Using Leaked Power to Measure Intrinsic AGN Power Spectra of Red-Noise Time Series

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East-Asia AGN Workshop, SNU, Seoul, 2016/09/23

THE 2 MS CDF-N SURVEY AND THE 250 KS E-CDF-S SURVEY: IMPROVED POINT-SOURCE CATALOGS

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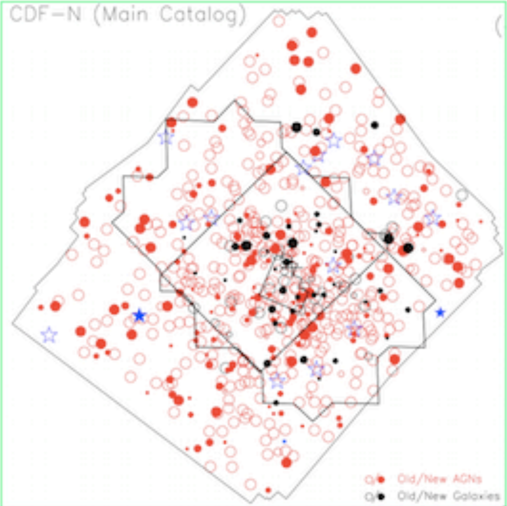
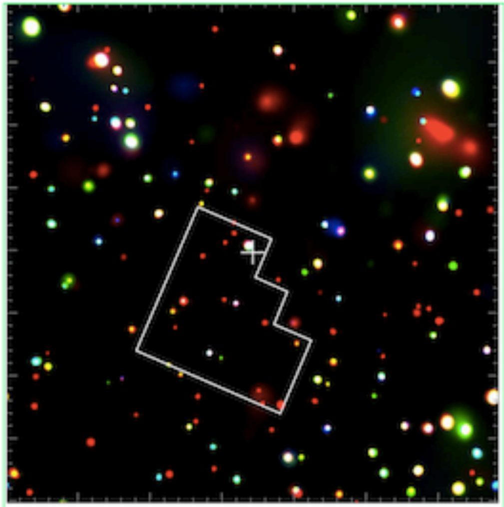
(1. USTC; 2. PSU; 3. Durham; 4. PUC; 5. JHU)   (* Send catalog requests to xuey@ustc.edu.cn http://staff.ustc.edu.cn/~xuey)
(2016, ApJS, in press; arXiv: 1602.06299)

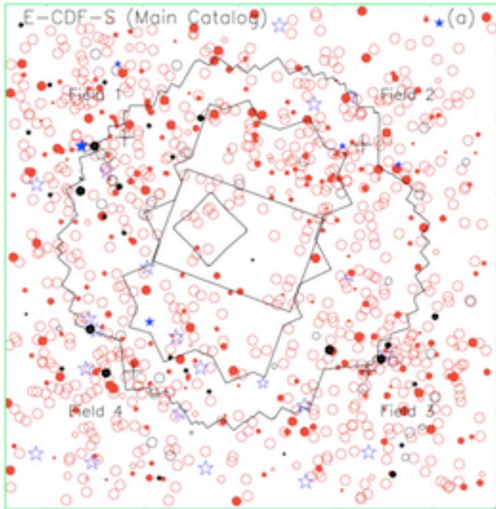
CDF-N



CDF-N (central part)



E-CDF-S



- **Two-stage** source-detection approach:
  - -- 1. wavdetect run at 1E-5 ➔ liberal candidate sources
  - -- 2. no-source probability cut ➔ reliable final sources
- **Sophisticated and reliable** X-ray photometry extraction
- **~1800 (~500 new)** sources detected in the two fields with lots of info:
  - -- X-ray positions, counts, fluxes, luminosity
  - -- multiwavelength identifications, redshifts
  - -- source classifications, observed AGN and galaxy source densities
- A **factor of ~1.5-2 improvement** in on-axis flux limits than before
- Catalogs, images, and data products **publicly available at**
  - -- http://www2.astro.psu.edu/users/niel/hdf/hdf-chandra.html

USTC

PSU

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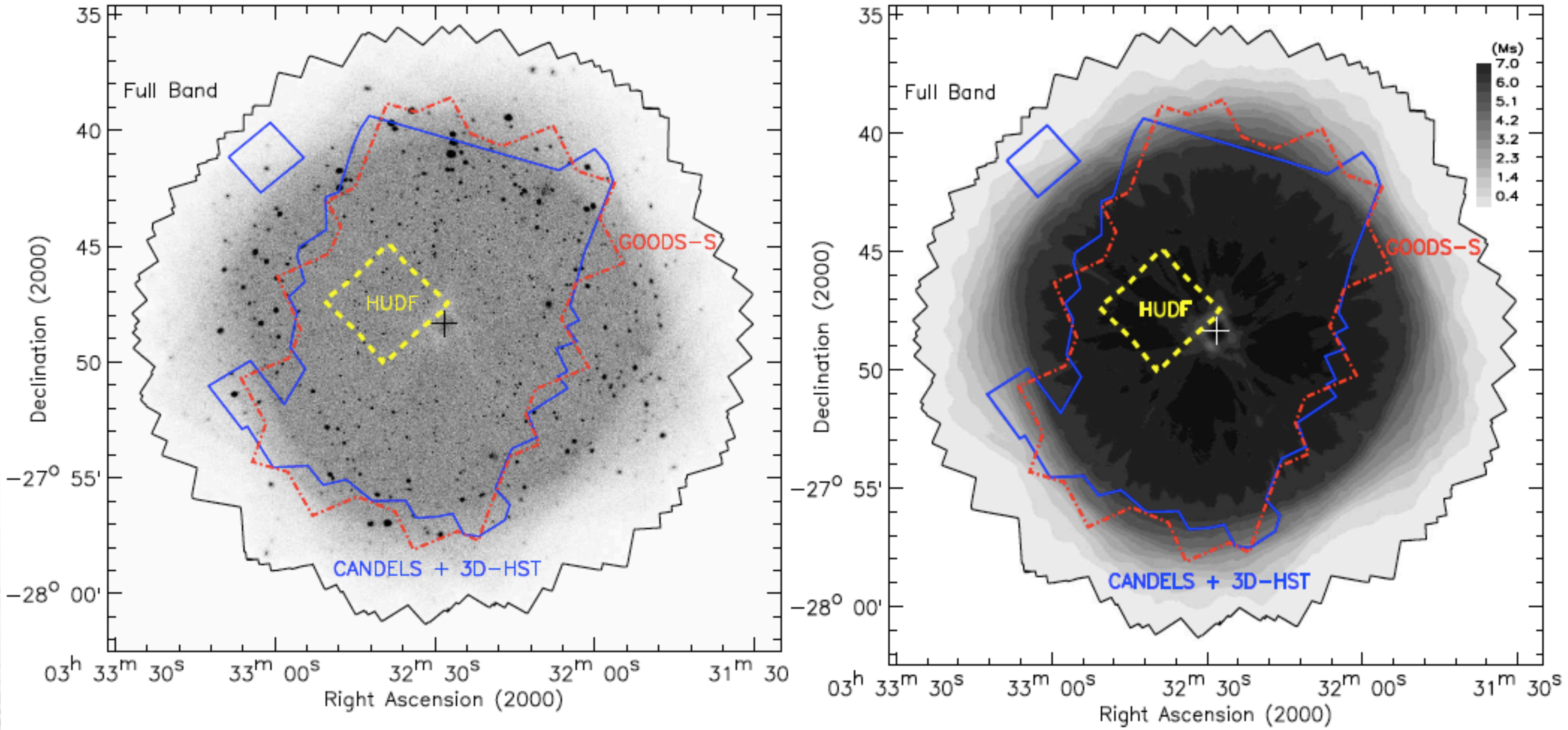
The 7 Ms CDF-S



(Luo, Brandt, Xue et al. 2016, ApJS, submitted)

THE ASTROPHYSICAL JOURNAL, 825:56 (14pp), 2016 July 1
doi:10.3847/0004-637X/825/1/56

USING LEAKED POWER TO MEASURE INTRINSIC AGN POWER SPECTRA OF RED-NOISE TIME SERIES

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- Why?
  -- account for red-noise leakage (unavoidable in reality)
  -- uncover the intrinsic high-frequency AGN PSD
- How?
  -- develop a novel and observable normalized leakage spectrum (NLS)
  -- NLS describes sensitively red-noise effects
  -- use NLS to effectively constrain the underlying PSD
- NLS: works regardless of sampling patterns and durations
  -- applicable to both X-ray and optical timing observations
  -- useful and effective tool to help probe the variability phenomenon and eventually the physical origins of AGN variabilities

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- Persistent intrinsic aperiodic variation is a defining character of AGNs.

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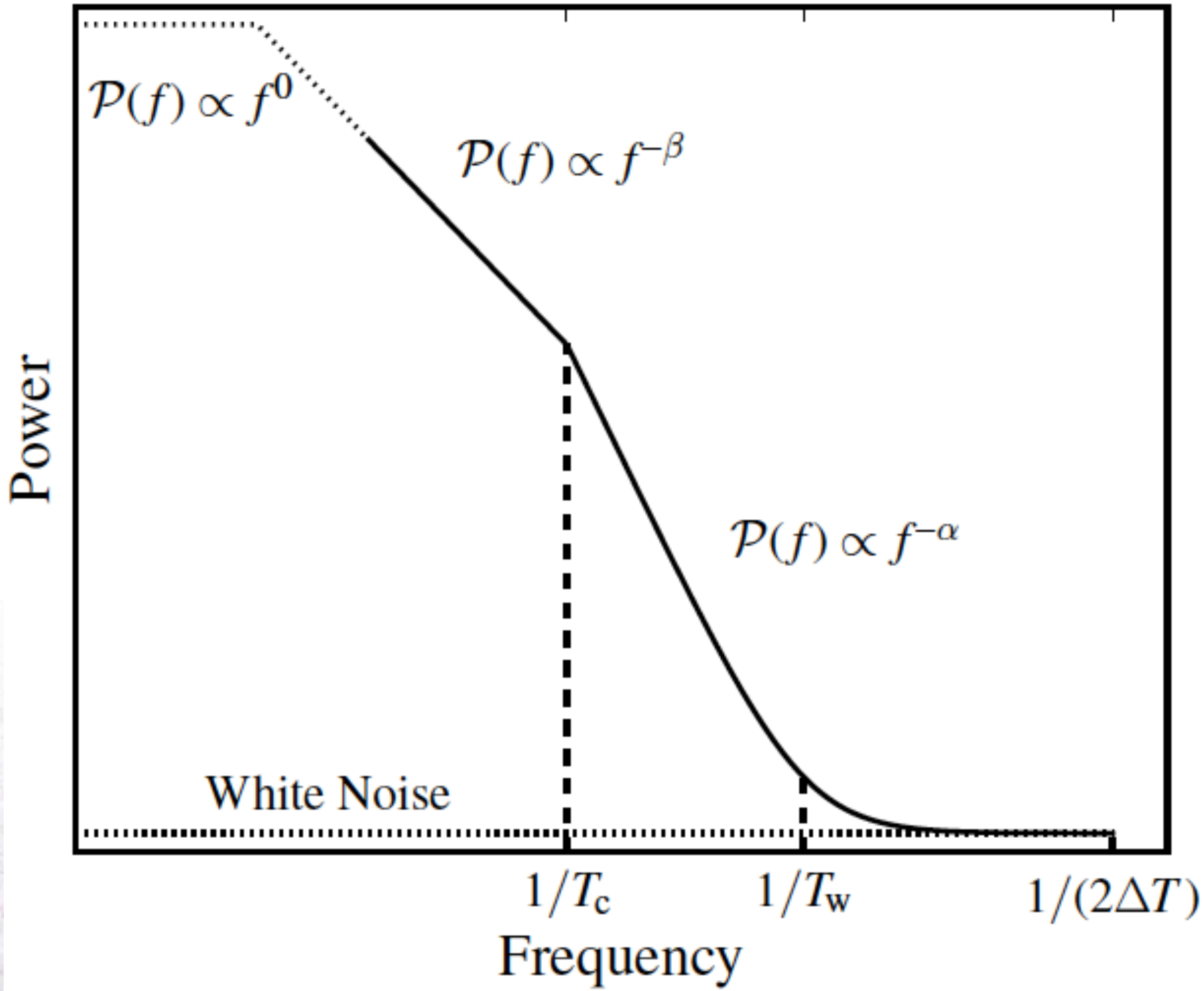
- PSD is the continuous Fourier transform of the autocovariance function of the underlying process:

$$P(f) = \int_{-\infty}^{+\infty} ACF(\tau) e^{-2\pi i f \tau} d\tau$$

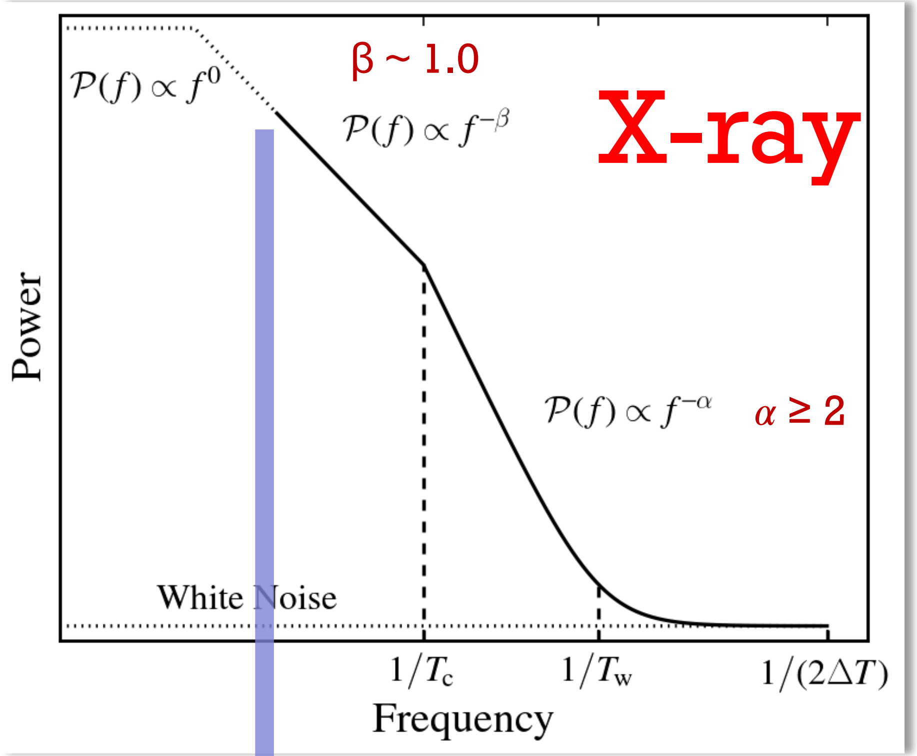
- PSD is estimated by periodogram at discrete frequencies:

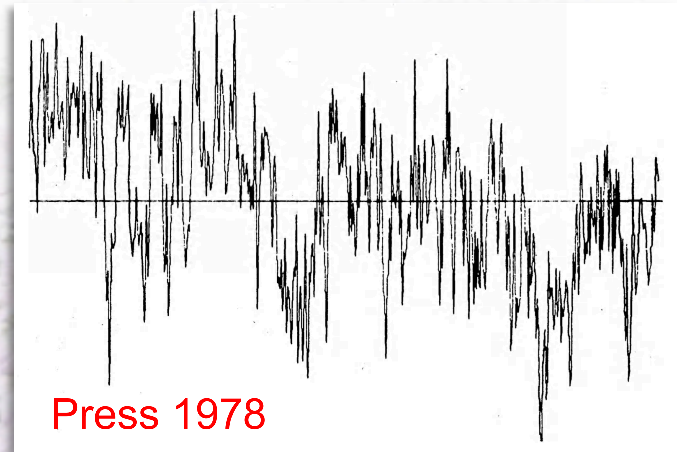
$$p(f_i) = A \left| \sum_{j=1}^{N} x(t_j) e^{-2\pi i f_i t_j} \right|^2$$

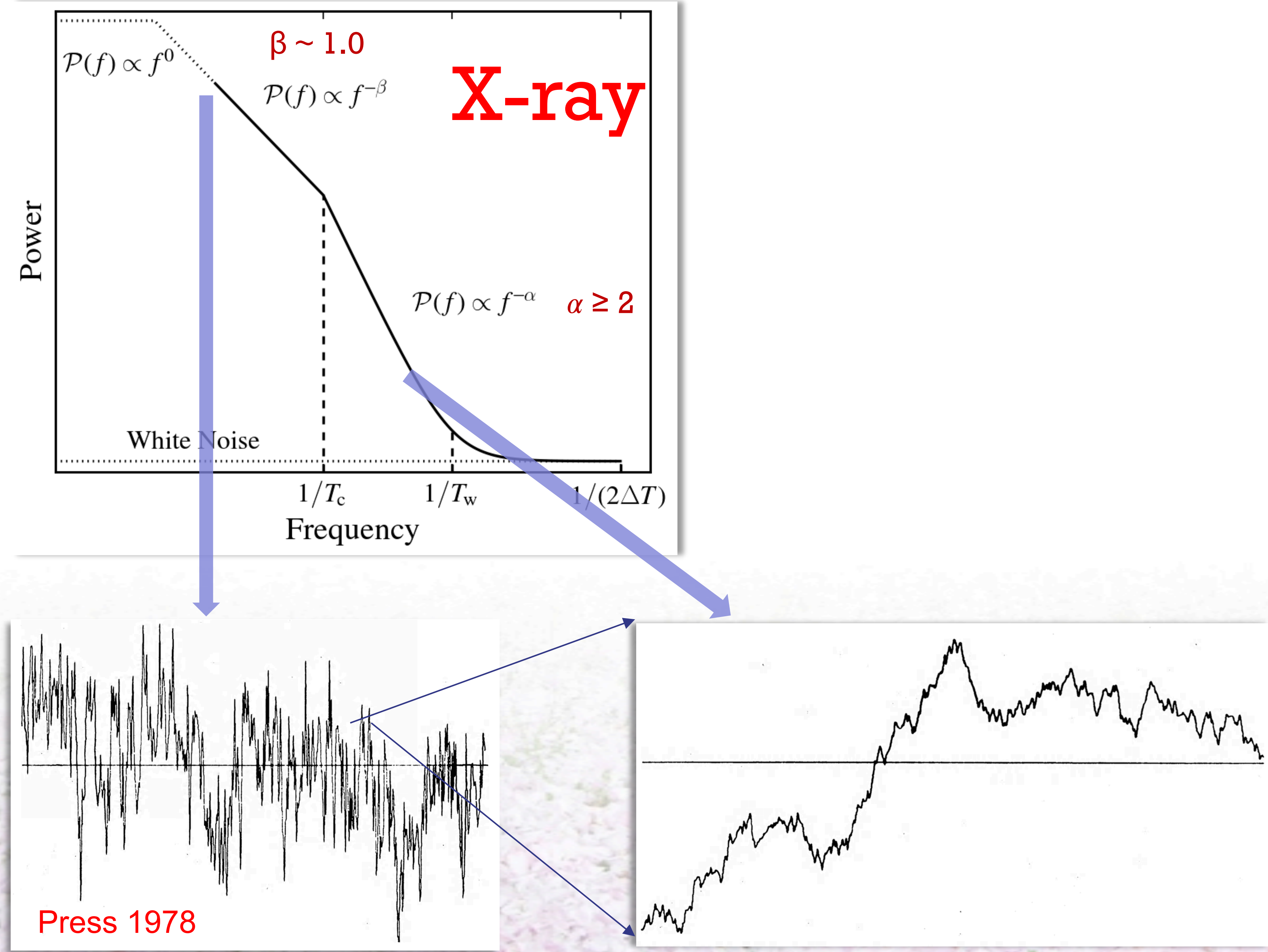
- The PSD of AGN variation is a red-noise.

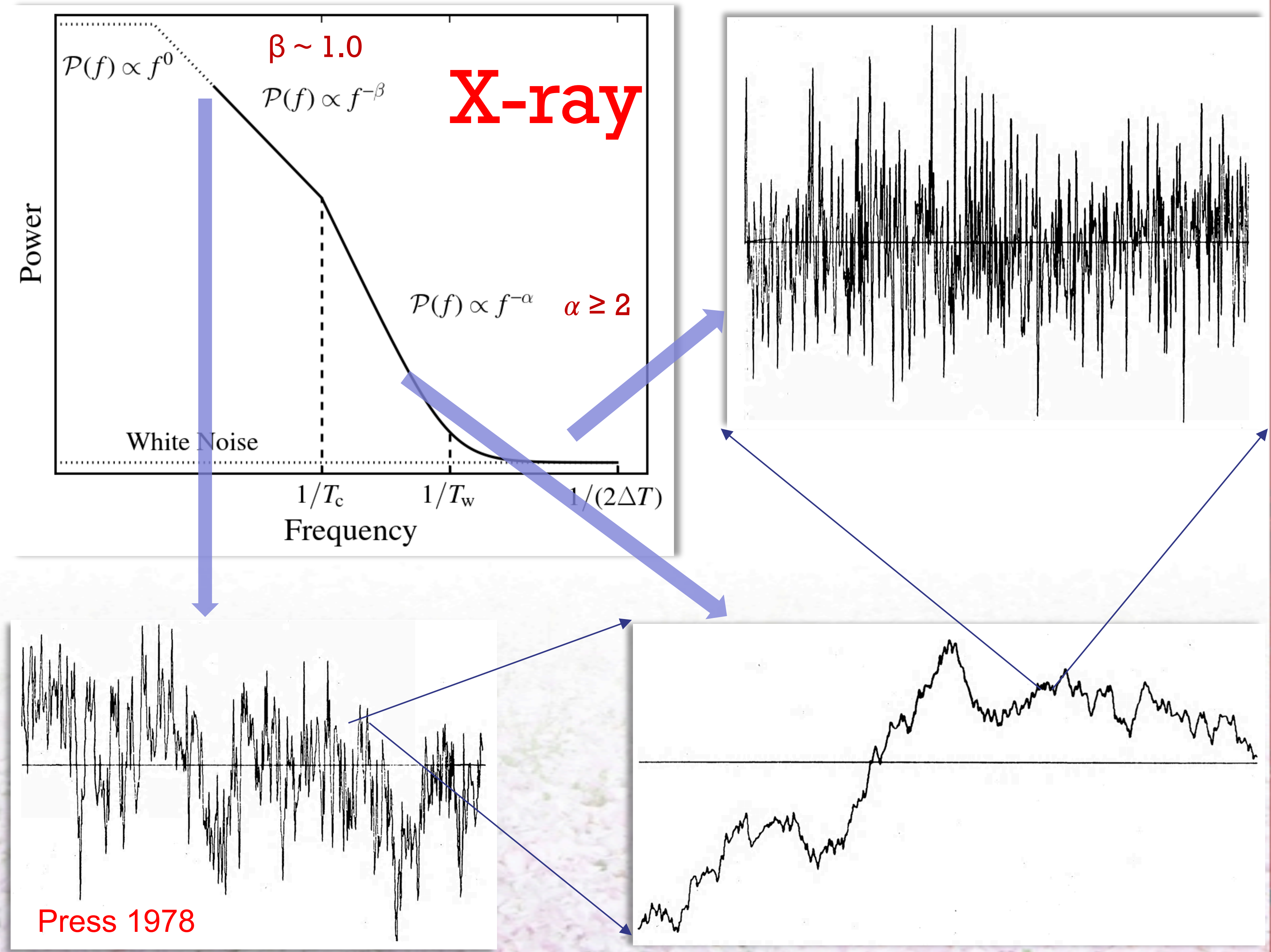


$\mathcal{P}(f) \propto f^{0}$
$\mathcal{P}(f) \propto f^{-\beta}$
$\mathcal{P}(f) \propto f^{-\alpha}$
White Noise
Power
$1/T_{\mathrm{c}}$
$1/T_{\mathrm{W}}$
$1/(2\Delta T)$
Frequency


$\beta \sim 1.0$
X-ray
$\mathcal{P}(f) \propto f^{0}$
$\mathcal{P}(f) \propto f^{-\beta}$
$\mathcal{P}(f) \propto f^{-\alpha}$
$\alpha \geq 2$
Power
White Noise
$1/T_c$
$1/T_w$
$1/(2\Delta T)$
Frequency


Press 1978


β ~ 1.0
X-ray
$\mathcal{P}(f) \propto f^0$
$\mathcal{P}(f) \propto f^{-\beta}$
$\mathcal{P}(f) \propto f^{-\alpha}$
α ≥ 2
Power
White Noise
$1/T_c$
$1/T_w$
$1/(2\Delta T)$
Frequency
Press 1978


β ~ 1.0
X-ray
$\mathcal{P}(f) \propto f^0$
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$\mathcal{P}(f) \propto f^{-\alpha}$
$\alpha \geq 2$
White Noise
Power
$1/T_c$
$1/T_w$
$1/(2\Delta T)$
Frequency
Press 1978

- Previous efforts to alleviate red-noise distortion
  -- “end-matching” technique
  -- damped random walk (DRW) models
  -- continuous-time autoregressive moving average (CARMA) models
  -- tapering

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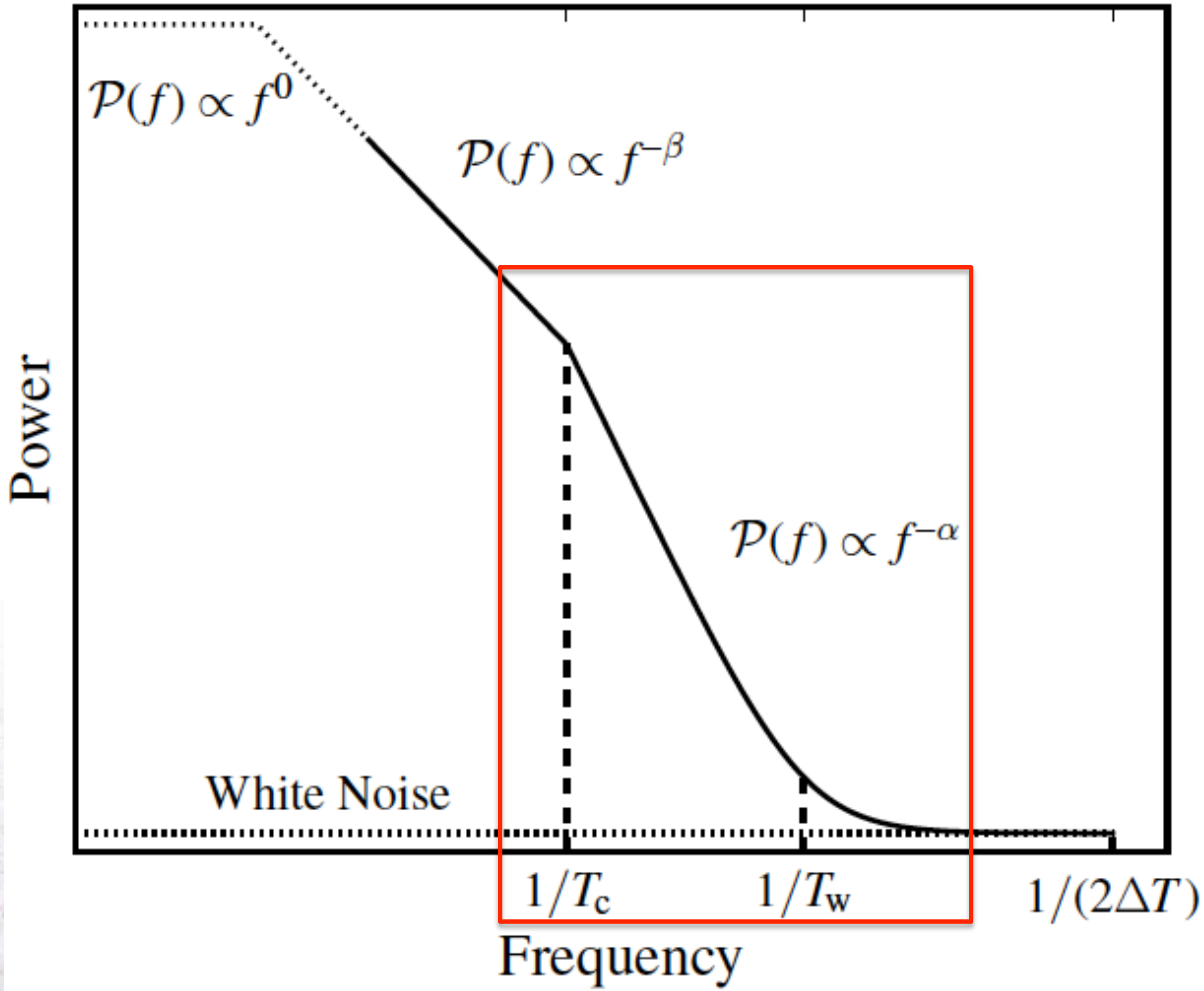
- Our NLS approach:
  -- without altering the lightcurve data
  -- without relying on any specific physical models
  -- novel and observable
  -- mimic sampling patterns and durations of real observations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$\mathcal{P}(f) \propto f^{-\beta}$
$\mathcal{P}(f) \propto f^{-\alpha}$
White Noise
Power
$1/T_c$
$1/T_w$
$1/(2\Delta T)$
Frequency

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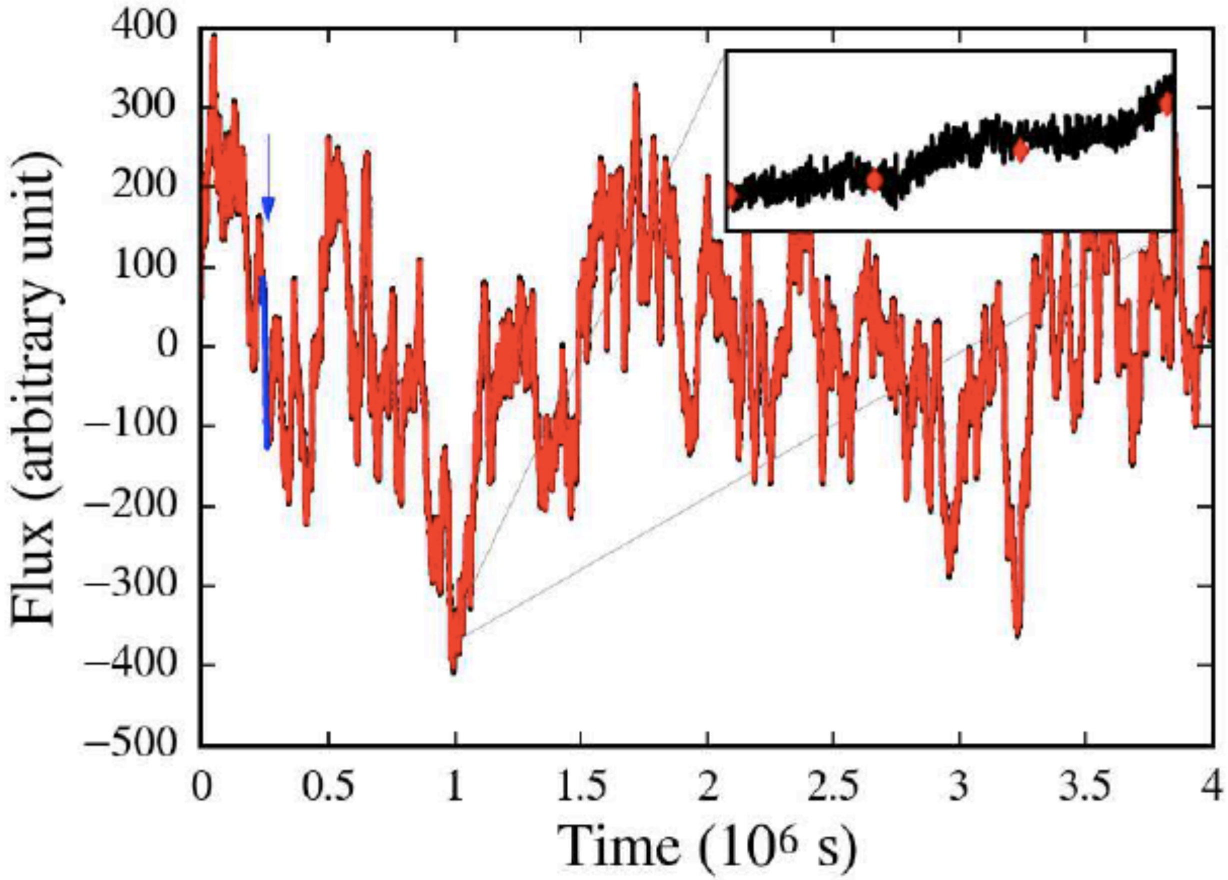
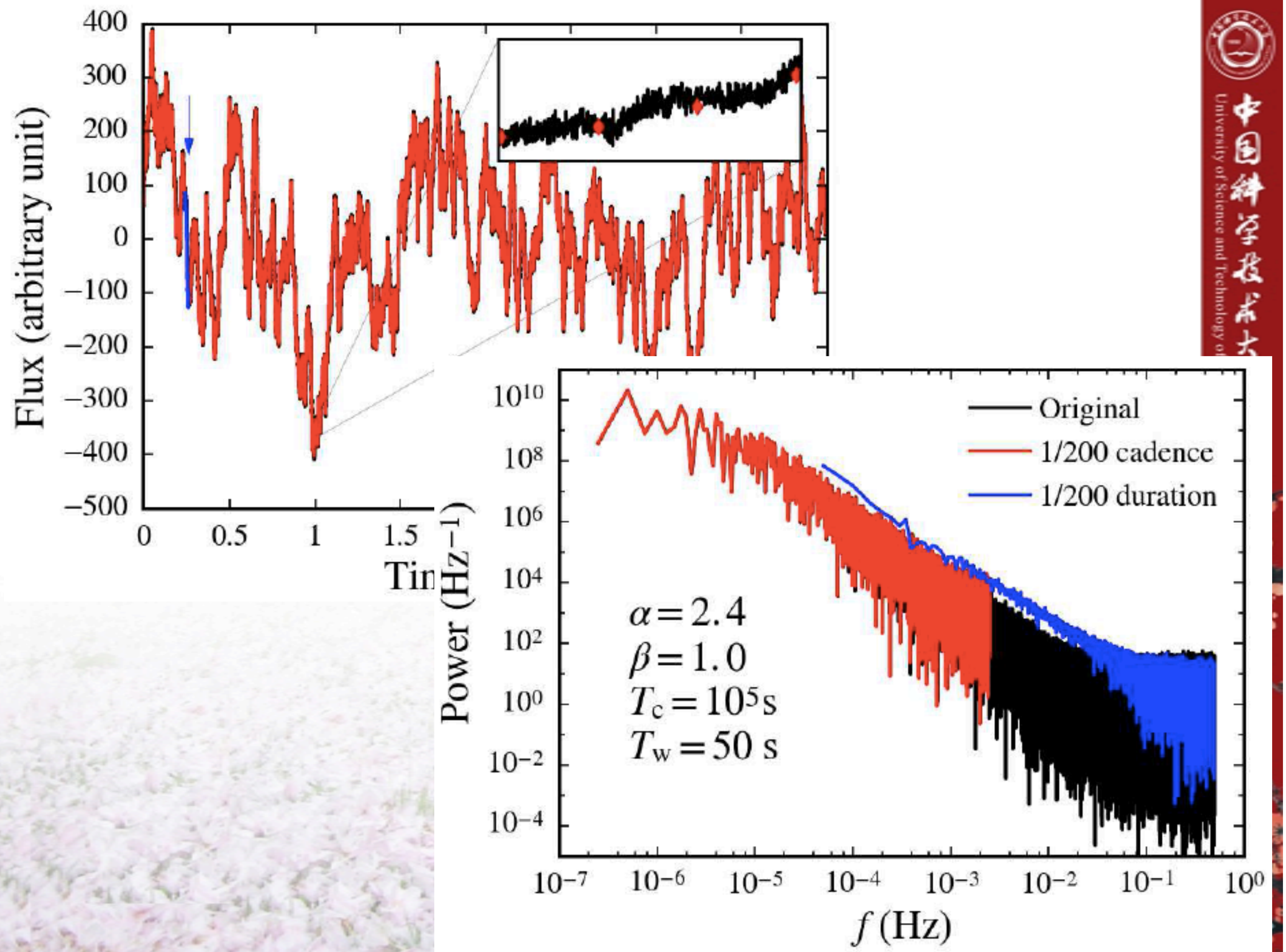
We use the algorithm of Timmer & Koenig (1995) to generate artificial lightcurves. As plotted in Fig. 1 (i.e., the solid line), a broken power law,

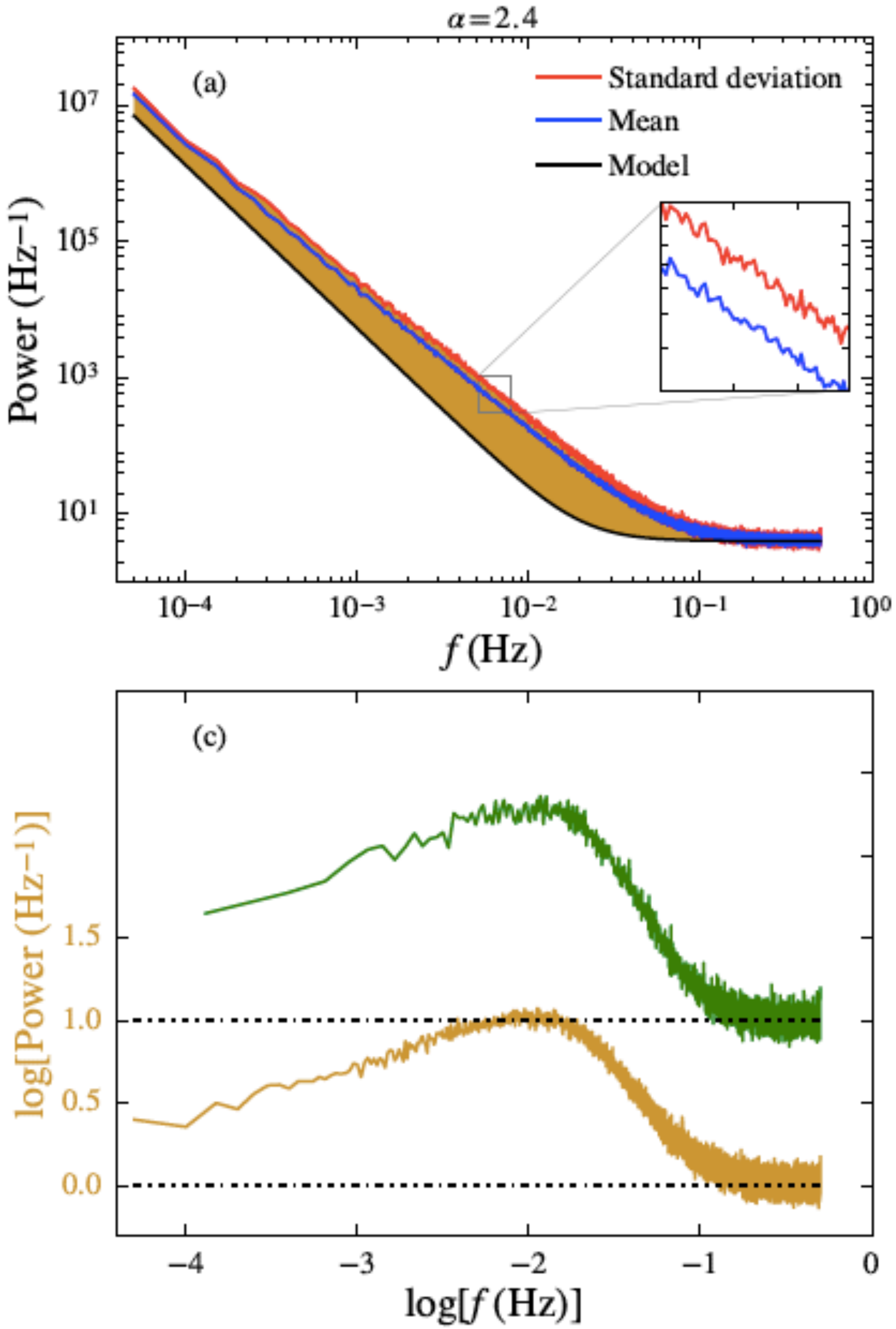
$$\mathcal{P}(f) = \begin{cases} A f^{-\alpha} + A(1/T_{\rm w})^{-\alpha}, & f > f_{\rm c} \\ A f_{\rm c}^{-\alpha} \left(f/f_{\rm c}\right)^{-\beta}, & f < f_{\rm c} \end{cases} \tag{3}$$

is used as the model PSD. $f_{\rm c}$ is the break frequency that corresponds to the characteristic timescale $T_{\rm c}$ by $f_{\rm c} = 1/T_{\rm c}$. While the low-frequency logarithmic slope β is fixed to 1.0 throughout the paper, the high-frequency logarithmic slope α varies around 2.0 in the simulations. We add a constant component to the model to represent Poisson noise. The timescale where the power law component equals the white noise component is denoted as $T_{\rm w}$. A is an arbitrary constant so that our simulated lightcurves are in arbitrary units.


Flux (arbitrary unit)
Time (10^6 s)
400
300
200
100
0
−100
−200
−300
−400
−500
0
0.5
1
1.5
2
2.5
3
3.5
4



Flux (arbitrary unit)
400
300
200
100
0
−100
−200
−300
−400
−500
0
0.5
1
1.5
Original
1/200 cadence
1/200 duration
α = 2.4
β = 1.0
Tc = 10^5 s
Tw = 50 s
Power (Hz^−1)
f (Hz)



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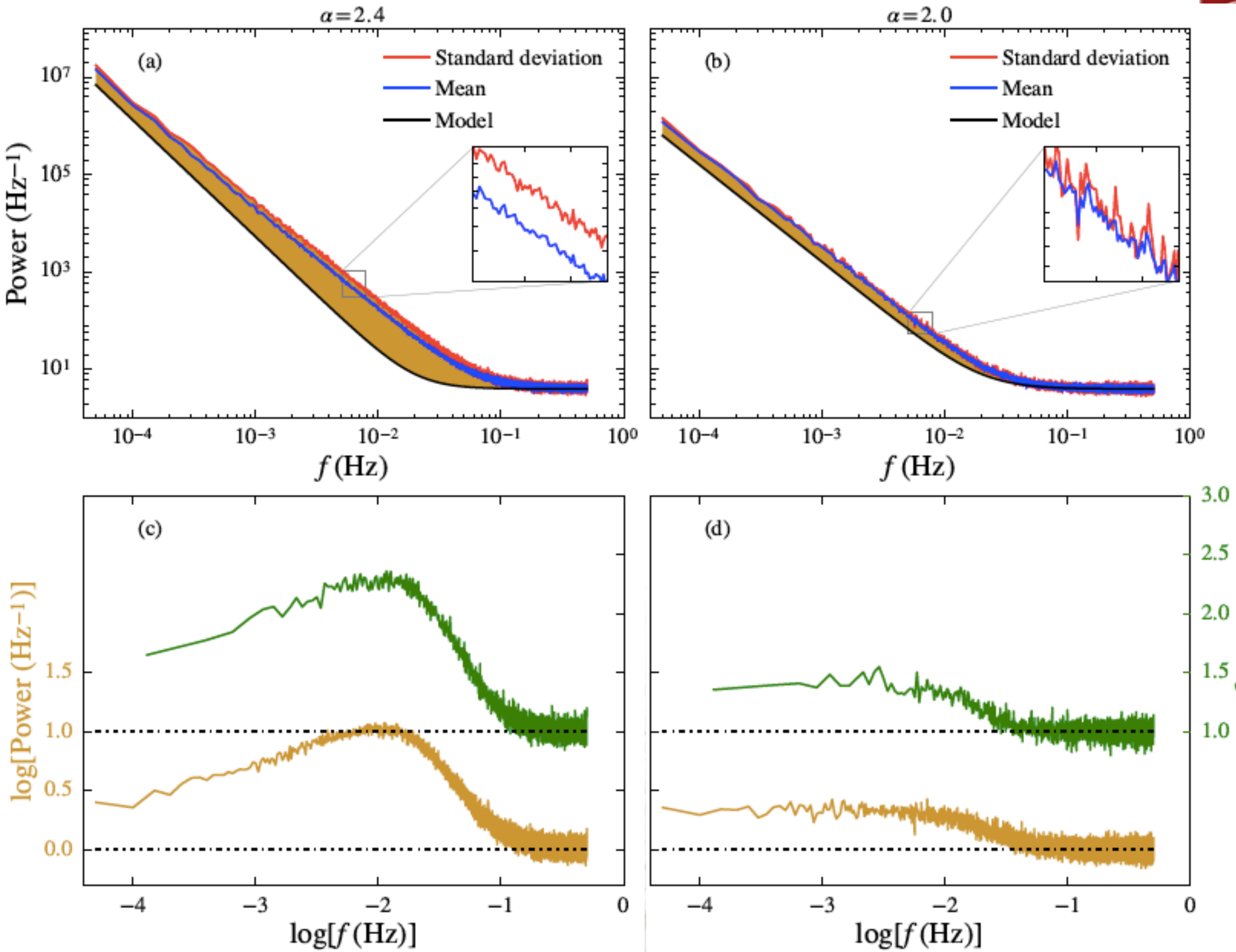


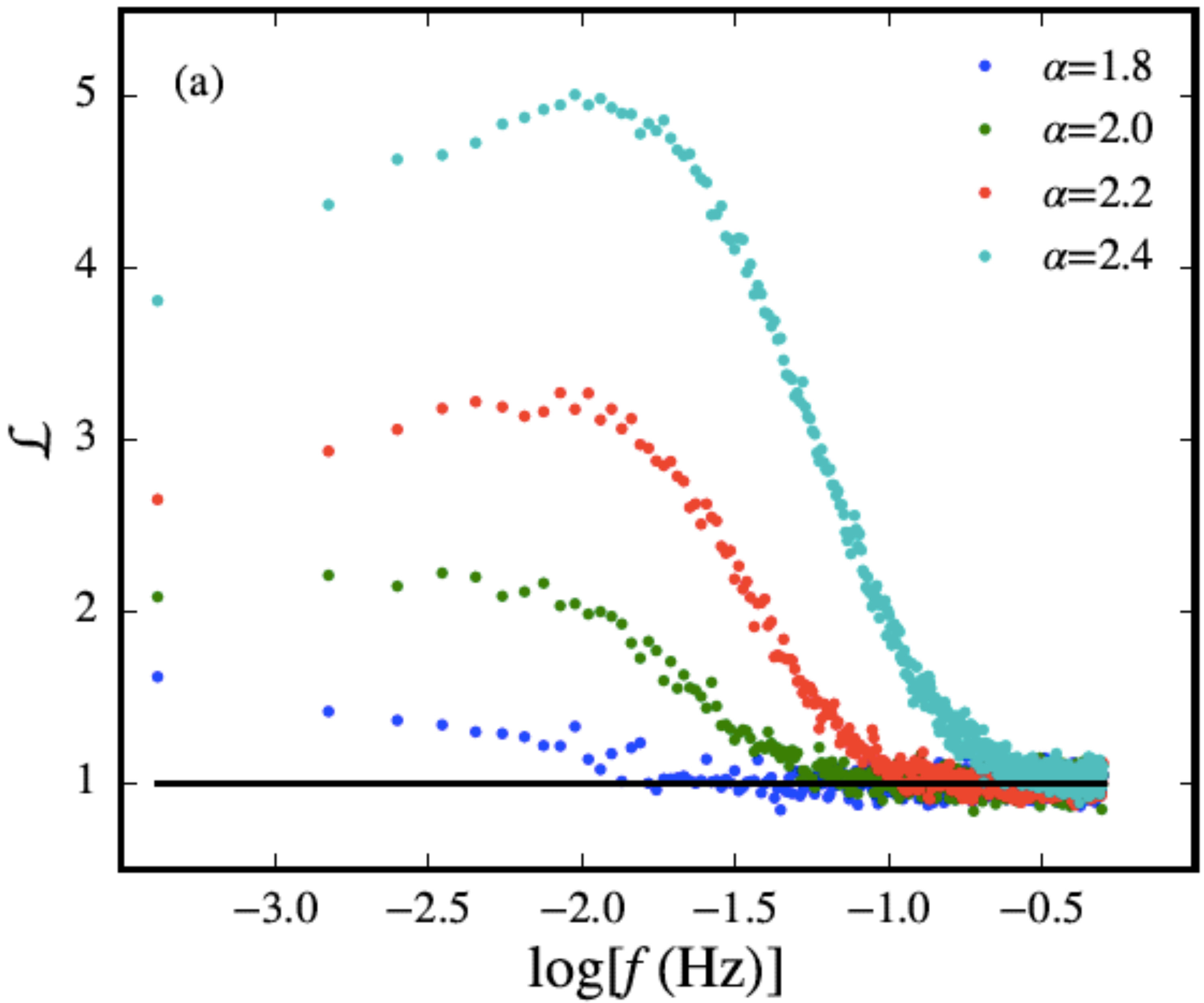
α=2.4
α=2.0
(a)
(b)
(c)
(d)
Standard deviation
Mean
Model
Power (Hz⁻¹)
f (Hz)
log[Power (Hz⁻¹)]
log[f (Hz)]
ℒ

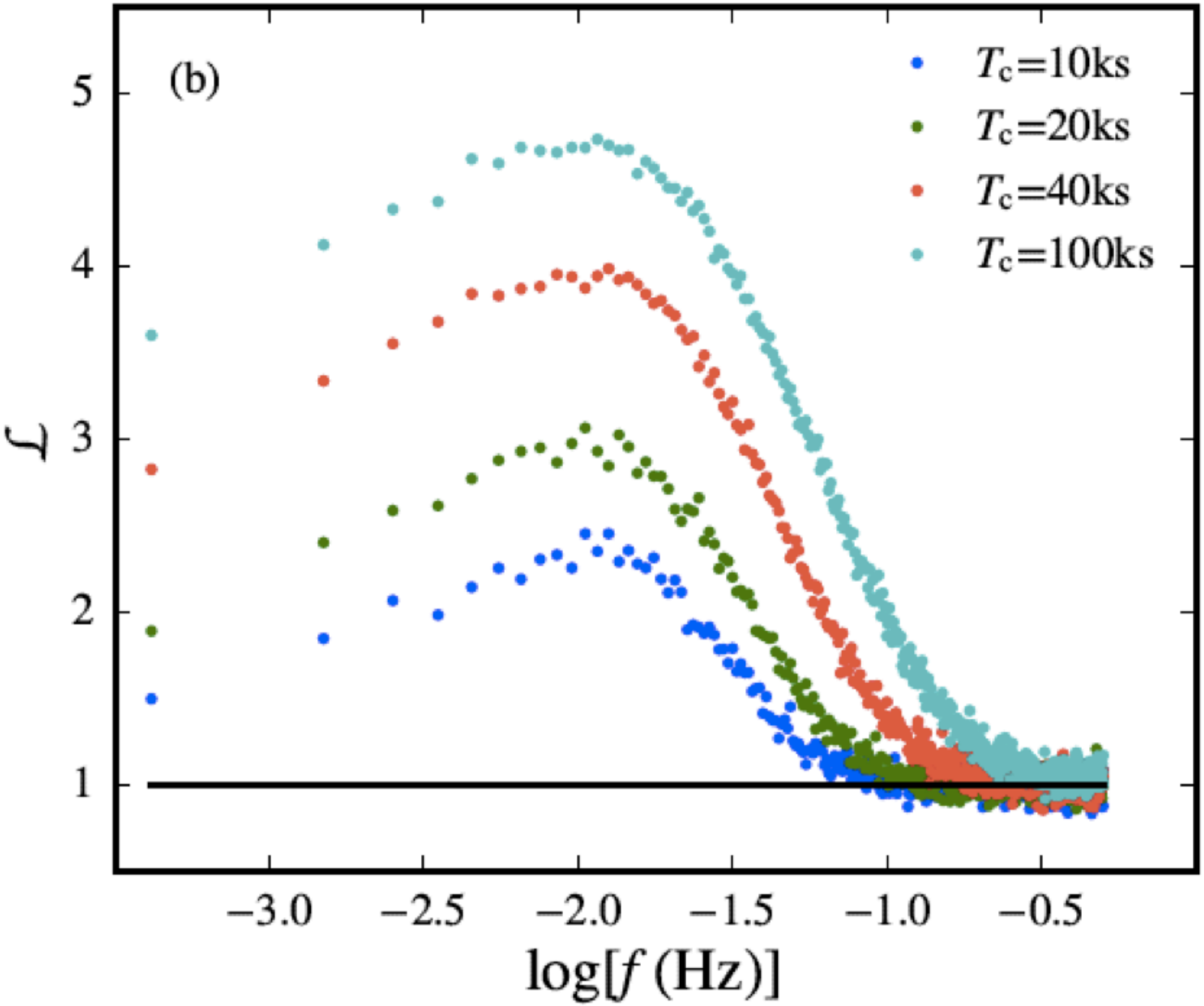
the biased periodogram of real data. With the M binned periodograms, we calculate the standard deviation at every frequency and denote it as $\mathrm{std}\{\log[\overline{P}(f)]\}$. Subsequently, we define a novel observable quantity, the normalized leakage spectrum $\mathcal{L}(f)$, i.e., NLS, as

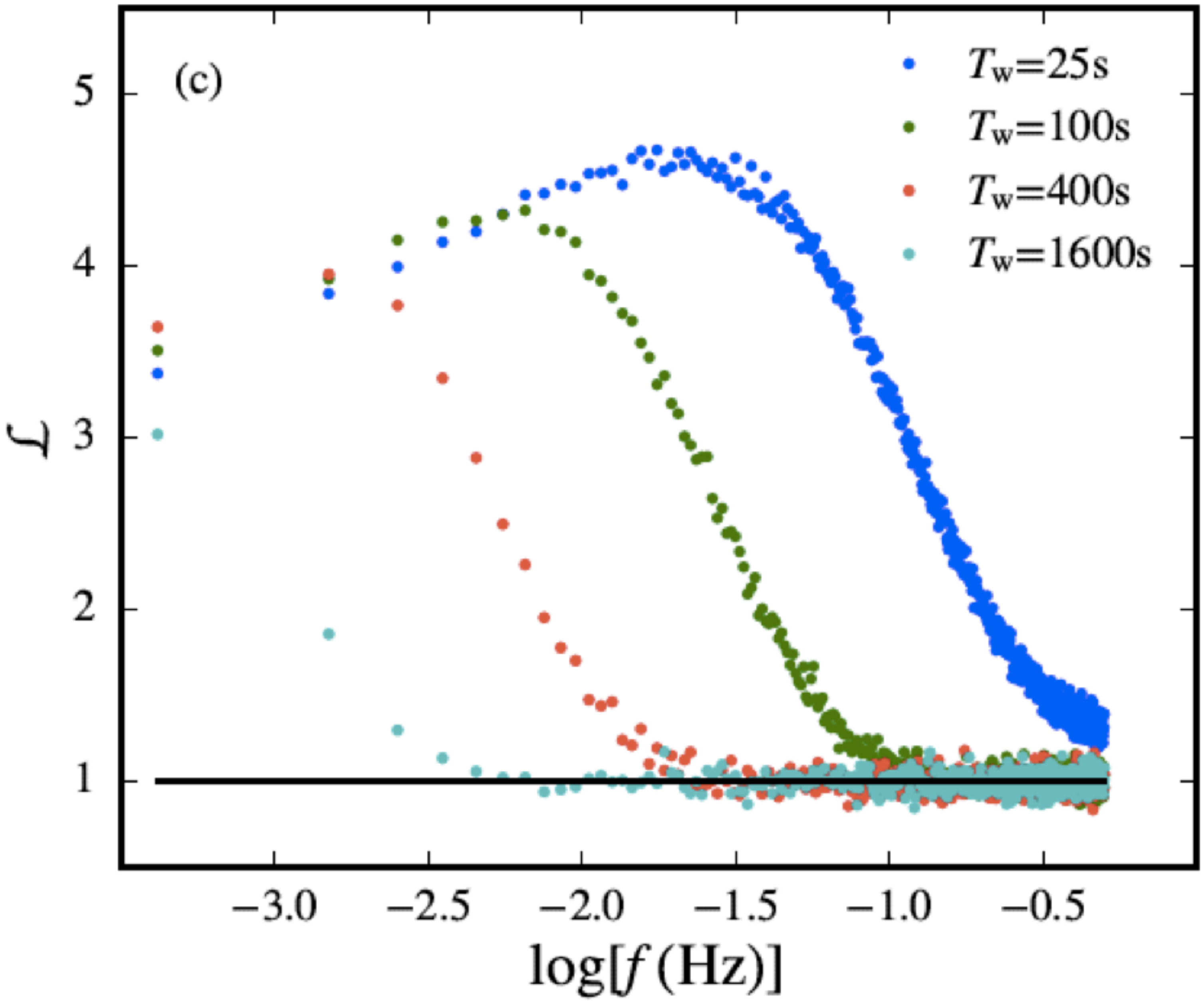
$$\mathcal{L}(f) = \frac{\mathrm{std}\{\log[\overline{P}(f)]\}}{\mathrm{std}\{\log[P]\}}, \text{where} \tag{6}$$

$$\mathrm{std}\{\log[P]\} = \frac{\pi}{\ln 10}\sqrt{\frac{1}{6N}}. \tag{7}$$

$\mathrm{std}\{\log[P]\}$ is solely determined by N and is an accurate estimation of the standard deviation of the binned periodogram if the red-noise leakage is totally absent, for the case of a single power-law distributed PSD that is valid for the high-frequency PSD above the break frequency as shown in Fig. 1 (cf. Eq. 20 of Papadakis & Lawrence (1993) for $\mathrm{std}\{\log[P]\}$). NLS is dimensionless and describes the severity of red-noise leakage across different frequencies. There is an obvious fact


(a)
α=1.8
α=2.0
α=2.2
α=2.4
$\mathcal{L}$
5
4
3
2
1
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
log[f (Hz)]


(b)
T_c=10ks
T_c=20ks
T_c=40ks
T_c=100ks
$\mathcal{L}$
1
2
3
4
5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
log[f (Hz)]



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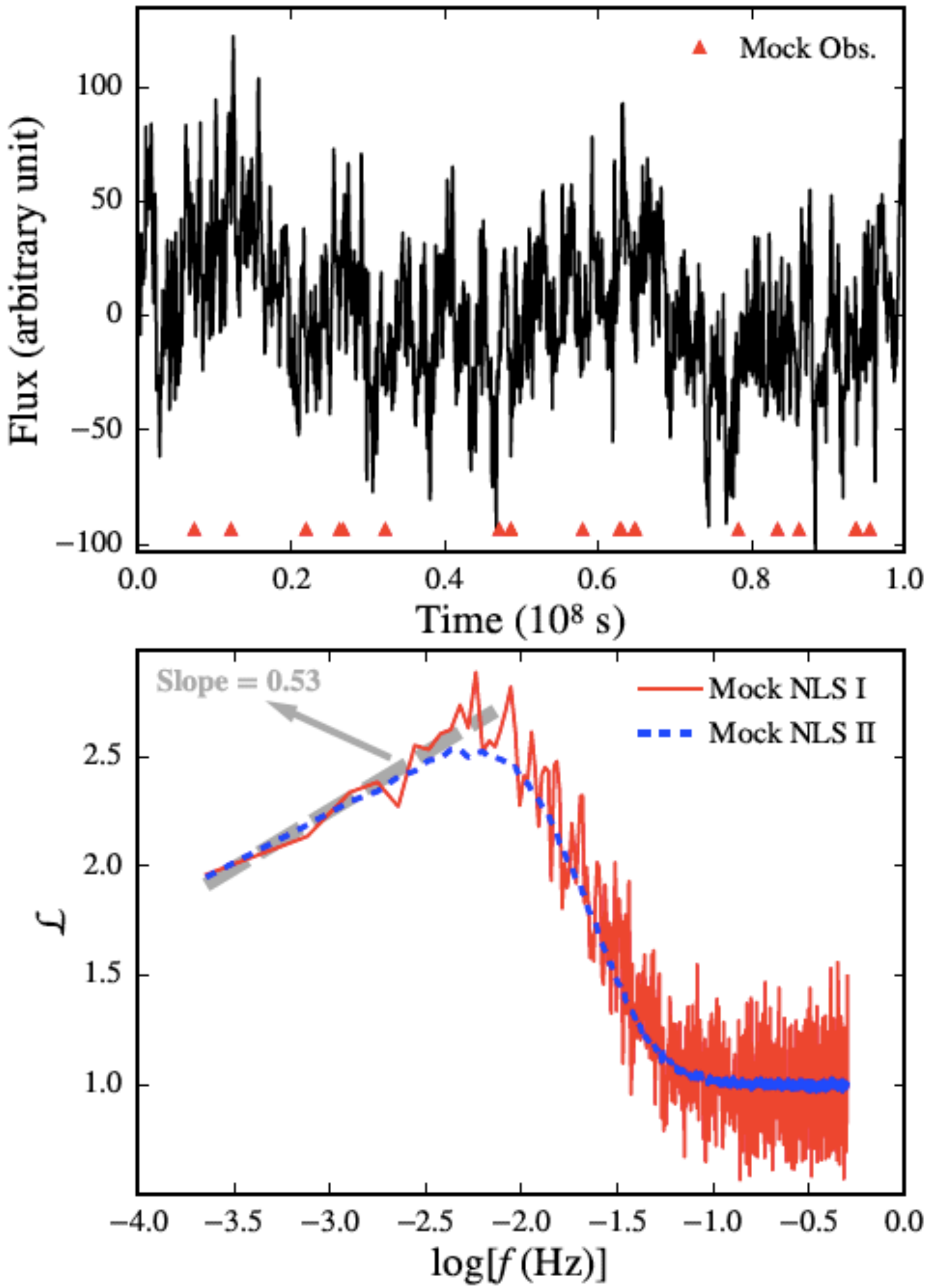
自由参数	Input Model Parameter
α	2.30
$\log(f_c)$	−4.70
T_W	80s



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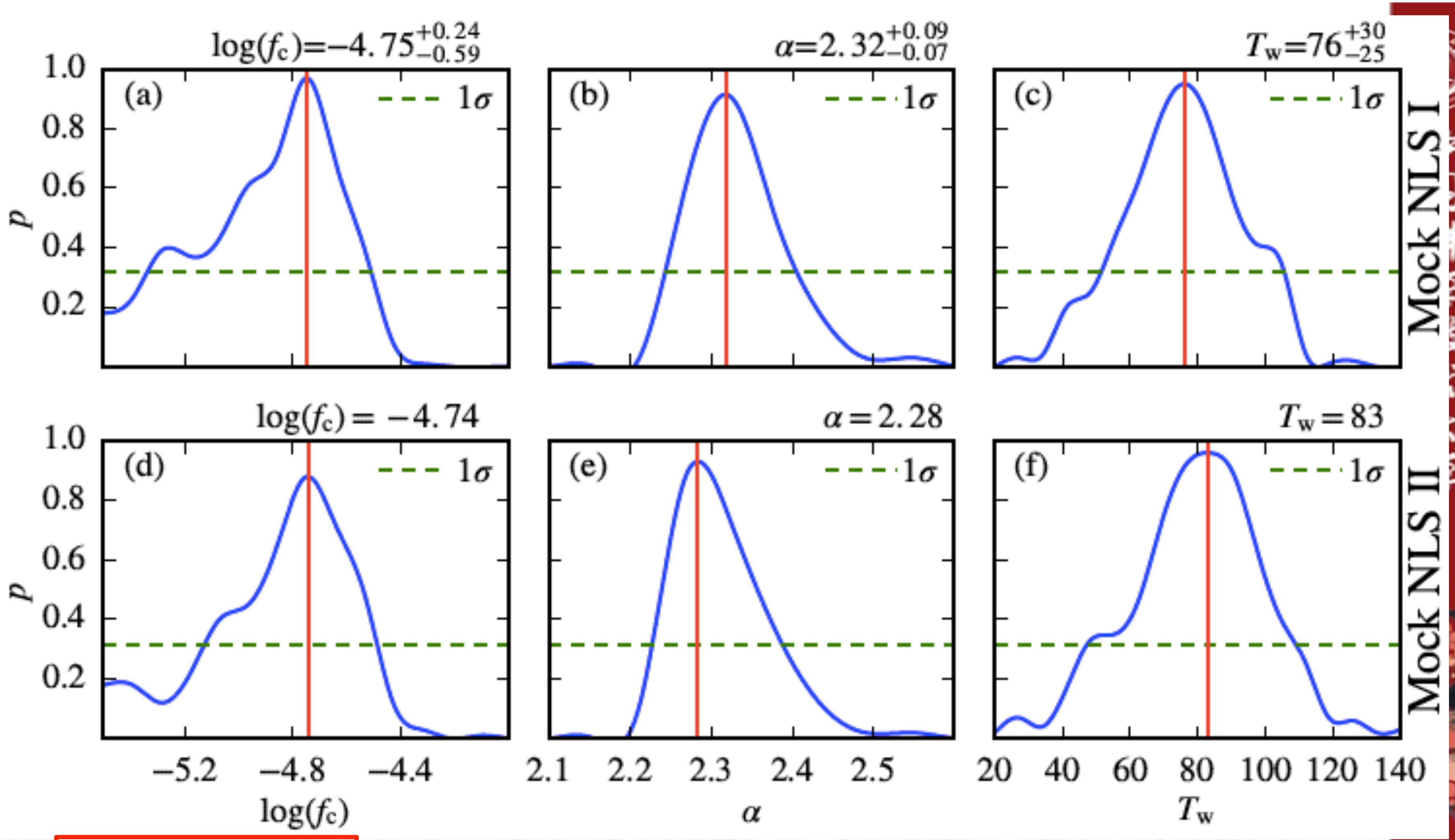

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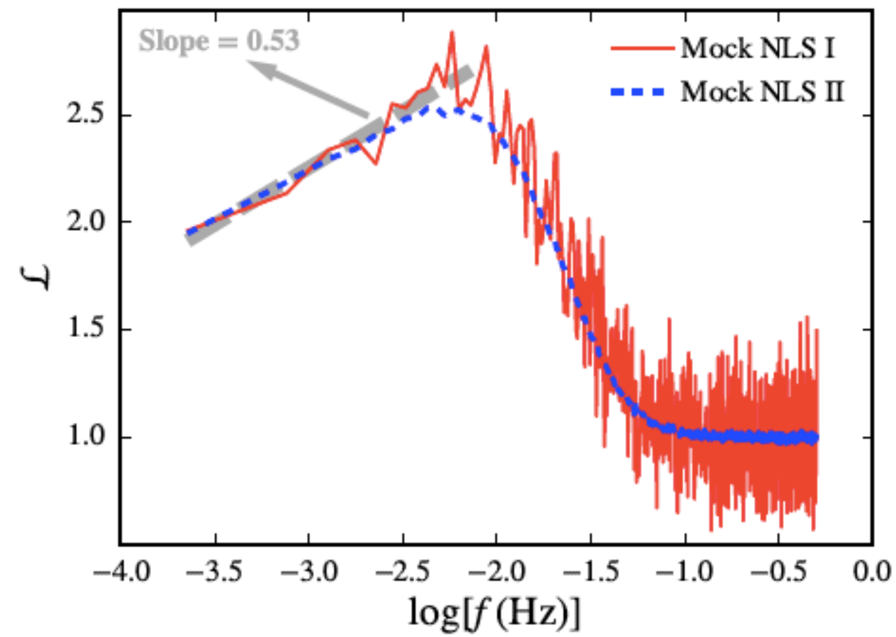
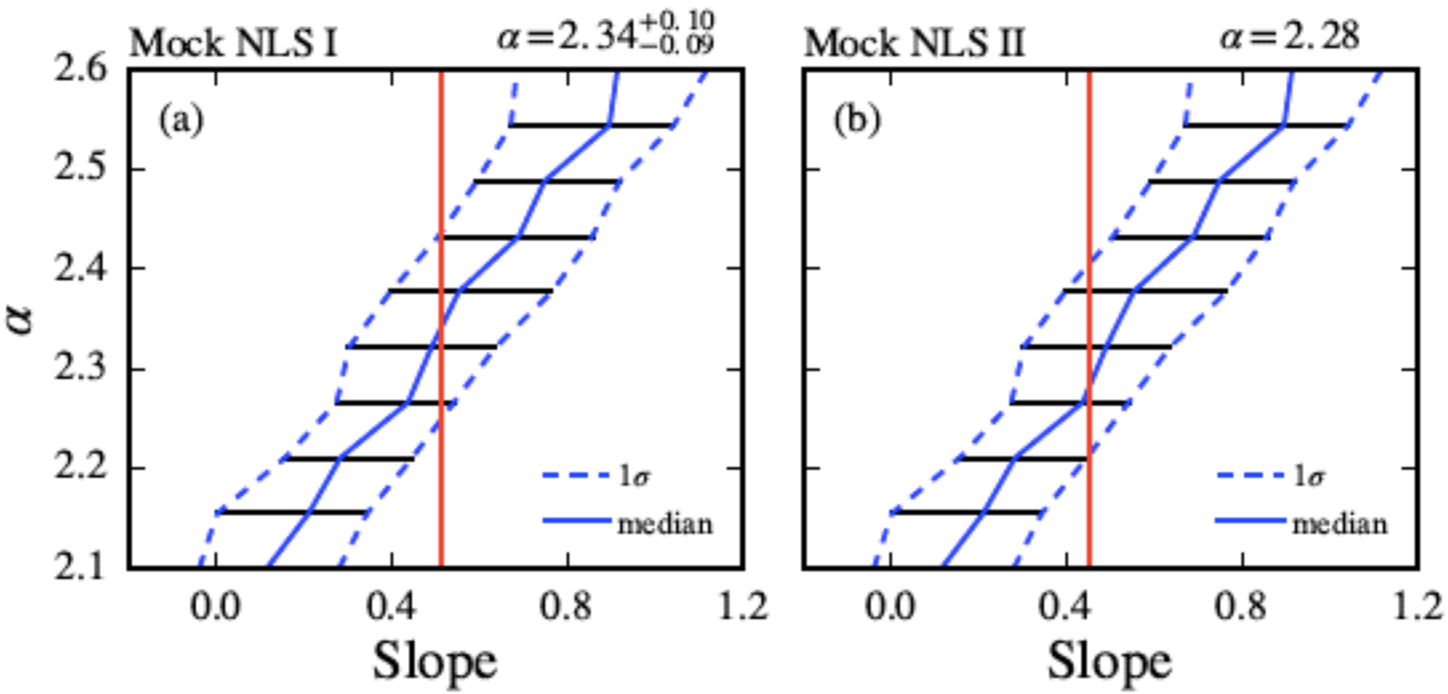
$$\chi^2_{\mathrm{NLS},*} = \sum_{f=f_{\min}}^{f_{\max}} \left(\frac{\overline{\mathcal{L}_{\mathrm{model}}}(f) - \mathcal{L}_*(f)}{\Delta \overline{\mathcal{L}_{\mathrm{model}}}(f)} \right)^2$$

$$p(\chi^2_{\mathrm{NLS,\,model}} > \chi^2_{\mathrm{NLS,\,mock}})$$





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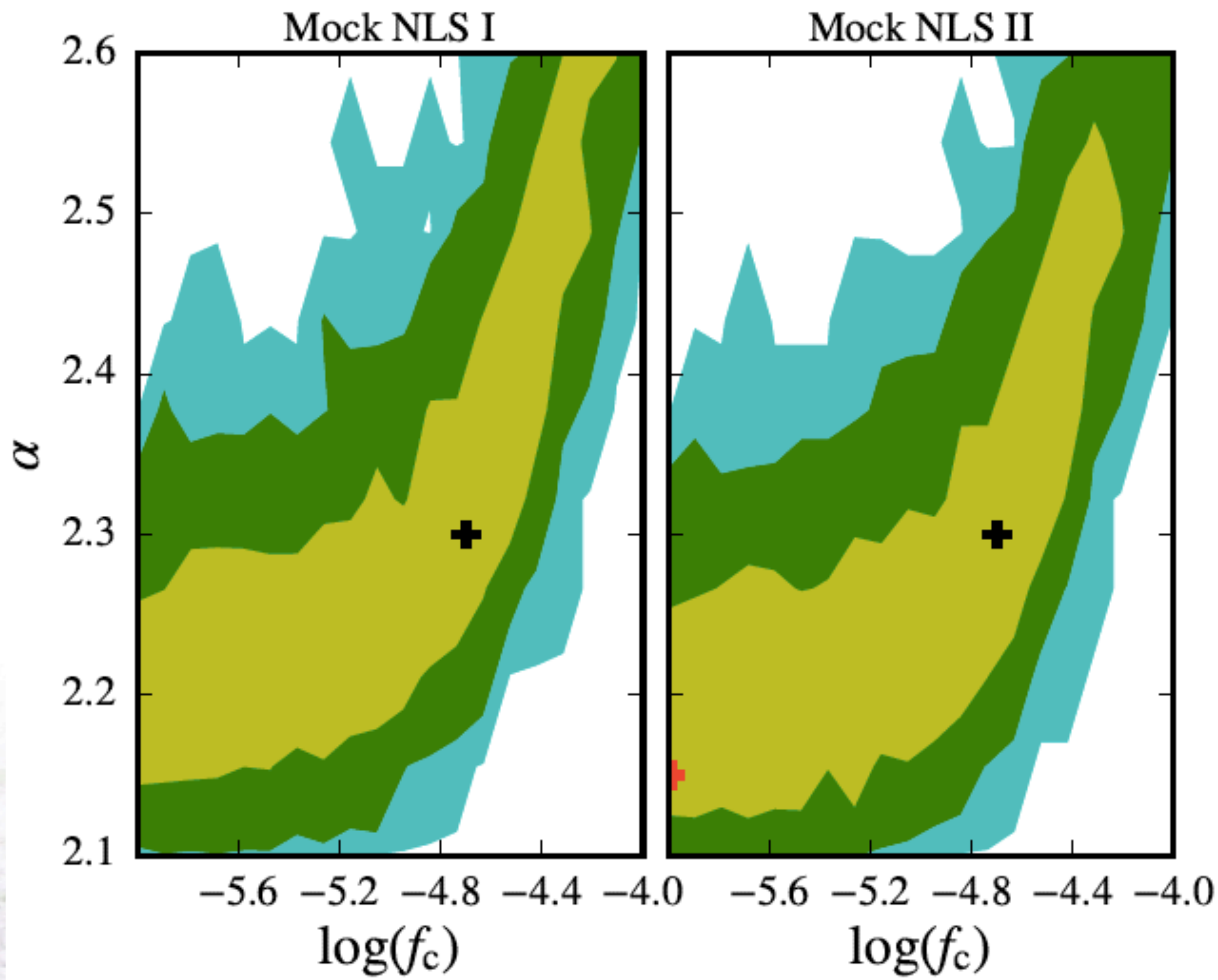
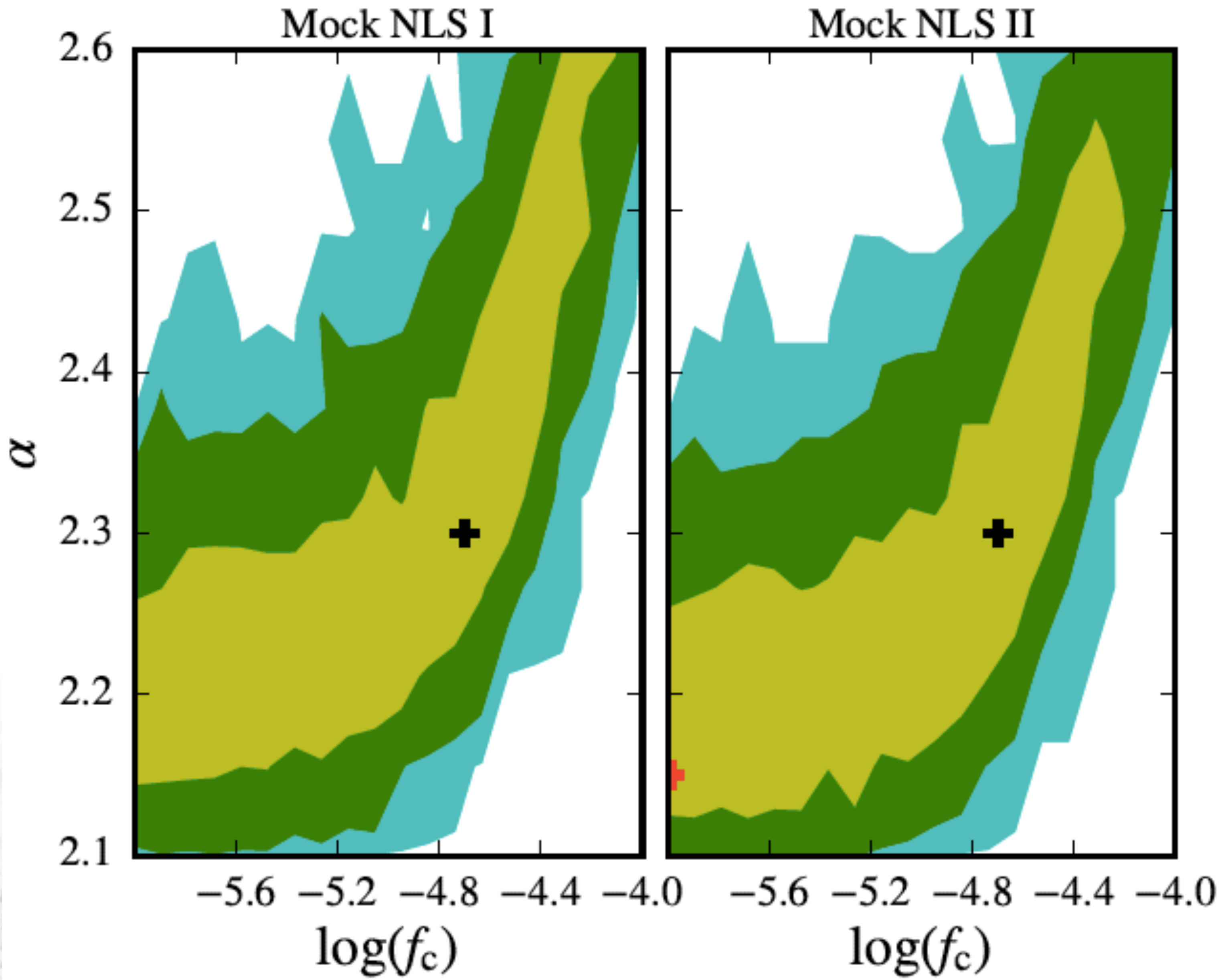

Mock NLS I
Mock NLS II
2.6
2.5
2.4
2.3
2.2
2.1
α
−5.6
−5.2
−4.8
−4.4
−4.0
log(fc)



NLS slope ➔ $\alpha = 2.36^{+0.10}_{-0.08}$

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  -- mimic sampling patterns and durations of real observations

  -- without requiring long-term continuous observations

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  -- without requiring long-term continuous observations

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  -- useful and effective tool to help probe the variability phenomenon and eventually the physical origins of AGN variabilities

  -- can widely used in the era of time-domain astronomy

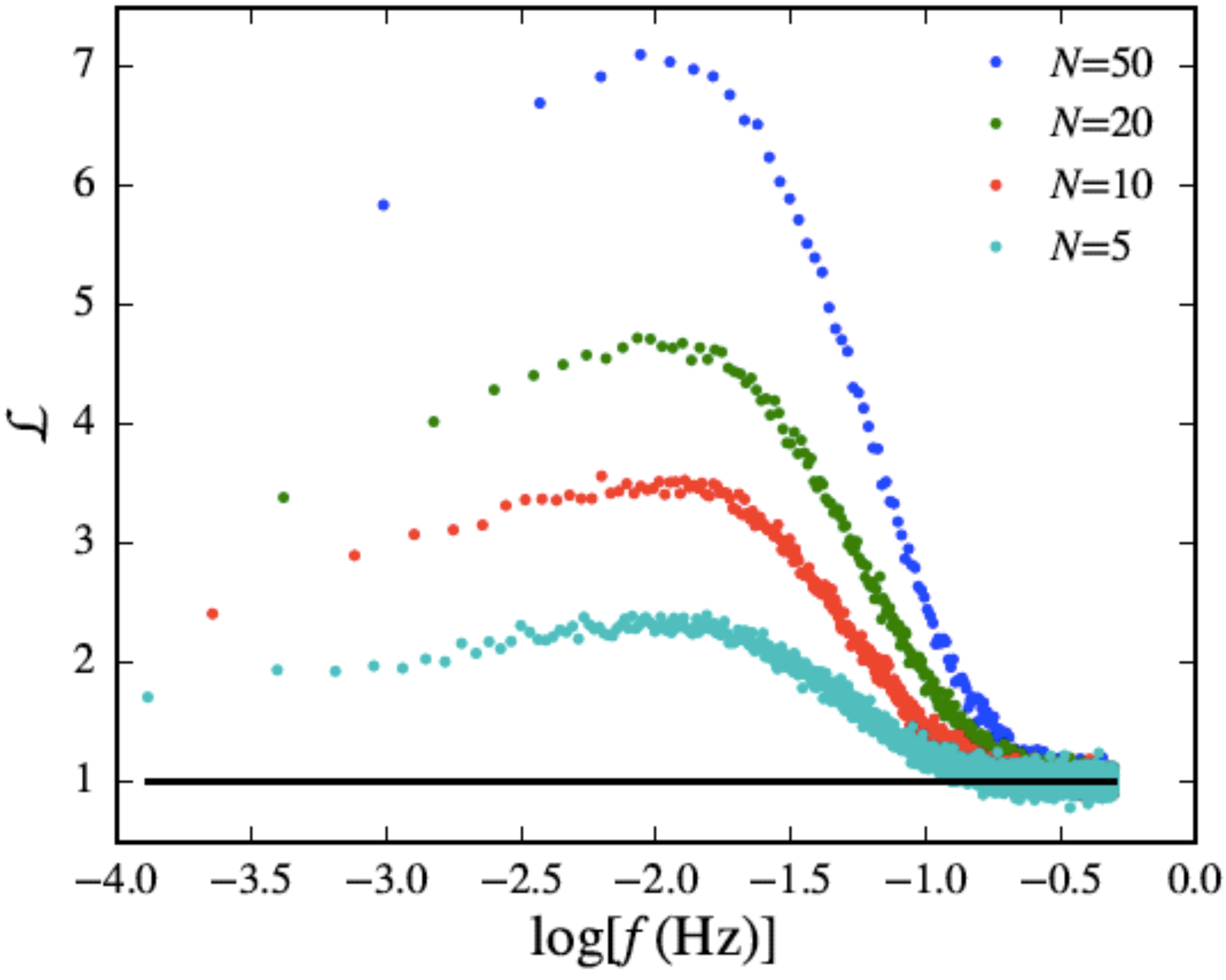
Referee Report
Reviewer's Comments:
This paper presents a novel approach to accounting for red-noise leak in the steep power spectra measured from data which is necessarily gapped or split into segments which are short compared to the break time-scale for the power spectrum to flatten (and red-noise-leak diminished).

The approach by the authors is novel and I find it rather clever - it makes use of the fact that an unbiased power spectrum of a noise process has a standard deviation of power measured at a given Fourier frequency, which is equal to the mean underlying power. However, red noise leak adds a component which, has a slope of -2 but a random amplitude (determined by the amount of long-time-scale power outside the sampled observing window, which itself depends on the steepness of the power spectrum). The authors show that this additive component distorts the standard deviation of the powers away from that expected for an unbiased process, such that the distortion can be quantified (by their "Normalised Leakage Spectrum" or NLS) and in this way the true undertlying PSD shape can be constrained. The authors demonstrate these effects using simulations of AGN-like light curves, showing how comparison of the NLS from the simulations with that of the data can be used to constrain the true
PSD shape (albeit with some degeneracy due to the break frequency, which may be unknown in some cases).

Best regards,
Phil Uttley

Prof. Phil Uttley
(University of Amsterdam)

Thank you!



N=50
N=20
N=10
N=5
$\mathcal{L}$
log[f (Hz)]
−4.0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
1
2
3
4
5
6
7