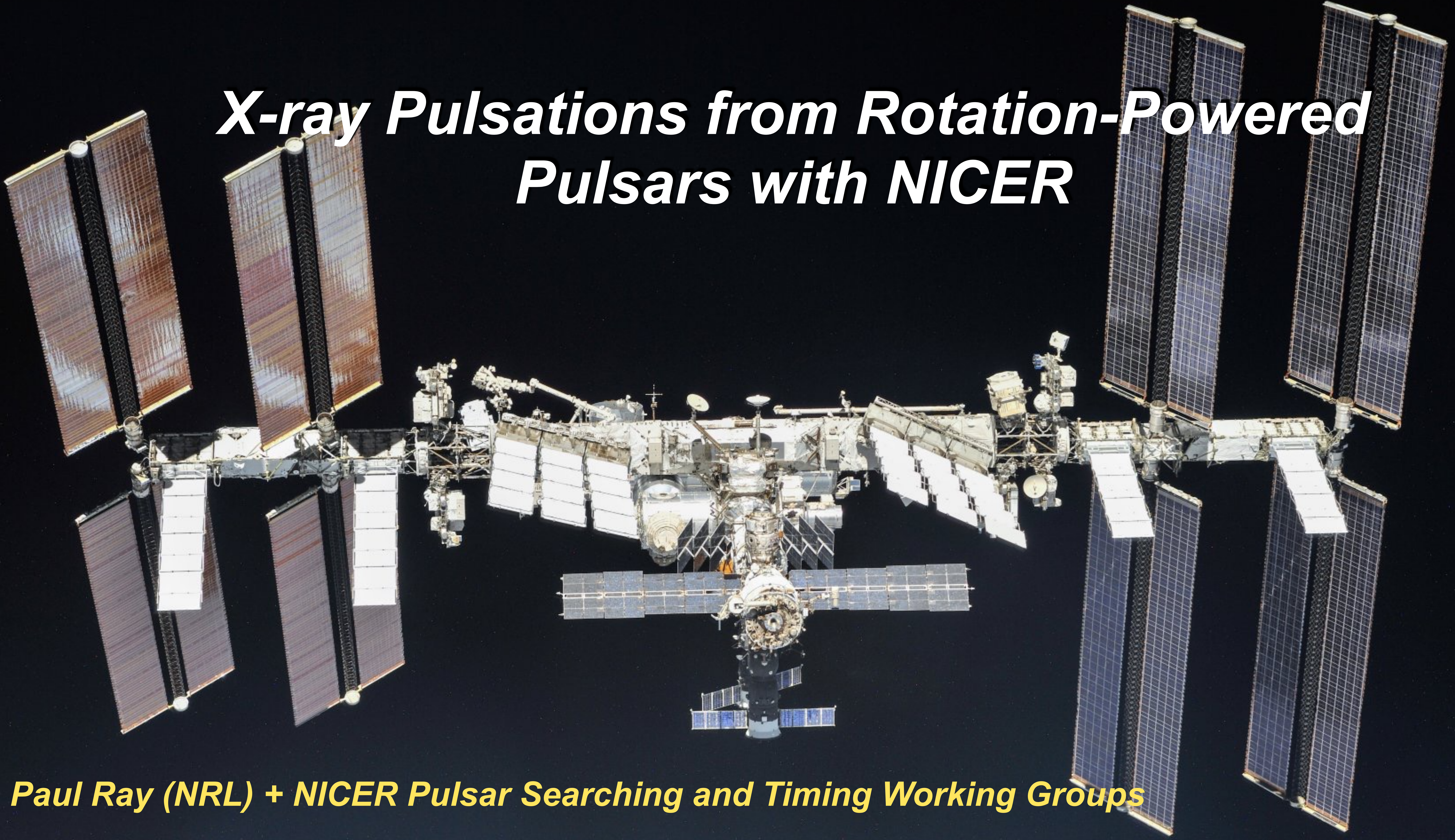
X-ray Pulsations from Rotation-Powered Pulsars with NICER



Paul Ray (NRL) + NICER Pulsar Searching and Timing Working Groups

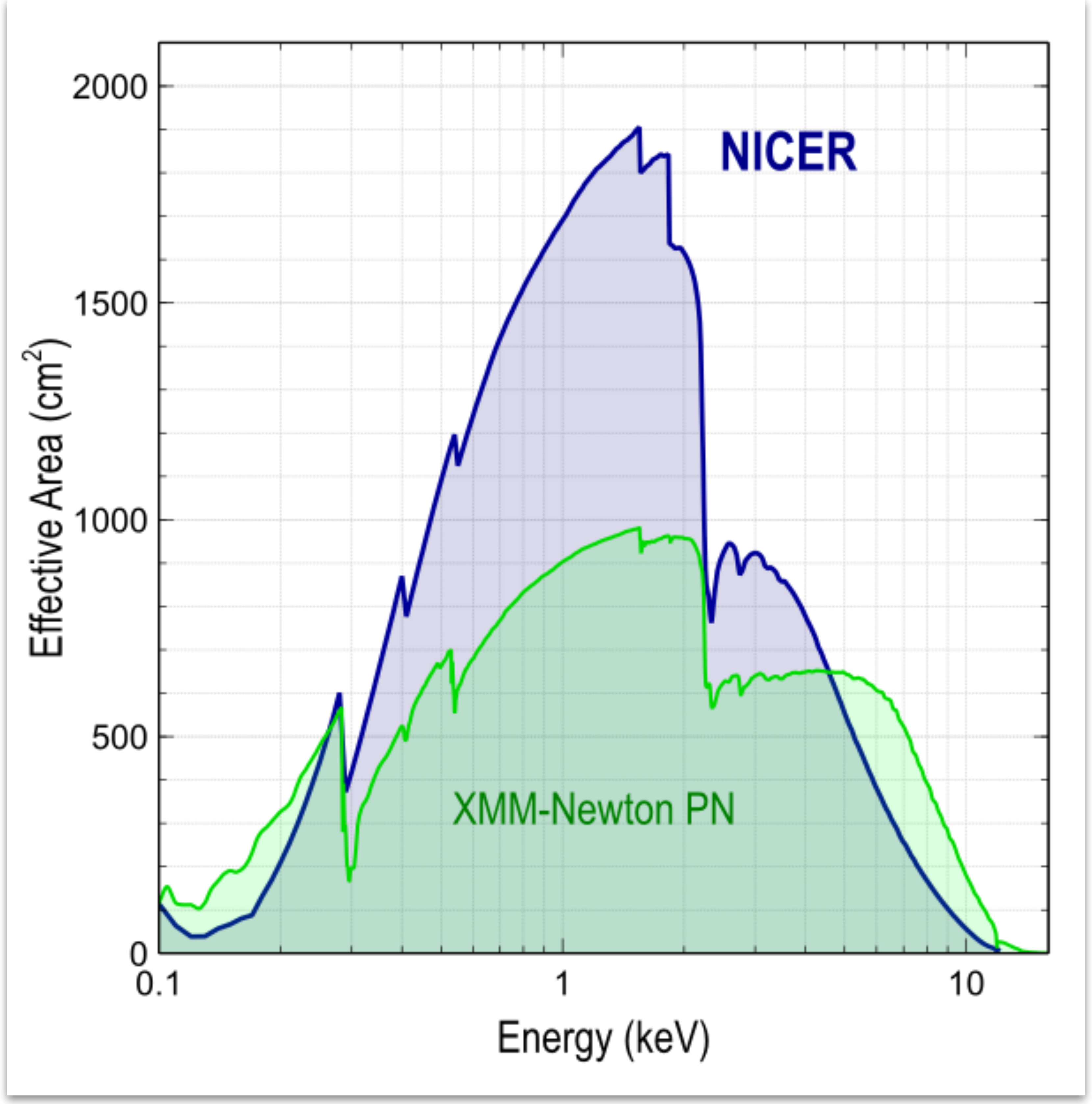
NICER is funded by NASA

Why study X-rays from rotation-powered pulsars?

- **See thermal emission from the surface:**
  - Dense matter Equation of State
  - Polar cap heating
  - Another handle on geometry, complementary to radio polarization and gamma-ray measurements
- **See non-thermal emission from magnetosphere**
- **No propagation effects on timing measurements**
- **Timing of radio quiet pulsars**

Science Opportunity

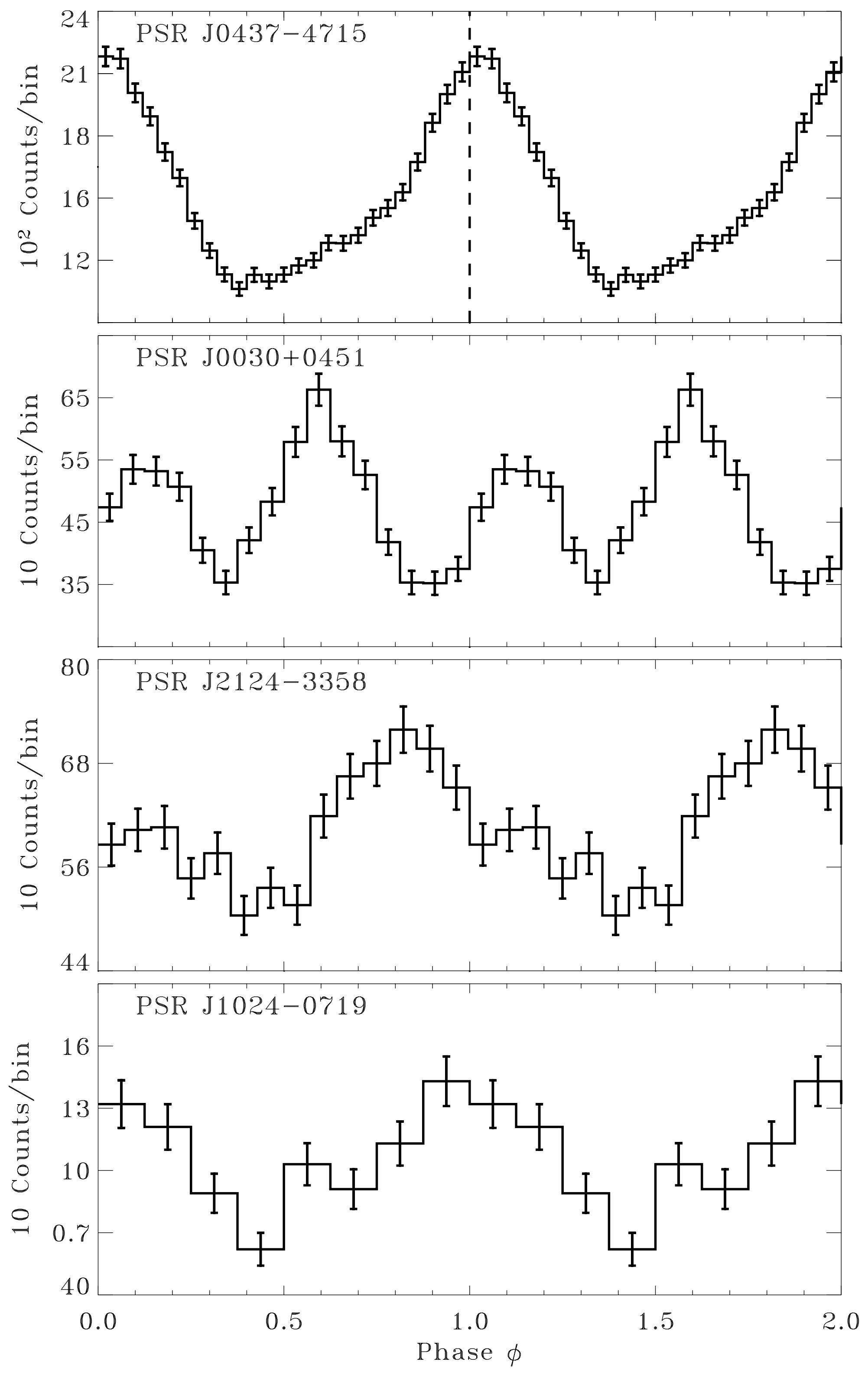
- NICER XTI has large effective area with high time resolution, low background, high rate capability, precise absolute timing and energy coverage down to 0.25 keV
  - Previous timing missions like RXTE didn't get much below 3 keV, so missed the thermal surface emission
  - NICER has twice the area of XMM EPIC-pn, is always in "timing" mode, and has GPS time



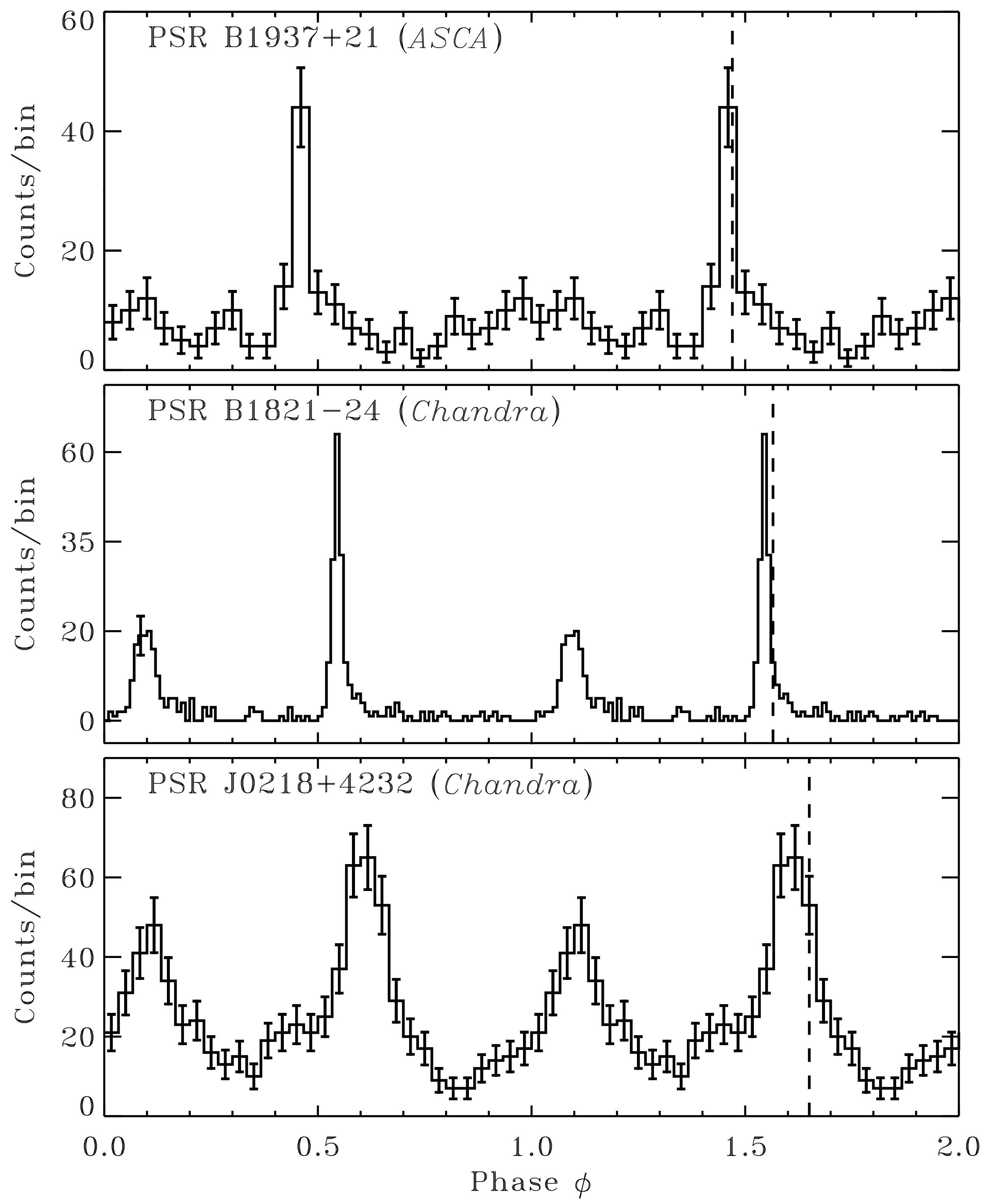
Essentially optimal instrument for X-ray studies of rotation-powered millisecond pulsars

X-rays from Rotation Powered MSPs

Thermal



Non-Thermal



Figures from Zavlin (2007)

Pre-NICER: One dozen pulsed detections, 3 are non-thermal

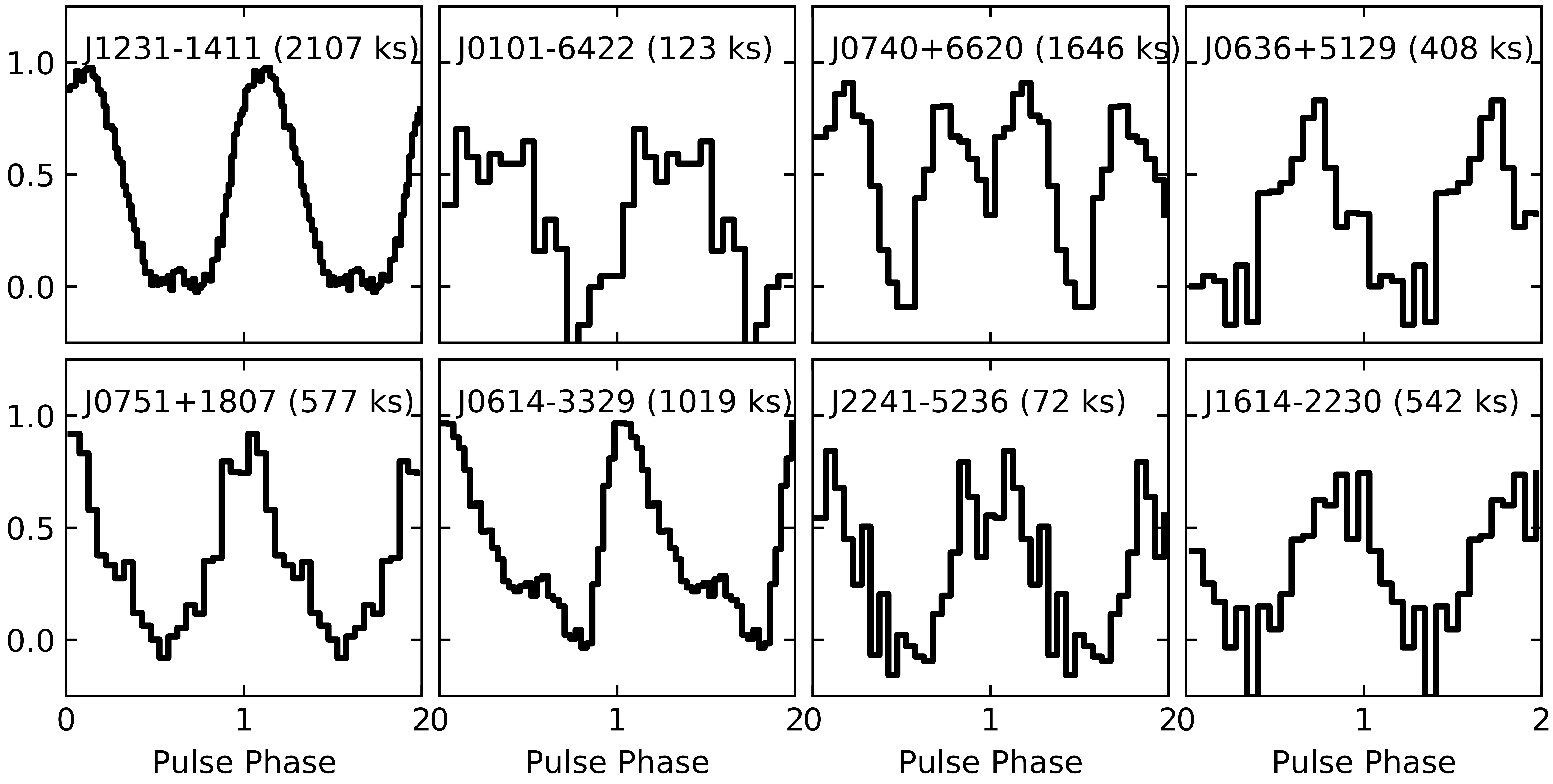
Pre-NICER Table of X-ray MSPs

One dozen pulsed detections (among field MSPs)

Non-Thermal

NAME	F0	DM	DIST	AGE	EDOT	EDOTD2	Pulsation Discovery Ref
B1821-24A	327.406	119.89	5.5	2.99E+07	2.24E+36	7.41E+34	1997ApJ...477L..37S
B1937+21	641.928	71.02	3.5	2.35E+08	1.1E+36	8.96E+34	2001ApJ...554..316T
J0218+4232	430.461	61.25	3.1	4.76E+08	2.44E+35	2.46E+34	1998A&A...336..545K
B1957+20	622.122	29.12	1.7	1.51E+09	1.6E+35	5.35E+34	2012ApJ...744...33G
J2214+3000	320.592	22.55	0.6	3.36E+09	1.92E+34	5.32E+34	Wolff (Unpublished)
J1614-2230	317.379	34.92	0.7	5.19E+09	1.21E+34	2.48E+34	2012A&A...544A.108P
J0437-4715	173.688	2.64	0.2	1.59E+09	1.19E+34	4.82E+35	1993Natur.365..528B
J0751+1807	287.458	30.25	1.1	7.08E+09	7.3E+33	5.93E+33	2004A&A...419..269W
J2124-3358	202.794	4.6	0.4	3.8E+09	6.77E+33	4.03E+34	2006ApJ...638..951Z
J1024-0719	193.716	6.48	1.2	4.41E+09	5.33E+33	3.58E+33	2006ApJ...638..951Z
J1012+5307	190.268	9.02	0.7	4.86E+09	4.66E+33	9.51E+33	2004A&A...419..269W
J0030+0451	205.531	4.34	0.3	7.58E+09	3.49E+33	3.31E+34	2000ApJ...545.1015B

NICER MSPs


J1231-1411 (2107 ks)
J0101-6422 (123 ks)
J0740+6620 (1646 ks)
J0636+5129 (408 ks)
J0751+1807 (577 ks)
J0614-3329 (1019 ks)
J2241-5236 (72 ks)
J1614-2230 (542 ks)
1.0
0.5
0.0
0
1
2
Pulse Phase

Current List with NICER Discoveries

Rotation-Powered MSPs with X-ray Pulsations

Non-thermal

NAME	F0	DM	DIST	EDOT	EDOTD2	Pulsation Discovery Ref	NICER Pulsations?	Fermi LAT Pulsations?
B1821-24A	327.406	119.89	5.5	2.24E+36	7.41E+34	1997ApJ...477L..37S	Yes	Yes
B1937+21	641.928	71.02	3.5	1.1E+36	8.96E+34	2001ApJ...554..316T	Yes	Yes
J0218+4232	430.461	61.25	3.15	2.44E+35	2.46E+34	1998A&A...336..545K	Yes	Yes
B1957+20	622.122	29.12	1.73	1.6E+35	5.35E+34	2012ApJ...744...33G		Yes
J2241-5236	457.310	11.41	0.96	2.51E+34	2.72E+34	2019ApJ...887L..27G	Yes	Yes
J0614-3329	317.594	37.05	0.63	2.22E+34	5.59E+34	2019ApJ...887L..27G	Yes	Yes
J0740+6620	346.532	14.96	0.43	2E+34	1.06E+35	2021ApJ...918L..26W	Yes	Yes
J2214+3000	320.592	22.55	0.6	1.92E+34	5.32E+34	In prep	Yes	Yes
J1231-1411	271.453	8.09	0.42	1.8E+34	1.02E+35	2019ApJ...878L..22R	Yes	Yes
J1614-2230	317.379	34.92	0.7	1.21E+34	2.48E+34	2012A&A...544A.108P	Yes	Yes
J0437-4715	173.688	2.64	0.16	1.19E+34	4.82E+35	1993Natur.365..528B	Yes	Yes
J0751+1807	287.458	30.25	1.11	7.3E+33	5.93E+33	2004A&A...419..269W	Yes	Yes
J2124-3358	202.794	4.6	0.41	6.77E+33	4.03E+34	2006ApJ...638..951Z	Yes	Yes
J0636+5129	348.559	11.11	0.21	5.75E+33	1.3E+35	2019ApJ...887L..27G	Yes	Yes
J1024-0719	193.716	6.48	1.22	5.33E+33	3.58E+33	2006ApJ...638..951Z	Yes	Yes
J1012+5307	190.268	9.02	0.7	4.66E+33	9.51E+33	2004A&A...419..269W	Yes	No
J0030+0451	205.531	4.34	0.32	3.49E+33	3.31E+34	2000ApJ...545.1015B	Yes	Yes
J0101-6422	388.628	11.9	1	1.2E+34	1.2E+34	In prep	Yes	Yes

Thermal

6 NICER discoveries   11 NICER confirmations

What determines detectability?

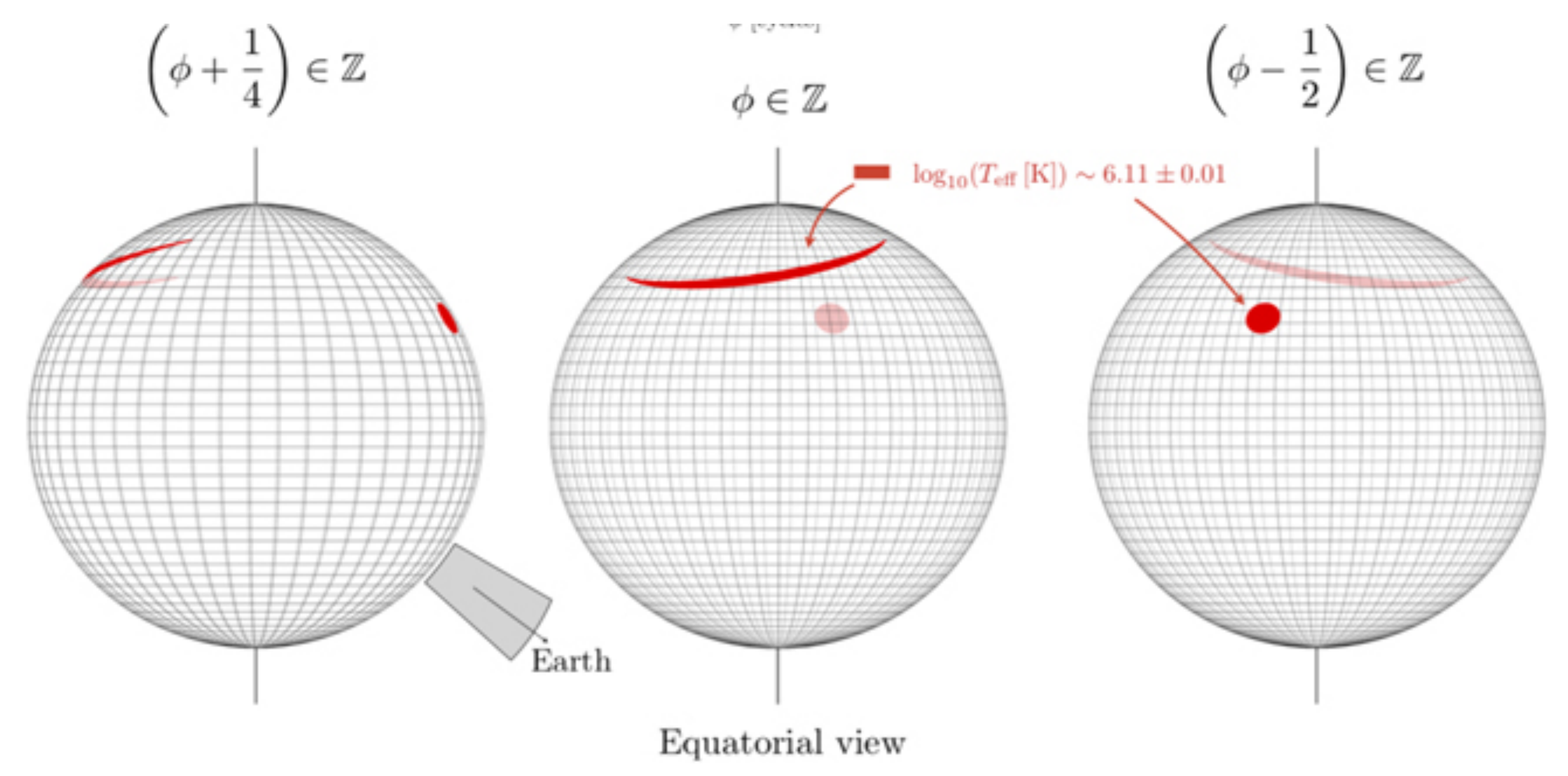
More complexity than expected!

- Return current energy deposition?
- Polar cap size?

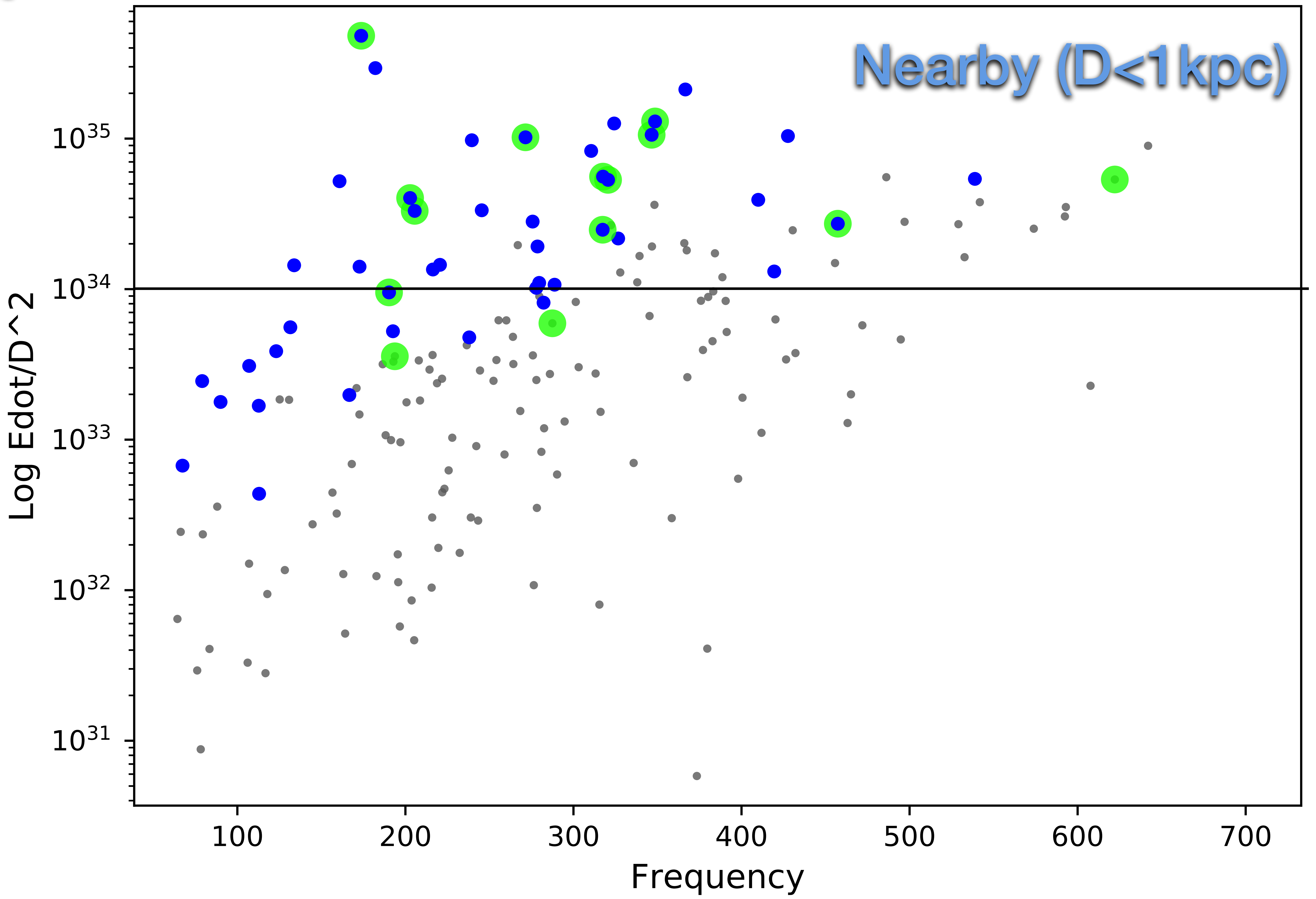
$$r_{p+}{}^{d} = \left(\frac{2}{3}\right)^{3/4} R \left(\frac{\Omega R}{c}\right)^{1/2} \approx 10^4 P^{-1/2}\ \mathrm{cm}$$ (RS75)

$$L_x = \sigma T_s^4 \pi r_p^2 = 1.2 \times 10^{32} (\dot{P}_{-15}/P^3)(\eta h/r_p)^2\ \mathrm{erg\ s^{-1}}$$ (Gil et al. 2007)

J0030+0451



X-ray pulsations



NICER Pulsar Catalog

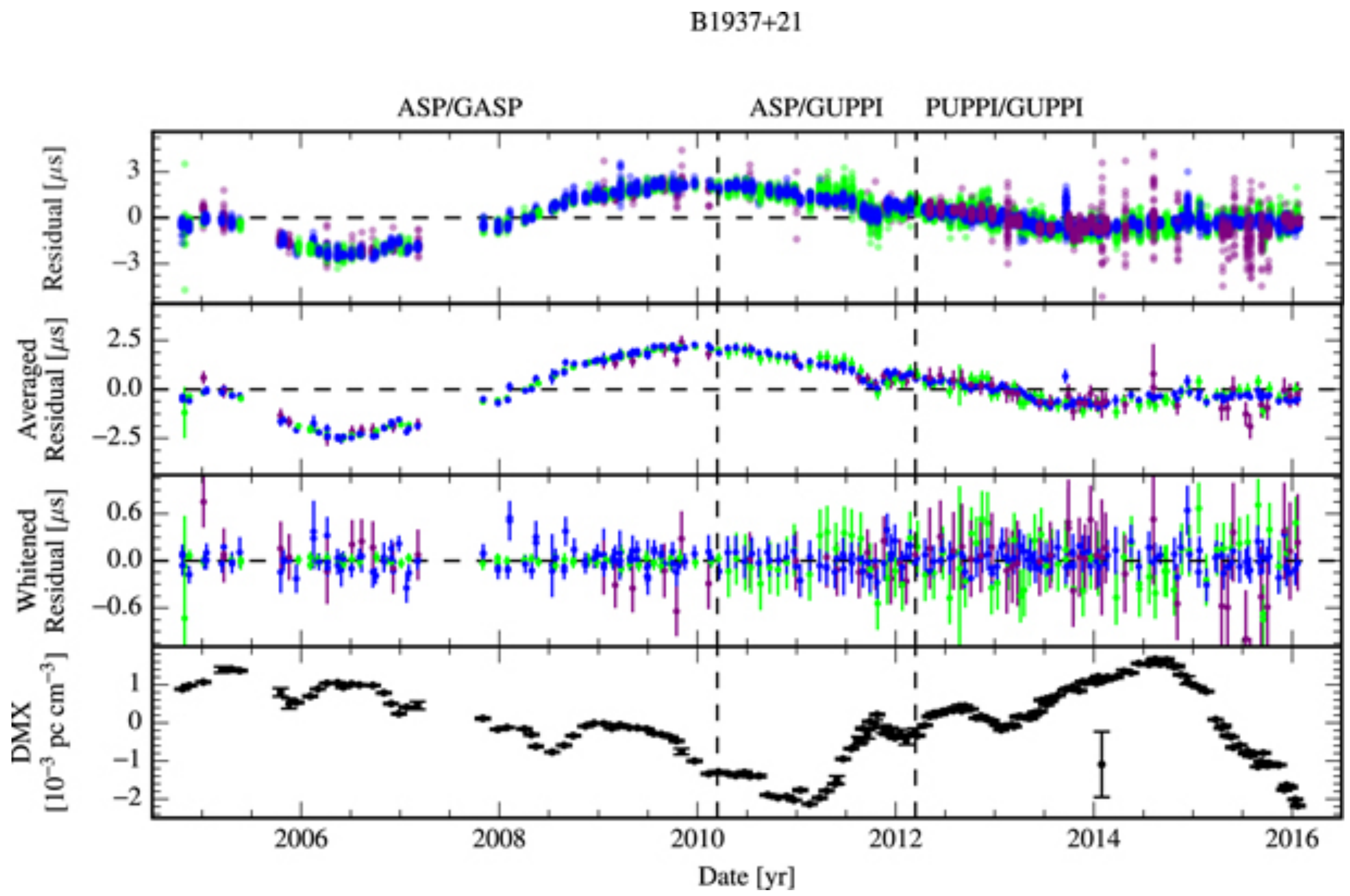
- NICER has also made many observations of young pulsars, but not nearly as complete as the MSPs
- New push to get more observations and produce catalog
  - Uniform spectral analysis from 0.25–12 keV give more comparable fluxes, excellent nH measurements and measurement of thermal and non-thermal spectral shapes.
    - Many prior compilations got either 0.2–2 keV or 2–10 keV but not both, complicating comparisons
  - Precise absolute timing clarifies relationship between X-ray, gamma-ray and radio pulses,
    - X-rays are often from surface hot spots, radio from above polar caps, and gamma-rays from outer magnetosphere, so multi-wavelength modeling must describe full geometry of the system.

Table 1. Rotation-powered Young Pulsars with X-ray Pulsations

PSR	Period (ms)	R.A. (hh:mm:ss)	Decl. (dd:mm:ss)	F_X (0.4–2) (10^{-14} erg/cm^2/s)	F_X (2–10) (10^{-14} erg/cm^2/s)	PF %	n_H (10^{21} cm^{-2})	kT (eV)	Γ
B0531+21	33.39	$05^h34^m32.0^s$	+22°00′52.1″	65200.00	266000.00	10	3.45	—	1.6
B0833-45	89.33	$08^h35^m20.6^s$	−45°10′34.9″	4200.00	2.30	50	0.22	128	2.7
B0540-69	50.57	$05^h40^m11.2^s$	−69°19′54.2″	969.00	2610.00	—	3.70	—	2.0
B0656+14	384.93	$06^h59^m48.2^s$	+14°14′19.4″	420.00	9.84	14	0.36	111	1.9
J0537-6910	16.12	$05^h37^m47.4^s$	−69°10′19.9″	380.00	380.00	—	2.70	—	2.6
J0633+1746	237.10	$06^h33^m54.2^s$	+17°46′12.9″	270.00	0.00	40	0.13	44	1.9
B1509-58	151.58	$15^h13^m55.8^s$	−59°08′09.6″	200.00	2800.00	87	9.70	—	1.2
J1741-2054	413.70	$17^h41^m57.3^s$	−20°54′11.8″	88.00	25.00	35	1.20	61	2.8
B1055-52	197.11	$10^h57^m59.0^s$	−52°26′56.3″	84.70	7.28	—	0.12	69	1.8
J0205+6449	65.72	$02^h05^m37.9^s$	+64°49′41.3″	78.70	110.00	—	4.50	162	1.8
B1951+32	39.53	$19^h52^m58.2^s$	+32°52′40.5″	51.20	200.00	2	3.00	—	1.6
J2229+6114	51.62	$22^h29^m05.3^s$	+61°14′09.3″	47.20	414.00	19	3.00	—	1.0
J1124-5916	135.48	$11^h24^m39.0^s$	−59°16′19.0″	21.40	68.00	28	2.80	—	1.6
B1929+10	226.52	$19^h32^m14.1^s$	+10°59′33.4″	15.00	1.80	39	0.17	300	1.7
J1846-0258	326.57	$18^h46^m24.9^s$	−02°58′30.1″	12.82	937.20	14	39.60	160	1.4
J1747-2958	98.81	$17^h47^m15.9^s$	−29°58′01.0″	9.94	330.00	29	26.00	—	1.4
J1357-6429	166.11	$13^h57^m02.4^s$	−64°29′30.2″	9.80	17.00	63	2.30	—	2.1
J1930+1852	136.86	$19^h30^m30.1^s$	+18°52′14.1″	9.53	201.00	—	19.50	—	1.4
J2021+3651	103.74	$20^h21^m05.5^s$	+36°51′04.8″	6.00	47.00	—	6.90	150	1.4
J1420-6048	68.18	$14^h20^m08.2^s$	−60°48′16.4″	5.06	22.90	—	22.00	—	1.6
J1811-1926	64.67	$18^h11^m29.2^s$	−19°25′25.4″	5.06	223.00	—	22.20	—	1.0
J1838-0655	70.50	$18^h38^m03.1^s$	−06°55′33.4″	4.16	751.90	5	54.00	—	1.3
B0950+08	253.07	$09^h53^m09.3^s$	+07°55′35.8″	4.00	6.30	57	0.19	—	1.8
J1617-5055	69.36	$16^h17^m29.3^s$	−50°55′13.2″	3.75	289.00	44	34.00	—	1.1
B1706-44	102.46	$17^h09^m42.7^s$	−44°29′08.2″	3.26	11.00	30	5.50	—	2.0
B0355+54	156.38	$03^h58^m53.7^s$	+54°13′13.8″	2.51	14.80	40	5.00	—	1.5
B0628-28	1244.42	$06^h30^m49.4^s$	−28°34′42.8″	2.17	1.05	39	0.60	—	2.6
J2021+4026	265.32	$20^h21^m30.0^s$	+40°26′45.1″	2.00	0.50	77	7.10	267	1.2
J1119-6127	407.96	$11^h19^m14.3^s$	−61°27′49.5″	1.56	7.44	74	18.50	185	1.7
J2022+3842	48.58	$20^h22^m21.7^s$	+38°42′14.8″	1.20	60.00	17	23.00	—	0.9
J1459-6053	103.15	$14^h59^m30.0^s$	−60°53′20.7″	0.68	2.26	—	6.40	—	2.1
J1826-1256	110.22	$18^h26^m08.5^s$	−12°56′33.0″	0.68	21.00	—	22.80	—	1.3
J0058-7218	21.77	$00^h58^m16.9^s$	−72°18′05.6″	—	—	—	6.00	—	1.4

Precise Timing

- Timing MSPs in X-rays eliminates propagation effects like dispersion and scattering that plague radio measurements
  - Also supports applications like SEXTANT, a the first real-time, on orbit demonstration of spacecraft navigation using X-ray pulsar observations
- Long term, carefully curated, radio timing (~15 years) is available from Pulsar Timing Array projects
  - In 11 year NANOGrav dataset, 11/45 pulsars exhibit significant red noise
- Goal is to compare to precise radio timing from PTAs to try to constrain contribution to red noise (led by A. Lommen)



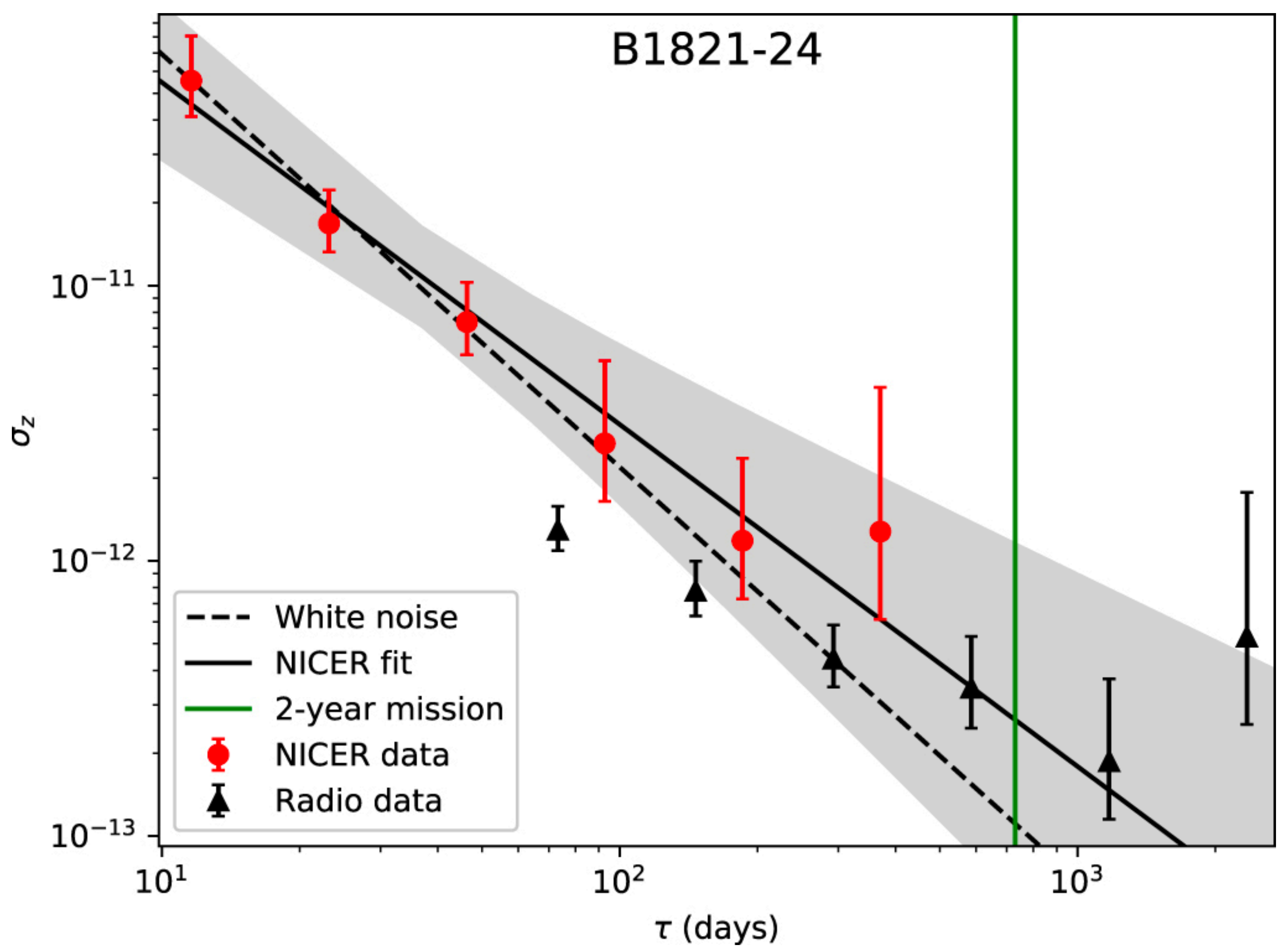
NANOGrav 11-year dataset
(Arzoumanian et al. 2018)

Characterizing Stability

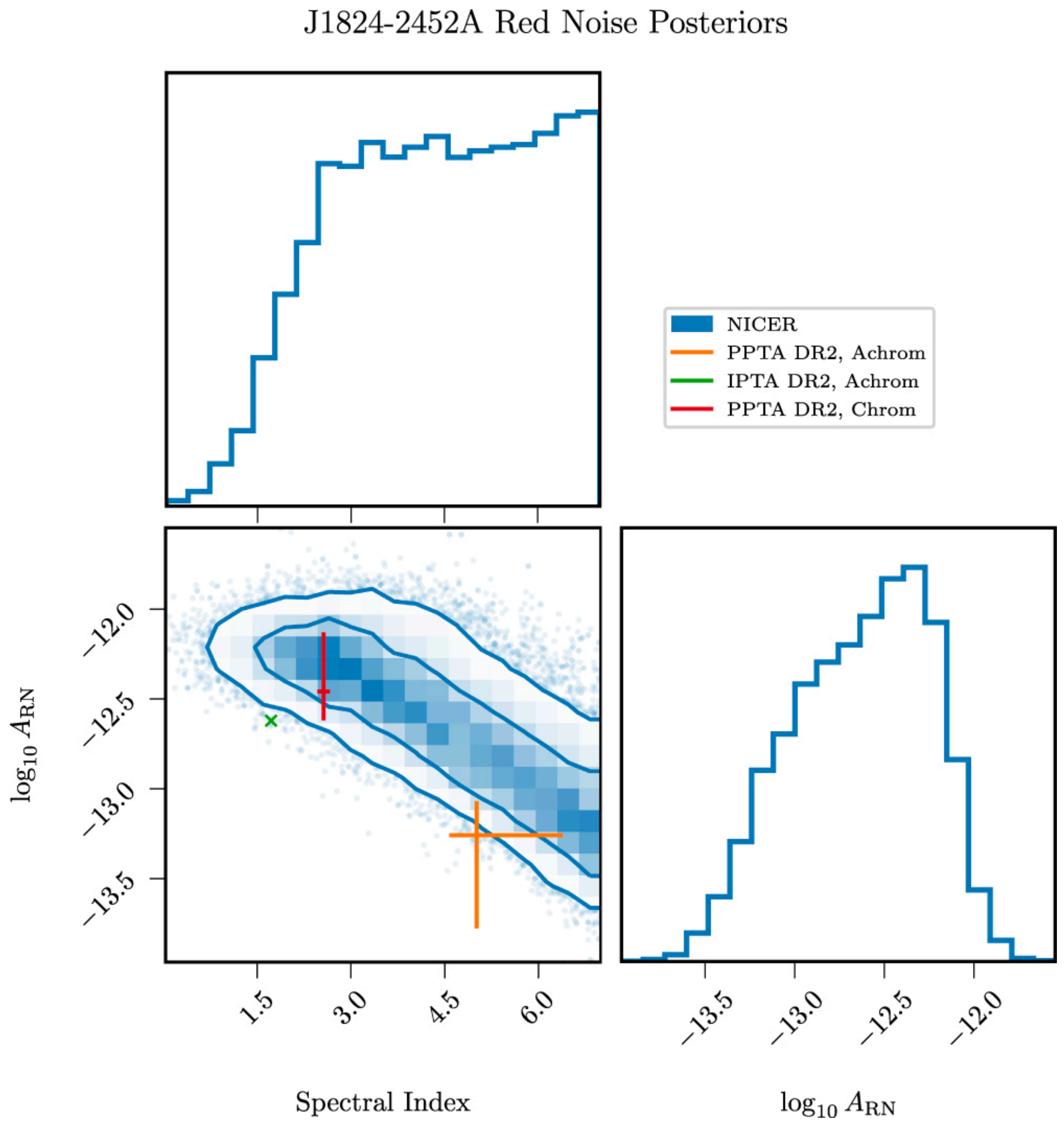
New: Red Noise spectral modeling with Enterprise

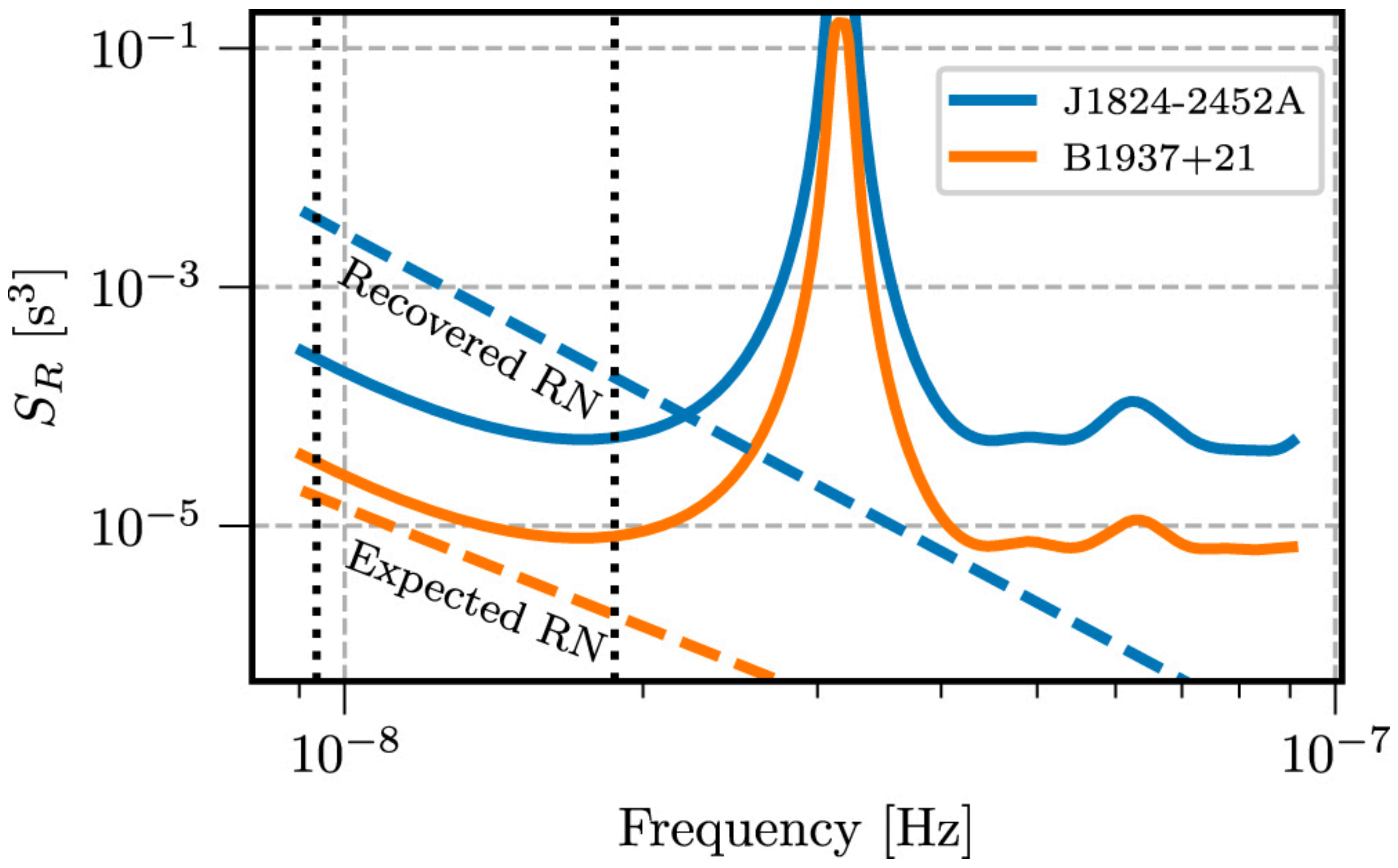
$$h = Af^{-\gamma}$$

Old: σ_z



Deneva et al. (2019)





Hazboun et al. (2022)

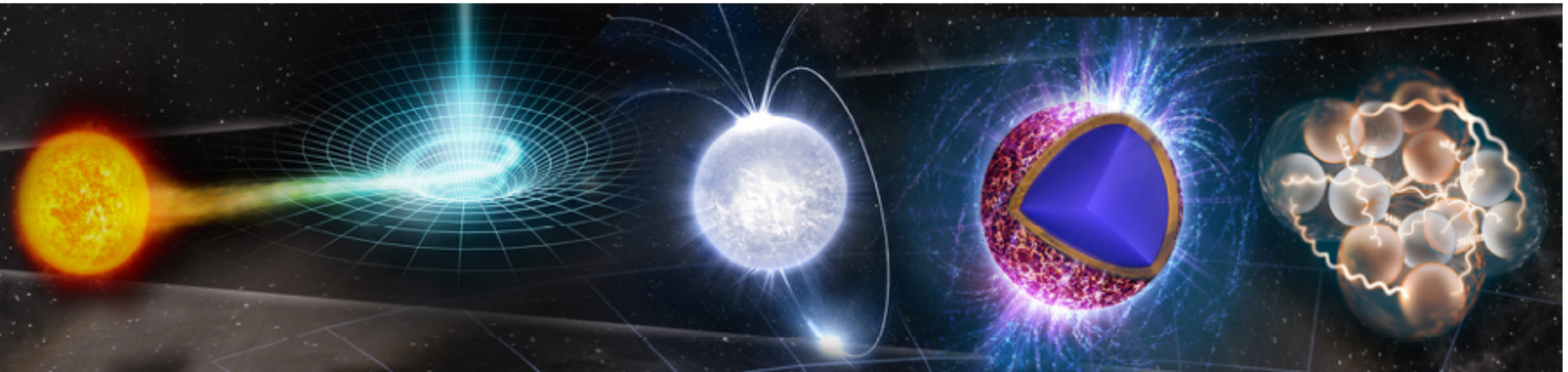
Tools

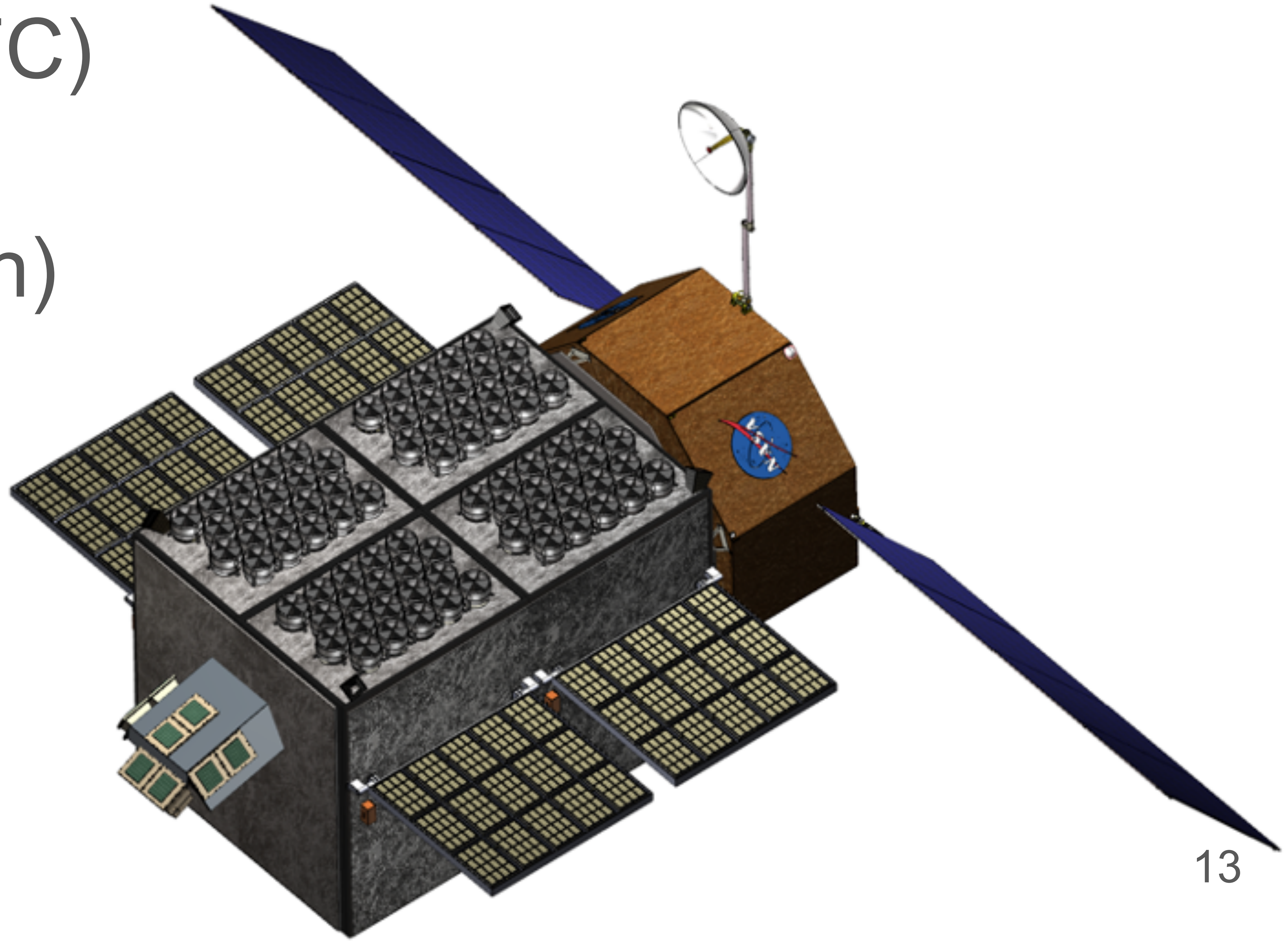
- **PINT (PINT Is Not Tempo3)**
  - New pulsar timing software suite, written in modern Python
  - Independent of TEMPO and Tempo2
  - Added components to handle assigning pulse phases to photon data from many different spacecraft (with or without barycentering first), and single-photon timing methods (e.g. MCMC)
- **NICERsoft user-contributed tools**
  - Available on GitHub, with useful additions to HEAsoft for NICER analysis

STROBE-X

Revealing fundamental physics via the life cycles of compact objects and the dynamic universe

PI: Paul Ray (NRL)
Deputy PI (Implementation): Keith Gendreau (GSFC)
Project Scientist: Colleen Wilson-Hodge (MSFC)
Science Group Lead: Tom Maccarone (Texas Tech)
+ over 200 person SWG



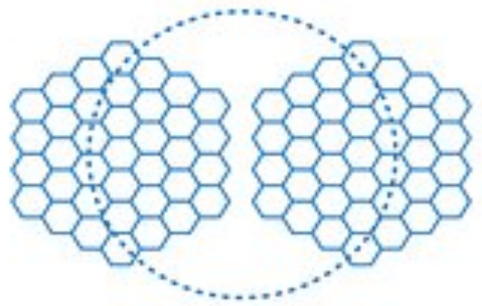


Transformational Capabilities

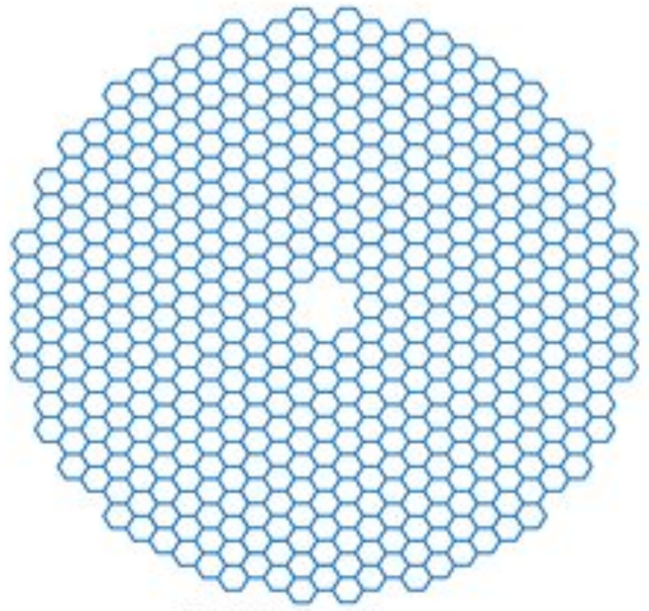
STROBE-X will measure the most fundamental physical parameters of compact objects, revealing how they form, grow, and die; and will be a critical high energy component of the decade of time domain surveys.

- STROBE-X will uniquely **apply multiple techniques to constrain mass and spin for both stellar and supermassive black holes**.
- STROBE-X will make **precise measurements of neutron star radii** and probe their spin evolution up to the fastest rates.
- STROBE-X will **monitor the X-ray sky for transients and variability** that will reveal multi-messenger counterparts, trigger pointed observations, and characterize long term evolution of sources.

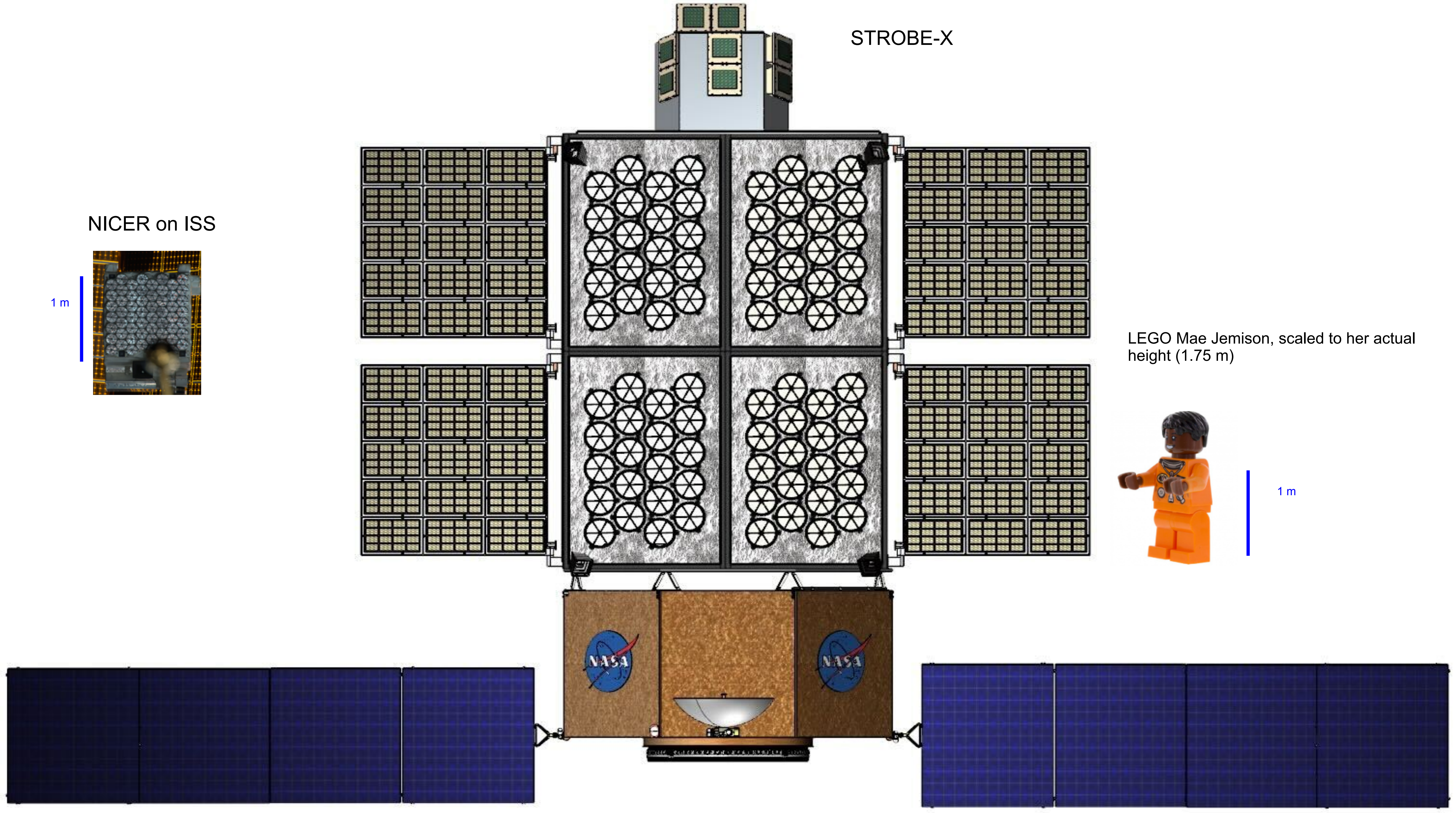
Also contributes more broadly to stellar physics, galaxy groups and clusters, accretion physics, and even some Solar System science.



Keck Telescope
Mauna Kea, Hawaii (1993–1996)

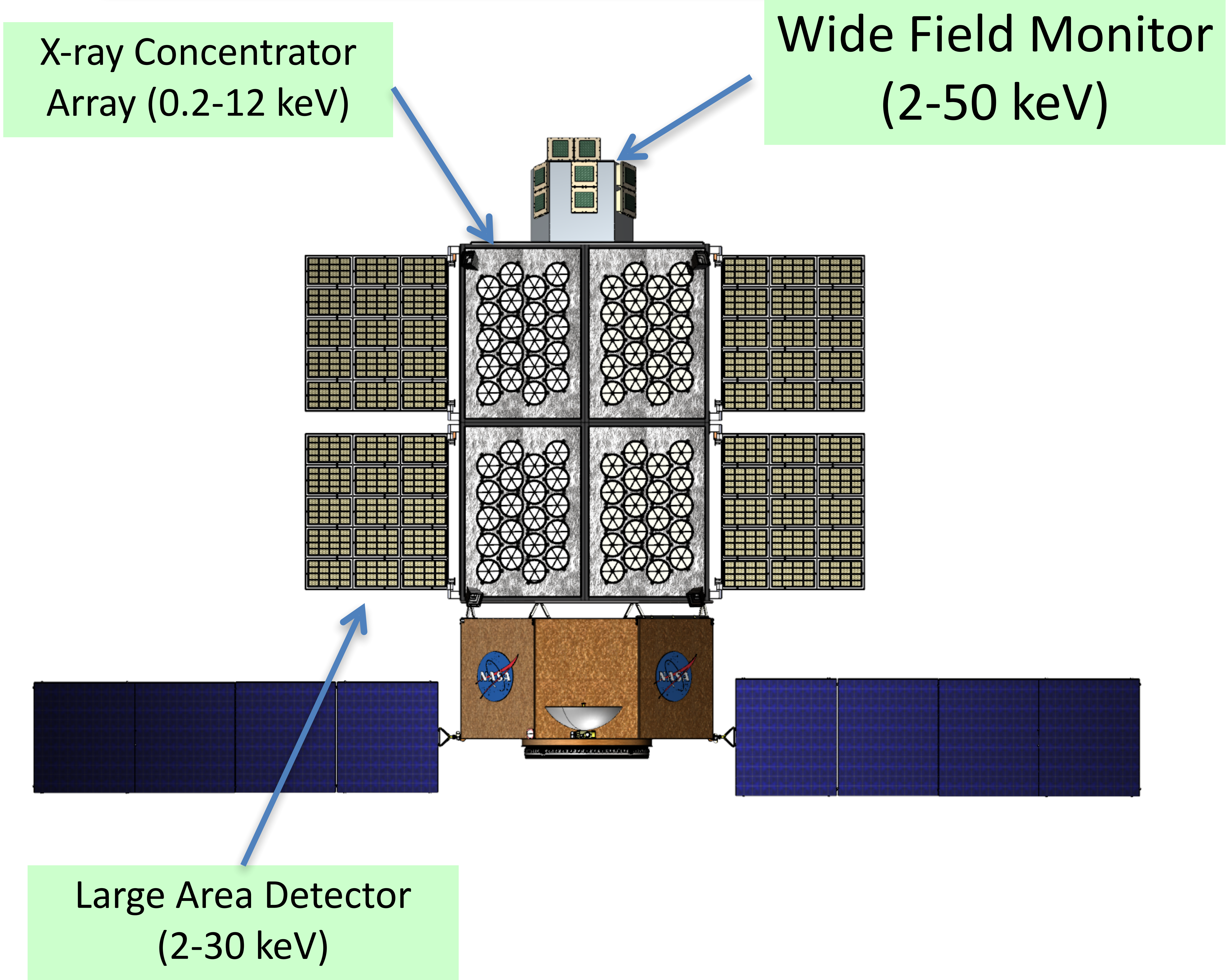


Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022+)

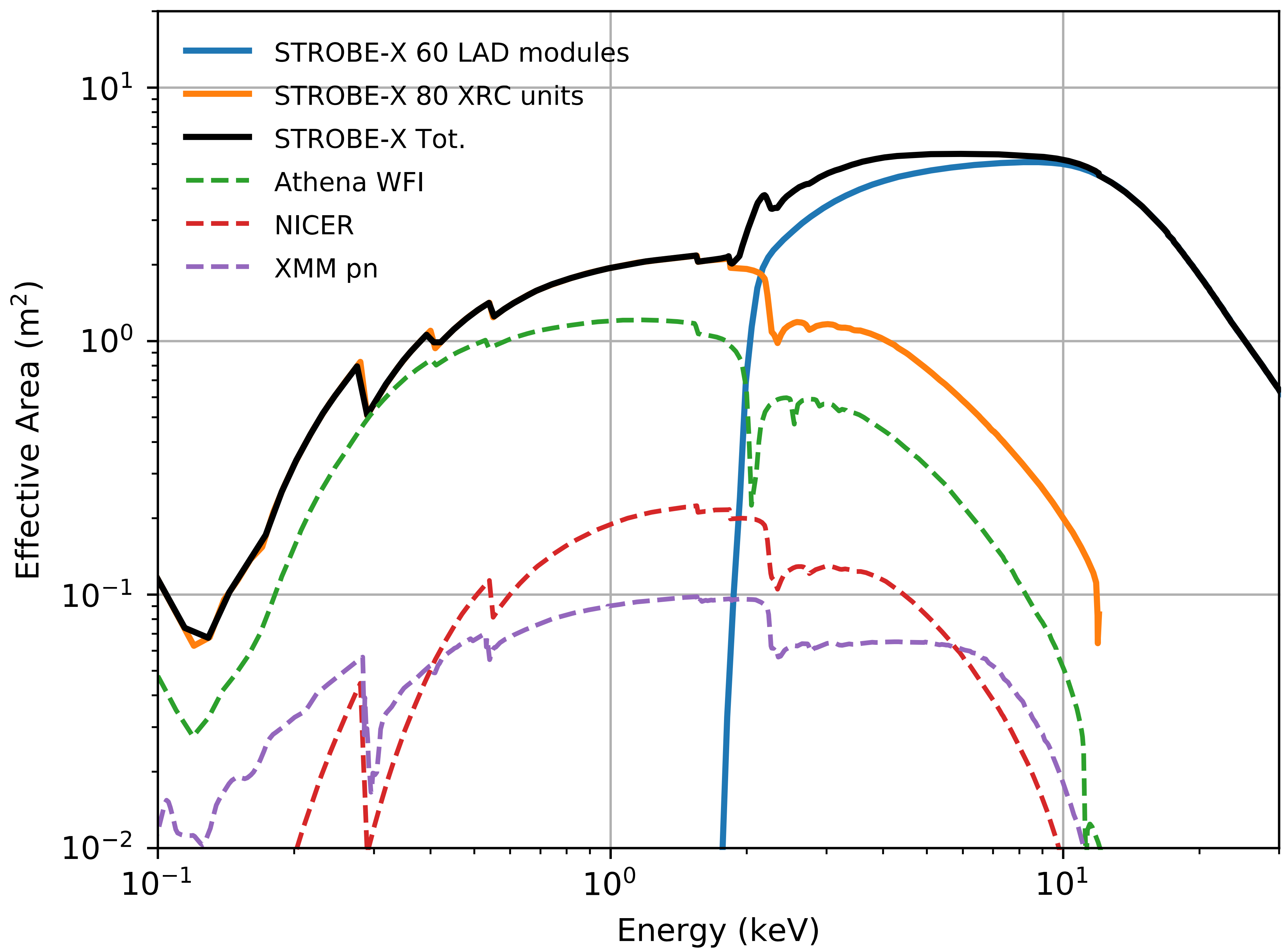


STROBE-X

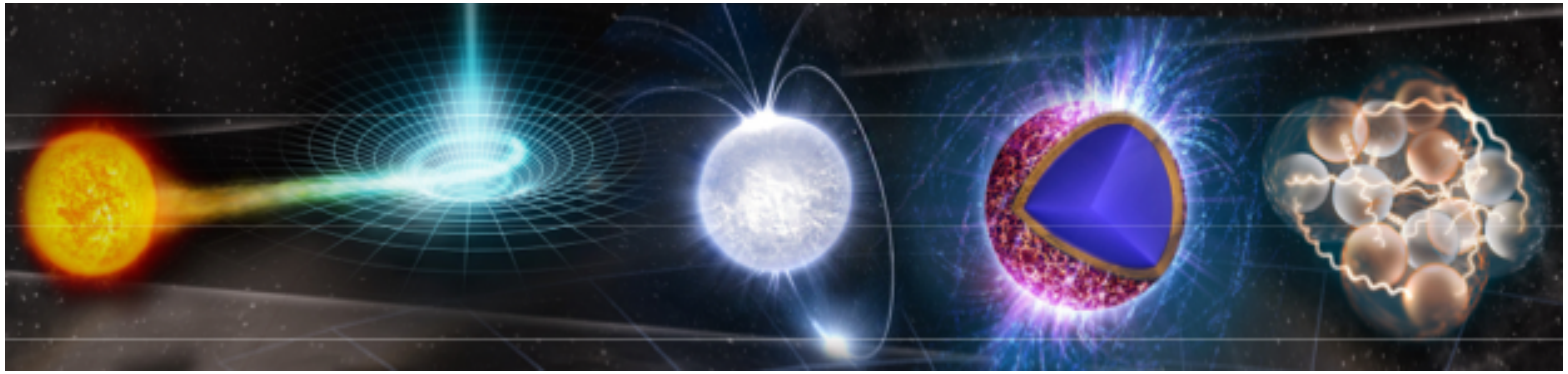
STROBE-X Instrument Concept



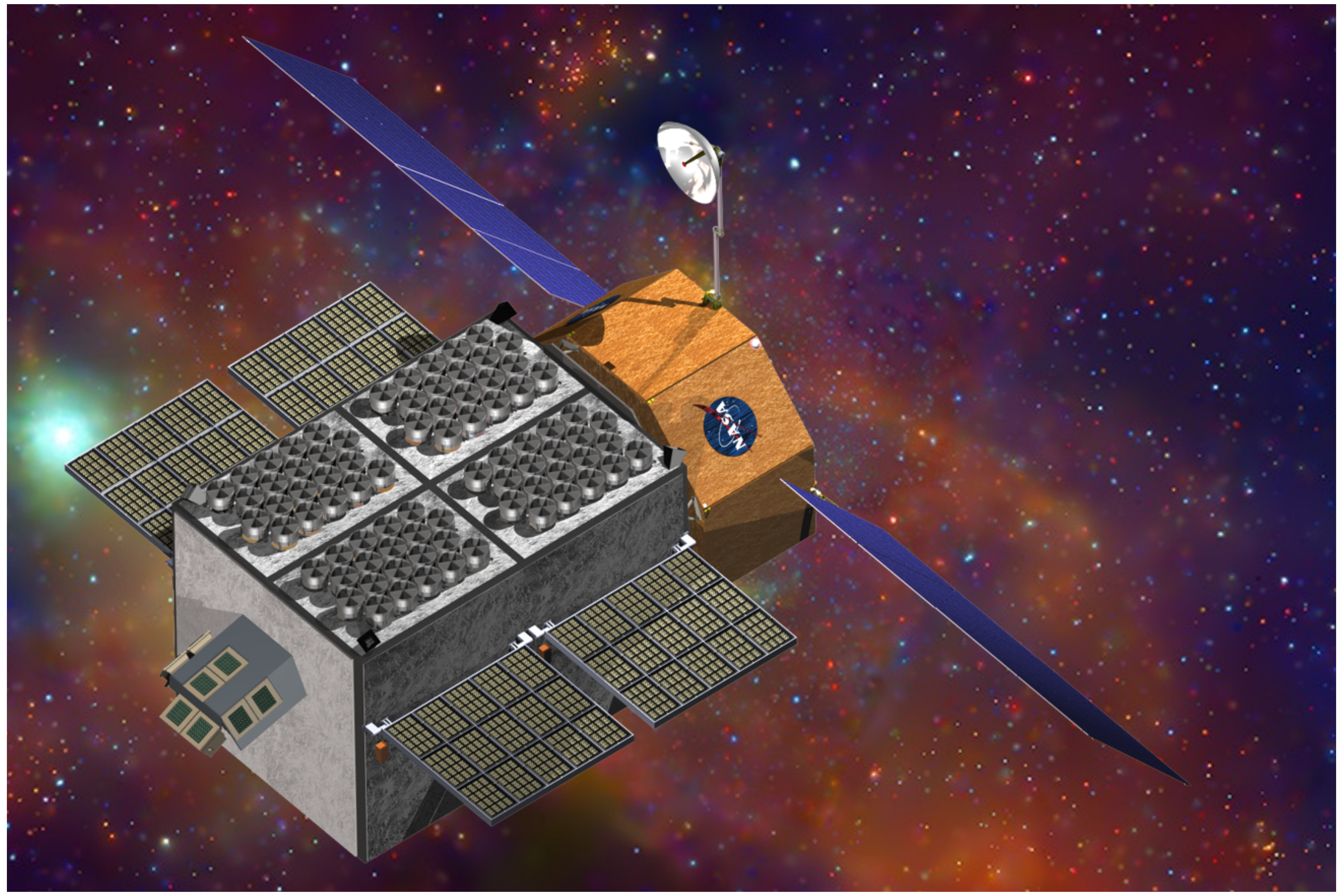
Large effective area >5 m² @ 6 keV



- STROBE-X combines the strengths of NICER and LOFT: High throughput X-ray spectral timing with good powerful sky monitor
- All components are already high TRL
- Highly modular design improves reliability at reduced cost and allows easy scaling.



STROBE-X



- Huge collecting area, fast timing, and good spectral resolution, flexible scheduling and rapid response. Addresses fundamental questions in accretion, dense matter, black hole formation and evolution
- Based on existing technology and builds on experience with NICER and LOFT, enabling confidence in cost estimates at this early stage. Highly modular design allows easy scaling. Comfortably under Probe-class cost cap
- Will serve a large community in a decade of time-domain and multi-messenger astronomy with **complementary** capabilities to the large high spectral and spatial resolution missions
  - Active SWG with over 2— members open for all to discuss science impacts of the mission

Follow us on Twitter (@STROBEXastro), Facebook, and at https://strobe-x.org

Summary

- NICER is a powerful mission for discovering and timing spin-powered pulsars and MSPs (plus LOTS of other things!)
- Searches have discovered pulsations from 6 MSPs and confirmed pulsations from 11 others
  - Best new discoveries (e.g. J1231–1411, J0614+3329) will be excellent for Lightcurve Modeling to constrain dense matter EOS
  - Continuing to look for new candidates to search
  - Working on uniform NICER catalog of spin-powered pulsars
- Timing has shown great promise to detect red noise without confounding propagation effects
  - Moving from simple σ_z to sophisticated red noise modeling and detecting MSP red noise in X-ray