Deep searches for broadband extended emission in gravitational-waves in nearby energetic core-collapse supernovae

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van Putten, Levinson, Frontera, Guidorzi, Amati & Della Valle,
2017, arXiv:1709.04455; JGW-G1707302-v1

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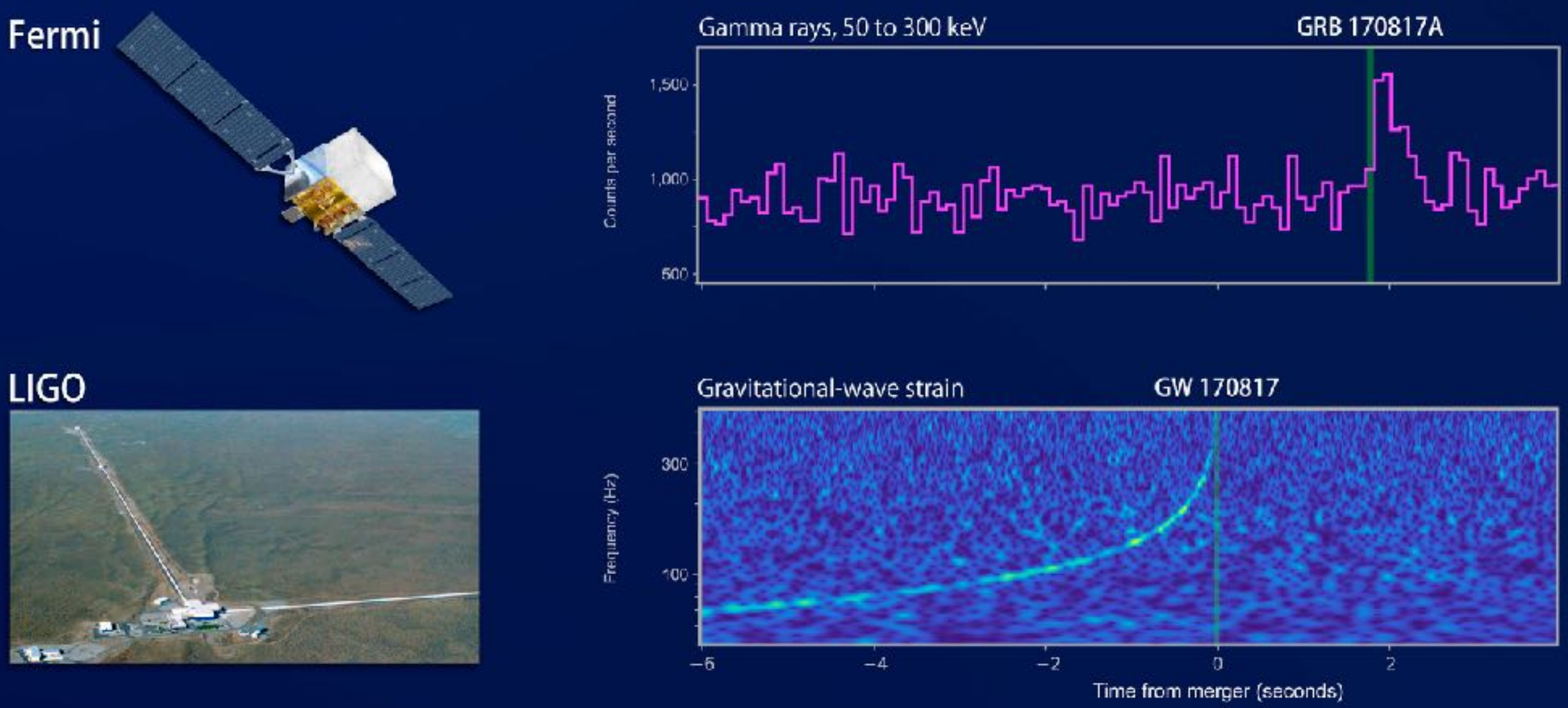
Outline

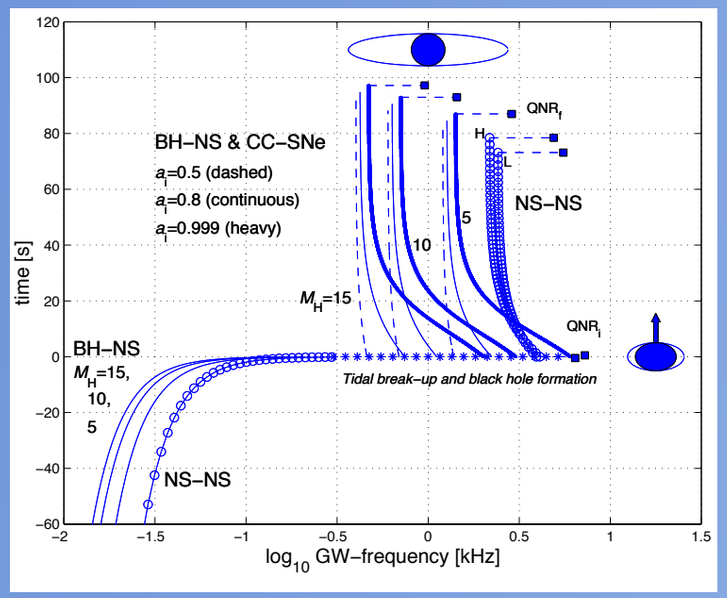
- GW170817: prelude to LGRB, SGRBEE and CC-SNe?
- *Butterfly filtering*: search for broadband extended gravitational-wave emission by matched filtering with chirp-like templates
- *GPU-accelerated* deep searches by banks of millions of templates
- *LIGO S6*: faint broadband correlations in H1 and L1
- *Conclusions and outlook*

GW170817


Fermi
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
LIGO
Gravitational-wave strain
GW 170817
Frequency (Hz)
300
100
−6
−4
−2
0
2
Time from merger (seconds)

GW170817: magnetar or BH?

van Putten, 2009, MNRAS 396 L81



Ascending chirp

Descending chirps?

~ $3M_o$ BH losing angular momentum to high density matter about the ISCO:
~ 2 kHz

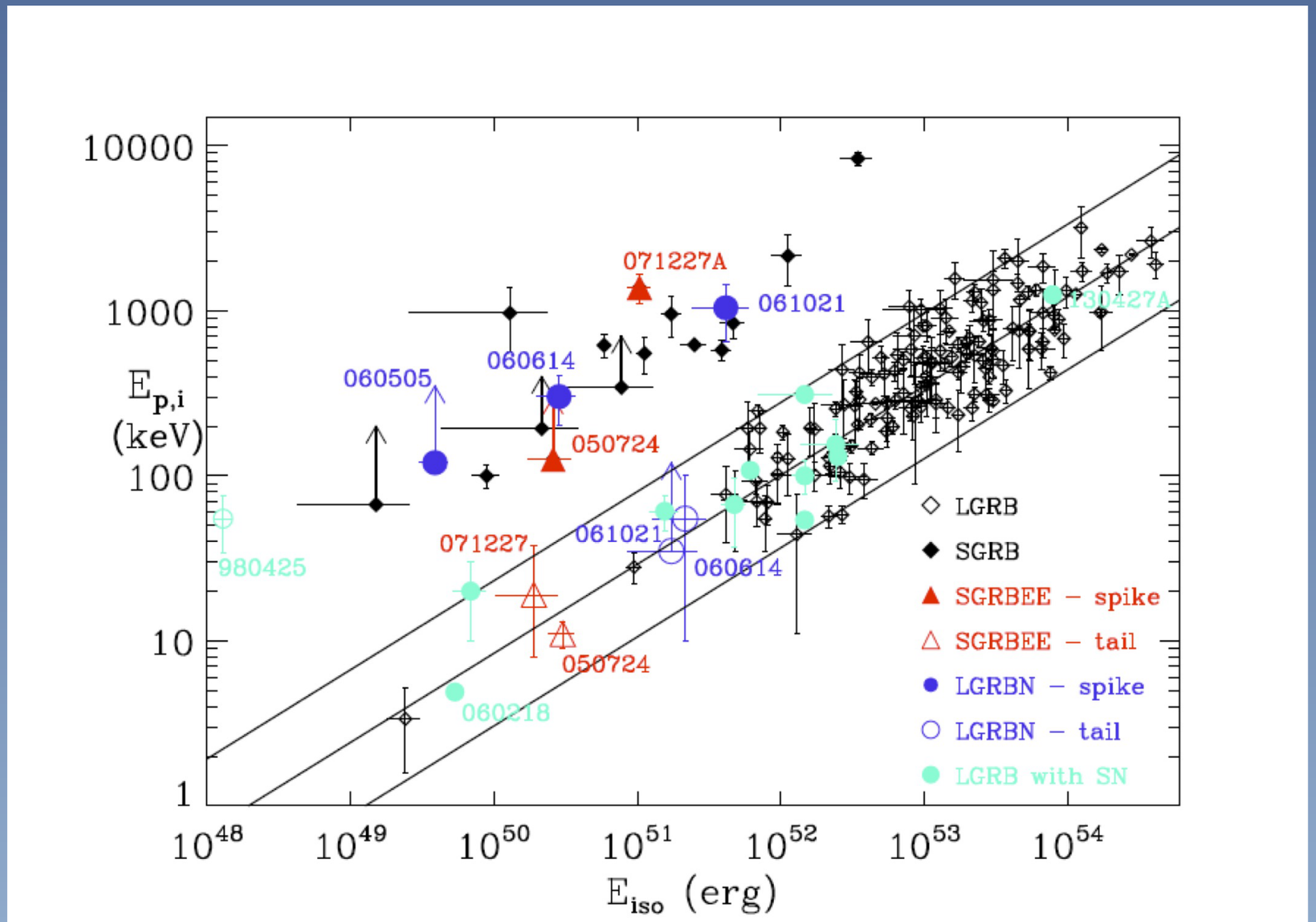
Magnetar losing angular momentum in magnetic winds

Central engines of gamma-ray bursts

- **BATSE**: SGRBs (< 2 s) and LGRBs (> 2 s)
- ***BeppoSAX***: cosmological origin, X-ray afterglows
- ***Swift***: SGRB with Extended Emission (EE)

Hyper-energetic events with ms scale variability

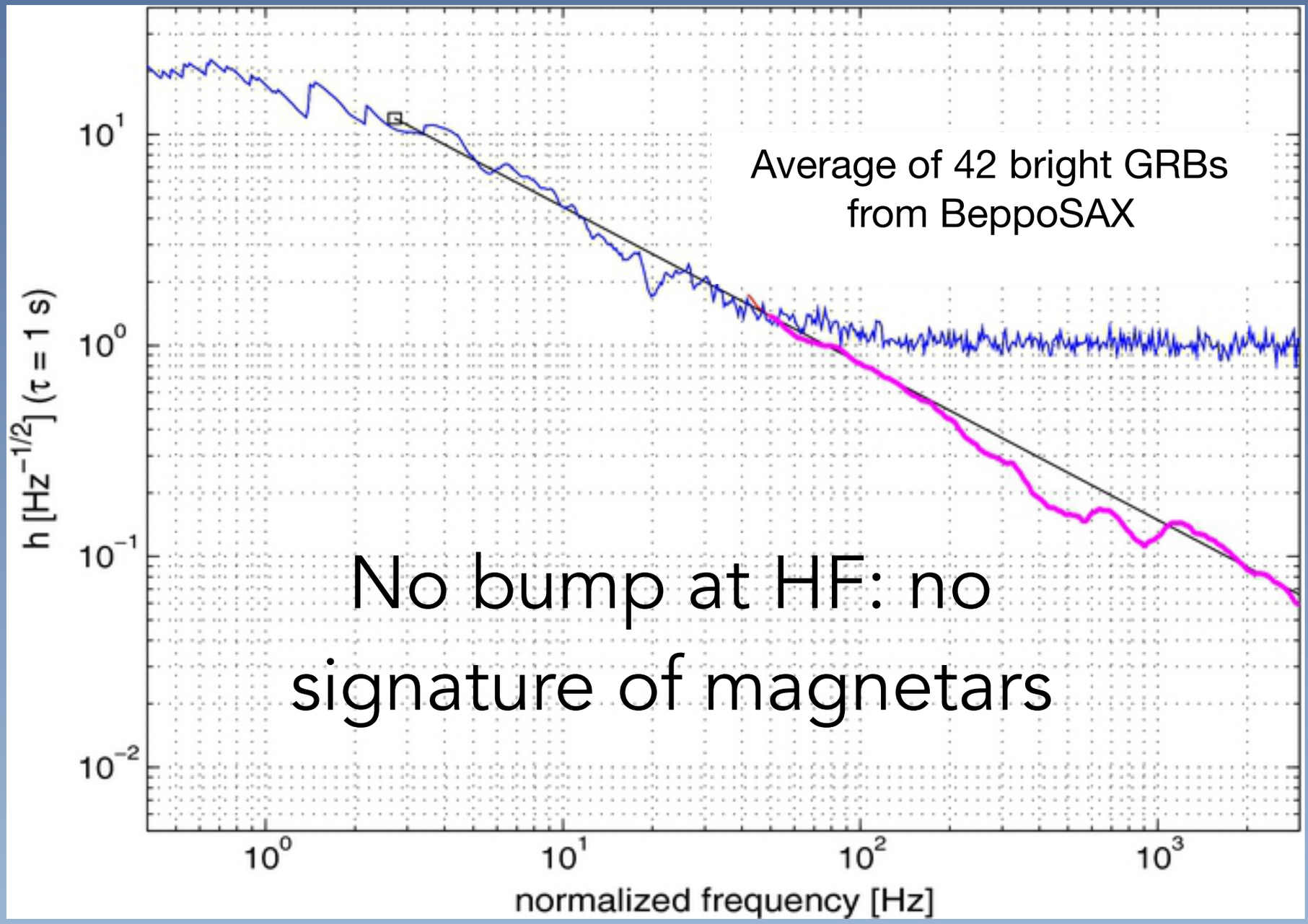
Amati relation



van Putten, Lee, Della Valle, Amati & Levinson, 2014, MNRAS, 444, L58

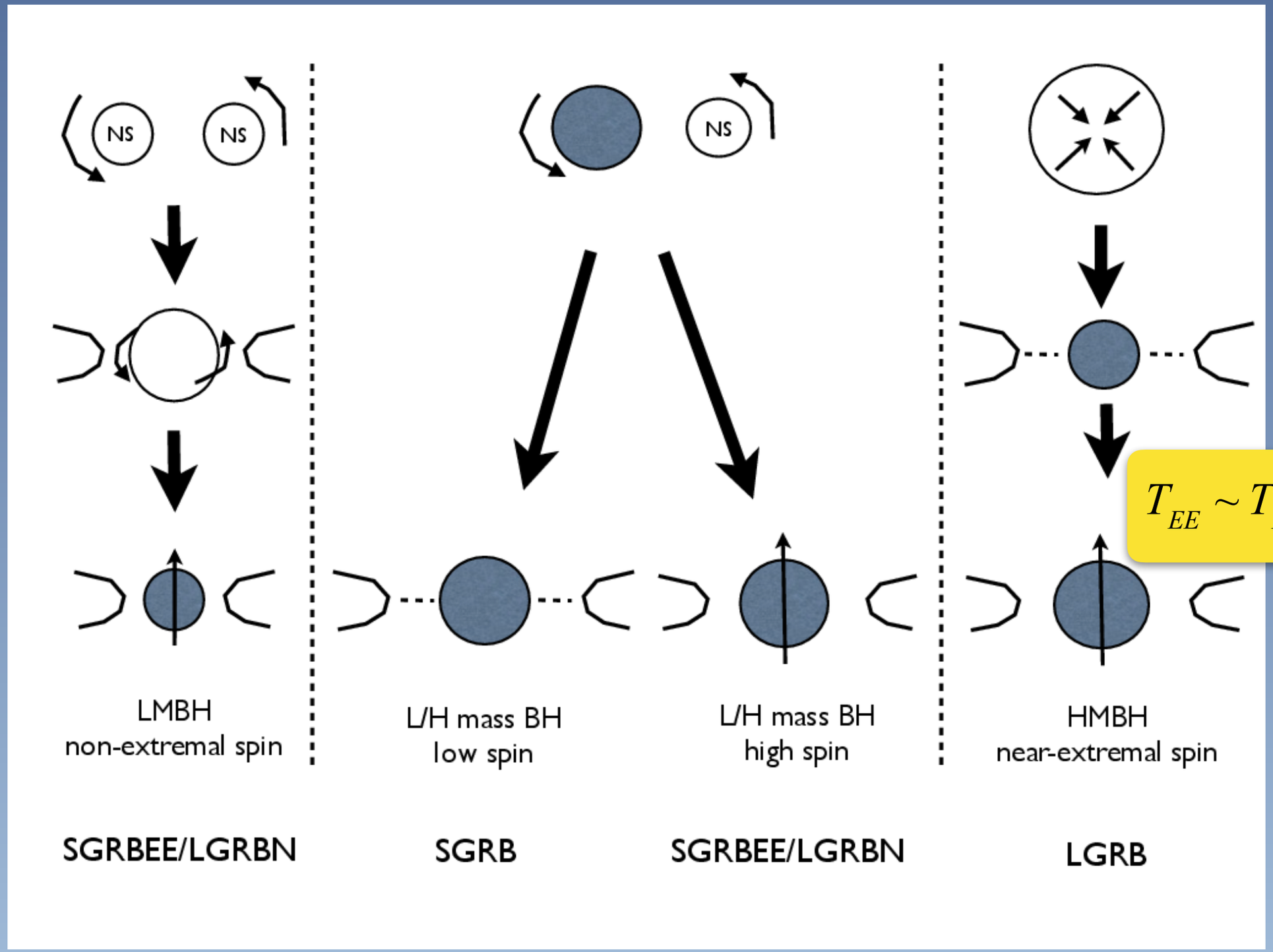
Common inner engine powering Extended Emission to short GRBs and LGRBs

Broadband Kolmogorov spectrum



Van Putten, Guidorzi & Frontera, 2014, ApJ, 786, 146; Amati, O'Brian, Goetz et al., 2017, arXiv:1710.04638

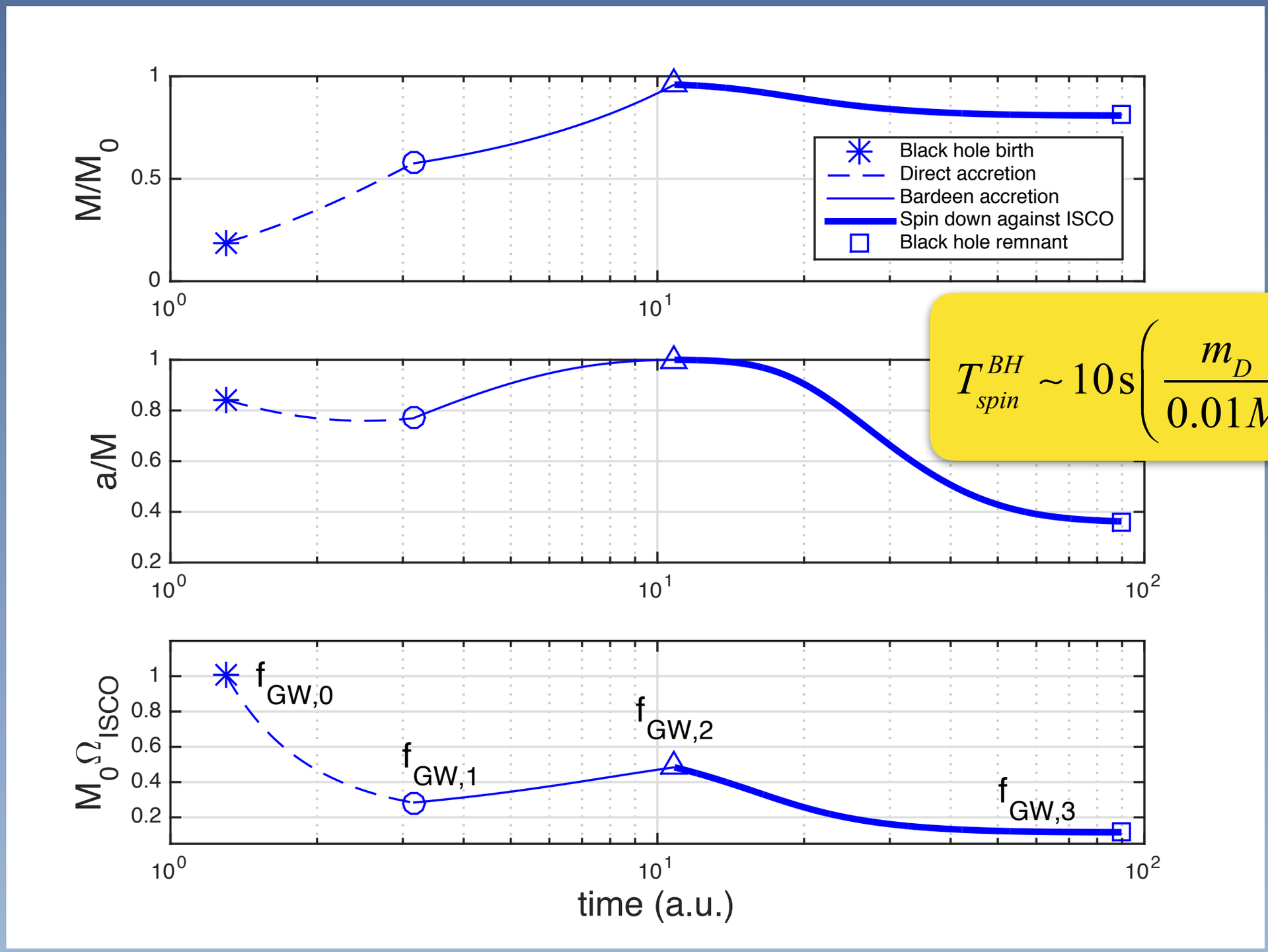
GRBs from rotating BHs



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

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

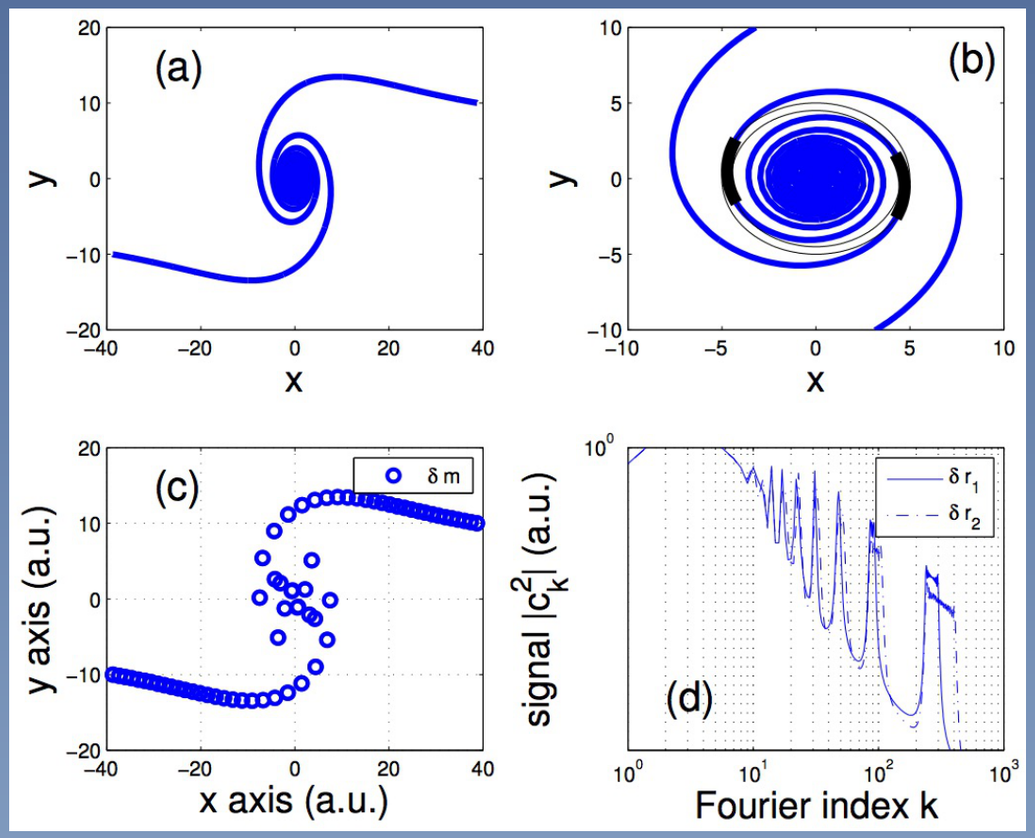
Black hole evolution



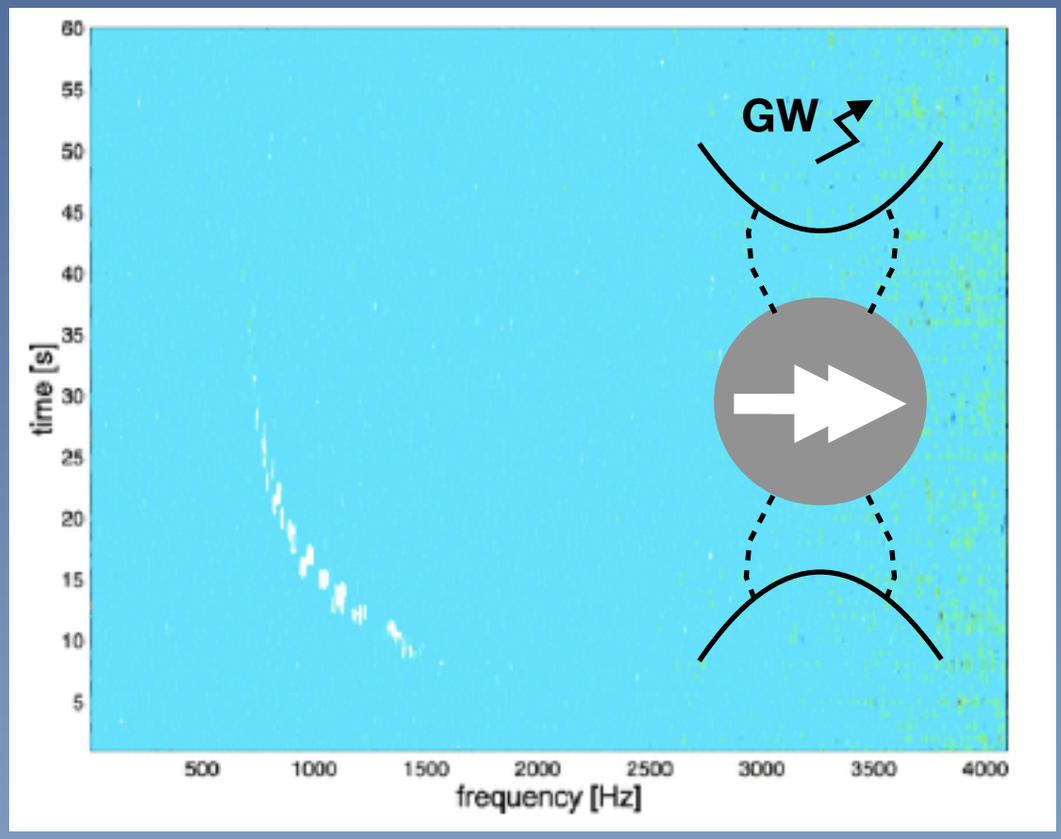
$$T_{spin}^{BH} \sim 10\,\mathrm{s}\left(\frac{m_D}{0.01M}\right)^{-1}$$

van Putten, Della Valle, 2017, MNRAS, 464, 3219

Chirps: long duration ascending and descending



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



Van Putten, 1999, Science, 284, 115
van Putten & Levinson, 2002, Science, 294, 1837
van Putten & Levinson 2003 ApJ 584 937
Van Putten, 2008, ApJ, 684, L91

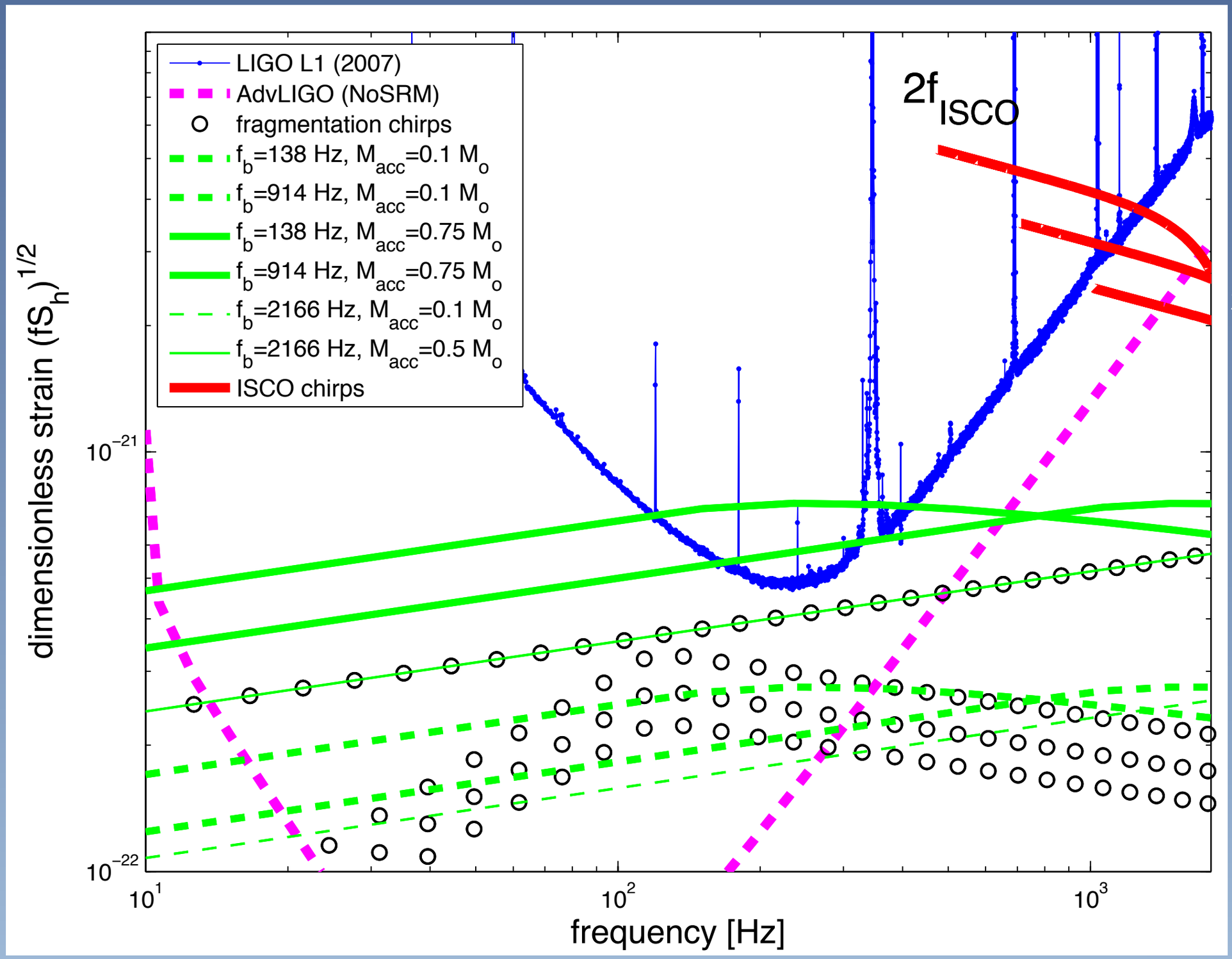
$$E \sim U_N \quad \text{(binding energy)}$$

$$f_{GW} \leq 600 - 700\left(\frac{10 M_\odot}{M}\right)$$

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

$$f_{GW} \geq 600 - 700\left(\frac{10 M_\odot}{M}\right)$$

Broadband extended emission from CC-SNe



van Putten, 2001, PRL, 87, 091101

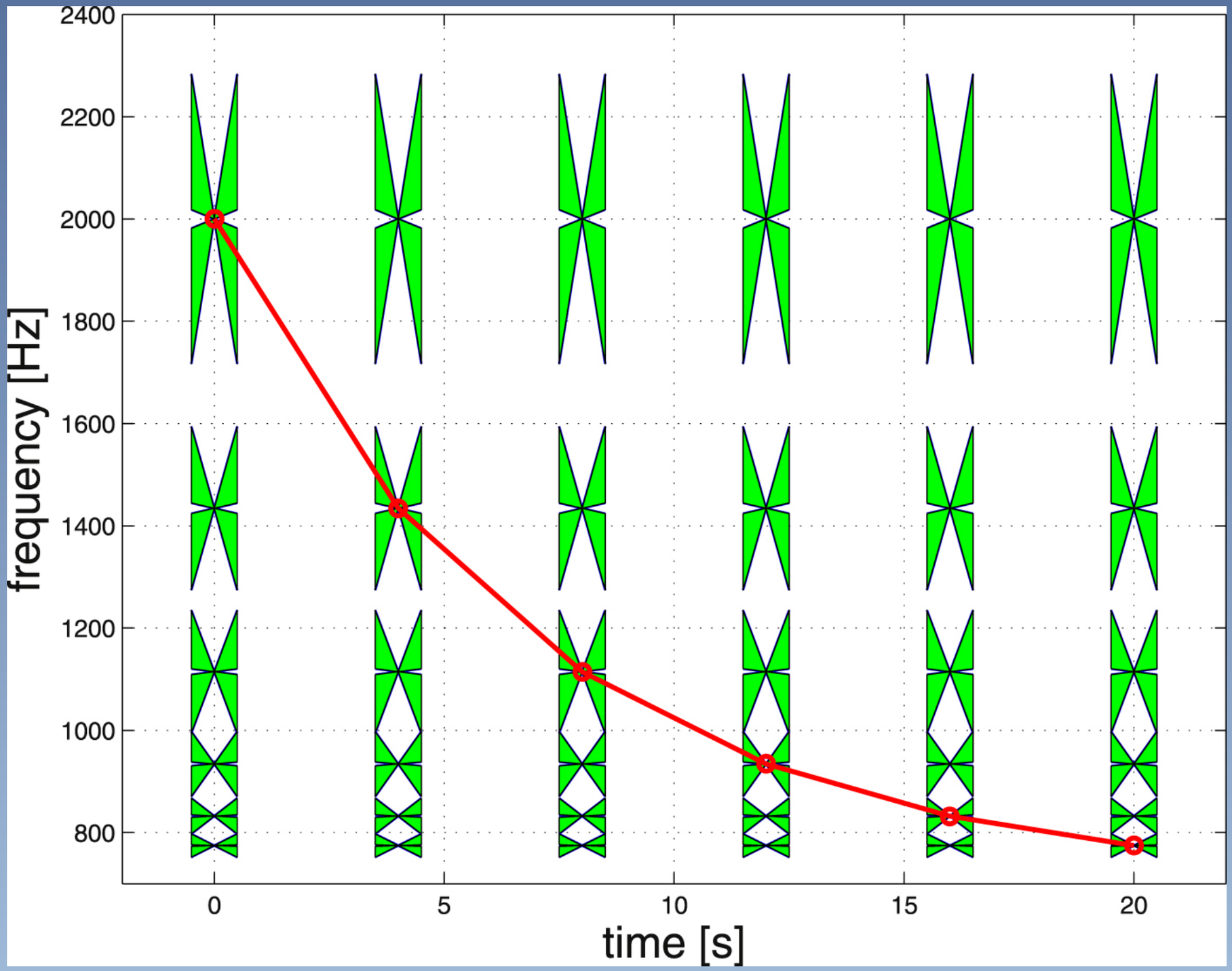
Levinson, van Putten & Pick, 2015, ApJ, 812, 124

Piro & Pfahl 2007, ApJ, 658, 1173

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

Butterfly filtering

$$\left| df(t)/dt \right| \geq \delta > 0$$



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

Typical MF output

For data-segment l and template m over samples t_k:

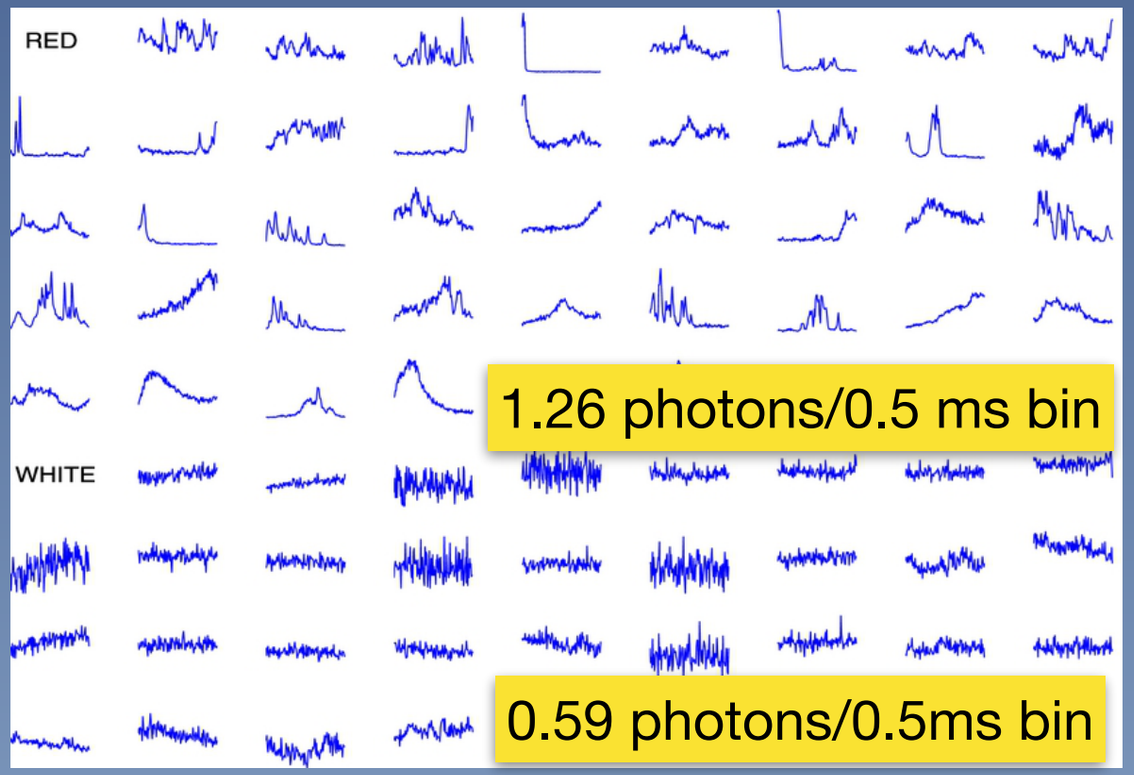
$$\varrho_{lm}(t_k)$$

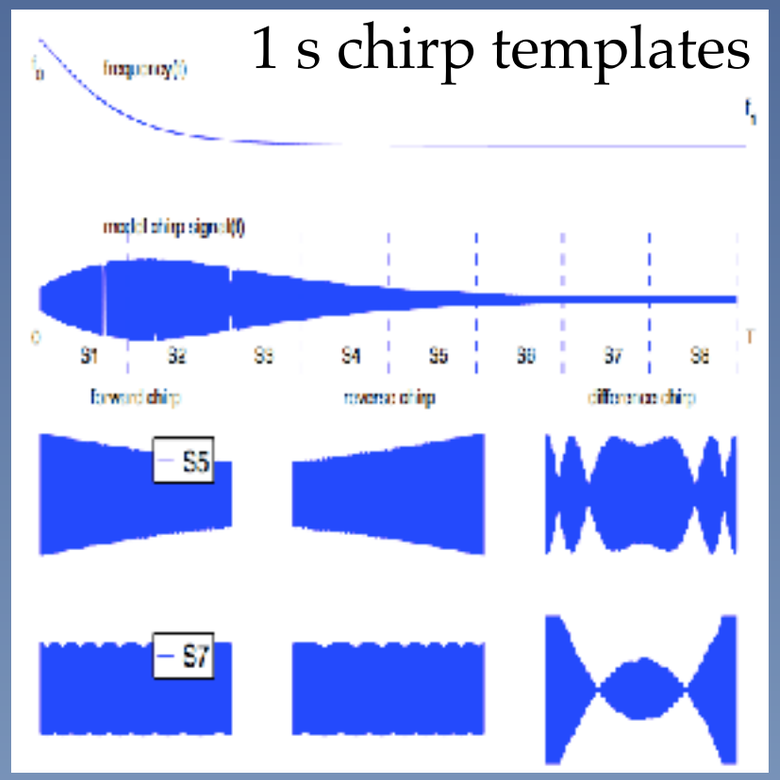
with

$$\sigma_{lm}$$

Tails (non-Gaussian)

Application to BeppoSAX

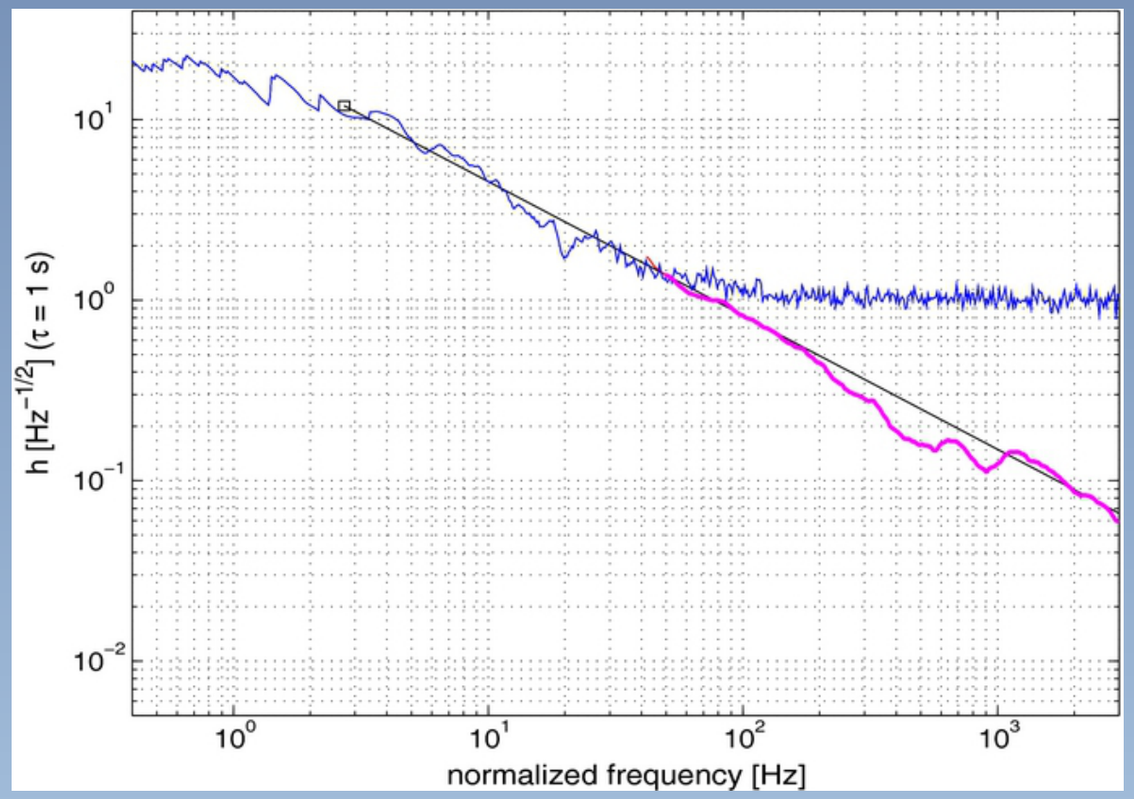




Average of 42 bright GRBs

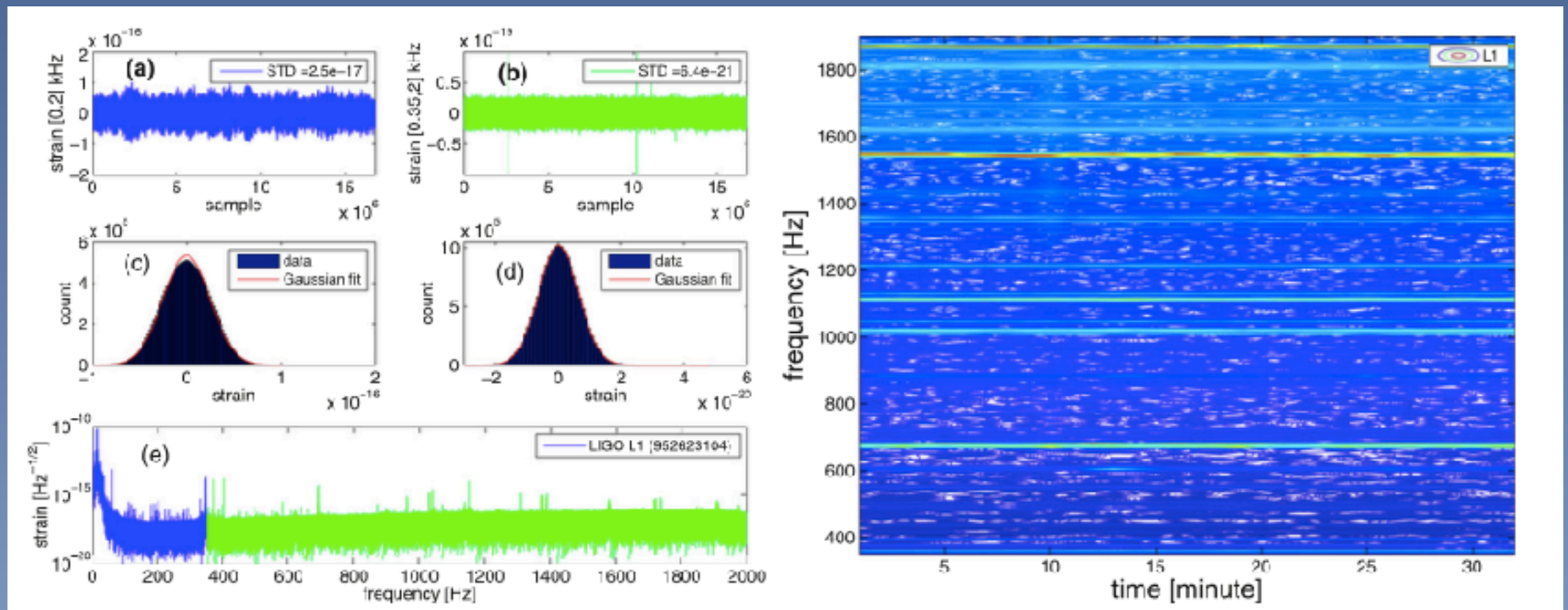
1.26 photons per 0.5 ms bin

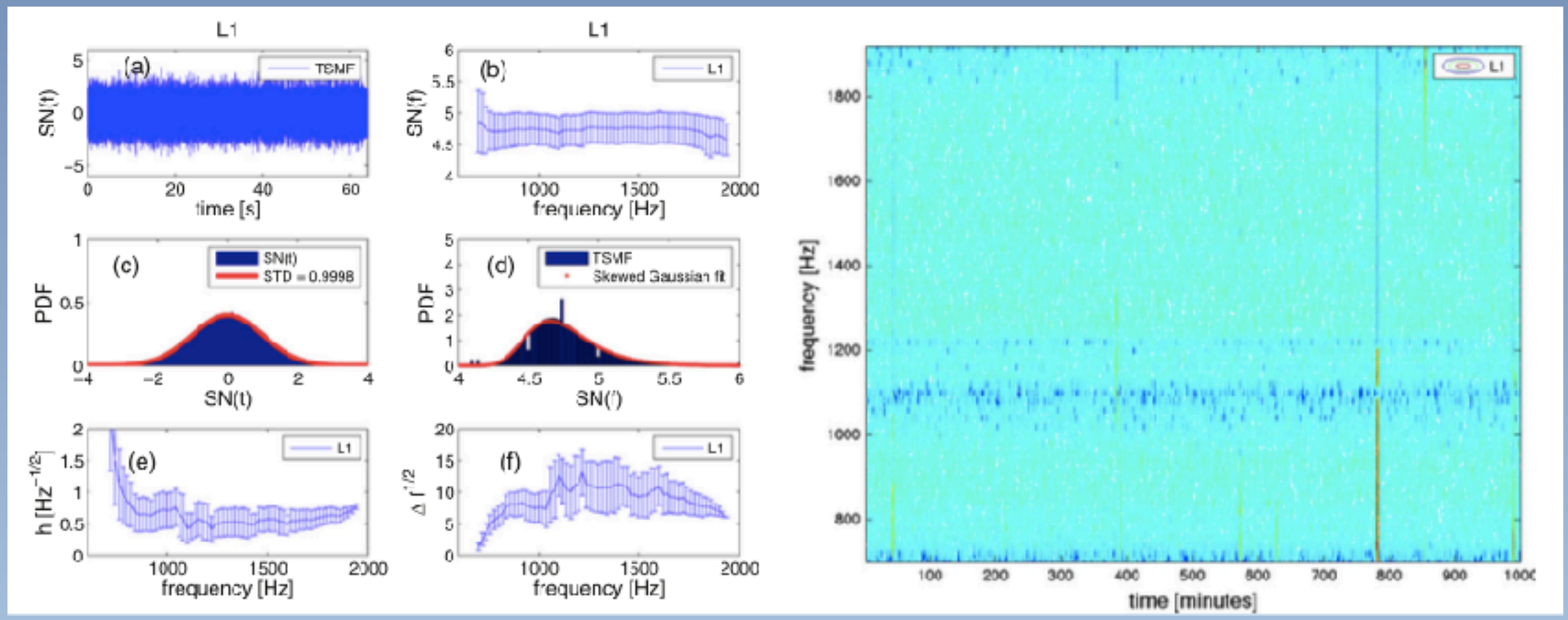
8.64 million chirp templates



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

Application to LIGO S6 (> 350 Hz)



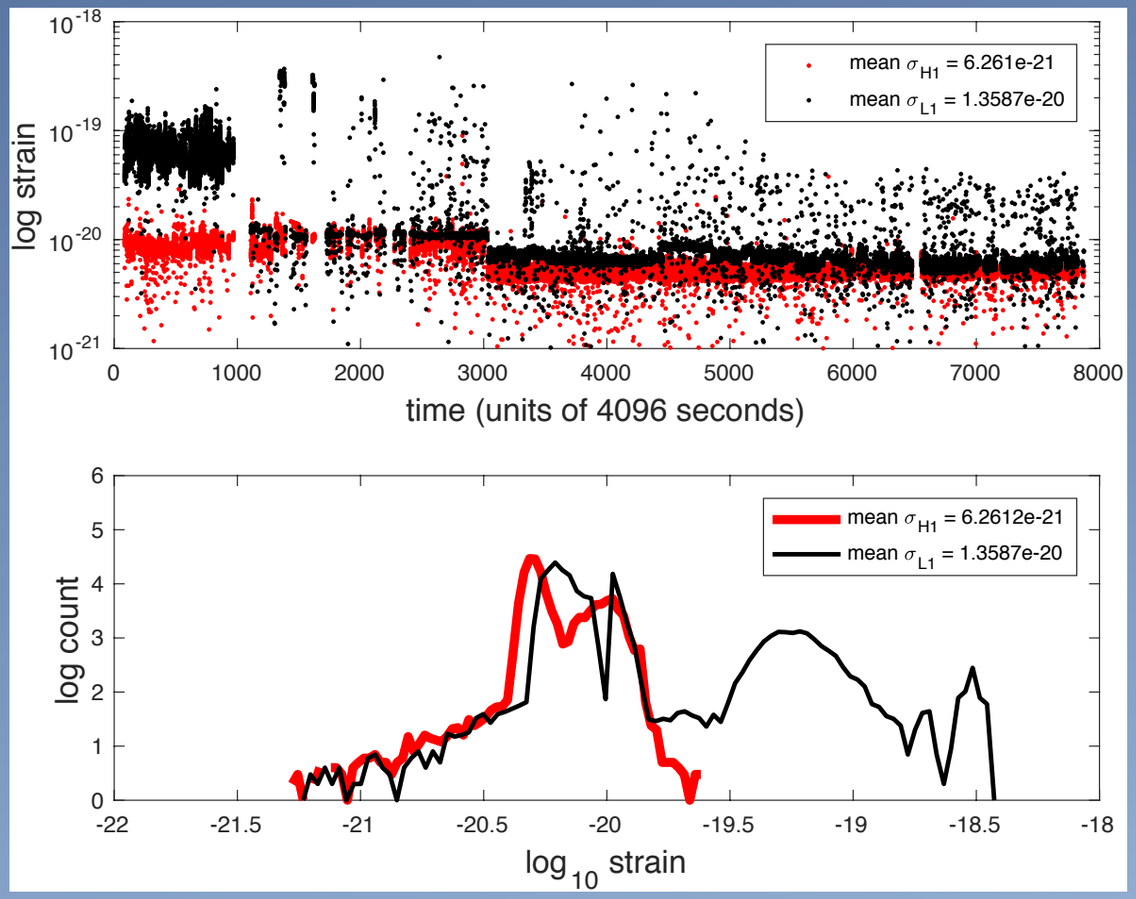


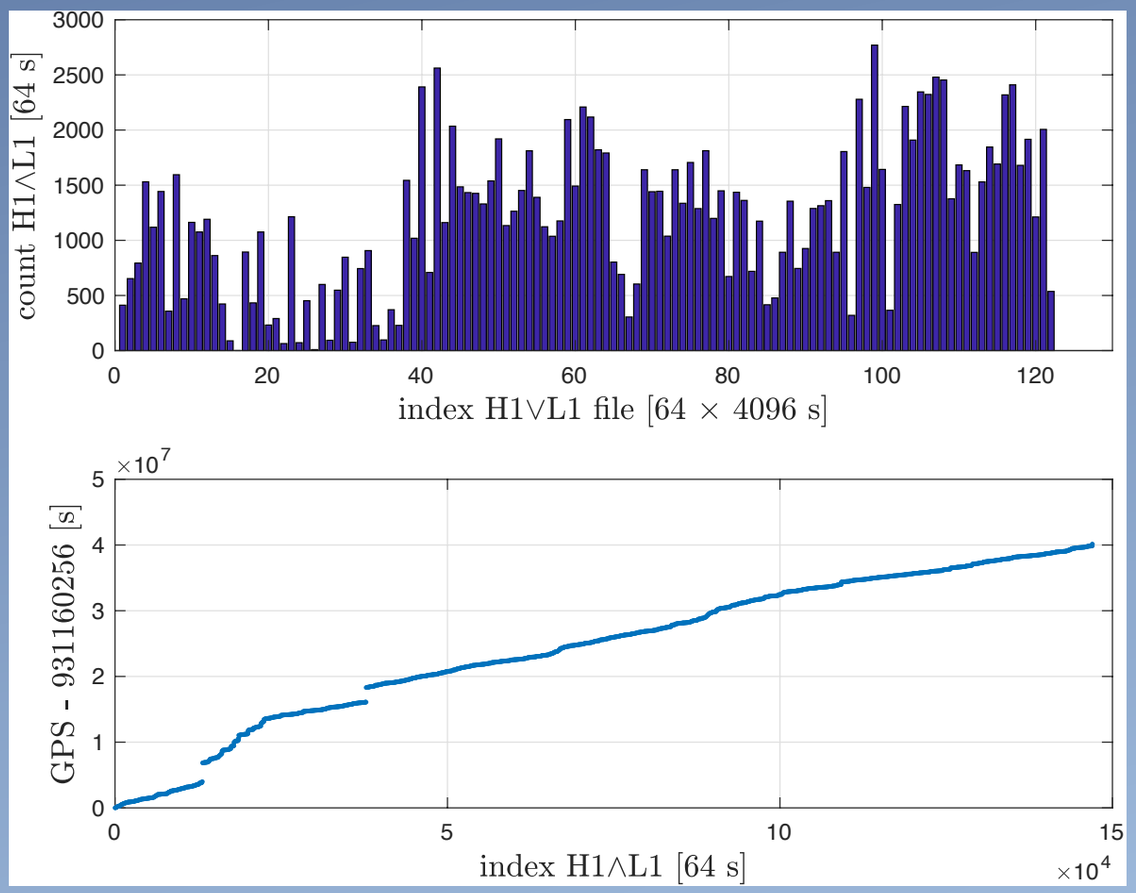
(van Putten, 2016, ApJ, 819, 169

Deep searches: the need for speed

LIGO S6

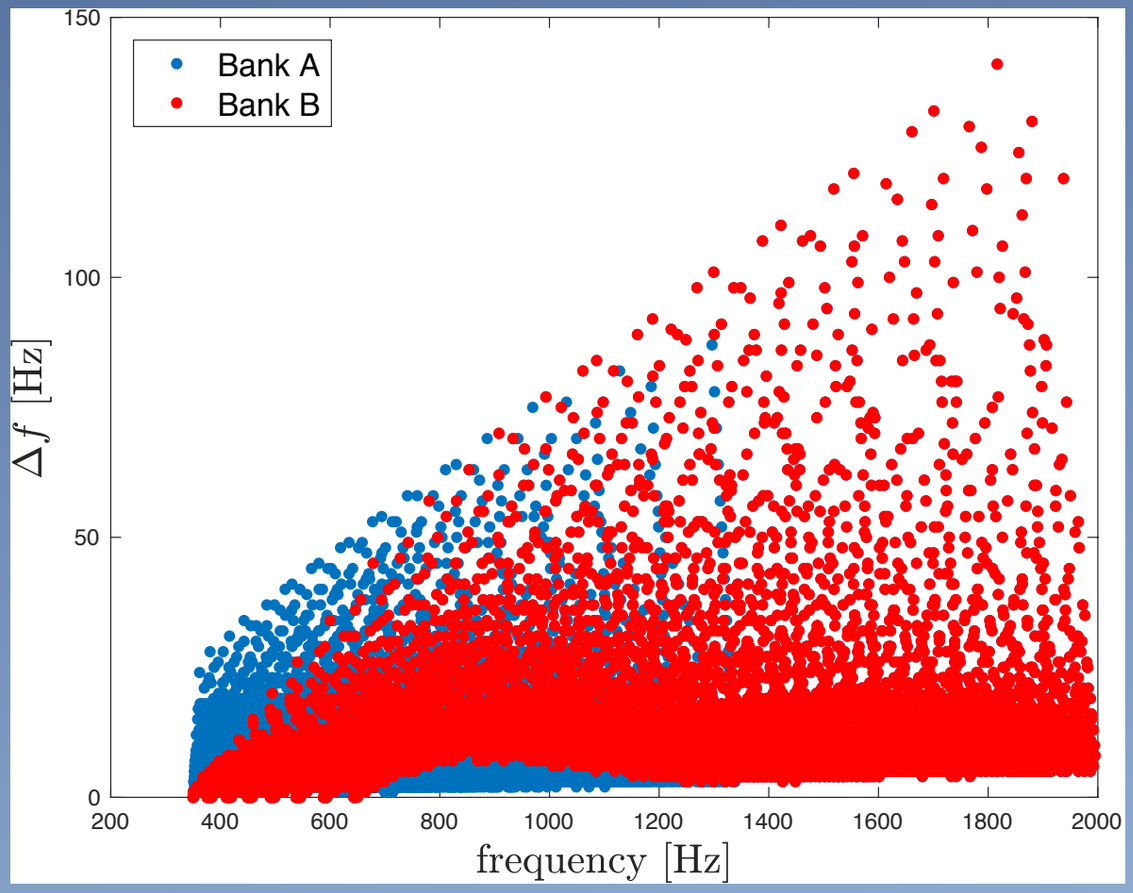
147,000 64 s segments H1 & L1 (29.4%)

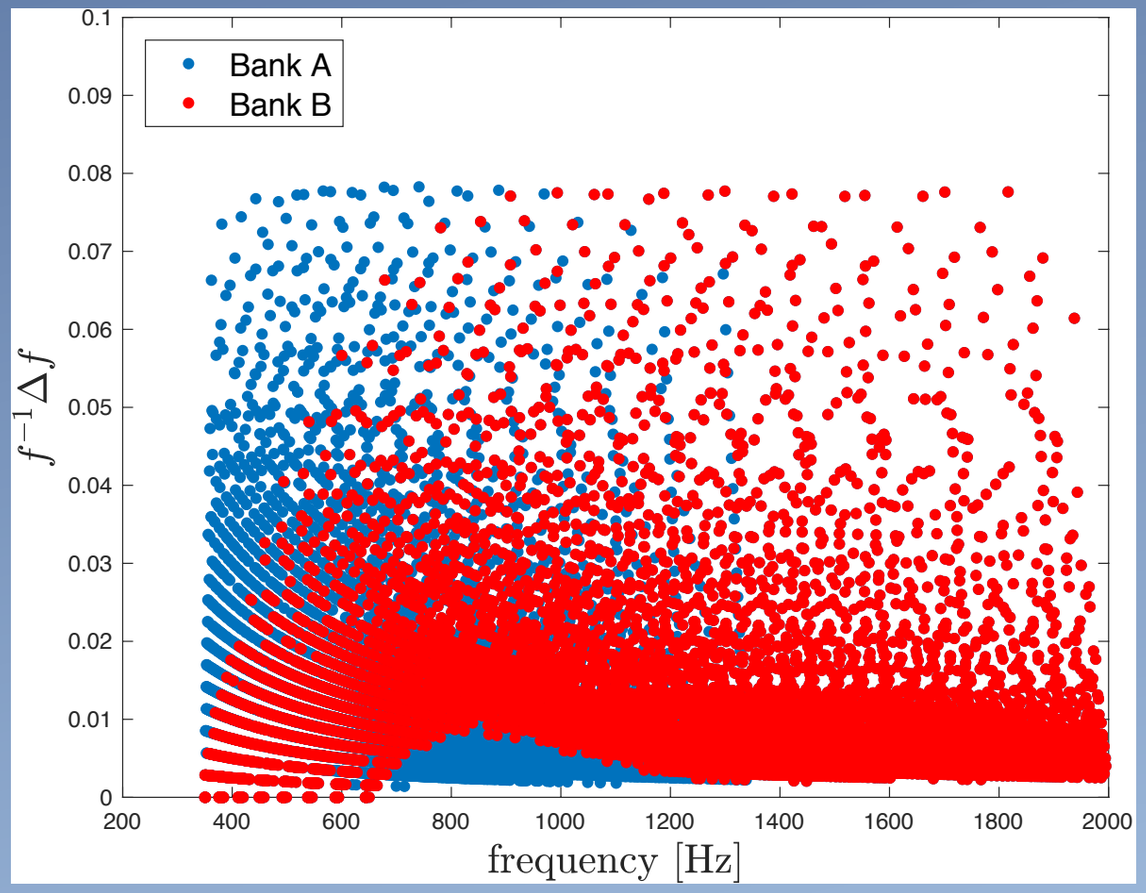




Template banks

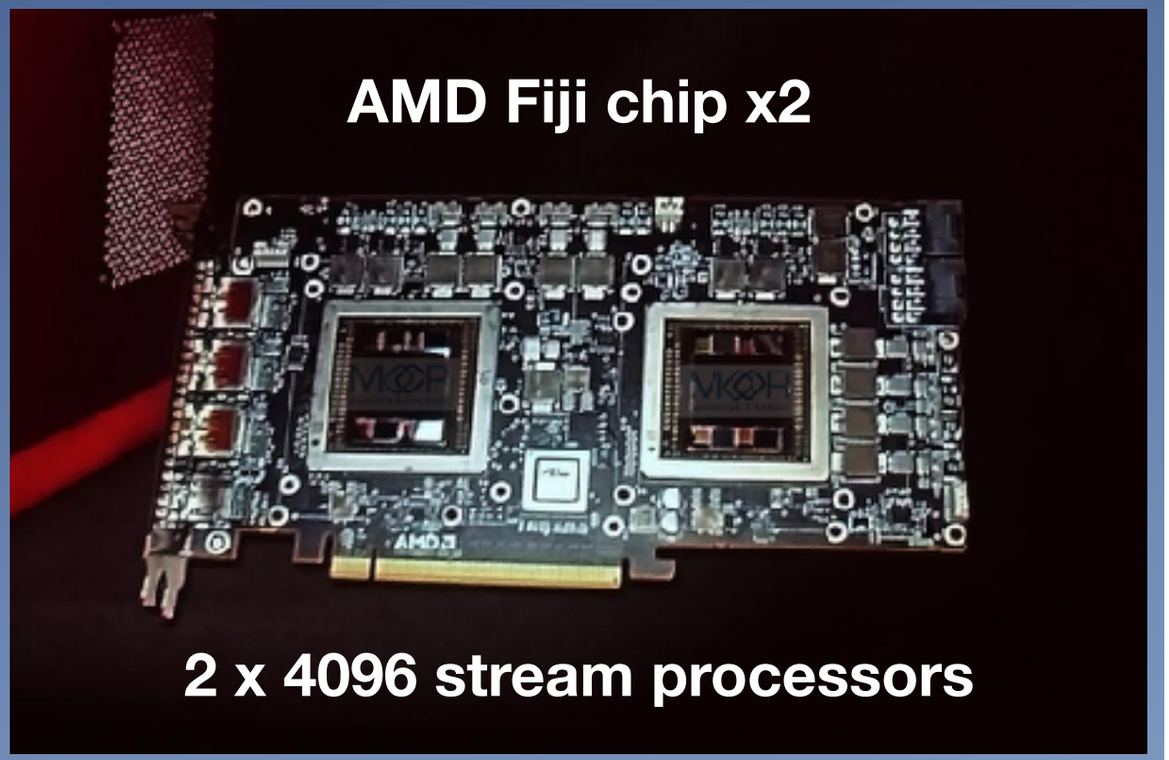
Chirp templates

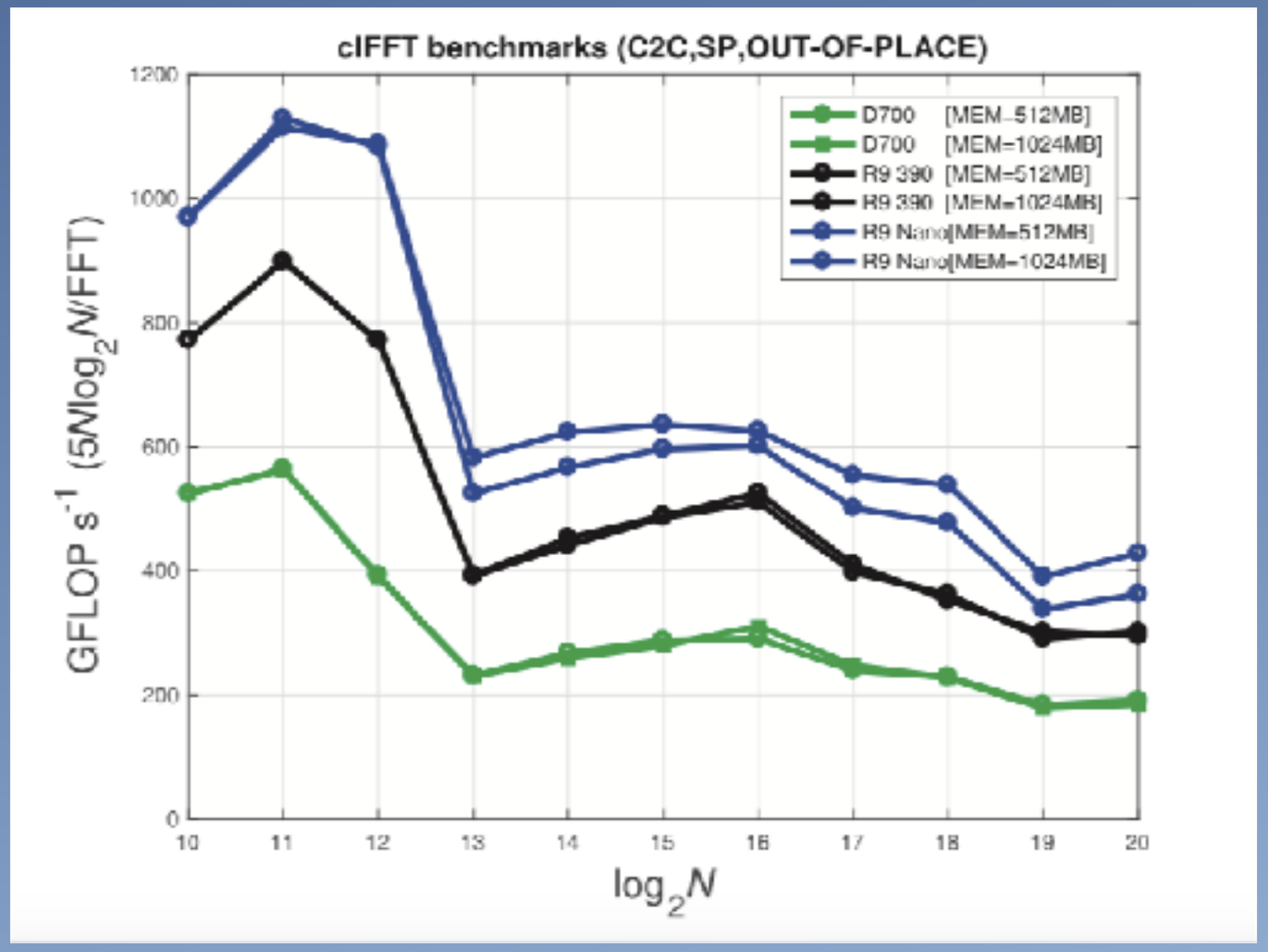




(van Putten, 2017, PTEP, 093F01)

GPUs with HBM2





FFT(N=2^{16}) C2C SP

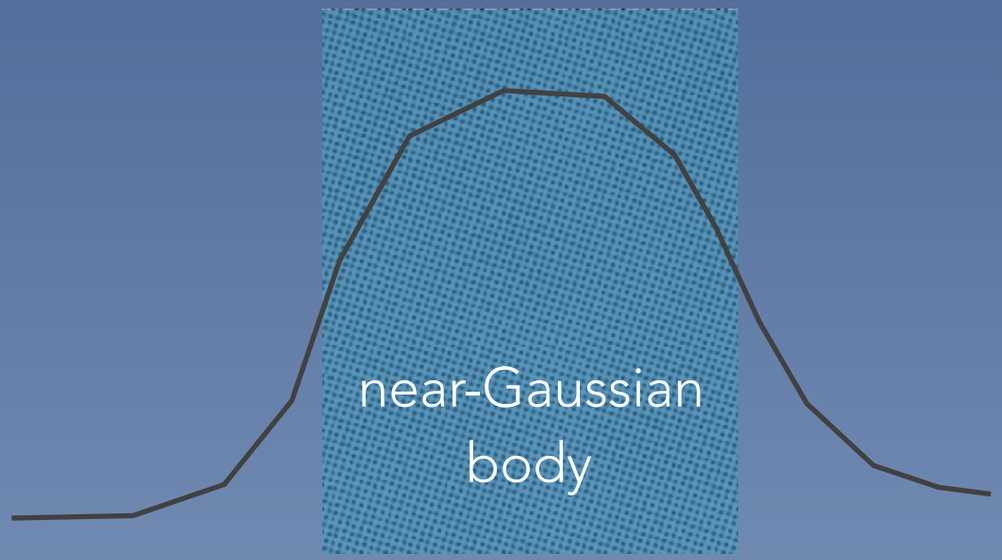
Performance: ~ 100,000 s^{-1} per Fiji chip

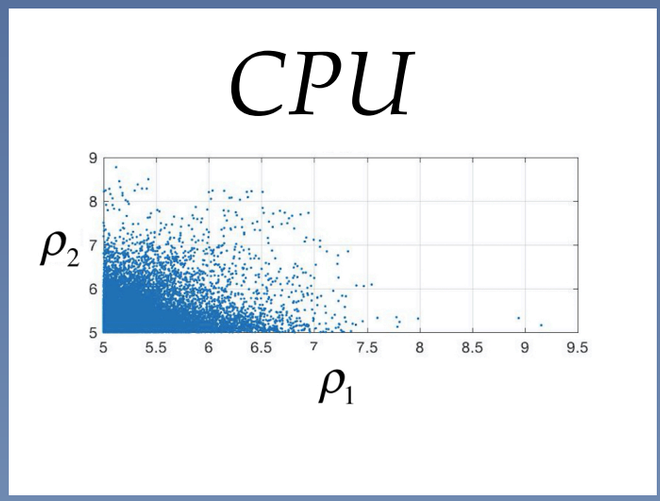
Output: ~ 50 GB s^{-1} per Fiji chip

PCI: < 10 GB s^{-1} $\Rightarrow\Leftarrow$

(van Putten, 2017, PTEP, 093F01)

Circumvent PCI bandwidth limitation





Pass back tails CPU

$$\varrho_{lm} > \kappa\sigma_{lm}$$

Reduction by

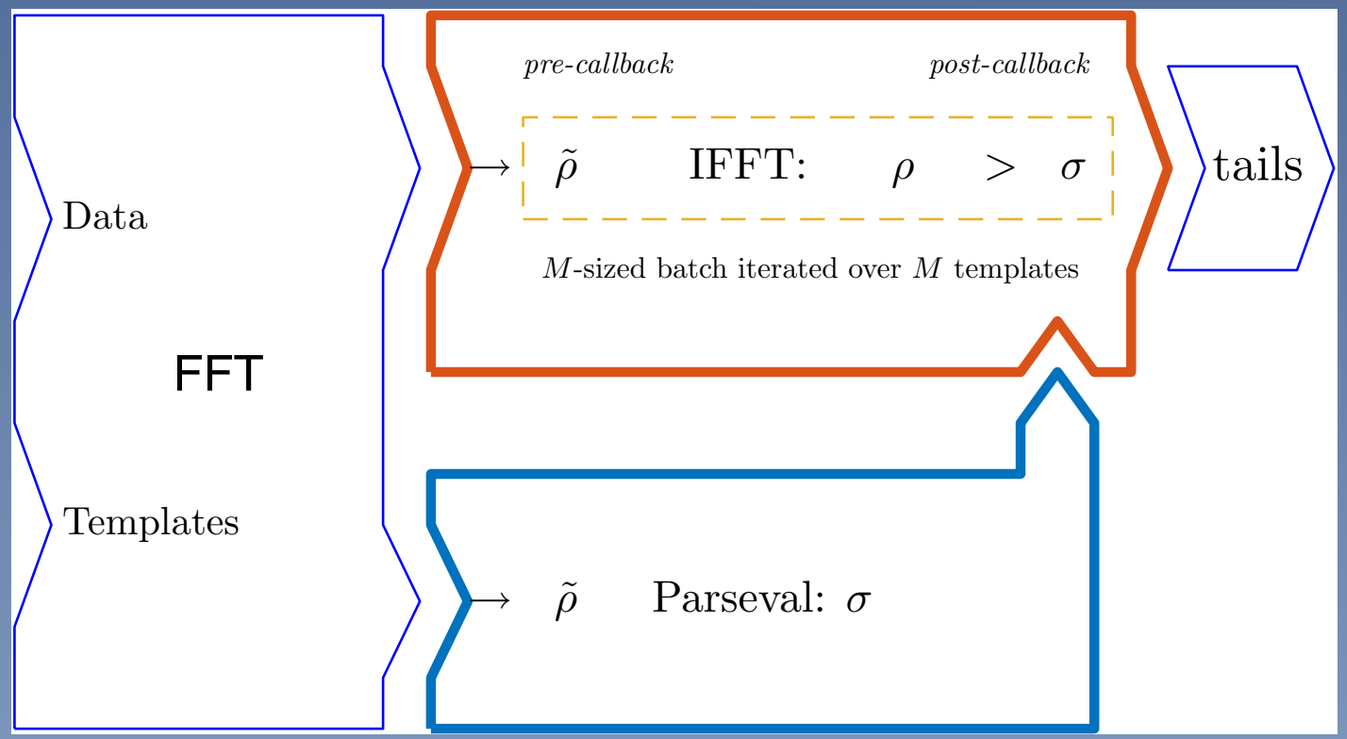
$$\mathrm{erfc}\left(\frac{\kappa}{\sqrt{2}}\right)$$

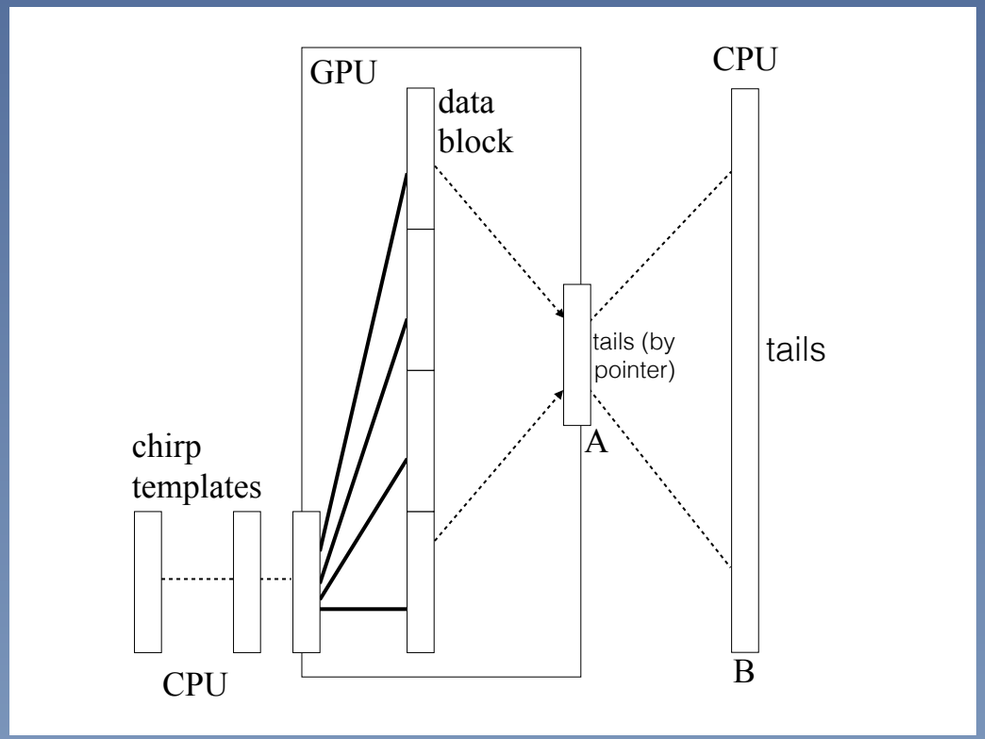
Maxima of n samples from a Gaussian distribution is a skewed Gaussian with PDF

$$p(x) = \frac{n}{\sigma}\sqrt{\frac{2}{\pi}}\,\mathrm{erf}\left(\frac{x}{\sqrt{2}\sigma}\right)e^{-y^2}$$

van Putten, 2016, ApJ, 819, 169

Post-callback functions





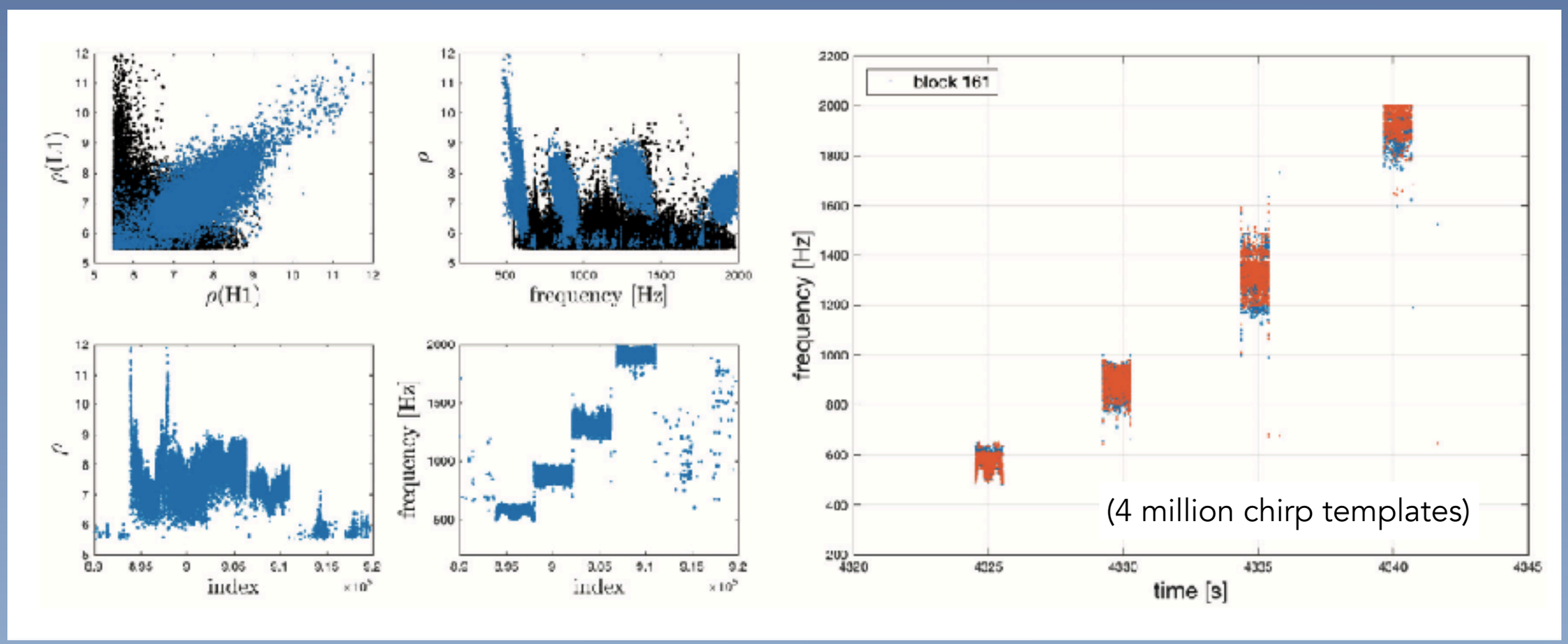
σ_{lm} *by Parseval's Theorem in predictor step - also on GPU*

Passing tails to CPU << PCI bandwidth

~ 1 million s^{-1} (16 s data-segments) on 12 Fiji chips

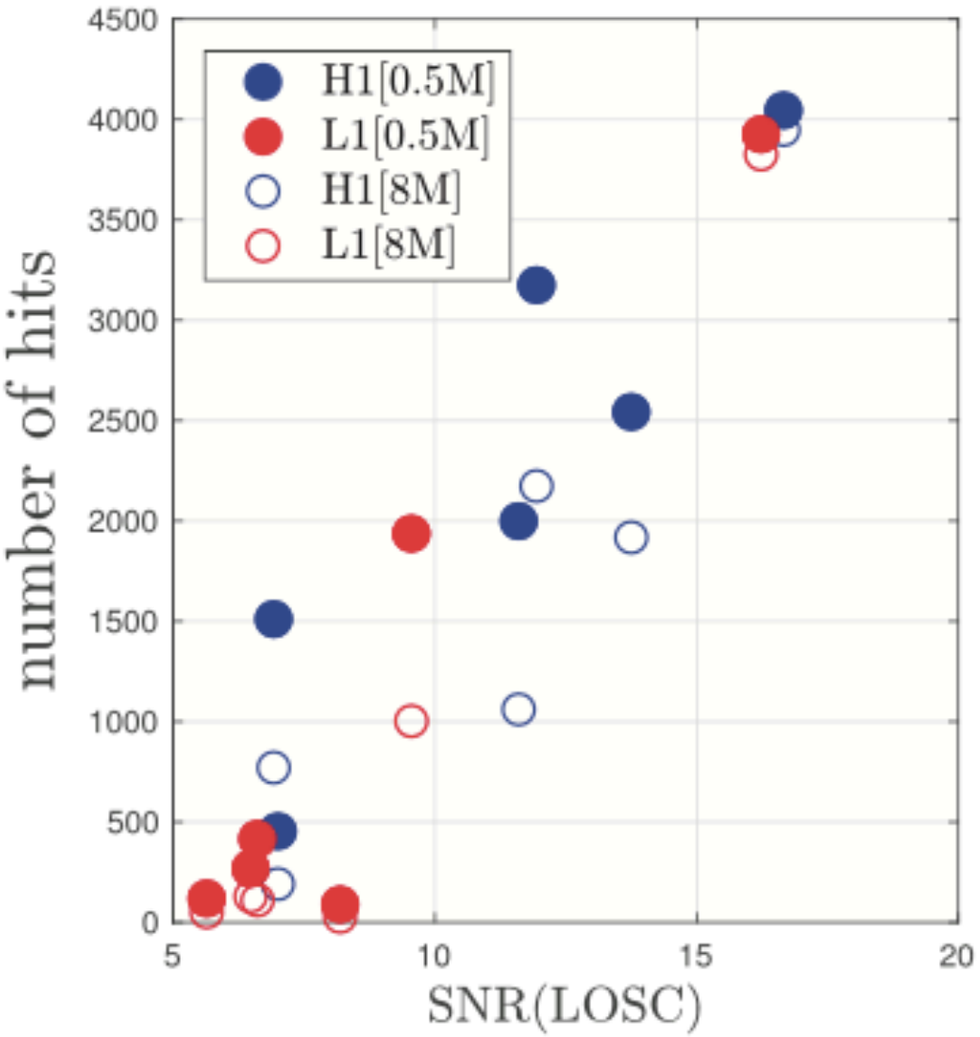
(van Putten, 2017, PTEP, 093F01)

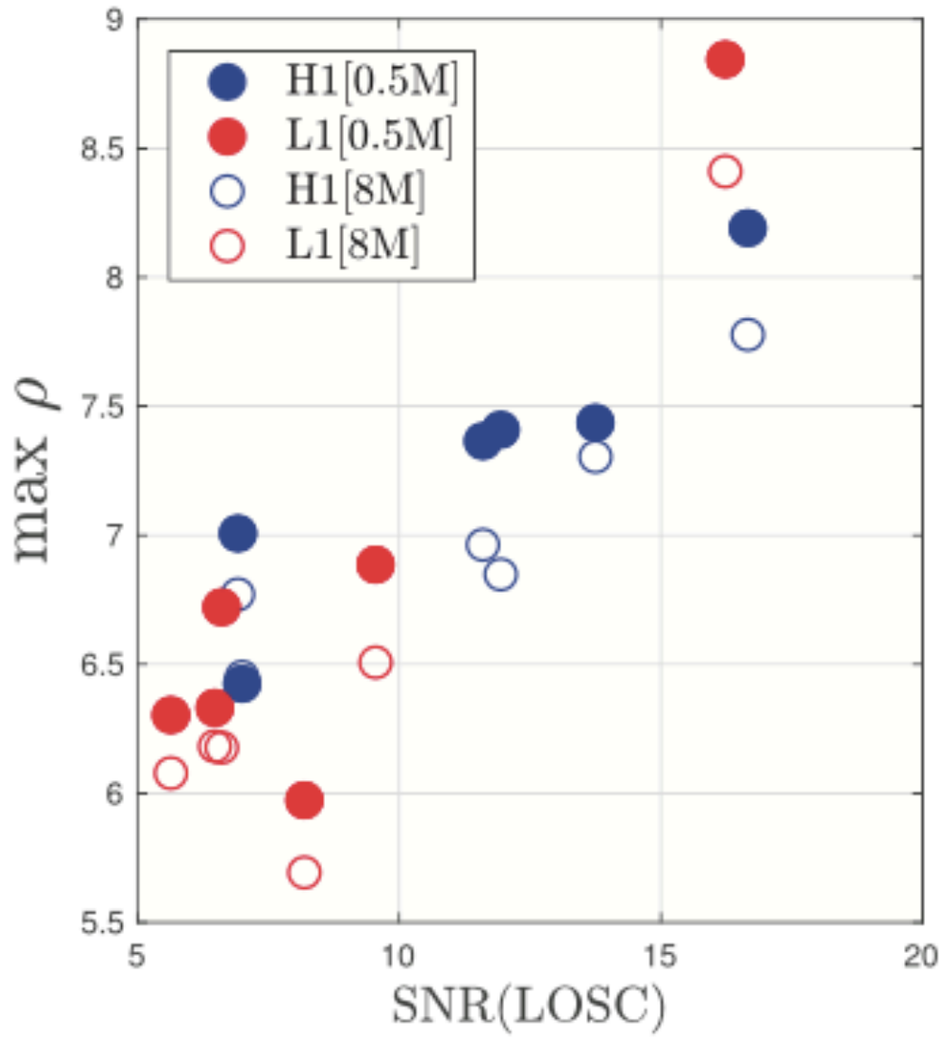
Validation on LIGO Injections



(van Putten, 2017, PTEP, 093F01)

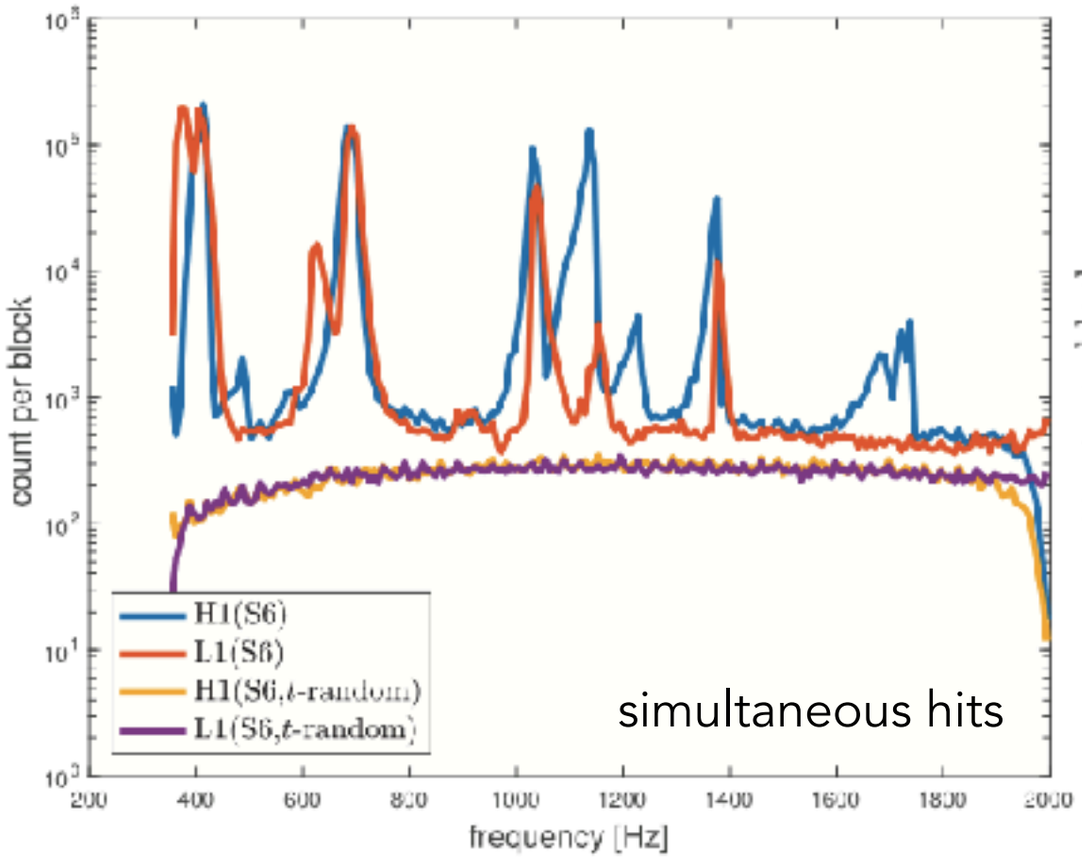
Sensitivity on LIGO Injections

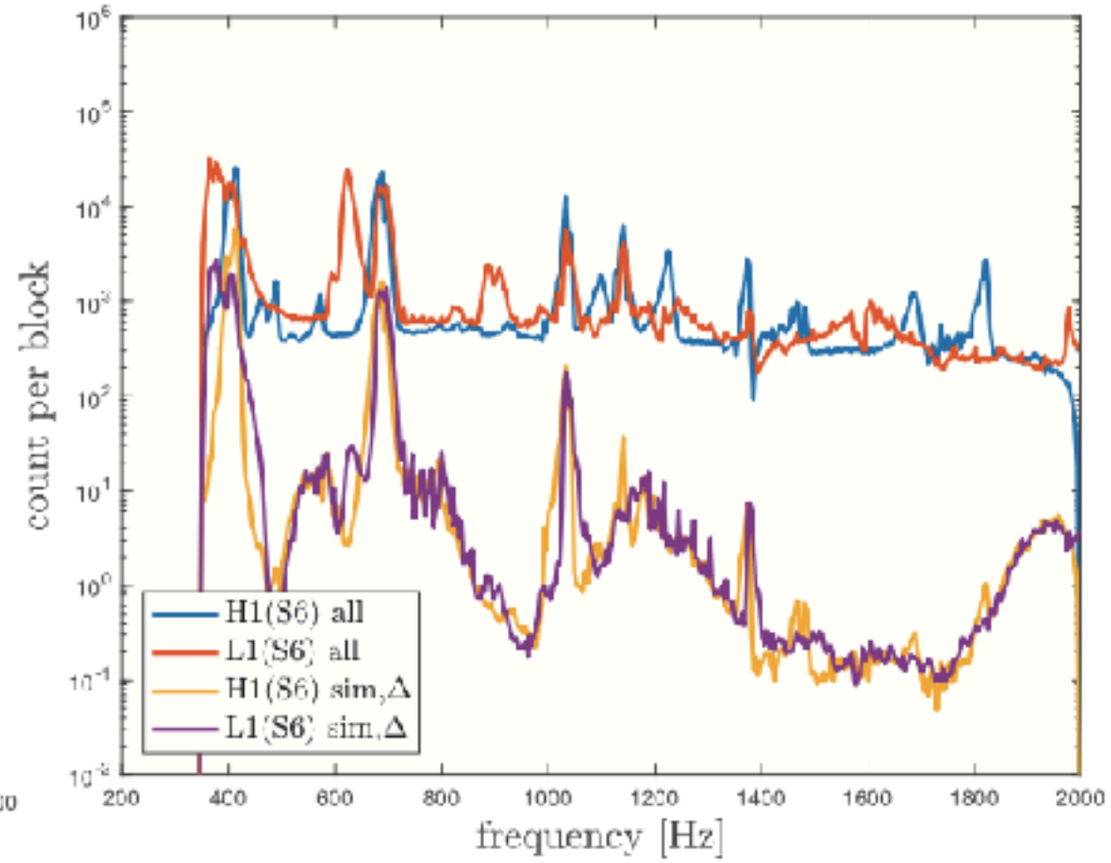




(van Putten, 2017, PTEP, 093F01)

Pseudo-spectra H1 & L1 tails





$$\mathrm{EPR} \equiv \frac{p_{12}}{p_1 p_2} = 5.11 \pm 0.0268$$ "excess probability ratio"

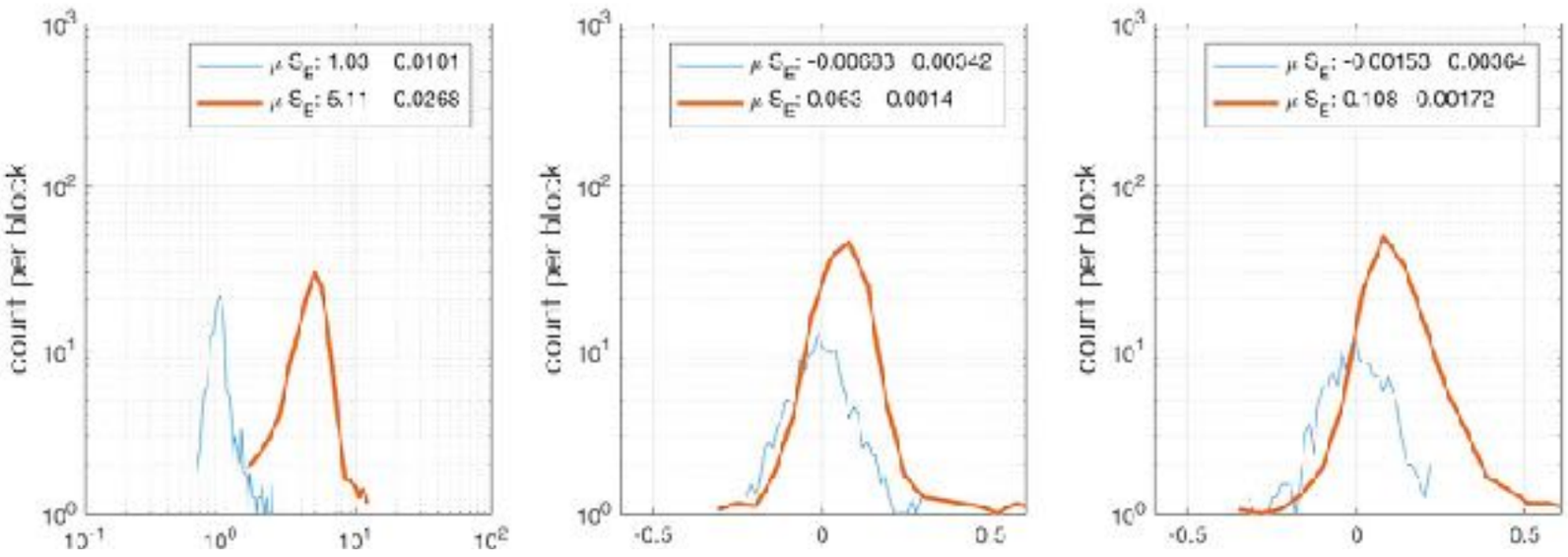
Strongly non-uniform, associated with violin modes etc.: *far from maximal entropy*

(van Putten, 2017, PTEP, 093F01)

Loudness and pitch

$$C_l = 0.0630 \pm 00014 \qquad \text{“loudness"}$$

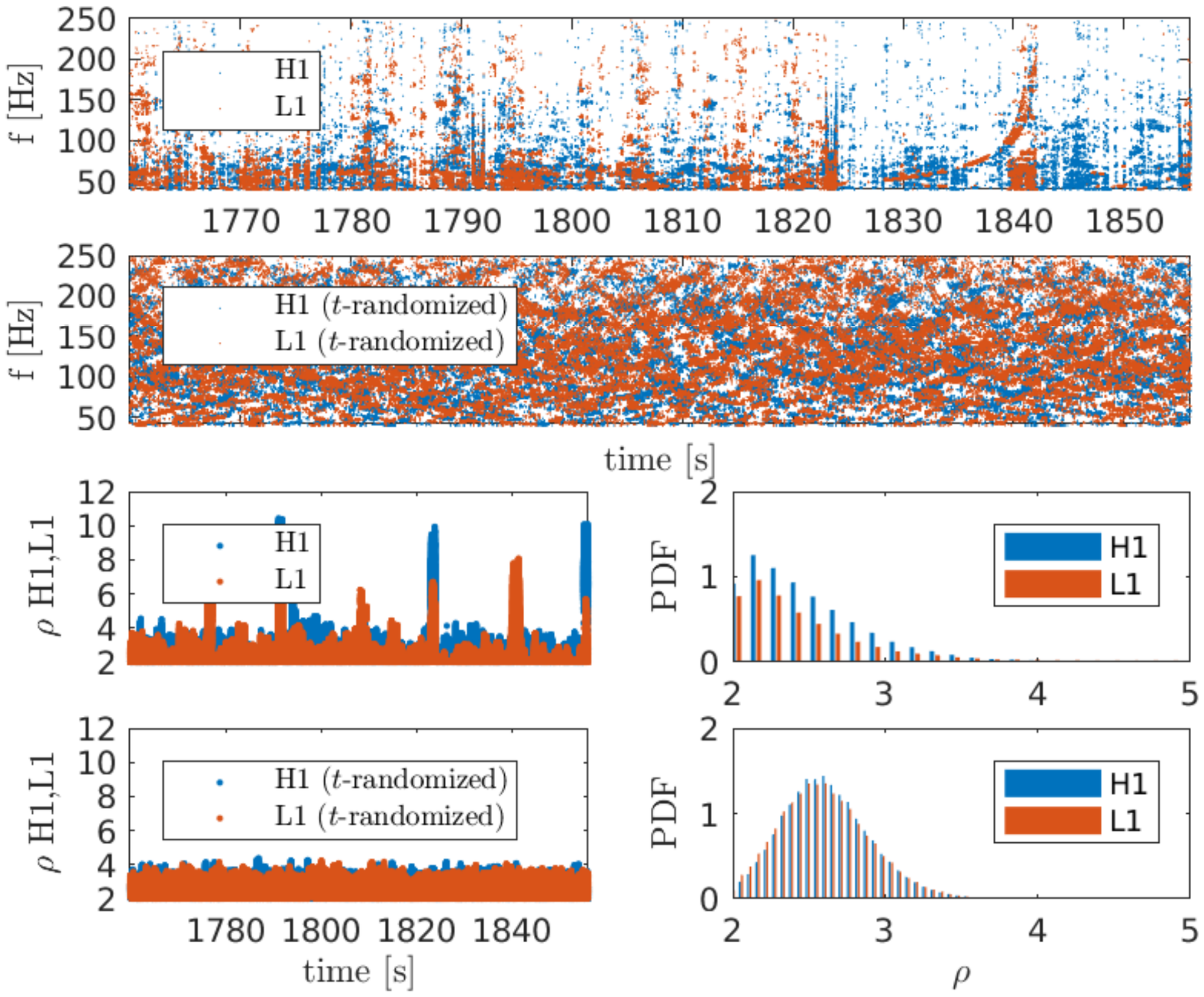
$$C_f = 0.1008 \pm 0.0017 \qquad \text{“pitch”}$$



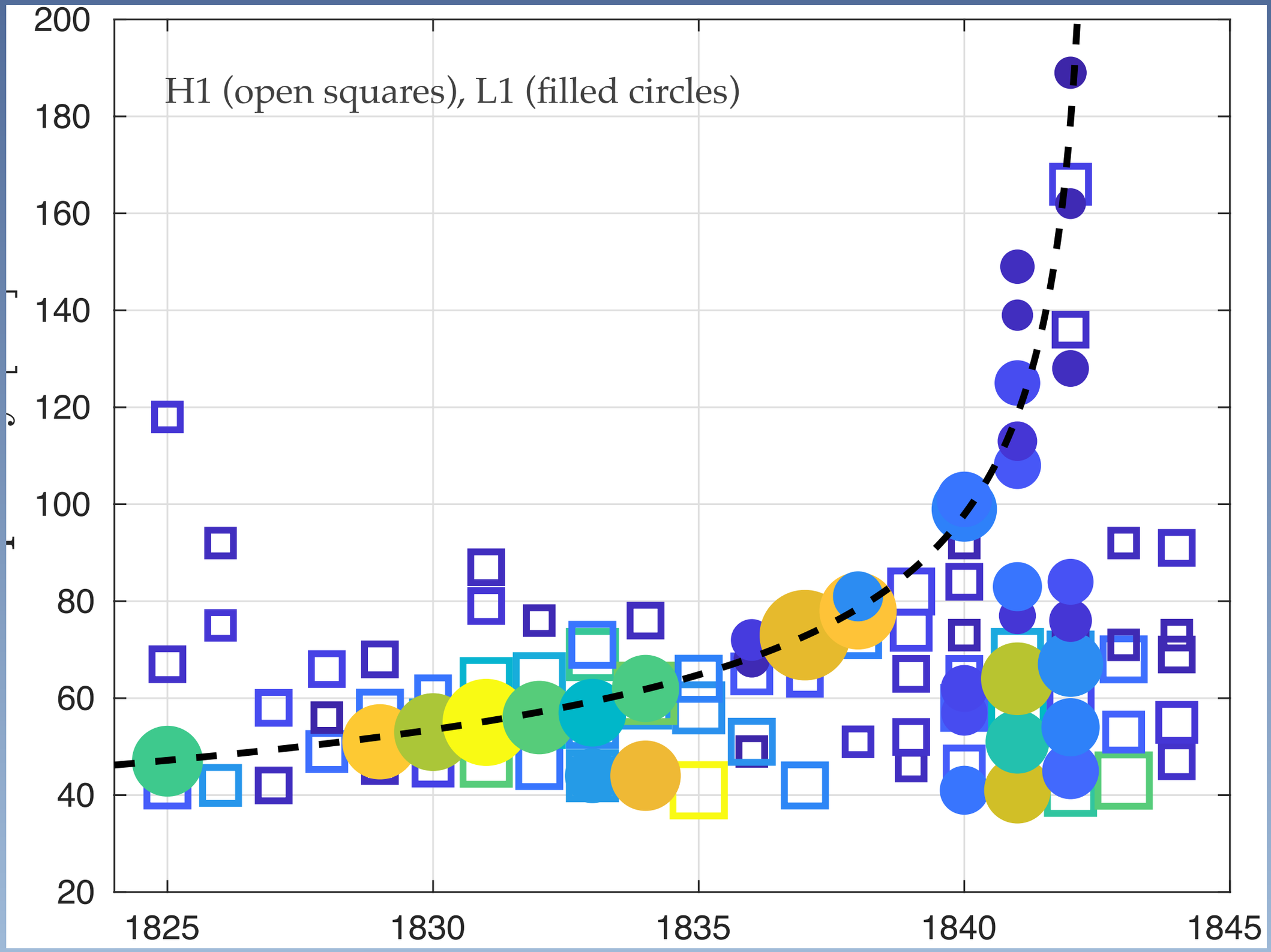
EPR C_l C_f

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

Application to GW170817



Application to GW170817



Conclusions and Outlook

- *GW170817:* tantalizingly close to central engines of GRBs: magnetars or BH - *can be identified in post-merger long duration chirps.*

- *HD accretion flows down to the ISCO of rotating black holes* may feature ascending and descending chirps - post-merger or in CC-SNe.

- *GPU-accelerated butterfly filtering* enables deep searches for broadband extended gravitational-wave emission at over 10^6 correlations per second.

- *Discovery power* demonstrated in applications to BeppoSAX (broadband Kolmogorov spectrum), LIGO S6 H1L1 (loudness and pitch correlations) and LIGO O2 (recovery GW170817).