

# GPU-accelerated broadband analysis of high-frequency GRB light curves

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*in collaboration with*

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Guidorzi, Lorenzo Amati, Massimo Della Valle

van Putten, Guidorzi & Frontera, 2014, ApJ, 786, 146

van Putten, 2016, ApJ, 819, 169

van Putten, Levinson, Frontera, Guidorzi, Amati & Della Valle, 2017, arXiv:1709.04455

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- Broadband Kolmogorov from BeppoSAX GRBs
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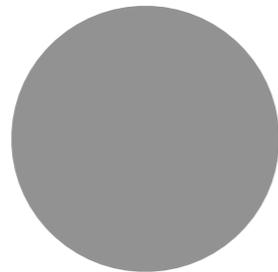
## ***Future searches***

- Broadband Extended Emission
- Theseus, LIGO-Virgo, KAGRA

# Strong and weak gravitation

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Neutron stars,  
black holes



$$R_g = \frac{GM}{c^2}$$

de Sitter scale of  
acceleration

$$a_{dS} = cH \sim 10^{-10} \text{ m s}^{-2}$$

Cosmological  
horizon  $\mathcal{H}$

## *GRBs physical properties*

- Multimessenger approaches
- LIGO-Virgo, KAGRA GW-detectors

## *GRBs as tracers*

- Over broad range of redshifts  $z$
- Extract cosmological parameters

e.g. Amati, Sawant & Della Valle, 2015, A ApTr, 29, 193

# Science cases - cosmology

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$$\Lambda = \omega_0^2 :$$

Dark energy:  
Static or dynamic?

$$H(z) = H_0 \sqrt{1 + \omega_m (6z + 12z^2 + 12z^3 + 6z^4 + (6/5)z^5)} / (1+z)$$

$$H_0 \cong 74 \text{ km s}^{-1} \text{ Mpc}^{-1}, \omega_m \cong 0.28$$

Sans  $H_0$  tension!

$\mathcal{H}$ : compact

$$\omega_0 = \sqrt{1 - q} H$$

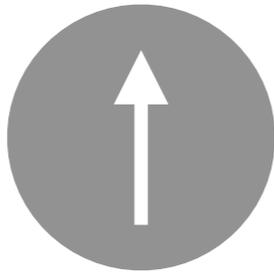
$$\Lambda\text{CDM: } H(z) = H_0 \sqrt{1 - \omega_m + \omega_m (1+z)^3} : H_0 \cong 67 \text{ km s}^{-1} \text{ Mpc}^{-1}, \omega_m \cong 0.33$$

# Science cases - central engines

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*GRB central engine:*

NS or BH?



$$\text{BH: } E_{rot} \sim 6 \times 10^{54} \text{ erg} \times (M / 10M_{\odot})$$

$$\text{NS: } E_{rot} \sim 3 \times 10^{52} \text{ erg}$$

*Dark energy:*

Static or dynamic?



# GRB phenomenology

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## BATSE

Short and long GRBs

## BeppoSAX

X-ray afterglows:

cosmological origin, LGRSBs from CC-SNe

## Swift

SGRB with Extended Emission (SGRBEE)

SGRBs from mergers

$$E = E_{52} 10^{52} \text{ erg}, \delta t = \delta t_{-3} \text{ ms}$$

$$\alpha_E = \frac{GE}{c^5 \delta t} = 2.75 \times 10^{-5} \left( \frac{E_{52}}{\delta t_{-3}} \right)$$

$$\alpha_E \leq 10^{-4}$$

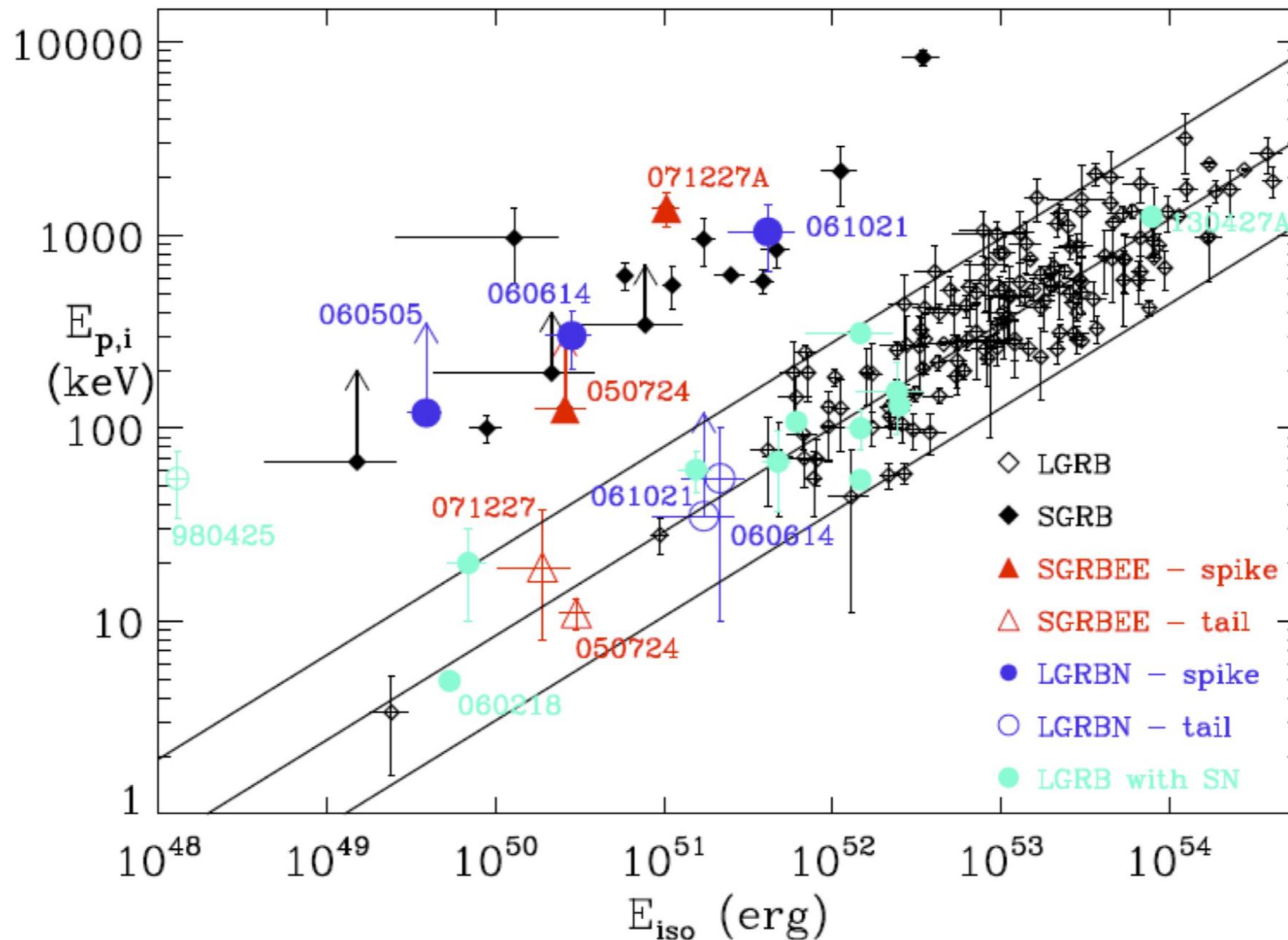
$$L_\gamma \gg L_{\text{Edd}}$$

$$E_{\text{res}} > E_c^{\text{NS}} \text{ (extreme events)}$$

$$T_{90}^{\text{SGRBEE}} \gg T_{\text{merger}}$$

Origin in compact central engine: NS or BH

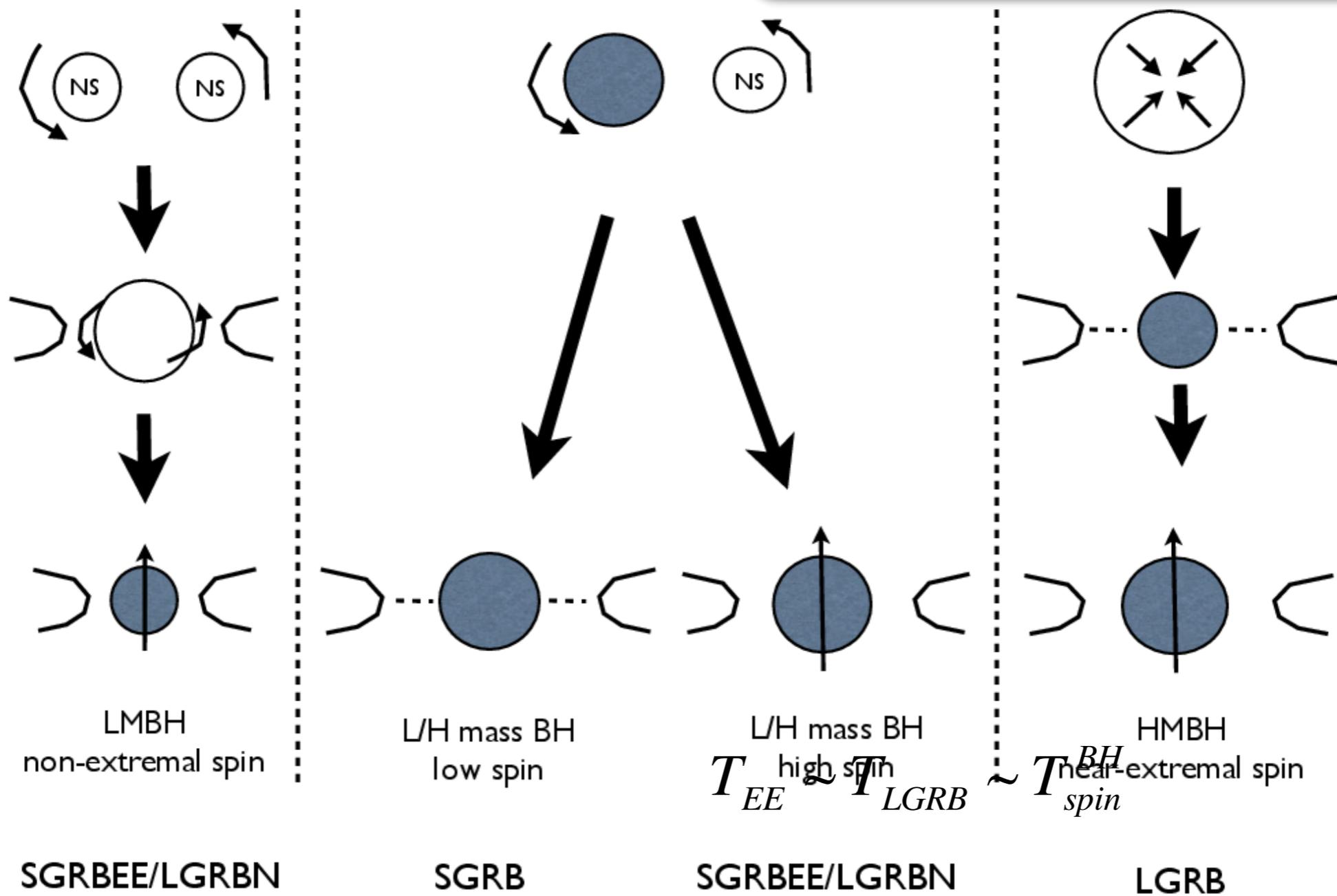
# Amati relation



Common inner engine powering Extended Emission to short GRBs and LGRBs

# Short/long GRBs from slowly/rapidly rotating black holes

$$T_{EE} \sim T_{LGRB} \sim T_{spin}^{BH} \sim O(10\text{ s})$$

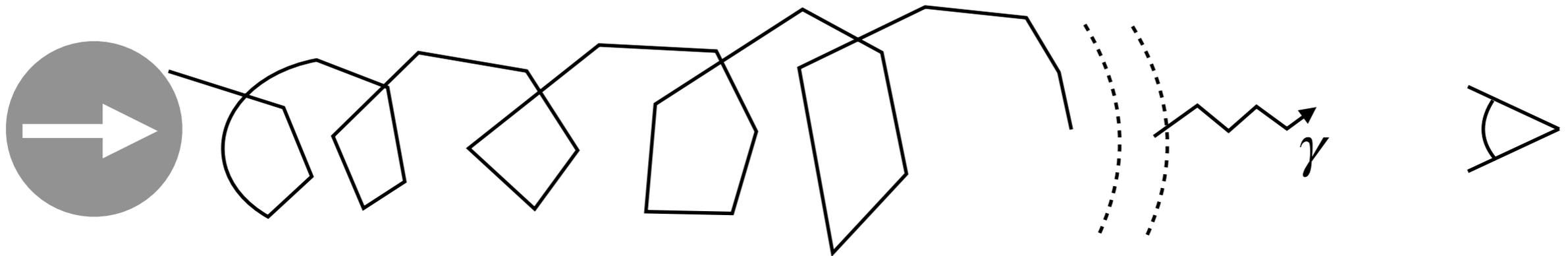


(van Putten & Ostriker, 2001, ApJ, 552, L31; van Putten, 2015, ApJ, 810, 7)

# Relativistic outflows

Energy reservoir: angular momentum of a compact central engine

(Bisonvatyi-Kogan 1970, Woosley 1993, MacFadyen & Woosley 1999)



## Magnetars

Usov 1994, Metzger et al. 2011, ...

## Rotating black holes

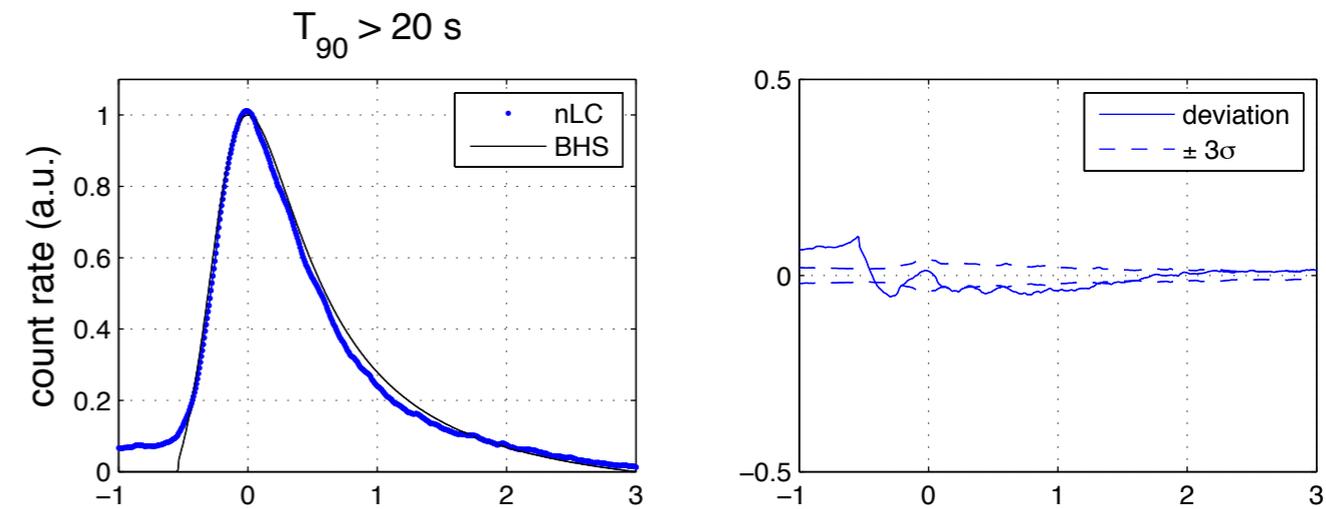
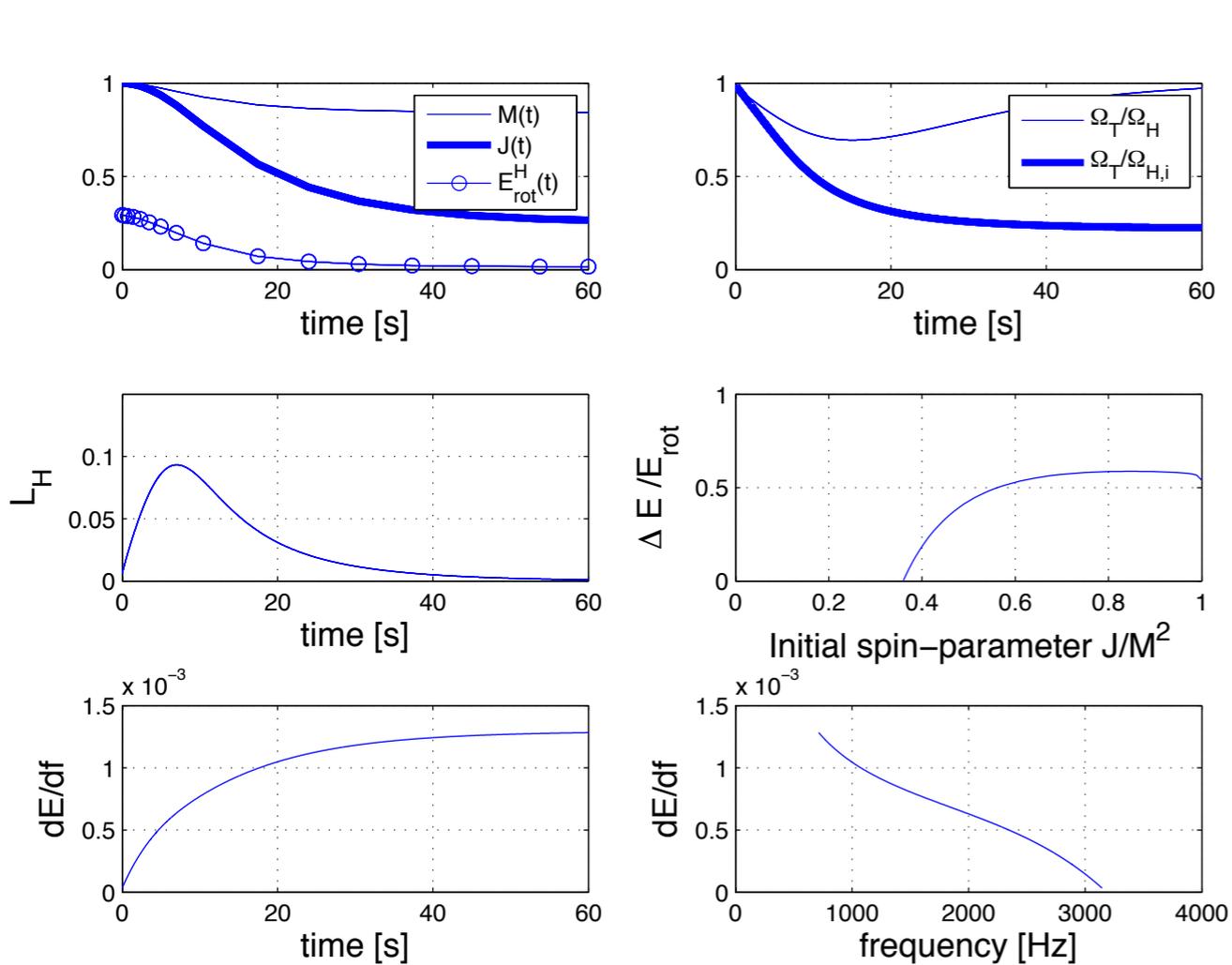
Kerr 1963

$$E_{res} > E_c^{NS} \text{ (extreme events)}$$

$$T_{EE} \sim T_{LGRB} \sim T_{spin}^{BH}$$

EE in SGRBs from mergers

# BH losing angular momentum in BATSE

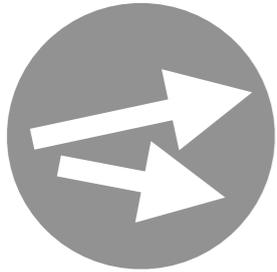


Normalized light curve from BATSE  
versus theory

(van Putten, 2012, PTP, 127, 331)

van Putten, Levinson, Frontera, Guidorzi,  
Amati & Della Valle, 2017, arXiv:1709.04455

# Observational signatures

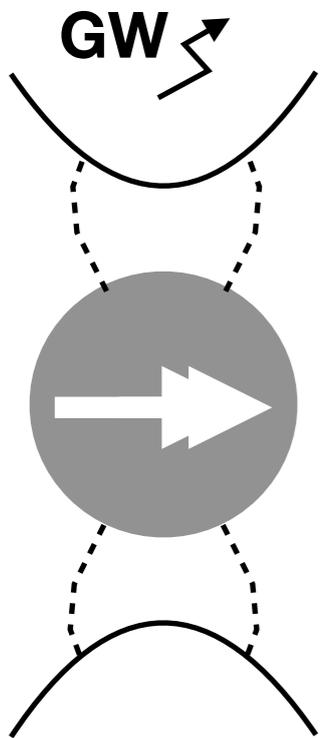


*Misaligned newly born magnetar or proto-neutron star:*

- HF modulation GRB light curves: **Bump at HF?**
- HF GW burst at twice spin frequency

**Magnetars spinning down by magnetic winds**

$$E_{res} \leq E_c^{NS} \cong \text{few} \times 10^{52} \text{ erg}$$



*Aligned angular momentum and magnetic moment (Carter 1968):*

- No modulation of GRB light curves directly by black hole
- Broadband Extended Gravitational-wave Emission (BEGE) from non-axisymmetric mass motion at the ISCO: **Long duration GWB?**

$$E_{res} = \text{few} \times 10^{54} \text{ erg} \gg E_c^{NS}$$

Van Putten, 1999, Science, 284, 115  
van Putten & Levinson, 2002, Science, 294, 1837  
van Putten & Levinson 2003 ApJ 584 937

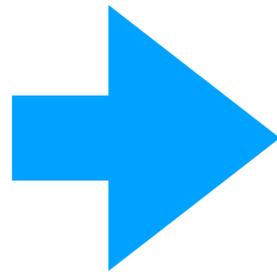
**Rotating black holes loosing angular momentum to an inner disk**

# Broadband extended emission in EM-GW

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GRBs (and their associated CC-SNe) are extreme events rapidly exhausting a central energy reservoir on a lifetime of tens of seconds or less.

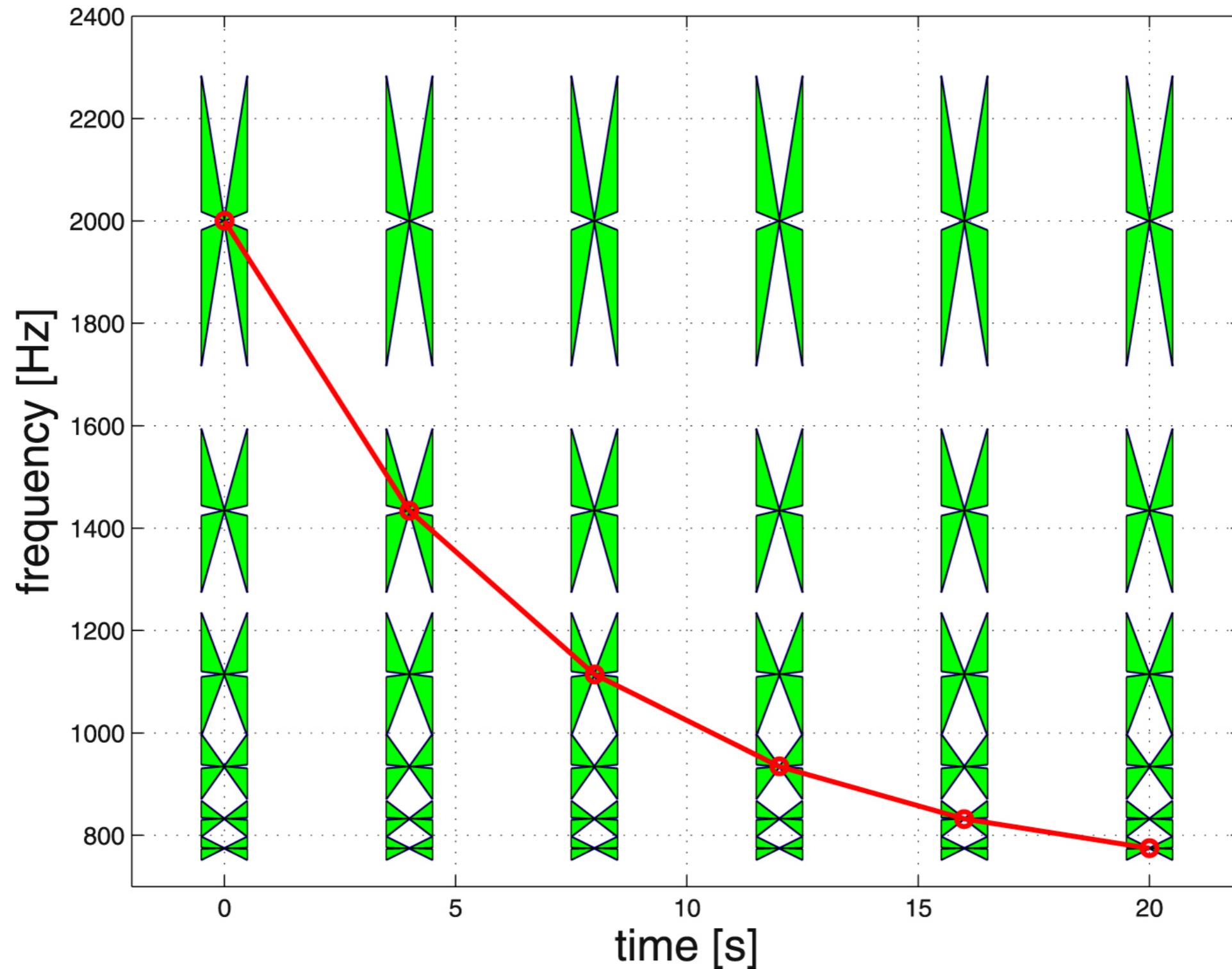
Principally different from any EM or GW emission from pulsars, whose lifetimes extend to Giga years.



Sidestep Fourier transforms

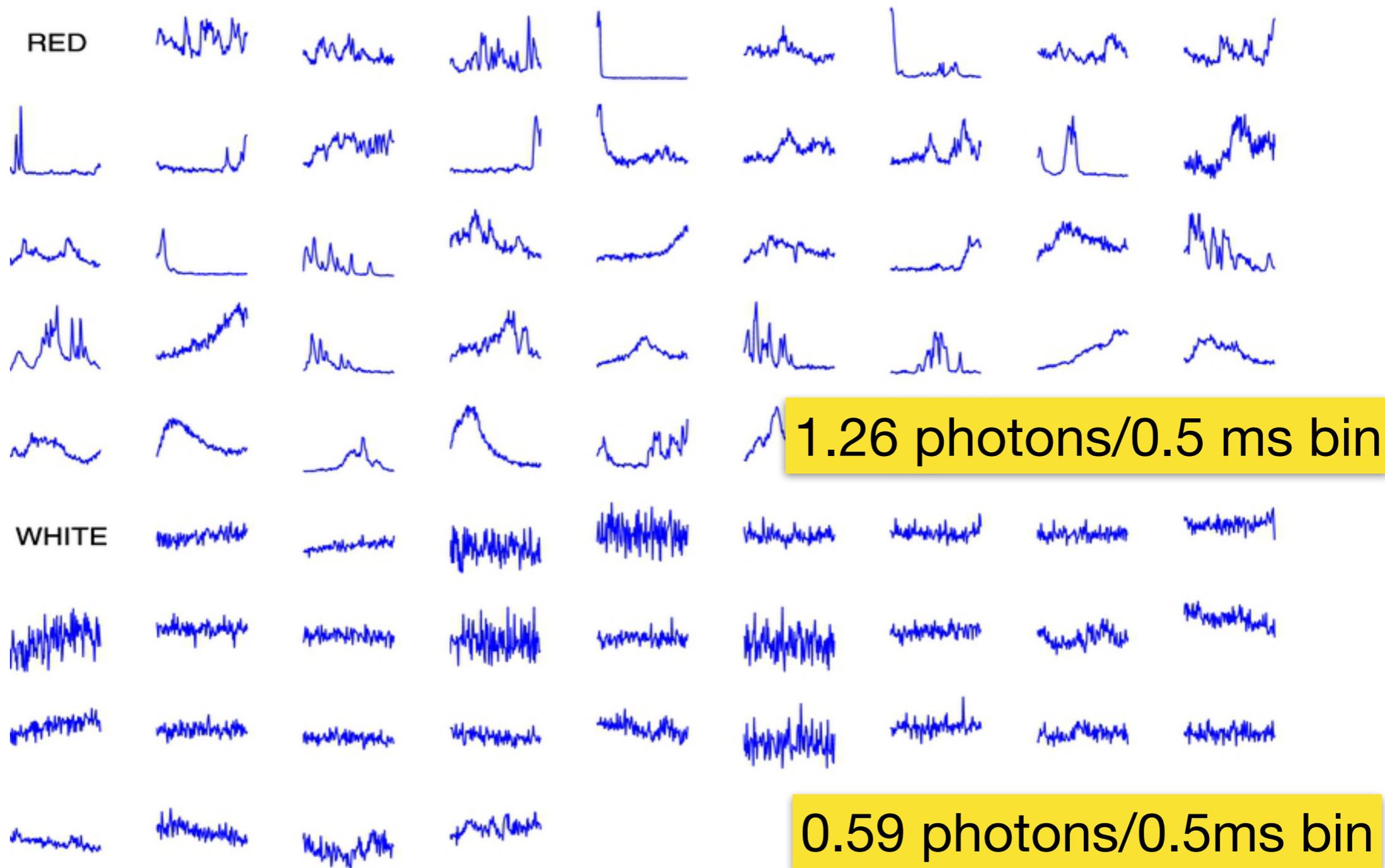
Search for signals with finite time rate-of-change of frequency

# Butterfly filtering



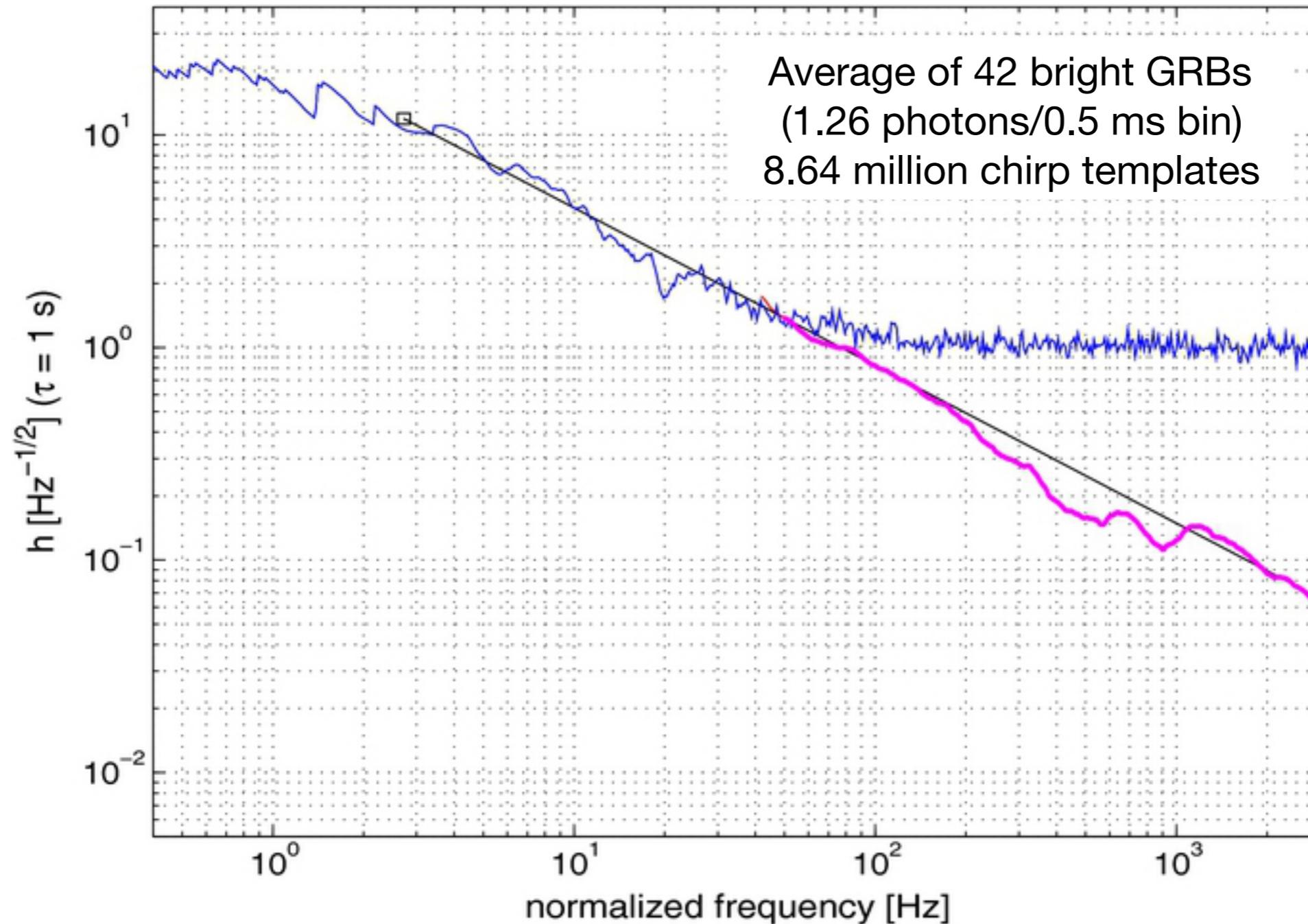
(van Putten, 2016, ApJ, 819, 169)

# 2 kHz light curves of bright GRBs of *BeppoSAX*



(van Putten, Guidorzi & Frontera, 2014, ApJ, 786, 146)

# Broadband Kolmogorov spectrum in LGRBs

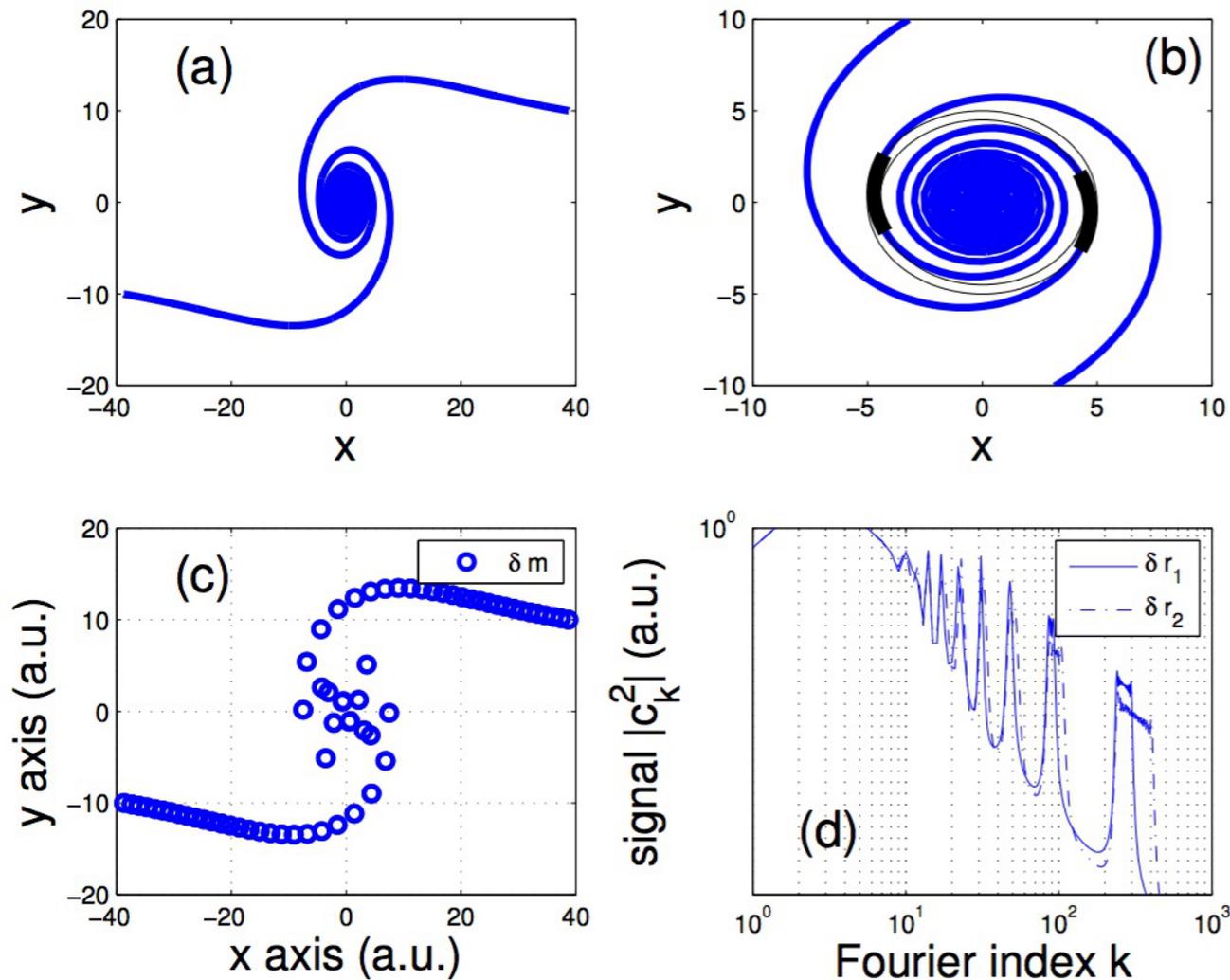


No evidence for a bump at high frequency, that might indicate formation of PNS or magnetars

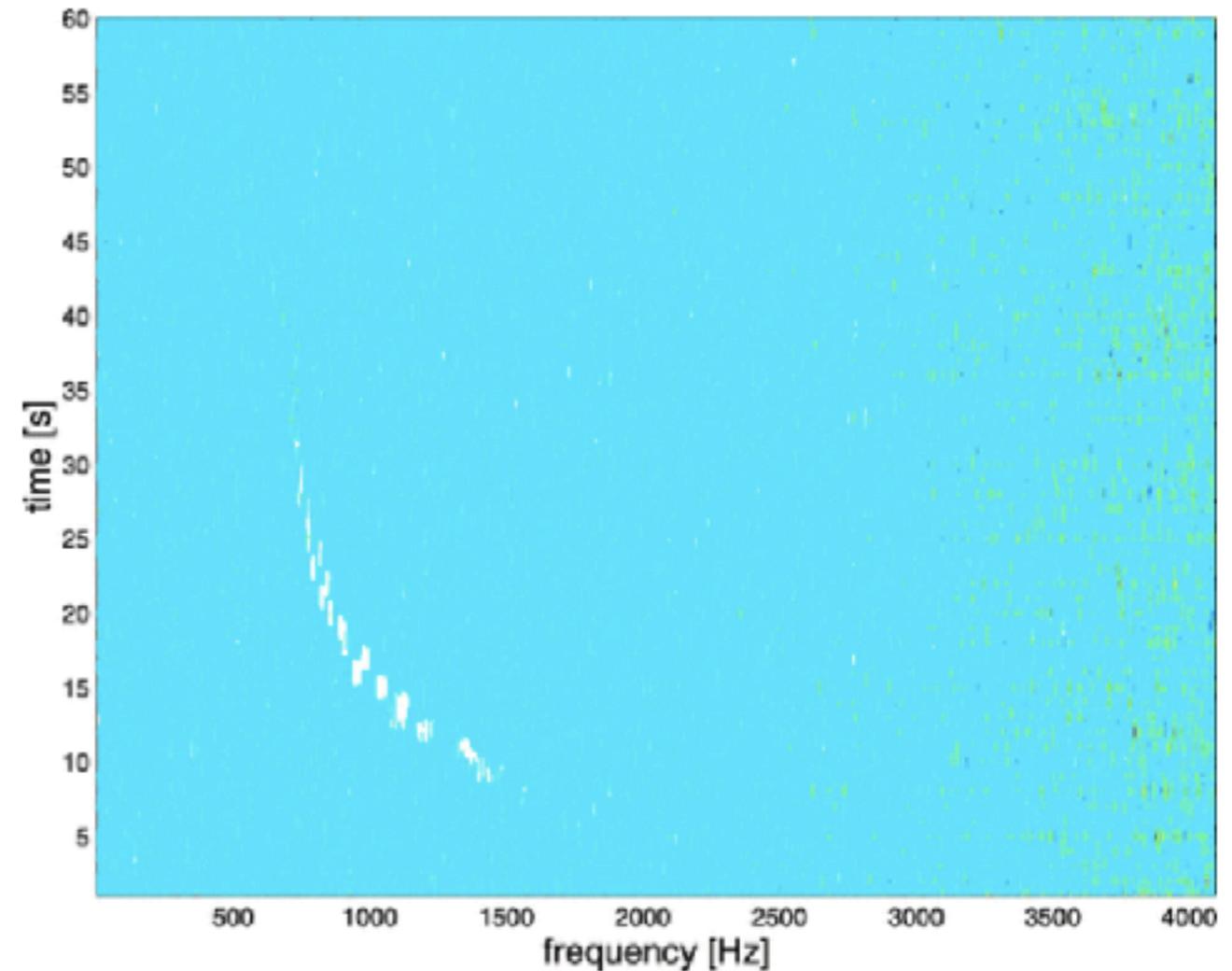
(van Putten, Guidorzi & Frontera, 2014, ApJ, 786, 146)

# Outlook on long GW chirps

Ascending



Descending



(Levinson, van Putten & Pick, 2015, ApJ, 812, 124)

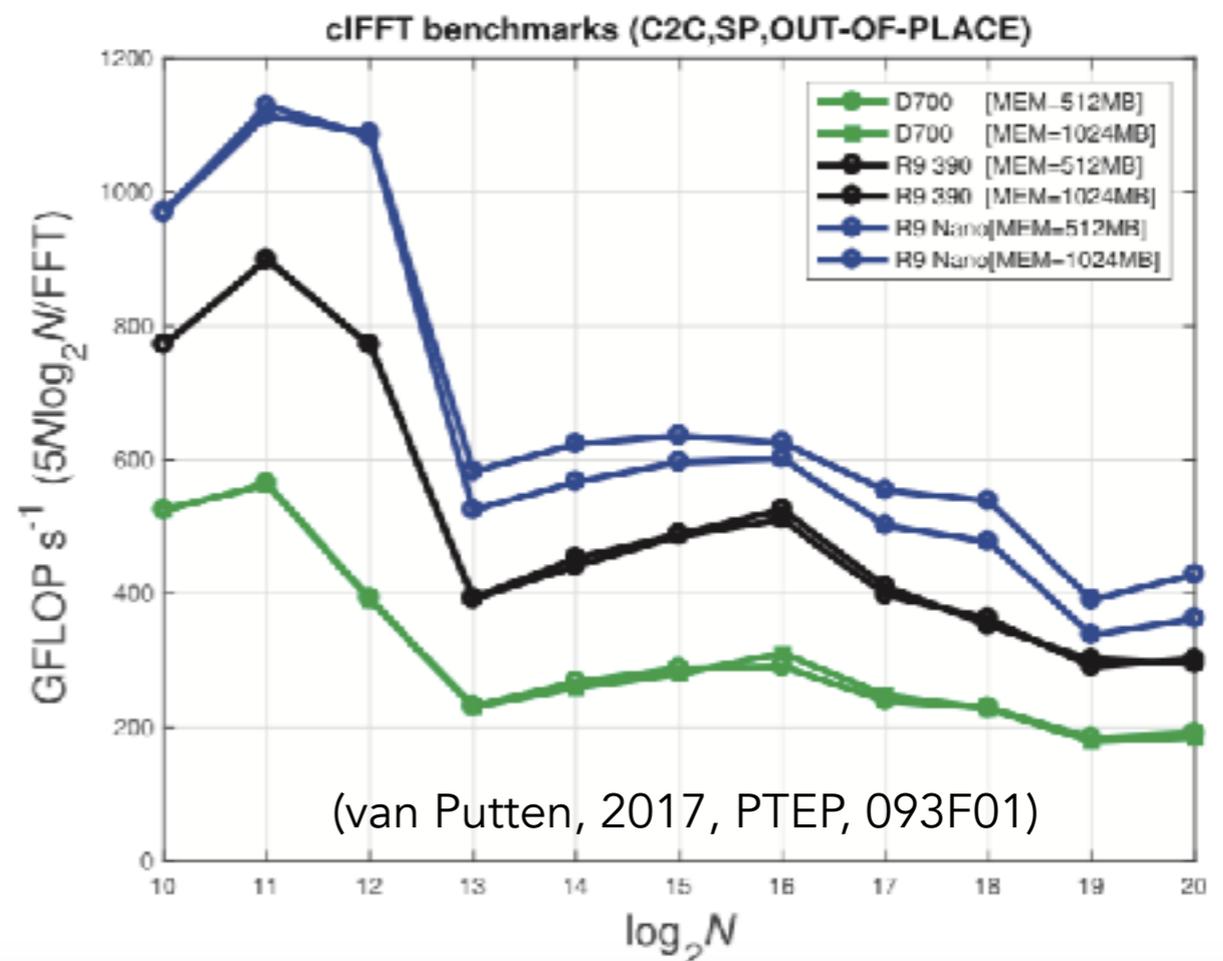
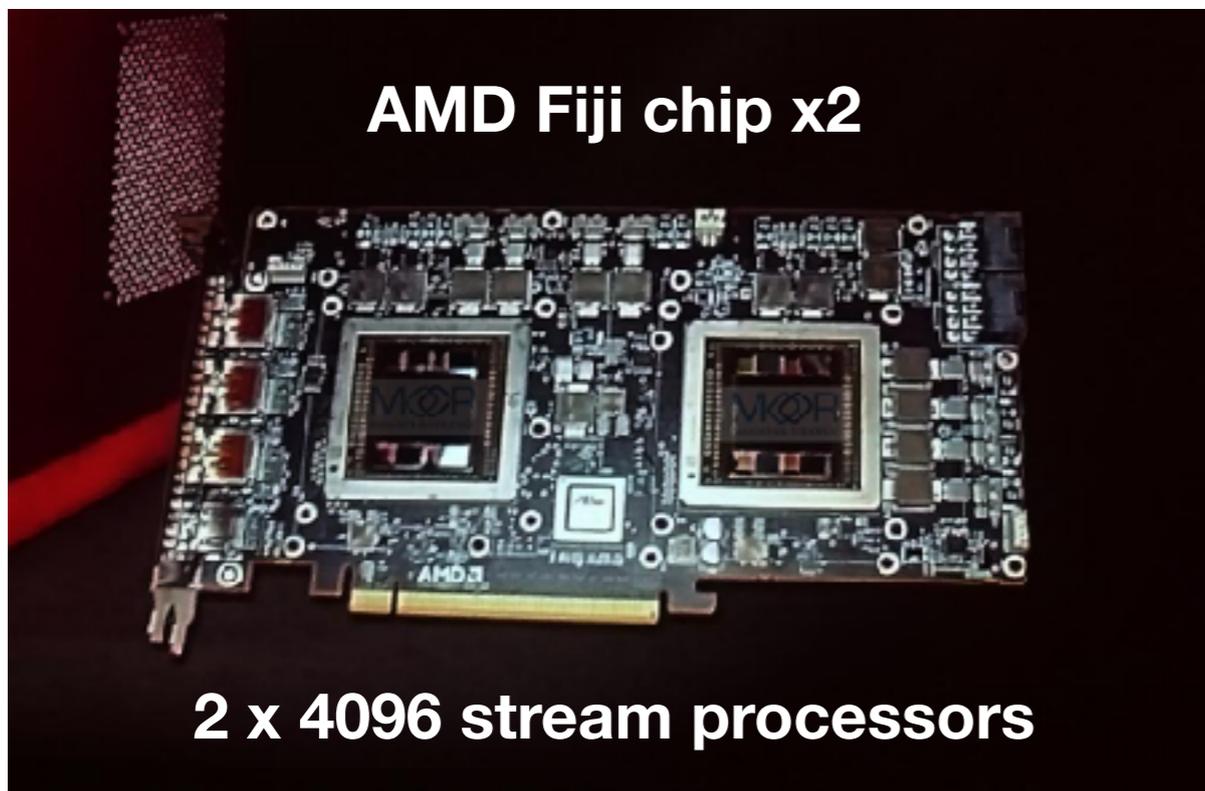
(van Putten, 2008, ApJ, 684, L91)

# GPU-accelerated butterfly filtering

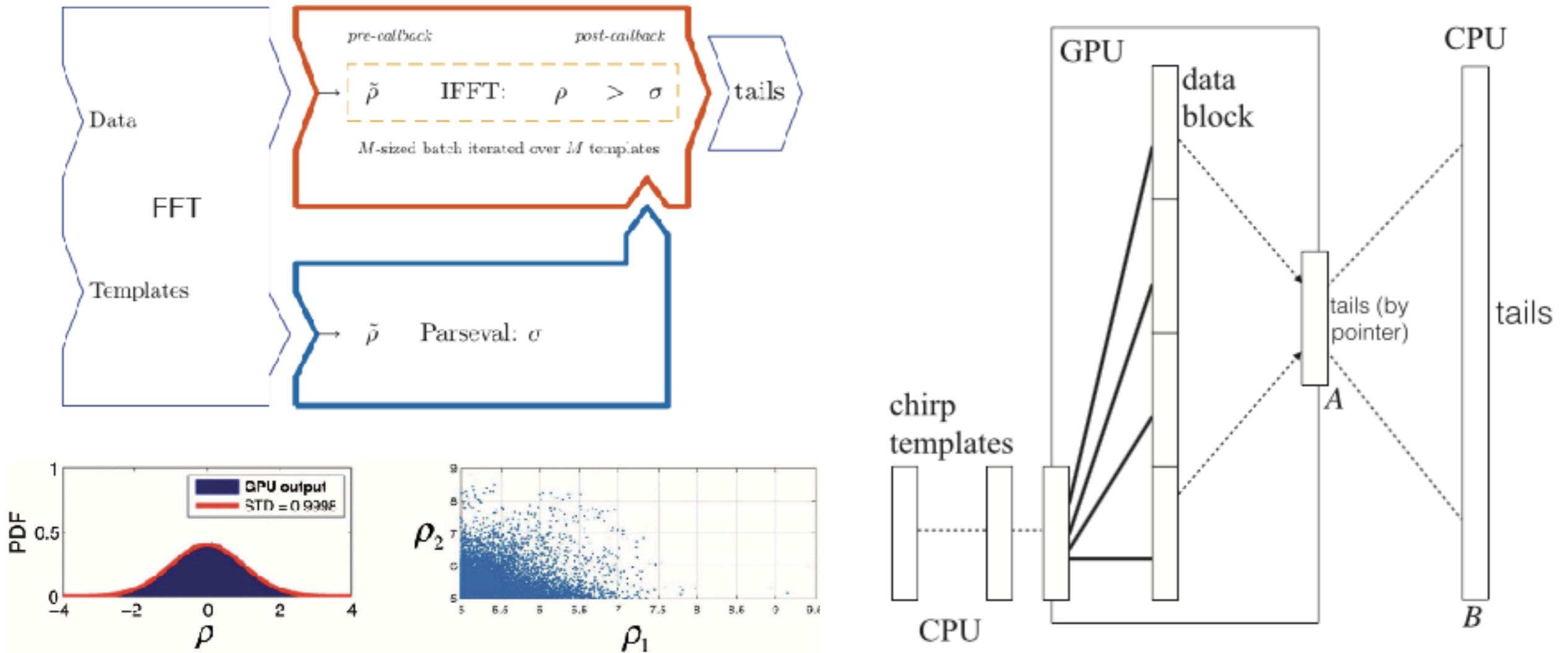
Deep searches requires massively parallel computation

- Butterfly filtering against a bank of up to 8 million chirp templates (ascending-descending). Implementation optimal by FFT.
- *Graphics Processor Units* (GPUs) are orders of magnitude *cheaper, greener and faster* than *Central Processing Units* (CPUs).

~ 100,000 FFT( $N=2^{16}$ )  
per Fiji chip



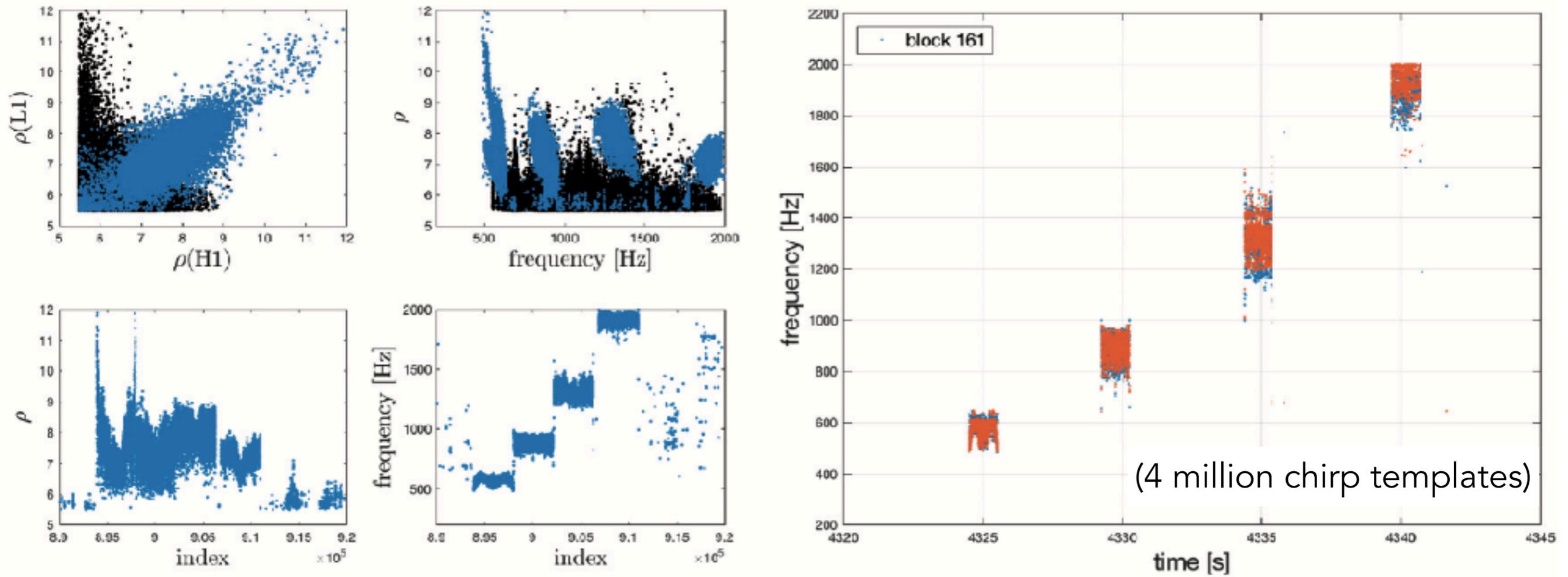
# GPU-acceleration by Parseval's Theorem



Tails of tens of kB/s down from tens of GB/s

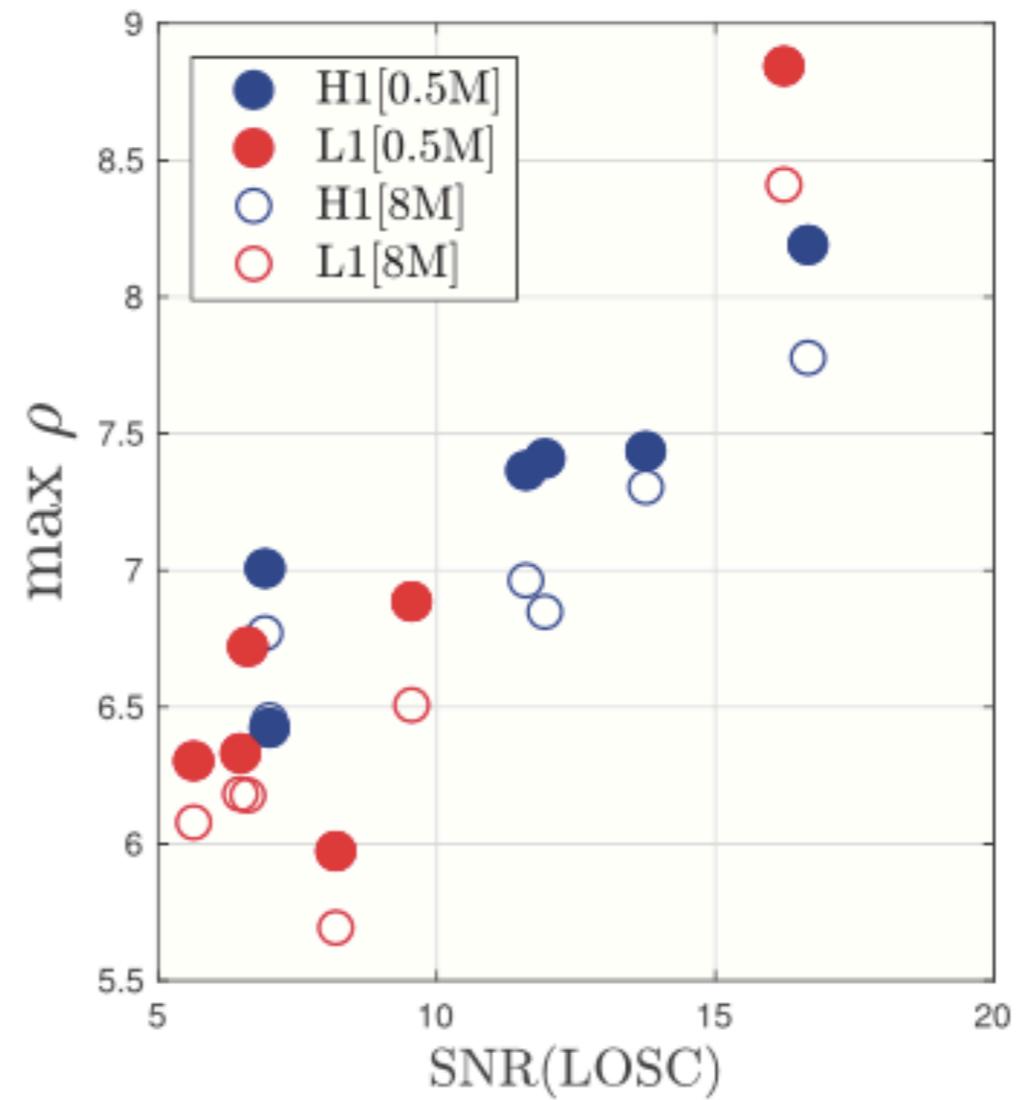
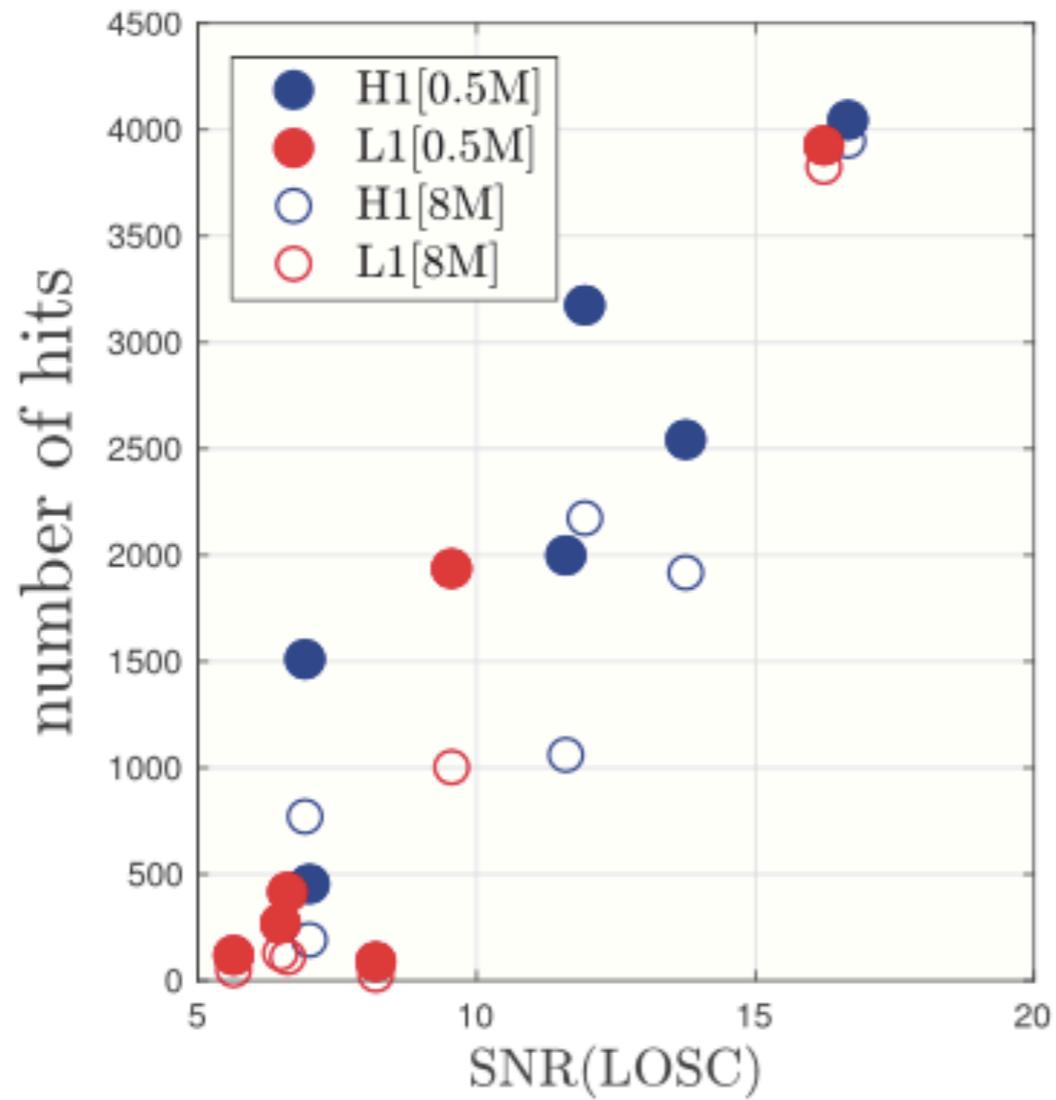
(van Putten, 2017, PTEP, 093F01)

# LIGO H1L1 injections



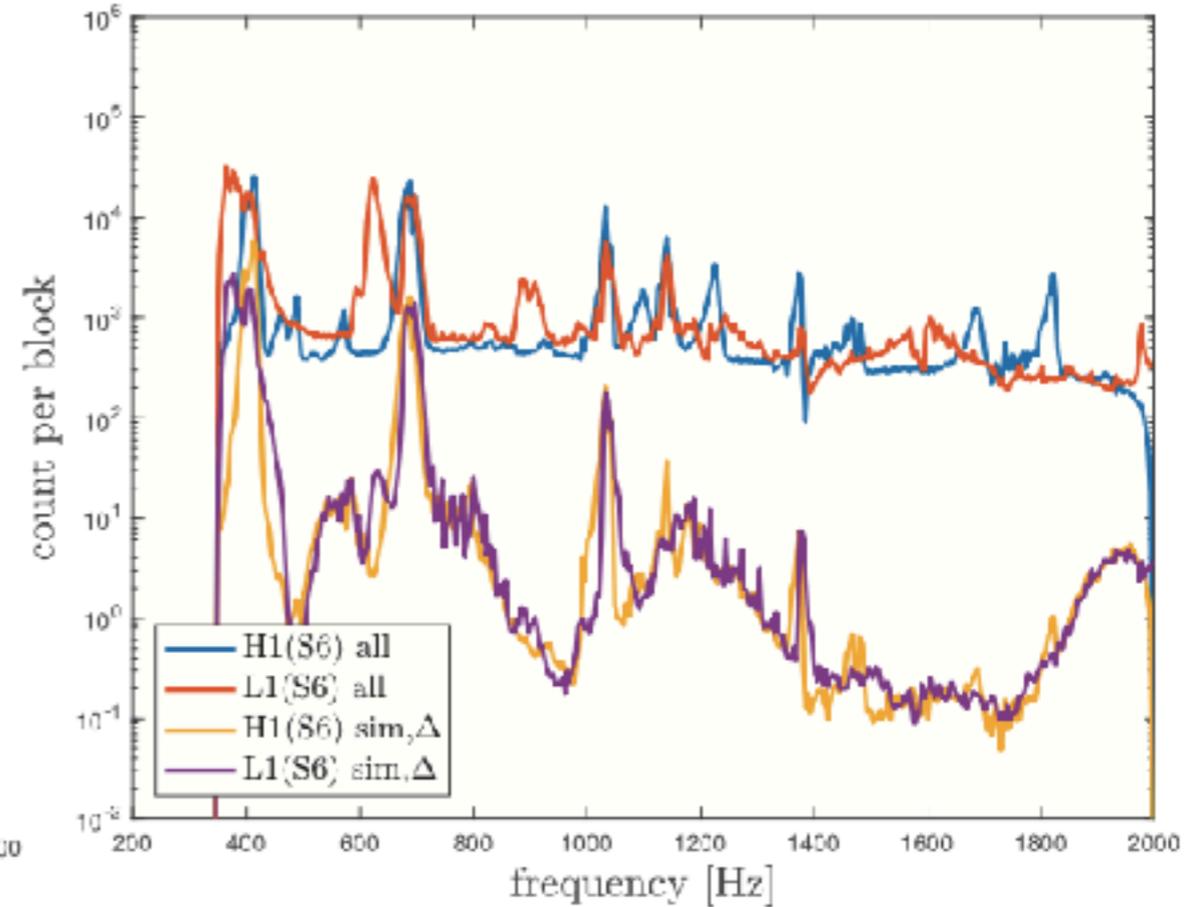
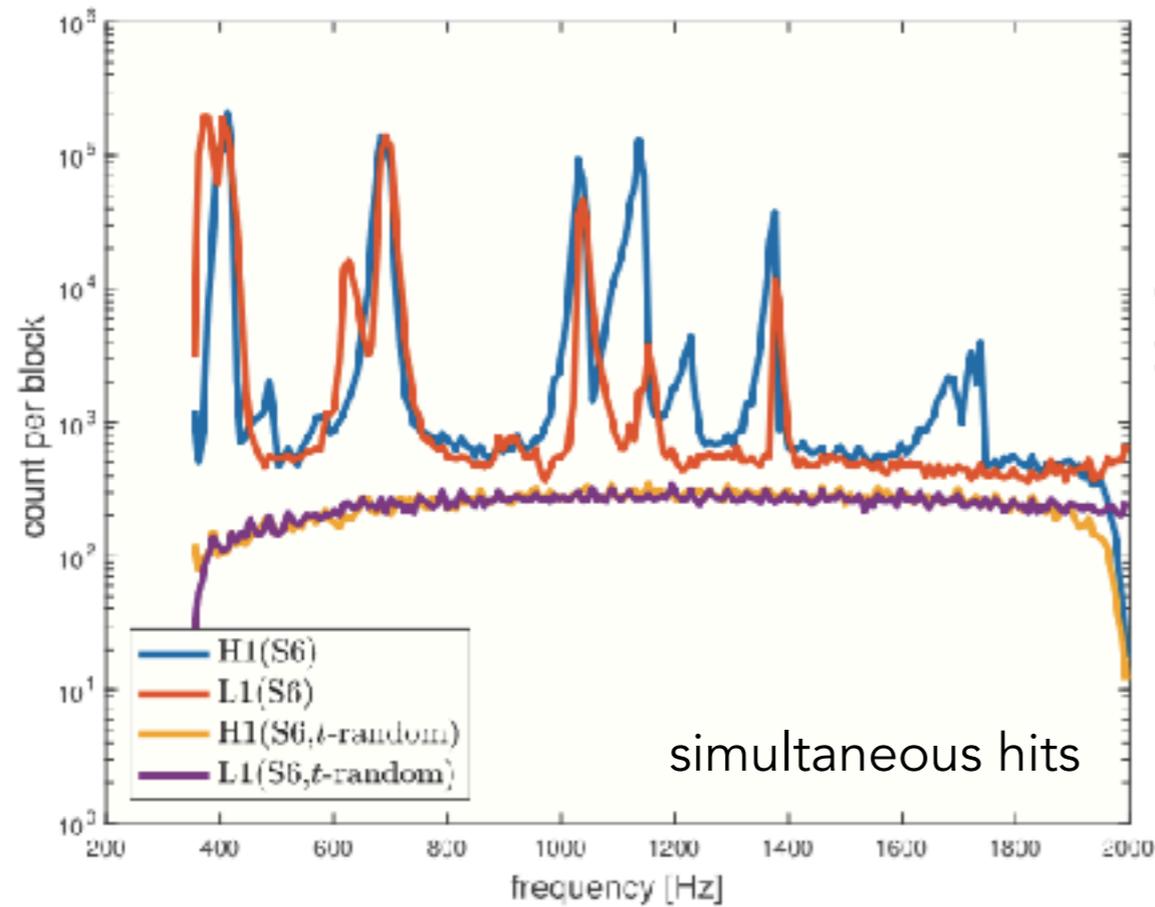
(van Putten, 2017, PTEP, 093F01)

# Sensitivity LIGO H1L1 injections



(van Putten, 2017, PTEP, 093F01)

# Pseudo-spectra of LIGO H1L1



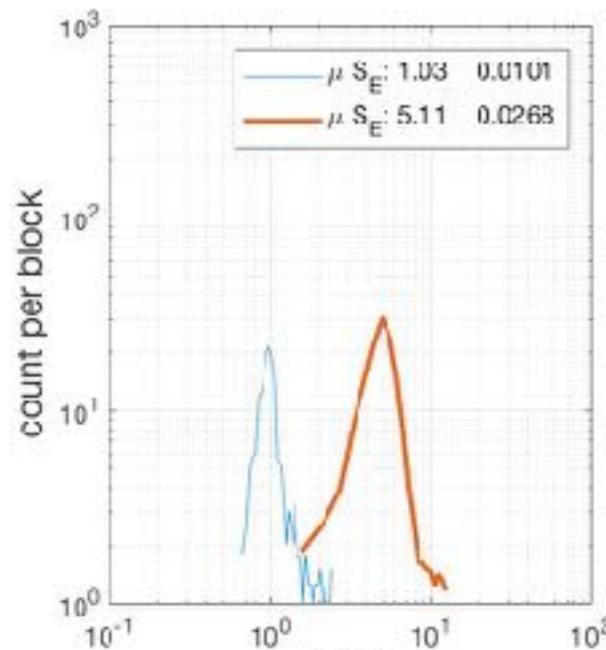
(van Putten, 2017, PTEP, 093F01)

# Correlations in LIGO H1L1

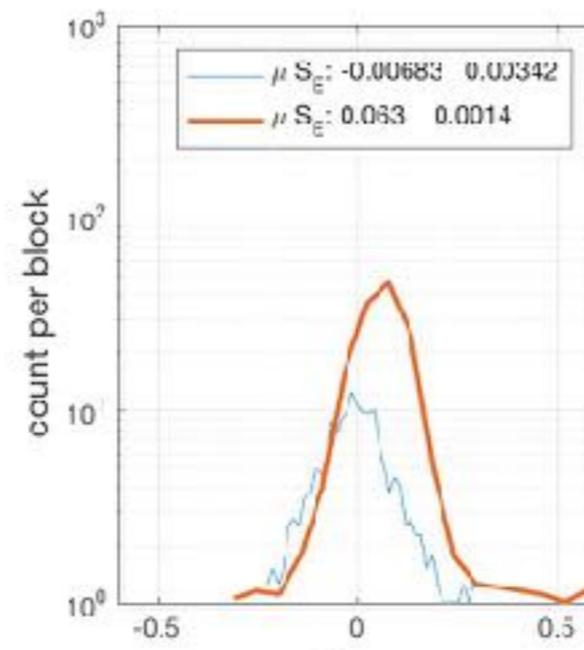
$$\text{EPR} \equiv \frac{p_{12}}{p_1 p_2} = 5.11 \pm 0.0268$$

$$C_\rho = 0.0630 \pm 0.0014$$

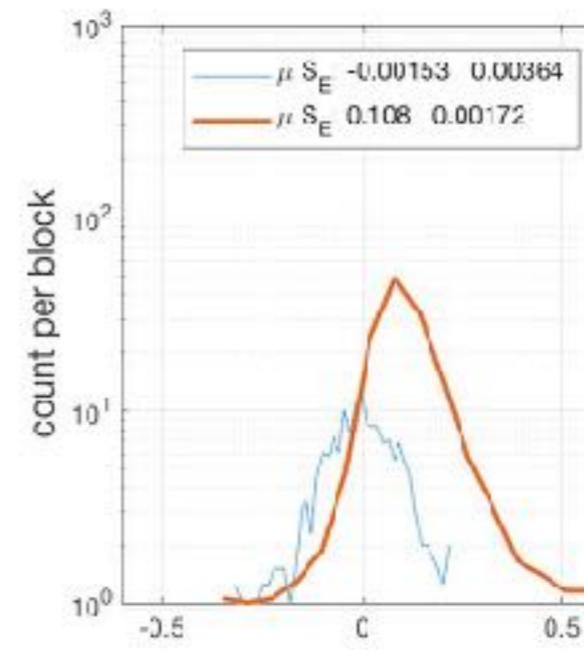
$$C_f = 0.1008 \pm 0.0017$$



EPR



C<sub>ρ</sub>



C<sub>f</sub>

van Putten, Levinson, Frontera, Guidorzi, Amati & Della Valle, 2017, arXiv:1709.04455

**THESEUS'** GRBs as probes of fundamental physics in strong and weak gravity:

- Identify signatures of central engine in HF broadband spectra: *BH or NS?*
- Estimate  $(H_0 > 70, \omega_m < 0.3)$  or  $(H_0 > 70, \omega_m > 0.3)$ :  $\Lambda = \omega_0^2$  or  $\Lambda$ CDM?

**GPU-accelerated butterfly filtering** is a new tool for *multi-messenger broadband time-domain analysis*.

Current highlights:

- *Broadband Kolmogorov spectrum* in GRB light curves at 1.26 photons/0.5 ms bin using 8.64 million templates: no evidence for PNS or magnetars.
- *511% correlation in H1-L1 LIGO S6* GW-data by over 1 million correlations  $s^{-1}$  on a dozen GPU-CPU nodes. Origin unknown (atmospheric, astrophysical)?