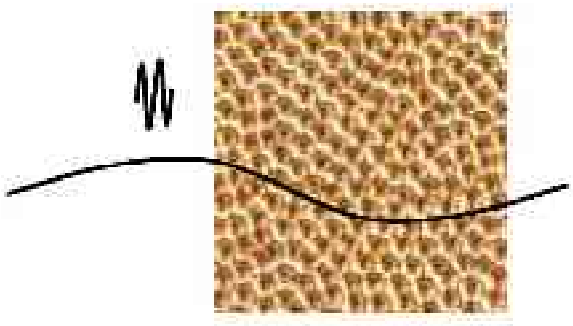
Variability and Propagation Effects



Stefan J. Wagner,
Landessternwarte Heidelberg

mostly a review talk

Blazar Variability across the EM spectrum, Palaiseau, France, April 22-25, 2008

Variability and Propagation Effects

Propagation effects: Worries and opportunities at high energies
EM, refractive: Intraday Variability at long wavelengths: Deja-vu
gravity, refractive: Panchromatic propagation-induced variability: -lensing

gravity, dispersive
Propagagation effects exclusively at high energies
Quantum gravity and violation of Lorentz Invariance
GRBs vs. Blazars
Methods and Statistics
Observations and Conclusions
Intrinsic vs. propagation-induced lags
Other constraints on LIV and QG
Future observations

Worries and opportunities

Do observations reflect physical changes in the source in an unbiased way?
What can we learn about the \`aether´ by studying variability?

Almost certainly not -

We believe the emitter is beamed: fluxes and time-scales require corrections
EBL absorbs VHE radiation, corrections of inferred luminosities required

The latter is independent of variability

Variable VHE absorption by variable intrinsic low-energy radiation field?
We observe variability at 1eV photon energies on similar time-scales?
Are they approximately co-spatial? Flares of different E_{max}
Mild spectral changes expected, look for dips associated with optical flares
Dips only? This depends on acceleration processes and plasma evolution

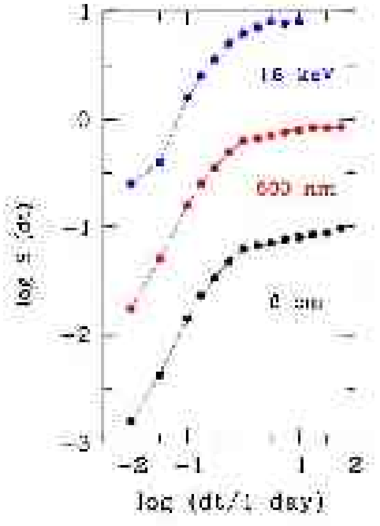
Worries and opportunities

Do observations reflect physical changes in the source in an unbiased way?
What can we learn about the `aether´ by studying variability?

Do we understand intrinsic processes well enough
to reliably postulate intrinsic variability properties?

Similarity to time-independent problem of EBL absorption:
Intrinsic spectrum ought to be known/constrained to infer photon-density of
the metagalactic radiation field from observed VHE spectra.

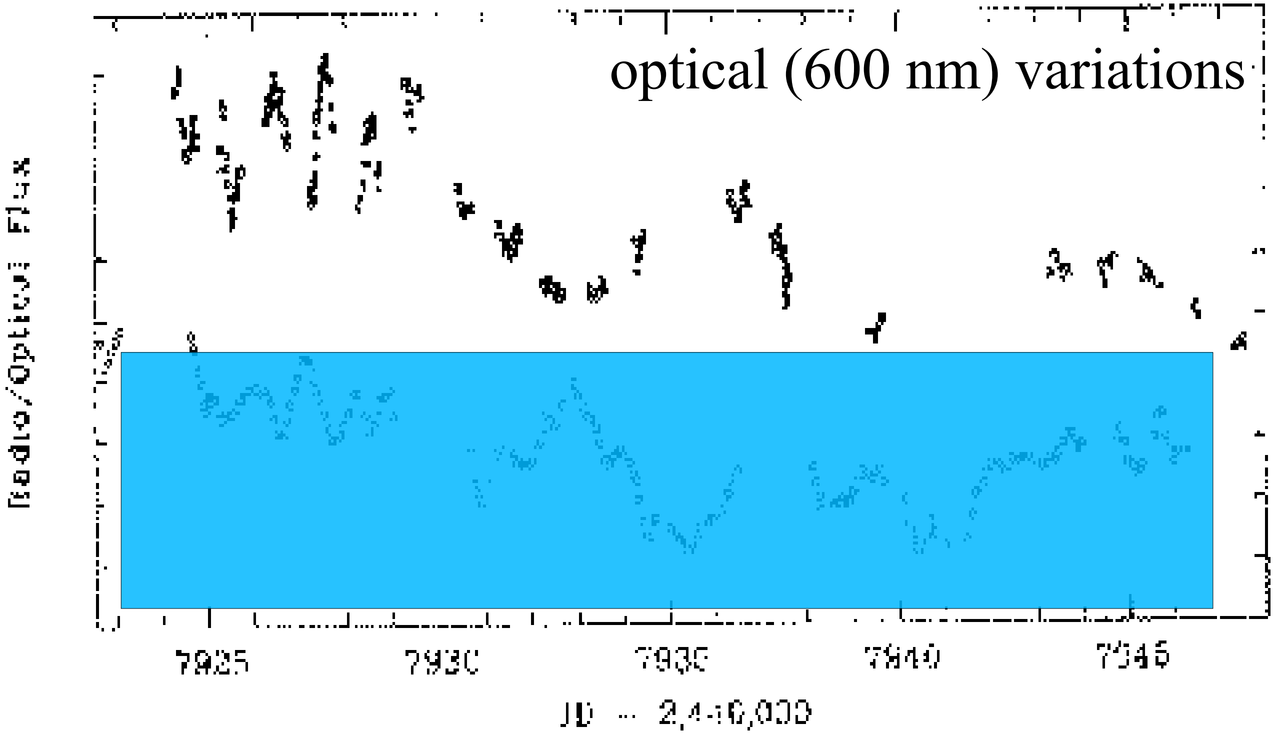
If instrinsic (spectral) variability characteristics are not understood,
propagation-induced modifications of patterns can be revealed
by repeating experiments with different initial conditions
(variability at different times, at different energies, in different sources)
[assuming modifications induced by propagation to vary slowly]



Intraday Variability (IDV)

What is IDV?

Wagner&Witzel, ARAA, 33, 345: $t = dt/(df/f)(1+z) < 50h$



optical (600 nm) variations

Intraday Variability (IDV)

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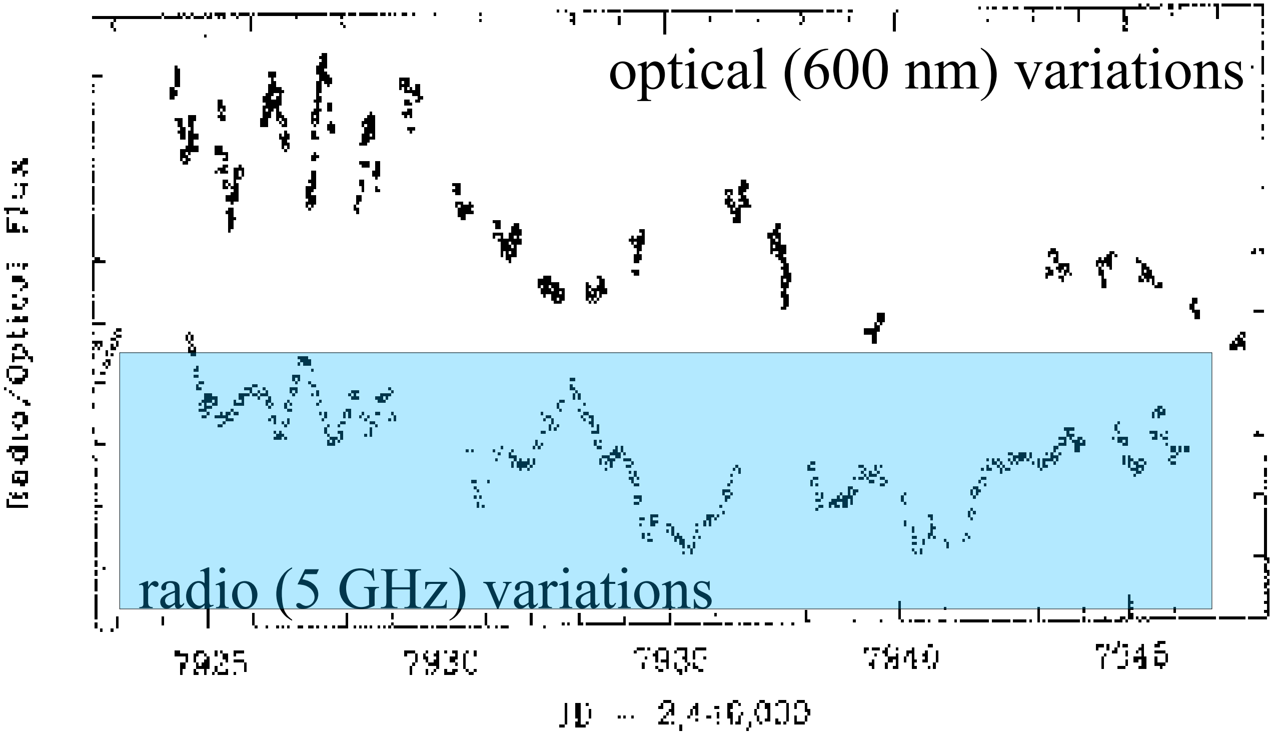
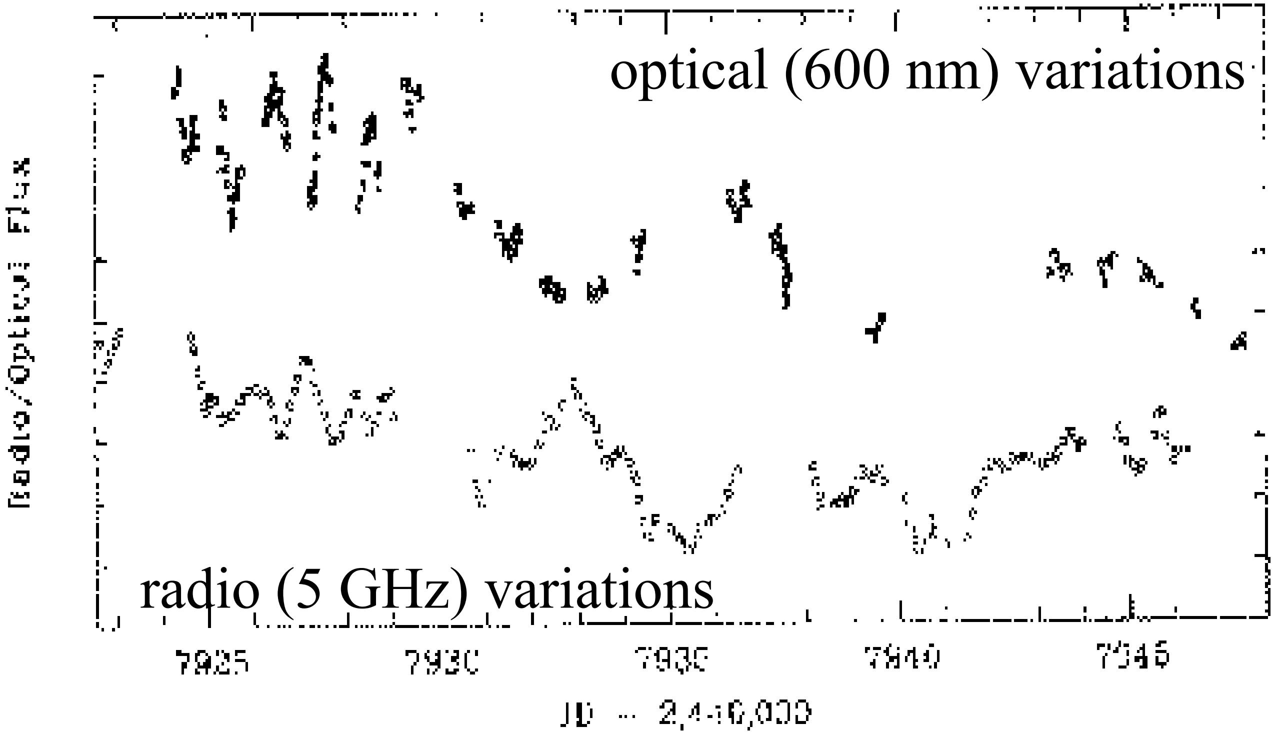


Intraday Variability (IDV)

The brightnes temperature problem of radio-IDV

$$\frac{L_C}{L_S} = 0.5\left(\frac{T}{10^{12}}\right)^5 \nu \quad \left[1 + 0.5\left(\frac{T}{10^{12}}\right)^5 \nu\right]$$



optical (600 nm) variations

radio (5 GHz) variations

Possible Solutions

$$\mathbf{T}_B \propto \mathbf{D}^2 \, \frac{\mathbf{S}}{\nu^2} \left[\frac{1}{\Delta t_{obs}(1+z)} \right]^2 < \mathbf{T}_{IC}$$

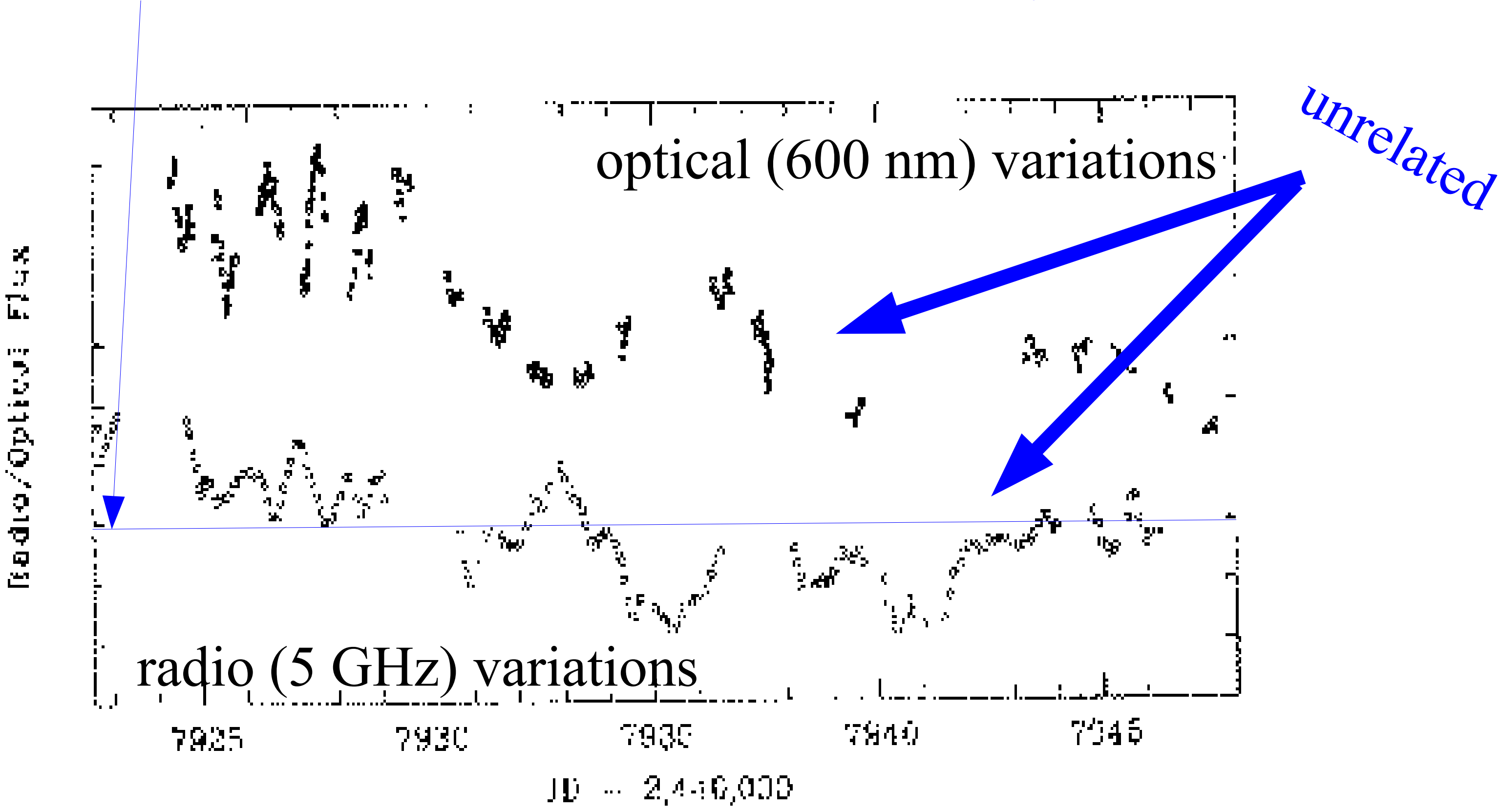
Limit wrong	Radiation mechanism (eg Coherent synchrotron)
Limit invalid	Ongoing IC catastrophes (e.g. Ostorero et al., 2006)
	Truncated electron spectra (e.g. Tsang&Kirk, 2007)
Diameters wrong	Geometry (e.g. Camenzind, Qian, Spada, Wagner)
Fluxes wrong	Relativistic amplification (Rees, Woltjer, Blandford)
Distances wrong	Non-cosmological redshifts (Burbidge, Hoyle,...)
Concept wrong	Extrinsic (propagation-induced) mechanisms

List of suggestions/references highly incomplete

Intraday Variability (IDV)

Claim: Radio – IDV is propagation induced

the source varies at 600nm and is steady at 5GHz



optical (600 nm) variations

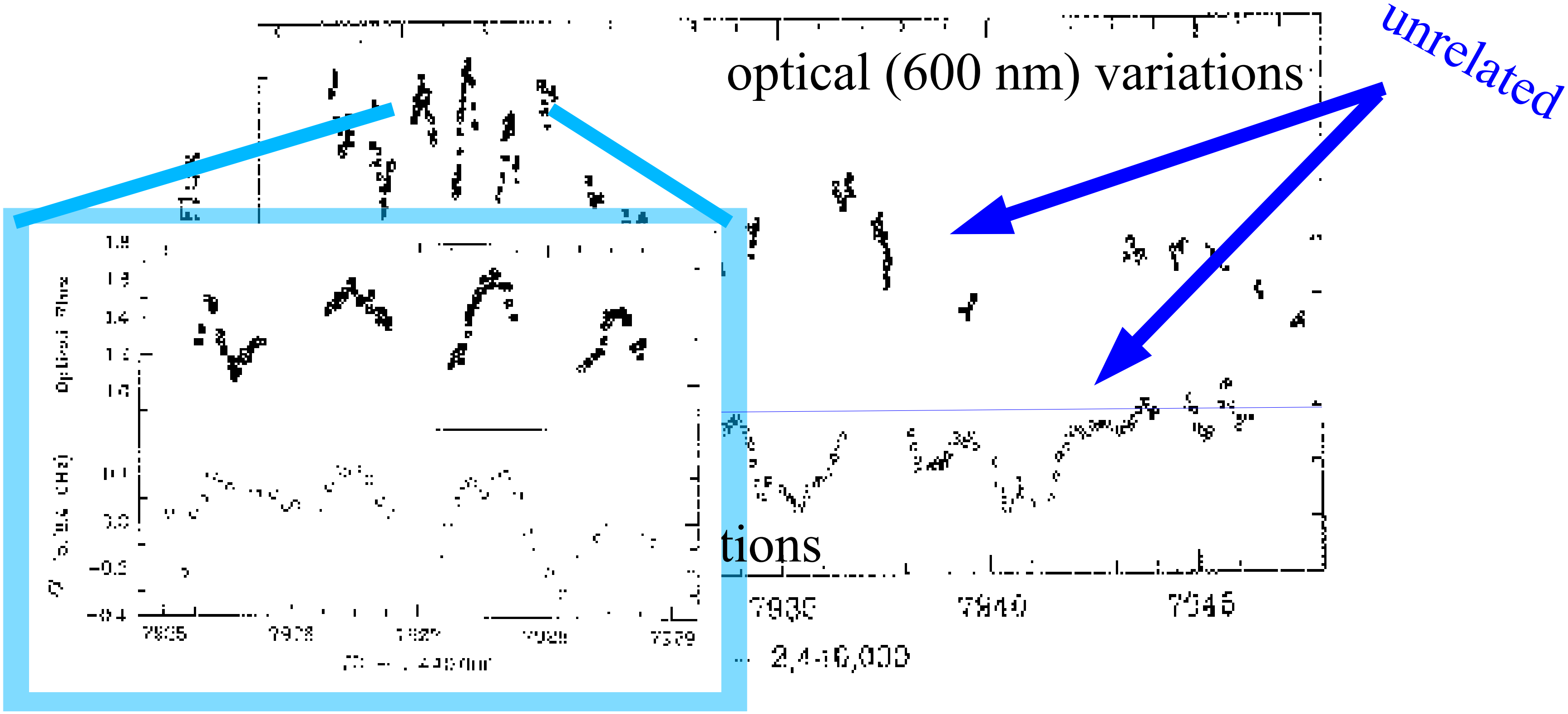
unrelated

radio (5 GHz) variations

Intraday Variability (IDV)

Claim: Radio – IDV is propagation induced

...and this is a coincidence



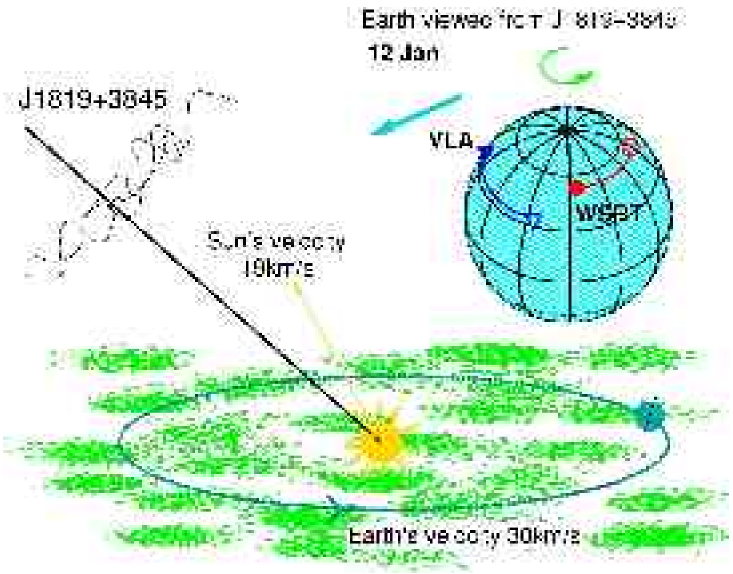
optical (600 nm) variations

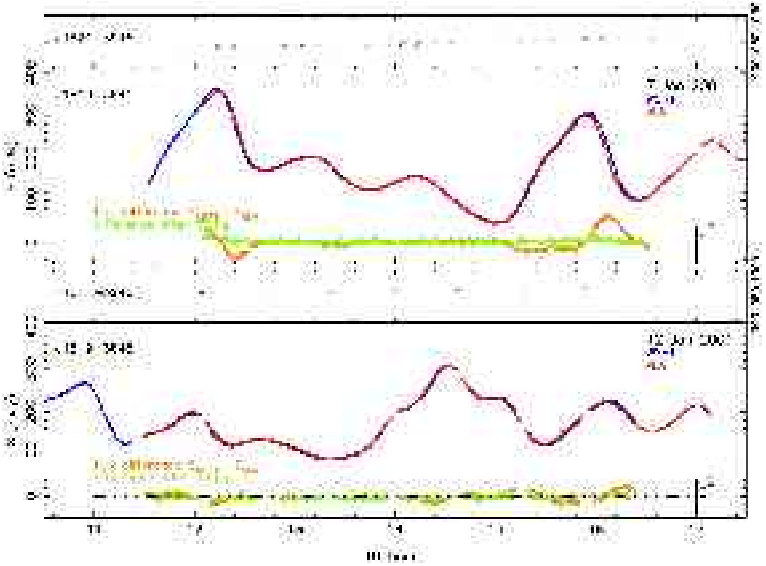
unrelated

tions

Interstellar Scintillation

ISS is unavoidable at some level and can be tested





1.) annual variation (confirmed) 1819+3845, JP Maquart, G deBruyn
2.) lags between different stations (confirmed)
3) diffractive scintillation (probable)
in sources with little intrinsic variations

...but it does not solve the problem (JP Maquart et al., 2006)

Intraday Variability (IDV)

Why is this relevant in the context of high energies?
Steep dependence with frequencies, even optical radiation unaffected.

1) If compact (rapidly variable) VHE component has low-e electrons, such regions ought to generate *diffractive* scintillation.

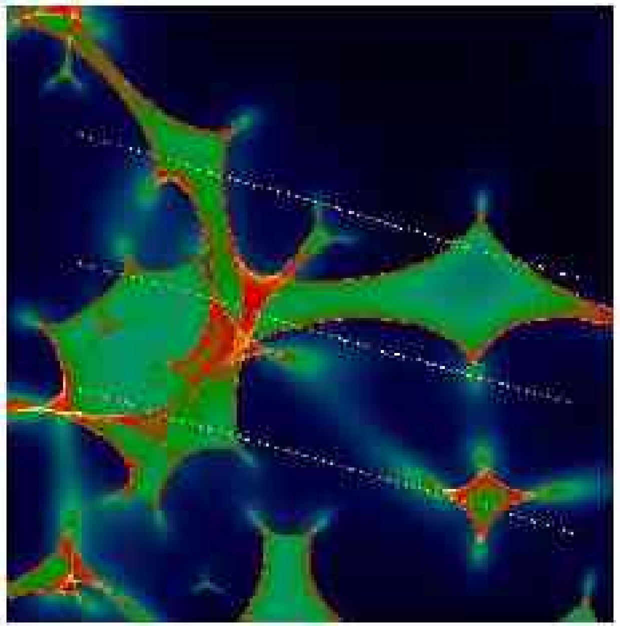
2) ISS (a propagation effect) pinpoints compact source with high T_B.

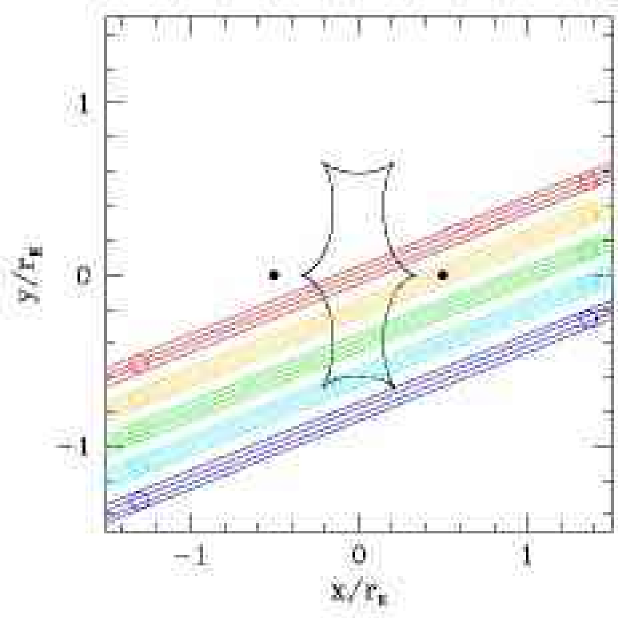
3) Given the problems with ISS (and the evidence for intrinsic IDV), we may not give up radio studies sampling short time-scales associated with VHE observations.

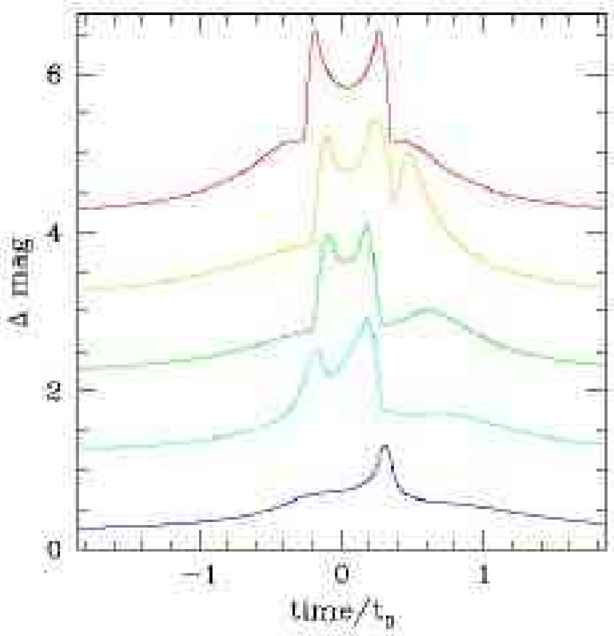
4) Many similarities in suggested explanations of fast VHE variations and earlier attempts in explaining intrinsic IDV (high Doppler factors, truncated particle distribution functions,...).

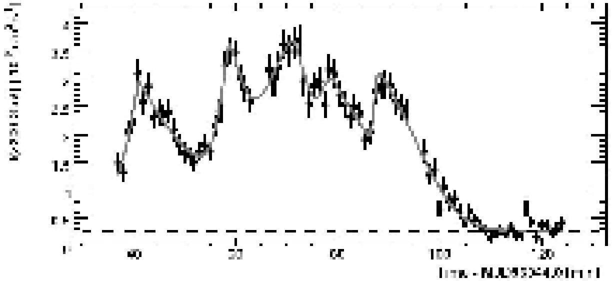
Microlensing

Panchromatic propagation-induced variability.
Grid of point-sources modify rectilinear propagation.
with amplification during crossing of caustic folds.
Independent of photon energy, would also work at VHE energies.
Had been suggested to explain the Blazar phenomenon.









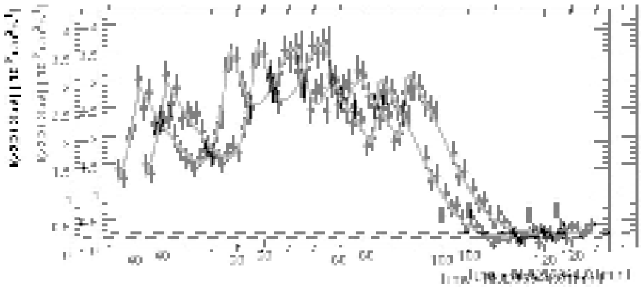
Microlensing

Microlensing often discussed in terms of lens-plane being about half the way between source-plane and image-plane, but this is unlikely to be the case in any (most) VHE Blazars.

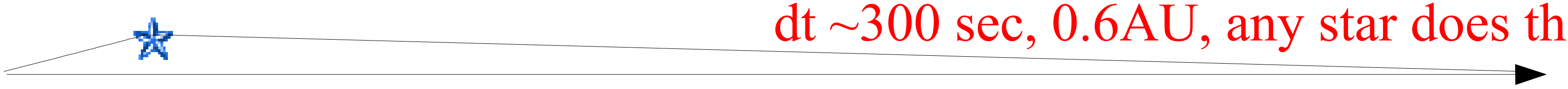
$$t_0 = \frac{R_E}{v} = \left(\sqrt{\frac{4GM}{c^2} \frac{D_{ol} D_{ls}}{D_{os}}} \right) v^{-1}$$

Works better for stars in host galaxy (fast changes, small Einstein rings)
If VHE emitting regions were significantly more compact than regions emitting at lower wavelengths, VHE obs would be more prone to microlensing induced patterns. Unlikely, but difficult to rule out.
Would be polychromatic, except for energy-dependent size.

Microlensing



Very small angular deflections induced in far-field approximations.
Tiny angular deflections result in small temporal delays.
Observed radiation may have taken different paths (of different pathlengths), diluting fast variability pattern.



dt ~300 sec, 0.6AU, any star does this

Observed variability pattern rules out such path-lengths smearing.
Similar constraints have been derived from GRBs.
Only exception: GRBs seem to originate preferentially from less dense environments (dense stellar clusters in centres of BL Lac objects?)

There are similar constraints on gravitational waves (related to accretion?)

Not so interesting (too many flares)

Propagation Effects in VHE regime

No electromagnetic dispersion, but quantum-gravity induced dispersion:
Lorentz-Invariance c = const. or c(P,E)?

Assuming QG have a semiclassical limit, one can search for falsifiable predictions from QG to low orders in E/E_{Planck}
(e.g. Amelino-Camelia, 1998, 2006; Ellis, 2004; Kostelecky, 2003)

Most QG models predict a distortion of the standard photon dispersion relation:

$$E^2 = k^2(1 + \xi_1 (k/M) + \xi_2 (k/M)^2 + \ldots)$$

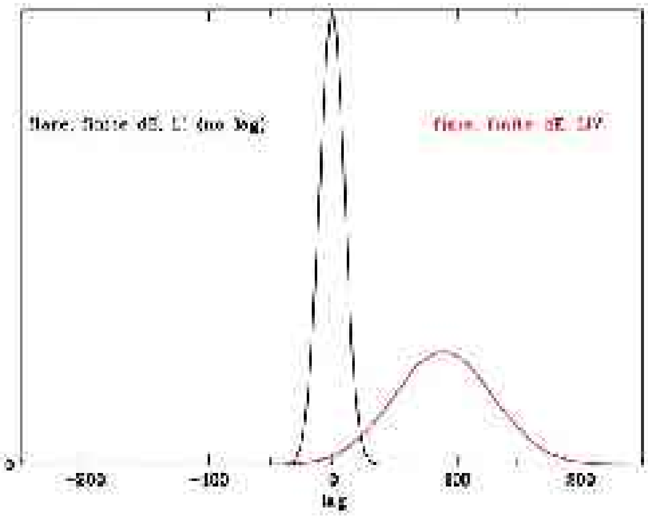
No unique model of quantum gravity.
k>0 avoids superluminal propagation, but loop-gravity does not respect this.
Some models suppress odd powers of *k/M* by selection rules
(e.g. rotational invariance in a preferred frame)
Variety of different predictions (e.g. Amelino-Camelia, Koltelecky)

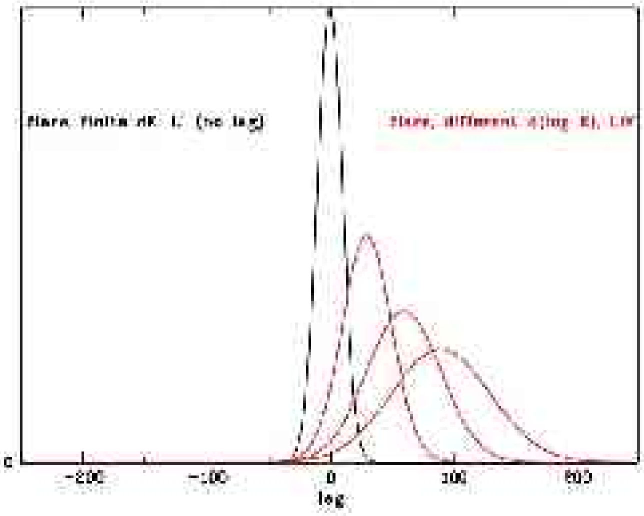
LIV in quantum gravity

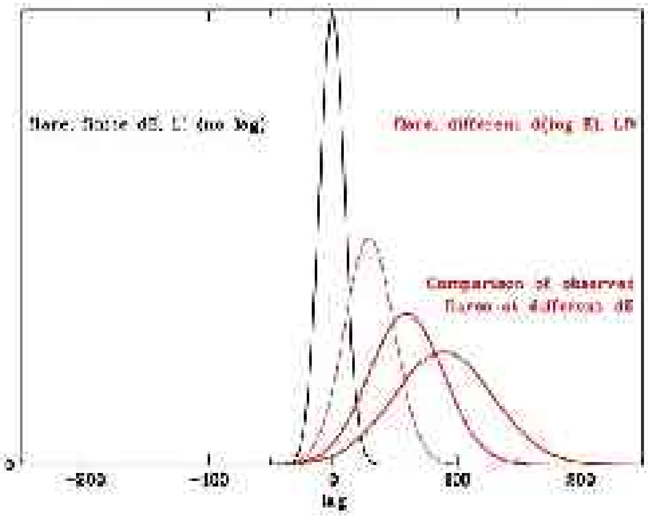
Lorentz invariance is violated and this is ONE test of SOME QG models.

Effective dispersion leads to energy dependent time-of-flight.
Photons of different energy emitted simultaneously will arrive
with energy dependent lag.
Finite bandpass: lags result in spread

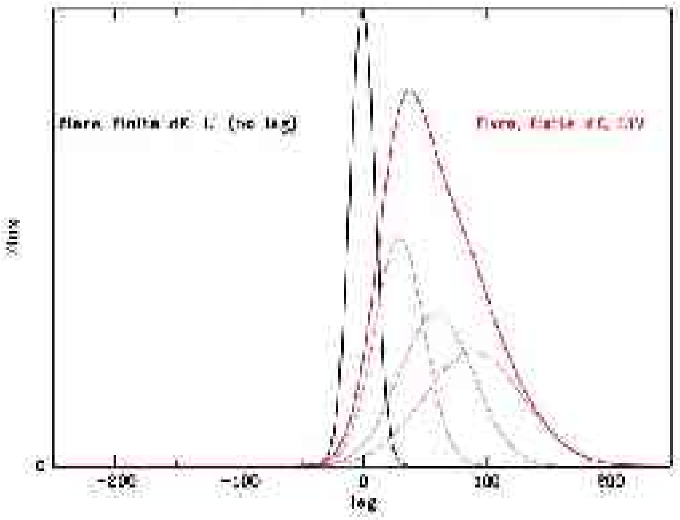
For $E/c^2 \ll M_{Planck}$ the dispersion is small and
leads to a measurable lag only for $ct \sim 1/H_0$

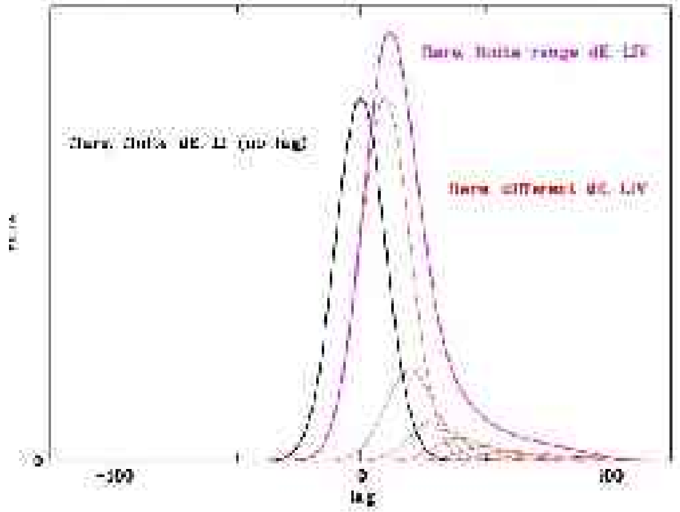


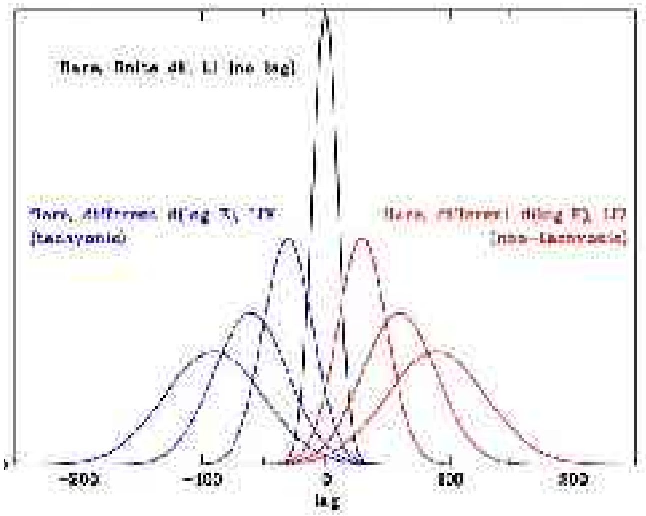




Lags vs. spread





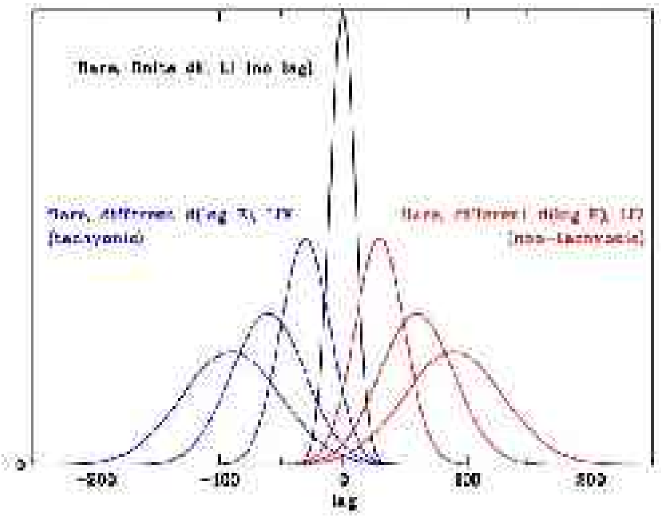


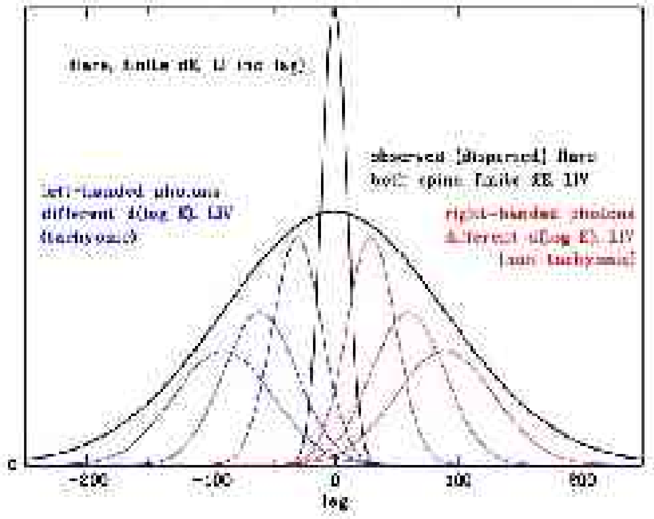
Potential observables: Lag between bands of equal dE bandpass of different dE would show dispersion (spread)

For given energy bins the shape of transfer function depends on the spectral index of the photons.

All of the above might also by tachyonic in loop-gravity

Polarisation





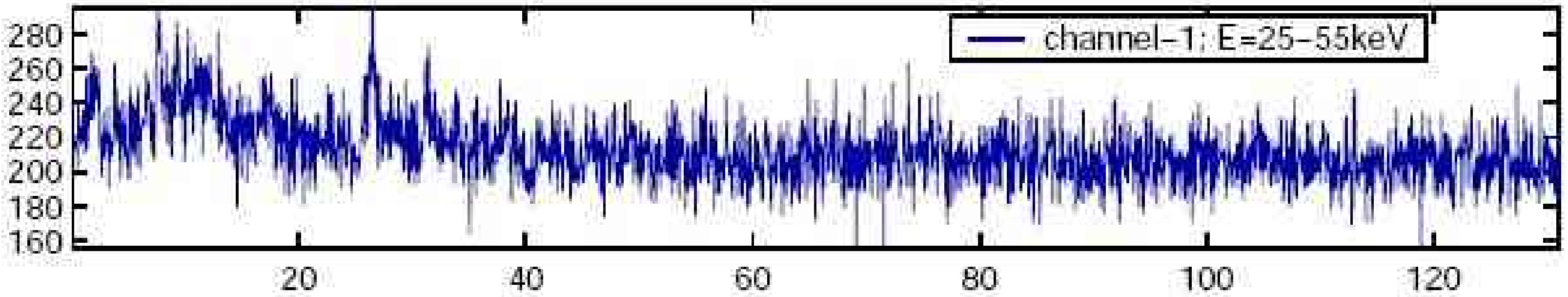
Depending on your prefered Standard Model Extension (SME),
the dispersion relation may be spin dependent c(E,P).

This would result in propagation-induced depolarisation and radio/optical
LIV limits from high-z polarized sources.
This would also require one polarisation to be tachyonic.

If sign of retardation depends on photon spin, flares of unpolarized
radiation would be dispersed rather than delayed.

Quantum Gravity and GRBs

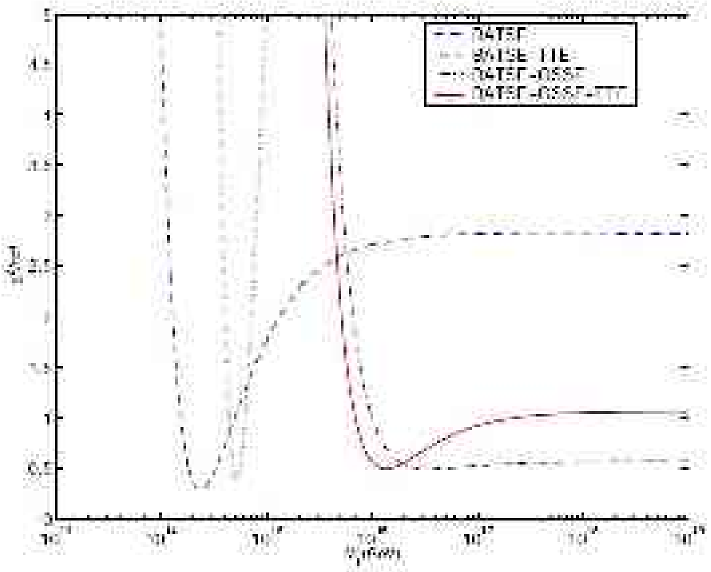
GRBs have intrinsic substructure on timescales of millisec.



Constraints using GRBs:

Norris et al., 1998, 2000 CCF
Ellis et al., 2002, 2006 wavelets
M_{linear} > 6.9E15 GeV
Lamon et al., 2007 ML

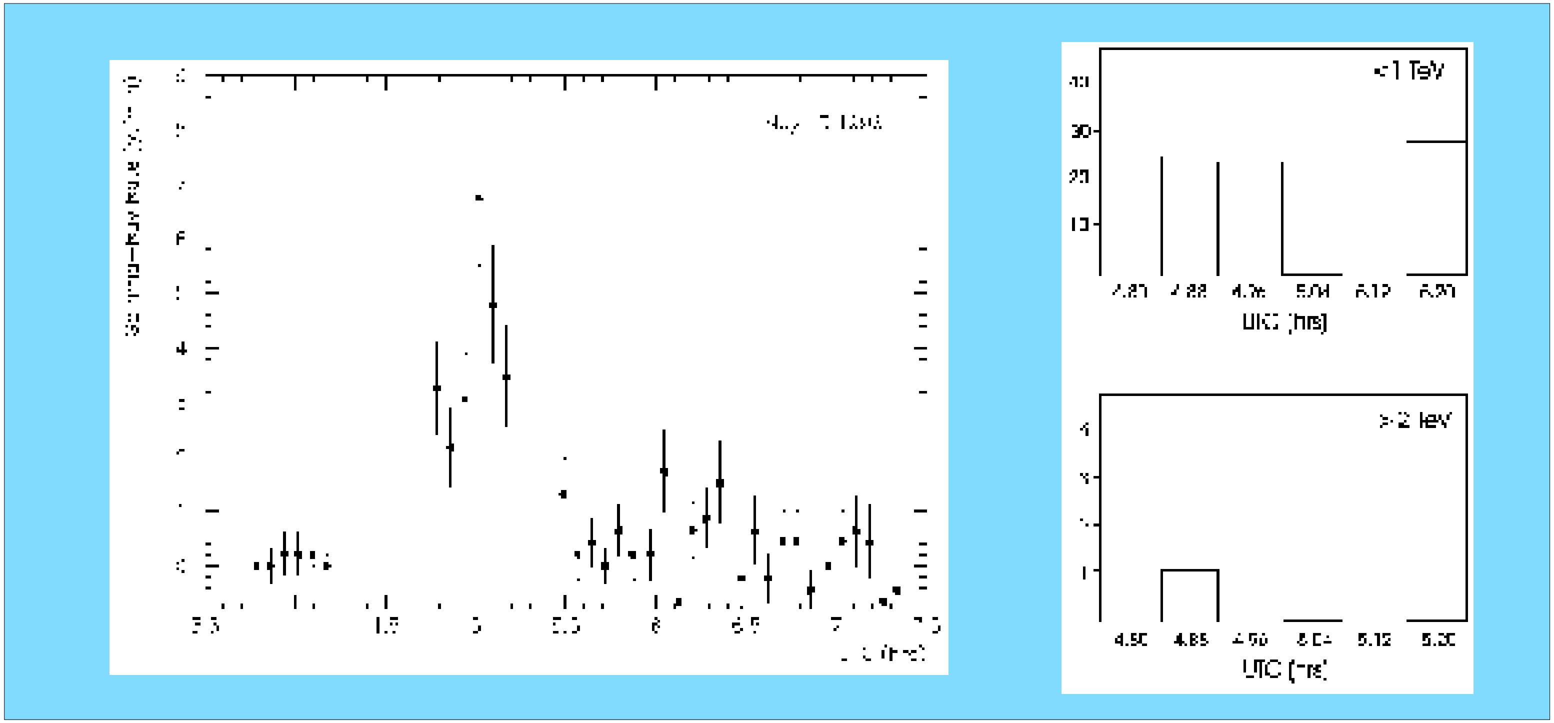
GRB vs. Blazars (same redshift):
100 keV - msec vs. 100 GeV - ksec



Intrinsic lags: Established in GRBs, plausible in AGN, time dependent ?

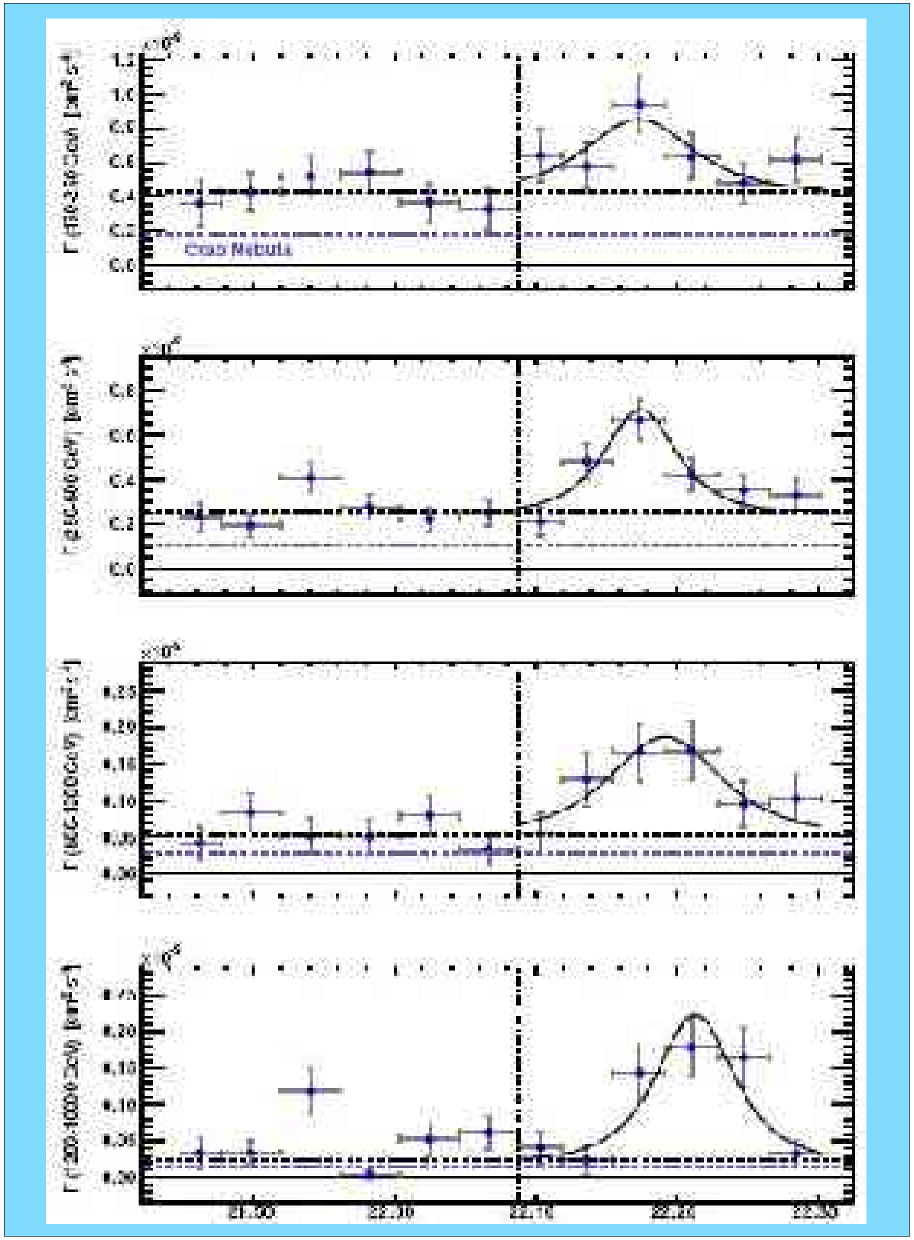
LIV tests in Blazars: 1) Mkn 421

Mrk 421 - Biller et al. ApJ, 1998 (Whipple-flare)

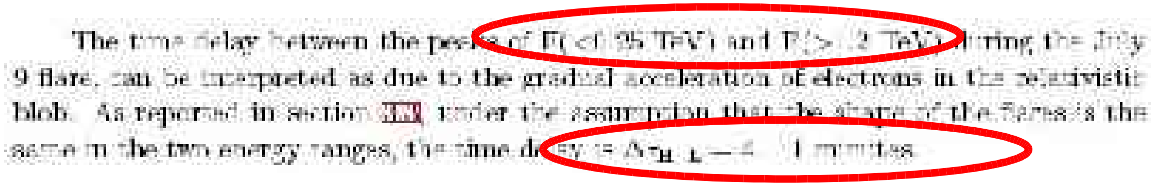


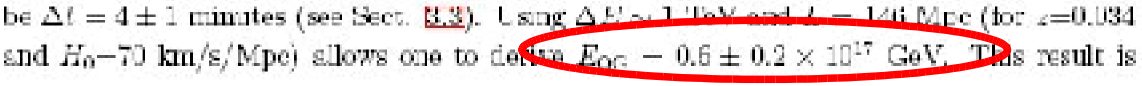
No significant time delay in three 280-s bins containing 7 γ (>2TeV)
suggesting M>4E16GeV (old cosmology)

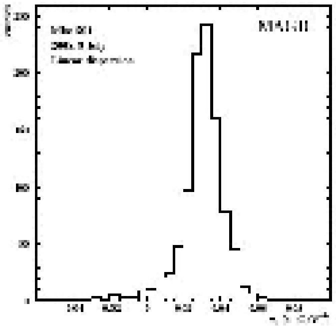
LIV tests in Blazars: 2) Mkn 501



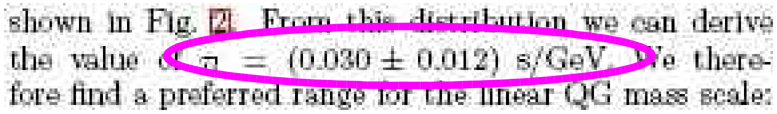
Mkn 501 - Albert et al. ApJ, 2007
[astro-ph/0702008] (MAGIC-flare)
and Albert et al., astro-ph/0708.2889

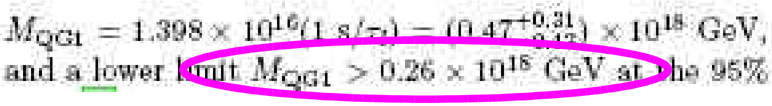

The time delay between the peaks of F(<0.25 TeV) and F(>1.2 TeV) during the July 9 flare, can be interpreted as due to the gradual acceleration of electrons in the relativistic blob. As reported in section [illegible], under the assumption that the shape of the flares is the same in the two energy ranges, the time delay is $\Delta\tau_{H,L} = 4 \pm 1$ minutes.


be $\Delta t = 4 \pm 1$ minutes (see Sect. 3.3). Using $\Delta E \sim 1$ TeV and $L = 146$ Mpc (for z=0.034 and H_0=70 km/s/Mpc) allows one to derive $E_{QG} = 0.6 \pm 0.2 \times 10^{17}$ GeV. This result is



240 + 60 sec/TeV,
i.e. 0.24 + 0.06 sec/GeV
-versus-


shown in Fig. 2. From this distribution we can derive the value of τ_l = (0.030 ± 0.012) s/GeV. We therefore find a preferred range for the linear QG mass scale:


$M_{QG1} = 1.398 \times 10^{16} (1\ \mathrm{s}/\tau_l) = (0.47^{+0.31}_{-0.13}) \times 10^{18}$ GeV, and a lower limit $M_{QG1} > 0.26 \times 10^{18}$ GeV at the 95%

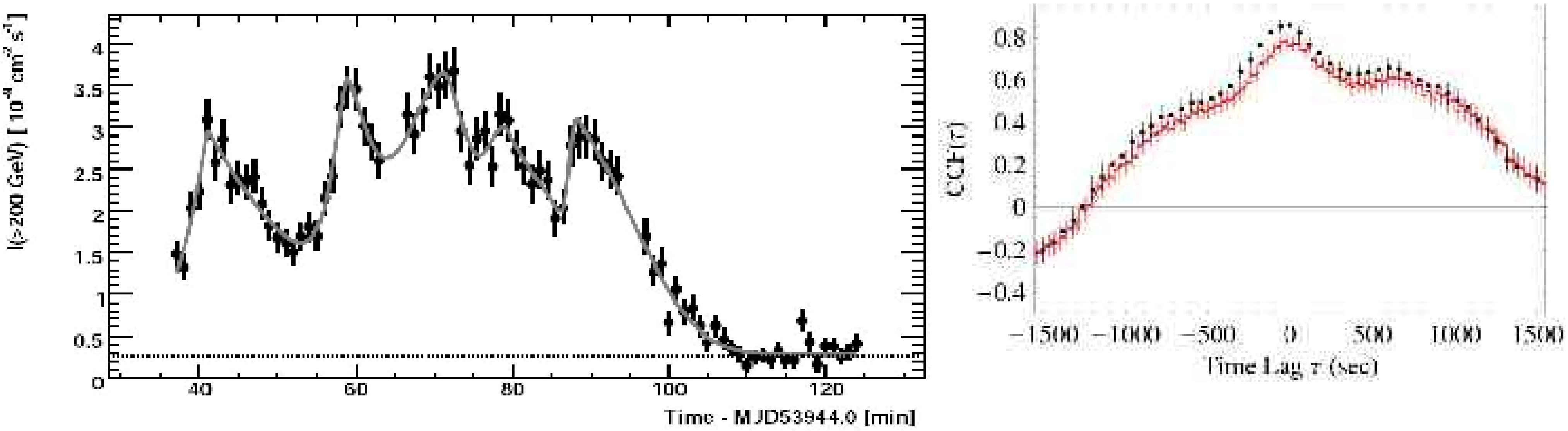
plus 2nd method used (likelihood)
with consistent results.

Variability and Propagation Effects

Stefan J. Wagner, Rolf Bühler, Agnieszka Jacholkovska, and
Dimitrios Emmanoulopoulos for the H.E.S.S. collaboration

Variability across the EM spectrum, Palaiseau, France, April 22-25, 2008

LIV tests in Blazars: 3) 2155-304

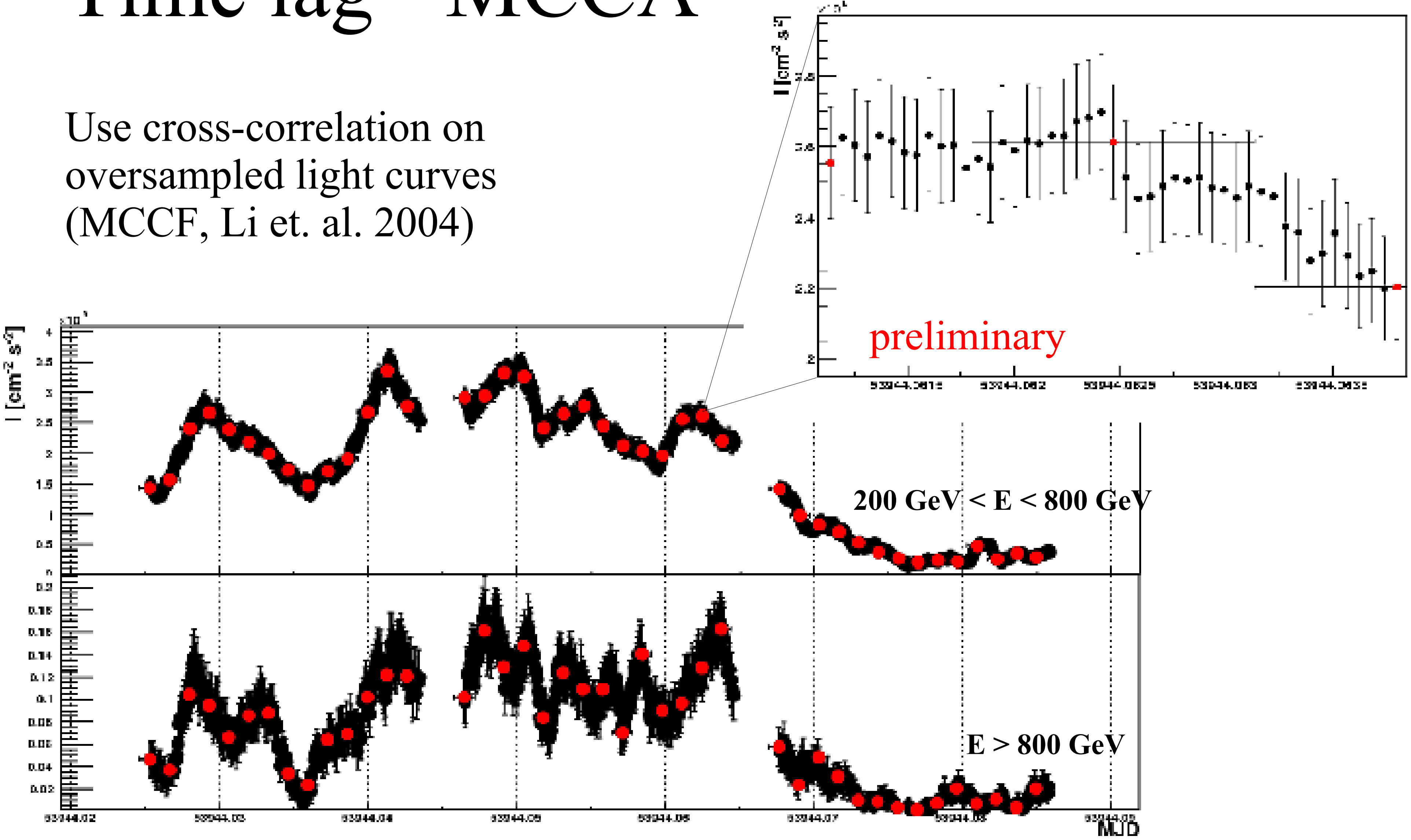


PKS 2155-304, flare in July 2006, very high photon statistics
1st step: break it up in energy bins and derive CCFs

usual problems/issues:
how to derive peak/centroid and errors,
dependence on choice of binning

Time lag - MCCA

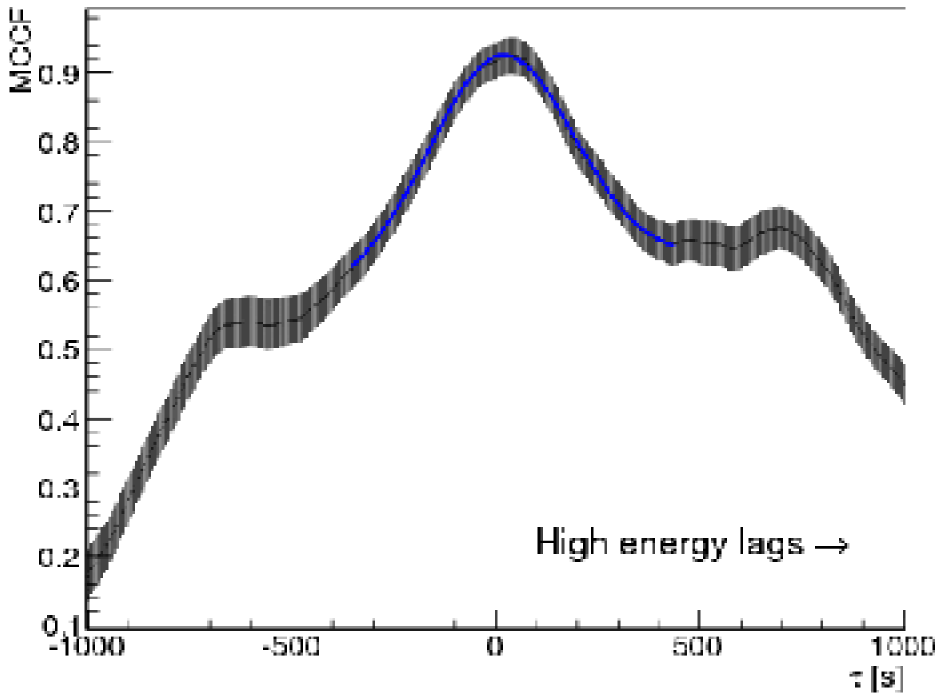
Use cross-correlation on oversampled light curves (MCCF, Li et. al. 2004)



Big Flare -Correlation analysis

MCCF provides:
Sensitivity below the time binning
No need for interpolations
Define peak by fitting gauss + linear:

$\tau_{\text{peak}} \approx 14$ s



preliminary

→ How to estimate error?

(Fit errors not meaningful)

Error from simulations

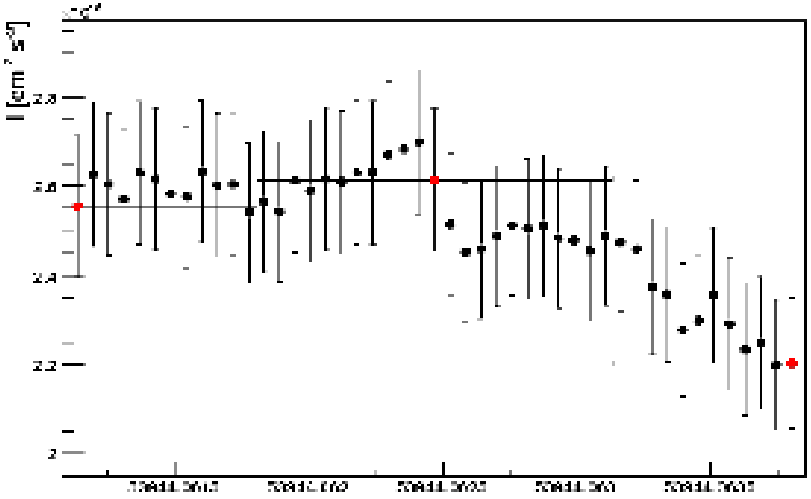
Two independent sets of simulations:

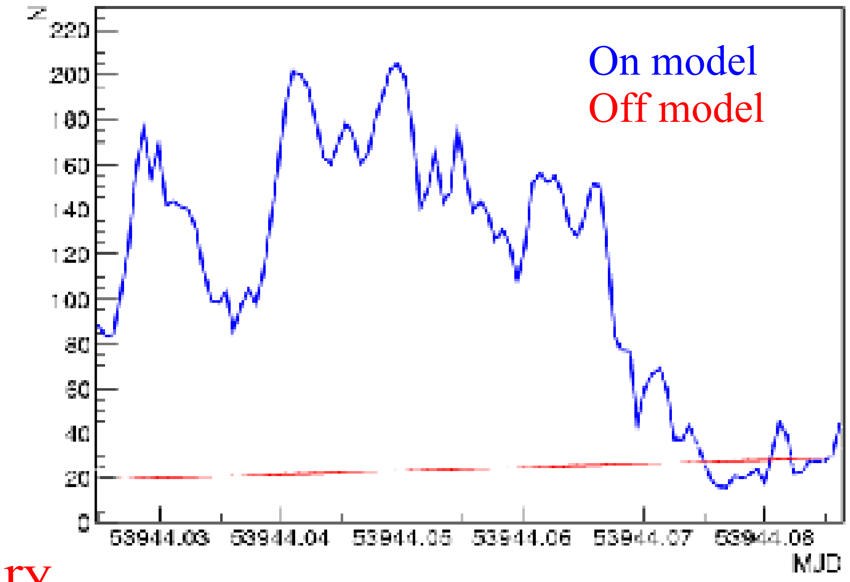
Method 1

Simulate new light curves within errors

Method 2

Simulate new photon list according to a light curve model



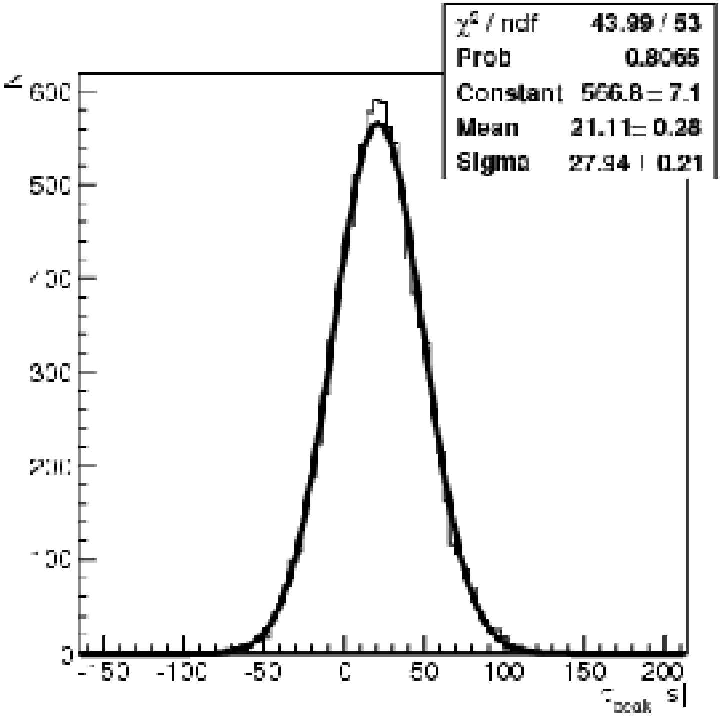


preliminary

Error from simulations

Error from distribution:

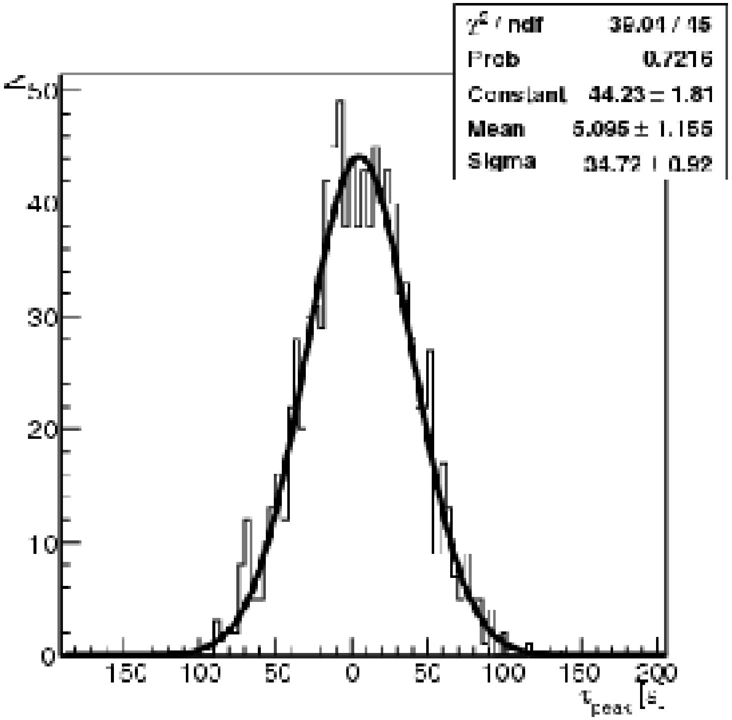
<u>Method 1</u>



$\Delta\tau_{peak} = 28$ s

preliminary

<u>Method 2</u>



$\Delta\tau_{peak} = 35$ s

LIV / Quantum Gravity limit

- No significant time lag found.

Assumption that source effect can be neglected, we get:

$$\Delta t_{QG} < 72\,s \qquad (95\,\%\,confidence)$$

$$\Delta E = \bar{E}_{800} - \bar{E}_{200-800} \approx 1.02\,TeV$$

preliminary

$$z = 0.116$$

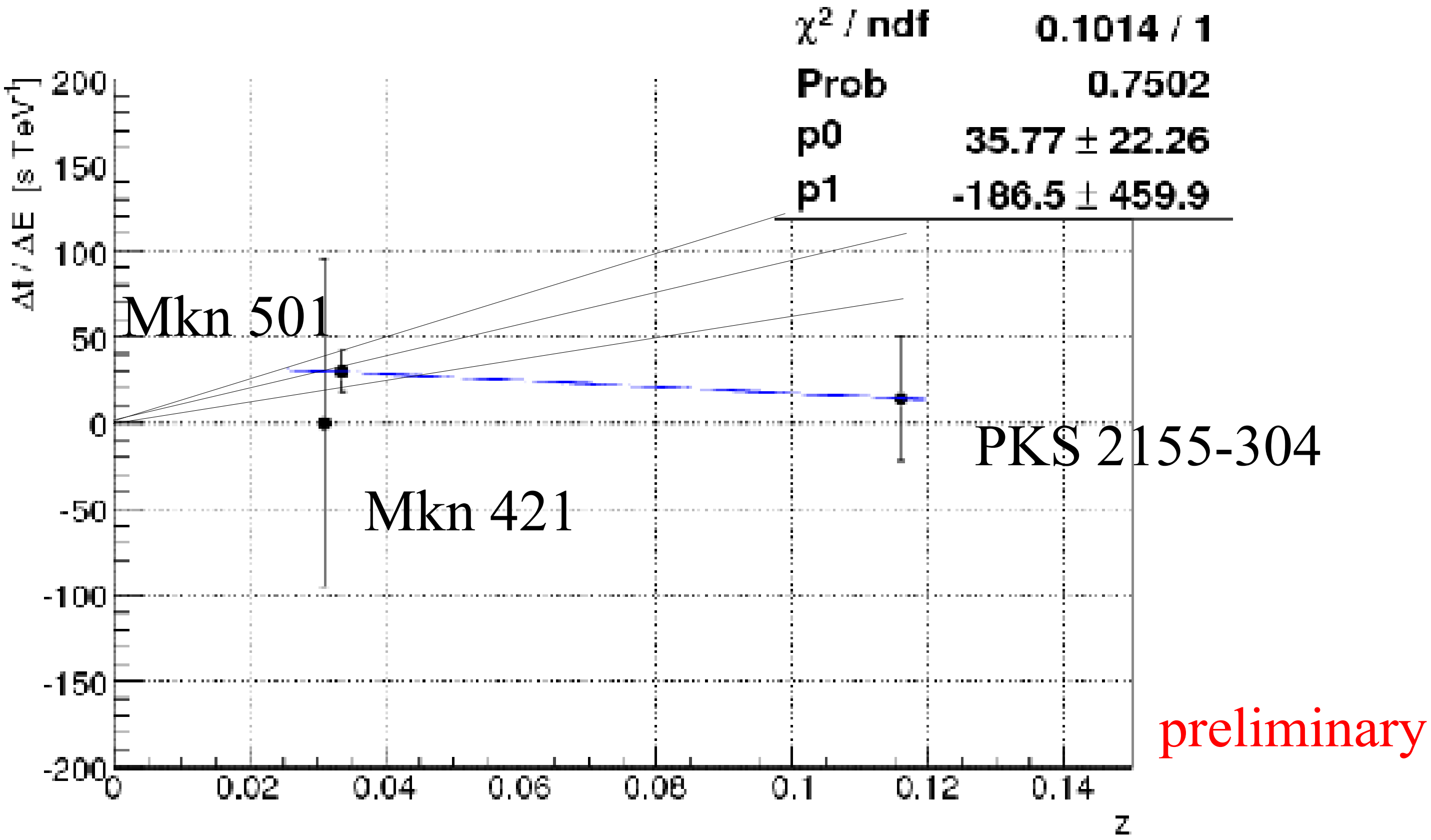
$\rightarrow k > 5.2$ % M$_{\text{Planck}}$ = 6.2 E17 GeV

reminder: $c' = c\left(1 \pm \frac{E}{\boldsymbol{k} \cdot M_p} + ..\right)$

Two other methods yield consistent results:
(minimum dispersion and wavelets)

Comparisons/Source effects ?

Most of the range in $\Delta t/\Delta E$ at z=0.116 inconsistent



All values (except for 1st paper on Mkn 501) consistent with zero.
No trend with redshift (as required for LIV)

Intrinsic vs. propagation-induced lags

Most acceleration and cooling mechanisms scale with energy.

$t_{acc} = f(E)$, $t_{cool} = f(E)$ but $t_{flare} = f(E)$?

if $t_{flare} \sim t_{acc} + t_{cross} + t_{cool}$ dominated by t_{cross}, there need not be strong energy dependence.
Attempts to measure lags have had mixed success.

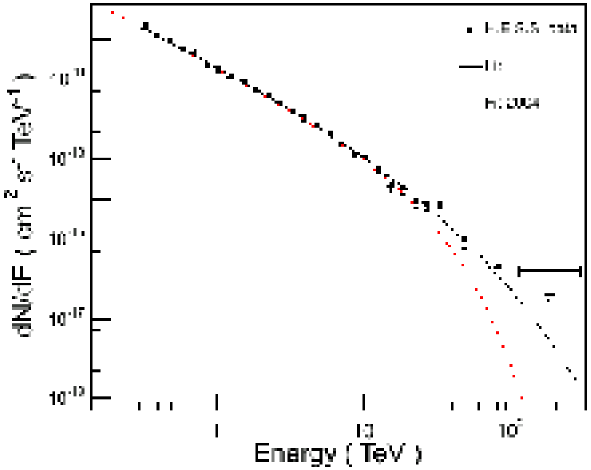
But: (1) flare profiles do not exhibit flat-topped profiles,
(2) X-rays exhibit soft and hard lags (loops in L-HR-plane)

intrinsic lags
would not scale with distance
would not be identical in all flares of one source
but would be very hard to correct for.

LI violation

Many other limits on LIV: Birefringence (k=50000) in VHE regime:

Violation of LI may lead to $c_{e,max} = c\ (1+\ \ )$, $0 < |\ \ | << 1$



For $c_e < c$ ($\ \ < 0$) photons with $E > m_e \sqrt{(2/|\ \ |)}$ decay quickly into pairs.

With $E_{max} = 100$ TeV one obtains $|\ \ | < 5\ 10^{-17}$

For $c_e > c$ electrons suffer losses by vacuum Cerenkov radiation, limiting $E_{max,\ e}$. $E_{max,e} > 2$ TeV implies $\ \ < 3\ 10^{-14}$

$c_e > c$ also modifies pair-creation threshold $\ \ \ \ $ -> ee

Spectral cut-offs in Blazars observed in VHE band have been interpreted as evidence for absorption on diffuse IR-EBL at classical threshold out to 20 TeV, implying $|\ \ | < 1.3\ 10^{-15}$

Room for improvement?

Better photon statistics: Shortest time-scales not accessible, photon noise limits constraints: Limitations even in PKS 2155-304 (>10000 photons).
Wait for brighter flares or build a more sensitive experiment.

Higher energies: Clearly desirable, however with spectra falling as E -2 to -4 in bright sources, unlikely to gain an order of magnitude.
Wait even longer or build a more sensitive experiment.

Faster variations: If there were (sub) flares with shorter time-scales, it would be easier to constrain lags (photon statistics, pattern vs delta)
GRBs would be interesting (but difficult).

More distant Blazars: Possibly gaining another factor of 5

Room for improvement?

Higher energies: A more sensitive experiment might reach out to higher energies (factor 10, gains half an order of magnitude in energy). Factor of 3

Faster variations: Nobody would have believed 3 min 5 years ago,
why not 30 sec? (another factor of 5)

More distant Blazars: 0.116 -> 0.6 factor of 5

A factor of 75 seems to be a conservative guess for the improvement. Exceptional flares may result in additional gain, but they would lack the chance of repeatability.

Summary

Propagation-induced variability at radio frequencies might be an interesting tool in understanding VHE emission.

Solving issues raised by VHE studies might eliminate need to invoke propagation-induced variability in many IDV sources.

Microlensing might contribute to VHE variability, but is unlikely to be a common phenomenon.

VHE observations of fast flares enable measurements of energy-dependence of speed-of-light and hence test LIV – a prediction of many models of QG.

3.5 sigma detection of an energy-dependent lag claimed for Mrk 501, but constraints derived from more distant PKS 2155-304 consistent with 0.

Current limits on QG from spin-insensitive LIV:
5.2% of M_{Planck} (best value to date).