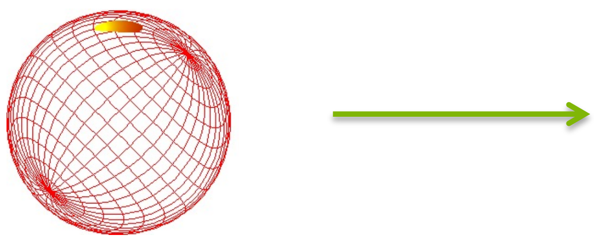
The Neutron Star Equation of State with NICER



Sharon Morsink

Department of Physics, University of Alberta, Edmonton, Canada

NICER Light Curves Working Group:

Slavko Bogdanov (chair), Zaven Arzoumanian, Keith Gendreau, Anna Bilous, Deepto Chakrabarty, Devarshi Choudhury, Alexander Dittmann, Sebastien Guillot, Alice Harding, Wynn Ho, Matthew Kerr, Fred Lamb, Jim Lattimer, Renee Ludlam, Simin Mahmoodifar, Cole Miller, Sharon Morsink, Chanda Prescod-Weinstein, Paul Ray, Thomas Riley, Tod Strohmayer, Zorawar Wadiasingh, Anna Watts, Michael Wolff, Kent Wood.

APS April Meeting, PCOS XRSIG Minisymposium, April 19, 2021, 1:30pm CDT

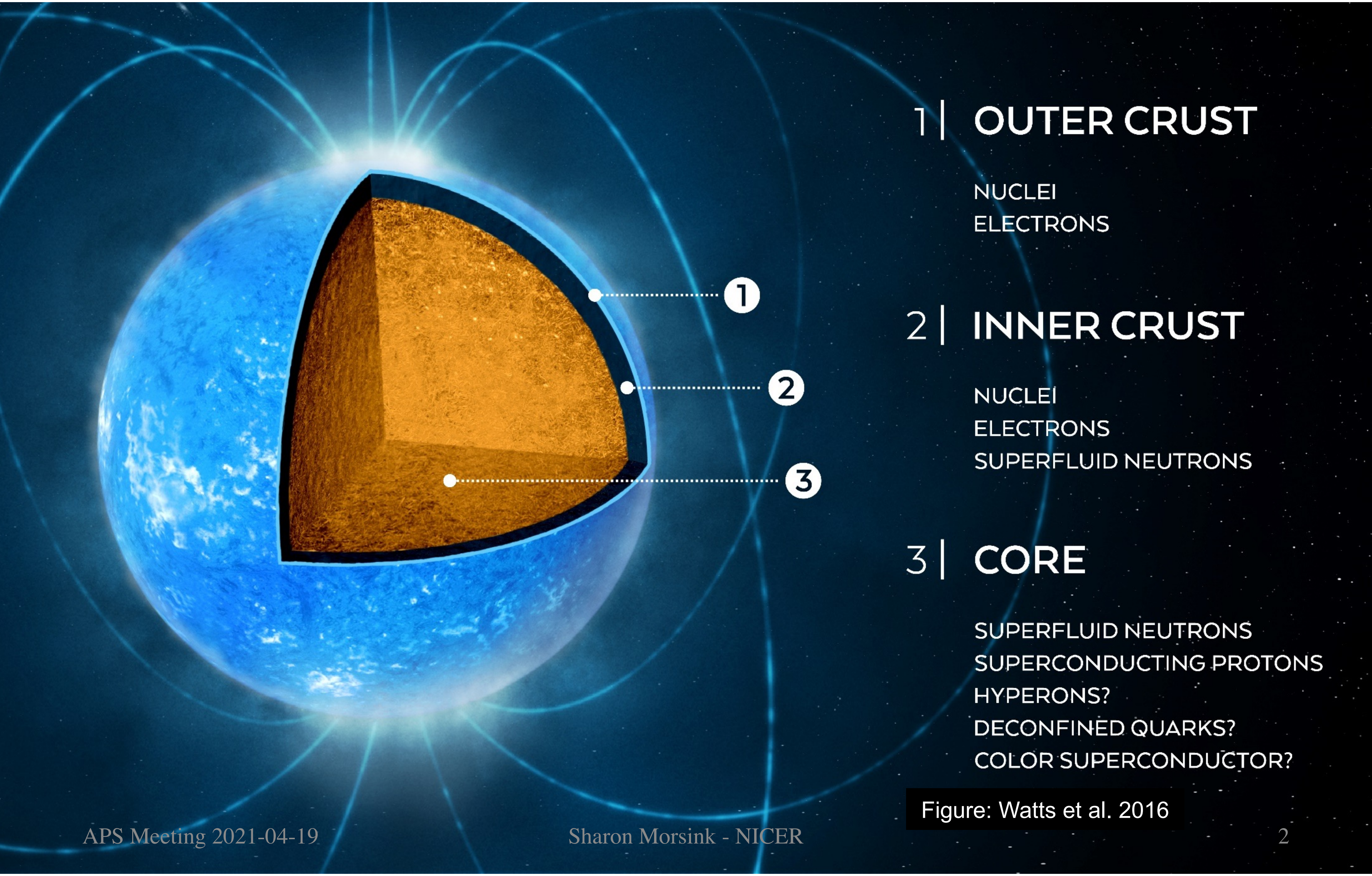
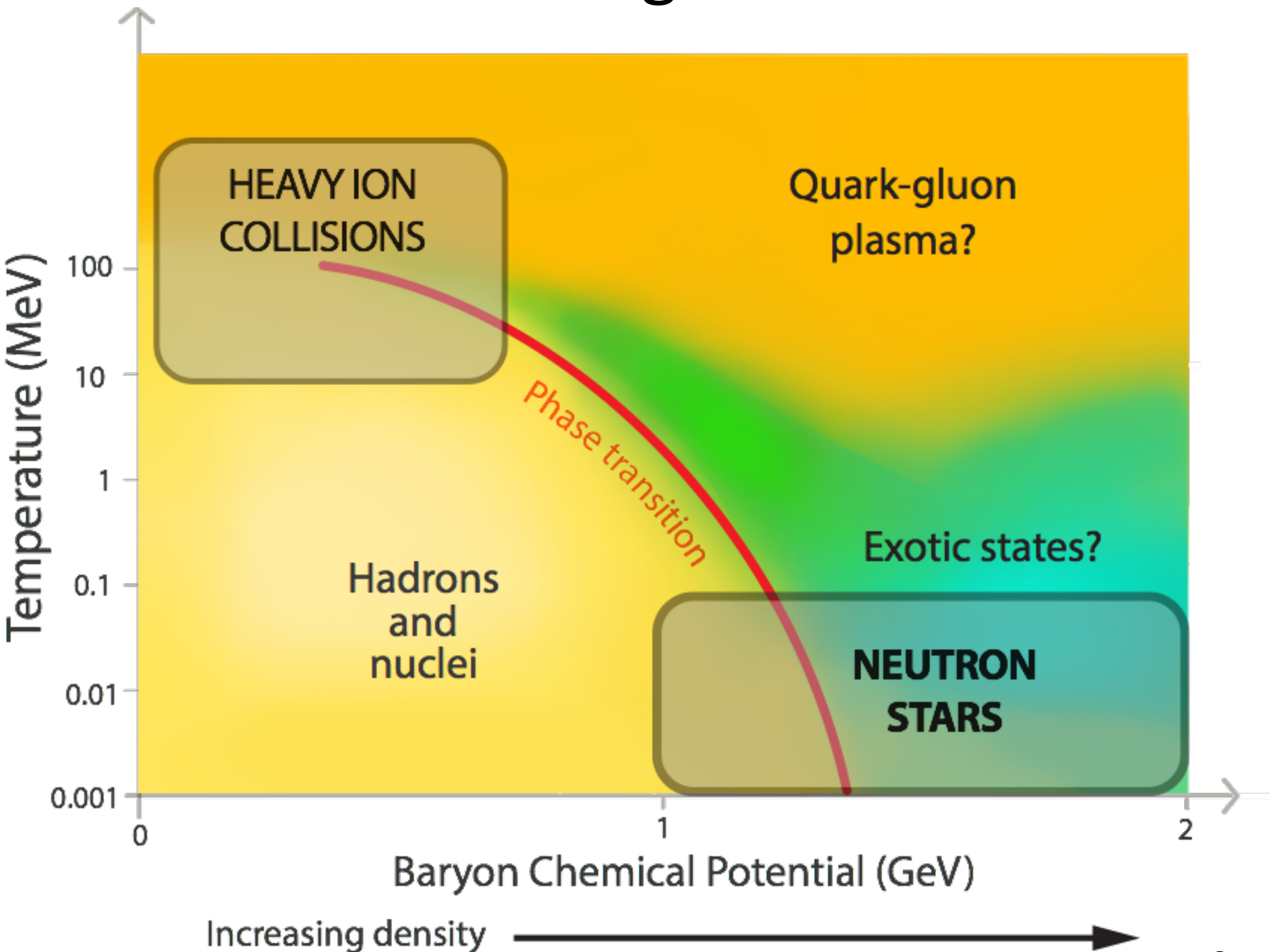


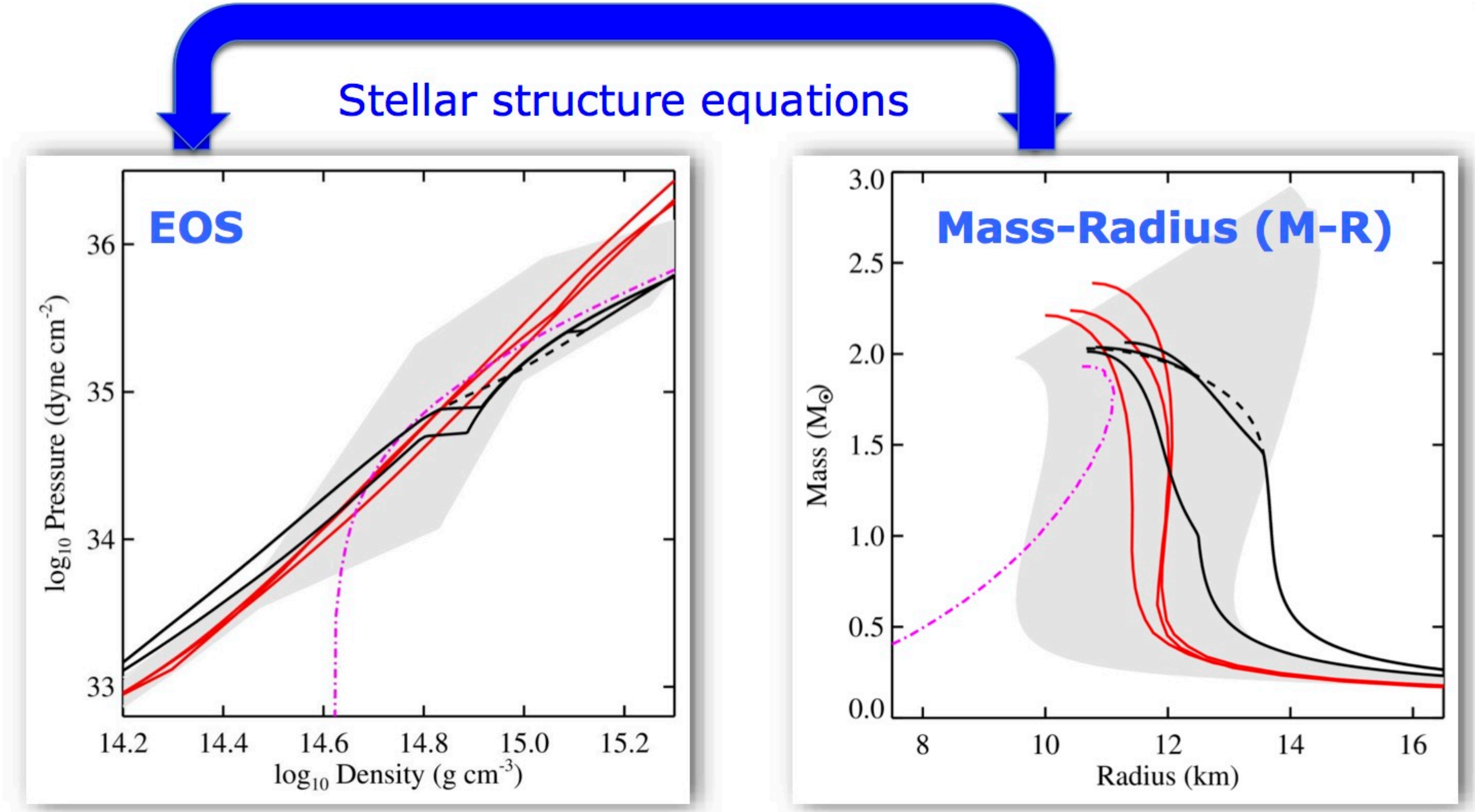
Figure: Watts et al. 2016

Possible Phase Diagram for Dense Matter

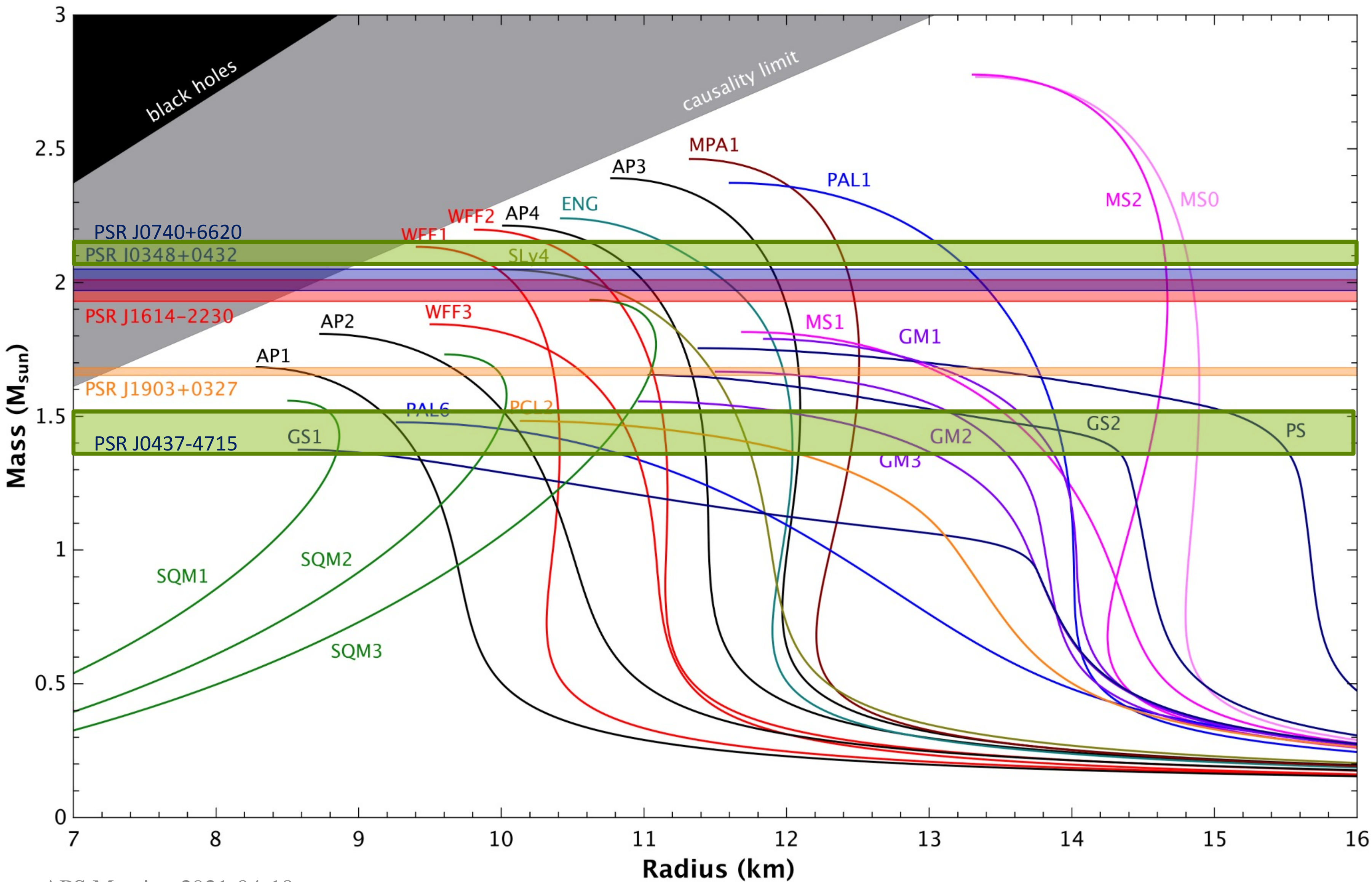


Concept: G. Baym
Figure: Watts et al. 2016

Equations of State vs Mass-Radius Curves



The neutron star mass-radius relation



Credit: N. Wex

How to measure Radius with X-rays?

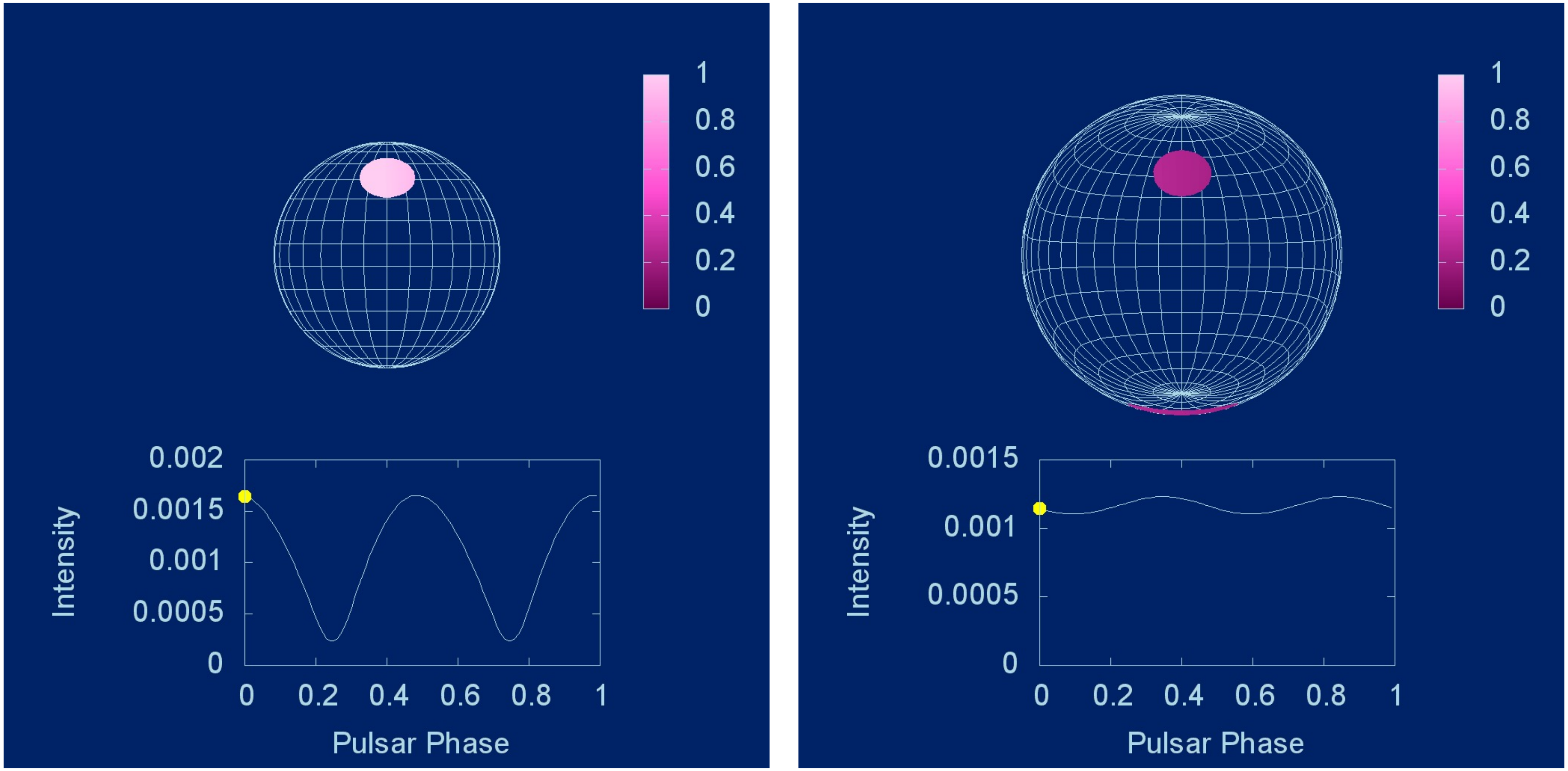
View X-rays emitted by the surface

- Types of Methods:
  – Non-pulsed emission from whole surface = measure surface area; Quiescent LMXBs, X-ray Bursts (Chandra, XMM, Athena)
  – Pulsed emission – look for effects of gravitational field (ie mass and radius) on time variations of flux; millisecond period X-ray pulsars

Dependence of Pulse Profiles on M/R

M/R = "compactness" affects light-bending

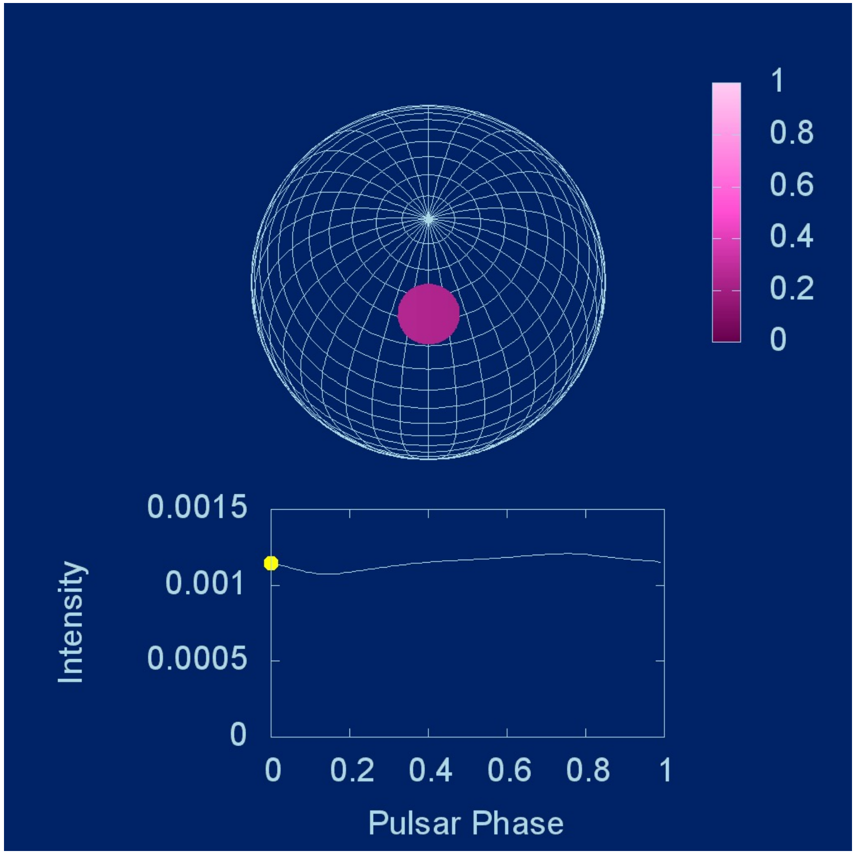
Larger M/R → less modulation



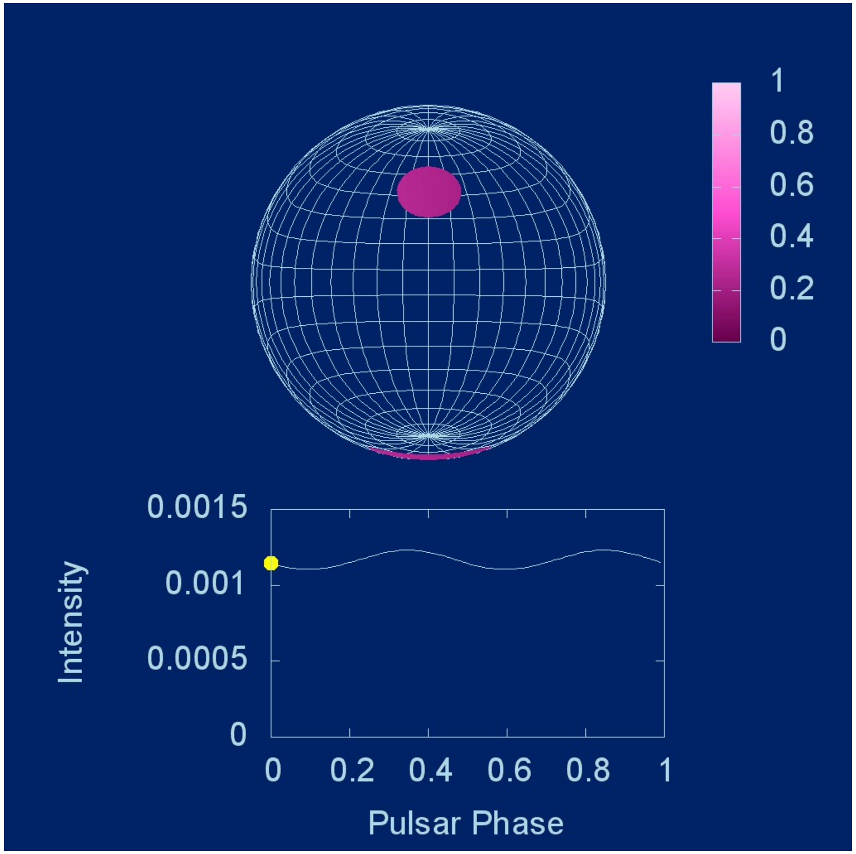
Newtonian Gravity

General Relativity M/R = 0.25

Effect of Observer's Viewing Angle

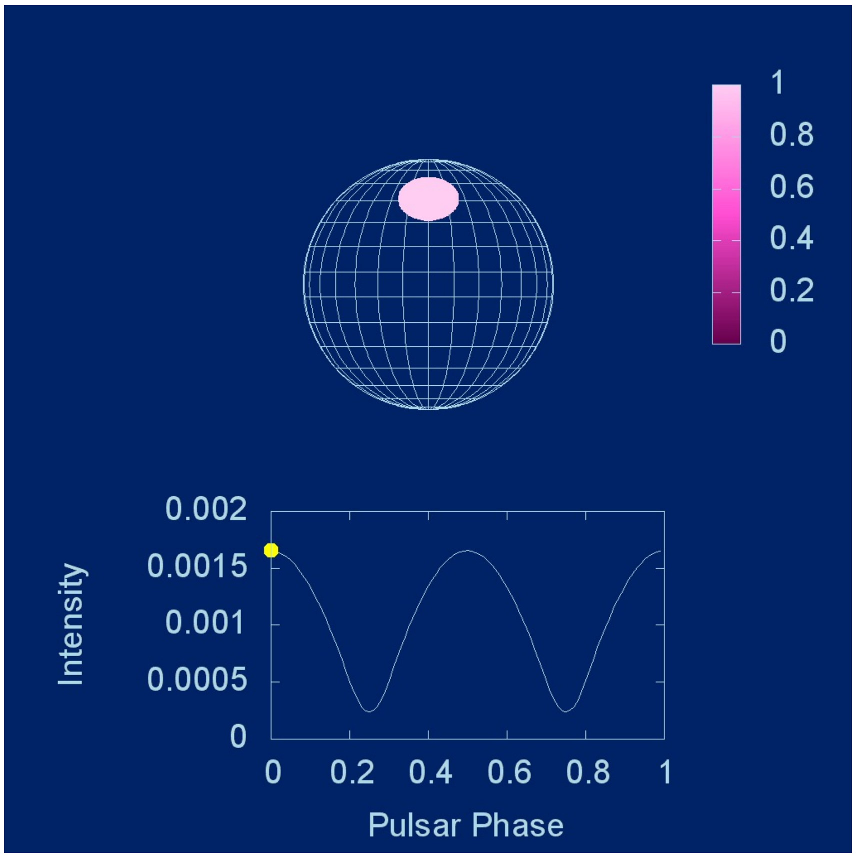


30 deg from Spin Axis

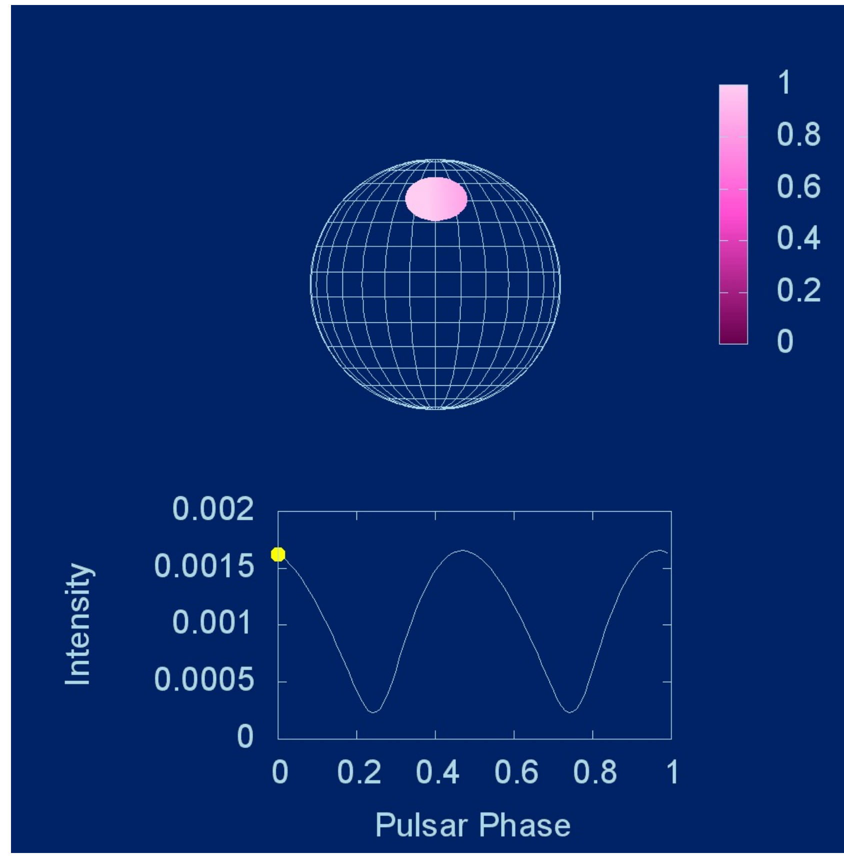


90 deg from Spin Axis

Effect of Rotational Speed ∝ R sini sinθ



v/c = 0.01



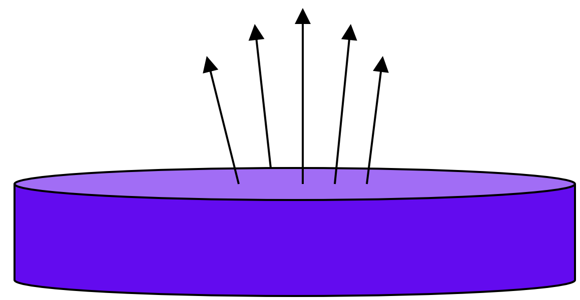
v/c = 0.2 (harmonics)

Anisotropic Emission

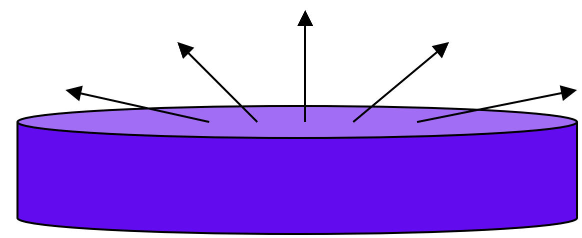
- Modulation: Normal beaming (A) gives higher pulsed fraction than anti-beaming (C)
- timing asymmetries: peak emission occurs earlier for C than for A
- Pulse shape: double-peaks or flattened peaks possible with C

  Anisotropy depends on the photon wavelength.

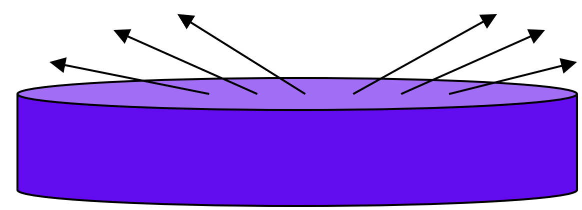
We require phase resolved spectroscopy!



A = Beamed towards the normal



B = Isotropic emission

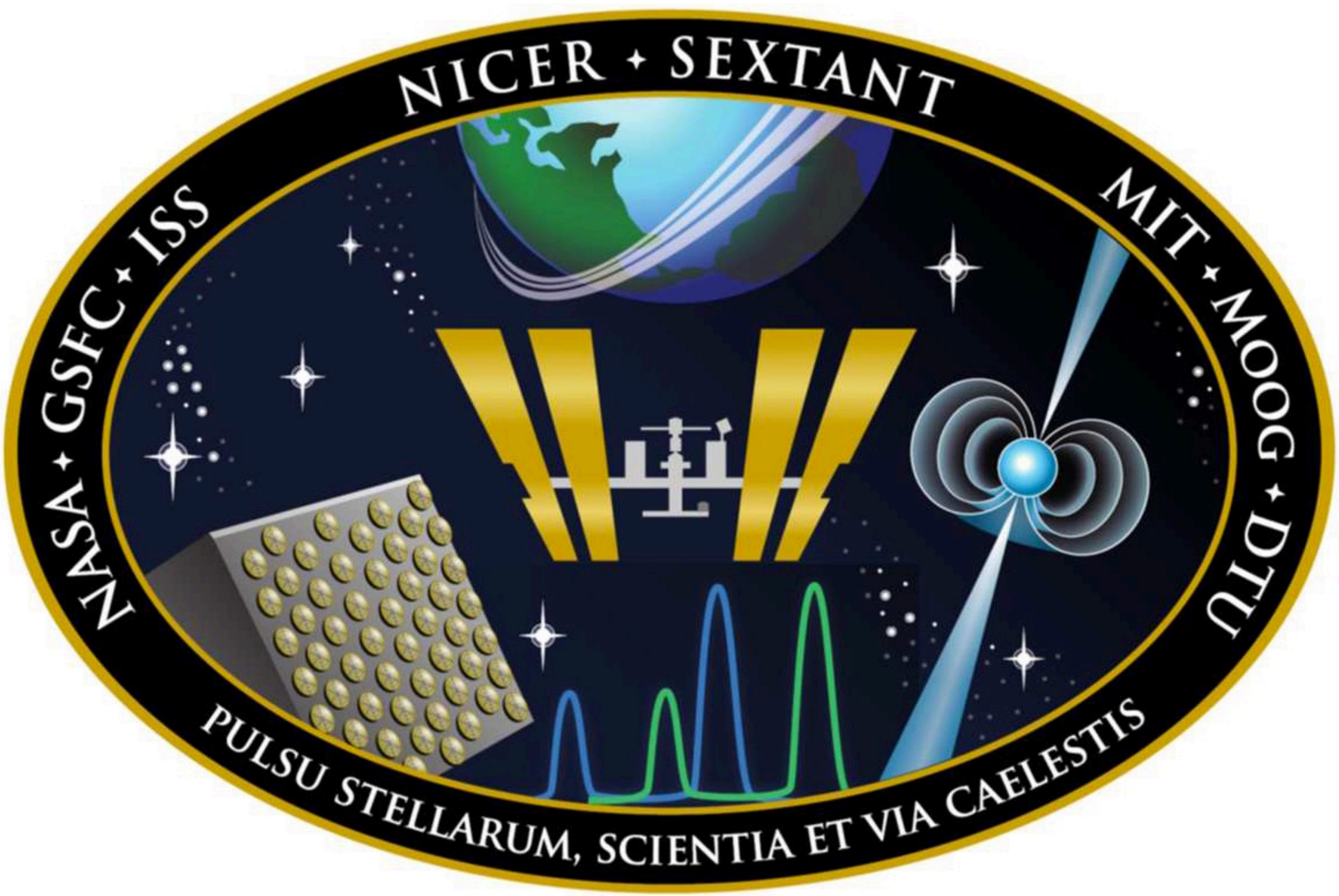


C = Beamed towards the surface

X-ray Timing Telescopes

- RXTE – Rossi X-ray Timing Explorer (1995-2012) X-ray timing
- XMM – great energy resolution, +timing mode
- AstroSAT – Indian RXTE-like mission
- NICER – great timing AND spectroscopy – designed for pulse profile observations!!!!
- Future:
  - eXTP, StrobeX = RXTE x 10 + spectra
    + polarization (eXTP)!!!

The Neutron Star Interior Composition Explorer



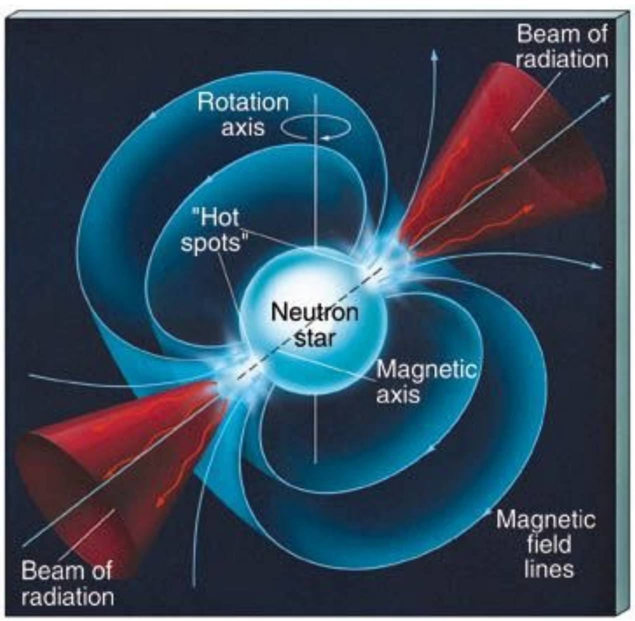
PI: Keith Gendreau

Science Lead: Zaven Arzoumanian

Installed on the ISS in June 2017

NICER 's Key Science Objective

Constrain the equation of state of bulk nuclear matter through precise mass and radius measurements of several neutron stars.



Targeting (mainly) thermal emission from rotation-powered MSPs and using the pulse profile modeling technique

- $\dot{E} \approx 10^{33-34}$ erg/s, $L_X \approx 10^{30-31}$ erg/s
- Soft, thermal X-ray emission from hot spots
- Non-magnetic (0 G, effectively $B < 10^{10}$ G) hydrogen or helium atmosphere
- Non-transient (always "on") and non-variable

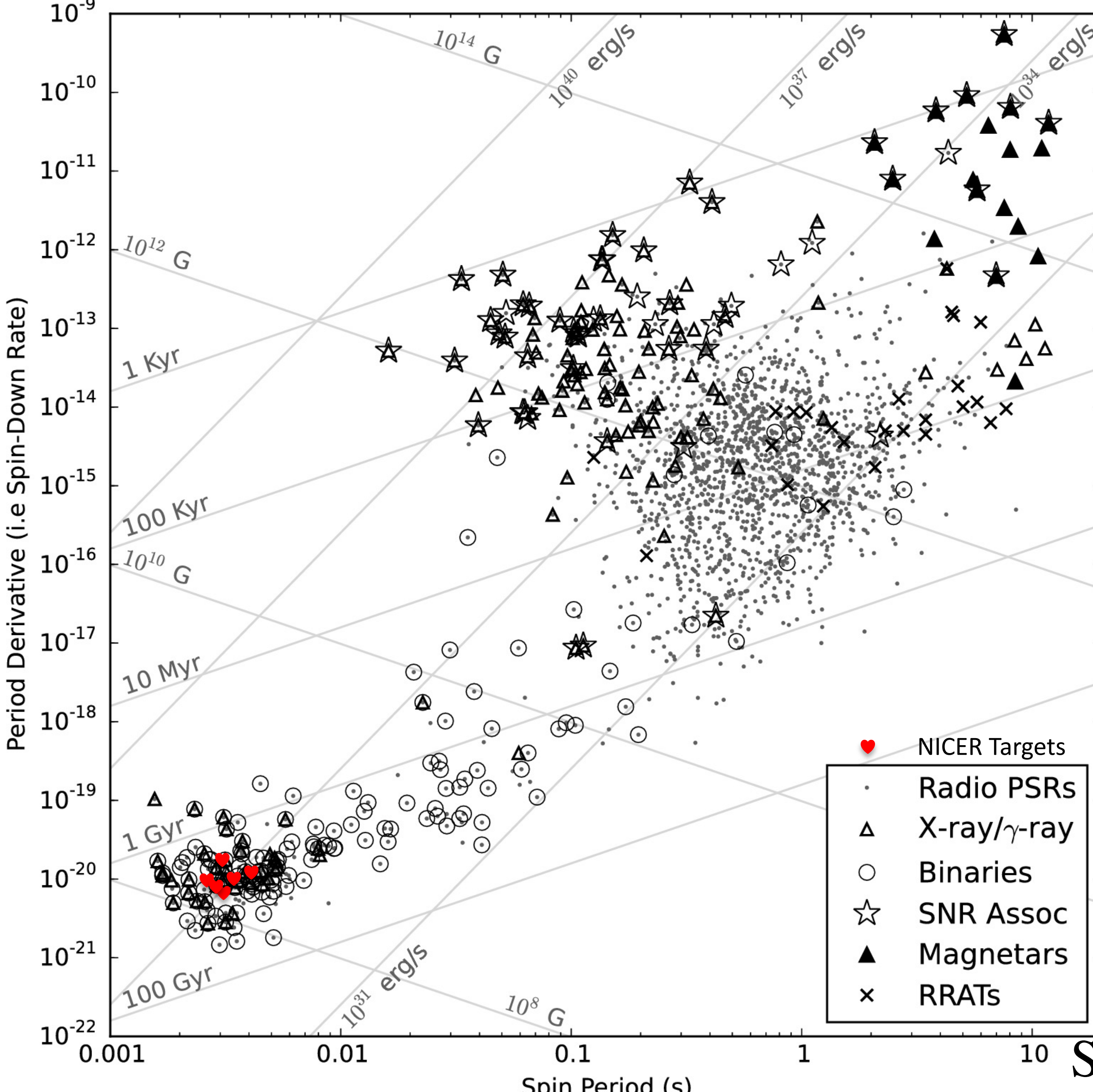
NICER Target List for M-R Constraints

	Spin Period (ms)	Distance (pc)	Mass * ($M_\odot$)	NICER Rate (photons/ks)
PSR J0437−4715	5.76	156.79±0.25	1.44±0.07	1319
PSR J0030+0451	4.87	325±9	isolated	314
PSR J1231−1411	3.68	440	?	210
PSR J2124−3358	4.93	410_{-70}^{+90}	isolated	100
PSR J0614−3329	3.10	~ 550	?	27
PSR J1614−2230	3.15	670_{-40}^{+50}	1.908±0.016	18
PSR J0740+6620	2.89	~ 1000	2.08±0.07	15

* Masses from radio timing for pulsars in a binary.

Pulsar P-Pdot Diagram

Rapid Change in Spin



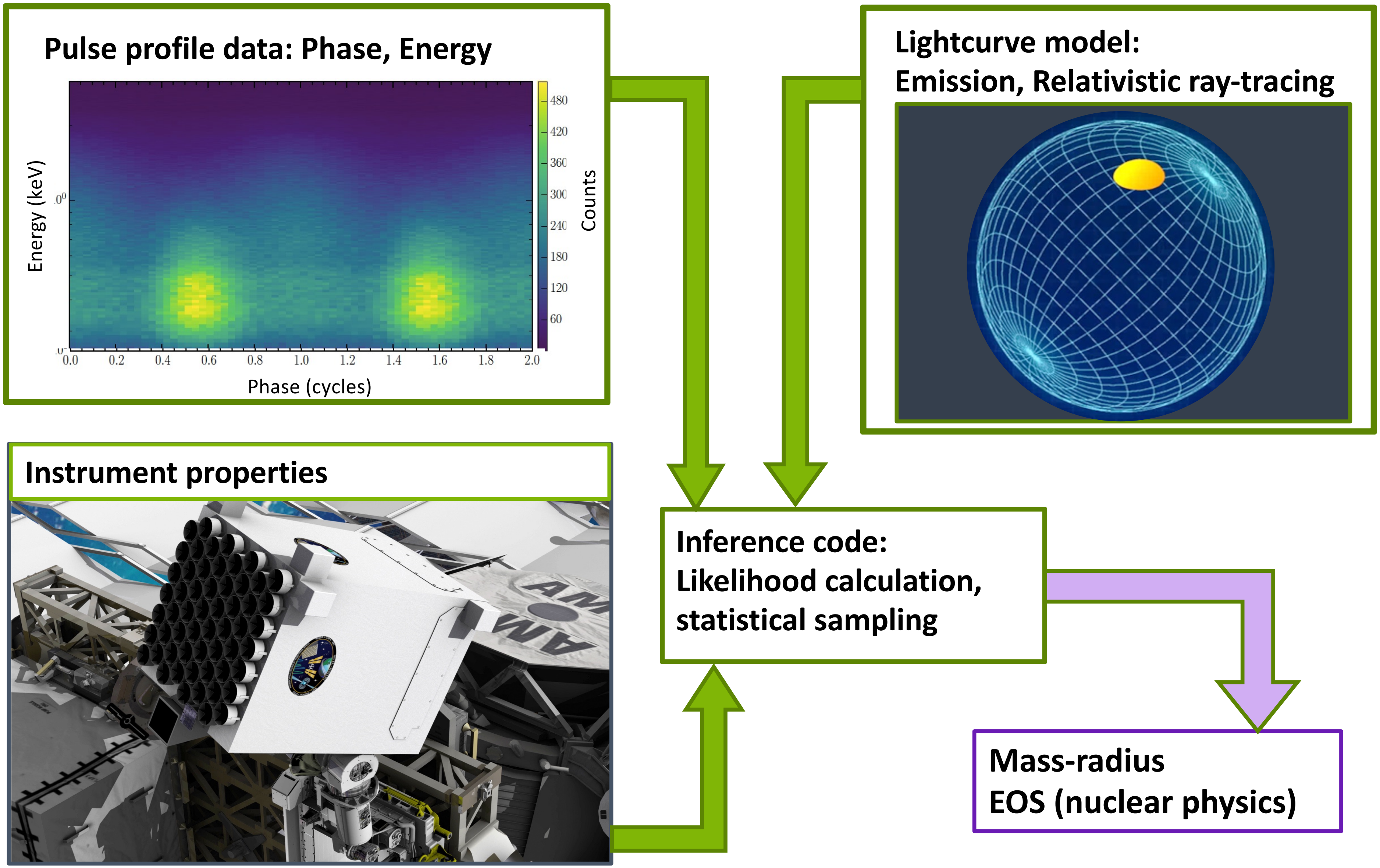
Stable spin

Fast spin

Slow spin

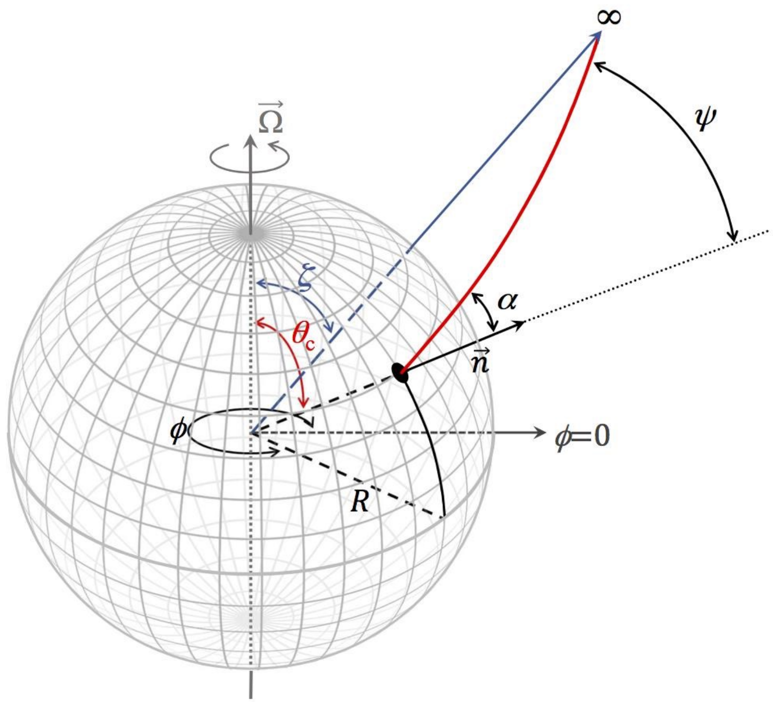
From Essential Pulsar Astronomy by Scott Ransom

The Pulse Profile Modelling process



Model Geometry and Relativistic Effects

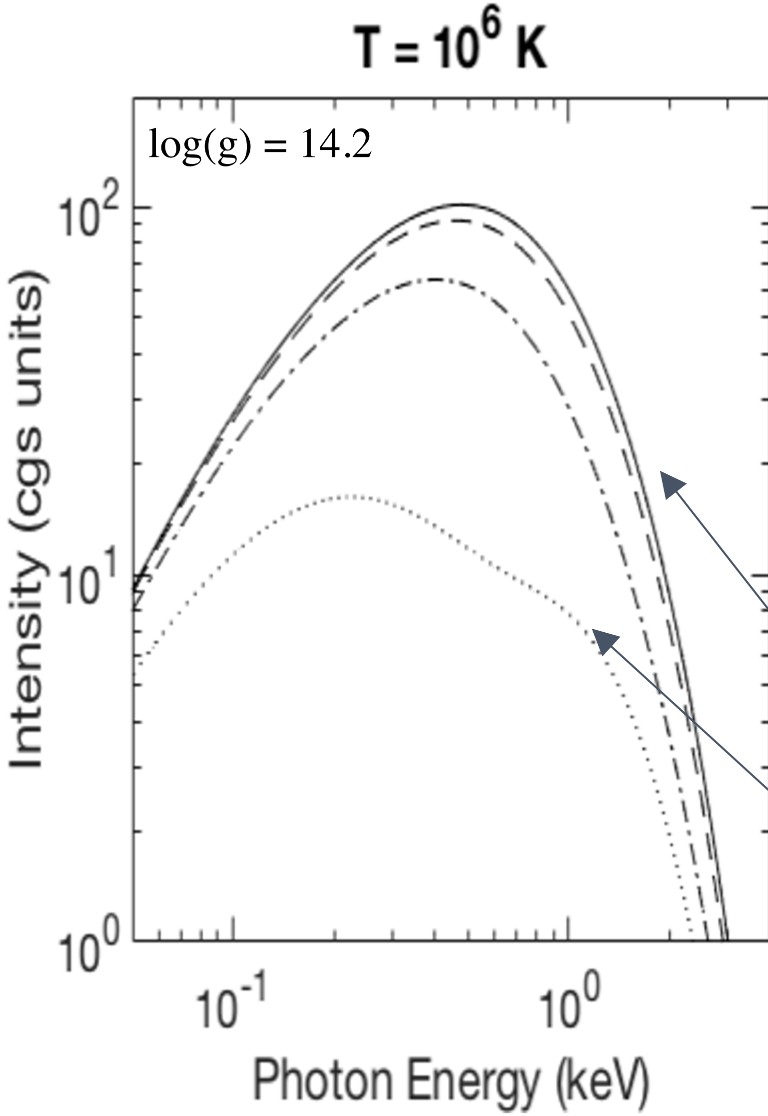
- Rotating star
- Two or more X-ray emitting "hot-spots"
- Relativistic effects:
    - Light bending in a Schwarzschild geometry
    - Gravitational redshift
    - Doppler shifts
    - Relativistic aberration
    - Propagation time differences



- Spot co-latitudes θ_{c1} , θ_{c2}, …
- Relative phase of the spots
- Spot angular radii $\rho_{1,2}$
- Observer inclination ζ
- Relation between ψ and α depends on M/R

(Miller & Lamb 1998; Beloborodov 2002; Poutanen & Gierlinski 2003; Poutanen & Beloborodov 2006; Morsink et al. 2007; Lo et al. 2013; Miller & Lamb 2015; Bogdanov; Ozel & Psaltis et al. ; Strohmayer & Mahmoodifar; Watts et al. , …)

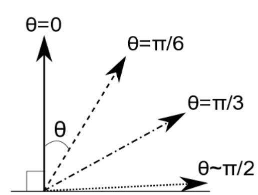
Hydrogen Atmosphere



- NSX - Hydrogen Atmosphere depends on Effective Surface Temperature and local acceleration due to gravity (Heinke+2006)
- Variation of surface g due to rotation (AlGendy & Morsink 2014)
- Fully ionized H (or He) atmosphere models (Ho & Lai 2001)
- Anisotropic emission

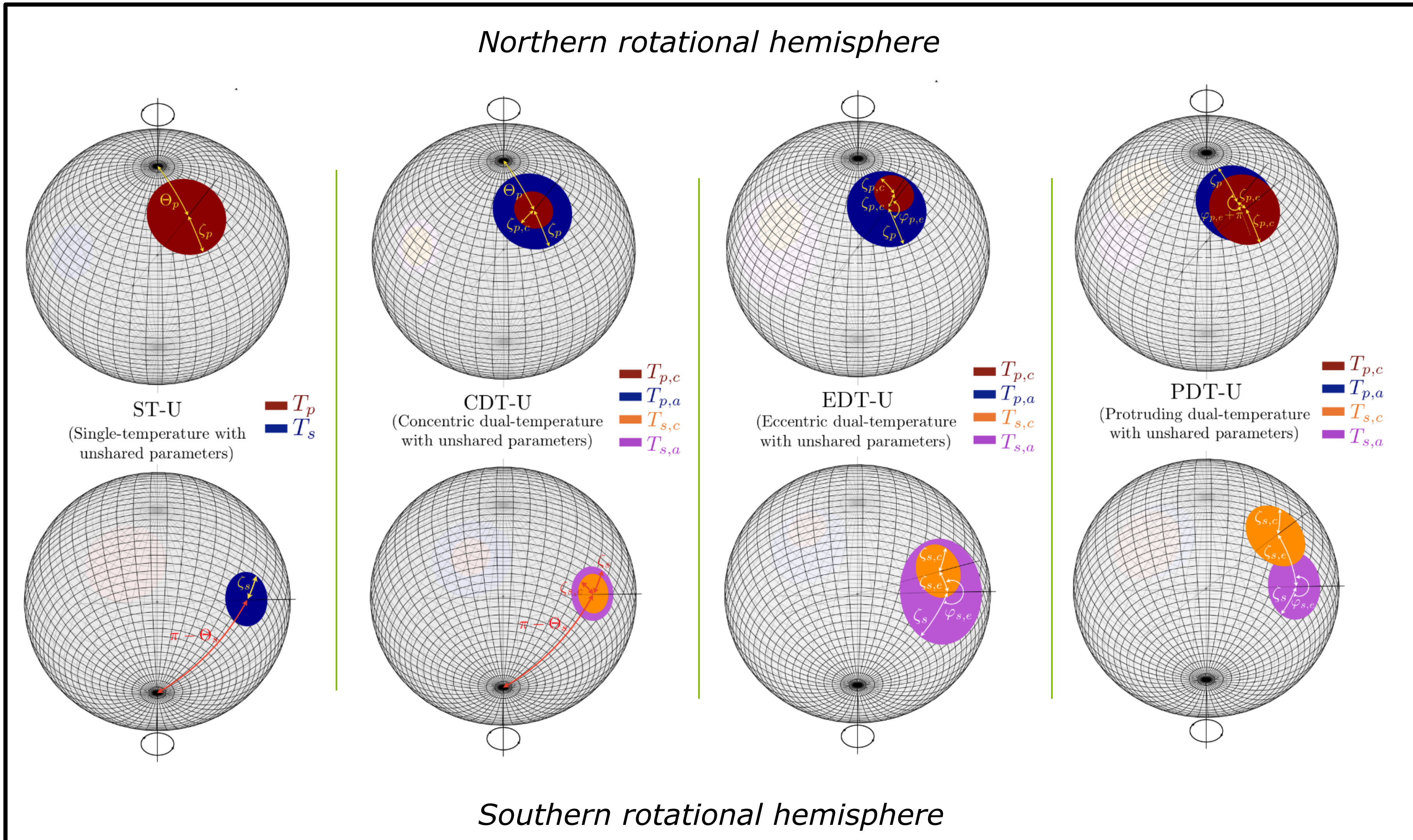
Emission normal to surface

Emission tangent to surface



Amsterdam Spot Shapes

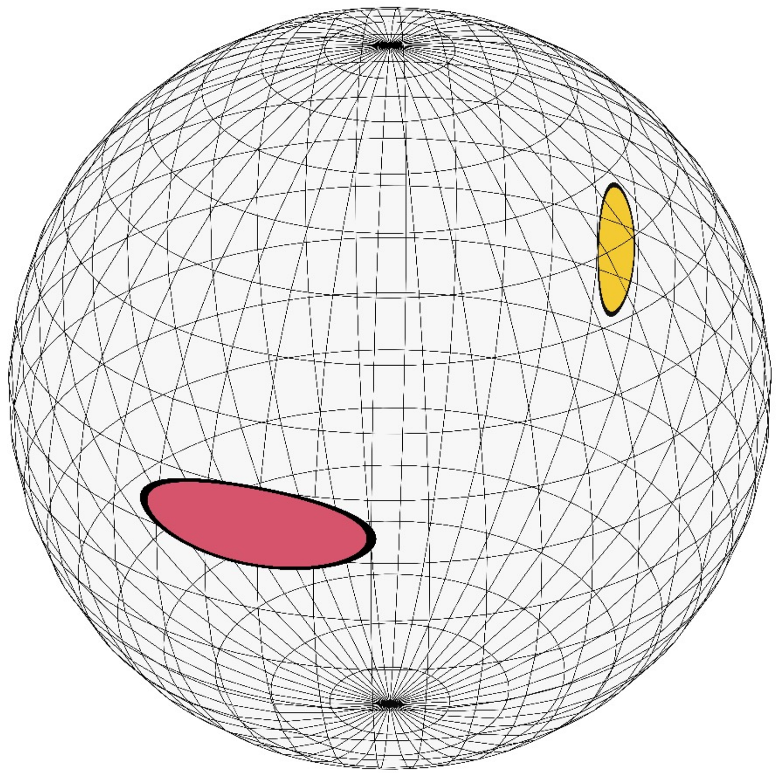
- Two-cap models of increasing surface pattern complexity.



Courtesy of Tom Riley & Anna Watts

Illinois-Maryland Spot Shapes

Two or more hot spot, allowing for elongated spots with arbitrary overlap

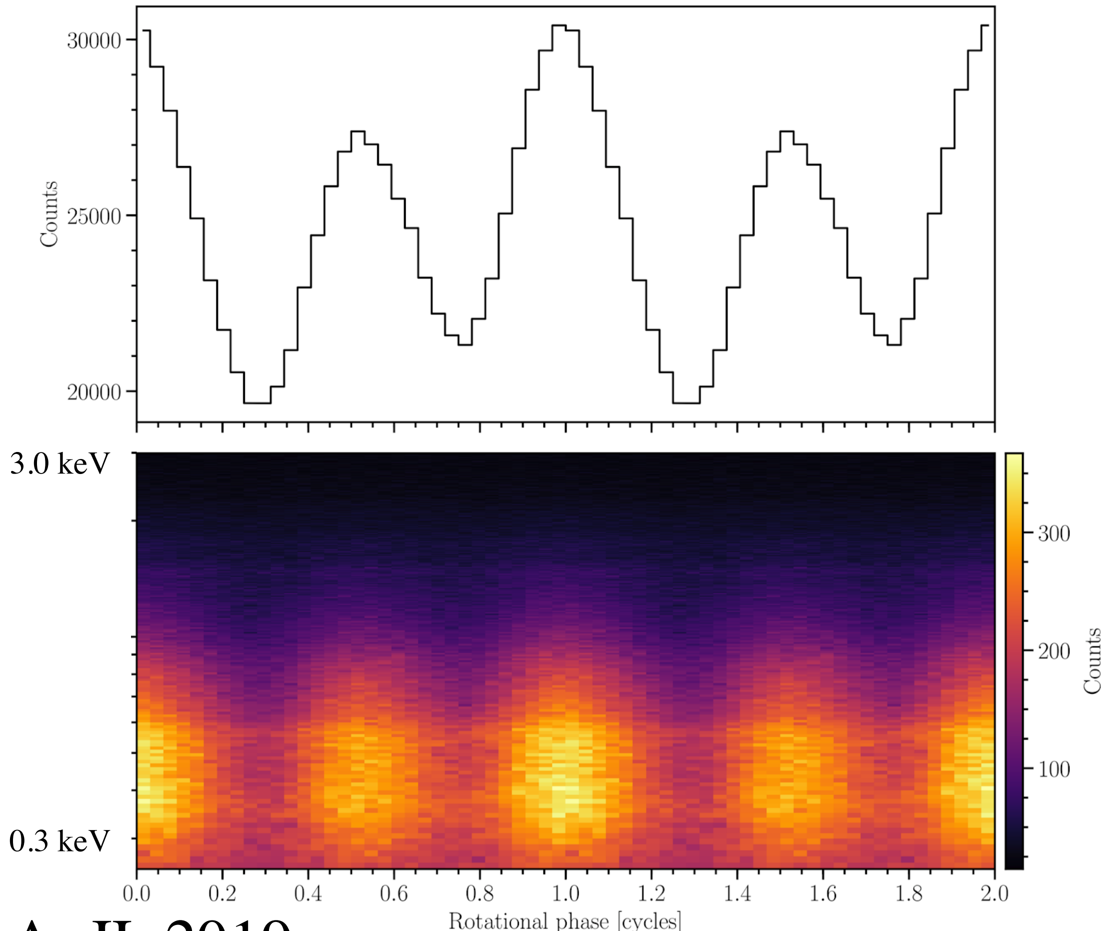


Courtesy of Alex Dittmann, Fred Lamb, & Cole Miller

NICER Data Analysis Parameters

- Up to 4 spots at arbitrary locations, sizes, & temperatures; mimic complex shapes
- Hydrogen atmosphere (with He possible)
- Mass, radius, observer inclination, distance with reasonably large range of priors
- ISM extinction
- Filtering/Background/Instrument Response
- Bayesian parameter estimation using multiple codes (based on MCMC, nested sampling)

J0030 Lightcurve (2019 dataset)



Bogdanov+, ApJL 2019

First Results on J0030

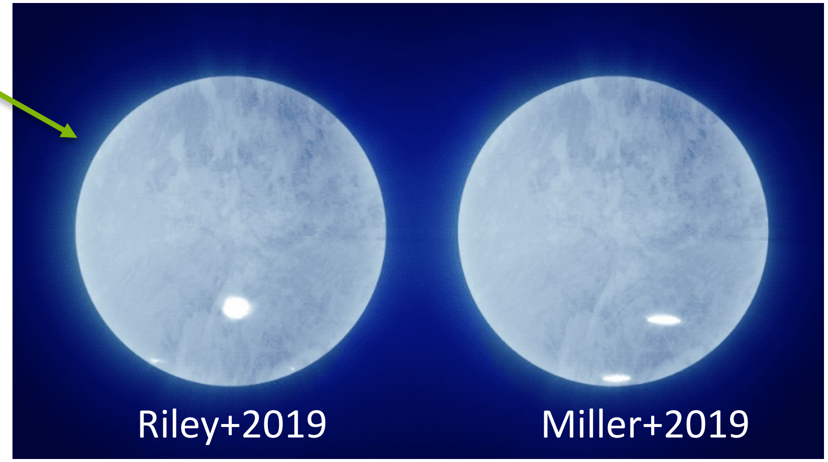
- No independent radio mass measurement
- Two independent analyses (crescents or ovals) Riley+ (ApJL 2019) and Miller+ (ApJL 2019)

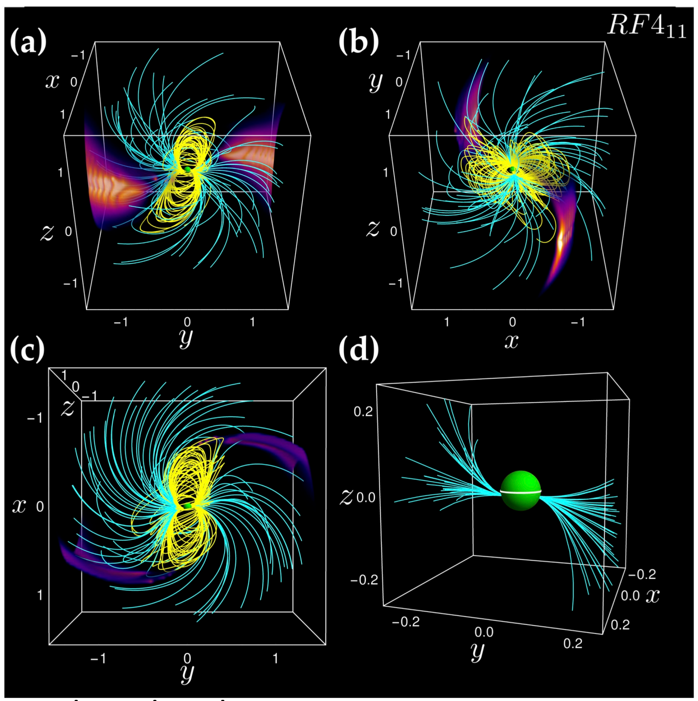
M = $1.34^{+0.15}_{-0.16}$ M_{sun} R = $12.71^{+1.14}_{-1.19}$ km   (Riley+)
M = $1.44^{+0.15}_{-0.14}$ M_{sun} R = $13.02^{+1.24}_{-1.06}$ km (Miller+)

- Similar observer inclinations, and spot locations
- Differences in M, R values show systematics in modelling choices
- Updated values (more observing time, improved background) expected in summer 2021

Inferred Spot Geometries

observer

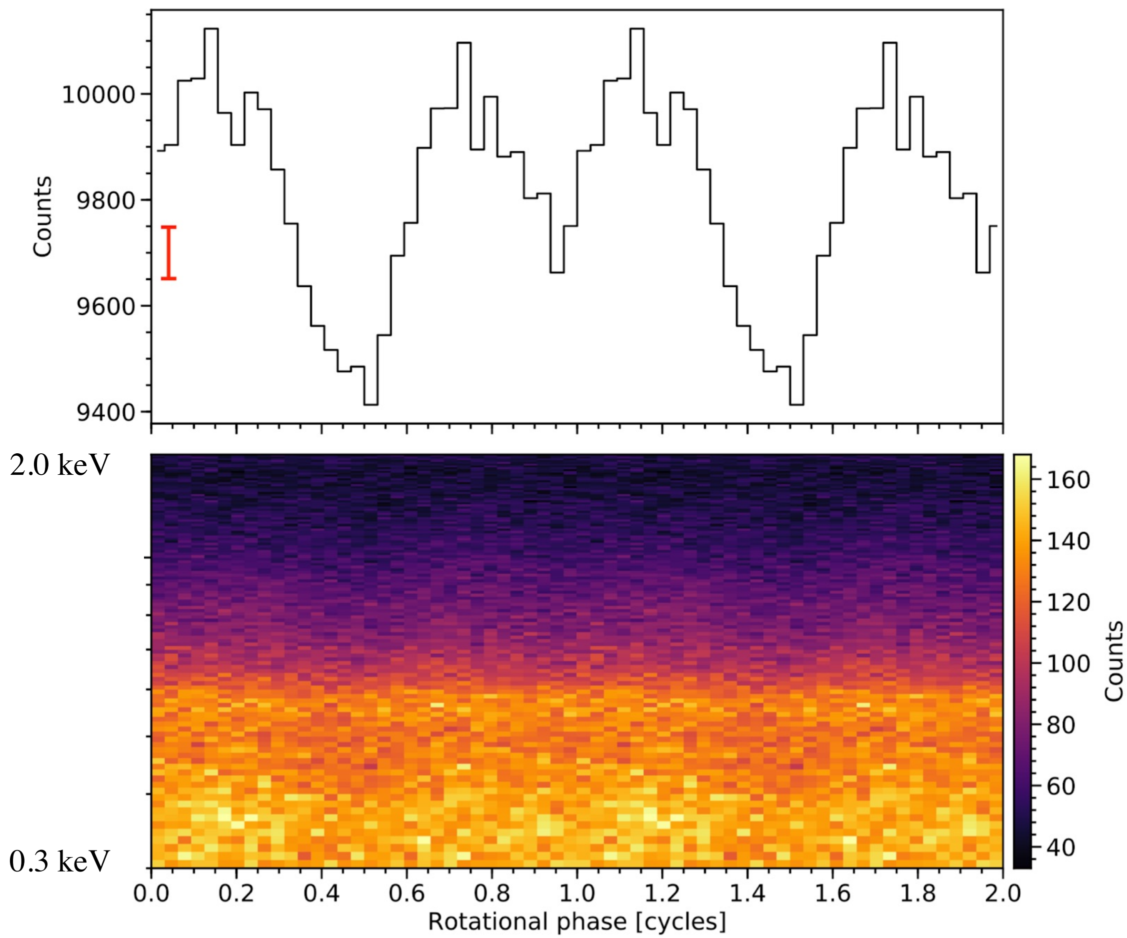




Kalapotharakos + 2021

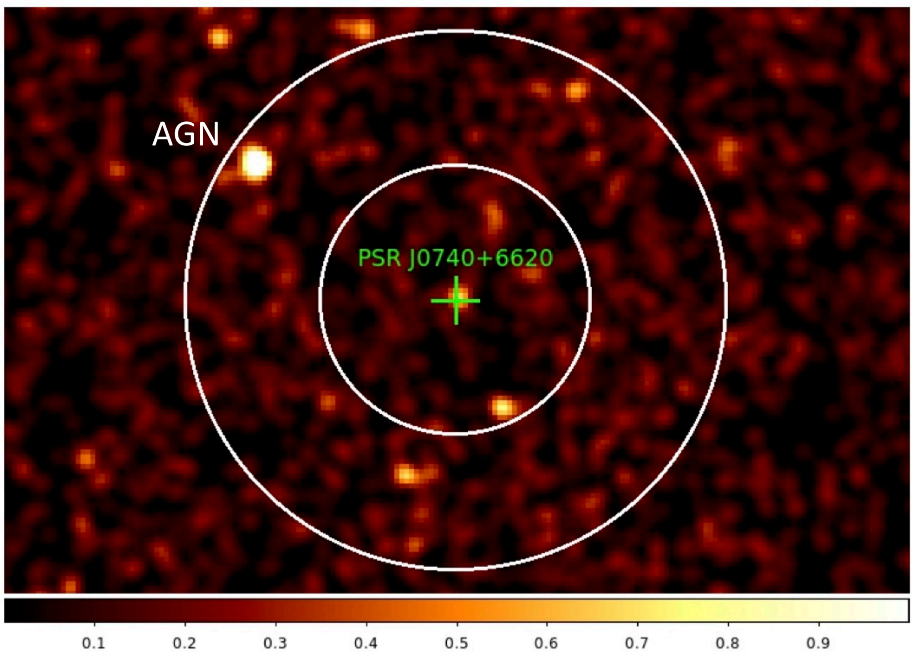
- Non-dipole magnetic field
- Example: Dipole + Quadrupole
- Kalapotharakos, Wadiasingh, Harding, & Kazanas ApJ (2021)

PSR J0740 Lightcurve



Wolff+ ApJL submitted, 2021

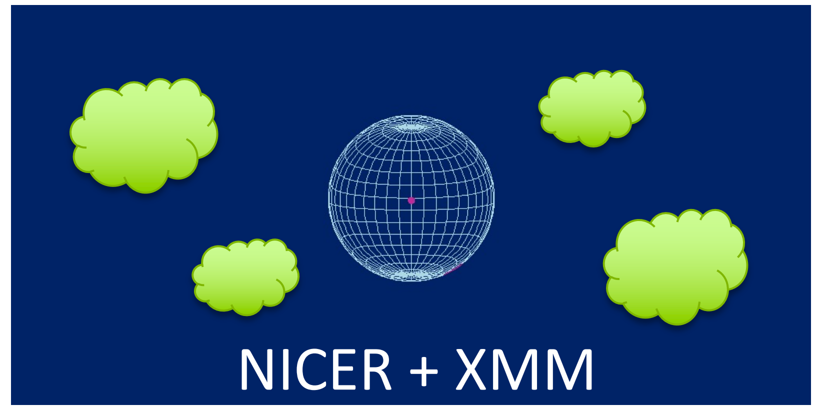
XMM Image of Region Near PSR J0740



- NICER is a “one-pixel” telescope
- No information about location of unpulsed emission
- J0740 is very faint
- Bright (harder) AGN and diffuse background

Wolff+ ApJL submitted, 2021

Effect of Adding Information about XMM Background



- Some of unpulsed signal comes from the spot pattern
- Inferred unpulsed background is small
- Smaller radius, larger spots

- Less unpulsed signal comes from the spot pattern
- Inferred unpulsed background is larger
- Larger radius, smaller spots

Adding XMM background information INCREASES inferred radius.

First Results on J0740 (submitted to ApJL)

- Mass measurement from NANOGrav + CHIME:
  $M = 2.08 \pm 0.07\ M_{\odot}$ (Shapiro Delay, Fonseca+2021)
- Inclination close to 90 degrees (from radio)
- 2 Circular spots, closer to dipole than J0030
- Different treatments of XMM background/normalizations/priors:

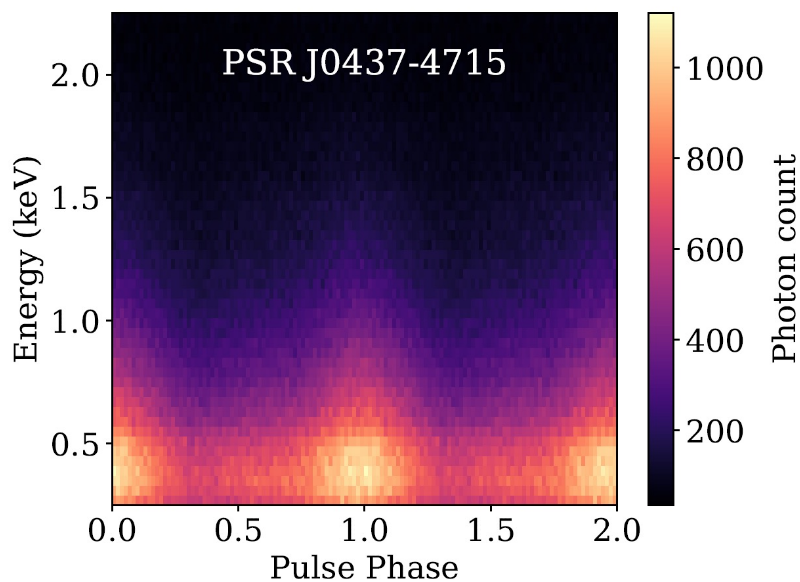
  $R = 12.4^{+1.3}_{-1.0}$ km (Riley+)

  $R = 13.7^{+2.6}_{-1.5}$ km (Miller+)
- 1-sigma lower limits on radius:

  $R_{1\sigma}$= 11.4 km (Riley+); $R_{1\sigma}$ = 12.2 km (Miller+)

Next: J0437

- We expect best radius measurement
- Precisely known value of mass and observer's viewing angle from radio observations
- Complication of contamination from background AGN in same field of view
- Results from J0437 and other pulsars in 2021



NICER Results on Core Science

- First precise measurement of mass through pulse-profile modelling (J0030)
- Radius inferred for 2 pulsars (J0030, J0740) with masses that differ by 0.5 M_{sun}
- Later this year
  - New results for J0437 (with precise radio prior for mass, inclination, distance)
  - Updated mass & radius results for J0030 with better precision than 2019 results
  - Results for J2124 probable

THE NICER LIGHTCURVE MODELING WORKING GROUP

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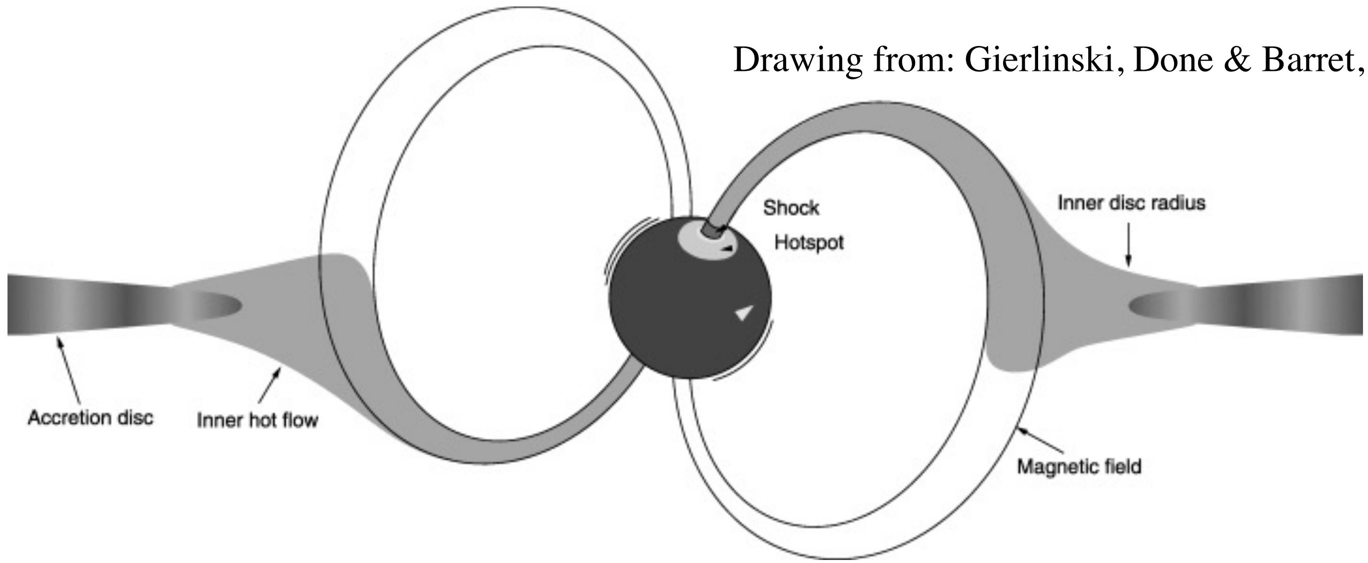
Extra slides

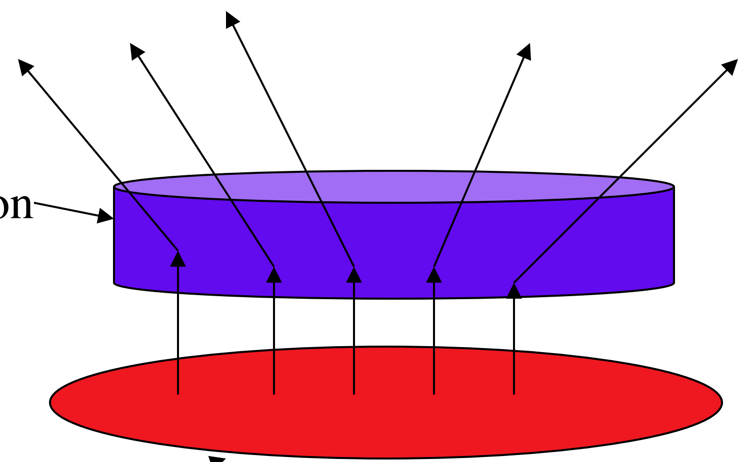
Hot Spot Model for Accreting X-ray Pulsars



Drawing from: Gierlinski, Done & Barret, 2002, MNRAS

Side View of Hot Spot:

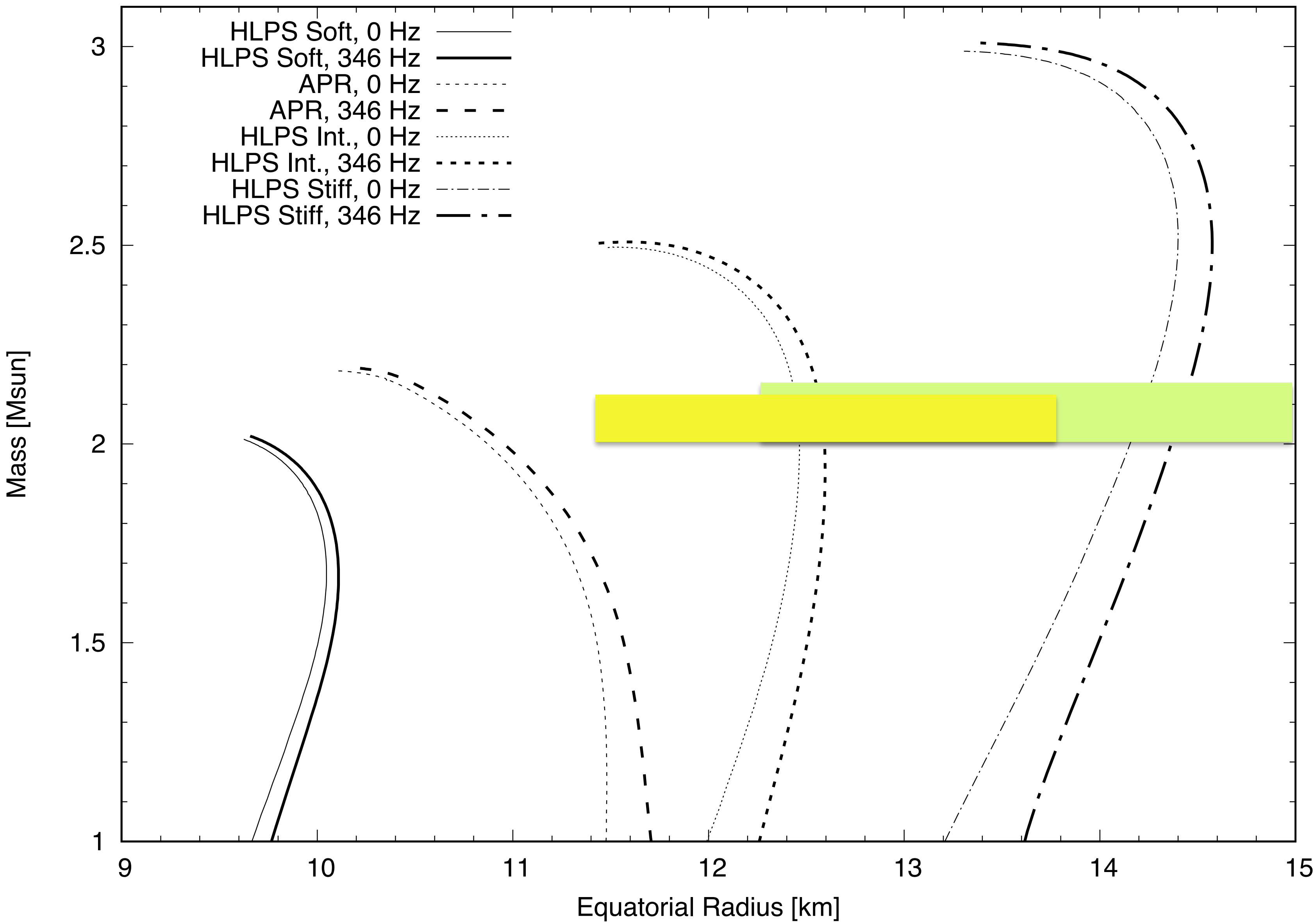
Electron plasma above spot Compton scatters “seed” blackbody photons



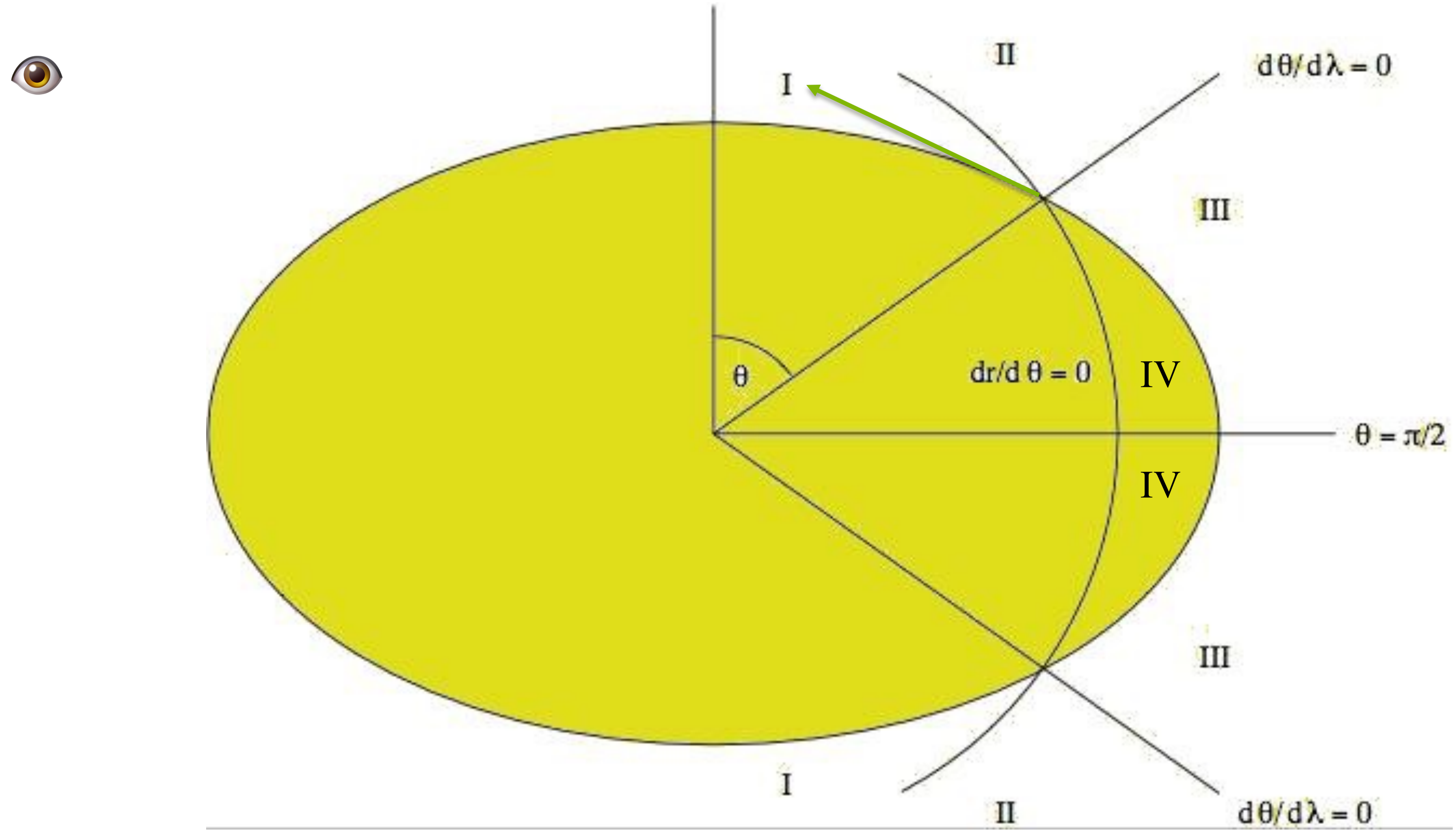
Anisotropic emission (anti-beaming) Sunyaev & Titarchuk

Isotropic emission

Blackbody emission from surface of star


HLPS Soft, 0 Hz
HLPS Soft, 346 Hz
APR, 0 Hz
APR, 346 Hz
HLPS Int., 0 Hz
HLPS Int., 346 Hz
HLPS Stiff, 0 Hz
HLPS Stiff, 346 Hz
Mass [Msun]
1
1.5
2
2.5
3
9
10
11
12
13
14
15
Equatorial Radius [km]

Effect of Stellar Oblateness



Morsink, Leahy, Cadeau & Braga 2007 ApJ