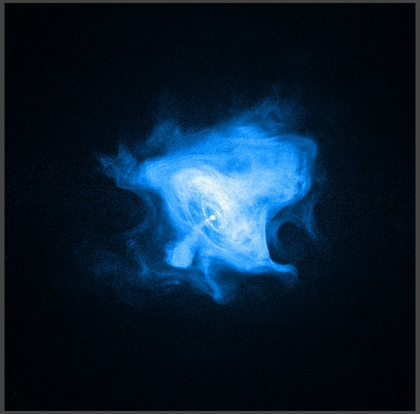
The multi-year 'absolute' timing of the Crab pulsar at high-energies using Jodrell Bank radio observations



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incl. INTEGRAL ISGRI,
XMM-Newton EPIC-pn TM/BU , RXTE PCA,
Fermi LAT, Fermi GBM BGO [NaI], [CXO]
and NICER data

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Jodrell Bank radio observations: our baseline

- Daily monitoring of the Crab pulsar (P ~ 33 ms) started 31 years ago with 42 Ft telescope at 610 Mhz

- Arrival time delay : $t_{arr} \sim DM/\nu^2_{obs}$
- DM variations due to nebular plasma fluctuations
- Occasionally observations at 1400-1700 Mhz with larger Lovell telescope to constrain DM=DM(t)
- Before Dec-2011: DM = c
  After : DM = c + dDM/dt x t
- Timing parameters (on monthly base) stored at JB database: pulse freq. and its first two time derivatives at epoch t_0 (JPL DE200)

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Crab pulsar (PSR B0531+21) as timing calibration target for HE-instruments

- INTEGRAL ISGRI: Revs. 47-1877 (Oct. 23, 2017)
  (20-100 keV; 61 μs; using revised Time Correlation
  files as of late 2007 i.e. correcting
  for 47 μs REDU gs offset; using
  measured orbit in propagation delay)

- XMM-Newton EPIC-pn Timing & Burst Mode
  (2-10 keV; 30 μs (TM), 7 μs (Bu))

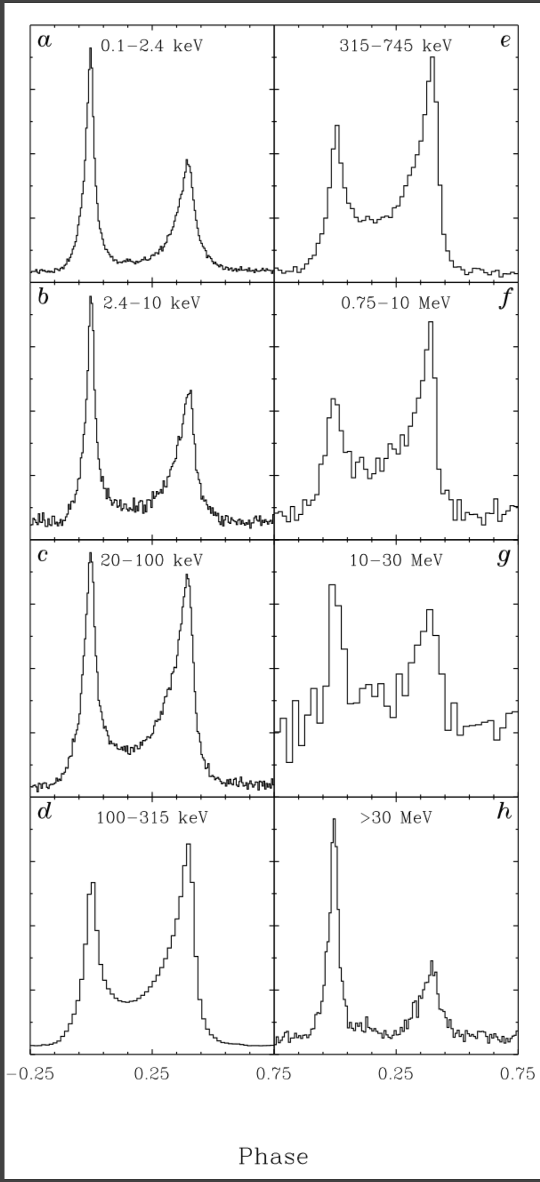
  XMM launch - Oct. 2017

- Fermi LAT: Aug. 2008 – Jan. 2018
  (>100 MeV; 1 μs; GPS)

- Fermi GBM BGO Nov. 26, 2011 – Jan. 2018
  (100 keV – 30 MeV; 2 μs; GPS)

- RXTE PCA: INTEGRAL launch – Dec. 2011
  (2-32 keV; 1 μs (Good Xenon modes), but Crab obs.
  in event mode with 250 μs

  (decommissioning in Jan. 2012)



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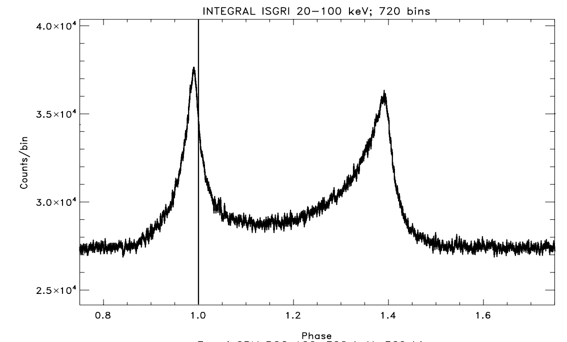
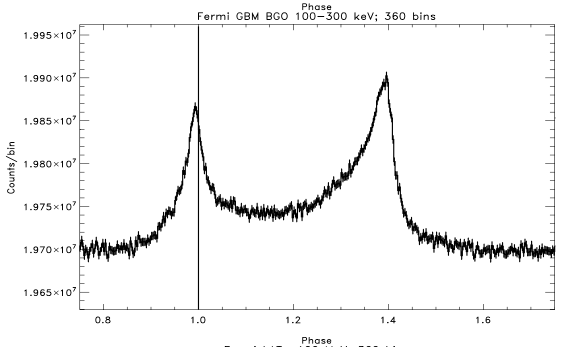
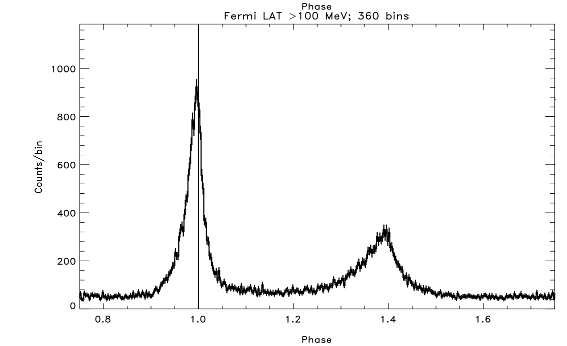
Barycentering (barycen (XMM), gtbary (LAT), faxbary (RXTE); own IDL), epoch folding and correlation etc. processes all use equivalent procedures!







The templates in the cross-correlation process

-332 ± 23 μs

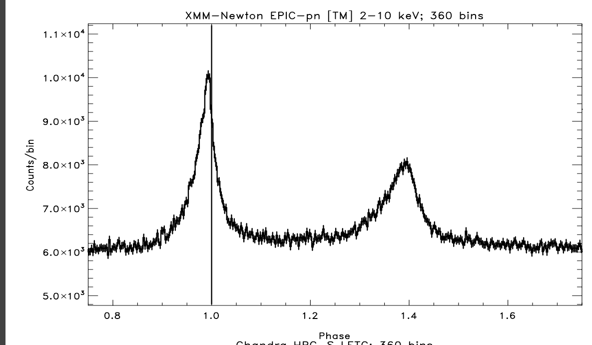
-251 ± 23 μs

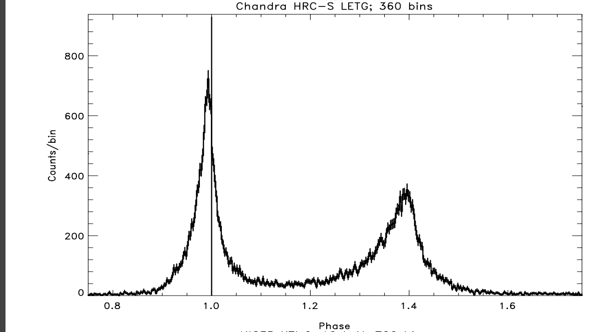
-223 ± 20 μs

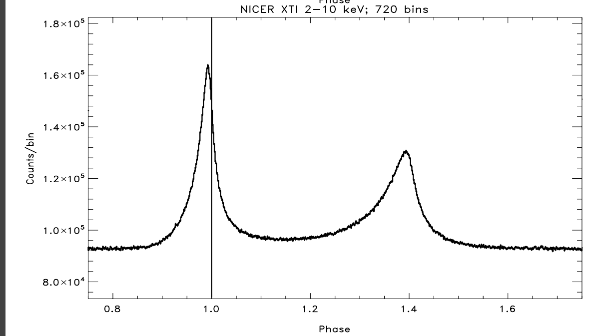
-269 ± 47 μs

-141 ± 34 μs

-258 ± 6 μs







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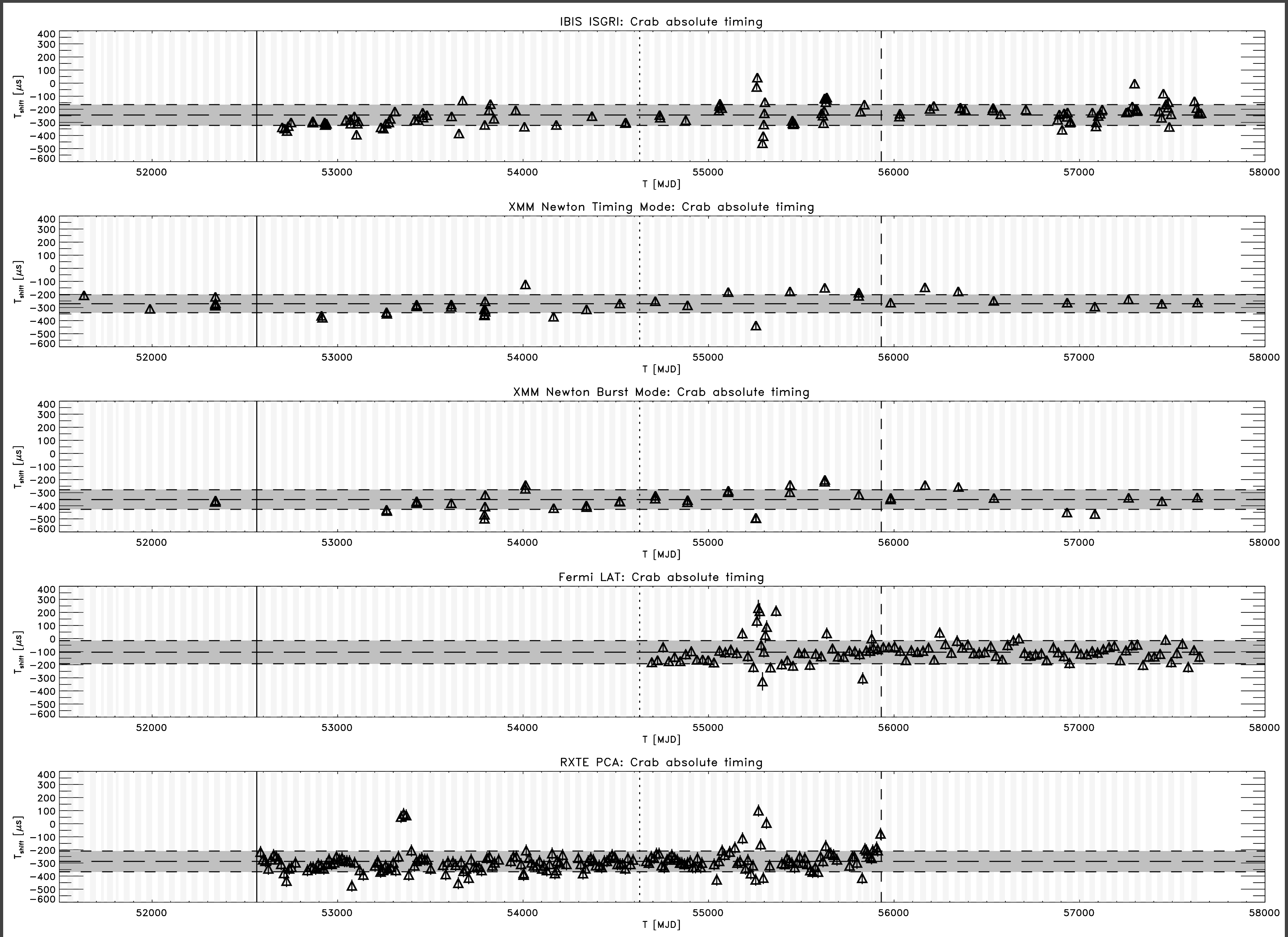
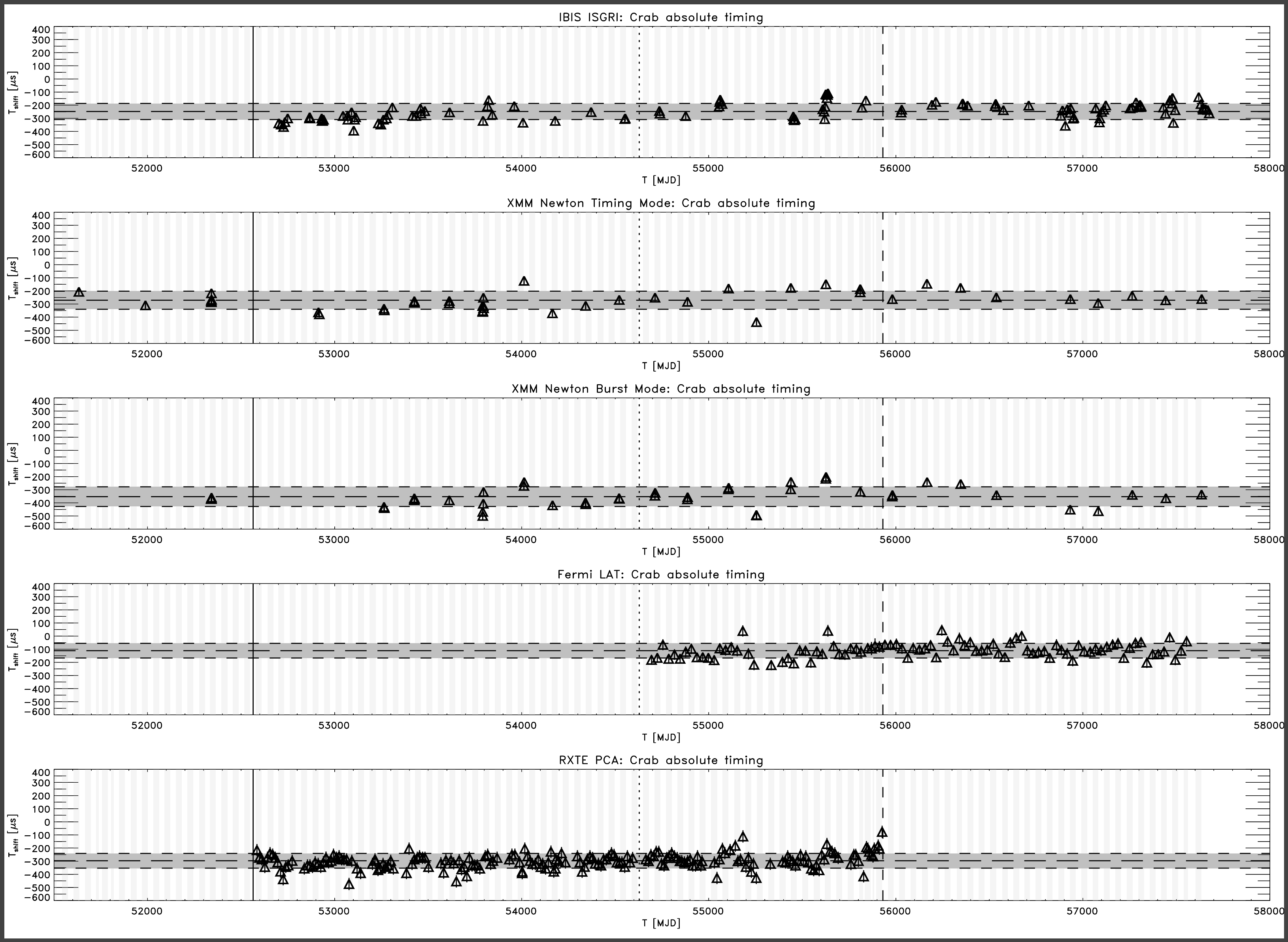
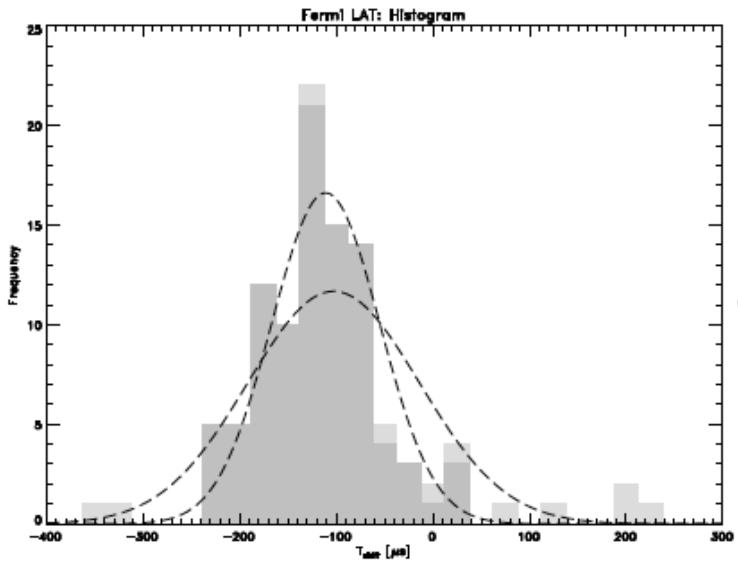
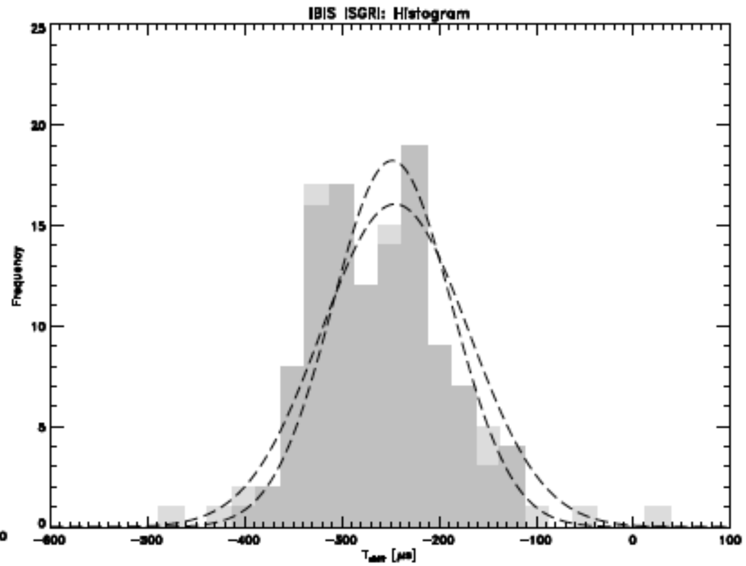
Absolute timing: All measurements

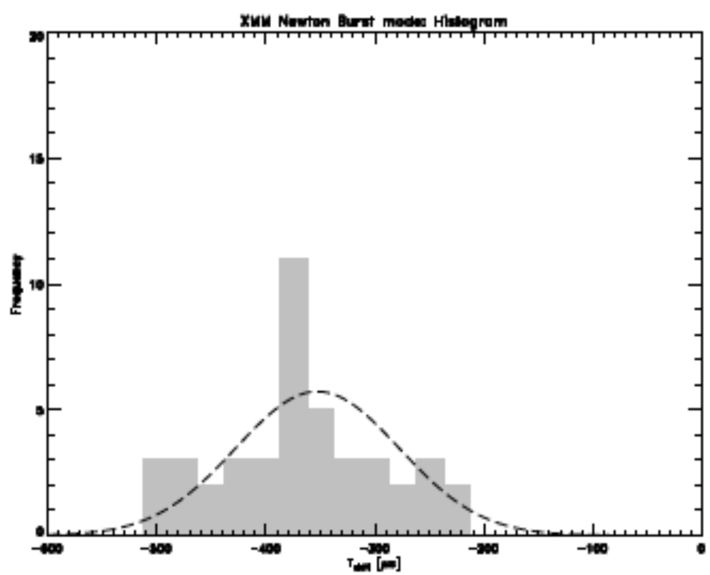


Absolute timing: Measurements minus outliers

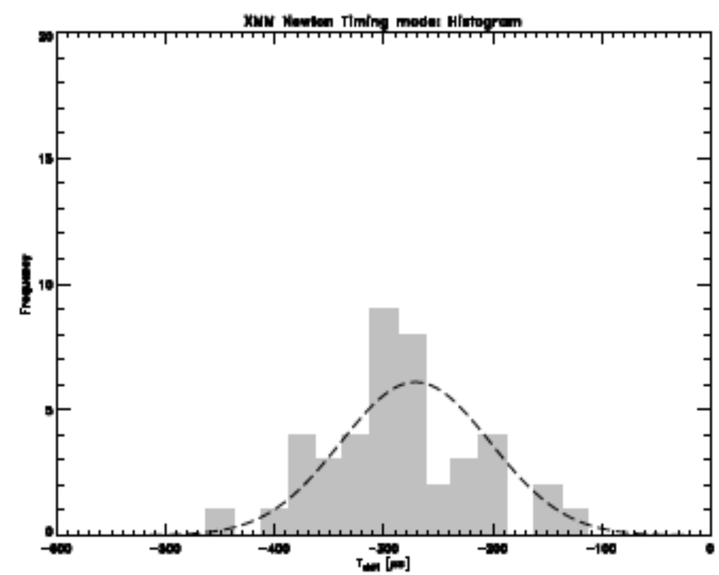








(a) XMM Newton EPIC PN Burst mode



(b) XMM Newton EPIC PN Timing mode

Instrument	τ (μs)	$\Delta\tau$ (μs)	σ (μs)	$\mathcal{S}$	$\mathcal{K}$	n
Fermi LAT						
With outliers	-104	±4	±88	1.4±0.2	3.8±0.5	107
Without outliers	-111	±4	±57	0.5±0.3	0.2±0.5	93
XMM Newton EPIC PN						
Burst mode	-353	±4	±75	-0.1±0.3	-0.6±0.7	43
Timing mode	-271	±4	±69	0.1±0.4	-0.3±0.7	42
Burst + Timing mode	-312	±3	±83	-0.1±0.3	-0.3±0.5	85
INTEGRAL IBIS ISGRI						
With outliers	-245	±2	±76	0.5±0.2	1.2±0.4	122
Without outliers	-248	±2	±61	0.1±0.2	-0.7±0.5	112
RXTE PCA						
With outliers	-288	±3	±79	2.0±0.2	7.7±0.3	205
Without outliers	-297	±3	±56	0.1±0.2	1.5±0.3	197

Table 4.1: Time shift (τ), uncertainty ($\Delta\tau$), standard deviation of the distribution (σ), skewness ($\mathcal{S}$), kurtosis ($\mathcal{K}$) and the number of measurements (n).

Distribution widths: ~60 μs ! (XMM-Newton ~10-15 μs wider)

$$\sigma_M^2 = \sigma_I^2 + \sigma_{JBO}^2$$

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Peak-to-peak uncertainty t_{acc} of Jodrell Bank (radio) arrival times

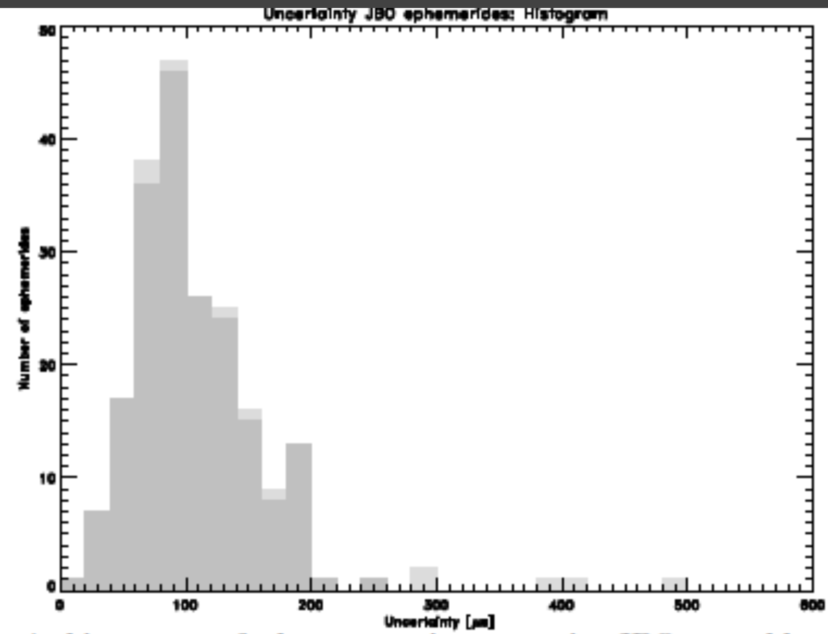

Figure 4.7: A histogram of the uncertainty t_{acc} in JBO monthly Crab pulsar ephemerides. Uncertainties without outliers are coloured dark-grey. Outliers are colored light grey. 3 outliers have an uncertainty of more than 600 μs and are outside the plot range of this figure.

Average t_{acc} : 118 ± 43 μs ➔
For sinusoidal variations, RMS or $\sigma_{JBO} = 118 / 2\sqrt{2} \sim 42 \pm 16$ μs

Thus, σ_M reflects for a significant part the uncertainty in σ_{JBO}

($\sigma_I = 35 \pm 20$ μs)

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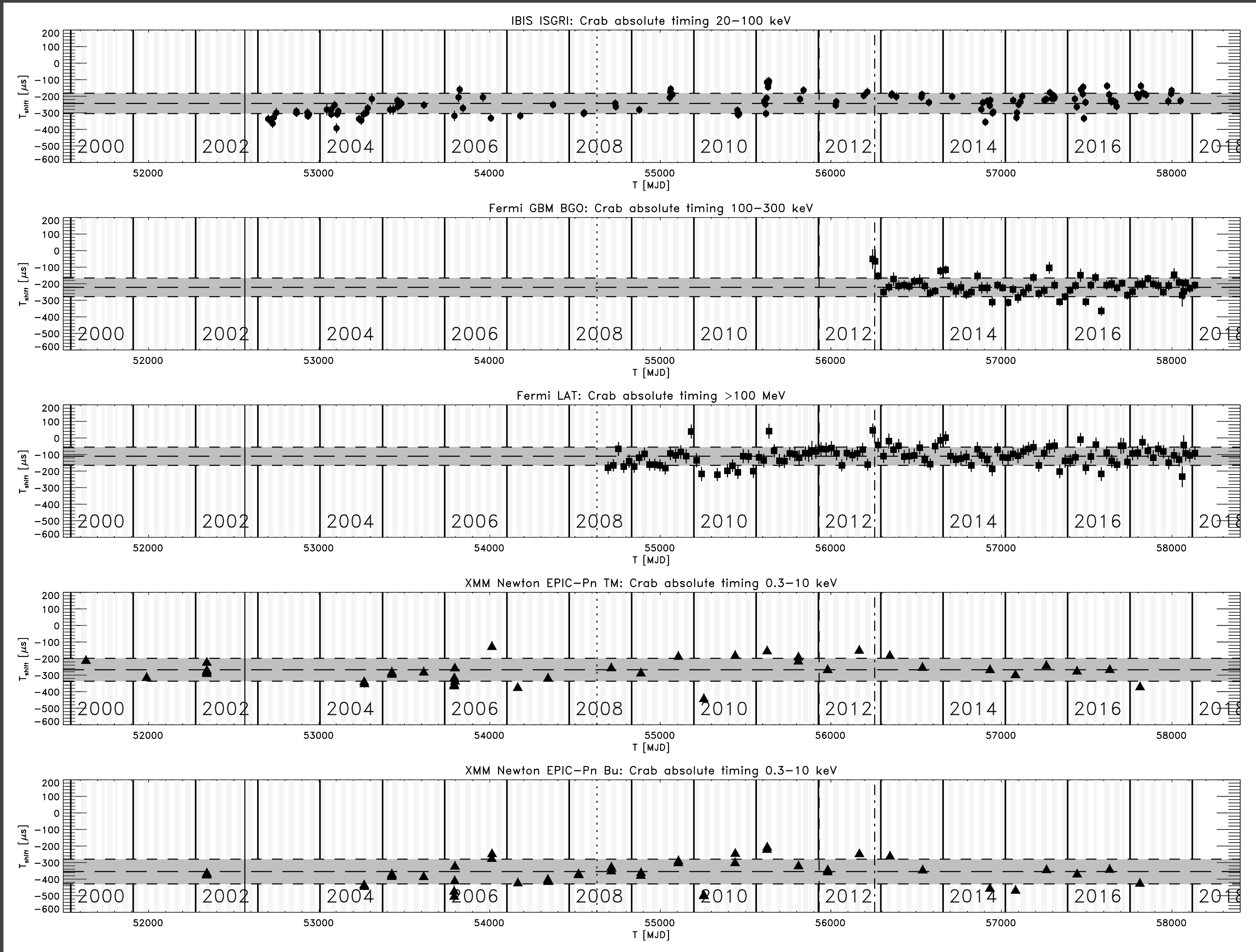
IBIS ISGRI: Crab absolute timing 20–100 keV
Fermi GBM BGO: Crab absolute timing 100–300 keV
Fermi LAT: Crab absolute timing >100 MeV
XMM Newton EPIC–Pn TM: Crab absolute timing 0.3–10 keV
XMM Newton EPIC–Pn Bu: Crab absolute timing 0.3–10 keV
T [MJD]
T_shift [μs]
2000
2002
2004
2006
2008
2010
2012
2014
2016
52000
53000
54000
55000
56000
57000
58000

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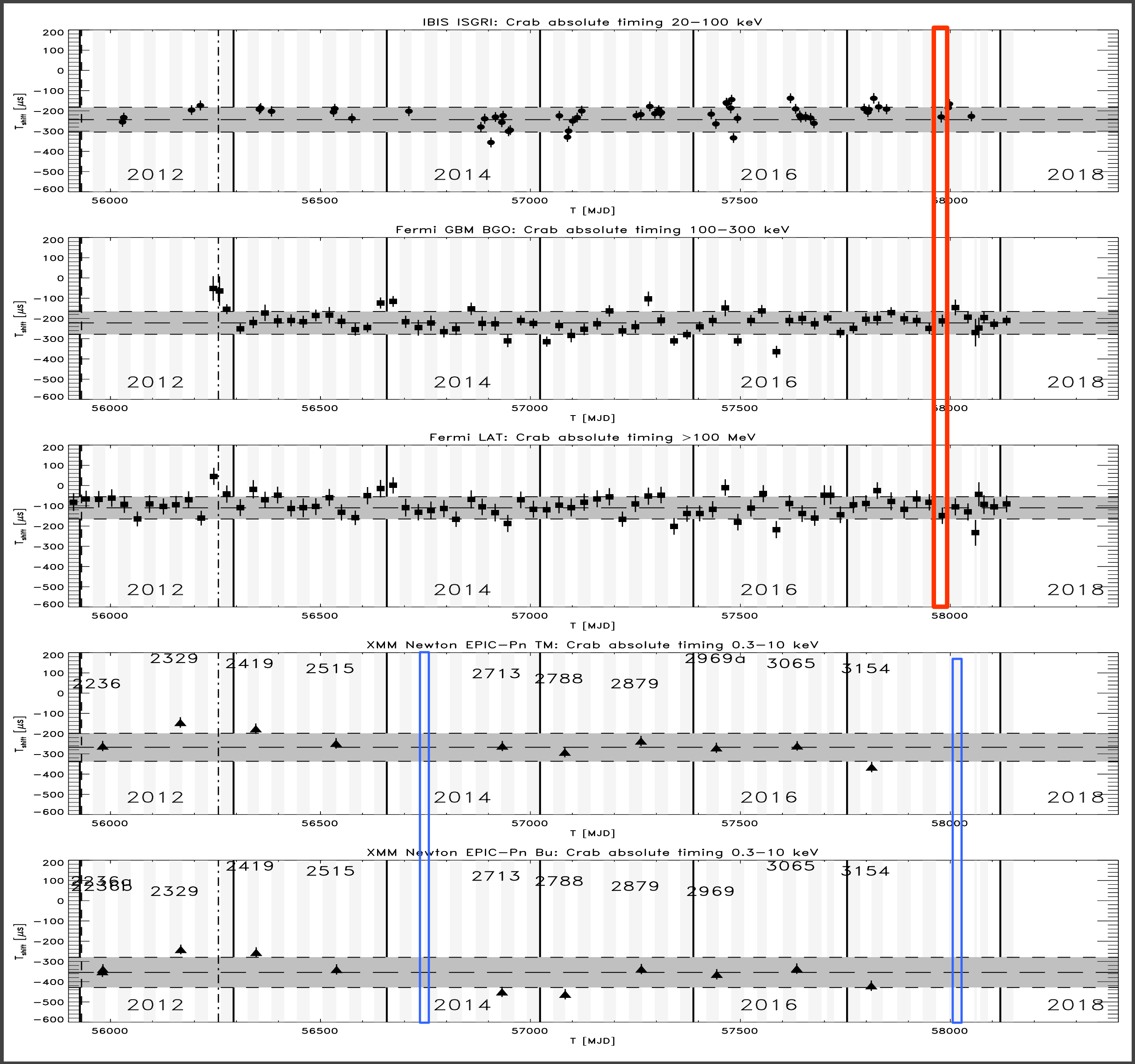
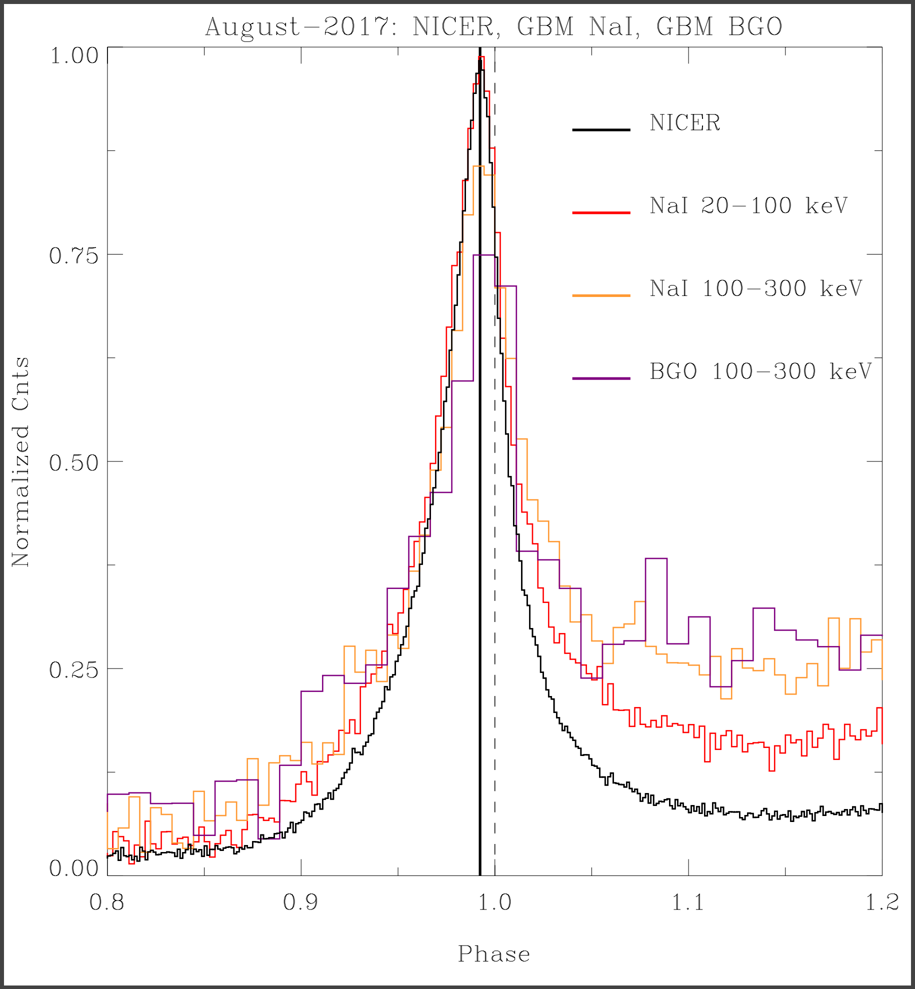
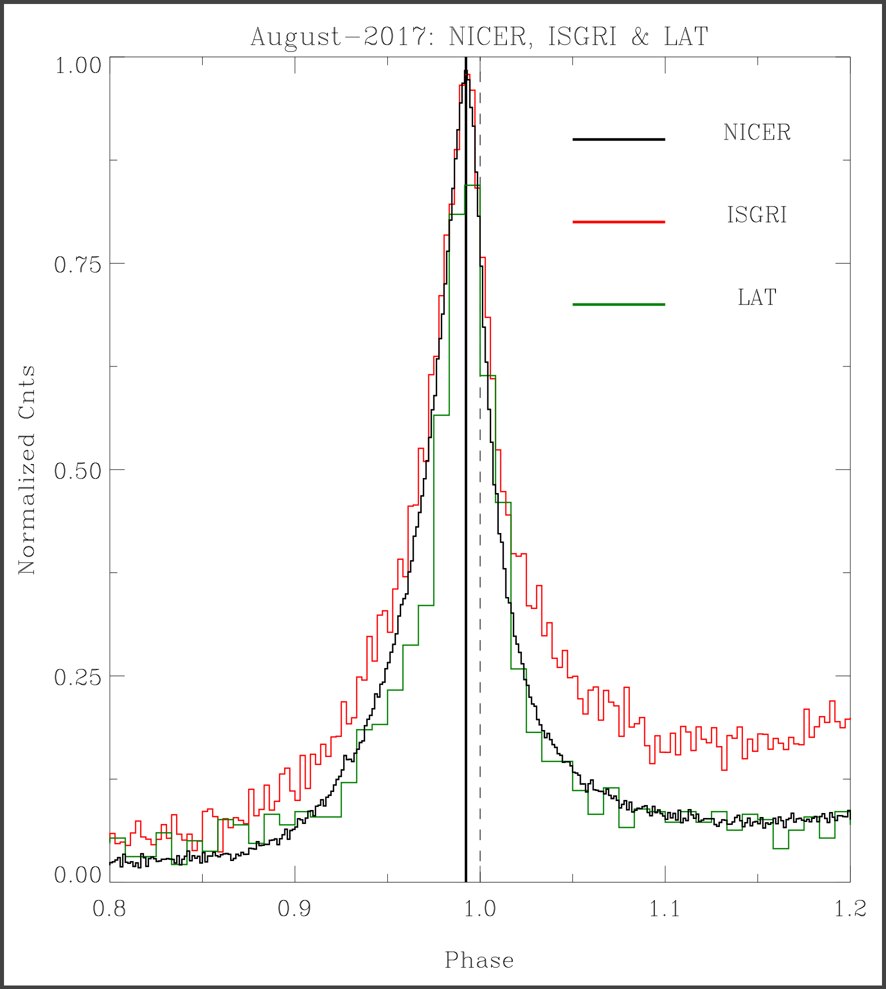

IBIS ISGRI: Crab absolute timing 20−100 keV
Fermi GBM BGO: Crab absolute timing 100−300 keV
Fermi LAT: Crab absolute timing >100 MeV
XMM Newton EPIC−Pn TM: Crab absolute timing 0.3−10 keV
XMM Newton EPIC−Pn Bu: Crab absolute timing 0.3−10 keV
T_{shift} [μs]
T [MJD]
2012
2014
2016
2018
2236
2329
2419
2515
2713
2788
2879
2969a
2969
3065
3154

In-depth study August 2017: NICER 5-15 Aug; 28.674 ks, ISGRI (Rev-1850; 12-13 Aug), Fermi LAT/GBM NaI BGO





NICER : -258 ± 6 μs

Shifts:		
	ISGRI	+4 ± 6 μs
	LAT	-96 ± 24 μs
	GBM NaI	+10 ± 2 μs
	GBM BGO	-80 ± 36 μs

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Instrument related notes: INTEGRAL ISGRI

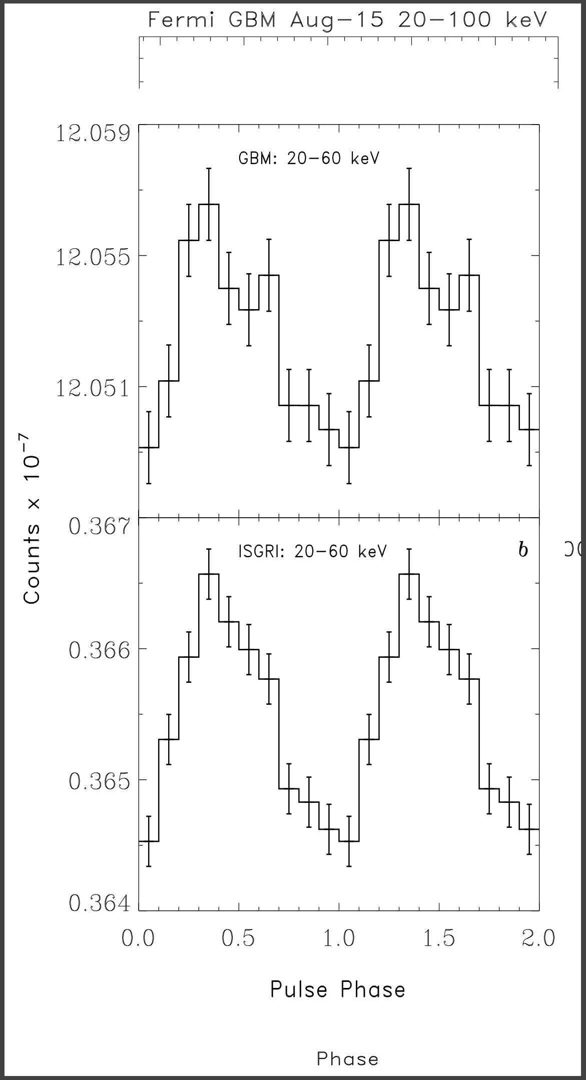
- Updated time delay Δt = -248 ± 2 μs is consistent with earlier value of -285 ± 12 μs (Kuiper et al. 2003), taking into account the 47 μs REDU ground station error

- Since 26/11/2012 Fermi GBM NaI/BGO in TTE mode i.e. 2 μs accuracy (GPS synchronized / s) in 128 chan.

  Comparison ISGRI/NaI Aug-2015 data yielded:
  $\Delta t_{GBM\text{-}ISGRI}$=+26.3 ± 6.4 μs

  (GBM a bit ahead)

- Comparison using the (transitional) ms-pulsar IGR J18245-2452 (P=3.9 ms) in M28 during April 2015 outburst yielded +23 ± 109 μs



Instrument related notes: Fermi LAT

- Abdo et al. (2010) ApJ 708, 1254 reported a delay -281 ± 12 ± 21 μs
- We report a delay of -111 ± 4 μs (9 years of LAT data) ….
- The Veritas collaboration reported in Sci. 334, 69 (2011) a corrigendum of the LAT result: -138 ± 12 ± 21 μs (Aug. 08 – Apr. 09)

  We found for same period : -141 ± 4 μs , now consistent!

Instrument related notes: XMM-Newton

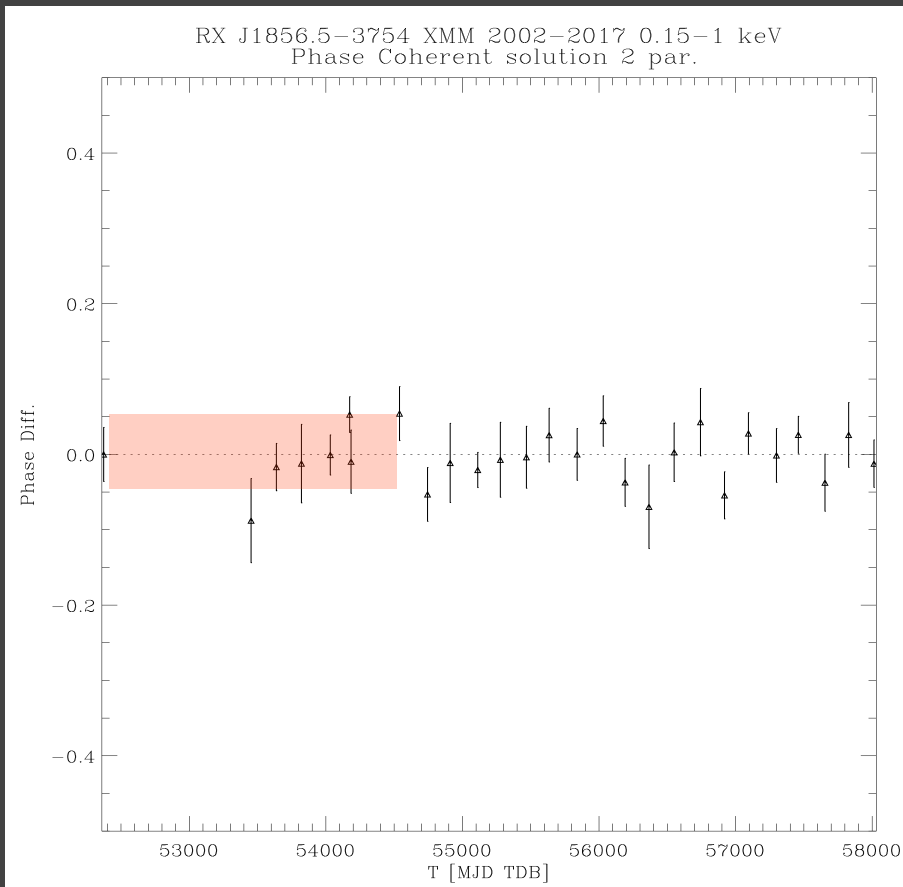
- The delays measured in TM and Bu mode differ significantly: 82 μs

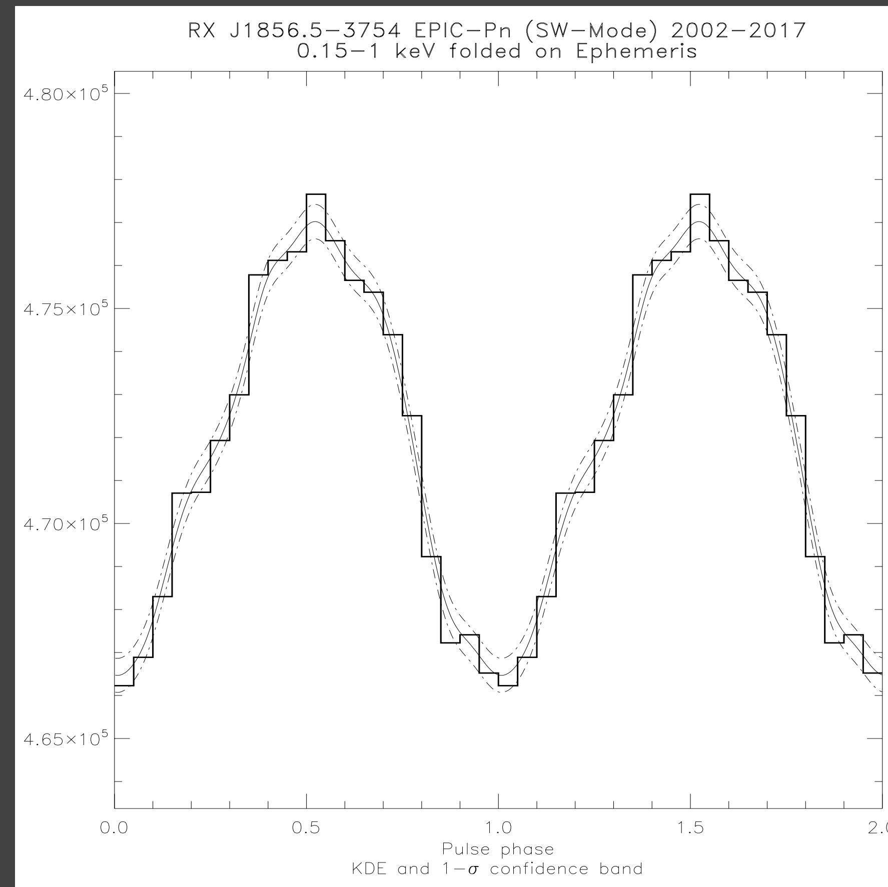
  Do NOT mix TM and Bu mode data!
- Some XMM obs. are excluded due to (uncorrectable) frame (?) jumps/shifts
- Distributions wider
- Pile-up in TM – mode (especially during the Fall observations; distorted pulse shape). Much better timing calibration sources are (radio) ms-pulsars:

  PSR B1937-21 (1.6 ms) & PSR J0218+4232 (2.3 ms)

  (PTA; NICER, NuSTAR, CXO, Fermi LAT)

Given these problems at ms-scales creating timing models from XMM EPIC Pn is tricky for pulsars with periods below ~10 ms For time scales >100 ms it is fine: e.g. coherent timing model (2002-2017) for INS RX J1856.5-3754 (P~7s) With a pulsed fraction of only 1%





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Concluding remarks / outlook

- Absolute timing accuracy of the HE-instruments is about 35 ± 20 μs
- Radio – soft / hard X-ray delay: energy dependent or (small) offsets between instruments e.g. GBM NaI – ISGRI ~ +20 μs?
- NICER data can be added (Aug. 2017 +>) and possibly later also NuSTAR data when RMS ~ 0.1 ms (now RMS 1 ms)

In future: Combined radio / Fermi LAT ToA analysis will enable proper DM modelling (reduction σ_{JBO}) → more accurate timing models!

Thank you for your attention!

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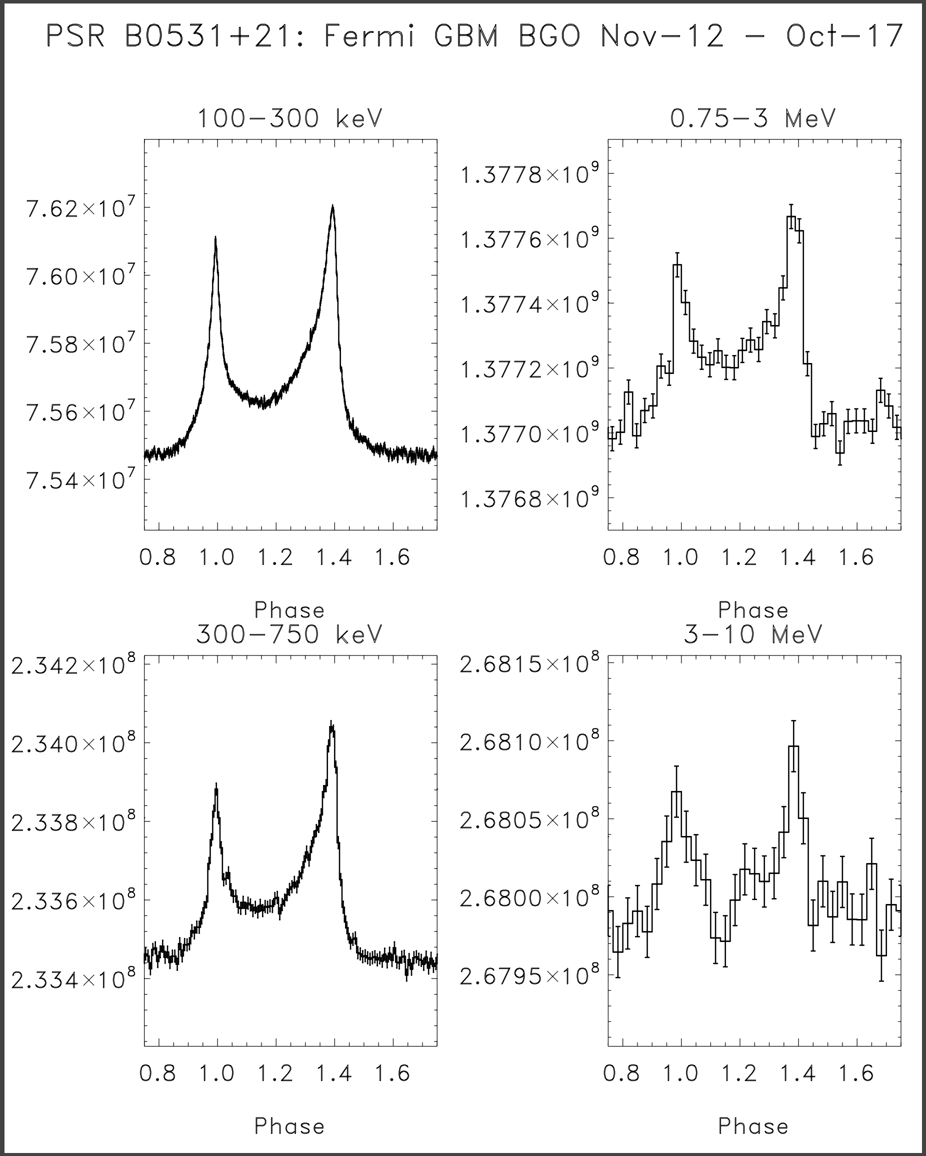
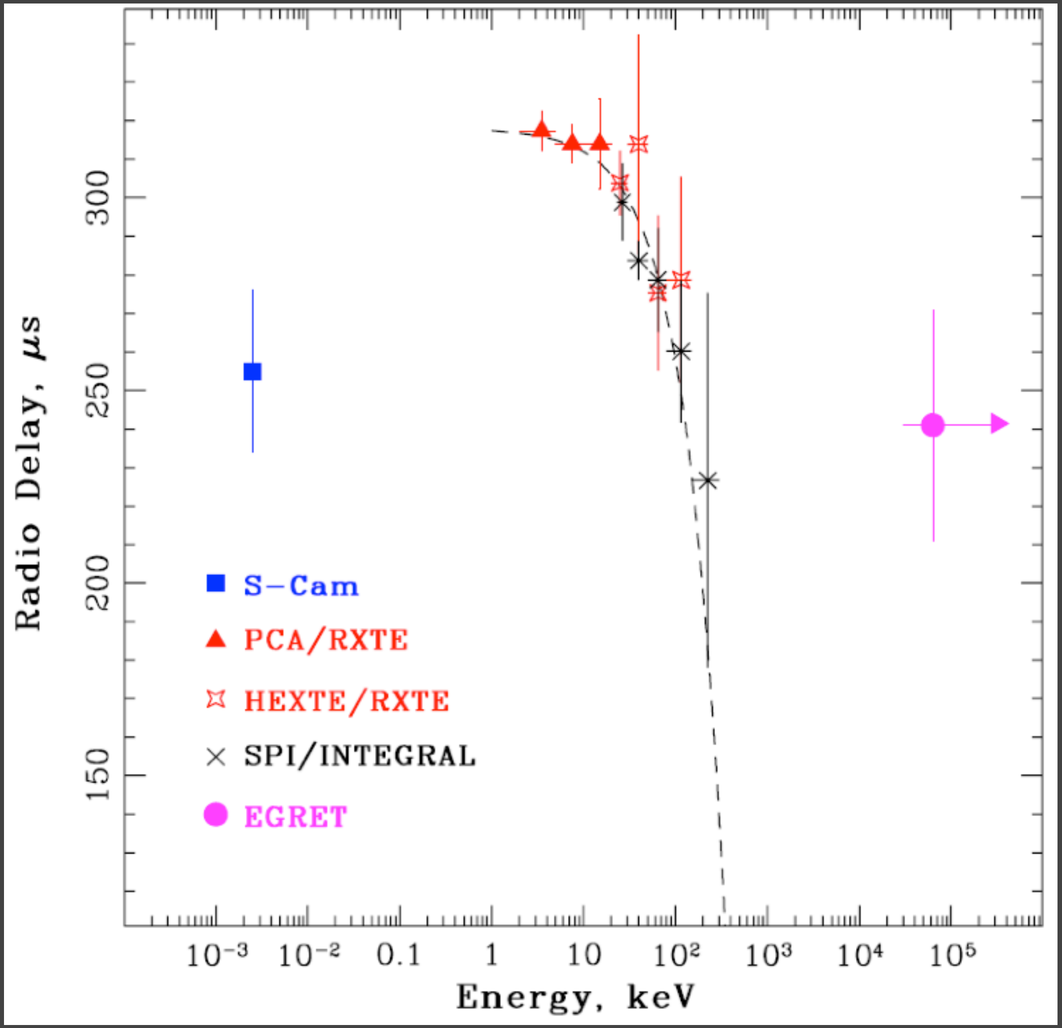

PSR B0531+21: Fermi GBM BGO Nov−12 − Oct−17
100−300 keV
0.75−3 MeV
300−750 keV
3−10 MeV
7.62×10^7
7.60×10^7
7.58×10^7
7.56×10^7
7.54×10^7
1.3778×10^9
1.3776×10^9
1.3774×10^9
1.3772×10^9
1.3770×10^9
1.3768×10^9
2.342×10^8
2.340×10^8
2.338×10^8
2.336×10^8
2.334×10^8
2.6815×10^8
2.6810×10^8
2.6805×10^8
2.6800×10^8
2.6795×10^8
0.8 1.0 1.2 1.4 1.6
Phase


Radio Delay, μs
300
250
200
150
S−Cam
PCA/RXTE
HEXTE/RXTE
SPI/INTEGRAL
EGRET
10⁻³
10⁻²
0.1
1
10
10²
10³
10⁴
10⁵
Energy, keV

Astrophysical result using ISGRI: shift between 20-100 keV and 100-300 keV profiles is only 4.9 ± 1.4 μs (Revs. 727-1736 combination; 720 bins), NOT following the trend seen (suggested) by Molkov et al. (2010), ApJ 708, 403 based on SPI data