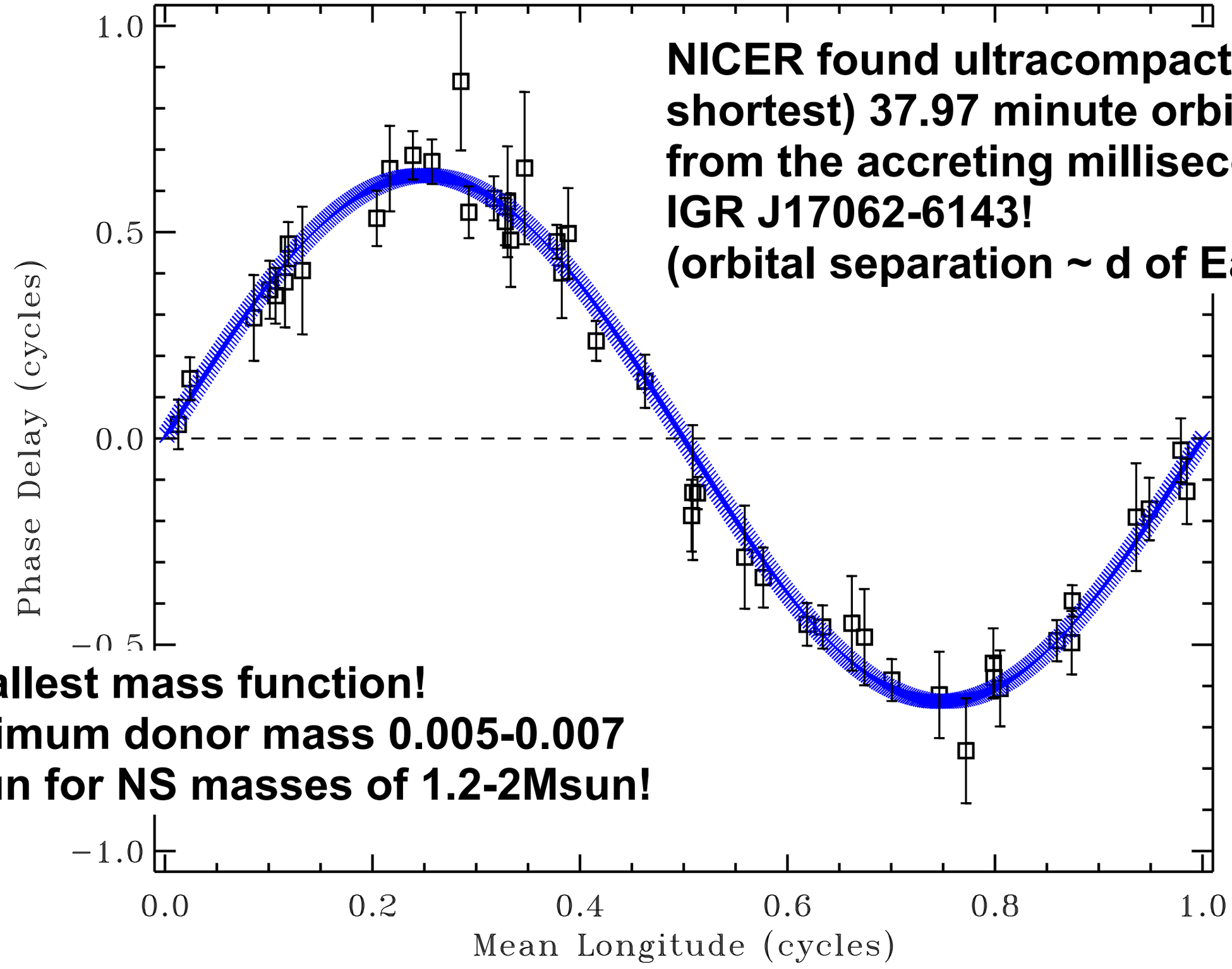
- **example: MUSST**
  (MAXI Unidentified Short Soft Transient)
- Detected only in **soft** X-rays (<10 keV)
- **Short** transients (duration <0.5 day)
- **Unidentified** (no detection with Swift XRT follow-ups)
- MAXI localisation (0.3°) is insufficient for optical follow-up observations.
- ~8 MUSSTs during 6 years of MAXI
- **Rapid X-ray follow-ups with NICER (100 mCrab within1min)**





Discussion with T. Mihara, W. Iwakiri & K. Gendreau et al. (Information & figures from Mihara-san)
http://www.washingtonpost.com/sf/national/2013/09/14/the-skies-the-limits/

Discovery of the Shortest Orbital Period

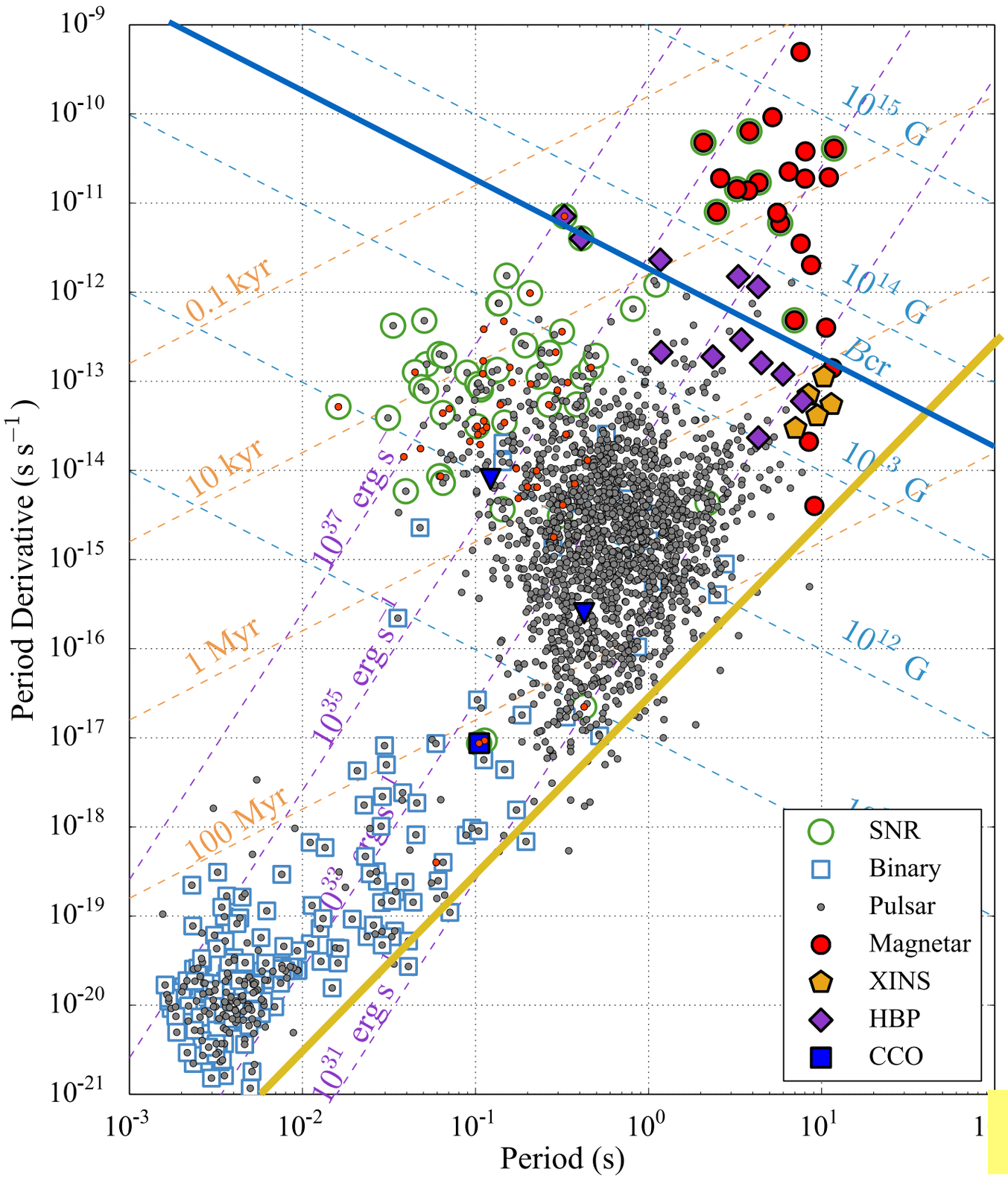


NICER found ultracompact (and the shortest) 37.97 minute orbital period from the accreting millisecond pulsar IGR J17062-6143!
(orbital separation ~ d of Earth-Moon)

Smallest mass function!
Minimum donor mass 0.005-0.007 Msun for NS masses of 1.2-2Msun!

(Strohmayer et al., ApJ 2018)

Magnetar & Magnetosphere (M&M) Science



- Covers highly magnetized neutron stars (NSs) with surface B>10^{11} G.
- Towards understanding of diversity and evolution of different classes.
  - Magnetars
  - Rotation-powered pulsars (RPPs)
  - High-B pulsar
  - XDINSs (X-ray Dim Isolated NSs)
- NICER will provide:
  - Long-term monitoring of timing behaviours for spin ephemeris
  - Phase-resolved spectroscopy (absorption, thermal/non-thermal)
  - Coordination of flexible multi-wavelength observations

Several example of NICER data!

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

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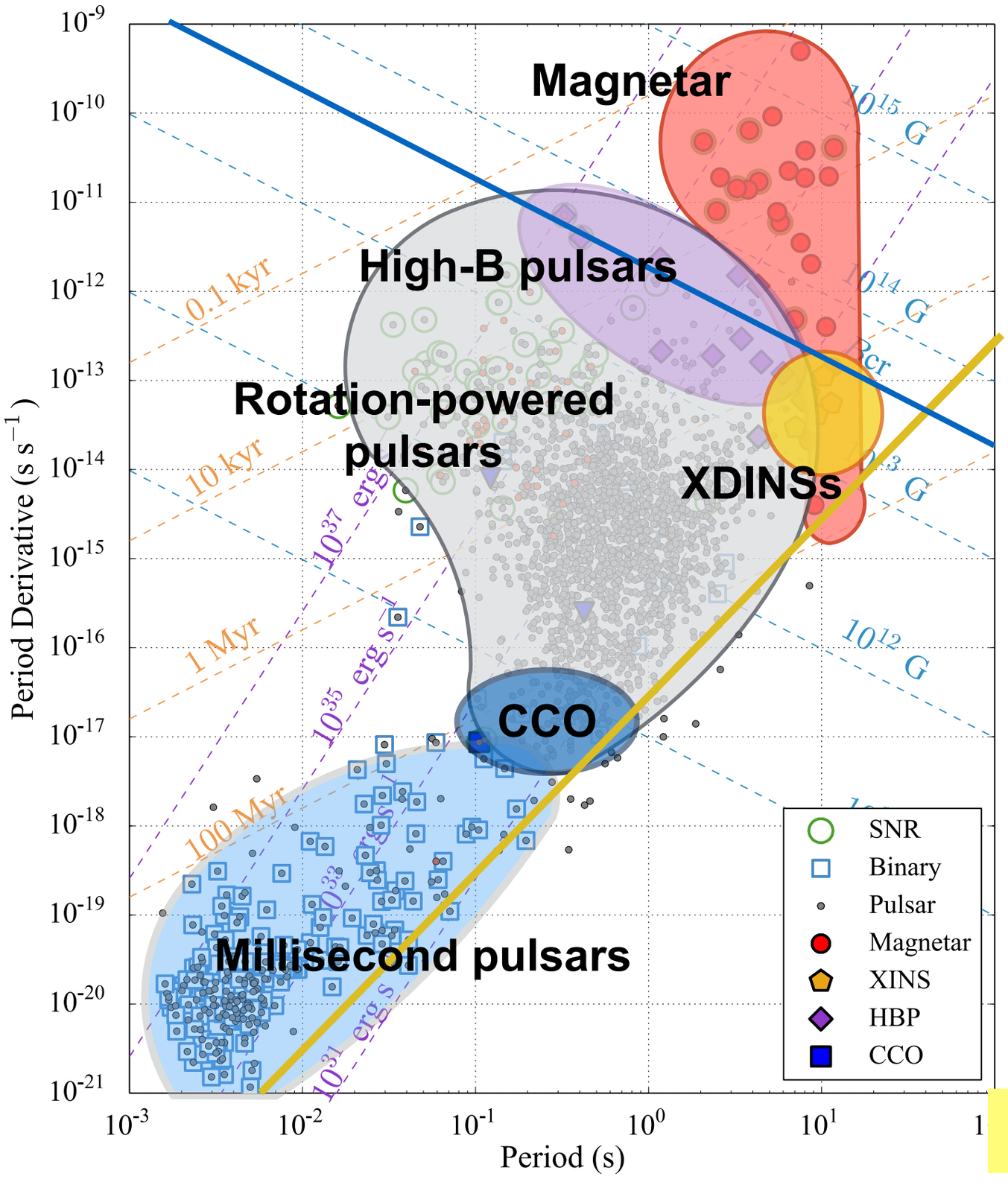

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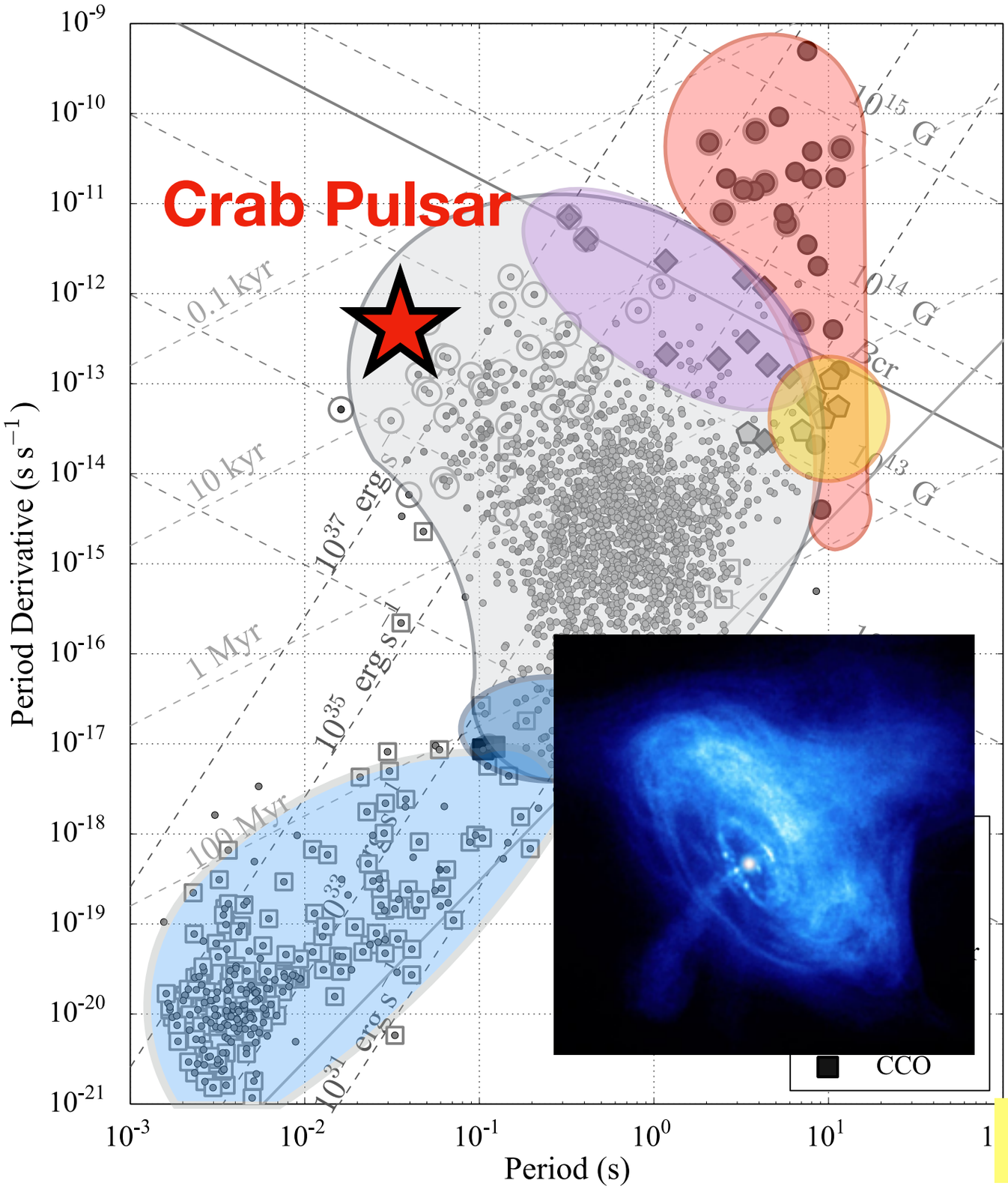

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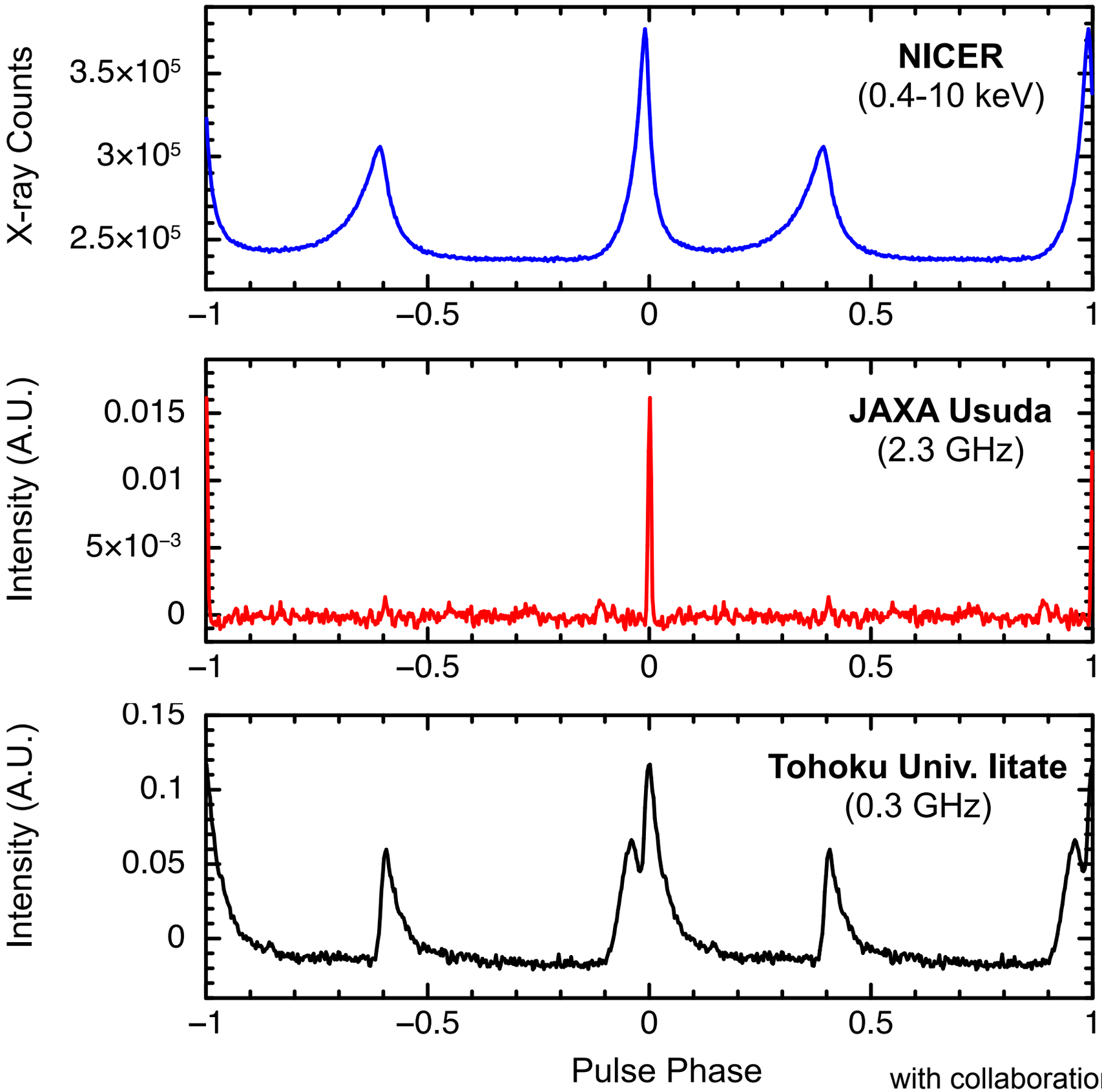
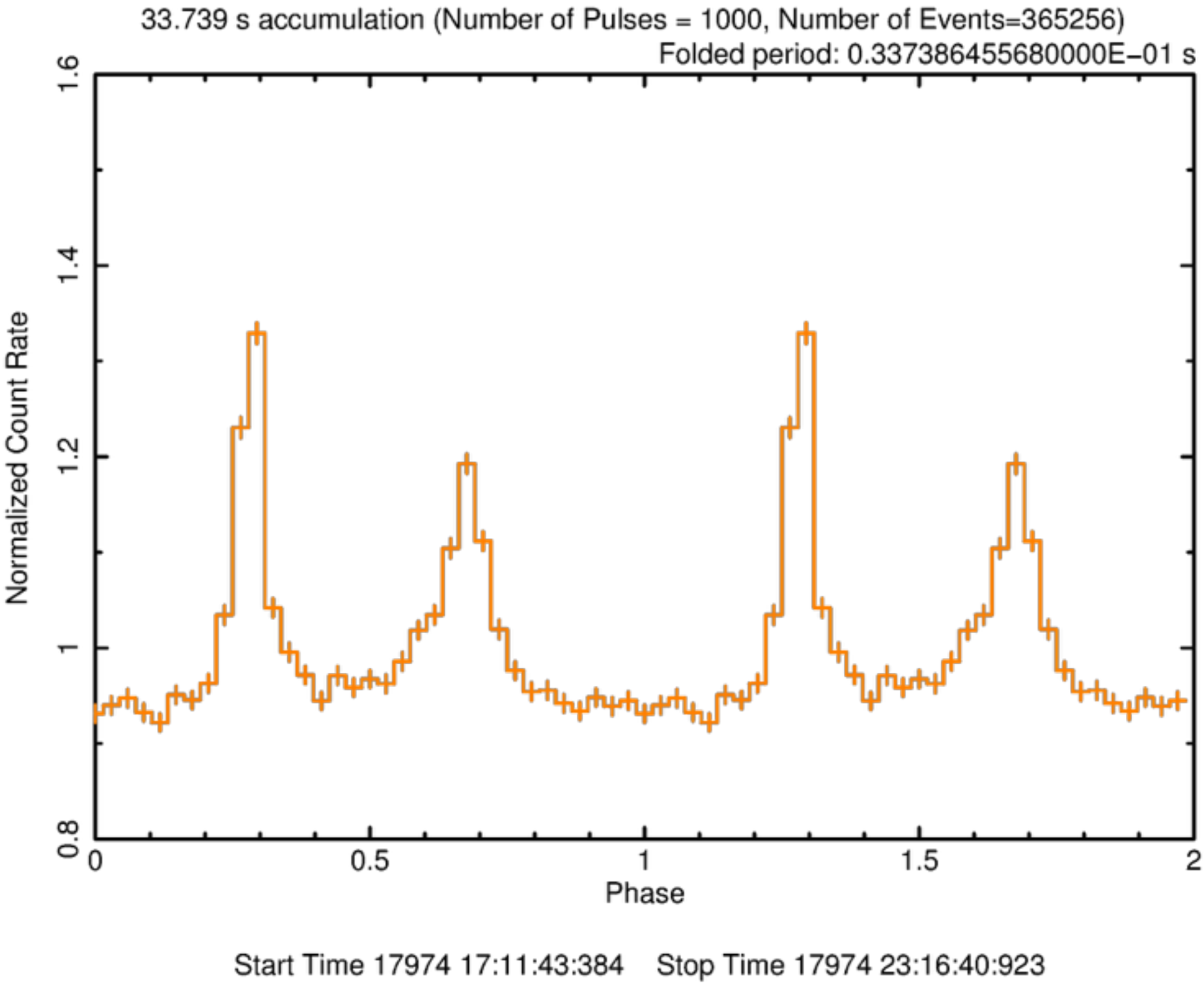
Crab Pulsar — Simultaneous with Radio



with collaboration for radio pulsar observation in Japan

Crab Pulsar — On-orbit actual NICER data



X-ray profile appears with accumulation in a short exposure (~1 sec) !

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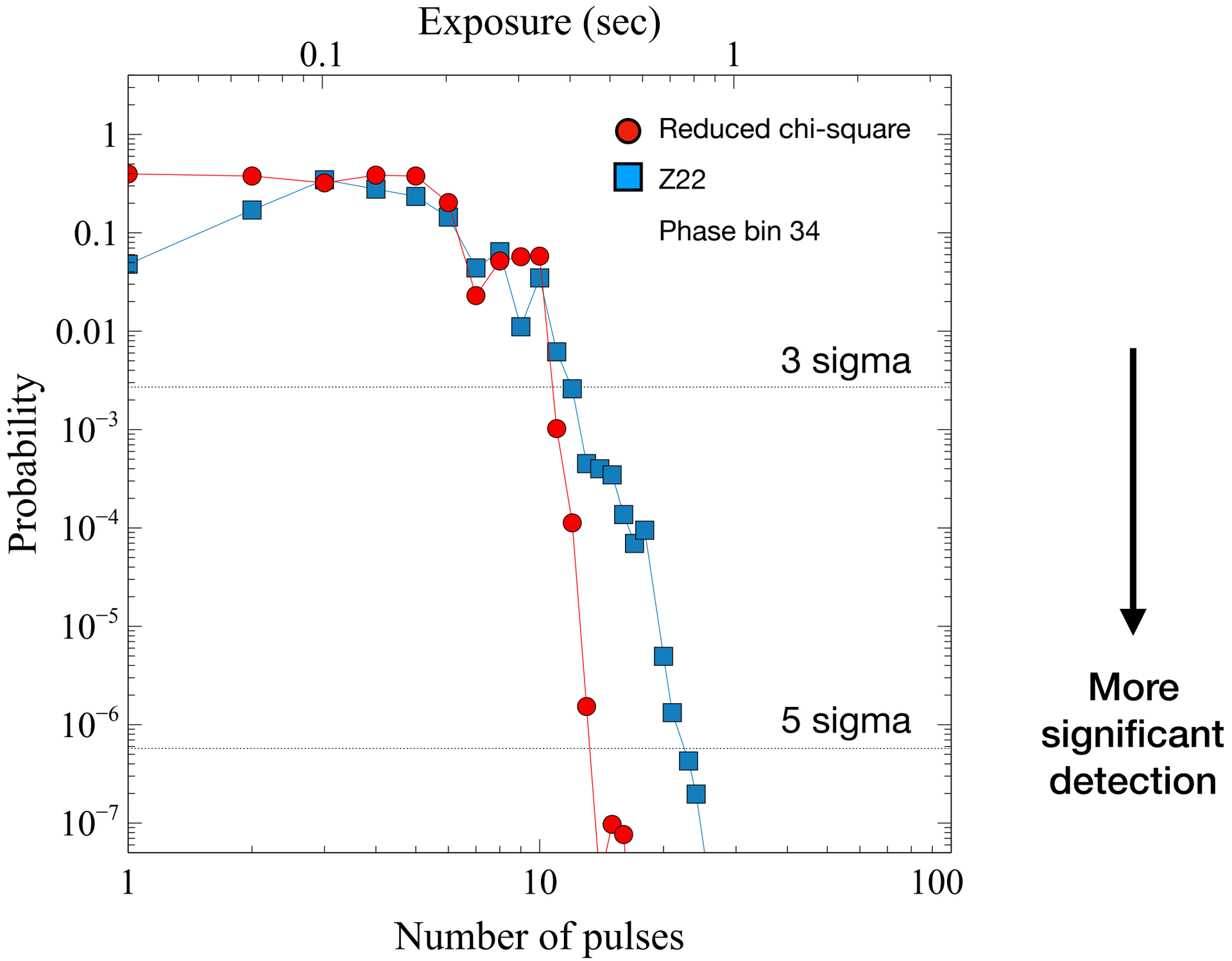
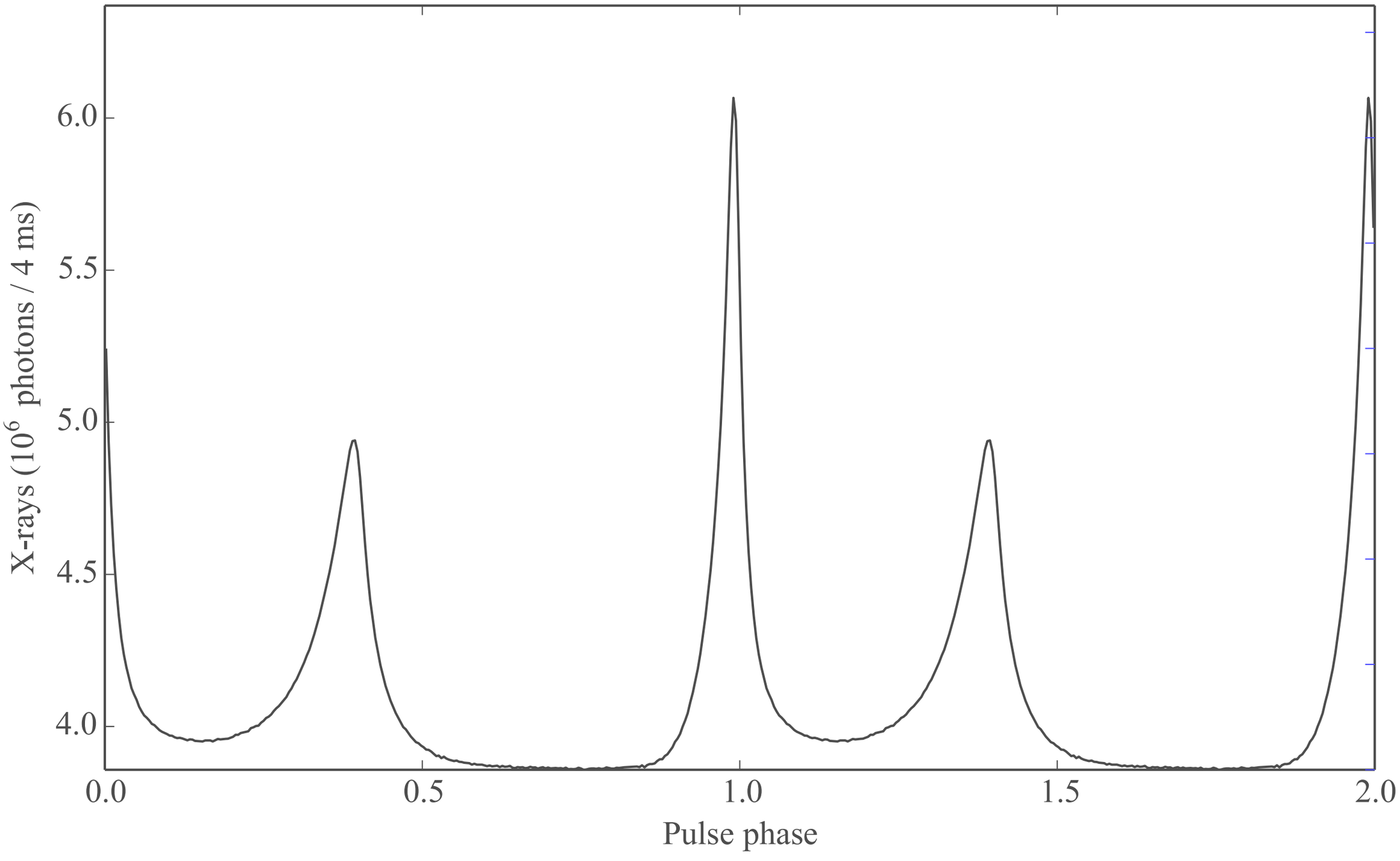


More significant detection

X-ray profile appears with accumulation in a short exposure (~1 sec) !

Crab Pulsar — NICER X-ray Profile



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How we can use this large effective area?

Giant Radio Pulse (GRP) of the Crab Pulsar

Radio IR Opt. X-ray γ-ray

Nebula: radiation from shock-accelerated relativistic electrons

Pulsar: radiation from e+/e- accelerated in the pulsar magnetosphere

GRP: Sporadic bright (~MJy) radio pulse emission, x$10^{2\text{-}3}$ stronger than regular pulse.

3-4 orders difference (Nebula > normal pulse)

νF_ν [erg cm^{-2} s^{-1}]

νL_ν [erg s^{-1}]

1.4 GHz

(Sallmen et al., 1999)

1 kJy

50 μs

Flux (Jy)

Time (μs)

Power-law energy distribution. Unknown radiation mechanism!
Connection to cosmological fast radio bursts?

(Bühler & Blandford, 2014)

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Optical enhancement!

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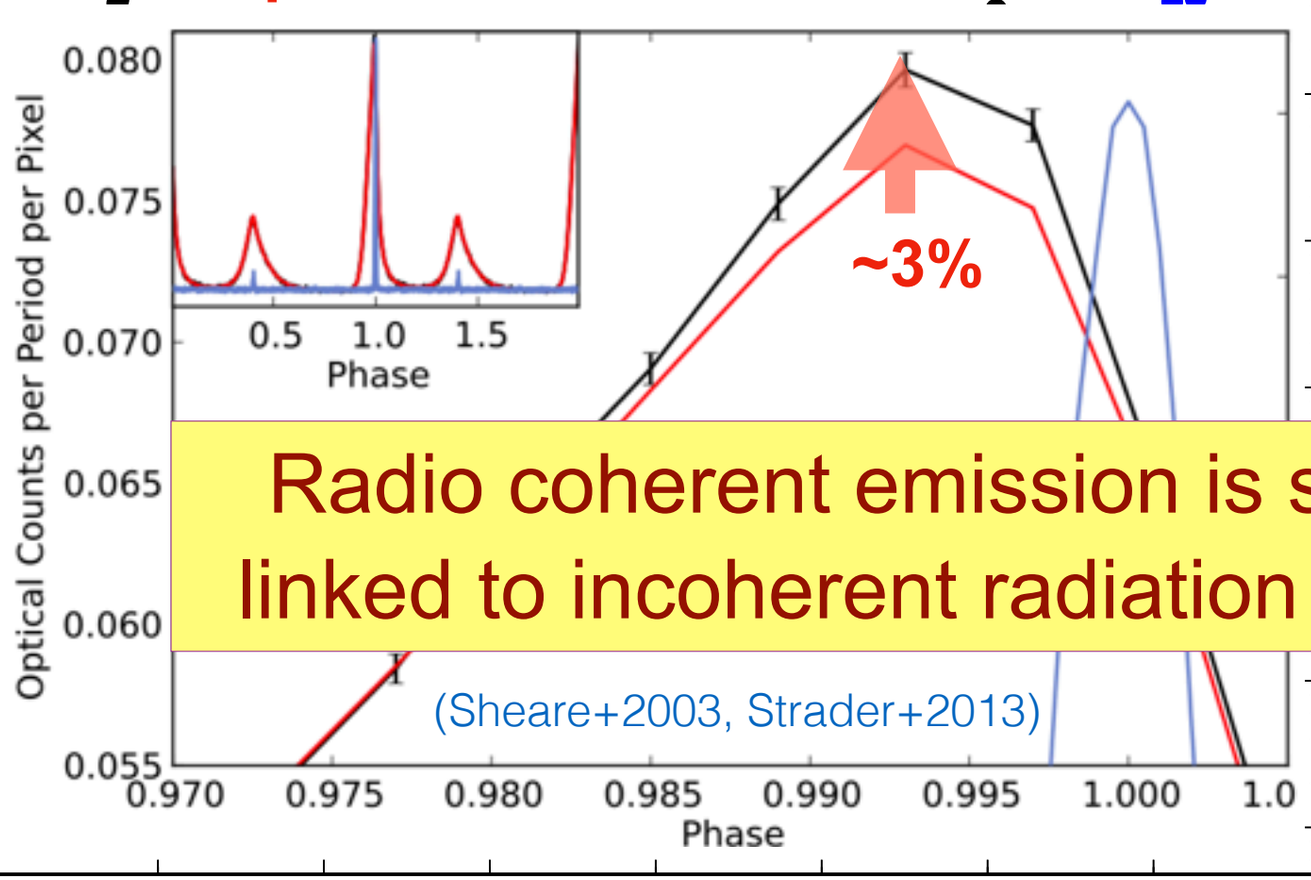


Radio coherent emission is somehow linked to incoherent radiation in optical.

(Sheare+2003, Strader+2013)

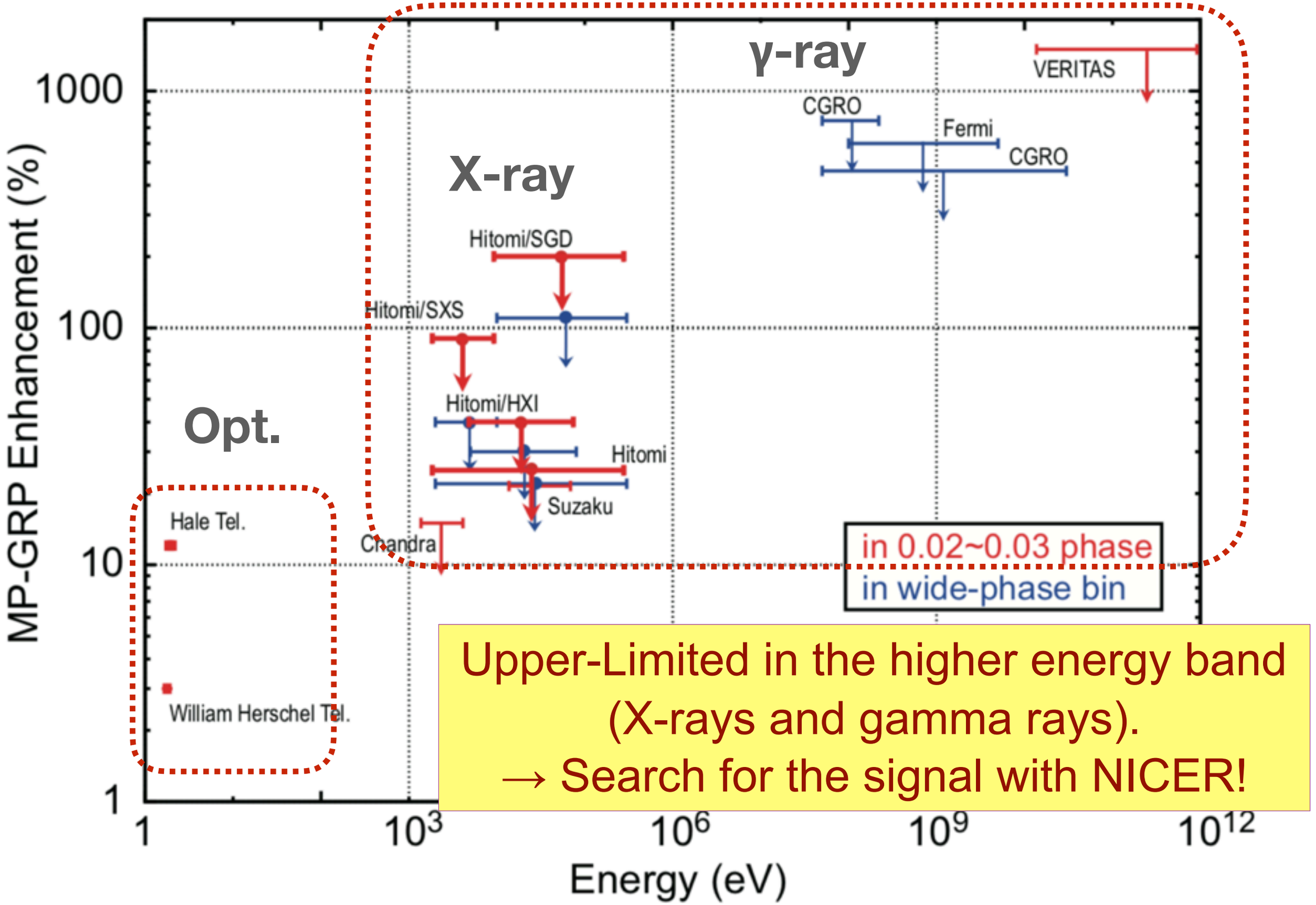
νF_ν [erg cm^{-2} s^{-1}]

νL_ν [erg s^{-1}]

Energy (eV)

(Buhler & Blandford, 2014)

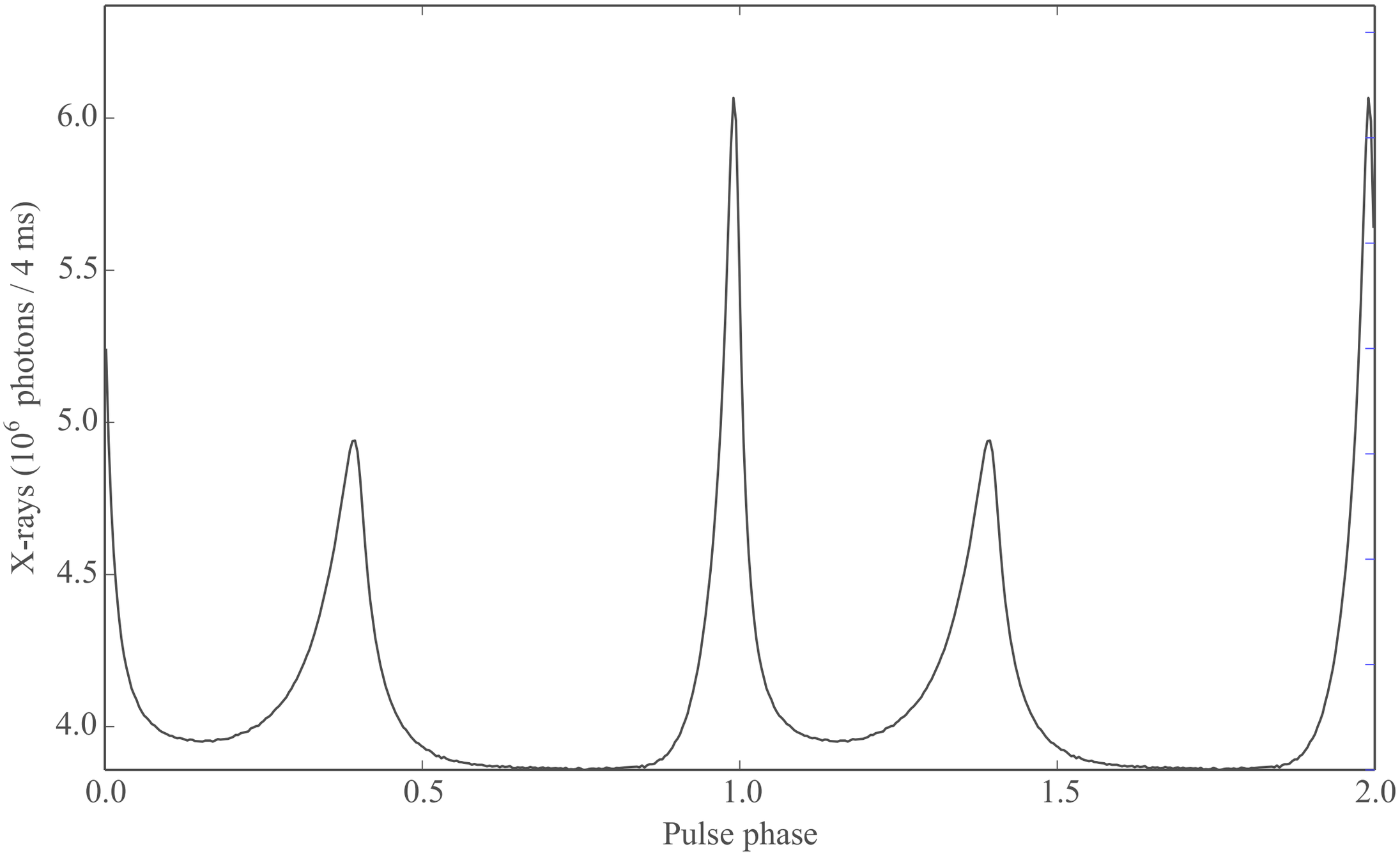
GRP Enhancement in High-Energy Bands?



Upper-Limited in the higher energy band
(X-rays and gamma rays).
→ Search for the signal with NICER!

(Hitomi Collaboration+2017)

Crab Pulsar — NICER X-ray Profile



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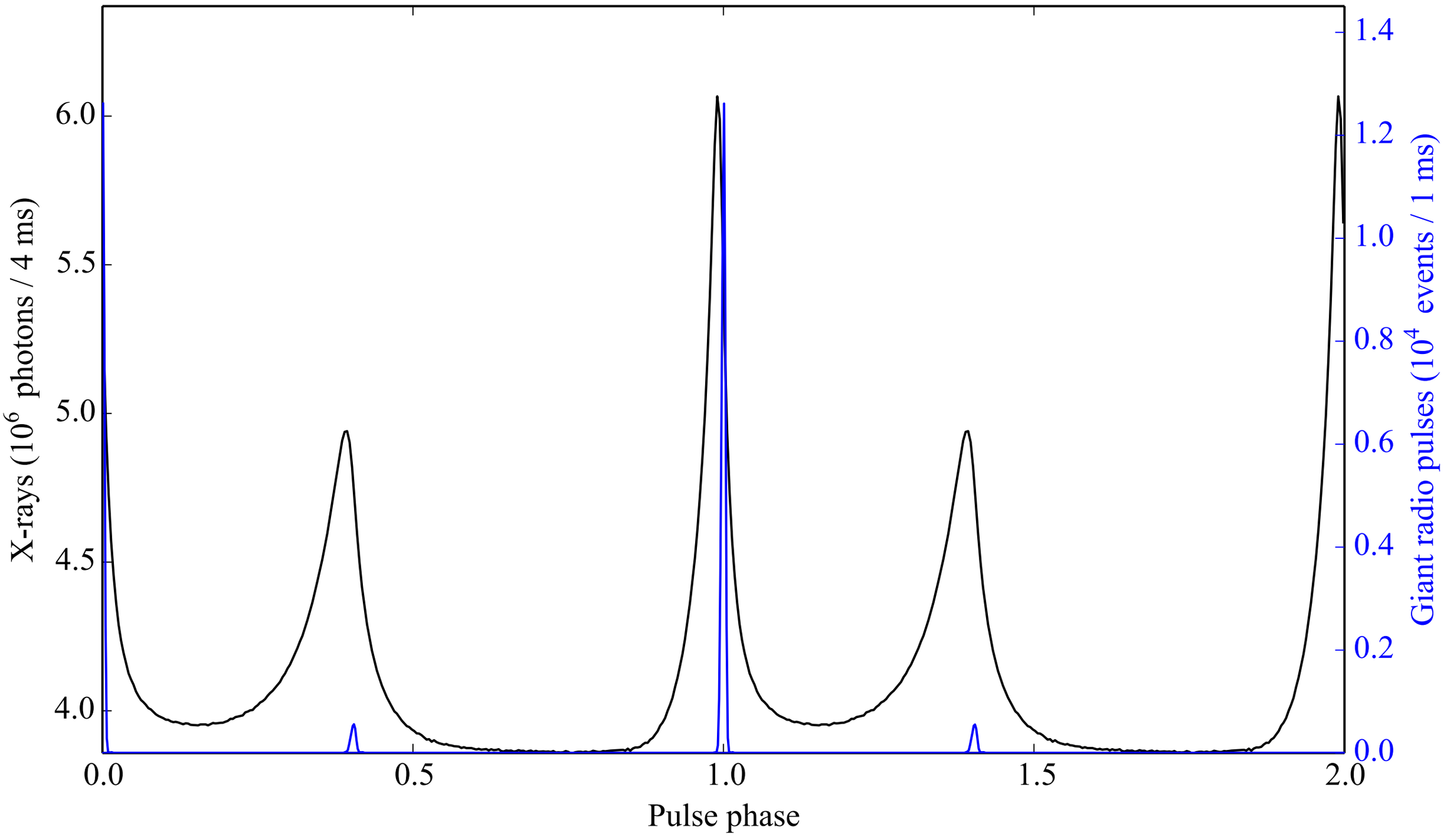

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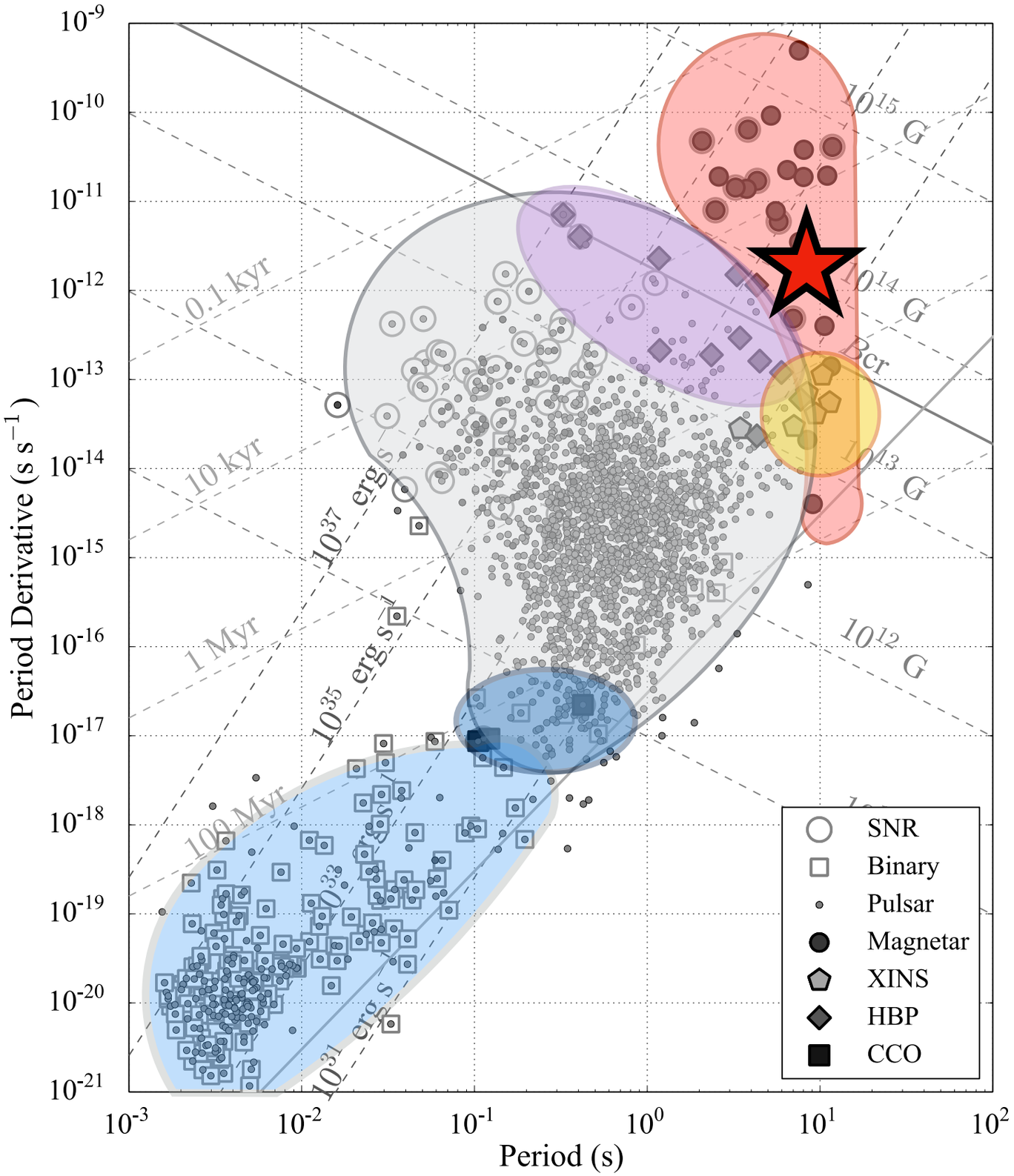
Magnetar Outbursts: 4U 0142+61



- A prototypical persistently bright anomalous pulsar at *P*=8.69 sec.
- SGR-like short burst detected with Fermi GBM on 13 July, 2017 during NICER's PV phase (GCN 21342).
- NICER ToO triggered 0.88 days after the burst, with a 3-month followup campaign (total ~96 ks)

Nynka et al., submitted

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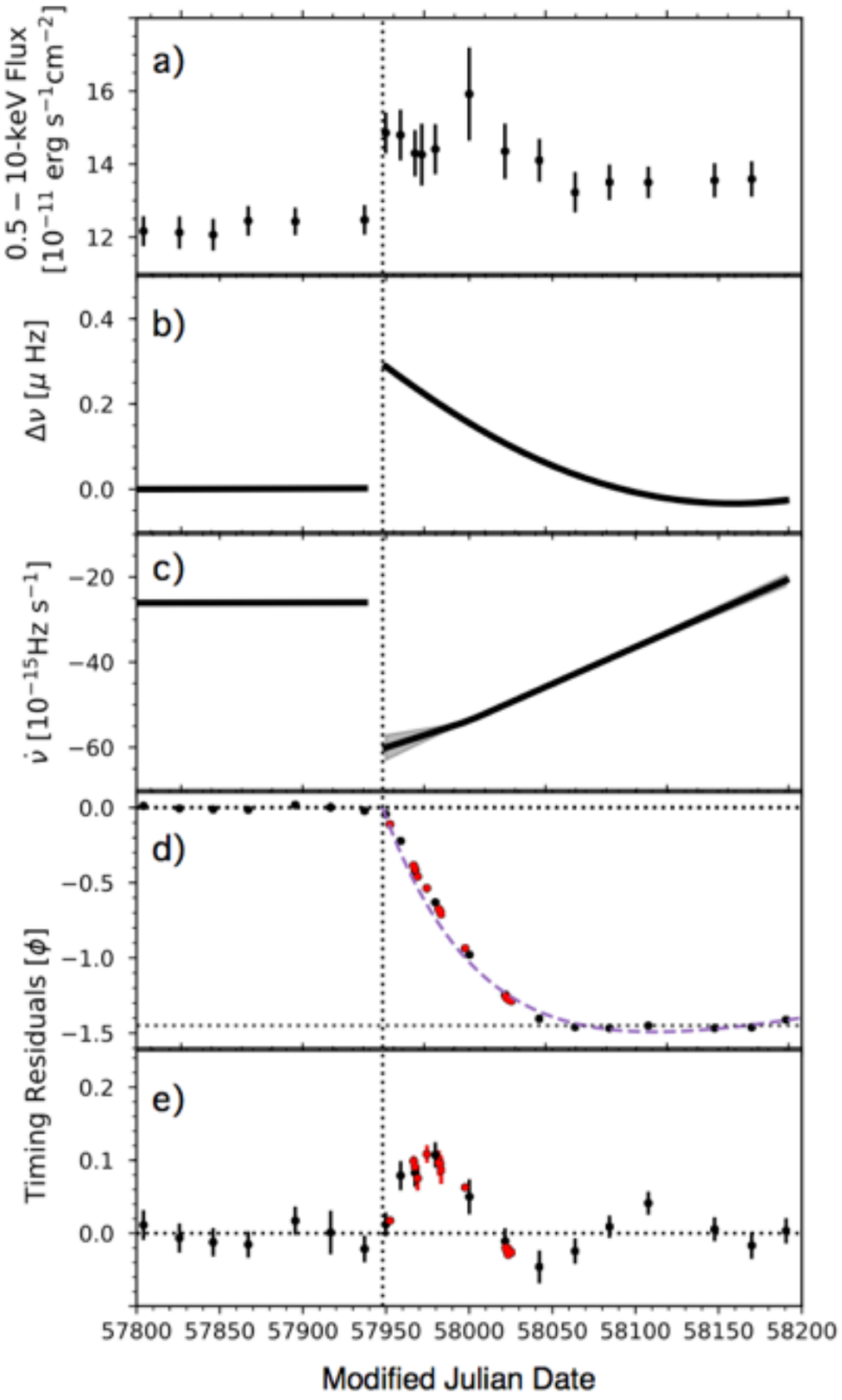

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NICER (complimented Swift and NuSTAR) observed:

- A glitch and its recovery: Δv=4.04e-7 Hz with a relaxation time scale of ~61 days.
- Spectral characteristics in outburst: Soft X-ray flux increased by ~30% for ~50 days
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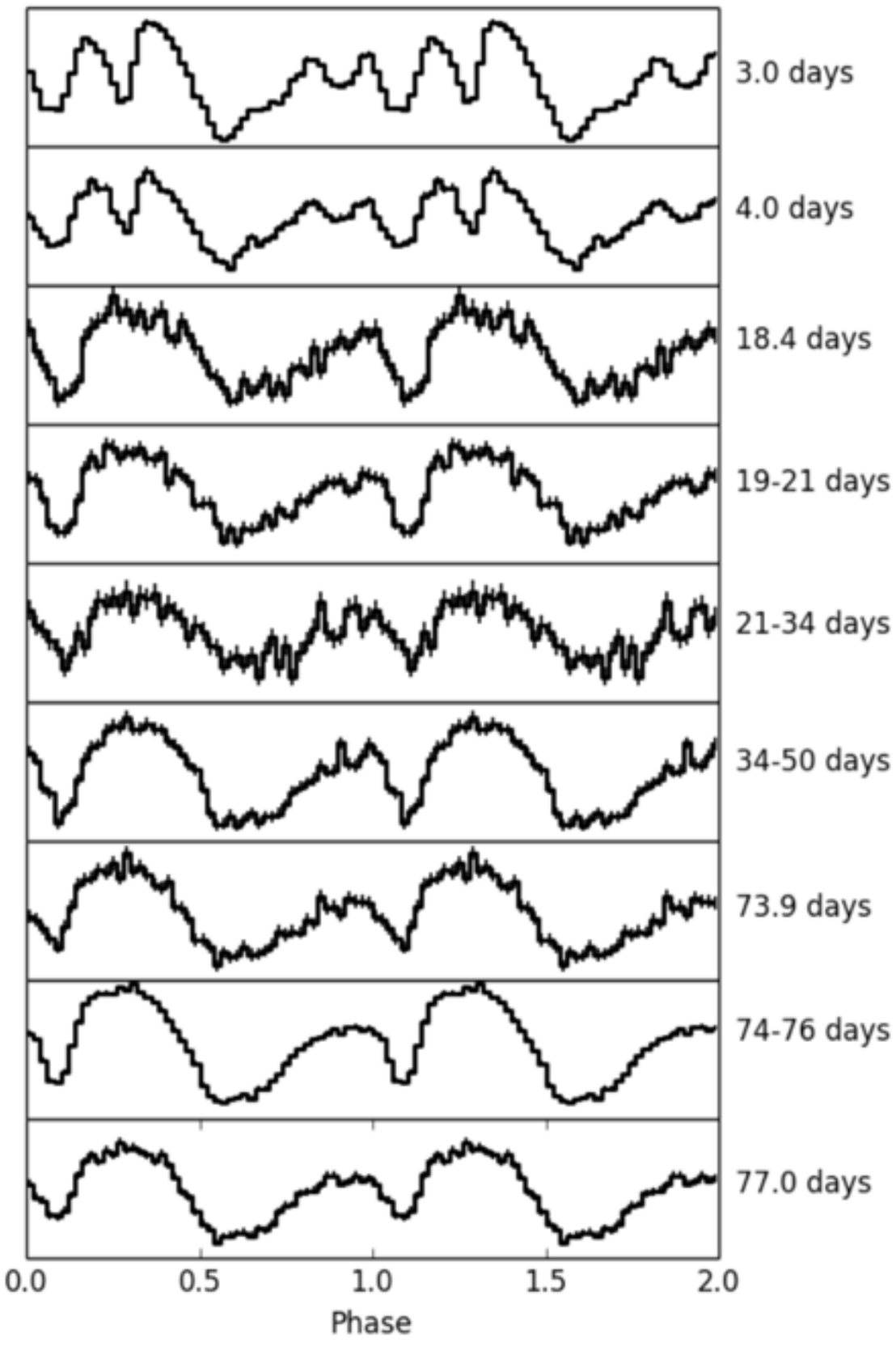

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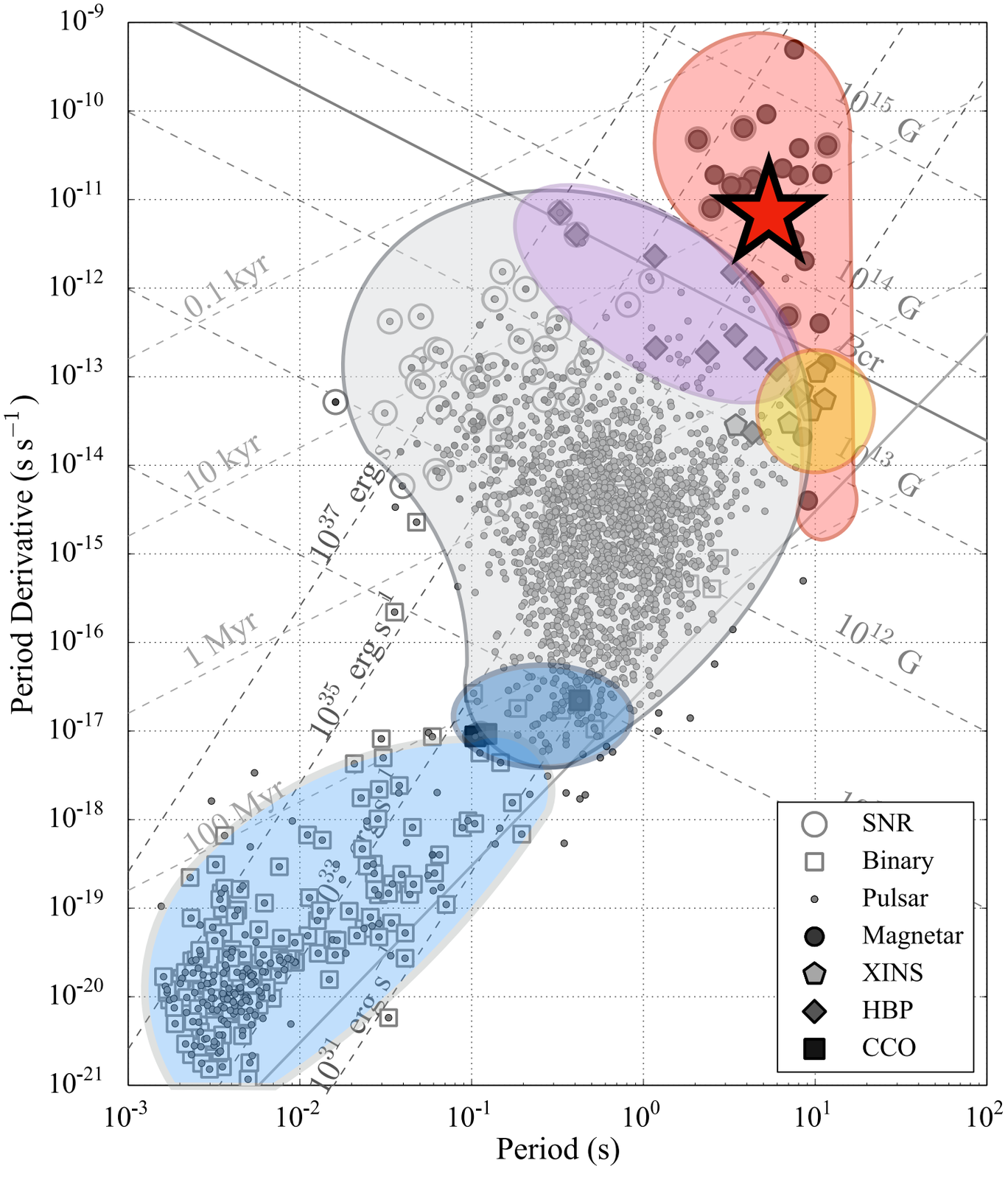
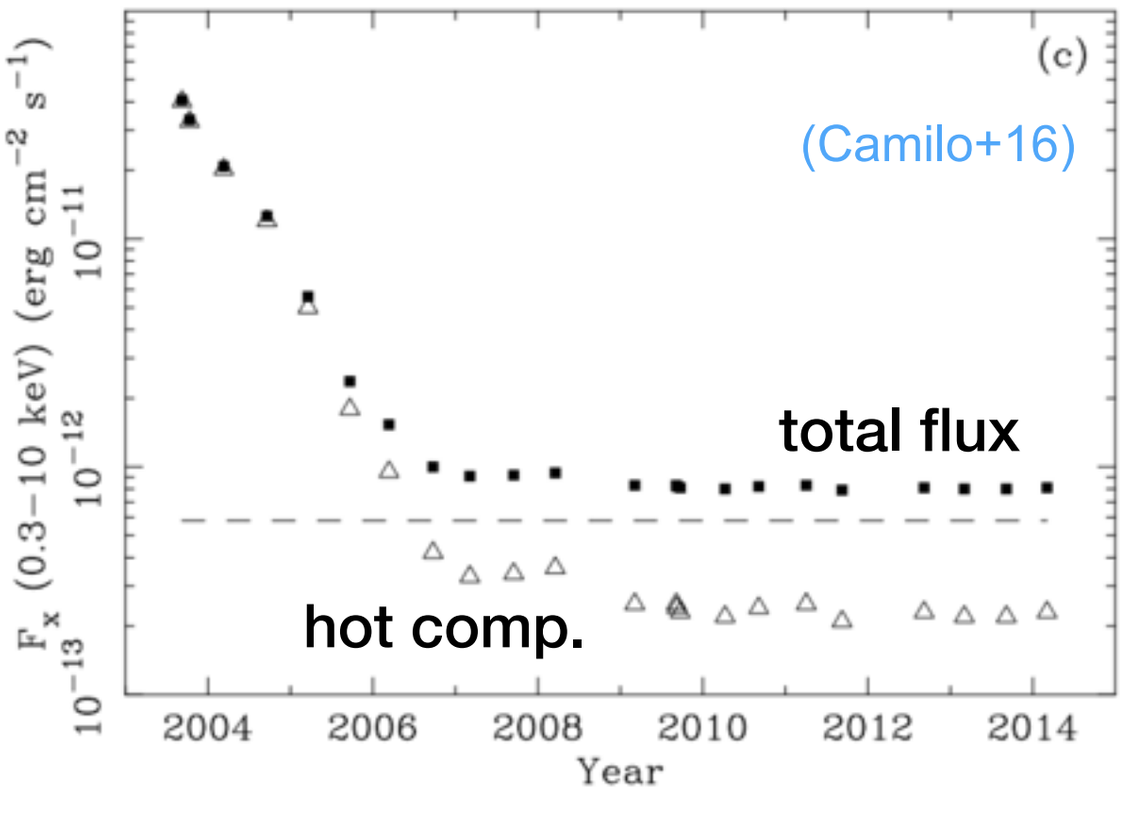
Magnetar Outbursts: XTE J1810-197

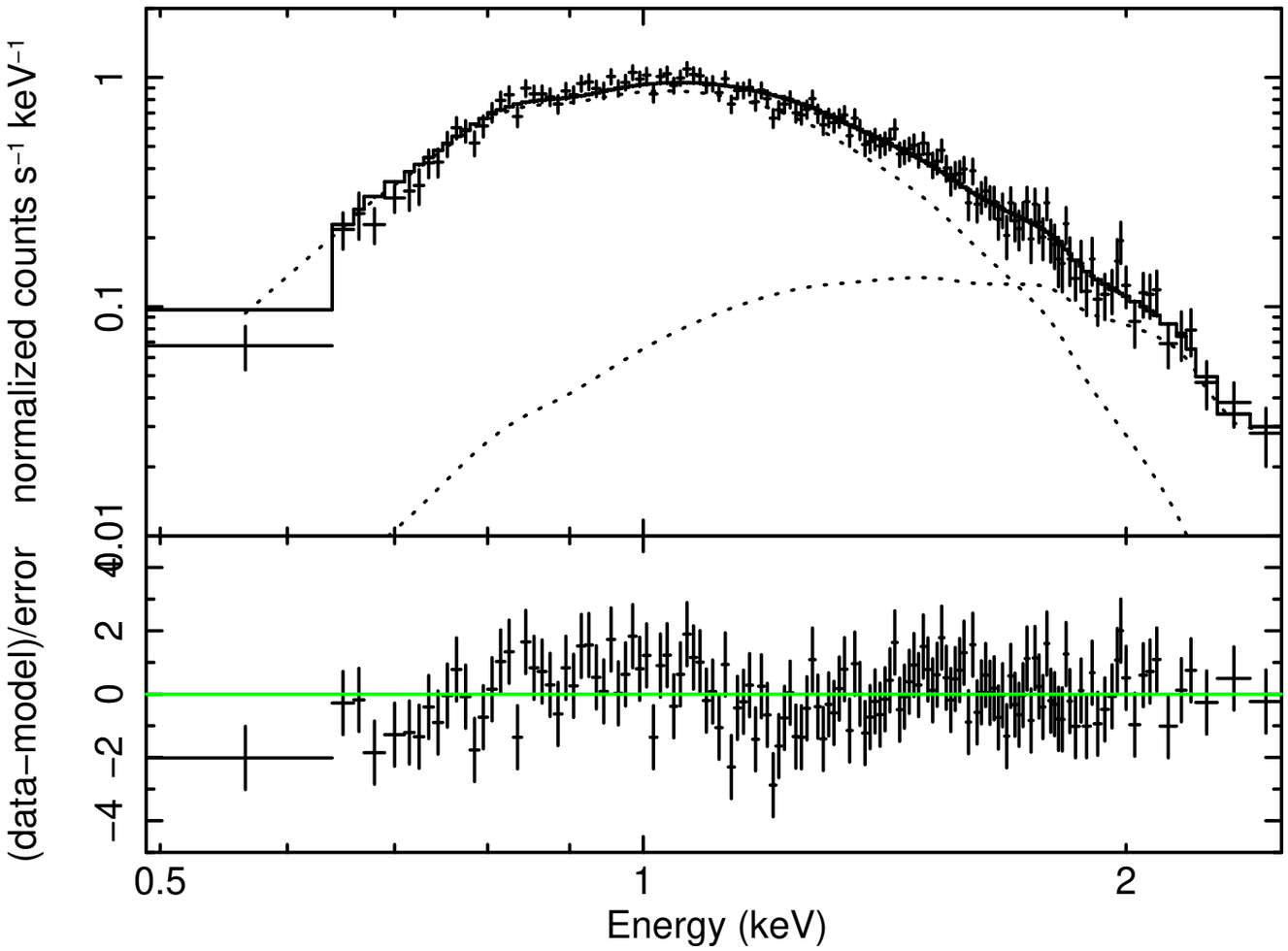


- P = 5.54 s and B_s = 2.1e+14 G
- The first magnetar to have detected radio pulsation, discovered from an X-ray outburst in 2003.
- X-ray flux decay for 4 years to the quiescent level
- **In December, 2018, a radio flux increase at 1.53 GHz (ATel 12284)**



PoC: Tolga Guver

Magnetar Outbursts: XTE J1810-197



A NICER snapshot “before” the recent burst
- June 22, 2017 (28 ks)
- 9.3e-13 erg/s/cm2 (0.5-3.0 keV)
- ~0.76 cps
- Two blackbody (~0.16 & 0.43 keV)

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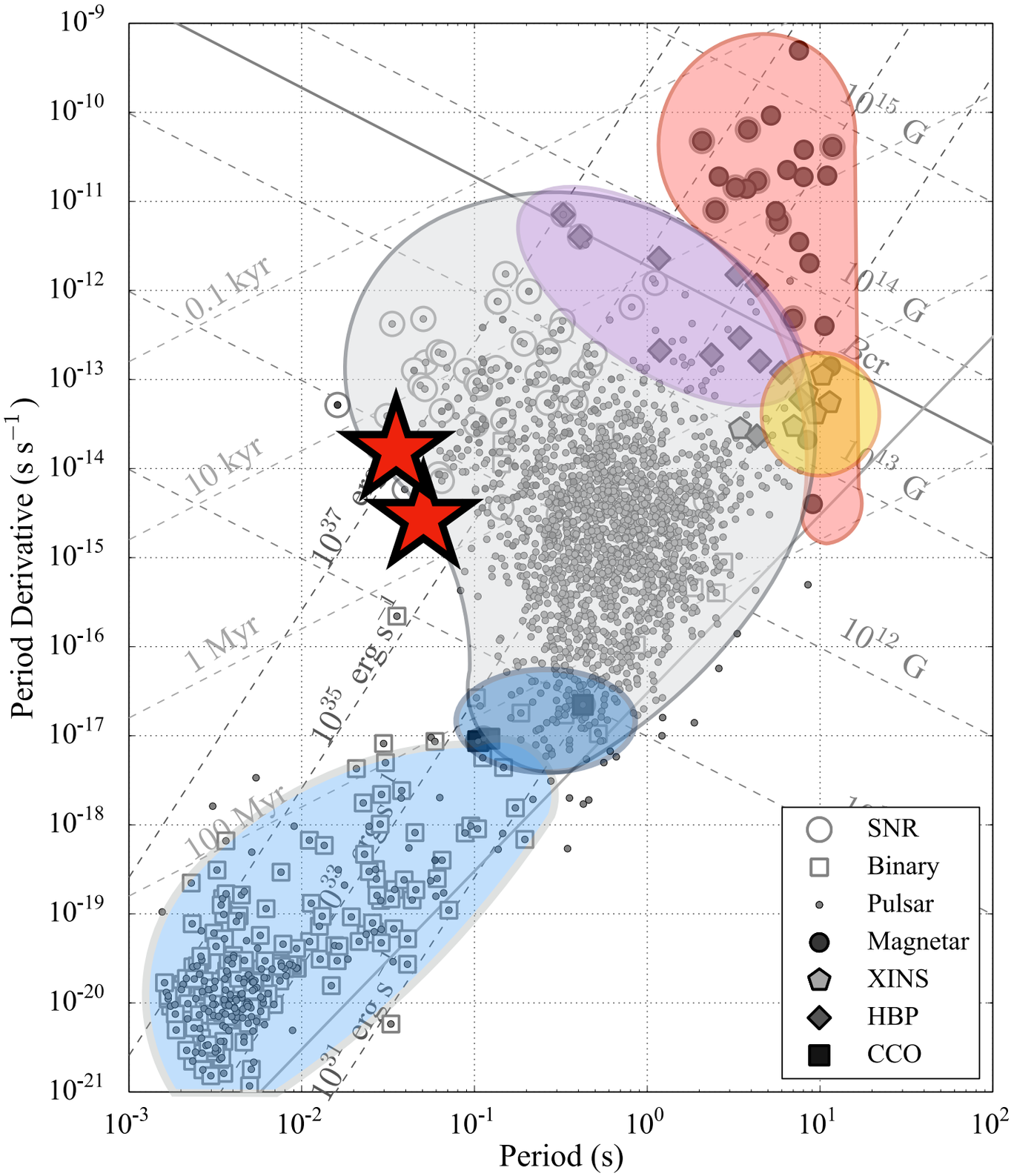
- X-ray flux decay for 4 years to the quiescent level
- **In December, 2018, a radio flux increase at 1.53 GHz (ATel 12284)**
- Most of X-ray observatories can not observe this magnetar in this winter due to the sun angle constraint except for a few cases: MAXI and NuSTAR (ATel 12291 and 12297)
- Once the Sun angle constraint will end in February, NICER will monitor this transient magnetar.

A new outburst will be monitored with NICER and radio

PoC: Tolga Guver

Monitoring of LIGO Targets for the CGW



- Two pulsars <u>only seen in X-rays</u>
  - PSR J1412+7922 (Calvera)
    - *P*=59.2 ms, Pdot=3.3e-15
    - Descendent of CCO?
  - PSR J1849-0001
    - *P*=38.5 ms, Pdot=1.4e-14
    - Energetic young RPP
- Targets of LIGO/Virgo searches for continuous GWs due to a mountain or fluid motion
- NICER factor of 100 improvement in Pdot uncertainty for both
- Timing model for more sensitive LIGO/Virgo searches and pulsation searches at other wavelengths

Bogdanov et al., to be submitted soon

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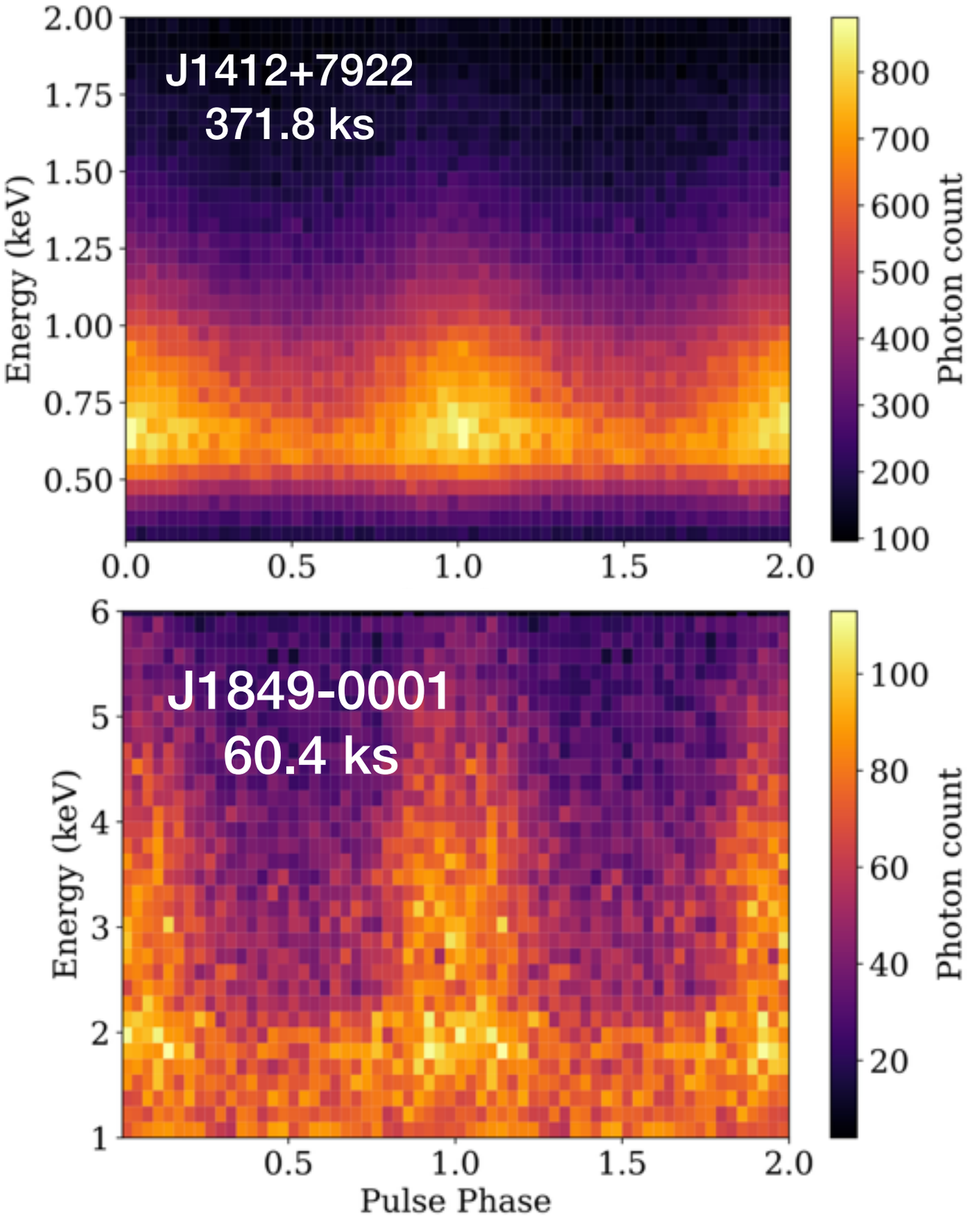

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NICER Data Analysis

NICER Data Analysis

This page contains links to documents and information on the NICER software (NICERDAS) necessary to calibrate and analyse the NICER data.

Current NICERDAS software version 5 distributed with HEAsoft version 6.25 (Oct 2018).

Documents	Release Date	Description
Analysis Guide	Feb 2018	Start up guide for NICER data analysis (pdf)
Software User Guide	Aug 2018	Detailed analysis guide
NICER Analysis Tips	Aug 2018	Tips and caveats

Caveats on the NICER calibration (Released Aug 2018)

NICER Calibration Archive and Software

The calibration data are archived in the HEASARC calibration database (CALDB). The latest releases of the calibration data and their supporting information are available in the NICER Caldb page . The latest software is available from the HEASARC software download page.

- History of calibration releases
- History of software releases
- History of processing versions

NICER Analysis Tips & Caveats

Here we list a number of issues of which users should be aware when analyzing NICER data. These include calibration uncertainties, data processing issues, and other issues.

Low Energy Noise

In general the useful energy band for NICER is $0.2 < E < 12$ keV. The lower bound is set by the detector noise, which peaks near 0.1 keV. However, for data taken during orbit day, the low energy noise peak may intrude into the low energy band. Users should examine carefully the band at the lowest NICER energies. The noise peak tends to increase during orbit day, so that users should be careful about interpreting events in the 0.25 – 0.5 keV range for data taken during orbit day. In some cases, data at $E \leq 0.5$ keV may need to be excluded from analysis.

Energy Calibration (Gain)

Nominally, the NICER PI detector channels are linearly spaced and 10 eV wide, covering the range 0.0-15.01 keV. The energy boundaries of the PI channels can be found in the `EBOUNDS` extension of the XTI response matrix file. There remain some residual uncertainties regarding the NICER energy scale (gain scale). Generally speaking, energy assignment is within 5 – 10 eV, except < 1 keV and in the 4 – 7 keV band (energy deviations in the 4 – 7 keV band are generally about 0 – 30 eV). At this time, users should be very **careful about claiming red/blue shifts of < 30 eV in the Fe-K range** (in particular) based solely on NICER spectra. In-flight testing found no strong dependence of gain on temperature or lighting conditions.

Photon Redistribution (Response Matrix) and Effective Area

Residuals of about 15% remain in the response matrix and effective area, with larger features at specific energy ranges. Users may want to include a systematic 15% uncertainty to spectral analysis.

Timing Calibration

After Level 2 calibration, the timing error is ≤ 100 ns. Note that, before calibration, a 1 second absolute timing offset exists due to the behavior of the on-board clock. As of August 2018, the archived data has a mix of calibration levels applied. For reliable absolute timing results, the user **must apply most recent NICER software `nicerl2`** and use the Calibration Database version `20180711` or later. After processing with `nicerl2`, the correction for this 1-second offset is recorded in the `TIMEZERO` keyword in the header of event files, GTIs and filter files. The NICER data extractor will automatically adjust time values using TIMEZERO when creating light curves. Users who have developed custom software for timing analysis will need to account for the `TIMEZERO` keyword offset.

Deadtime

Deadtime is the time when the detector electronics are "busy" so no events can be recorded. All events, including resets, overshoots and forced triggers, create deadtime. Deadtime is recorded on a per-event basis in the `UFA` event file. Each MPU is parallel. Deadtime is also recorded in the `MPU_DEADTIME` column of the `.mkf` file. The "cleaned" event file (as found, for example, in `xti/event_cl/niNNNNNNNNNN_0mpu7_cl.evt`) excludes < 0.25 keV pulse heights, 5 forced triggers per second per FPM, undershoot resets (dark current), overshoot resets (typically charged particles).

Deadtime is particularly important for bright sources (≥ 20,000 NICER counts/s using 52 FPM). Very bright sources will cause telemetry saturation and a large increase in deadtime. For bright sources, telemetry saturation can be mitigated by using only a subset of the 52 FPMs to observe the source. This will reduce deadtime, but users should be aware that this will also reduce the total effective area of the XTI, so that this reduction in effective area needs to be corrected when deriving source fluxes. To first order, when `N` FPMs, are used the effective area is simply reduced by a factor `N/52` compared to the standard, 52-FPM effective area normally used.

NICER データ解析について

- NICER は Chandra, XMM, Suzaku のような大規模グループではなく、Calibration を少人数（<5人) でやっている現状です。

- 時間解析は現状でも十分な解析が可能です: 例 パルス探査、GRP同期のＸ線増光、パルス波形解析、ブラックホールのQPO など

- 検出器キャリブレーションが不十分でレスポンス関数も改訂中。スペクトルの詳細解析はまだ先: 吸収構造、<5% フラックス測定

- NICER は非撮像系で、バックグラウンドはモデル化する必要がある。極めて暗い天体はまだこれから。

- 現状のオススメは、「明るい天体の速い時間変動」や「パルス探査、パルス波形の解析」などから始める。まだデータがあふれています。解析したい人がいたら、サポートします。

京大白眉→理研白眉研究チーム(2019年10月~)

- 雷雲と雷放電の高エネルギー大気物理学
- 超小型衛星を用いたスケーラブルなＸ線天文学
- 多波長連携を中心においた中性子星の天体物理学

2020年4月以降に着任の以下の受け入れが可能です。

- 基礎科学特別研究員制度: http://www.riken.jp/careers/programs/spdr/
- 大学院生リサーチ・アソシエイト（JRA）:http://www.riken.jp/careers/programs/jra/
- 国際プログラム・アソシエイト（IPA）:http://www.riken.jp/careers/programs/ipa/

Summary

- NICER Magnetar and Magnetosphere (M&M) group covers magnetized neutron stars.
- NICER detected a signature for X-ray enhancement associated with giant radio pulses from the Crab pulsar, a similar percentage increase as reported in the optical band.
- NICER continued follow-up observations of magnetar transient activities: 4U 0142+61, PSR J1622-4950, XTE J1810-197, and SGR 1806-20.
- NICER improved pulsar ephemerides of PSR J1412+7922 and J1849-0001 providing timing models for future LIGO/ Virgo continuous GW search.
- NICER are monitoring rotation-powered pulsars, such as Vela pulsar and PSR B0656+14.