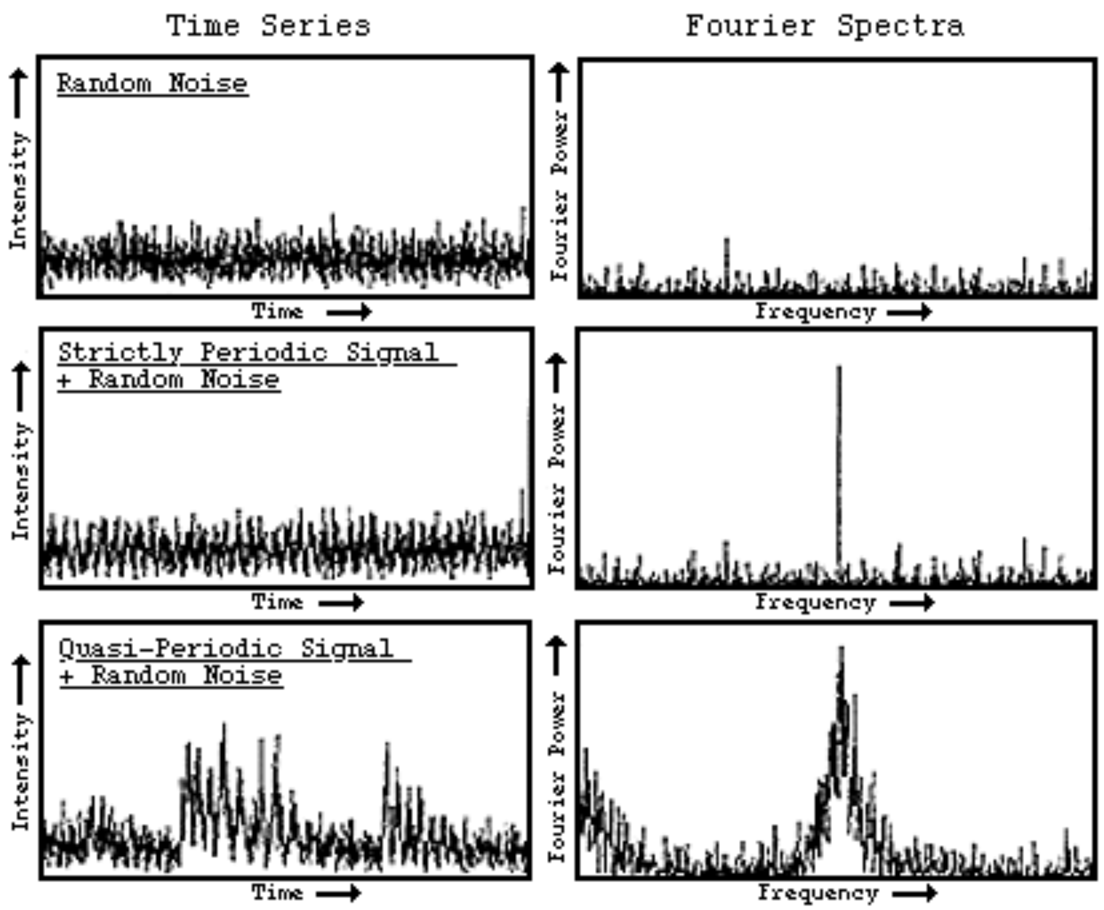
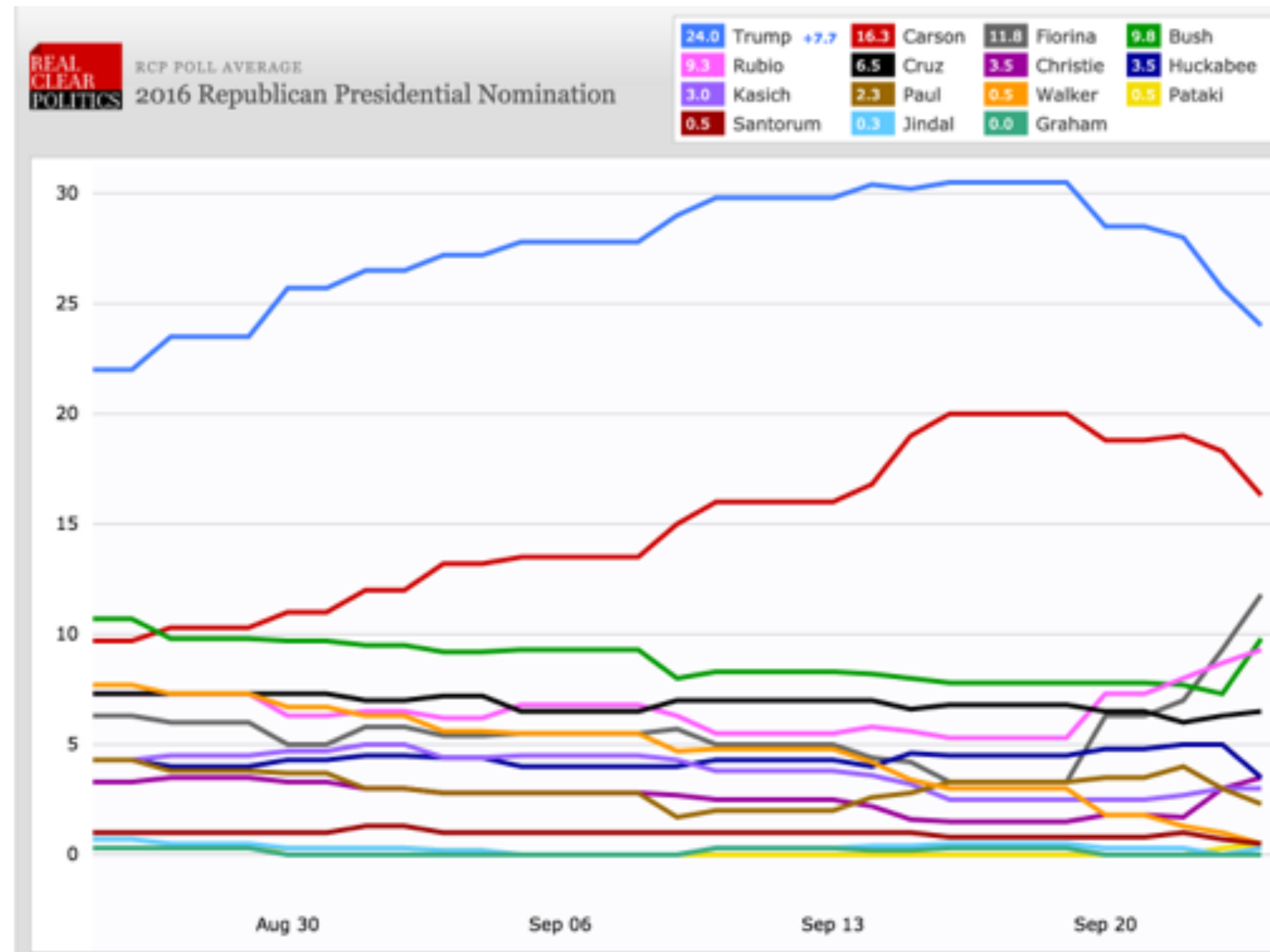
(High Energy) Astrophysics with Novel Observables





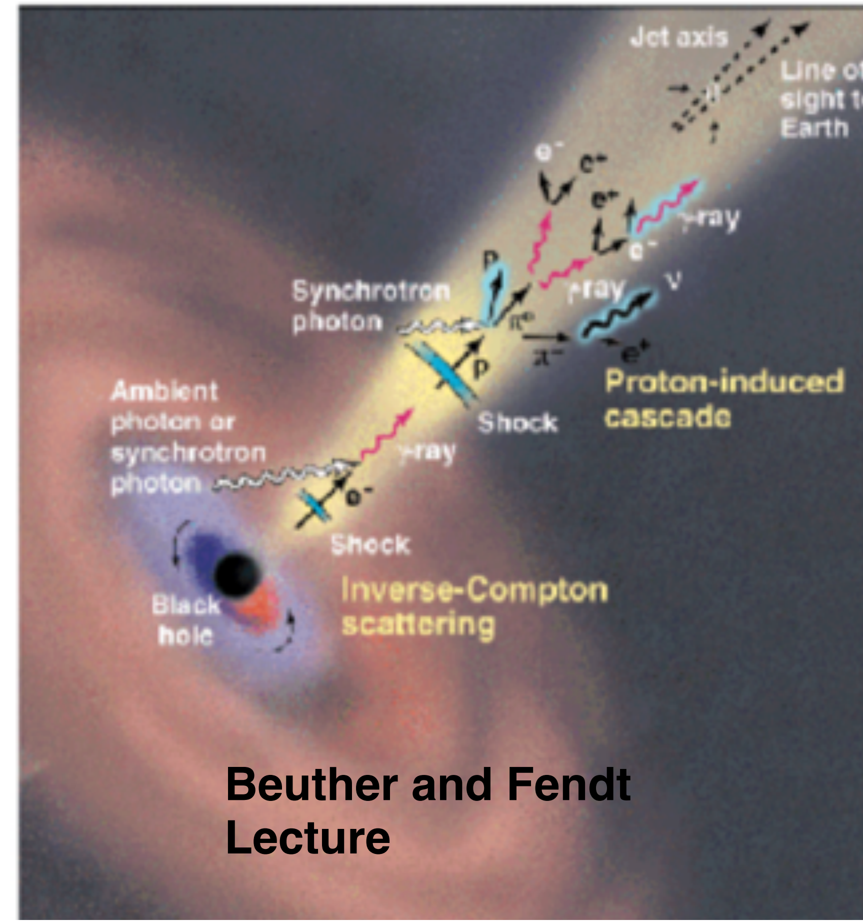
Nachiketa Chakraborty,

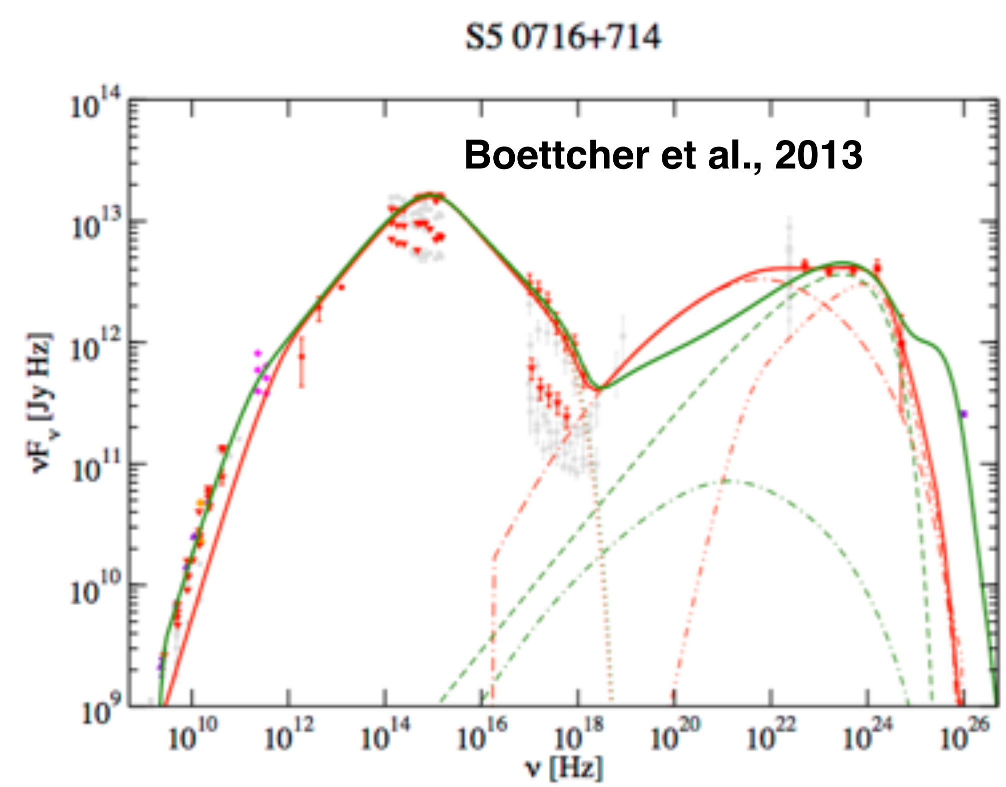
HAP Workshop, 8th December, 2016 Cochem

Alexander von Humboldt
Stiftung/Foundation

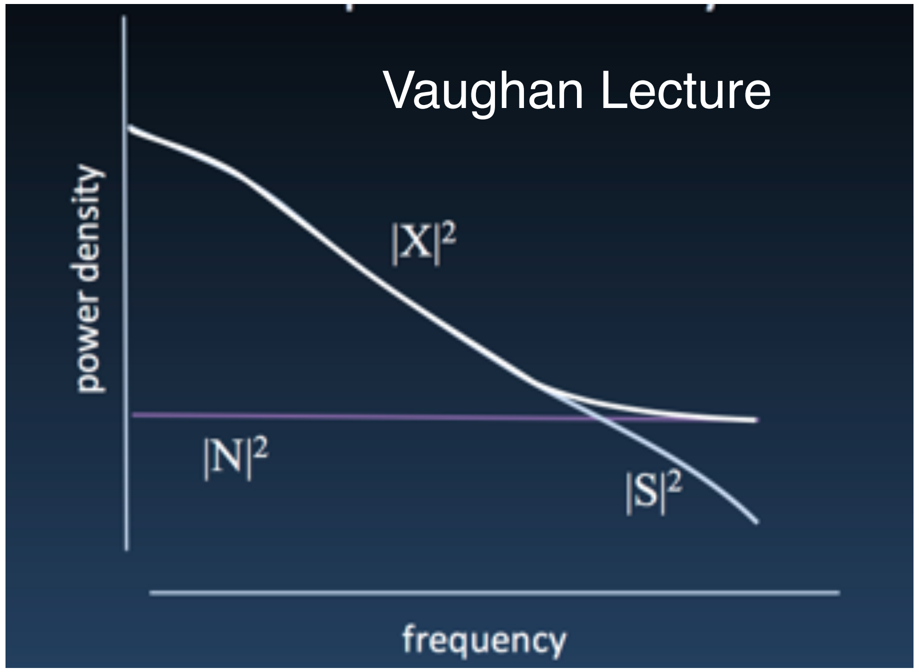
Motivation

- Complexity of physical processes and environment lead to degeneracies (AGNs, GRBs, etc)
- Standard SED modeling, morphology, “eyeballing” lightcurves insufficient - extract more from MWL LCs ?
- Need **newer and novel “observables”** for sharper understanding
- Large datasets <=> Statistical Methods (both individual and population) e.g. time series methods

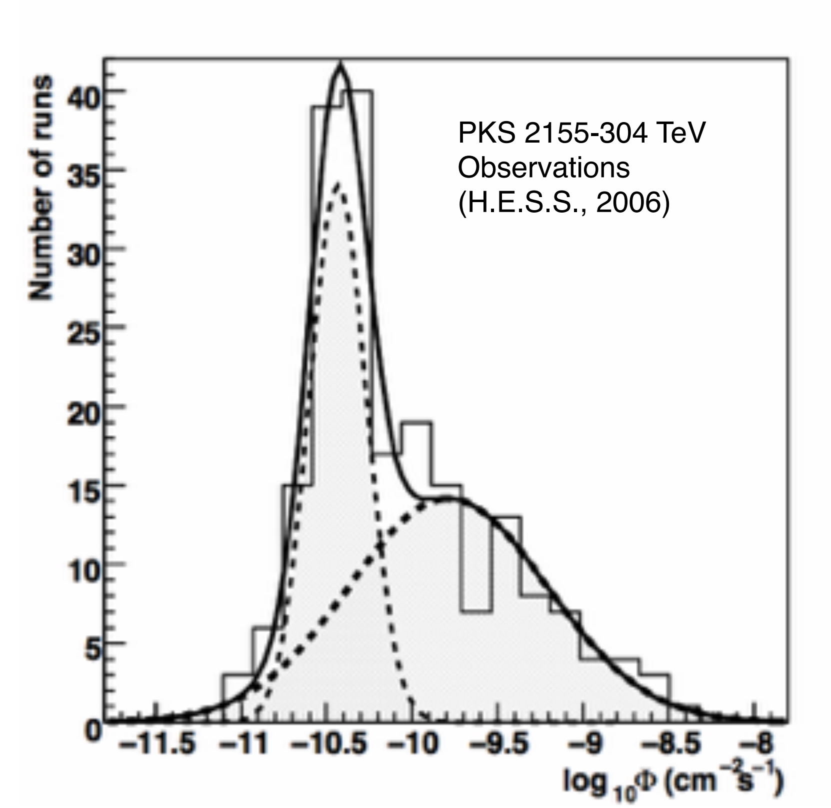




Additional Observables ? : PSD and PDF



- **Power spectral density** or PSD *encodes temporal structure* - "power distribution in timescales"
- Time : x = s + n (Vaughan Lecture)
  Fourier : X = S + N
  $|X|^2 = |S|^2 + |N|^2$ + Cross
  $PSD(f) = \langle |S|^2 \rangle = \langle |X|^2 \rangle - \langle |N|^2 \rangle$
- Formally (for AGNs and others)
  Time : Lightcurve(t) = Dynamical(t) x Acceleration(t) x Radiation(t) x Observation(t) [**Product**]
- Fourier : Lightcurve(f) = Dynamical(f) * Acceleration(f) * Radiation(f) * Observation(f) [**Convolution**]
- First 2 moments - mean and variance



- **Probability Distribution Function** or PDF probes the fundamental form of the physical processes
- Default assumption is Gaussian ; evidence for lognormality => Multiplicative **(Lyubarskii 97, Uttley et a., 2005)** or Cascade like processes (exception see Biteau and Giebels, 2012)
- Contains the skewness and kurtosis of the underlying data

General Approach

- Observed Emission
  - Function of **time (lightcurve)**, space (morphology), energy (energy spectrum) **How tells us why**
  - Individual sources : physical mechanisms at emission sites
  - Population : general trends

- **Timing analysis** : Observed light curve is 1 sample or realisation -> we need to "repeat" to get significant results
  (Timmer and Koenig, 1995, Emmanoulopoulos, McHardy and Papadakis, 2013)

- Signal coupled with noise
  - Either disentangle deterministic signal from random fluctuations (for eg. detecting periodic/QPOs)
  - Or the interesting signals are random fluctuations themselves (for eg. flaring vs quiescence)

- Observational Irregularities : Allocation, satellite cycles, visibility, competing targets, etc
  - gaps
  - coarse or uneven sampling
  - length of observation limited

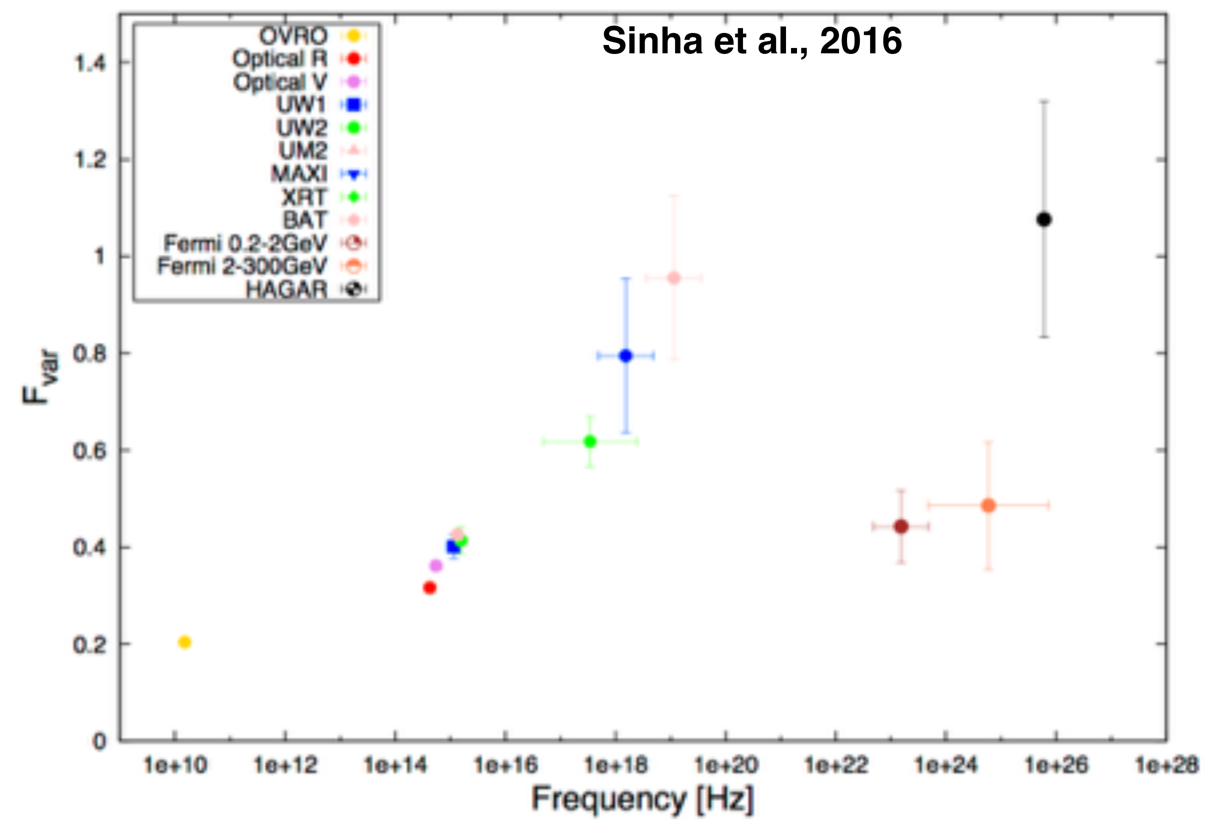
Emmanoulopoulos et al., 2013, Allevato et al., 2013, Chakraborty & Biteau (In prep)

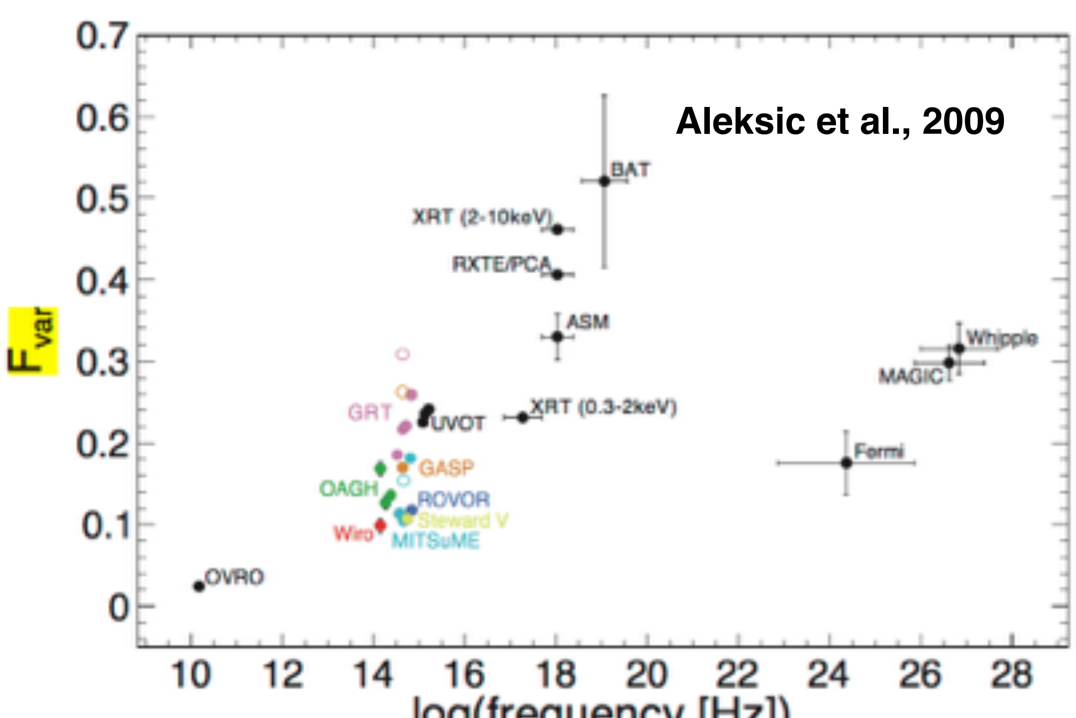
Start with "fundamental observables" : PSD and PDF → Generate realisations / surrogate data (for e.g. lightcurves TK95,DE13, etc) → Impose observational conditions (cadence, cuts, uncertainties, etc) → Evaluate estimators (Fvar, CCF, Spectral shape, etc.) for each realisation → Likelihood Analysis as function of the "fundamental parameters"

Fvar and VED

$$Fvar = \frac{\sqrt{S^2 - \sigma^2}}{\phi_{\text{mean}}}$$

- Increasingly used for MWL studies
- Simple yet ***not unbiased estimator***
- Energy / wavelength dependent Fvar => VED





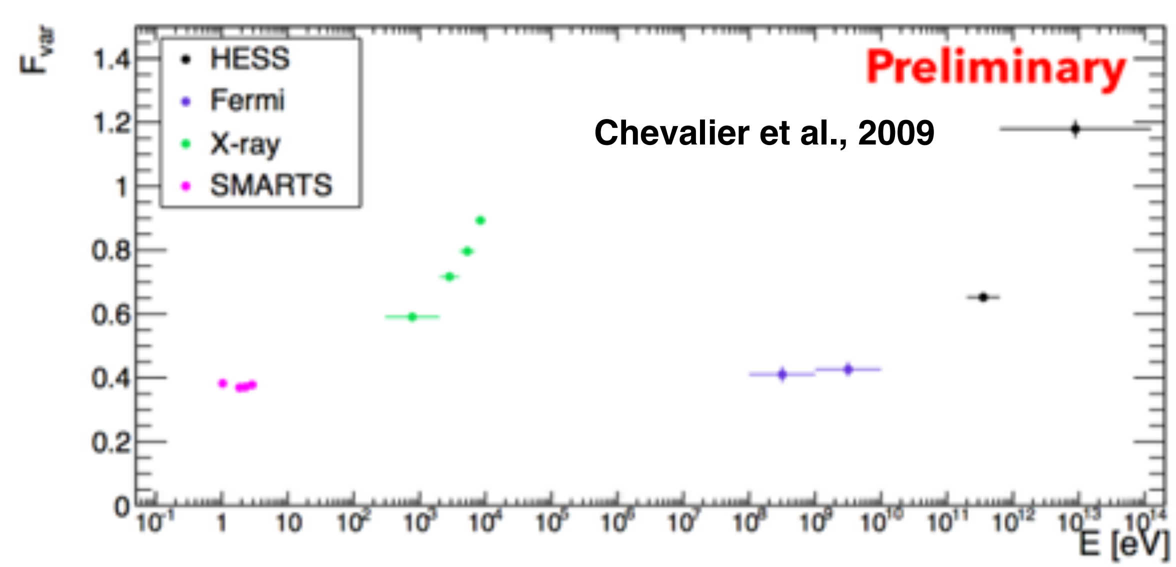
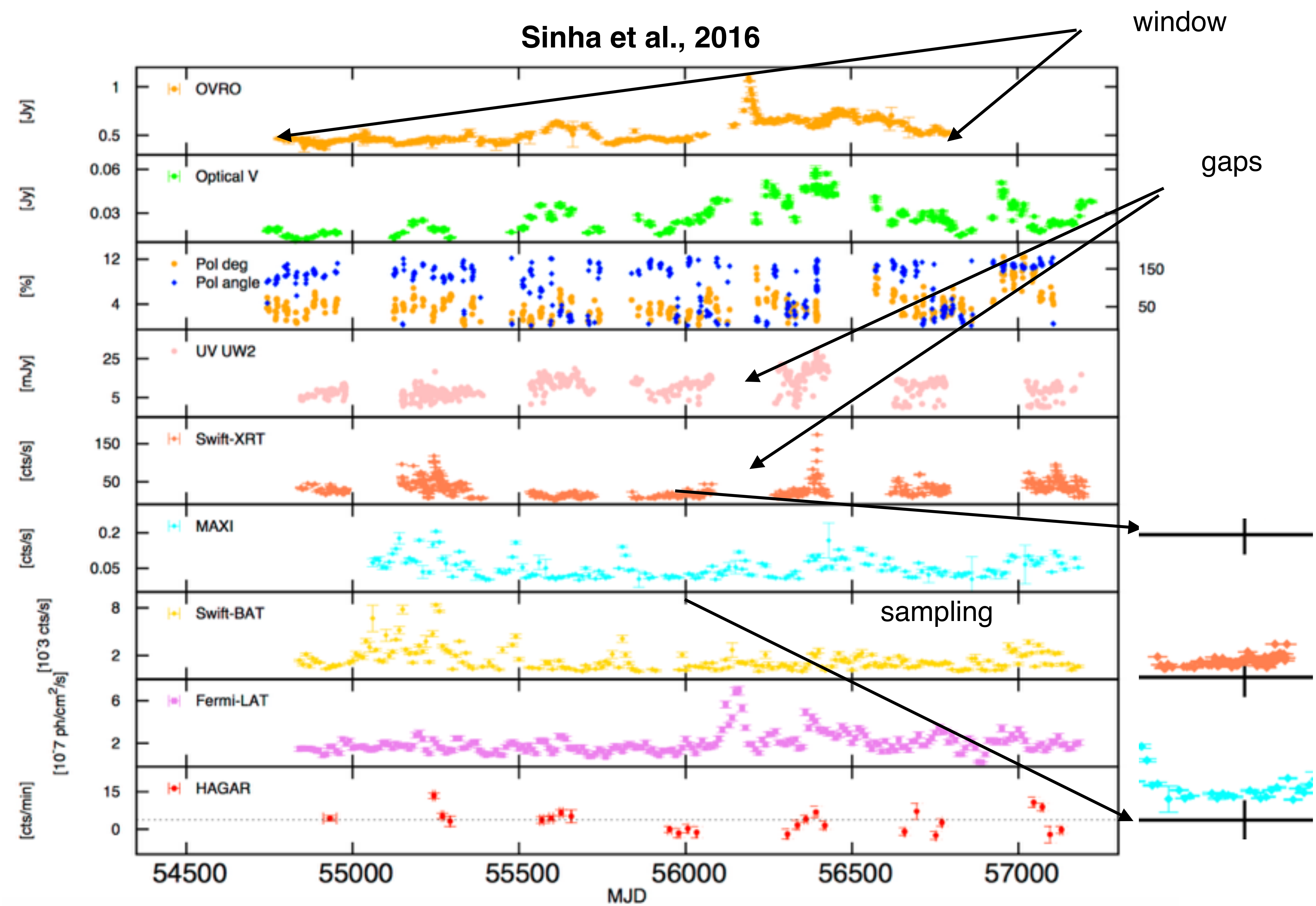


Figure 3: VED of PKS 2155-304.

- Lightcurve(f) = Dynamical(f) * Acceleration(f) * Radiation(f) * **Observation**(f)

MWL Observations of Mrk 421



Method to estimate Fvar

Start with “fundamental observables” : PSD **(PL)** and PDF **(Gaussian)**

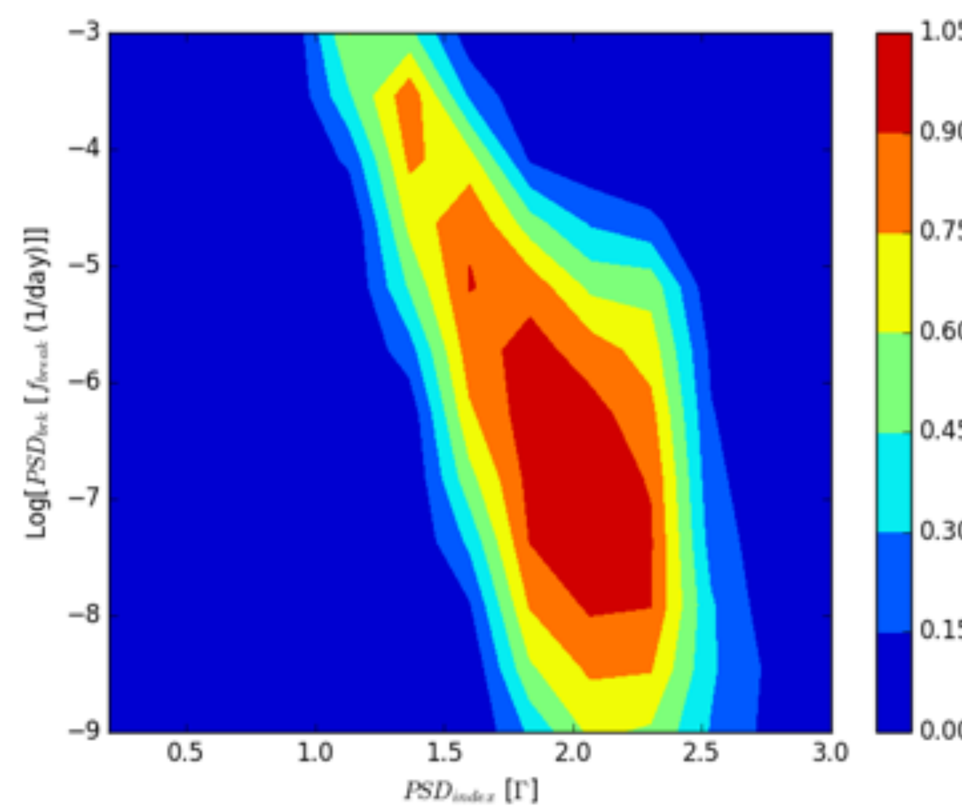
→ Generate realisations / surrogate data (for e.g. lightcurves **TK95**,DE13, etc)

→ Impose observational conditions (**cadence**, cuts, uncertainties, etc)

→ Evaluate estimators (**Fvar**, CCF, Spectral shape, etc.) for each realisation

→ Likelihood Analysis as function of the “fundamental parameters” **(Map of index and norm)**

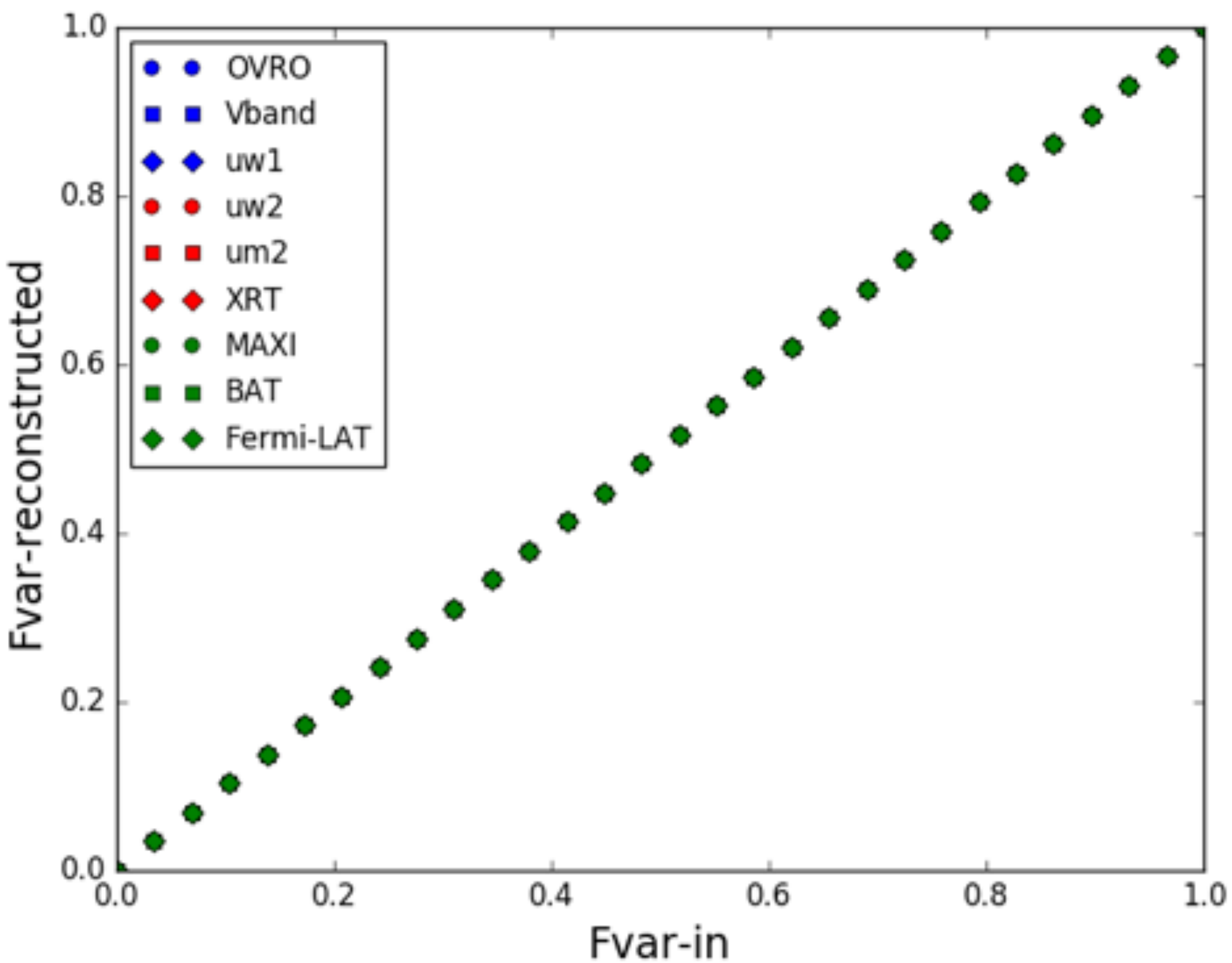
Sinha et al., 2016



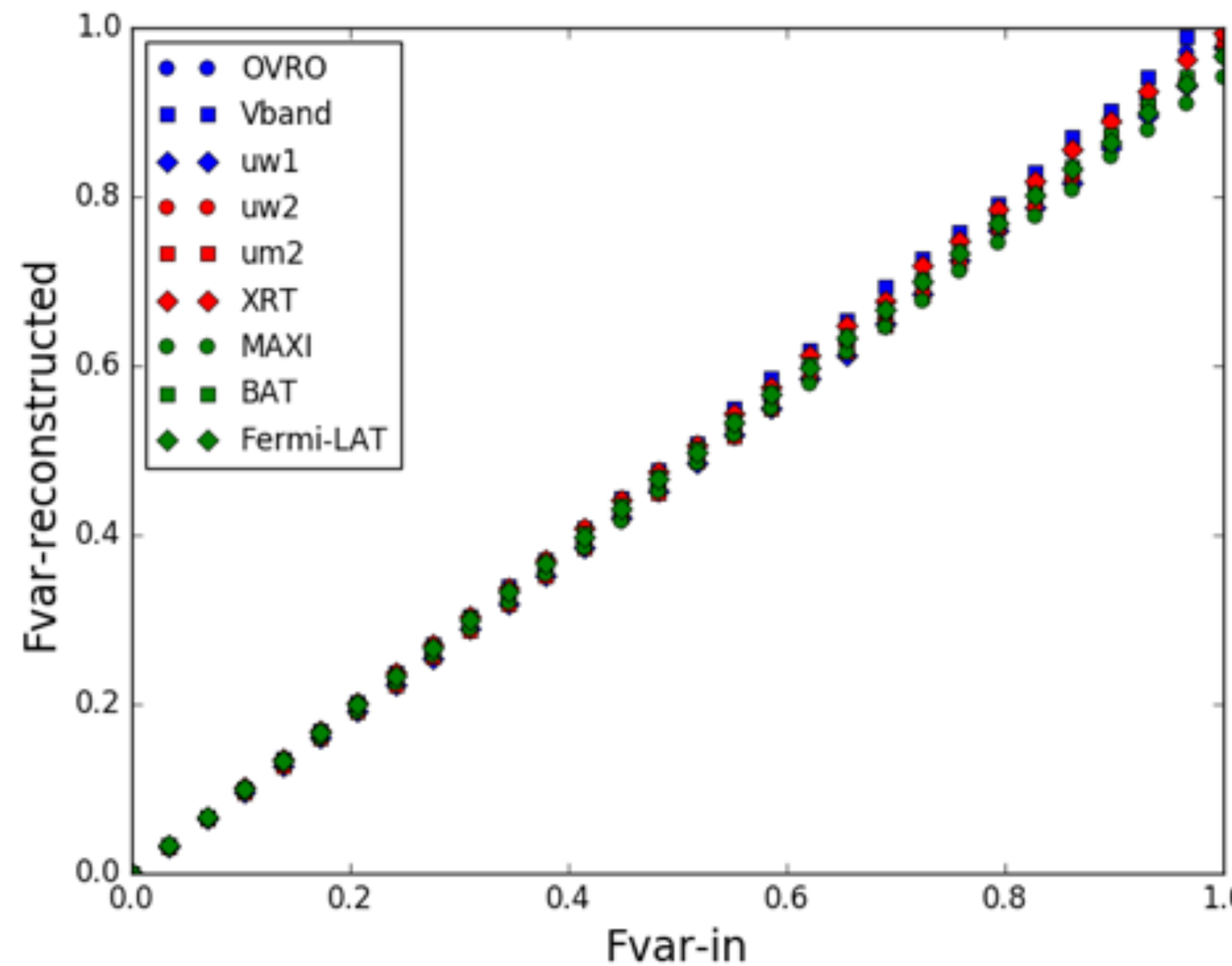
Fvar reconstruction

Red Noise : Index = 2.0

“Ideal” Cadence



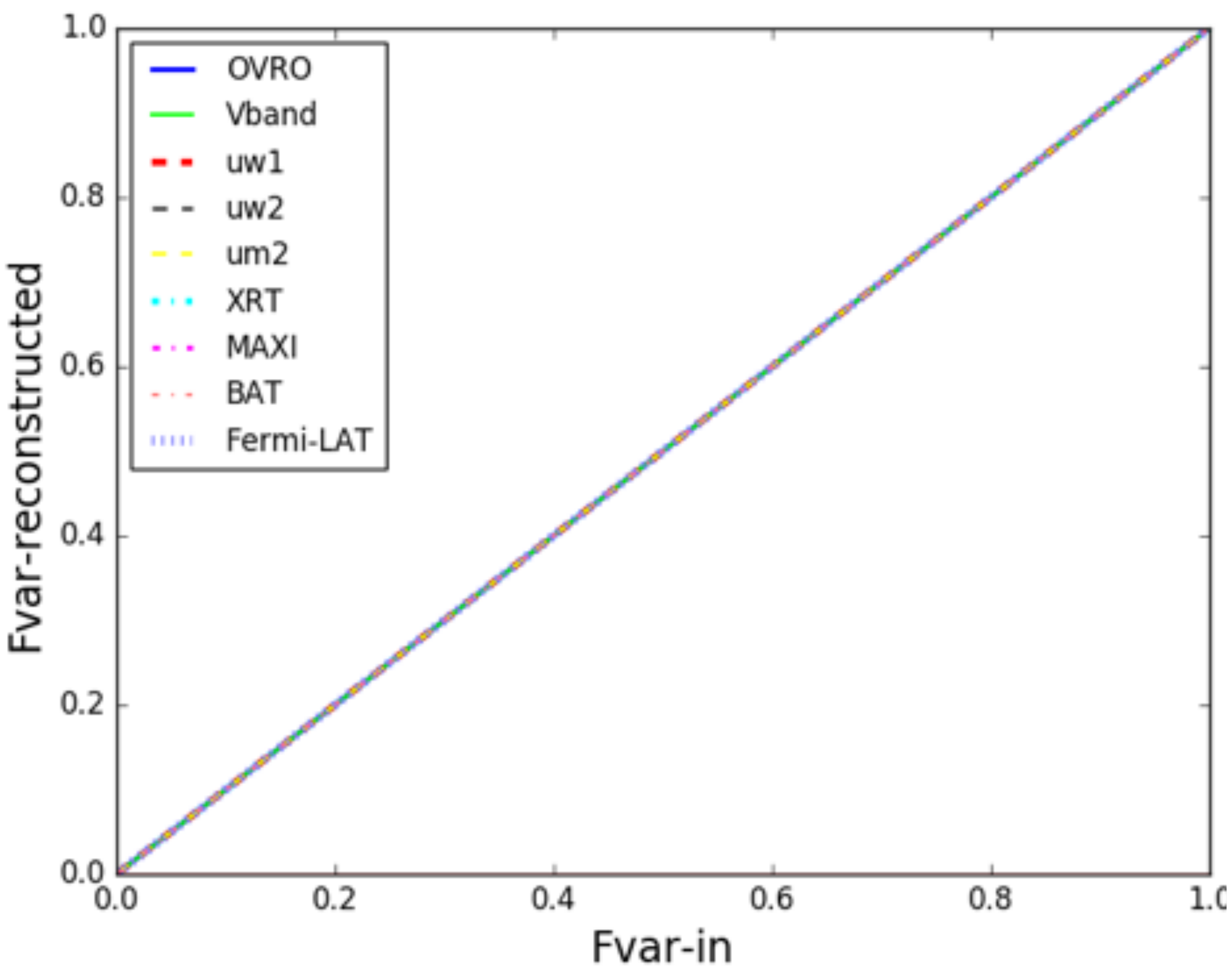
Observed Cadence



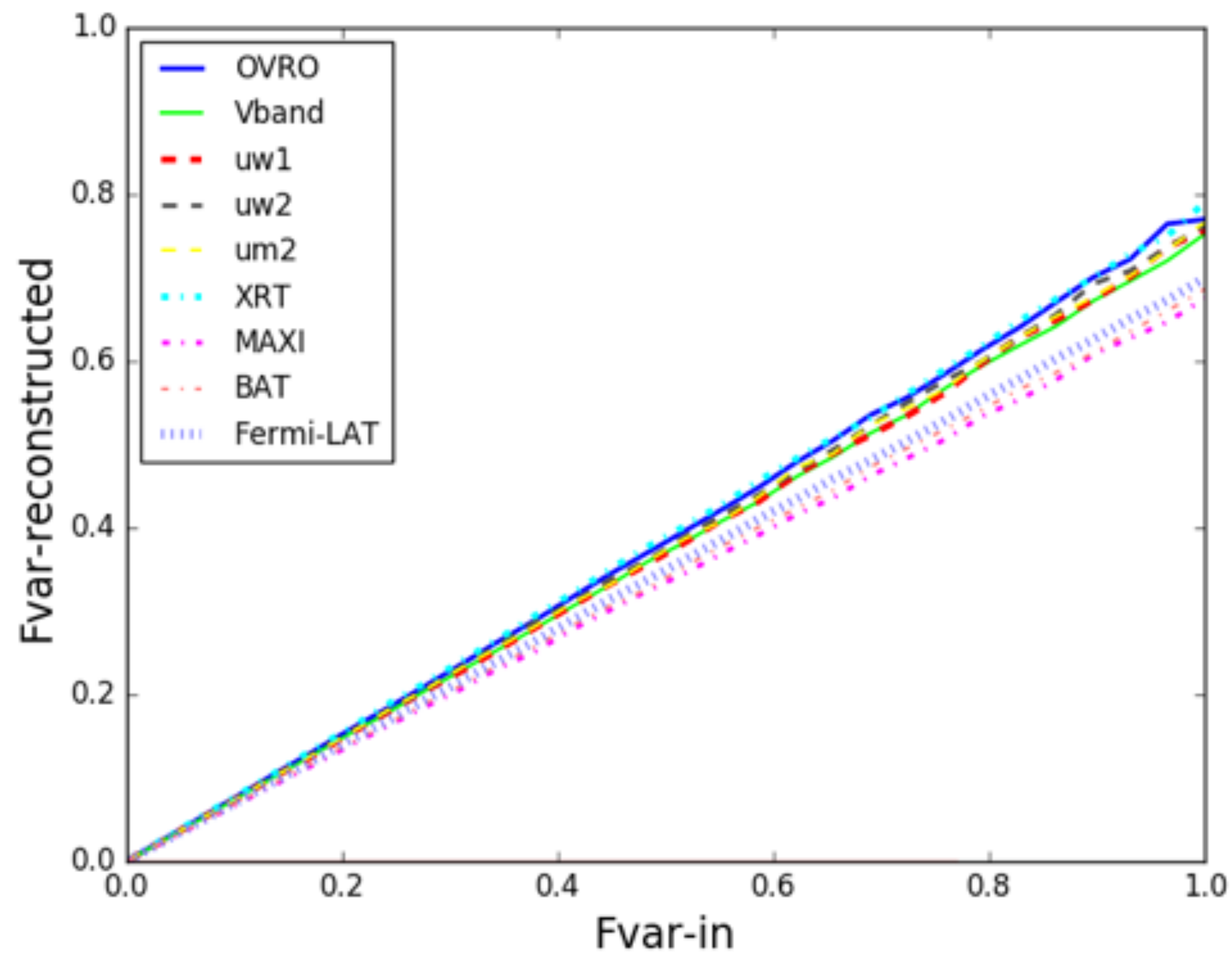
Fvar reconstruction

Pink Noise : Index = 1.0

“Ideal” Cadence

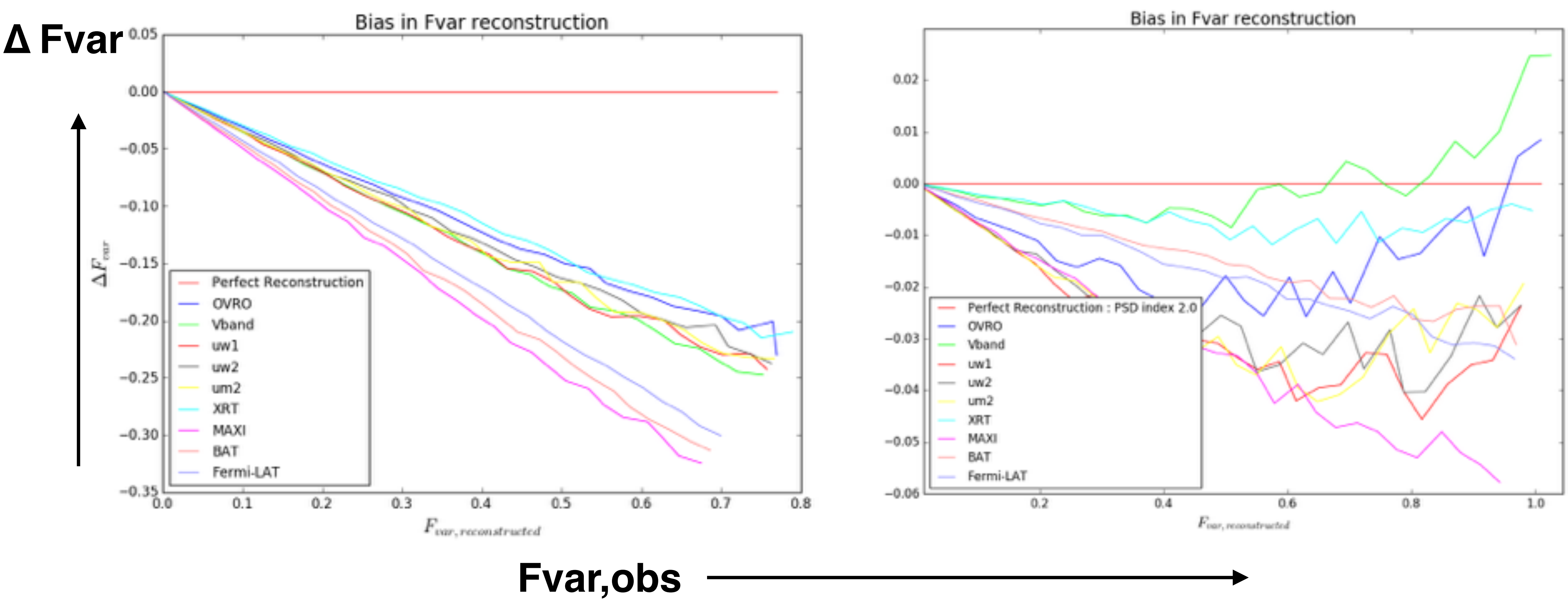


Observed Cadence



Fvar reconstruction

simulation PSD index = 1.0 simulation PSD index = 2.0

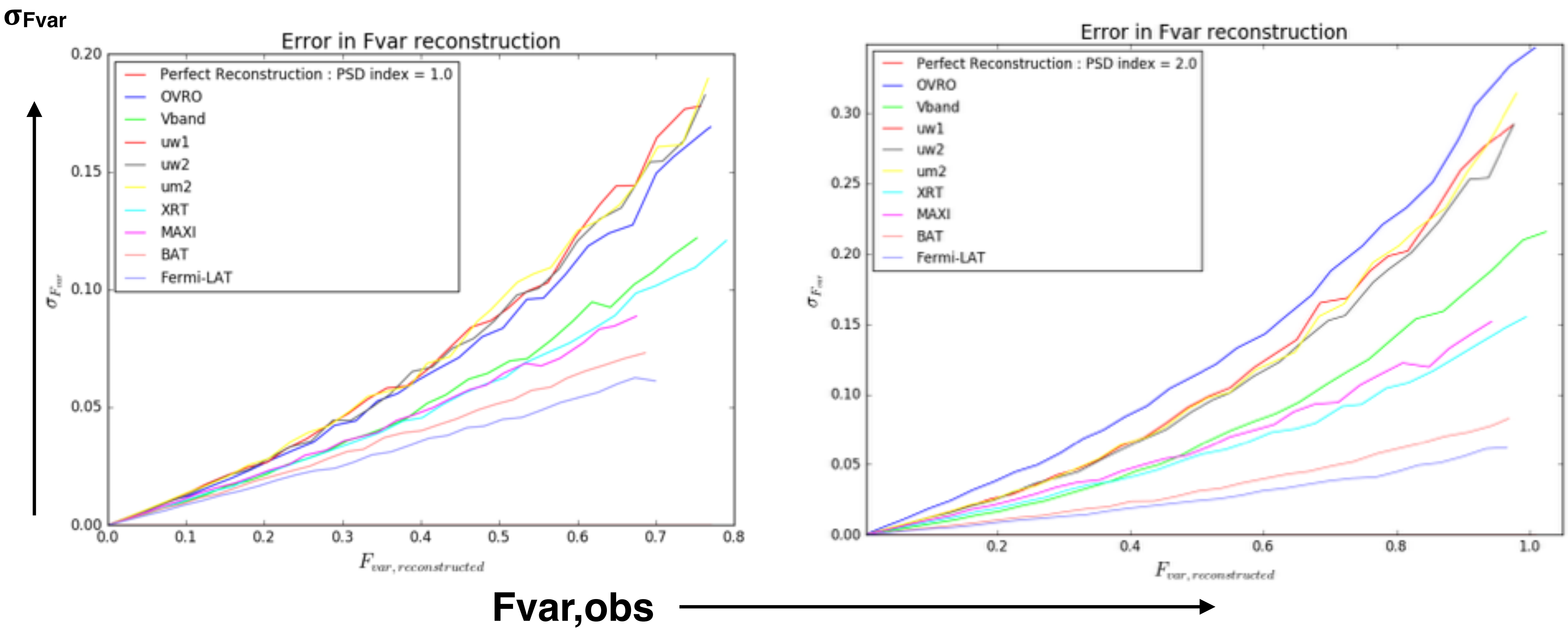


- Bias due to observational effects - larger for harder PSD (brown vs red) -> sampling effects ?
- Relatively, best reconstructions for finely sampled, least “gapped” (OVRO, Vband)
- Length of observational window less important for long enough durations and slow variations

Fvar reconstruction….

simulation PSD index = 1.0

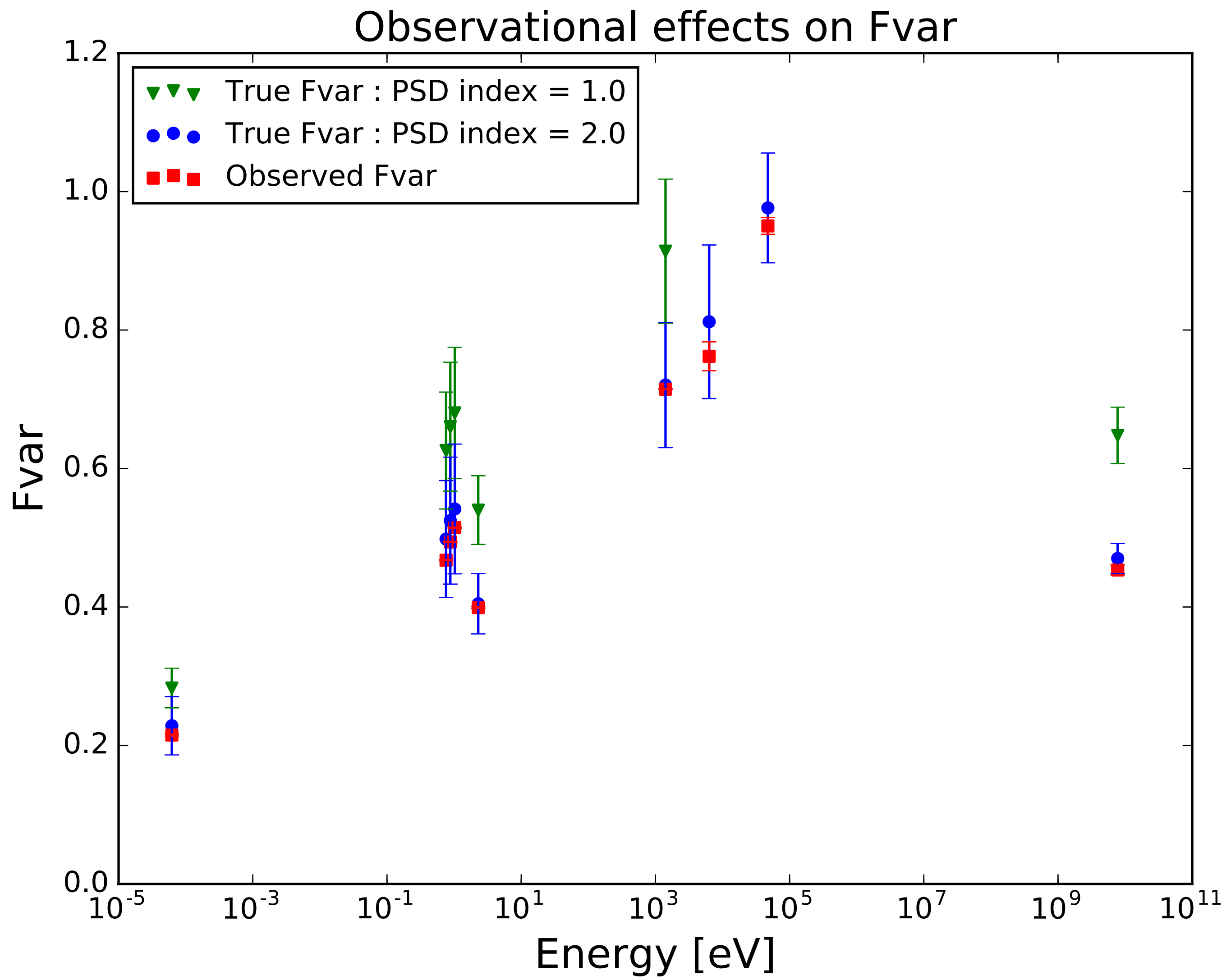
simulation PSD index = 2.0



- Uncertainty in Fvar comparable for brown vs red noise
- Relative uncertainty larger for longer wavelengths - larger dispersion (**σ** does not include flux errors)

Variability **E**nergy **D**istribution

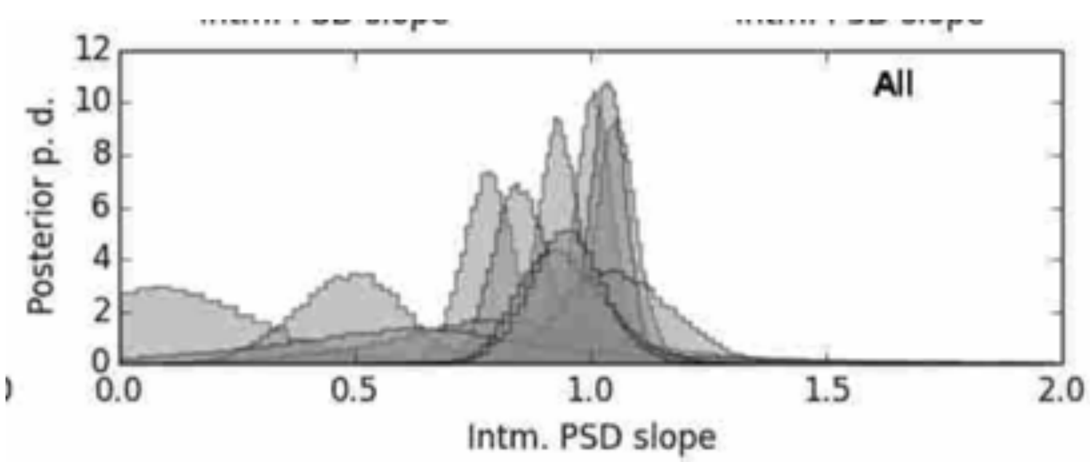
- Even with red noise, both the **uncertainty and bias due to observational effects are non-trivial**
- Correct estimate of variability necessitates incorporating these systematic uncertainties
- Crucial to have coordinated observational cadence across wavelengths
- Further work - **non-Gaussian PDFs**, tests for stationarity



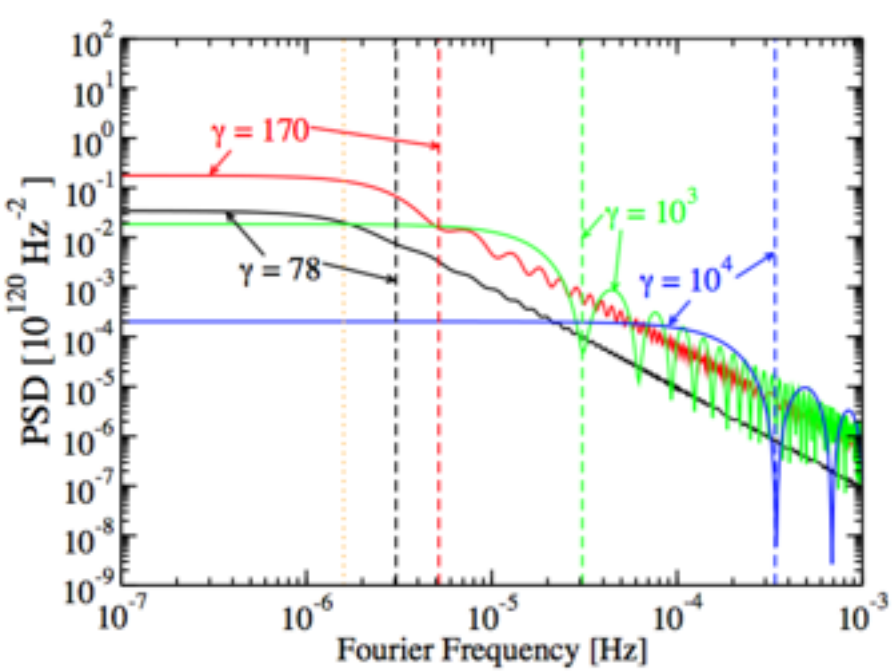
- ***Several applications with simulated LCs***
  - Other estimators like CCF, doubling times, etc. (previous talks, Vaughan, Emmanuoulopoulos et 13)
  - Polarisation variability (Blinov - RoboPol first season results)
  - Estimation of flaring in AGNs
  etc…..

Origin of Power-laws

- Lightcurve(f) = **Dynamical(f) * Acceleration(f) * Radiation**(f) * Observation(f)



LAT : 100 MeV - 300 GeV LCs, 4 years
Sobolewska et al.,2014



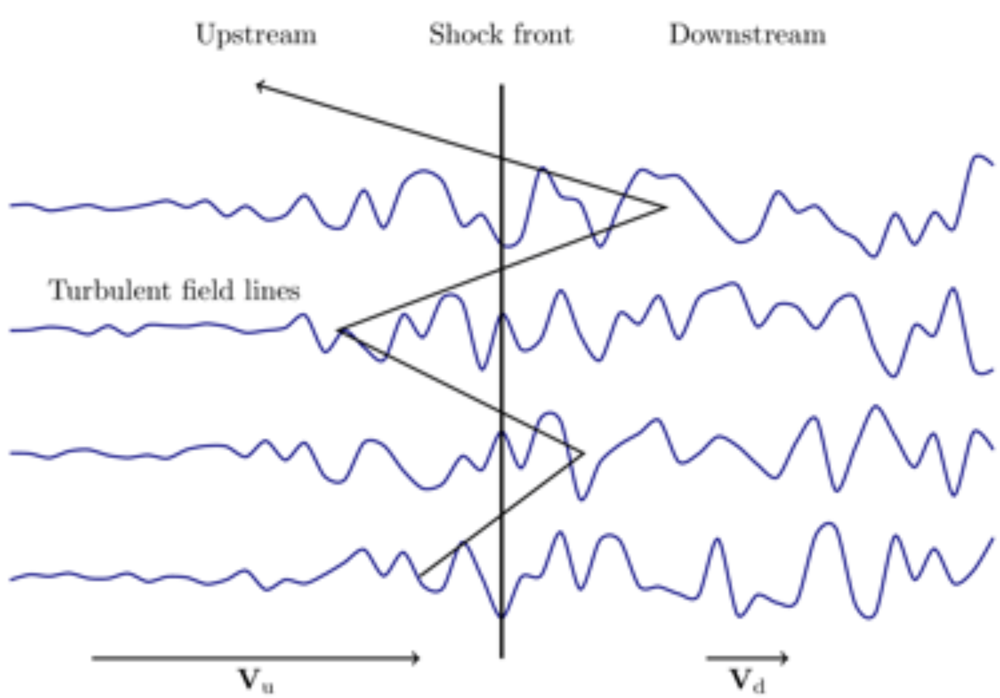
Finke et al.,2014

- Attempts at deeper theoretical understanding of timing characteristics (Lyubarskii et al., 1997, Rieger and Volpe 2010, Finke et al., 2014,2015, Pollack et al.2016)

- Understanding origin of temporal structure of fluctuations (PSD)
  - why power-law PSDs ?
  - fluctuations in injection - but what is the source ?
  - fluctuations in accretion flow -> flicker noise (PSD index 1 - 2)
  - jet-disk connection cannot account for minutes timescales in TeVs (no Doppler)
  - MHD turbulence -> shortest timescales

Particle Acceleration -> Power-Laws

- Lightcurve(f) = Dynamical(f) * **Acceleration**(f) * Radiation(f) * Observation(f)



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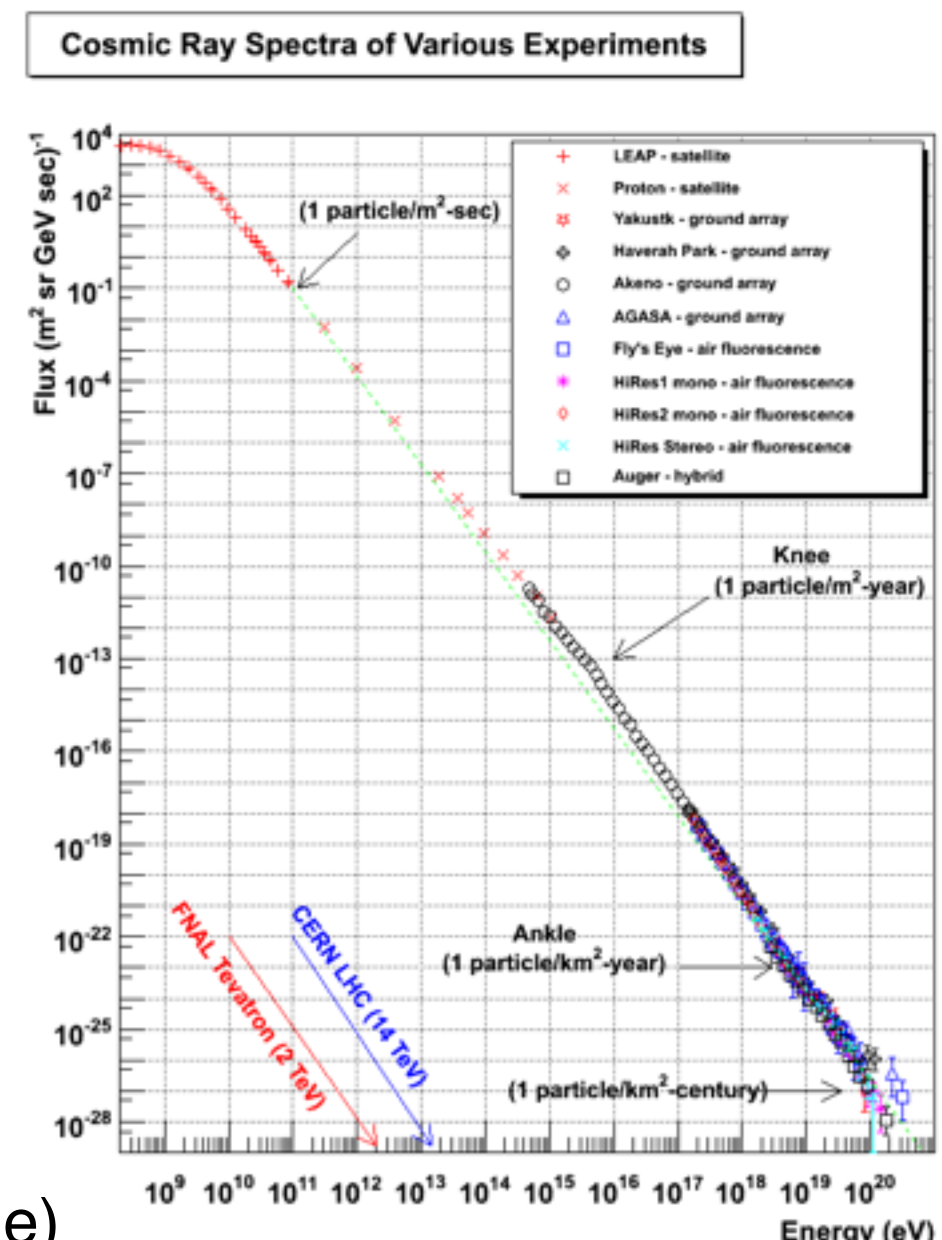


Could they have same origin ?

(Analytical / simulations with Simone Giacche)

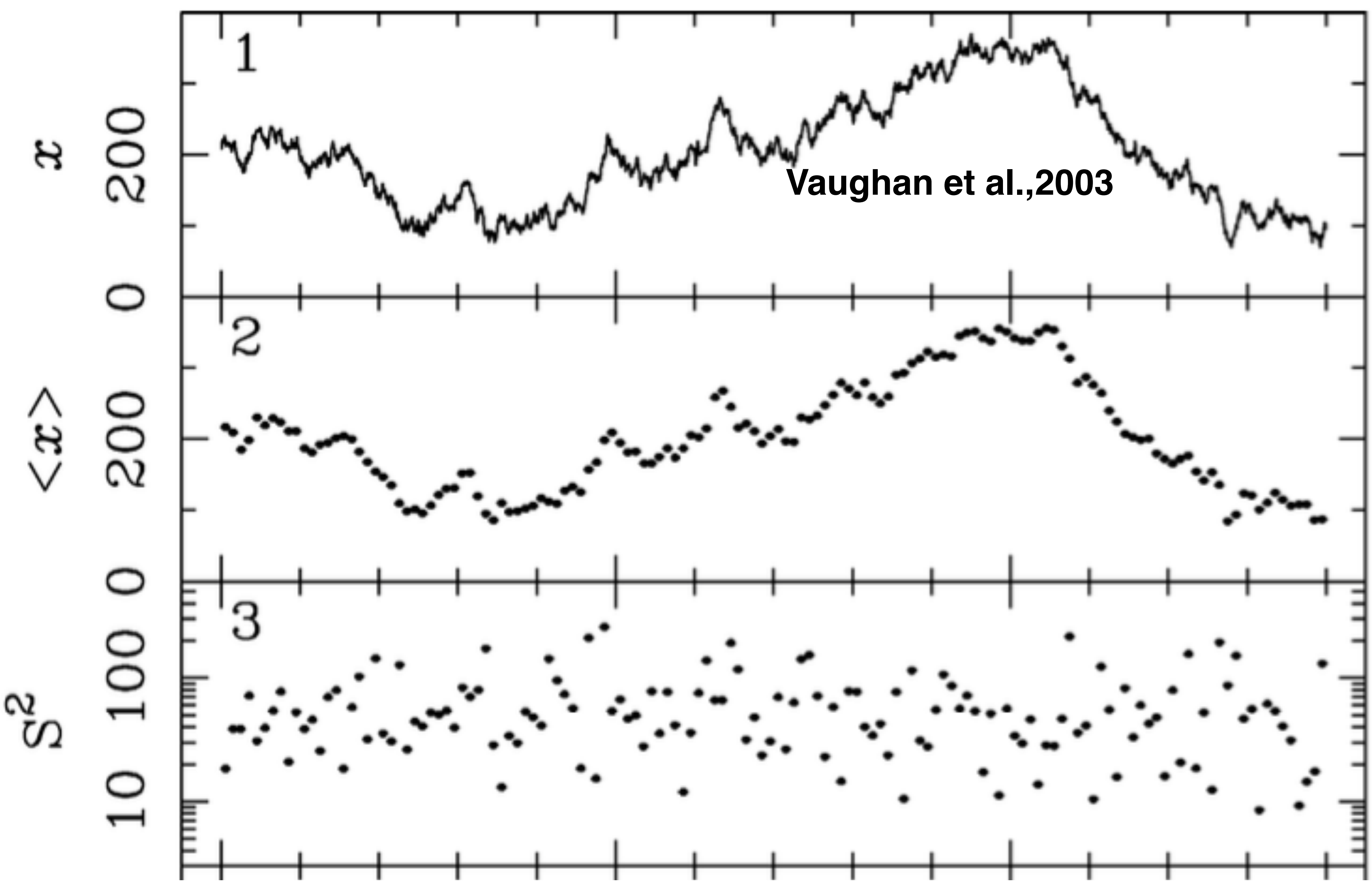
Conclusions

- Complexity of AGN processes and environment necessitates “novel observables”
- Statistical methods may provide these via PSD and PDF => naturally emerge from big datasets
- Estimates of variability require simulations - uncertainties and biases related to cadence are important
- Estimates of observables from simulations
- Reaffirms need for coordinated MWL observations
- Increasing theoretical understanding of PSD and PDF in terms of physical processes

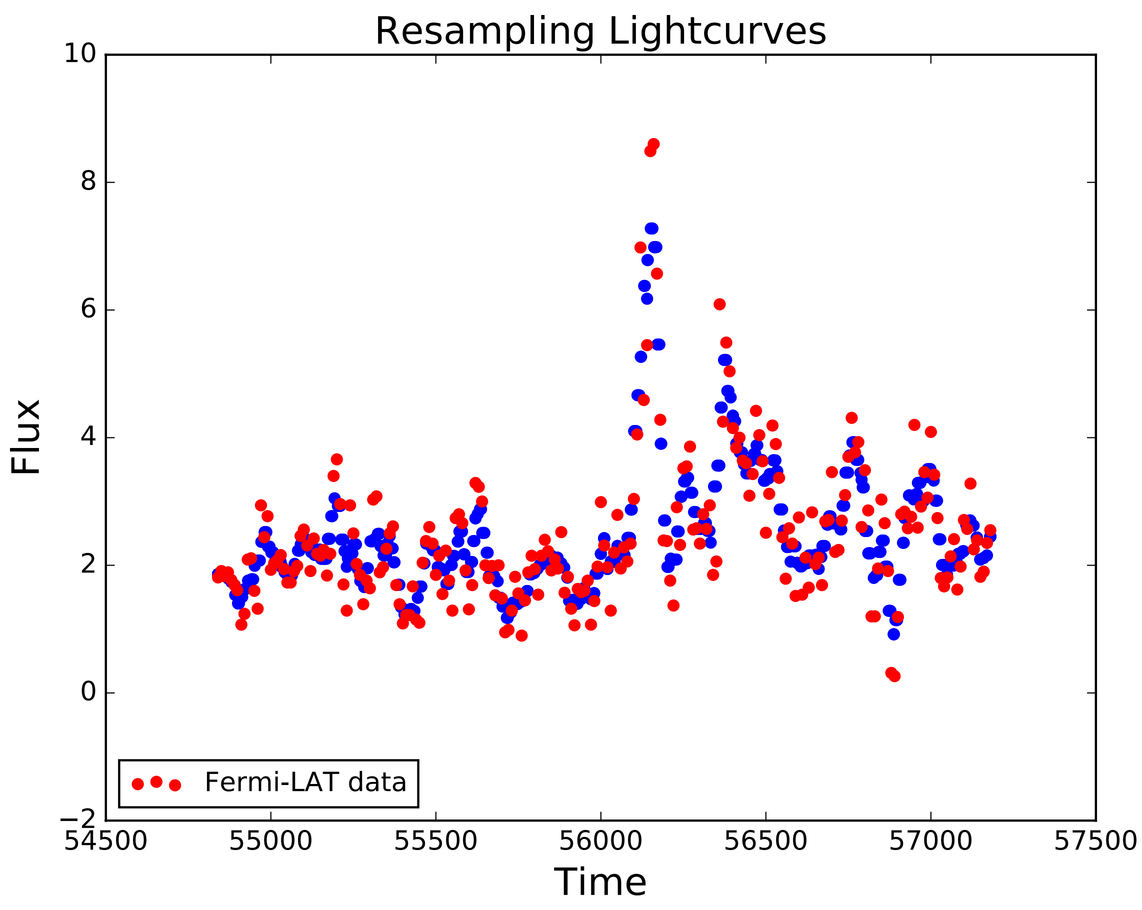
THANK YOU

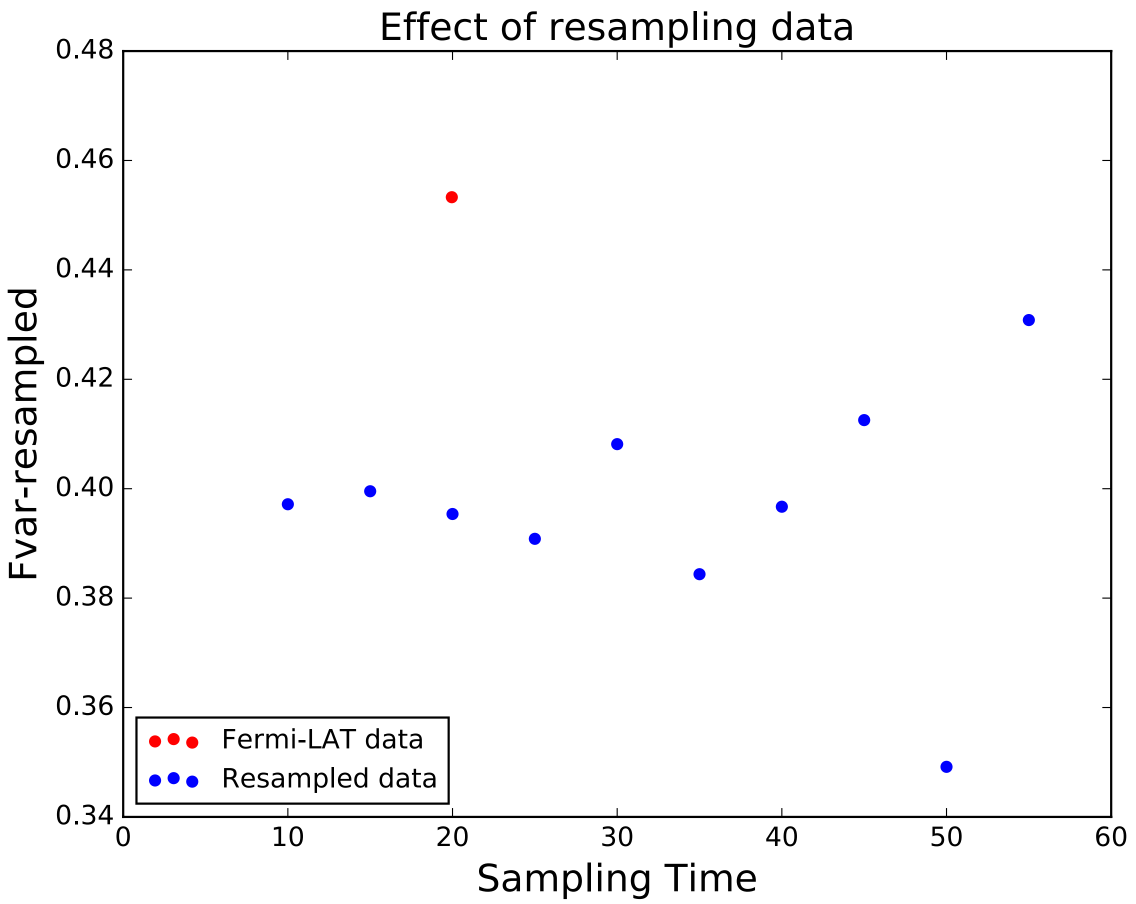
- In collaboration with
  - Frank Rieger, Simone Giacche (MPIK)
  - Jonathan Biteau (IPNO)
  - Paul Morris, Garret Cotter (Oxford)

Backup

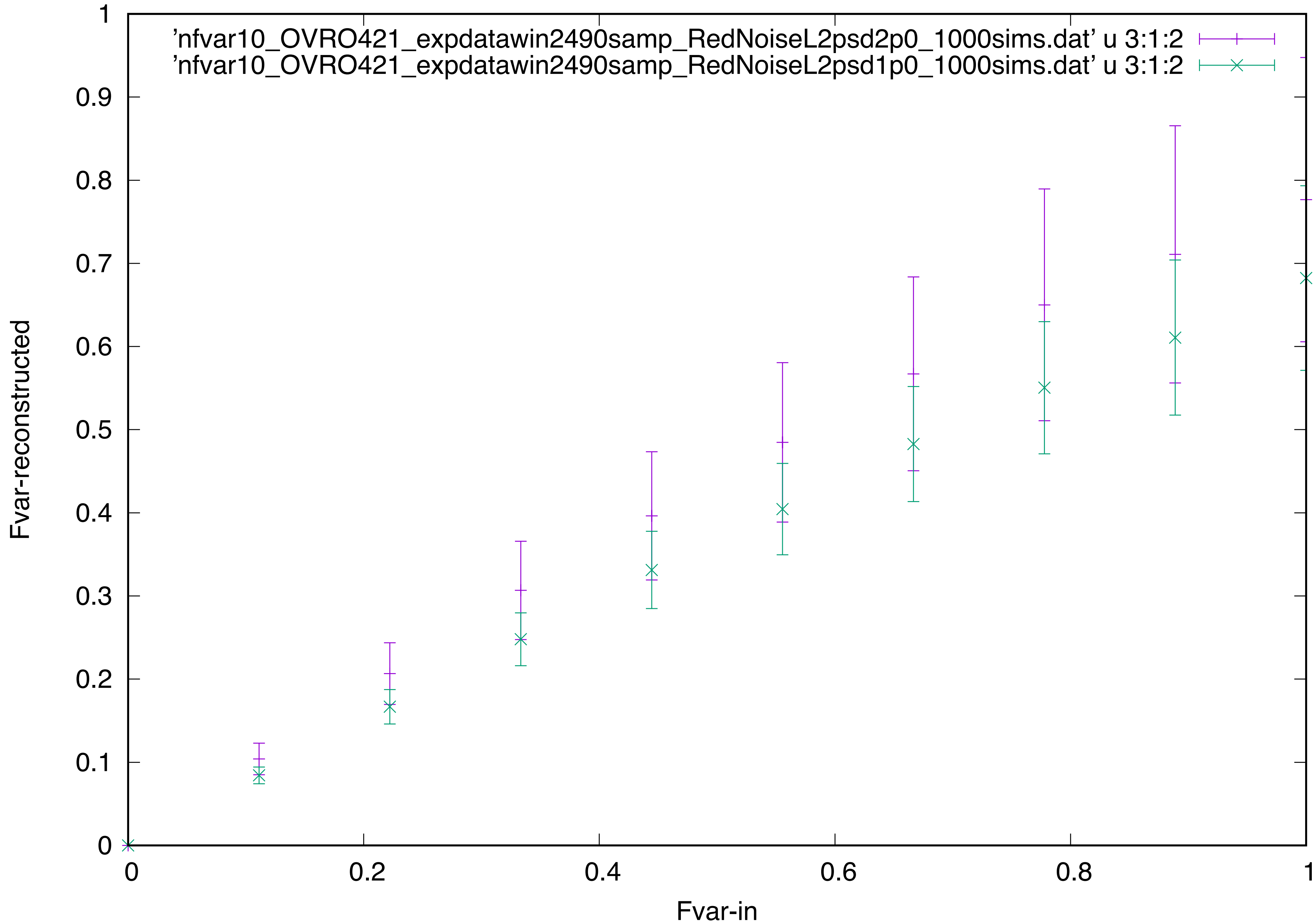


Simple Resampling Effects





Non-gaussian PDF



Motivation

- Sources vary with time ! How tells us why
  - Individual sources : physical mechanisms at emission sites
  - Population : general trends
- Unlike other experiments we cannot manipulate or repeat exactly the same way
- Observed light curve is 1 sample or realisation -> we need to "repeat" to detect
- Signal coupled with noise
  - Either disentangle deterministic signal from random fluctuations
  - Or the interesting signals are random fluctuations themselves
- Observational Irregularities : Allocation, satellite cycles, visibility, competing targets, etc
  - gaps
  - coarse or uneven sampling
  - length of observation limited

Power Spectral Density

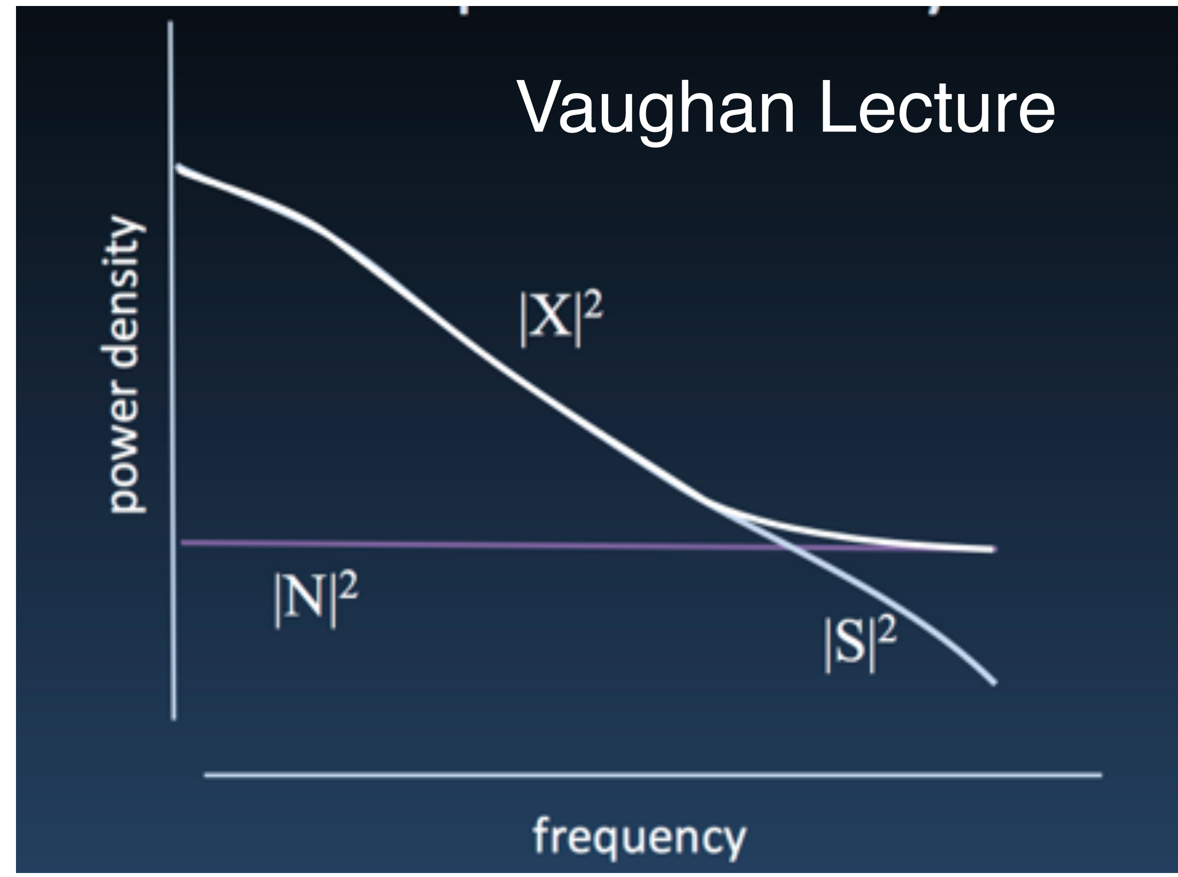
- Power spectral density or PSD is the "distribution of timescales"

- Frequency <-> timescales

- Time : $x = s + n$
  Fourier : $X = S + N$
  $|X|^2 = |S|^2 + |N|^2 + \text{Cross}$
  $PSD(f) = \langle |S|^2 \rangle = \langle |X|^2 \rangle - \langle |N|^2 \rangle$
  <=> Related to the variance

- Formally (for AGNs and others)
  Time : Lightcurve(t) = Dynamical(t) x Acceleration(t) x Radiation(t) x Observation(t) [**Product**]

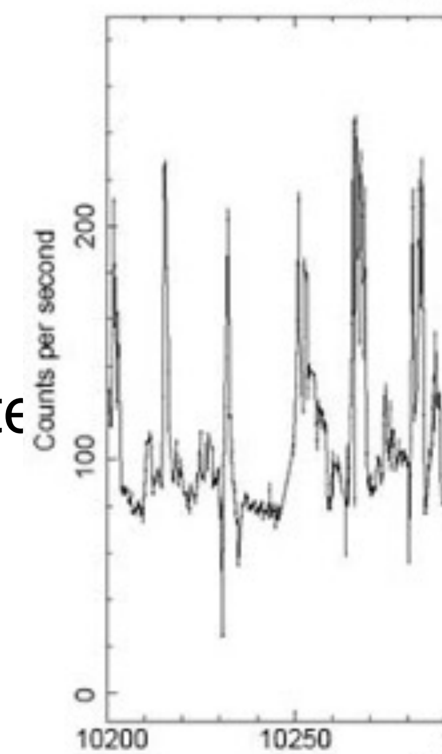
- Fourier : Lightcurve(f) = Dynamical(f) * Acceleration(f) * Radiation(f) * Observation(f) [**Convolution**]



- Dynamical -> Periodic, slow variations
  Acceleration -> Stochastic / Shocks
  (Sironi et al., 2015, Giacche and Chakraborty, in progress)
  Radiation-> (LC simulations <-> "Observables")
  Observation-> Potential (CTCs, others)

Types of lightcurves

- **Periodic** - differentiate deterministic from noisy background
- **Transient** - differentia… deterministic from noisy background
- **Stochastic** - noisy (from noisy background ?)



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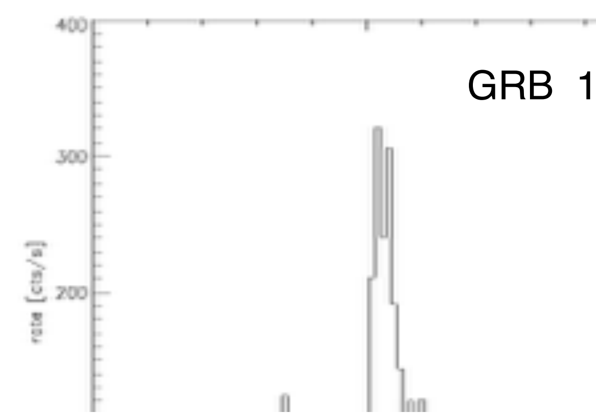
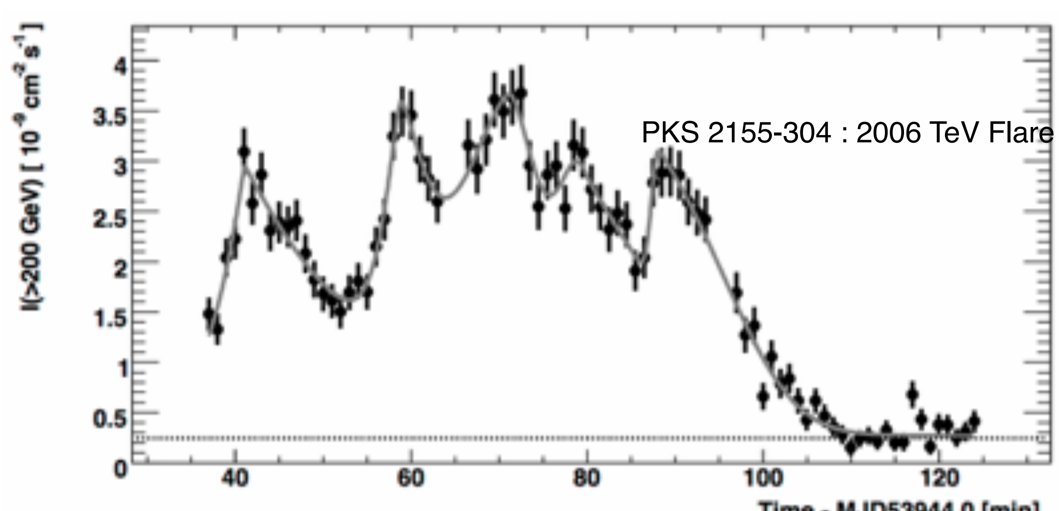
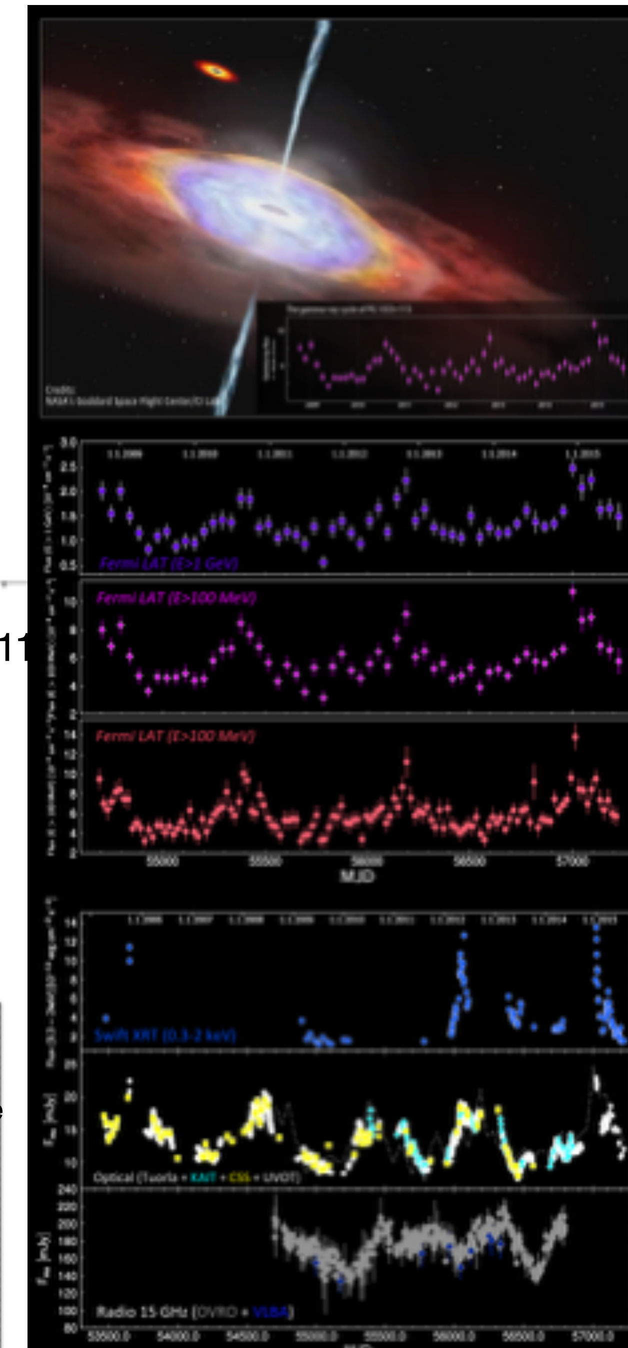
http://imagine.gsfc.nasa.…



GRB 11





PG 1553+113

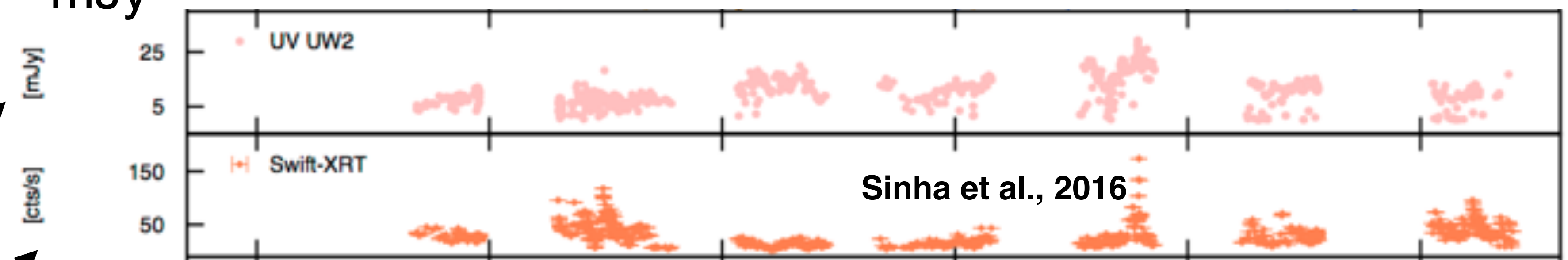
Types of data analyses

- Depending on the wavelength
  - (quasi-)continuous, binned signals or fluxes
  - discrete : time tagged events
  - discrete : counts per time bins

- Naturally analyses methods are also different(ly used)

- Temporal vs Fourier Analyses ; mixed

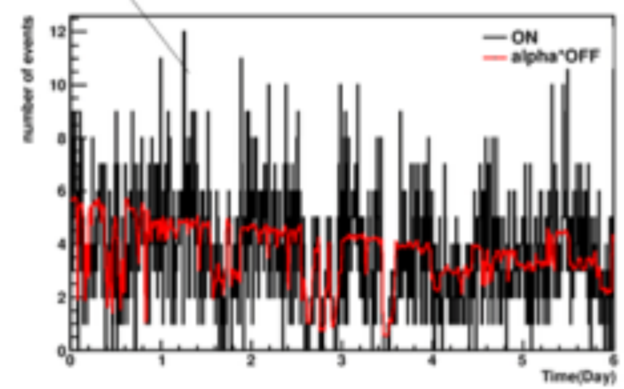
mJy

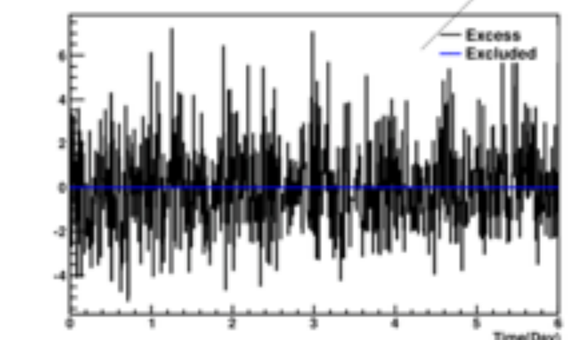


cts/sec

ON/OFF events

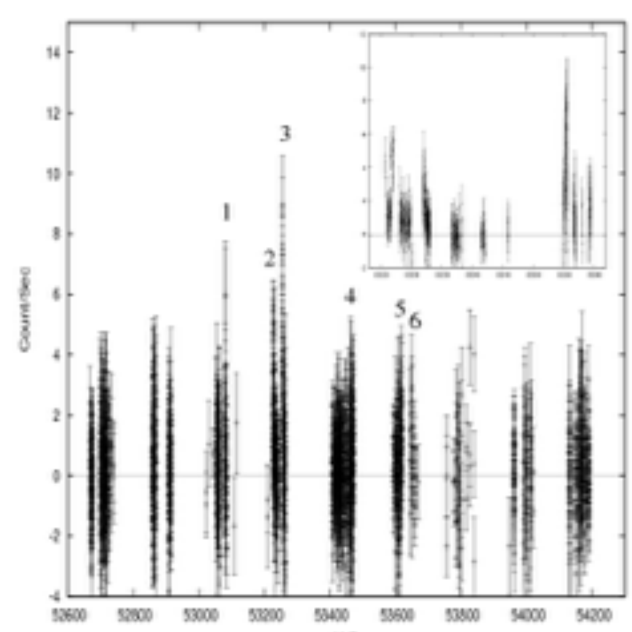
Excess





Helen Poon : GC Analysis

Time vs Frequency domain



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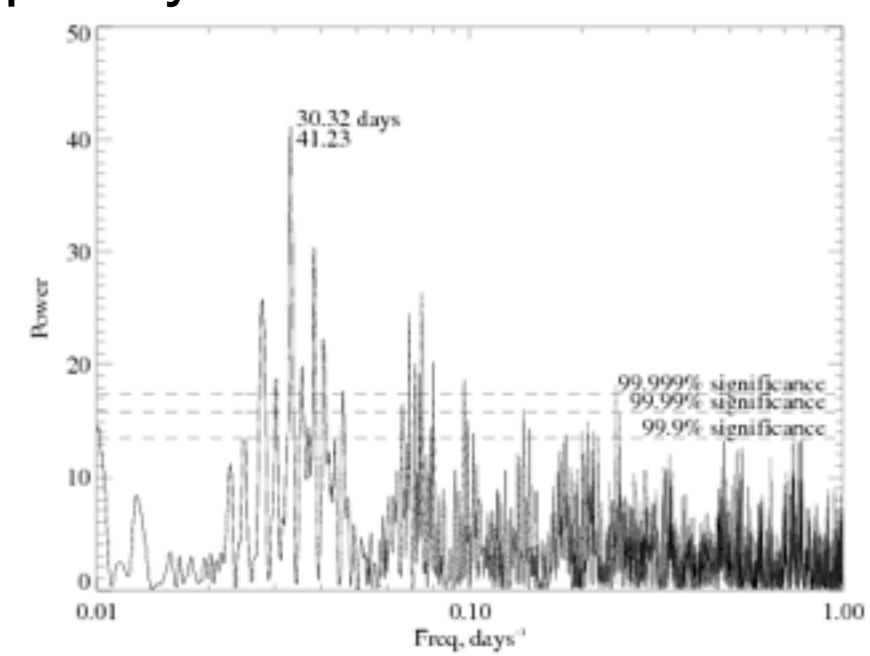
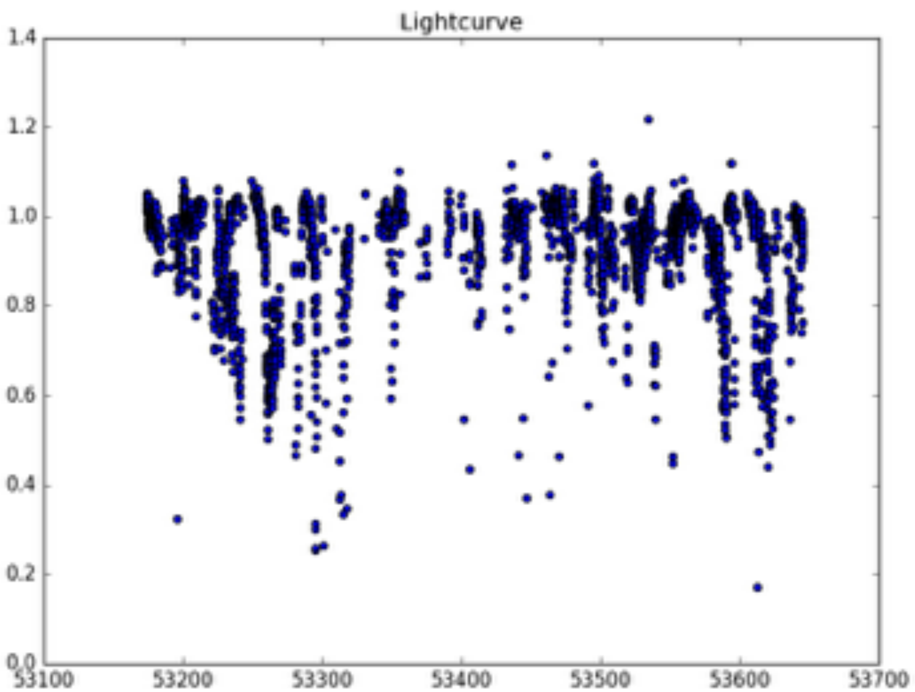
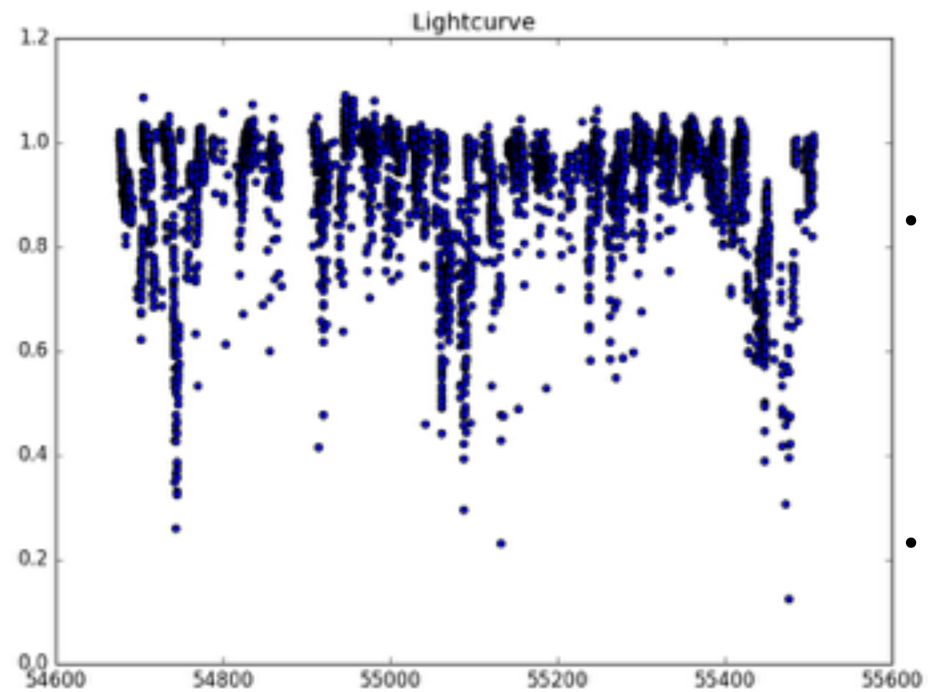


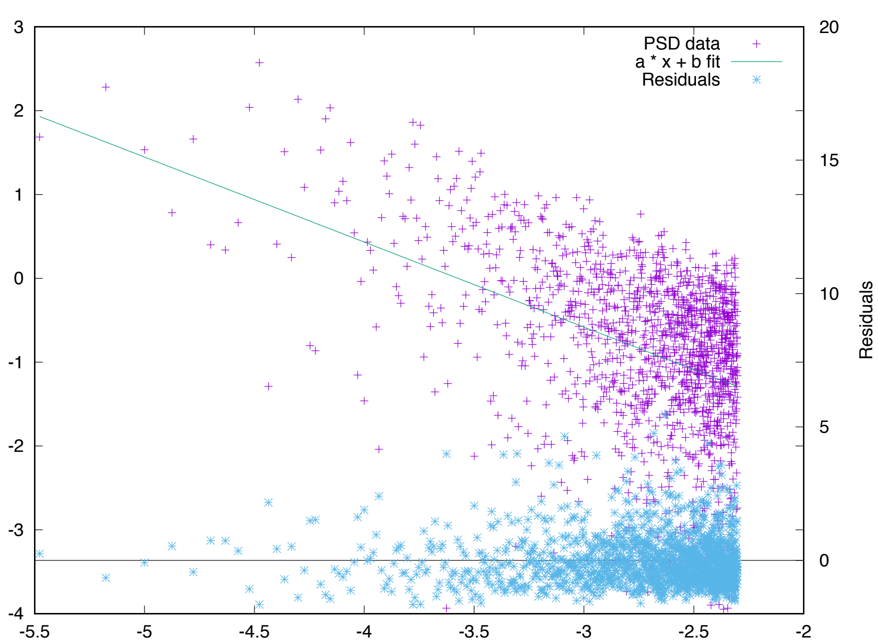
IBIS/ISGRI long term LC (18-60\,keV) of IGR J16465--4507

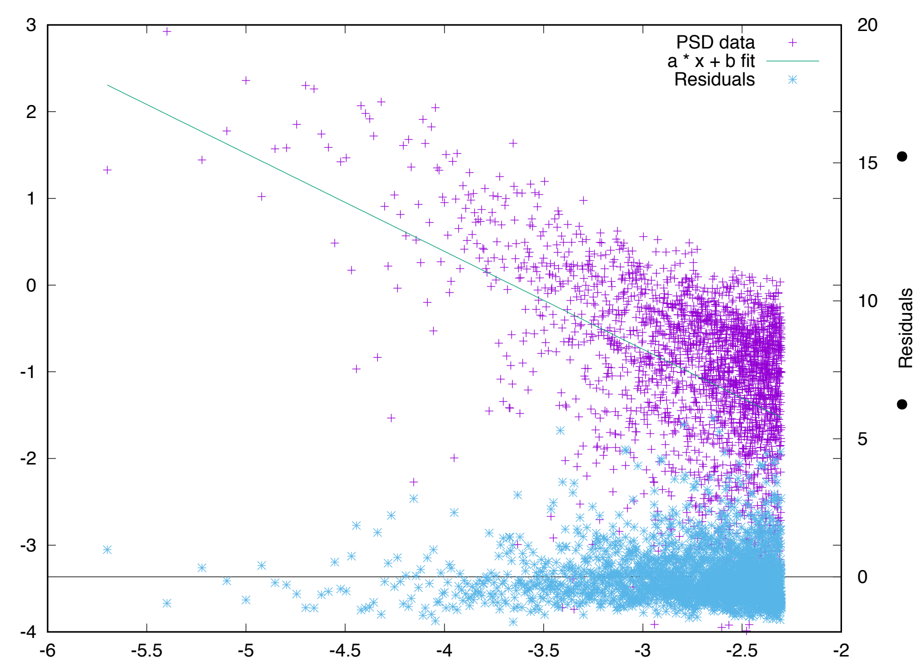
- Lightcurve(f) = Dynamical(f) * Acceleration(f) * Radiation(f) * **Observation**(f)

Applications for foreground diagnostics









- Source of variations -> Foreground contamination
- eg. Atmospheric transparency coeff themselves have structure - brown noise (1.0)
- Either correct directly (better) or model
- Could use PSD as discriminator