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Mass-radius constraints on the EOS using phase-resolved X-ray observations of neutron stars including prospects for X-ray polarimetry

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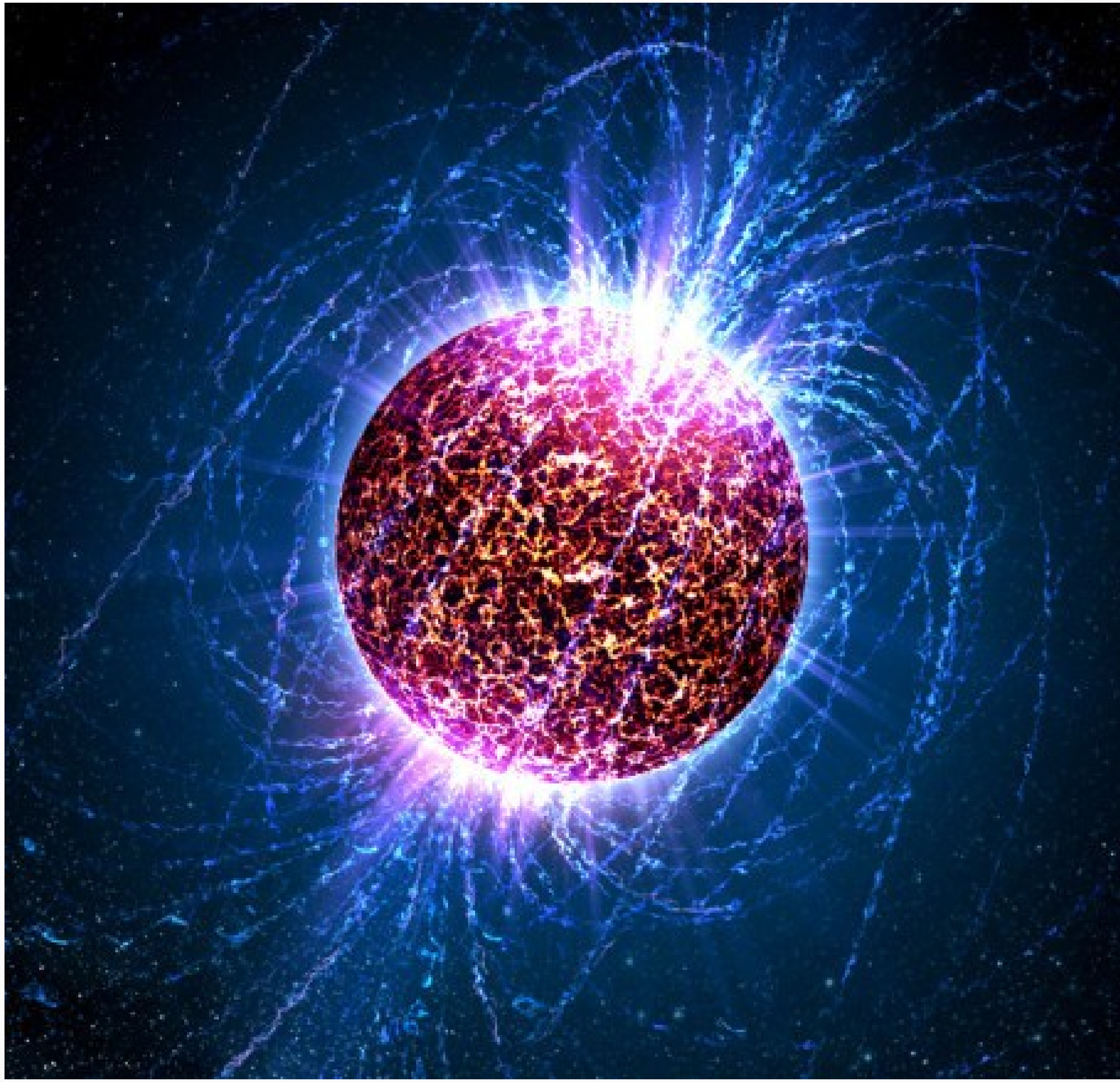
- Thermonuclear-powered millisecond pulsars (TMP)
- Prospects of X-ray polarimetry to improve EOS constraints

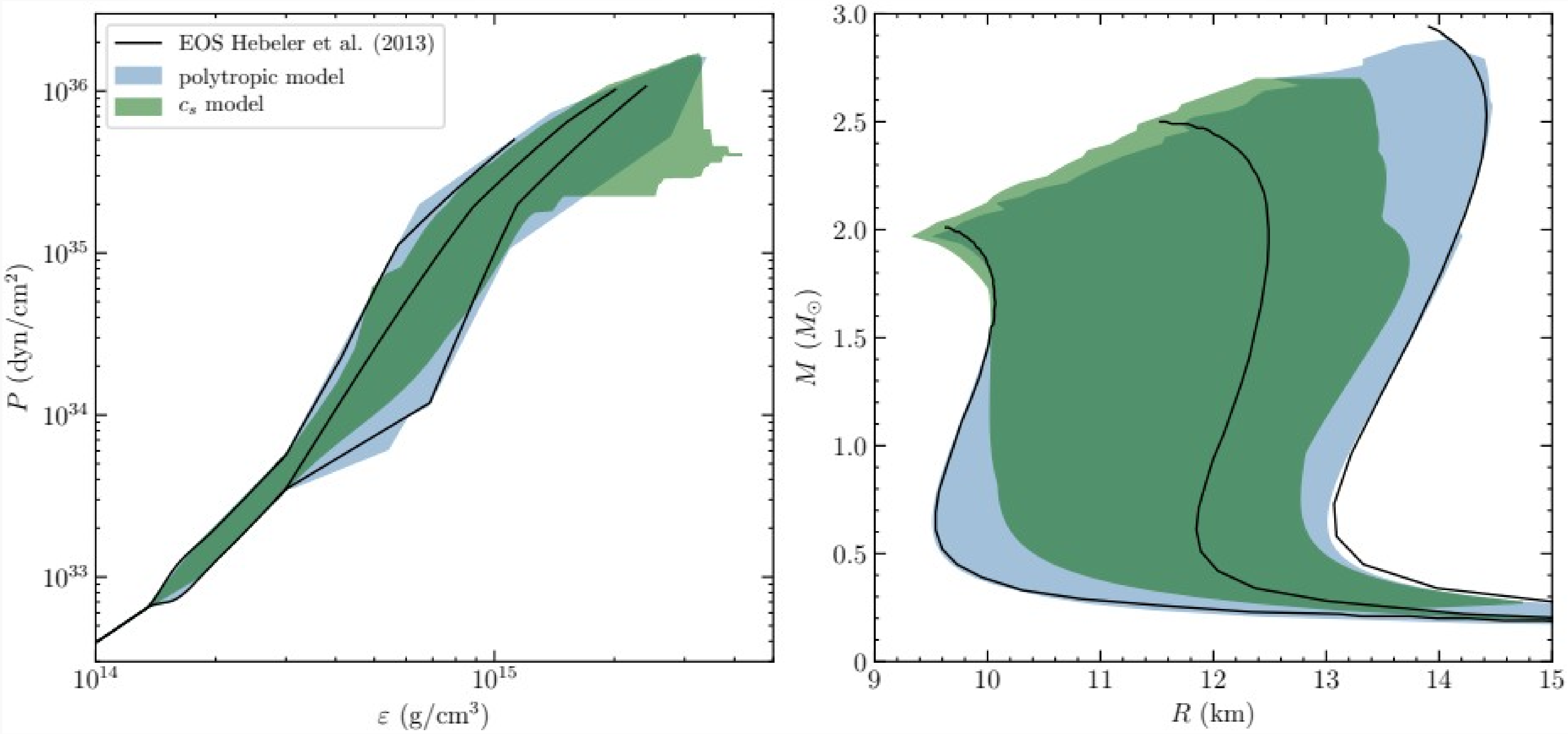
Introduction

- Neutron stars (NS)
  - Properties of the inner core unknown.
  - Aim to constrain the equation of state (EOS).
- (Millisecond) Pulsars
  - X-ray pulses encode information of mass M and radius R.
  - Polarization measurements can be used to get tighter constraints for both NS geometry and EOS



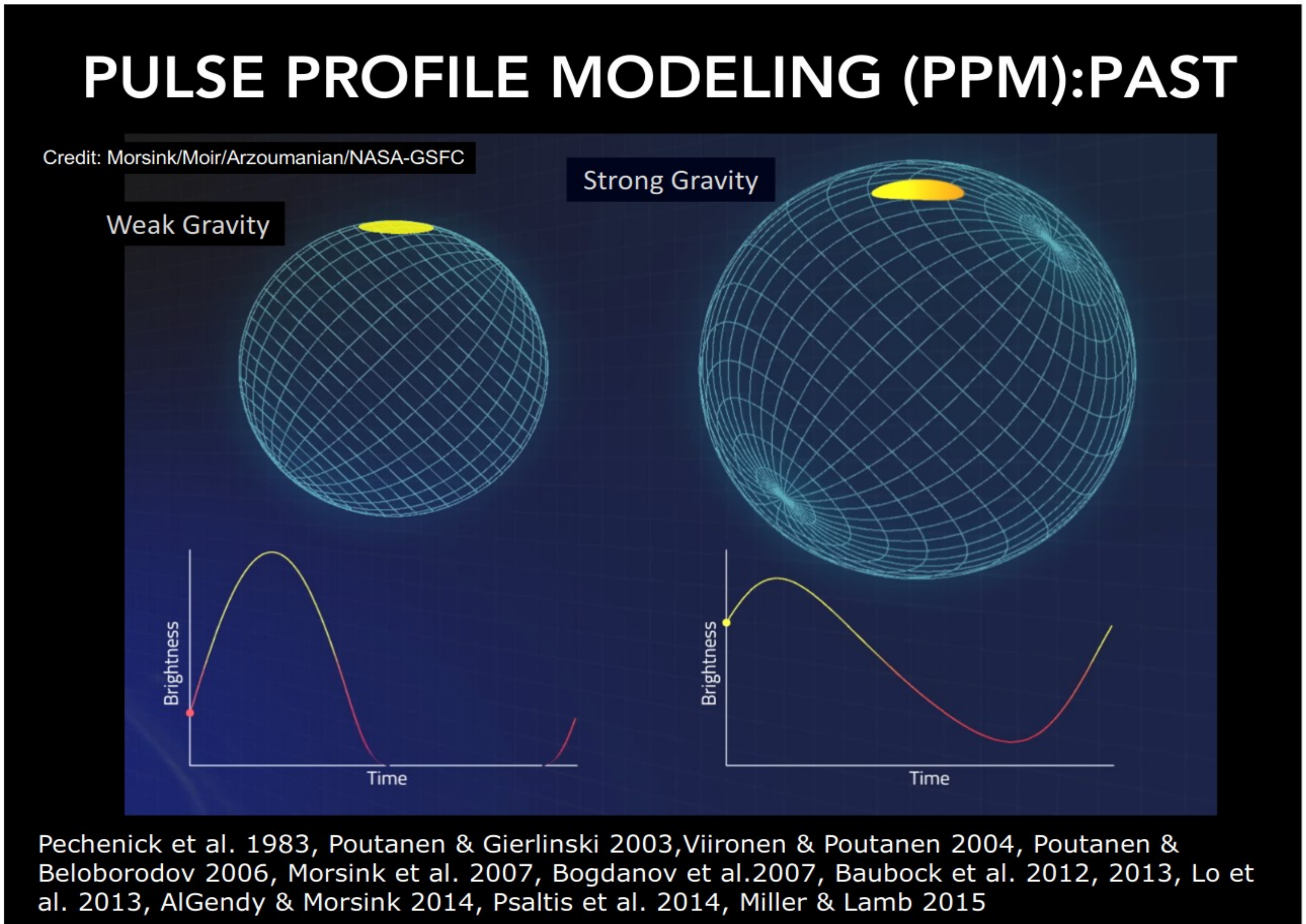
M&R and EoS

- Connection between M&R and EoS



Greif+2019

Modeling phase-resolved pulses



General and special relativistic effects modify the pulse shape

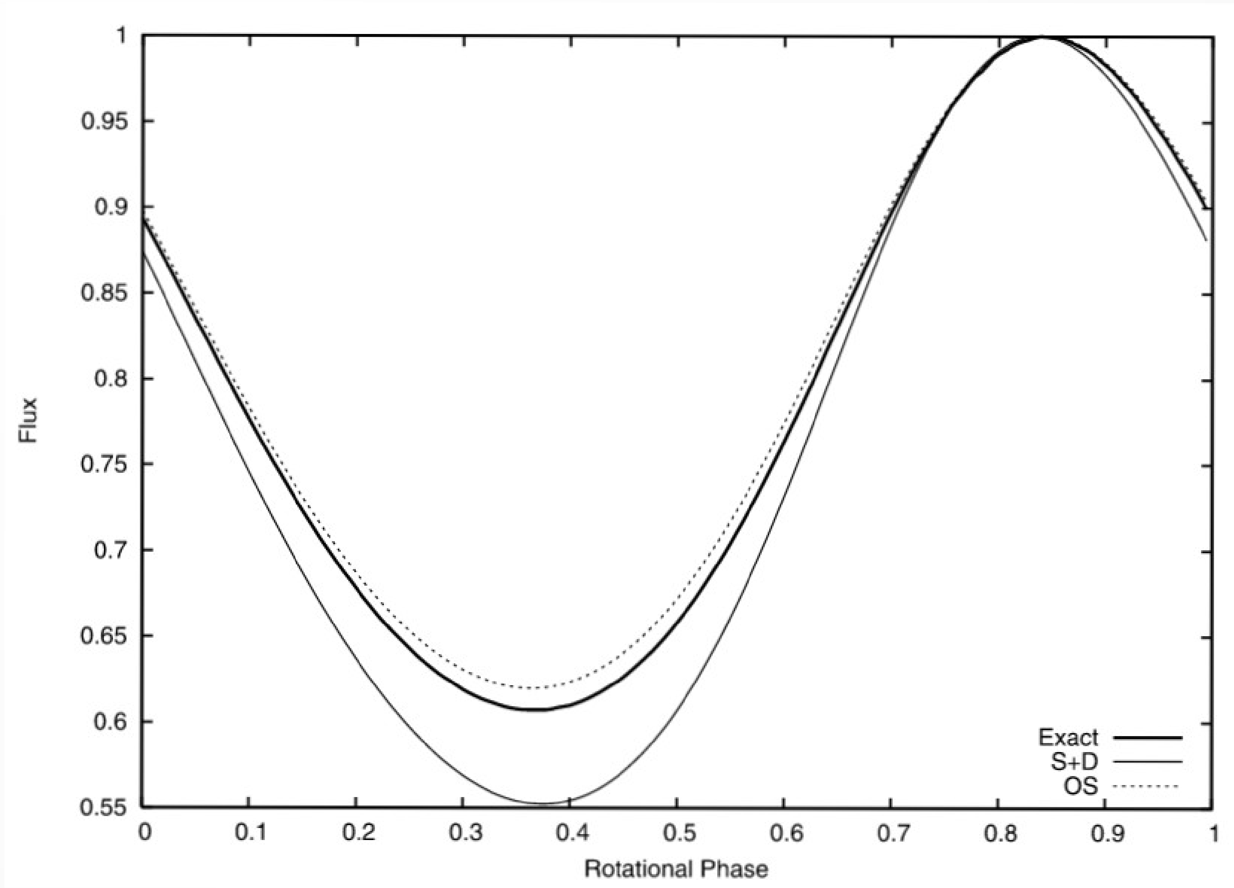
M/R affects the light bending and gravitational redshift.

Effects of relativistic rotation at NS surface depend on R.

Credit: A. Watts

Pulse profile modeling (PPM)

- Oblate-Schwarschild approxmation
- General and special relativistic effects taken separately into account.
  - Spherical non-rotating space time for light bending, time delays...
  - Relativistic Doppler corrections done, assuming no gravity.
- Only small deviation from exact spacetime metric, but fast enough for statistical inference.
- Shape of the star more important (Morsink+2007, AlGendy+2014).



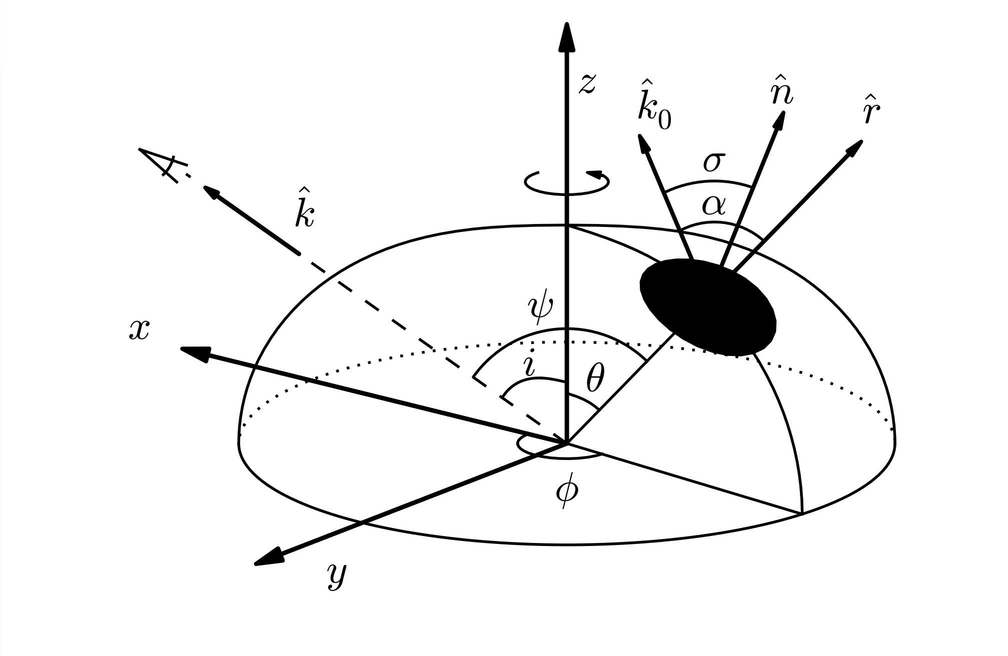
Morsink+2007

PPM: Equation

- Flux depends on:
  - Gravitational redshift R_{S}/R
  - Doppler factor $\delta(\phi)$
  - Emitted intensity I'
  - Light bending $\alpha(\psi)$
  - Oblate shape $\sigma(\alpha)$
  - Surface area S'
  - Distance D
  - Time delays

$$dF(E) = (1 - R_S/R)^{1/2}\delta^3 I'(E', \sigma') \times \cos\sigma' \left|\frac{\partial \cos\alpha}{\partial \cos\psi}\right|_R \frac{dS'}{D^2},$$

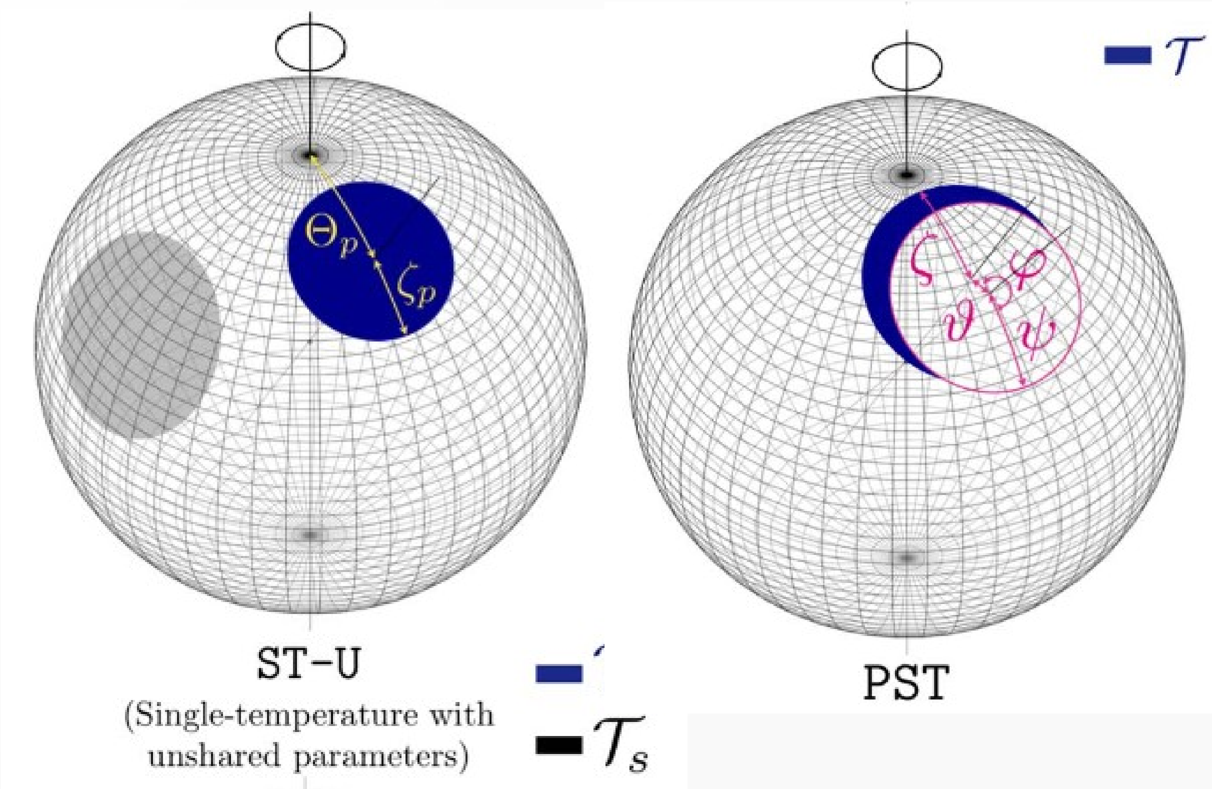
Bogdanov+2019



Salmi+2018

PPM: Uncertainties

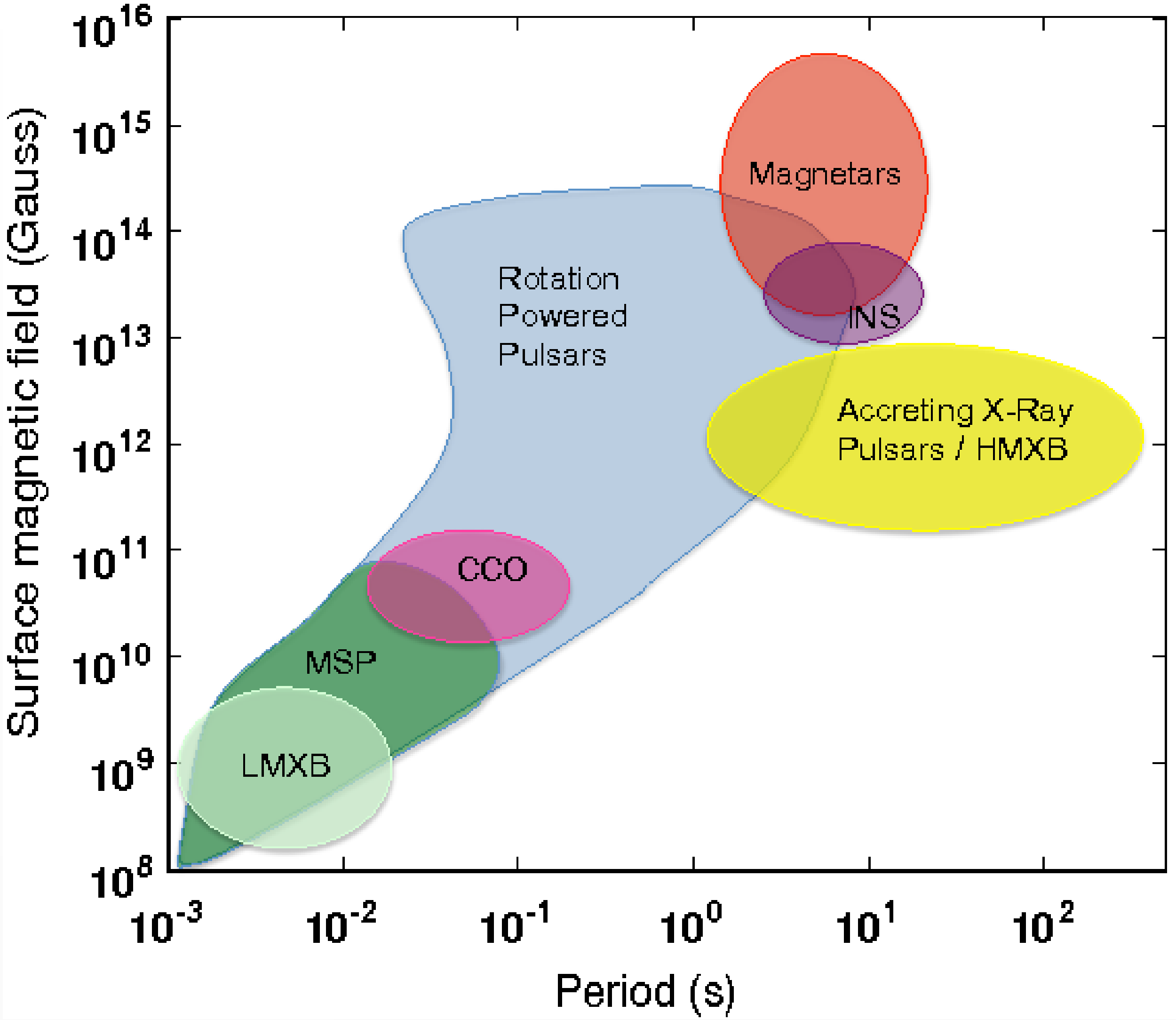
- Possible uncertainties:
  - Hot region shape geometry
  - Atmosphere model $I'(E', \sigma')$
  - Interstellar medium
  - Instrumental properties
  - Background photons (both astrophysical and instrumental)
- X-PSI code (Riley 2021)



Riley+2019

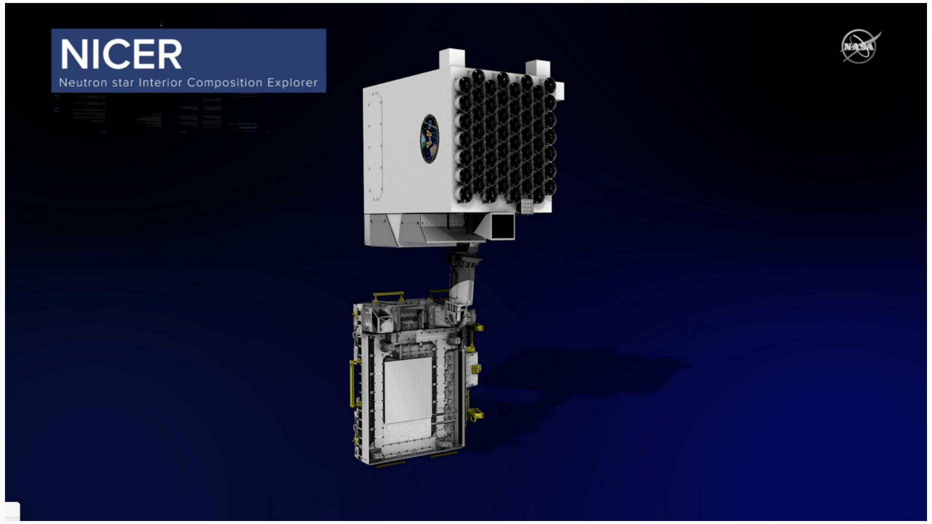
Millisecond pulsars (MP)

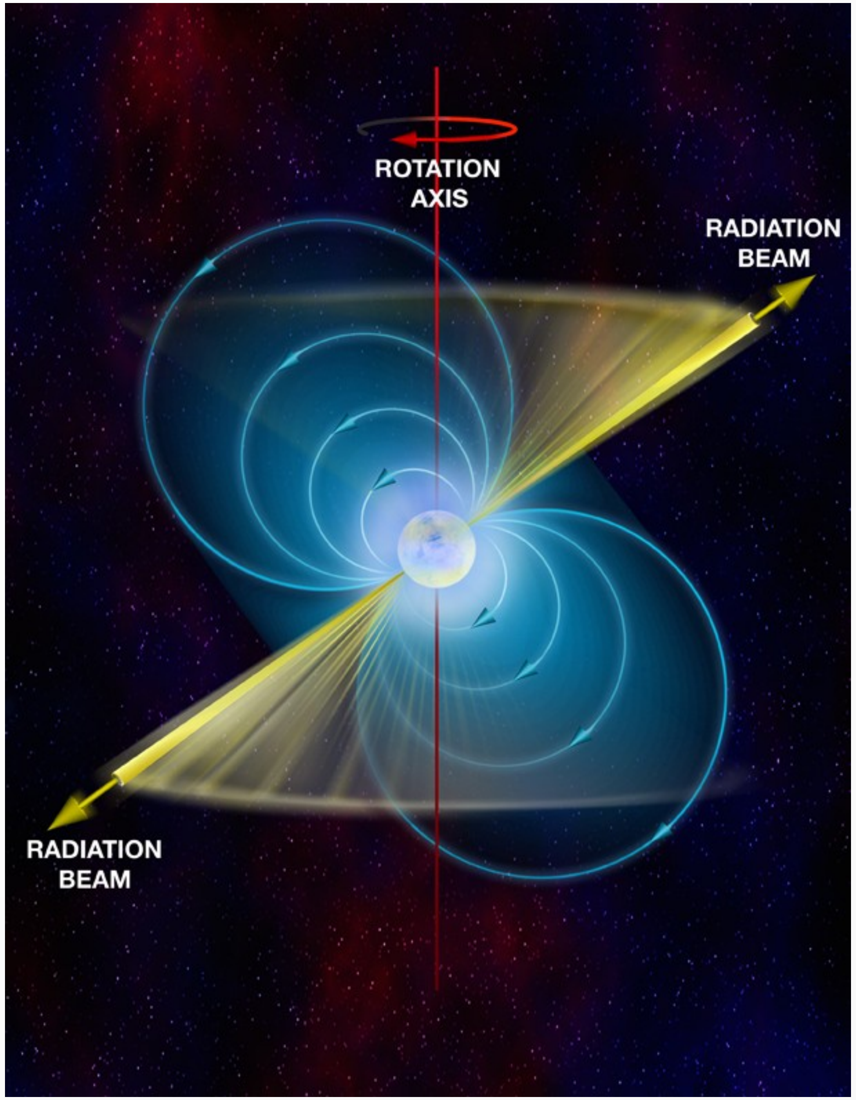
- Fast rotation of MPs: Pulse shape sensitive to R and not only M/R.
- Emission powered in 3 ways:
  - Rotation (RMP)
  - Accretion (AMP)
  - Thermo-nuclear (TMP)



Harding (2013)

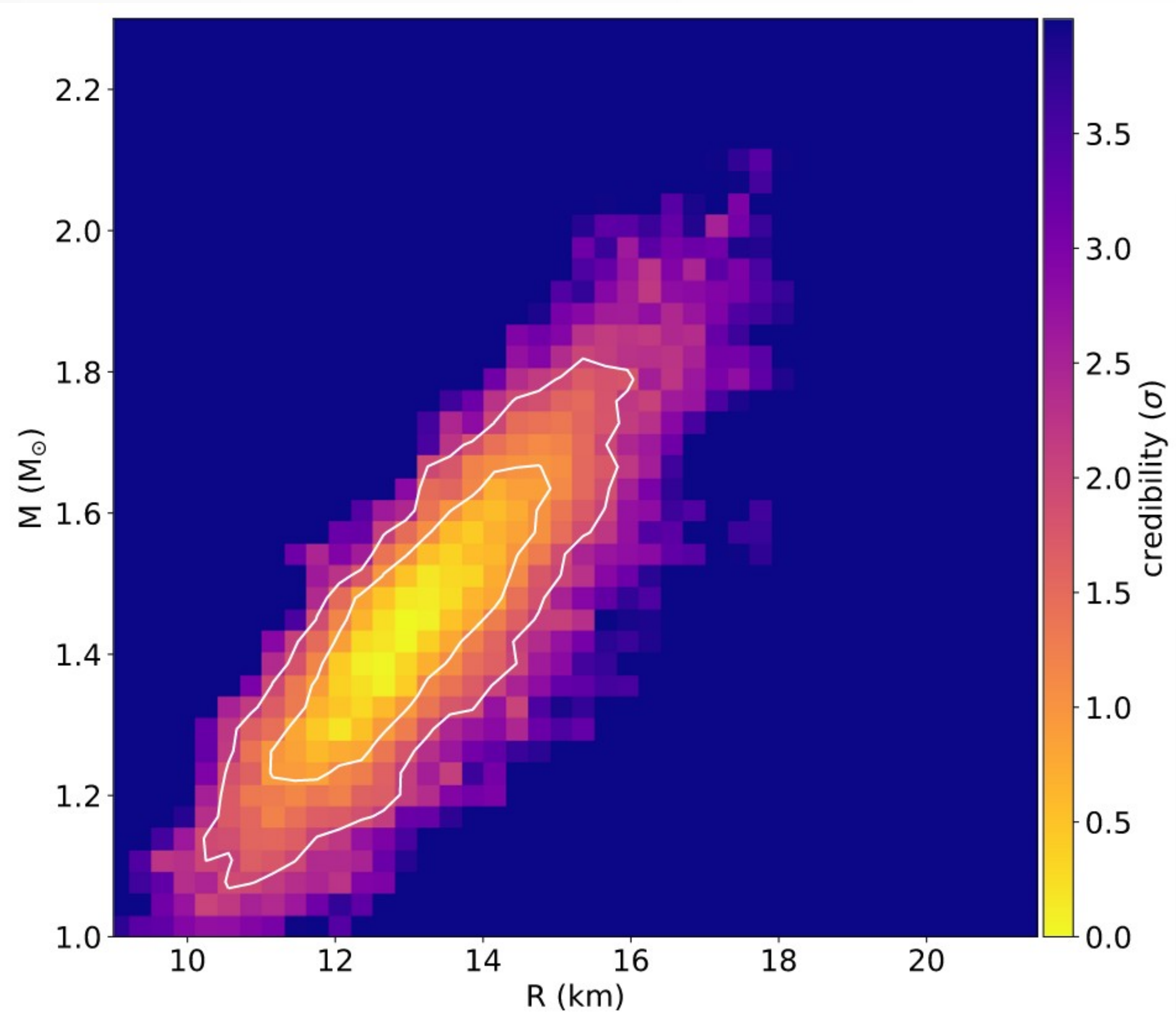
Rotation-powered millisecond pulsars (RMPs)



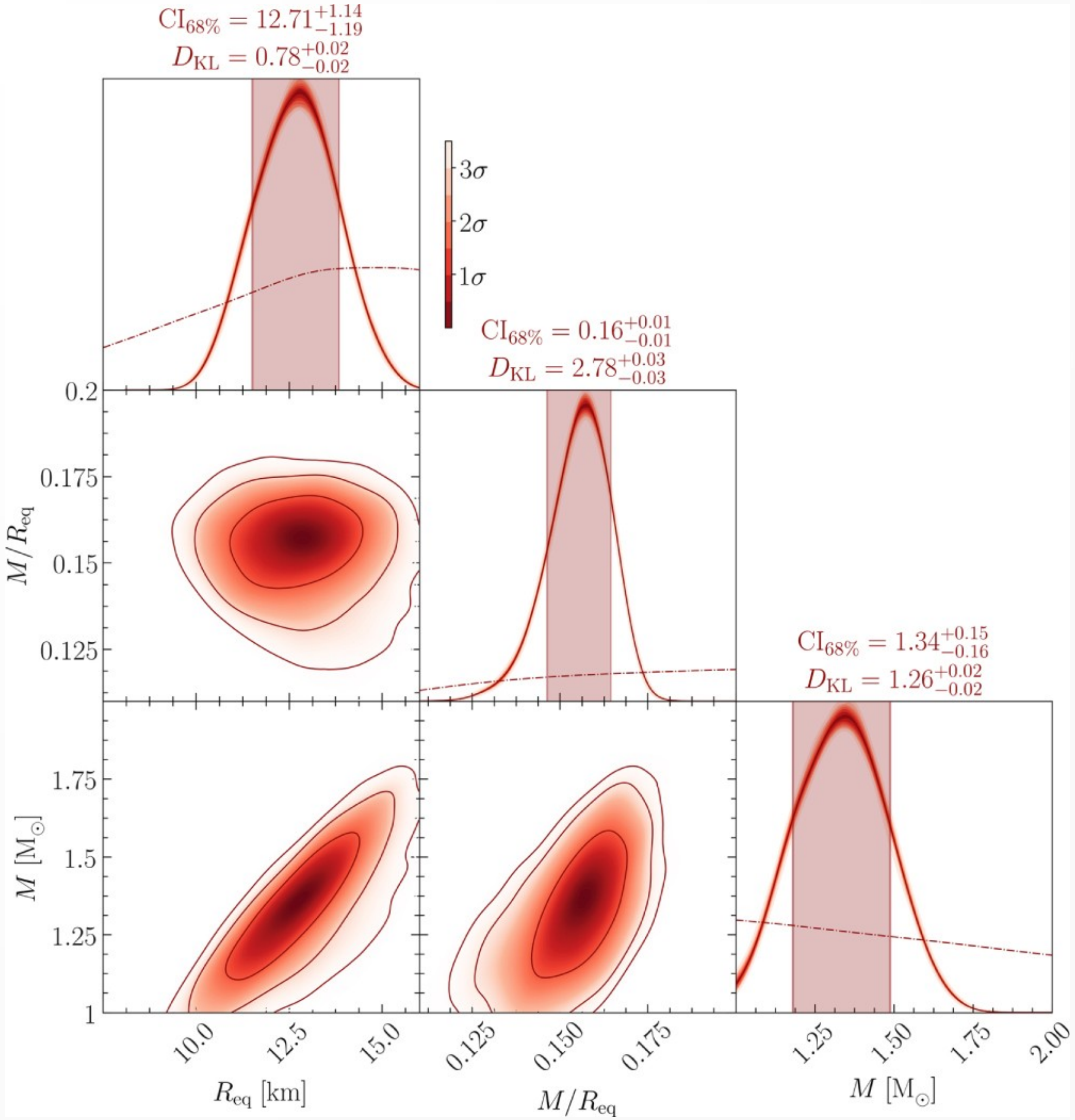


- Primary NICER targets.
- Recycled pulsars with no accretion
- Magnetospheric return-current heats the polar caps.
- Well established atmosphere models (still composition, deep-heating, etc assumptions).
- Faint but stable: Very long exposure time possible.

RMPs: J0030 results

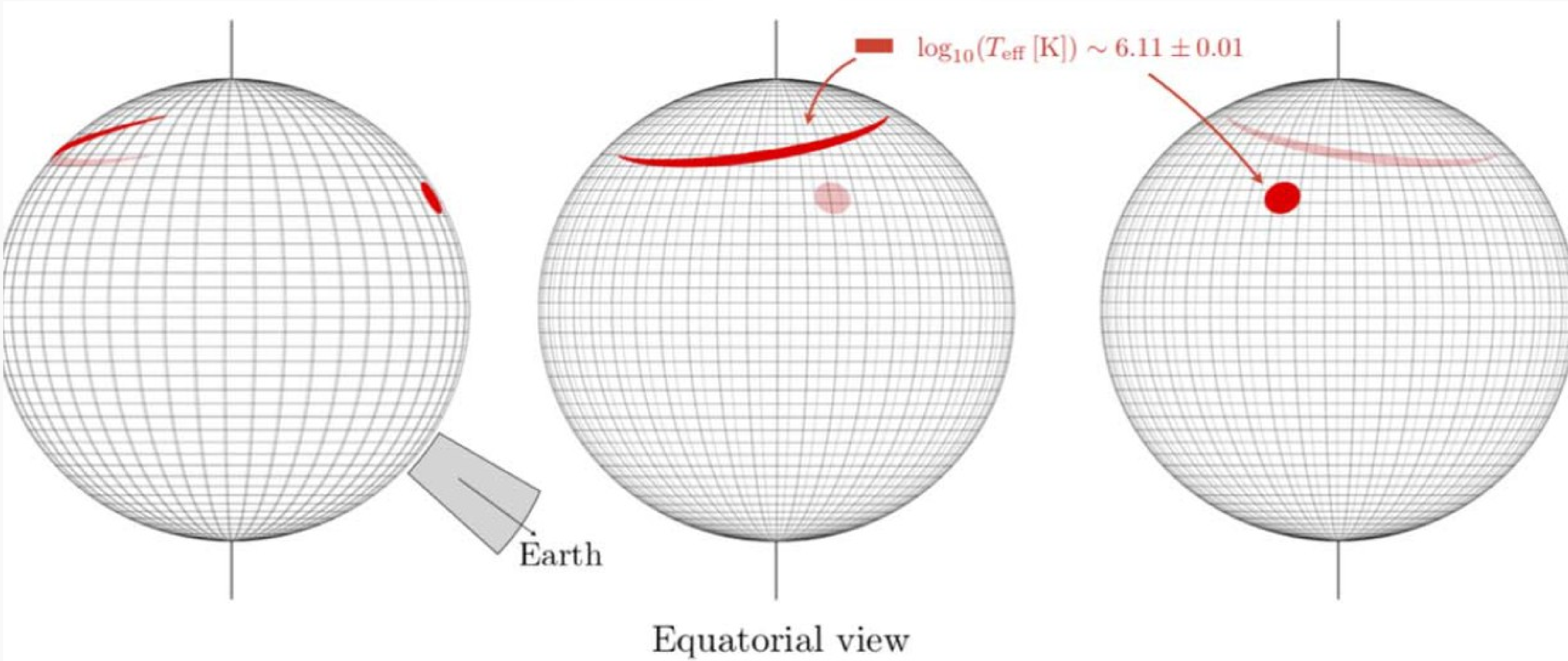


Miller+2019



Riley+2019

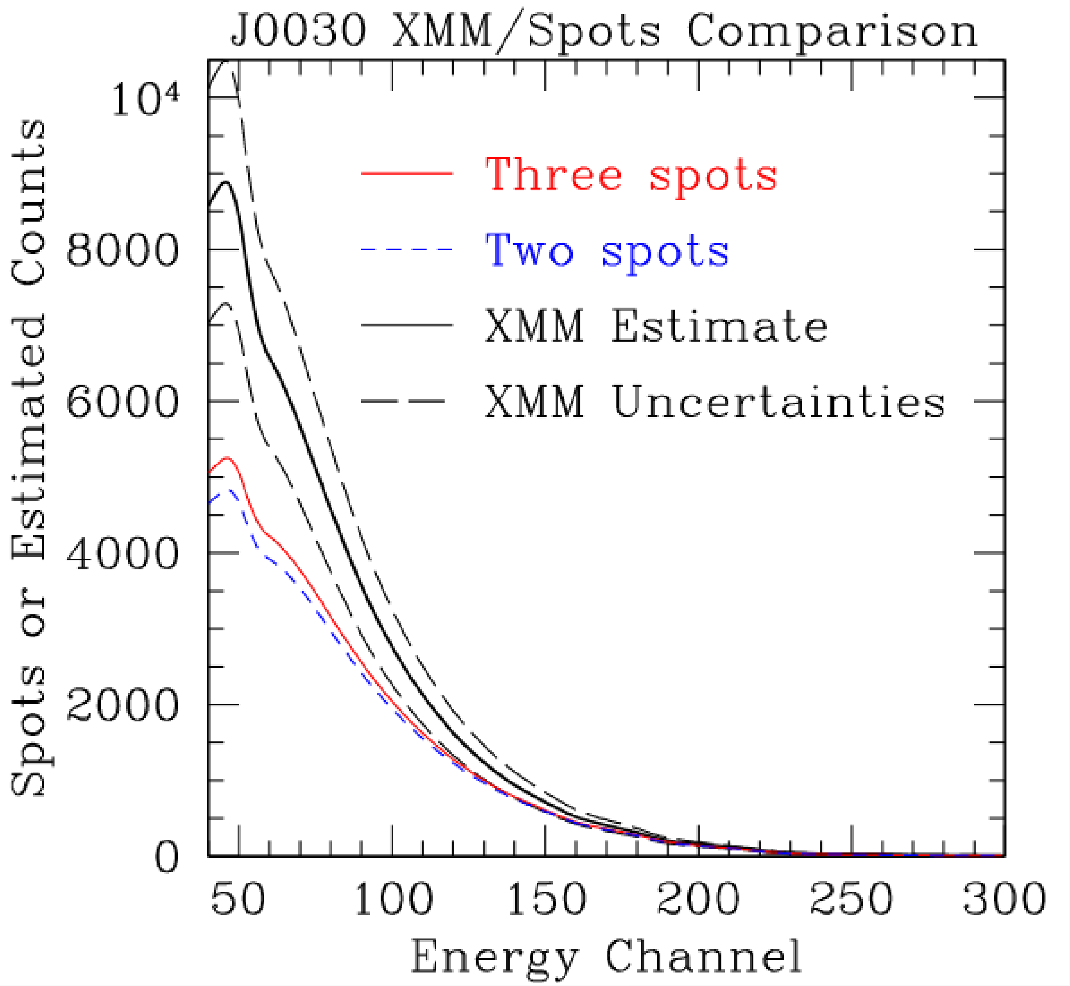
RMPs: J0030 results



Riley+2019

RMPs: J0030 caveats

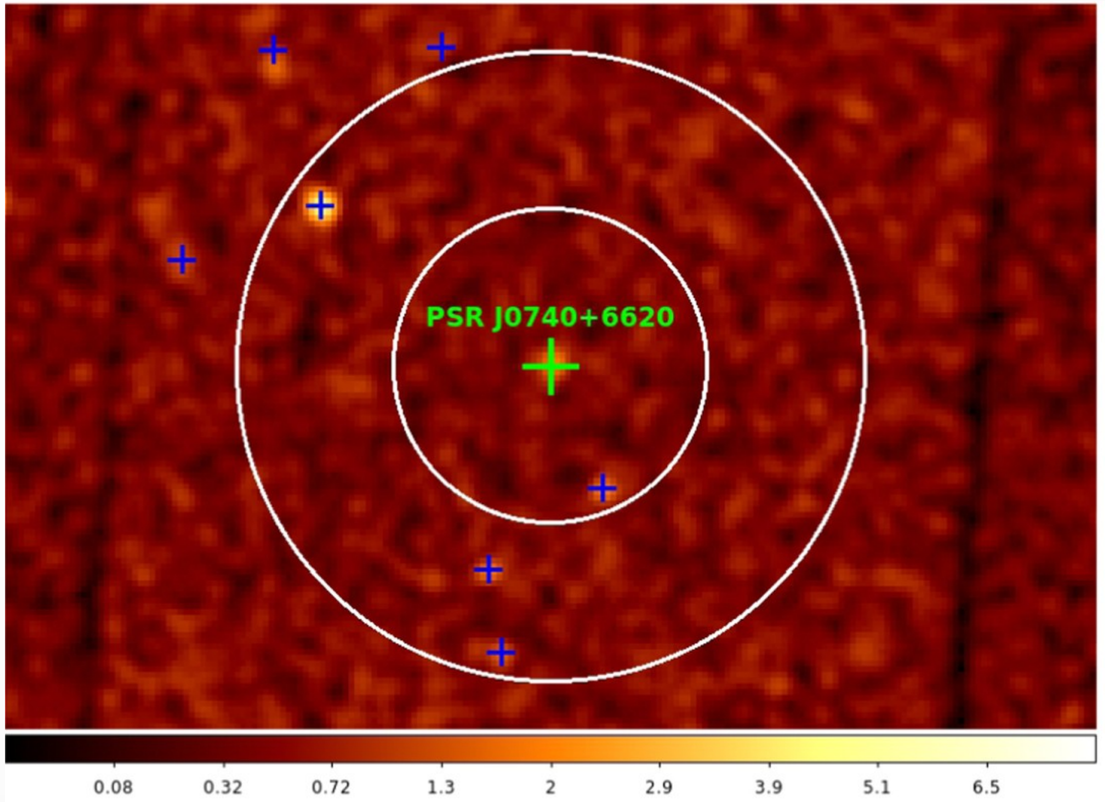
- J0030 assumptions:
  - Fully ionized non-magnetic deep-heated Hydrogen atmosphere.
  - Unconstrained background.
- Coming J0030 updates (Vinciguerra+, in prep.):
  - Updated instrument calibration.
  - Background constraints.
  - New data.



Miller+2019

RMPs: Background

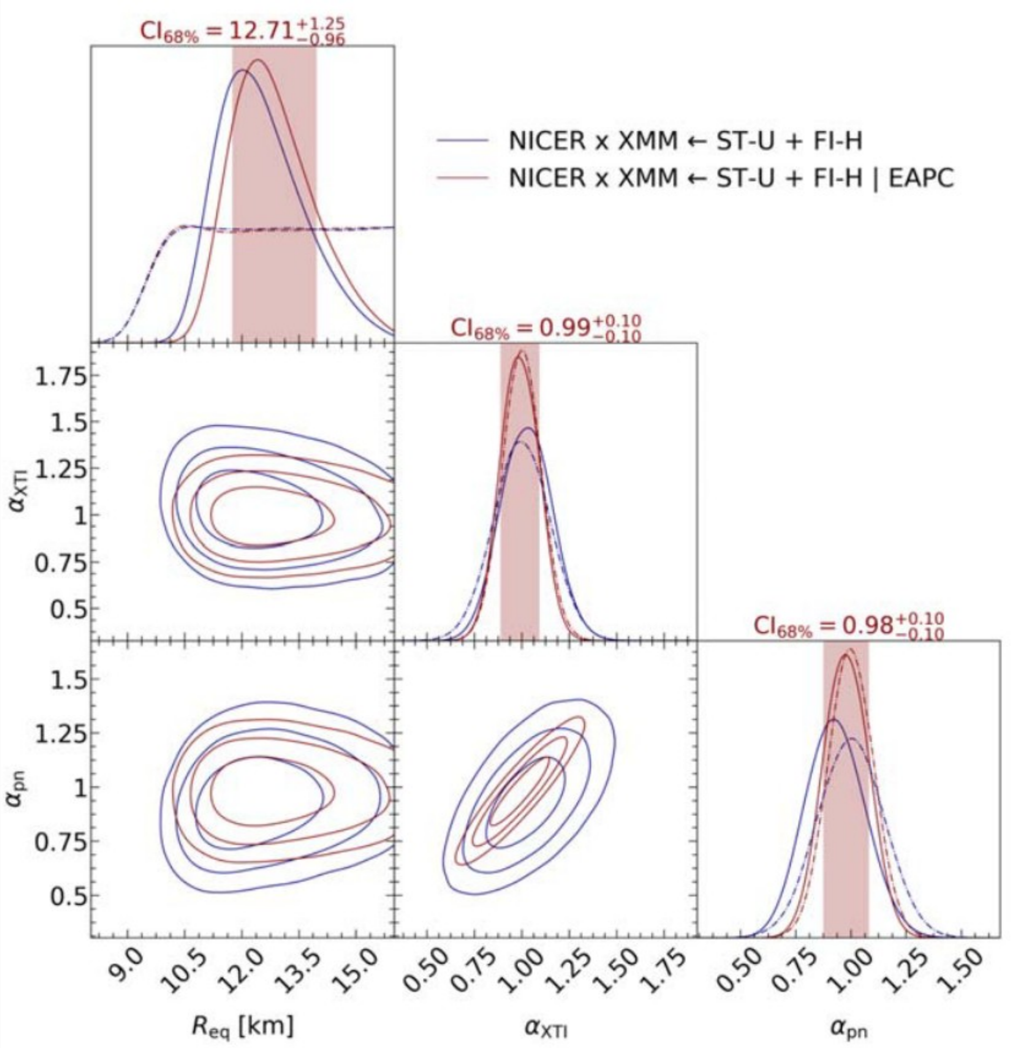
- Pulsed component:
  - Only hot spots
- Unpulsed component:
  - Hot spots (for high compactness or certain geometries)
  - Anything else: Background
- Background sources: Instrumental particles, cosmic X-ray background, other sources in the field of view.

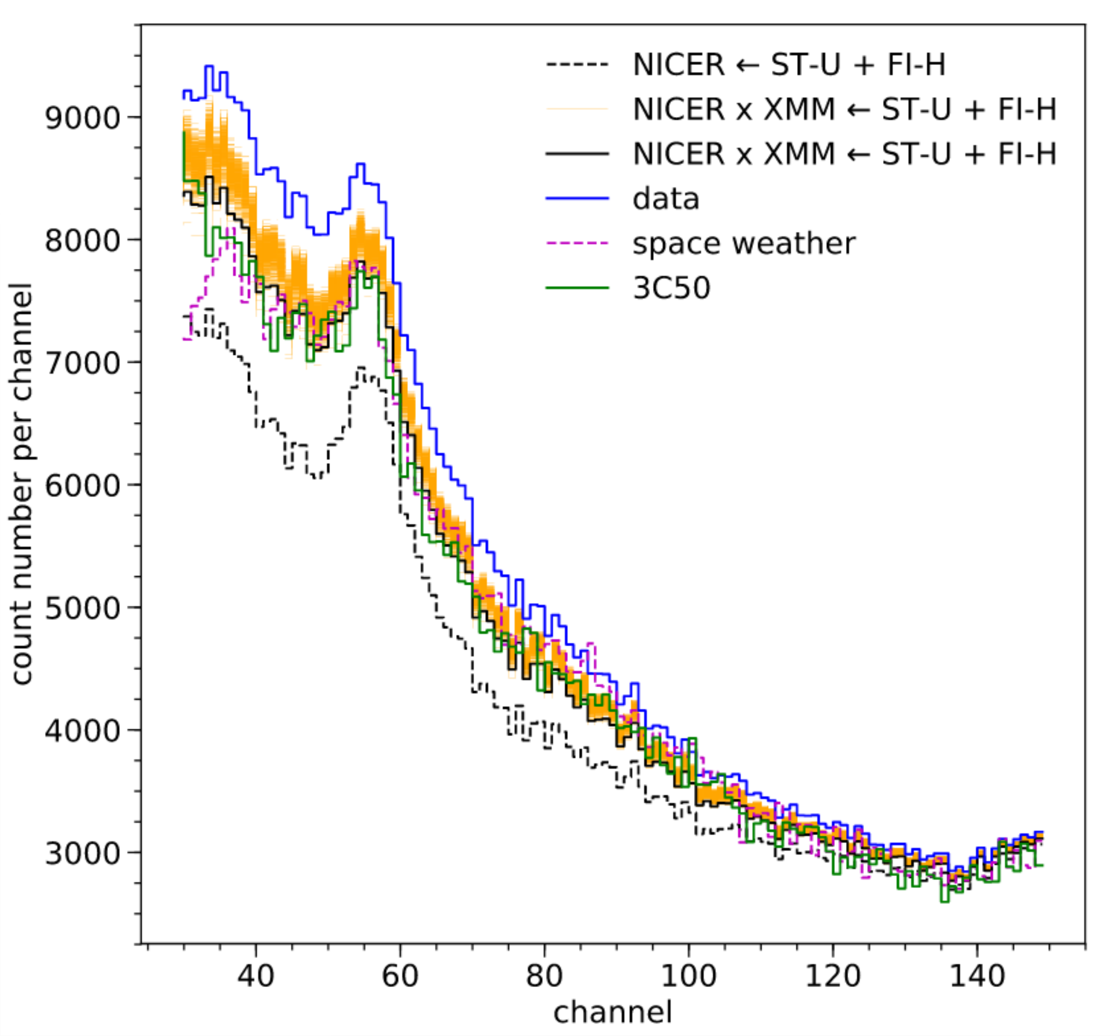


Wolff+2021

RMPs: J0740 results

- Background constrained using XMM
- Cross-calibration effects

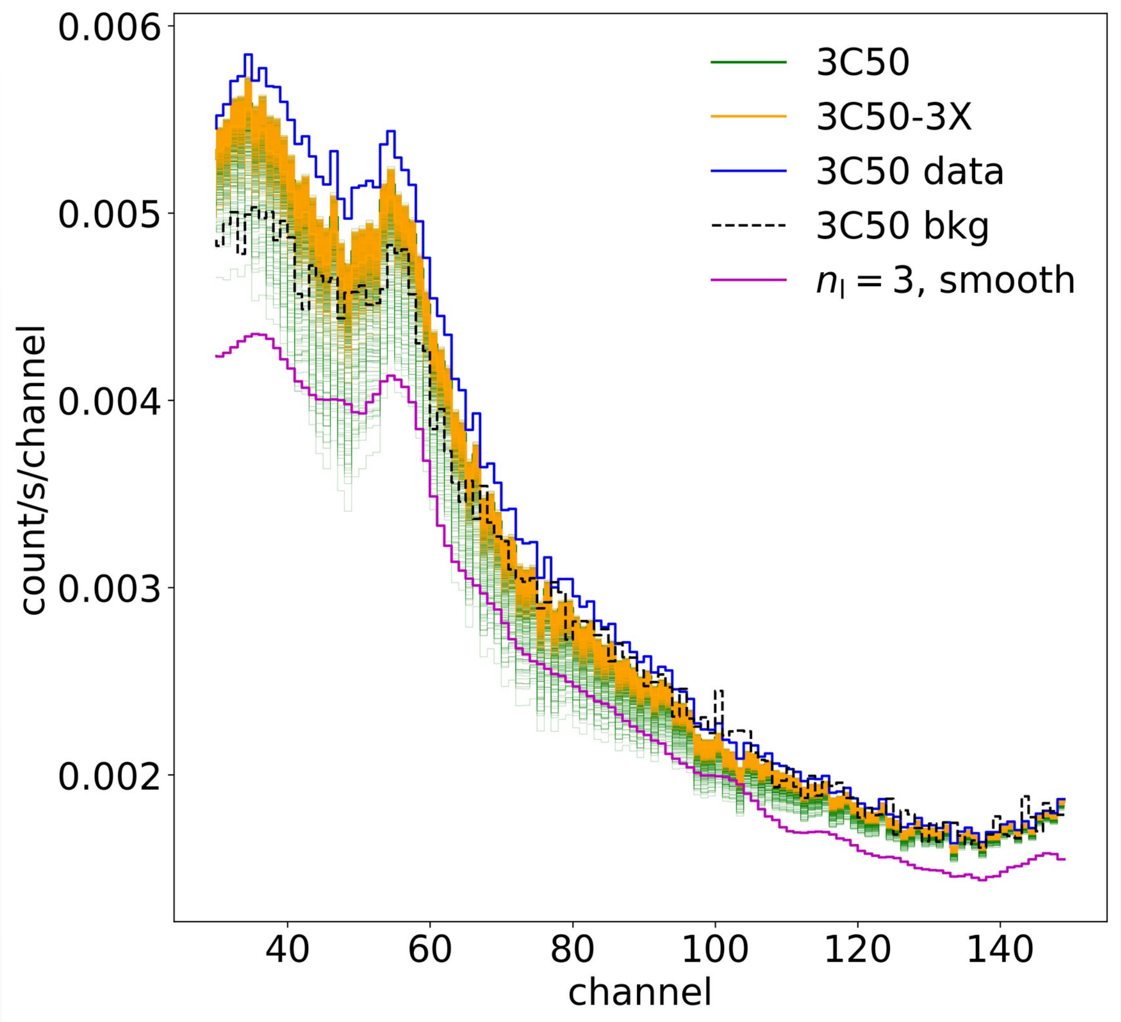




Riley+2021, Miller+2021

RMPs: New J0740 analysis

- J0740 with NICER background estimates instead of XMM.
- New NICER background estimates directly used to limit background.
- More cleaned 3C50 data set (Remillard+2022) used to quantify the uncertainty in background.



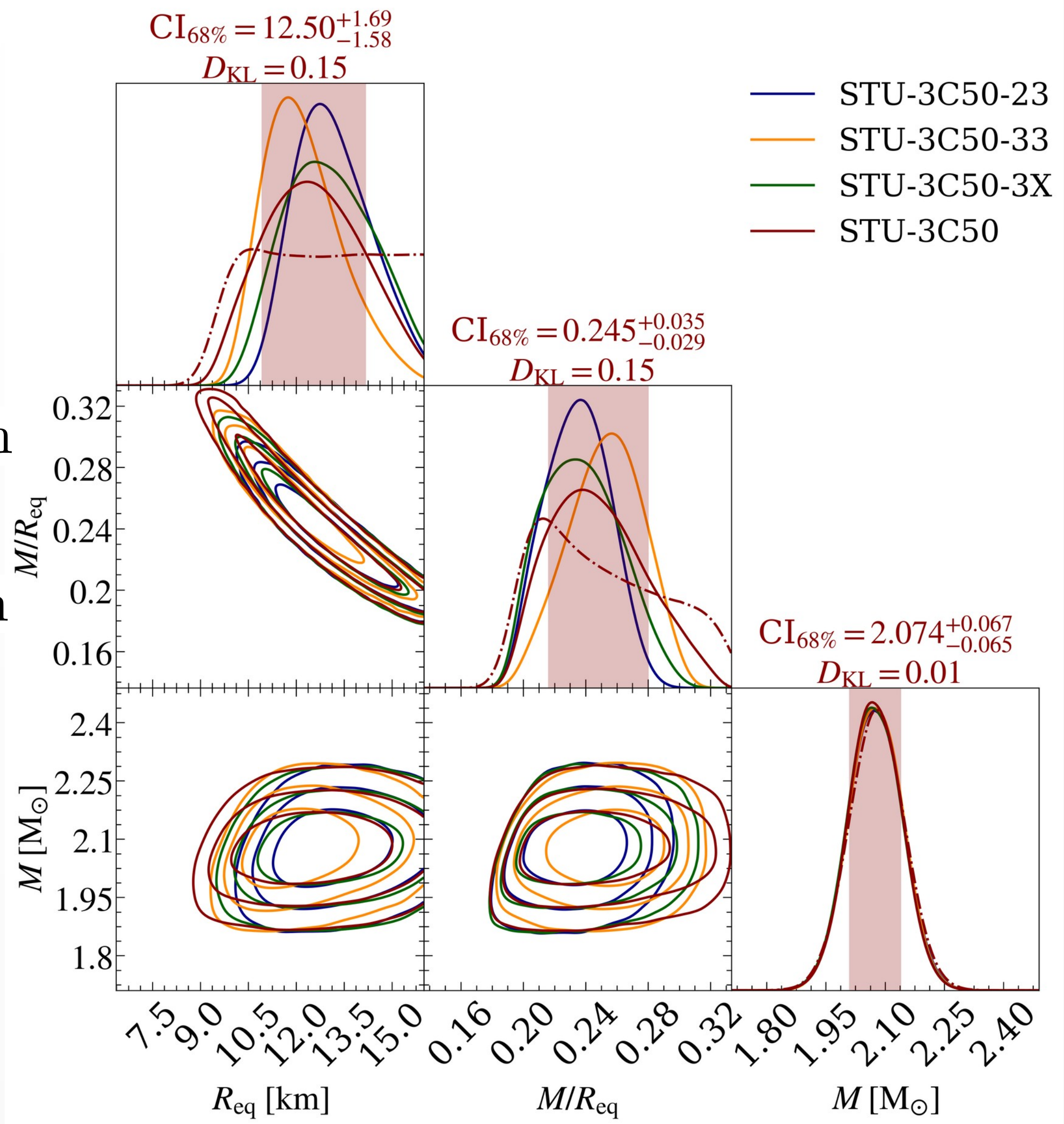
Salmi+2022, submitted

RMPs: New J0740 analysis

- J0740 Radius intervals for different background prior choices.
- XX = No lower limit, no upper limit
- 33 = 3σ lower limit, 3σ upper limit
- Riley+2021 NICER-only: $R = 11.29^{+1.20}_{-0.81}$ km
- Riley+2021 NICER+XMM ("compressed scaling"): $R = 12.70^{+1.25}_{-0.96}$ km
- Salmi+2022 NICER-3C50-3X:

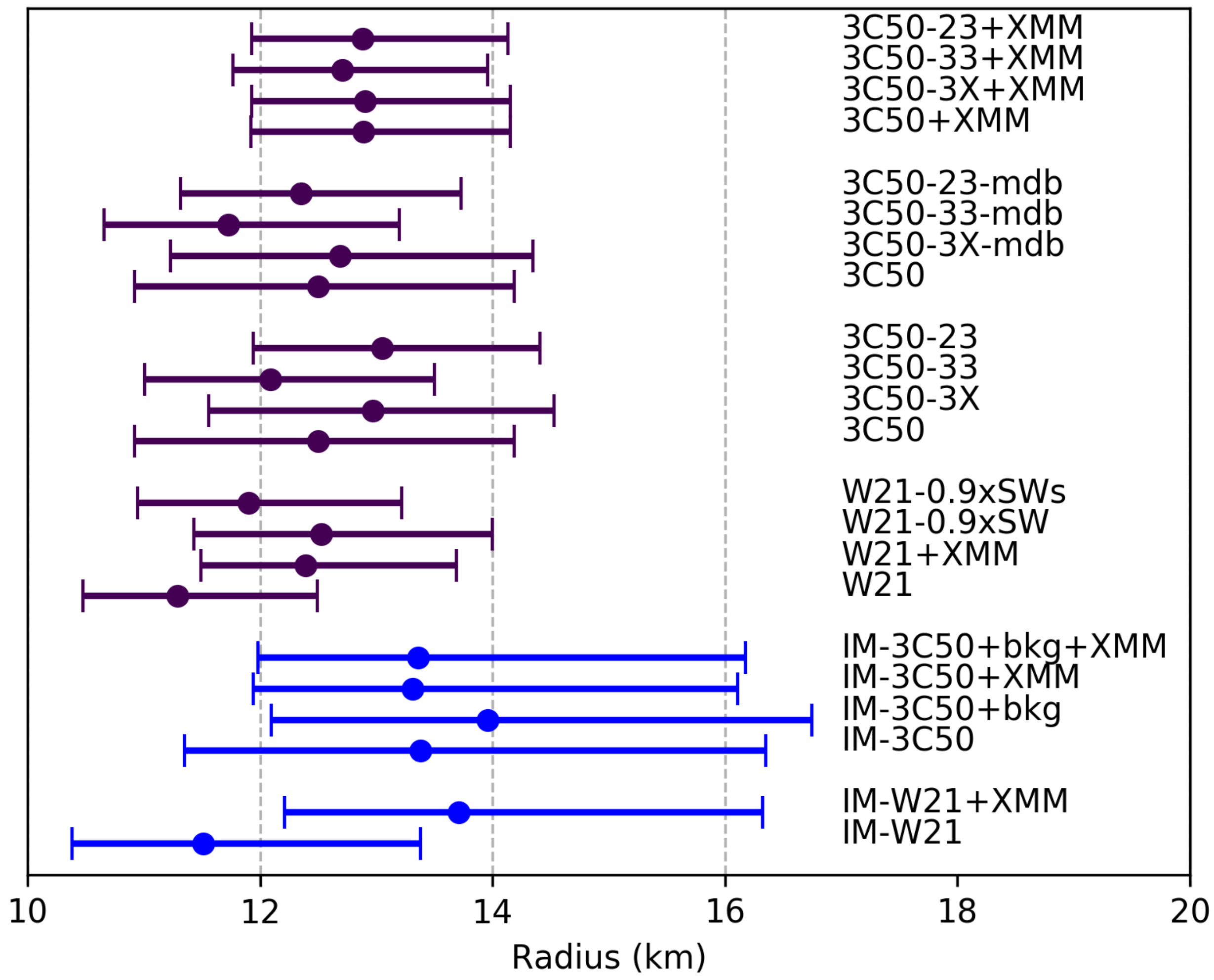
  $R = 12.97^{+1.56}_{-1.39}$ km

  - Setting upper limit for background non-trivial since the AGN in the FoV not accounted in the estimate.



RMPs: New J0740 analysis

- Conclusions:
  - Inferred compactness affected by constraining background.
  - Consistent results with NICER+XMM.
  - No EOS re-analysis needed for J0740.
- New data for J0740 being analyzed.

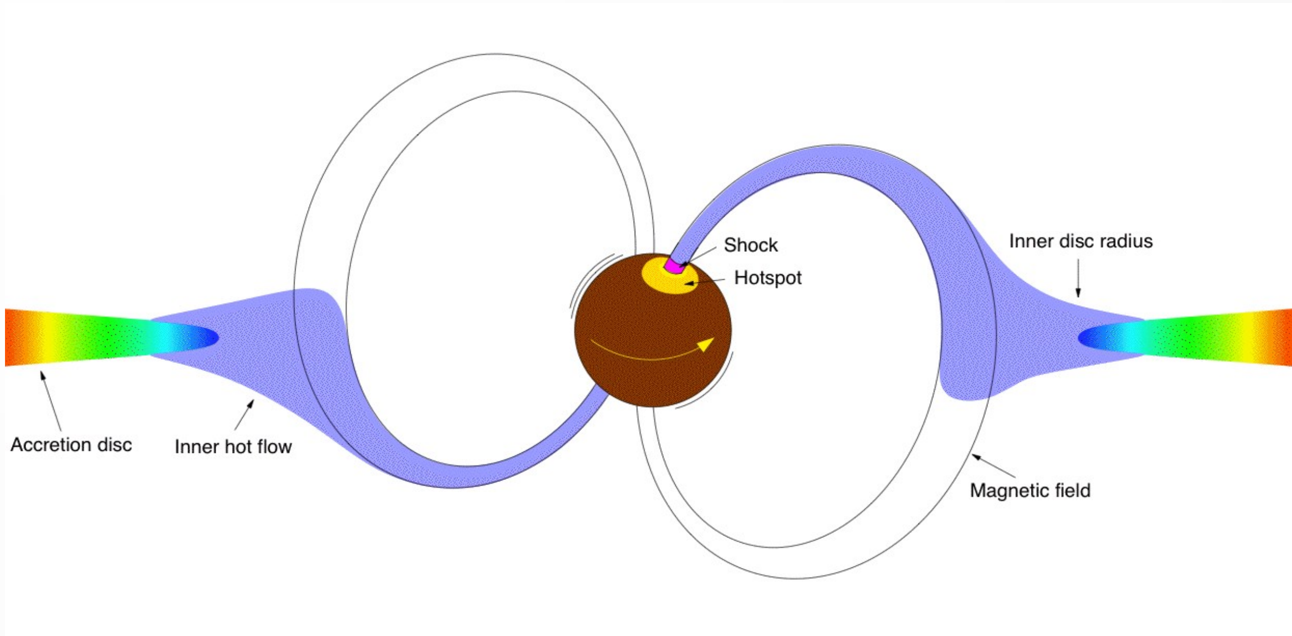


Salmi+2022, submitted

Accretion-powered millisecond pulsars (AMPs)

- Gas from a companion forms an accretion disk and channels to the magnetic poles.
- AMPs are bright and rotate very rapidly.
- Downside:
  - Detected only during outbursts (duration ~weeks).
- Radiation polarized due to Compton scattering in the accretion column

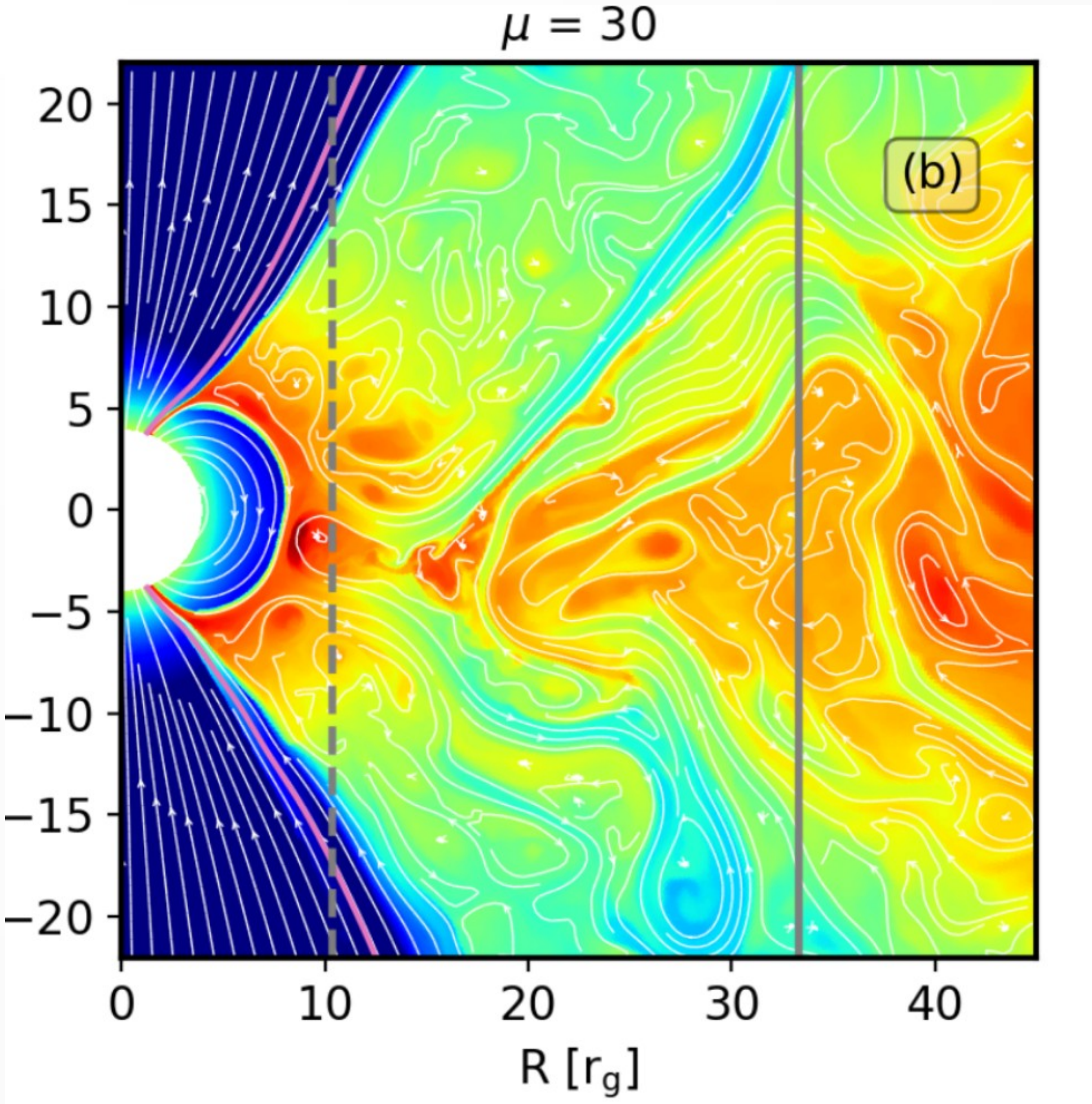
→ Observed in harder X-rays.



Gierliński+2002

AMPs: Additional effects

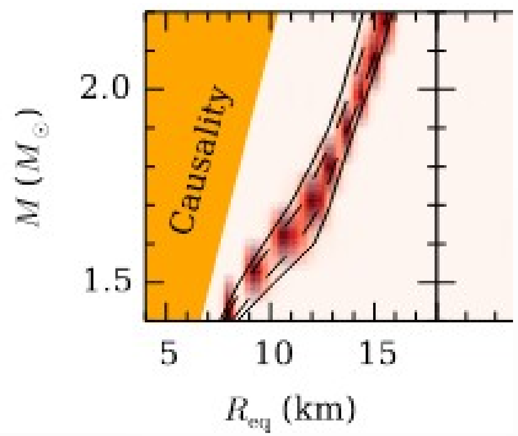
- Other complications compared to RMPs:
  - Accretion shock?
  - Accretion column?
  - Accretion disc?
  - Atmosphere model?
  - Time variability?

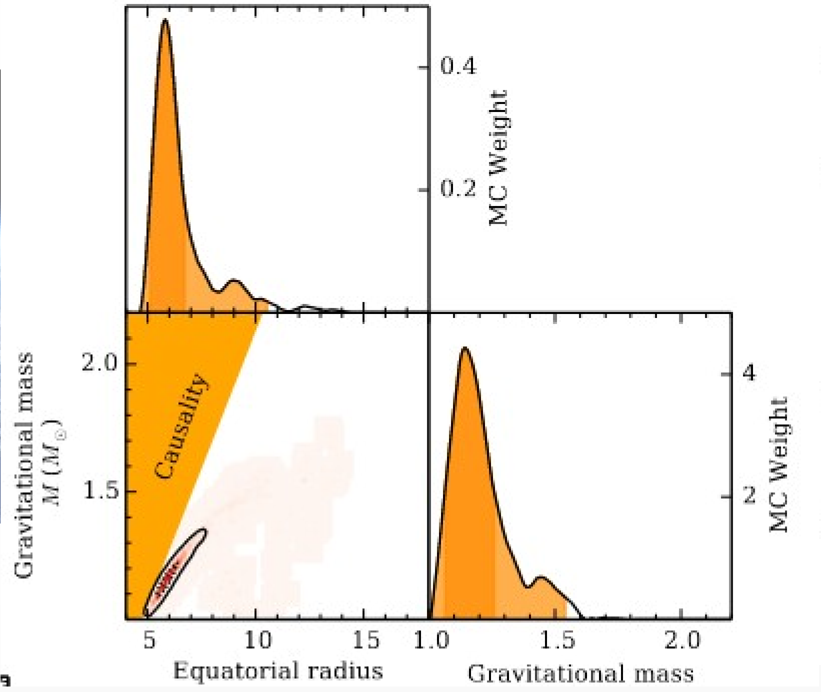


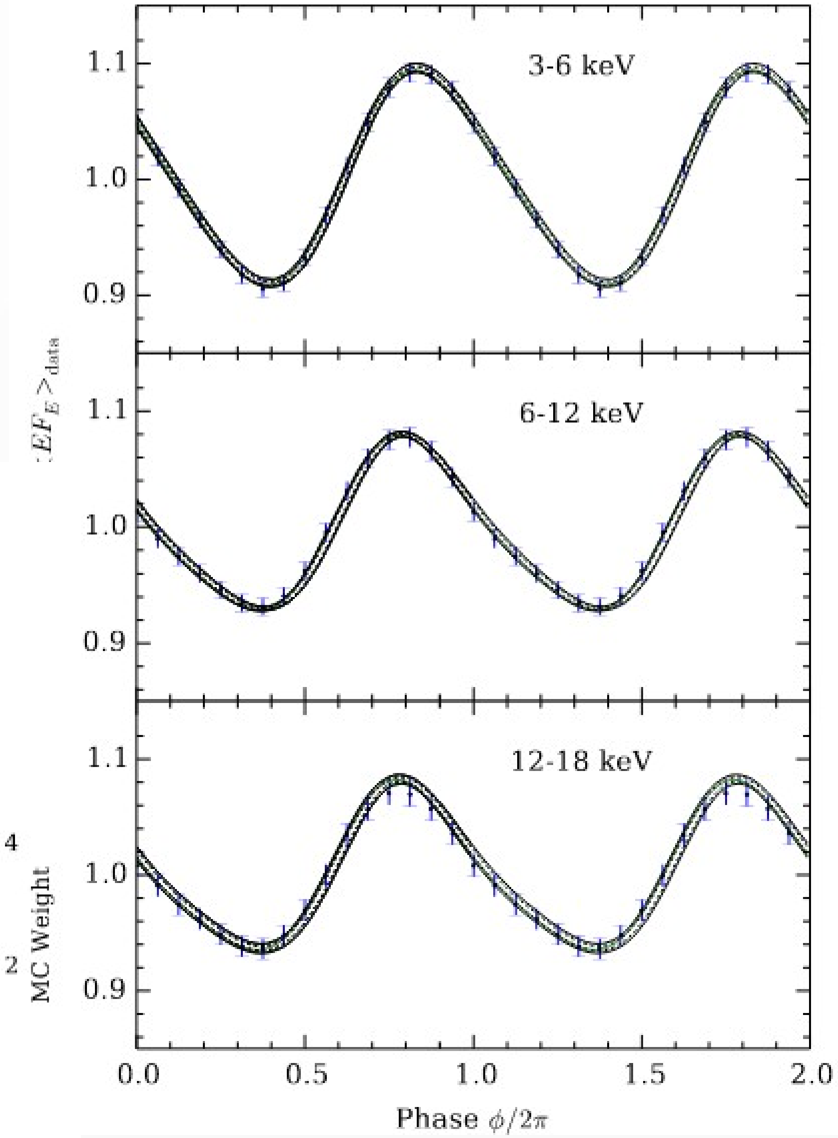
Das+2022

AMPs: Efforts so far

- Simplified emission models (Salmi+2018, Leahy+2008 Poutanen & Gierlinski 2003)
- RXTE, Nicer, eXTP, Strobe-X

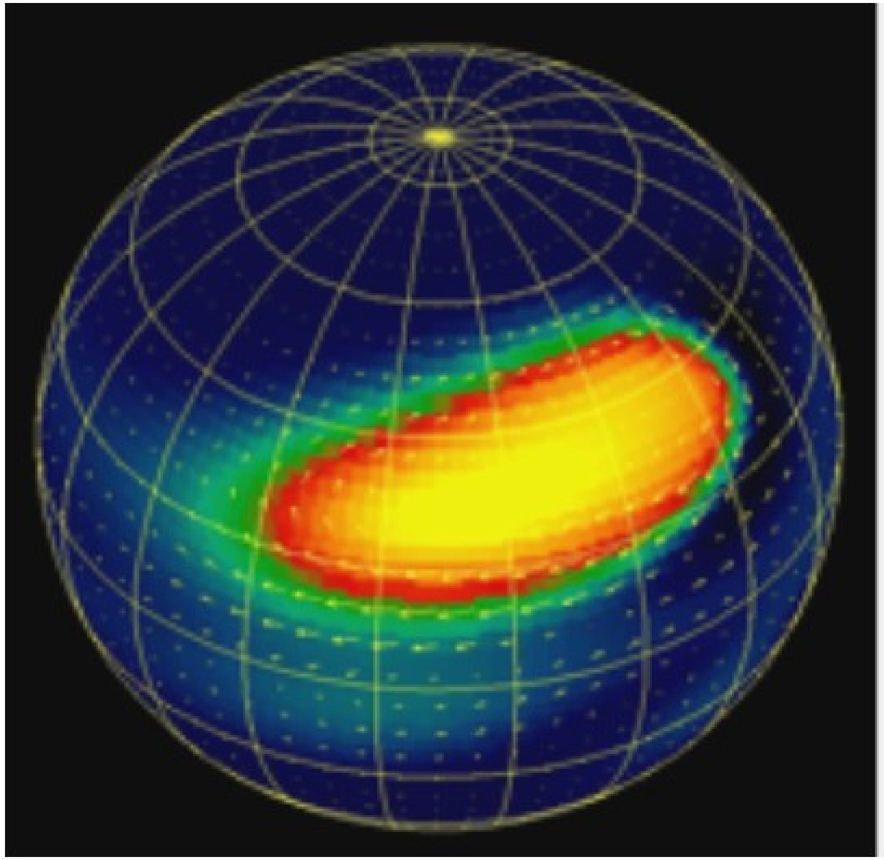






Thermo-nuclear powered millisecond pulsars (TMPs)

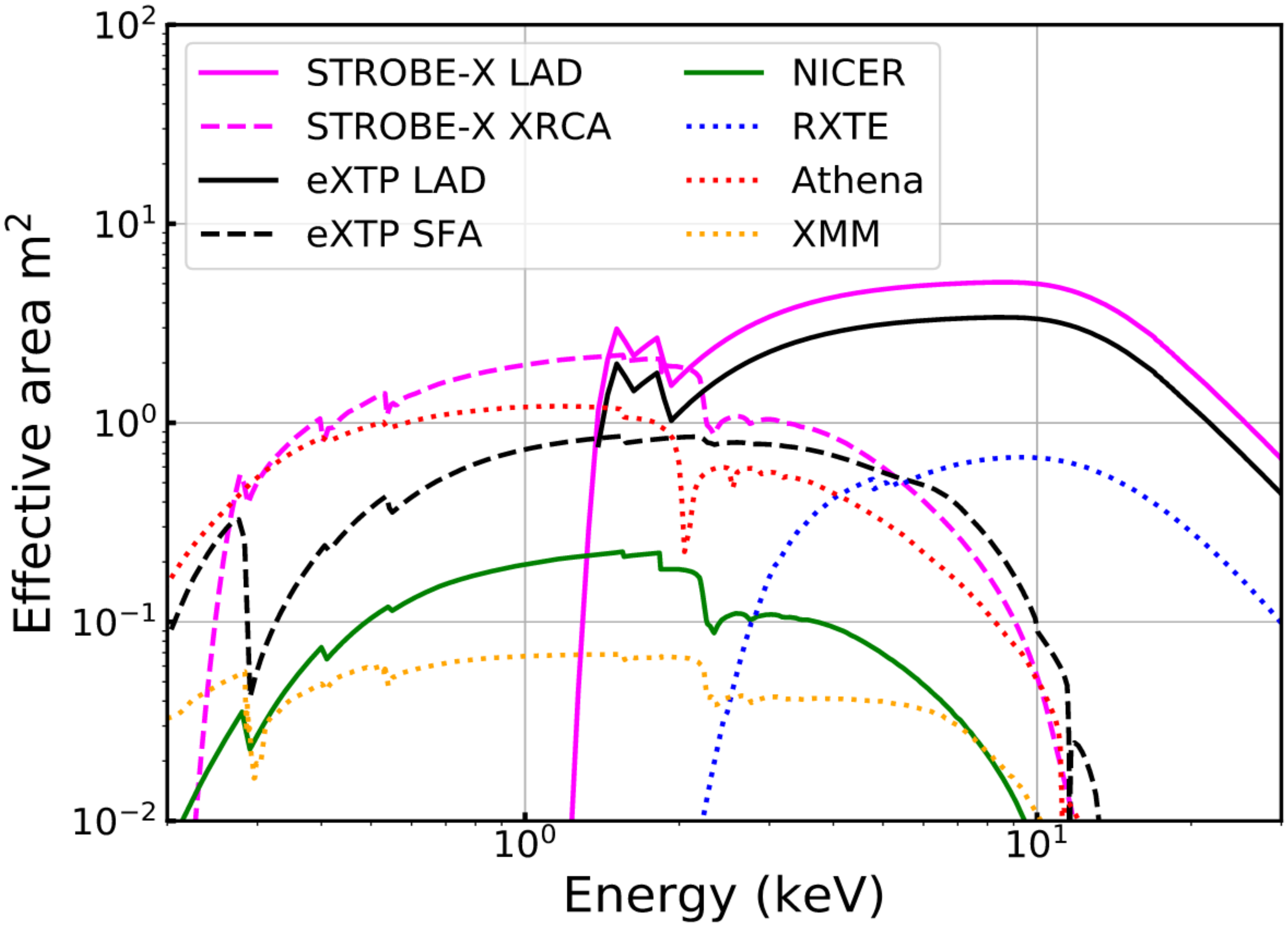
- Thermonuclear burning of accreted matter (X-ray bursts).
- Seen burst oscillations some times: Origin not sure.
- Very bright but short (seconds).
- Burst atmosphere models exist, but not sure if they are consistent with burst pulsations (Suleimanov+2012, Suleimanov+2018).
- Likely variable of spot properties (temperature, spot size, location).



Spitkovsky, Levin & Ushomirsky

TMPs: Future

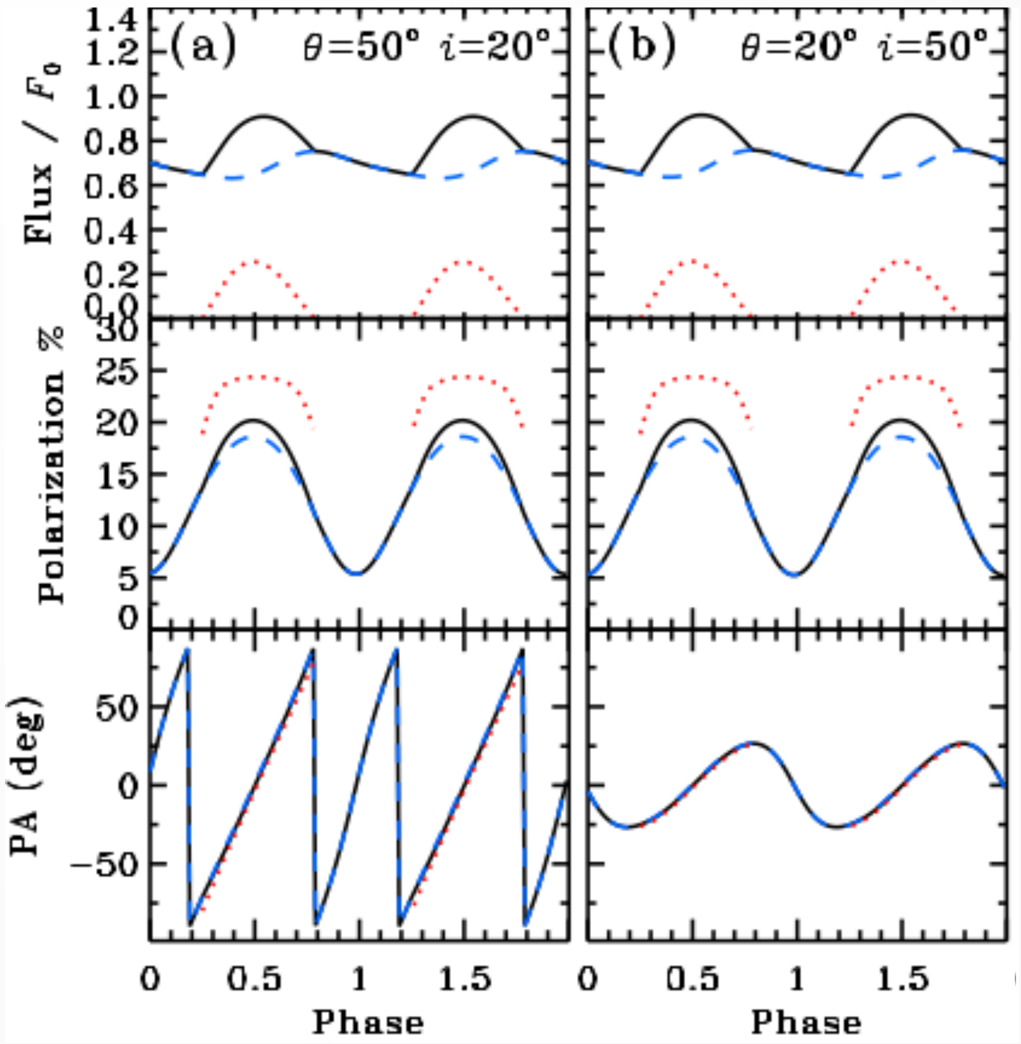
- Prospects for current and future instruments with TMPs.



Watts 2019

Prospects for polarimetry

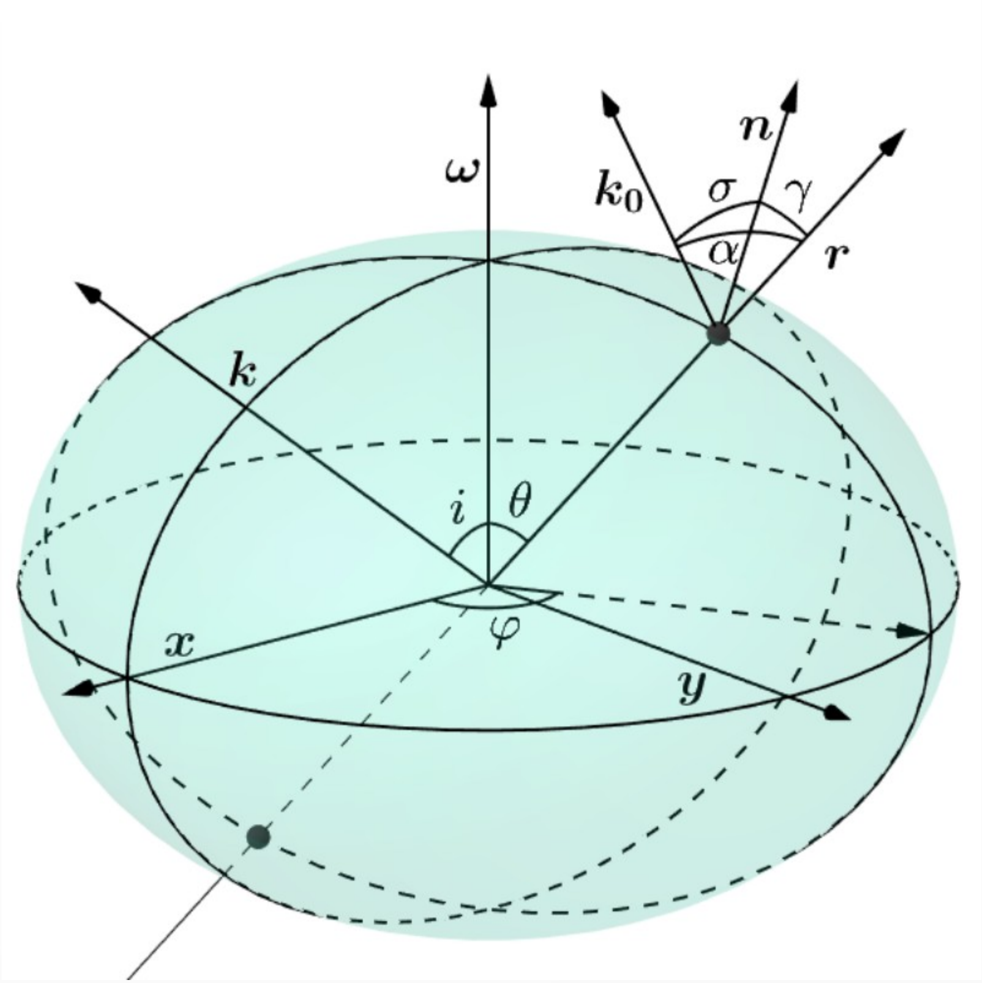
- Polarimetry can be used to constrain hot spot geometry, linked to M and R.
- Polarization angle (PA) dependence on geometry helpful to break degeneracy.
- Detectable polarization expected from AMPs.
  - RMPs too weakly polarized?
  - TMPs too short duration?



Viironen & Poutanen 2004

Polarimetry: Radiation transport

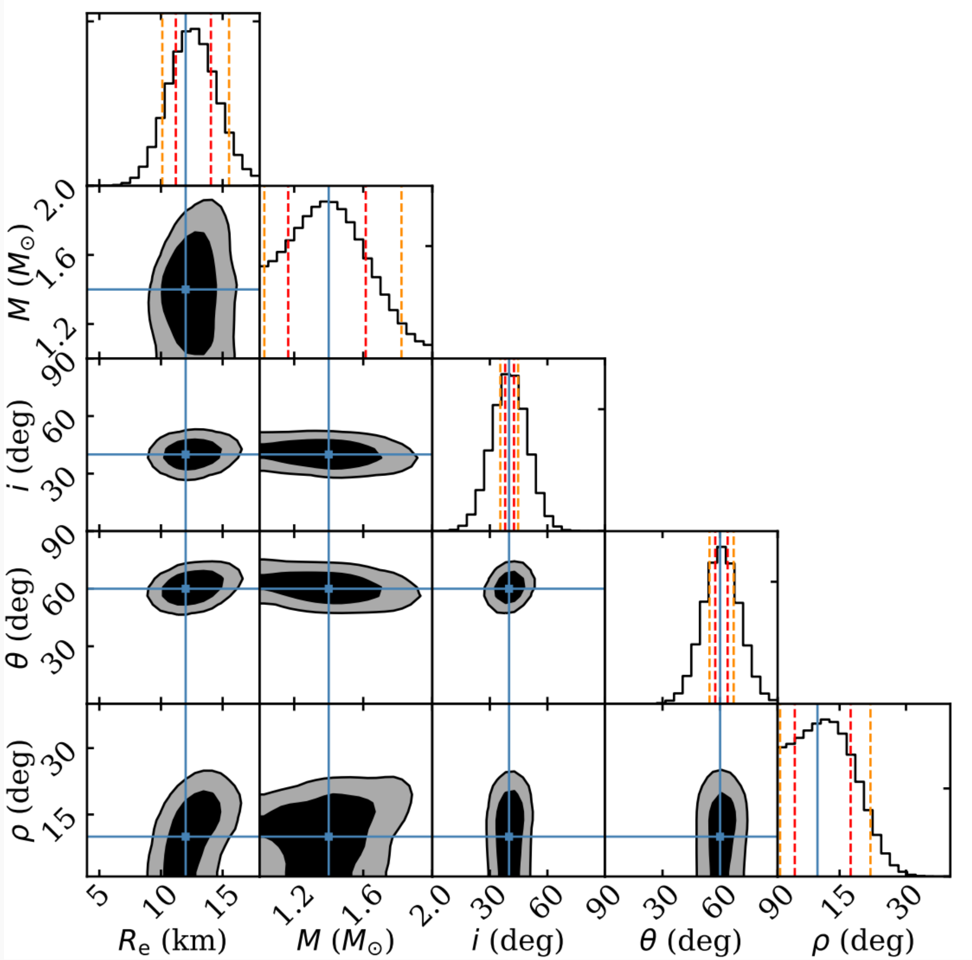
- Polarized Oblate-Schwarzschild approxmation (Loktev+2020)
- PA transport from spot to observer accounting for relativistic and oblateness effects.
- $\chi_{\rm obl} = \chi_0 + \chi_1 + \chi'$
- Stokes parameters integrated over surface area
- $$\begin{pmatrix} {\rm d}F_{\rm I} \\ {\rm d}F_{\rm Q} \\ {\rm d}F_{\rm U} \end{pmatrix} = {\rm d}F_{\rm I} \begin{pmatrix} 1 \\ P\cos 2\chi \\ P\sin 2\chi \end{pmatrix}$$

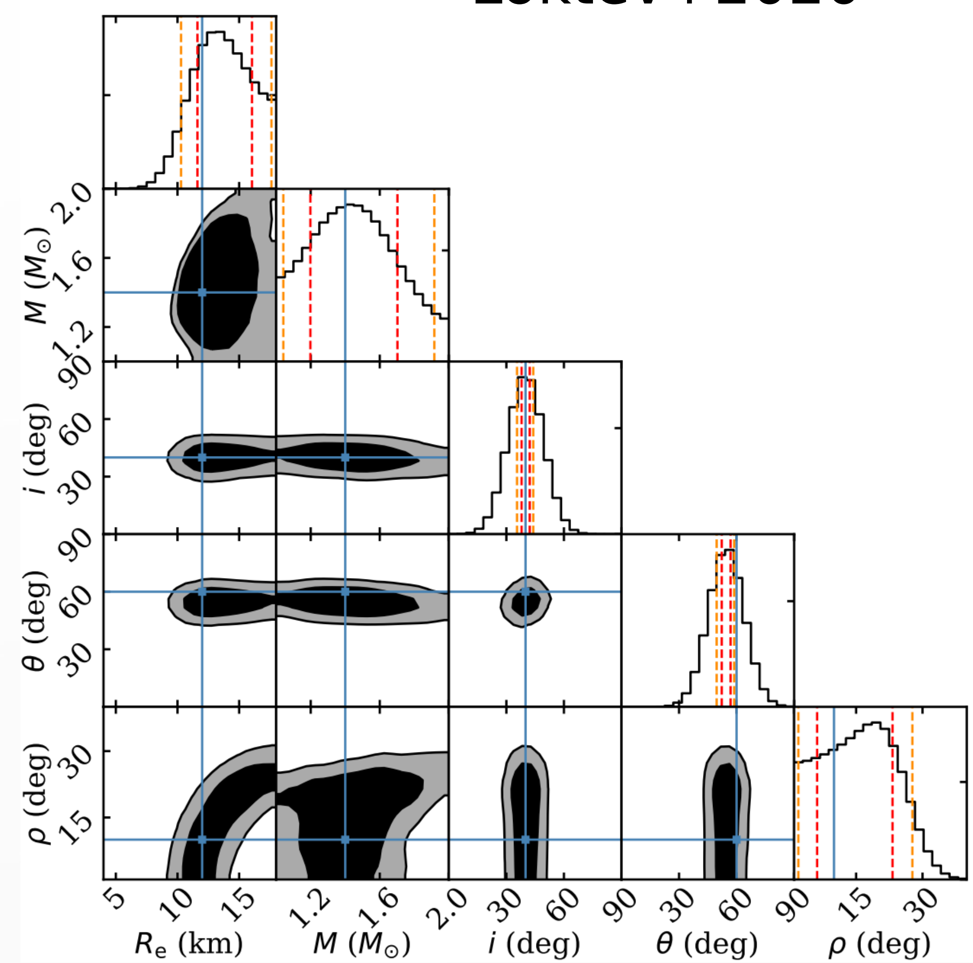


$$\cos 2\chi^{\rm tot} = \frac{F_{\rm Q}^{\rm tot}}{F_{\rm I}^{\rm tot}}, \quad \sin 2\chi^{\rm tot} = \frac{F_{\rm U}^{\rm tot}}{F_{\rm I}^{\rm tot}}.$$

Polarimetry: Simple PA fitting

Loktev+2020





Oblate fit to oblate PA profile with 2 deg PA uncertainty

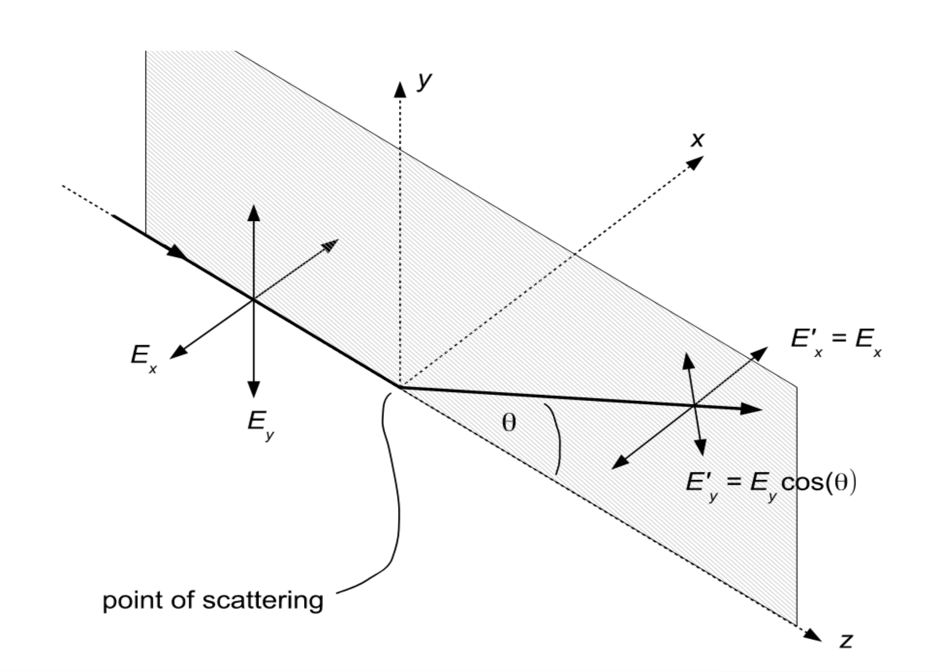
Spherical fit to oblate PA profile with 2 deg PA uncertainty

Polarimetry: Emission models

- Model for escaping radiation in the hot spot frame:

  $I(E, \mu)$ and $Q(E, \mu)$, $\mu = \cos\sigma$

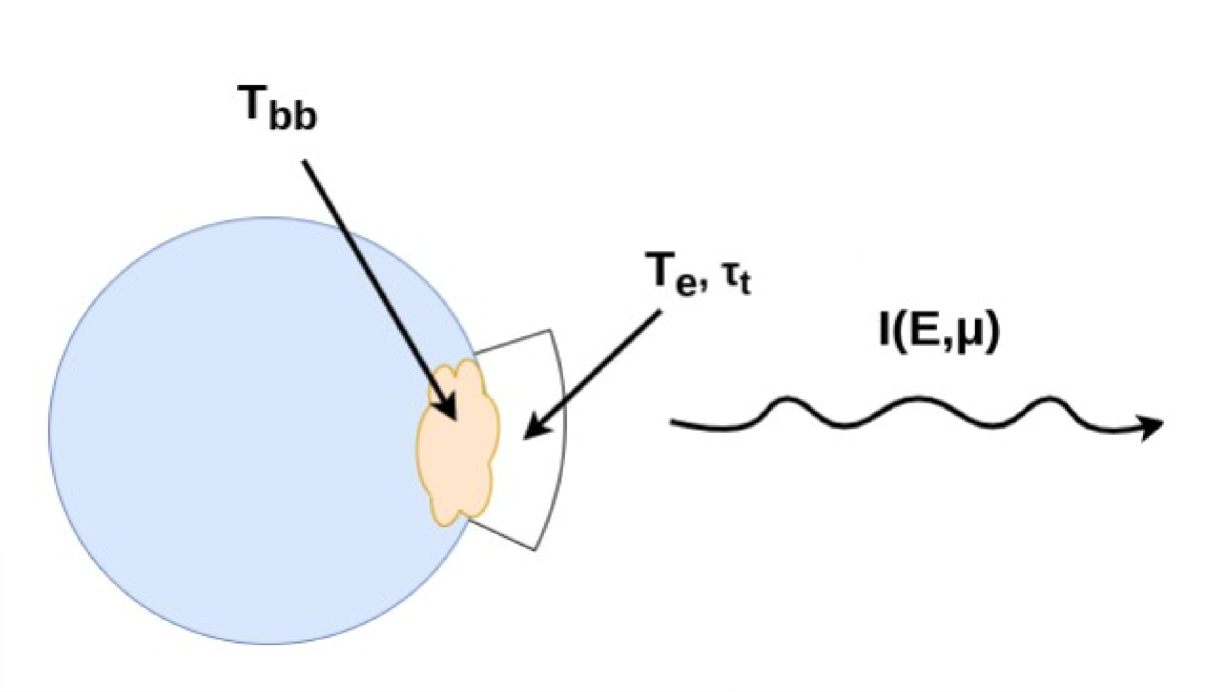
  - Thomson slab model (Salmi+2021, Viironen & Poutanen 2004, Sunyaev & Titarchuk 1985)
  - Compton slab model (Bobrikova et al., In prep., Poutanen & Svensson 1996)
- Thermal seed photons get polarized, change energies (for Compton case) and emission angles, due to scatterings with electrons.
- Scattering layer close to the surface for AMP luminosity.



Trippe 2014

Polarimetry: Compton slab model

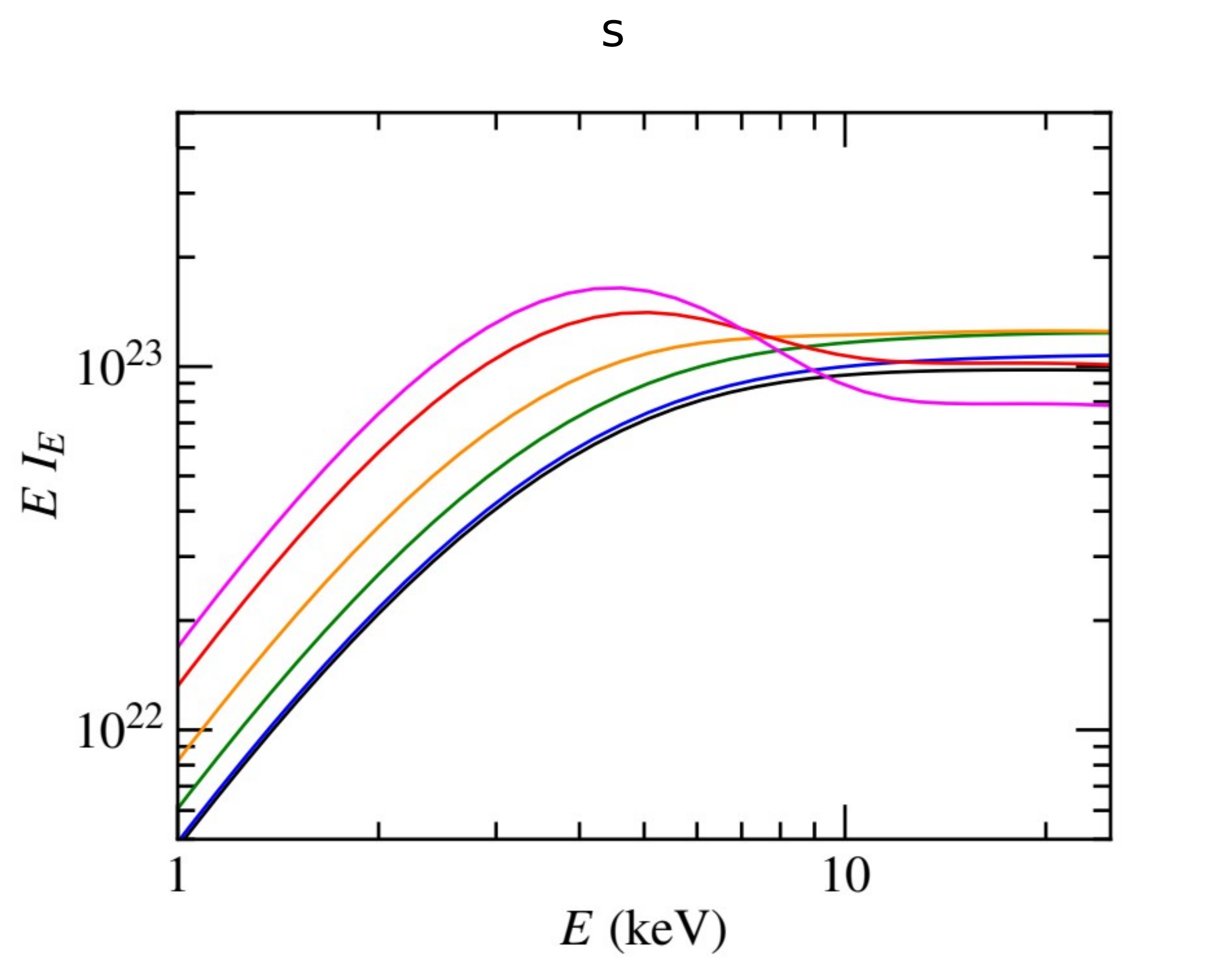
- Isothermal hot slab on top of thermal seed photons.
- Polarized radiative transfer with exact Compton redistribution matrix.
- Faster than full self-consistent accretion-heated atmosphere model (Suleimanov+2018).
- Produces AMP spectra consistent with observations.



Credit: Bas Dorsman

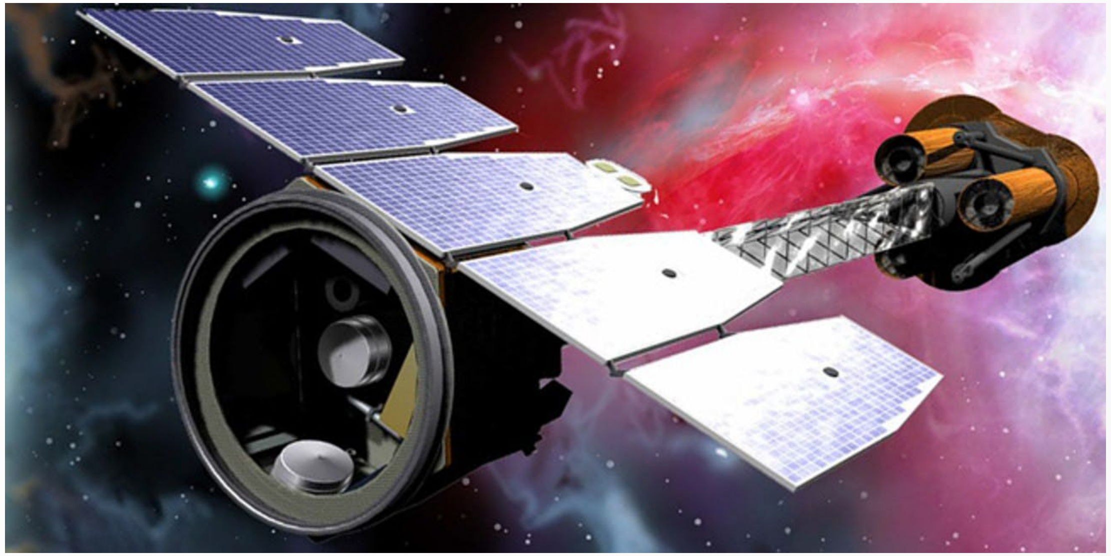
Polarimetry: Compton slab model

- A pre-computed grid produced to be used for upcoming analyses (Bobrikova+, in prep.)
- T_bb [0.5 - 1.5 keV]
- T_e [30 - 100 keV]
- τ [0.5 – 3.5]
- μ = 0.0, 0.2, 0.4, 0.6, 0.8, 1.0



Polarimetry: Instruments

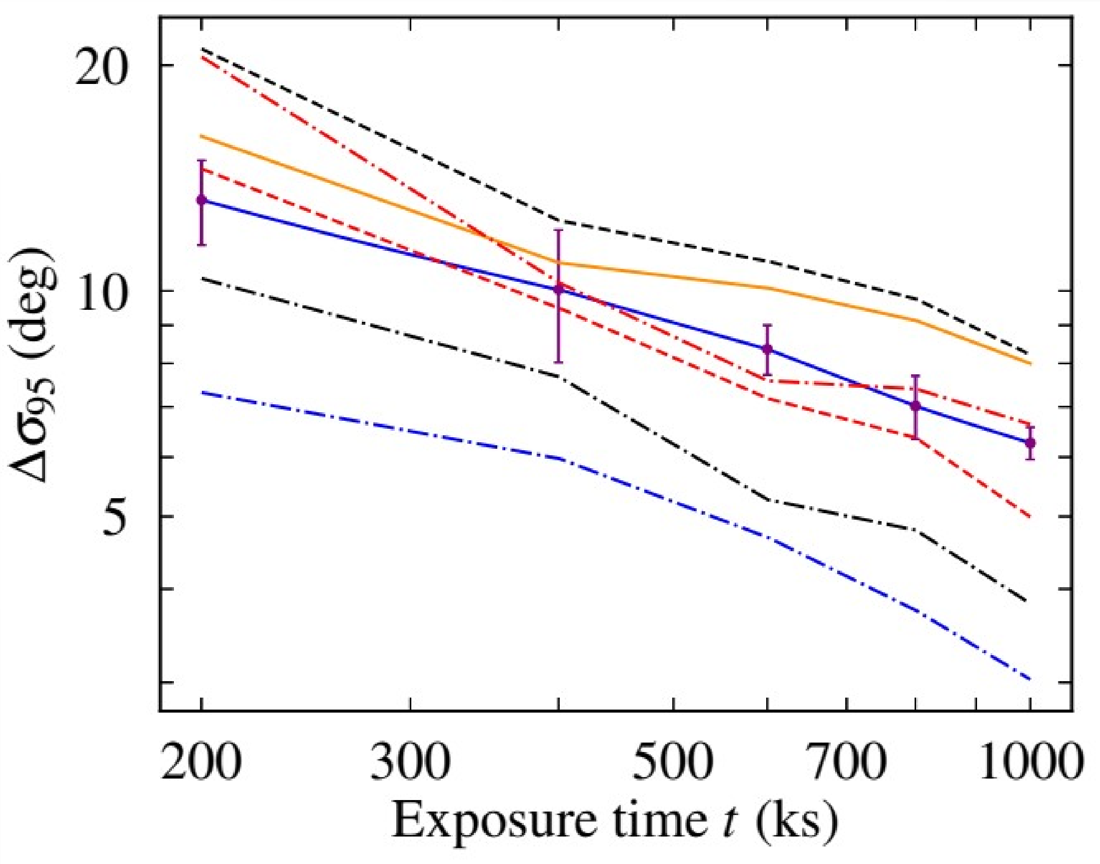
- IXPE
  - Launched in 2021 Dec.
  - No AMPs observed yet.
  - ~10 sources waiting for starting an ouburst.
- eXTP
  - Launch in 2027?
  - Larger effective area.
  - More possible candidates and shorter exposure times required.



Polarimetry: Simulations

- Predictions for the inferred credible intervals for geometry model parameters* based on simulated IXPE data and Stokes parameter fitting.

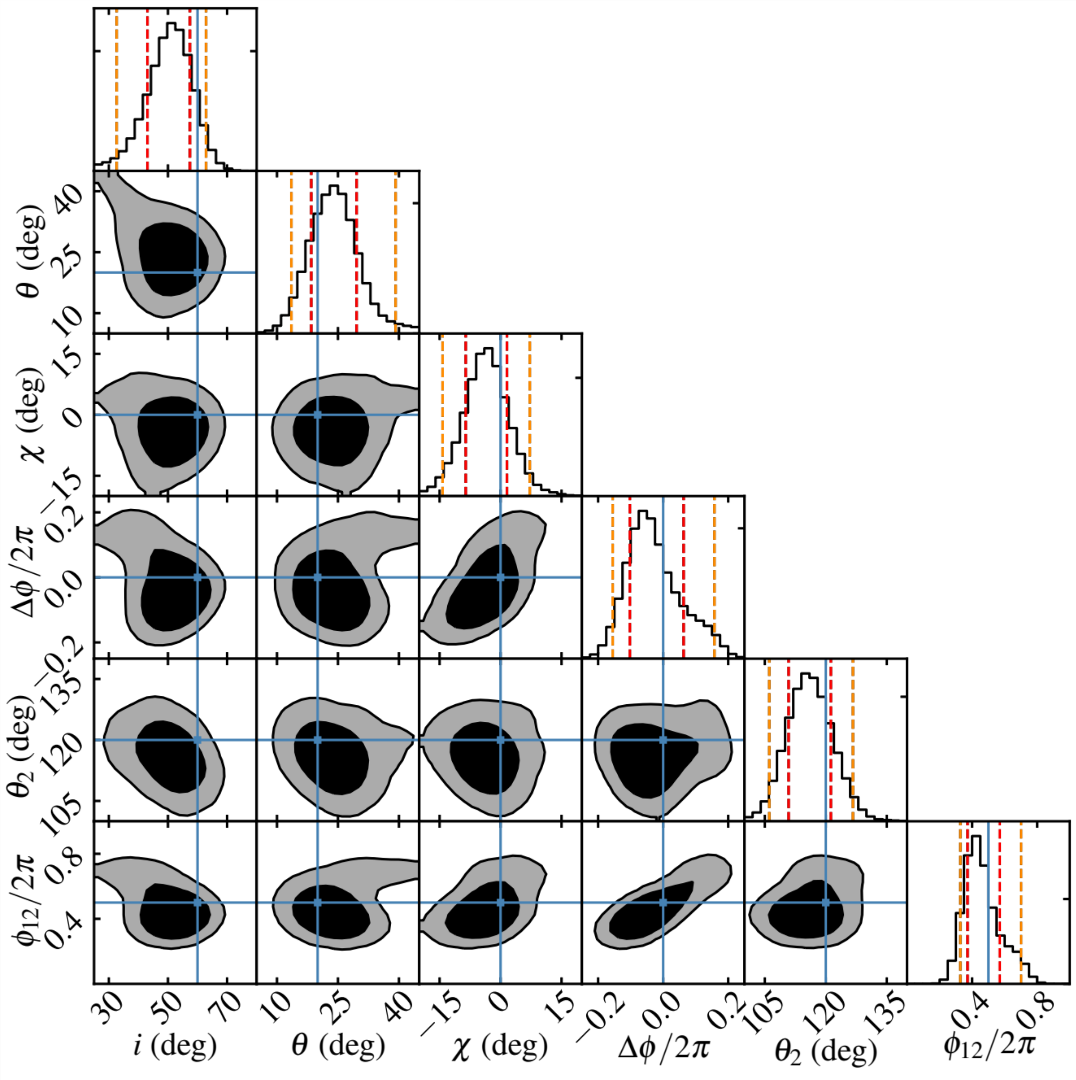
* Spot colatitude and observer inclination.



Salmi+2021

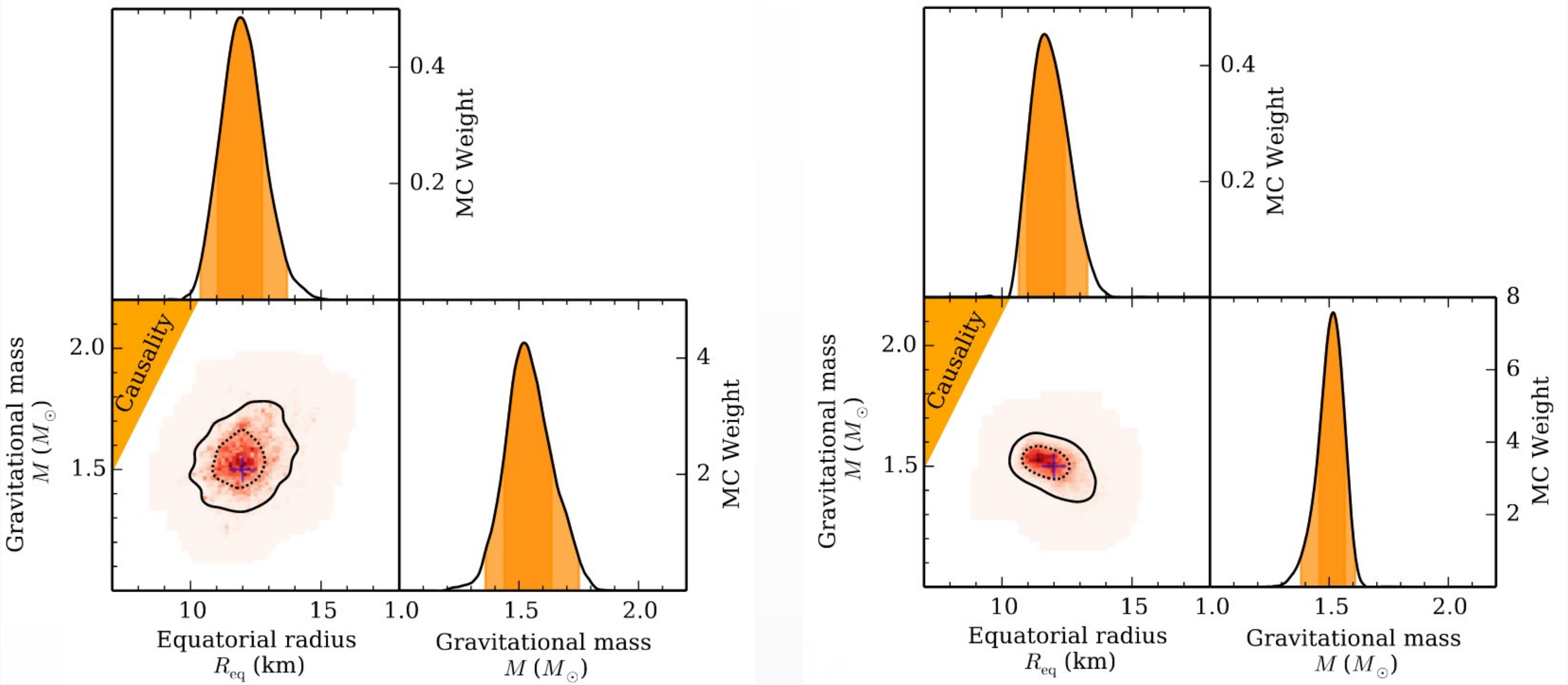
Polarimetry: Simulations

- Magnetic field configuration can be constrained as well when the other spot not hidden behind the accretion disk.
- Constraining the shapes of the spots to be studied.



Salmi+2021

Polarimetry: Effect on M&R



Salmi+2018 detected a few % improvement even when geometry already limited due to radio observations.

Conclusions and Future

- More new and old M&R constraints coming from modeling RMPs with NICER.
  - Nicer+XMM J0740 results consistent with Nicer-only, if using new Nicer background estimates.
- Fast rotating AMPs and TMPs are promising targets to further constrain M&R, especially with future instruments.
  - New models for emission developed.
- Polarimetry helps to constrain parameter degeneracies in PPM, and enables tighter constraints on M&R.