NICER

Neutron star Interior Composition ExploreR

APS Briefing

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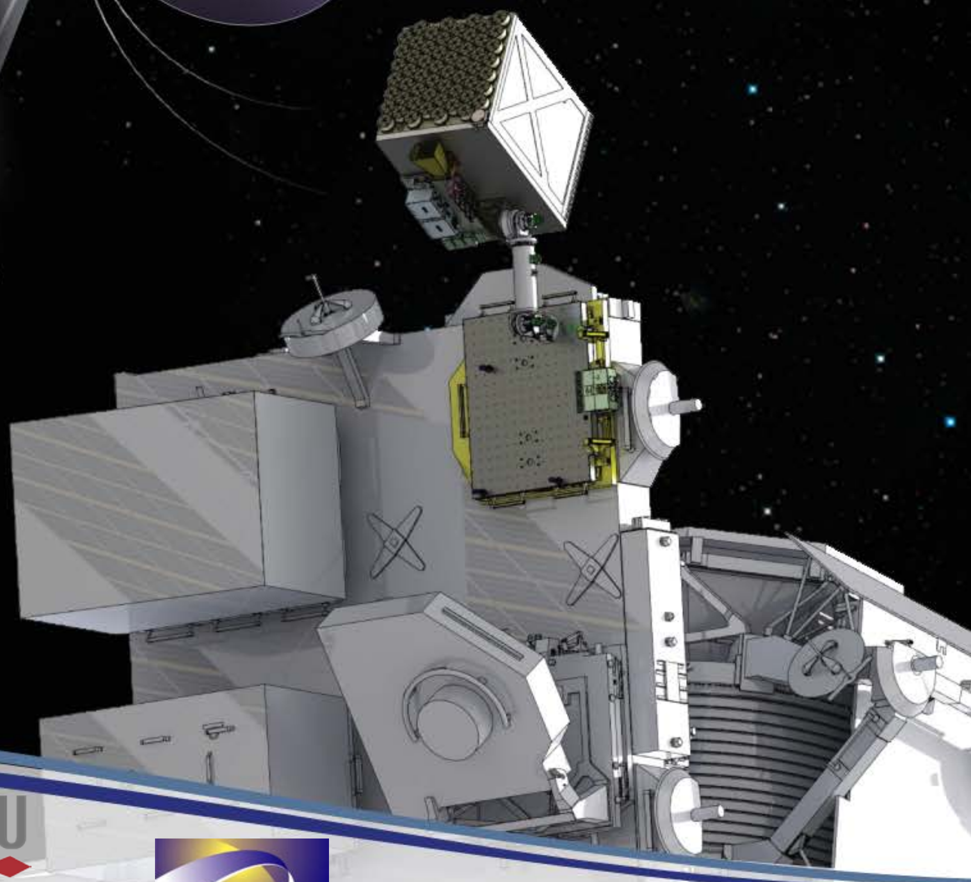
NICER Principal Investigator

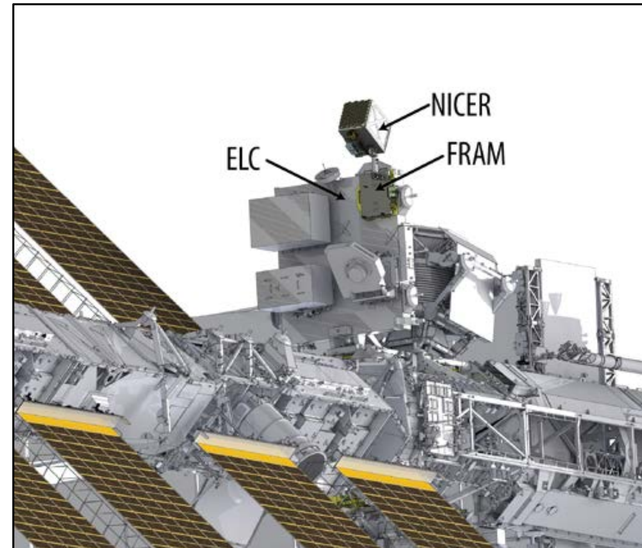
April 16, 2013

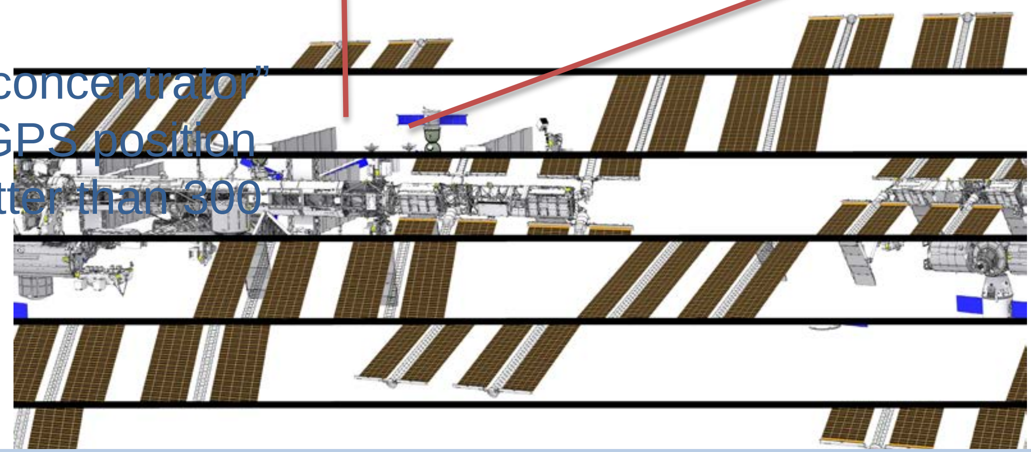


NASA GSFC MIT KAVLI INSTITUTE DTU BROAD REACH MOOG

NICER is an exciting opportunity to use the ISS as a platform for science

- ***Science:*** Understanding ultra-dense matter through soft X-ray timing of *neutron stars*
- ***Launch***: Late 2016, JAXA *HII-B* or SpaceX Falcon 9
- ***Platform:*** ISS ExPRESS Logistics Carrier (ELC), with active pointing over a full hemisphere
- ***Duration:*** 18 (min. 12) months, with an optional Guest Observer program (6-month extension)
- ***Instrument:*** X-ray (0.2–12 keV) “concentrator” optics and silicon-drift detectors. GPS position and absolute time reference to better than 300 ns
- **Rewarding Enhancements:**
  - SEO
  - E/PO
  - Pulsar navigation demonstration



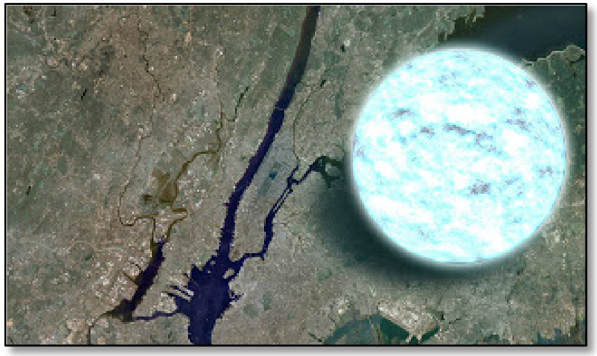


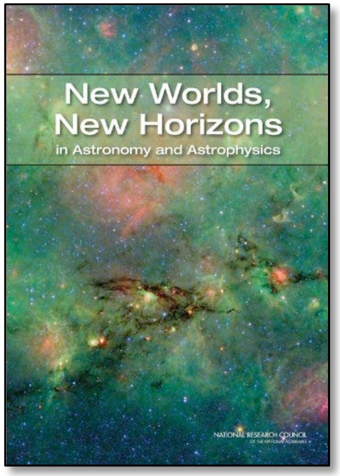
Why study neutron stars?

NICER offers a fundamental investigation of extremes in gravity, material density, and electromagnetic fields

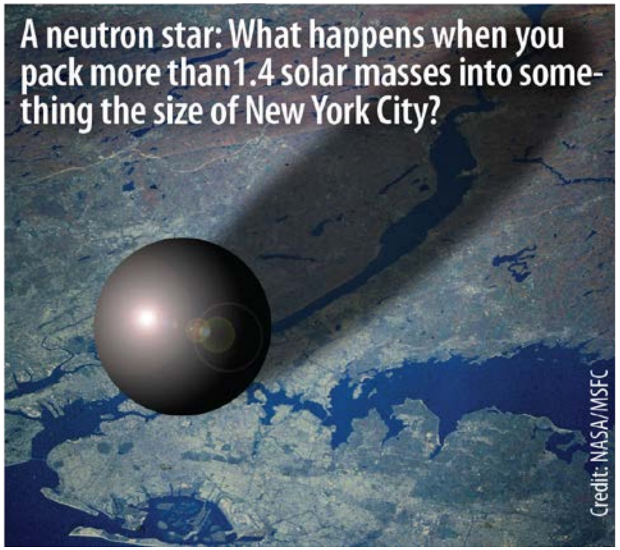
NICER responds to:

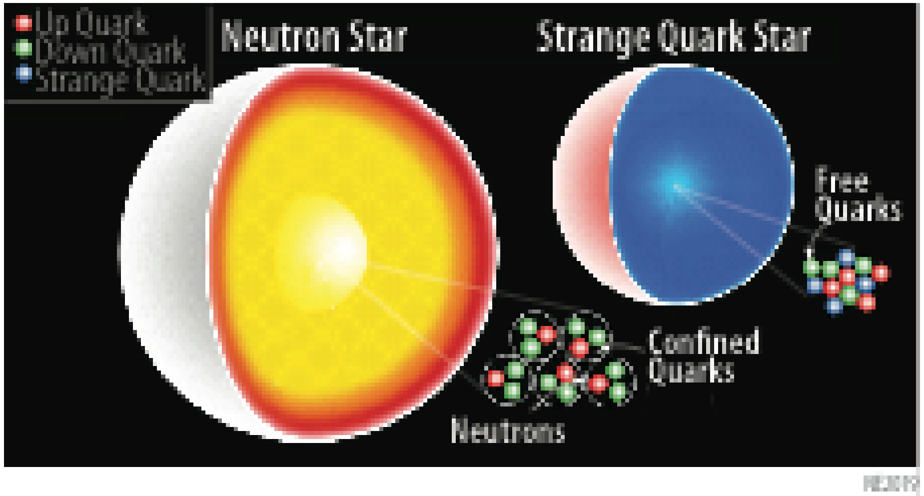
- SMD's *Science Plan* — "How do matter, energy, space and time behave under the extraordinarily diverse conditions of the cosmos?"
- *Physics of the Cosmos* program — "Explore the most extreme physical conditions of the universe"
- *2010 NAS Decadal Survey* — High discovery potential in time-domain and gravitational-wave astronomy. Questions about compact stellar remnants "ripe for answering"



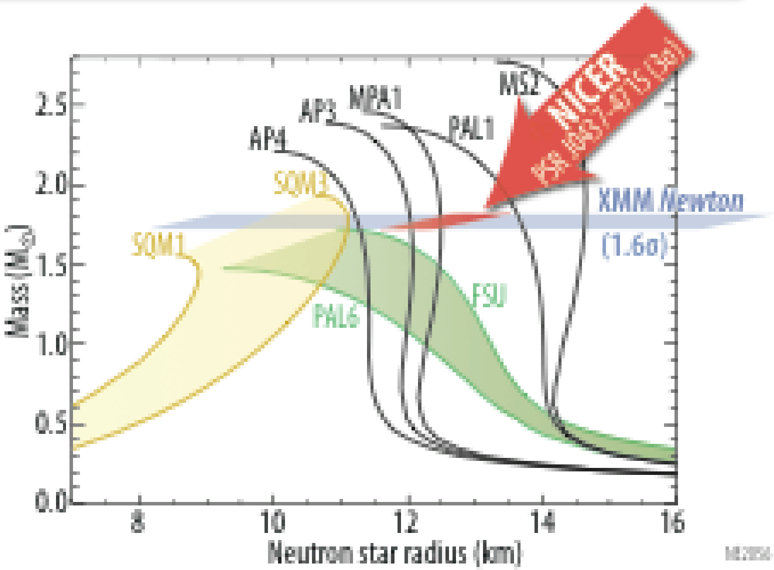


How big is a neutron star? Its size reveals what it's made of…





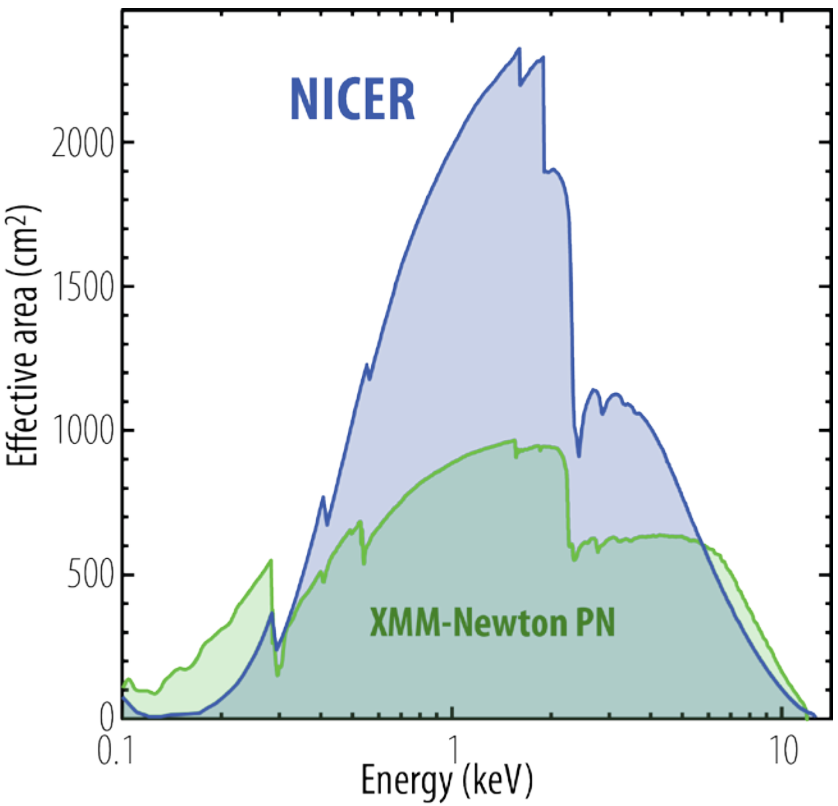
NICER will determine the radii of neutron stars to 5%, an order of magnitude better than known today



NICER opens a new discovery window

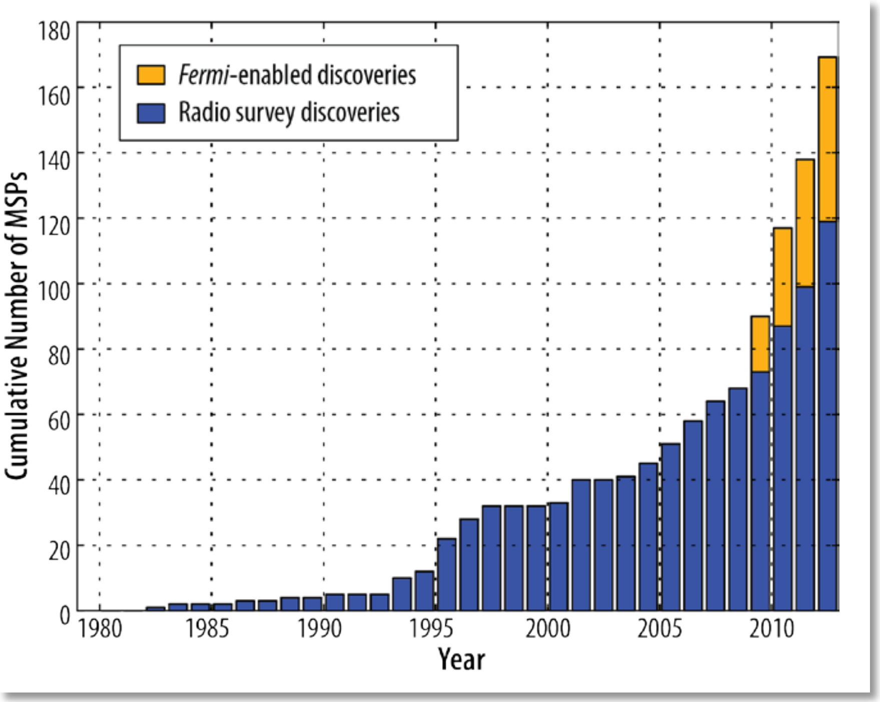
NICER will deliver X-ray measurements with an unprecedented combination of sensitivity, time resolution, and energy resolution

- Spectral band: 0.2–12 keV (soft X-rays)
  - Well matched to neutron stars
  - Overlaps RXTE and XMM-*Newton*
- Timing resolution: 213 nsec
  - 25x better than RXTE
  - 100x–1000x better than XMM-*Newton*
- Energy resolution: 2% @ 6 keV
  - 10x better than RXTE
- Angular resolution: 5 arcmin
  - 12x better than RXTE
- Sensitivity, 5σ: 3.3 x 10^{-14} erg/s/cm^2
  - 0.5–10 keV in 10 ksec (Crab-like spectrum)
  - 30x better than RXTE
  - 4x better than XMM-*Newton*'s timing capability

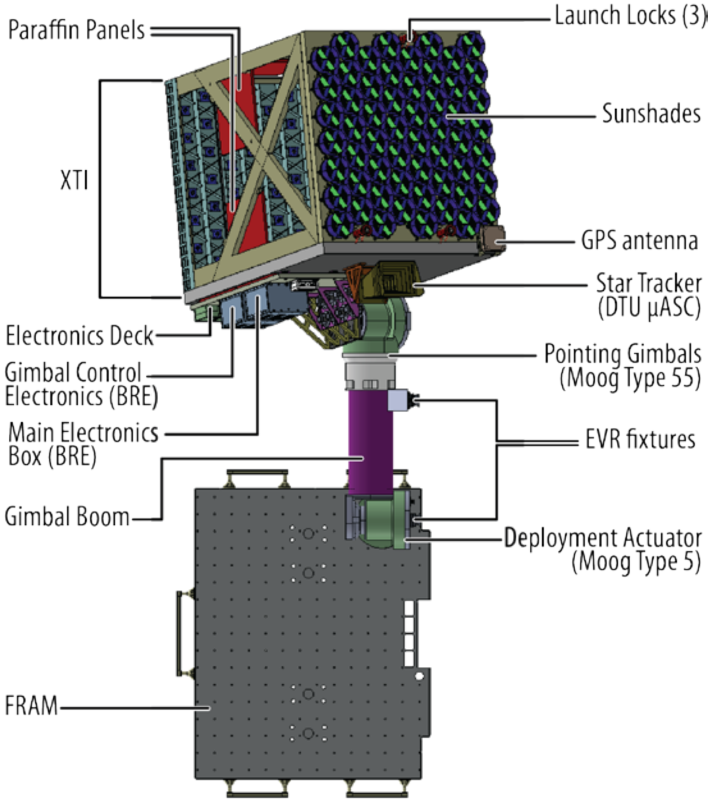


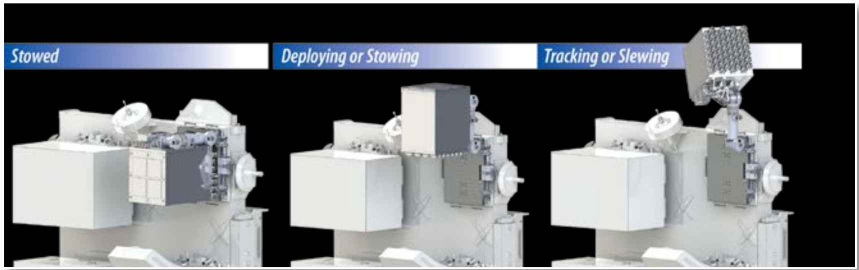
Now is the time for NICER

- Millisecond pulsar discovery rate is booming, offers many NICER targets
- Overlap with Fermi — science synergies boost returns from both missions
- RXTE is done, but community awaits next instrument
  - RXTE produced 2,500 publications and counting
  - After 16 years of operation, last proposal cycle still oversubscribed
- NICER technology is mature
- ISS is ready to support science experiments



The NICER payload



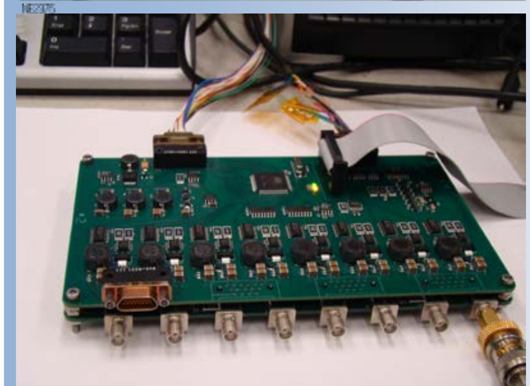


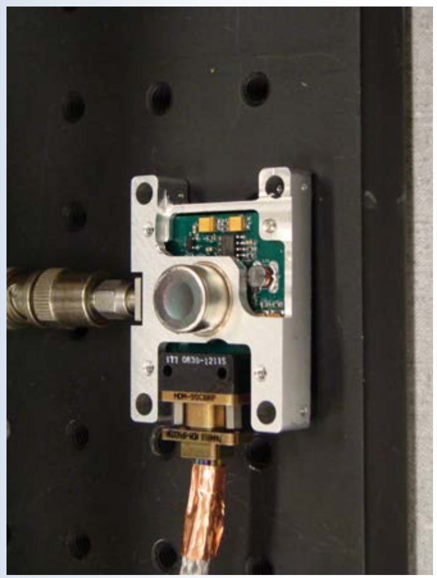
- **X-ray Timing Instrument (XTI)**
  - Assembly of 56 X-ray concentrators and detectors
  - Detects individual X-ray photons, returns energy and time of arrival
  - Held together in the Instrument Optical Bench
- **Simple thermal system**
  - Maintains thermal-mechanical alignment
- **Pointing System**
  - Composed of high-heritage components
  - Allows the XTI to track pulsars
  - Slews XTI between targets
- **C&DH**
  - Digital interface to ISS for commands, data
  - Supports pointing system
- **Flight Releasable Attachment Mechanism**
  - Electrical & mechanical interface to ISS and transfer vehicle
  - Provided by ISS program

NICER is an innovative combination of high-heritage components

- All technologies are ≥ TRL 6
- The team has developed EDUs of key components

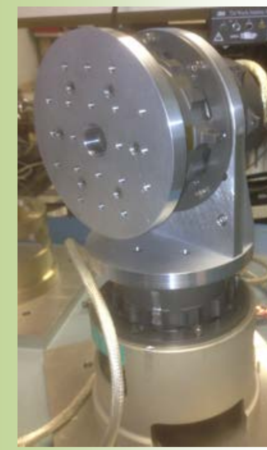
Optics and Detectors





Avionics

Pointing System



ISS is a great place to do NICER science

NICER

An established platform and a benign environment

ISS offers:

- Established infrastructure (transport, power, comm, etc.)
  that reduces risk
- Generous resources that simplify design and reduce cost.
- A stable platform for arcminute astronomy

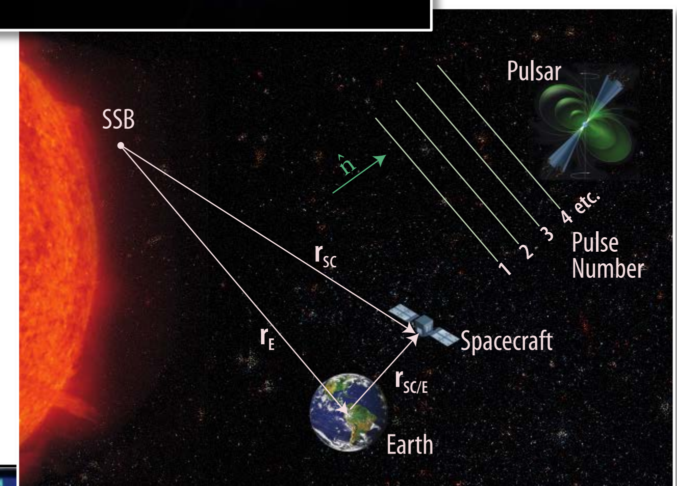
NICER's design:

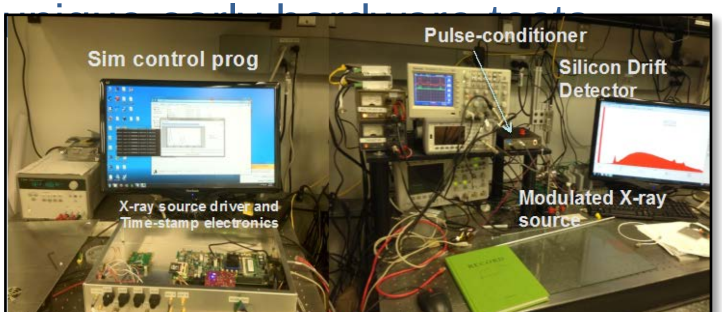
- Is tolerant of ISS vibrations
- Is insensitive to the ISS contamination and radiation environments, with safe-stow capability
- Provides high (> 63%) observing efficiency

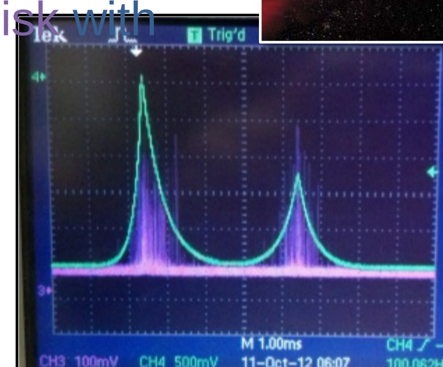
The NICER team is well interfaced with the ISS Research Integration Office (RIO), including several TIMs to ensure common understanding of payload and ISS requirements

NICER is more than your average opportunity

- Space Technology Mission Directorate (STMD) supports NICER through the Station Explorer for X-ray Timing And Navigation Technology program
  - First flight demo of pulsar-based navigation
  - Fits cleanly into NICER science program, no additional hardware
  - STMD has provided > 90% of NICER funding to date, promises > $15M in Phases B–E
- SMD gets more bang for the buck
  - NICER offers full mission science at the cost of an instrument to SMD
  - Pulsar nav will ultimately enable novel SMD missions
  - SEXTANT testbed mitigates NICER risk with



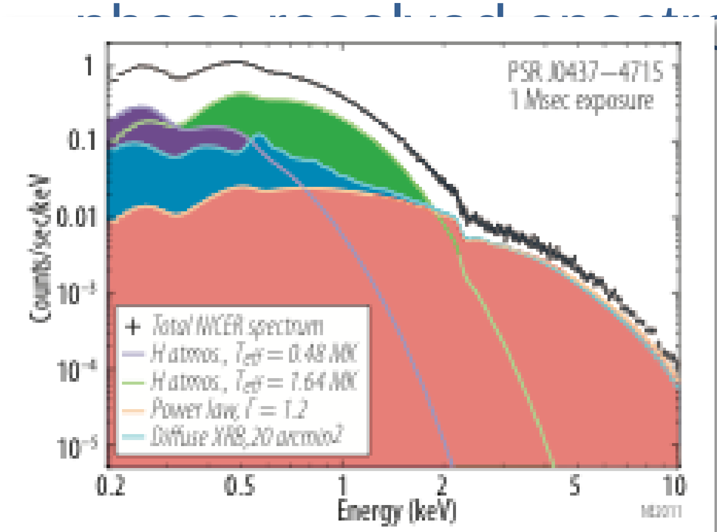




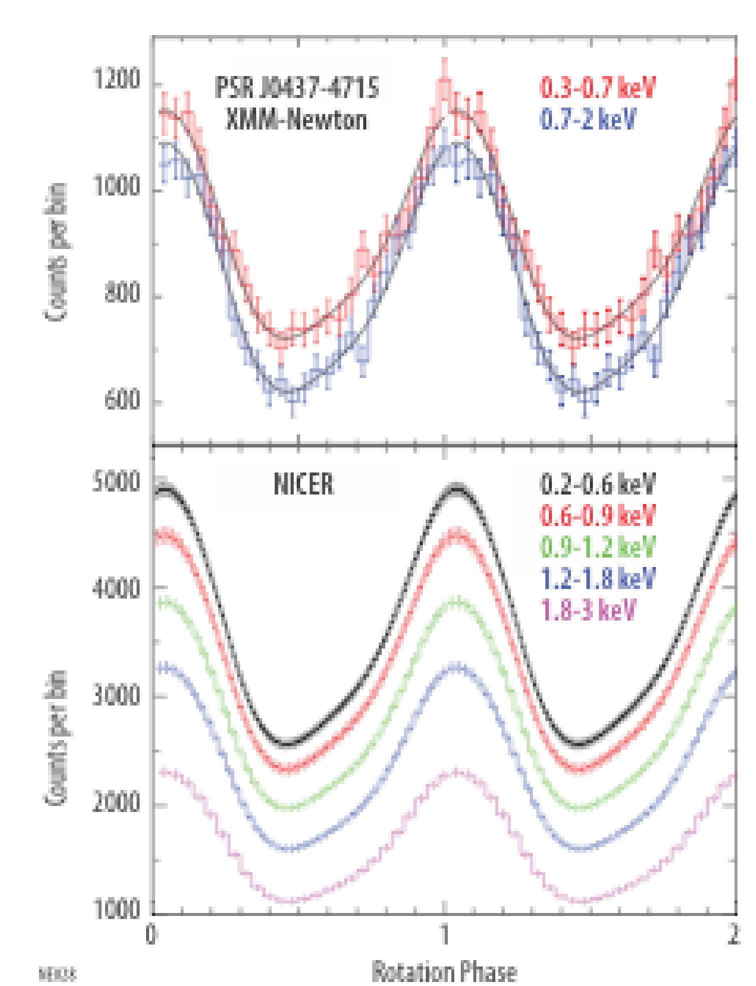
Simulated Crab Pulsar in the Lab

NICER science requirements are met by mission and instrument design

- NICER is most sensitive where neutron stars are brightest
- Absolute time resolution enables coherent light curve integration over years
- Energy resolution enables phase resolved spectroscopy

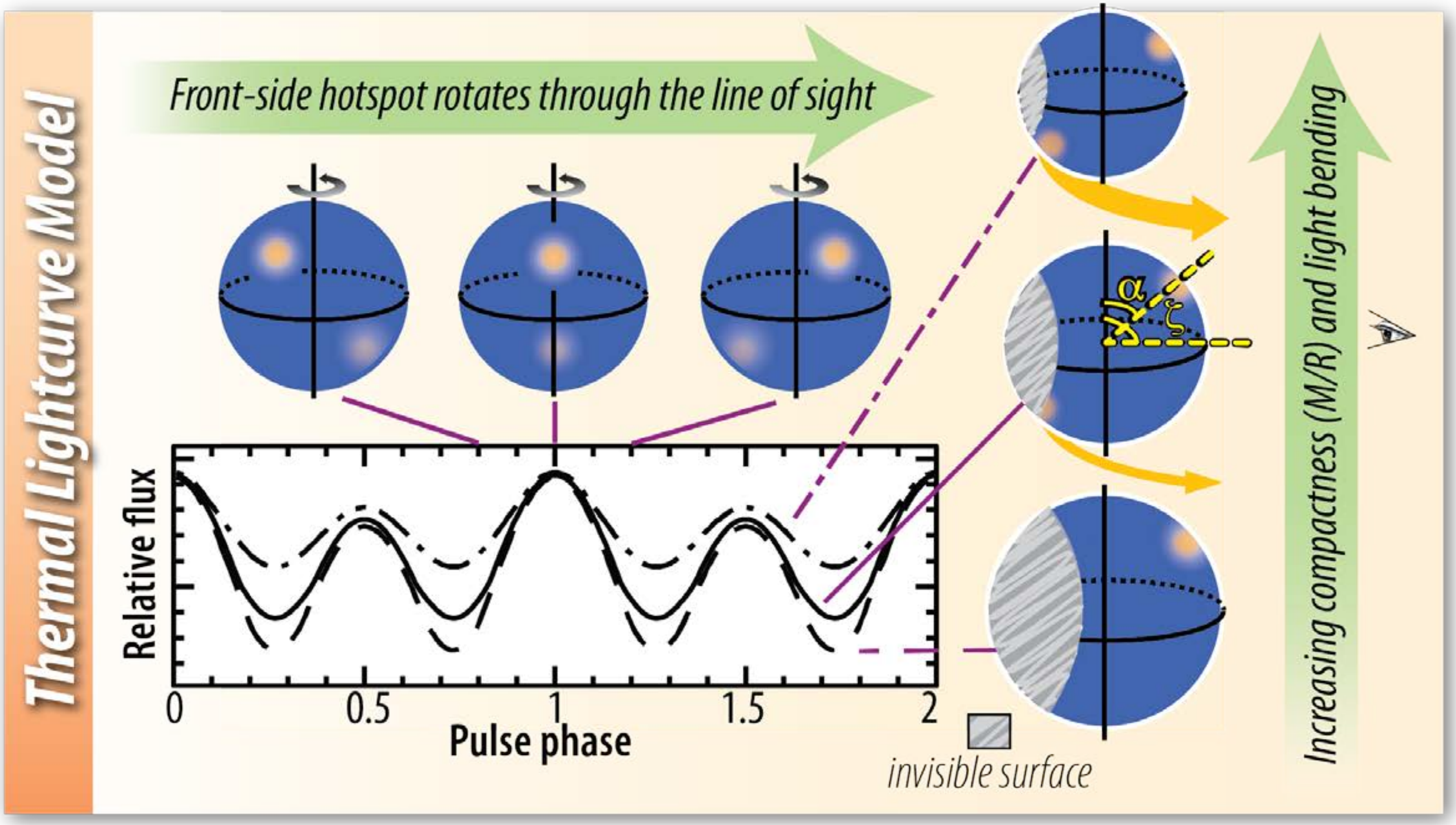


~10^6 K thermal emission peaks in soft X-rays



NICER infers the radii of neutron stars through lightcurve modeling

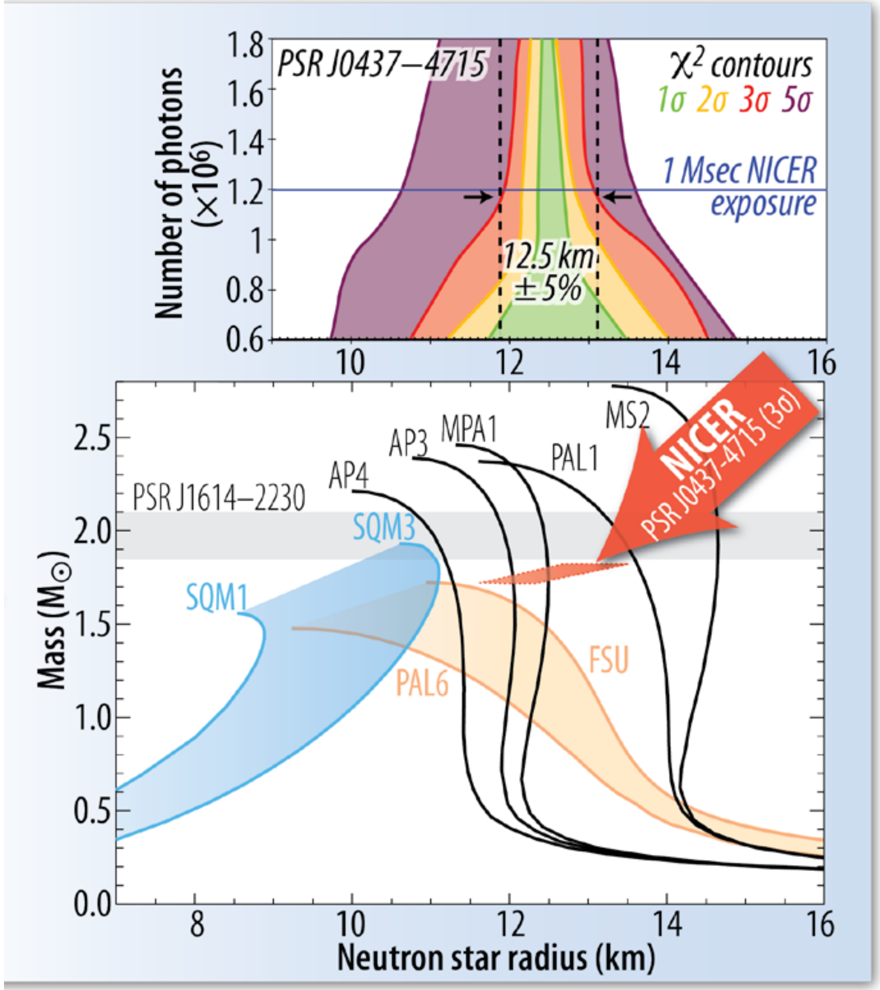
Understanding ultra-dense matter through soft X-ray timing



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

To what degree will NICER fully reveal interior composition of neutron stars?

- Sufficiency of the collected data (e.g., $10^{5–6}$ photons for thermal lightcurves of MSPs) is demonstrated through a comprehensive set of simulations performed by the NICER science team using NICER responses
- Literature* shows we need such measurements for only 3 objects — the NICER base-line mission will deliver 4



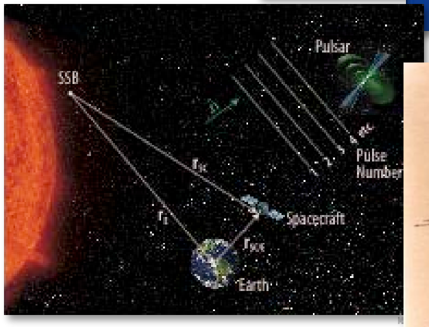
Simulations show the assumed radius is recovered to ±5% with ~10^6 photons

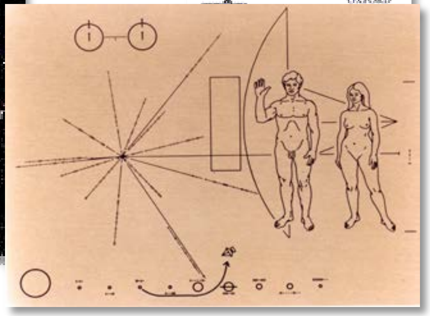
*For example: Özel & Psaltis (2009), *Reconstructing the neutron star equation of state from astrophysical measurements*, Phys. Rev. D

NASA will be proud of NICER

- NICER will deliver high-visibility science using the ISS as a platform
- Scientific publication rate from the ISS will increase substantially
- Education and Public Outreach program will connect with the American public
  - Pulsar navigation in analogy with GPS will be a significant hook for public interest
- NICER is a productive partnership between STMD, HEOMD, and SMD

http://heasarc.gsfc.nasa.gov/docs/nicer

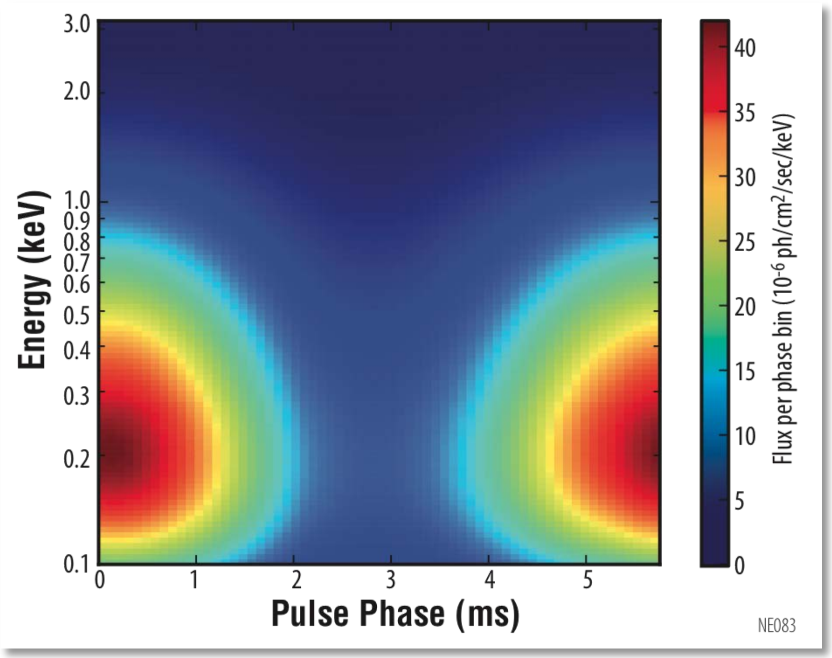


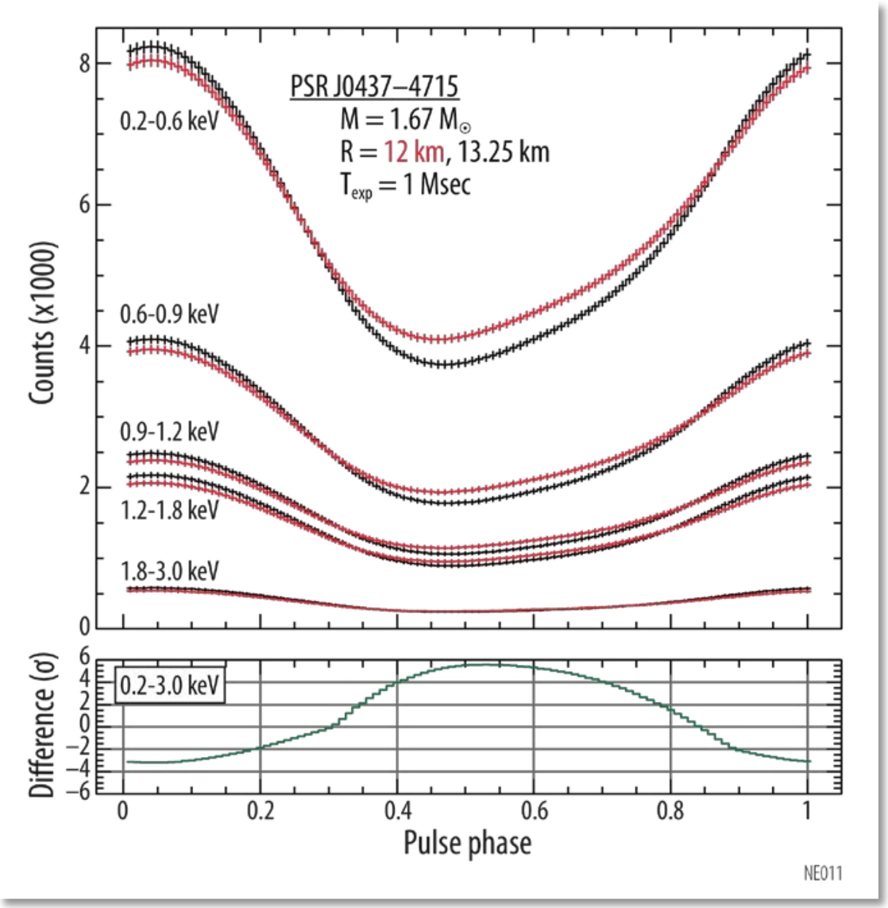


Backup

NICER infers the radii of neutron stars through lightcurve modeling (cont.)

Lightcurves with unprecedented photon statistics enable high-precision astrophysical measurement





Robust pulsar thermal emission models include light-bending, limb darkening in a realistic atmosphere, and viewing geometry

NICER mission life cycle

NICER

- Integrated at GSFC with high-heritage components made by experienced, competitively chosen partners
- Compatible with JAXA HTV and SpaceX Dragon for transport to ISS
- Robotic installation on the ISS
- Operated on a non-interference, no-harm basis with ISS for an 18-month baseline science program
- Established ground system and data processing/distribution system
- Defined disposal via Dragon or

GSFC

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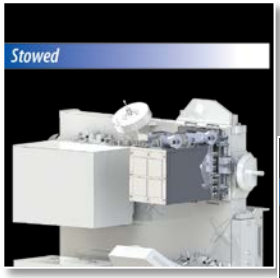
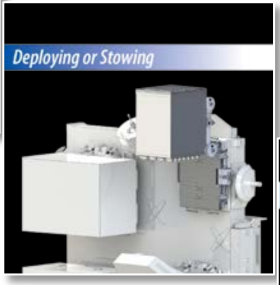
MOOG

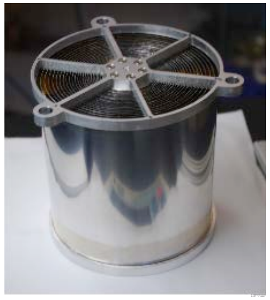
DTU





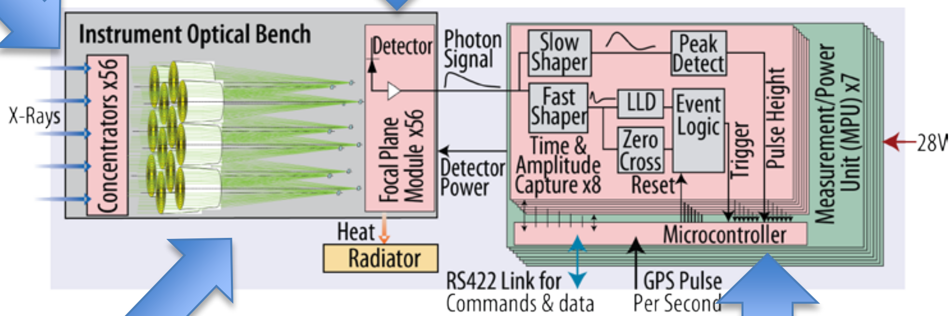
NASA

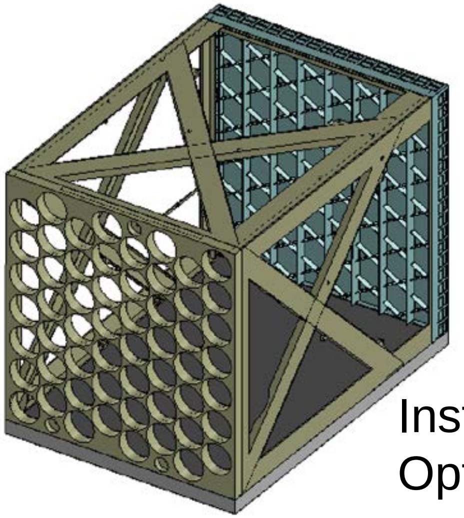
NICER X-ray Timing Instrument (XTI) Block Diagram



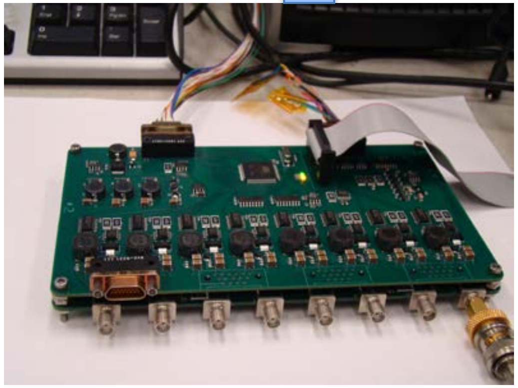
X-ray Concentrators (56)

Focal Plane Modules (56)





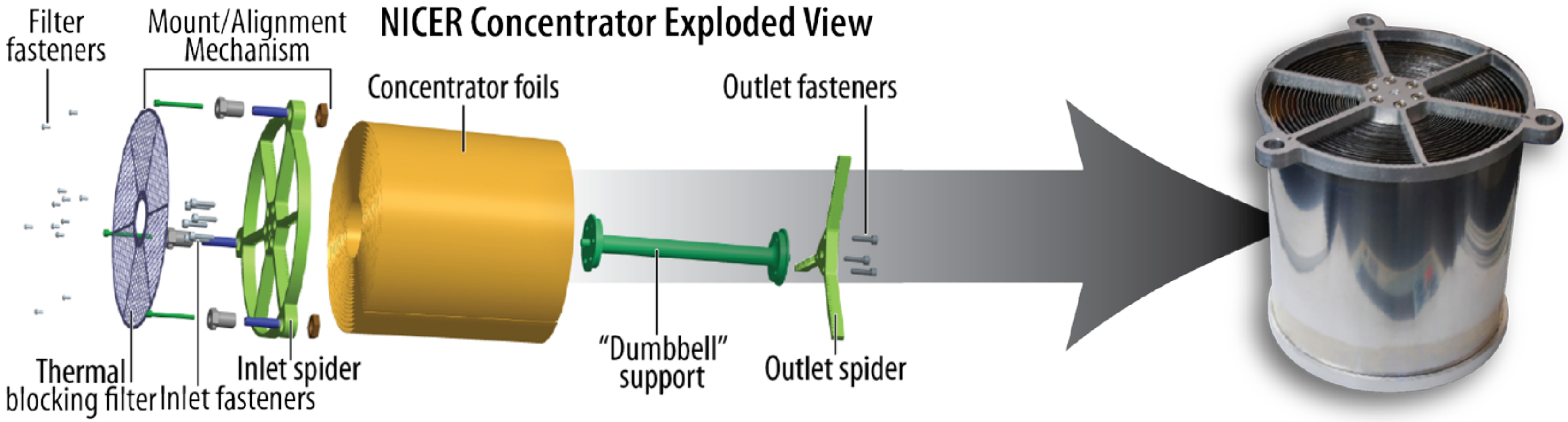
Instrument Optical Bench



Measurement Power Units (7)

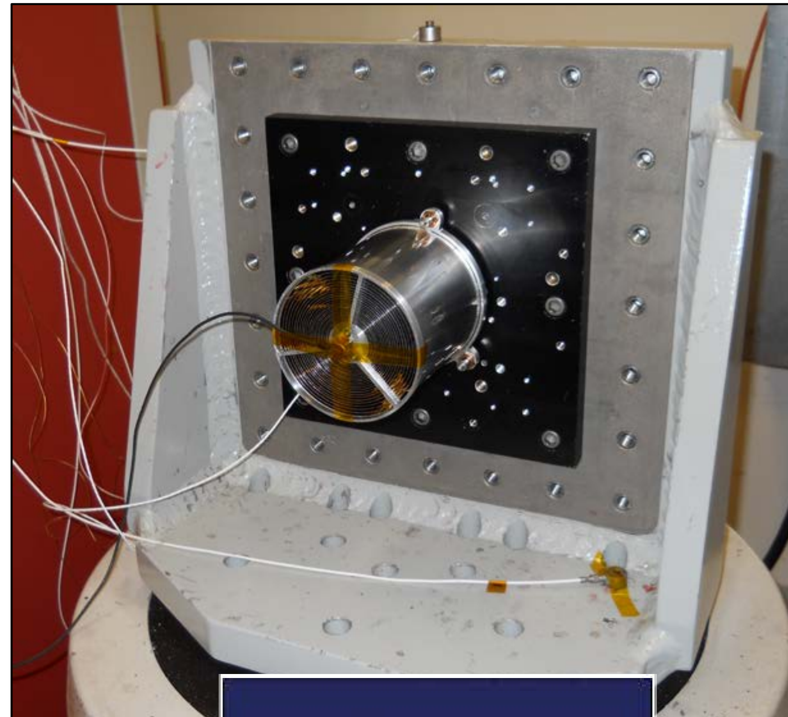
XTI optics are the latest in a long line of successful GSFC foil optics

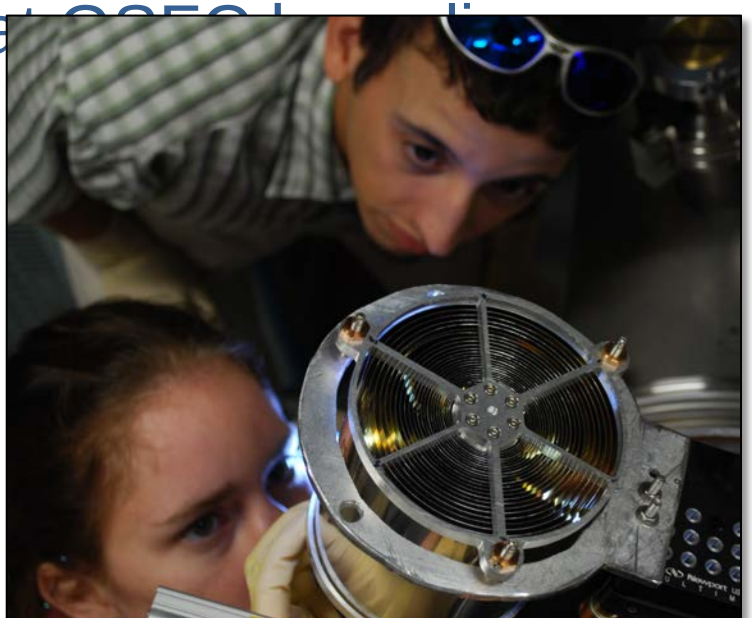
- Single-bounce concentrator design maximizes throughput for isolated point sources while minimizing mass and cost
- Flight-proven replication process yields robust and easy to manufacture reflecting surfaces
- TRL 6 with EDUs built and tested

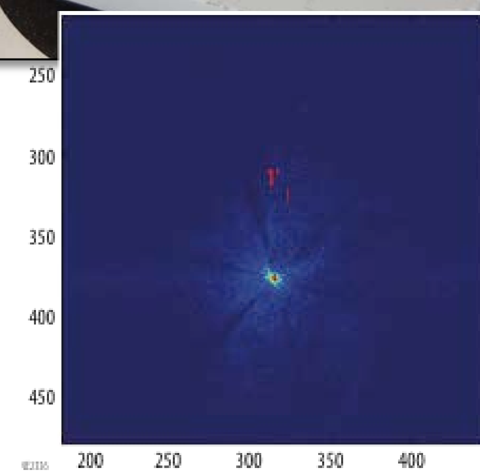


EDU concentrators have survived rigorous testing and perform well

- EDU concentrator vibrated at GEVS qualification levels maintains performance
- EDU concentrators tested







Detector system is mature and built by an experienced team

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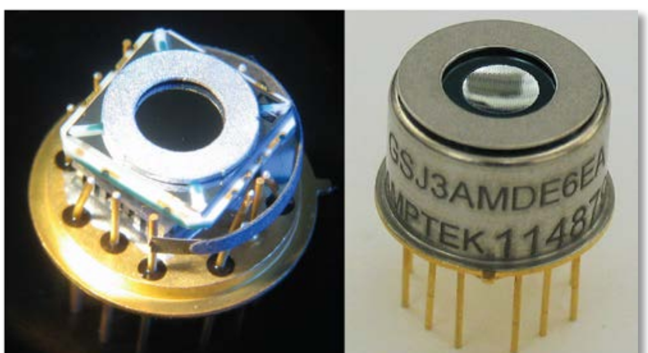
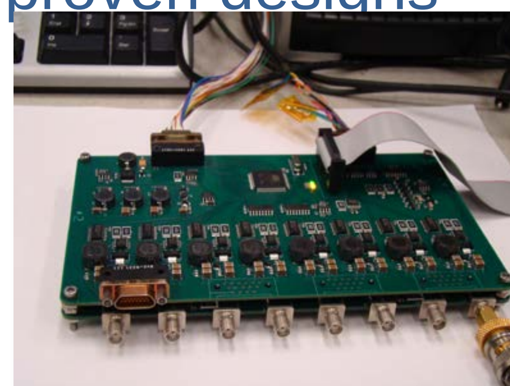
- MIT leads the detector subsystem
  - Decades of flight experience for X-ray detectors
- Sensors are Silicon Drift Detectors (SDDs)
  - Off-the-shelf items from Amptek, Inc. (4000+/yr delivered)
  - SDDs are now working on Mars
- Electronics are modular and based on proven designs



SDD

FPM



MPU

MEB to FPM
From X-Rays to Bits and Beyond

NICER

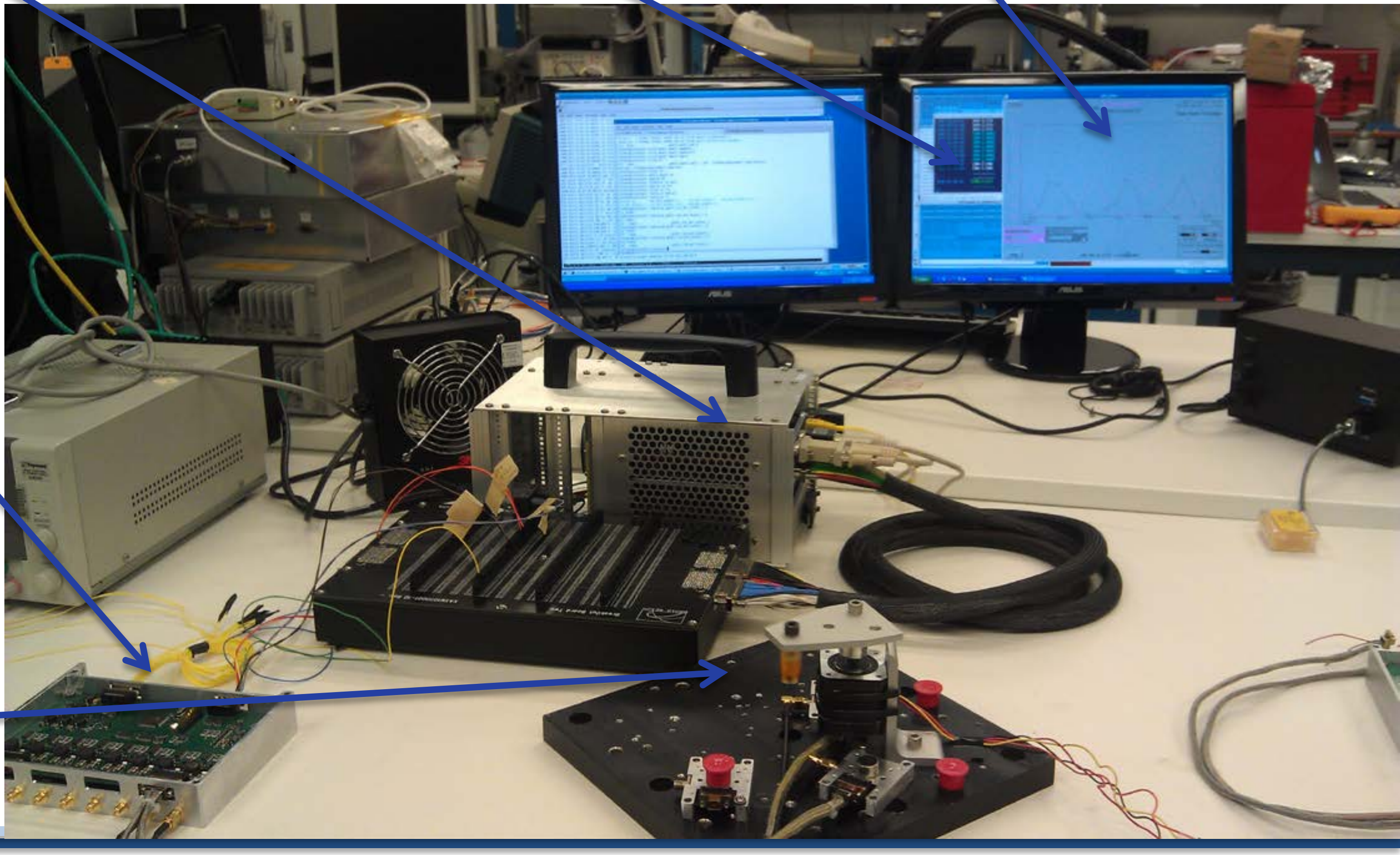
Main Electronics Box (MEB)
(MEB FSW interfaces with MPU and ground system)

Ground System
(Interfaces with MEB FSW for commands, telem.)

Lightcurve Plot
(X-rays detected)

Measurement/Power Unit (MPU)
(Interfaces with MEB FSW and detectors)

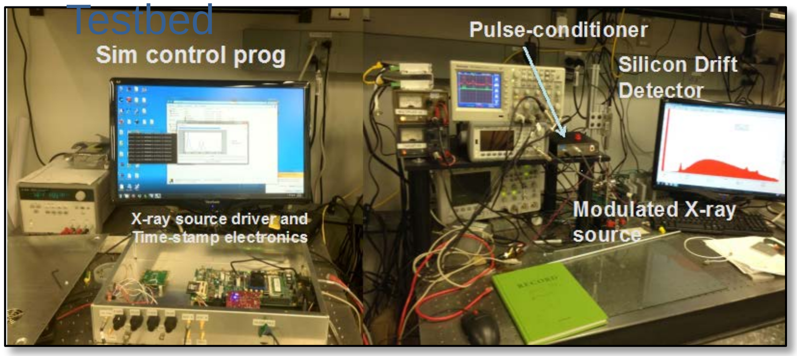
Detectors & X-ray source
(Spinning X-ray source on stepper motor)



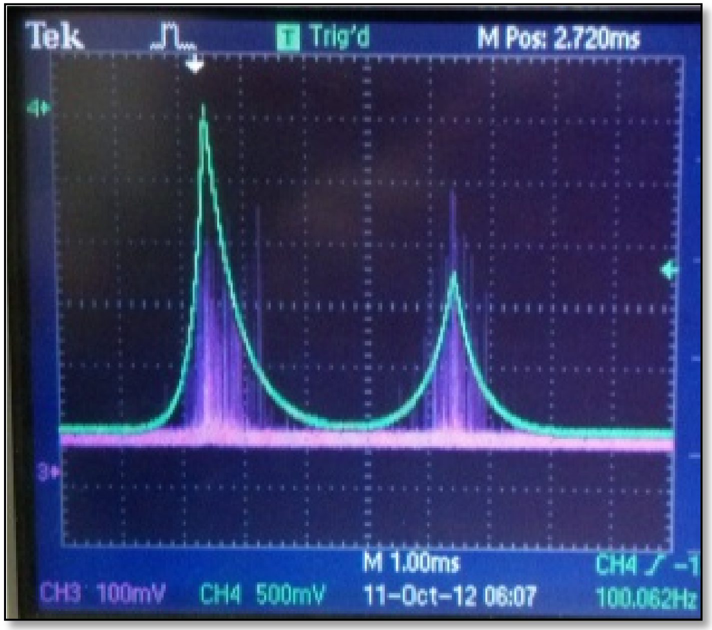
SEXTANT reduces risk for NICER

- STMD support thus far has:
  - Enabled building up a great team
  - Kept the team together and focused
  - Funded key EDU and ETU builds
  - Developed a unique pulsar testbed on the ground to test NICER
- STMD promises to continue this support now that SMD has selected NICER
  - > $15M in Phases B–E
- This is an excellent example of a productive partnership between SMD and STMD!

The GSFC XNAV Laboratory Testbed



Simulated Crab Pulsar in the Lab

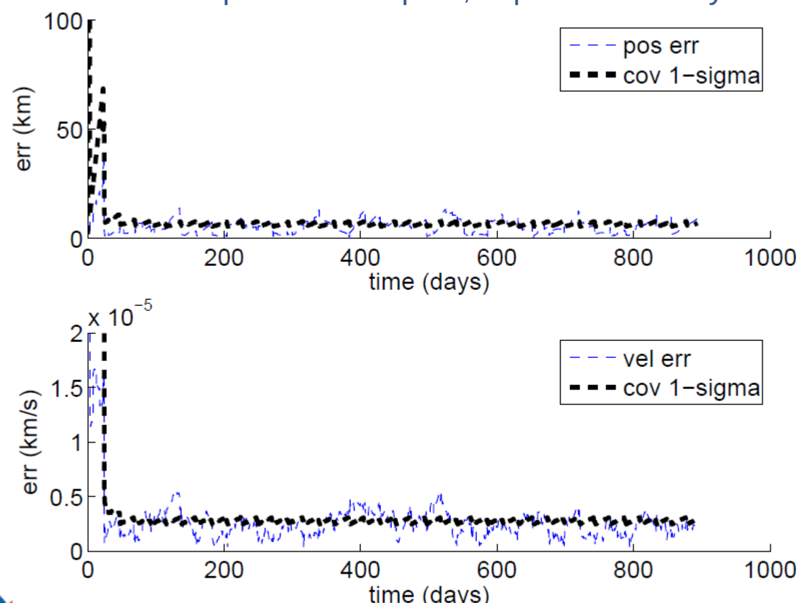


NICER/SEXTANT — A productive partnership between SMD and STMD

Cassini Cruise (2—7 AU) Comparison to DSN w/ Range, Doppler, & ΔDOR

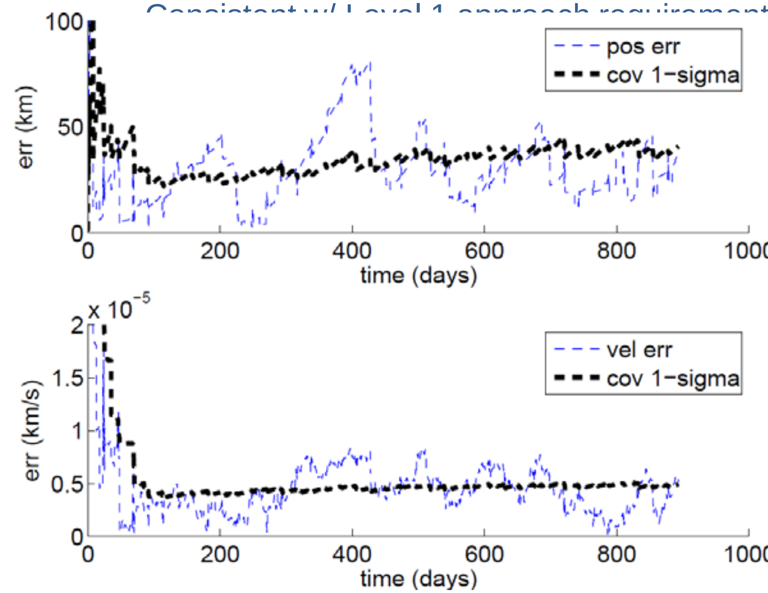
XNAV

- Realistic XNAV sensor
  - SWaP: < 0.023 m^3, < 4 kg, < 4 W
  - Single NICER-like Sensor (1/56th of NICER A_{eff})
  - Less accurate TOAs
  - Observation schedule
    - SEXTANT-like pulsar sequence
    - Targeted for km level measurement accuracy
- Performance: uniform ~10 km (1σ)
  - Competitive to Jupiter, improvement beyond



DSN

- DSN tracking characteristics used
  - Realistic measurement accuracies
    - Range: 1.0m (1σ)
    - Doppler (0.05 mm/s 1σ)
    - ΔDOR (4cm 1σ)
  - Optimistic tracking schedule
    - *Continuous* range & Doppler
    - 1 pair for 24 hrs , once/week
- Performance: growing 20—30 km (1σ)
  - Consistent w/ Level 1 approach requirements



Science Objectives II — neutron star dynamics

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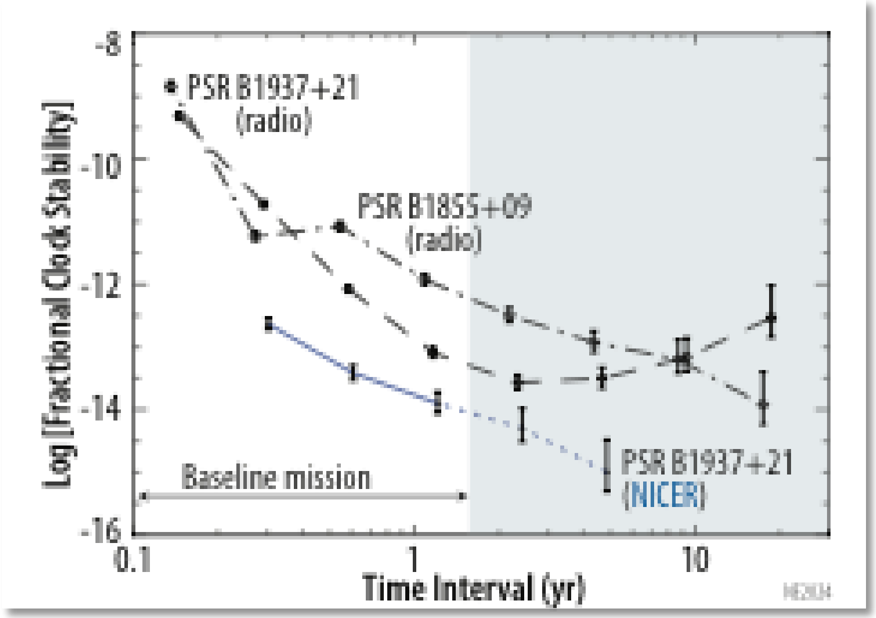
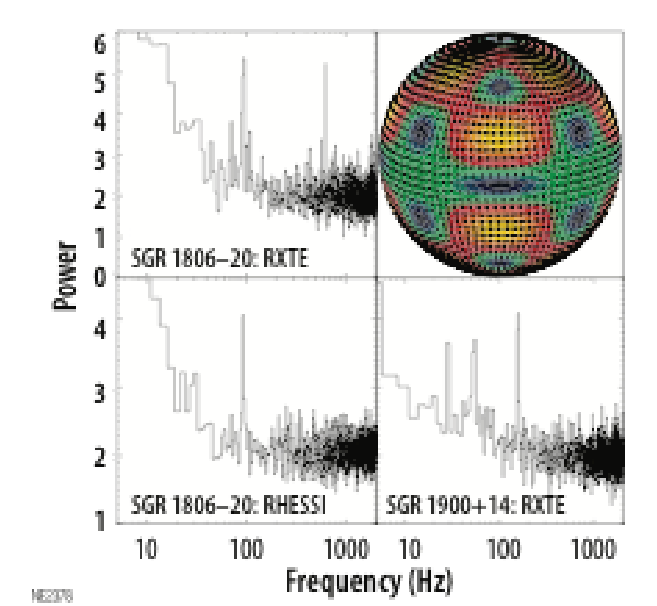
Characterizing dynamic spin, accretion, and interior phenomena



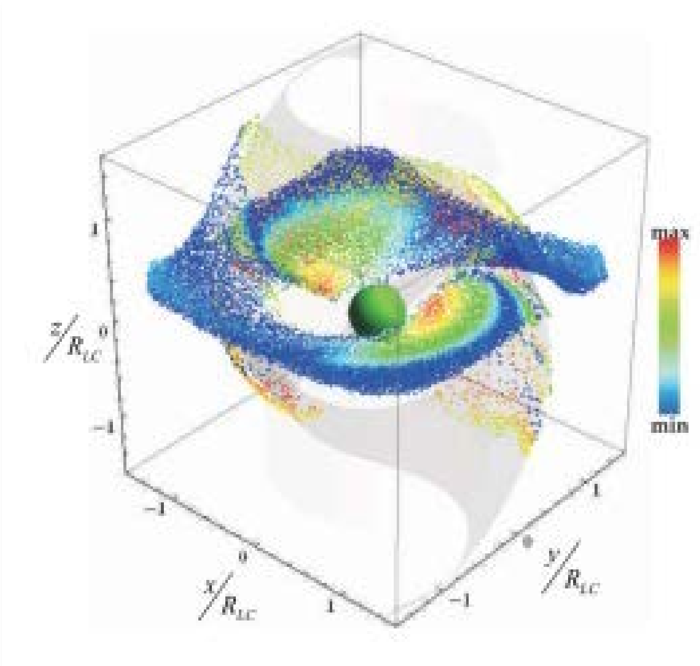


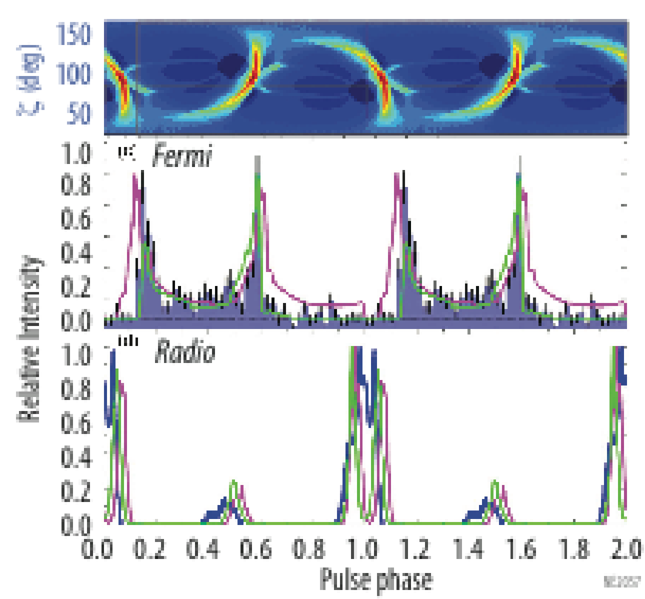
Starquakes, thermonuclear explosions, and bulk quantum phenomena

Objective	Measurements
Structure — Reveal the nature of matter in the interiors of neutron stars	Neutron star radii to ±5%. Cooling timescales
Dynamics — Uncover the physics of dynamic phenomena associated with neutron stars	Stability of pulsars as clocks. Properties of outbursts, oscillations, and precession
Energetics — Determine how energy is extracted from neutron stars.	Intrinsic radiation patterns, spectra, and luminosities

Science Objectives III – neutron star energetics

Establishing the sites and mechanisms of radiation in neutron star magnetos





The most powerful magnetic fields known anywhere, only now beginning to be understood…

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Energetics — Determine how energy is extracted from neutron stars.	Intrinsic radiation patterns, spectra, and luminosities

Science Team Roles

NICER

Name	Role	Relevant Experience	Institution
Keith Gendreau	Principal Investigator	ASCA, Astro-E, Swift, XNAV	NASA's GSFC*
Zaven Arzoumanian	Deputy Principal Investigator	Radio, Chandra, XMM, RXTE neutron star science	NASA's GSFC and USRA*
Takashi Okajima	Optics Lead	Suzaku, InFocus, ASTRO-H, GEMS	NASA's GSFC*
George Ricker	Detector Lead	ASCA, HETE-2, Chandra /ACIS, Suzaku	MIT*
Craig Markwardt	Calibration Lead, transient science	Instrumentation, RXTE, Swift observations	NASA's GSFC*
Lorella Angelini	Pipeline data processing	ASCA, Suzaku, Swift, RXTE	NASA's GSFC*
Tod Strohmayer	Burst oscillations and LMXB science	RXTE, Chandra, XMM observations	NASA's GSFC*
Alice Harding	Neutron star emissions and magnetosphere studies	Theory, RXTE, Fermi, GEMS neutron star science	NASA's GSFC*
Paul Ray	Precision timing science	USA, XNAV, RXTE, Fermi, radio neutron star science	NRL*
Kent Wood	X-ray timing astrophysics	USA, XNAV, HEAO-1, Fermi science	NRL*
Michael Wolff	Fermi follow-up	USA, XNAV, Fermi science	NRL*
Andrea Lommen	Multiwavelength and gravitational-wave studies	Radio and X-ray observations and analysis	F&M*
Scott Ransom	Pulsation searches	Radio, X-ray, g-ray observations and analysis	NRAO*
Slavko Bogdanov	Lightcurve, atmosphere models	Chandra, XMM neutron star science	Columbia U.*
Victoria Kaspi	Magnetar science	XMM, Chandra, RXTE data analysis	McGill U.+
Fotis Gavriil	Magnetar transients	RXTE, Swift, XMM magnetar science	NASA's GSFC and UMBC*
Dimitrios Psaltis	EOS constraints, GR tests	Relativity theory	U. of Arizona*
Feryal Özel	EOS constraints, accretion physics	Theory, RXTE, Chandra, XMM neutron star science	U. of Arizona*
James Lattimer	EOS constraints and interior physics	Nuclear and neutron star theory, HST data analysis	SUNY Stony Brook*
Bennett Link	Interpretation of dynamic phenomena	Neutron star theory	Montana State U.*
Cole Miller	EOS constraints, GR, evolutionary astrophysics	Theory of neutron star structure and astrophysics	UMCP*
Michael Loewenstein	Spectroscopy, lightcurve analysis	XMM, Chandra, Swift observations and analysis	NASA's GSFC and UMCP*
Dany Page	Cooling phenomena	Neutron star theory	UNAM+
Colleen Wilson-Hodge	High-mass X-ray binaries	BATSE, RXTE observations & analysis	NASA's MSFC+
Stephen Drake	Stellar coronae	ROSAT, ASCA, Swift, Chandra, XMM observations	NASA's GSFC and USRA+
Jesus Noel S. Villasenor	Detector subsystem	HETE-2, XNAV	MIT*
John Doty	Detector subsystem	ASCA, HETE-2, Chandra/ACIS, Suzaku	MIT/Espace Inc./Noqsi*
Roland Vanderspek	Detector subsystem	ASCA, HETE-2, XNAV	MIT*
Gregory Prigozhin	Detector subsystem	HETE-2, Chandra/ACIS, Suzaku	MIT*

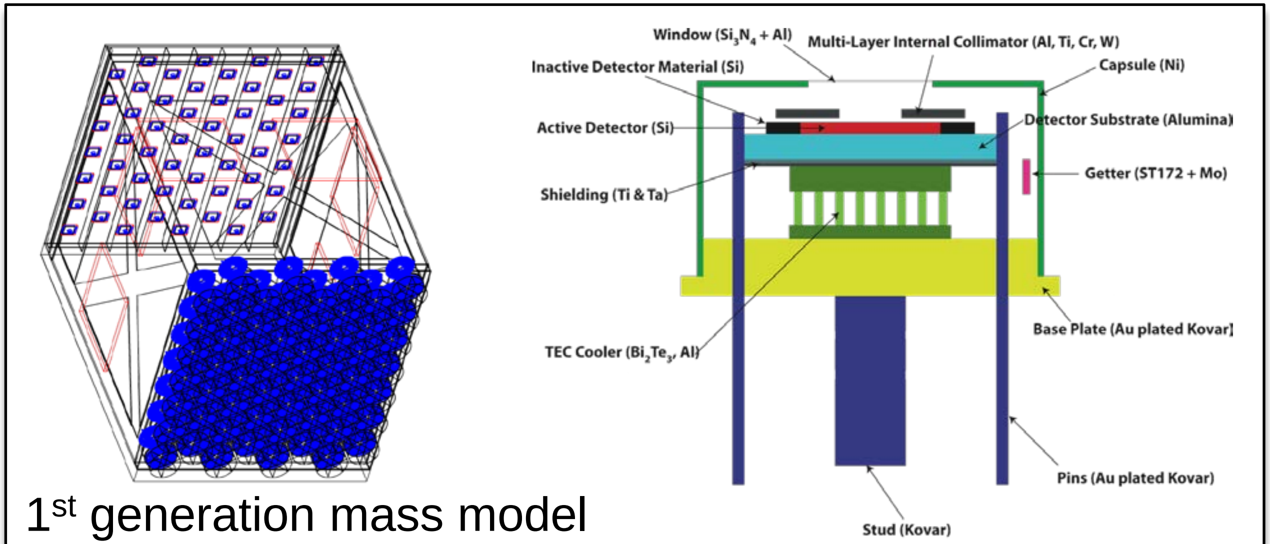
Background rates

- At CSR submission, optics response and particle radiation analysis were not yet mature, so reasonable estimates were made:
  - *Effective* sky coverage (20 arcmin^2 instead of 31 arcmin^2) for diffuse emission, and
  - Straightforward scaling of particle flux together with a rejection efficiency.
  - The overall rate requirement was allocated evenly between diffuse and particle background, < 0.1 cts/sec each.

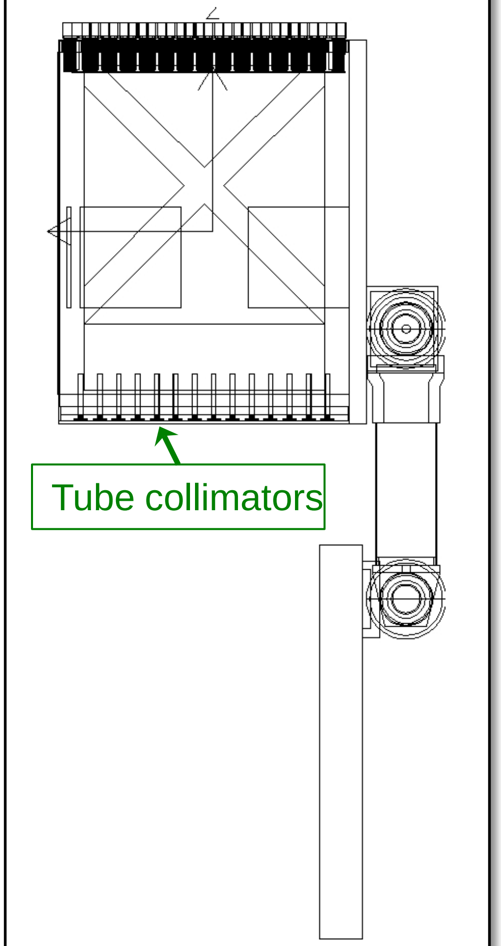
More-sophisticated analyses have been performed post-CSR submission

Particle background — modeling

- MGEANT simulation with a high-fidelity mass model
- *Cosmic primary* and *atmospheric secondary* fluxes adapted from Fermi models spanning geomagnetic latitudes (θ_M) of the ISS orbit
- Particle and photon rates derived, binned according to geomagnetic latitude.



1st generation mass model

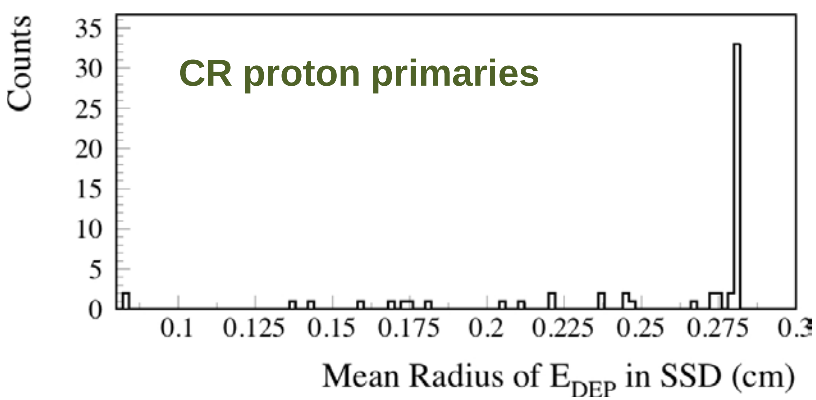


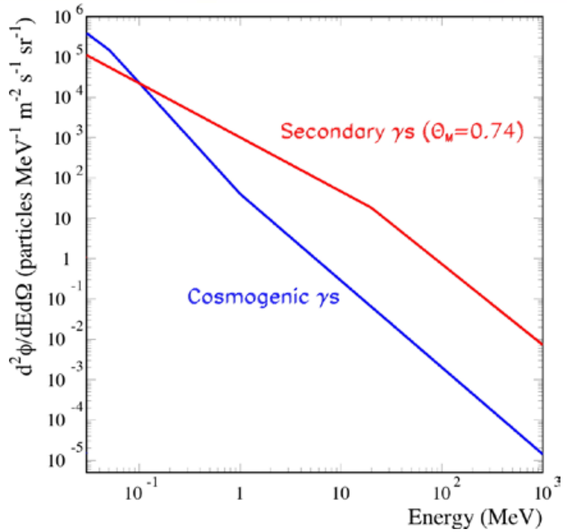
2nd gen. mass model

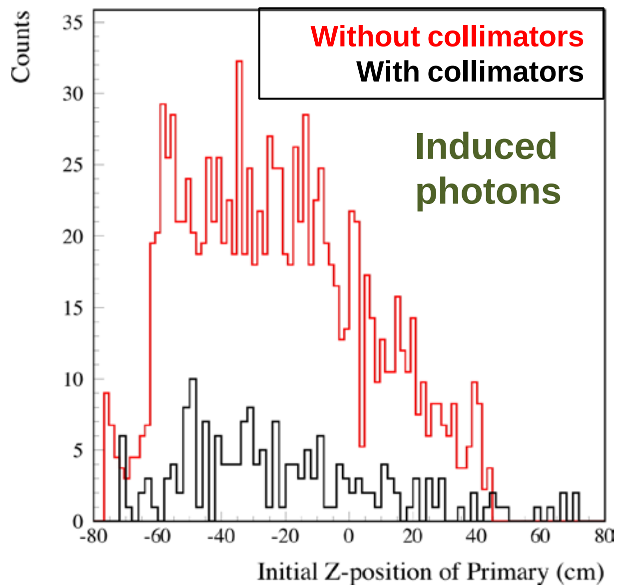
Particle background — rejection

- **Particle-induced photon background** — significant 0.2–10 keV rate of energy deposition events from side-entering 20–80 keV photons
  Solution: Add short collimators around the SDDs

- **Charged particle background** — More than 98% of events are > 10 keV. For remaining 2%, majority of events interact at detector edges
  Solution: Rise-time discrimination offers a factor of 7 further reduction in event rate

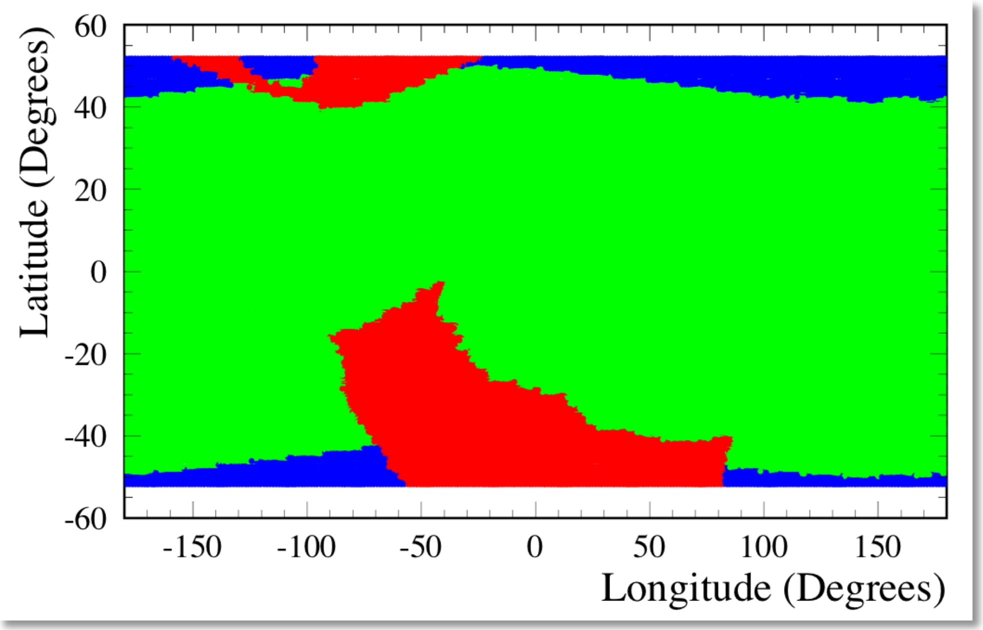






Particle background — rate results

- MGEANT simulation results demonstrate that 74% (time fraction) of the orbit has a background rate of < 0.01 cnts/s/keV
- Also excluding regions of trapped particle radiation (via Spenvis): 66% of the ISS orbit has a background rate of < 0.01 cnts/s/keV.



KEY

Green:
|Geomagnetic latitude| < 0.8 radians, with simulated background rate that meets requirements

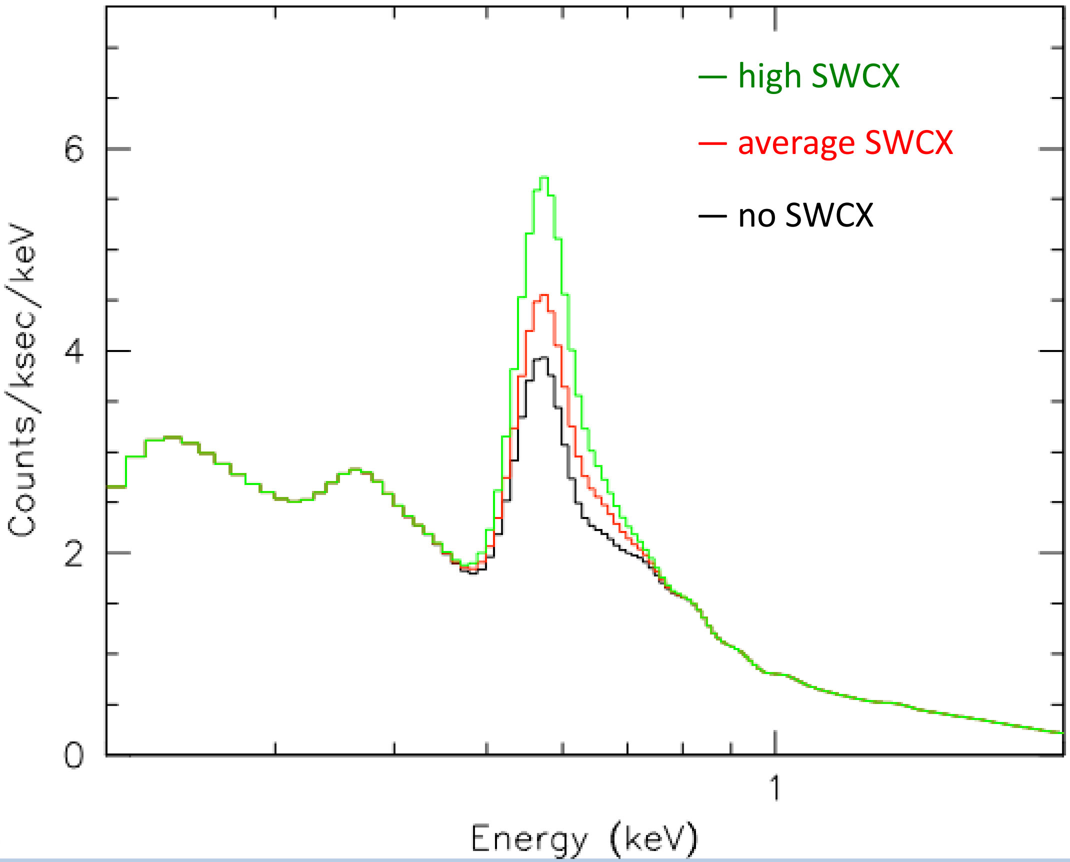
Blue:
Geomagnetic latitude > 0.8 radians

Red:
Excluded regions of trapped particle radiation.

These are conservative in that shielding of atmospheric secondaries from ISS is not considered.

Diffuse background

- Ray-tracing obviates need for effective solid-angle scaling — diffuse response (A_{eff}) of XRCs now available
- Used with CXB + SWCX spectral models to estimate total countrate



Assumptions:

- CXB is mid Galactic latitude
- Average SWCX is high ecliptic latitude, low solar activity; 2 LU in 0.57 keV OVII + 0.5 LU in 0.65 keV OVIII
- High SWCX is high ecliptic latitude, high solar activity; 4 LU in OVII + 1 LU in OVIII

  (1 LU = 1 ph/s/cm^2/sr)
- Mitsuda et al. 2010, MmSAI 81, 69; Yoshitake, et al. 2013, arXiv:1301.5174

Diffuse background (cont.)

NICER will fly at solar minimum, and key MSPs are at high ecliptic latitude

Simulation Results:

	0.2–2 keV rate (cts/sec)	0.5–1 keV rate (cts/sec)
No SWCX	0.14	0.06
With avg. SWCX	0.15	0.07

Simulated countrate exceeds the allocation (0.1 cts/sec) for the diffuse background

Mitigation options:

- **Total background still meets 0.2 cts/sec requirement** over 60% of the orbit, with particle-induced rate < 0.05 cts/sec (next slide)
- Make the detector aperture smaller, at the cost of reduced A_{eff}. E.g., if background is 40% high, reduce aperture diam. from 2 mm to 1.7 mm. A_{eff} @ 1.5 keV drops from 1900 cm^2 to 1774 cm^2 (33.5% margin on 1333 cm^2 req.)
- Science simulations underway to assess impact—already appears that we can dispense with 0.2–0.3 keV if necessary.

Further background rejection results

Further background rejection is realized for photon primary sources by imposing a rise-time requirement. As opposed to the charged-particle induced background, the photon-induced background rise-time rejection is more sensitive to the value of the selection. Excluding regions in the SSD > 2 mm radius leads to another factor of 2 rejection for photon primary sources.

GeoMagnetic Latitude Bin (radians)	Fraction of Orbit within Bin	Orbit Running Total	Background Rate within Bin (CPS) (0.2 keV ≤ E_{DEP} ≤ 2 keV) Goal: < 0.02 CPS	Background Rate within Bin (CPS) (2 keV ≤ E_{DEP} ≤ 10 keV) Goal: < 0.08 CPS	Background Rate within Bin (CPS) (0.2 keV ≤ E_{DEP} ≤ 10 keV) Goal: < 0.1 CPS
0 – 0.1	0.082	0.082	7.80E-03	2.94E-02	3.72E-02
0.1 – 0.2	0.083	0.165	7.84E-03	2.96E-02	3.74E-02
0.2 – 0.3	0.084	0.249	7.87E-03	2.95E-02	3.74E-02
0.3 – 0.4	0.086	0.335	8.04E-03	3.03E-02	3.83E-02
0.4 – 0.5	0.089	0.424	8.52E-03	3.23E-02	4.09E-02
0.5 – 0.6	0.095	0.519	8.26E-03	3.12E-02	3.94E-02
0.6 – 0.7	0.107	0.626	1.04E-02	4.03E-02	5.07E-02
0.7 – 0.8	0.134	0.760	1.10E-02	4.41E-02	5.50E-02
0.8 – 0.9	0.173	0.933	1.29E-02	5.29E-02	6.58E-02
0.9 – 1.0	0.067	1	1.65E-02	6.98E-02	8.63E-02