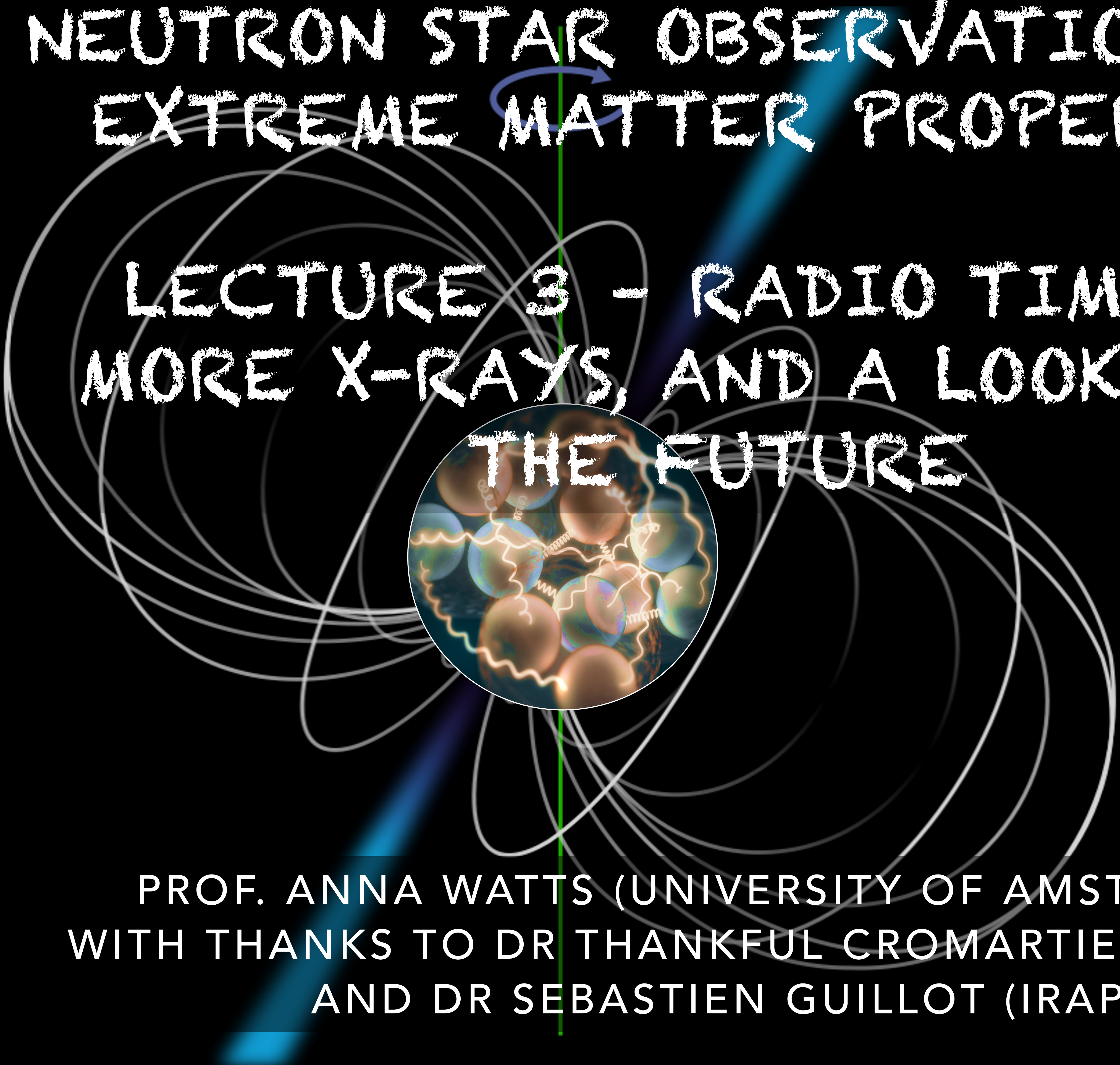
NEUTRON STAR OBSERVATIONS AND EXTREME MATTER PROPERTIES

LECTURE 3 - RADIO TIMING, MORE X-RAYS, AND A LOOK INTO THE FUTURE



PROF. ANNA WATTS (UNIVERSITY OF AMSTERDAM)
WITH THANKS TO DR THANKFUL CROMARTIE (CORNELL)
AND DR SEBASTIEN GUILLOT (IRAP)

FROM NUCLEAR PHYSICS TO TELESCOPE

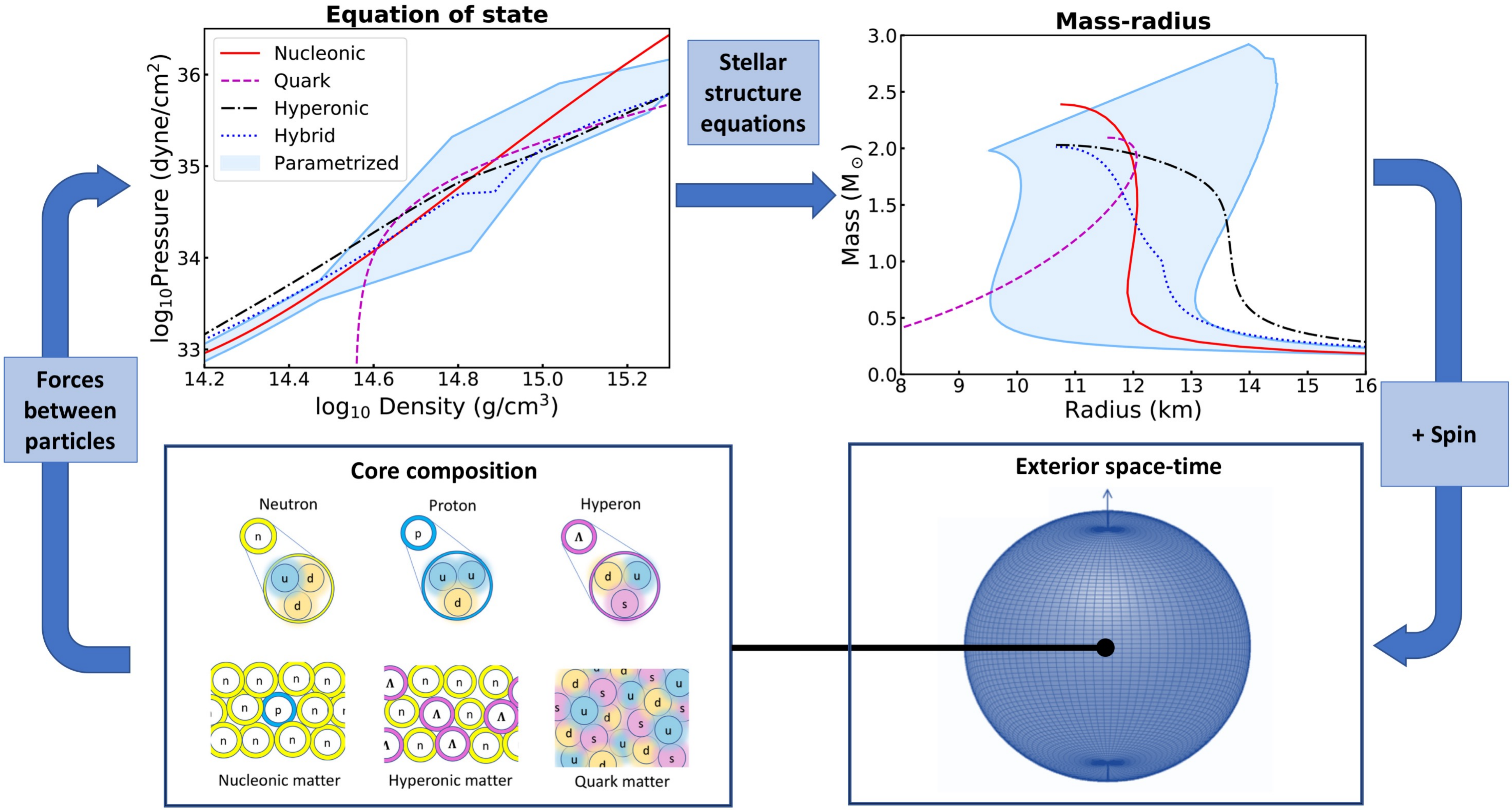
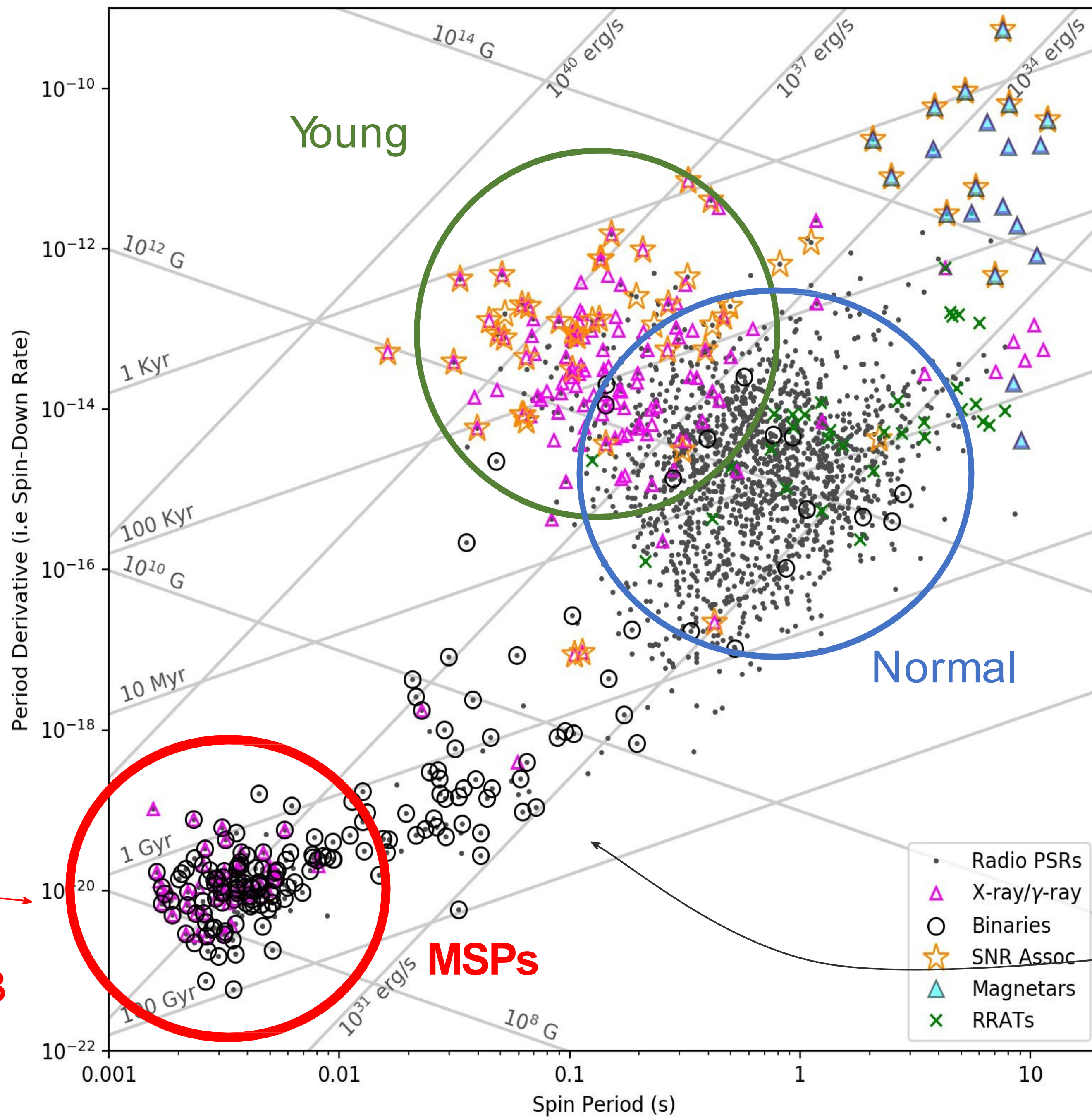


Figure: Adapted from Ray et al. 2019

The Radio Pulsar population

MSPs:
fully recycled,
low-eccentricity
orbits, stable,
fast!



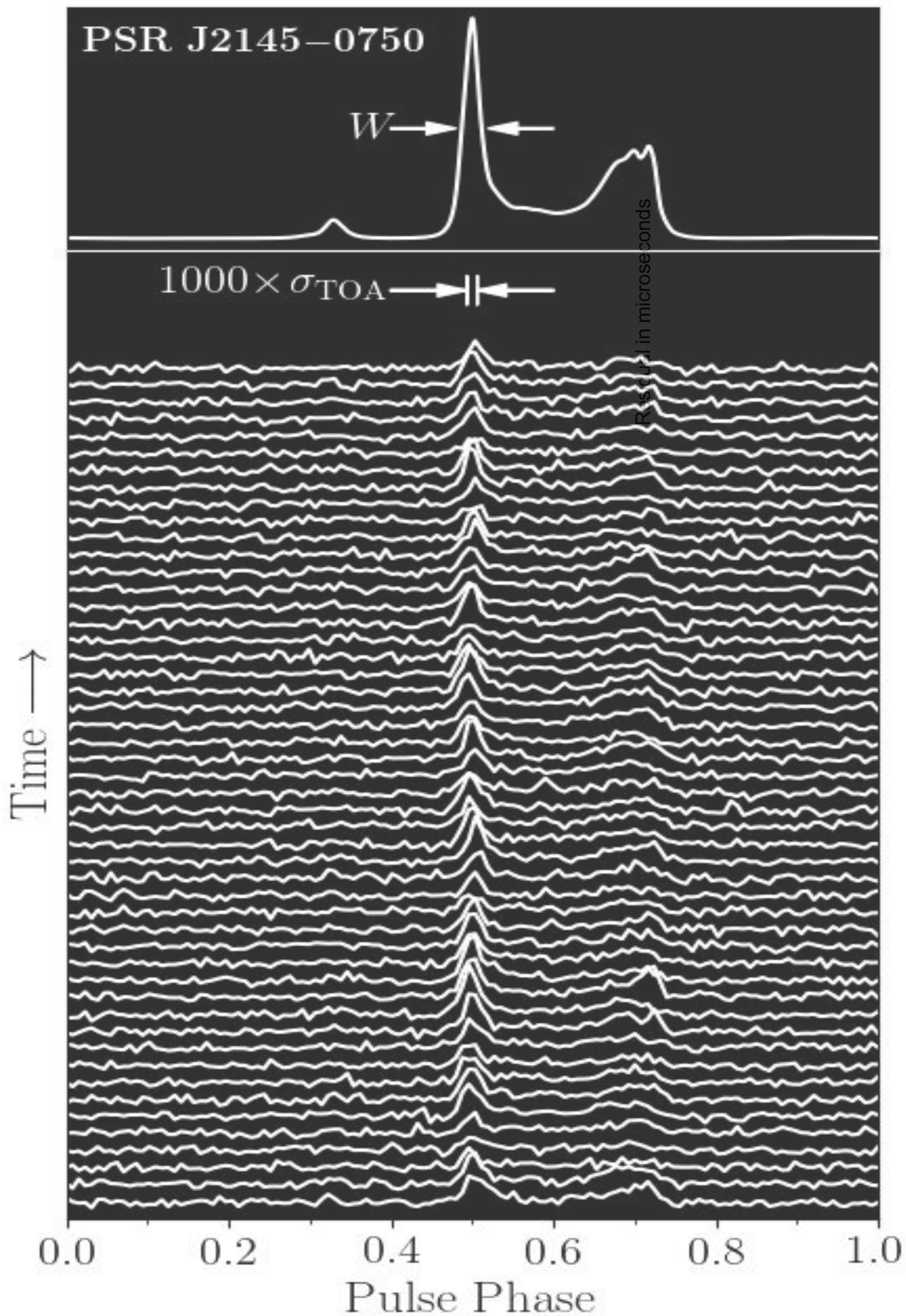
High B

Low B

Double NS:
~17; mildly recycled,
high-eccentricity
orbits, good GR tests

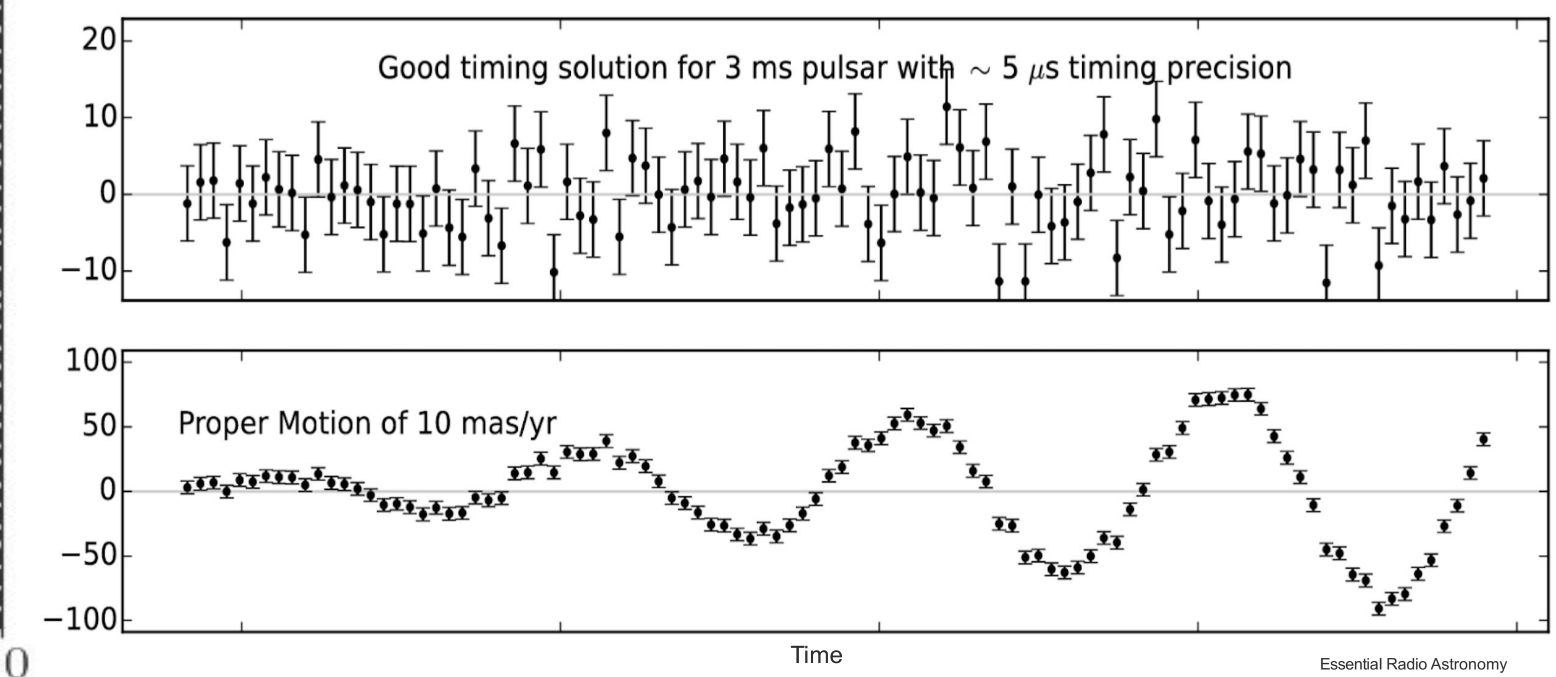
Courtesy of Thankful Cromartie

Pulsar Timing



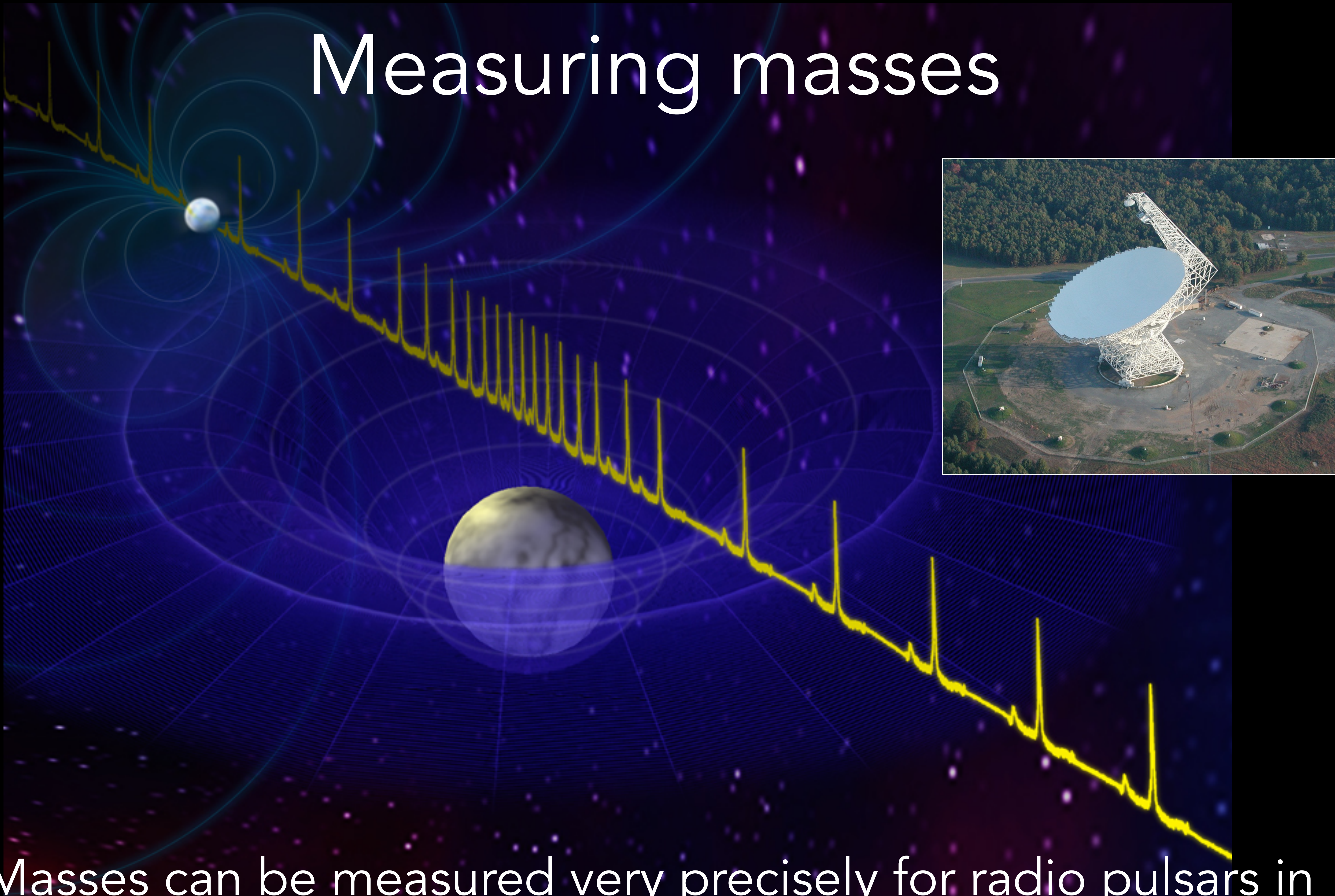
Courtesy of Thankful Cromartie

- Account for each rotation
- In addition to basic parameters, models account for ISM dispersion (DM), GR effects, ephemeris, etc.
- Deviations (measurement - model) = residuals
- Precision rivals atomic clocks



NANOGrav (Lam 2019)

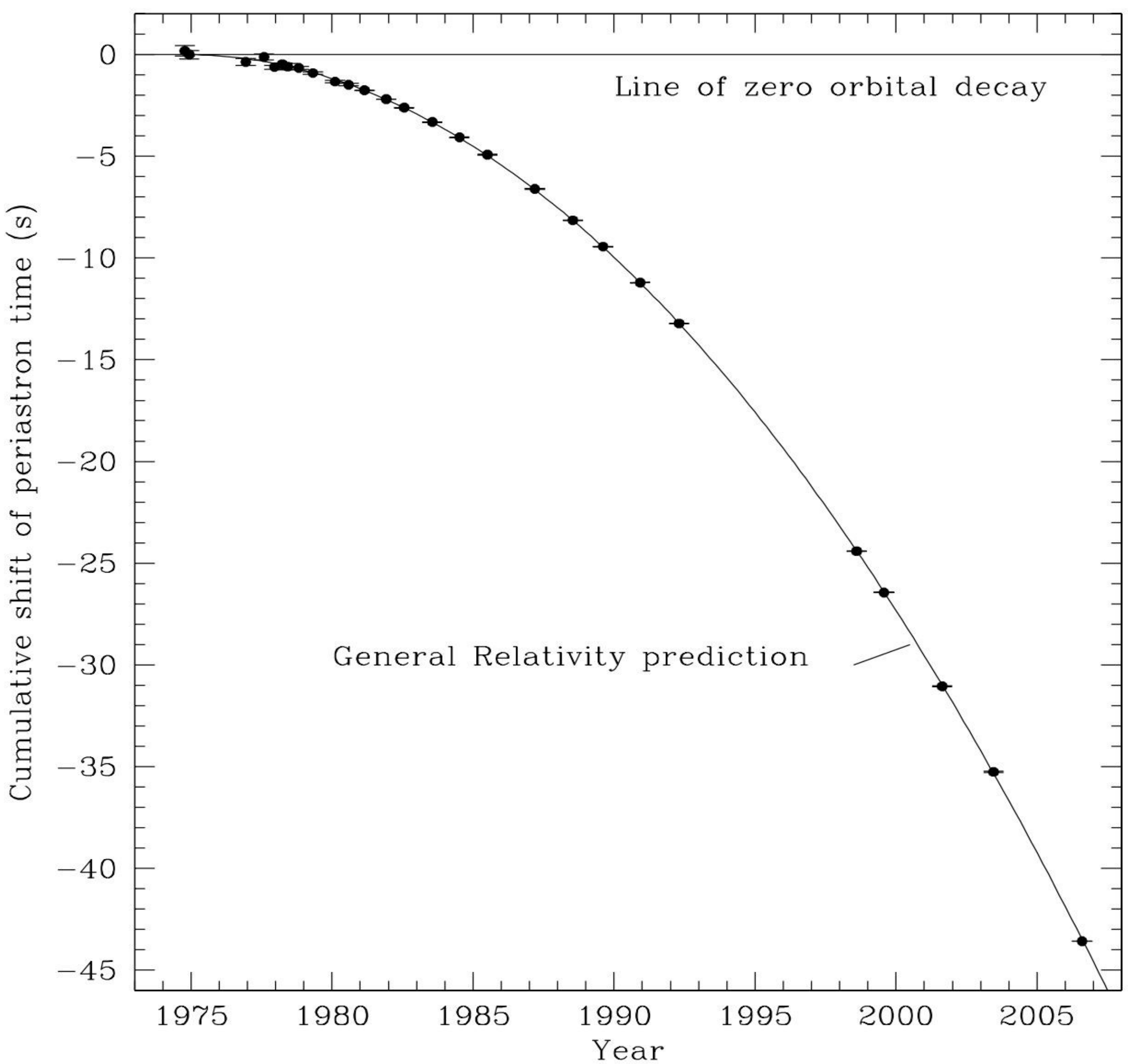
Measuring masses



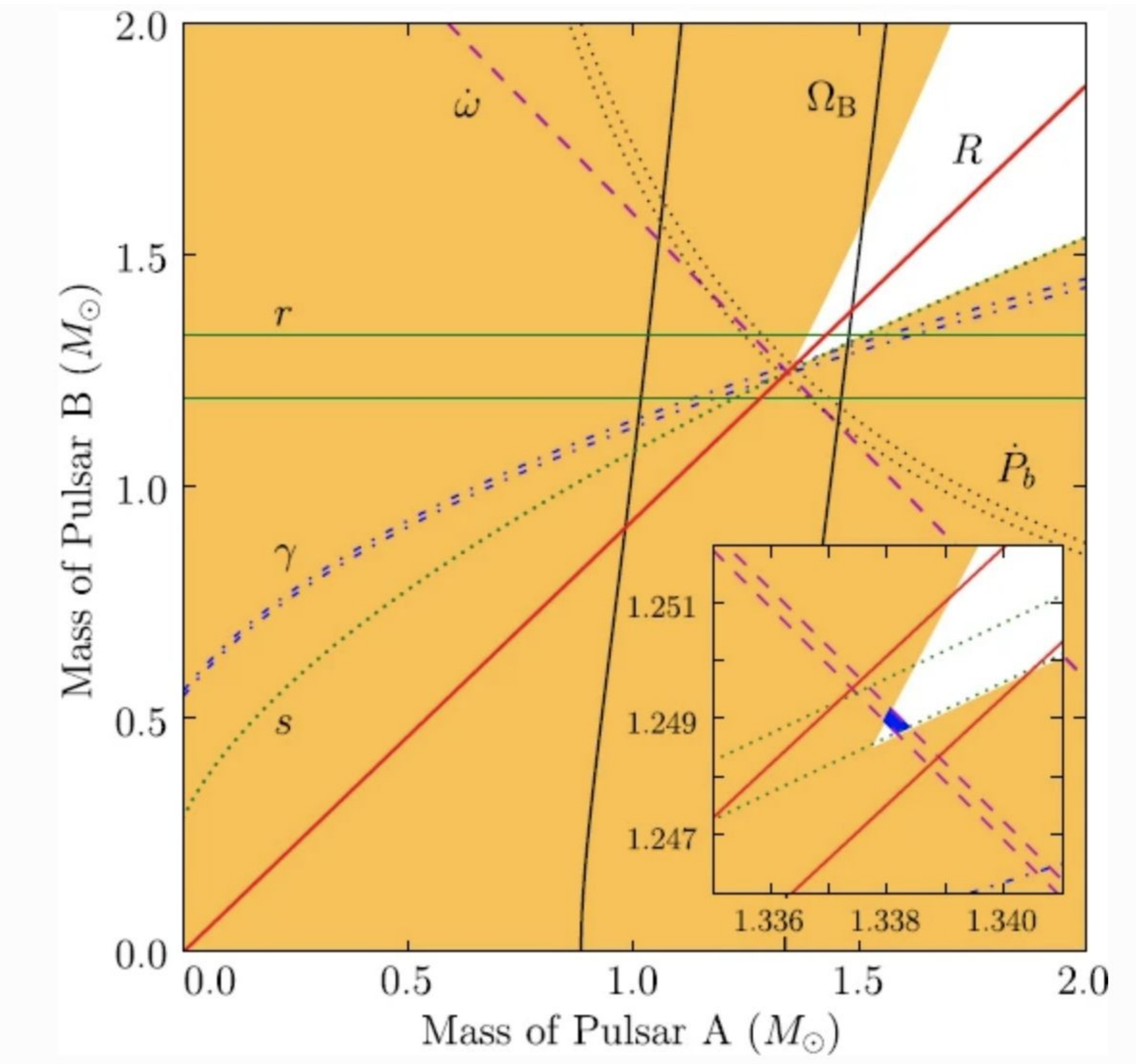
Masses can be measured very precisely for radio pulsars in relativistic binaries (if geometry is favourable), using Post-Keplerian parameters such as Shapiro delay.

B1913+16
“Hulse-Taylor pulsar”

J0737-3039
“Double pulsar"



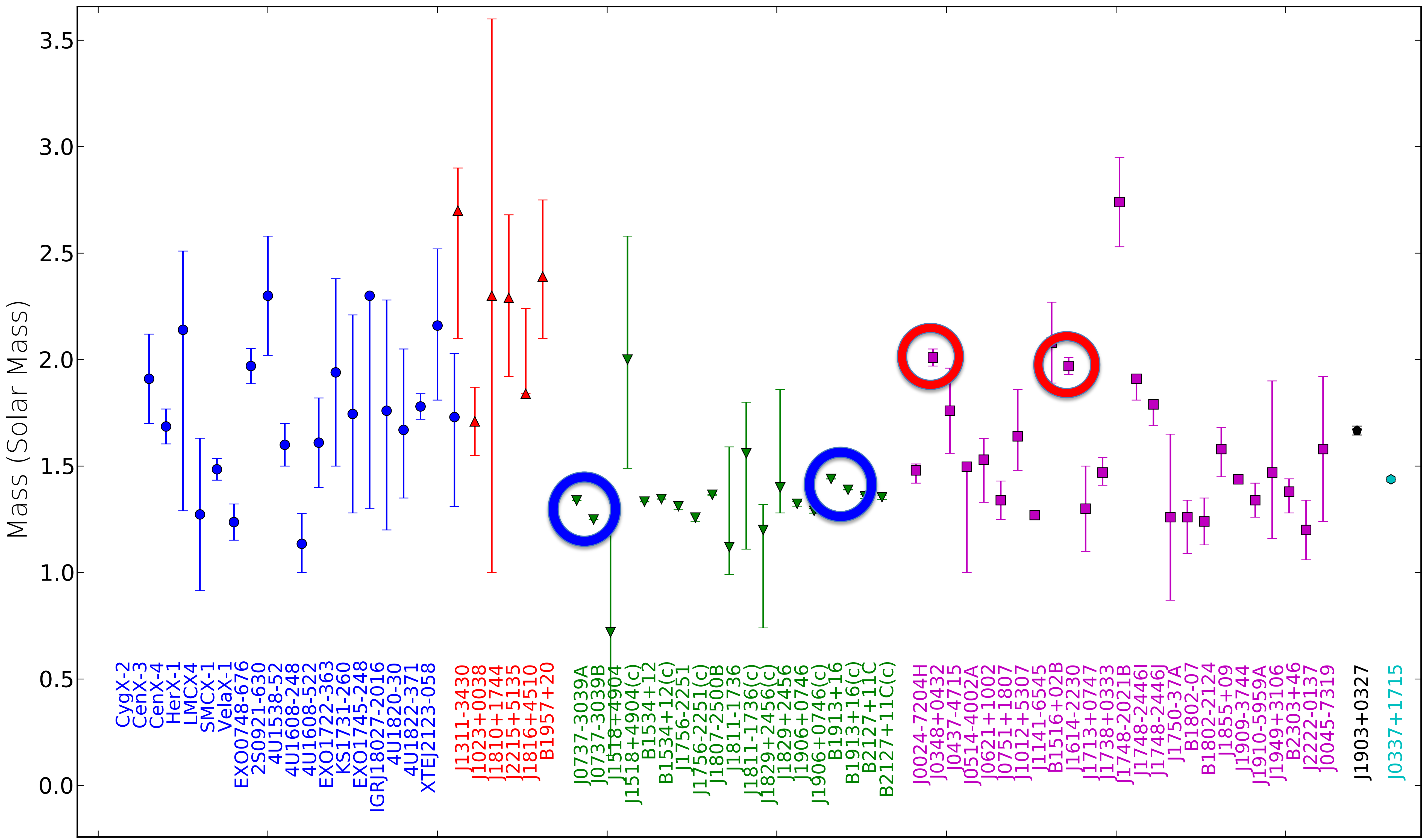
Weisberg, Nice & Taylor (2010)



Kramer et al. 2006 via R. Breton

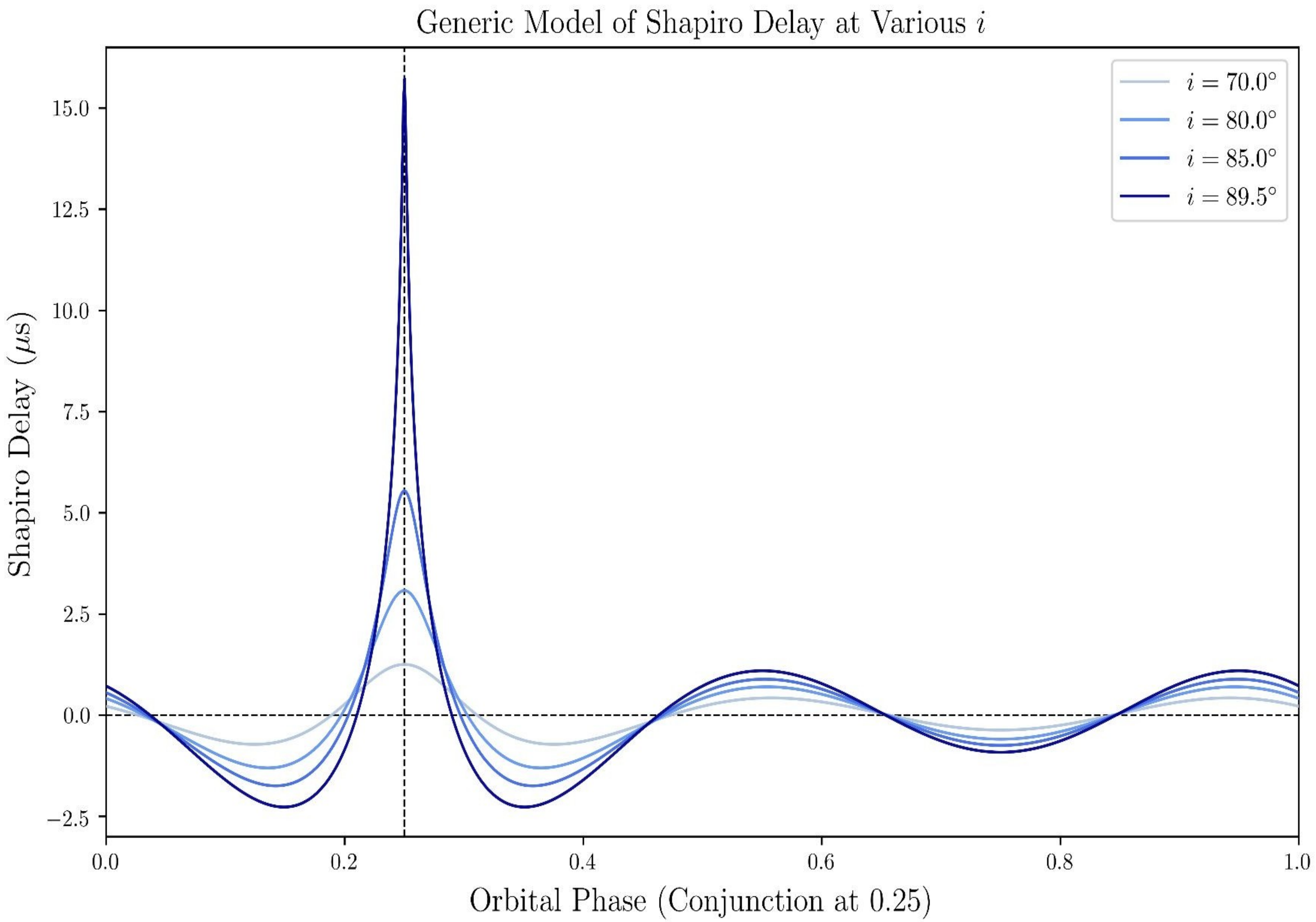
Courtesy of Thankful Cromartie

(Nearly) current mass measurements



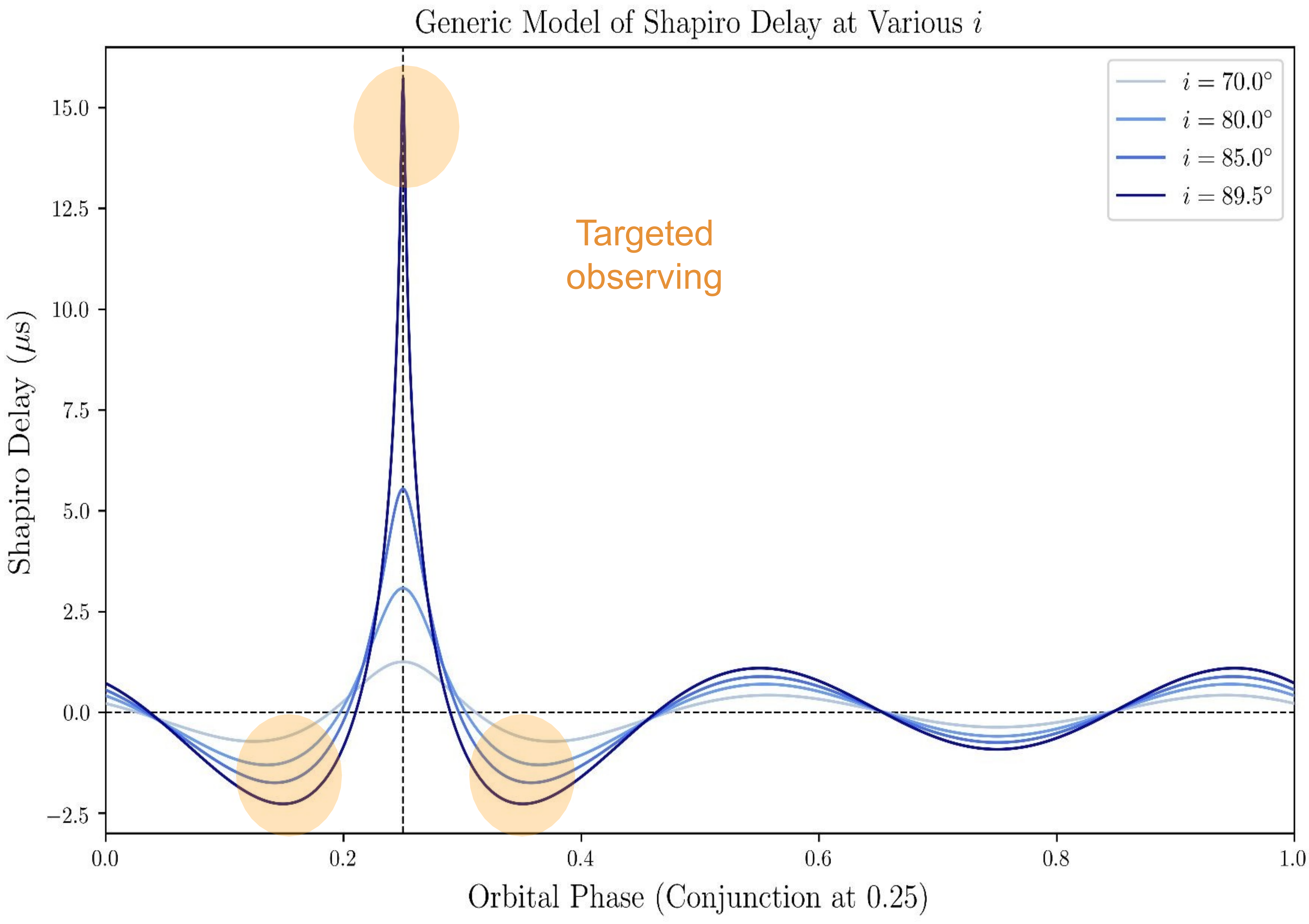
Watts et al. 2015 (SKA EOS paper), see J.Antoniadis website for updates

Shapiro delay



Courtesy of Thankful Cromartie

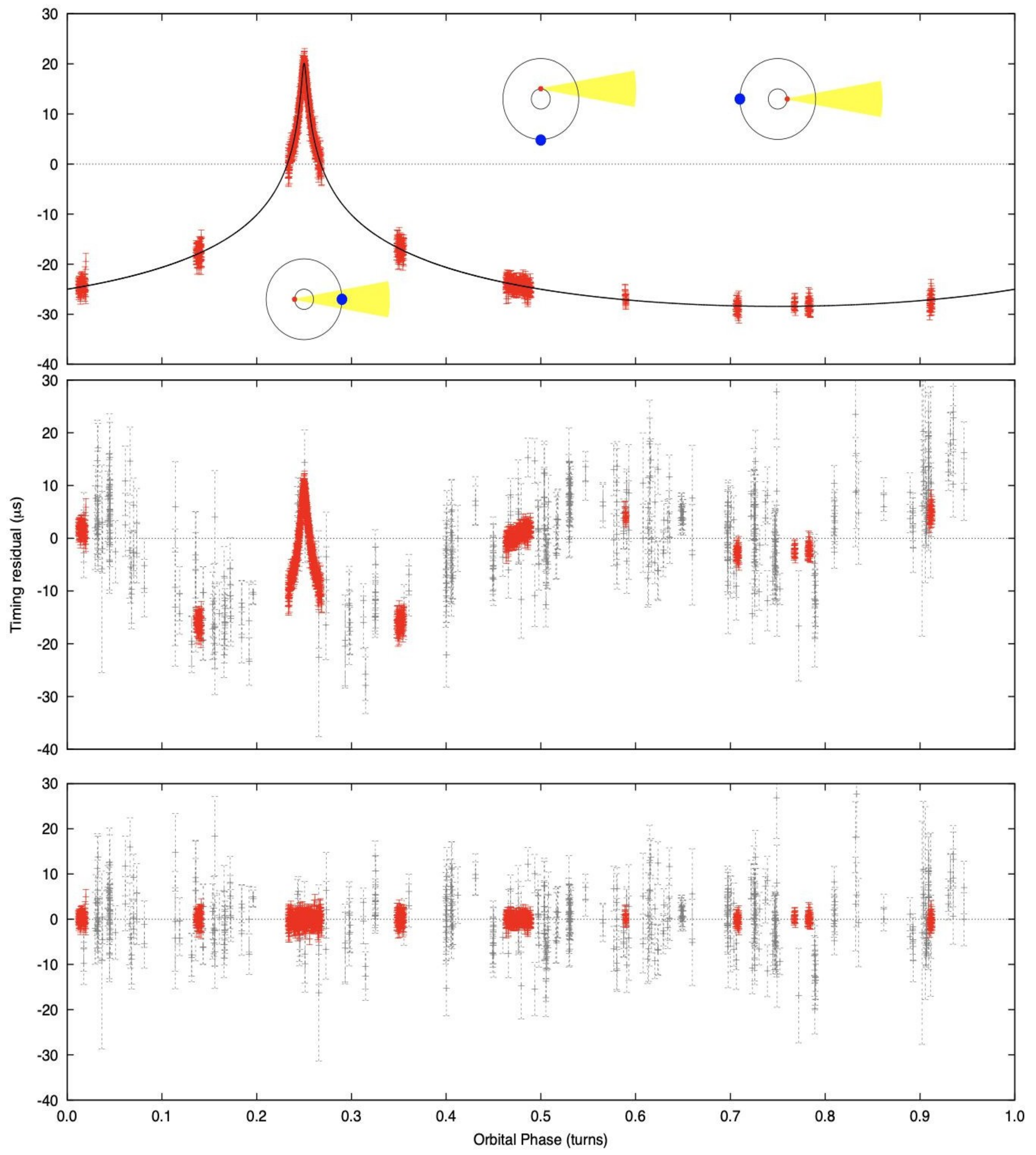
Shapiro delay



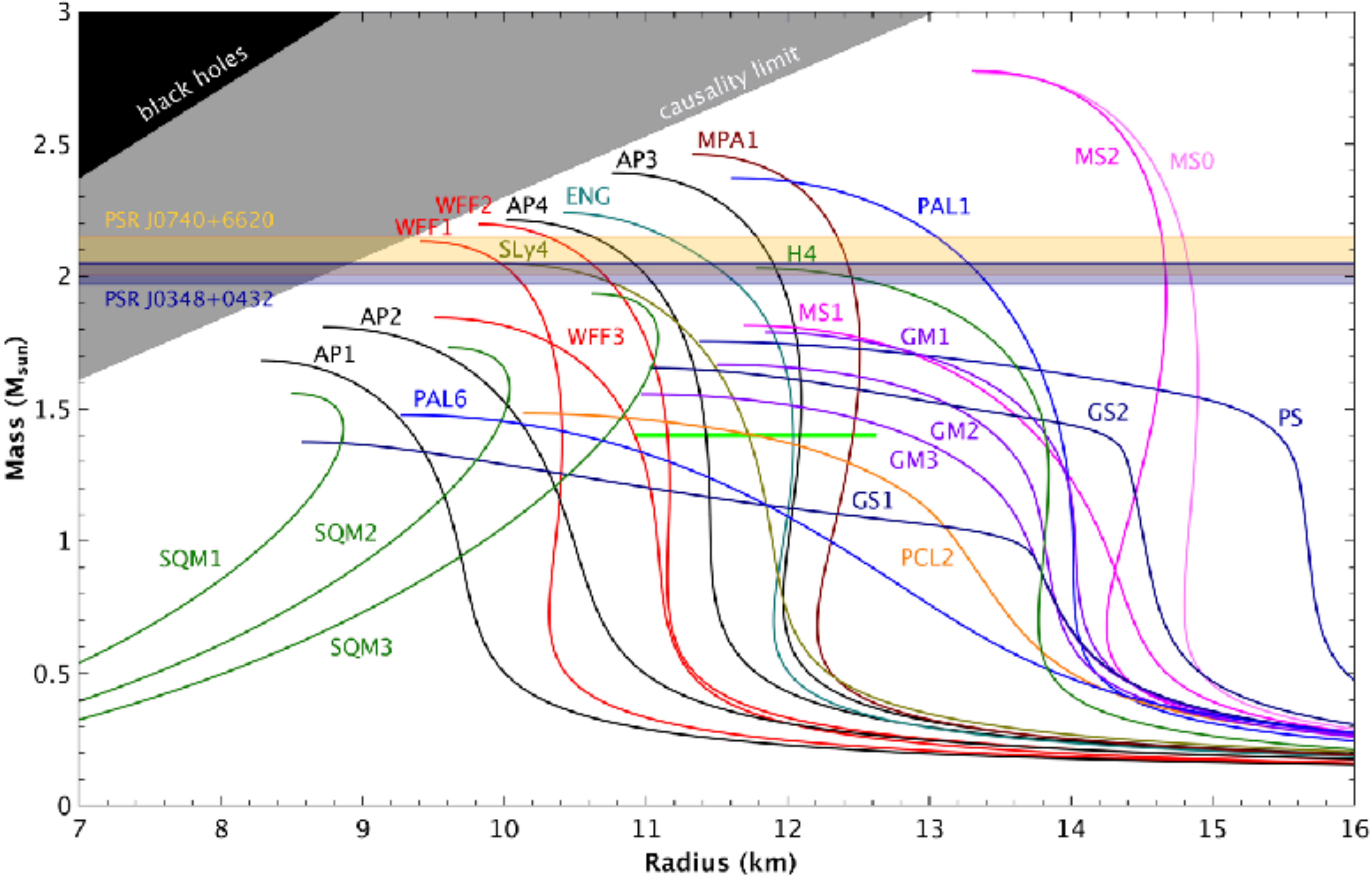
Courtesy of Thankful Cromartie

Massive NS via Shapiro Delay (J1614-2230)

- Demorest et al. 2010: Long-term timing + phase-targeted campaign 1.97 ± 0.04 $M_\odot$
- Fonseca et al. 2016: 1.928 ± 0.017 $M_\odot$
- First ~2 $M_\odot$ NS rules out softer EoS (kaon condensates, etc.)



Courtesy of Thankful Cromartie



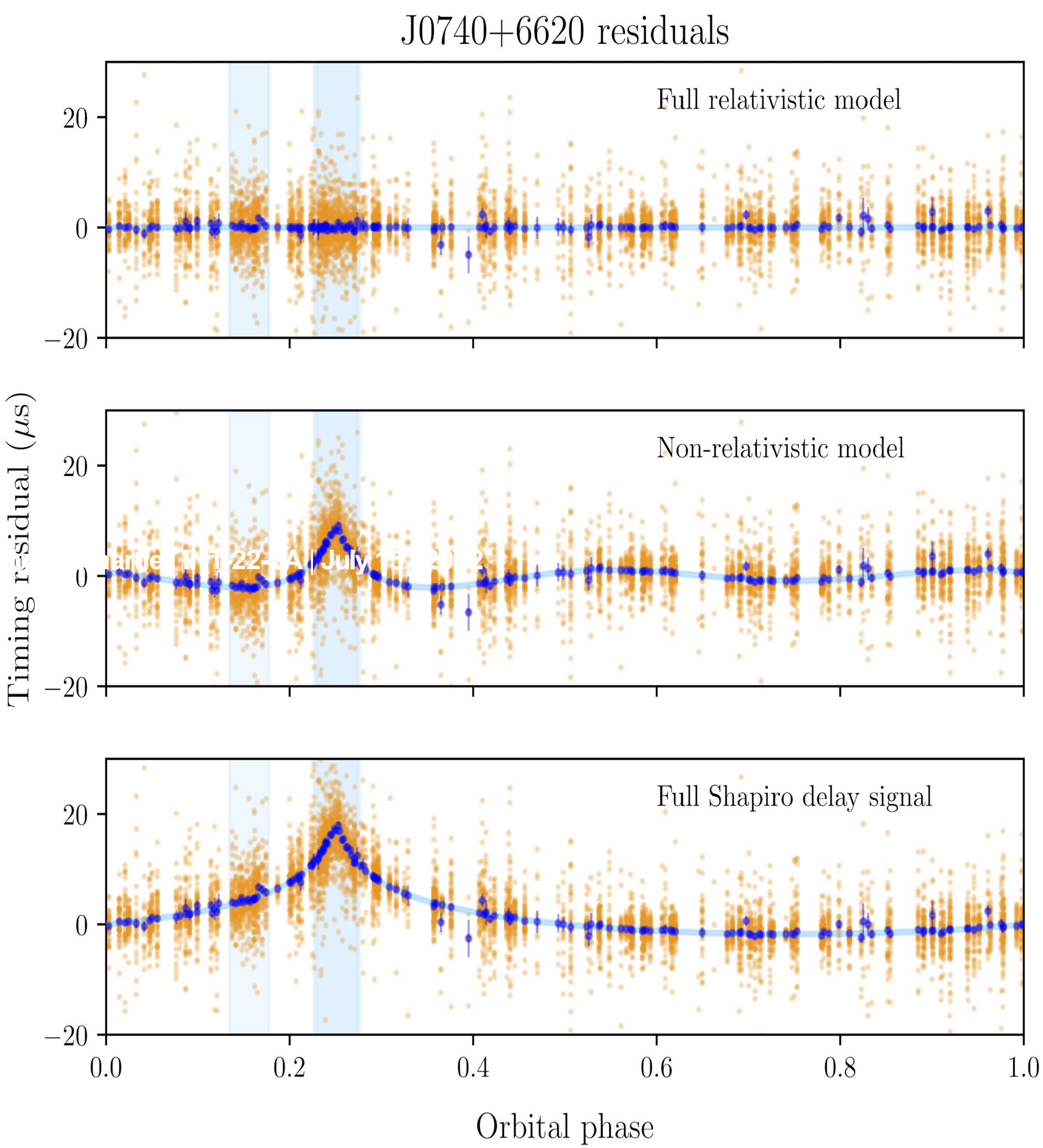
black holes
causality limit
PSR J0740+6620
PSR J0348+0432
MPA1
AP3
MS2
MS0
PAL1
WFF2
AP4
ENG
WFF1
SLy4
H4
AP2
WFF3
MS1
GM1
AP1
PAL6
GS2
PS
GM2
GM3
GS1
SQM2
SQM1
PCL2
SQM3
Mass (M_{sun})
Radius (km)

Massive NS via Shapiro Delay (J0740+6620)

- Found in GBNCC survey (Stovall et al. 2014)
- P = 2.9 ms, P_binary = 4.8 days
- NANOGrav MSP since 2014 that showed hint of Shapiro delay ($2.0 \pm 0.2\ M_{\odot}$)
- GBT 6-hr supplemental campaign targeted conjunction; saw significant Shapiro delay (yielded $2.18 \pm 0.15\ M_{\odot}$ combined with NANOGrav data)
- Random orbital sampling wasn't enough

Courtesy of Thankful Cromartie

Massive NS via Shapiro Delay (J0740+6620)

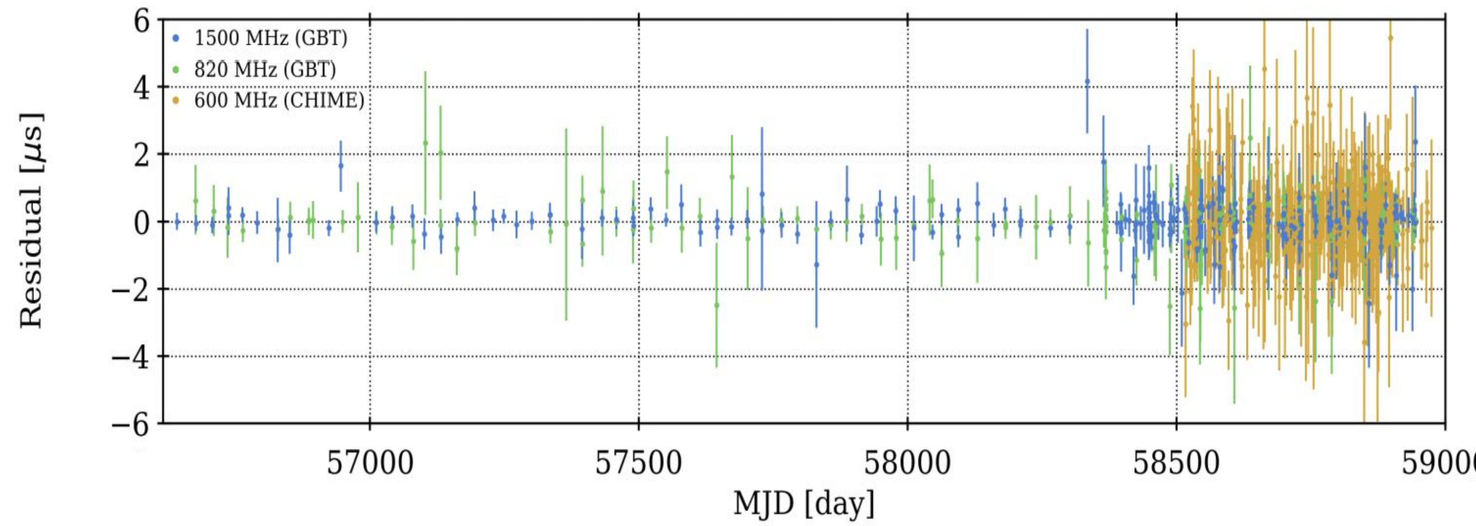


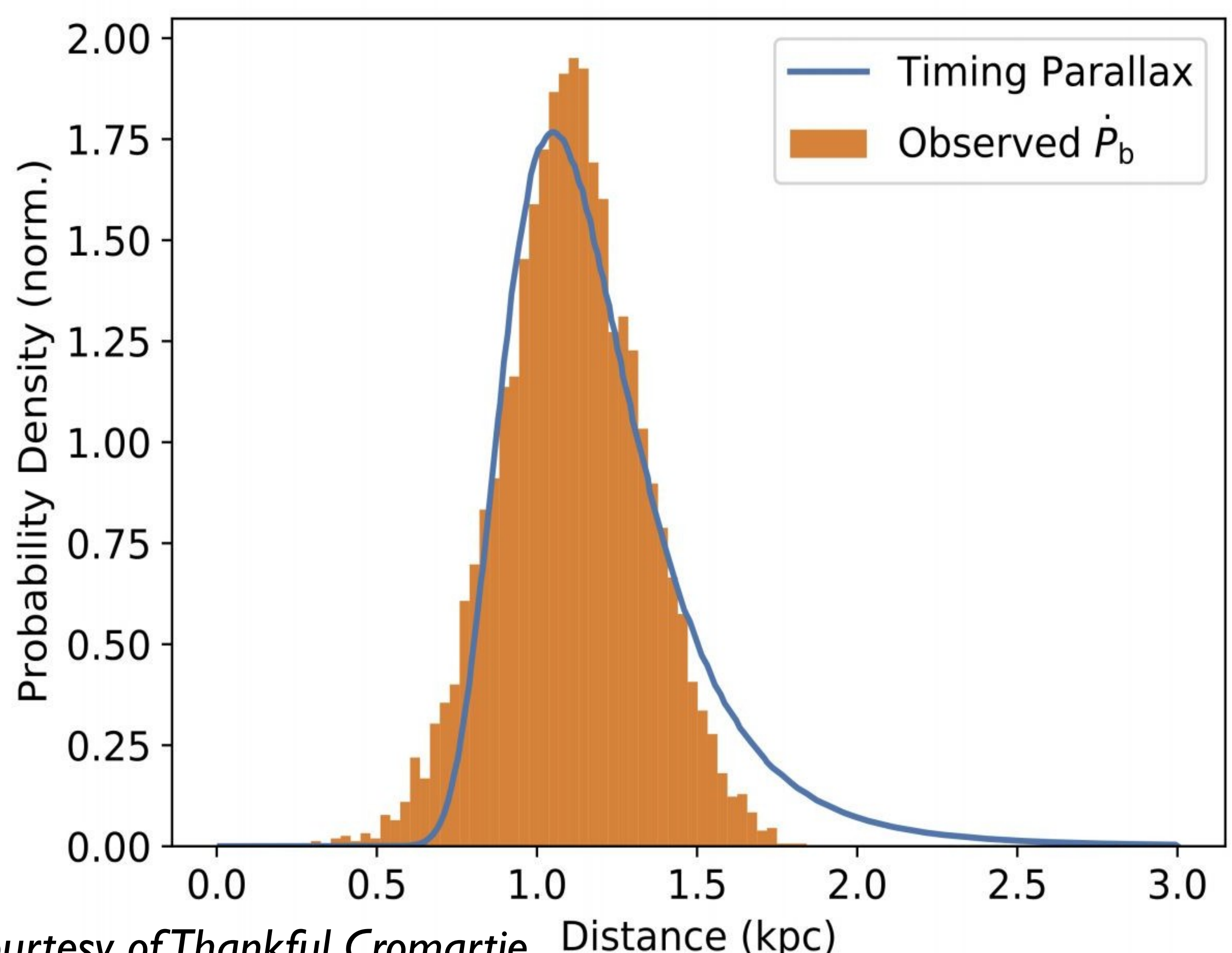
NANOGrav + targeted campaigns, m ~2.14 ± 0.09 solar mass (Cromartie et al. 2020)

Courtesy of Thankful Cromartie

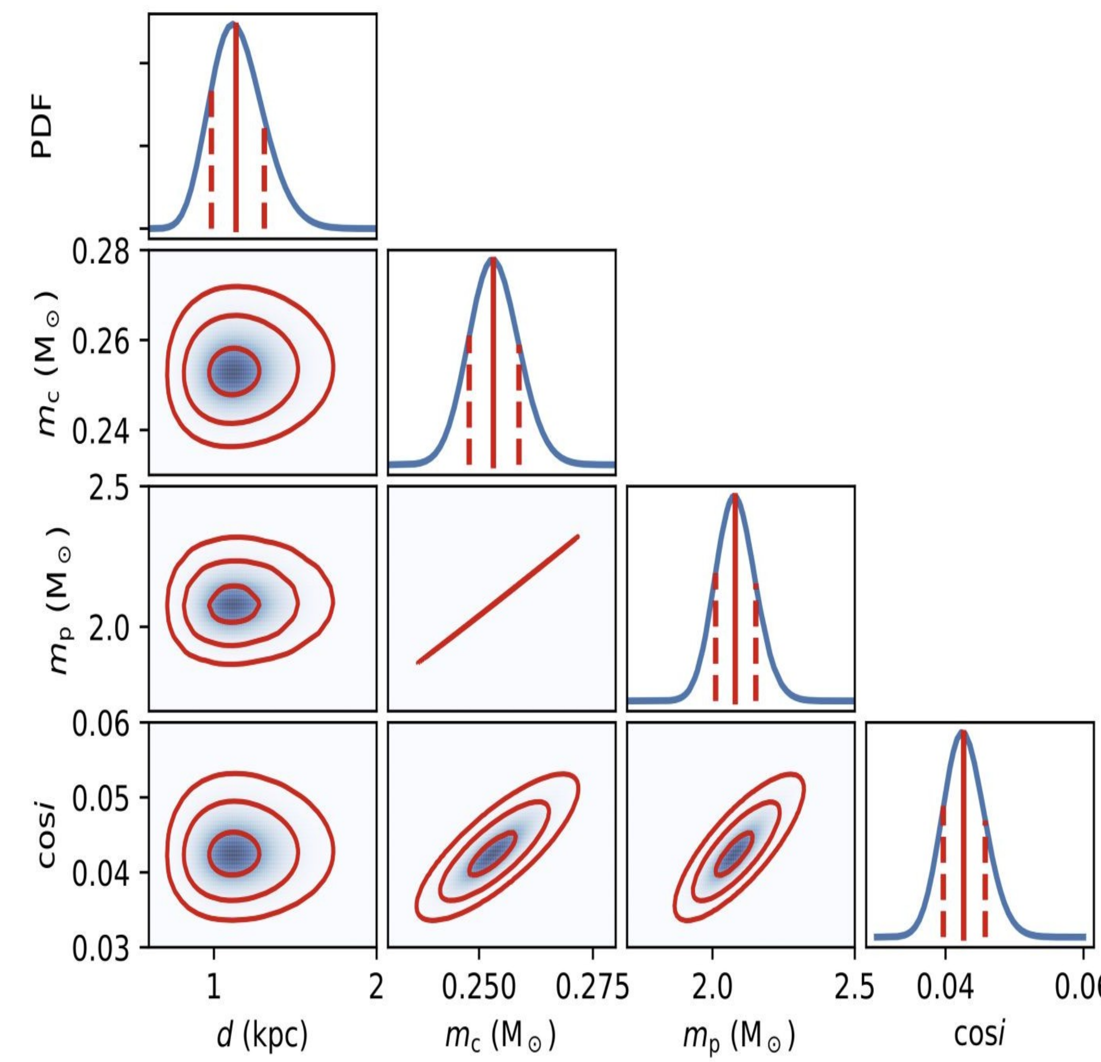
Massive NS via Shapiro Delay (J0740+6620)

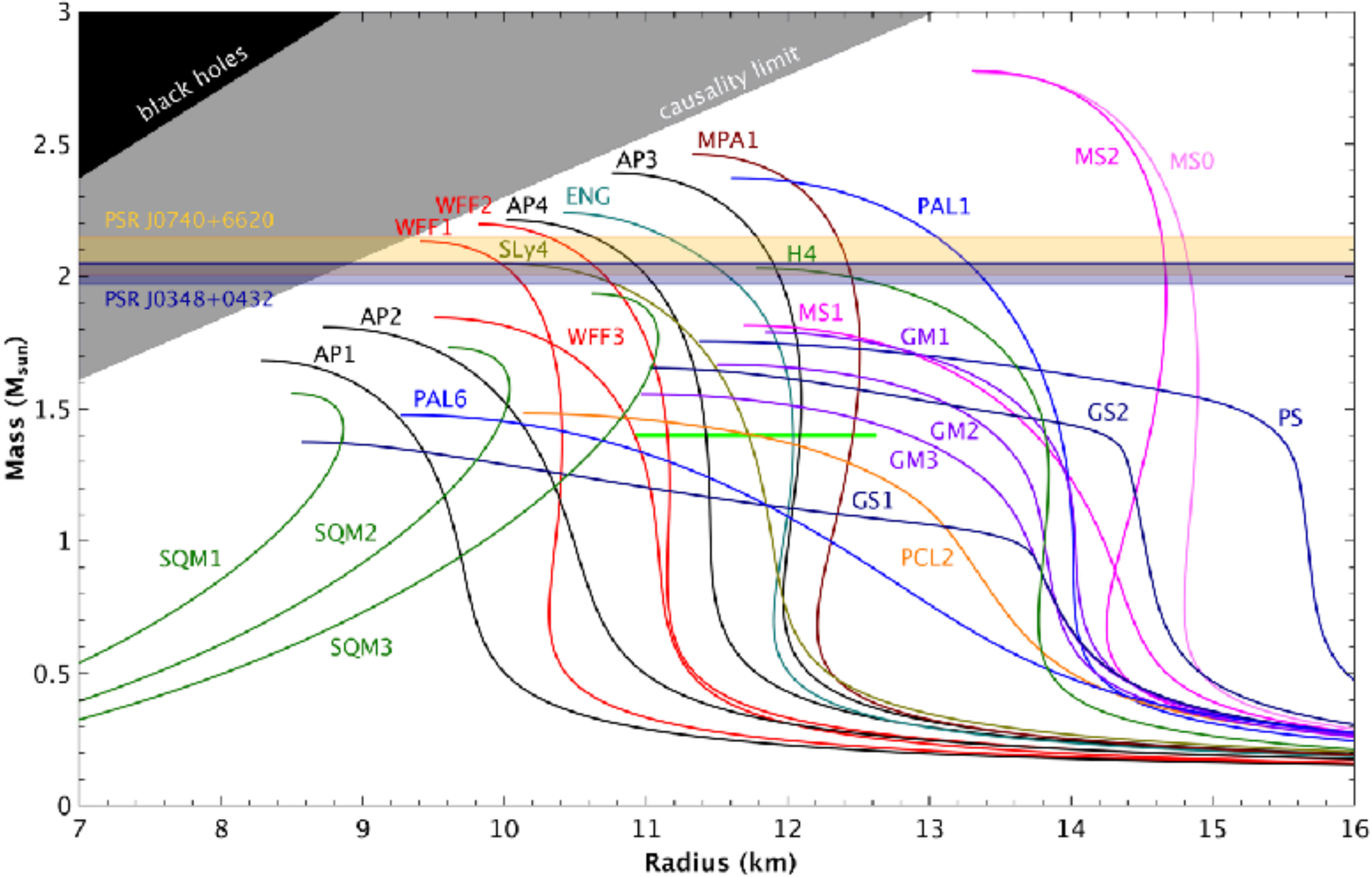
- Updated in Fonseca et al. 2021
- Additional 1.5 years of GBT w/NANOGrav at high cadence
- 1.5 years daily CHIME observations $2.08 \pm 0.07\,M_\odot$,
- Used in NICER analysis.





Courtesy of Thankful Cromartie





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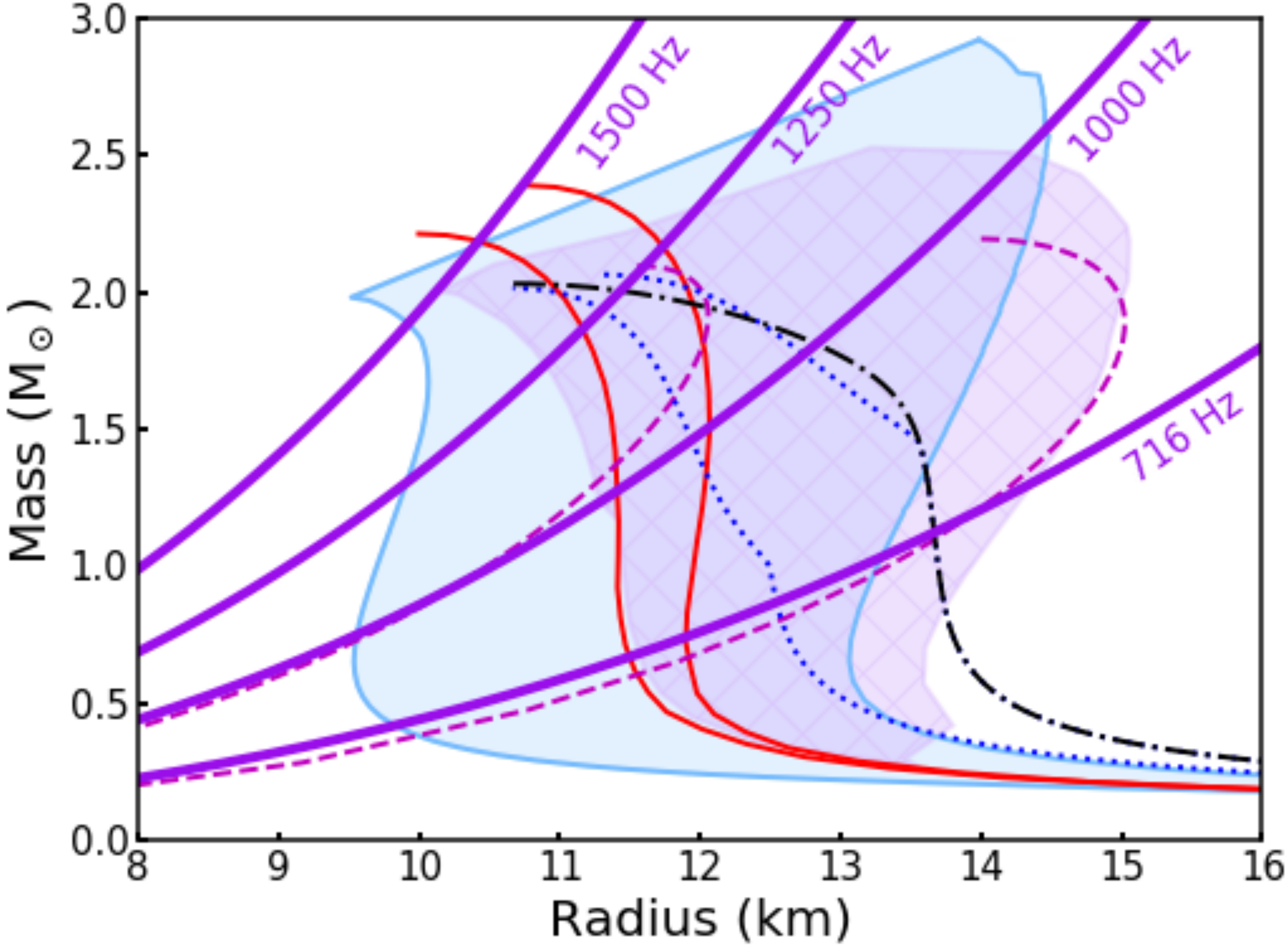
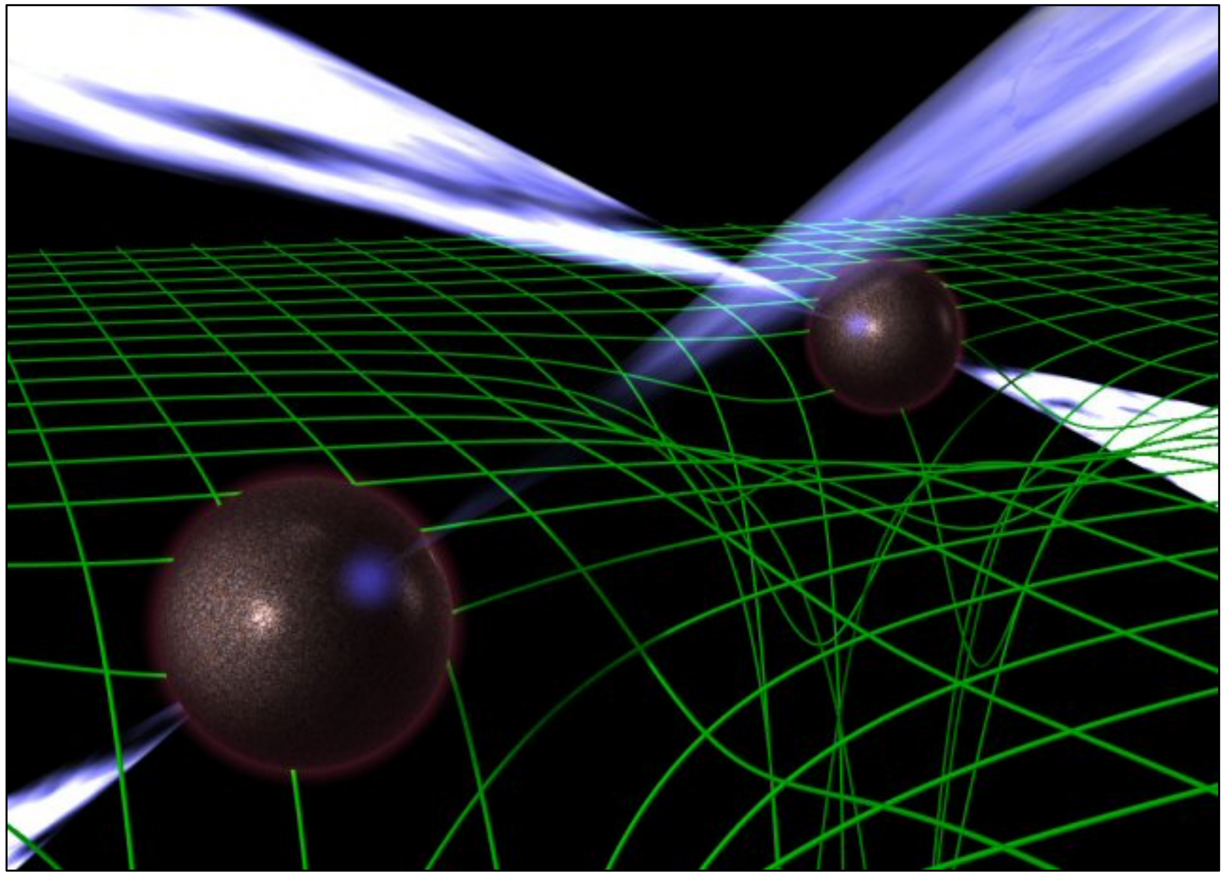
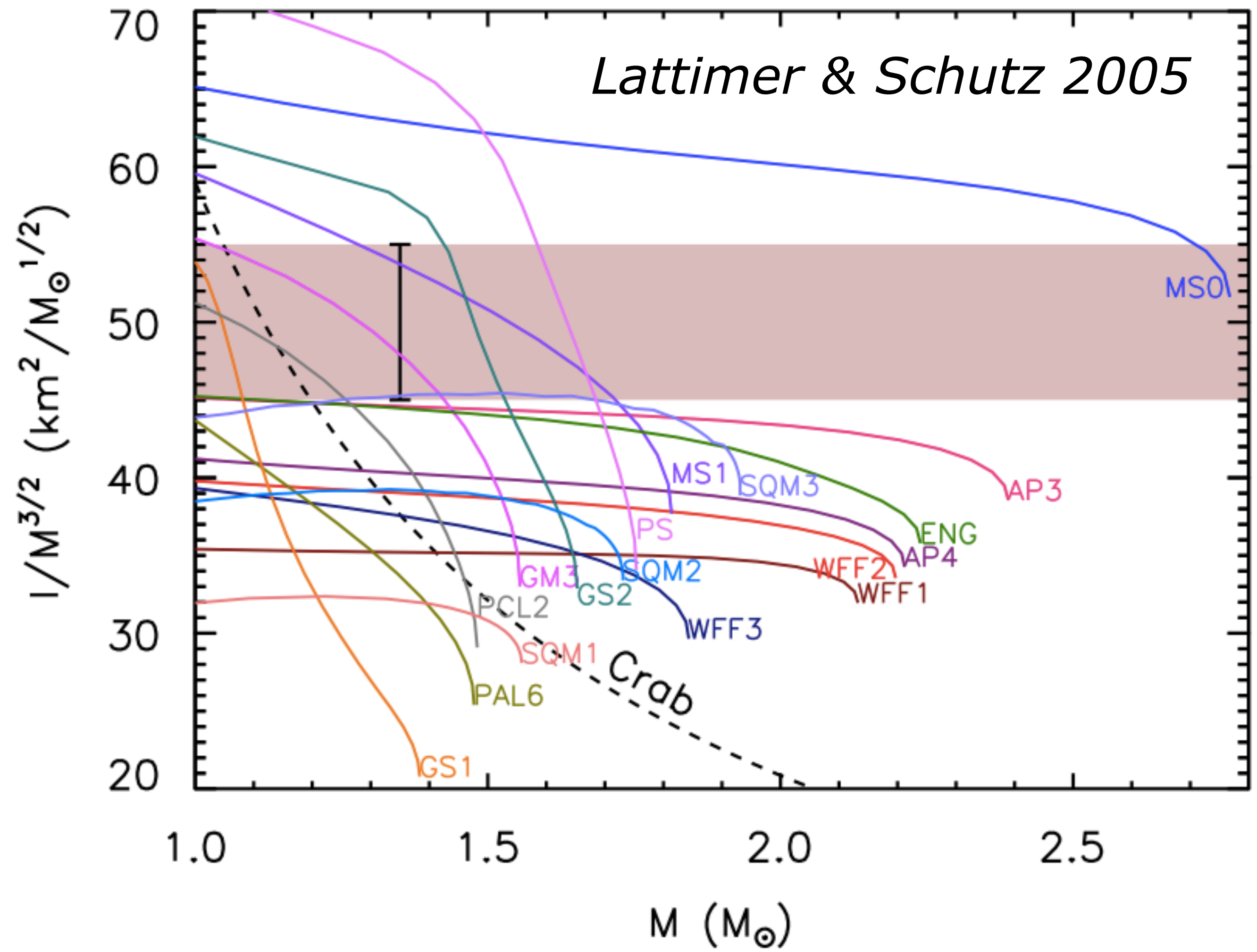
GM1
AP1
PAL6
GS2
PS
GM2
GM3
GS1
SQM2
SQM1
PCL2
SQM3
Mass (M_{sun})
Radius (km)
3
2.5
2
1.5
1
0.5
0
7
8
9
10
11
12
13
14
15
16

Constraints from spins



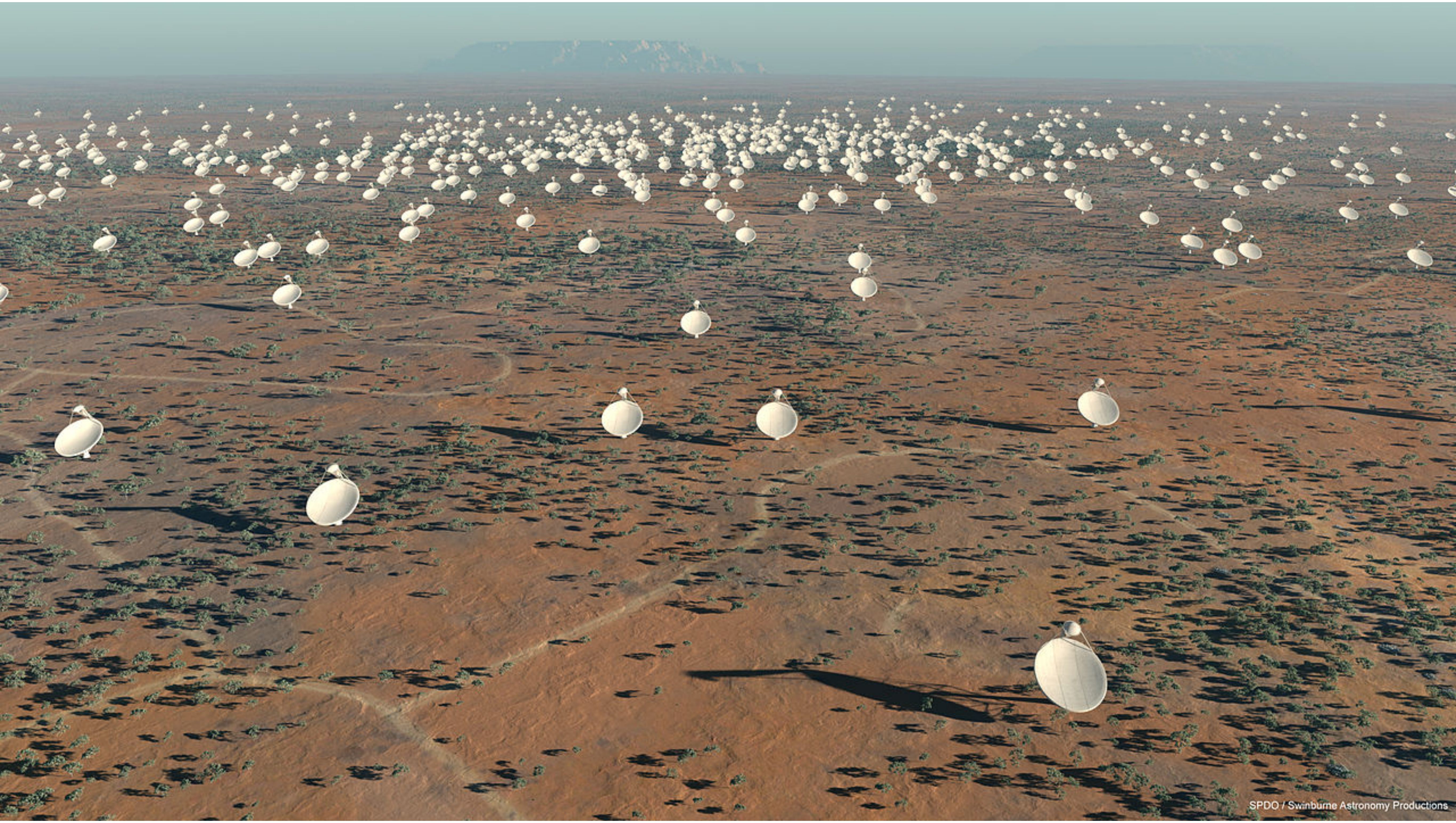
Moments of inertia

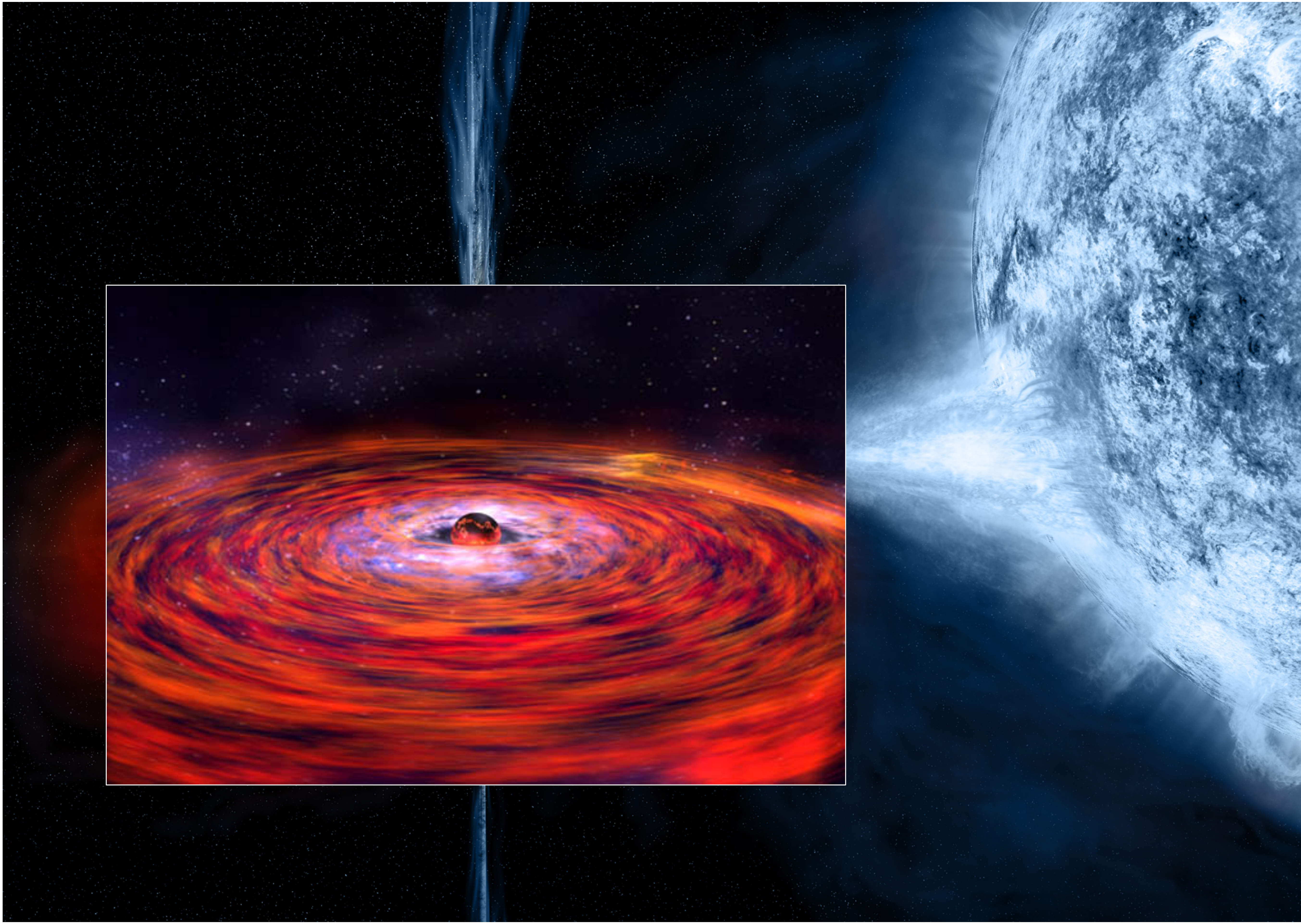




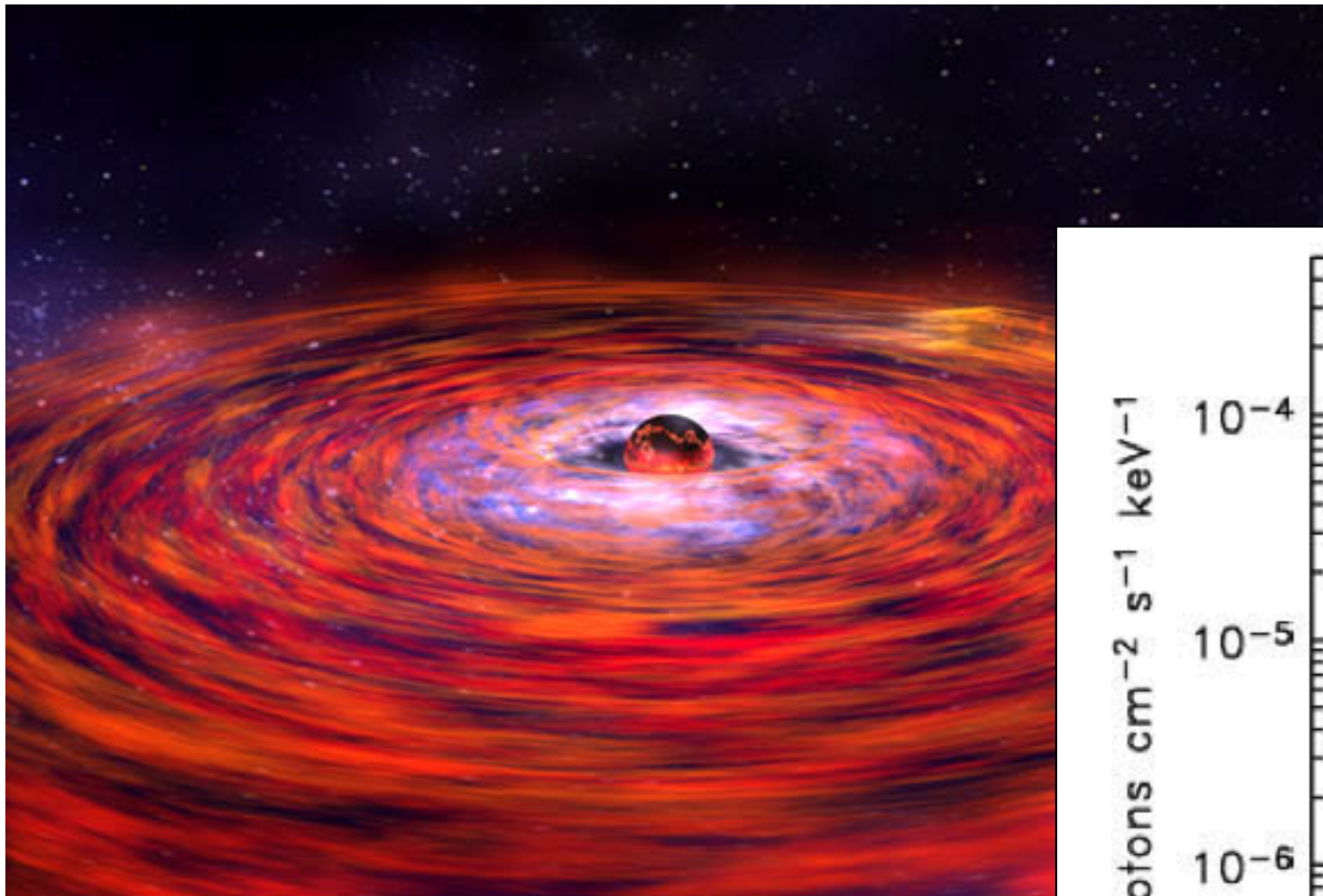
- Requires highly relativistic binaries.
- For the Double Pulsar, SKA will allow I to be measured to ±10% over next 20 years. This gives R to ±5%.
- SKA may lead to discovery of other double neutron star systems with favourable parameters (see Watts et al. 2015)

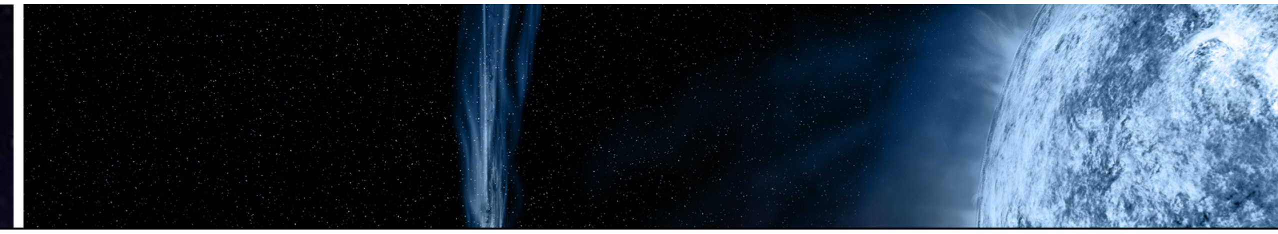
The future: Square Kilometer Array

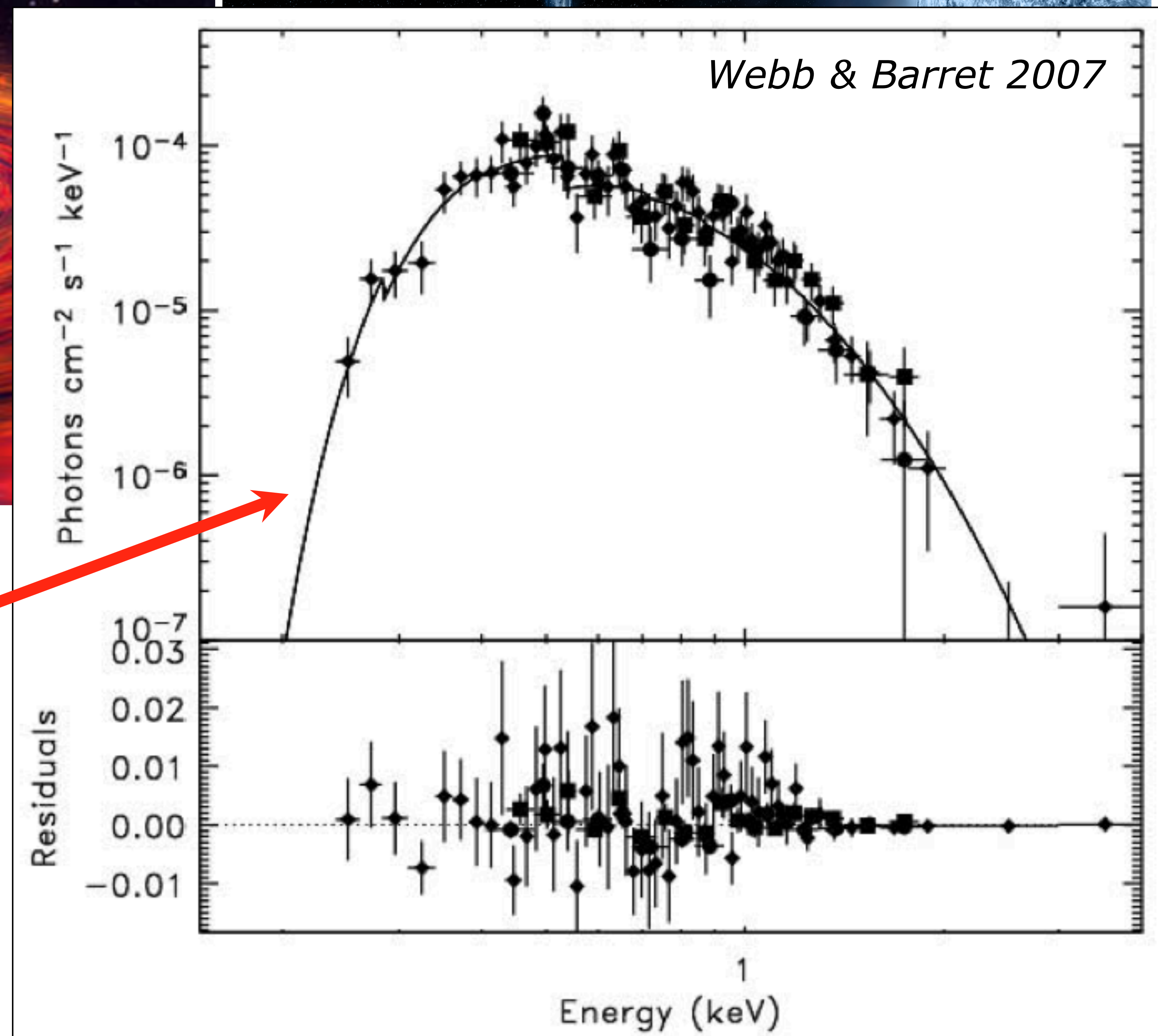




X-ray spectral modelling (quiescence)





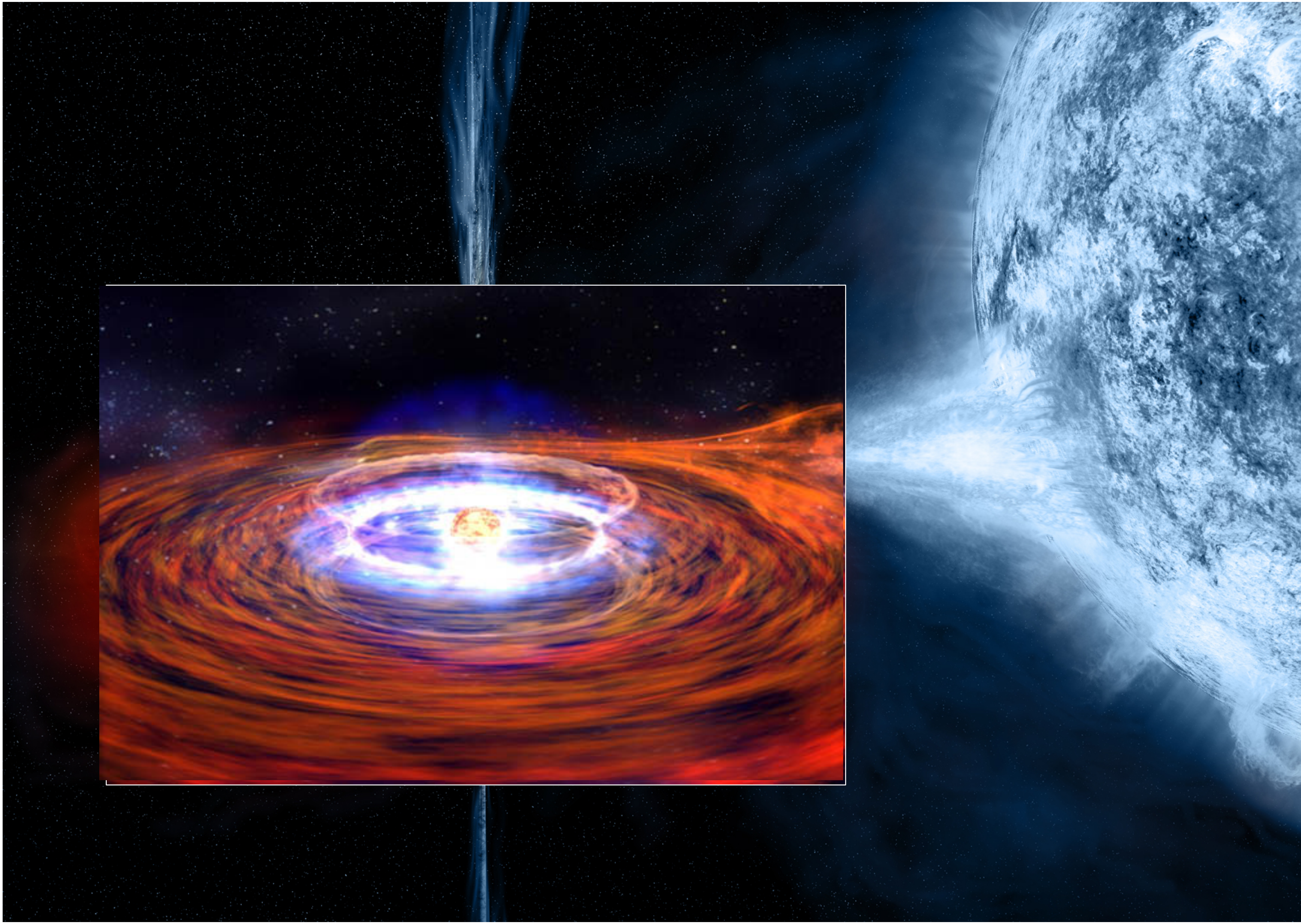


Accretion off - thermal spectrum from NS.

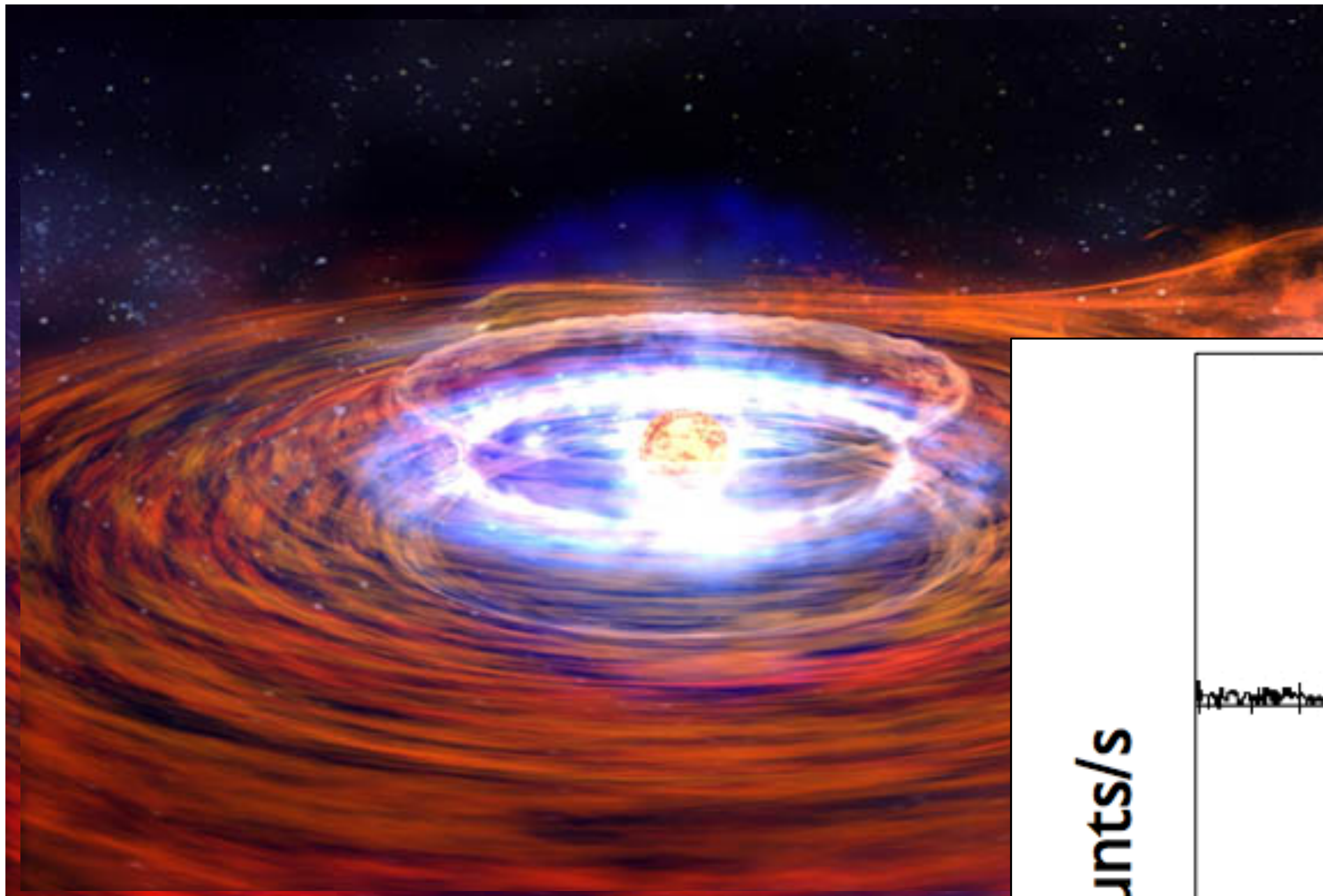
$$L = 4xR^2 a T_{\rm eff}^4 \longrightarrow F = \left(\frac{R}{D}\right)^2 a T_{\rm eff}^4$$

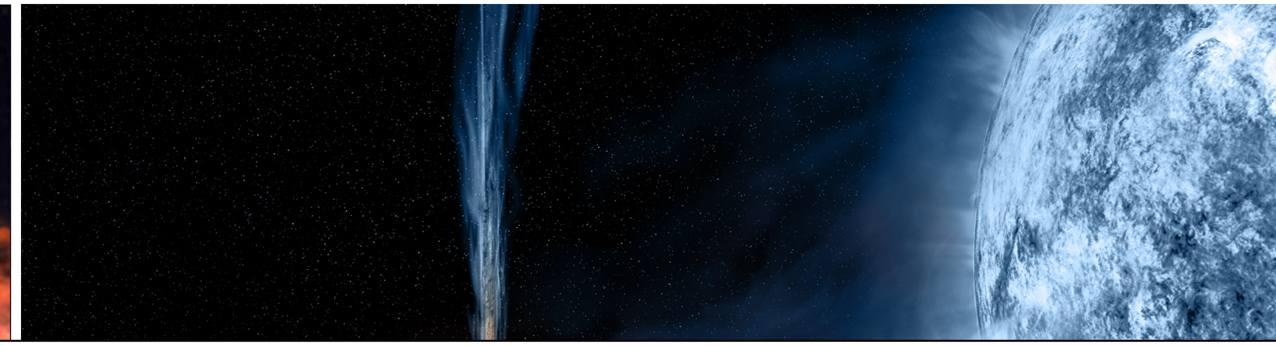
Example constraints: quiescent NS

Guillot et al. 2013

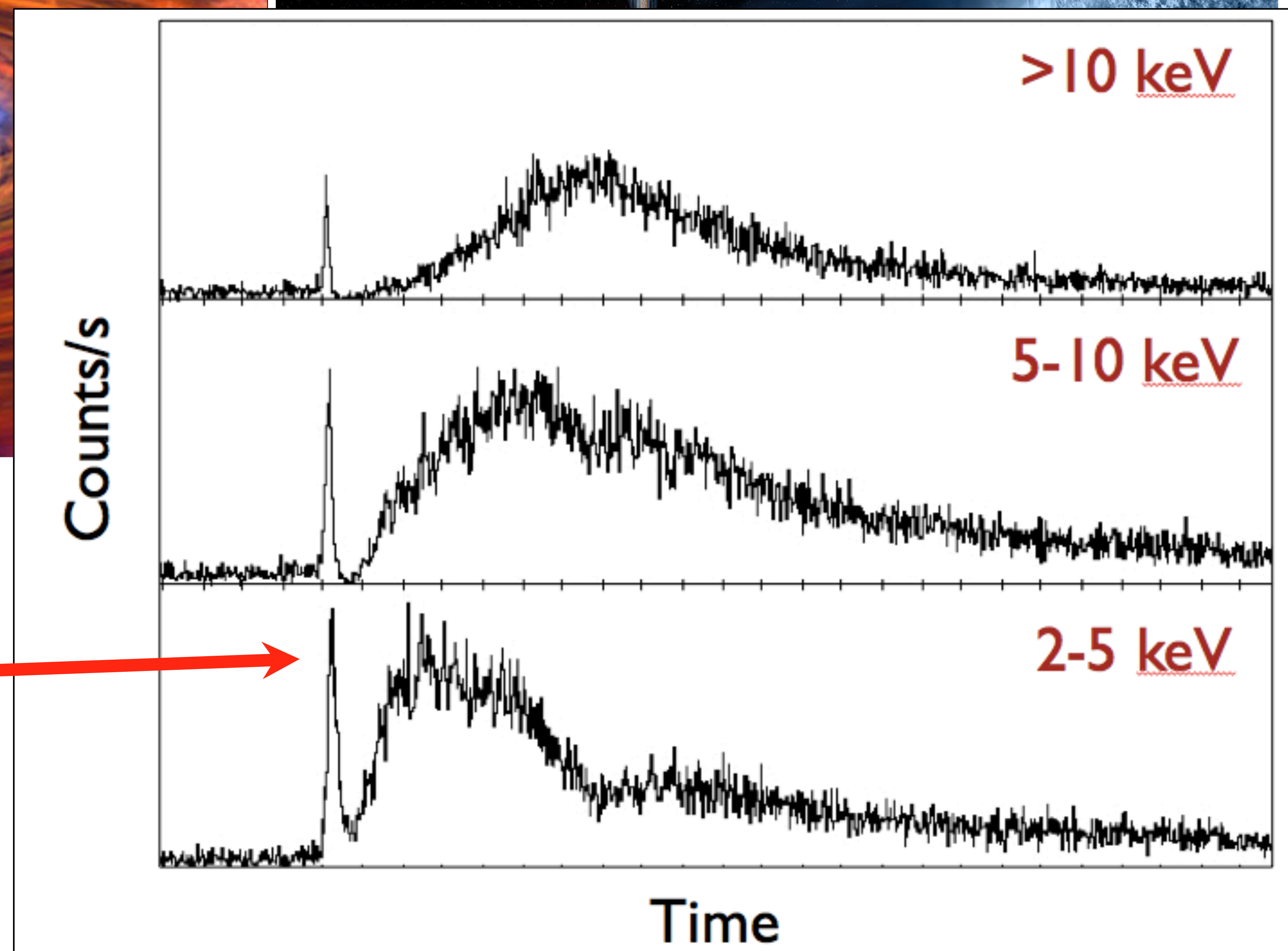


X-ray spectral modelling (bursts)

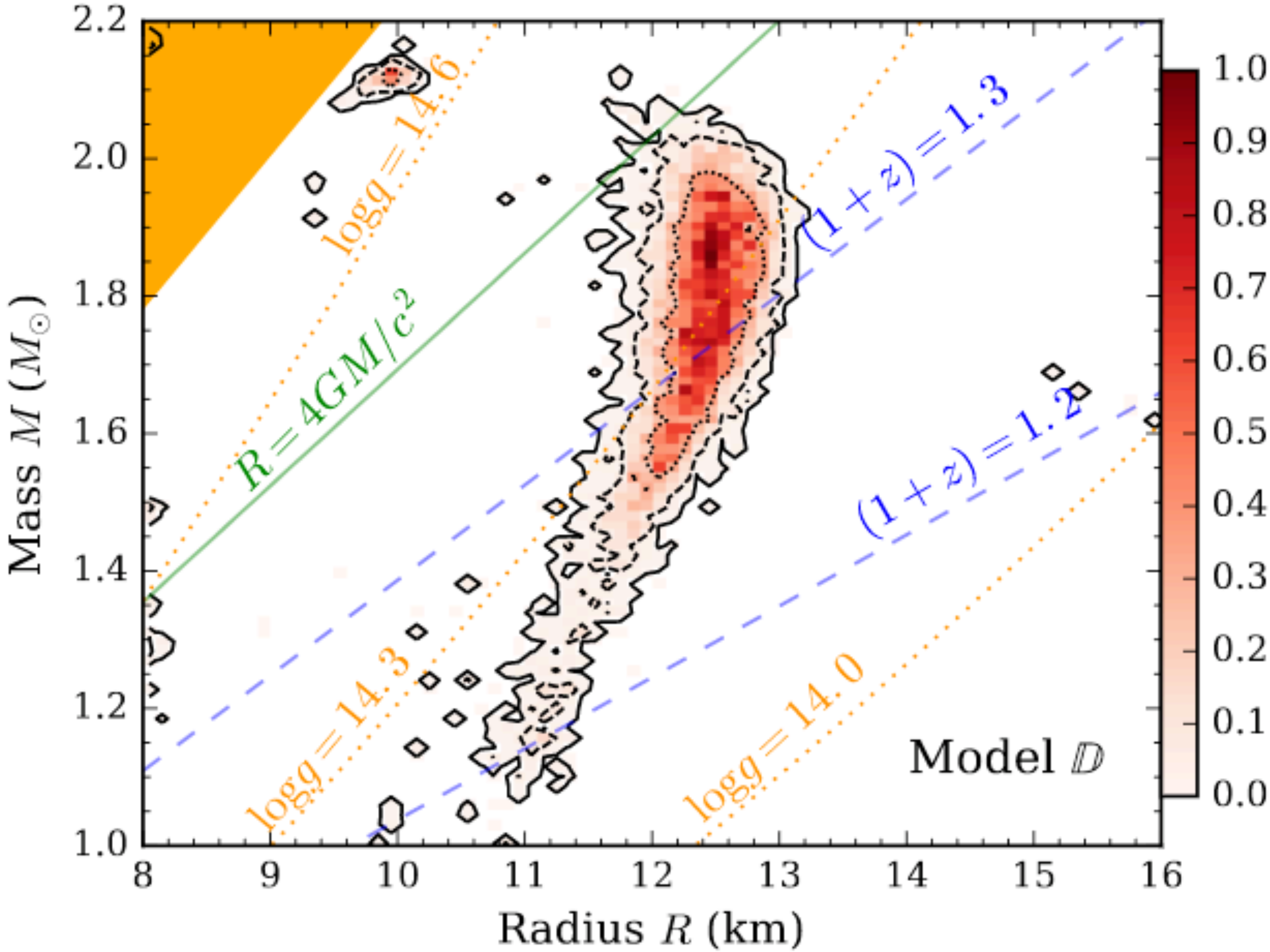




Accretion on: bright thermonuclear bursts with Photospheric Radius Expansion

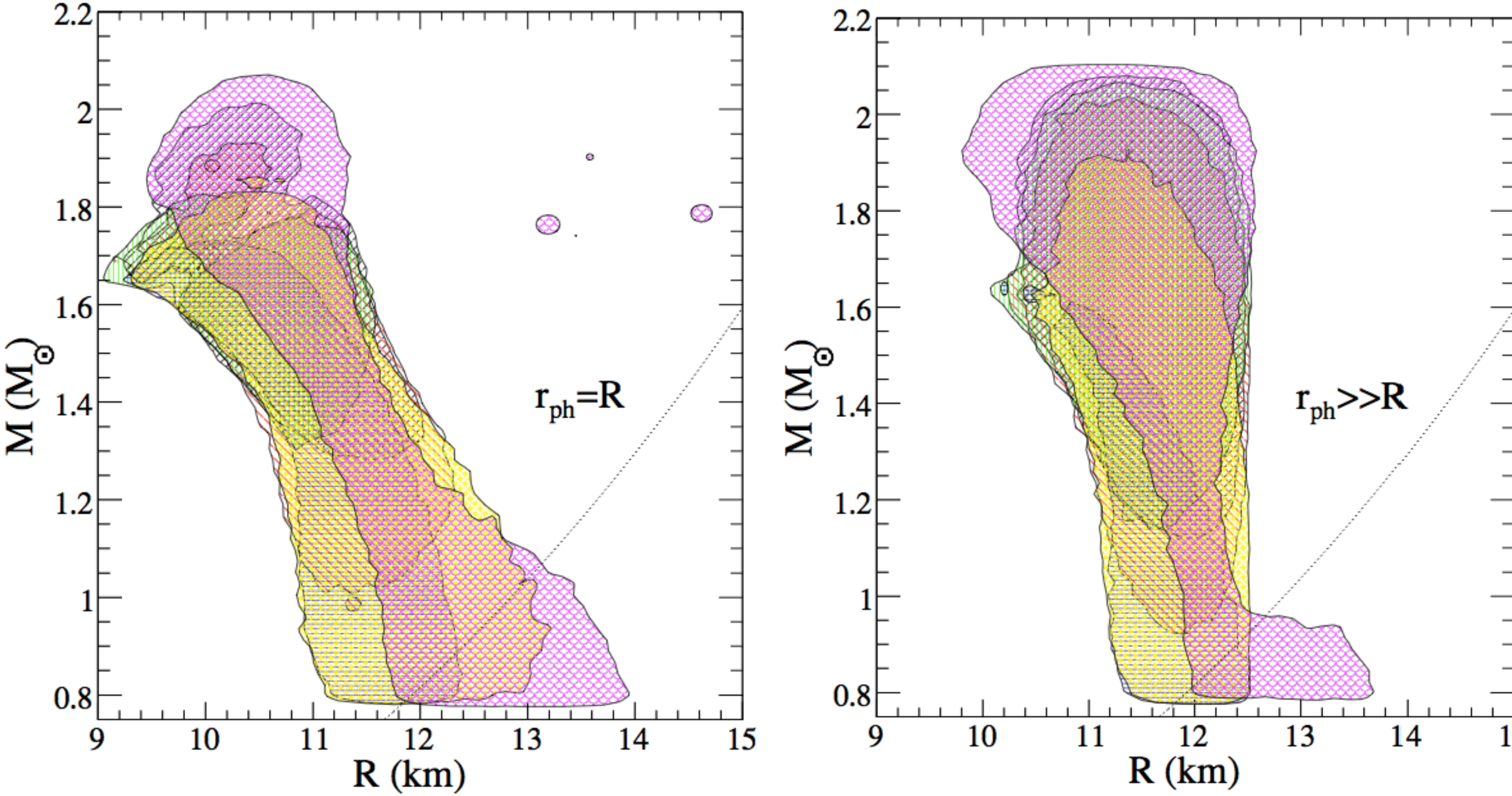


Example constraints: bursts



Nattila et al. 2017

Example constraints: combined



Steiner et al. 2013

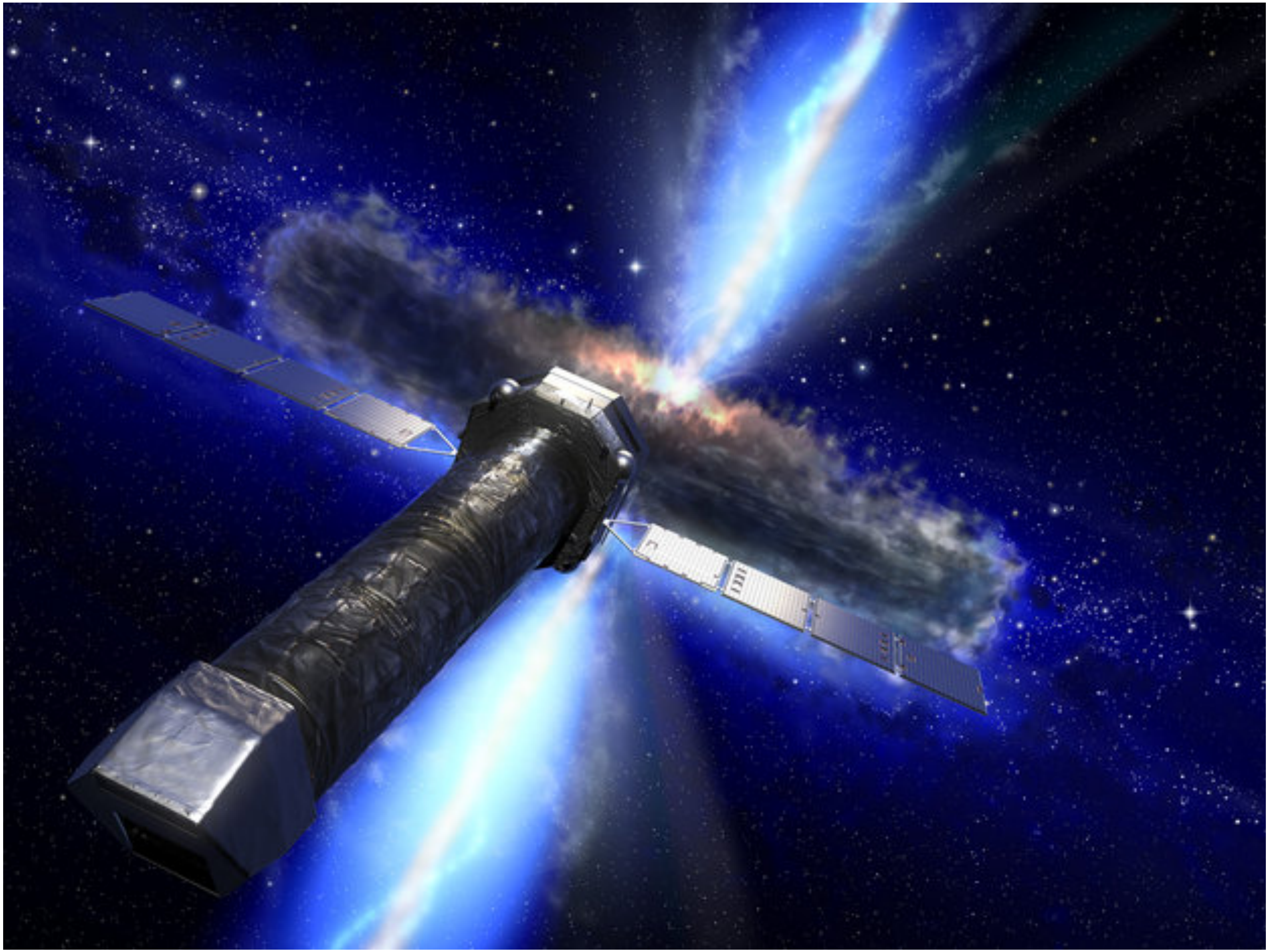
For review of X-ray spectral techniques see Miller 2013

There remains some discussion points and possible caveats!

- Why only use qLMXBs in globular clusters ? → Field LMXB may not return to full quiescence
- What is the **composition** of the neutron star atmosphere ? → Hydrogen, Helium or something else
- Is the **surface magnetic** field really negligible ? → No measurement, but expected for LXMBs
- Is the emission really from the **entire surface** ? → No constraints exist, but …
- What are the effects of assuming **slowly rotating** neutron stars? → Fast rotation may bias the R measurement

Courtesy of Sebastien Guillot

The future: Athena X-ray Observatory



PPM WITH ACCRETING NS?

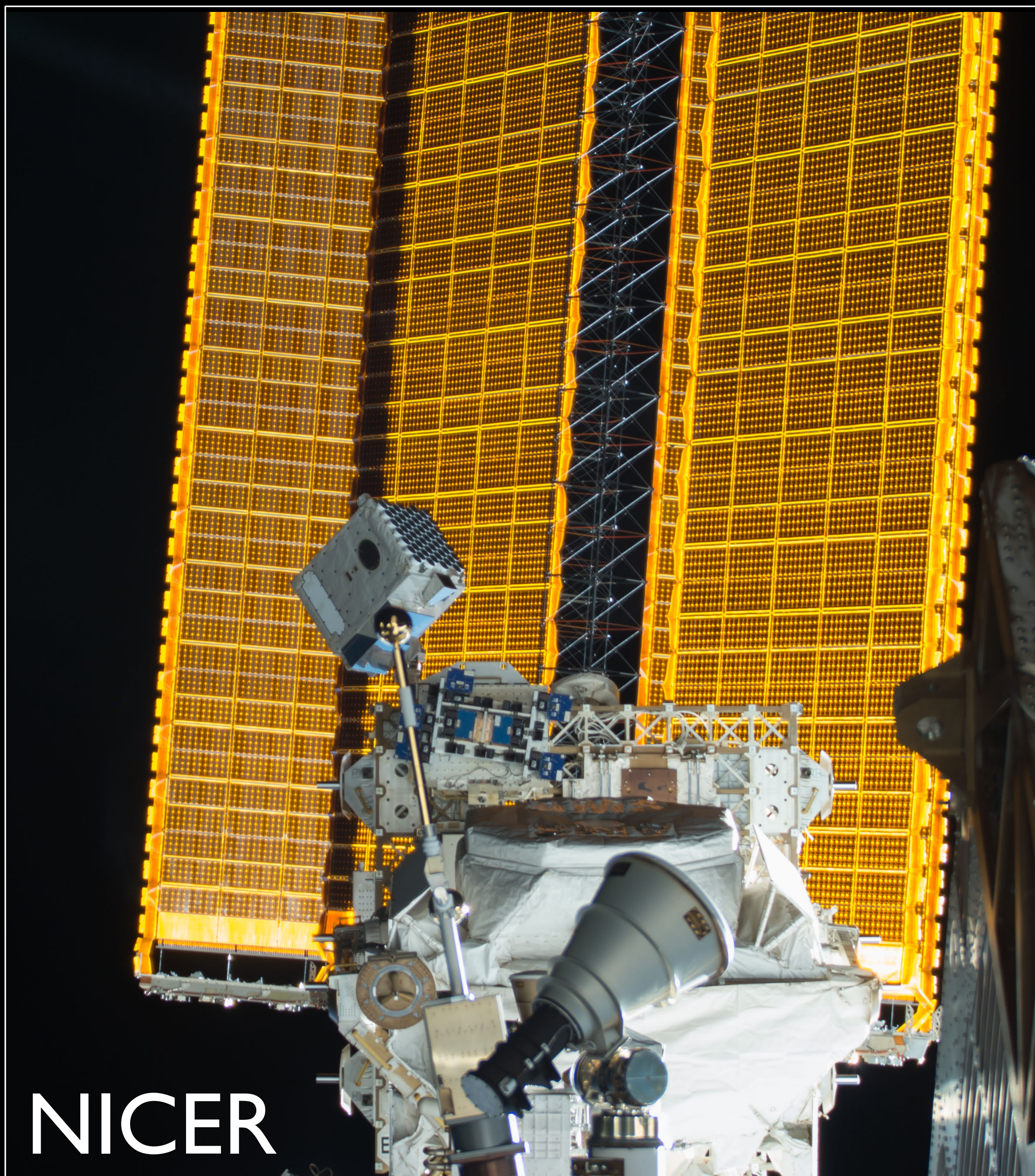
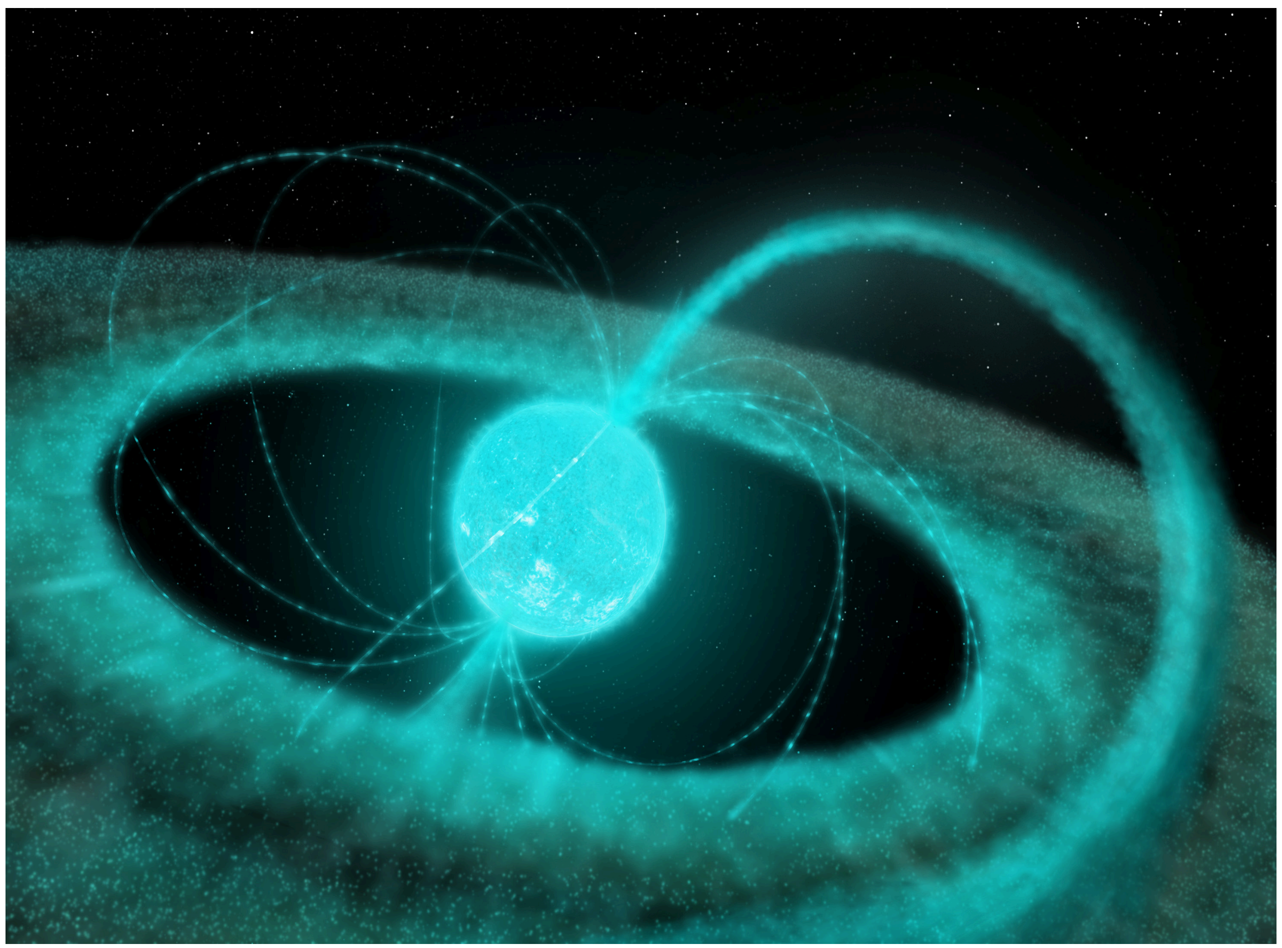


Image credits: NASA

PPM FOR ACCRETING NS

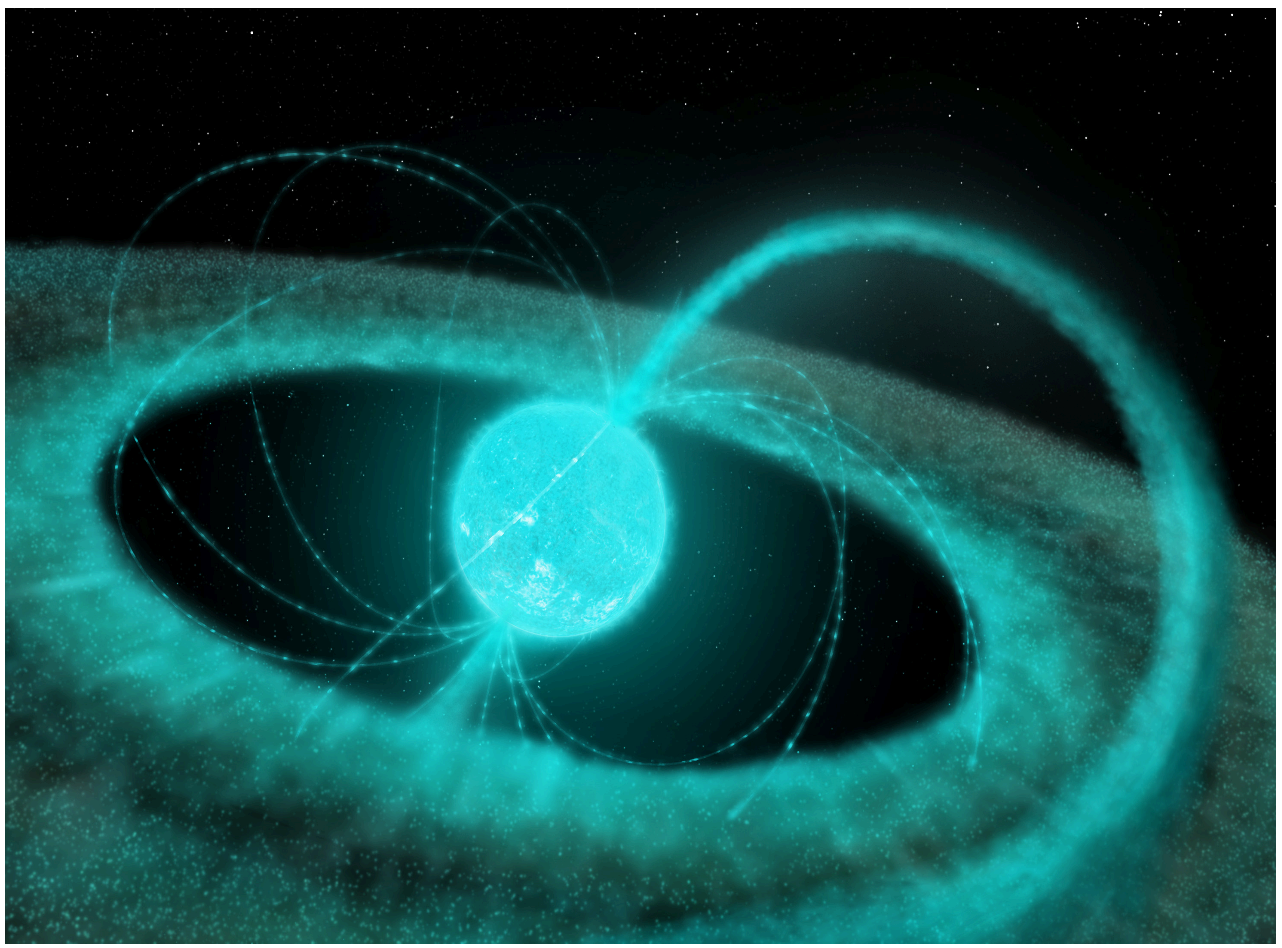
The relativistic effects pulse profile modeling exploits are larger for the more rapidly-rotating **accreting** neutron stars.



New astrophysical modeling and analysis challenges!

CAN X-RAY POLARIMETRY HELP?

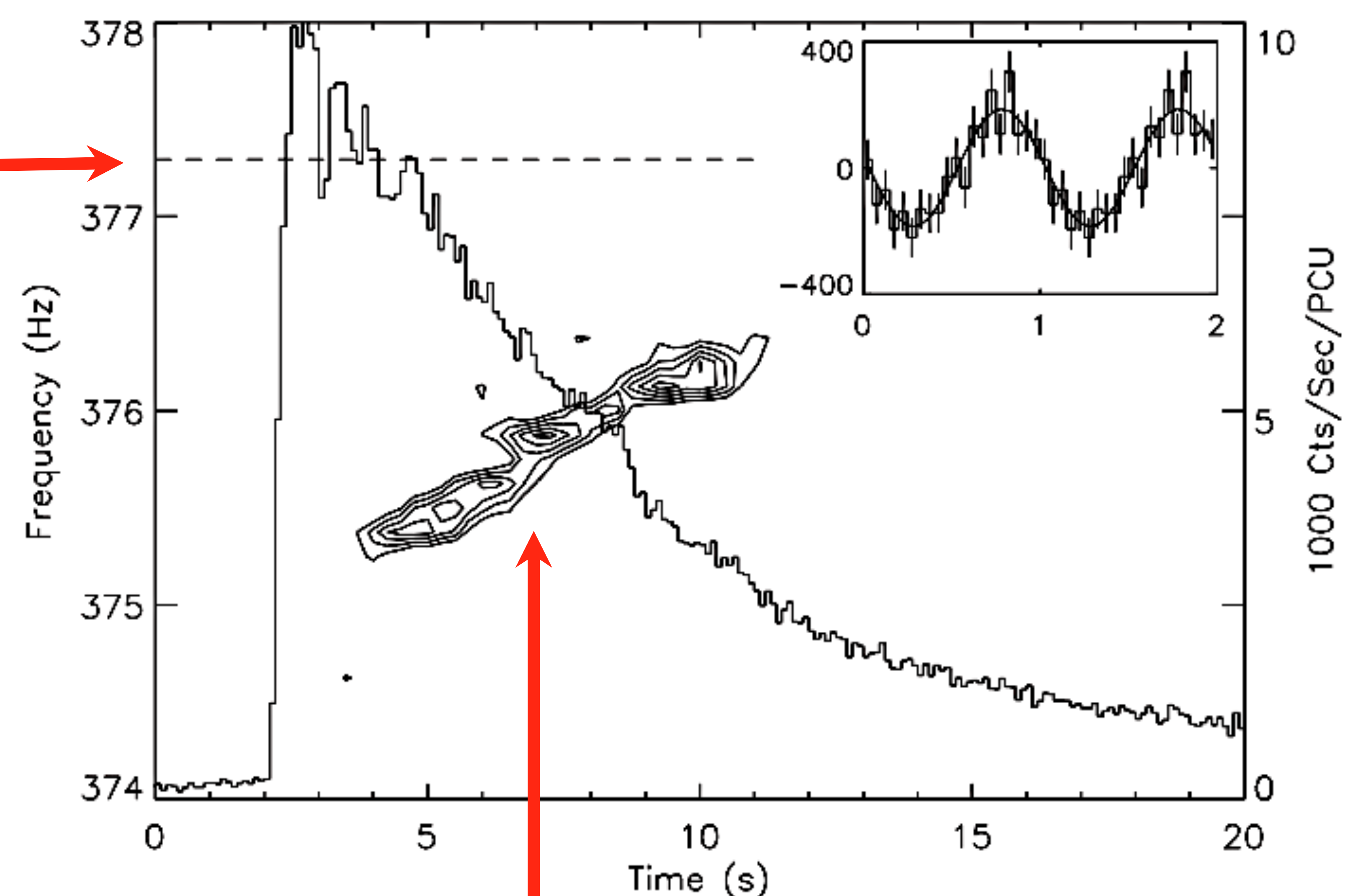
X-ray polarimetry may help to constrain geometry (e.g. inclination) for accreting neutron stars, especially the pulsars



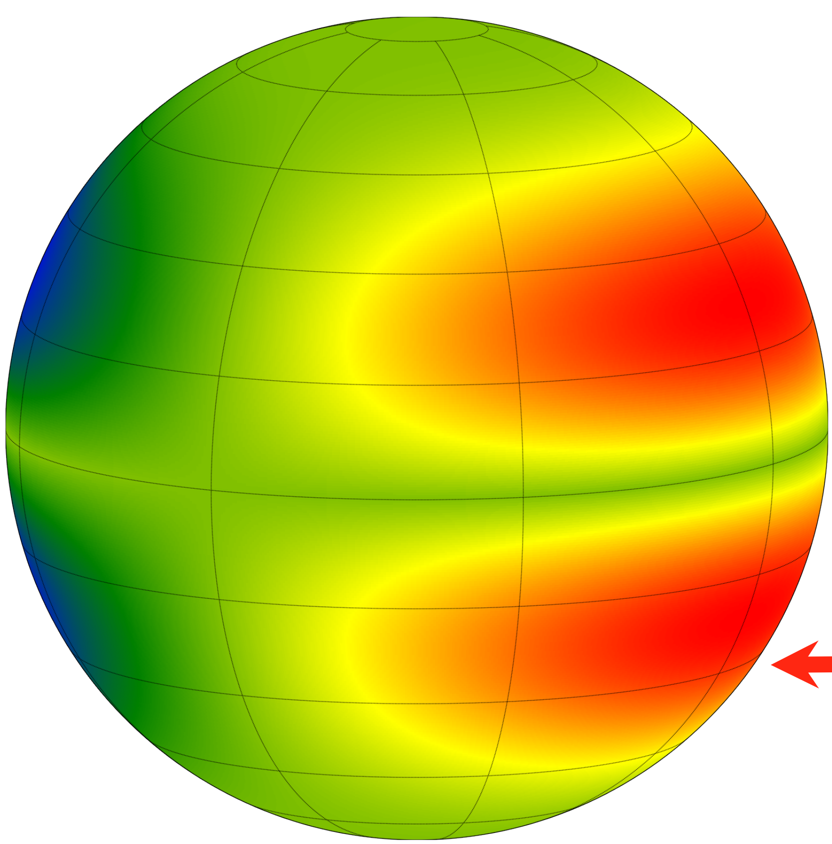
IXPE, launched December 2021

SPOTS ARE DYNAMIC

Spin frequency

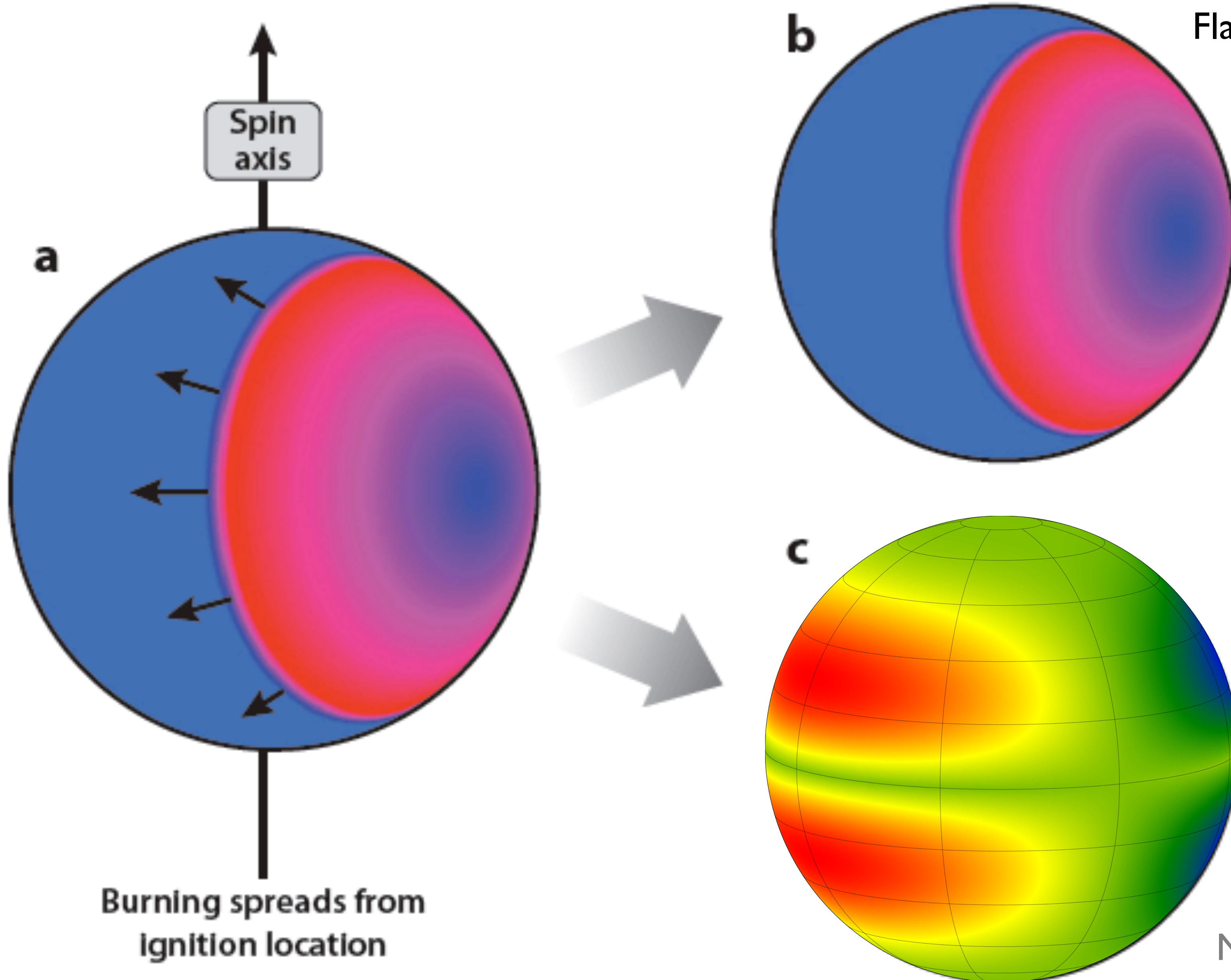


Watts et al. 2009



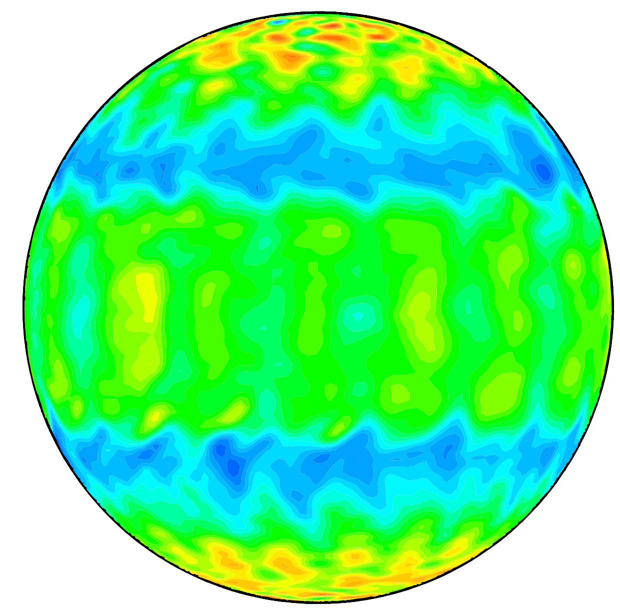
Drifting hotspot

SURFACE PATTERN MODELS



Model 1:
Flame spread stalls

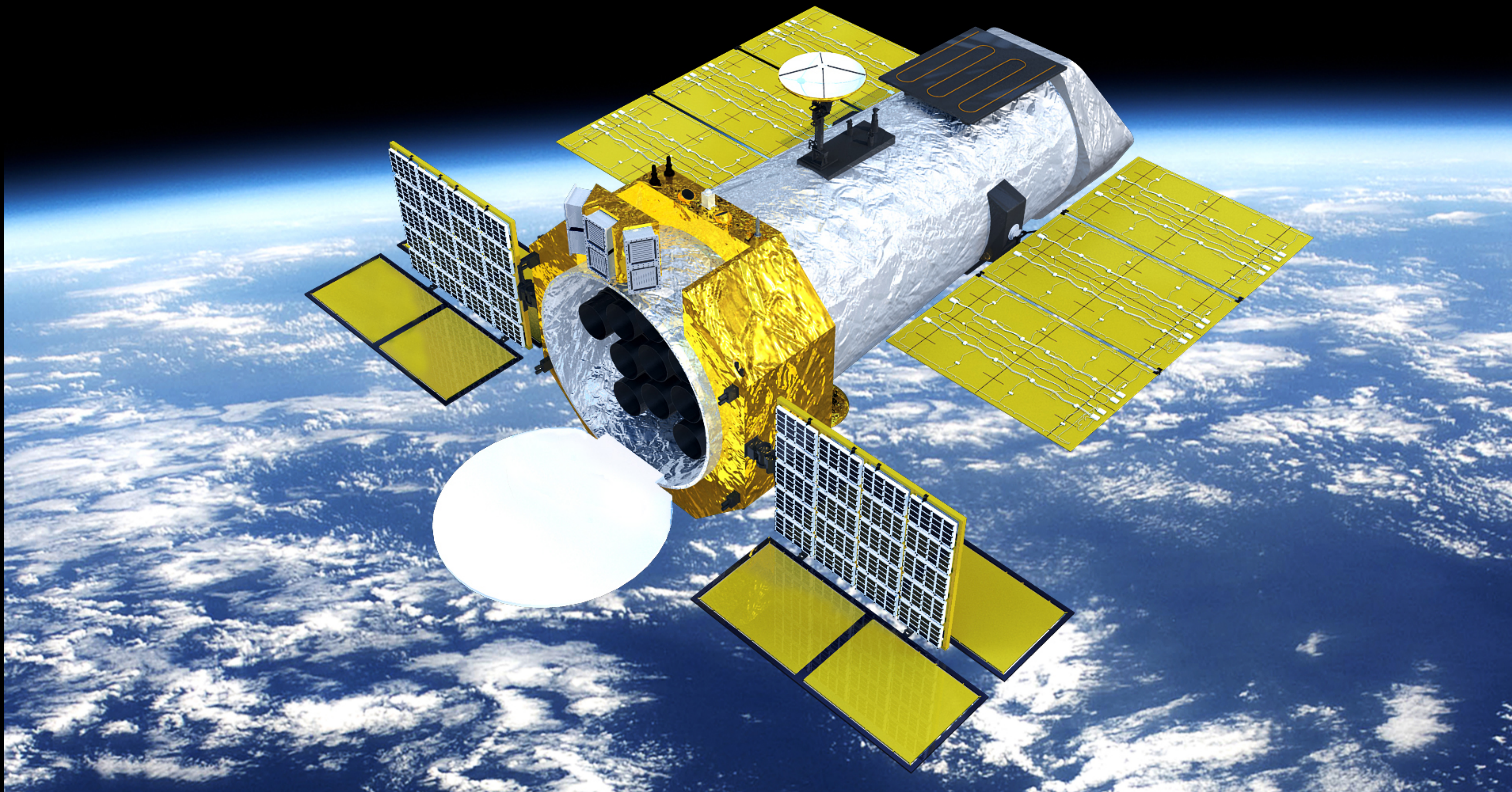
Model 2:
Large-scale waves

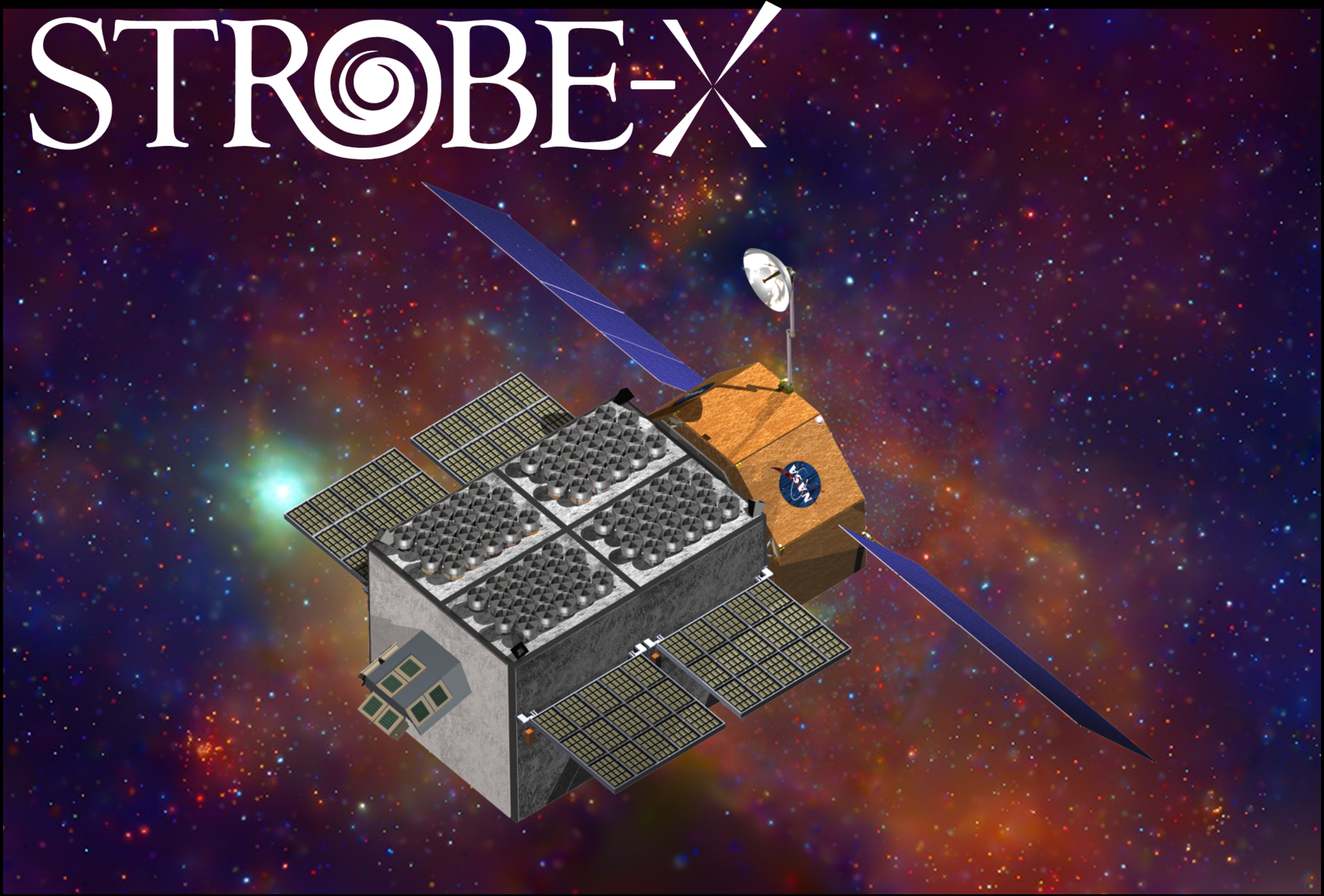


Model 3:
Convective patterns
and zonal flows

Some recent papers: Garcia et al. 2018a,b, 2019, 2020, Bilous et al. 2018, Bilous & Watts 2019, Chambers et al. 2018, 2019, Chambers & Watts 2020, van Baal et al. 2020, Goodwin et al. 2021, Cavecchi & Spitkovsky 2019, Cavecchi & Patruno 2022, Harpole et al. 2021.

Enhanced X-ray Timing and Polarimetry (eXTP) mission





Probe class observatory Ray et al. 2019. Follow @STROBEXAstro on Twitter.