Unravelling the complex behavior of Mrk 421 with simultaneous X-ray and VHE observations during an extreme flaring activity in April 2013

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Mrk 421 — model blazar

- Nearby blazar
  - z~0.03, ~140 Mpc
  - Imaging with VLBA possible down to scales <0.01-0.1 pc (<100-1000 r_g)
  - Not strongly affected by Extragalactic Background Light absorption
- Bright blazar
  - Easily detected with Imaging Atmospheric Cerenkov Telescopes (IACTs), Fermi, and X-rays, Optical, Radio instruments over short integration times
  - Allows to construct high-quality SED for short time scale and study its evolution
  - Allows study of variability in different bands and across different time scales: possible detection down to minutes time scale during average or high state, but also detectable in very low states
  - Possible to observe not only during flares, but during low states too

- Emission from the Broad Line Region not visible in Spectral Energy Distribution, simplifying modelling of the jet emissions and interactions

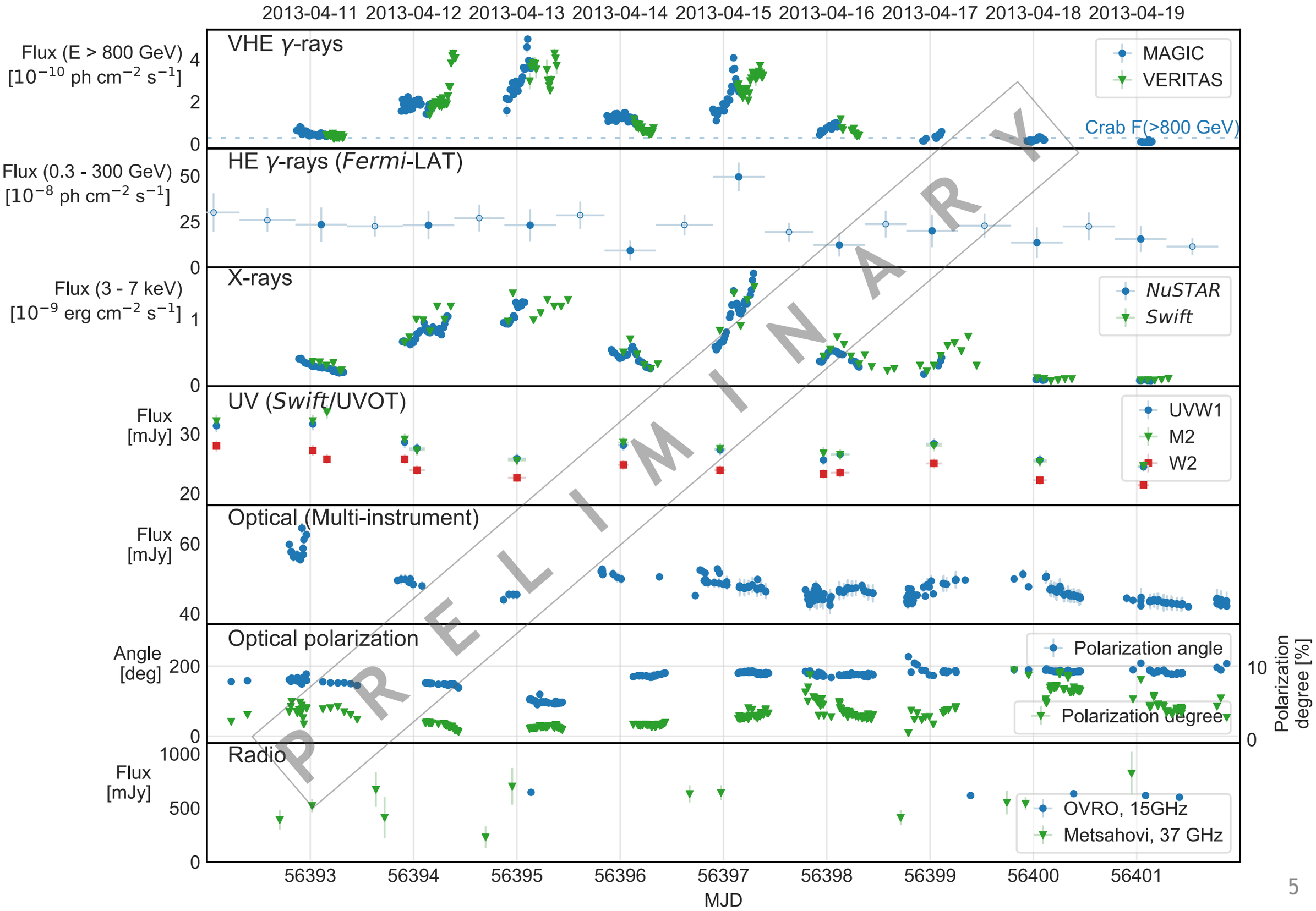
Monitoring campaigns

- Multi-Instrument Monitoring campaigns since 2009
  - Along with the other nearby blazar Mrk 501, subject of extensive monitoring
  - Observations 4.5-6 months/year
  - Every ~1-5 days, regardless of activity (i.e. low states)
  - Monitoring increased during flaring activities
- Instruments
  - Radio: VLBA, OVRO, Effelsberg, Metsahovi...
  - mm: SMA, IRAM-PV
  - Infrared: WIRO, OAGH
  - Optical: GASP, GRT, MITSuMe, Kanata...
  - UV: Swift-UVOT
  - X-ray: Swift/XRT, RXTE/PCA, RXTE/ASM, Swift/BAT, XMM, NuSTAR
  - Gamma-ray: Fermi-LAT
  - VHE: MAGIC, VERITAS, FACT

11 - 19 April 2013 flare

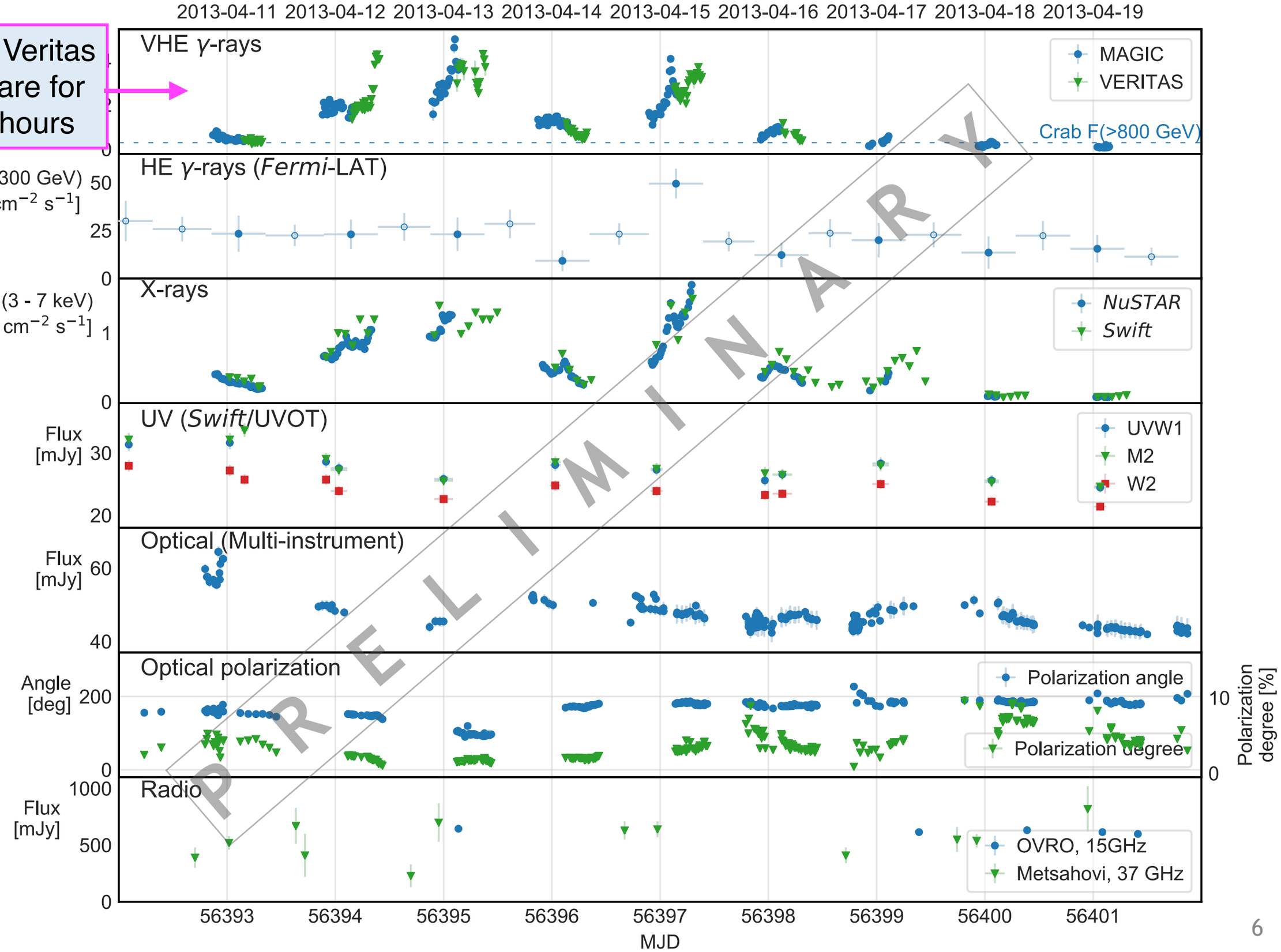
- High activity recorded during the 9 days
  - Exceptionally high flux in VHE and X-ray bands
  - Activity in radio, optical, and MeV bands does not show similar level of flux enhancement or variability
  - Activity in radio-MeV bands is similar to January-March 2013 activity, when the source was in low VHE state (Baloković et al., 2016)
- Light curves
  - VHE: MAGIC and VERITAS (Benbow et al., 2017AIPC.1792e0001B) above 200 GeV, with some time overlap, providing ~10 hours of coverage per night
  - X-rays: NuSTAR 3-80 keV, ~10 hours of coverage per night
  - VHE and X-ray produced in 15-min. time bins, and in 3 energy bins each
  - Present light curves in radio, optical, UV, MeV, and optical polarization
- Correlations and variability
  - VHE and X-ray light curves in 15-min time bins and 3 energy bins will allow separating flux variations into slow trends and fast-flares
  - Allow study of correlation between flux changes in VHE and X-rays

MWL observations



MWL observations

MAGIC and Veritas cover the flare for almost 70 hours



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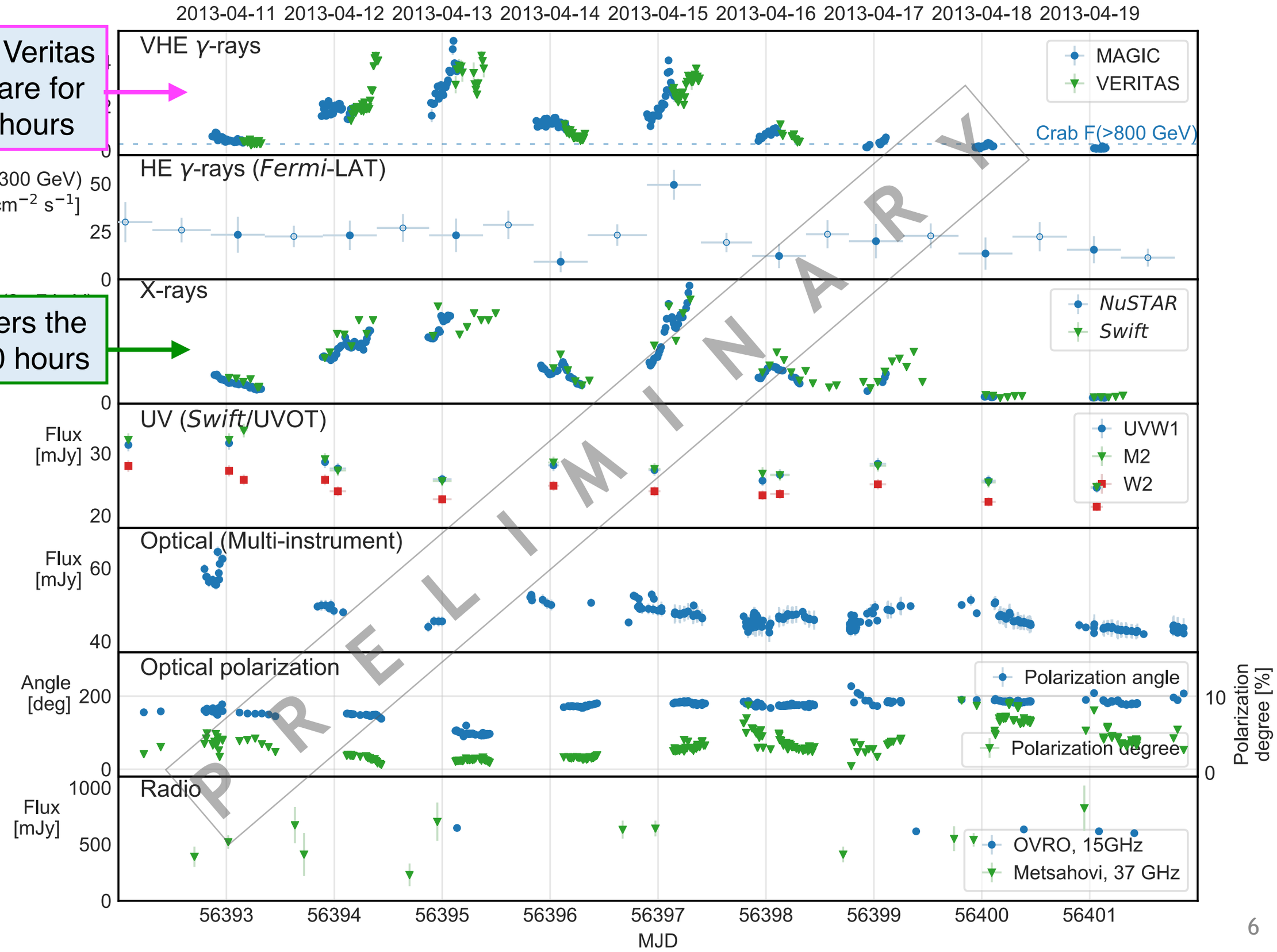

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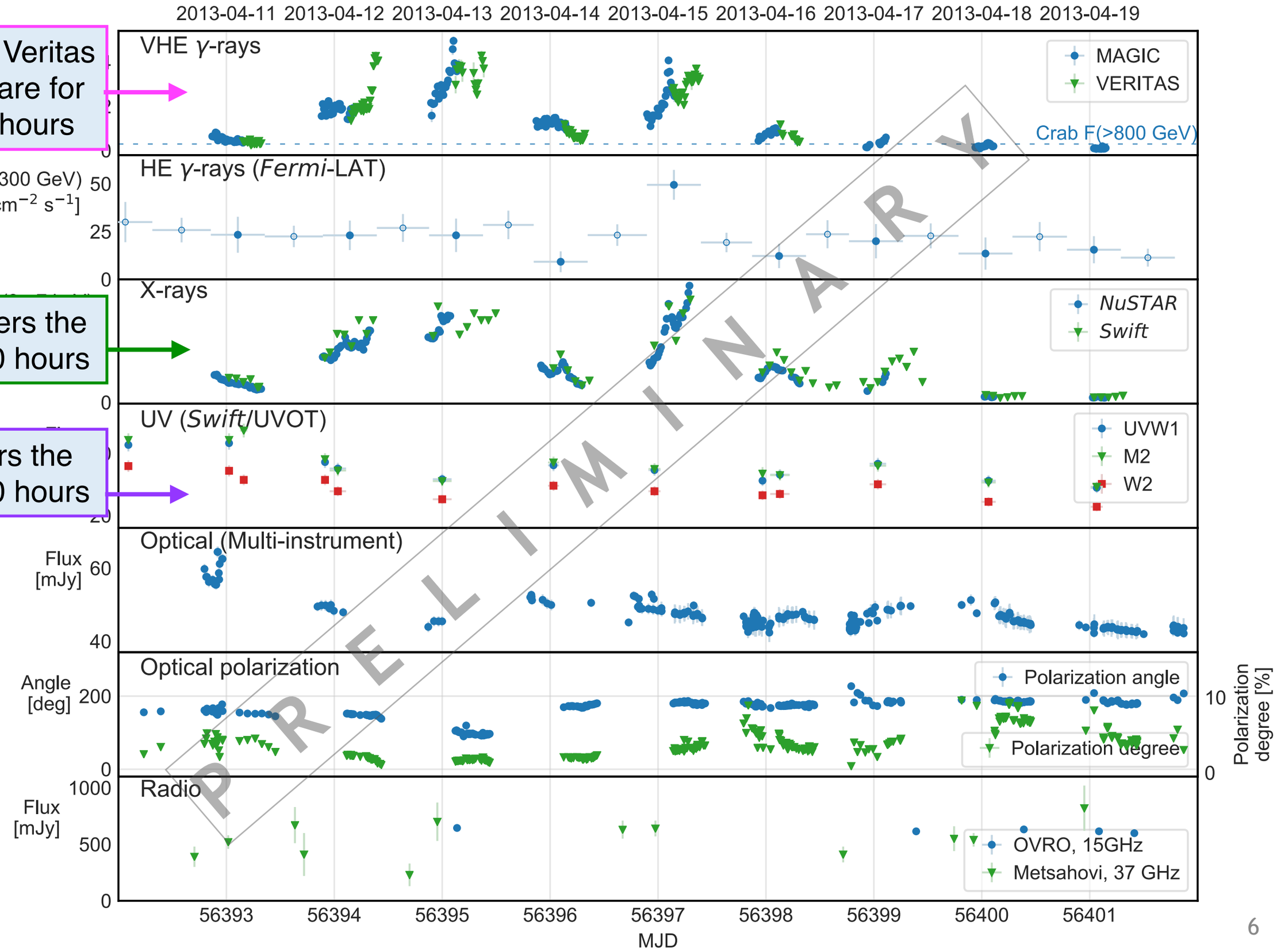

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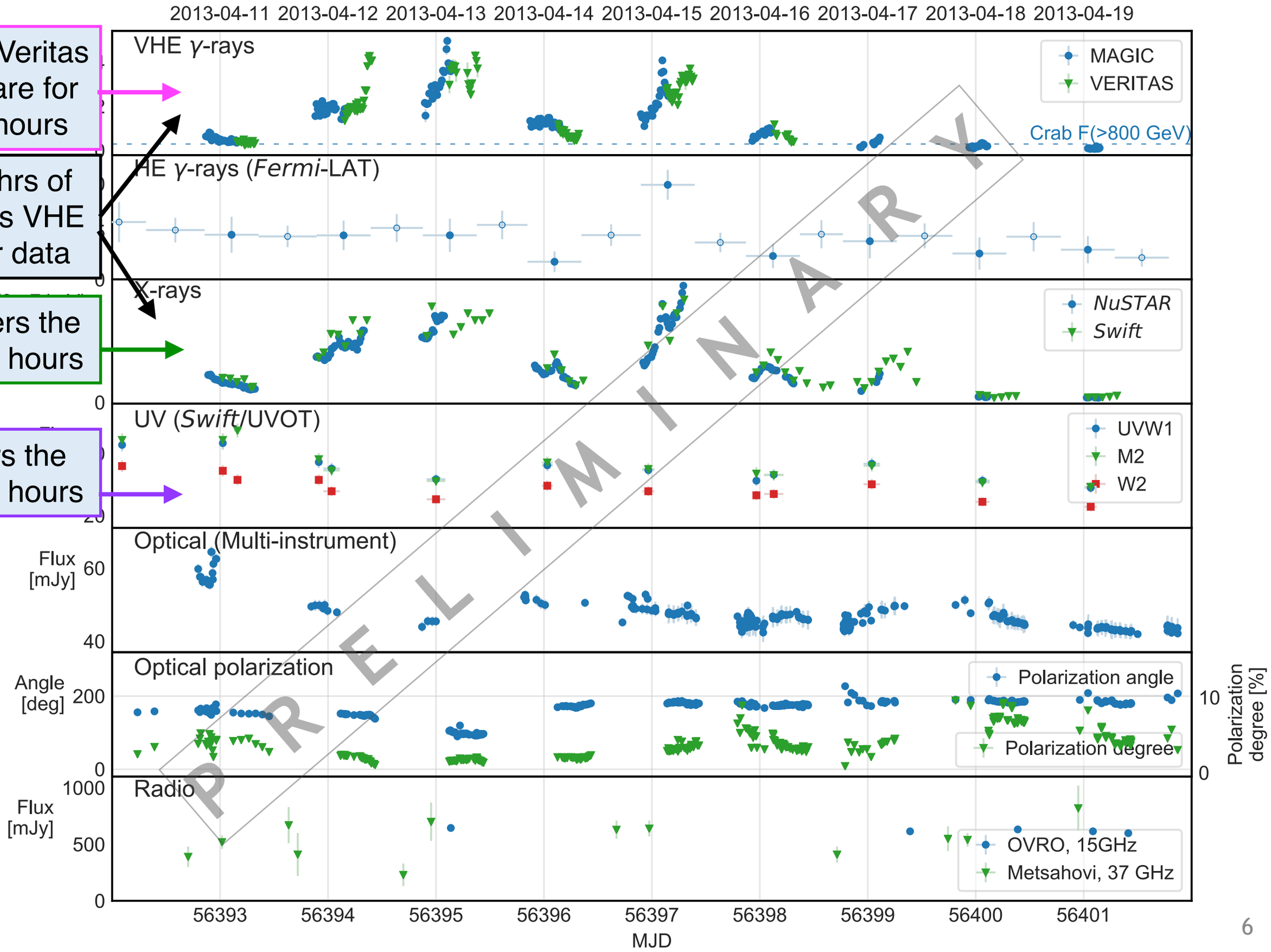

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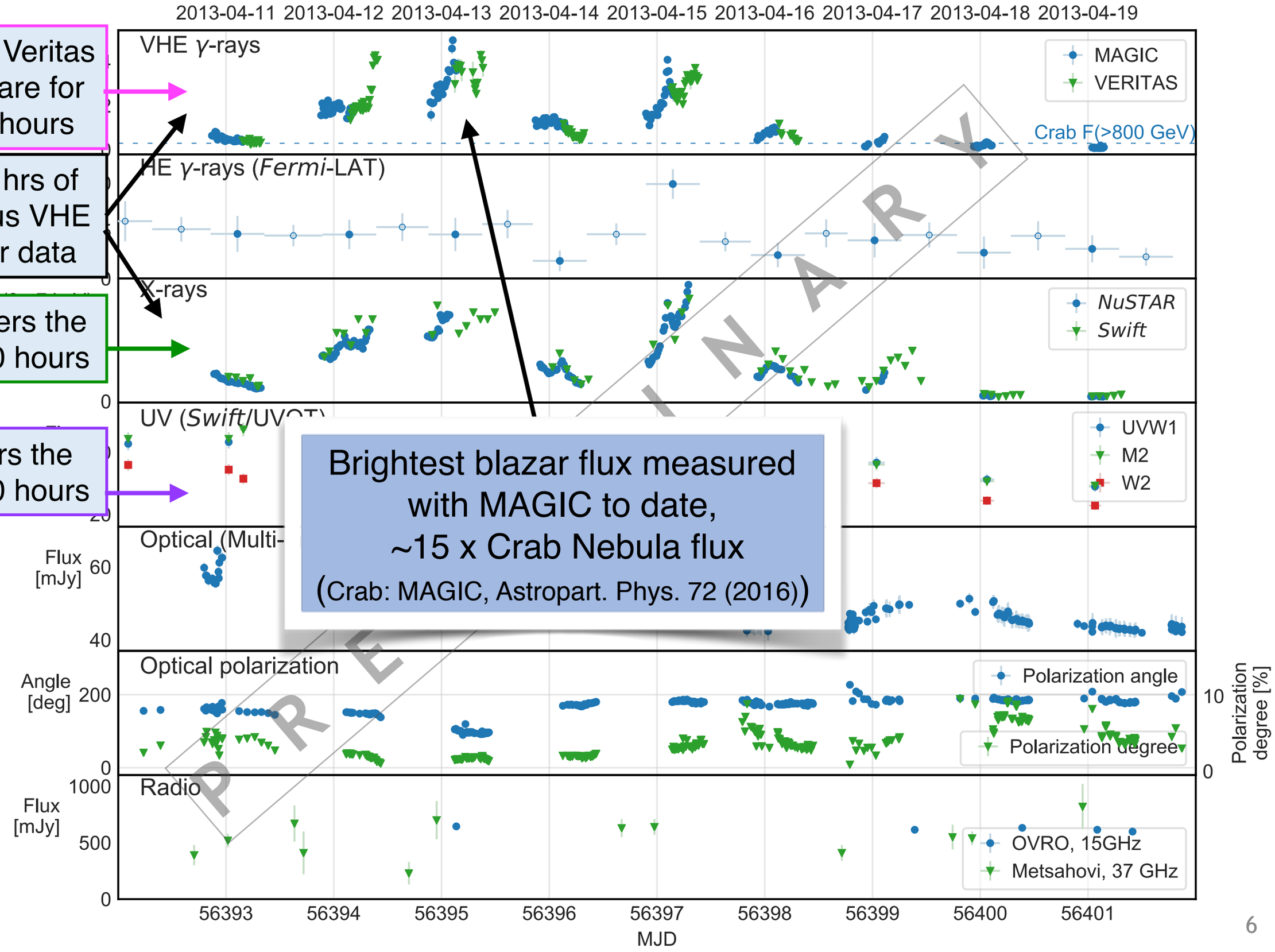
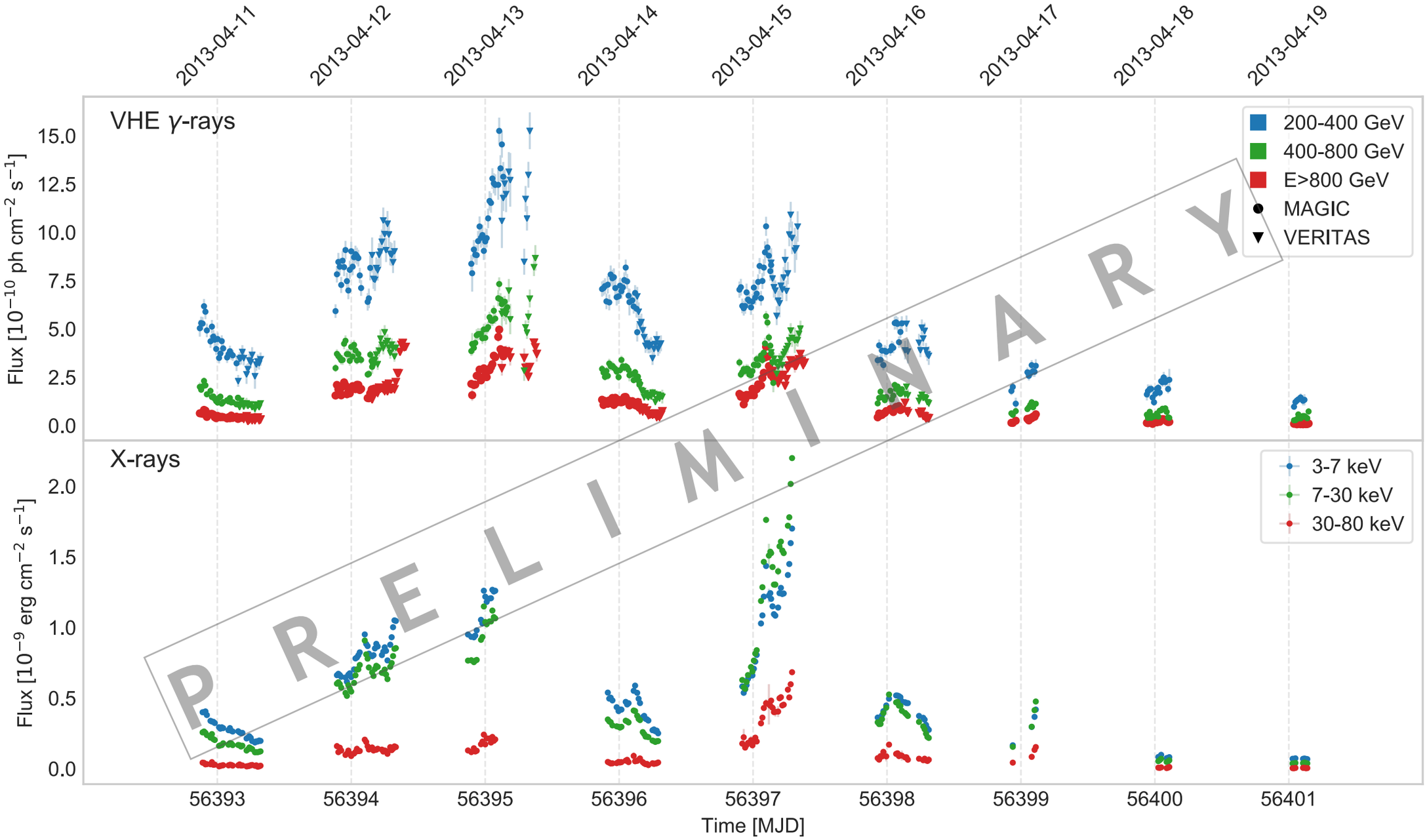


Brightest blazar flux measured with MAGIC to date, ~15 x Crab Nebula flux

(Crab: MAGIC, Astropart. Phys. 72 (2016))

MWL observations

- 45 hours of strictly simultaneous VHE (MAGIC+VERITAS) and X-ray data
  - The most detailed X-ray/VHE dataset collected during a flaring activity on Mrk 421, or any blazar



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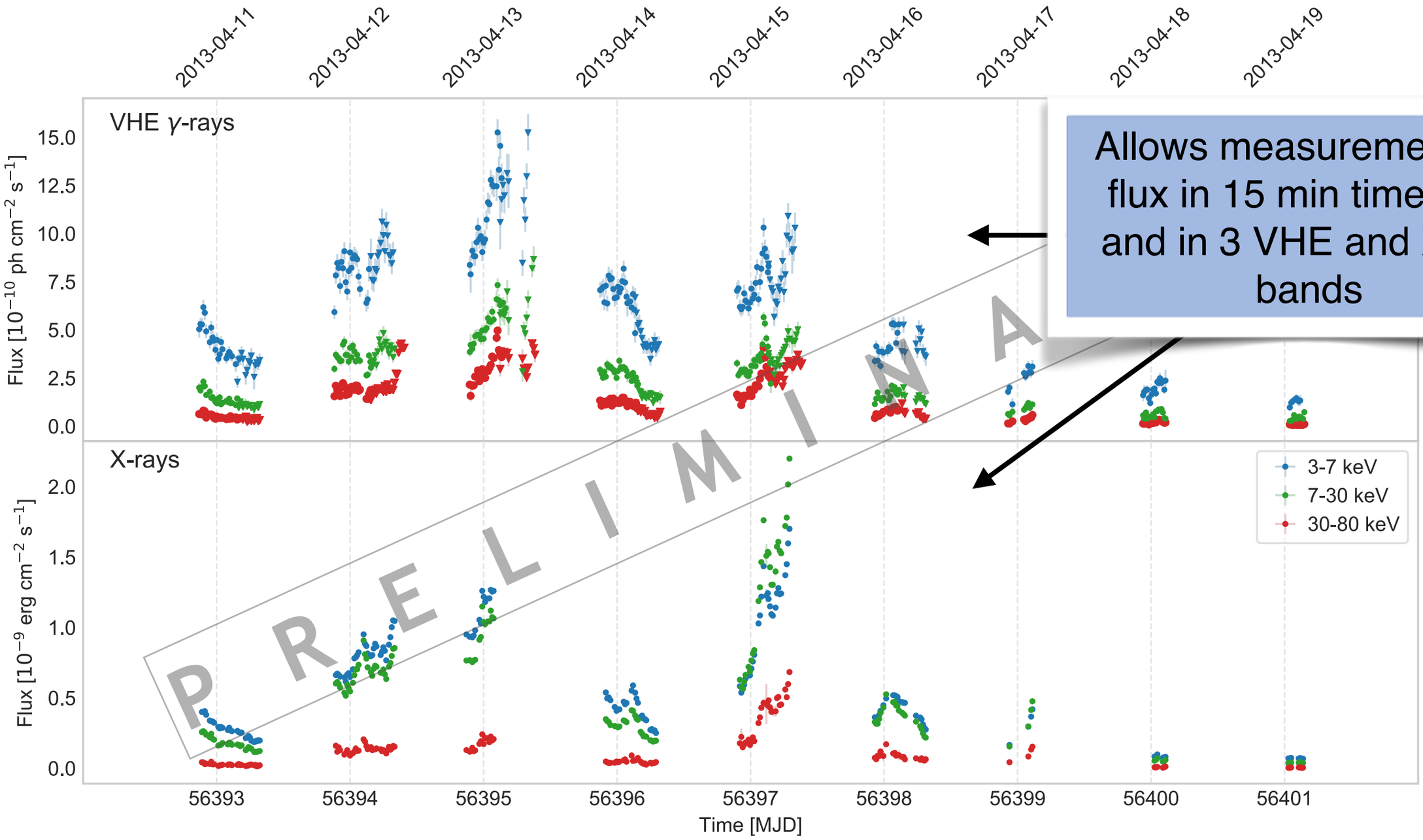


Allows measurements of flux in 15 min time bins and in 3 VHE and X-ray bands

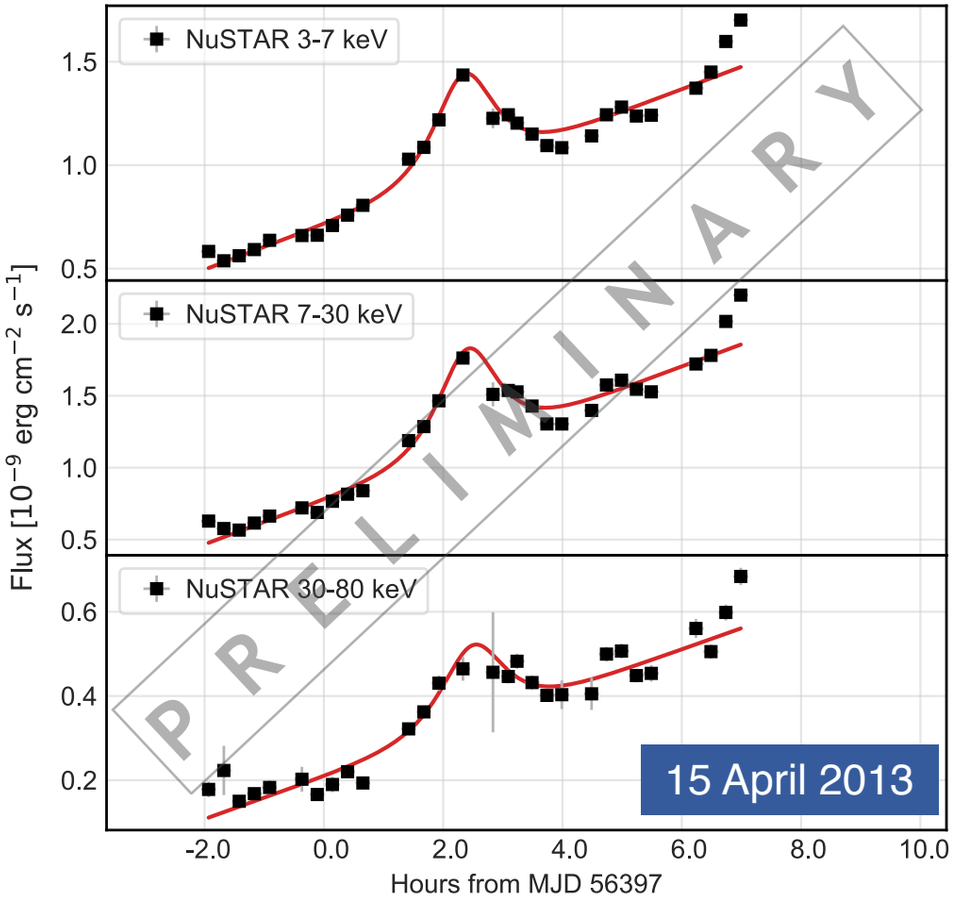
Intra-night variability

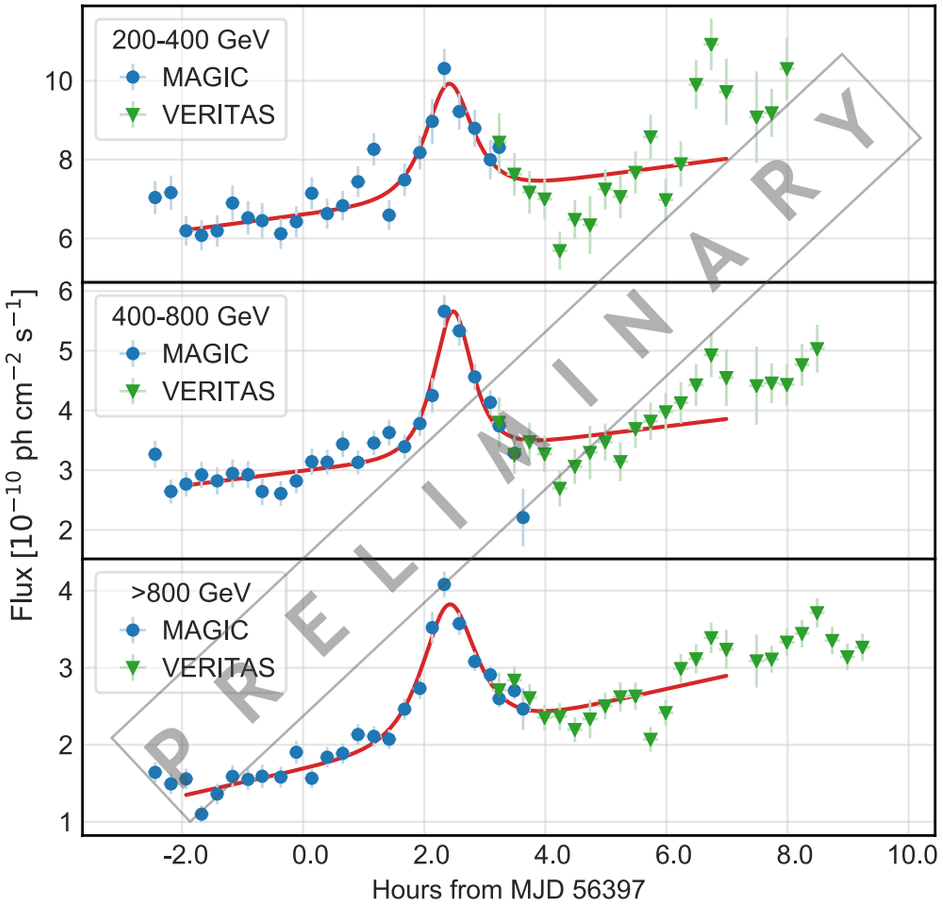
- Difference between variability for the 9-days and single night in X-rays and VHE
  - Model as trend + fast-flare component:

$$\mathrm{Flux}(t) = \mathrm{Slow}(t) + \mathrm{Fast}(t)$$

$$\mathrm{Slow}(t) = \mathrm{Offset} \cdot (1 + \mathrm{Slope} \cdot t)$$

$$\mathrm{Fast}(t) = \frac{2}{2^{-\frac{t-t_0}{t_{\mathrm{rise}}}} + 2^{\frac{t-t_0}{t_{\mathrm{fall}}}}} \cdot \mathrm{FlareAmpl.} \cdot \mathrm{Slow}(t_0)$$





Intra-night variability

Band	Offset[a] VHE: 10^{-10} ph cm^{-2} s^{-1} X-ray: 10^{-9} erg cm^{-2} s^{-1}.	Slope [h^{-1}]	Flare Amplitude	Flare doubling time[b] [h]	t_0[c] [h]	χ^2/d.o.f
15 April 2013						
200-400 GeV	6.60 ± 0.17	0.031 ± 0.008	0.40 ± 0.09	0.23 ± 0.07	2.41 ± 0.09	96.9/38
400-800 GeV	2.99 ± 0.07	0.042 ± 0.008	0.72 ± 0.09	0.19 ± 0.03	2.47 ± 0.04	68.1/42
>800 GeV	1.68 ± 0.05	0.103 ± 0.010	0.82 ± 0.08	0.27 ± 0.03	2.41 ± 0.04	90.0/45
3-7 keV	0.71 ± 0.01	0.153 ± 0.006	0.49 ± 0.07	0.30 ± 0.04	2.35 ± 0.06	836/24
7-30 keV	0.78 ± 0.02	0.199 ± 0.009	0.59 ± 0.11	0.30 ± 0.04	2.41 ± 0.06	889/24
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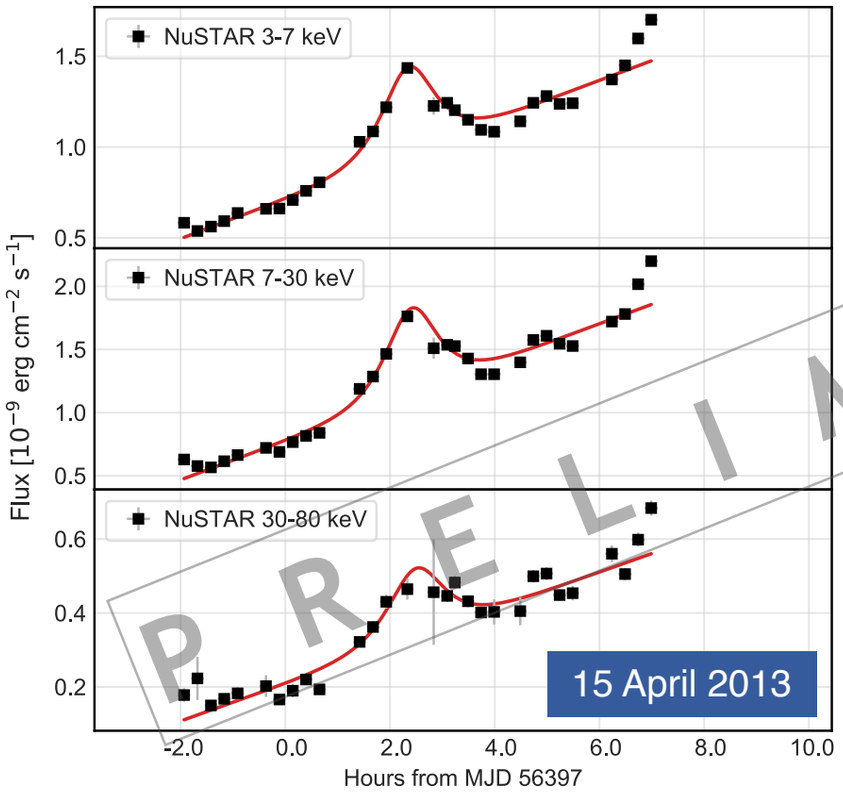

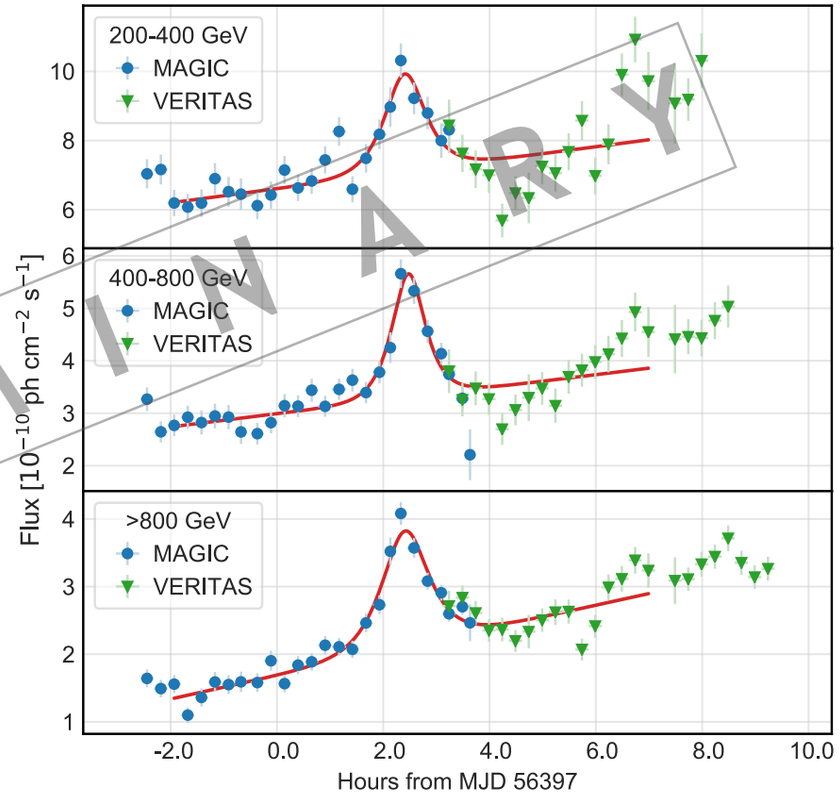

PRELIMINARY

Directly compare **between different bands** strength of slow change (Slope), and relative strength of fast-flare (Flare Amplitude)

Intra-night variability

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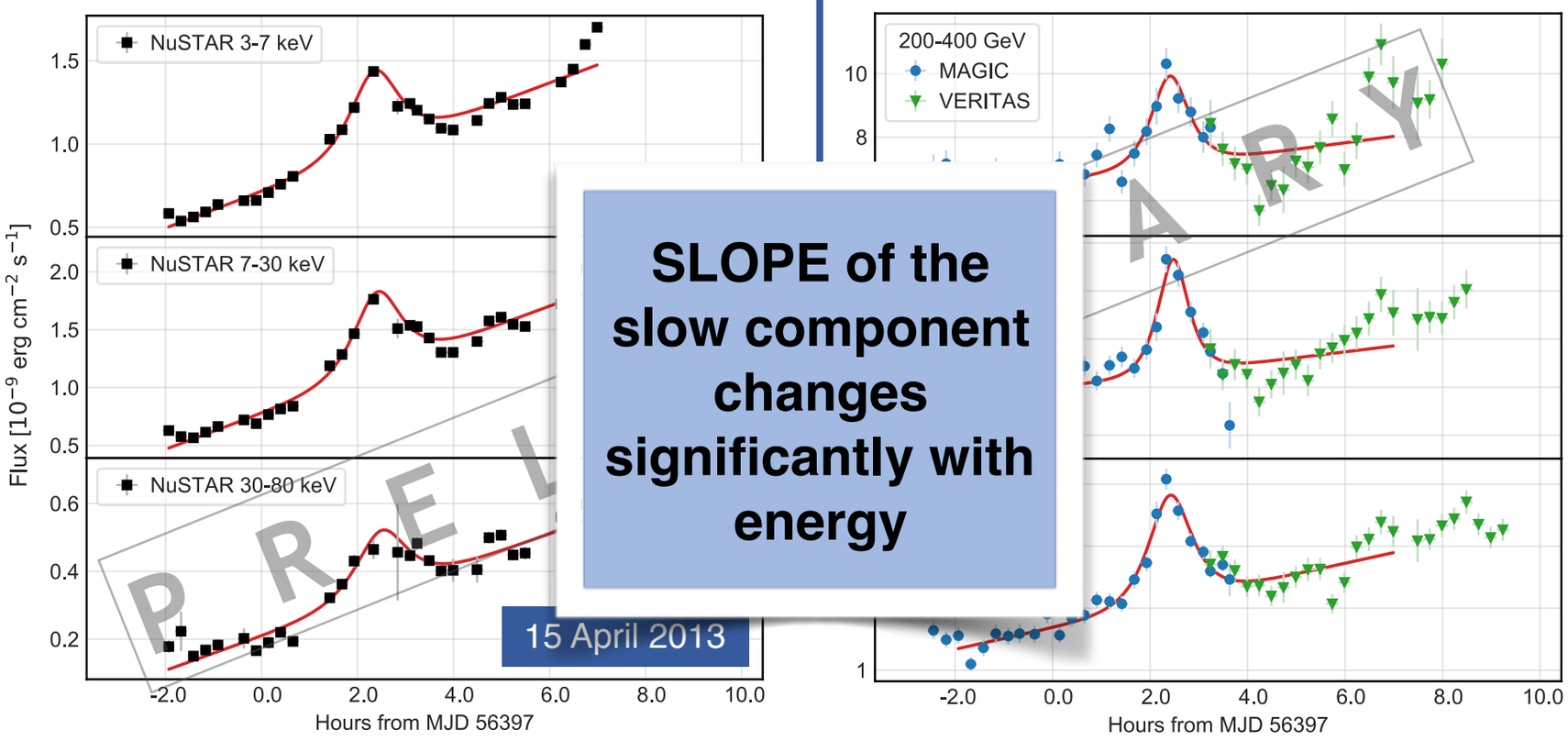

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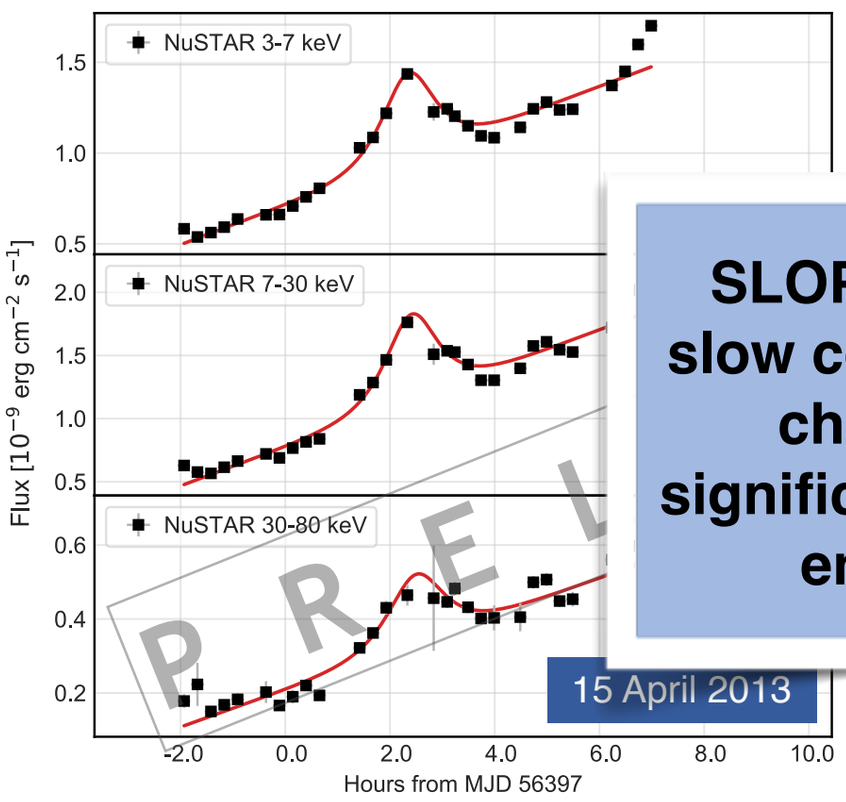

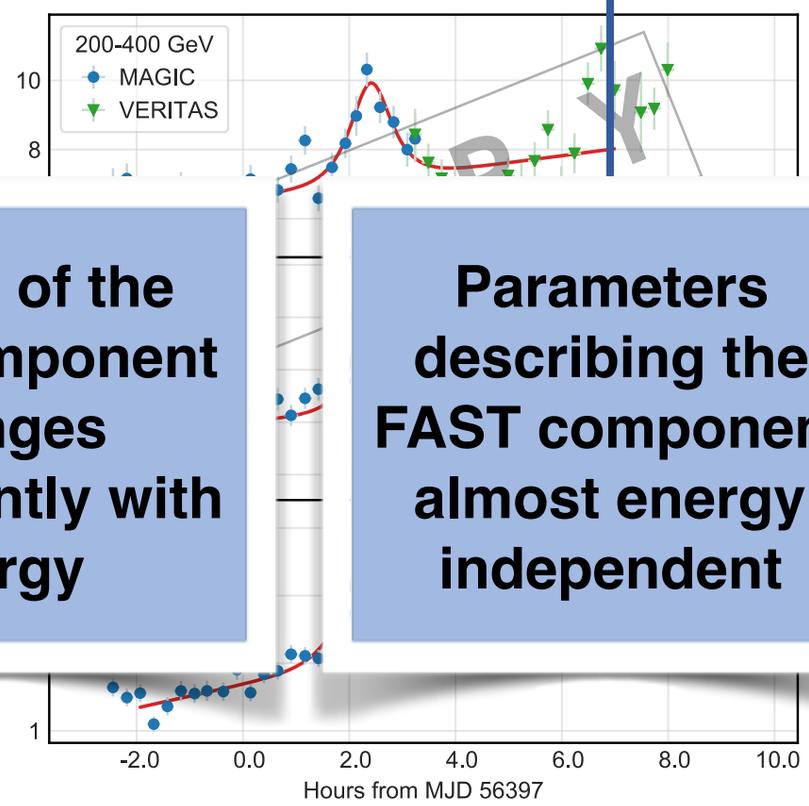

SLOPE of the slow component changes significantly with energy

Parameters describing the FAST component almost energy independent

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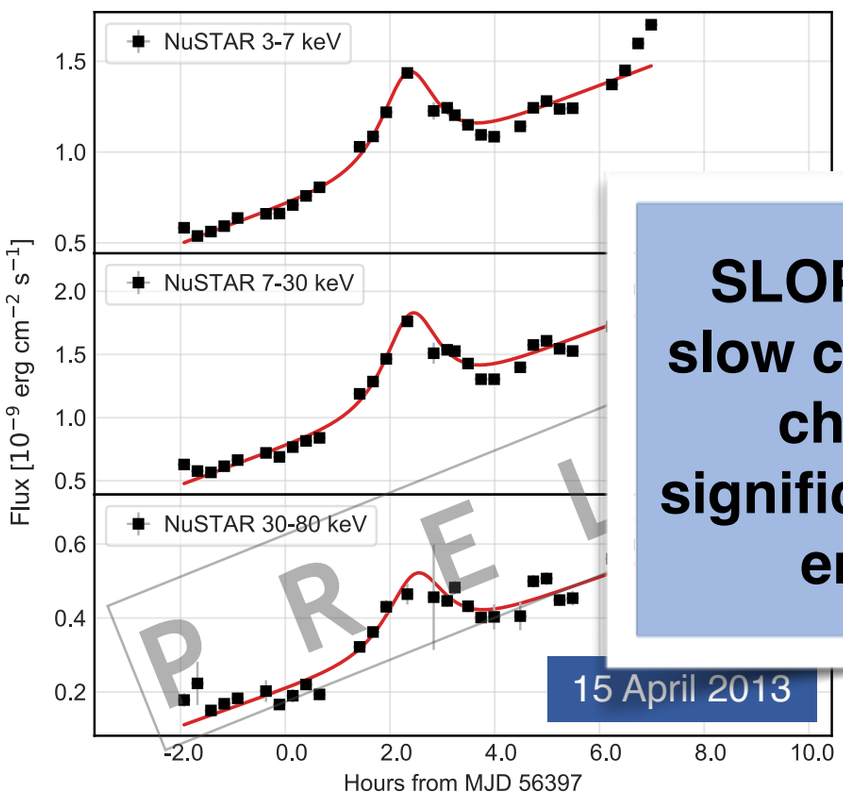

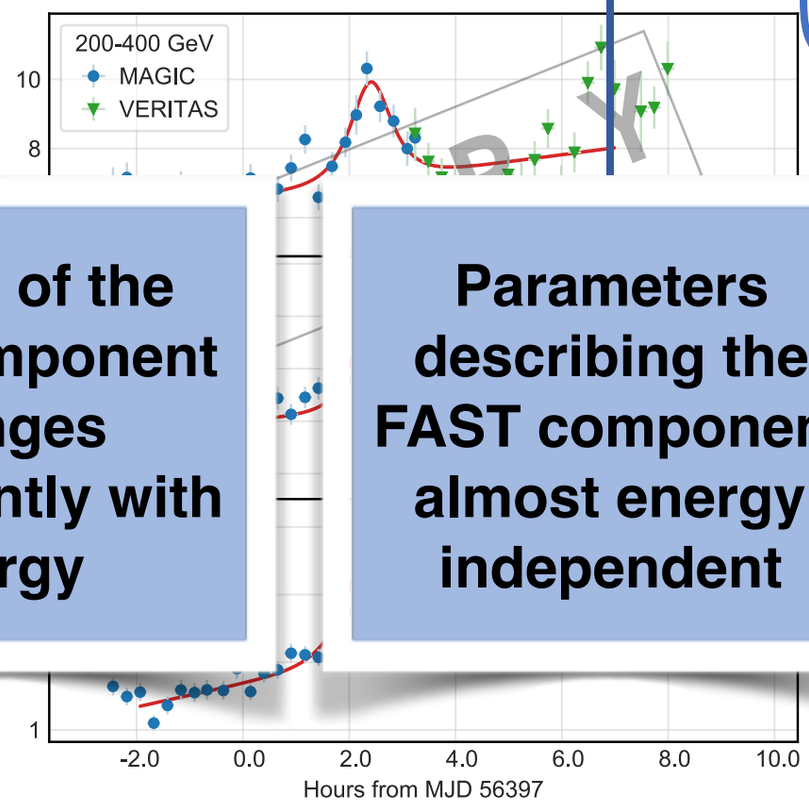

SLOPE of the slow component changes significantly with energy

Parameters describing the FAST component almost energy independent

The location of the flare t_0 appears the same in all bands

Intra-night variability

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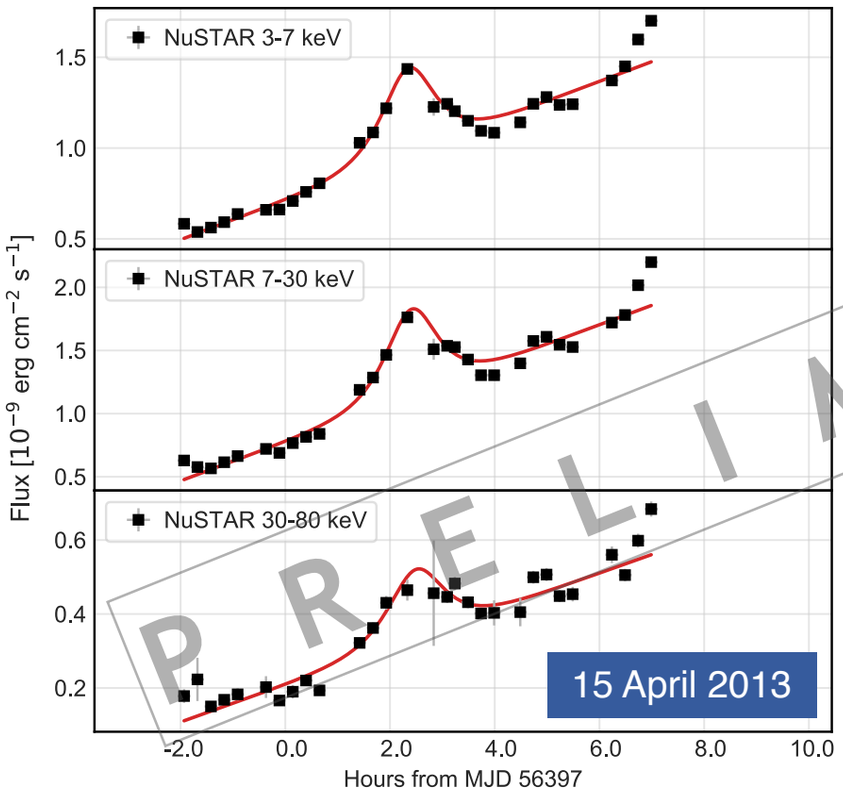
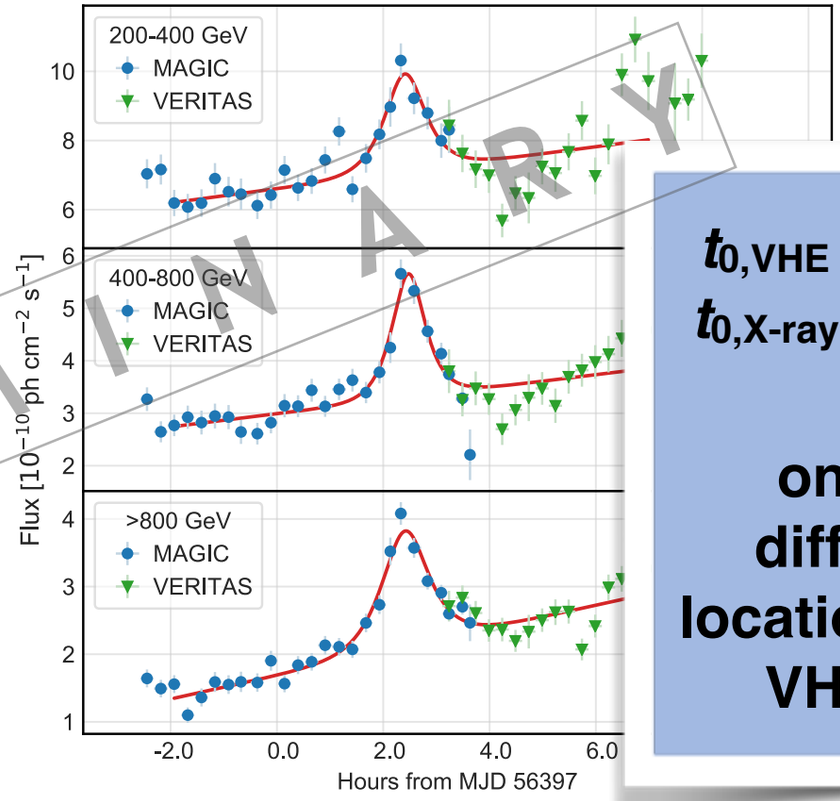




PRELIMINARY

$t_{0,\mathrm{VHE}} = 2.44 \pm 0.03$ hr

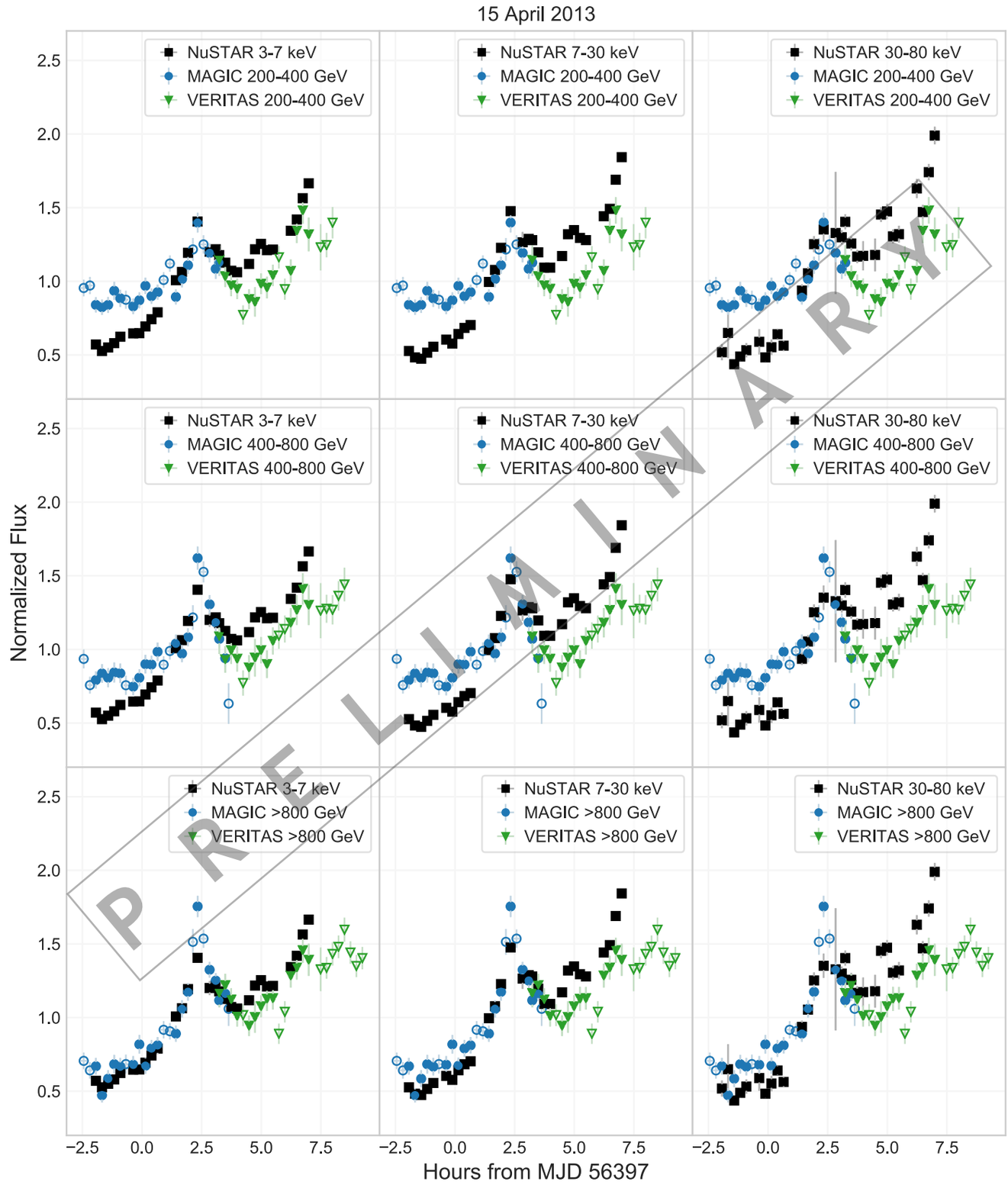
$t_{0,\text{X-ray}} = 2.41 \pm 0.04$ hr

⬇

only 3 minutes difference in the location of the flare in VHE and X-rays

Normalized light-curves

- Directly compare intra-night variability in different bands
  - ~8-10 hours coverage in each night (11-15 April)
  - Correlation between different X-ray and VHE bands changes
  - Correlation is different for the fast and for the slow component



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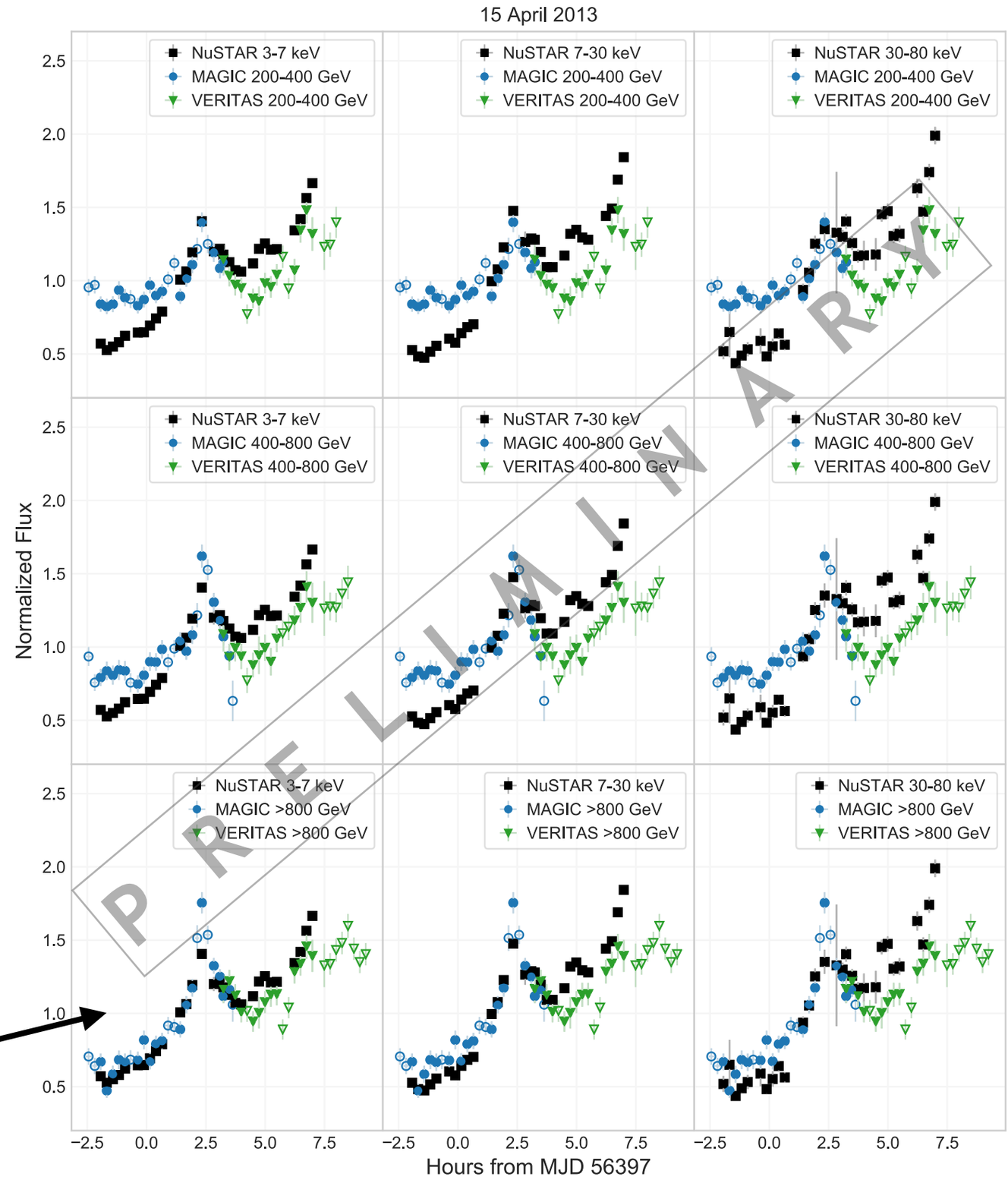

Strong correlation between 3-7 keV and >800 GeV fluxes.

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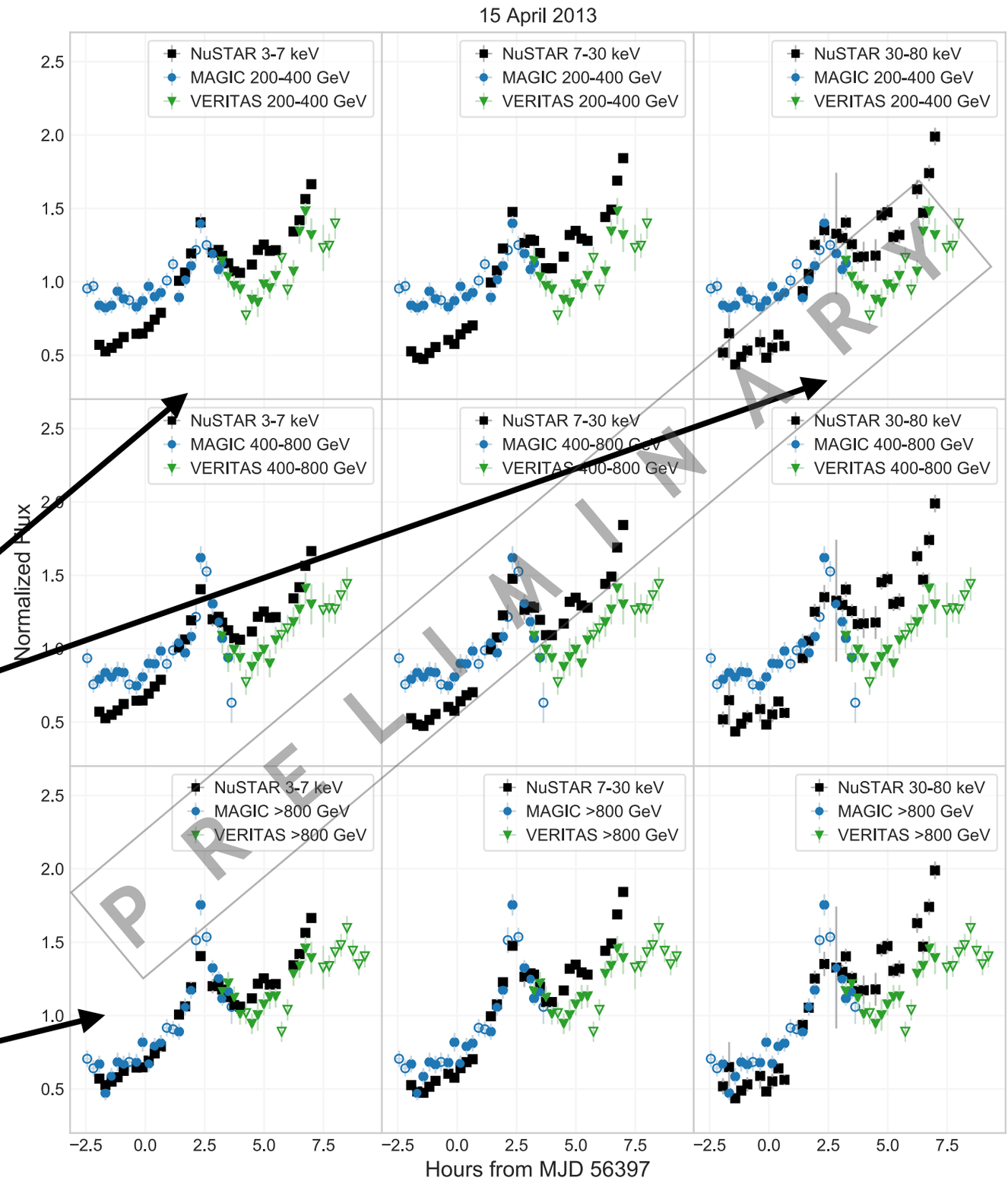
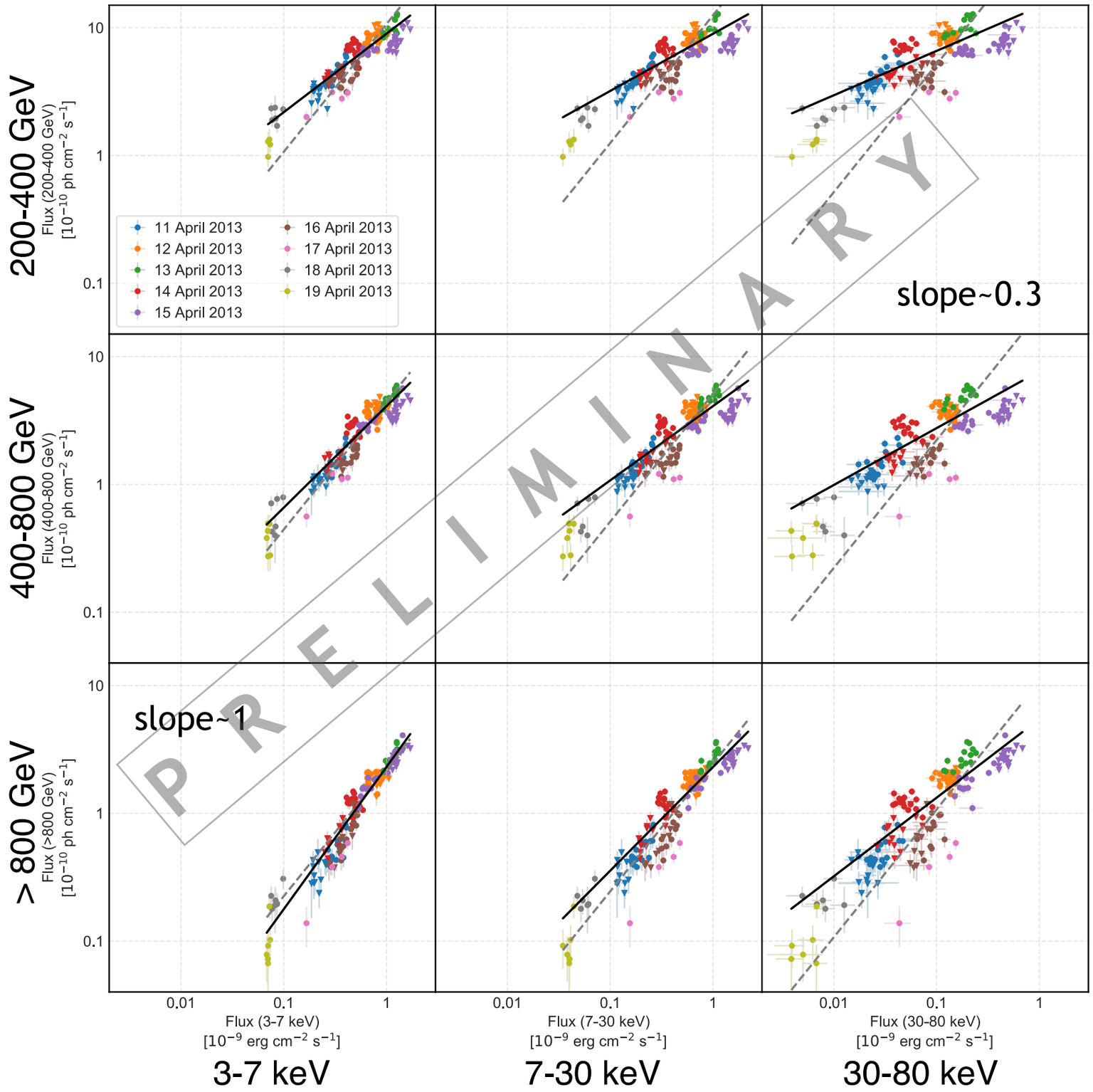
Fast-flare is still strongly correlated, but correlation is weak for the slow trend

Strong correlation between 3-7 keV and >800 GeV fluxes.



VHE and X-ray flux correlations

- Only X-ray and VHE fluxes are correlated
  - Different strength of correlation between bands
  - Strongest correlation for nearly linear flux relation
  - Correlation changes significantly with small changes in energy



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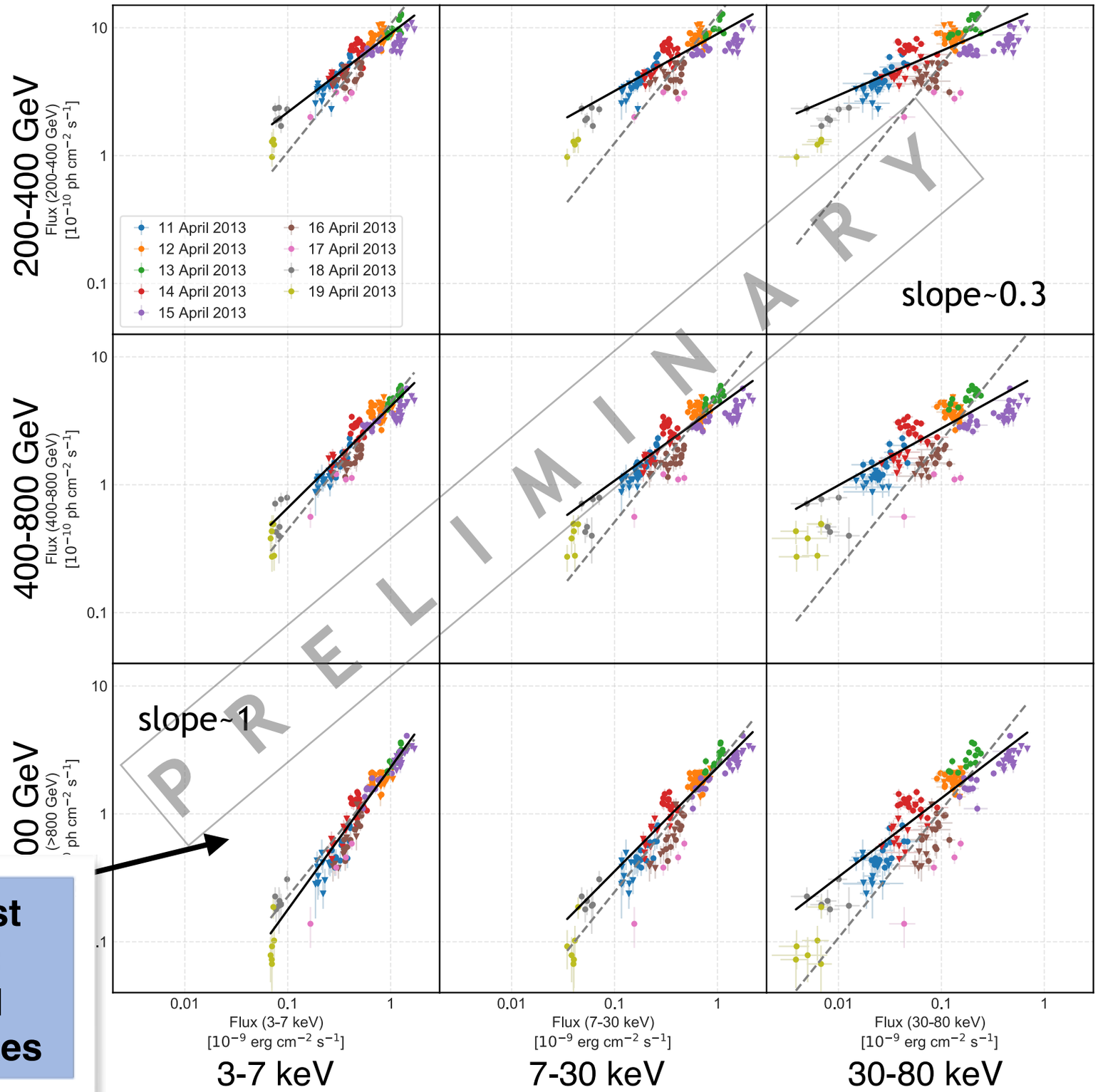

The strongest correlation: 3-7 keV and >800 GeV fluxes

VHE and X-ray flux correlations

- Only X-ray and VHE fluxes are correlated
  - Different strength of correlation between bands
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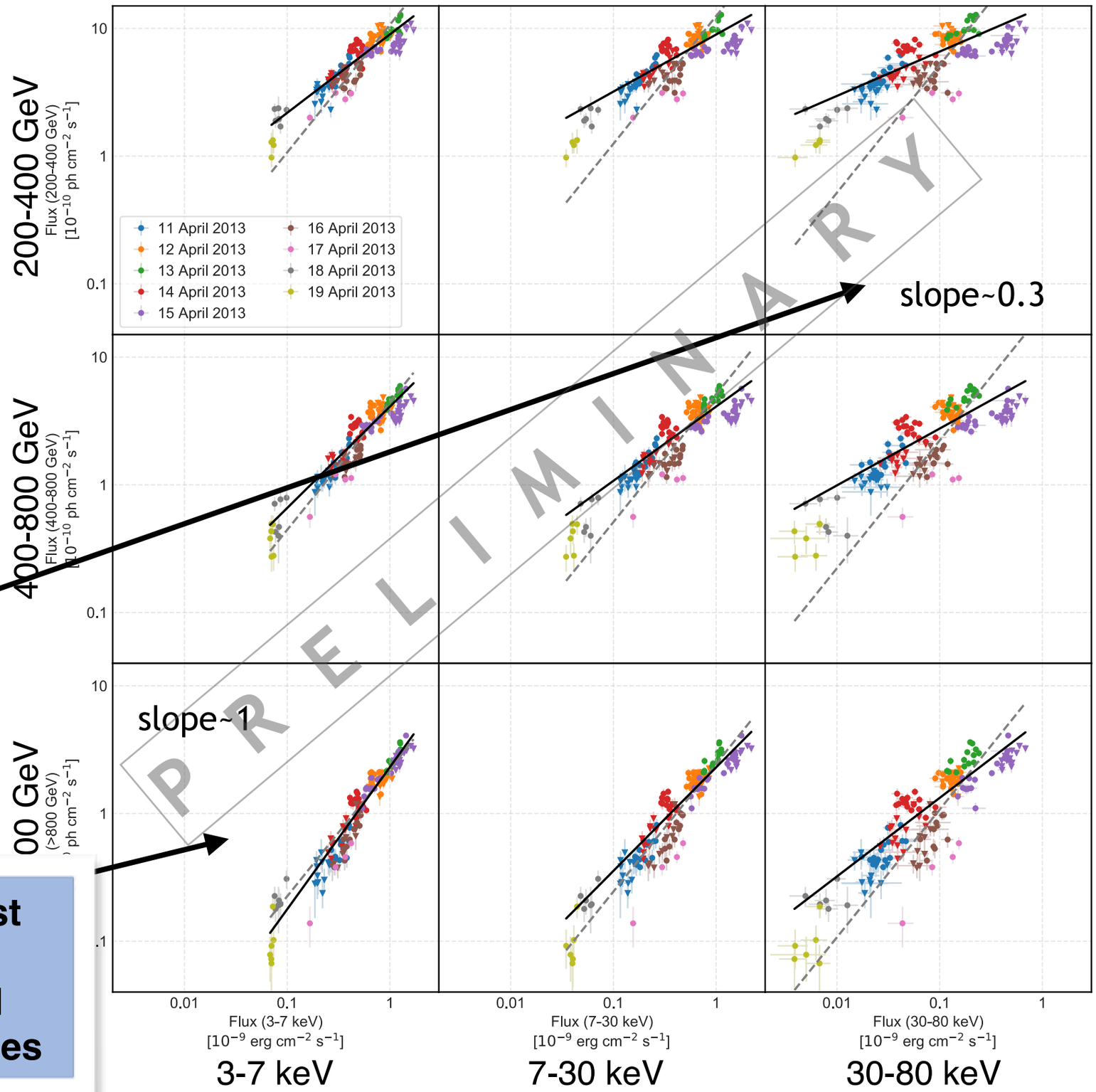
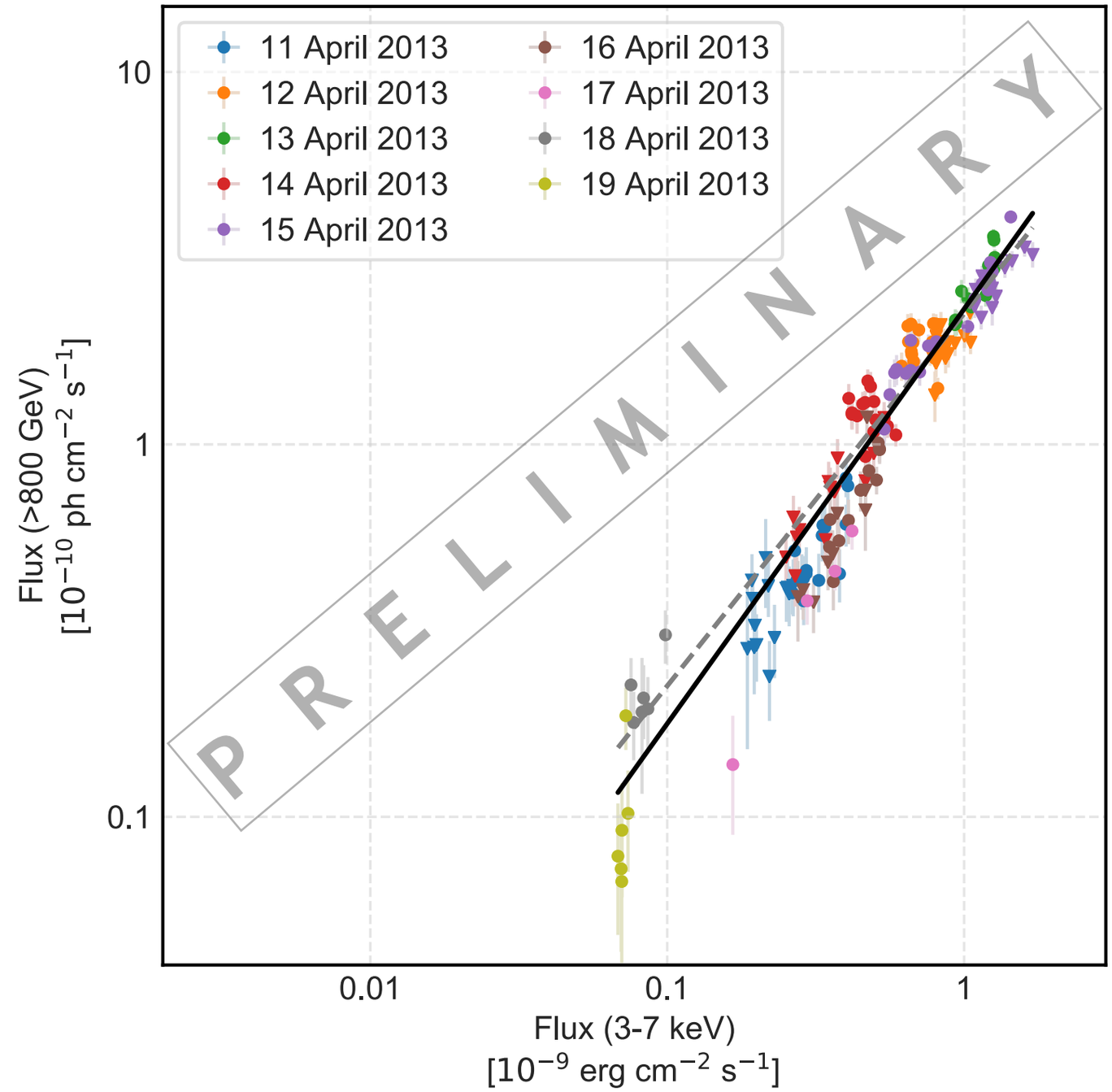
The weakest correlation: 30-80 keV and 200-400 GeV fluxes

The strongest correlation: 3-7 keV and >800 GeV fluxes



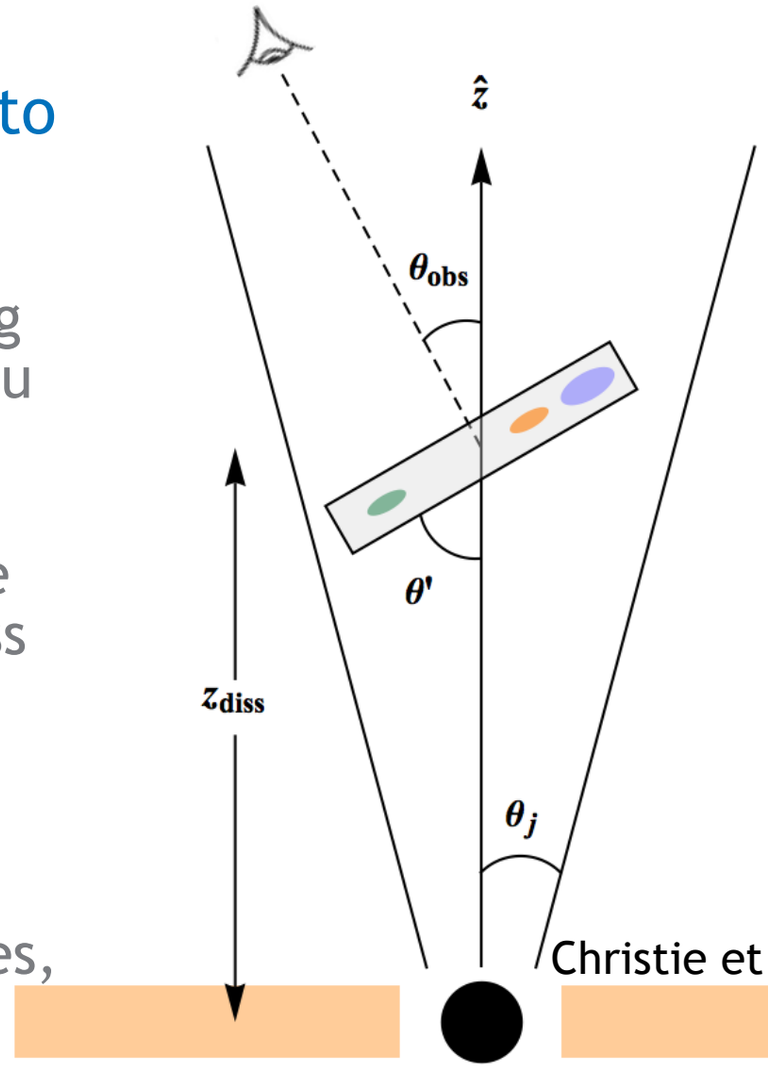
VHE and X-ray flux correlations

- Strongly correlated 3-7 keV and >800 GeV fluxes
  - Imply that the two emission are co-spatial
  - Produced by electrons with approximately same energy
  - Synchrotron in X-rays, Synchrotron Self-Compton (SSC) in VHE
  - Correlation weakens, or disappears on certain days implying different components

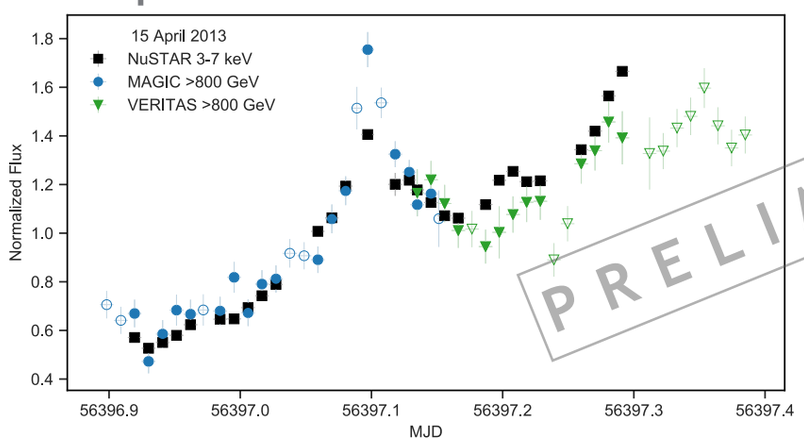


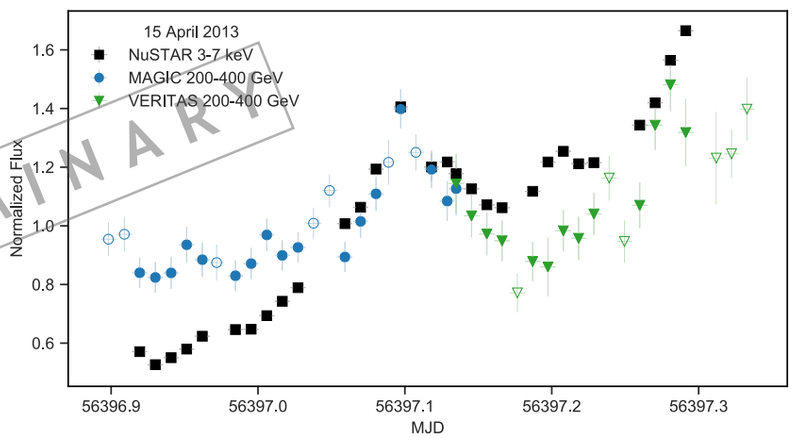
Variability and correlations

- Need theoretical scenarios with multiple zones to explain all data
  - X-ray and VHE gamma-ray emission may be produced in a magnetic reconnection layer moving reativistically along the jet of Mrk 421(Petropoulou et al. 2016, Christie et al. 2018)
  - **Fast flux variations** (which seem **achromatic**) would be dominated by the emission from a single small plasmoid moving highly relativistically across the magnetic reconnection layer
  - **The multi-hour flux variations**, which make the majority of the flux that is detected, may be produced by the combined emission of many plasmoids, possibly of different sizes and velocities, giving rise to different gamma ray and X-ray variability and correlation patterns



Christie et al. 2018





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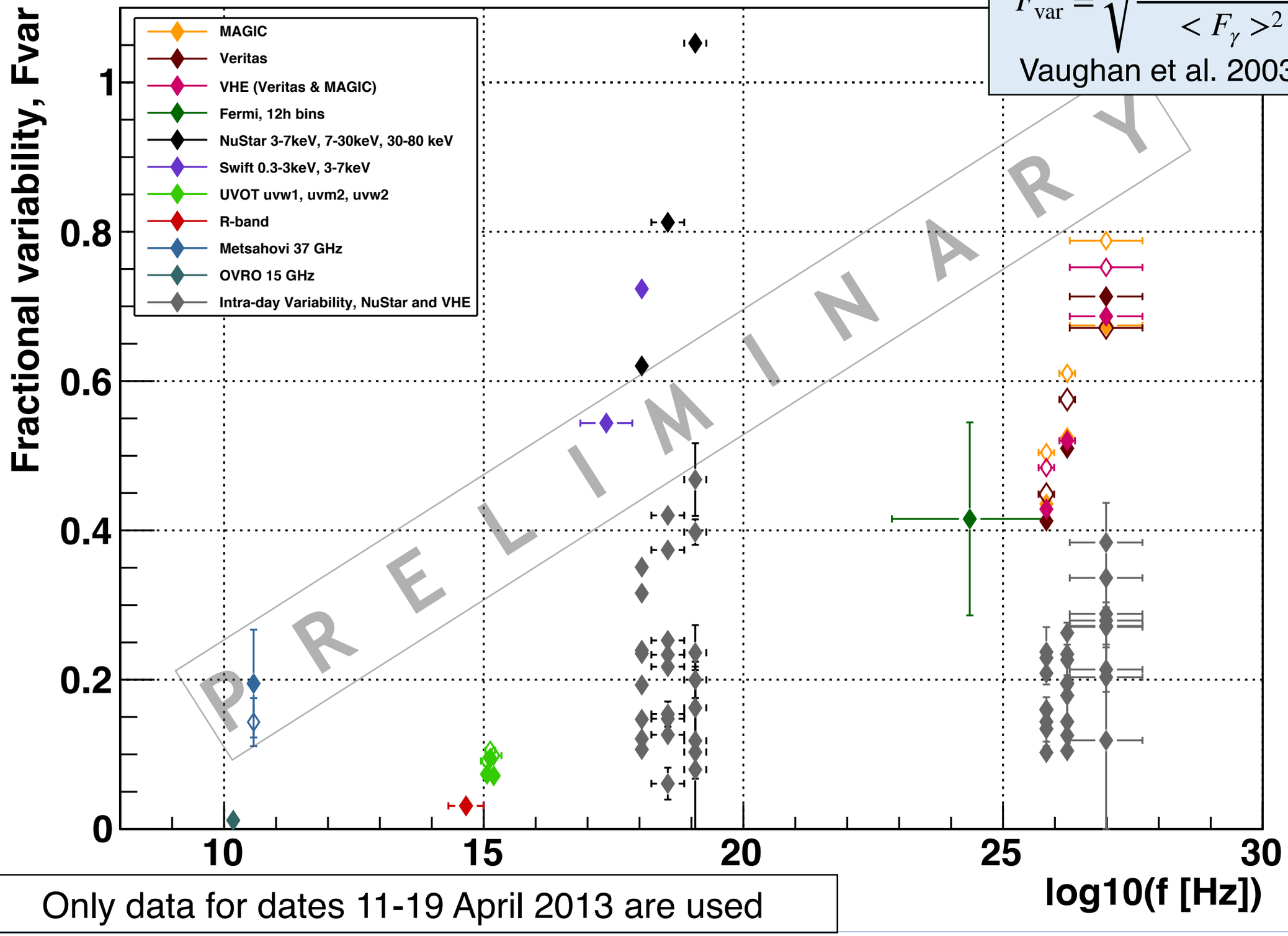
Thank you!

Supplement

Fractional variability

$$F_{\mathrm{var}} = \sqrt{\frac{S^2 - < \sigma_{\mathrm{err}}^2 >}{< F_\gamma >^2}}$$

Vaughan et al. 2003



Only data for dates 11-19 April 2013 are used

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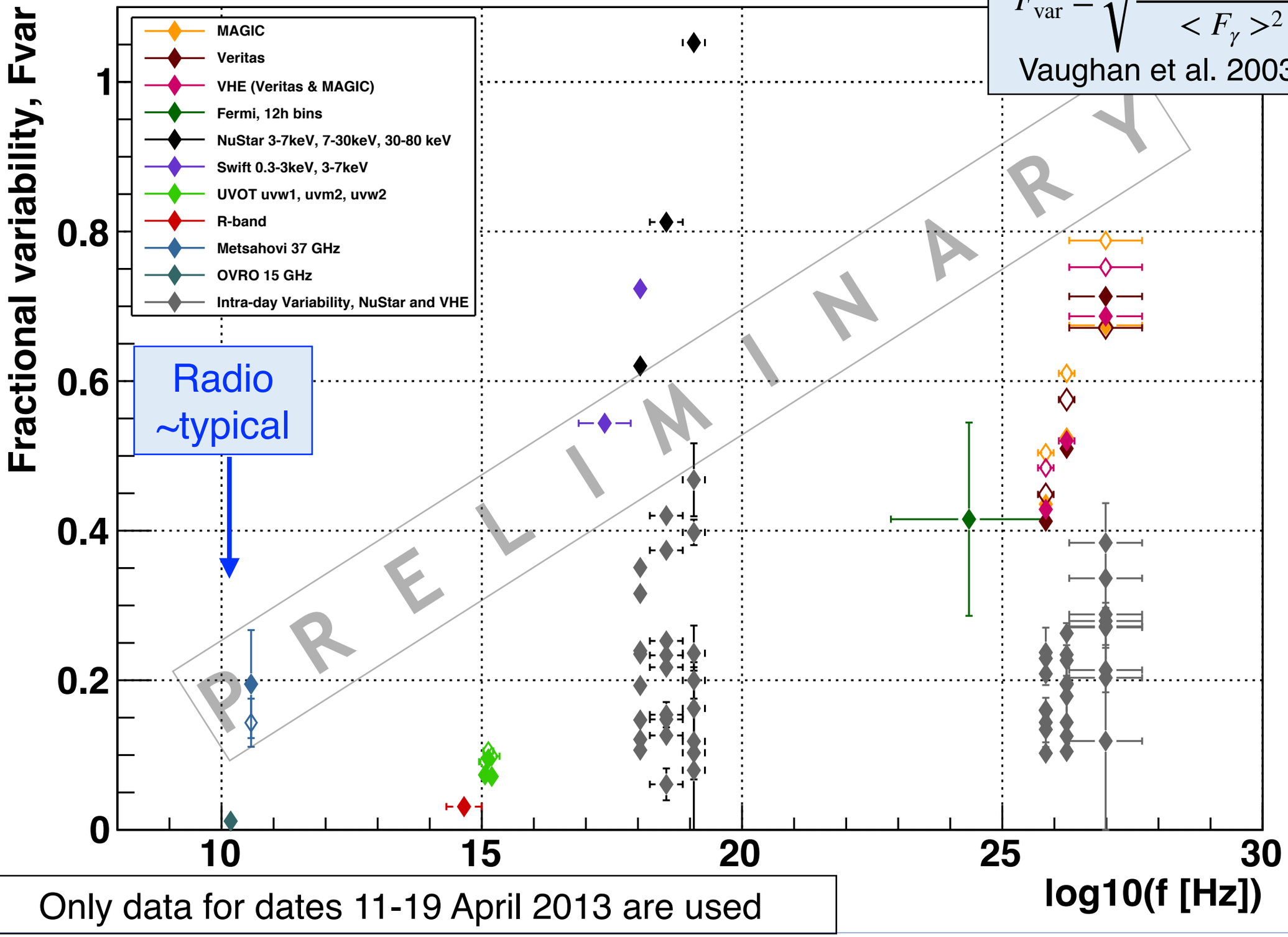

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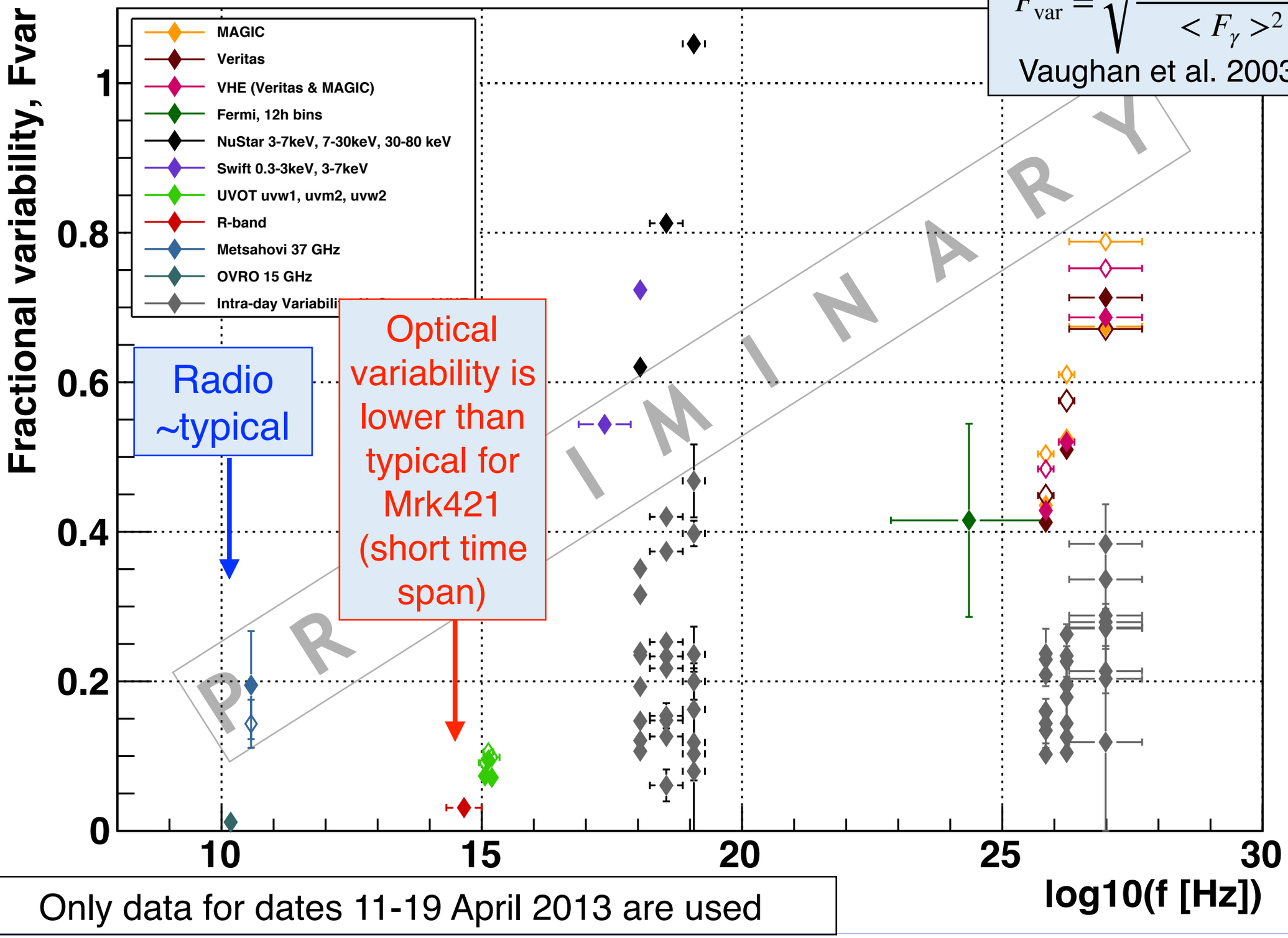

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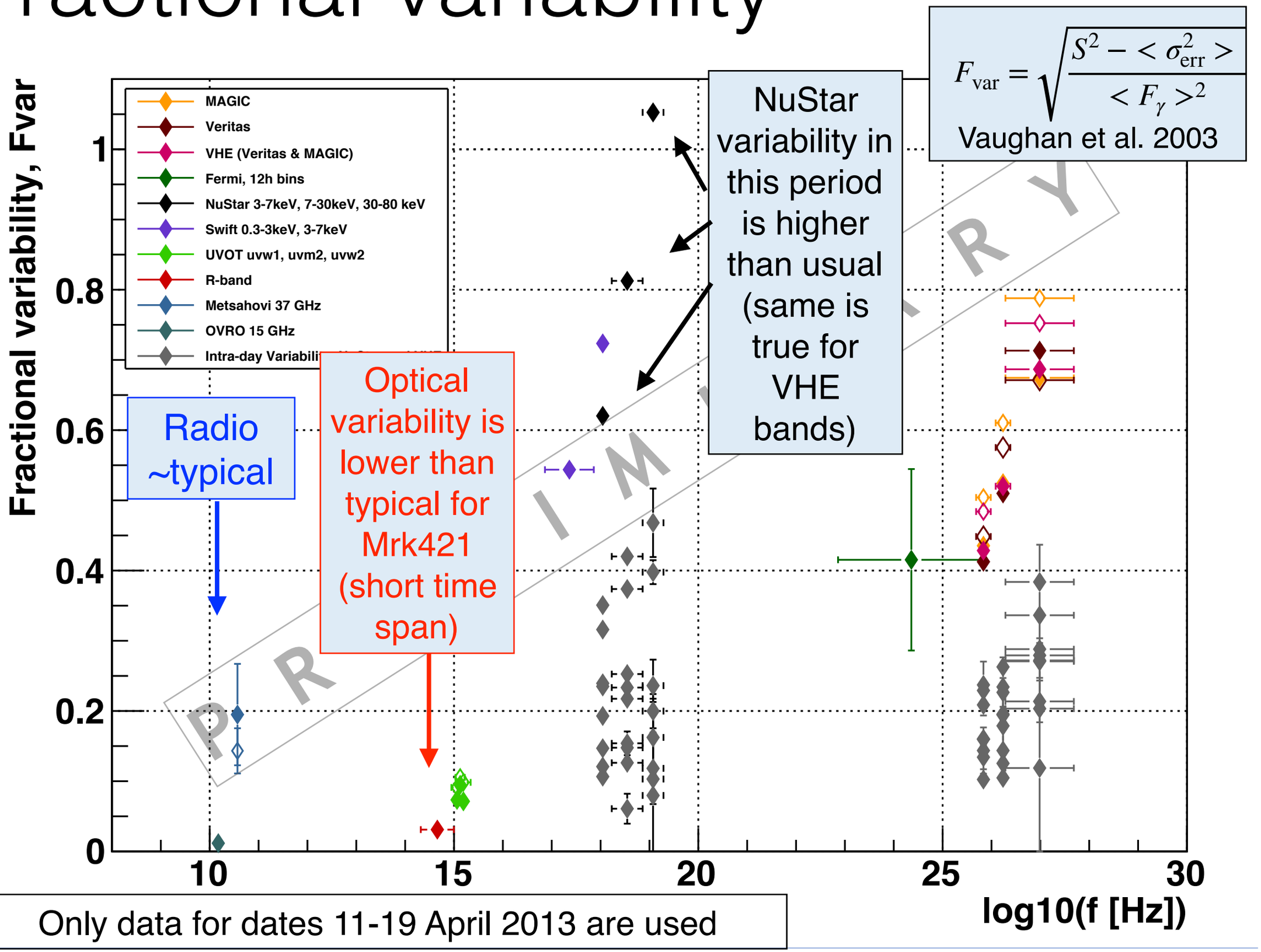

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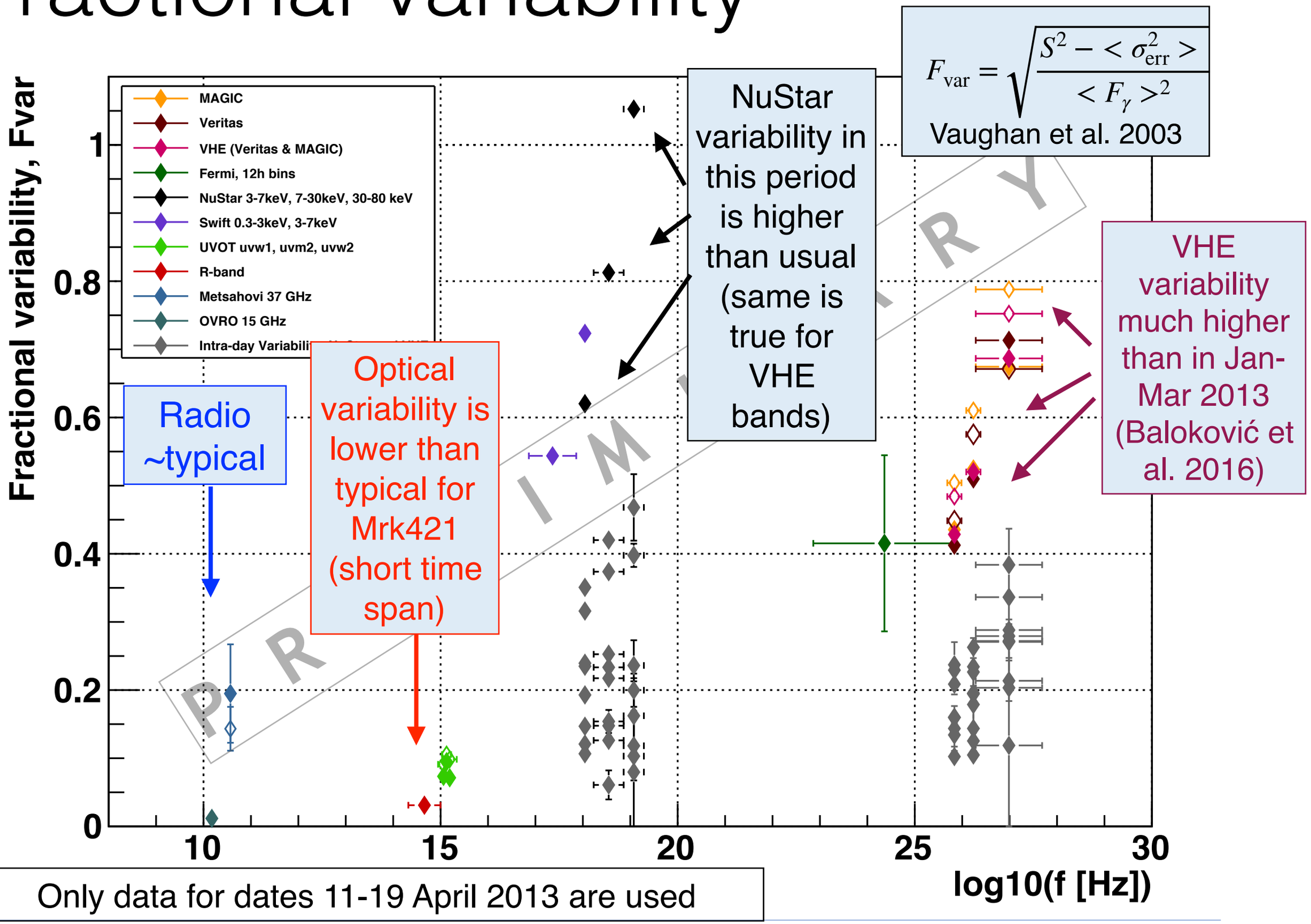

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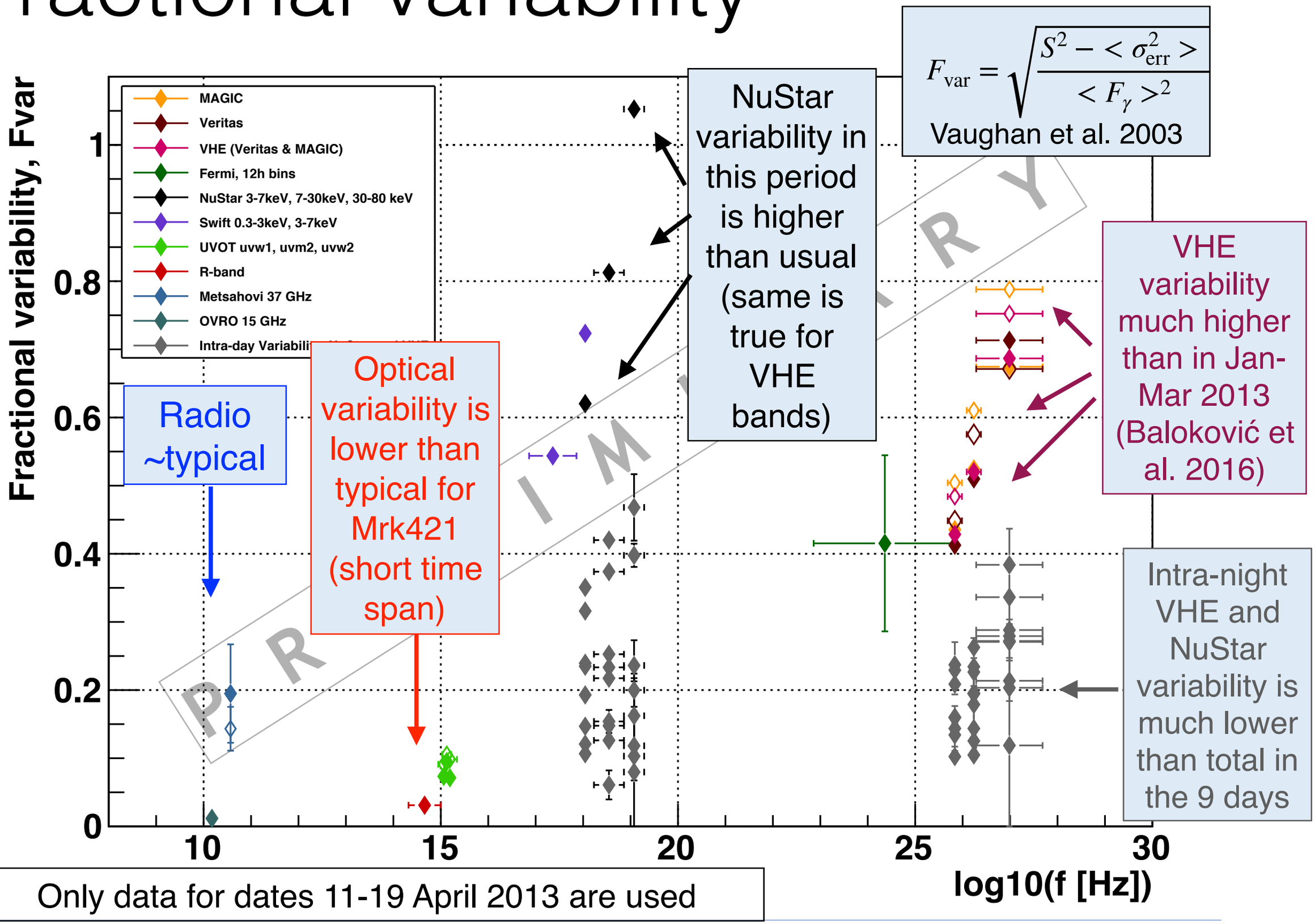

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