Biases in Gamma-ray and MWL timing studies of AGN

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Variability

AGN are variable → AGN are compact

Variability provides unprecedented resolution at all energies
albeit with poor imaging qualities.

Variability probes physical processes and hence
Variability studies are closer to lab-physics than most of astronomy

Unfortunately it is very resource intensive and we are very
limited in temporal coverage, resolution and dynamic range.

The effects of limitations depends on the questions

What are we talking about?

Not instrumental (noise, gain, dead-time) → calibrations

Measurements: sampling (window), binning, bias (trigger), flux limits
Measuring: amplitudes, time scales, higher-order moments, phases
Interpreting: time scales as heating, crossing, cooling
Implying: Sizes, geometries, topology and radiation densities
Separating: base, long-term-trends, de-blending, confusion

Correction: relativistic aberration, acceleration (rotation), cosmology
Considering: Propagation-induced effects (lensing, absorption, LIV, …)

Narrow band: slow spectral changes → fast changes in flux
Broad-band: signals propagating in energy are washed out.

And more: multiband-correlations, lags, images, (quasi-) periodicities

Size, Geometry, Topology, Density

‘Variability time-scale’ as a measure of ‘Duration of a flare’

“Characteristic time-scale” characteristic of what?

Sizes:

The duration (Δ t) matters, not the amplitude, nor dI/dt (unless you worry about radiation energy densities, to be derived from Δ I and Δ t)

Size, Geometry, Topology, Density

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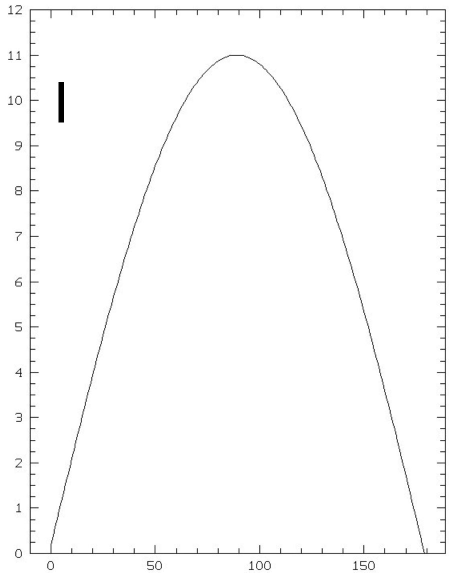

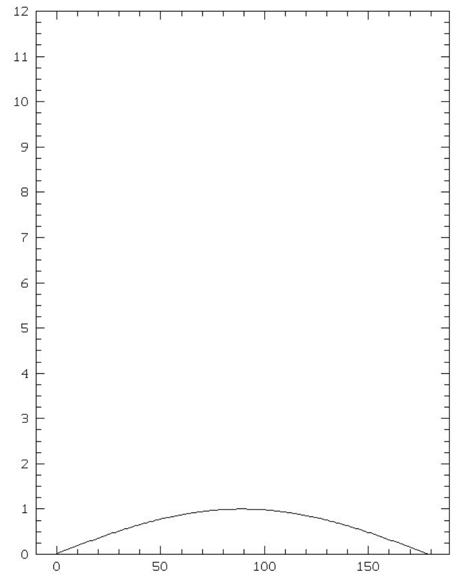

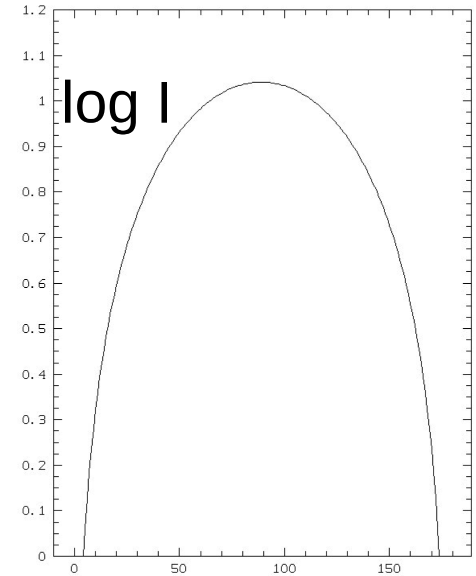

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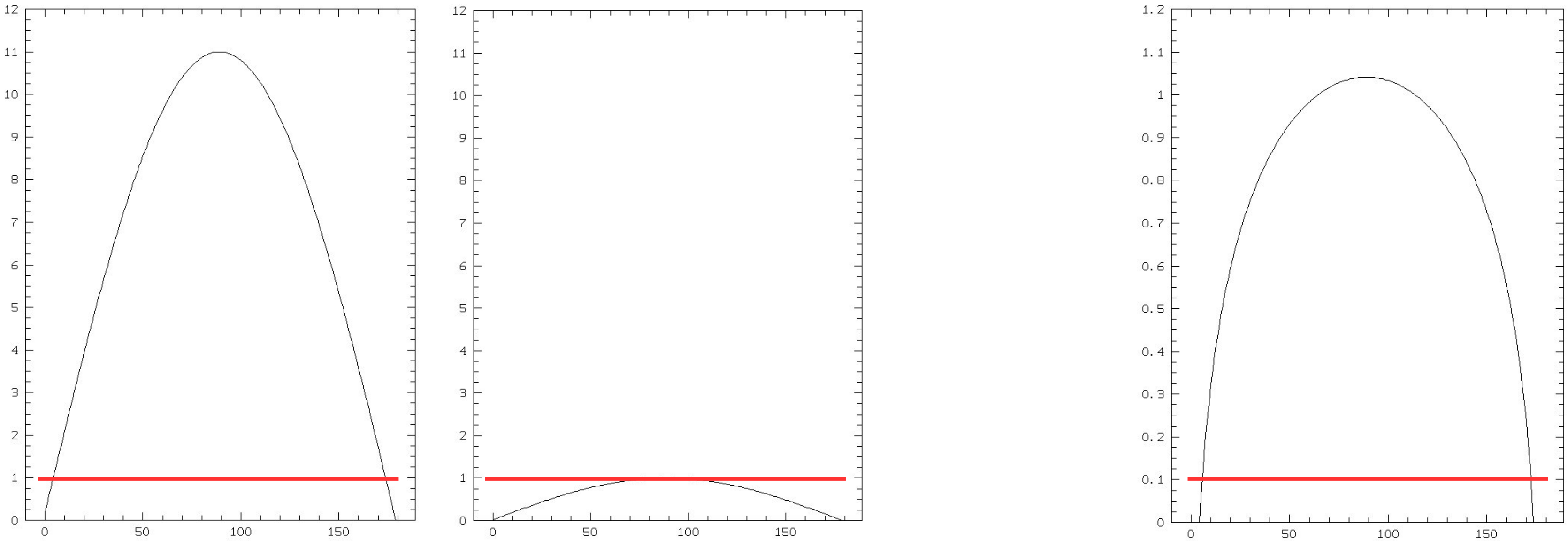

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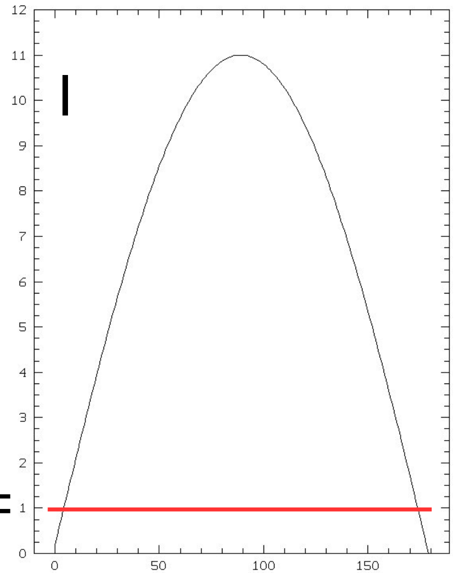

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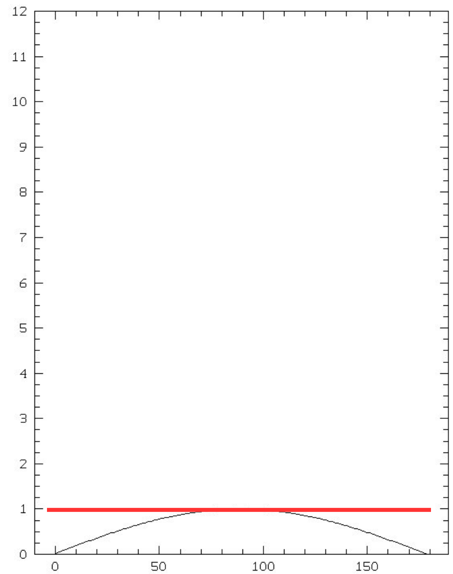
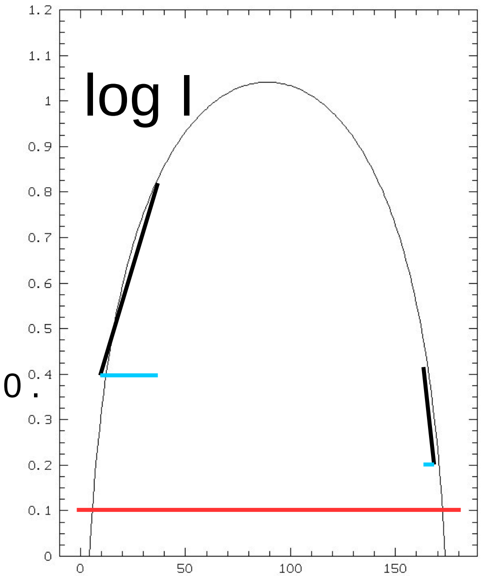


not $dt|dI=I_0$.



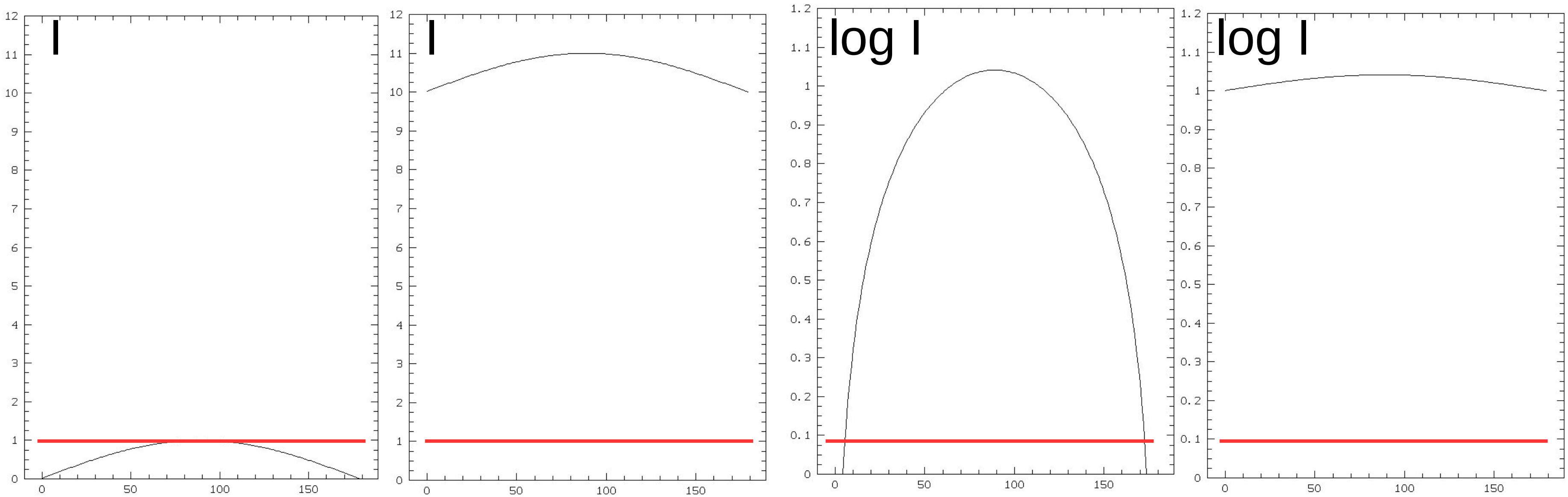
Variability time-scales should not be derived from ‘factor 2 changes’ in I, or the corresponding derivation of exponential fits to lightcurves

Size, Geometry, Topology, Density

This gets even more misleading if baselevel flux is considered,
Exponential time scales more related to ΔI/I than dt.

Sizes:

Δt =



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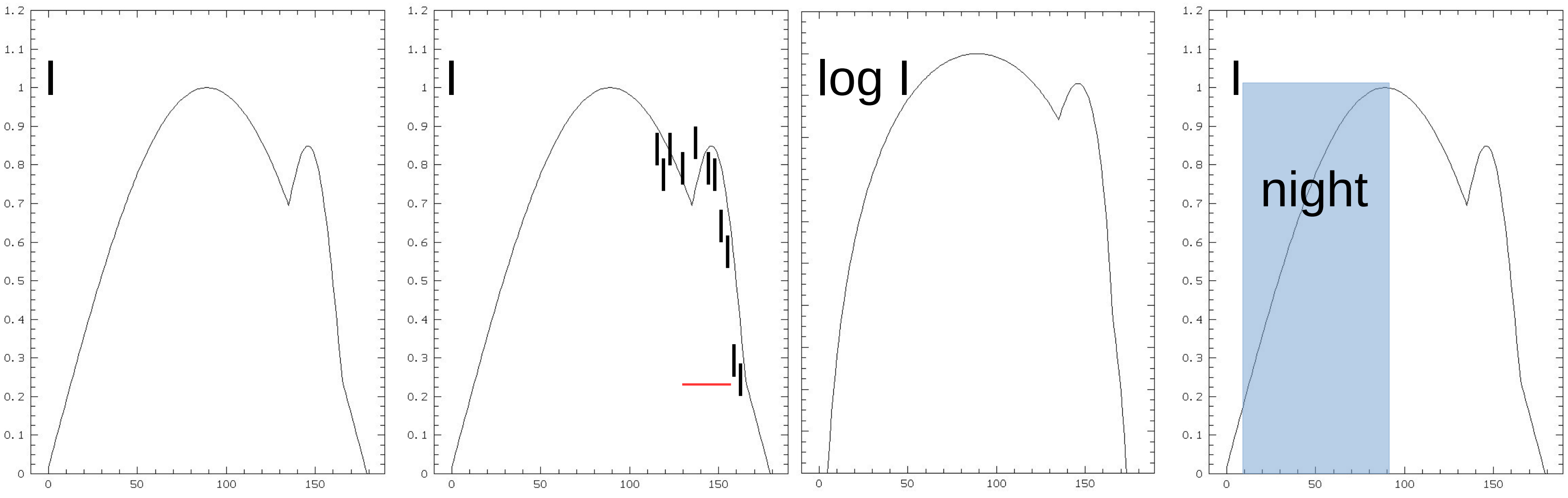
Size, Geometry, Topology, Density

Fitting slopes rather than measure duration because of blending?
or incomplete coverage



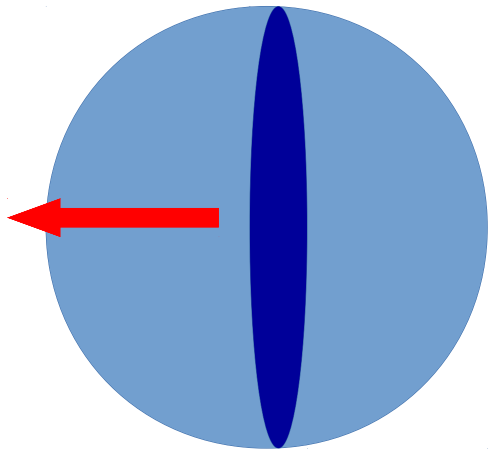
Main points: Duration of flare ←→ Size of emitting region
Not distances (small regions at large distances)
Constraints on emitting volume, not on environment (eg jet)

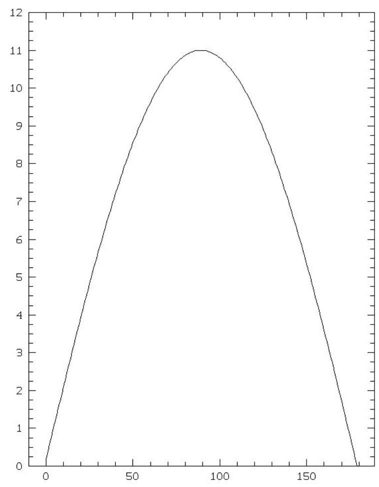
Flare shapes and sizes

The ‘Duration of a flare’ is independent of the shape of the flare.
The size would correspond to the duration.

Do the examples depend on the shape of the flare? - No
Why do I chose this example anyway?
Couldn’t flares have exponential rises/decays?

(thin) planar shock, spherical (homogeneous) overdensity → cos bell





This ignores aberration and relativity (serious oversight!)

→ Homework

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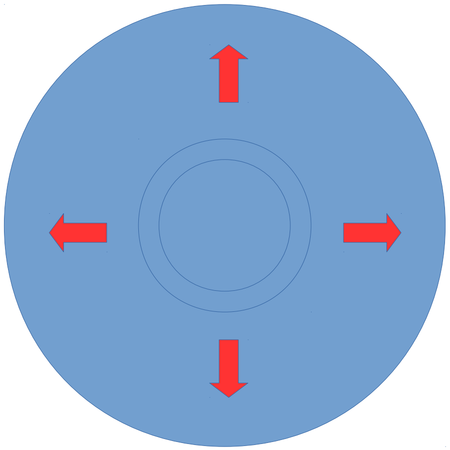
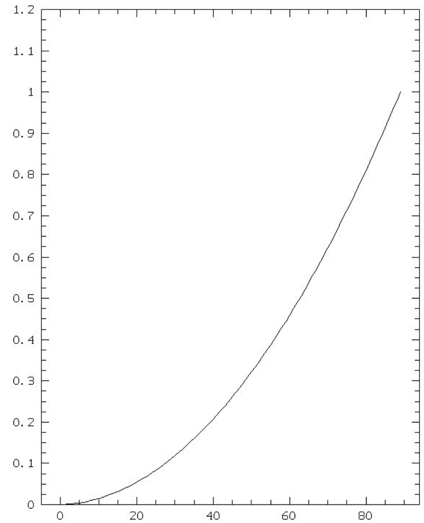
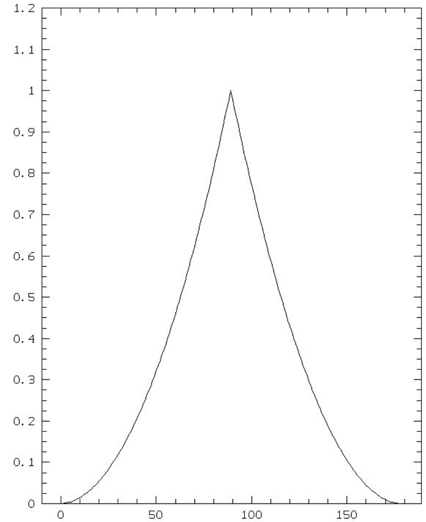




not



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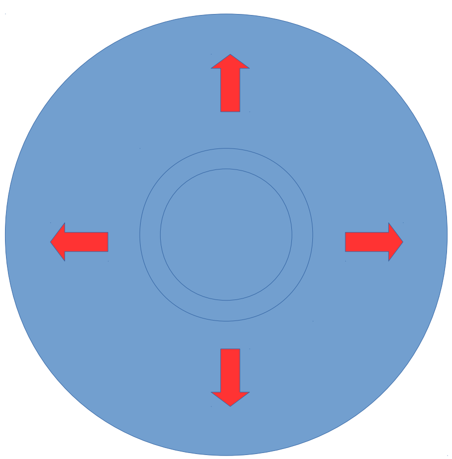
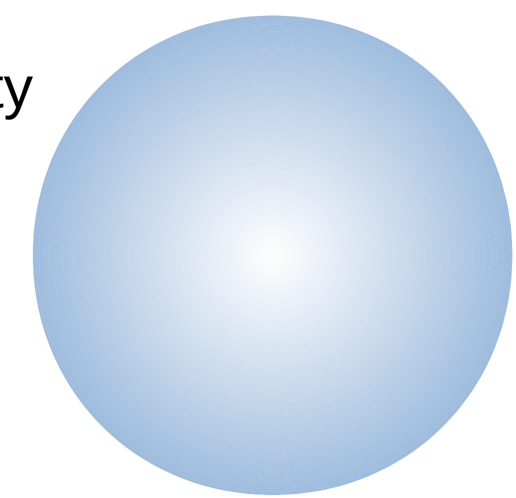
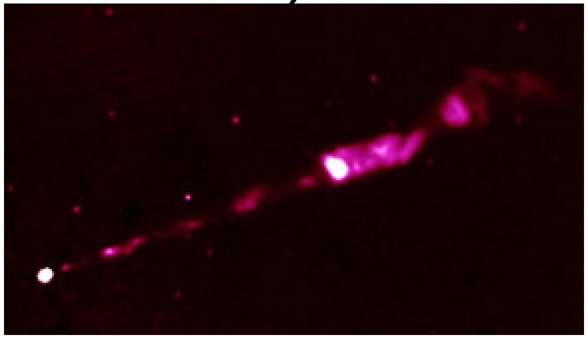


(Potential exponential density
profile within cloud
would not translate
into exponential rise/decay)



Size, Geometry, Topology, Density

It is unlikely that the volumes are spherical (no forces that encourage sphericity, many forces that act otherwise)



Nearby (resolved) knots are not spherical
(X-ray: Cen A, opt. M87, radio: plenty
(but beware of interferometric bias)

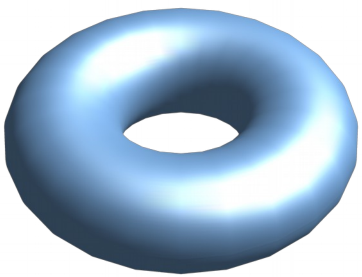
Duration measures maximum extent (‘diameter’) along line-of-sight
True volume could be larger or smaller than assumed implying sphericity
Duration and lightcurves in aspherical volumes depend on orientation.

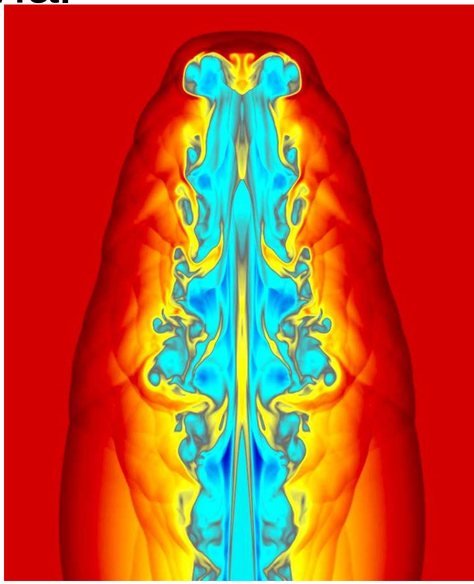
Geometry and orientation depend on relativistic aberration
Iso-delay-surfaces get non-trivial geometry even for simple shapes

Geometry may depend on propagation and location
(different knots may be different)

Size, Geometry, Topology, Density

The topology of emitting regions may be non-trivial



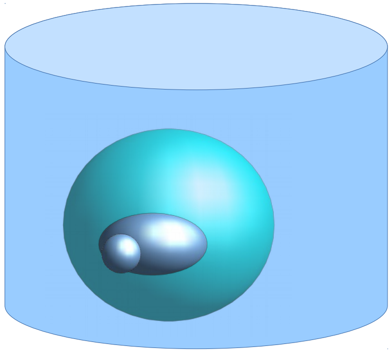


Toroidal magnetic fields in jet/knots?

Turbulence (cf MHD simulations)

Reconnection as emitting volumes
(lightning-like)

Nested structures



Size, Geometry, Topology, Density

All of the above (spherical, aspherical, complex topology) were considered to be defined by a single isodensity surface separating insides (homogeneous density) from outsides with a bimodal local radiation energy density.

Not realistic (boundary conditions)

Fairly complex situation
(we still assume that variability is all due to light-travel
(los integration) and ignore acceleration (heating), cooling, escape).

What are our observables?

Moments

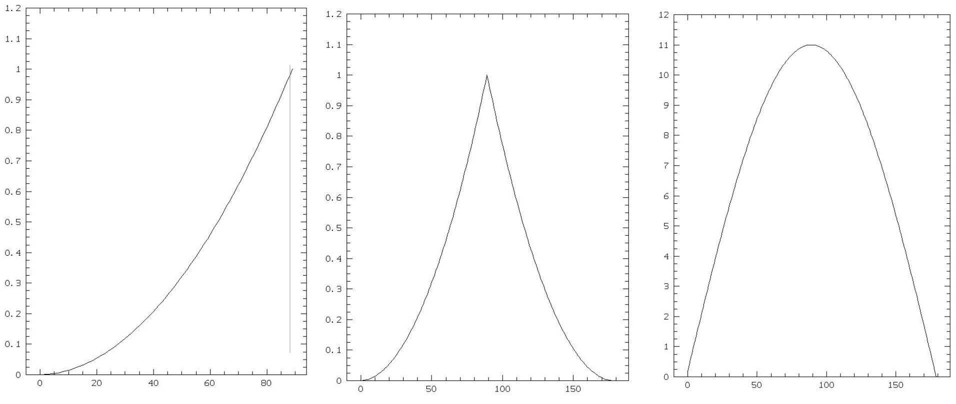
Characterisation of *single* flares through moments (distributions):

First moment, centroid, flare time (peak) [e.g. stat. Correlation]

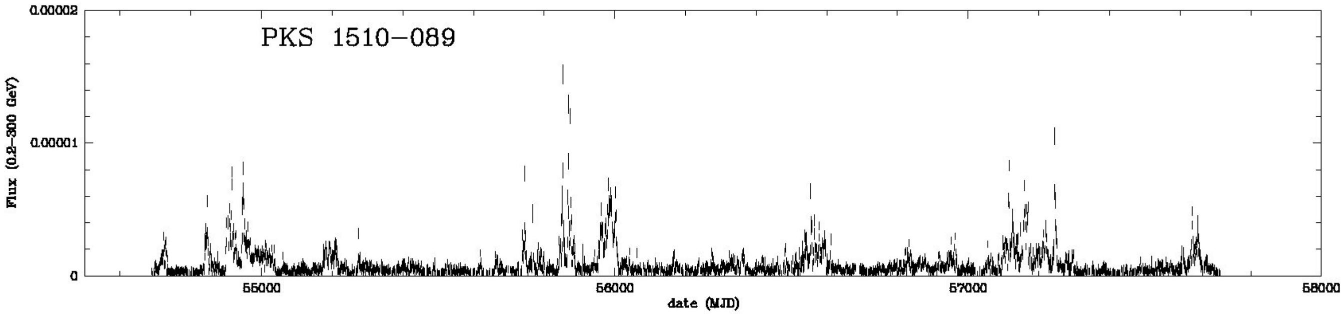
Second moment, width – replace by duration, since basic property
(duration) should be separated from flare shape
– better defined than (noise on baseline)
[for known flare shapes] {not the case}

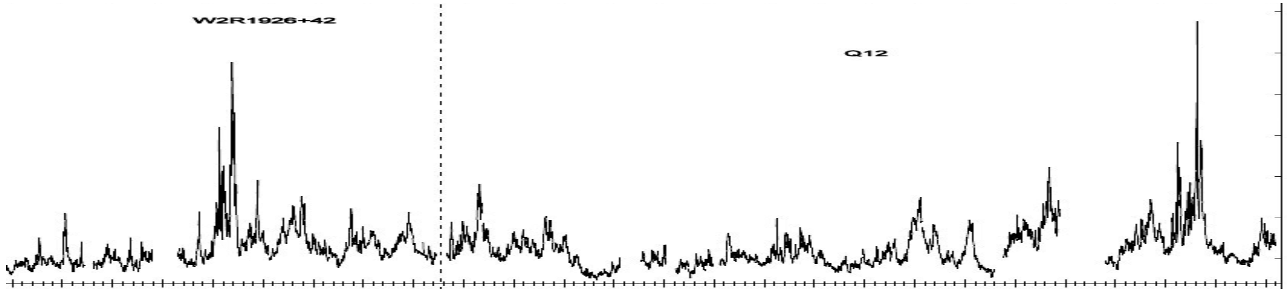
Third moment, skewness, asymmetry (cooling, heating, topology)

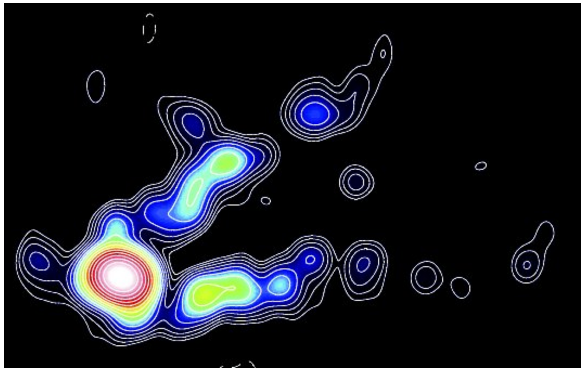
Fourth moment, kurtosis, tail/peak ratio,
individual fingerprint?

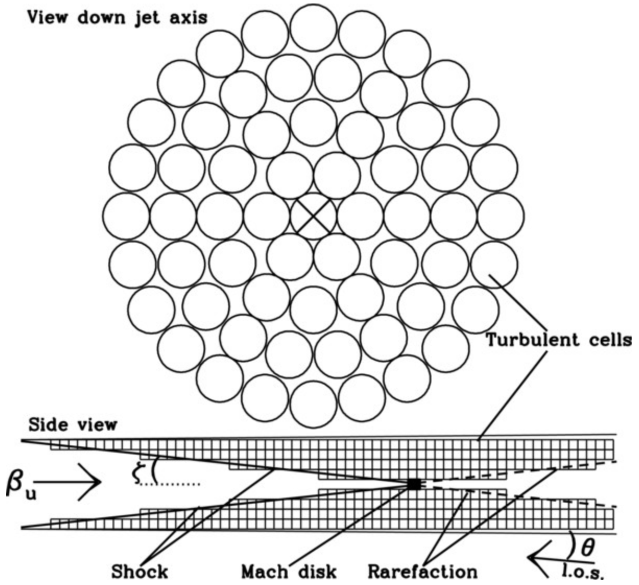


Deblending, confusion, clustering



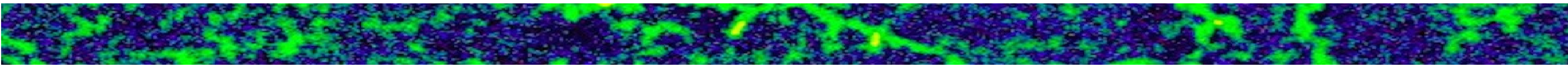






Flares are blending, implying multiple zones at a given time. Consistent with imaging and models.
Nesting or clustering of subvolumes (spatial correlation function) translates to temporal correlation of flares (not PDS).
Clustering would lead to Log-normal behavior.
Implications for assumption of causality.

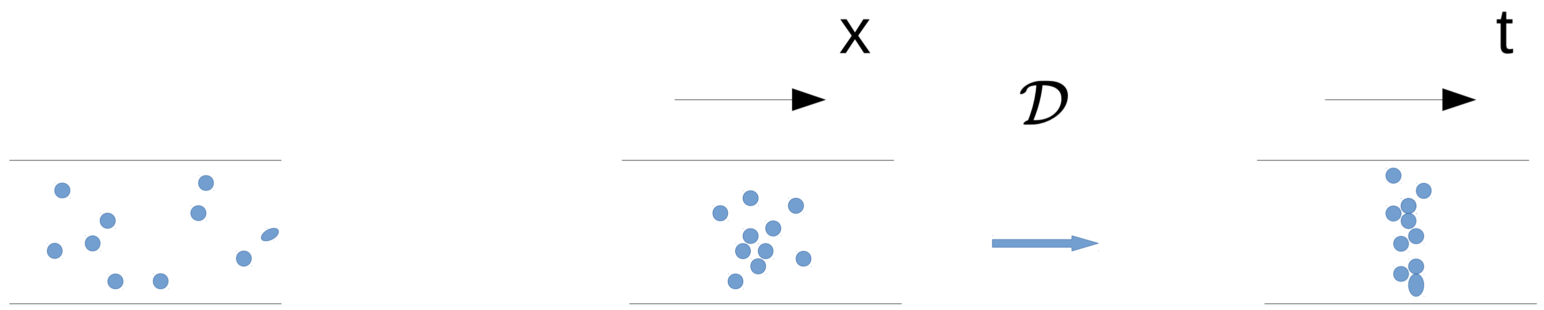
Clustering



Topology of substructure in jets translates into temporal correlation.

Nesting of substructures as a discretized description of density.

Multiplicative processes → lognormal flux distribution.
Does not imply that the inverse implication applies



Does the assumption of causality hold?

Sizes and Radiation Densities

Apart from Signal-to-Noise variability studies for simple resolution is independent of amplitudes (not part of definition).

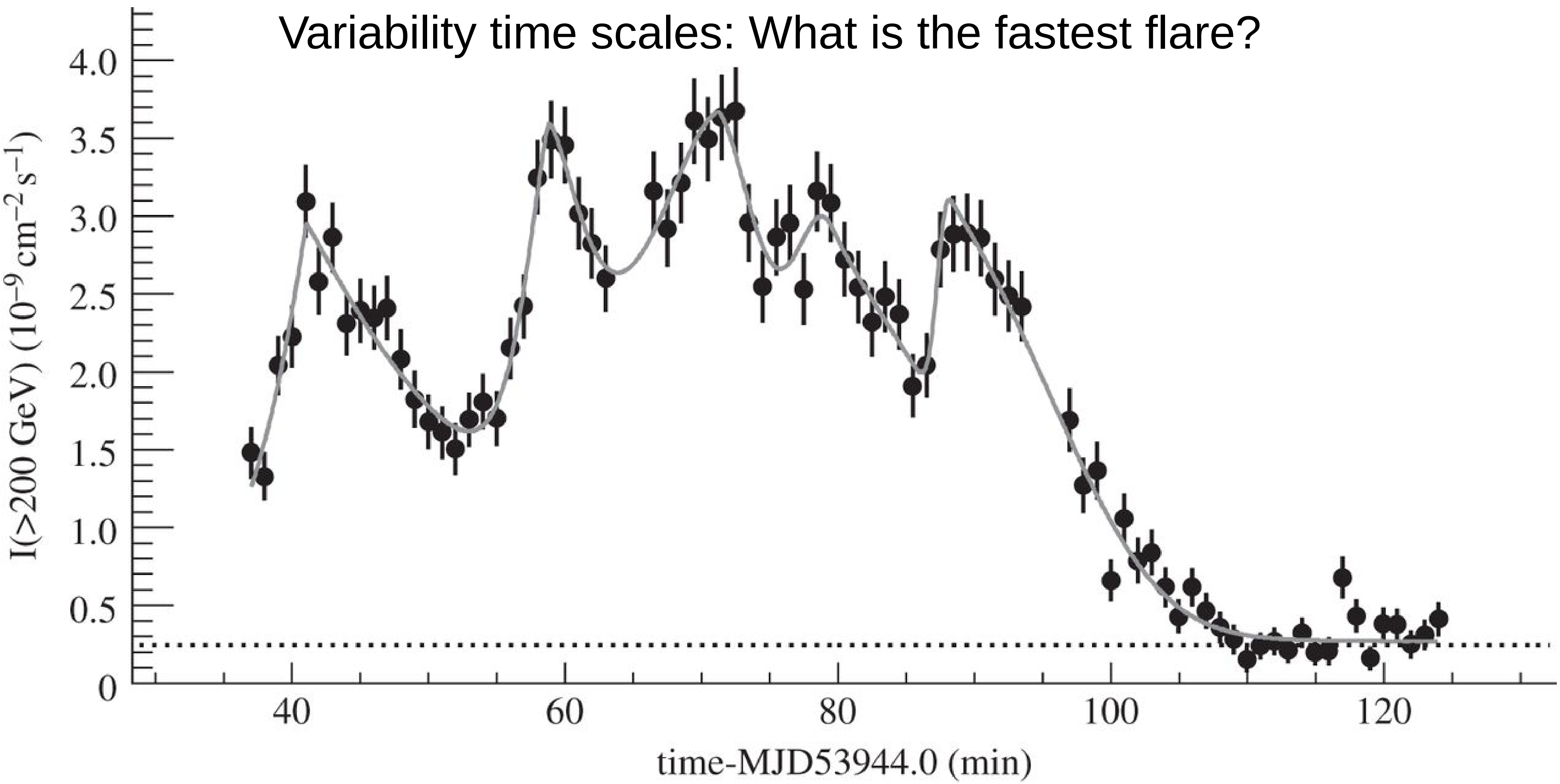
(Radiation) Density measurements more important
Compactness, absorption, relativistic corrections,…
Sizes **and** amplitudes important, but should not be coupled (error propagation).

Exact time-scales more relevant than exact fluxes (deblending)

e.g.

The fastest flare

Variability time scales: What is the fastest flare?



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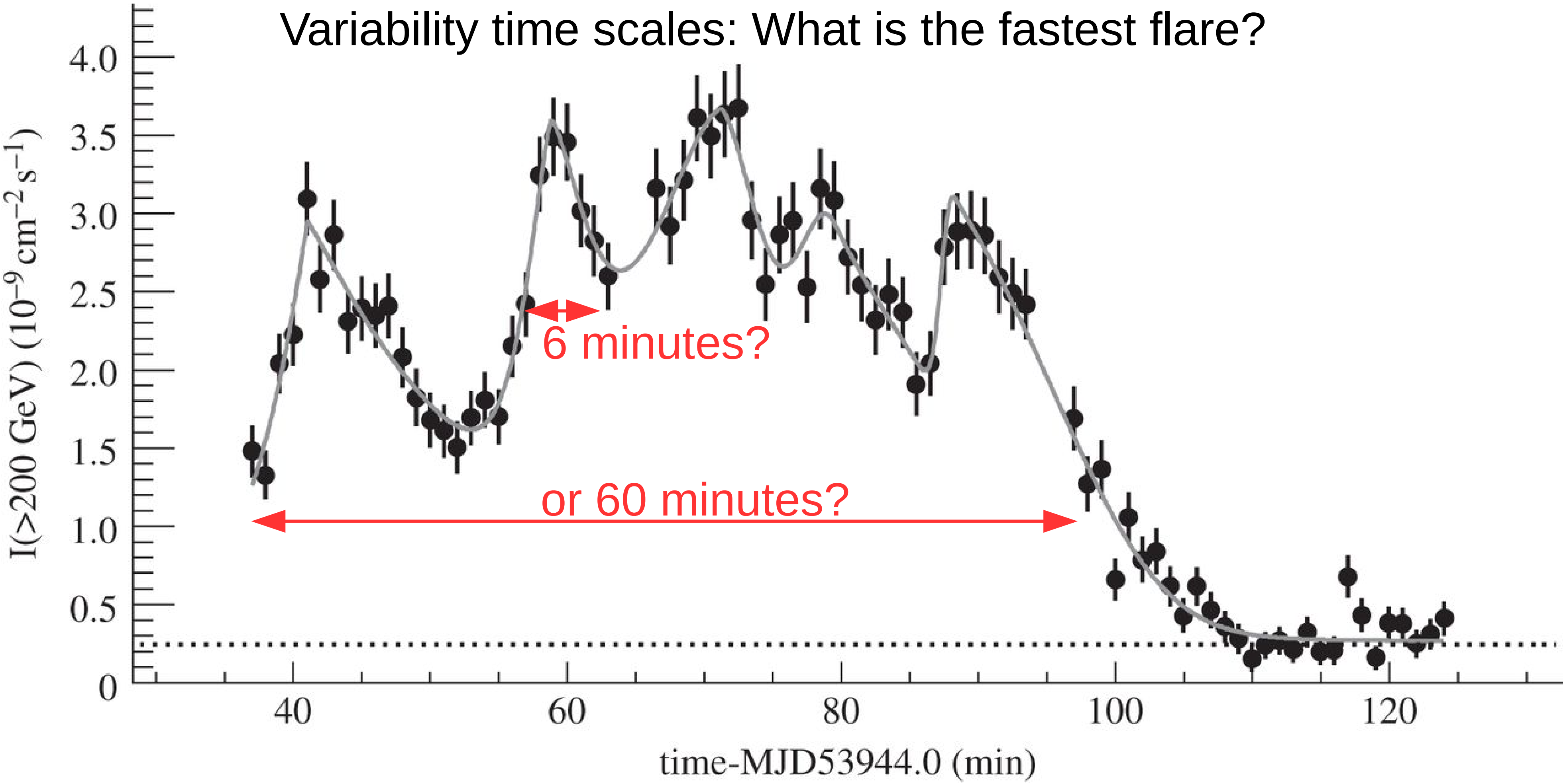

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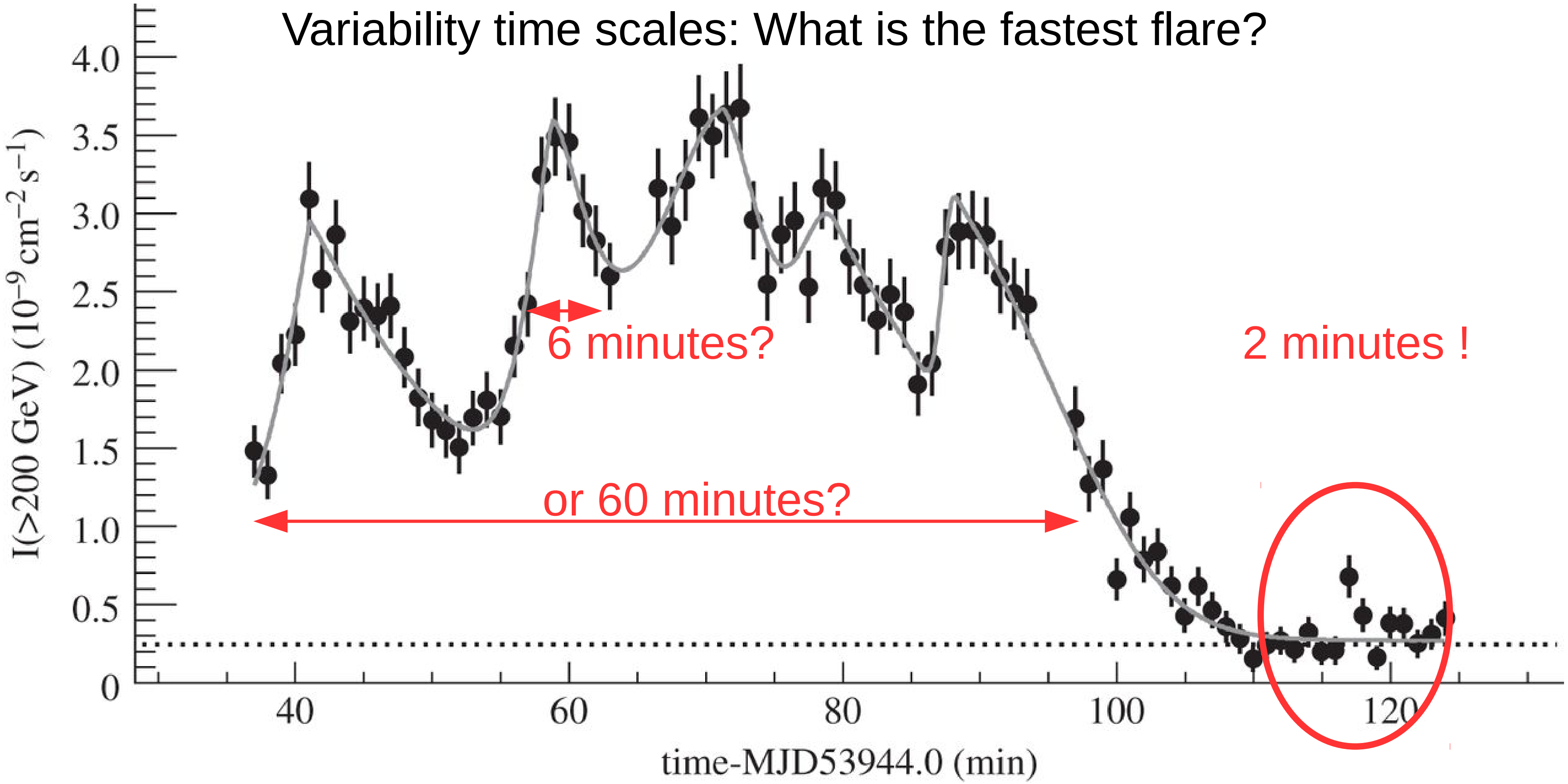

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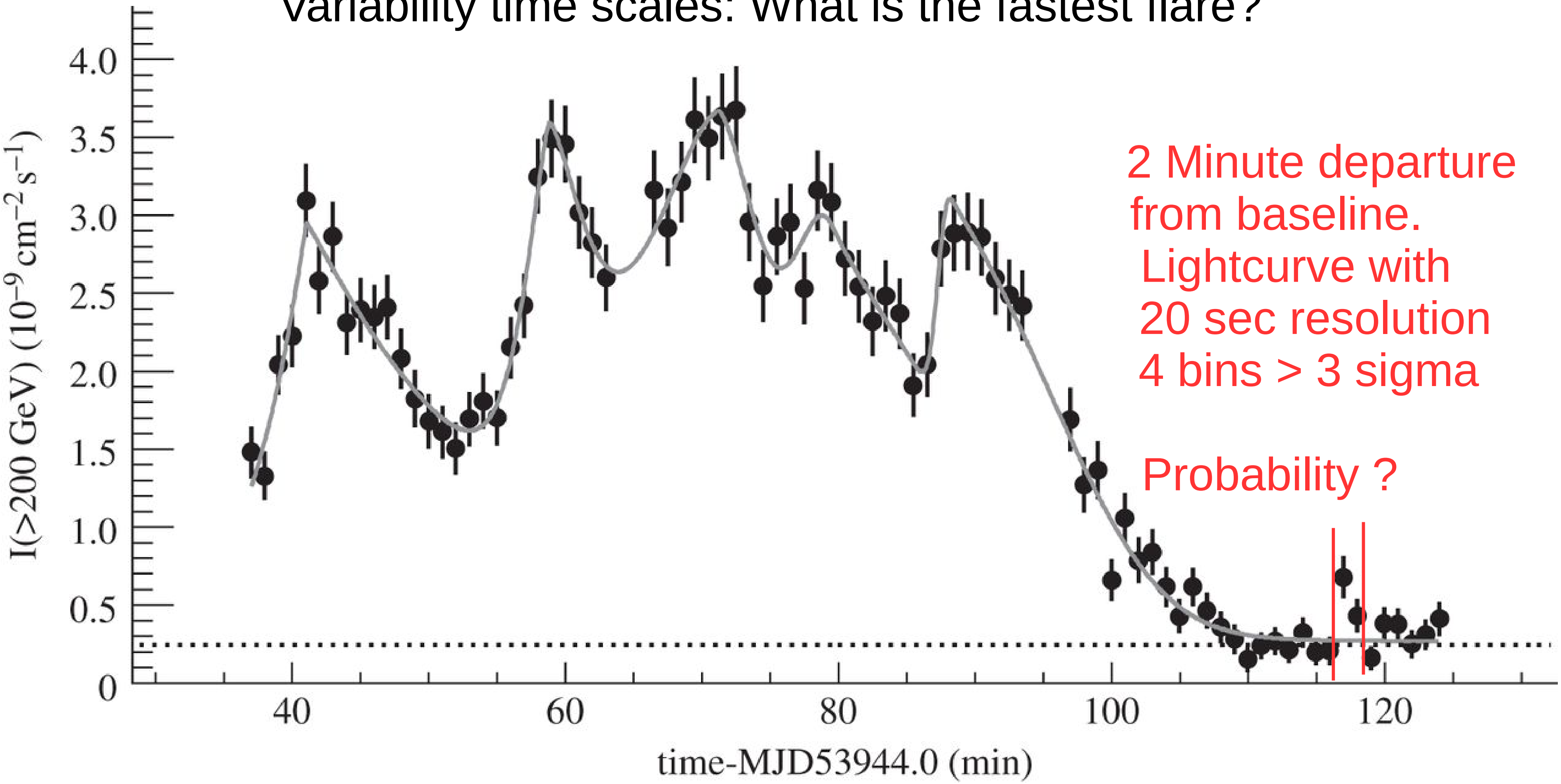

2 Minute departure
from baseline.
Lightcurve with
20 sec resolution
4 bins > 3 sigma

Probability ?

Time-scales, binning, photon noise

Amplitudes: 0.5/1.5, Volumes: $(2/8)^3$,
In fast flare the energy density 20 times higher !

(How) can we rule out, that fast, low-amplitude flare has the same shape (duration) as longer (brighter) flare, but simply emerges above the noise for a shorter period?

Error propagation (assume flare shape), FWHM conversion (vanishing kurtosis), comparative studies (scale flares)

Chance probability of fast, low-amplitude flare?

Understand error distribution function, symmetry of errors, internal correlations (multiple bins, split energies) boost significances

Adaptive binning, bayesian blocks, fixed-sum binning: **MC your results**

Summary

Be very clear of your question (sizes are independent of amplitudes)

Be very clear on the assumptions (e.g. relativistic aberrations)

More quantities, more uncertainties (measurements, assumptions)
→ error propagation

Be very clear of biases in your data,
(inc. the homogeneity of biases in statistical and/or sample analyses)
(especially if these are not your measurements)

Oversampled binning is the only MC-confirmed characterisation
(that I am aware of)

Light-curves can fool you

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