EBERHARD KARLS
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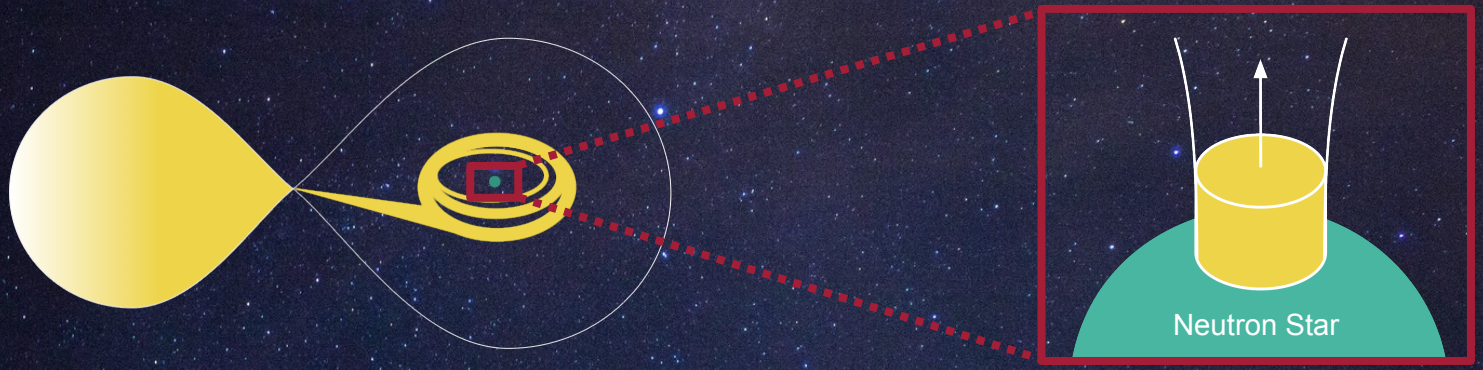


Investigations of the pulse profiles of Her X-1 and the pulse profile fitting method

BeXRB 2021 – July 26, 2021 – Inga Saathoff – saathoff@astro.uni-tuebingen.de

ROADMAP

INTRODUCTION

- HZ Her / Her X-1
  - System Parameters
  - Super-orbital period
  - Two Clocks?
  - Light Curve
  - Pulse Profiles

DATA

- *NuSTAR*
- *HXMT/Insight*

METHOD

- Pulse Profile Fitting Method
- Phase Zero / Turn-On Time Determination

RESULTS

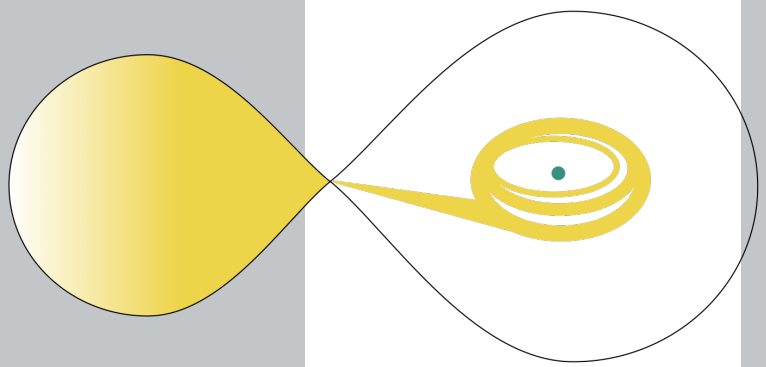
- (O-C) Diagram

SUMMARY

- Open questions
- Next steps

HZ Her / Her X-1:

System Parameters



- Companion: HZ Her, B3-B4
- M_{NS} = (1.5 ± 0.3) $M_\odot$
- M_{HZ} = (2.3 ± 0.3) $M_\odot$
- R_{HZ} = (4.2 ± 0.2) $R_\odot$

Reynolds et al. (1997)

→ IMXB, accretion mechanism: Roche lobe overflow (typical for LMXB)

- d ≅ 6 kpc

Leahy & Abdallah (2014)

- Variability on three timescales:
  - P_{NS} ≅ 1.24 s
  - P_{binary} ≅ 1.7 d
  - $P_{super\text{-}orbital}$ ≅ 35 d

Staubert et al. (2009)

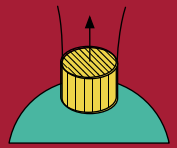
HZ Her / Her X-1:

Super-Orbital Period:

Two Clocks?

1: Accretion Disk

2: Neutron Star



1: Accretion Disk

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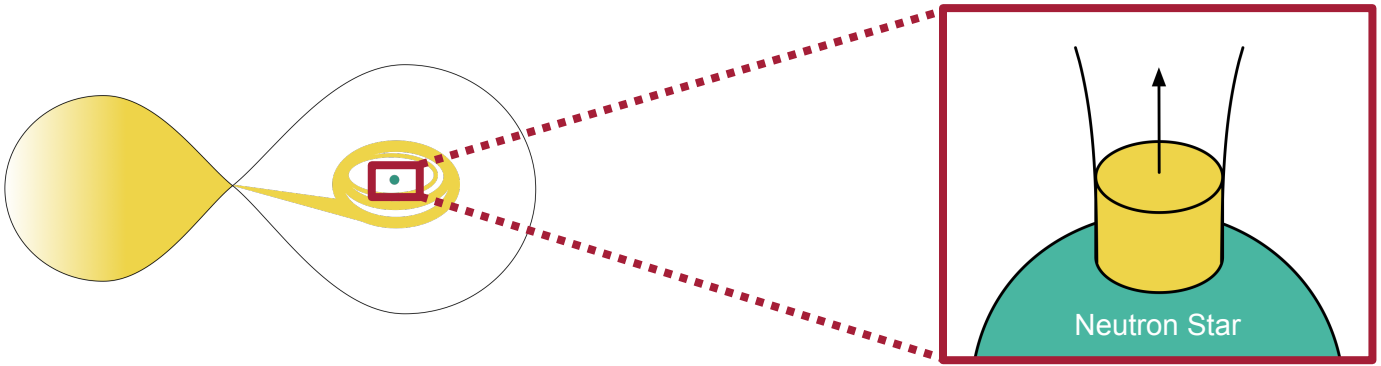


Observable: light curve

Observable: pulse profile

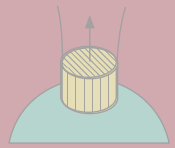
HZ Her / Her X-1:

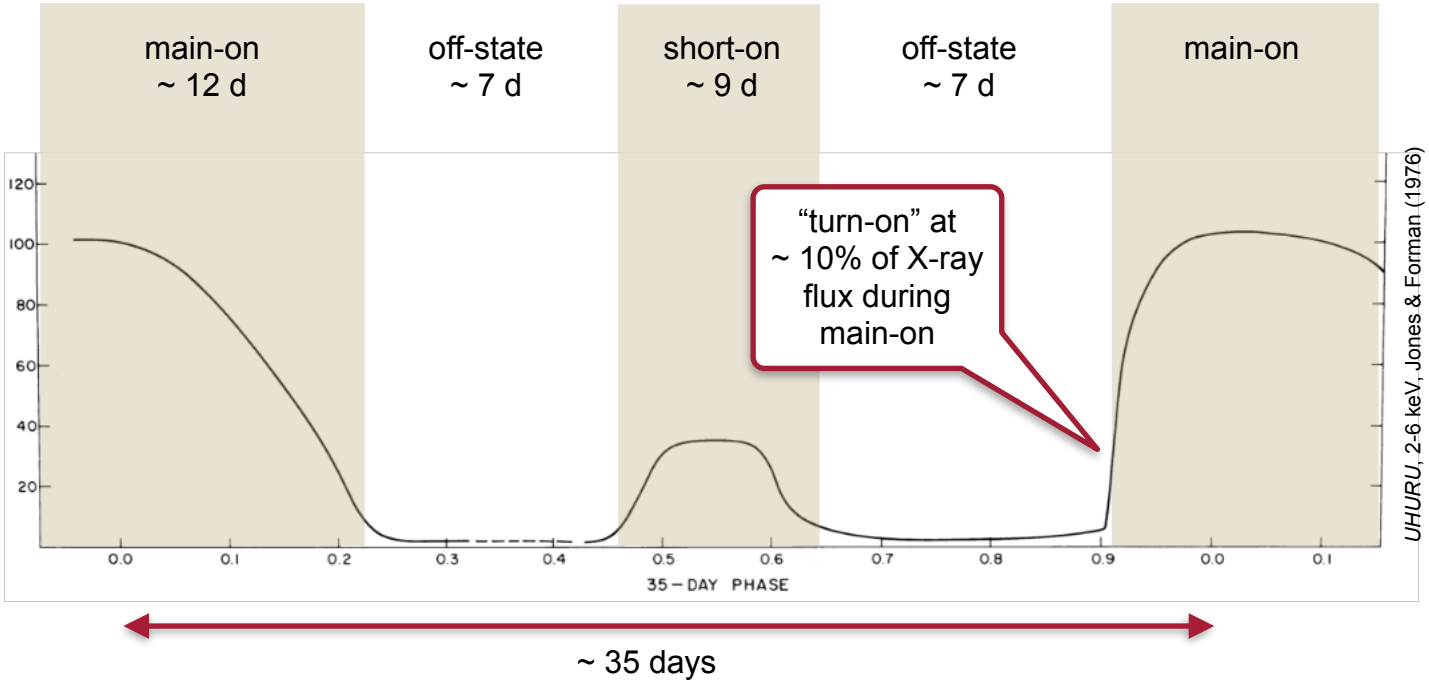
Super-Orbital Period:

- X-ray Light Curve
- Turn-On
- (O^{LC} - C) Diagram

1: Accretion Disk

2: Neutron Star





HZ Her / Her X-1:

Super-Orbital Period:

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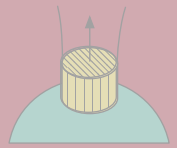
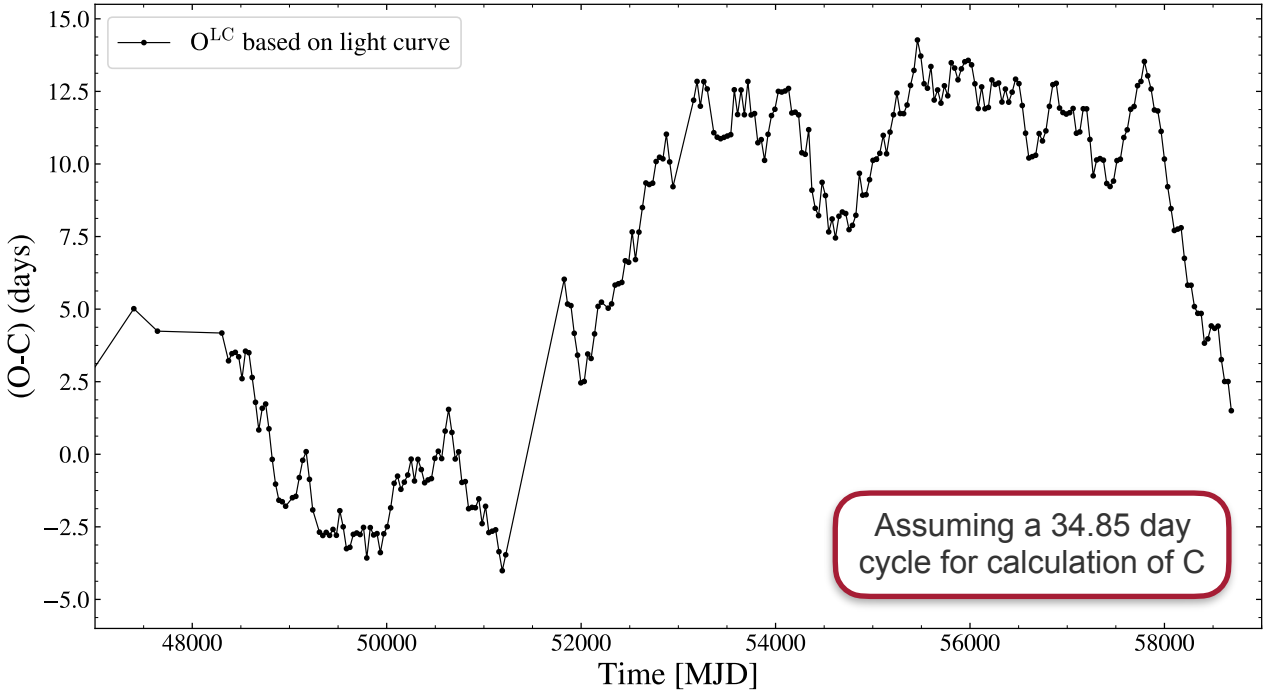


X-ray Light Curve ➔ (O^{LC} - C) Diagram



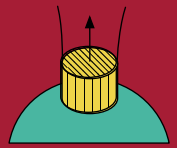
HZ Her / Her X-1:

Super-Orbital Period:

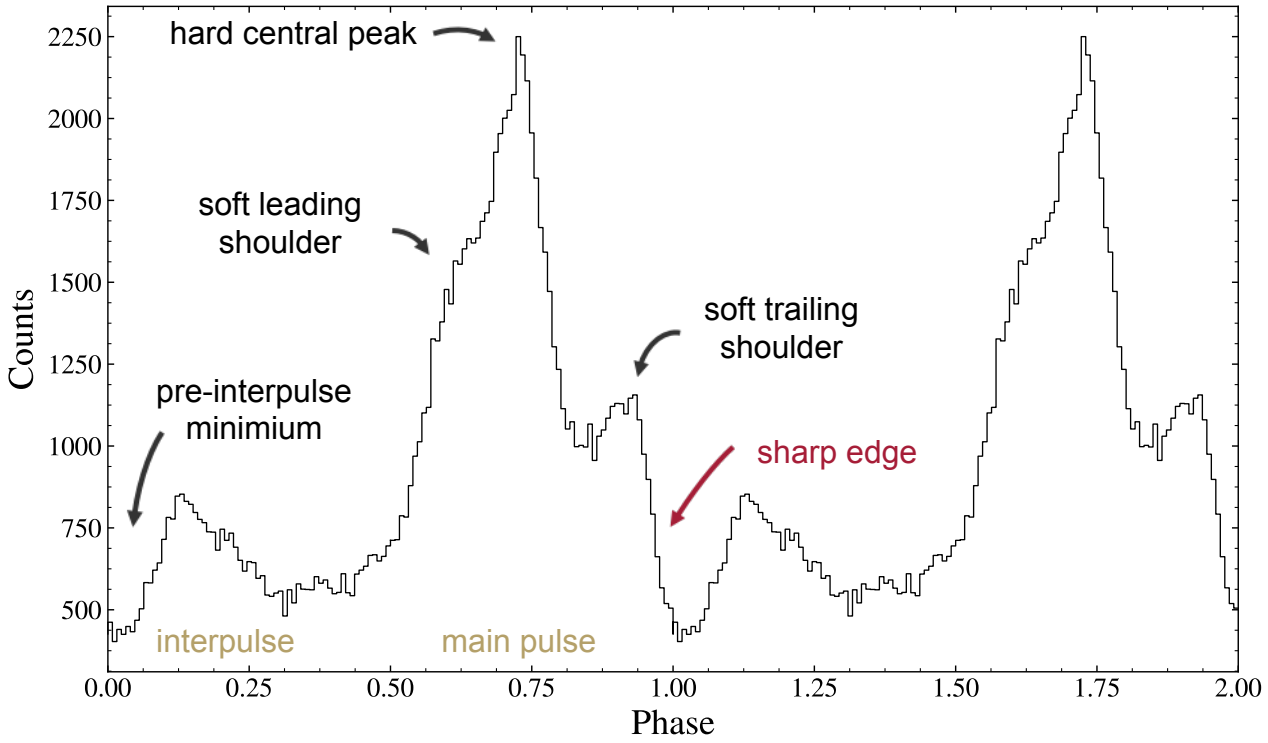
- Pulse Profile
- Turn-On
- (O^{PP} - C) Diagram

1: Accretion Disk

2: Neutron Star



NuSTAR data 9-13 keV



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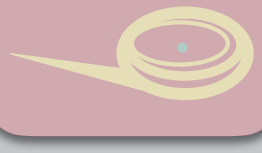
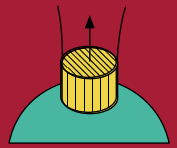
Super-Orbital Period:

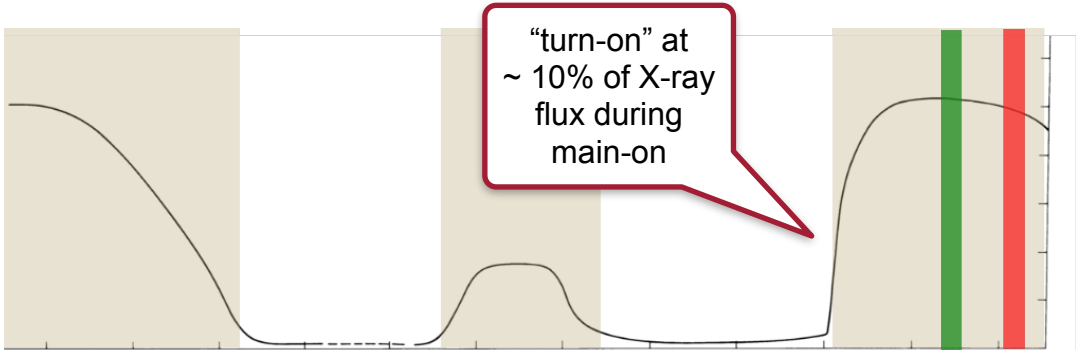
- Pulse Profile
- Turn-On
- (O^{PP} - C) Diagram

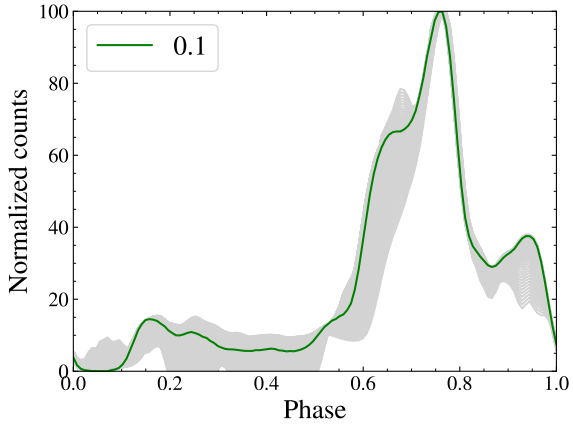
1: Accretion Disk

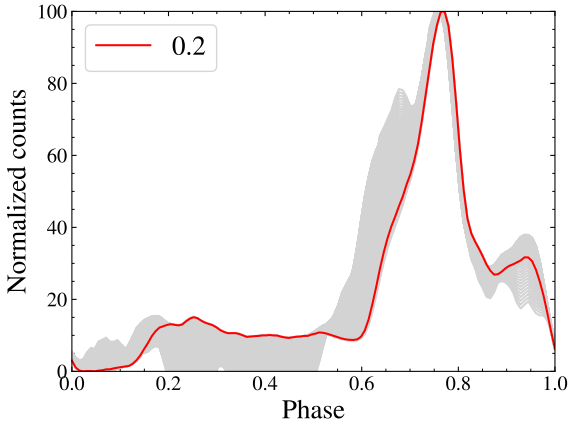


2: Neutron Star







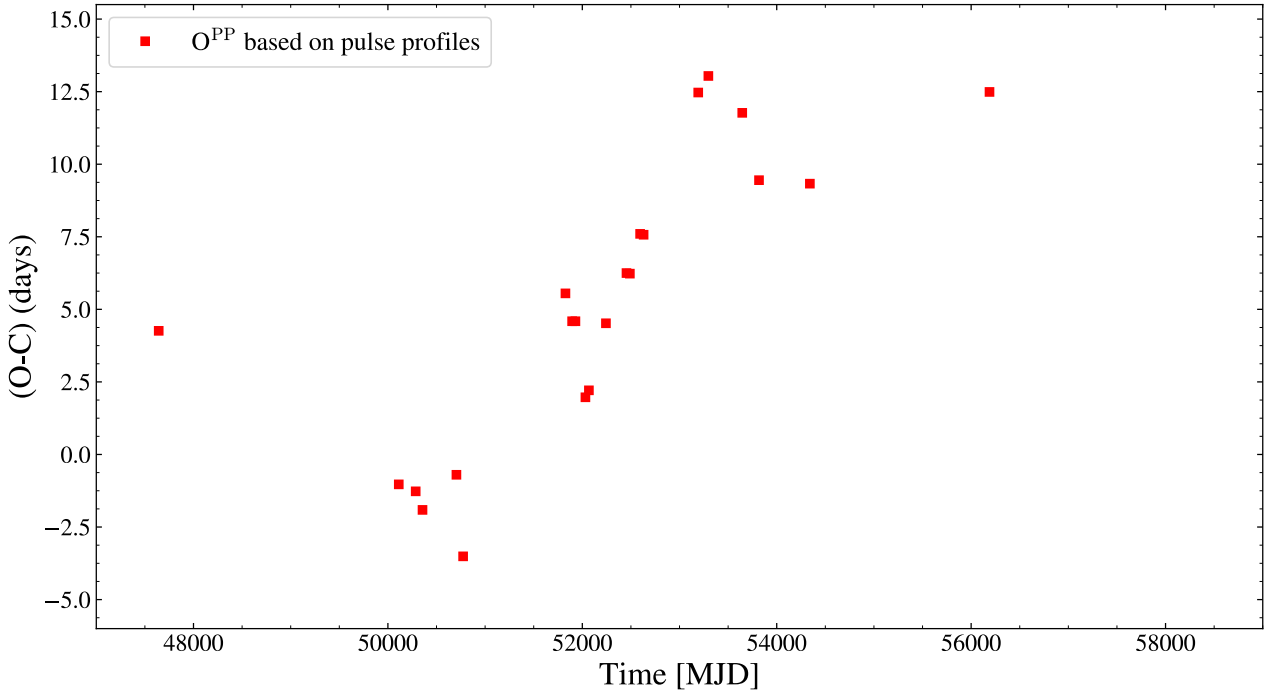


HZ Her / Her X-1:

Super-Orbital Period:

- Pulse Profile
- Turn-On
- (O^{PP} - C) Diagram

Pulse Profile Evolution ➔ (O^{PP} - C) Diagram



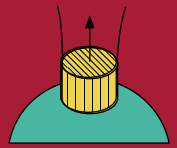
HZ Her / Her X-1:

Super-Orbital Period:

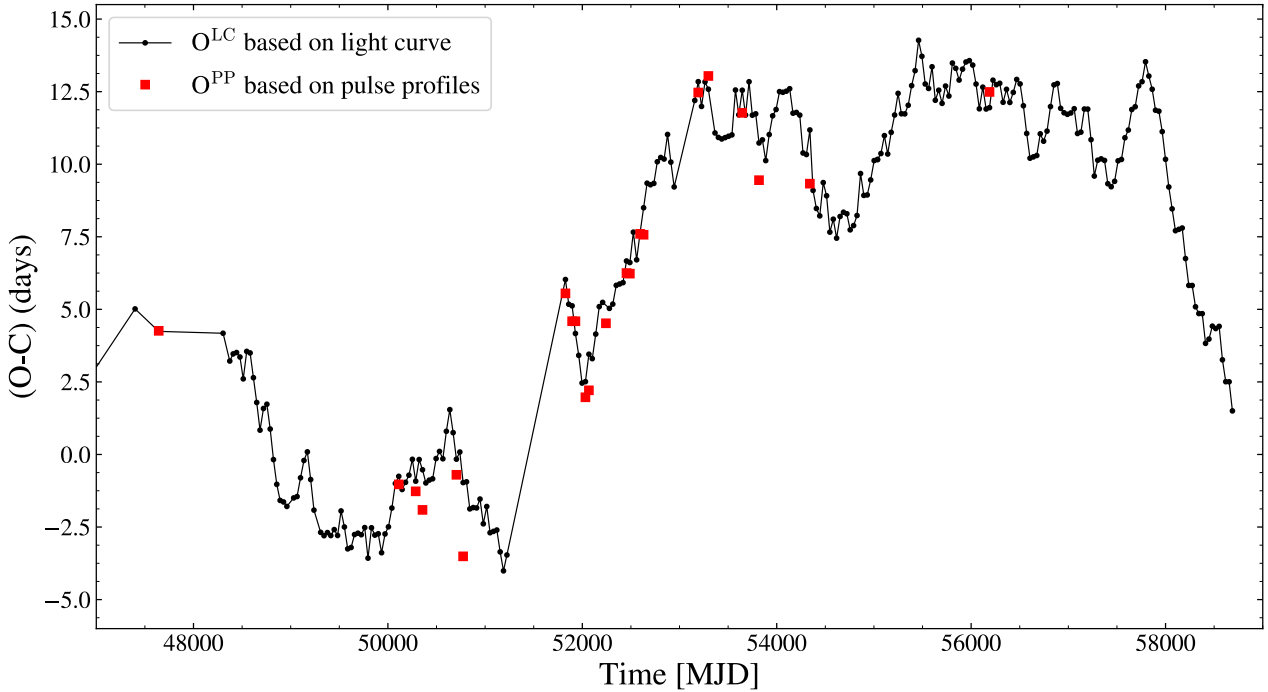
- Comparison:
  - (O^{LC} - C) Diagram
  - (O^{PP} - C) Diagram

1: Accretion Disk

2: Neutron Star



Comparing the (O^{LC} - C) and (O^{PP} - C) diagrams

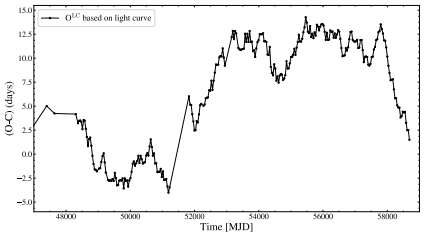


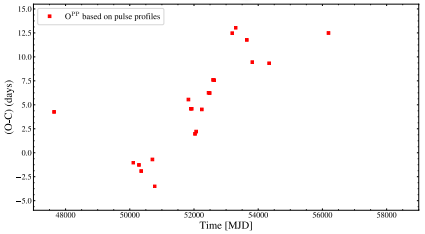
HZ Her / Her X-1:

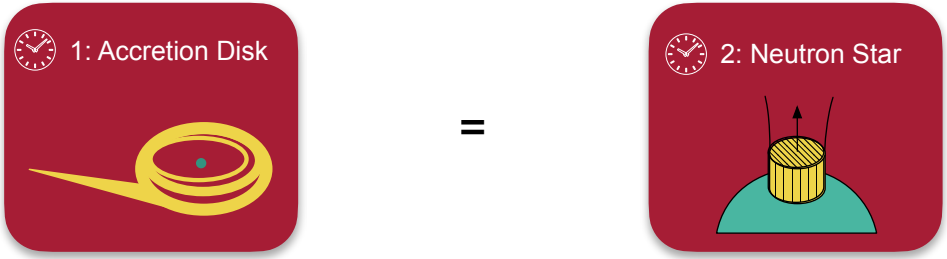
Super-Orbital Period:

- Comparison:
  - (O^{LC} - C) Diagram
  - (O^{PP} - C) Diagram

Comparing the (O^{LC} - C) and (O^{PP} - C) diagrams







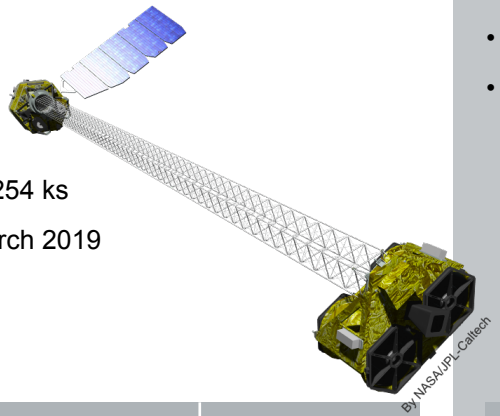
Satellites & Observations

1: Accretion Disk

2: Neutron Star

NuSTAR - Nuclear Spectroscopic Telescope Array

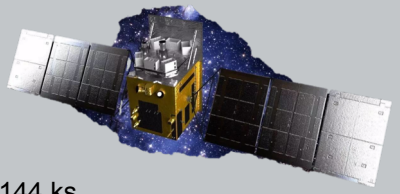
- NASA Small Explorer SMEX-11
- Launch: 13 June 2012
- Data:
  - 10 observations
  - Exposure time total: 254 ks
  - September 2012- March 2019



Parameter	Value
Energy range	3 to 79 keV
Energy resolution (FWHM) at 10 keV	400 eV
Energy resolution (FWHM) at 68 keV	900 eV
Relative time resolution	2 µs

HXMT/Insight - Hard X-ray Modulation Telescope

- CAS/IHEP (China)
- Launch: 14 June 2017
- Data:
  - 23 observations
  - Exposure time total: 1144 ks
  - July 2017- March 2019



Parameter	Value
Energy range HE Energy range ME Energy range LE	20 to 250 keV 5 to 30 keV 1 to 15 keV
Energy resolution (FWHM) HE Energy resolution (FWHM) ME Energy resolution (FWHM) LE	14-16% at 60 keV 3 keV at 20 keV 140 eV at 5.9 keV

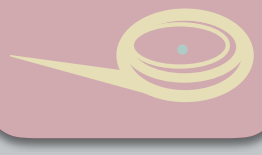
HZ Her / Her X-1:

RXTE Template

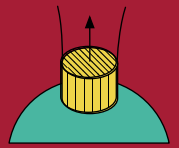
&

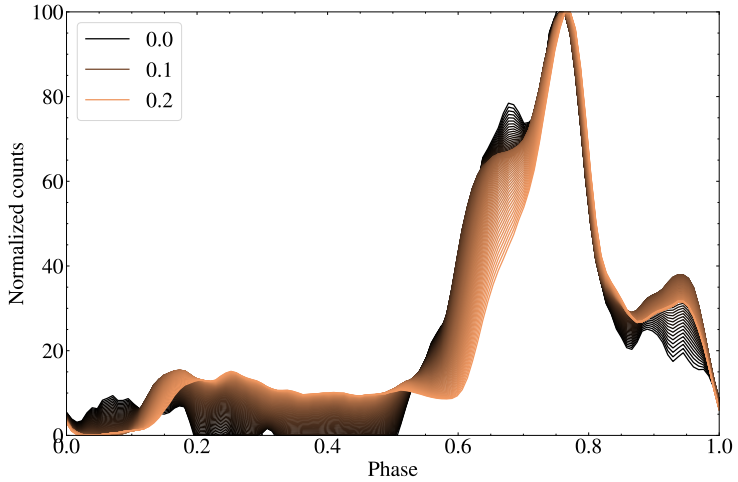
Template Fitting

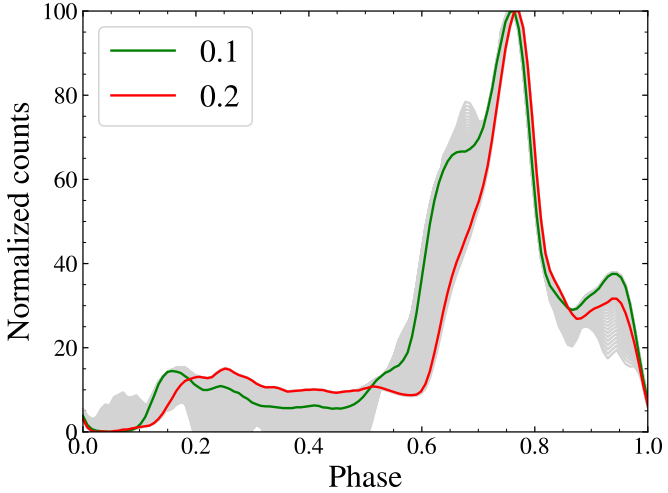
1: Accretion Disk



2: Neutron Star







➡ Determine 35 day phase for multiple times during the same main-on / cycle

➡ Determine the turn-on/phase zero time

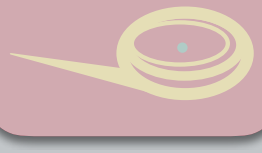
HZ Her / Her X-1:

Phase Zero /

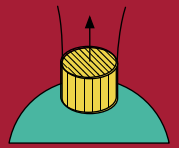
Turn-on Time

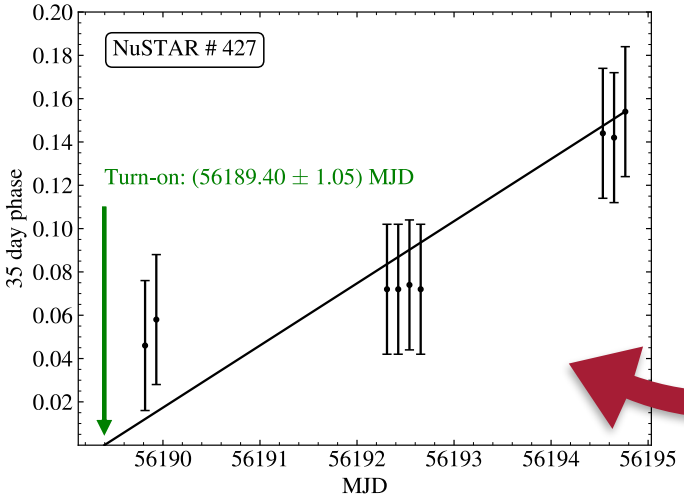
Determination

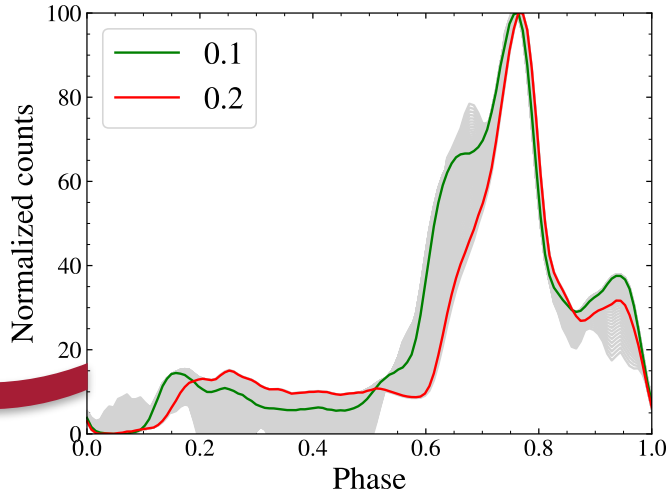
1: Accretion Disk



2: Neutron Star







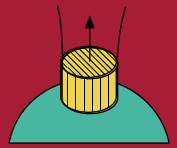
➡ Extrapolation to phase zero based on a super-orbital phase of 34.85 d (this is not a linear fit, the slope is fixed to 34.85 d)

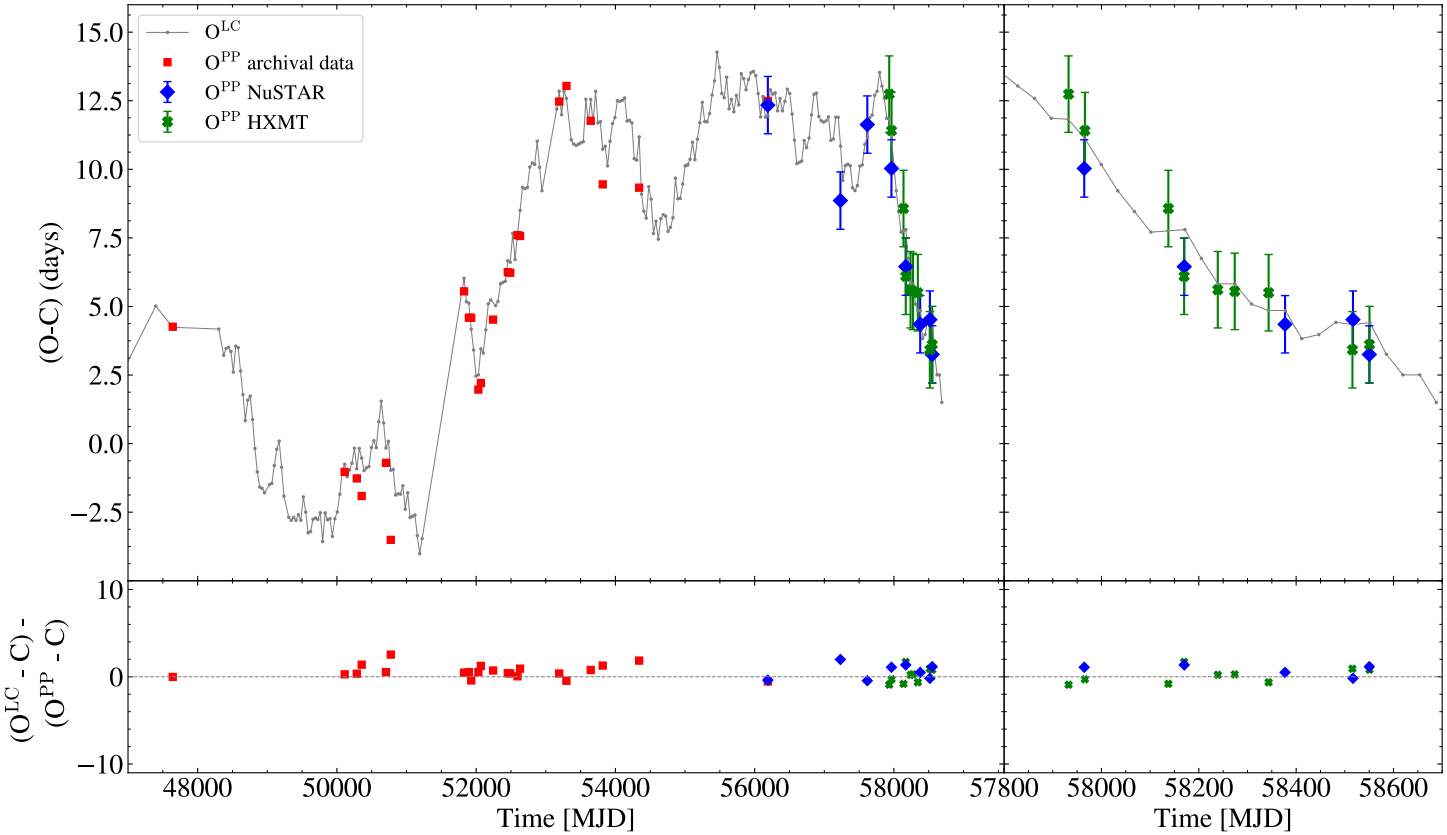
HZ Her / Her X-1:

(O-C) diagrams

1: Accretion Disk

2: Neutron Star





HZ Her / Her X-1:

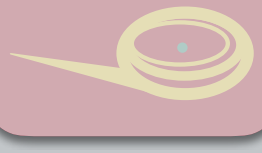
Phase Zero /

Turn-on Time

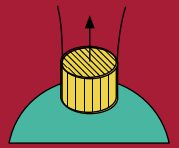
Determination

A closer look

1: Accretion Disk



2: Neutron Star

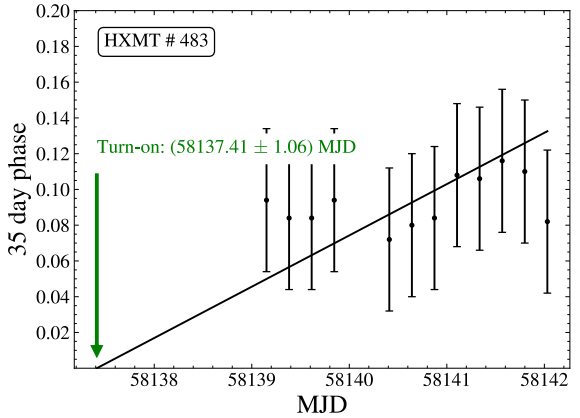


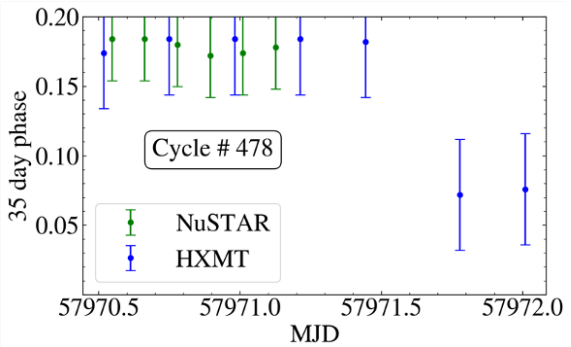
Changes in pulse profile with super-orbital period: *RXTE* template with 34.85d does not seem to be represented in the *NuSTAR* and *HXMT* data.

Possible explanations:

- Observations too short compared to an entire main-on?
- Has something changed since the *RXTE* template time?

➡ Going back to the turn-on time determination





HZ Her / Her X-1:

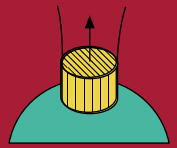
Phase Zero /

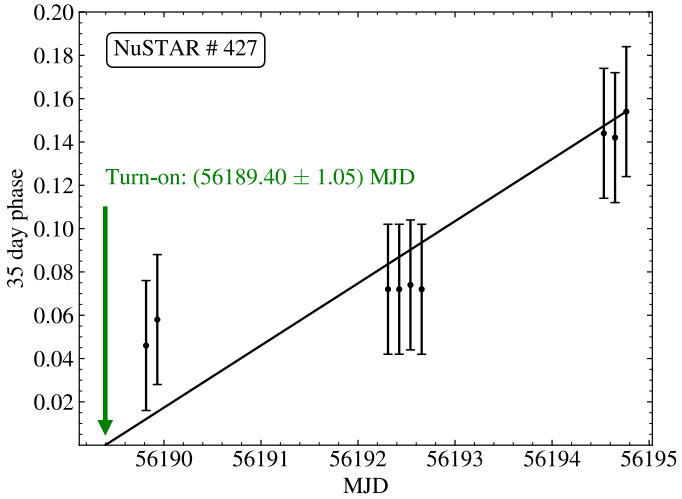
Turn-on Time

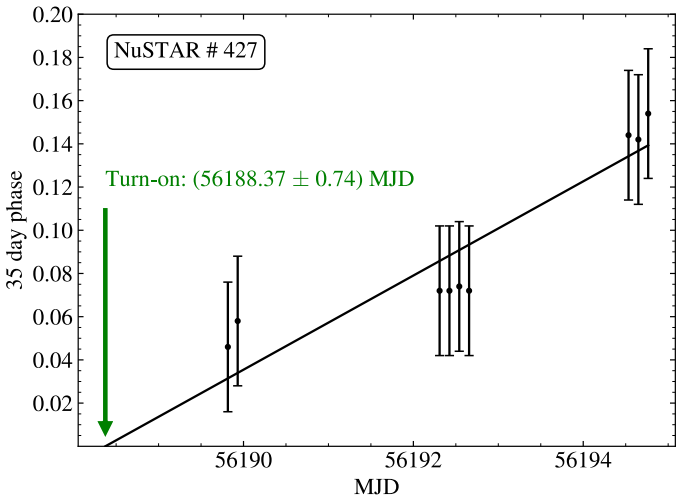
Determination

1: Accretion Disk

2: Neutron Star







➡ Extrapolation to phase zero based on a super-orbital phase of 34.85 d (not a linear fit, slope is fixed)

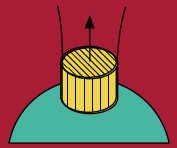
➡ Linear regression; super-orbital phase (slope) is a free parameter

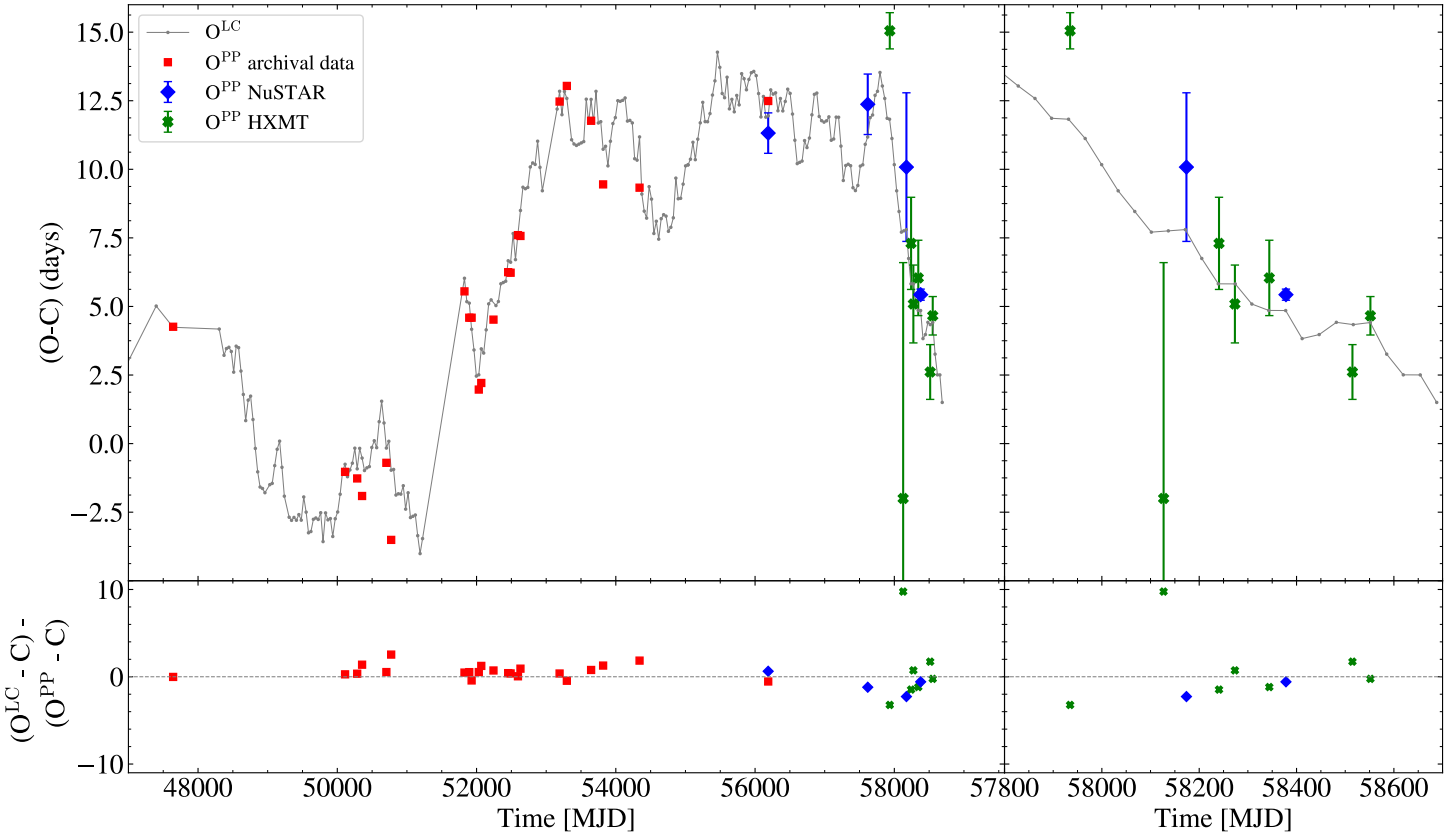
HZ Her / Her X-1:

(O-C) diagrams

1: Accretion Disk

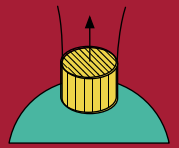
2: Neutron Star





1: Accretion Disk

2: Neutron Star



Two clocks in Her X-1?

- Accretion disk & light curve
- Neutron star & pulse profiles

Method

- Pulse profile fitting
- Turn-on determination

Results

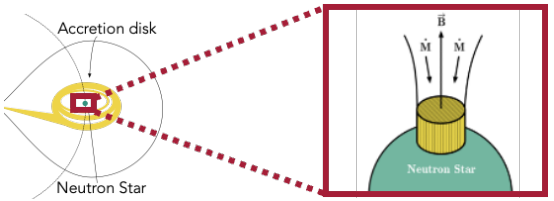
- (O-C) Diagrams
- Closer Look

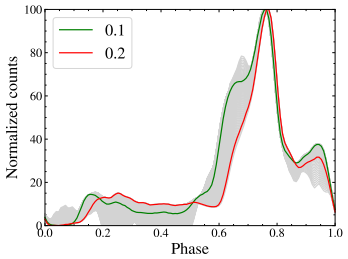
Open questions

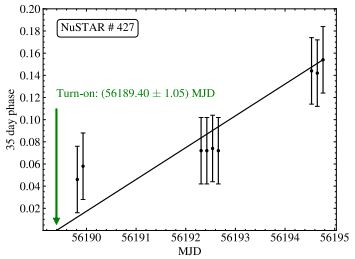
- Does the pulse profile change as systematically with 35 day phase as needed for the pulse profile fitting method?

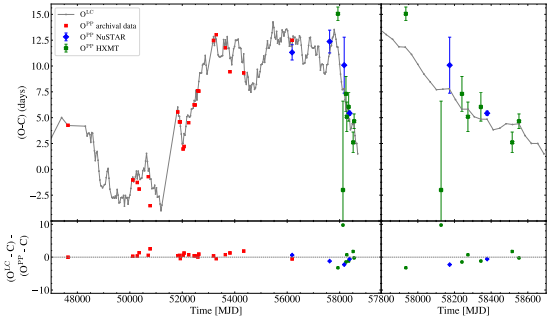
Next steps

- In-depth analysis of *RXTE* data to examine the method
- New template









Thank you!