Spectral–Timing Methods and Insights with GHATS:
Listening to Accretion in Compact Objects

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Outline

Origins & Philosophy of GHATS

- *The RXTE era and Tomaso's (TMB) vision*

Core Methodology & Early Discoveries

- *Production, analysis workflows, and early X-ray binary results*

The Journey to GHATS v3.2-v3.3

- *Cross-spectral analysis and transition to a multi-mission suite*

Introducing GHATS Version 4.0.0

- *New observatories, improved documentation and help platform, the Bispectrum module, and standardized I/O*

Scientific Demonstrations & Summary

- *2D bicoherence in action and beyond*

The origin of GHATS

- **The RXTE/PCA Era:** Fast aperiodic variability required efficient, direct processing of raw event data.

- **Core Design Philosophy:**

  1. ***Process raw event files*** directly without generating intermediate light curves.

  2. ***Modular separation:*** Automated **Production** vs. Highly Interactive **Analysis**.

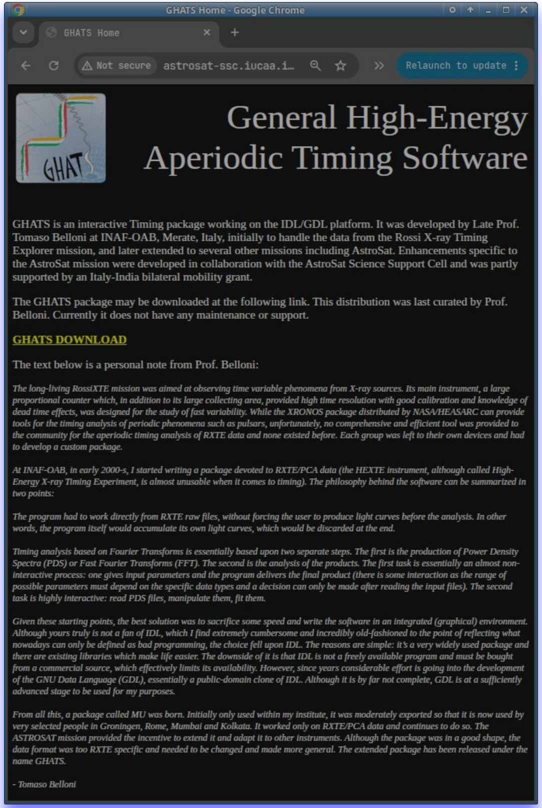
```
$ ls FS3f* > @sb.lis
$ ls FS3b* > @event.lis
$ ls @sb.lis @event.lis > @@all.lis
```

- **The Legacy:** Born as **MU** (Merate–Utrecht) → Evolved into **GHATS** (*General High-energy Aperiodic Time-series Software*) after *ASTROSAT* came to life.

  1. Written in IDL - but *fully compatible with GDL* (GNU version).

  2. Essentially designed for ***RXTE*** but later extended to ***ASTROSAT***, *Swift*, XMM-*Newton*, *NuSTAR* (incl. co-spectrum), ***NICER*** and *HXMT*.

  3. Exporting timing products to PHA/RMF XSPEC format for fitting.



Core Fourier Timing Methodology

GHATS Architecture & Workflow

- **Step 1: Production (`gh_xte`, `gh_*`)**
  - Light curves accumulated in memory from raw event data.
  - Generates native binary products: `.pds` or `.fft` (Complex Fourier amplitudes).

REFERENCE

GH_XTE

```
gh_xte, [/ghx], [/turbo],[bands=[s1,e1,s2,e2,s3,e3]],[gti=usergtifile], [/sliding], [/
        bary][,window=window][,wpar=wpar]
gh_xte,infilename,outtype,channels,treb,npds,oufilename, [/ghx], [/turbo],
        [bands=[s1,e1,s2,e2,s3,e3]],[gti=usergtifile], [/sliding], [/bary]
        [,window=window][,wpar=wpar]
gh_xte,parameterfile
```

Program for the production of PDS/FFT files starting from RXTE/PCA science/event array files. It is the main extraction procedure of the software.

```
---------------------------------------------------------------
Program gh_xte Tue Jan 3 15:26:00 2012 User: belloni
---------------------------------------------------------------
Working directory :
/Users/belloni/data/xte/u1636/realtime/96087-01-84-10/pca
Input filename :
/Users/belloni/data/xte/u1636/realtime/96087-01-84-10/pca/@event.lis
Instrument : XTE/PCA
Observation ID : 96087-01-84-10
Source name : 4U_1636-53
Start date of observation : 2011-12-29T04:01:36
Channels for accumulation : 0-249
Type of output : POWER
Output filename : event.pds
Time resolution (s) : 1/8192
Nyquist frequency (Hz) : 4096.0000
Number of points per FFT : 262144
Corresponding to length (s) : 32.000000
Total number of FFTs : 64
Time step : 32.000000
---------------------------------------------------------------
```

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  - Fast plots of the lightcurve and the averaged power spectrum.

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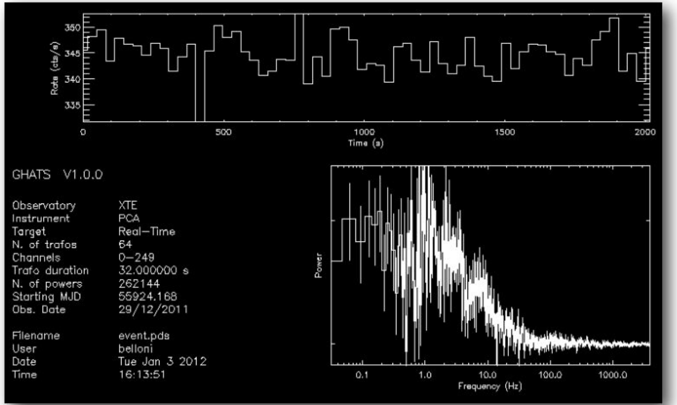

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- **Step 3: Interactive Analysis (`ghx, gh_cross`)**
  - Filtering by time, count rate, or index.
  - Noise subtraction (Poisson) & fractional rms conversion.
- **Step 4: Rebinning (`gh_reb`)**
  - Linear/Logarithmic frequency rebinning.

REFERENCE

GH_XTE

```
gh_xte, [/ghx], [/turbo],[bands=[s1,e1,s2,e2,s3,e3]],[gti=usergtifile], [/sliding], [/
        bary][,window=window][,wpar=wpar]
gh_xte,infilename,outtype,channels,treb,npds,oufilename, [/ghx], [/turbo],
        [bands=[s1,e1,s2,e2,s3,e3]],[gti=usergtifile], [/sliding], [/bary]
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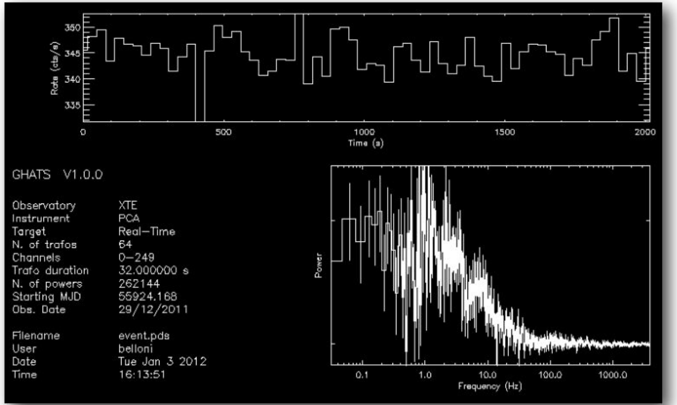

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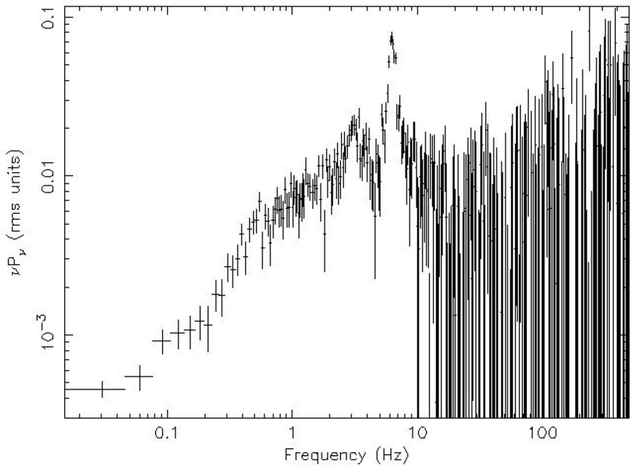
- **Step 5: Output to XSPEC for fitting (gh_xspec)**
  - PDS, Re/Im CDS, lags, coherence.

```
GHATS> gh_xspec,nu,pow,powerr,'mypds'

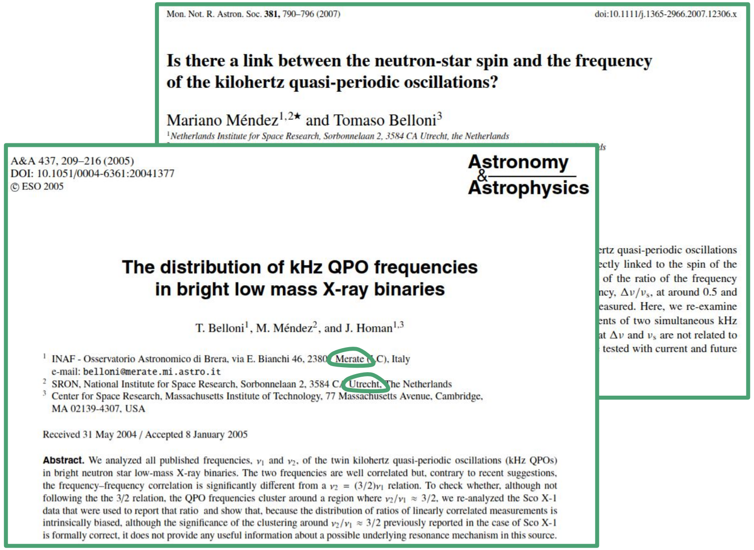
XSPEC> data mypds.pha
XSPEC> cpd /xs
XSPEC> setpl energy
XSPEC> setpl com la y \\gnP\\d\\gn\\u (rms units)
XSPEC> setpl com la x Frequency (Hz)
XSPEC> pl leda
```



Early Discoveries in Neutron Star X-ray Binaries

Timing Discoveries in Neutron Star Binaries

- **Kilohertz QPOs (kHz QPOs):**
  - Probing inner disk motions near the neutron star surface and ISCO (e.g., Sco X-1, 4U 1608-52, 4U 1636-53).
  - Discovery of frequency correlations and upper/lower peak behavior.
- **Atoll vs. Z-Source Dynamics:**
  - Mapping state transitions along the Z-track and Atoll tracks.
- **Thermonuclear Burst Oscillations:**
  - High-time-resolution tracking of fast spin and boundary-layer phenomena during type-I X-ray bursts.


Mon. Not. R. Astron. Soc. **381**, 790–796 (2007) doi:10.1111/j.1365-2966.2007.12306.x

Is there a link between the neutron-star spin and the frequency of the kilohertz quasi-periodic oscillations?

Mariano Méndez[1,2]★ and Tomaso Belloni[3]
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A&A 437, 209–216 (2005)
DOI: 10.1051/0004-6361:20041377

Astronomy & Astrophysics

The distribution of kHz QPO frequencies in bright low mass X-ray binaries

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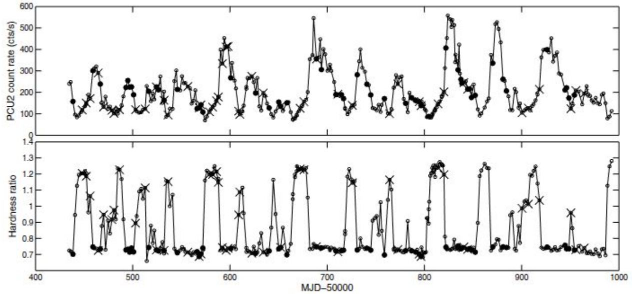
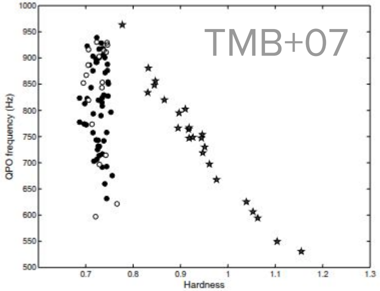
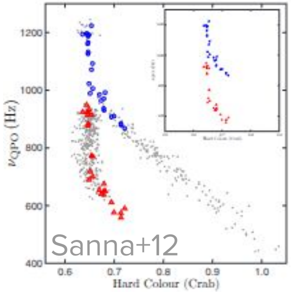
e-mail: belloni@merate.mi.astro.it
[2] SRON, National Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
[3] Center for Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA

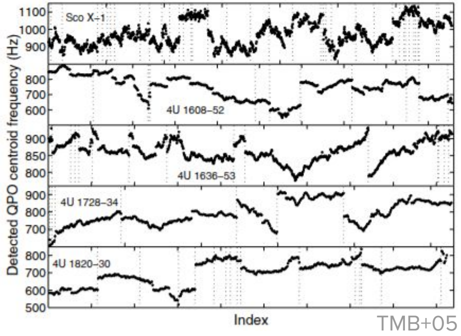
Received 31 May 2004 / Accepted 8 January 2005

Abstract. We analyzed all published frequencies, ν_1 and ν_2, of the twin kilohertz quasi-periodic oscillations (kHz QPOs) in bright neutron star low-mass X-ray binaries. The two frequencies are well correlated but, contrary to recent suggestions, the frequency–frequency correlation is significantly different from a $\nu_2 = (3/2)\nu_1$ relation. To check whether, although not following the the 3/2 relation, the QPO frequencies cluster around a region where $\nu_2/\nu_1 \approx 3/2$, we re-analyzed the Sco X-1 data that were used to report that ratio and show that, because the distribution of ratios of linearly correlated measurements is intrinsically biased, although the significance of the clustering around $\nu_2/\nu_1 \approx 3/2$ previously reported in the case of Sco X-1 is formally correct, it does not provide any useful information about a possible underlying resonance mechanism in this source.





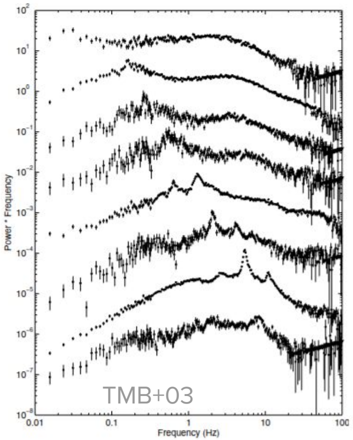


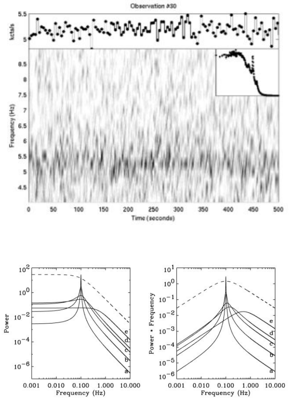


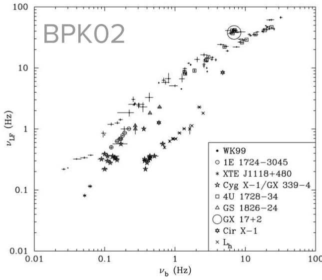
Timing studies of Black Hole Binaries

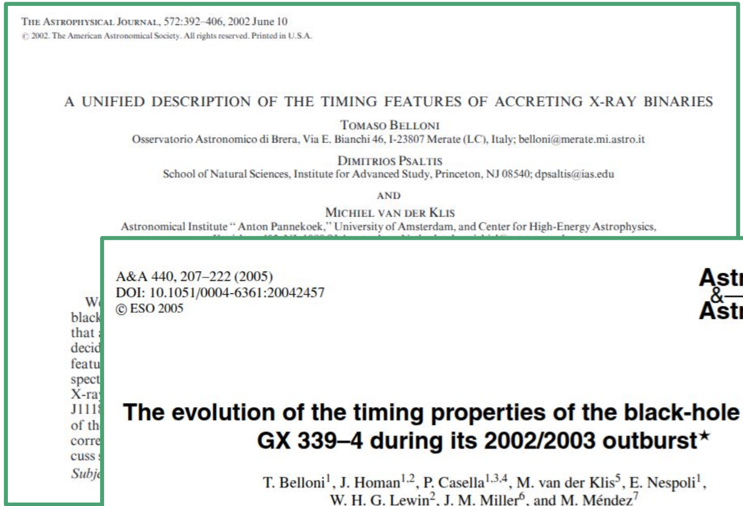
Scientific Breakthroughs in the RXTE Era

- **Accretion State Mapping:** Systematic tracking along the Hardness-Intensity Diagram (HID) in BHCs (e.g., GX 339–4, XTE J1550–564).









The Astrophysical Journal, 572:392–406, 2002 June 10

A UNIFIED DESCRIPTION OF THE TIMING FEATURES OF ACCRETING X-RAY BINARIES

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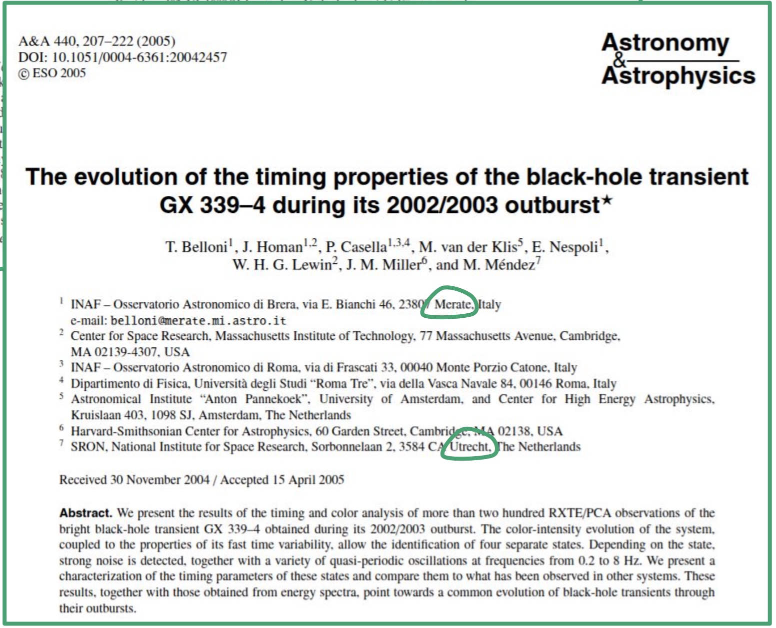
Dimitrios Psaltis
School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540; dpsaltis@ias.edu
and
Michiel van der Klis
Astronomical Institute "Anton Pannekoek," University of Amsterdam, and Center for High-Energy Astrophysics,



A&A 440, 207–222 (2005)
DOI: 10.1051/0004-6361:20042457

Astronomy & Astrophysics

The evolution of the timing properties of the black-hole transient GX 339–4 during its 2002/2003 outburst★

T. Belloni[1], J. Homan[1,2], P. Casella[1,3,4], M. van der Klis[5], E. Nespoli[1], W. H. G. Lewin[2], J. M. Miller[6], and M. Méndez[7]

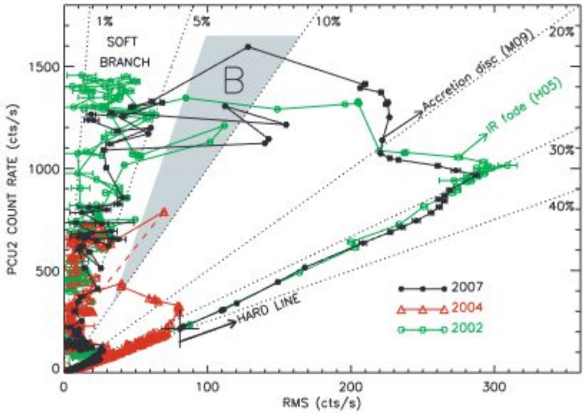
1 INAF – Osservatorio Astronomico di Brera, via E. Bianchi 46, 23807 Merate, Italy
e-mail: belloni@merate.mi.astro.it
2 Center for Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA
3 INAF – Osservatorio Astronomico di Roma, via di Frascati 33, 00040 Monte Porzio Catone, Italy
4 Dipartimento di Fisica, Università degli Studi "Roma Tre", via della Vasca Navale 84, 00146 Roma, Italy
5 Astronomical Institute "Anton Pannekoek", University of Amsterdam, and Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ, Amsterdam, The Netherlands
6 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
7 SRON, National Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

Received 30 November 2004 / Accepted 15 April 2005

Abstract. We present the results of the timing and color analysis of more than two hundred RXTE/PCA observations of the bright black-hole transient GX 339–4 obtained during its 2002/2003 outburst. The color-intensity evolution of the system, coupled to the properties of its fast time variability, allow the identification of four separate states. Depending on the state, strong noise is detected, together with a variety of quasi-periodic oscillations at frequencies from 0.2 to 8 Hz. We present a characterization of the timing parameters of these states and compare them to what has been observed in other systems. These results, together with those obtained from energy spectra, point towards a common evolution of black-hole transients through their outbursts.

Timing studies of Black Hole Binaries

Muñoz-Darias+11



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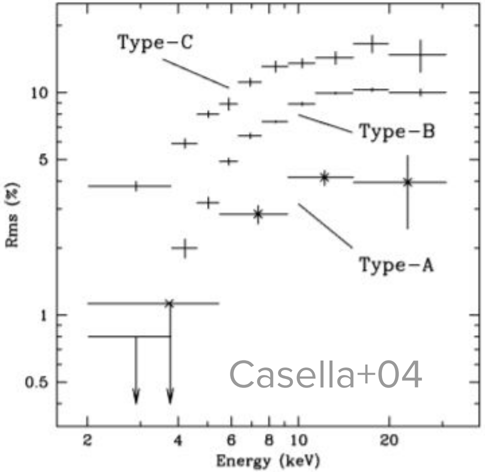
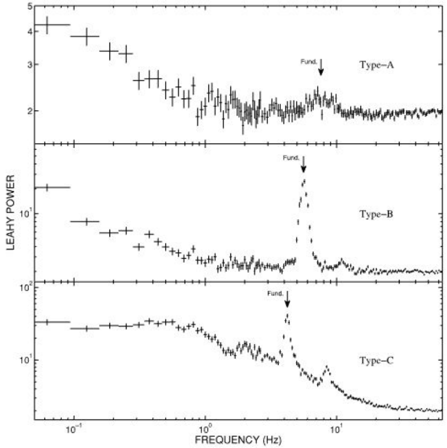
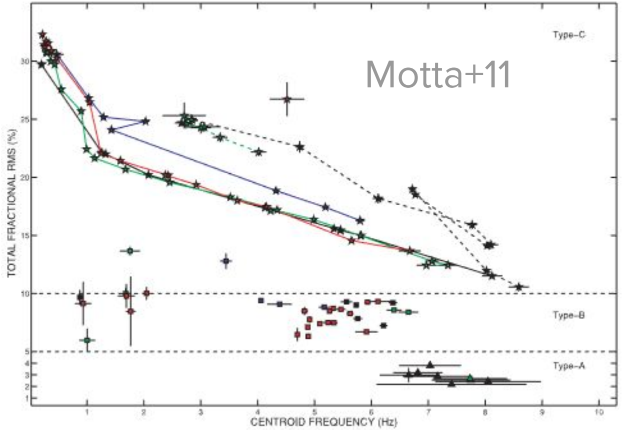
- **Accretion State Mapping:** Systematic tracking along the Hardness-Intensity Diagram (HID) in BHCs (e.g., GX 339–4, XTE J1550–564).
- **LFQPO Classification:** Characterization and phase-resolved behavior of **Type A, B, and C** Low-Frequency QPOs.

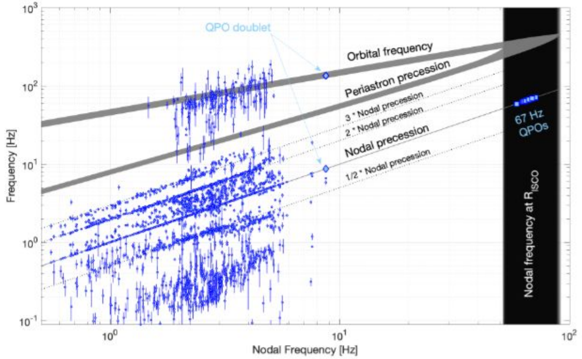






Timing studies of Black Hole Binaries

Motta&TMB24



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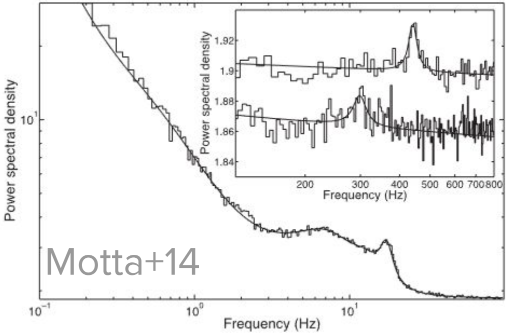
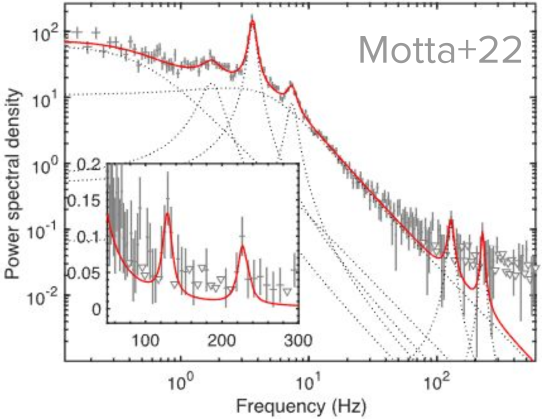
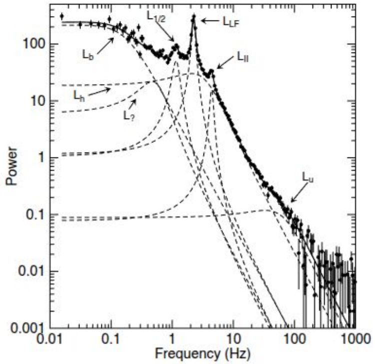
- **LFQPO Classification:** Characterization and phase-resolved behavior of **Type A, B, and C** Low-Frequency QPOs.
- **High-Frequency QPOs:** Probing relativistic timescales near the Innermost Stable Circular Orbit (ISCO).



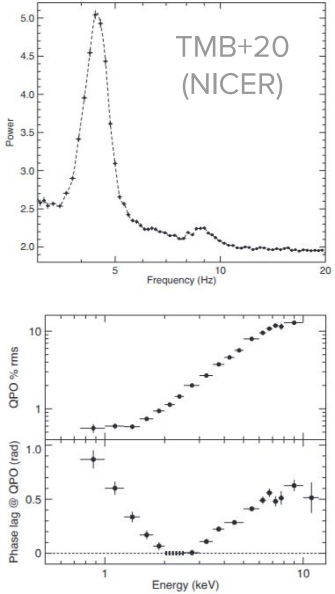




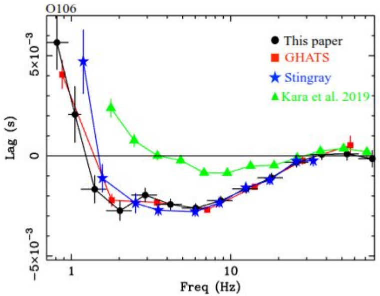
GHATS v3.2: The Multi-Mission Expansion

Tomaso's last GHATS version included support for more missions:

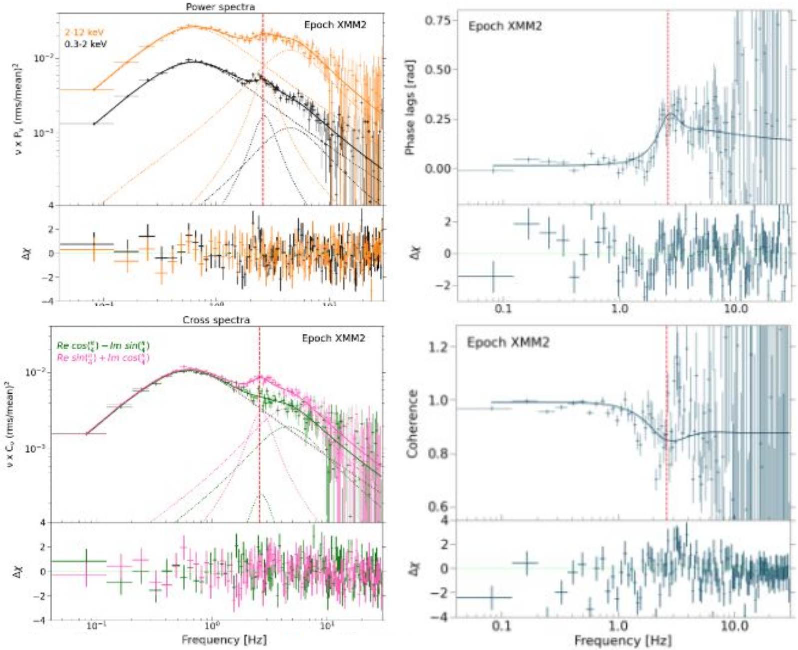
- **Swift, XMM-Newton, NuSTAR, NICER**
- **ASTROSAT (LAXPC and CZTI)**
- **Insight-HXMT (LE, ME, HE)**



TMB+20 (NICER)



B. De Marco+21 (NICER)



M. Brigitte+25 (XMM)

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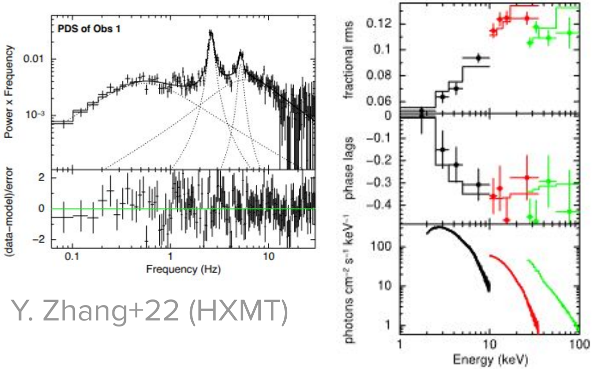
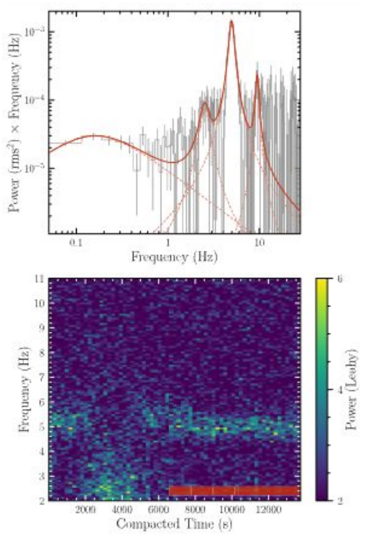
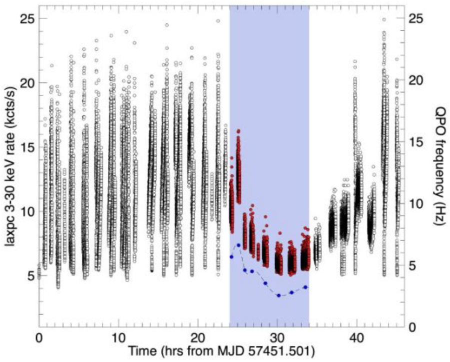


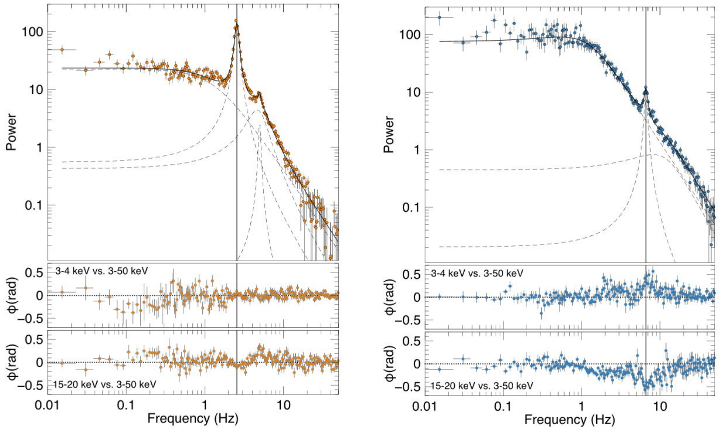
Y. Zhang+22 (HXMT)



Peirano+22 (NICER+ASTROSAT)



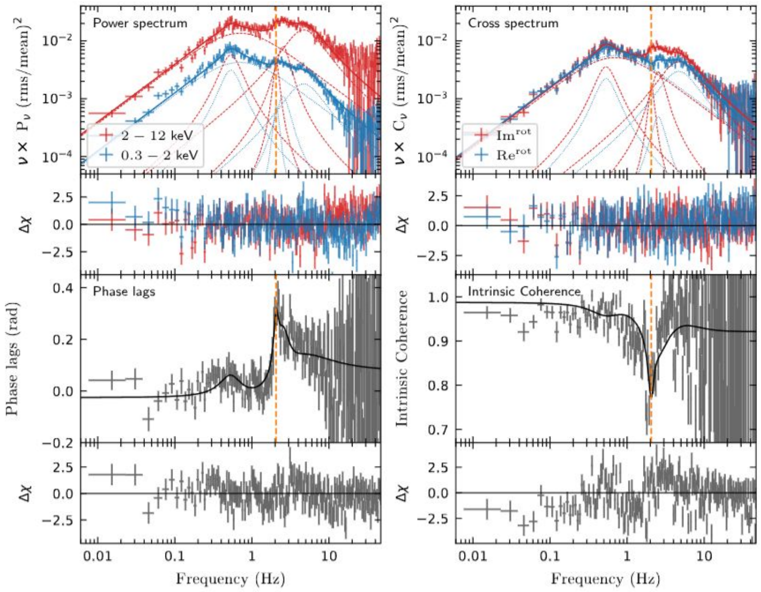
TMB+24 (ASTROSAT)



GHATS v3.3: Cross-Spectral Analysis

Expanding to Cross-Spectra, Lags & Coherence

- **Multi-Band `.fft` integration:** Computing cross-spectral products between energy bands, including a *full reference band* (Ingram19).



C. Bellavita+25, M. Méndez+24

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  - Segment selections (as ghx) and rebinning.
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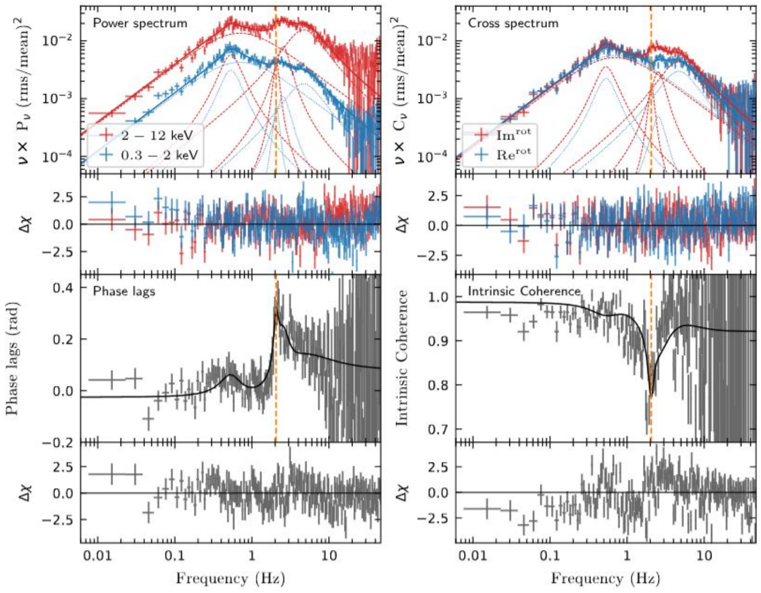

C. Bellavita+25, M. Méndez+24

High powers, high measured coherence.—

$$\gamma_I^2 = \frac{|\langle C\rangle|^2 - n^2}{|S_1|^2|S_2|^2}\left(1 \pm m^{-1/2}\left[\frac{2n^4 m}{(|\langle C\rangle|^2 - n^2)^2} + \frac{|N_1|^4}{|S_1|^4} + \frac{|N_2|^4}{|S_2|^4} + \frac{m\delta\gamma_I^2}{\gamma_I^4}\right]^{1/2}\right) . \qquad (8)$$

Vaughan & Nowak 97

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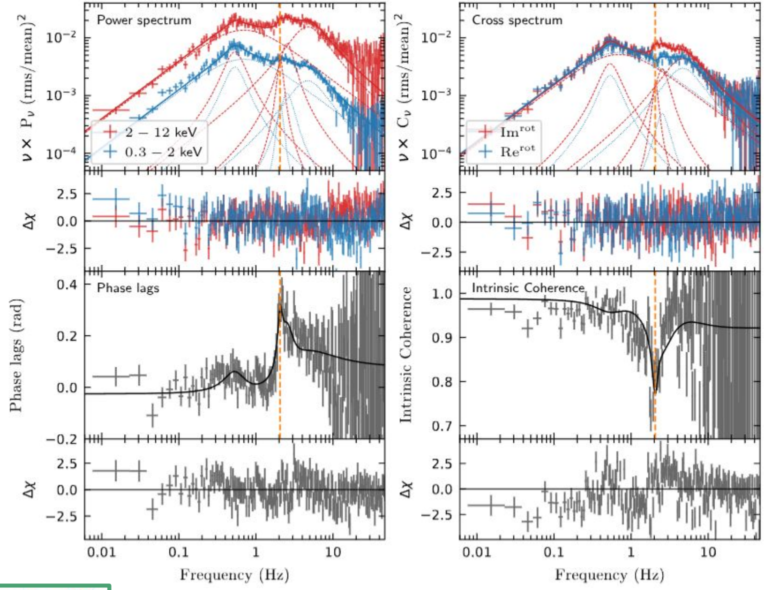
    - Segment selections (as ghx) and rebinning.
    - Study reverberation delays and Comptonization timescales.
- **Intrinsic Coherence (`gh_cs,…,/lowcoh`):**
    - Energy-band correlations and non-linearities (VN97, eq.9).



C. Bellavita+25, M. Méndez+24

High powers, high measured coherence.—

$$\gamma_I^2 = \frac{|\langle C\rangle|^2 - n^2}{|S_1|^2|S_2|^2}\left(1 \pm m^{-1/2}\left[\frac{2n^4 m}{(|\langle C\rangle|^2 - n^2)^2} + \frac{|N_1|^4}{|S_1|^4} + \frac{|N_2|^4}{|S_2|^4} + \frac{m\delta\gamma_I^2}{\gamma_I^4}\right]^{1/2}\right). \quad (8)$$

High powers, low measured coherence.—Use equation (6) to determine confidence limits, $|\langle S_1^* S_2\rangle|^2_{\min}$ and $|\langle S_1^* S_2\rangle|^2_{\max}$, on $|\langle S_1^* S_2\rangle|^2$. Confidence limits on γ_I^2 are then

$$\gamma^2_{I,\,{\max \atop \min}} = \frac{|\langle S_1^* S_2\rangle|^2_{\max \atop \min}}{|S_1|^2|S_2|^2}\left(1 \pm \sqrt{\frac{|N_1|^4}{m|S_1|^4} + \frac{|N_2|^4}{m|S_2|^4} + \frac{\delta\gamma_I^2}{\gamma_I^4}}\right). \quad (9)$$

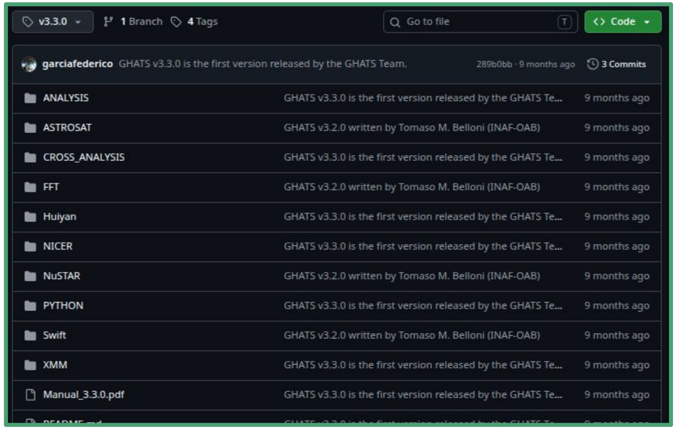
Vaughan & Nowak 97

GHATS v3.2 and v3.3 @ GitHub

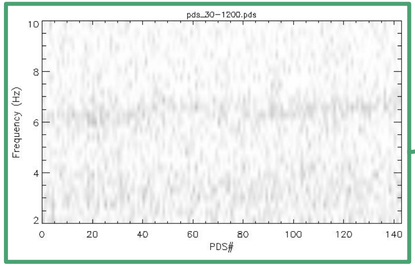
GHATS v3.2 and v3.3: Opening Code to the Community

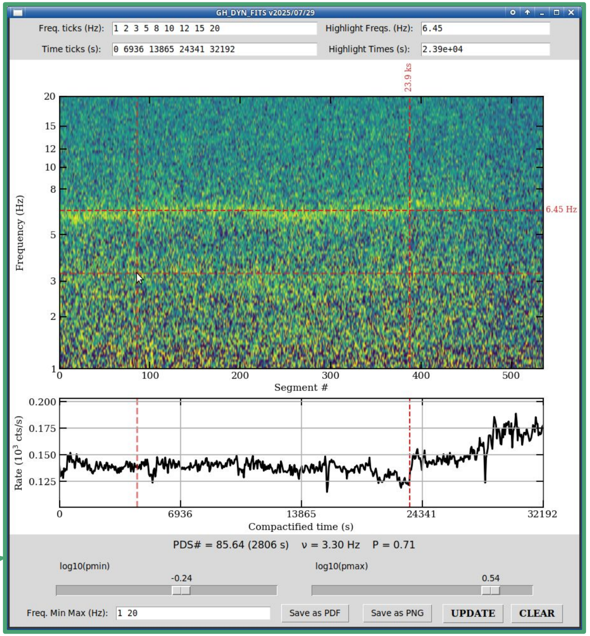
- **Public Open-Source Repository:** Hosted on GitHub (`ghats-timing/ghats`)

  - **Additional Python Tools:**
    - From *static* dynamical PDS to gh_dyn …
    - to fully *interactive* dynPDS analyzer gh_dyn_fits …



Ghats> gh_dyn.pro





Ghats> gh_dyn_fits, …, /SHOW

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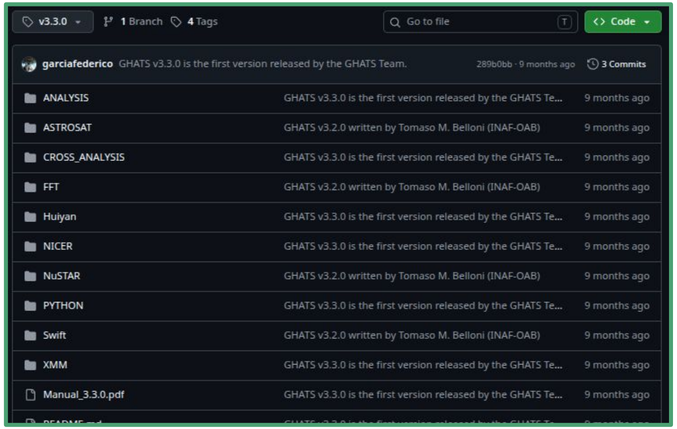


```
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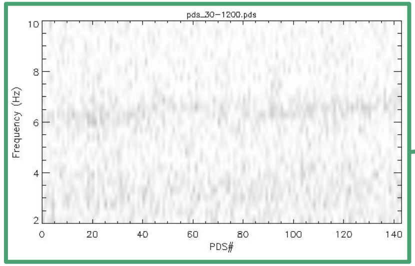
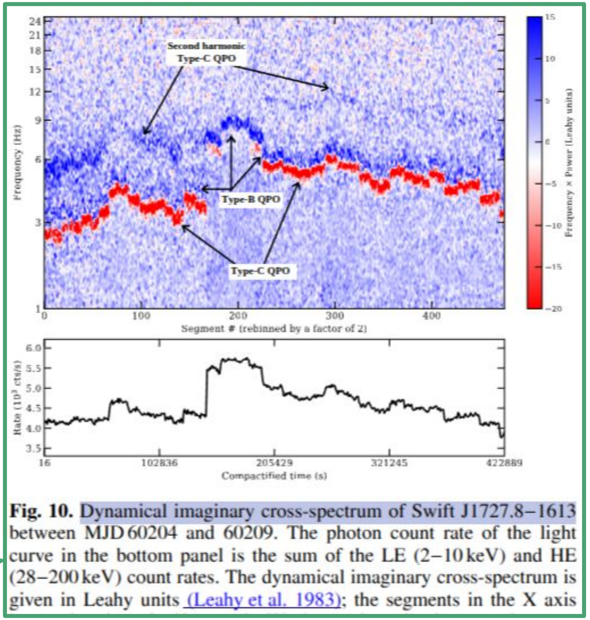
```





P. Jin+26

Introducing GHATS Version 4.0.0

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Presenting GHATS v4.0.0 (Released August 2026)

- **Major New Observatories:**
  - Native support added for **Einstein Probe (FXT)** and **IXPE**.

- **Pipeline Standardization:**
  - Consistent event reading, channel selection, time-resolution detection, and FITS metadata handling across all front-ends.

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Routine	Mission	Purpose
gh_xte	RXTE/PCA	Produce GHATS PDS or FFT files from RXTE/PCA data.
gh_nicer	NICER	Produce GHATS PDS or FFT files from NICER event data.
gh_ep	Einstein Probe	Produce GHATS PDS or FFT files from Einstein Probe event data.
gh_nustar	NuSTAR	Produce GHATS PDS or FFT files from NuSTAR event data.
gh_xmm	XMM	Produce GHATS PDS or FFT files from XMM event data.
gh_swift	Swift/XRT	Produce GHATS PDS or FFT files from Swift/XRT event data.
gh_ixpe	IXPE	Produce GHATS PDS or FFT files from IXPE event data.
gh_laxpc	AstroSat/LAXPC	Produce GHATS PDS or FFT files from AstroSat/LAXPC data.
gh_laxpc_misra	AstroSat/LAXPC	Produce GHATS PDS or FFT files from AstroSat/LAXPC event data.
gh_czti	AstroSat/CZTI	Produce GHATS PDS or FFT files from AstroSat/CZTI event data.
gh_huiyan	Huiyan/HXMT	Produce GHATS PDS or FFT files from Huiyan/HXMT data.
gh_huiyan_le	Huiyan/HXMT LE	Produce GHATS PDS or FFT files from Huiyan/HXMT LE data.
gh_huiyan_me	Huiyan/HXMT ME	Produce GHATS PDS or FFT files from Huiyan/HXMT ME data.
gh_huiyan_he	Huiyan/HXMT HE	Produce GHATS PDS or FFT files from Huiyan/HXMT HE data.
gh_ascii_lcfft	Contributed	Produce GHATS PDS or FFT files from an ASCII light curve.

Each routine can be queried from GHATS:

```
Ghats> gh_xte, /help
Ghats> gh_nicer, /help
Ghats> gh_ep, /help
```

Introducing GHATS Version 4.0.0

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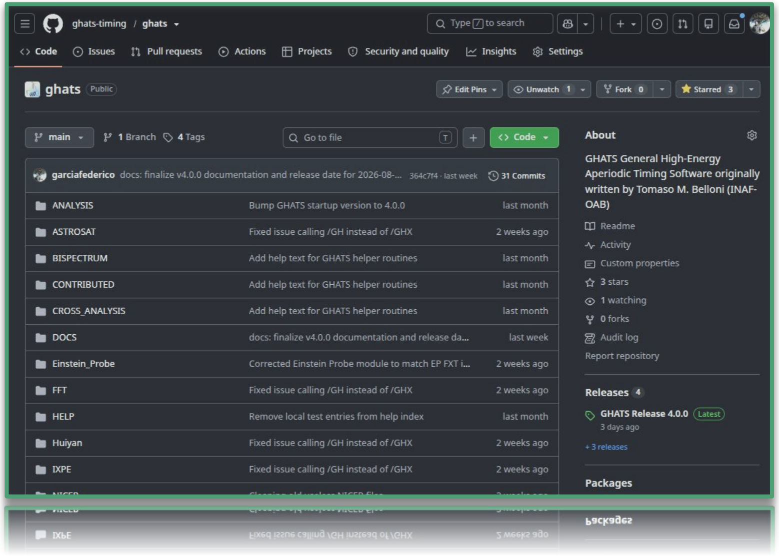
- **Major New Observatories:**
  - Native support added for **Einstein Probe (FXT)** and **IXPE**.
- **Pipeline Standardization:**
  - Consistent event reading, channel selection, time-resolution detection, and FITS metadata handling across all front-ends.
- **GitHub Release:** Official *Release* and *Tags* available at https://github.com/ghats-timing/ghats.



Adding more Comprehensive Documentation

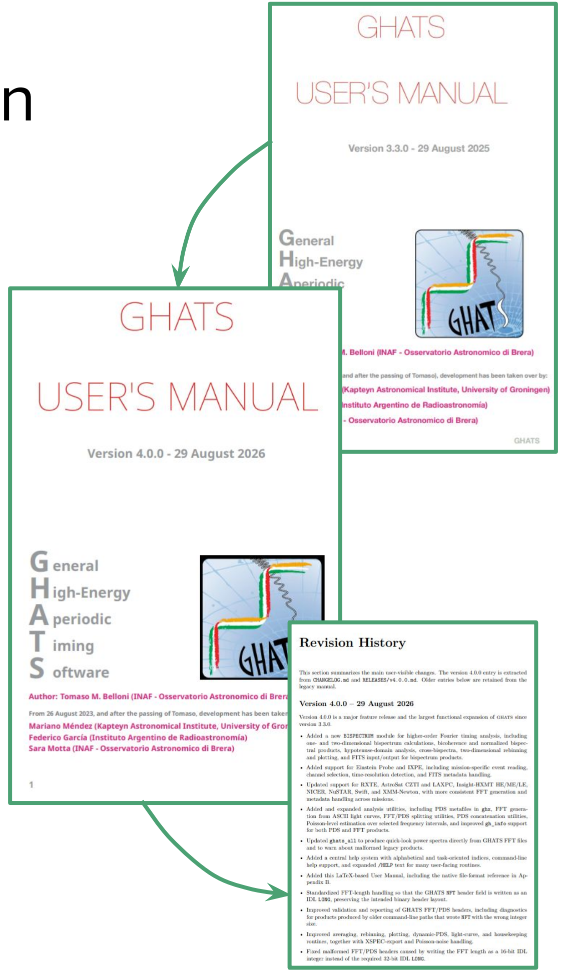
Technical Reliability, Help System & LaTeX User Manual

- **Binary Header Fixes:**
  - Standardized FFT length header field as a 32-bit `LONG` integer.
  - `gh_info` now correctly reads those headers and warns users.

- **Interactive Central Help System (`gh_help`):**
  - Searchable keywords, task-oriented and alphabetical indices.
  - Quick CLI usage:

```
Ghats> gh_help, /task
Ghats> gh_cs, /help
```

- **LaTeX User Manual (70+ pages):**
  - Complete installation guides, walkthroughs, and routine directory.
  - Native binary and FITS file-format specifications.



Higher-Order Fourier Timing: the **bispectrum** suite

Main scientific addition: Bispectrum analysis

- **Beyond the Power- and Cross-Spectra:** using Fourier transforms to capture non-linear frequency interactions (Maccarone13, Arur&Maccarone22):

$$B(f_1, f_2) = \left\langle X(f_1)\, X(f_2)\, X^*(f_1 + f_2) \right\rangle$$

bi-phase and the **bi-coherence:**

$$b^2(f_1, f_2) = \frac{\left| \left\langle X(f_1)\, X(f_2)\, X^*(f_1 + f_2) \right\rangle \right|^2}{\left\langle |X(f_1) X(f_2)|^2 \right\rangle \left\langle |X(f_1 + f_2)|^2 \right\rangle}$$

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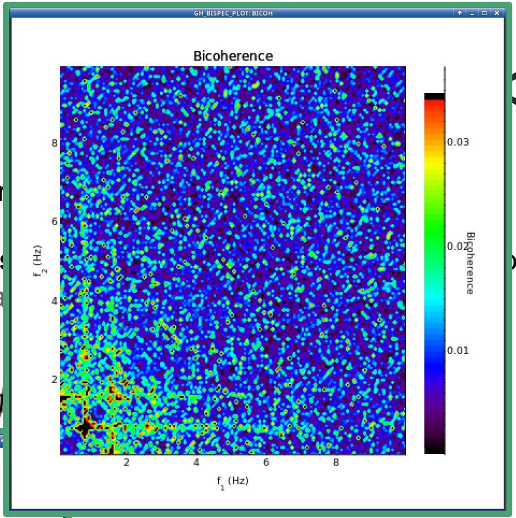
- **New Capabilities (BISPECTRUM module):**
  - 2D full bispectrum calculations (*bmod*, *bphase*, *bicoh*)
  - 1D row and hypotenuse-domain product extraction.
  - *Linear* and *Logarithmic* rebinning of *bispectrum* products
  - *Cross-bispectra* between different energy bands and different instruments.
  - Native multi-extension FITS I/O (gh_write_bispec_fits).

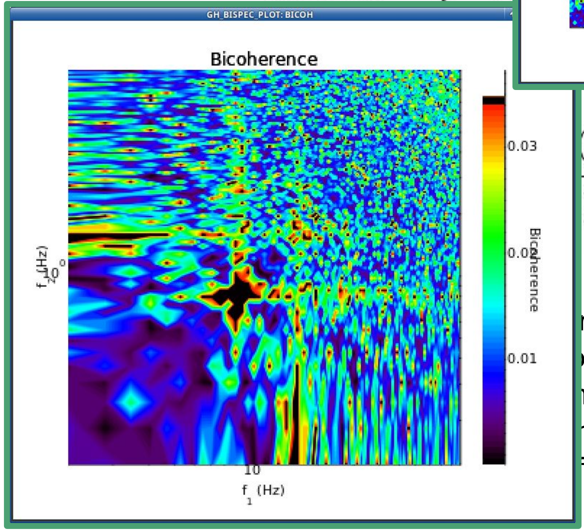
Higher-Order Fo bispectrum suite

Main scientific addition: Bispectrur

- **Beyond the Power- and Cros** capture non-linear frequency interactions (Macca

$$B(f_1, f_2) = \Big\langle X(f$$





$$(f_2)\, X^*(f_1 + f_2)\Big\rangle\Big|^2$$
$$)|^2\Big\rangle \Big\langle |X(f_1 + f_2)|^2\Big\rangle$$

module):

ns (*bmod*, *bphase*, *bicoh*)
nain product extraction.
nning of *bispectrum* products
fferent energy bands and different instruments.
I/O (gh_write_bispec_fits).

```
Bispectrum calculation from an FFT:

Ghats> gh_bispec2d,'myfft.fft',f1,f2, $
                  breal,bimag,bmod,bphase,bicoh,nprod,nseg, $
                  f1range=[0.1,10.0],f2range=[0.1,10.0]

Export Bispectral products to multi-extension FITS files:

Ghats> gh_bispec_fits,'myfft.fits',f1,f2, $
                  breal,bimag,bmod,bphase,bicoh,nprod

         Linear Rebinning:
         Ghats> gh_bispec_fits,'myfft_LinRebin.fits',f1,f2, $
                  breal,bimag,bmod,bphase,bicoh,nprod, $
                  irf1=4,irf2=4

         Logarithmic Rebinning:
         Ghats> gh_bispec_fits,'myfft_LogRebin.fits',f1,f2, $
                  breal,bimag,bmod,bphase,bicoh,nprod, $
                  irf1=-100,irf2=-100

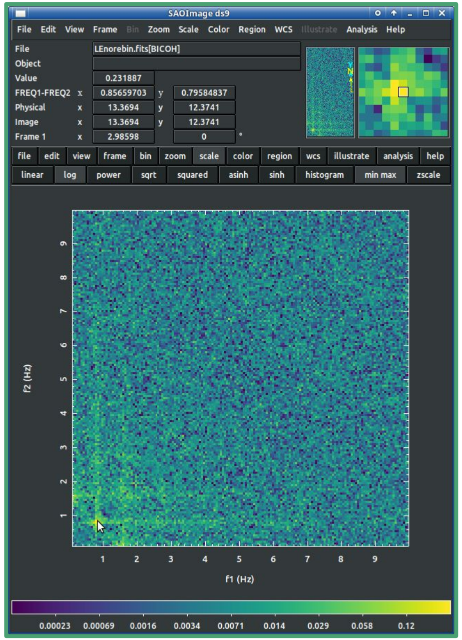
Quick-look plots within GHATS:

Ghats> gh_bispec_plot,'myfft.fits','BICOH'
```

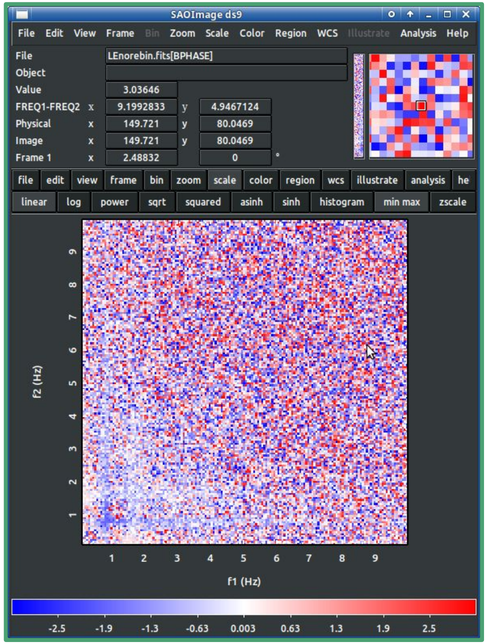
Plotting and interacting with the 2D Bispectrum

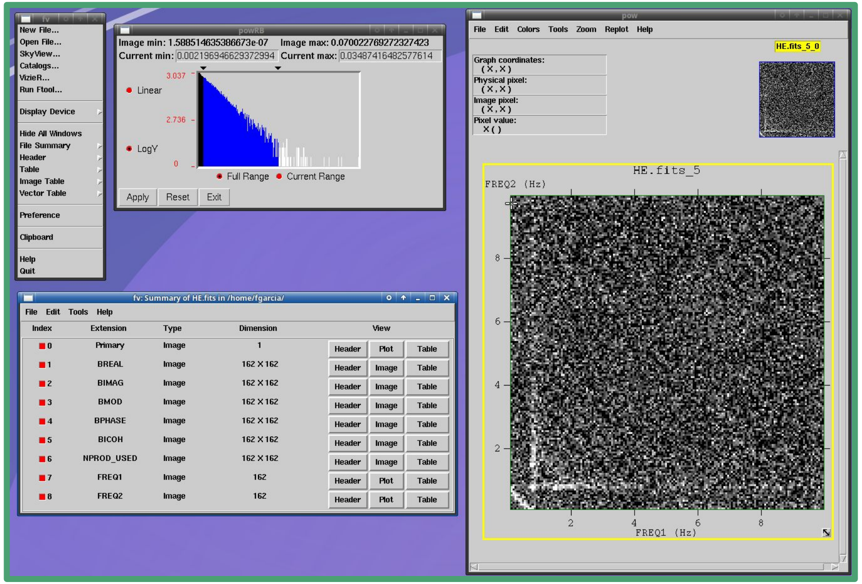
Multi-extension FITS files porting the 2D Bicoherence, Biphase and Bispectrum data can be displayed and analyzed with standard tools like ***fv*** and ***ds9***, or with through the ***astropy*** suite.

```
> ds9 myfft.fits[BICOH]
```




```
> ds9 myfft.fits[BPHASE]
```





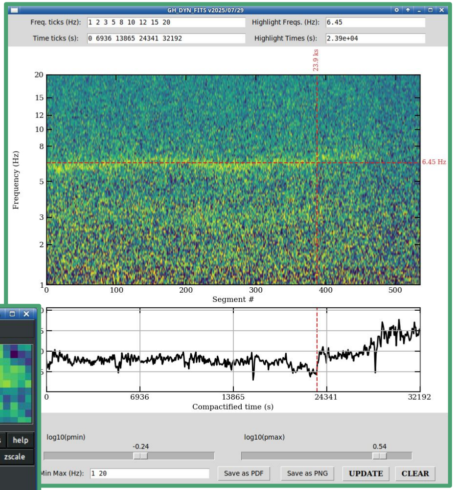

```
> fv myfft.fits
```

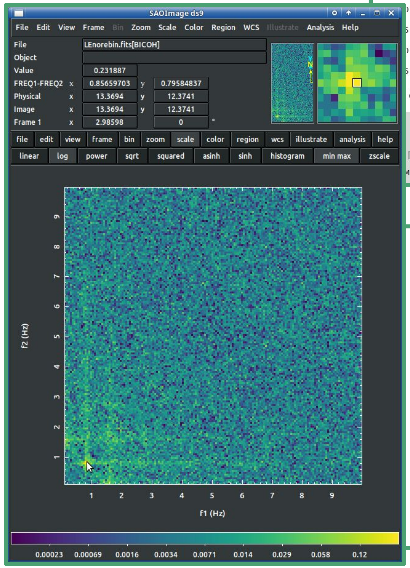
Summary

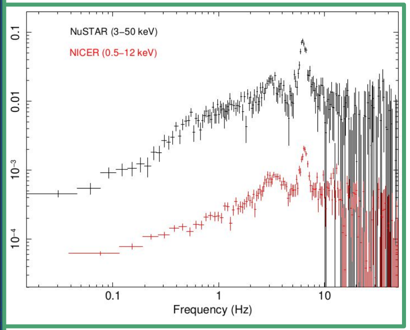
GHATS: General High-energy Aperiodic Time-series Software

- **Complete Spectral–Timing Suite:** PDS, cross-spectra, lags, intrinsic coherence, XSPEC integration, and now also a bispectrum module.
- **Multi-Mission Capability:** From RXTE and NICER to XMM, ASTROSAT, HXMT, and now also EP and IXPE.
- **Complementary Ecosystem:** Designed to coexist alongside community suites like *Stingray*, enabling independent cross-checks and multi-platform validation.
- **Community-Driven:** Open-source code fully available on GitHub.

🔗 **Repository:** https://github.com/ghats-timing/ghats







“NOISE, n. A stench in the ear. Undomesticated music. The chief product and authenticating sign of civilization.” — A. Bierce (*The Devil's Dictionary*)

“It is of a flawless white color, right from its nose to its magnificent tail.” — Mahabharata (*The Story of Garuda*)

Thank you, Tomaso, for your passion, and inspiring legacy.