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MAGIC

Fermi Gamma-ray Space Telescope

# What we can learn from blazar light curves

Lea Heckmann, David Paneque & Axel Arbet-Engels

# Active Galactic Nuclei

- Most luminous persistent sources in the universe
- Bright compact nucleus in the center of galaxy
- Variable in time

- Potential emitters of neutrinos and UHECRs
- Highly energetic physics laboratories

Credit: http://www.astro.princeton.edu/~lilew/

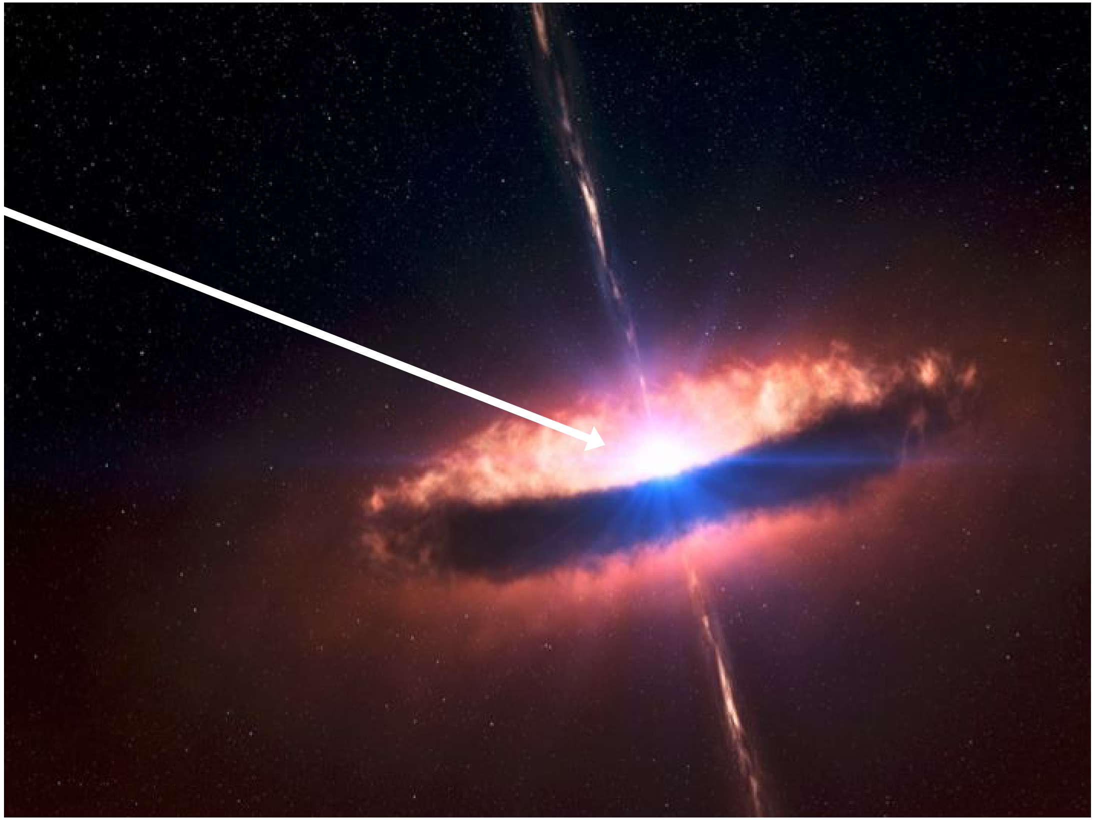
# Active Galactic Nuclei

Credit: http://www.astro.princeton.edu/~lilew/

# Active Galactic Nuclei

Supermassive
black hole
($10^{10}$ - $10^{14}$ m )

with
accretion disc
($10^{10}$ - $10^{16}$ m )



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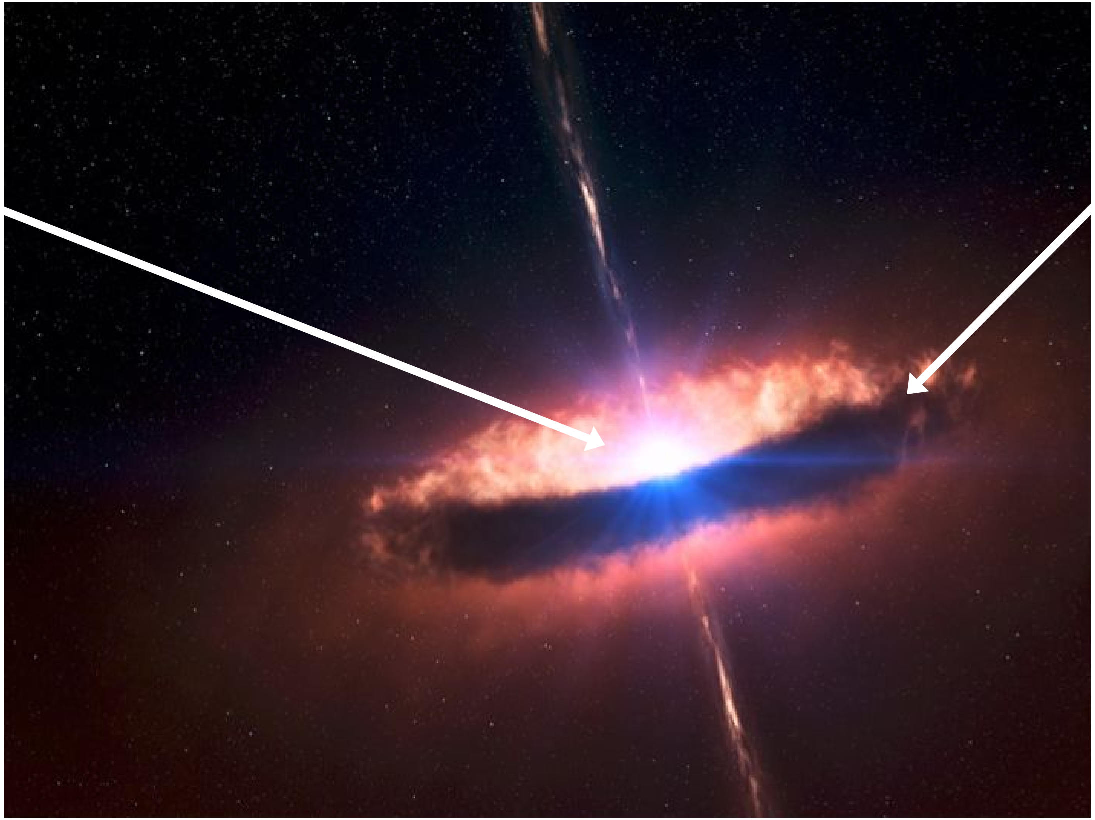


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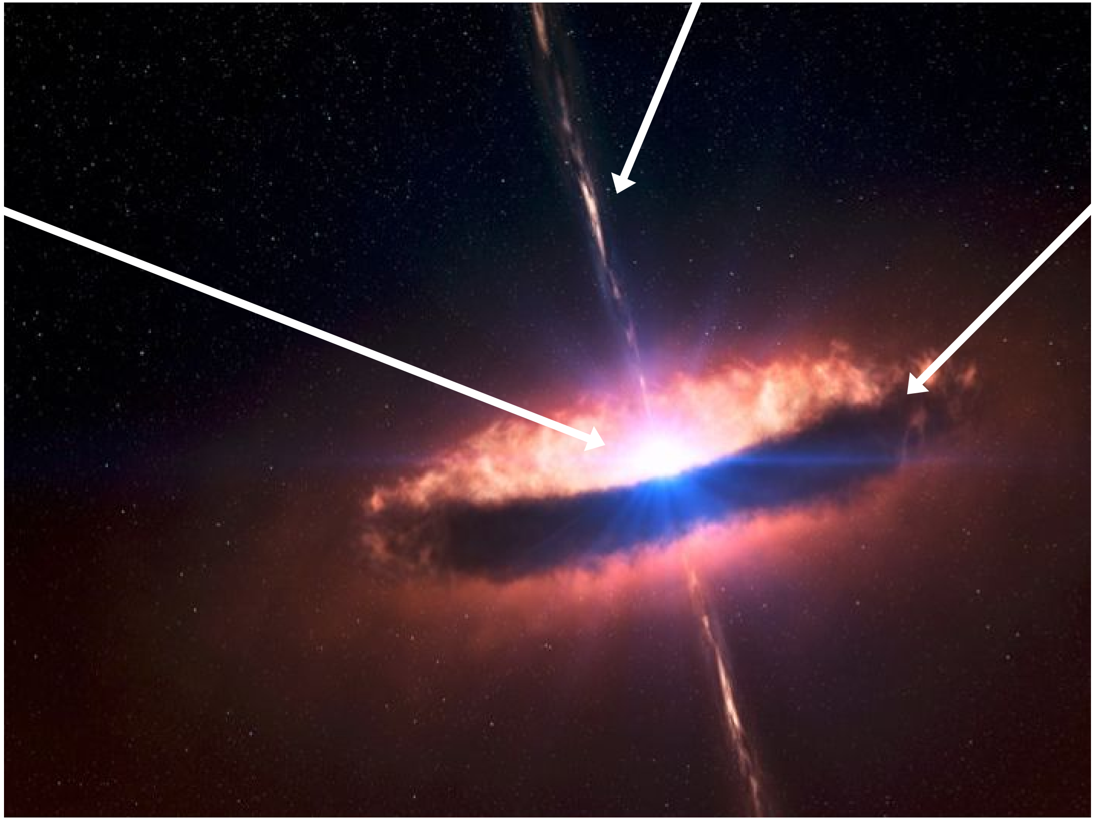
# Active Galactic Nuclei

Jets ($10^{16}$ - $10^{22}$ m ~ 0.1pc to Mpc )

Supermassive black hole ($10^{10}$ - $10^{14}$ m )

with accretion disc ($10^{10}$ - $10^{16}$ m )



Dusty torus ($10^{14}$ - $10^{17}$ m )

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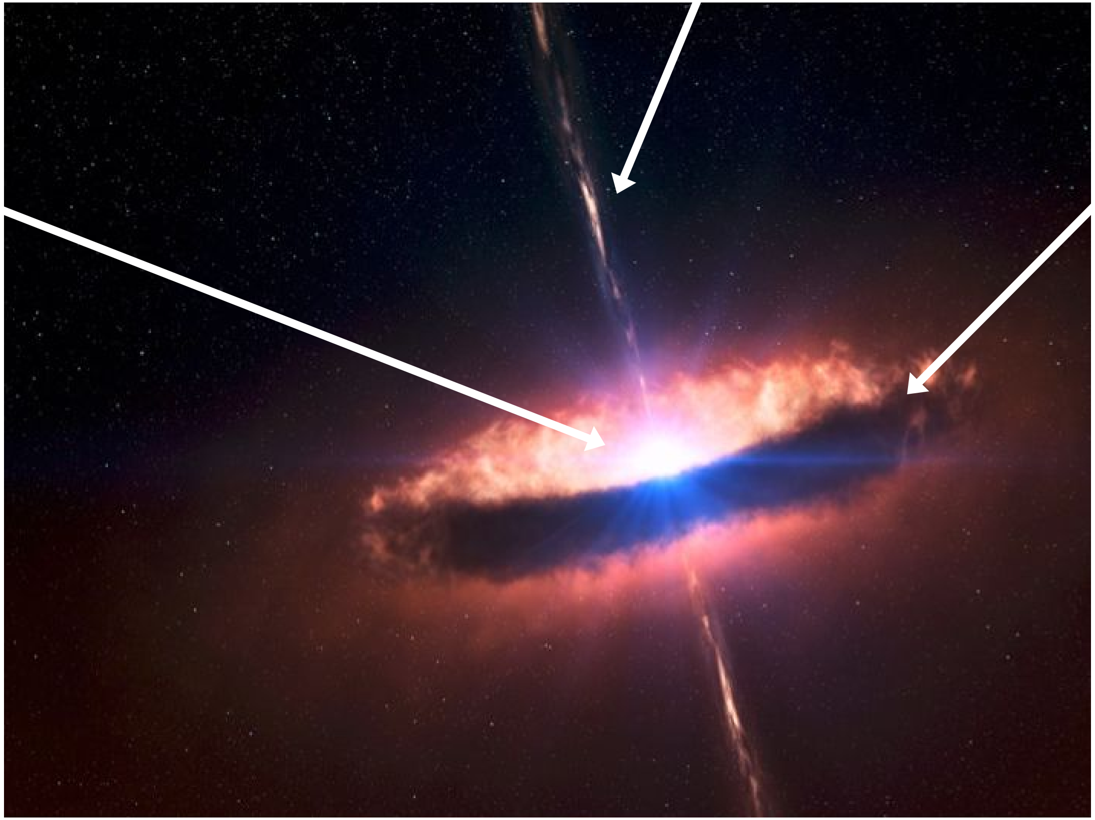

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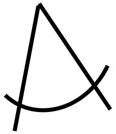
# Blazars



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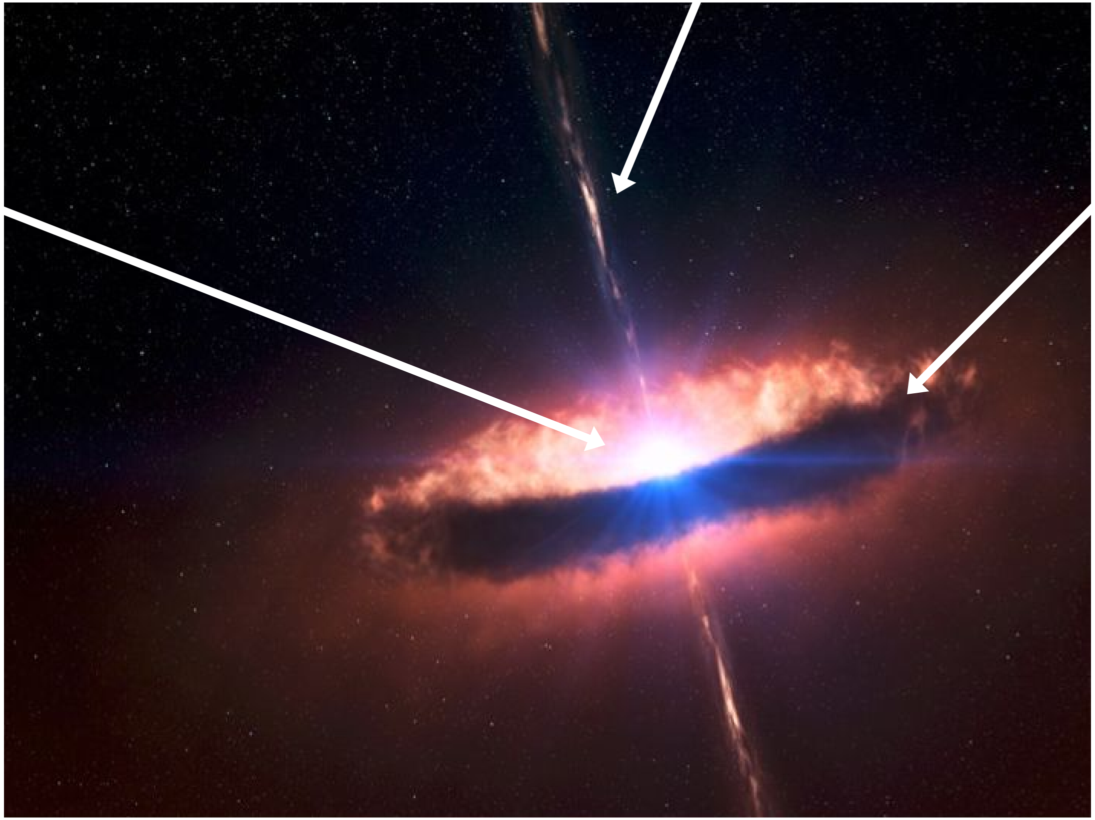

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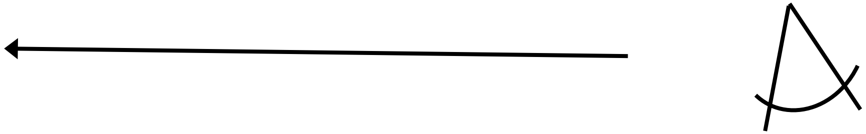
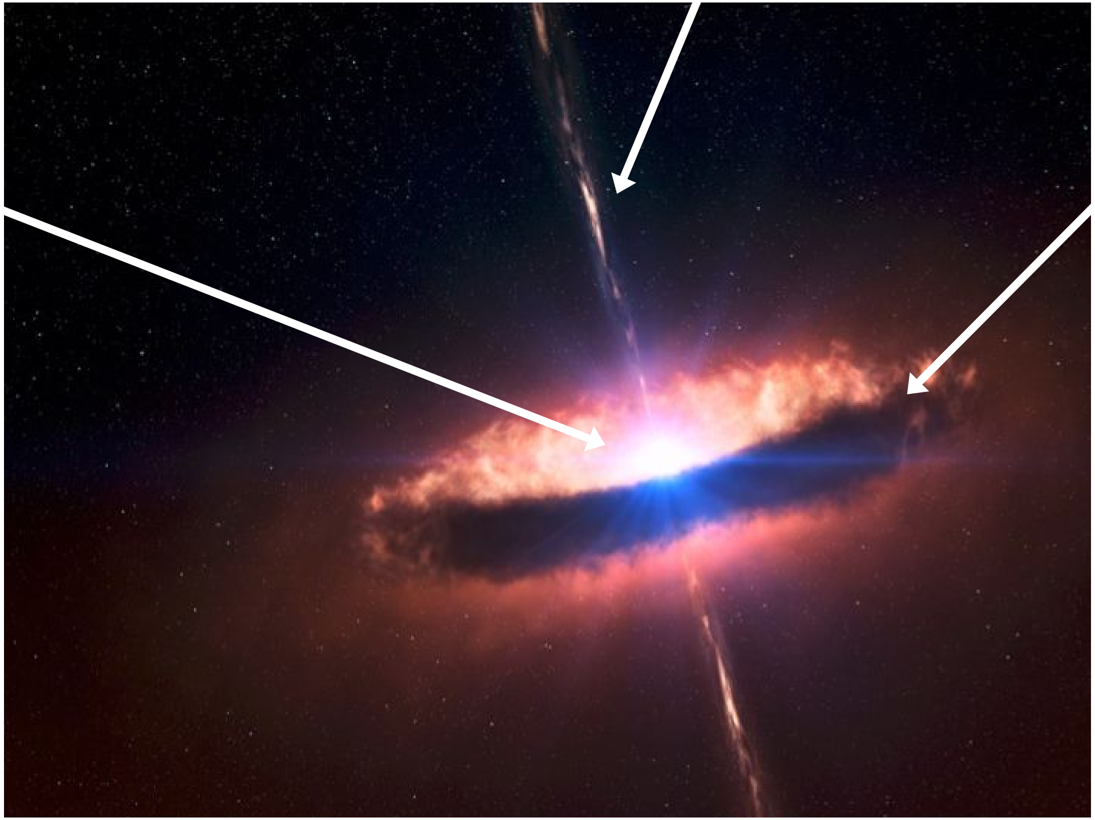


- AGNs with jets in our direction
- Strong boosting along the jet

  → even higher variability

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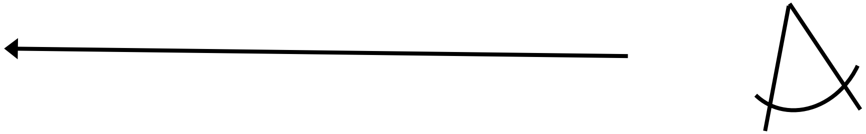

- AGNs with jets in our direction
- Strong boosting along the jet
  → even higher variability
- Many open questions:
  - What is radiating?
  - In which environment?
  - ...

Jets ($10^{16}$ - $10^{22}$ m ~ 0.1pc to Mpc)

Supermassive black hole ($10^{10}$ - $10^{14}$ m)

with accretion disc ($10^{10}$ - $10^{16}$ m)

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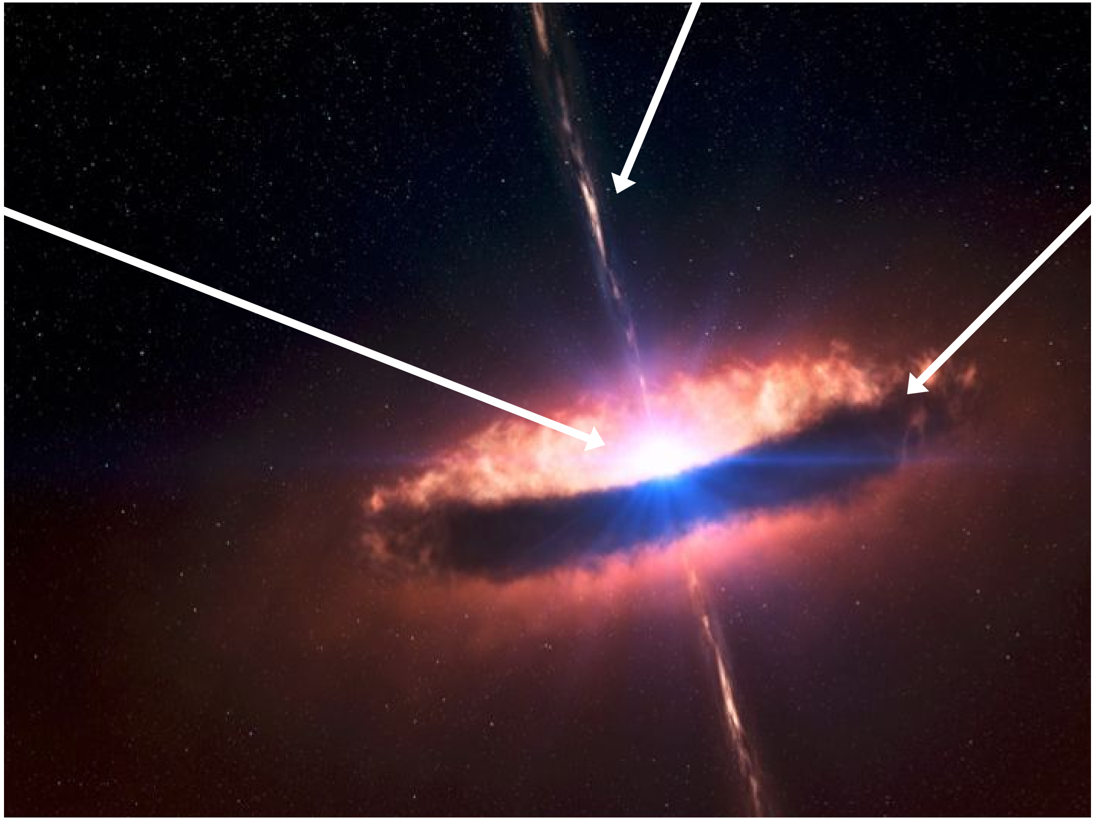

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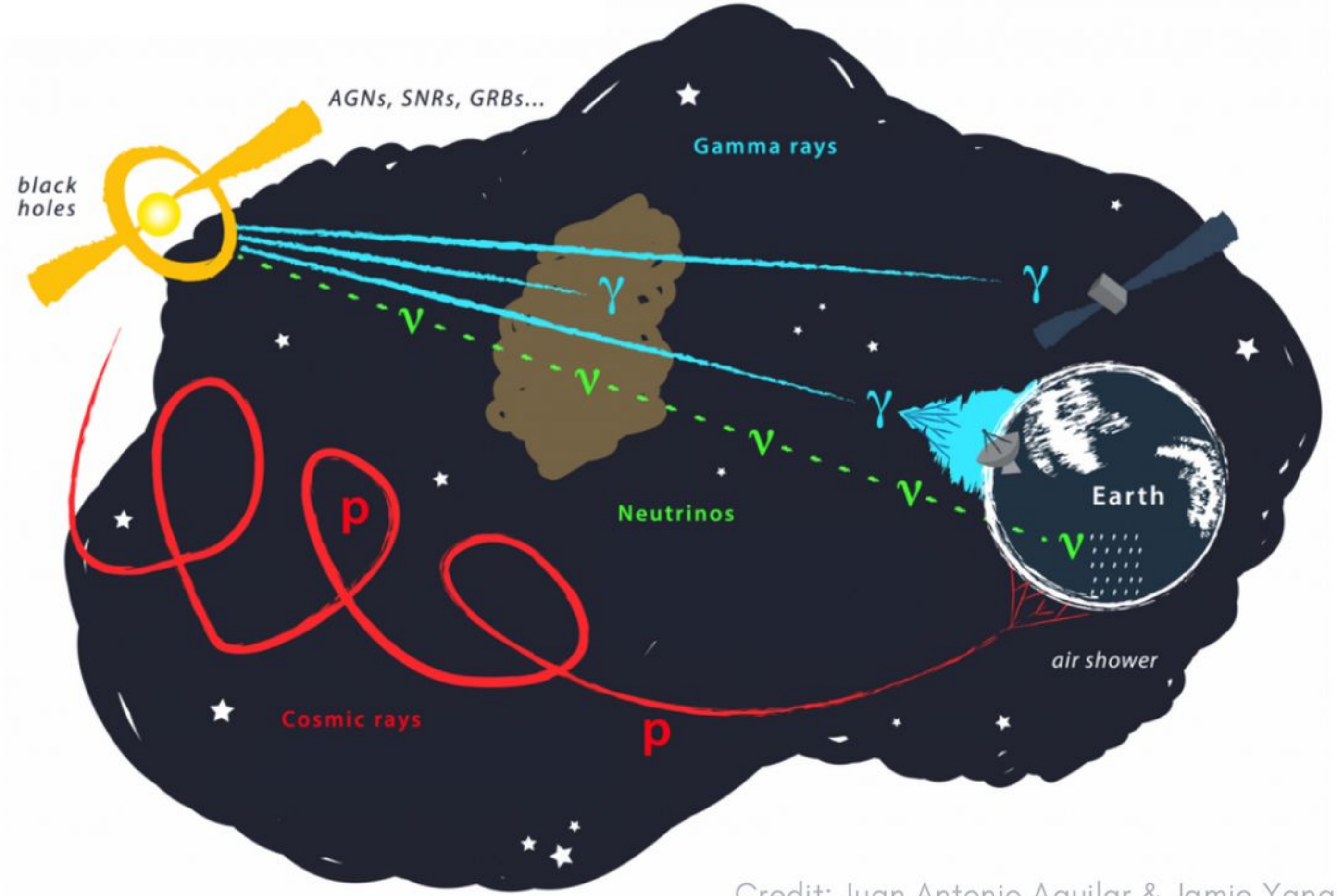
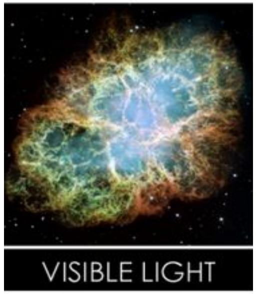
# Multimessenger astronomy




Credit: Juan Antonio Aguilar & Jamie Yang, IceCube/WIPAC

# Multiwavelength (MWL) astronomy




Credit: Wikipedia

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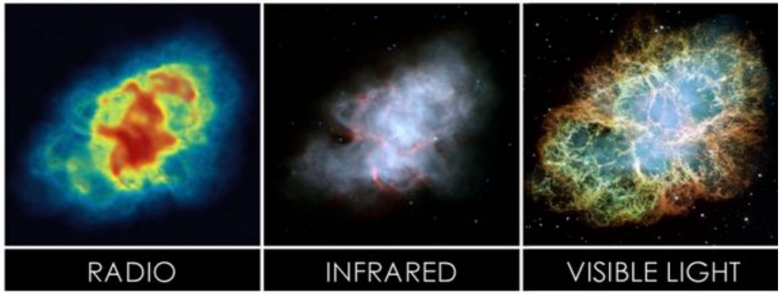


Credit: Wikipedia

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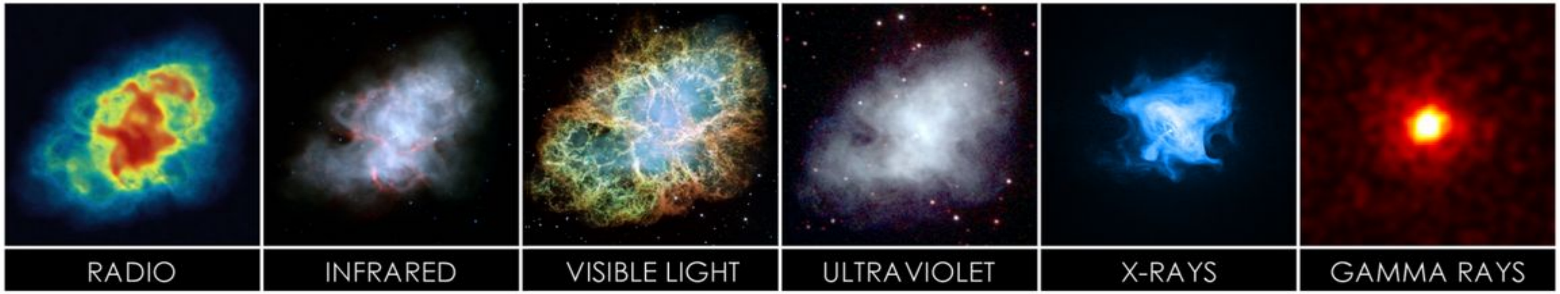
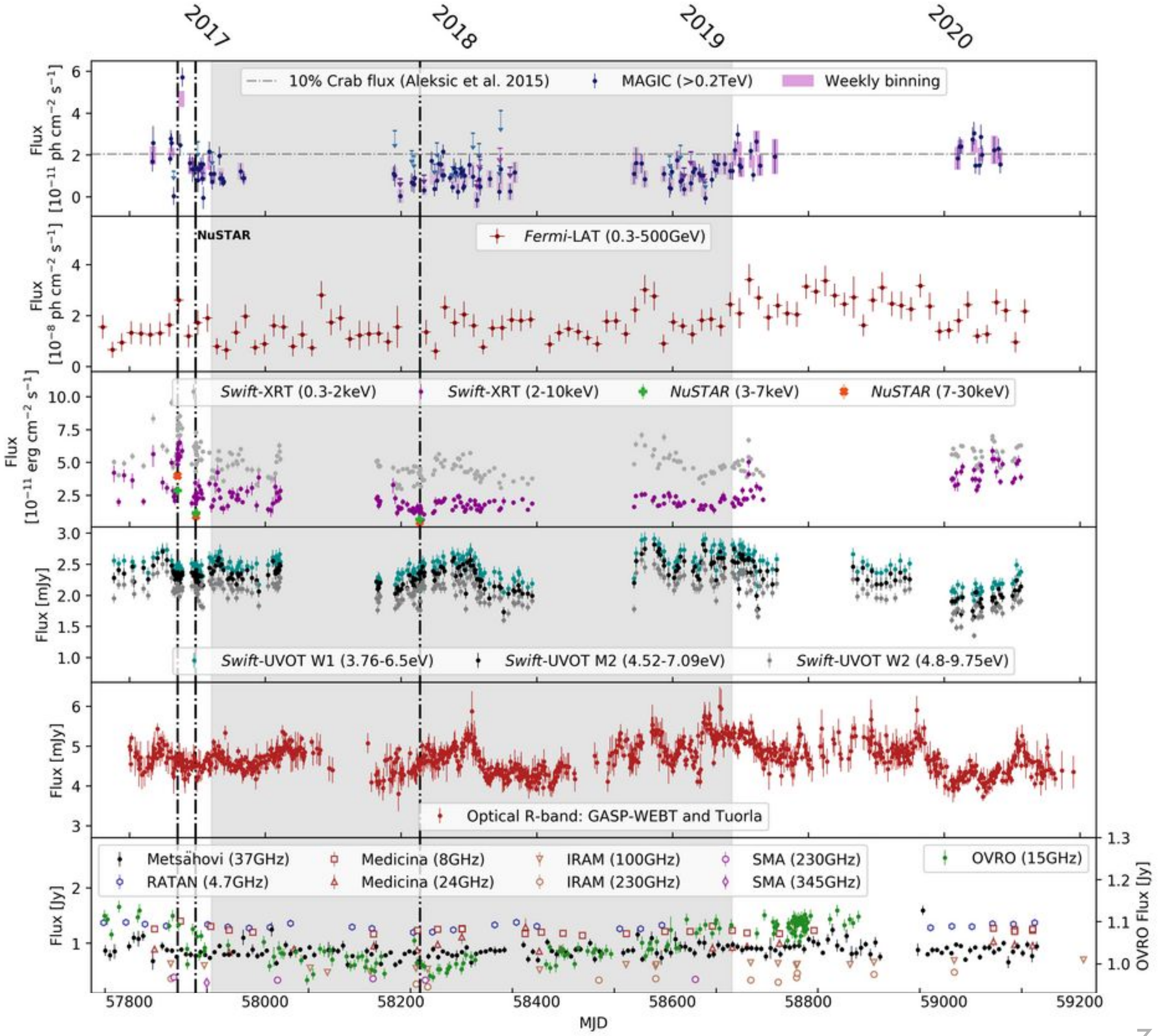



Credit: Wikipedia

# MWL light curves

H. Abe et al., accepted by ApJS, arxiv:2210.02547 (2023).



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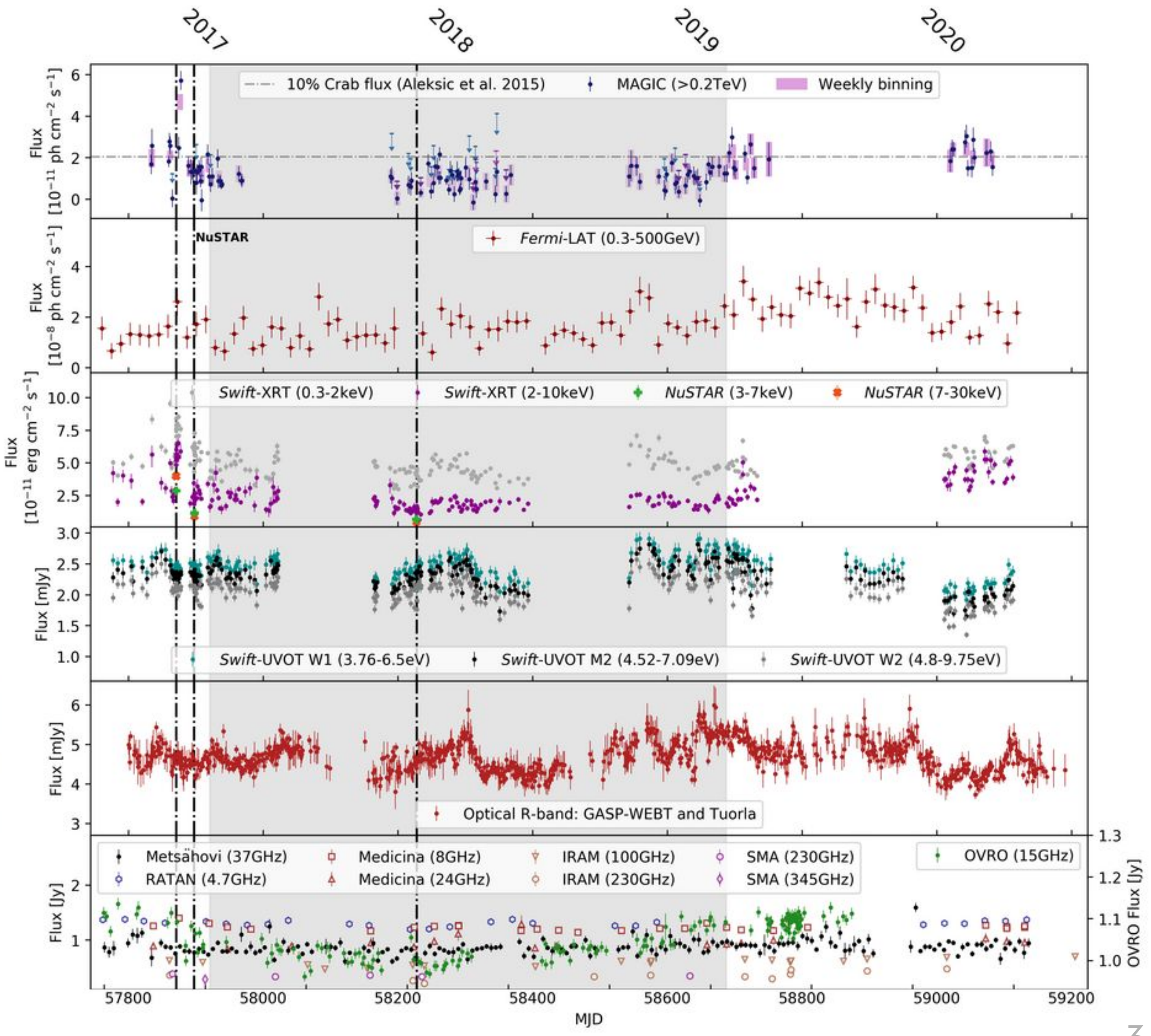

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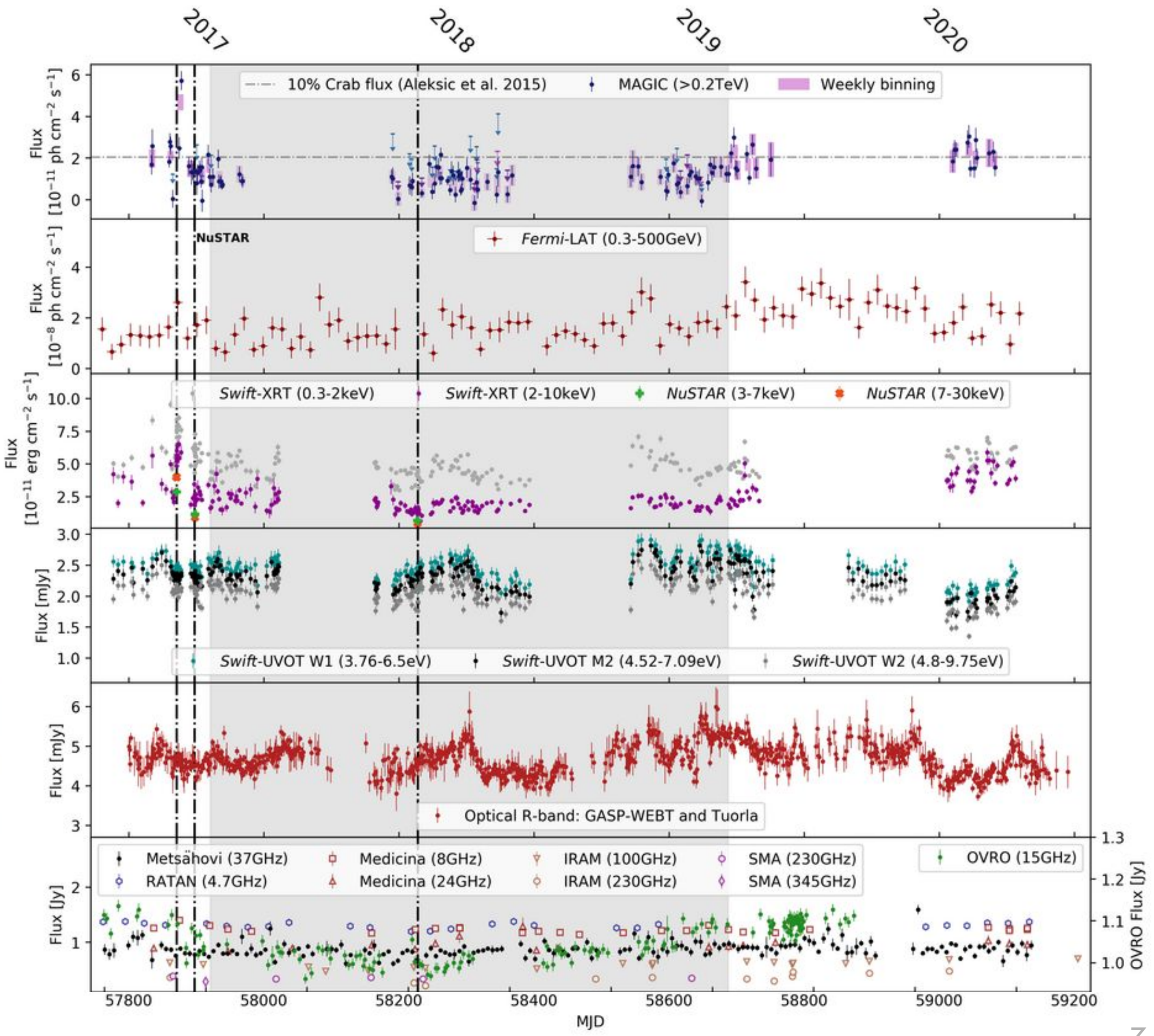


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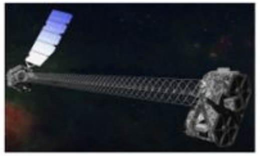

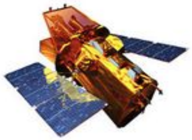

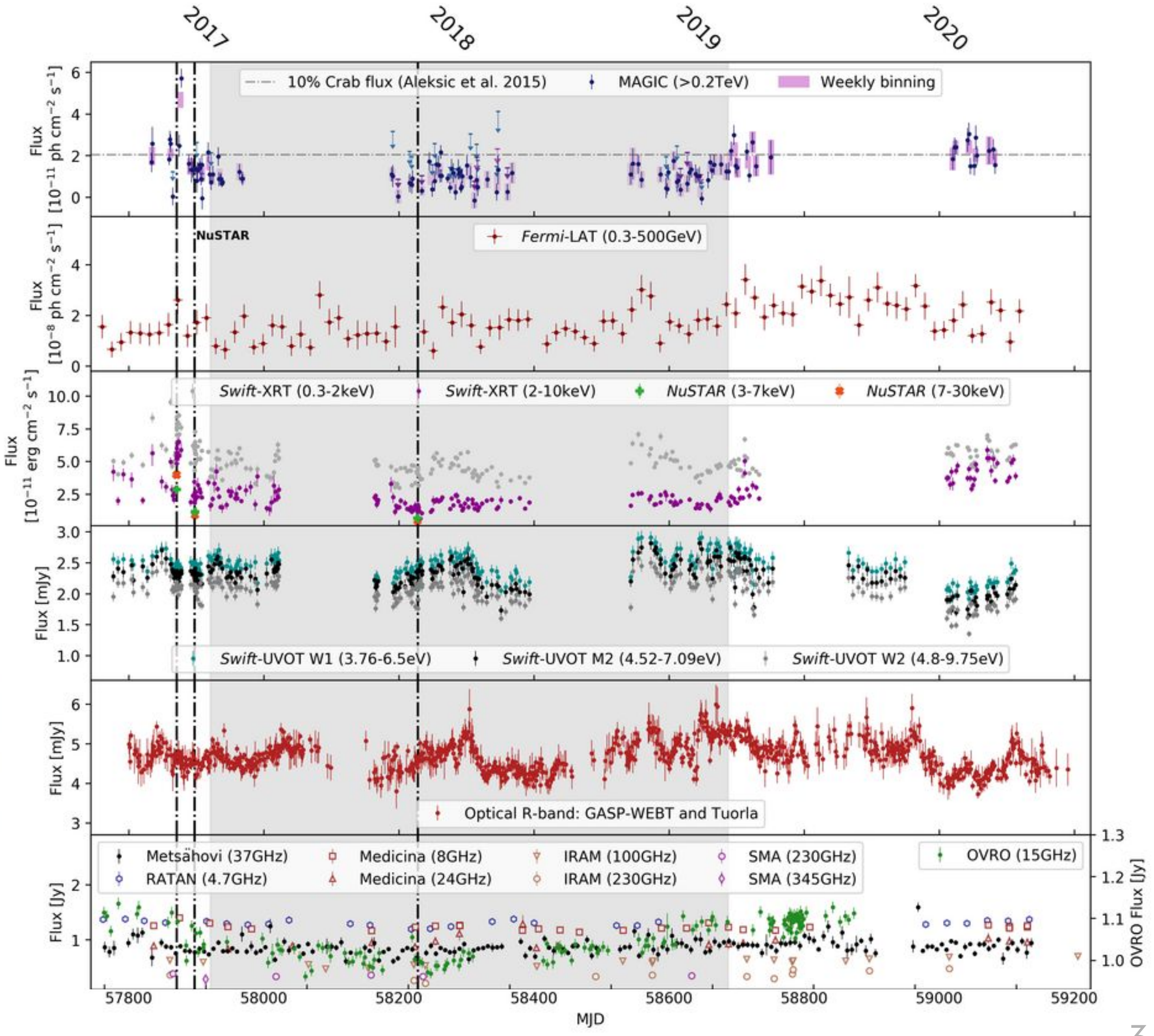


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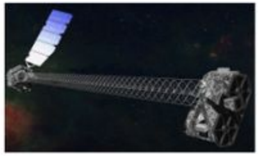

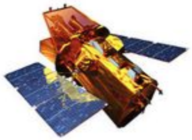

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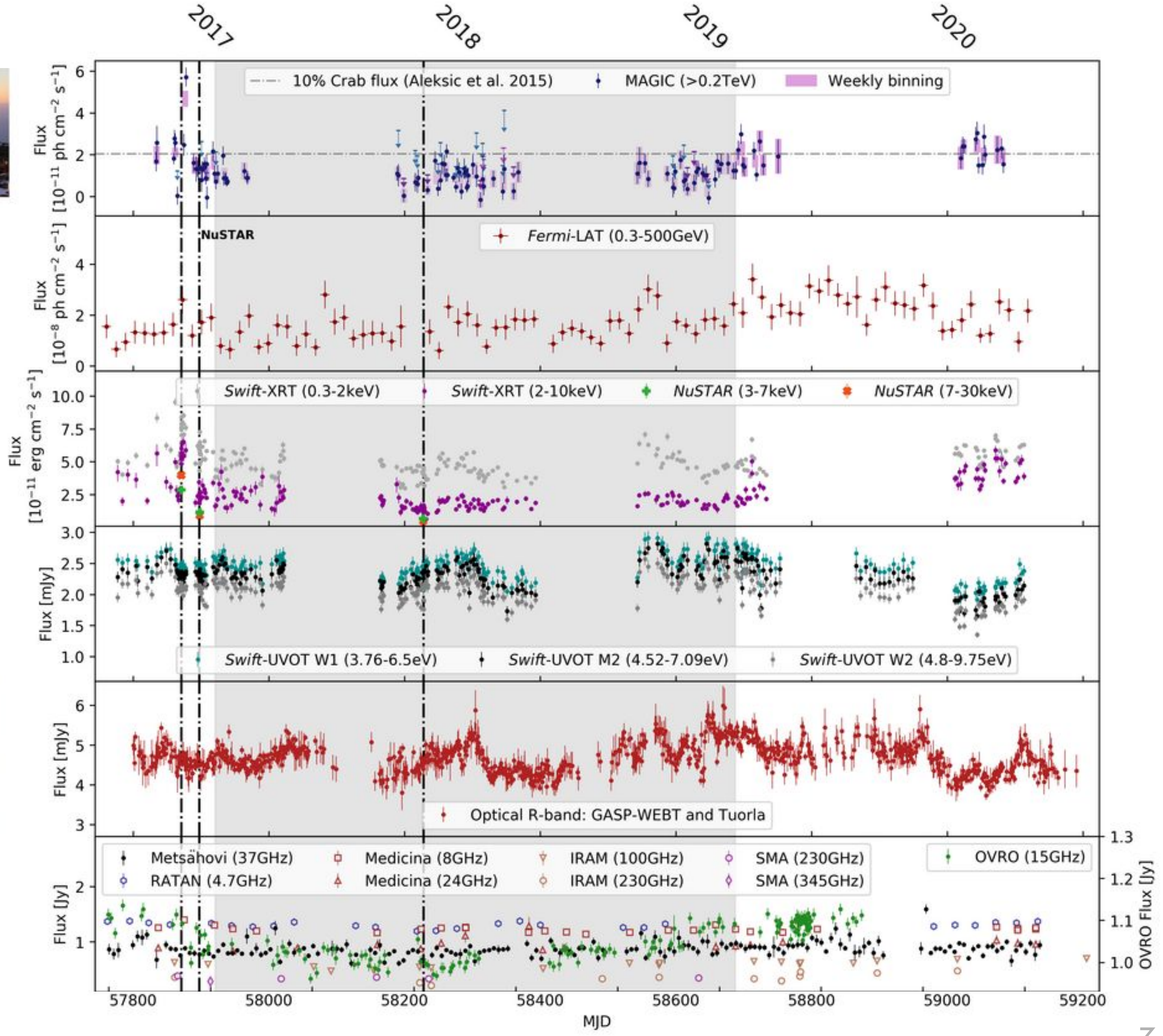


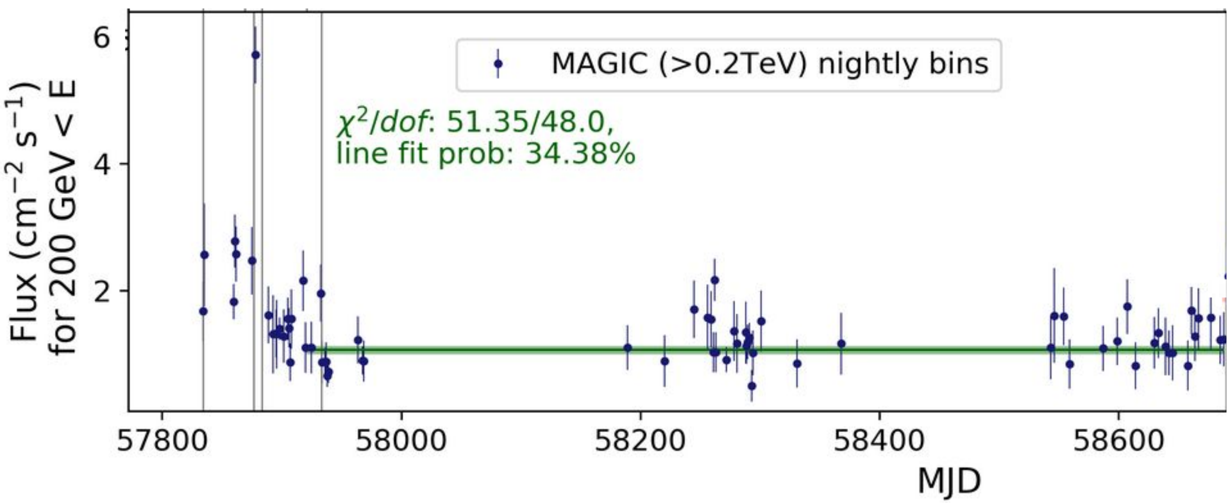
# Bayesian blocks J. D. Scargle et al., ApJ 764.2 (2013)

- Algorithm that identifies specific time intervals, blocks, in a data set:
  - Defines a number of change points defining a block
  - Prior distribution for the number of blocks penalizing for more blocks
  - Likelihood of the model =
    combination of the individual likelihoods of each block + prior
  - Maximixation of a fitness function adjusted to the specific data type used (e.g. binned or unbinned event data, measured sequences with Gaussian errors,...)

# Bayesian blocks J. D. Scargle et al., ApJ 764.2 (2013)

- Applied to the 4-year very-high-energy (VHE) γ-ray LC of Mrk 501

L. Heckmann, PhD Thesis, Leopold-Franzens Universität Innsbruck (May 2023)



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  → Identified 2-year long historically low state

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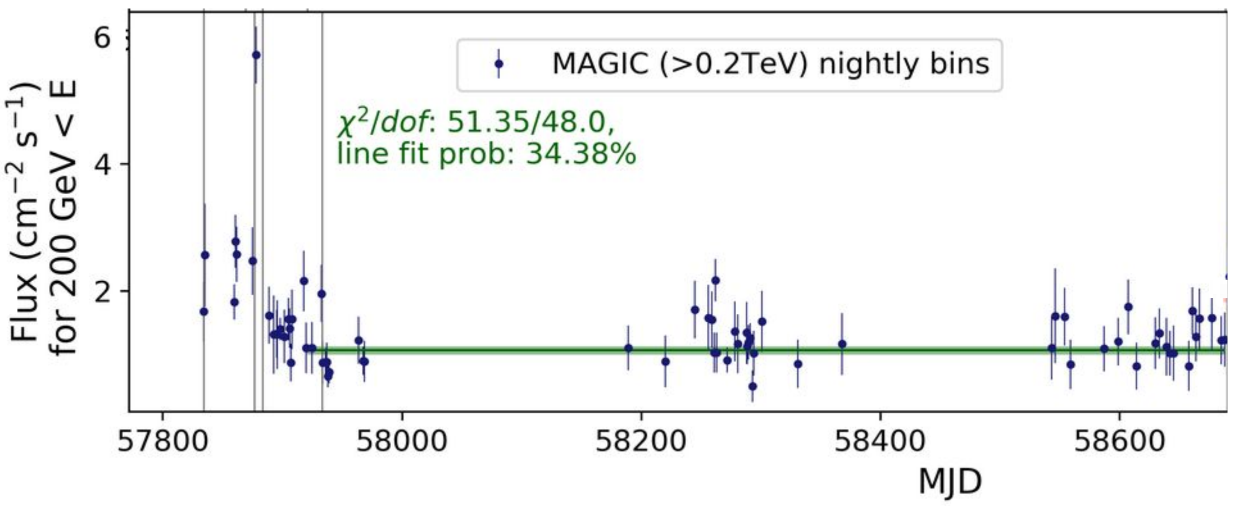

# Fractional variability S. Vaughan et al., MNRAS 345.4 ( 2003)

- Evaluates variance of the data points with taking into account measurement uncertainties

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

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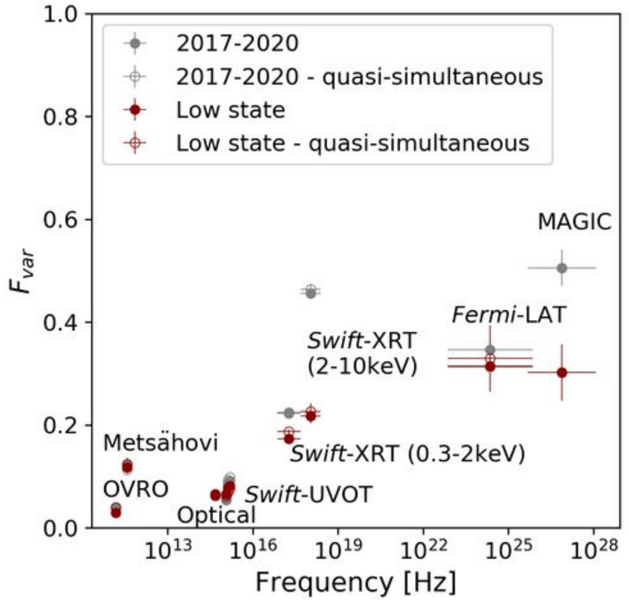
- Applied to the 4-years MWL LCs of Mrk 501
  - Two peak structure

    → highest variability in X-rays and VHE γ-rays produced by highly-energetic particles
  - Plateau for the low-state

H. Abe et al., accepted by ApJS, arxiv:2210.02547 (2023).



# Discrete Correlation Function R. A. Edelson and J. H. Krolik, ApJ 333 (1988)

- Correlation measure adjusted to astrophysical data (uneven sampling,...)

$$DCF(\tau) = \frac{1}{M} UDCF_{ij} \qquad UDCF_{ij} = \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sqrt{(\sigma_a^2 - e_a^2)(\sigma_b^2 - e_b^2)}}$$

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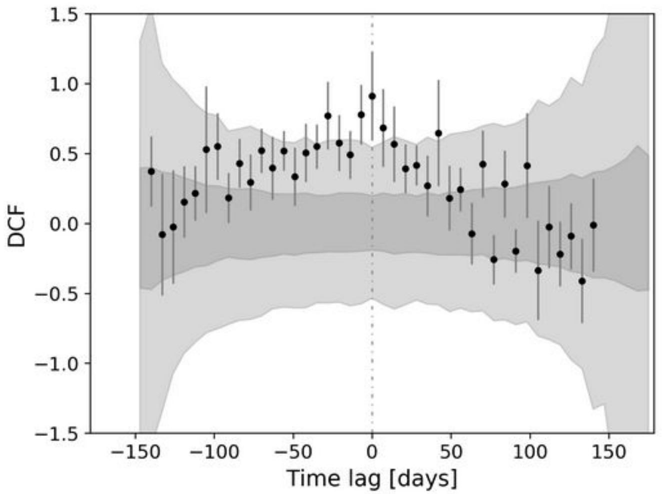
H. Abe et al., accepted by ApJS, arxiv:2210.02547 (2023).

- Applied to the 4-years MWL LCs of Mrk 501
  - Significant correlation (>3σ) without a time lag between the X-rays and VHE γ-rays

    → produced by the same population of particles



# Lomb-Scargle-Periodigram

N. R. Lomb, Ap&SS 39.2 (1976)
J. D. Scargle, ApJ 263 (1982)

- Evaluate periodicity in data set
- Classical periodigram adjusted to astrophysical data

$$P_X(\omega) = \frac{1}{2}\left\{ \frac{\left[\sum_j X_j \cos\omega(t_j-\tau)\right]^2}{\sum_j \cos^2\omega(t_j-\tau)} + \frac{\left[\sum_j X_j \sin\omega(t_j-\tau)\right]^2}{\sum_j \sin^2\omega(t_j-\tau)} \right\}$$

$$tan(2\omega\tau) = \frac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j}$$

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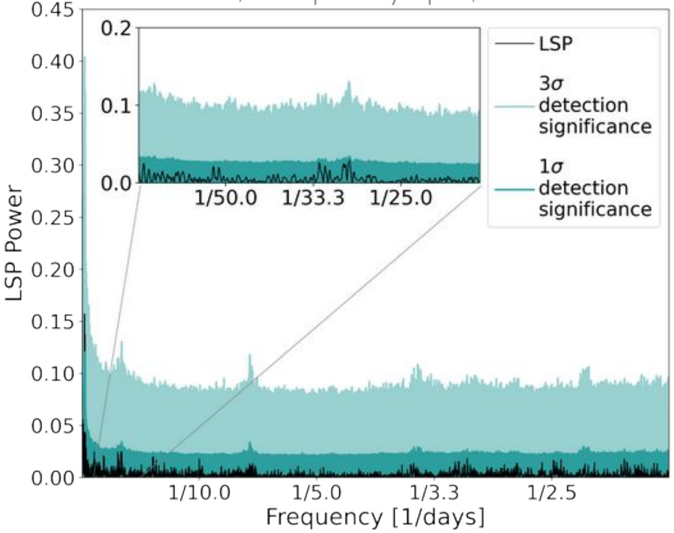
$$tan(2\omega\tau) = \frac{\sum_j \sin 2\omega t_j}{\sum_j \cos 2\omega t_j}$$

- Applied to long-ter MWL LCs of Mrk 501
  - Previous claim, e.g. 30 days in X-rays
    → binary black hole system?
  - Checked 12-years of X-ray data
    - No significant periodicity found

H. Abe et al., accepted by ApJS, arxiv:2210.02547 (2023).



# Summary & Conclusions

- **Blazars** are interesting objects to study, especially because their jets **accelerate particles to extremely high energies**
- **Multi-messenger** and **Multiwavelength studies** are vital to understand these powerful sources
- Data sets are growing and there are many **statistical methods** which are valuable tools to gain more insights

Credit: http://www.astro.princeton.edu/~lilew/

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# Thank you for your attention!