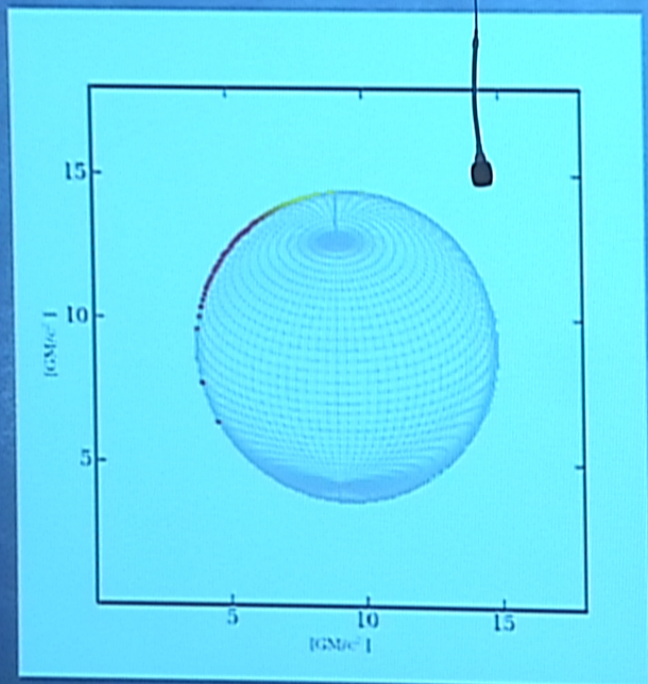
Title: Exploiting the Strong Gravitational Fields of Neutron Stars to Measure their Properties

Date: Feb 28, 2013 01:00 PM

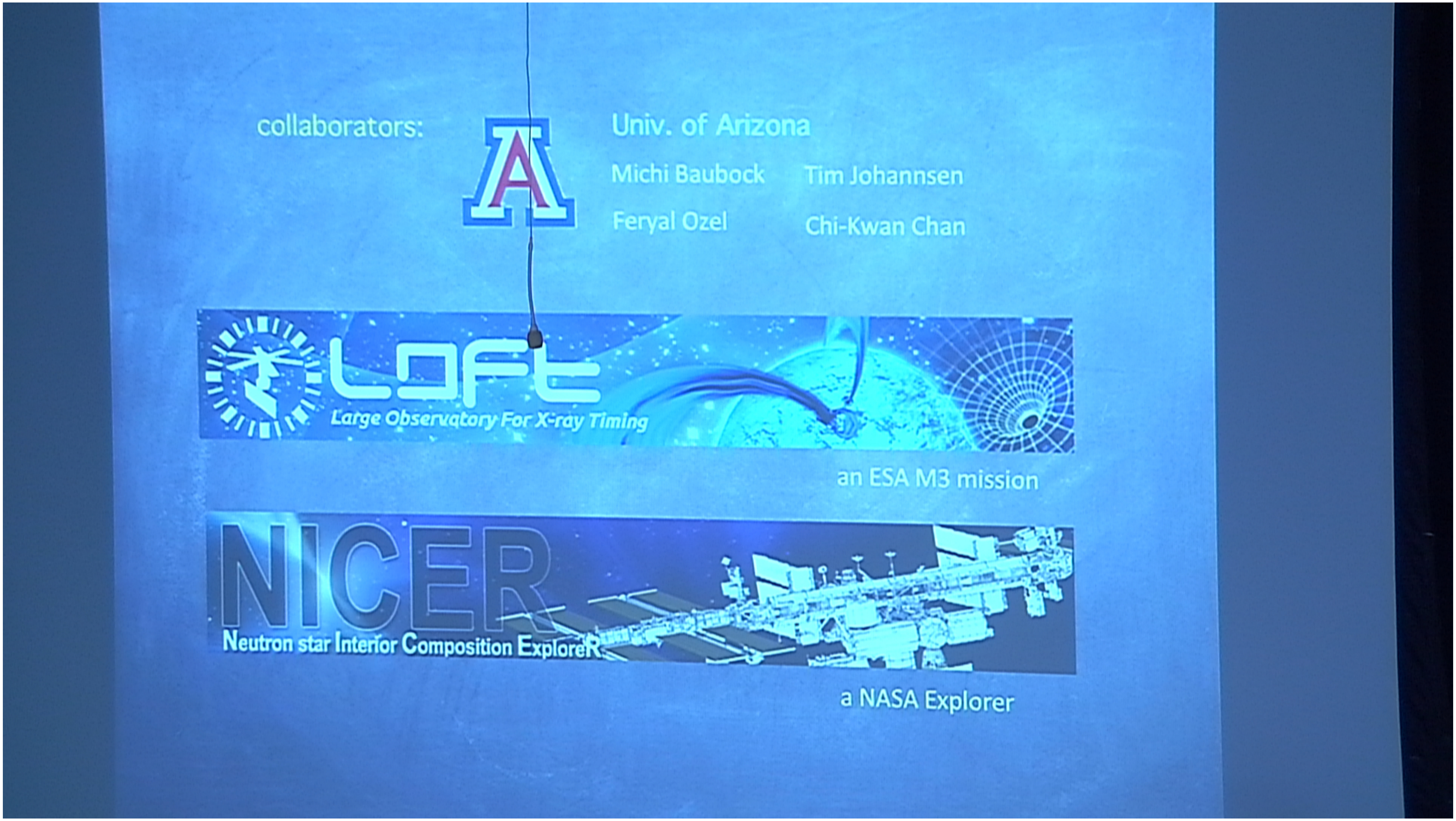
URL: http://pirsa.org/13020126

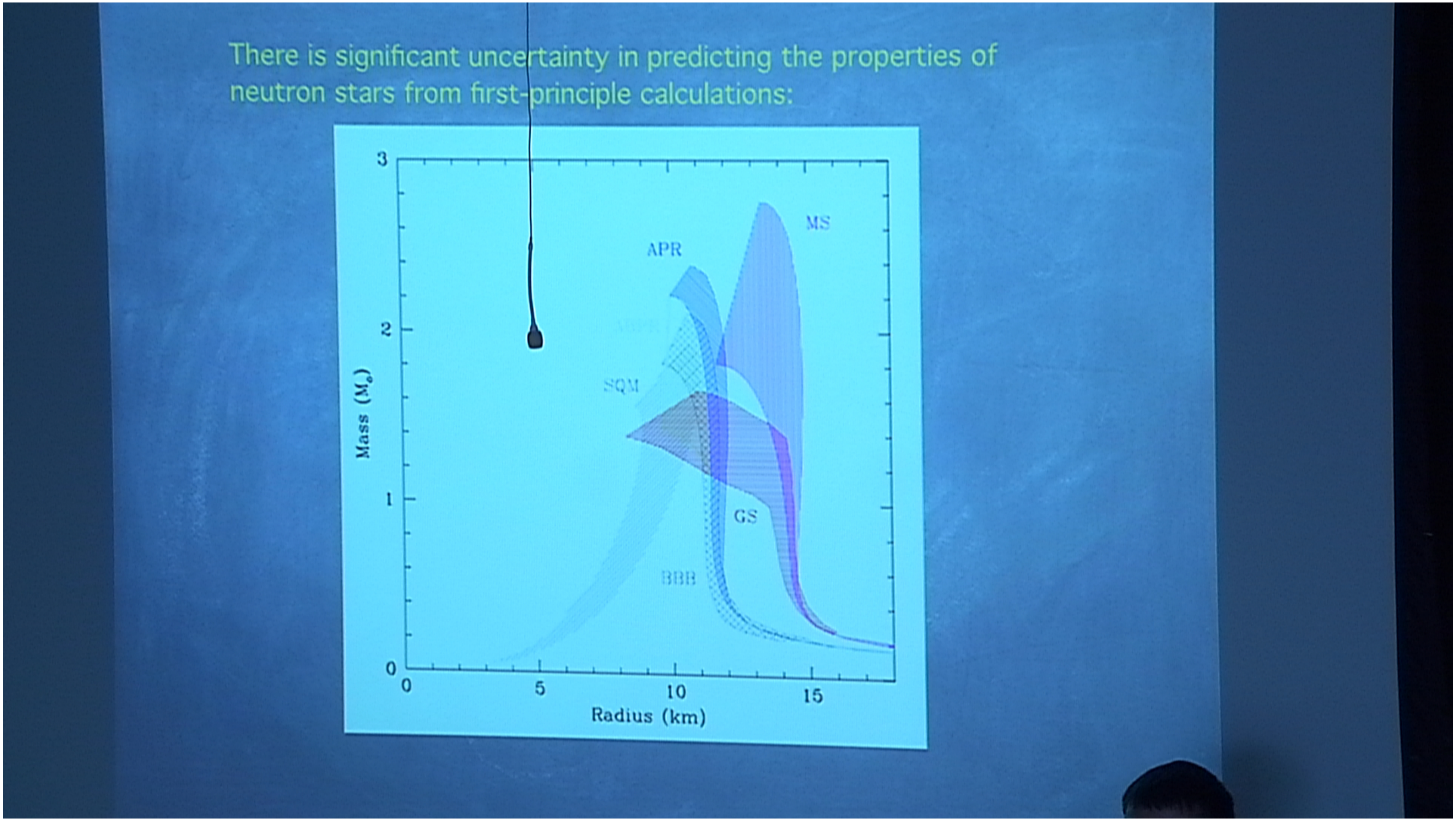
Abstract: Neutron stars possess the strongest gravitational fields among stellar objects in the Universe that are not surrounded by a horizon. This causes the emission from their surfaces to be strongly lensed and deformed. Two upcoming space X-ray missions, ESA's LOFT and NASA's NICER, aim to use observations of lightcurves from spinning neutron stars to map their gravitational fields as well as measure their masses and radii. In this talk, I will discuss some unexpected strong-field phenomena that affect gravitational lensing in the vicinity of neutron stars. I will then show how we can use these phenomena to measure strong-field frame dragging and break degeneracies in the measured neutron-star masses and radii.

Exploiting the Strong Gravitational Fields of Neutron Stars to Measure their Properties

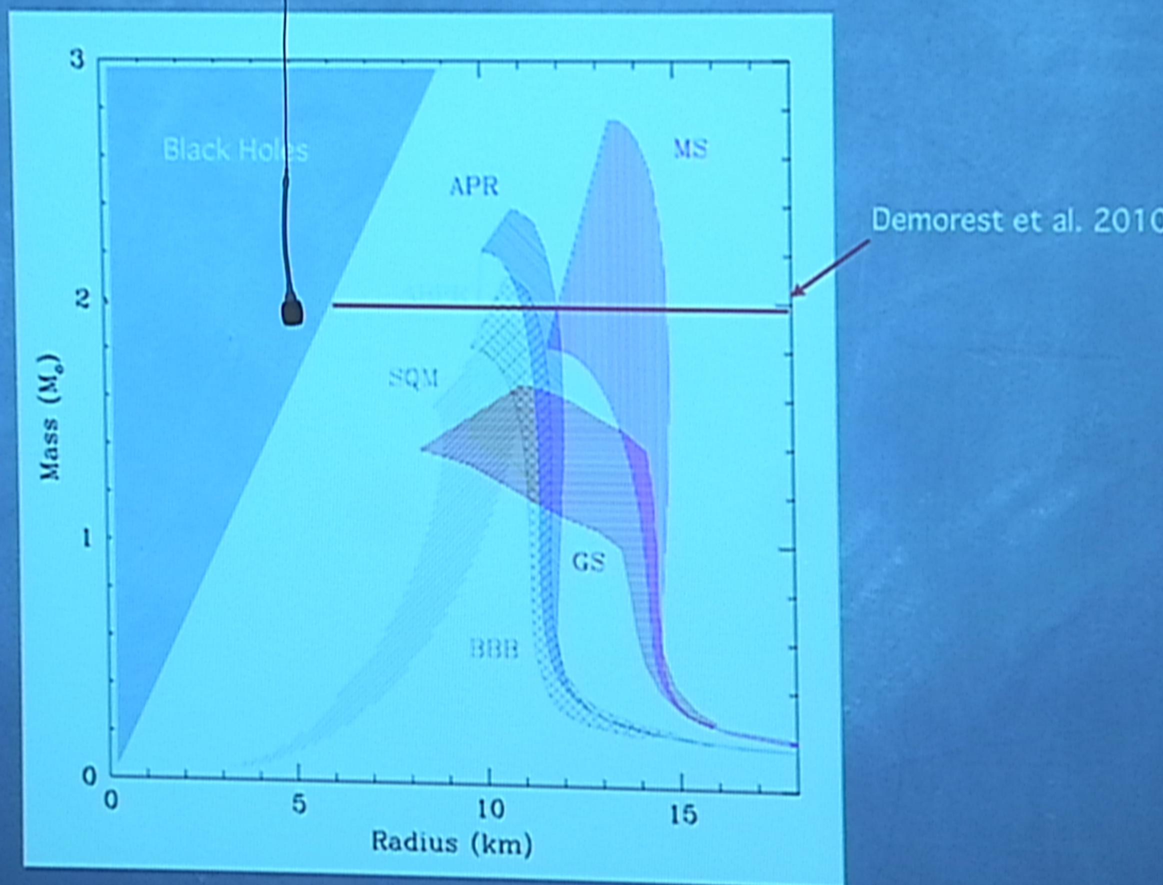


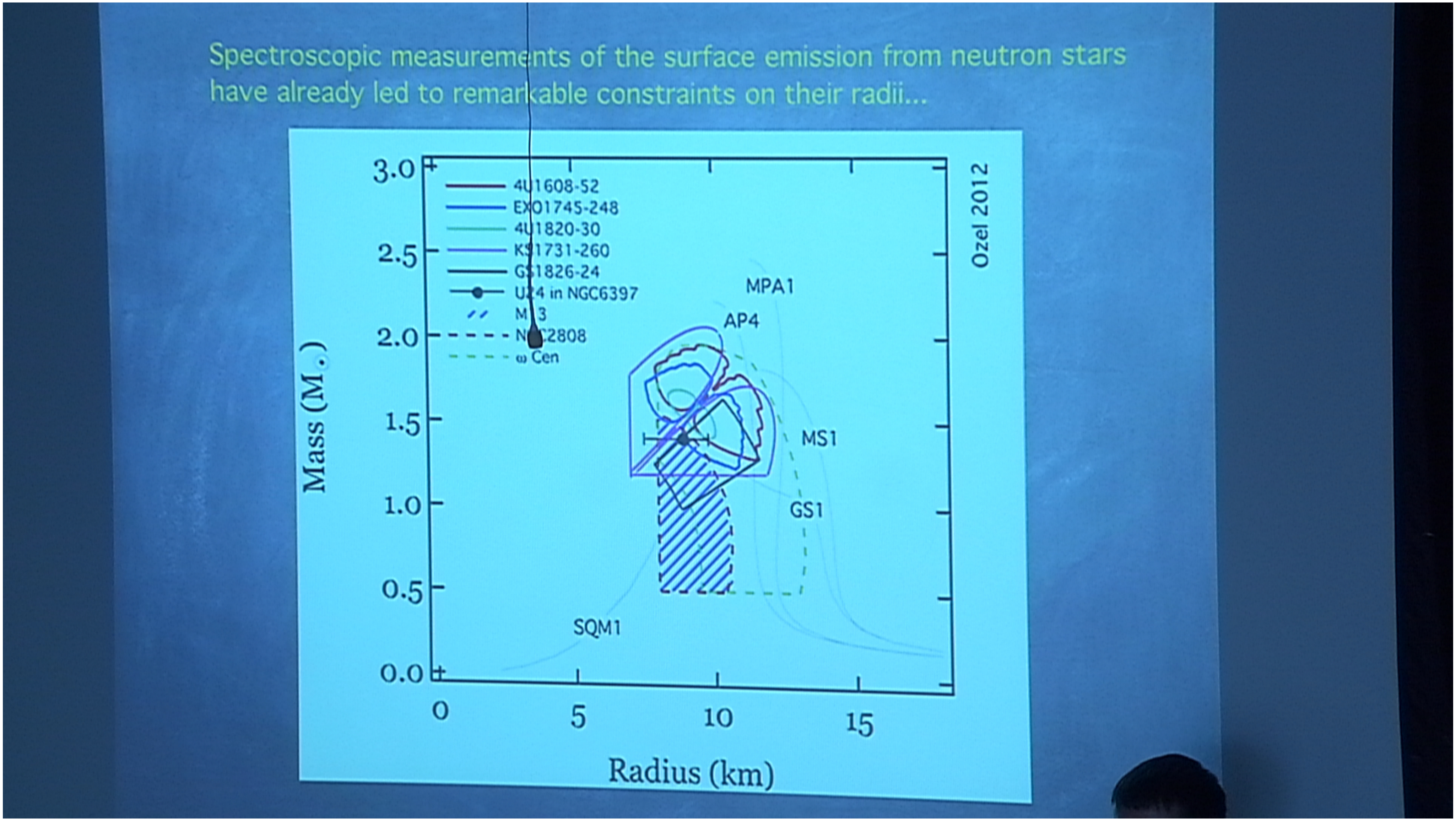
Dimitrios Psaltis
University of Arizona


collaborators:
Univ. of Arizona
Michi Baubock
Tim Johannsen
Feryal Ozel
Chi-Kwan Chan
LOFT
Large Observatory For X-ray Timing
an ESA M3 mission
NICER
Neutron star Interior Composition ExploreR
a NASA Explorer

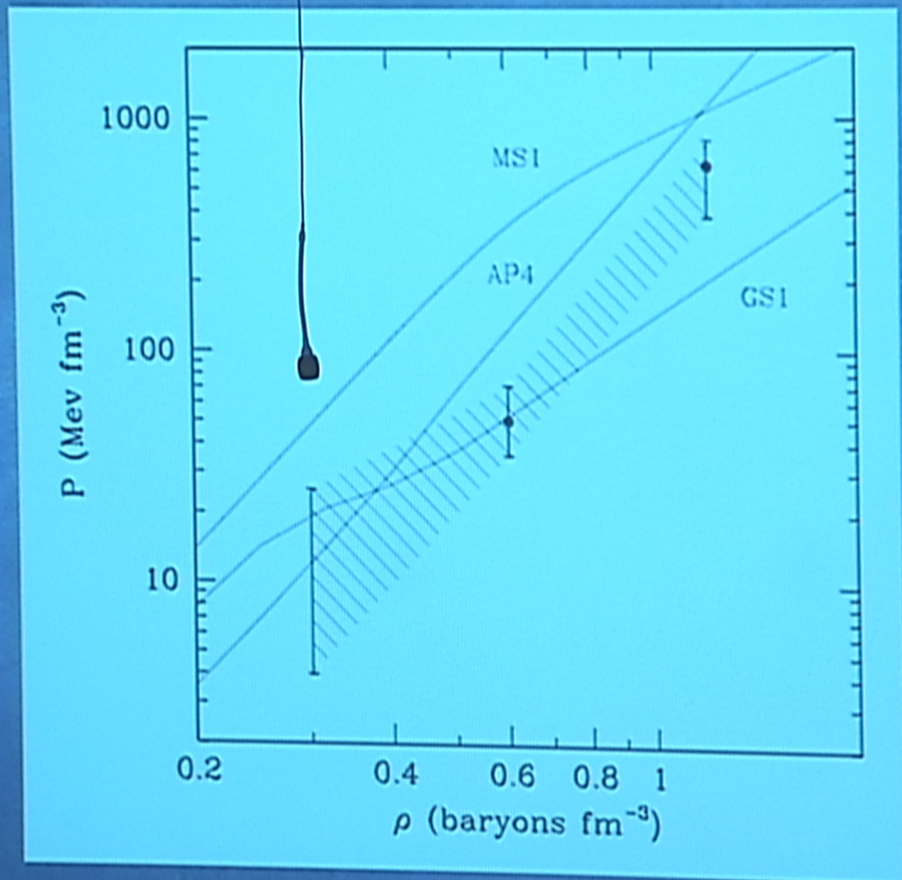

There is significant uncertainty in predicting the properties of neutron stars from first-principle calculations:
APR
MS
SQM
GS
BBB
Mass (M⊙)
Radius (km)
0
1
2
3
0
5
10
15

There is significant uncertainty in predicting the properties of neutron stars from first-principle calculations:



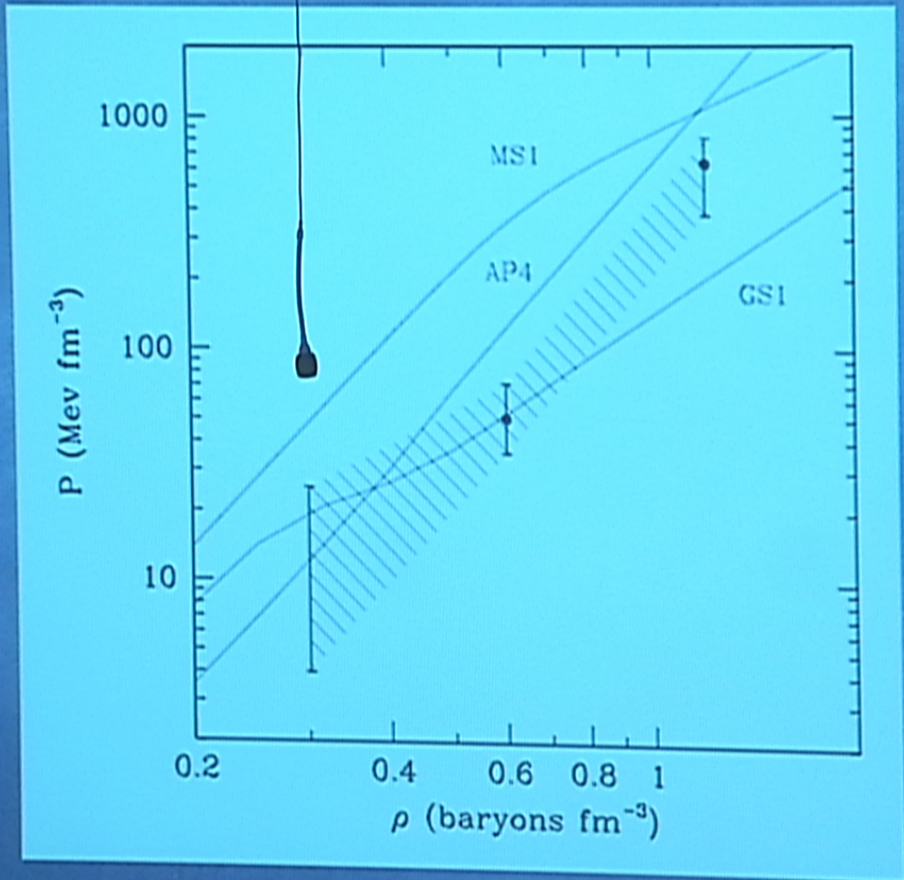

Spectroscopic measurements of the surface emission from neutron stars
have already led to remarkable constraints on their radii...
4U1608-52
EXO1745-248
4U1820-30
KS1731-260
GS1826-24
ω Cen
Ozel 2012
MPA1
AP4
MS1
GS1
SQM1
Mass (M☉)
Radius (km)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15

... and on the underlying physics



Ozel, Baym, & Guver 2010
based on inversion procedure of Ozel & Psaltis 2009
(see also Steiner, Lattimer, & Brown 2010)

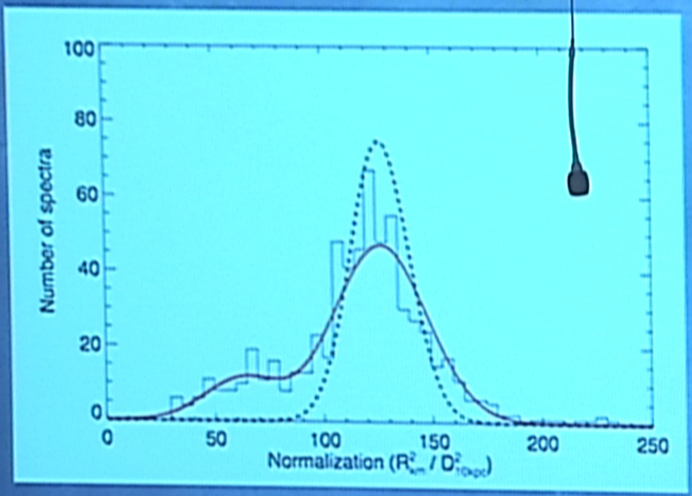
... and on the underlying physics



Ozel, Baym, & Guver 2010
based on inversion procedure of Ozel & Psaltis 2009
(see also Steiner, Lattimer, & Brown 2010)

Spectroscopic techniques have reached their limiting accuracy
as dictated by:

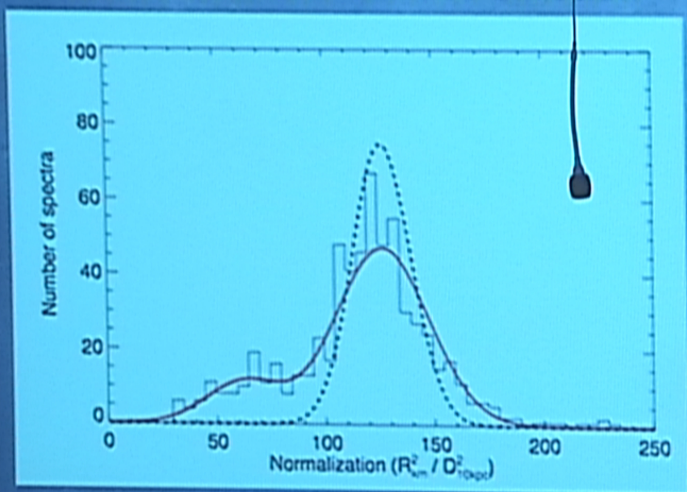
The intrinsic variability of
the neutron-star surface emission



Guver, Psaltis, Ozel 2012

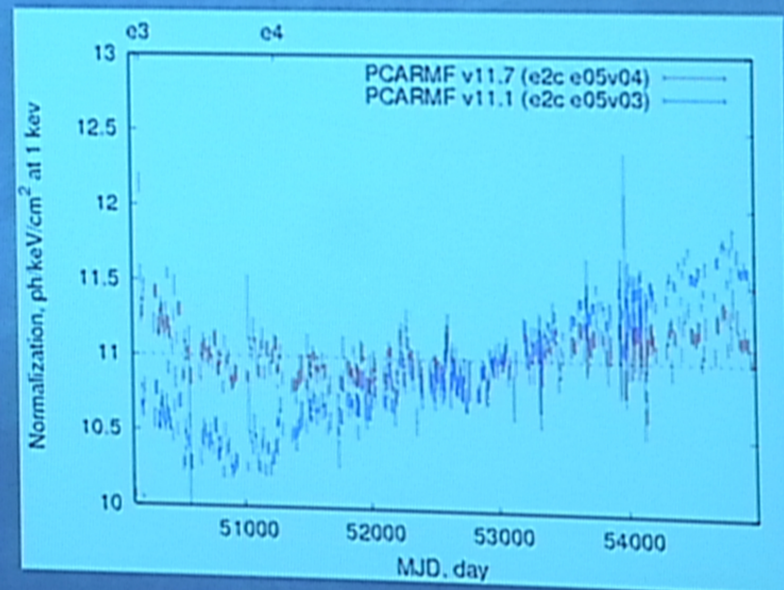
Spectroscopic techniques have reached their limiting accuracy as dictated by:

The intrinsic variability of the neutron-star surface emission



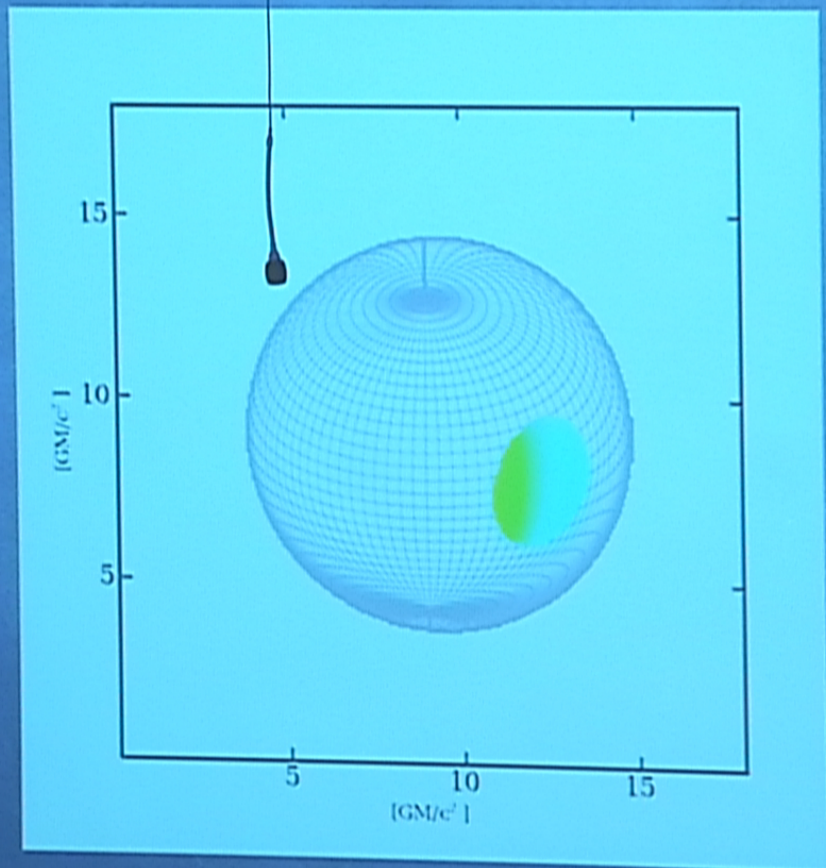
Guver, Psaltis, Ozel 2012

Uncertainties in the flux calibration of X-ray detectors

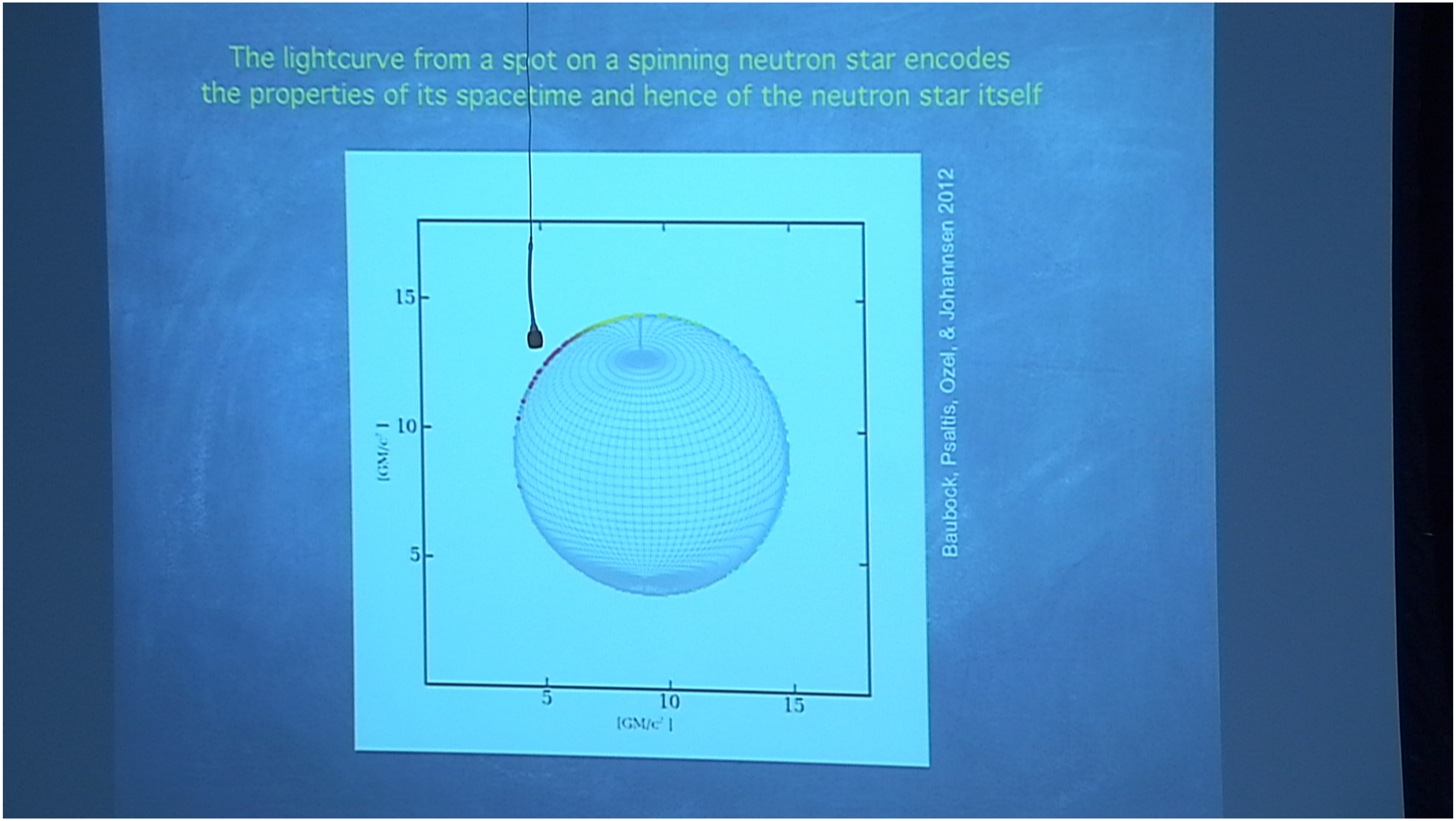


Shaposhnikov, Jahoda, & Markwardt

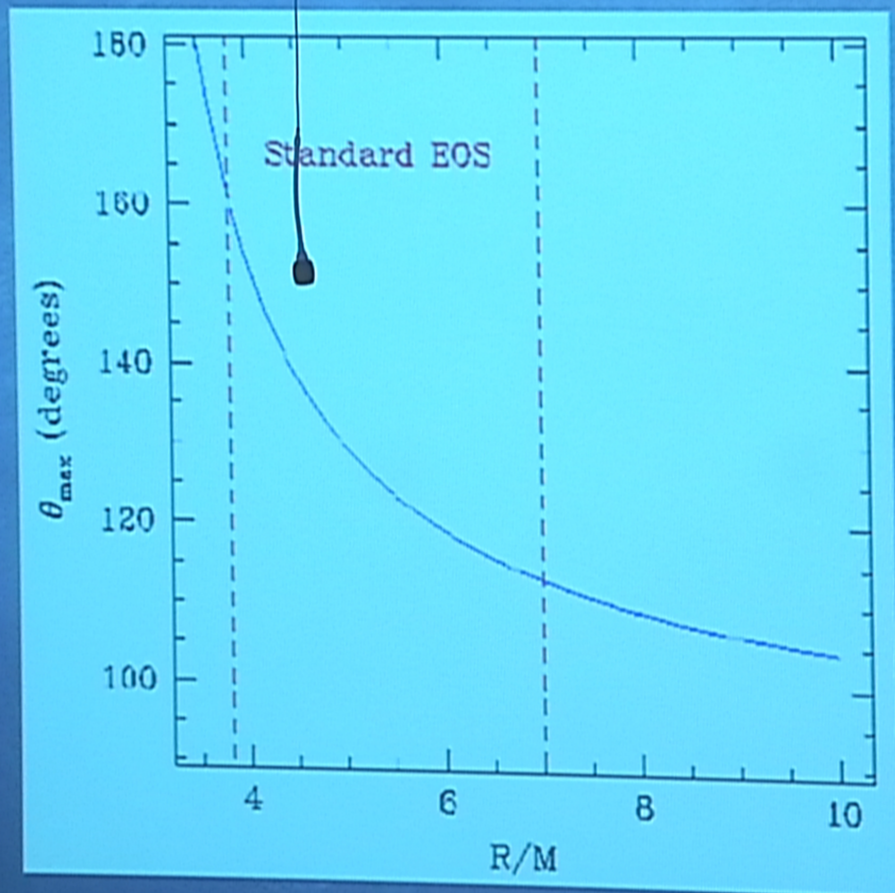
The lightcurve from a spot on a spinning neutron star encodes the properties of its spacetime and hence of the neutron star itself



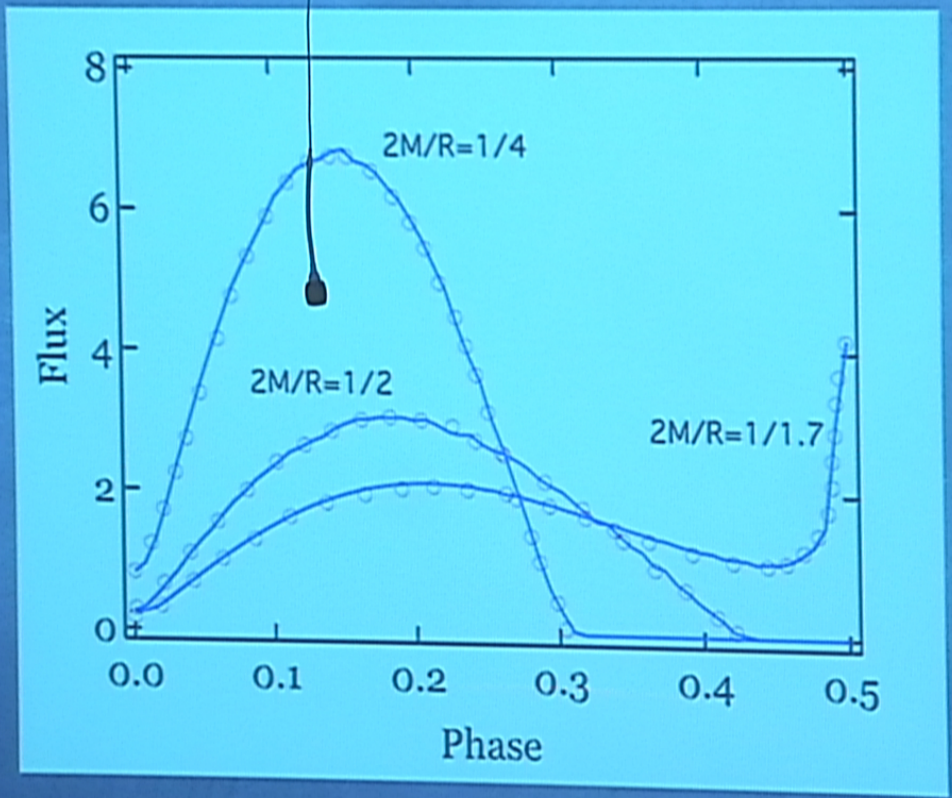
Baubock, Psaltis, Ozel, & Johannsen 2012


The lightcurve from a spot on a spinning neutron star encodes
the properties of its spacetime and hence of the neutron star itself
Baubock, Psaltis, Ozel, & Johannsen 2012
15
10
5
[GM/c²]
5
10
15
[GM/c²]

Strong-field lensing allows us to observe the "back" side of neutron stars



Lightcurves from neutron stars with strong gravitational fields are heavily suppressed

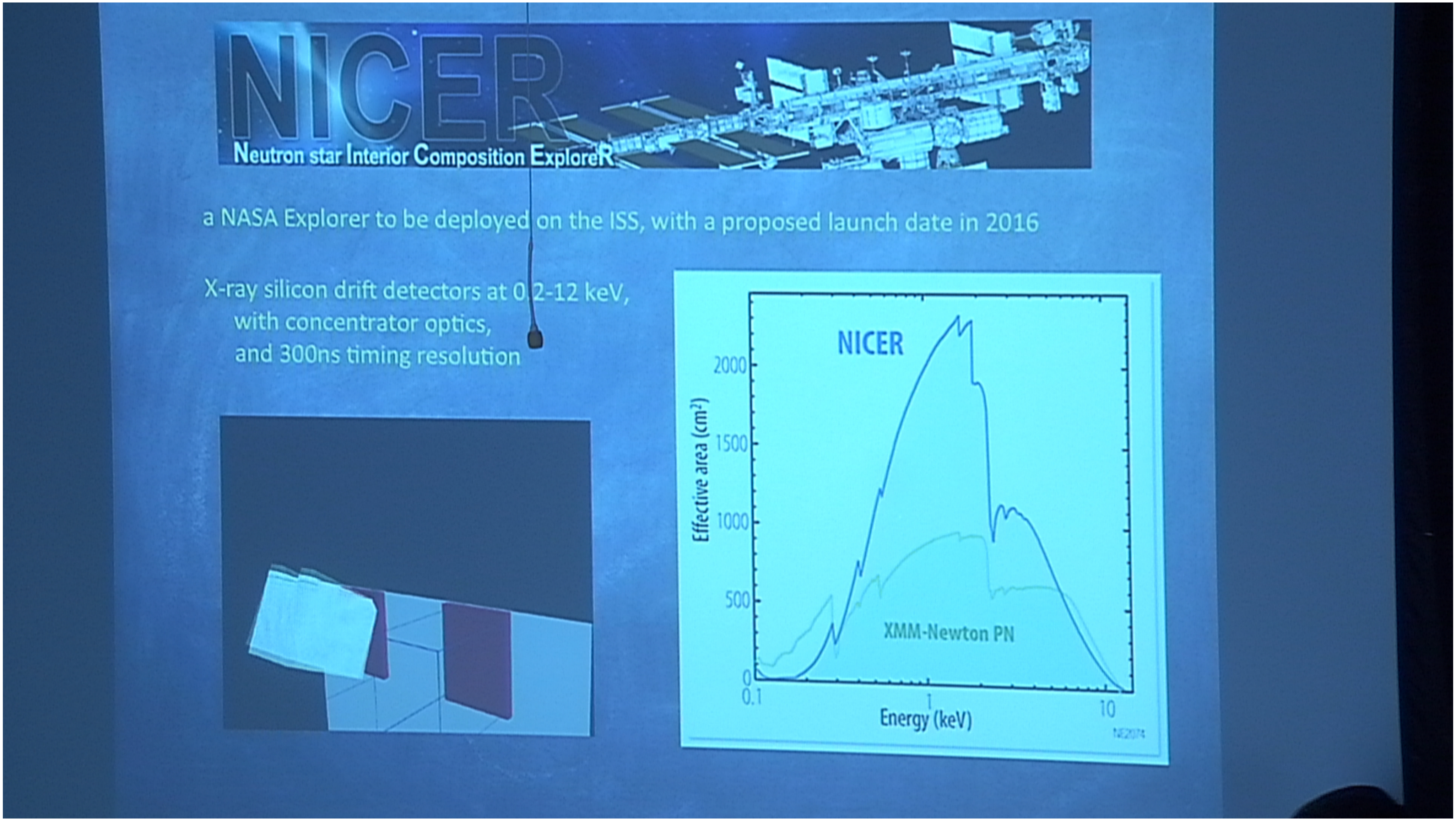


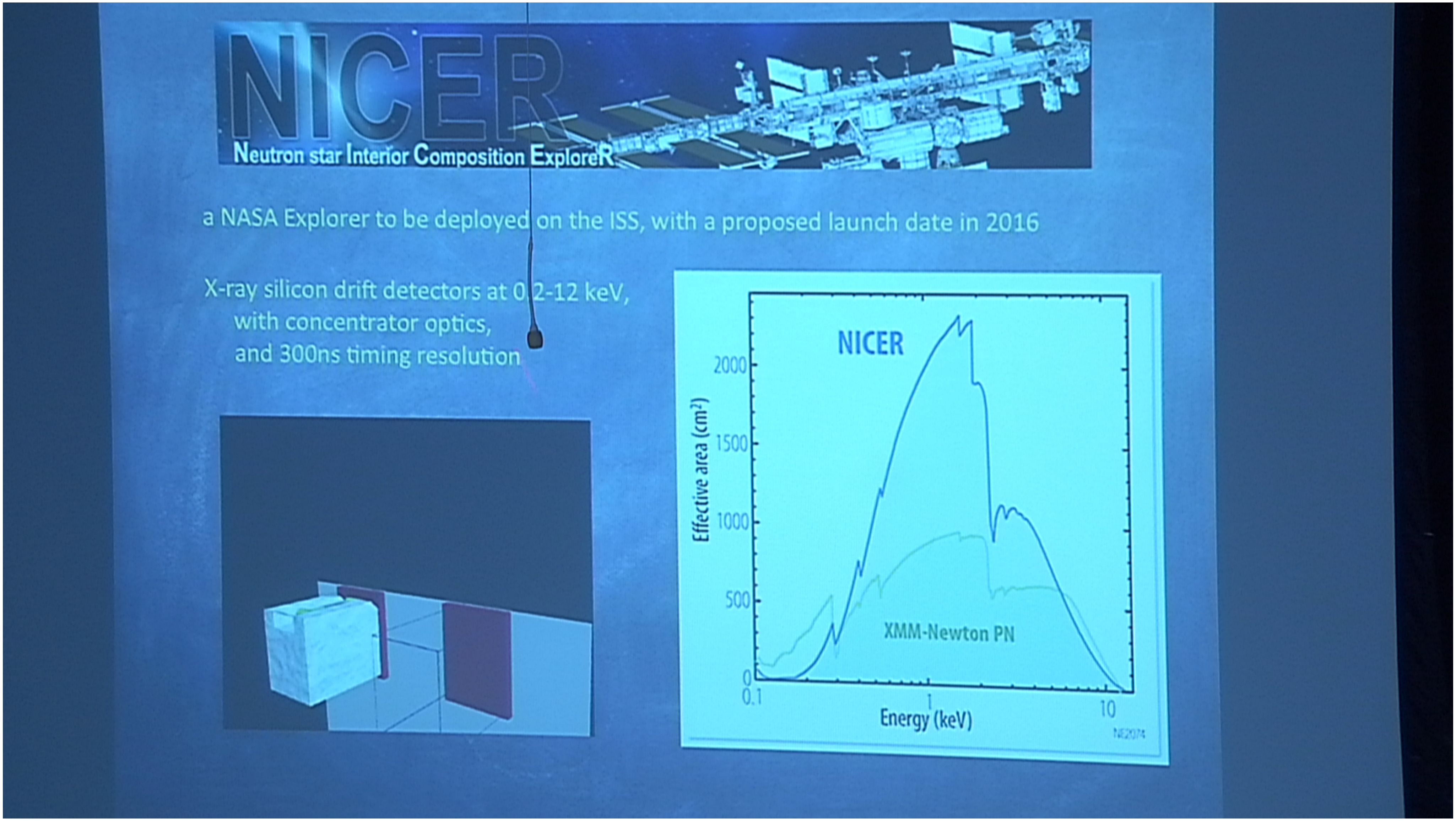
measuring the amplitude of pulsations (modulo geometric factors) leads to measurement of the M/R ratio of each neutron star

measuring the amplitude of pulsations
(and hence the M/R ratio of each neutron star) requires:

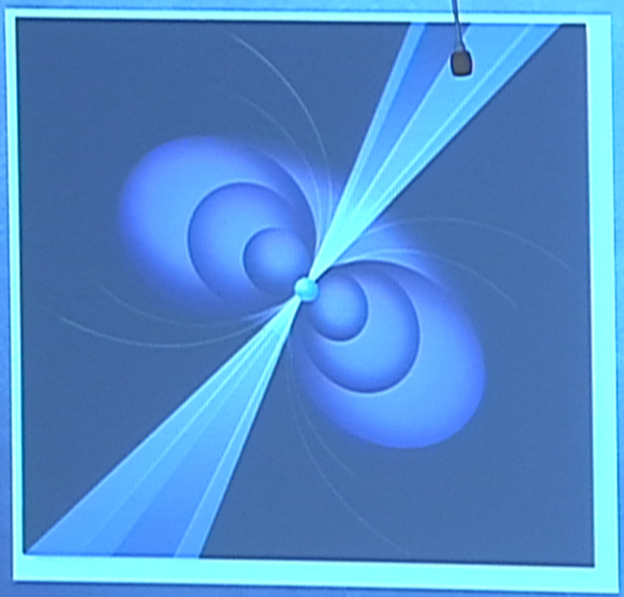
(i) identifying neutron stars with emission that is predominantly from their surfaces

(ii) dealing with the unknown geometric factors


NICER
Neutron star Interior Composition ExploreR
a NASA Explorer to be deployed on the ISS, with a proposed launch date in 2016
X-ray silicon drift detectors at 0.2-12 keV,
with concentrator optics,
and 300ns timing resolution
NICER
XMM-Newton PN
Effective area (cm²)
Energy (keV)
0
500
1000
1500
2000
0.1
1
10


NICER
Neutron star Interior Composition ExploreR
a NASA Explorer to be deployed on the ISS, with a proposed launch date in 2016
X-ray silicon drift detectors at 0.2-12 keV,
with concentrator optics,
and 300ns timing resolution
NICER
XMM-Newton PN
Effective area (cm²)
Energy (keV)
0.1
1
10
0
500
1000
1500
2000

The primary targets for NICER are millisecond, rotation-powered pulsars

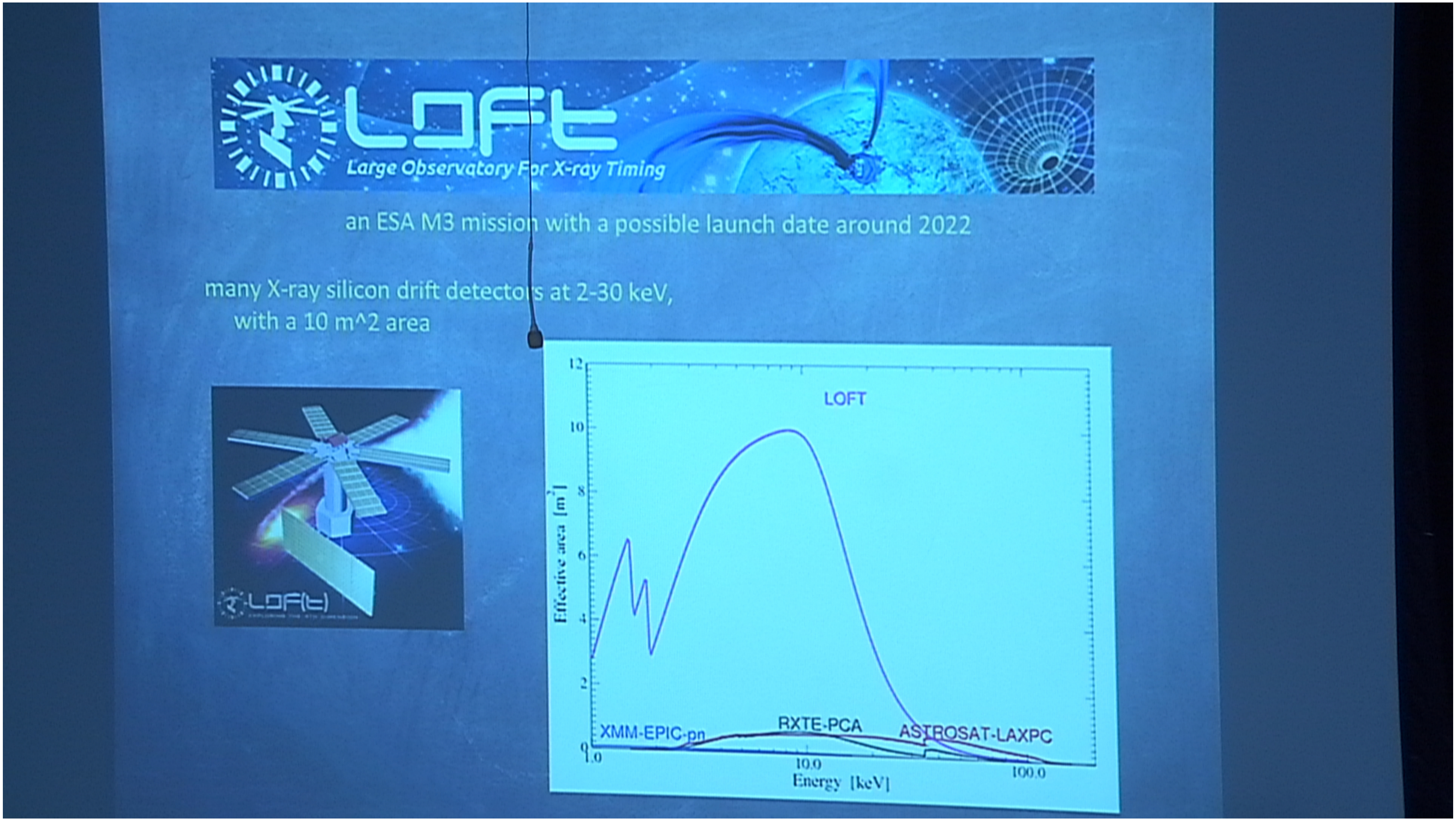


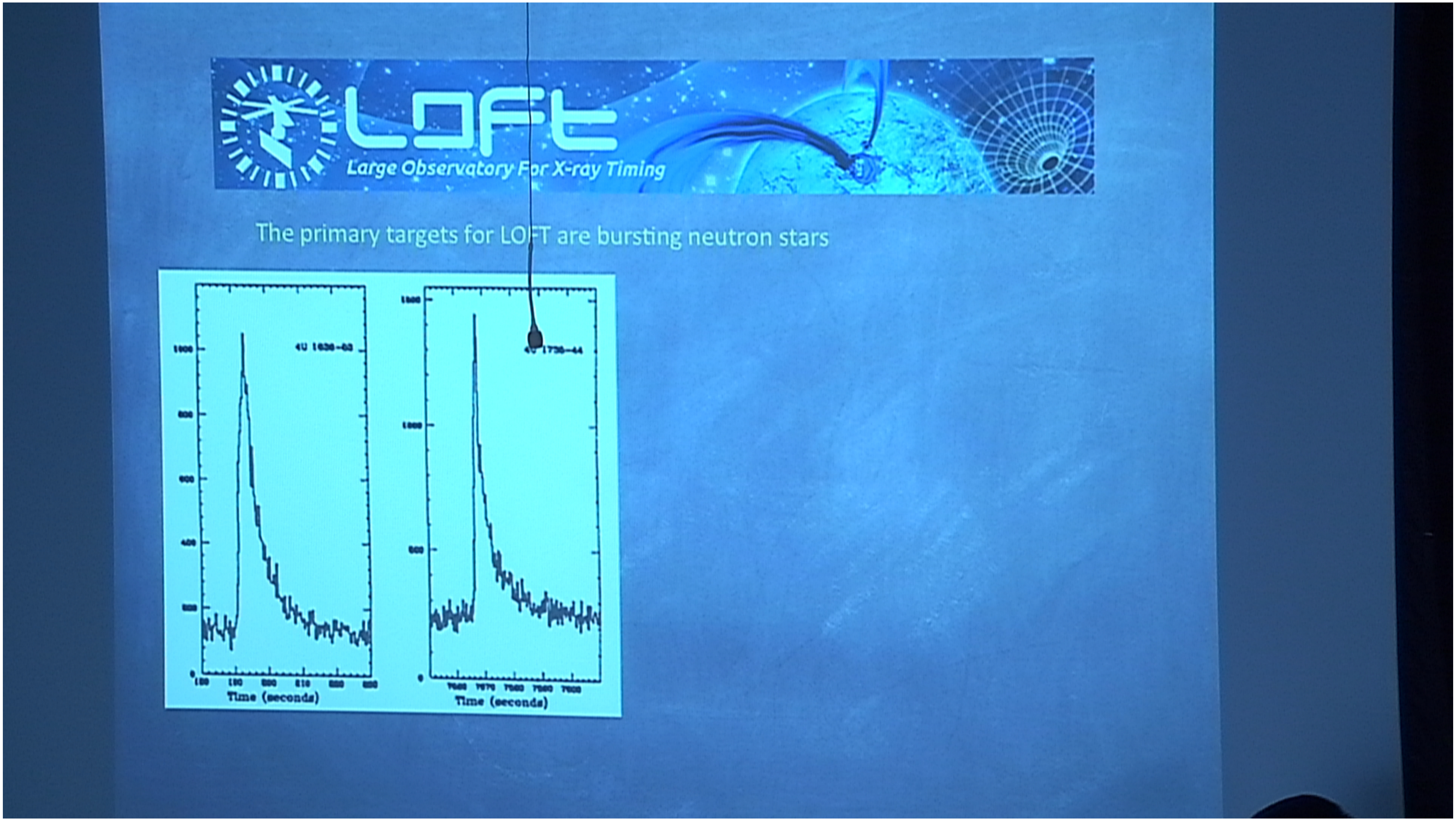
pros:

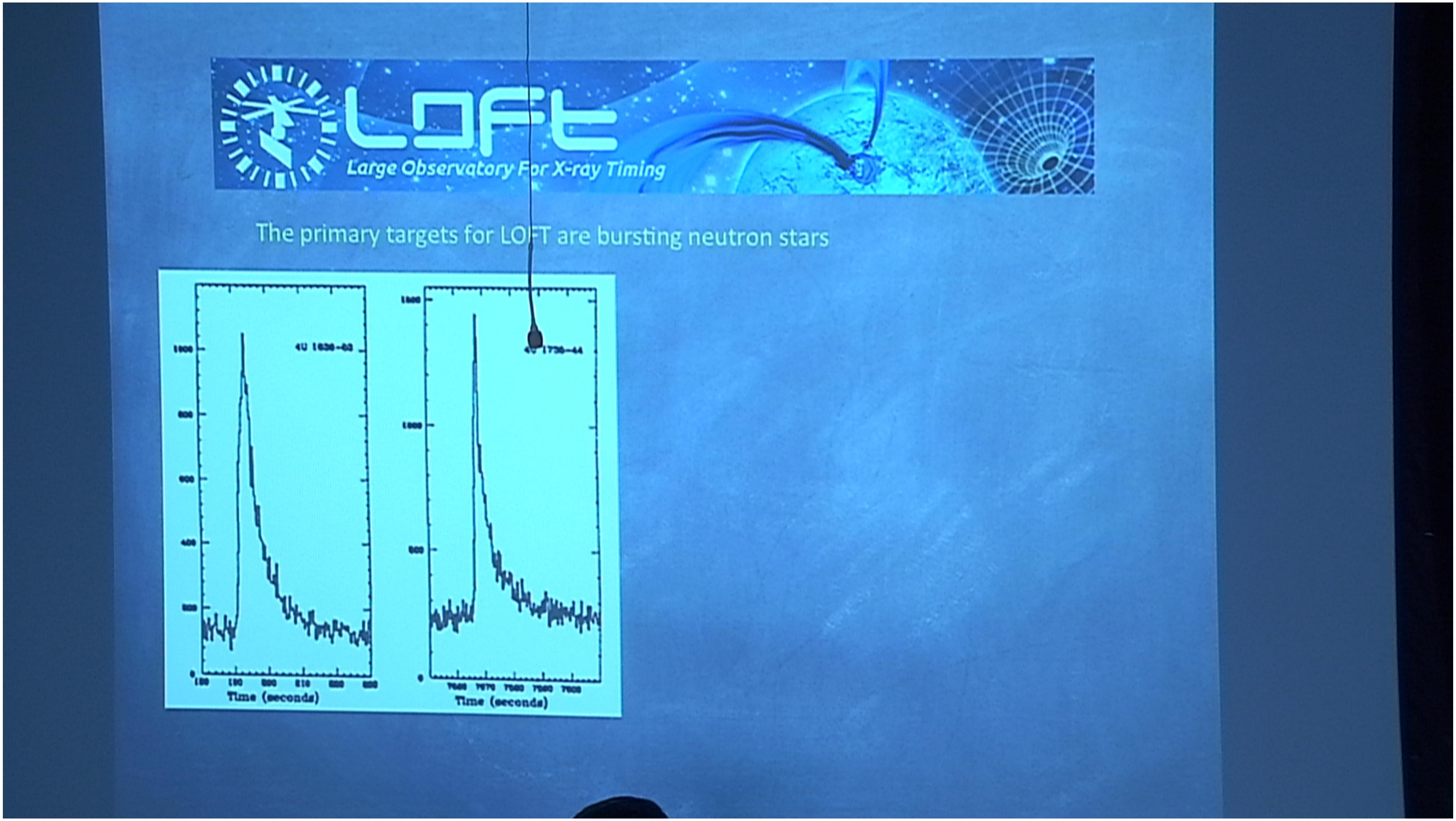
- very stable spin frequencies
- known masses (in some cases)

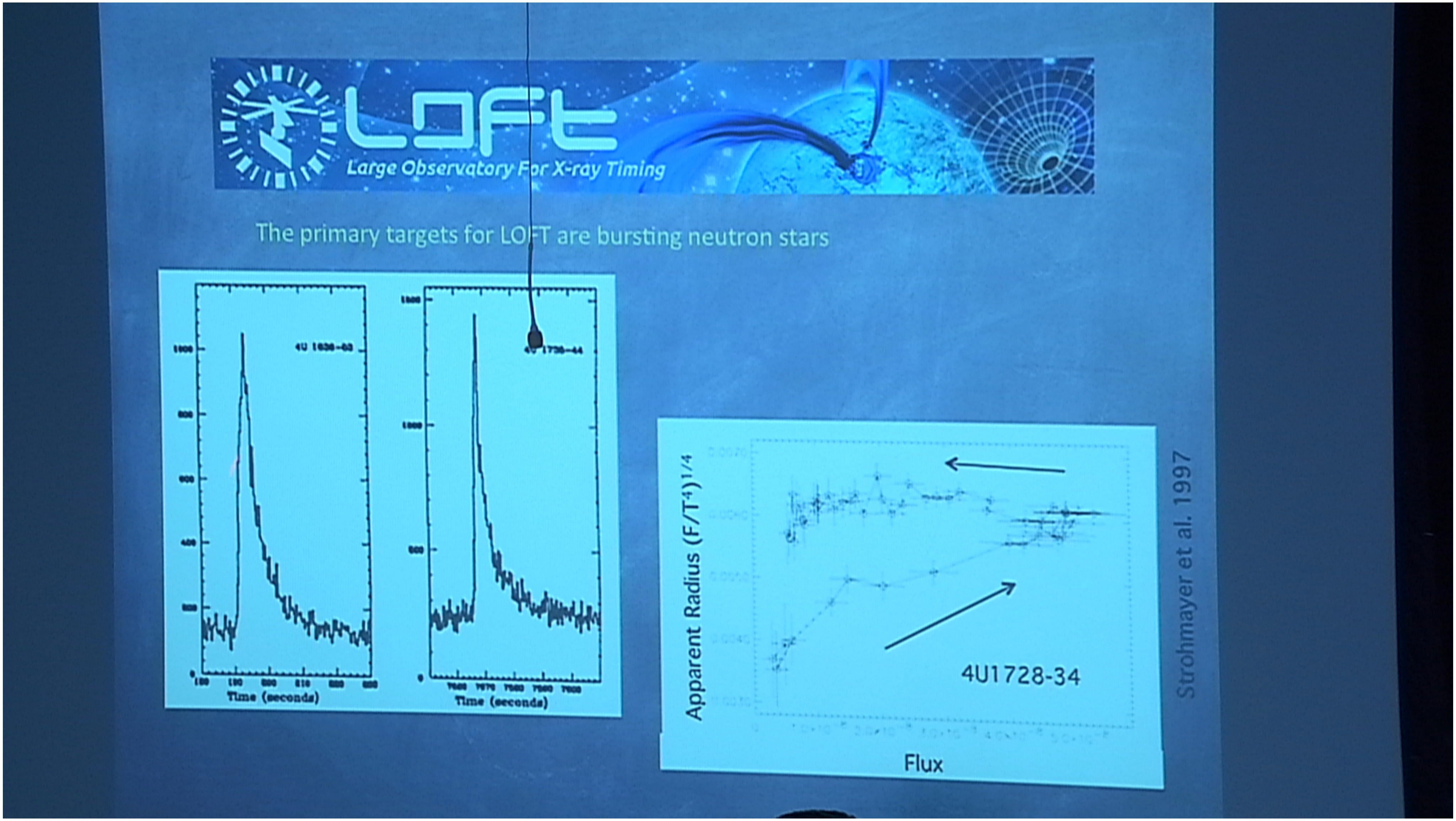
cons:

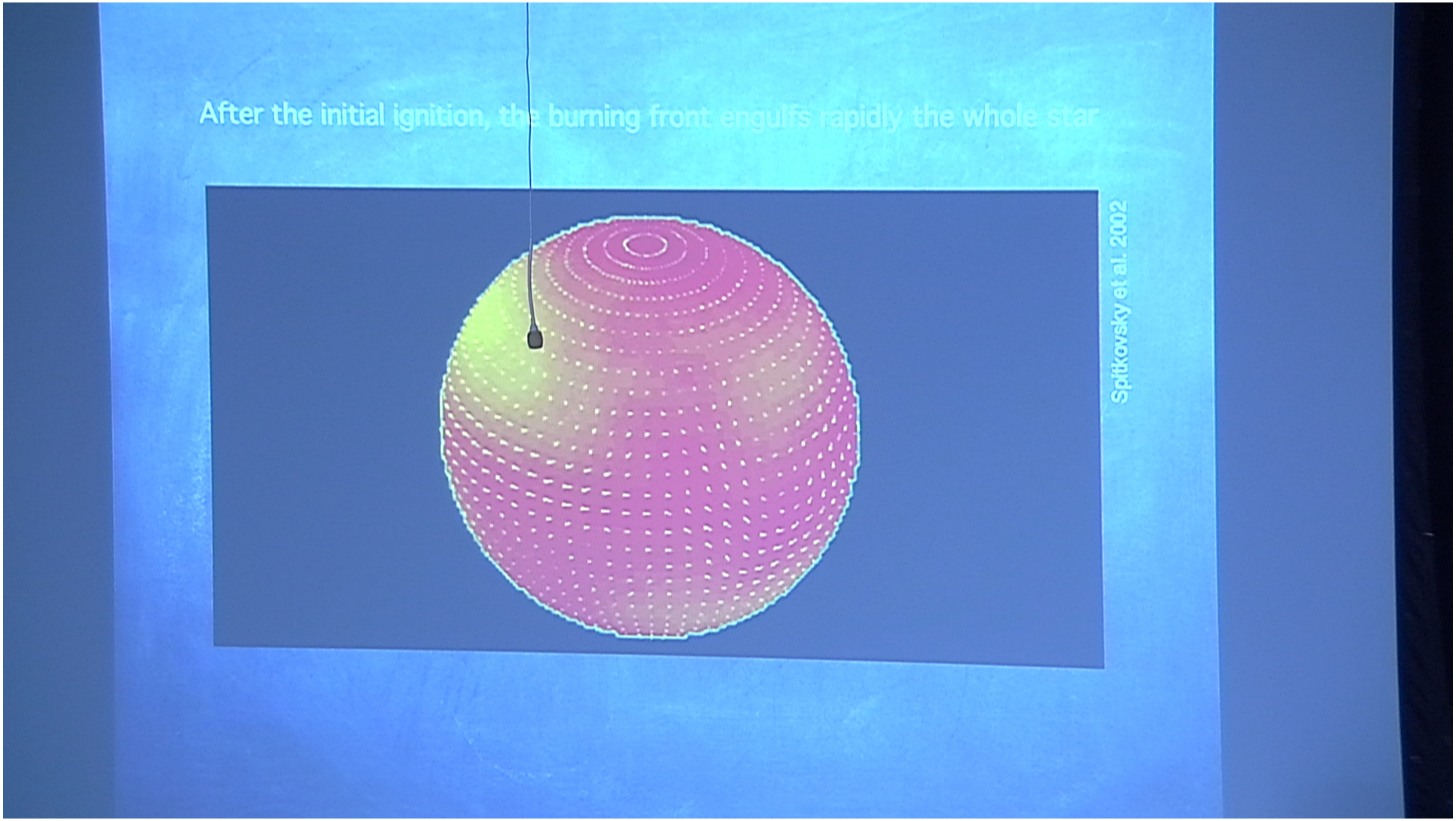
- emission might be contaminated by magnetosphere
- uncertain emerging radiation pattern

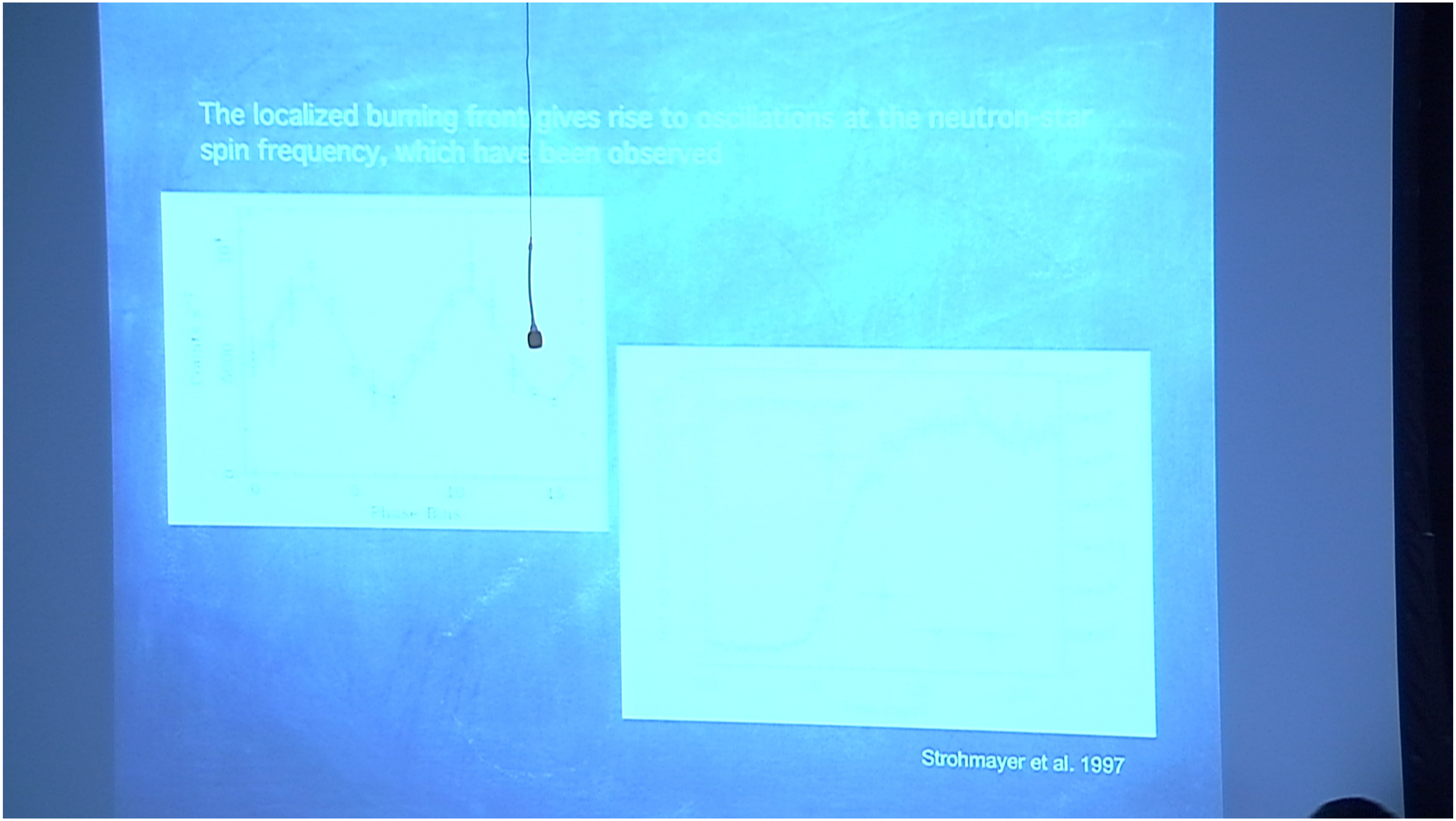

LOFT
Large Observatory For X-ray Timing
an ESA M3 mission with a possible launch date around 2022
many X-ray silicon drift detectors at 2-30 keV,
with a 10 m^2 area
LOFT
Effective area [m^2]
Energy [keV]
XMM-EPIC-pn
RXTE-PCA
ASTROSAT-LAXPC
0
2
4
6
8
10
12
1.0
10.0
100.0


LOFT
Large Observatory For X-ray Timing
The primary targets for LOFT are bursting neutron stars
4U 1636-53
Time (seconds)
Time (seconds)

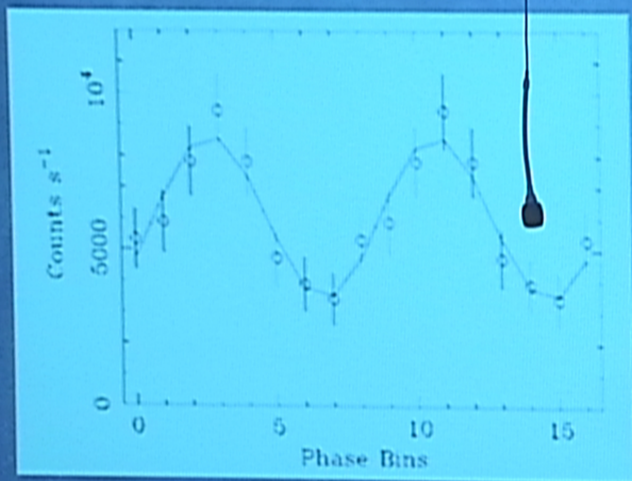

LOFT
Large Observatory For X-ray Timing
The primary targets for LOFT are bursting neutron stars
4U 1636-53
Time (seconds)
Time (seconds)

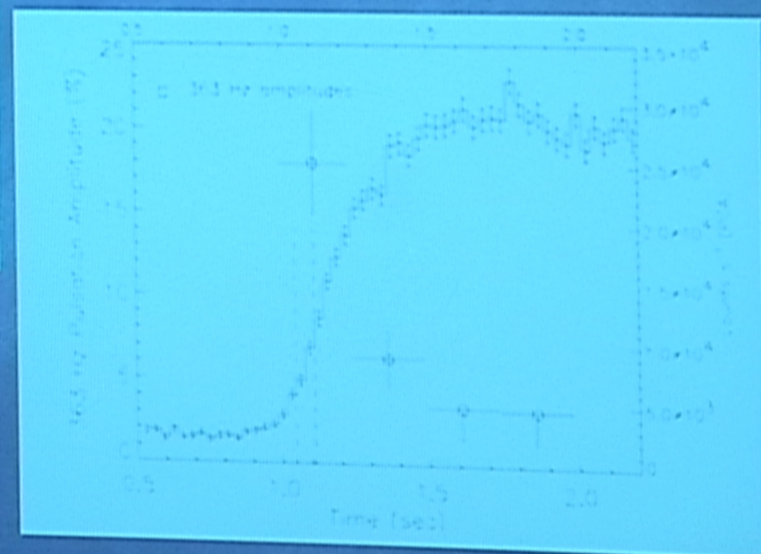

LOFT
Large Observatory For X-ray Timing
The primary targets for LOFT are bursting neutron stars
4U 1636-53
Time (seconds)
Time (seconds)
Apparent Radius (F/T^4)^1/4
4U1728-34
Flux
Strohmayer et al. 1997


After the initial ignition, the burning front engulfs rapidly the whole star
Spitkovsky et al. 2002

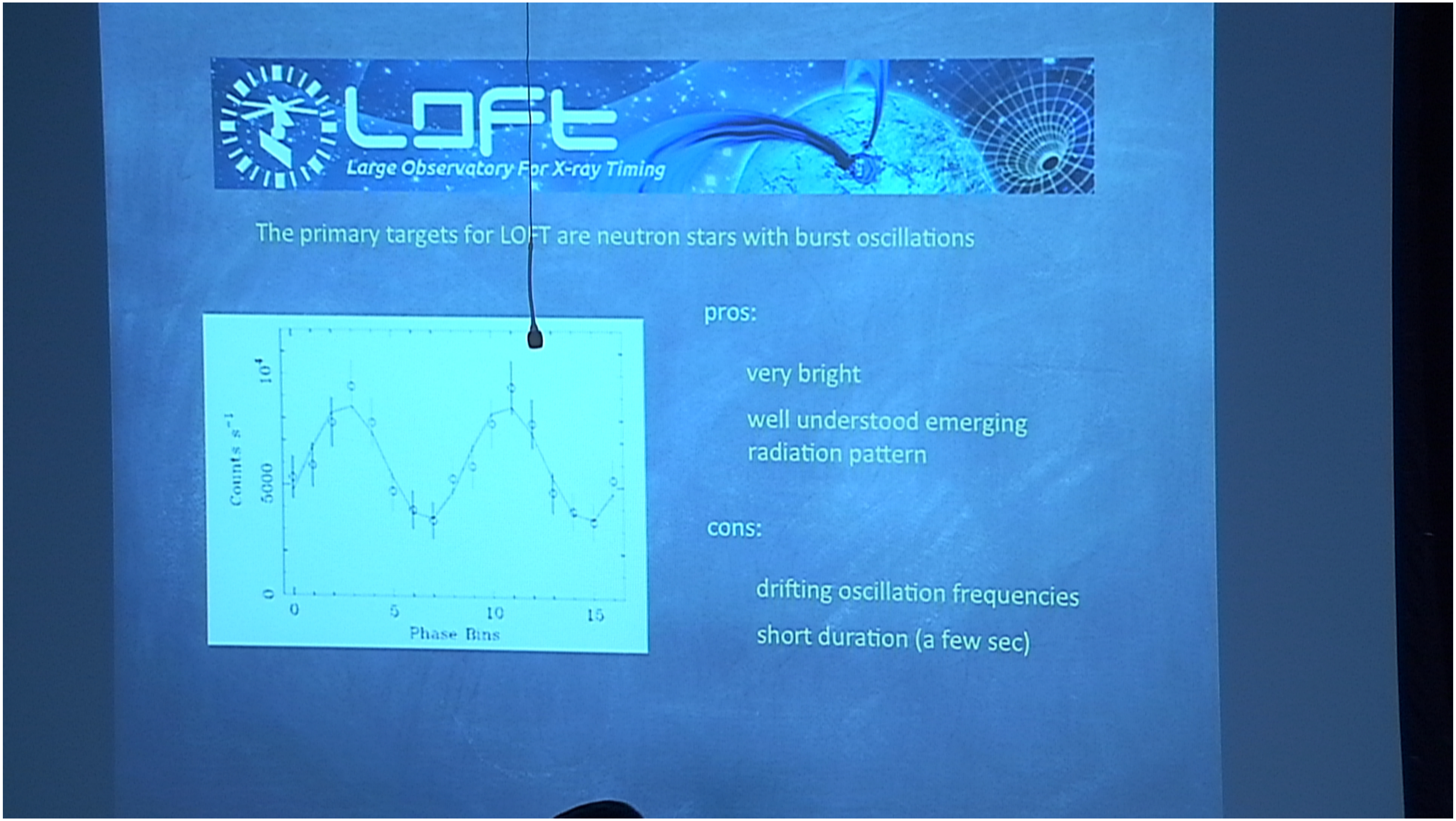

The localized burning front gives rise to oscillations at the neutron-star spin frequency, which have been observed
Strohmayer et al. 1997

The localized burning front gives rise to oscillations at the neutron-star spin frequency, which have been observed

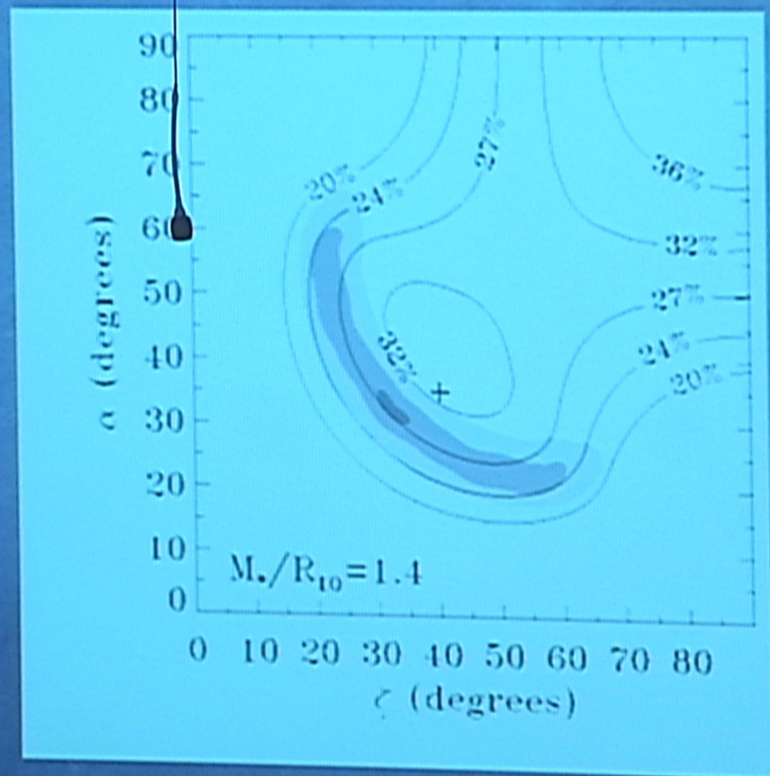




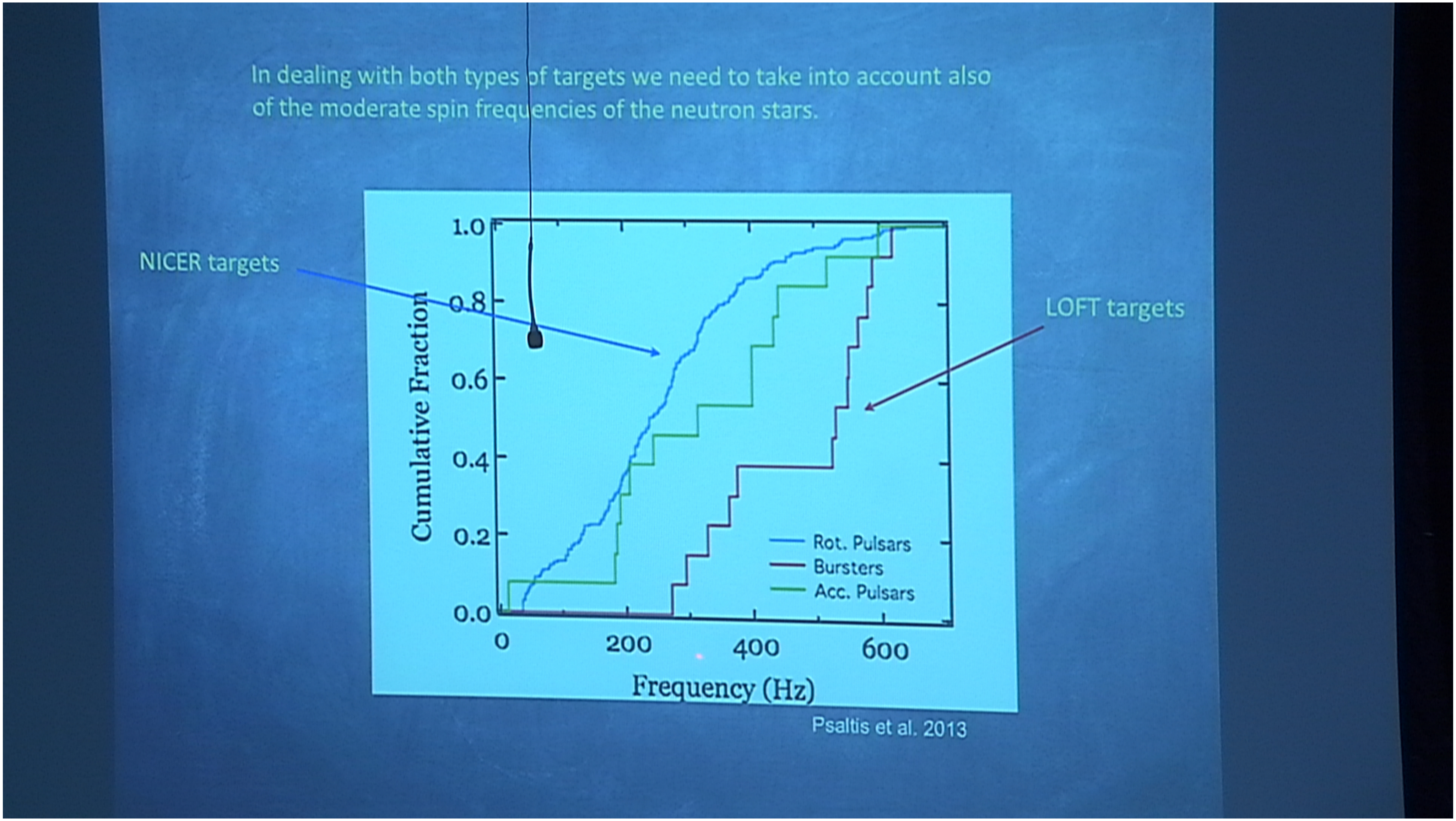
Strohmayer et al. 1997


LOFT
Large Observatory For X-ray Timing
The primary targets for LOFT are neutron stars with burst oscillations
Counts s⁻¹
0
5000
10⁴
0
5
10
15
Phase Bins
pros:
very bright
well understood emerging radiation pattern
cons:
drifting oscillation frequencies
short duration (a few sec)

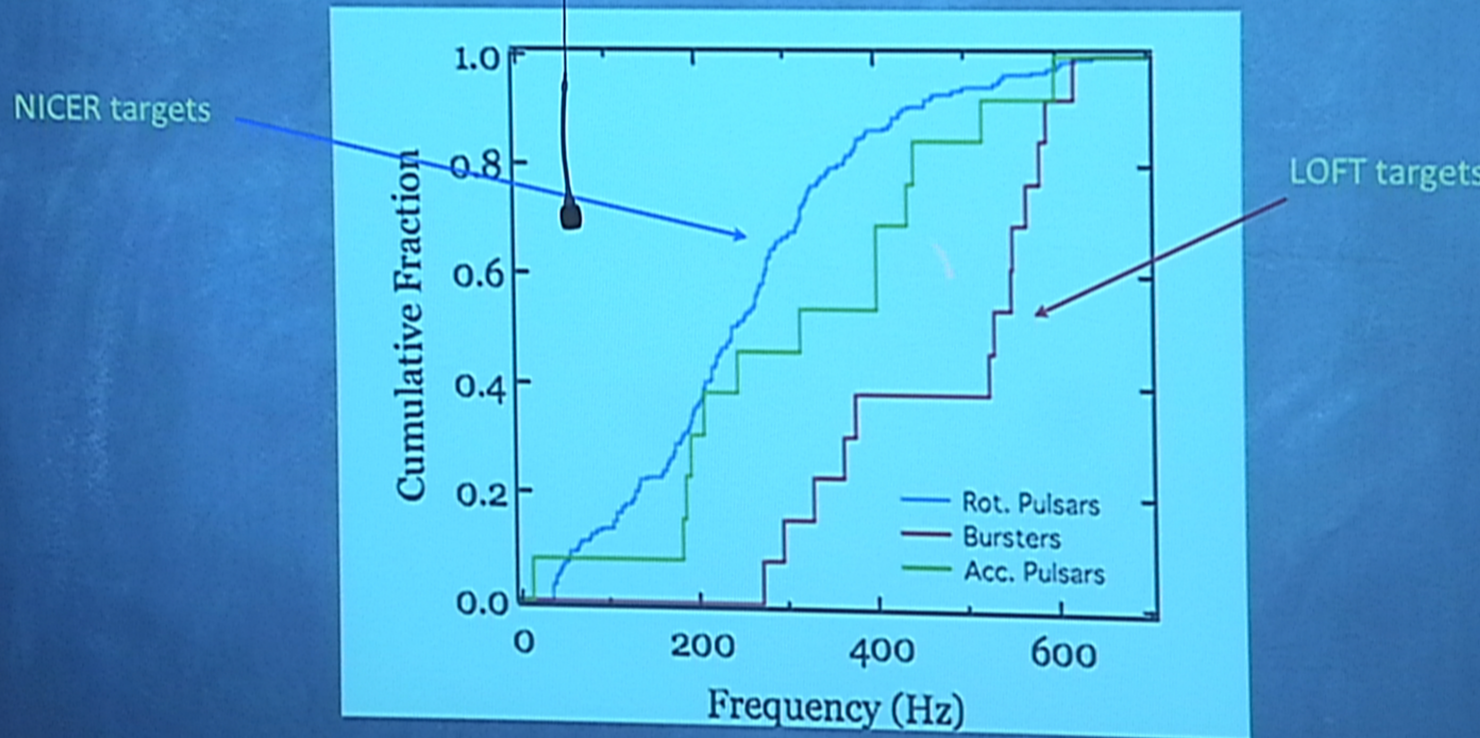
In dealing with both types of targets we need to take into account of the geometric factors:



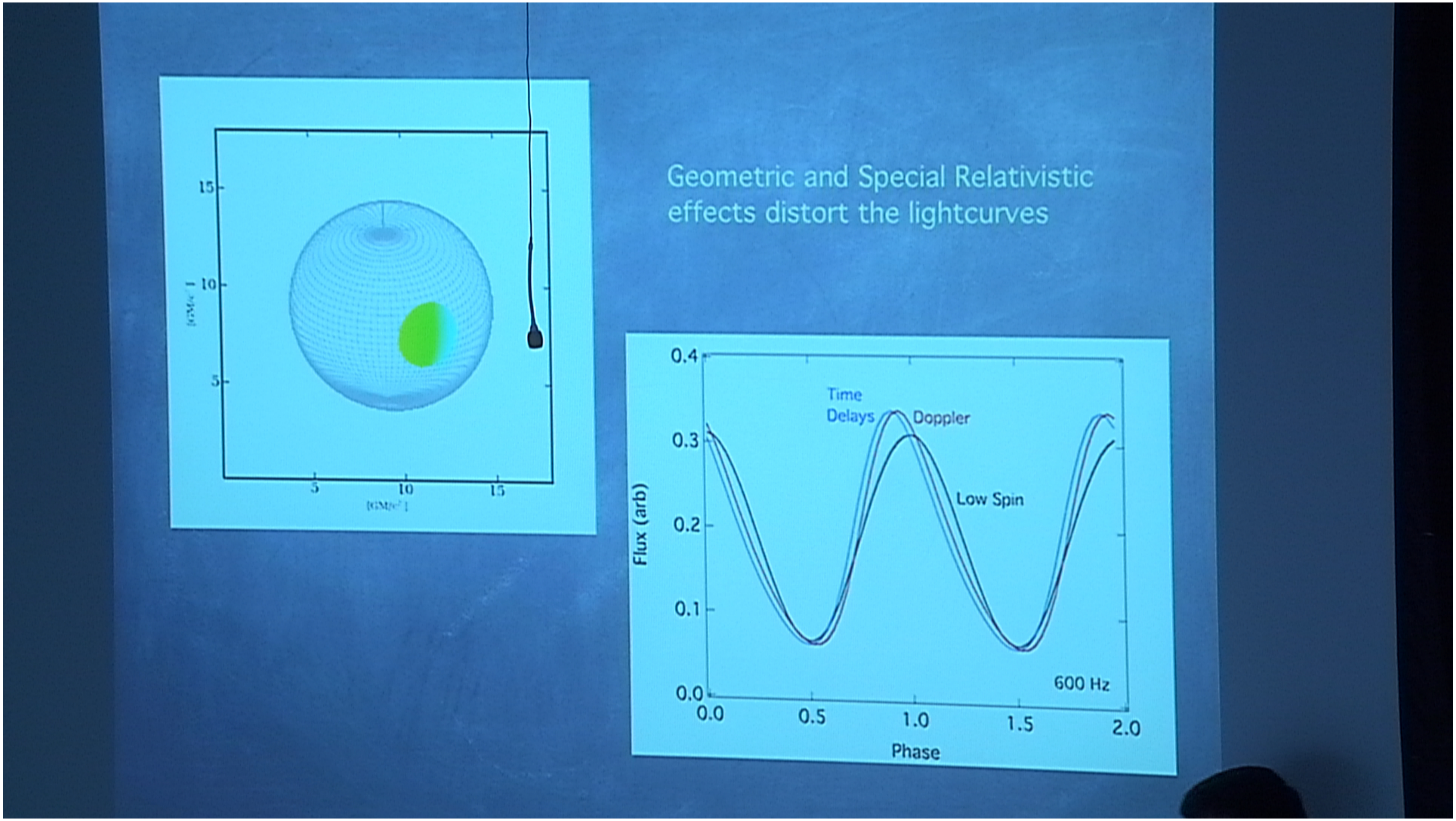
Pavlov & Zavlin 1997

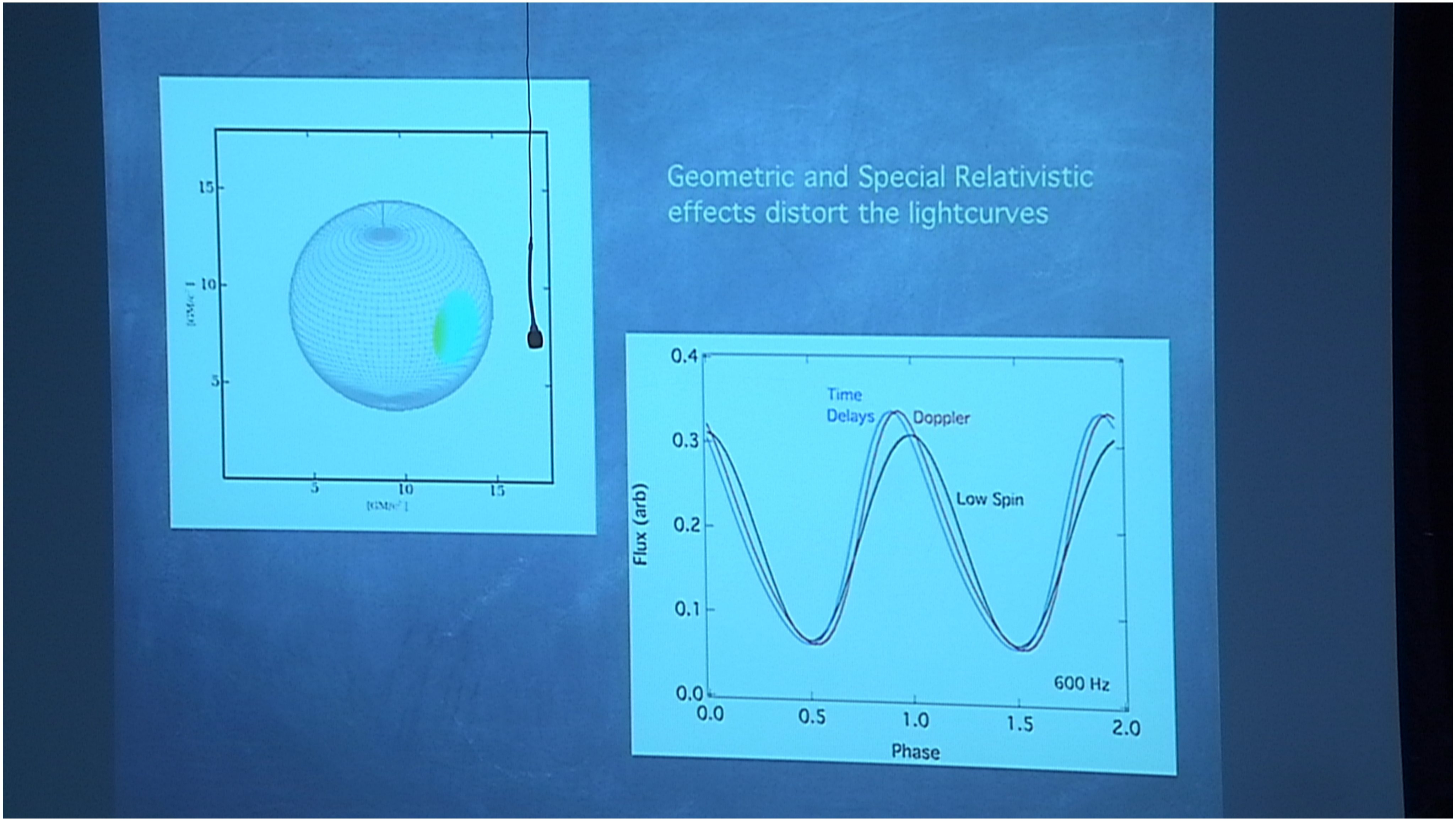

In dealing with both types of targets we need to take into account also
of the moderate spin frequencies of the neutron stars.
NICER targets
LOFT targets
Cumulative Fraction
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
Frequency (Hz)
Rot. Pulsars
Bursters
Acc. Pulsars
Psaltis et al. 2013

In dealing with both types of targets we need to take into account also of the moderate spin frequencies of the neutron stars.



Psaltis et al. 2013

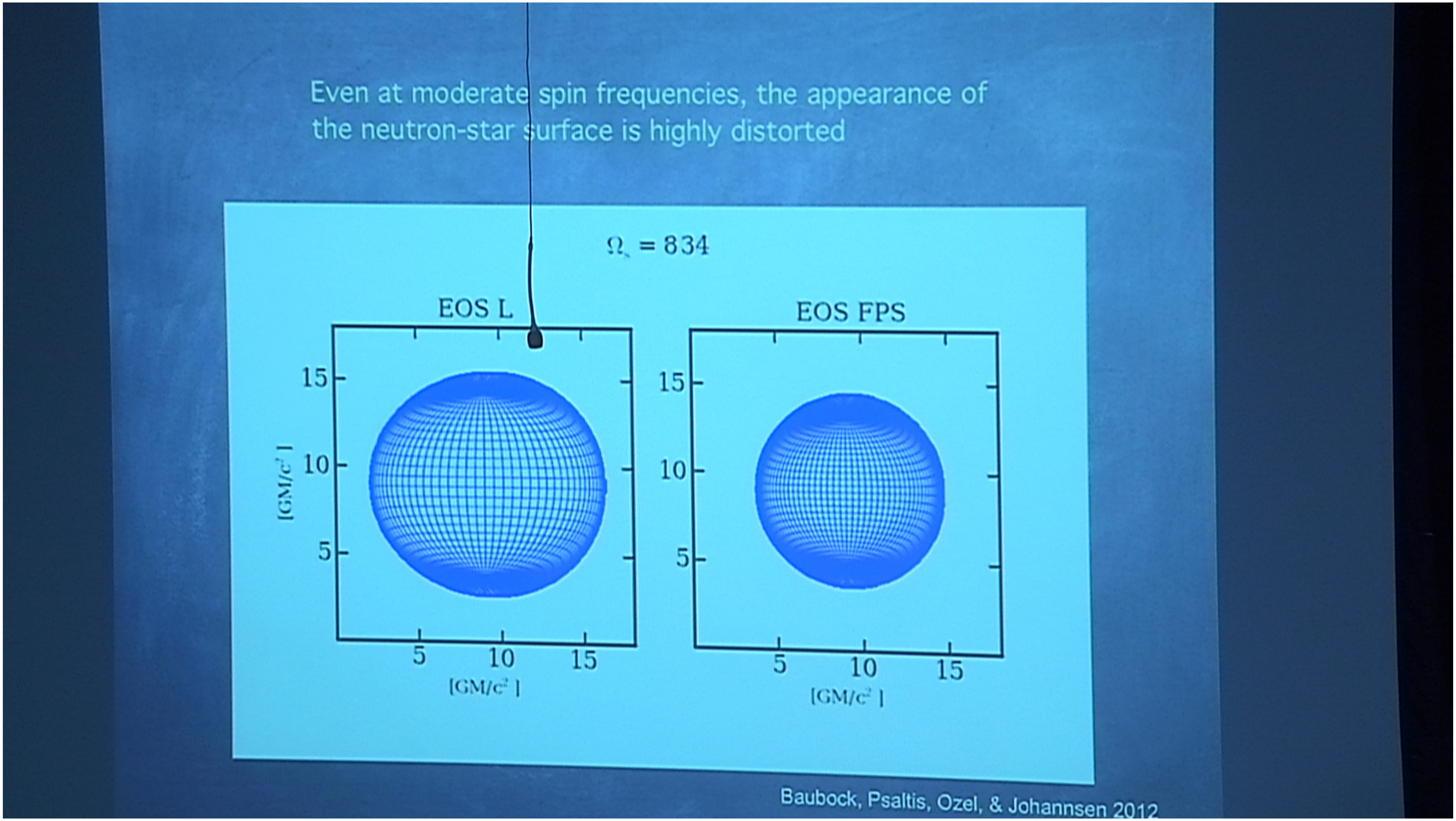

Geometric and Special Relativistic
effects distort the lightcurves
Time
Delays
Doppler
Low Spin
600 Hz
Flux (arb)
Phase
0.0
0.1
0.2
0.3
0.4
0.5
1.0
1.5
2.0
5
10
15


Geometric and Special Relativistic
effects distort the lightcurves
15
10
5
5
10
15
Time
Delays
Doppler
Low Spin
600 Hz
0.4
0.3
0.2
0.1
0.0
Flux (arb)
0.0
0.5
1.0
1.5
2.0
Phase

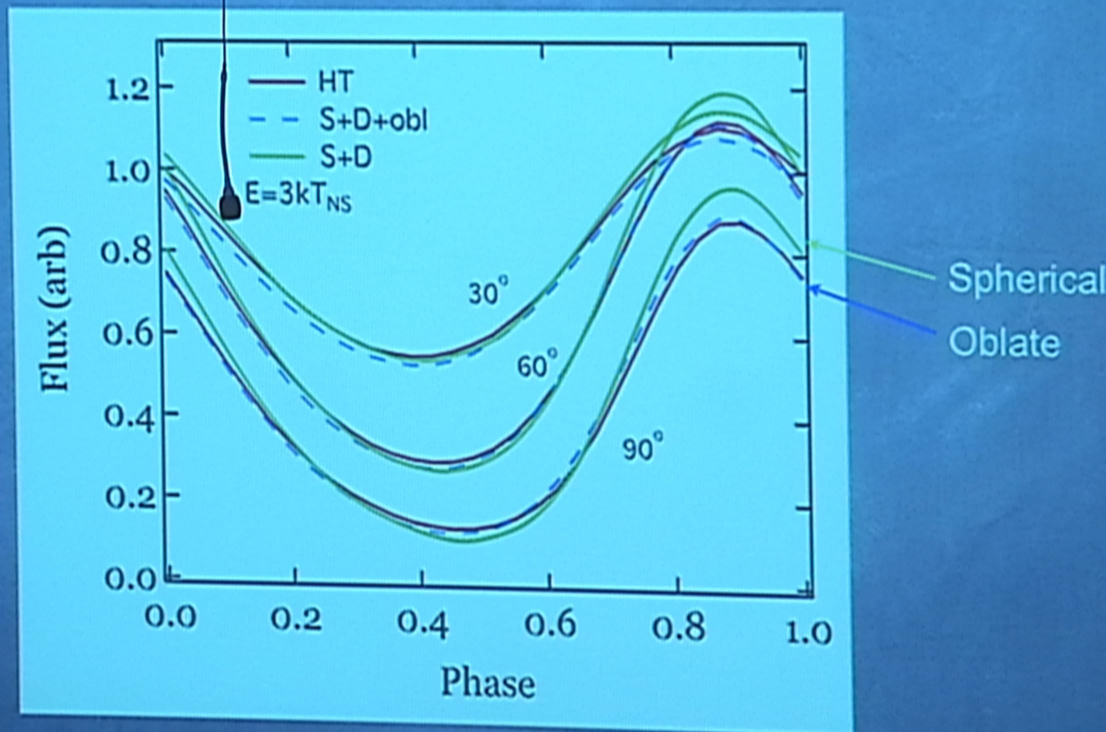
What is the Spacetime of a Neutron Star?

	Star	Spacetime	Parameters	Maximum Spin[1]
Non-Spinning	Spherical	Schwarzschild	GM/Rc^2	≤100 Hz
Slowly Spinning	Spherical	Kerr	M, R, I	≤500 Hz
Moderately Spinning	Oblate	Hartle-Thorne	M, R, I, Q, R_p/R_{eq}	≤800 Hz
Fast Spinning	Oblate	Numerical	Details of EOS	

[1]For spacetime elements to be accurate to within ~5%, for a neutron star with $M=1.4\ M_{\odot}$, $R=10$ km, and $I=10^{45}$ g cm^2

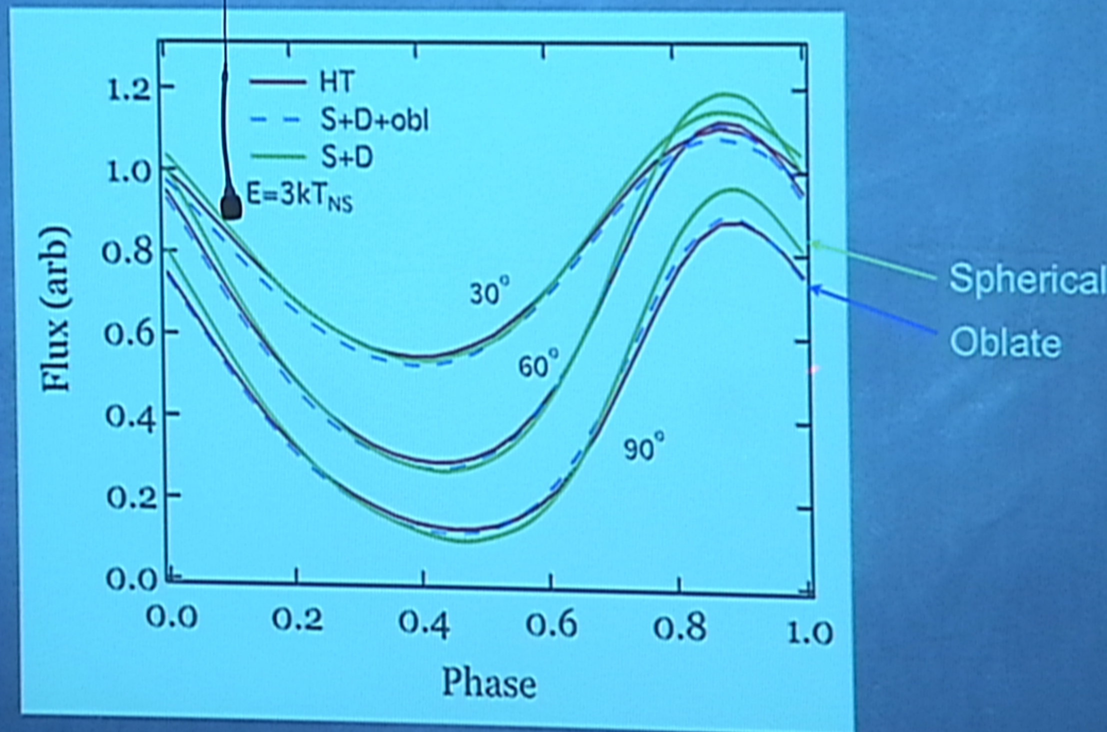

Even at moderate spin frequencies, the appearance of
the neutron-star surface is highly distorted
EOS L
EOS FPS
[GM/c²]
Baubock, Psaltis, Ozel, & Johannsen 2012

Neglecting the oblateness leads to >5-10% errors in the predicted lightcurves



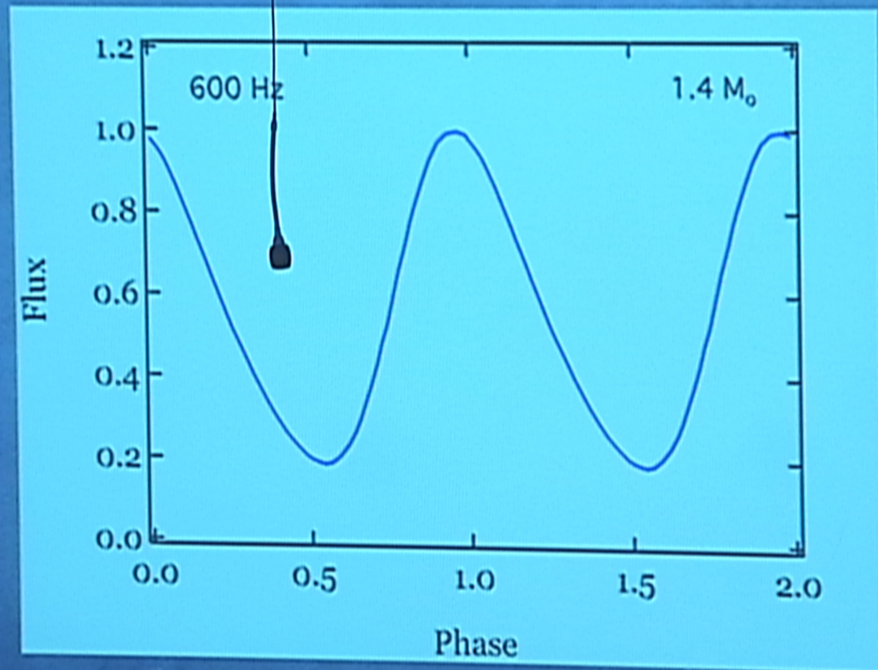
Morsink et al. 2007;
Psaltis et al 2013

Neglecting the oblateness leads to >5-10% errors in the predicted lightcurves



Morsink et al. 2007;
Psaltis et al 2013

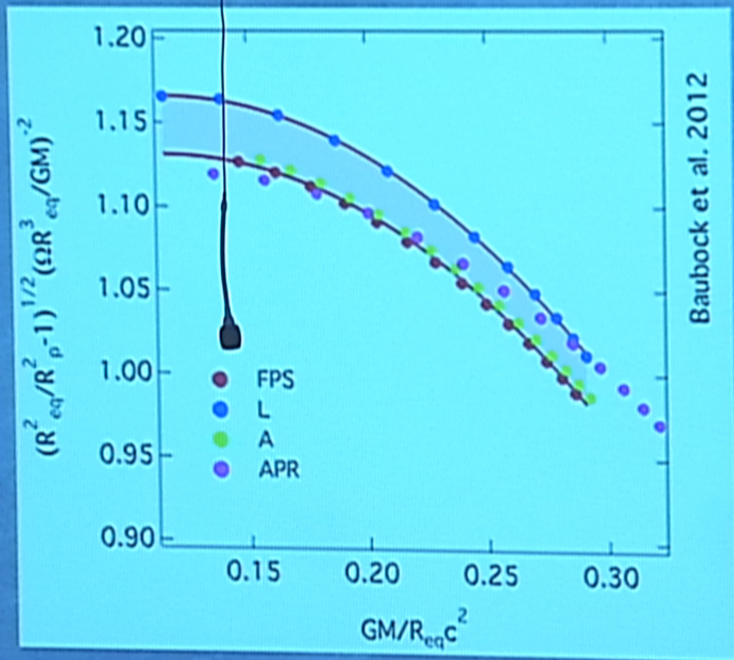
The goal is to use an observed lightcurve



To infer eight parameters:

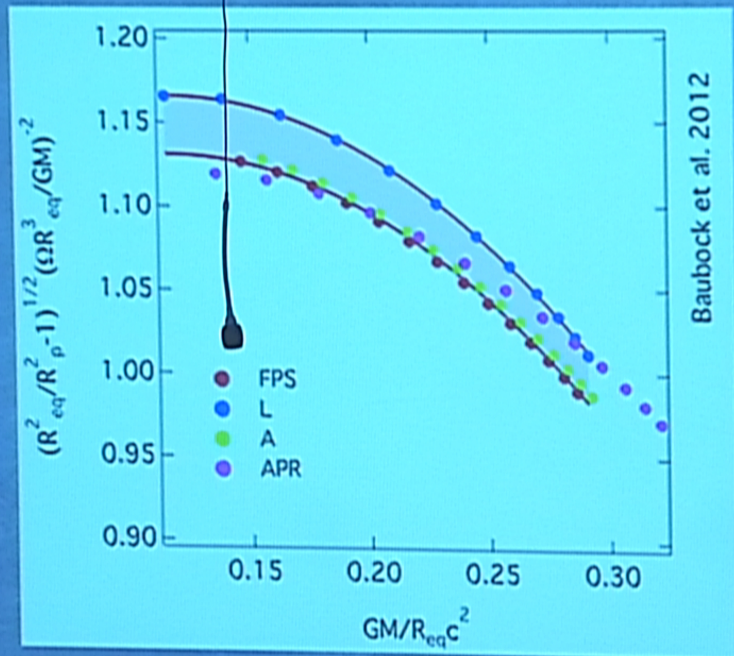
Mass, Radius, Oblateness, Moment of Inertia, Quadrupole
Size of Spot, Colatitude of Spot, Observer's Inclination

We can reduce the number of parameters by using approximate relations for the Oblateness, Moment of Inertia, and Quadrupole, e.g.,



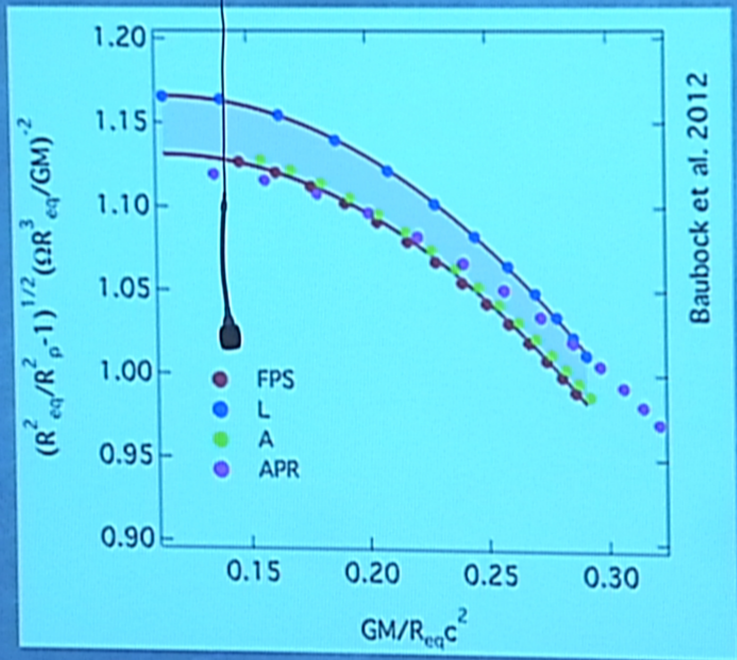
$$\frac{R_p}{R_{eq}} = 1 - 2\left(\frac{\Omega R_{eq}^3}{GM}\right)^4 \left(1.10 + 1.11\left(\frac{GM}{R_{eq}c^2}\right) - 4.88\left(\frac{GM}{R_{eq}c^2}\right)^2\right)^2 \pm 2\%$$

We can reduce the number of parameters by using approximate relations for the Oblateness, Moment of Inertia, and Quadrupole, e.g.,

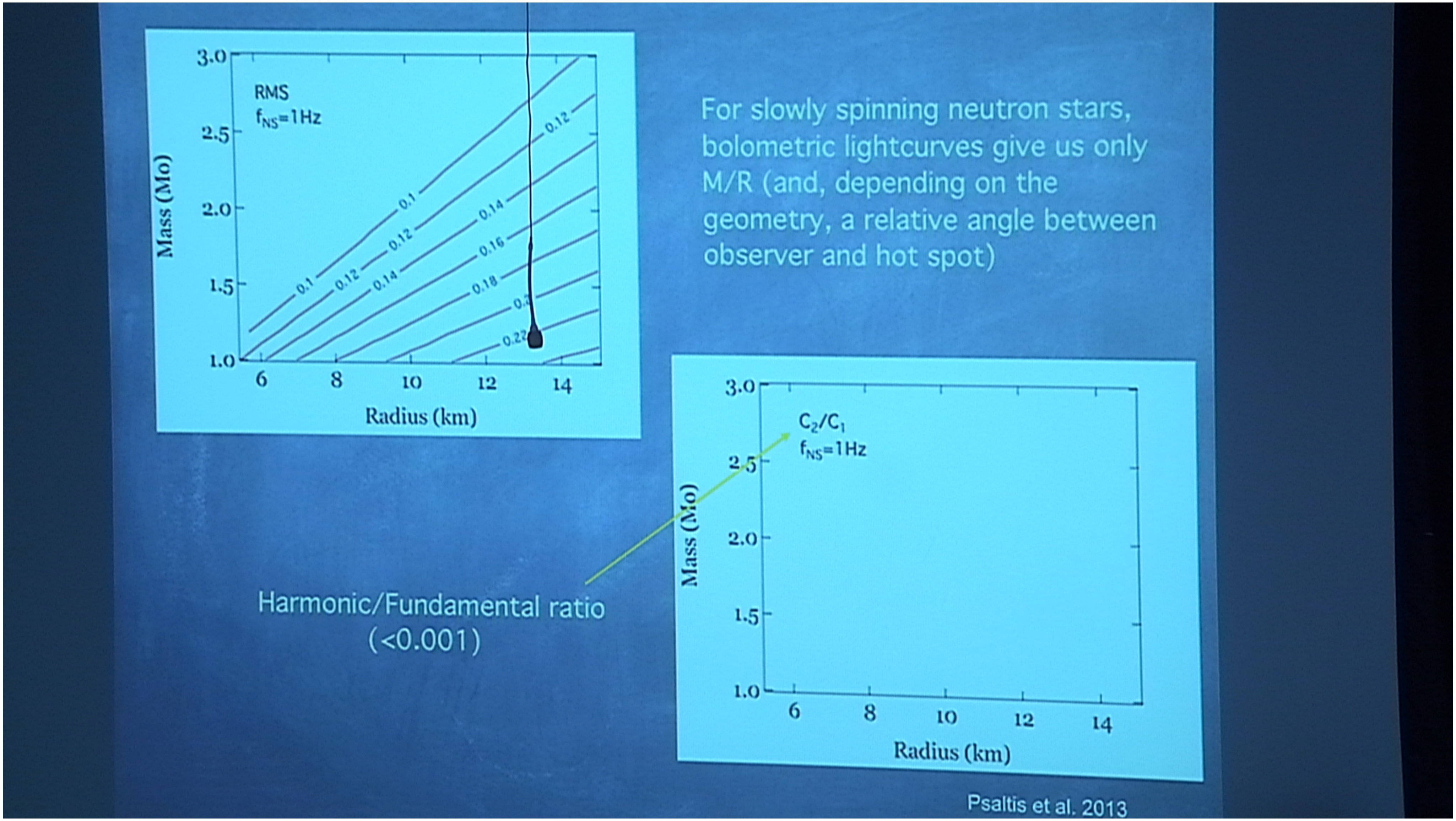


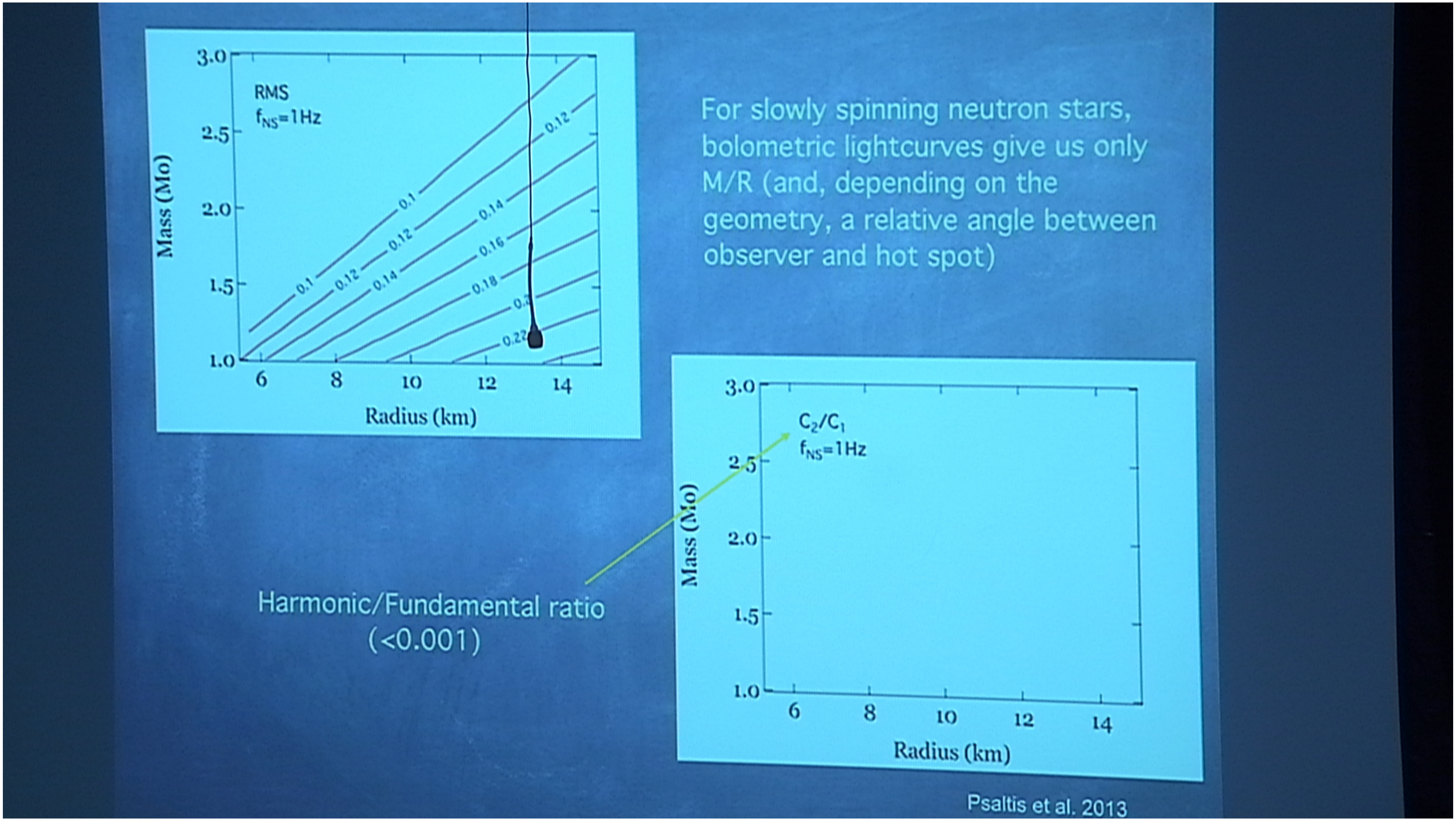
$$\frac{R_p}{R_{eq}} = 1 - 2\left(\frac{\Omega R_{eq}^3}{GM}\right)^4 \left(1.10 + 1.11\left(\frac{GM}{R_{eq}c^2}\right) - 4.88\left(\frac{GM}{R_{eq}c^2}\right)^2\right)^2 \pm 2\%$$

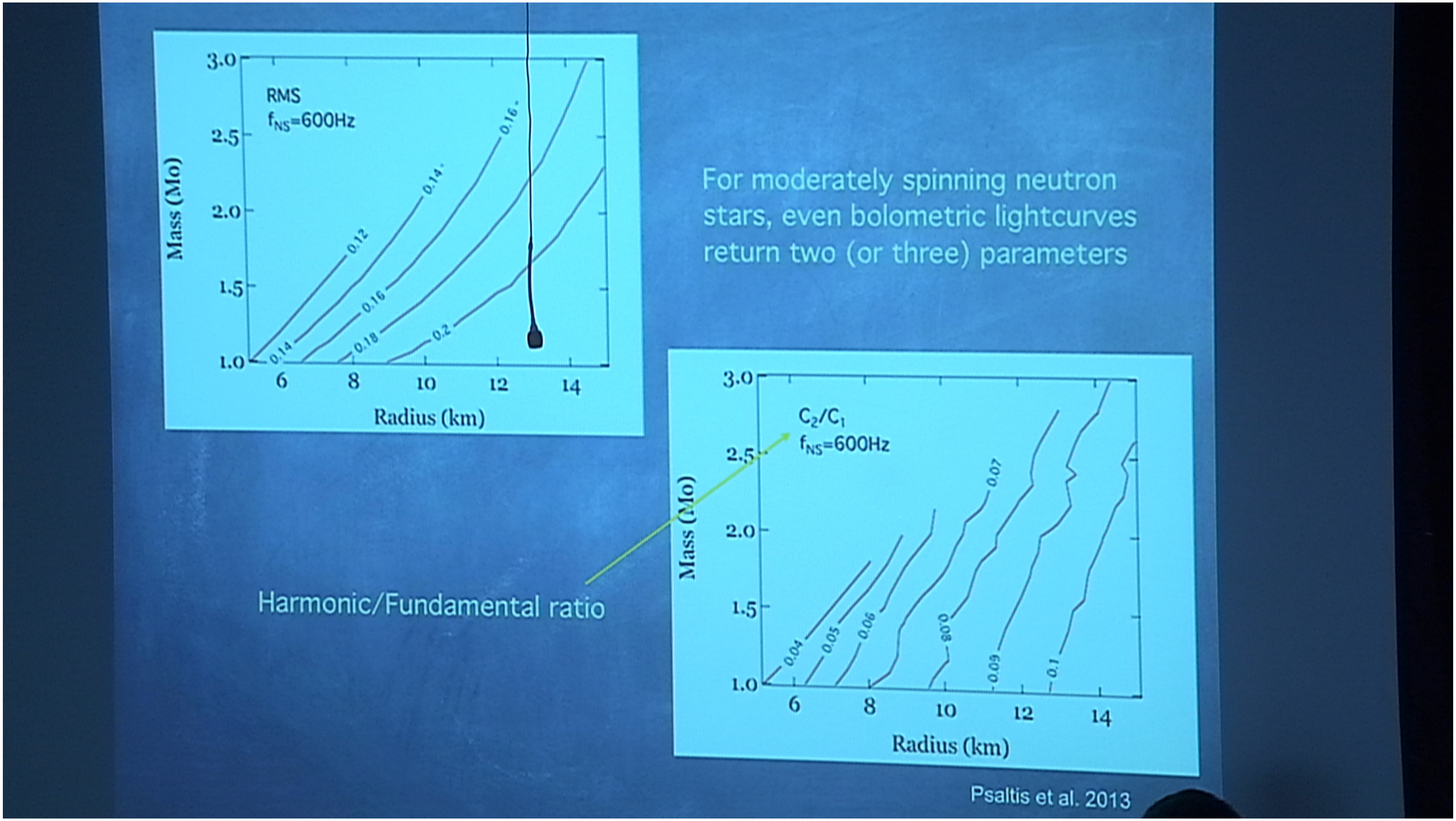
We can reduce the number of parameters by using approximate relations for the Oblateness, Moment of Inertia, and Quadrupole, e.g.,

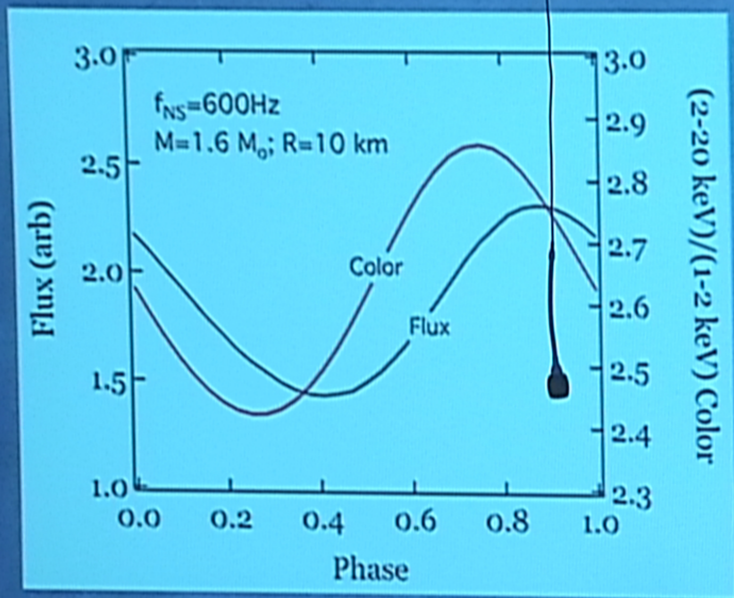


$$\frac{R_p}{R_{eq}} = 1 - 2\left(\frac{\Omega R_{eq}^3}{GM}\right)^4\left(1.10 + 1.11\left(\frac{GM}{R_{eq}c^2}\right) - 4.88\left(\frac{GM}{R_{eq}c^2}\right)^2\right)^2 \pm 2\%$$

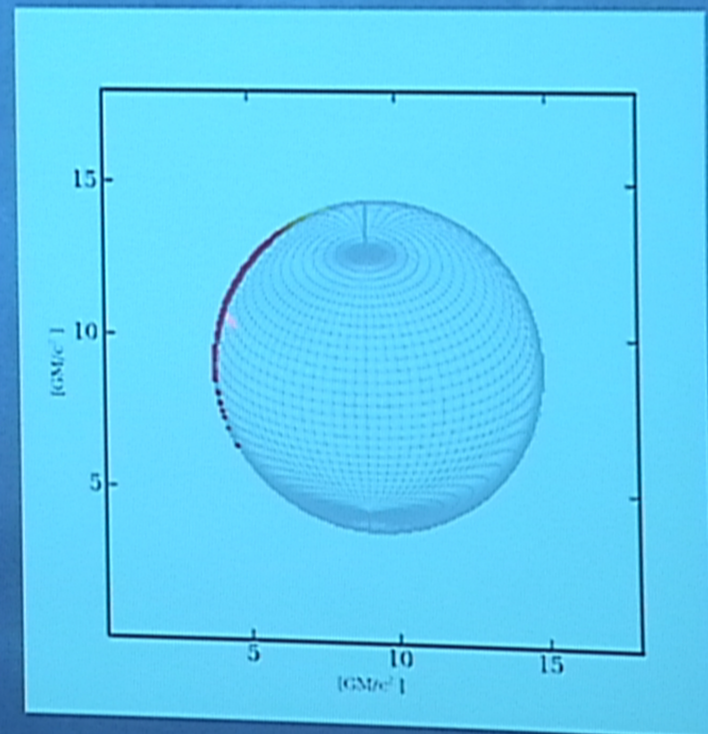

RMS
fNS=1Hz
Mass (Mo)
Radius (km)
For slowly spinning neutron stars, bolometric lightcurves give us only M/R (and, depending on the geometry, a relative angle between observer and hot spot)
Harmonic/Fundamental ratio
(<0.001)
C2/C1
fNS=1Hz
Mass (Mo)
Radius (km)
Psaltis et al. 2013


3.0
2.5
2.0
1.5
1.0
RMS
f_{NS}=1Hz
0.1
0.12
0.14
0.16
0.18
0.2
0.22
6
8
10
12
14
Radius (km)
Mass (Mo)
For slowly spinning neutron stars, bolometric lightcurves give us only M/R (and, depending on the geometry, a relative angle between observer and hot spot)
C_2/C_1
f_{NS}=1Hz
Harmonic/Fundamental ratio
(<0.001)
Psaltis et al. 2013

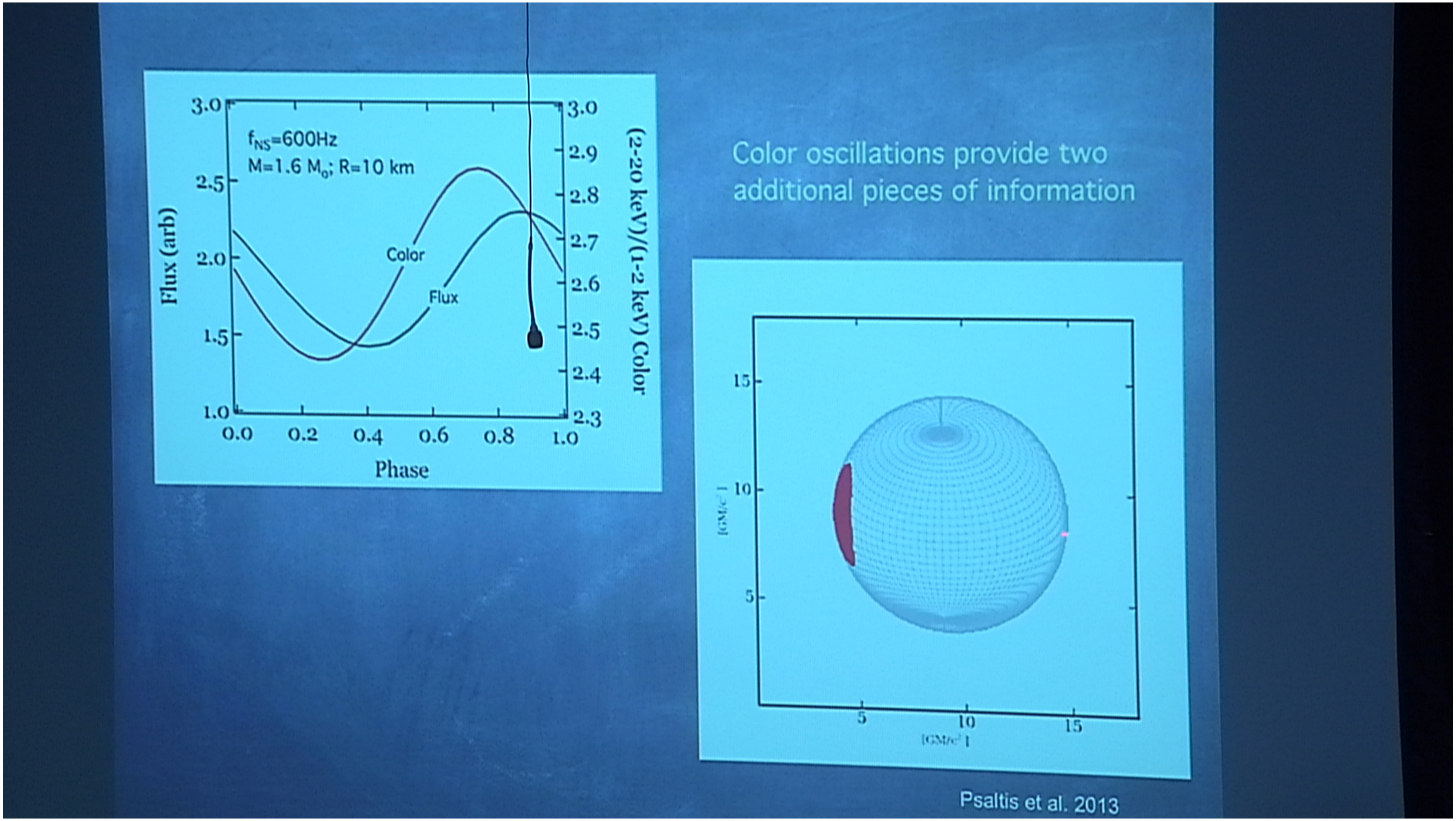

RMS
f_{NS}=600Hz
Mass (Mo)
Radius (km)
3.0
2.5
2.0
1.5
1.0
6
8
10
12
14
0.12
0.14
0.16
0.18
0.2
For moderately spinning neutron stars, even bolometric lightcurves return two (or three) parameters
C_2/C_1
f_{NS}=600Hz
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Harmonic/Fundamental ratio
Psaltis et al. 2013



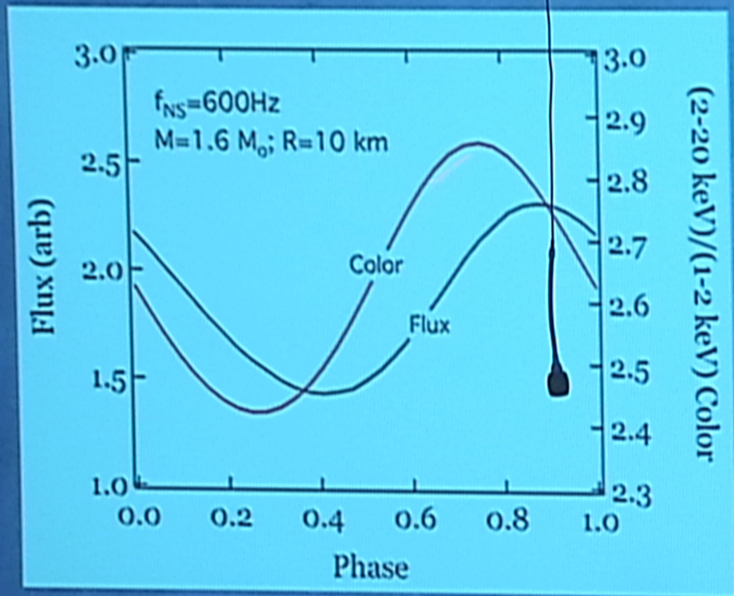
Color oscillations provide two additional pieces of information



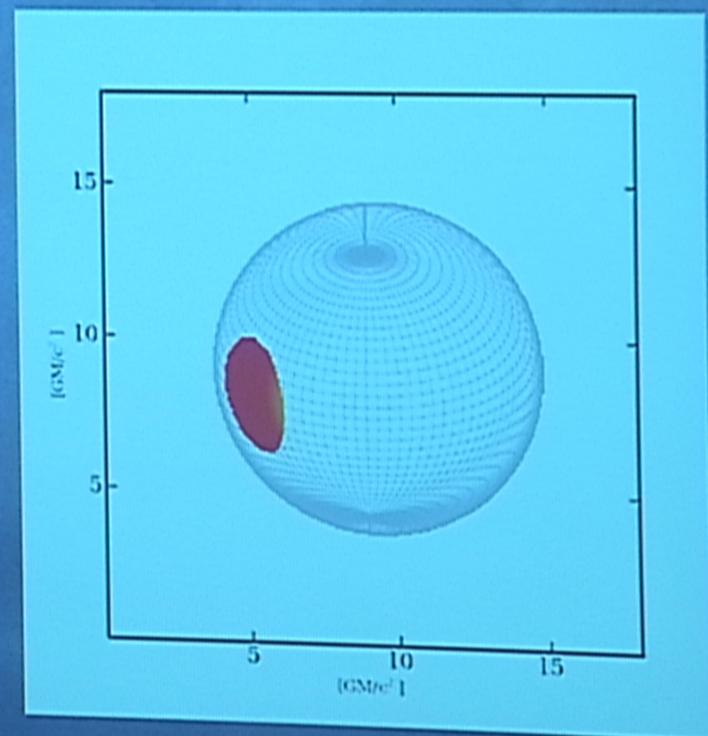
Psaltis et al. 2013



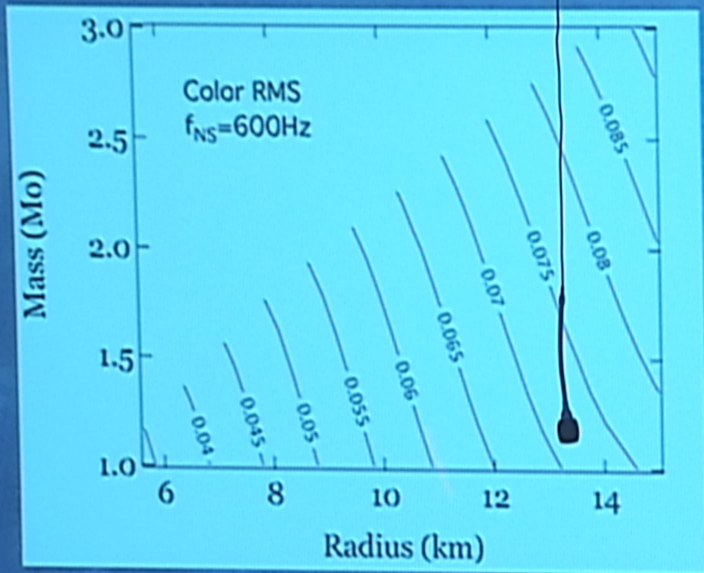
Color oscillations provide two additional pieces of information
f_NS=600Hz
M=1.6 M_o; R=10 km
Color
Flux
Flux (arb)
(2-20 keV)/(1-2 keV) Color
Phase
[GM/c²]
Psaltis et al. 2013



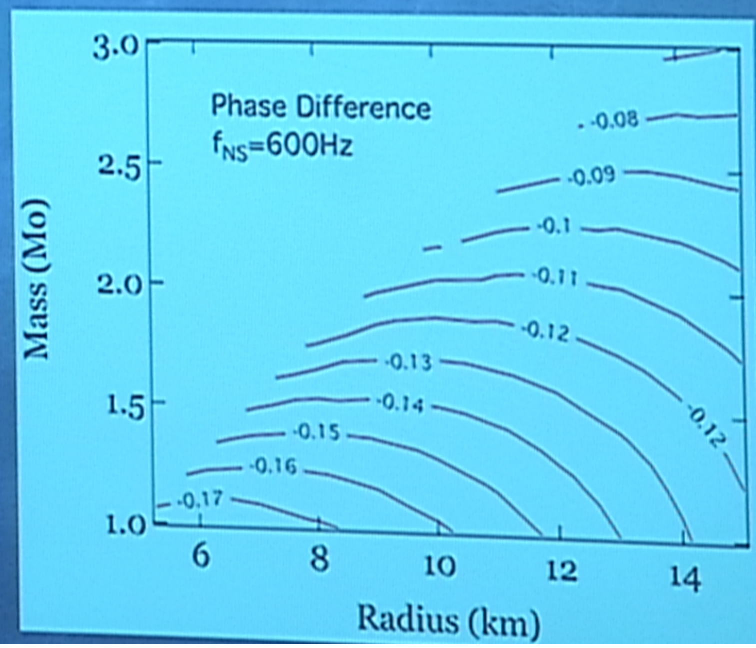
Color oscillations provide two additional pieces of information

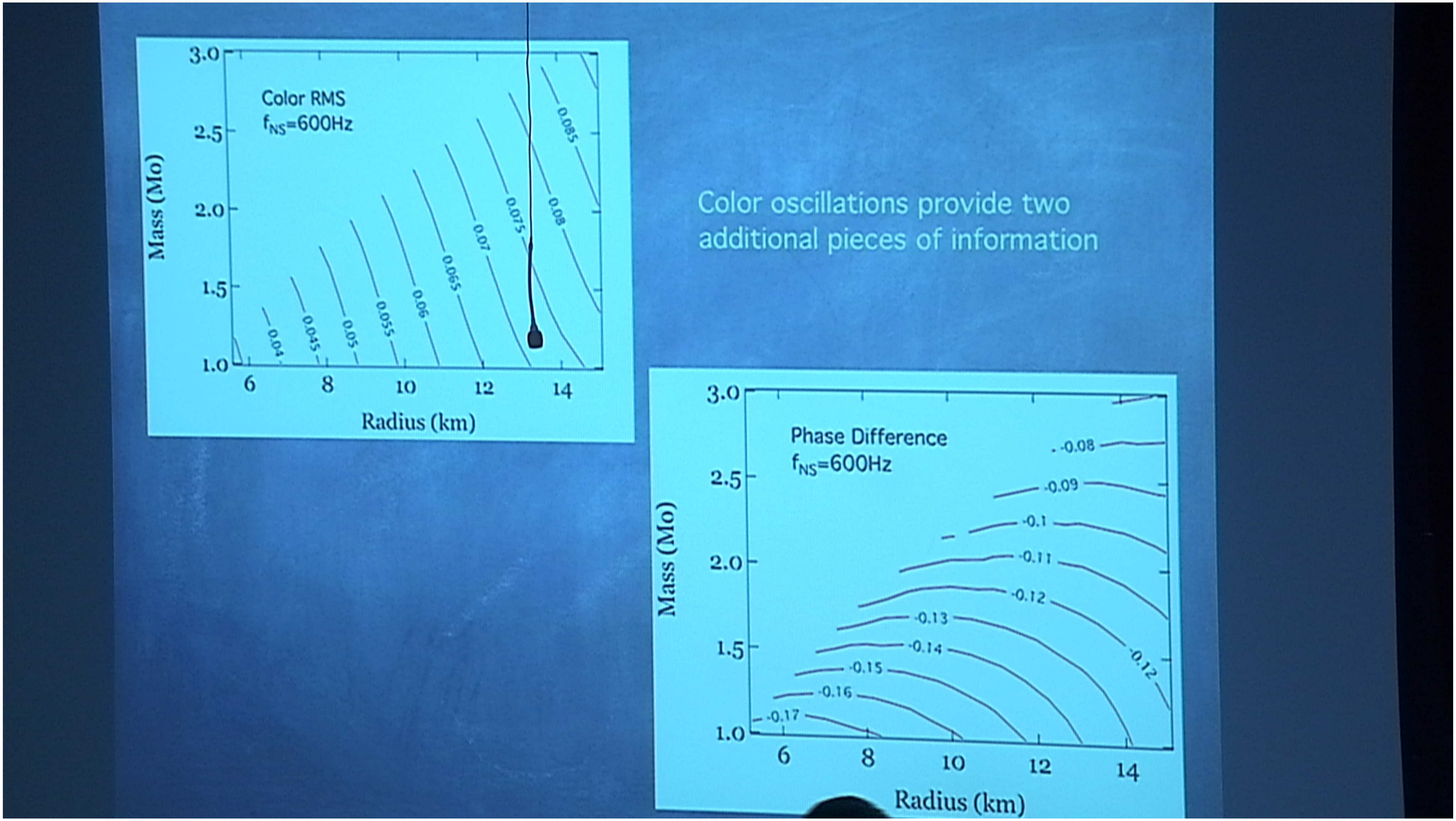


Psaltis et al. 2013



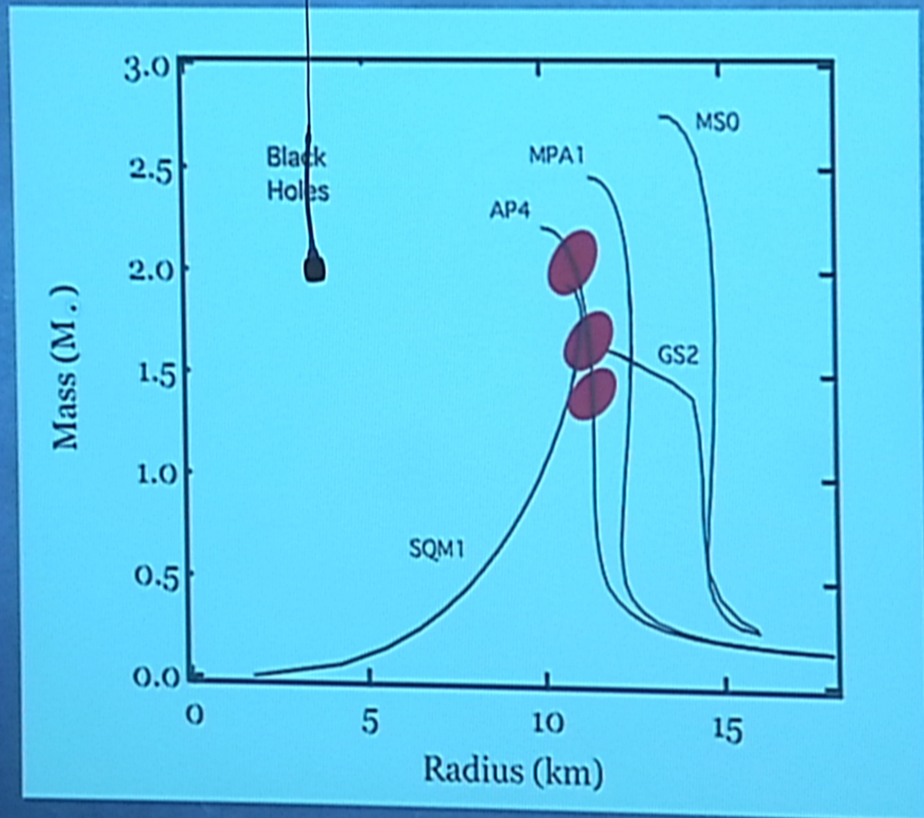
Color oscillations provide two additional pieces of information





Color oscillations provide two additional pieces of information
Color RMS
f_{NS}=600Hz
Mass (Mo)
Radius (km)
0.04
0.045
0.05
0.055
0.06
0.065
0.07
0.075
0.08
0.085
Phase Difference
f_{NS}=600Hz
-0.08
-0.09
-0.1
-0.11
-0.12
-0.13
-0.14
-0.15
-0.16
-0.17

Combining these measurements breaks the degeneracies between the fundamental and geometric parameters



LOFT simulation; 1Mphotons

Psaltis et al. 2013

CONCLUSIONS

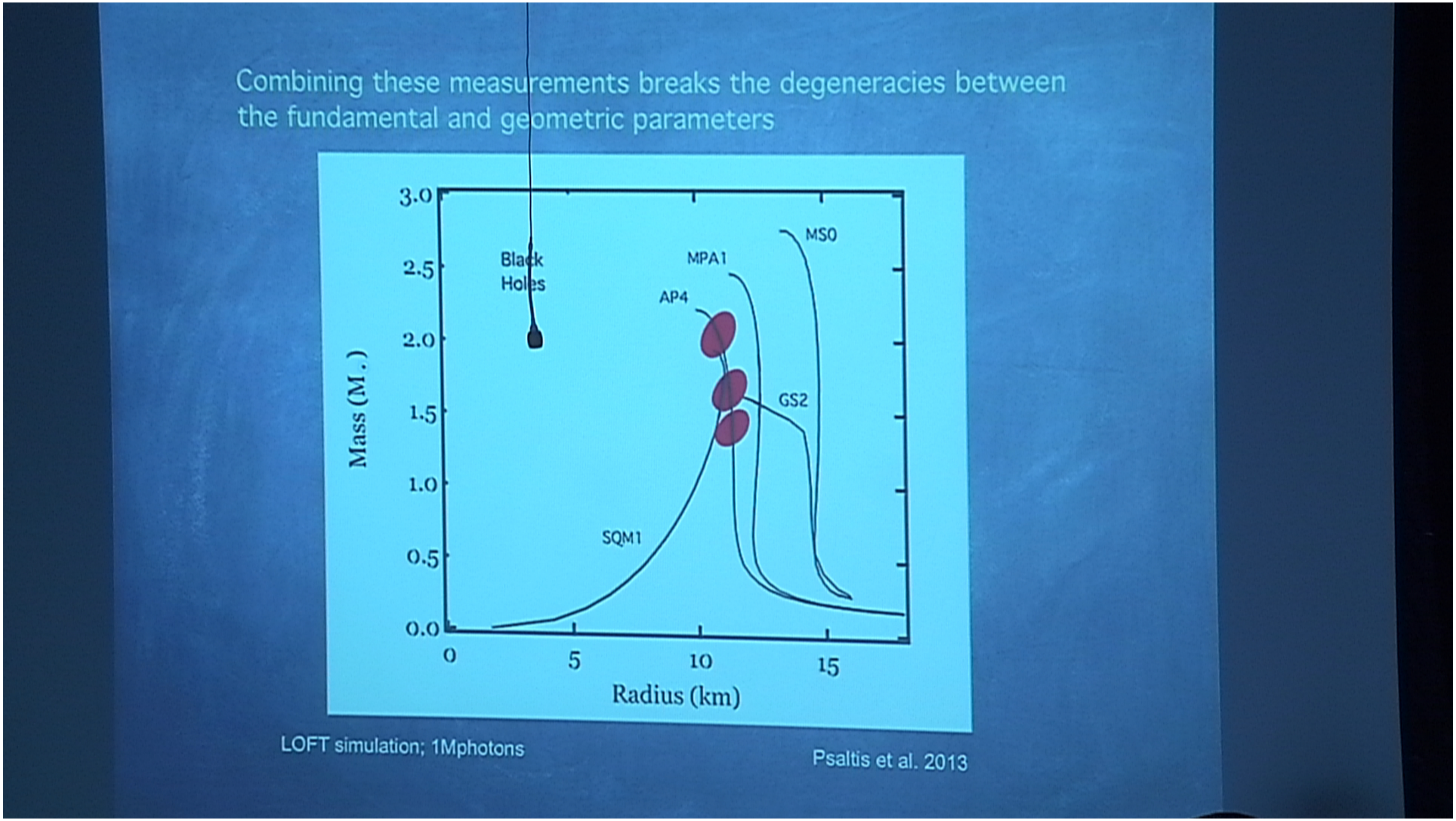
- Observations of lightcurves from spinning neutron stars with NICER and LOFT will lead to accurate measurements of their masses, radii, and EOS

- The rapid spins of neutron stars that show thermonuclear bursts is both bad (we need elaborate spacetimes) and good (they can help break degeneracies) news.

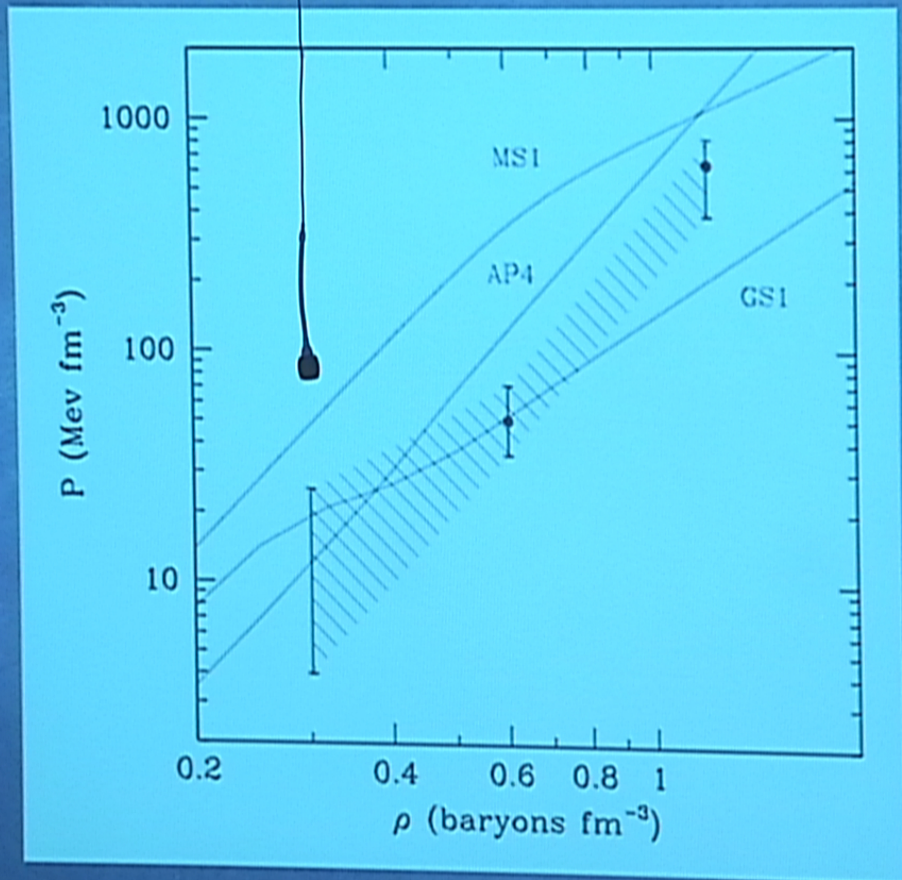
- Breaking the degeneracies in the measurements requires
  (i) measuring harmonic amplitudes to a 0.1% level
  (ii) measuring color oscillation amplitudes to a 0.5% level
  (iii) measuring phase differences between flux and color oscillations to <1% of a cycle

CONCLUSIONS

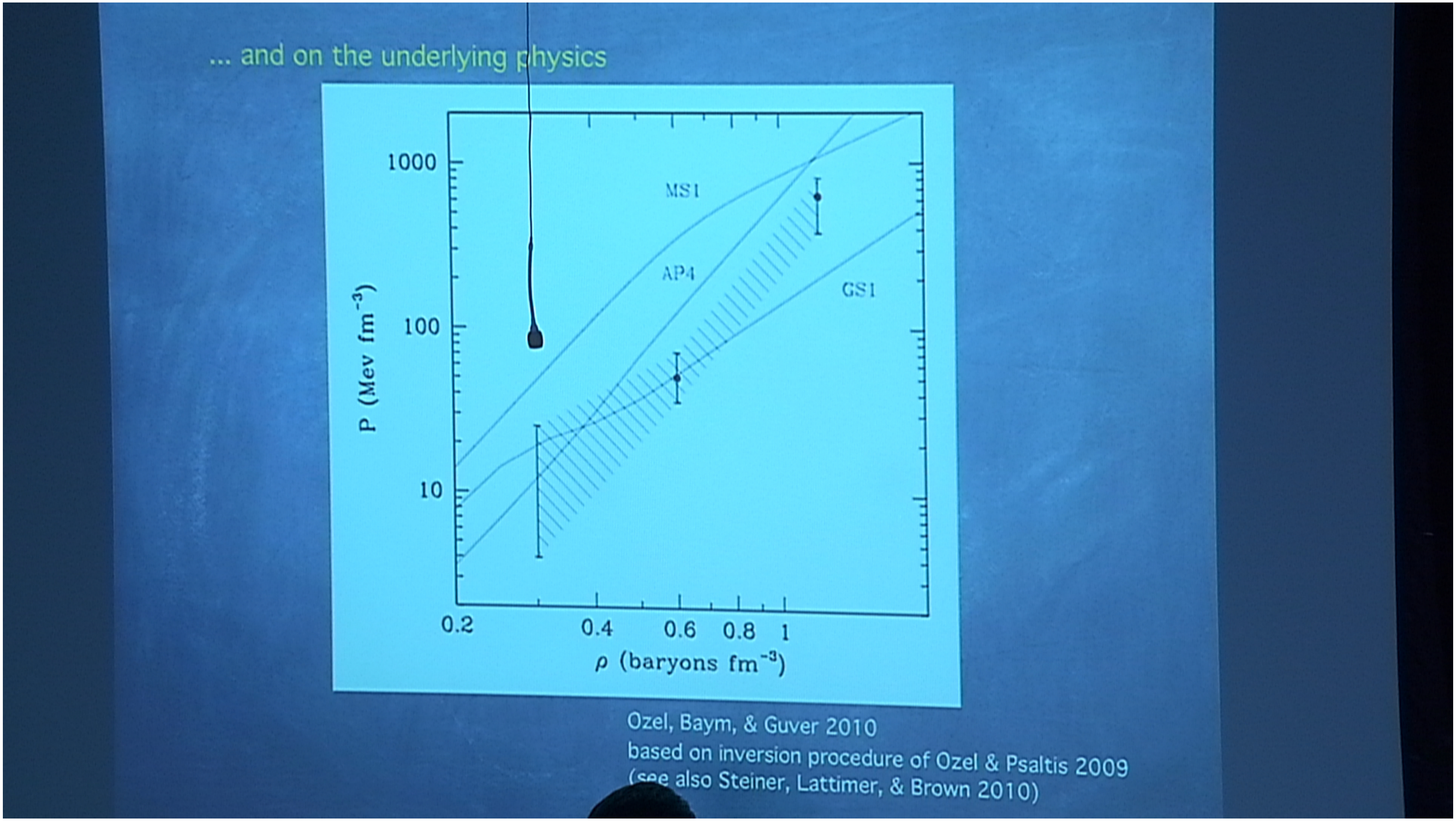
- Observations of lightcurves from spinning neutron stars with NICER and LOFT will lead to accurate measurements of their masses, radii, and EOS
- The rapid spins of neutron stars that show thermonuclear bursts is both bad (we need elaborate spacetimes) and good (they can help break degeneracies) news.
- Breaking the degeneracies in the measurements requires
  (i) measuring harmonic amplitudes to a 0.1% level
  (ii) measuring color oscillation amplitudes to a 0.5% level
  (iii) measuring phase differences between flux and color oscillations to <1% of a cycle

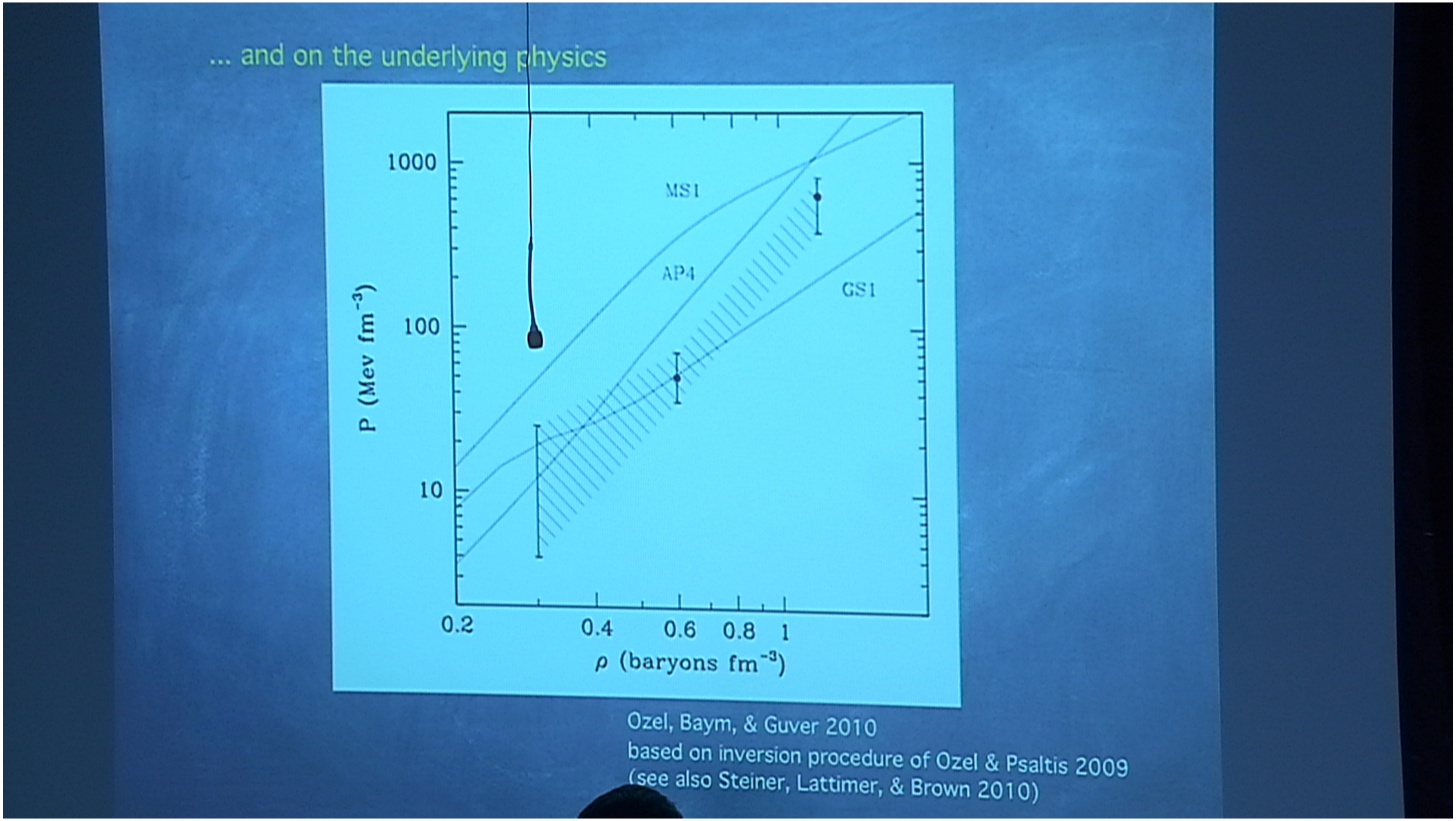

Combining these measurements breaks the degeneracies between the fundamental and geometric parameters
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Mass (M.)
0
5
10
15
Radius (km)
Black Holes
MS0
MPA1
AP4
GS2
SQM1
LOFT simulation; 1Mphotons
Psaltis et al. 2013

... and on the underlying physics



Ozel, Baym, & Guver 2010
based on inversion procedure of Ozel & Psaltis 2009
(see also Steiner, Lattimer, & Brown 2010)


... and on the underlying physics
1000
100
10
P (Mev fm^{-3})
MS1
AP4
GS1
0.2
0.4
0.6
0.8
1
ρ (baryons fm^{-3})
Ozel, Baym, & Guver 2010
based on inversion procedure of Ozel & Psaltis 2009
(see also Steiner, Lattimer, & Brown 2010)


... and on the underlying physics
1000
100
10
P (Mev fm^{-3})
MS1
AP4
GS1
0.2
0.4
0.6
0.8
1
ρ (baryons fm^{-3})
Ozel, Baym, & Guver 2010
based on inversion procedure of Ozel & Psaltis 2009
(see also Steiner, Lattimer, & Brown 2010)