X-ray variability of Active Galactic Nuclei (and other recent topics)

Greg Madejski
Stanford and SLAC

Some slides “borrowed” from friends:
Ioannis Liodakis,
Sarah Wagner,
Rubin Community Science Team,

X-ray variability of active galactic nuclei

Greg Madejski, Stanford University (Stanford / SLAC and KIPAC)

Talk content:

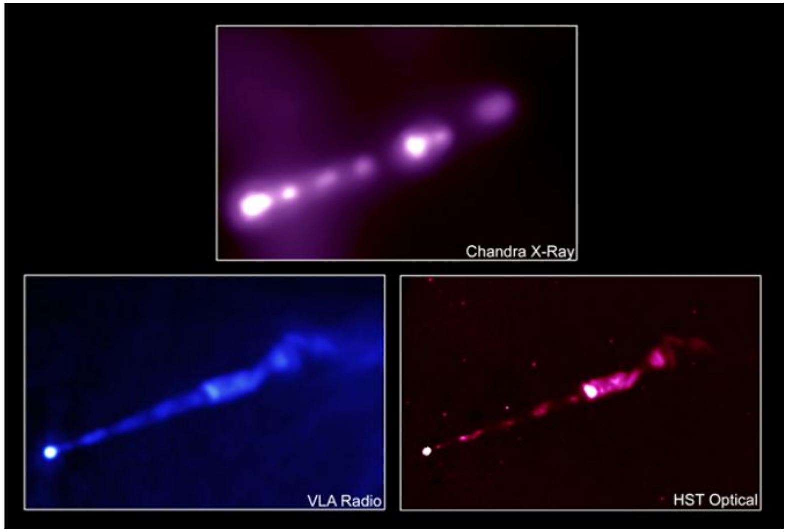
Overview:

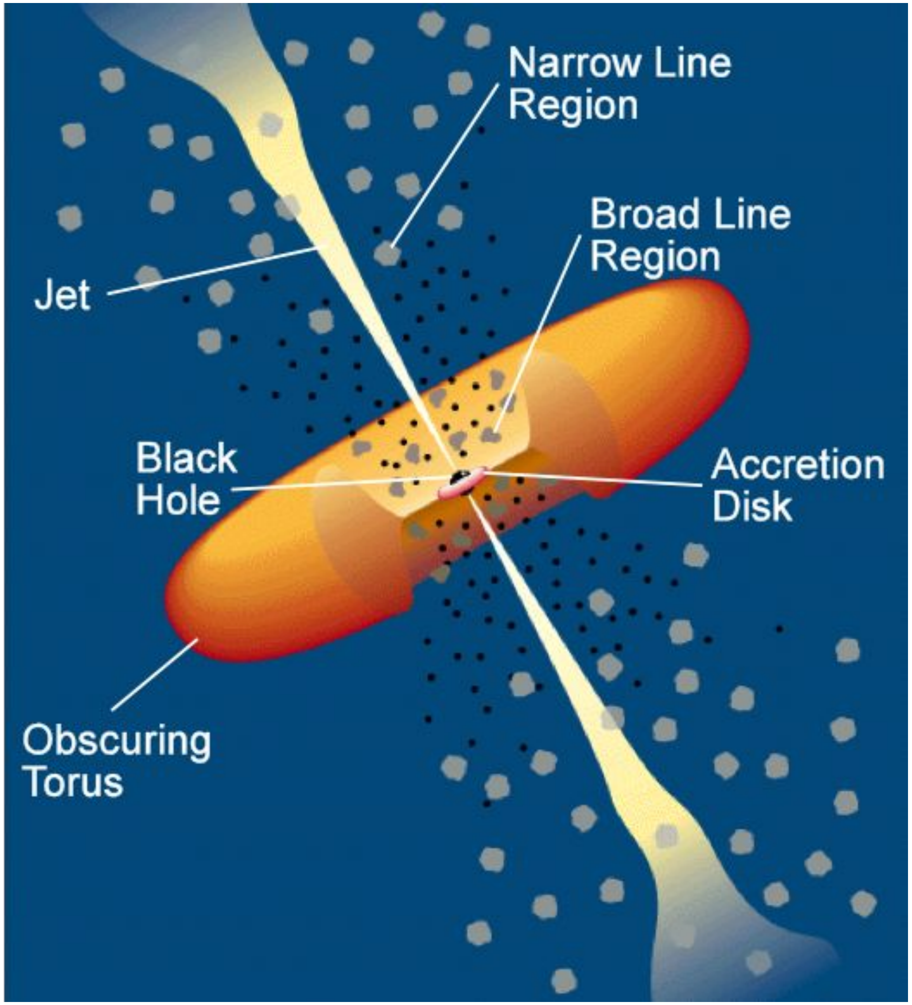
- Disk dominated vs. jet dominated AGN - as inferred from their observational properties - X-ray variability properties of both classes
- IXPE and X-ray polarimetric results supporting the “unified picture” of AGN
- Special Fermi blazar - gravitationally lensed FSRQ PKS 1830-211
- The future - where Berrie helped: quick overview of the Rubin Observatory

Overview: general picture of active galactic nuclei

“Vintage’”, somewhat overused schematic of an AGN (from Padovani and Urry)

- Many - if not all - galaxies contain a supermassive black hole
- In the process of growth, the circum-nuclear material falls onto the black hole and loses energy and angular momentum in an accretion disk - presumably via dissipation in an accretion disk
- The dissipation of energy in the accretion disk takes place (most likely) via MRI-like process accelerating particles, and emission appears to be thermal Comptonization
- In a fraction of cases, the black hole - disk system is accompanied by a relativistic jet
- The jet is visible in many EM bands

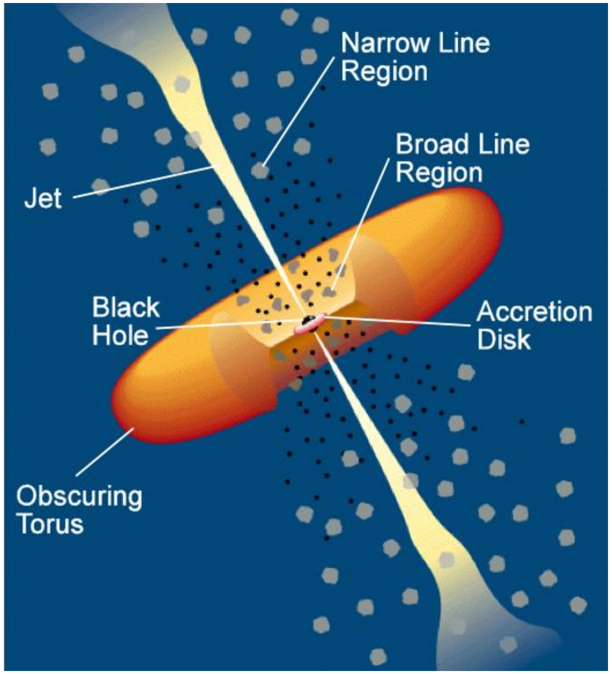


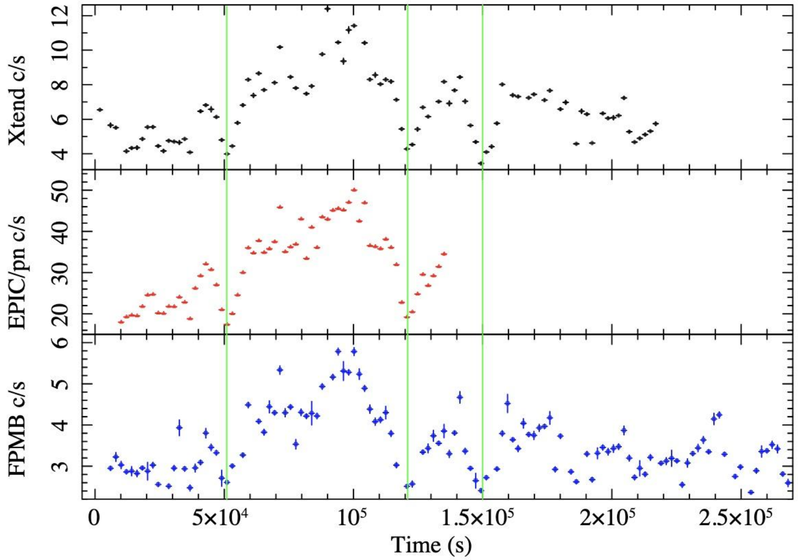


We still don’t have a clear picture as to when / why AGN have jets!

The accretion-dominated AGN

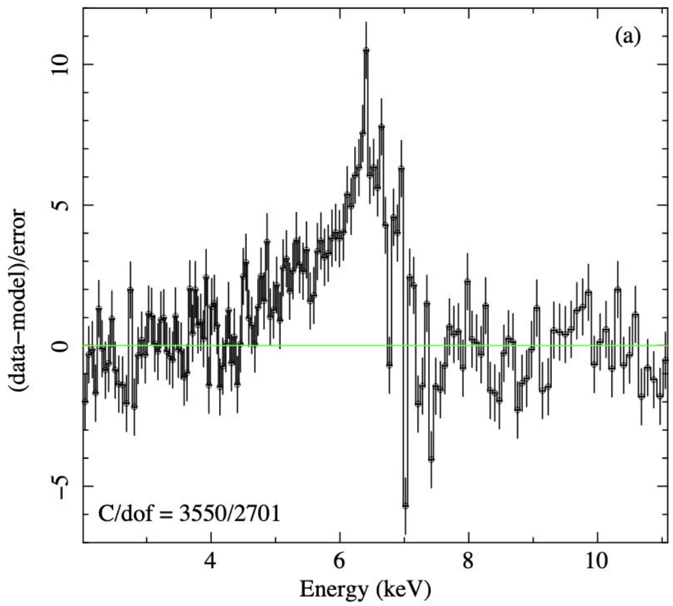
- In most AGN, the jet is subdominant - weak radio emission, no gamma-rays - but often bright in X-rays
- Those are extensively studied in the X-ray band
- They are generally “somewhat” variable in X-rays rarely more than x2 (MCG-6 below)





Spectral studies in X-rays:

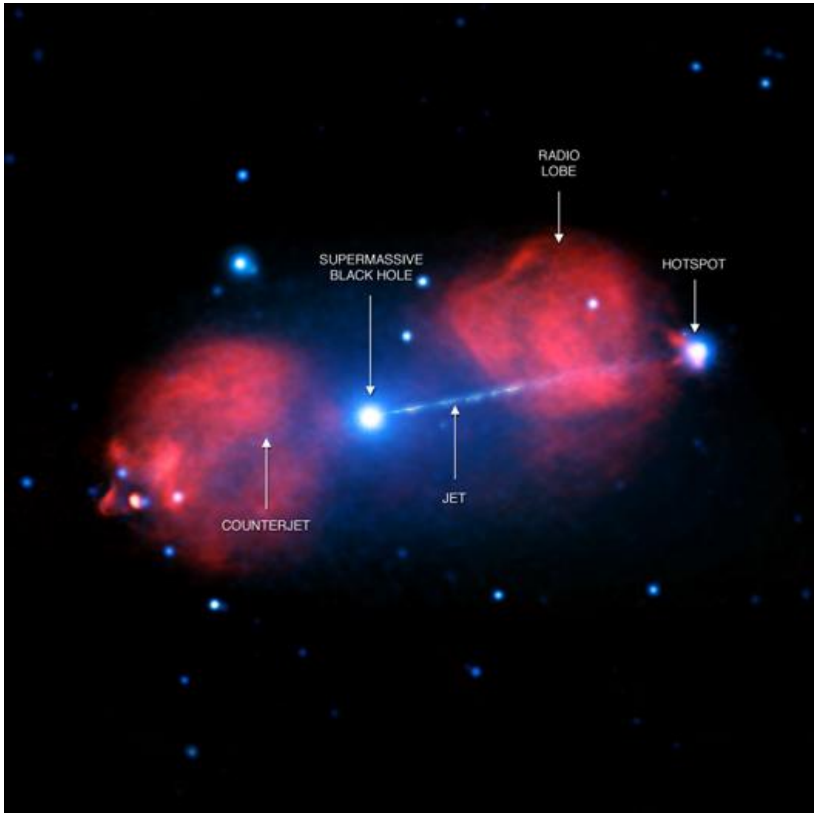
- The presence of the Fe K line implies nearly-isotropic emission

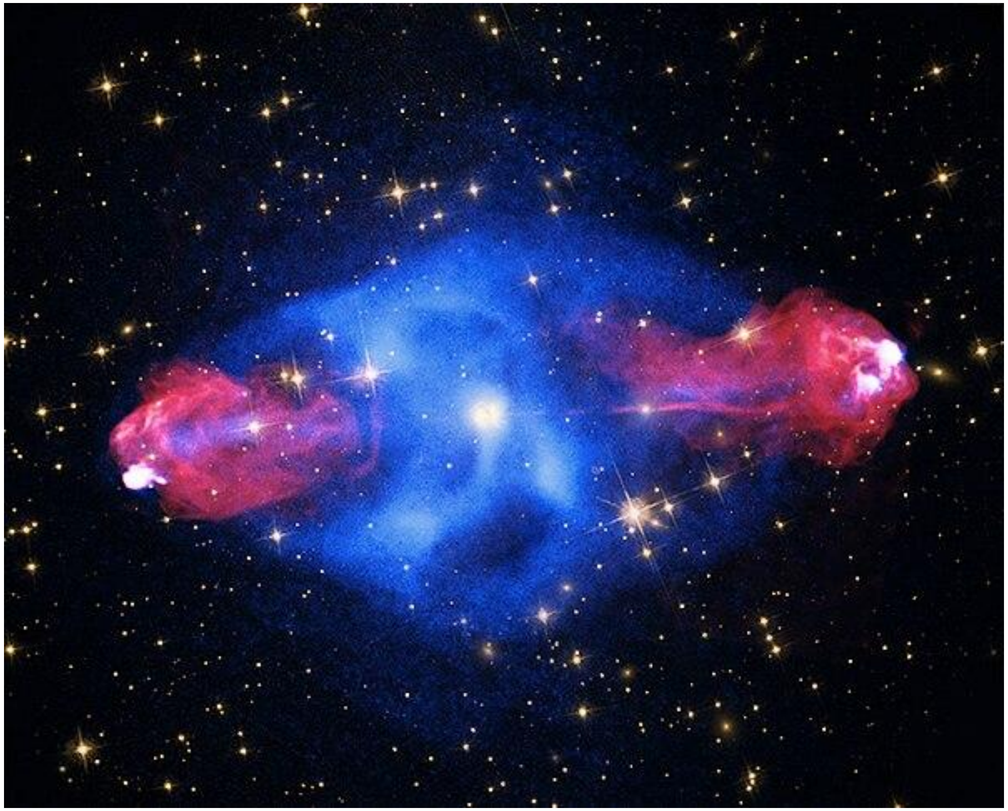


Generally, no polarization is detected in any band, including X-rays (more on this later!)

The AGN with jets: observationally quite different

- In a sub-class of AGN, the broad-band emission is very prominent from radio to γ-rays (including VHE gammas) - those are radio galaxies
- Radio galaxies often show strong diffuse radio & X-ray emission, plus narrow "streams" emanating from their centers - known as jets
- Possibly best known example is M87 (also showing the "shadow of the black hole")
- Another prominent examples are the radio galaxy Pictor A (left) and Cygnus A (right)





Very rapid, broad-band variability of AGN - jets!

- In some cases, very rapid, large amplitude variability is observed in many spectral bands
- Such rapid, broad-band variability is best explained as arising in a relativistic jet pointing close to our line of sight - those objects are called blazars
- Perhaps the most extreme case was the VHE γ-ray emission from blazar PKS 2155-304 (below, left) but also quite extreme is X-ray variability from Mkn 421 (below, right; in prep.)

An Exceptional VHE Gamma-Ray Flare of PKS 2155−304 5

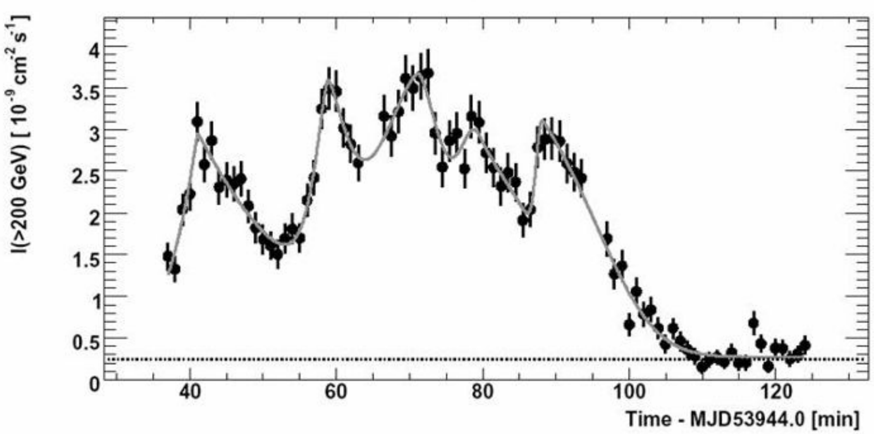
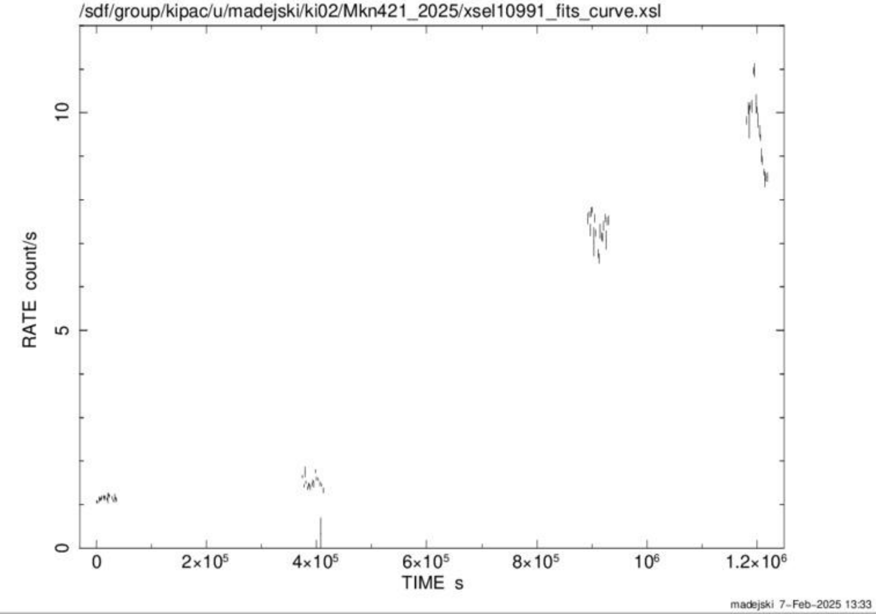
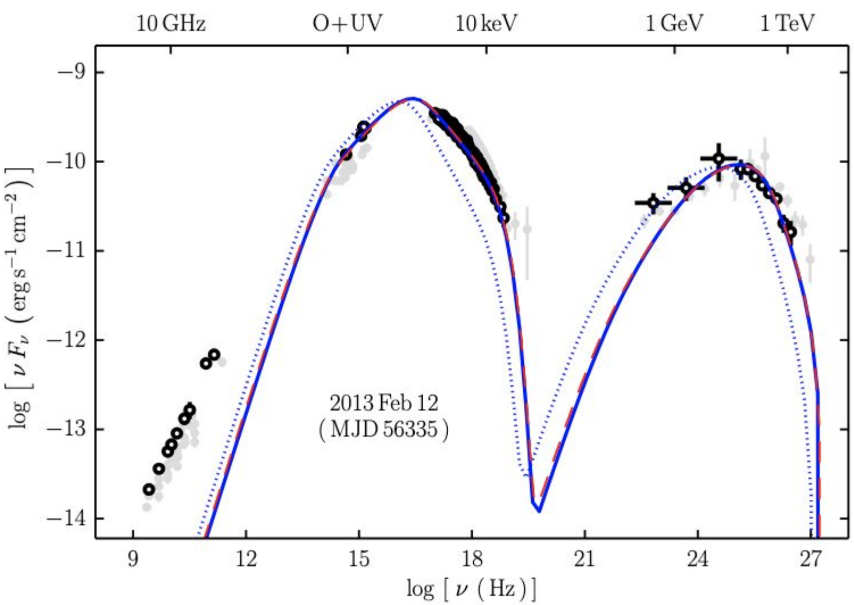


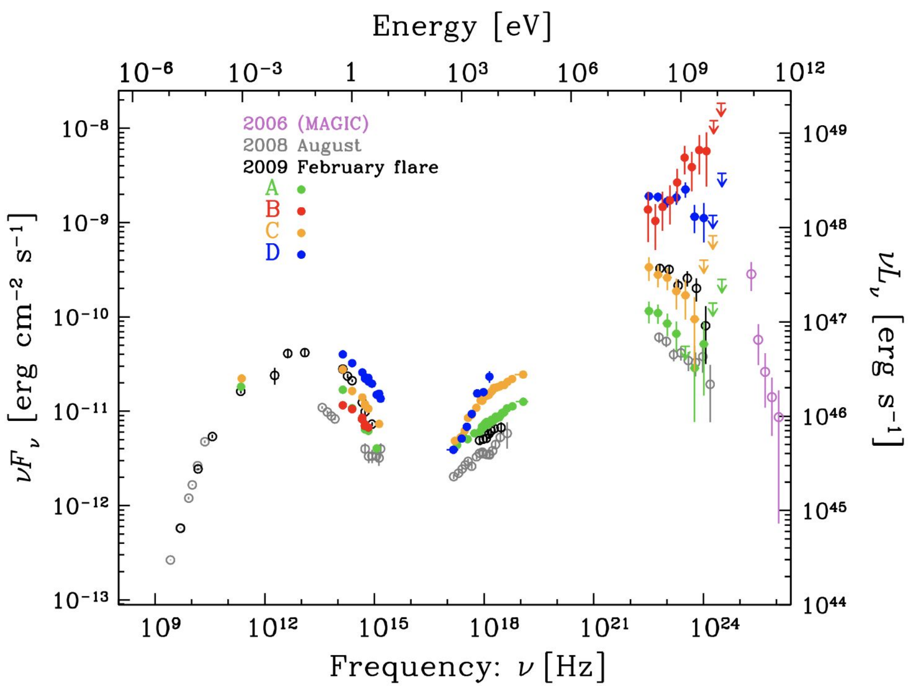
FIG. 1.— The integral flux above 200 GeV observed from PKS 2155−304 on MJD 53944 versus time. The data are binned in 1-minute intervals. The horizontal line represents I(>200 GeV) observed (Aharonian et al. 2006) from the Crab Nebula. The curve is the fit to these data of the superposition of five bursts (see text) and a constant flux.



Basic blazar phenomenology

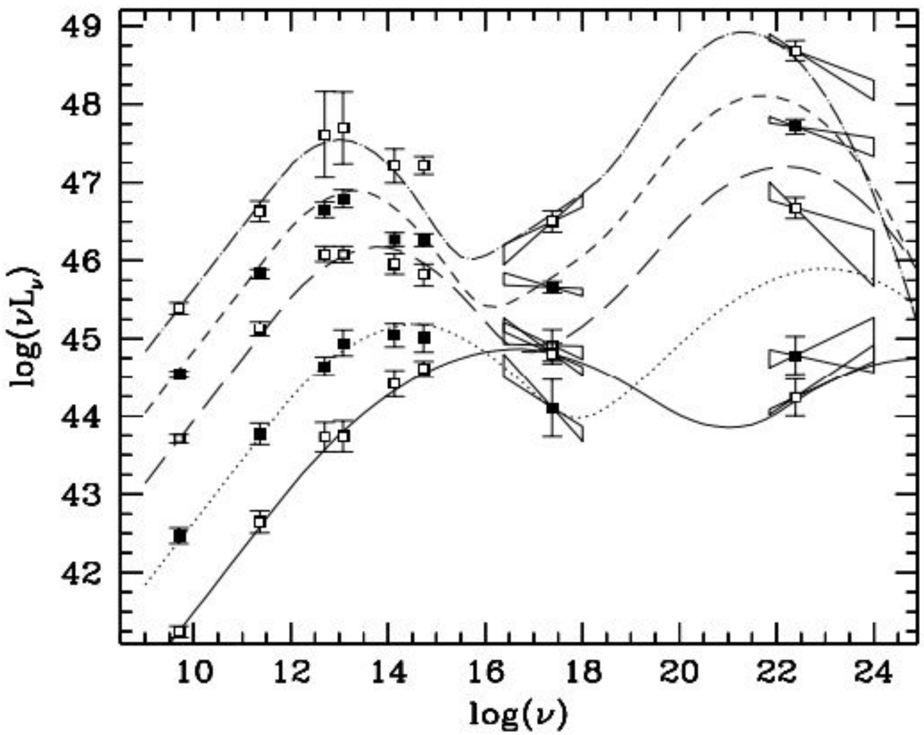
- Blazars radiate over *all* accessible spectral bands, and their broad-band spectra are remarkably similar to each other
- 2 general "types" - lower luminosity has peaks at higher energies (Mkn 421, right below) than the high-luminosity variety (3C279, left below)
- Those spectra consist of two broad "humps" one peaking in the far IR – to – soft X-rays, another peaking in the MeV – Gev γ-ray range, sometimes extends to the TeV VHE γ-ray regime
- Understanding the jet structure is a bit like "peeling of an onion" start with photons, > radiating particles, > content of the jet, > connection to the black hole, …





Broad-band SED of two classes of blazars: Mkn 421 (Balokovic et al. 2015, left) and 3C279 (Hayashida et al. 2015, right)

Blazar sequence (from Fossati et al)



X-rays in BL Lac blazars originate from a different component than in FSRQs

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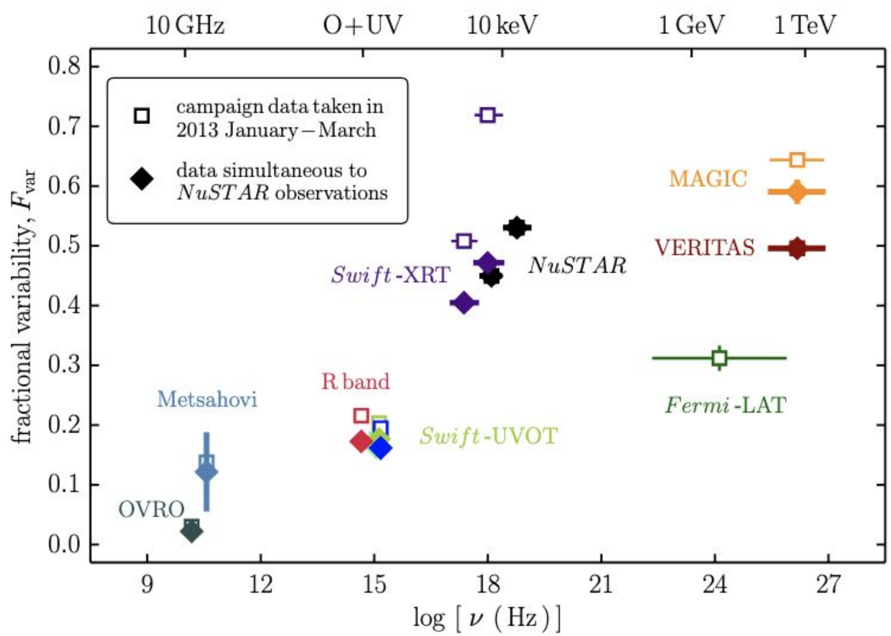
Radiation mechanisms in blazars

- The low-energy hump emission (radio, opt.) is polarized, and generally thought to originate via synchrotron emission of relativistic particles accelerated in the jet
- The high-energy peak is thought to originate via inverse Compton process, by the same electrons that produced the synchrotron hump
- “Seed” photons for Compton scattering: synchrotron photons (low-luminosity blazars) or external (BLR, IR torus) photons (high-luminosity blazars)
- Very clear predictions as to the X-ray polarization! (results in a few slides)
- All this takes place in a volume that can be estimated from variability time scales + relativity
- The variability amplitude in each “hump” generally seems greater with increasing photon energy



Fractional variability of blazar Mkn 421 as a function of photon frequency (Balokovic+ 2015)

Berrie's work on blazars

- Berrie started to work on blazars even before launch of Fermi
  - (paper in 1ES1959+65, Giebels et al. 2002)
- Worked on x-ray variability of BL Lac (log-normal variability - connection to the accretion disk, Giebels and Degrange 2009)
- Shepherded many blazar observations with H.E.S.S. including joint observations of PKS 2155-304 with NuSTAR (Madejski, … Giebels, … 2016)
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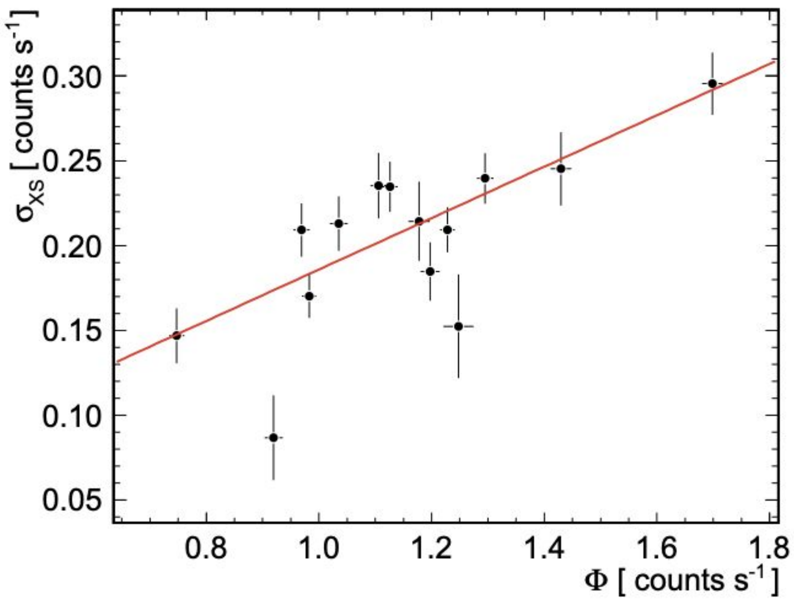


Fig. 3. Scatter plot of the excess variance versus the average of the fluxes for which the excess was determined. The line is a linear fit showing $\sigma_{XS} \propto (0.15 \pm 0.02)\,\Phi$.

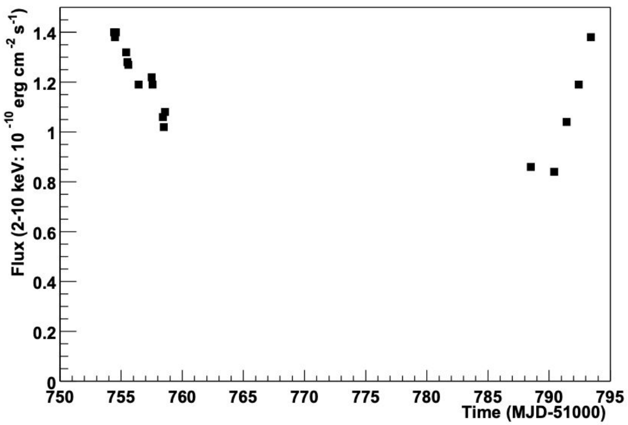


Fig. 2.— Time history of 1ES1959+65 emission obtained from the PCA. The first part of the observations go from July 28 to Aug 2 (2000), and the second part from Sep 1 to Sep 4. For comparison with Fig. 1, a flux level of 1 mCrab is approximately 1.7×10^{-11} erg cm^{-2} s^{-1} in the 2–10 keV band.

Giebels and Degrange (2009)

Giebels et al. (2002)

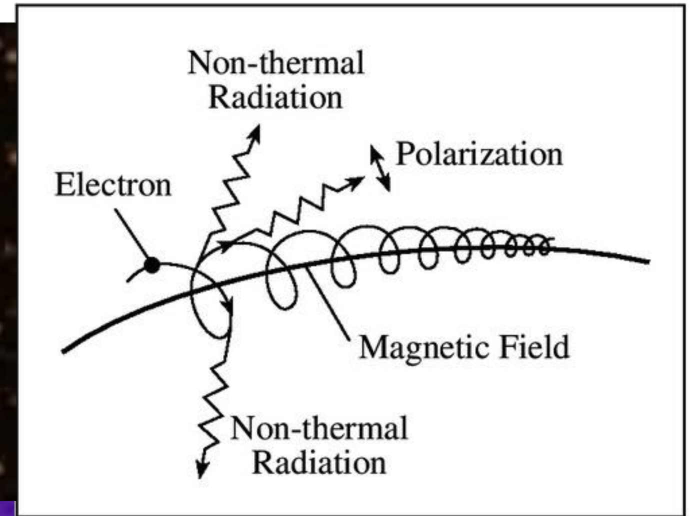
New kid on the block - X-ray polarization

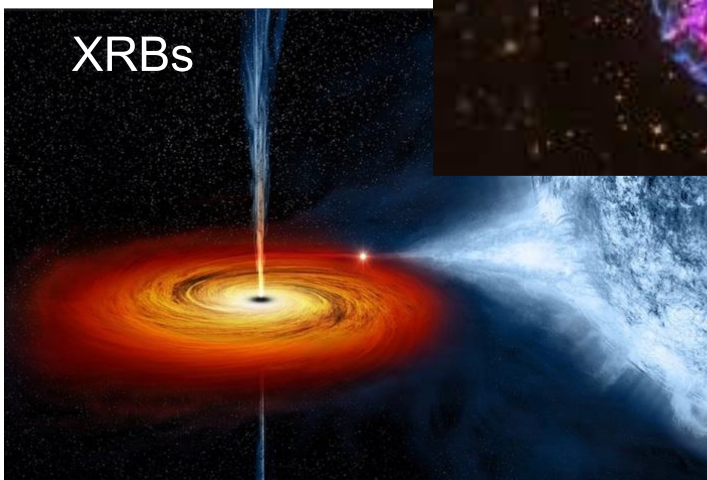
What would be its origin? two good possibilities:

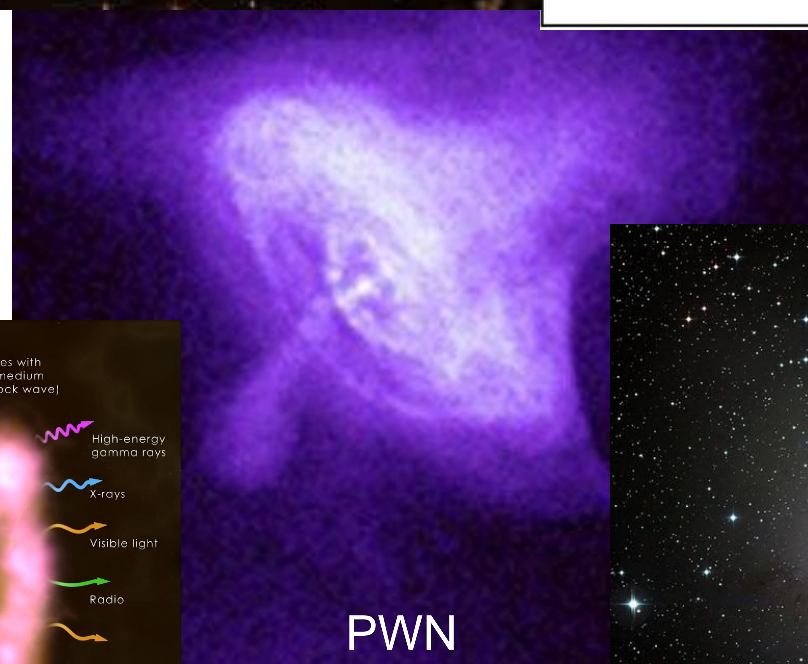
Magnetic fields

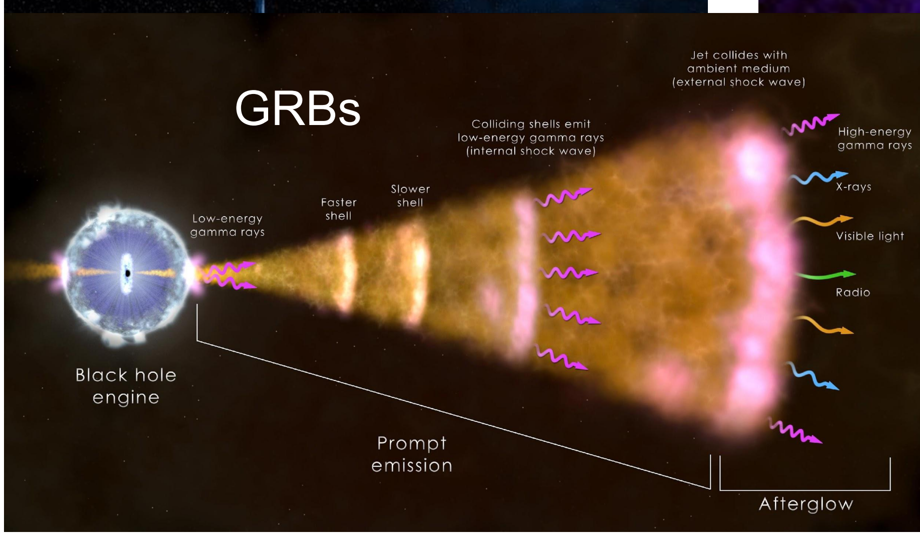
Geometry

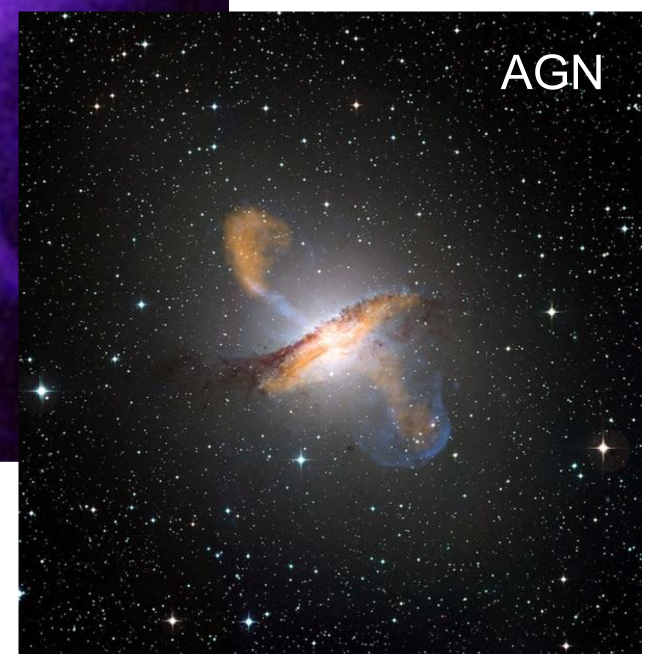
Synchrotron radiation





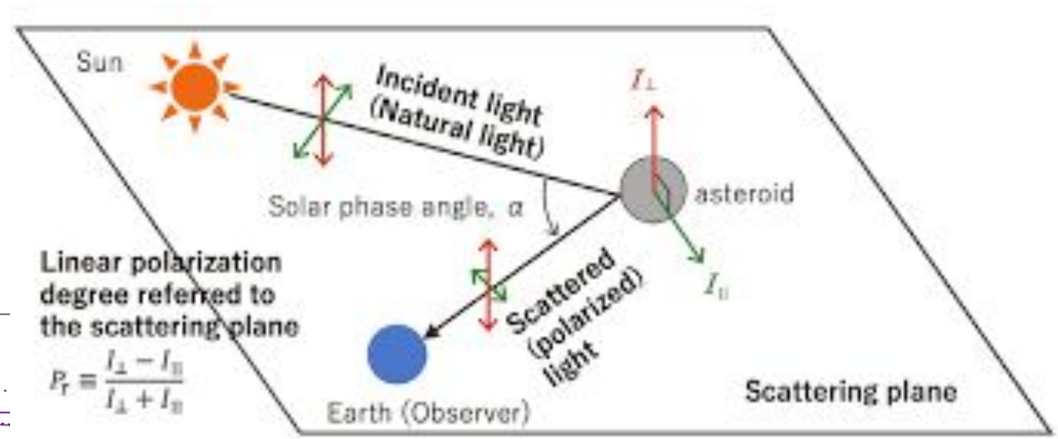






Origin of X-ray polarization

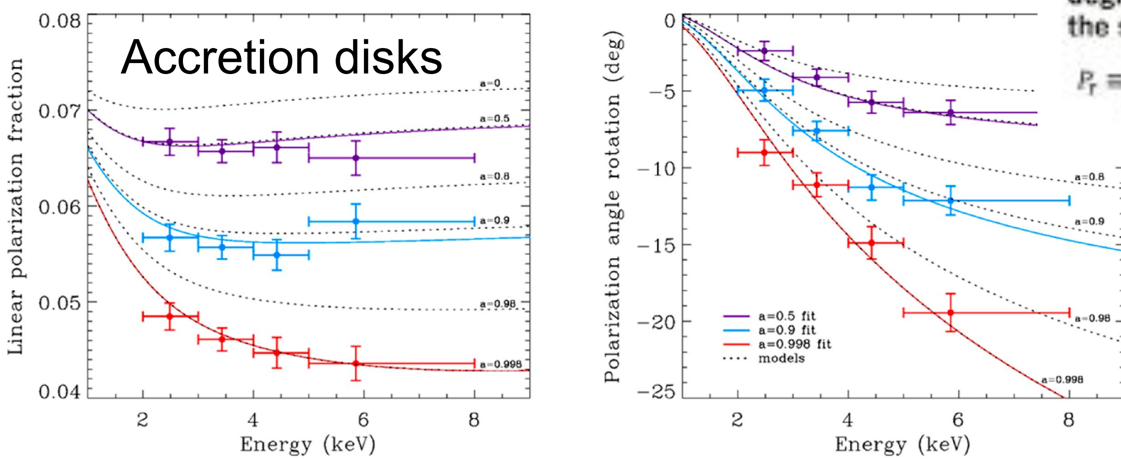
electron scattering

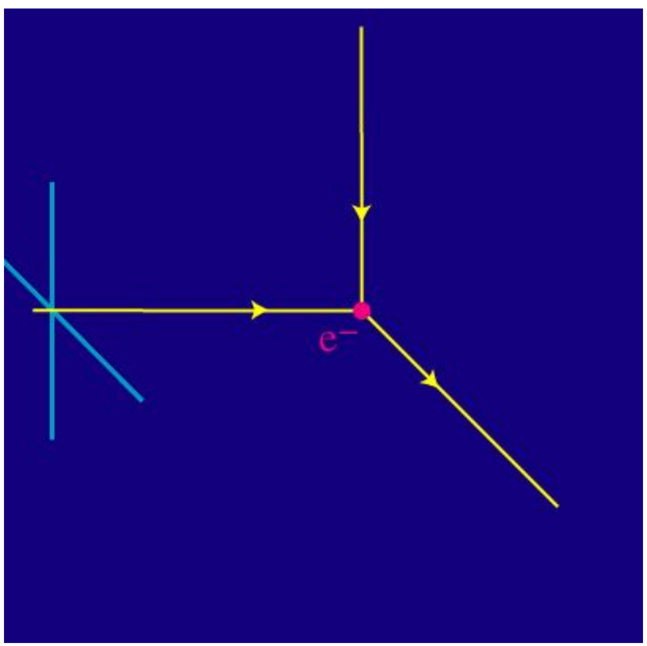


Magnetic fields

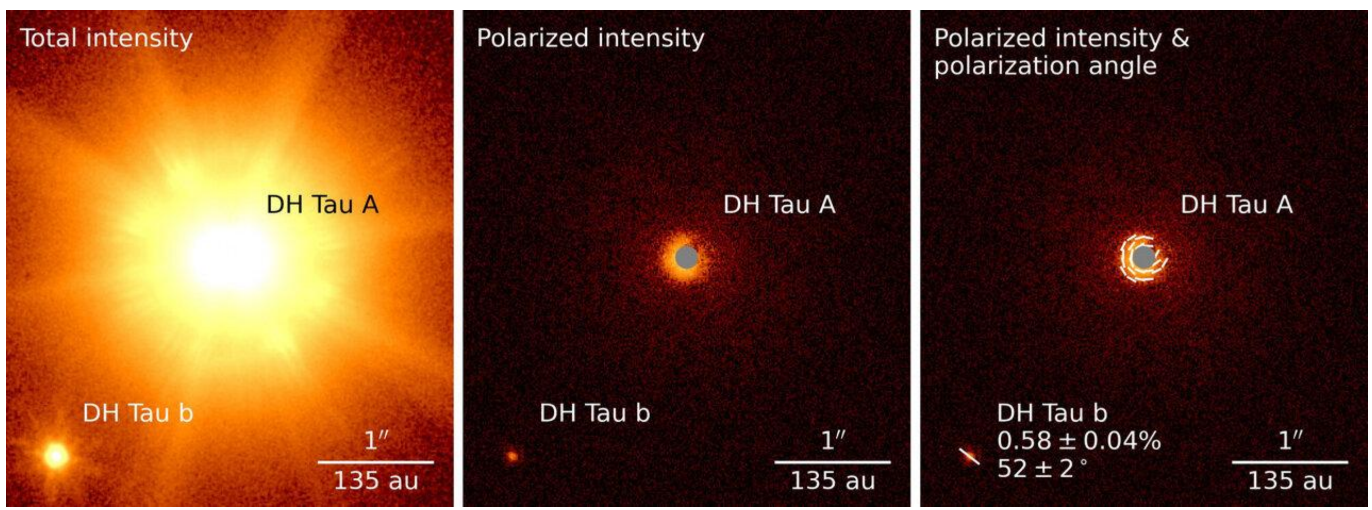
Geometry

Accretion disks



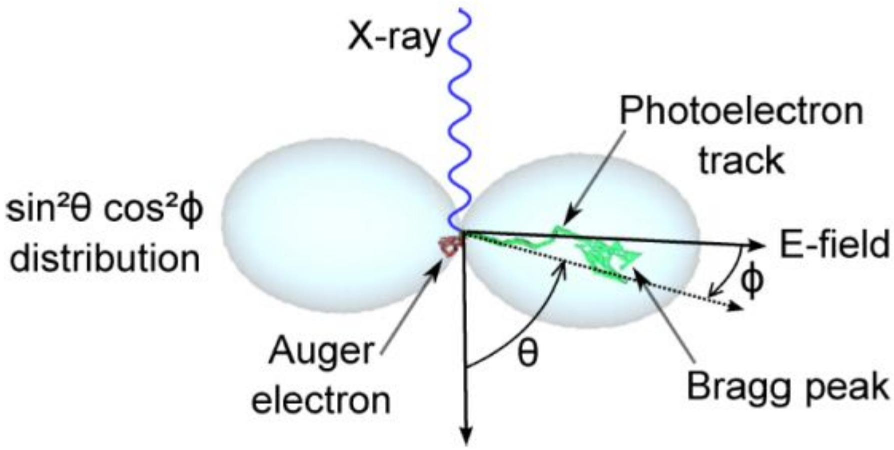


Exoplanets

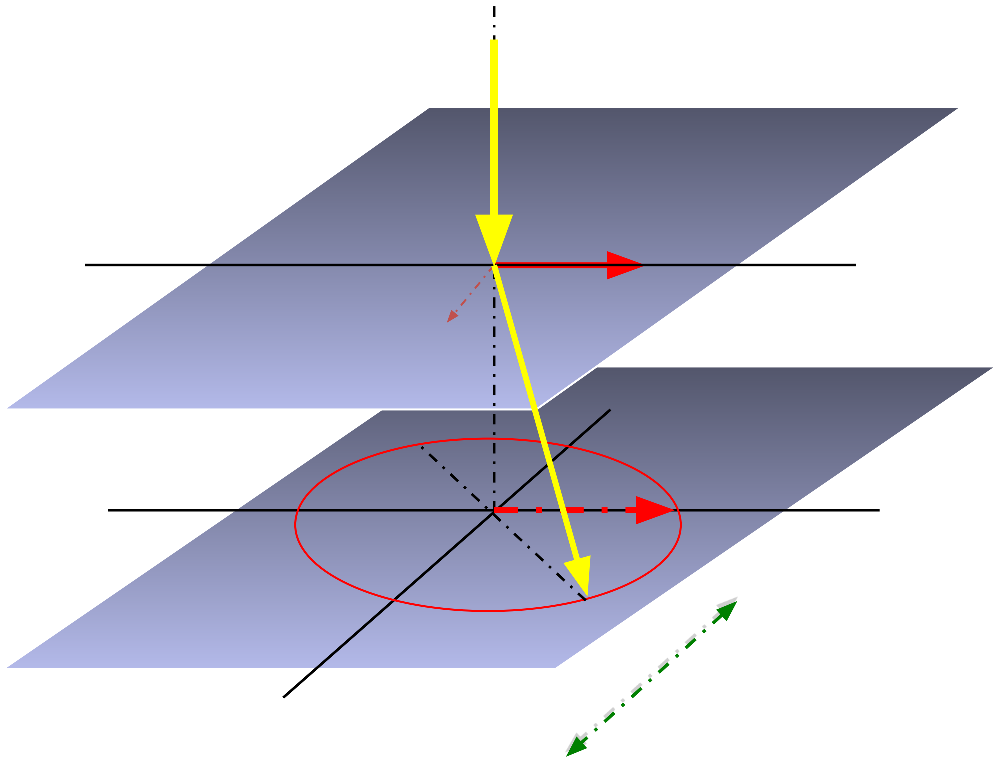


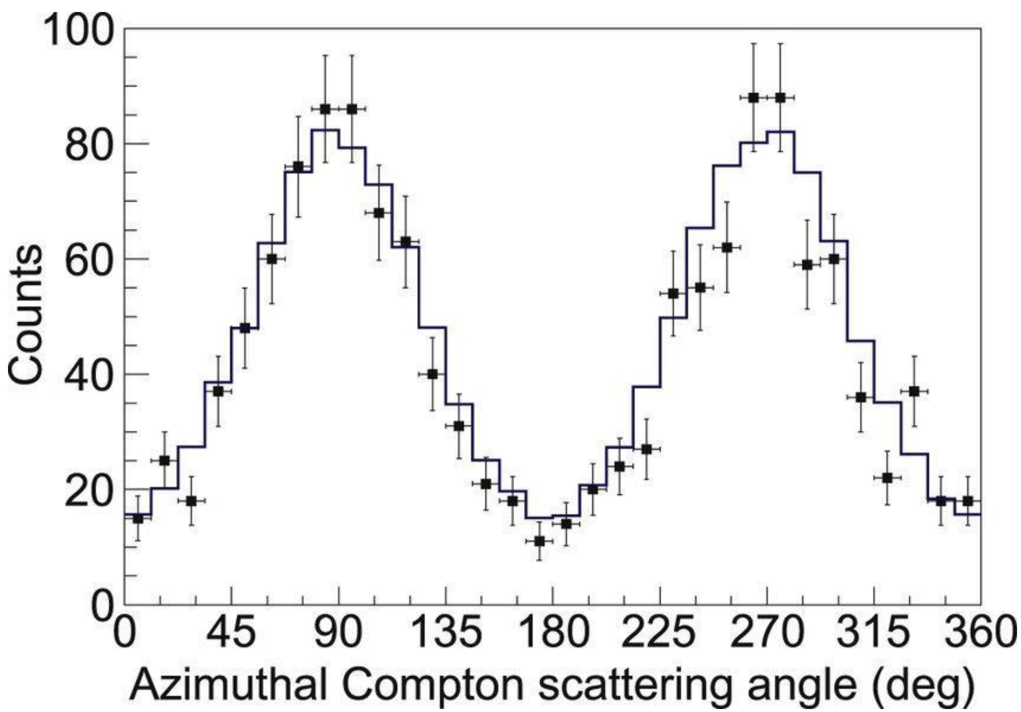
Polarization at high energies

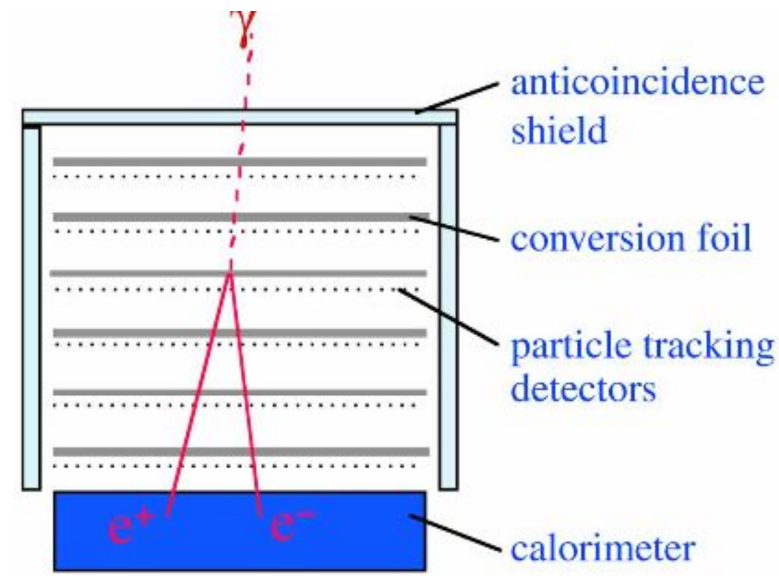
Photoelectric effect (~1-30 keV)



Compton scattering (~50 keV-30 Mev)

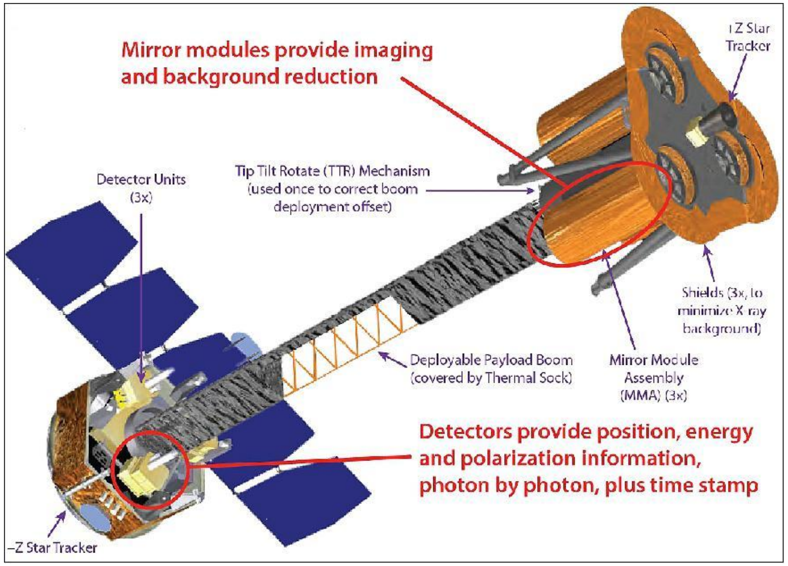






Pair creation (~20 MeV-300 GeV)

A new era with the Imaging X-ray Polarimetry Explorer



IXPE Topical Working Groups

TWG1 Pulsar Wind Nebulae
TWG2 Supernova Remnants
TWG3 Accreting Black Holes
TWG4 Accreting Neutron Stars
TWG5 Magnetars
TWG6 Radio-Quiet AGN & Sgr A
TWG7 Blazars & Radio Galaxies

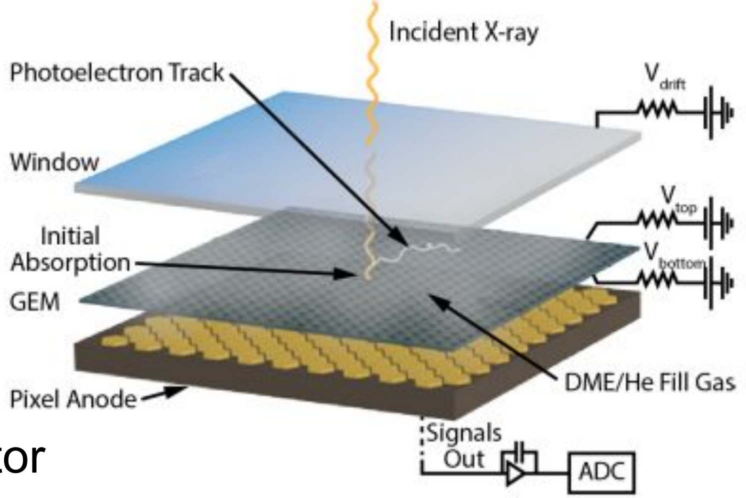
Small NASA mission

Launched Dec 2021

Measuring X-rays in the 2-8 keV energy range

70+ published papers!
More on the way...

Spatially-resolved X-ray polarization requires loooong observations…



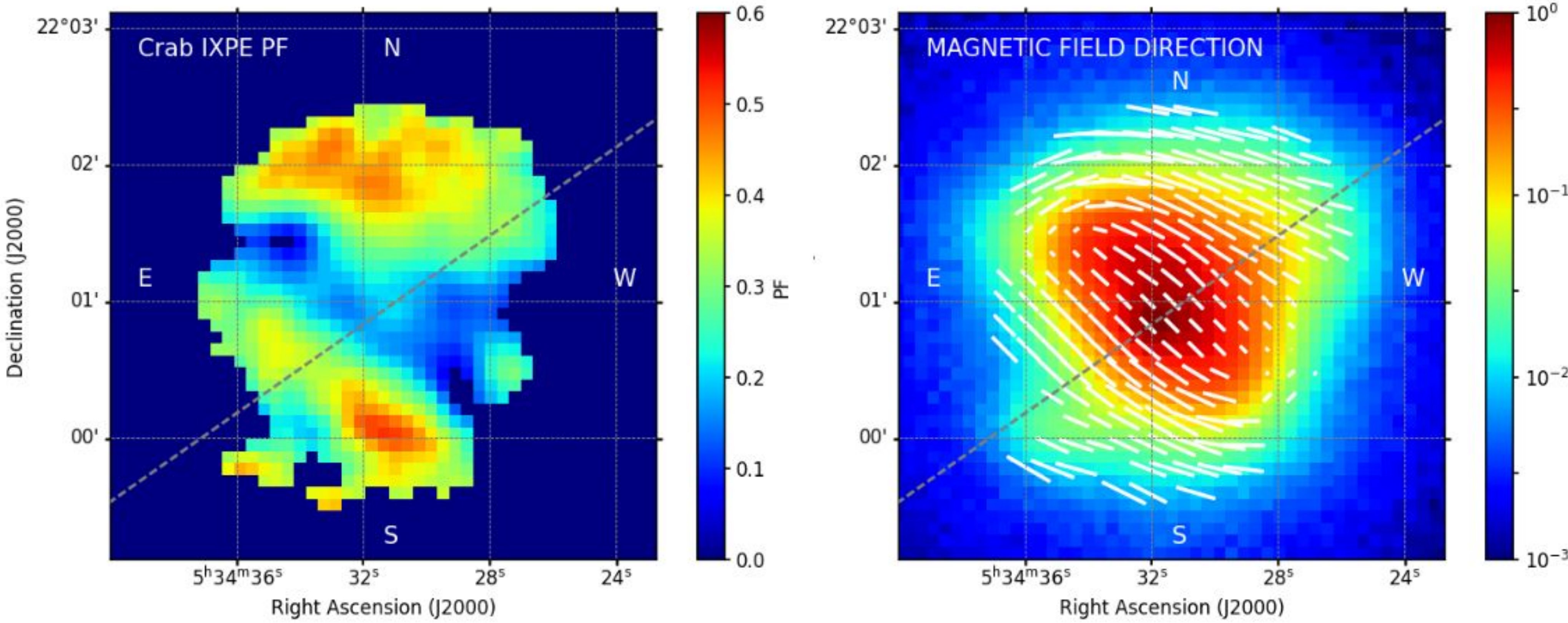
Gas pixel detector

Some IXPE highlights: Crab Nebula & Pulsar

– Integrated polarization consistent with the Weisskopf et al., (1976) measurement

– pulsed emission mostly unpolarized

– large scale toroidal magnetic field



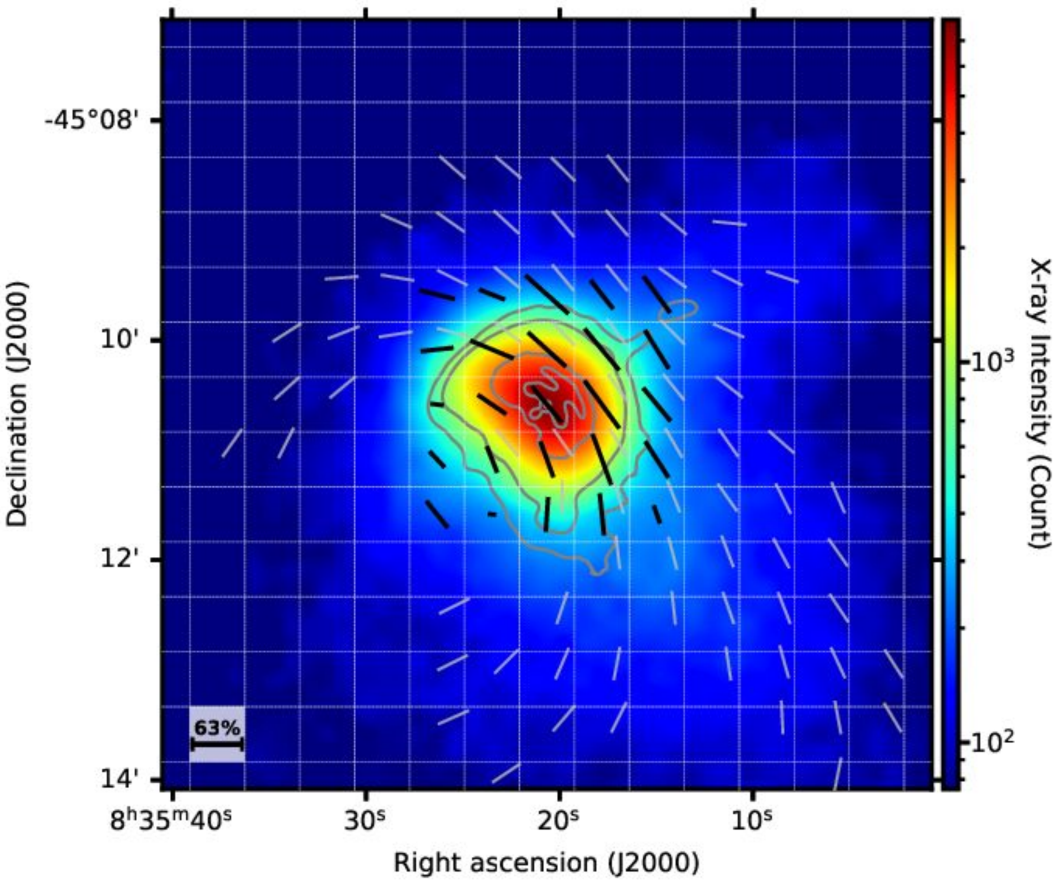
Bucciantini et al. (2022)

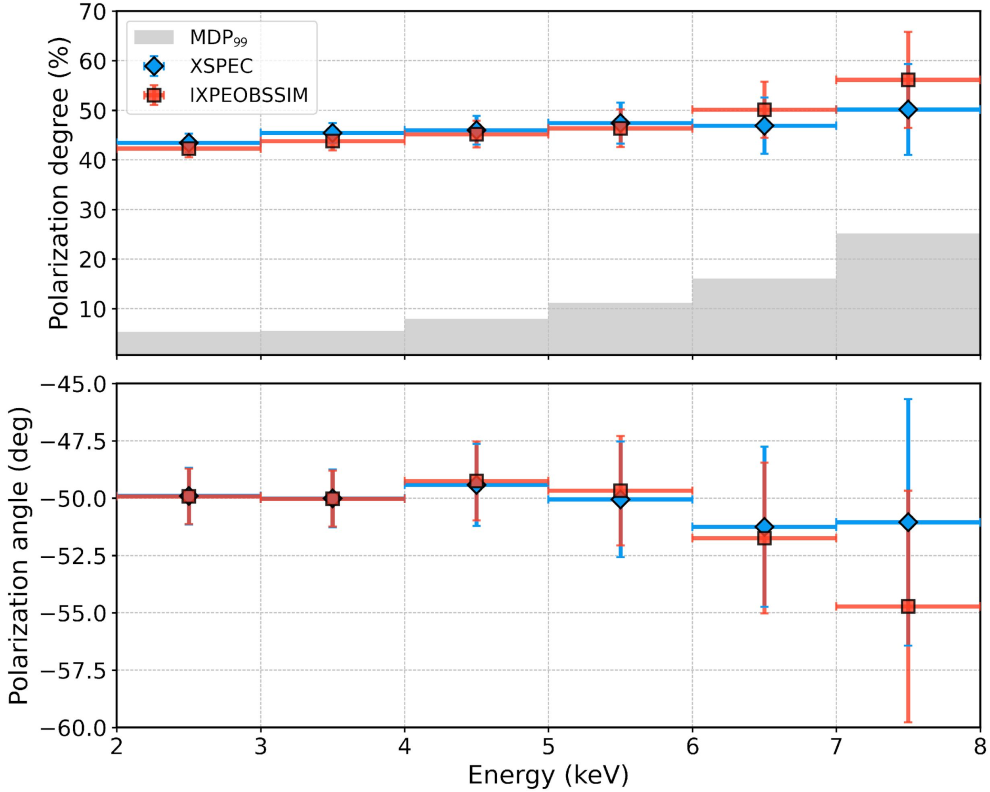
Xie et al. (2023)

Vela pulsar wind nebula

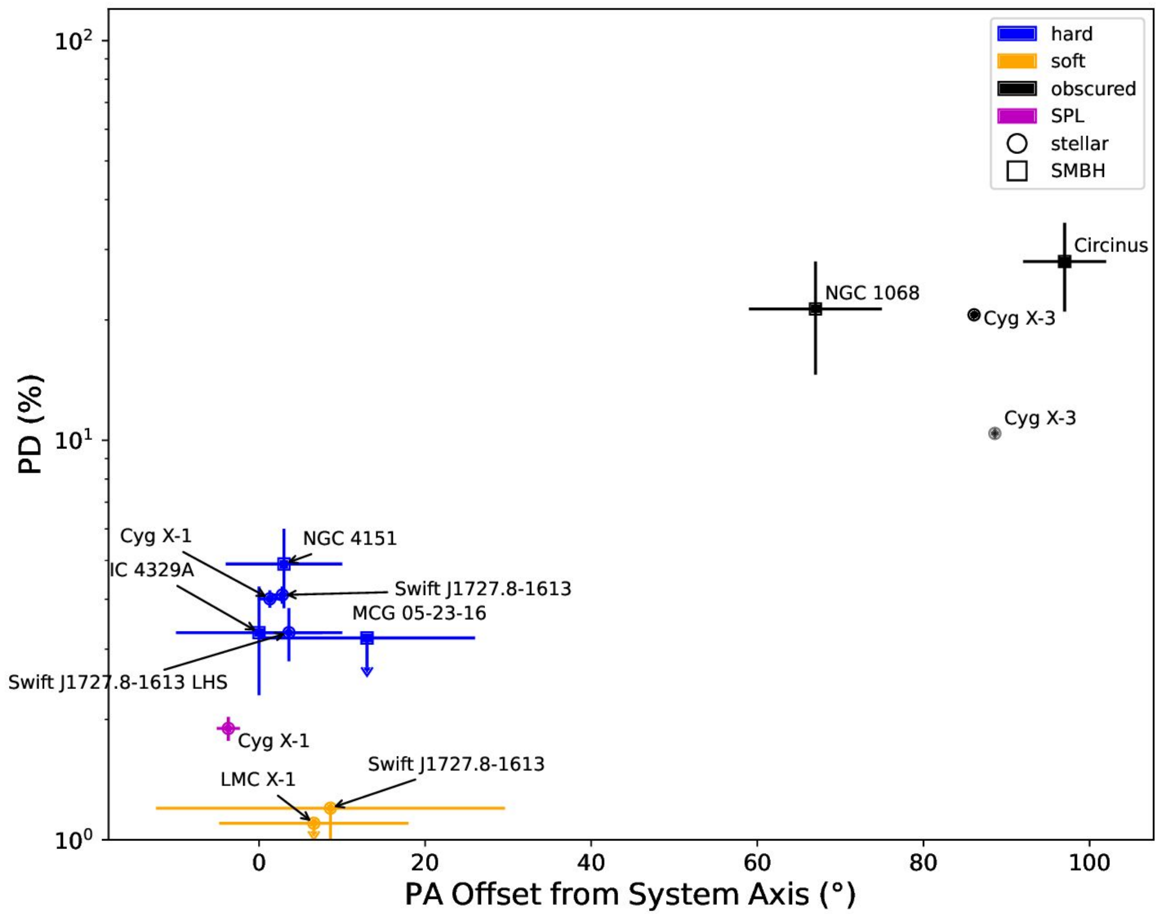
– ~44% integrated polarization (>60% locally!)

– Polarization angle aligned with the radio jet





X-ray polarization properties of jet-less, radio - quiet AGN



Saade et al. (2024)

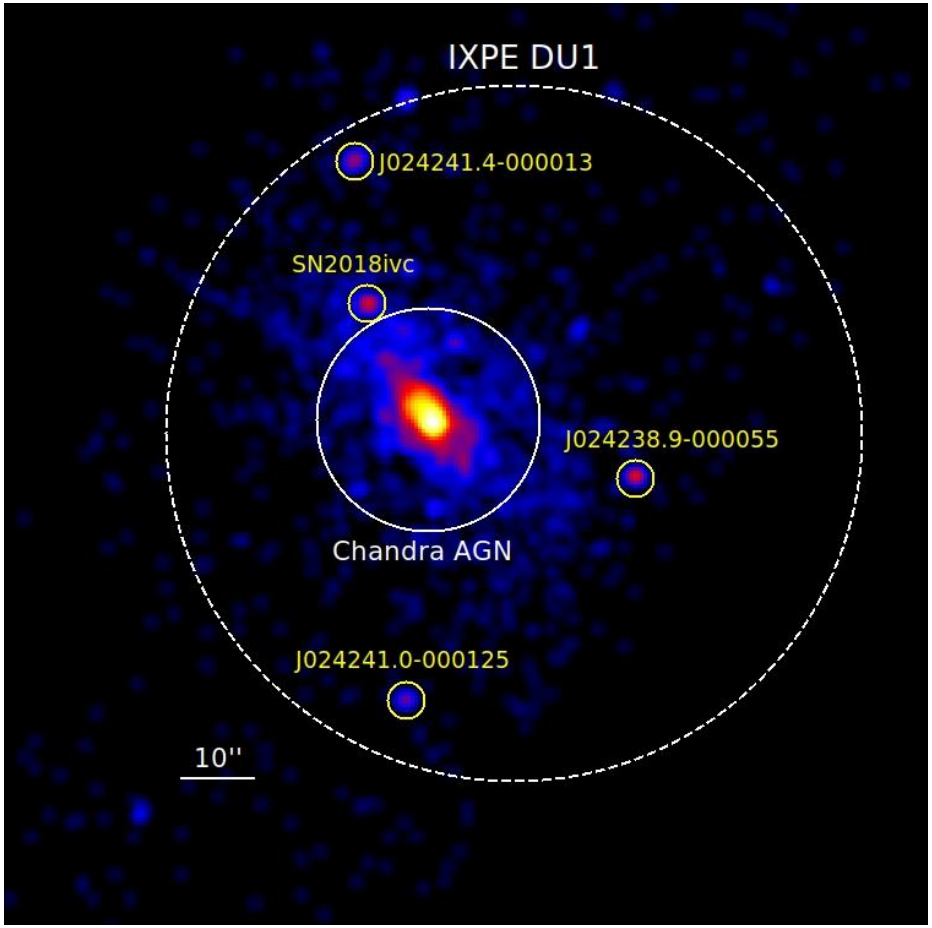
AGN with X-ray emission dominated by accretion disk seems to be low, originating via electron scattering in the ionized accretion disk corona

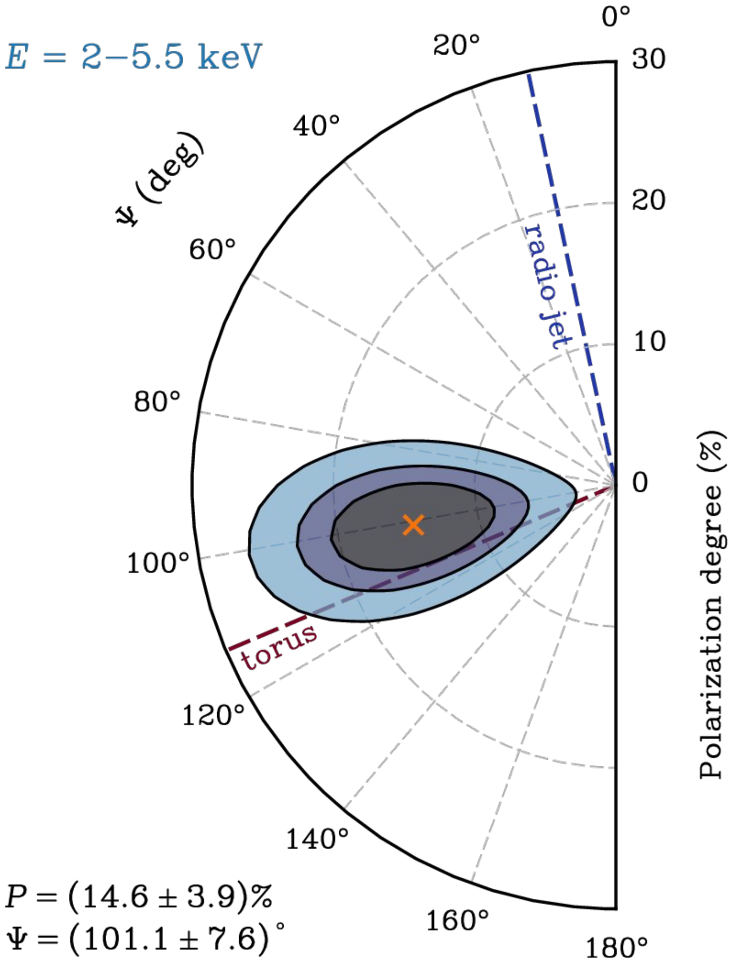
Such corona is independently inferred in Seyfert-II type AGN, observed edge-on with primary emission obscured by the accretion disk / torus

Example: Seyfert-II AGN NGC 1068:

THE poster child of the AGN Unification Model (Antonucci & Miller)

~14% roughly perpendicular to the radio jet
(~21% at the 3.5-6 keV)





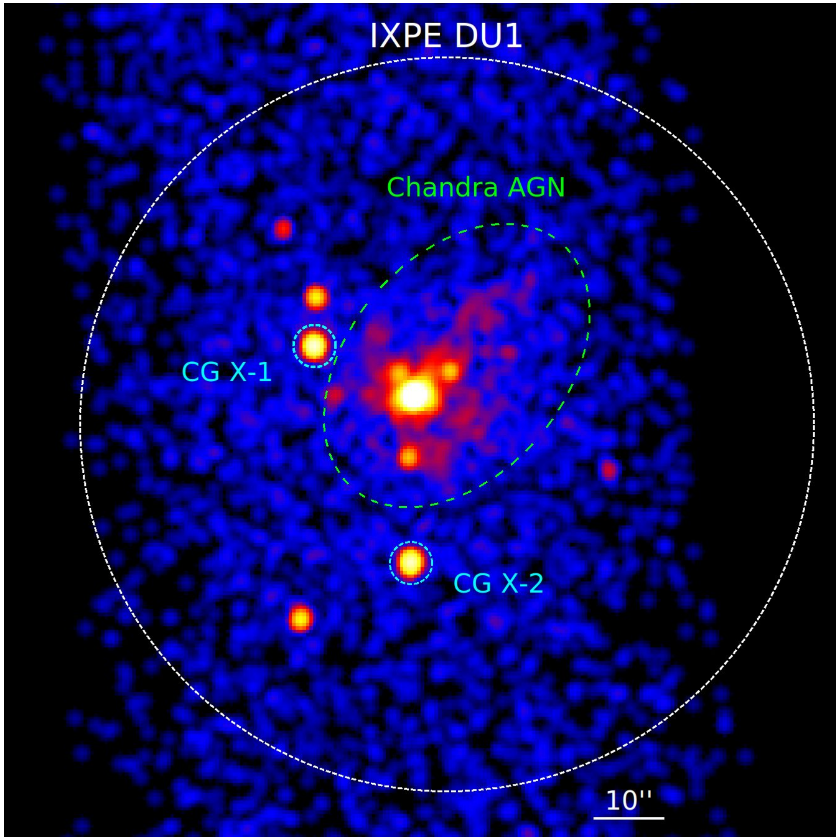
Polarized X-ray emission most likely due to scattering of AGN's X-rays by free electron above the accretion disk

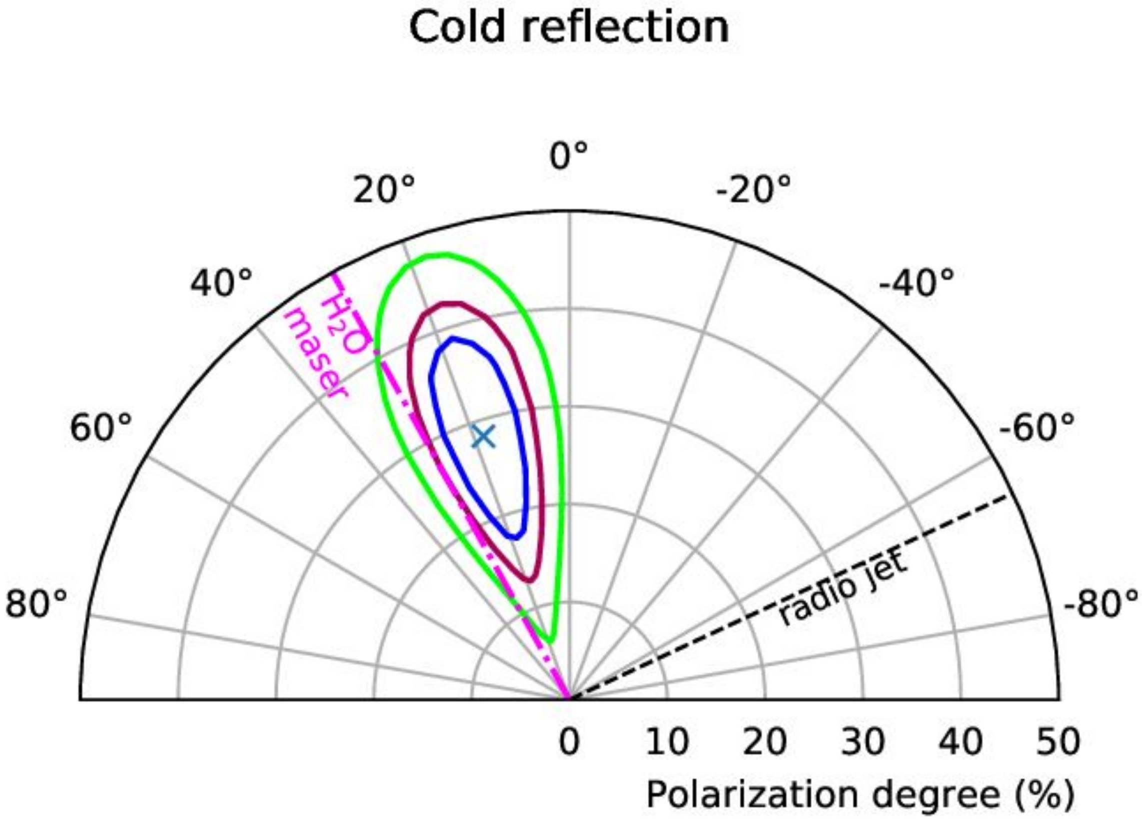
Marin et al. (2024)

Another edge-on AGN: Circinus galaxy

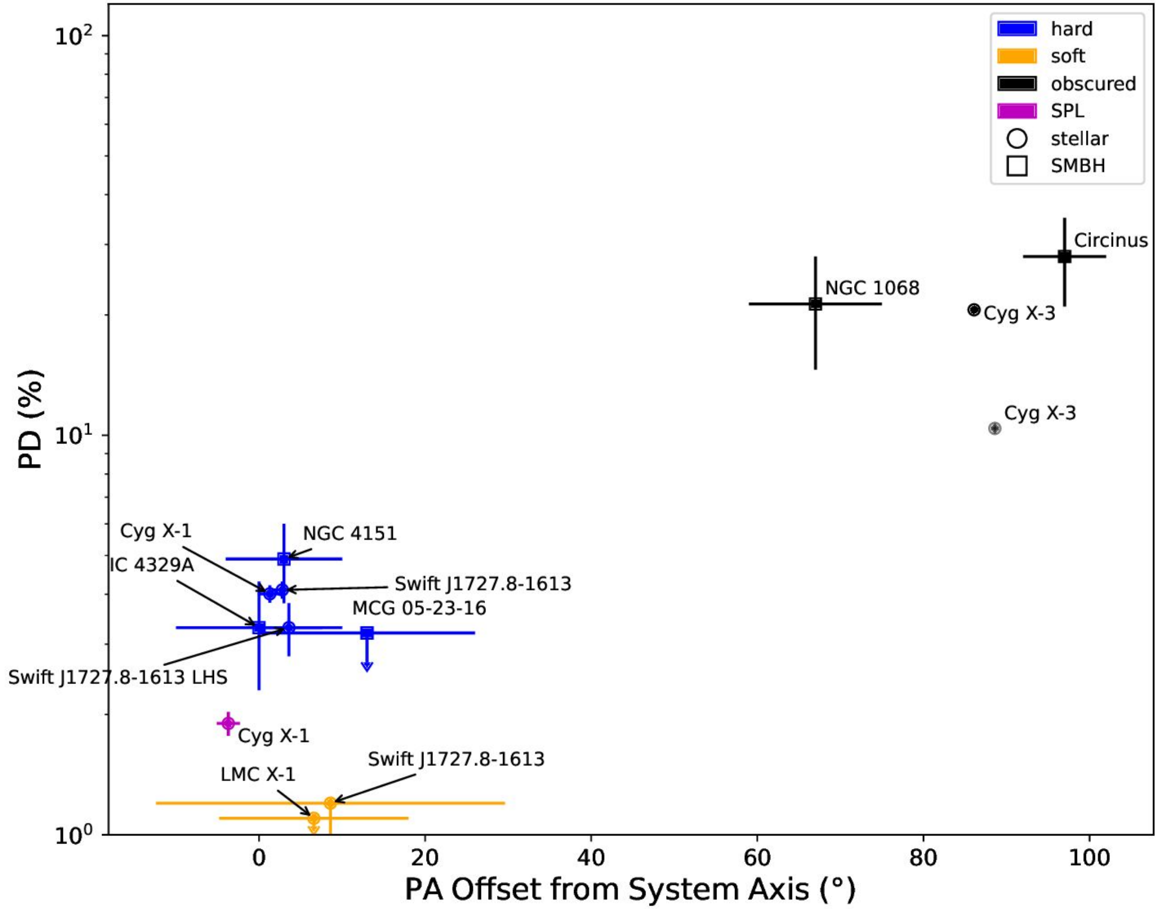
~28% roughly perpendicular to the radio jet

Ursini et al. (2022)





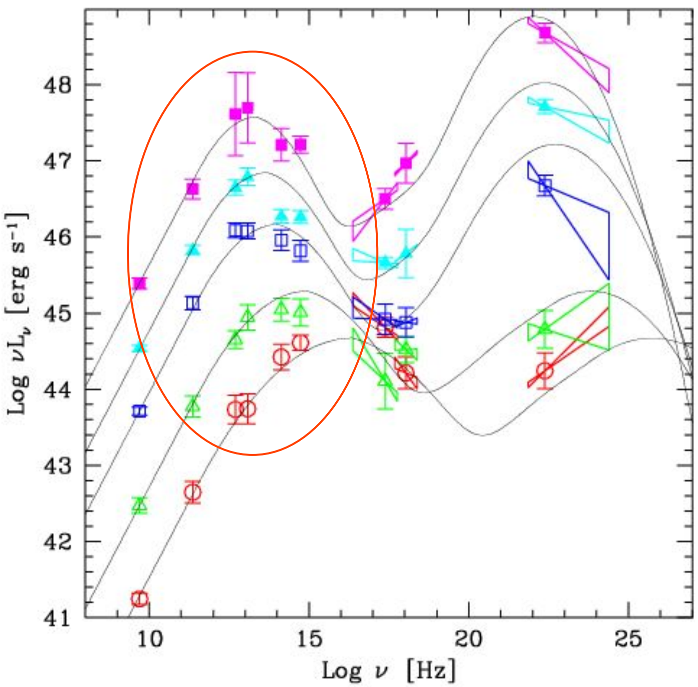
X-ray polarization properties of jet-less, radio - quiet AGN



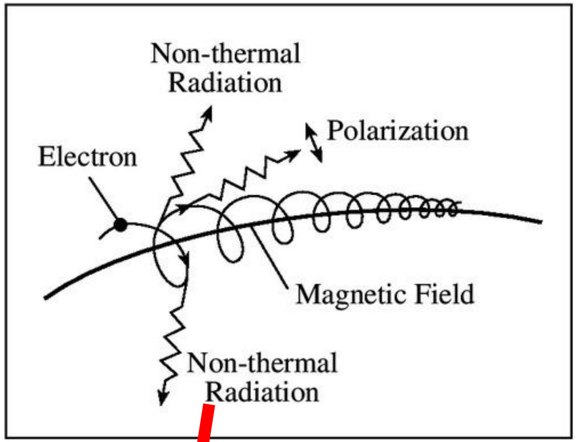
Saade et al. (2024)

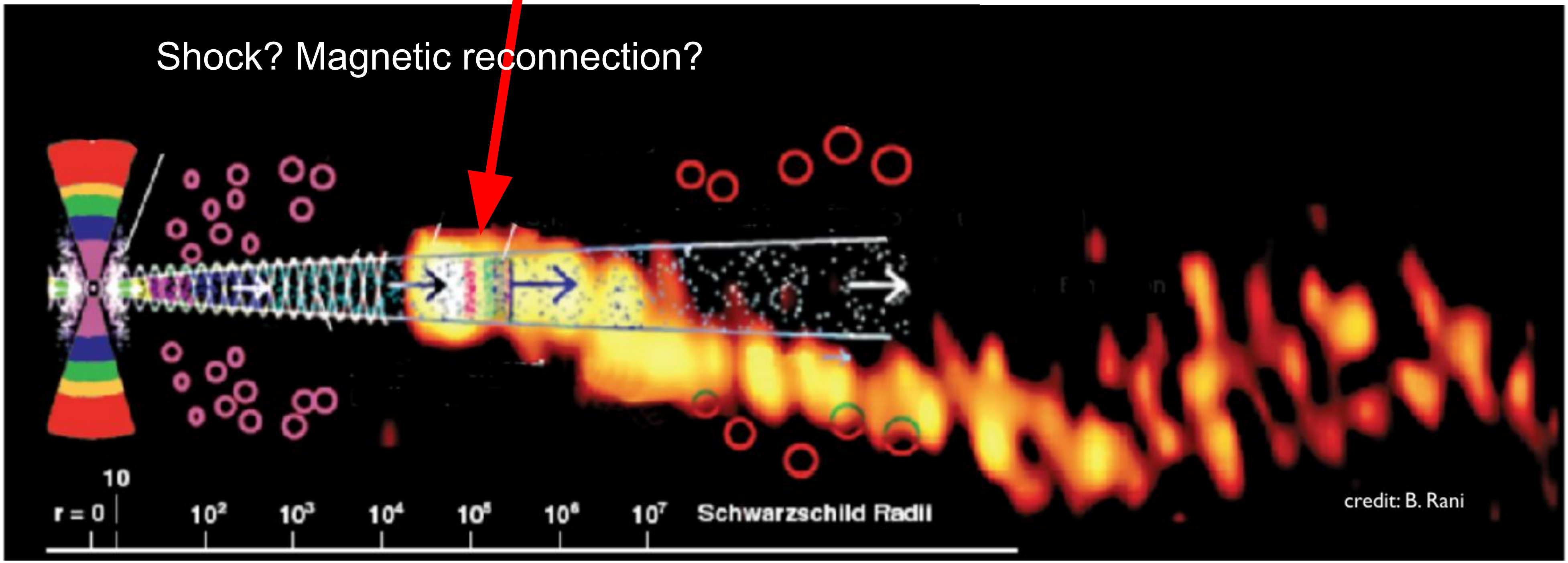
Modest polarization in Seyfert Is can be explained by electron scattering (as in Sey II)
We can rule out large scale, organized magnetic fields in accretion-dominated AGN

Back to jet-dominated AGN:
How do blazars make light?

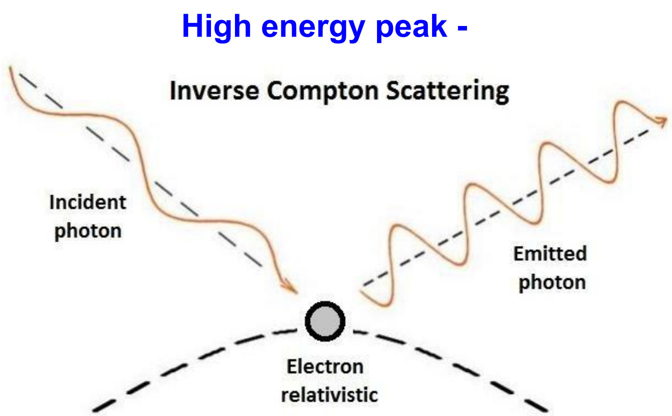


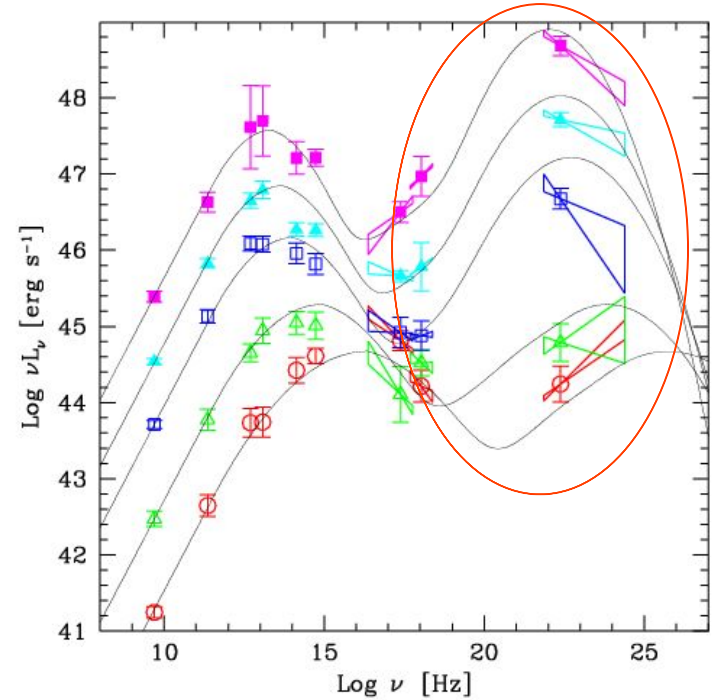
Low energy peak - synchrotron radiation

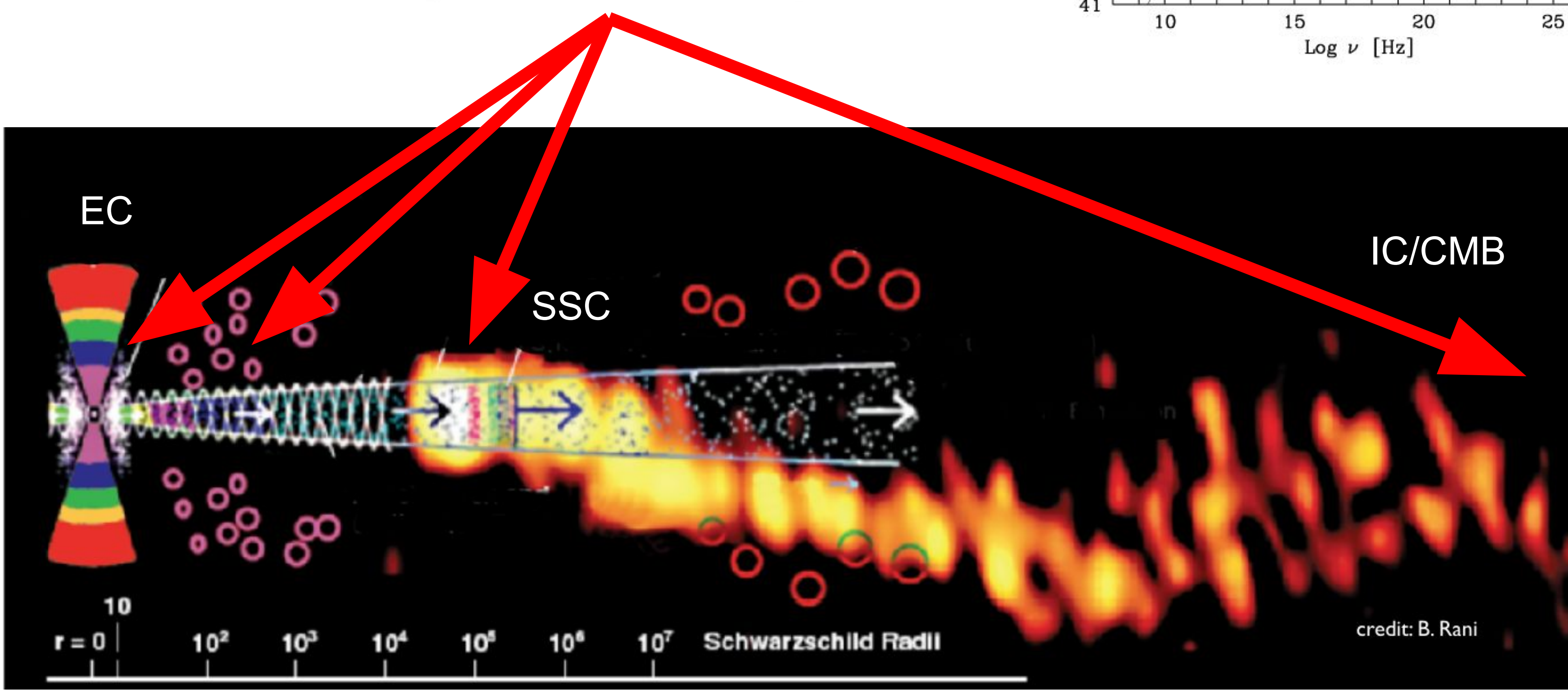




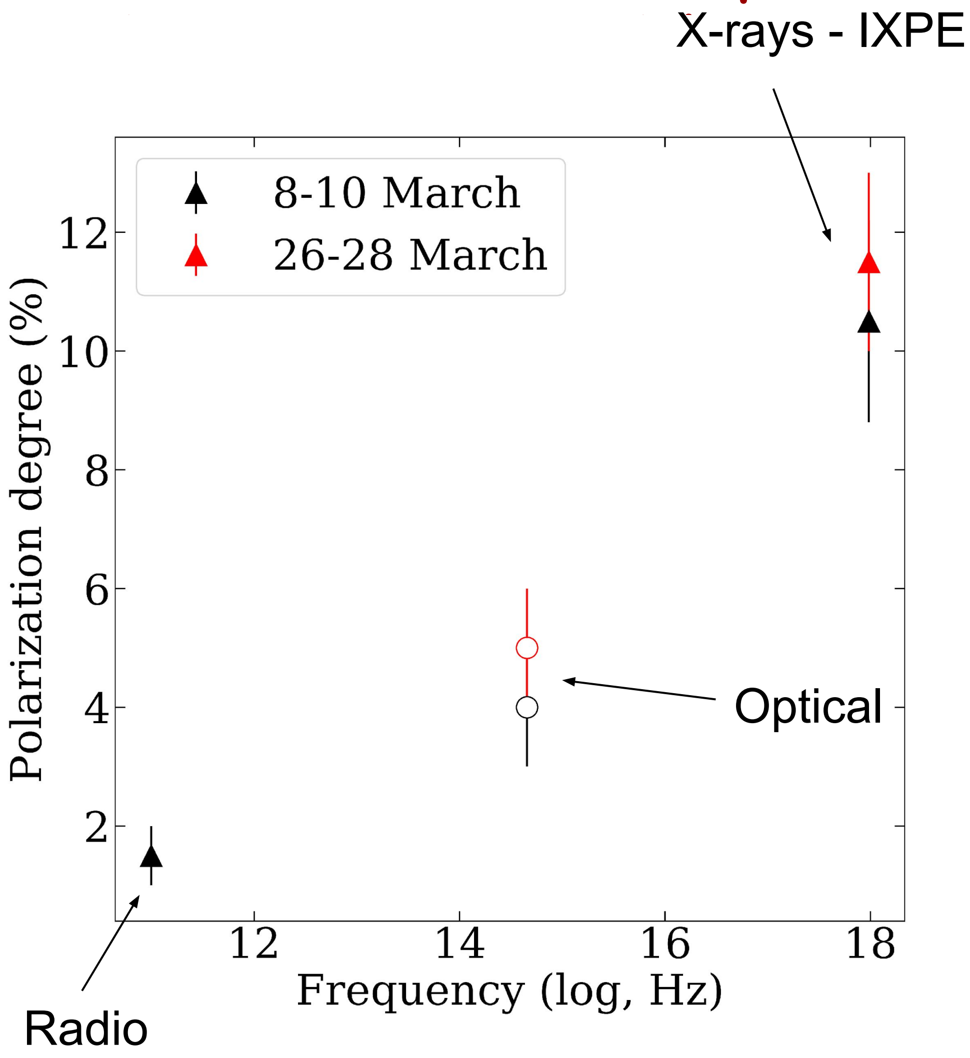
How do blazars make light?







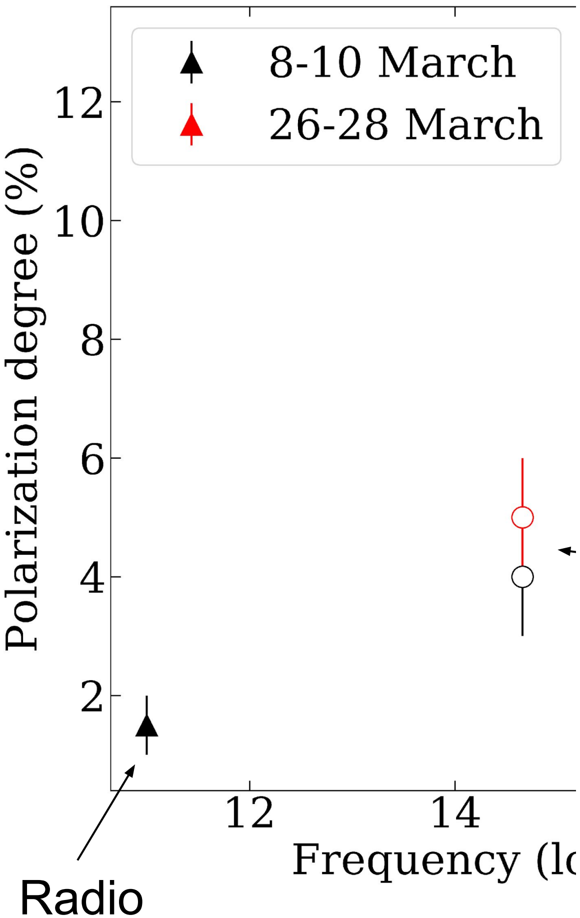
First detection of X-ray polarization from a jet powered by an accretion onto a supermassive black hole in a BL Lac

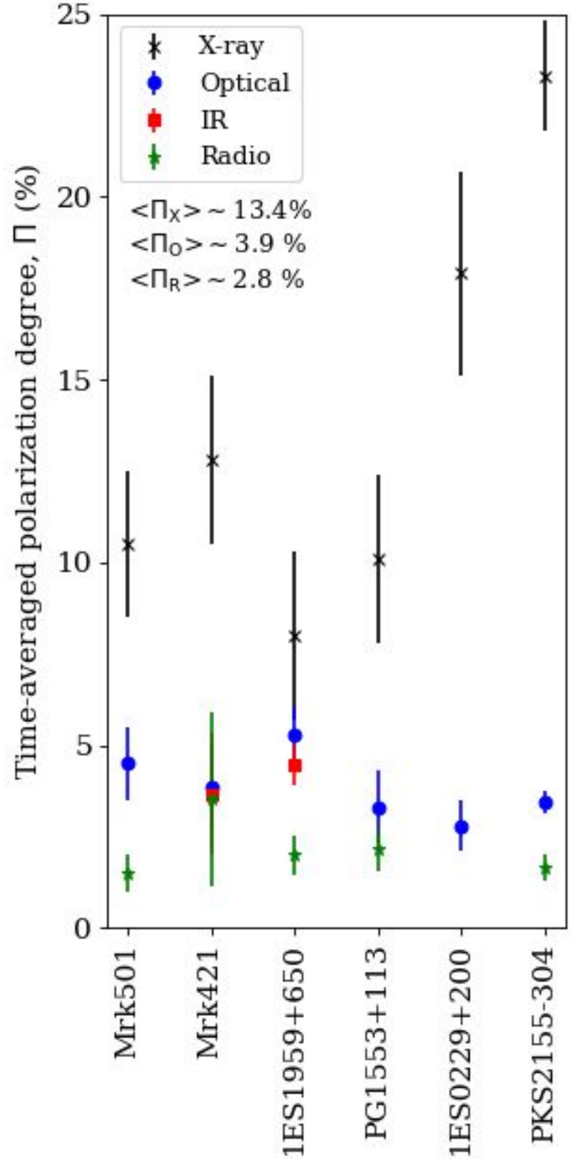


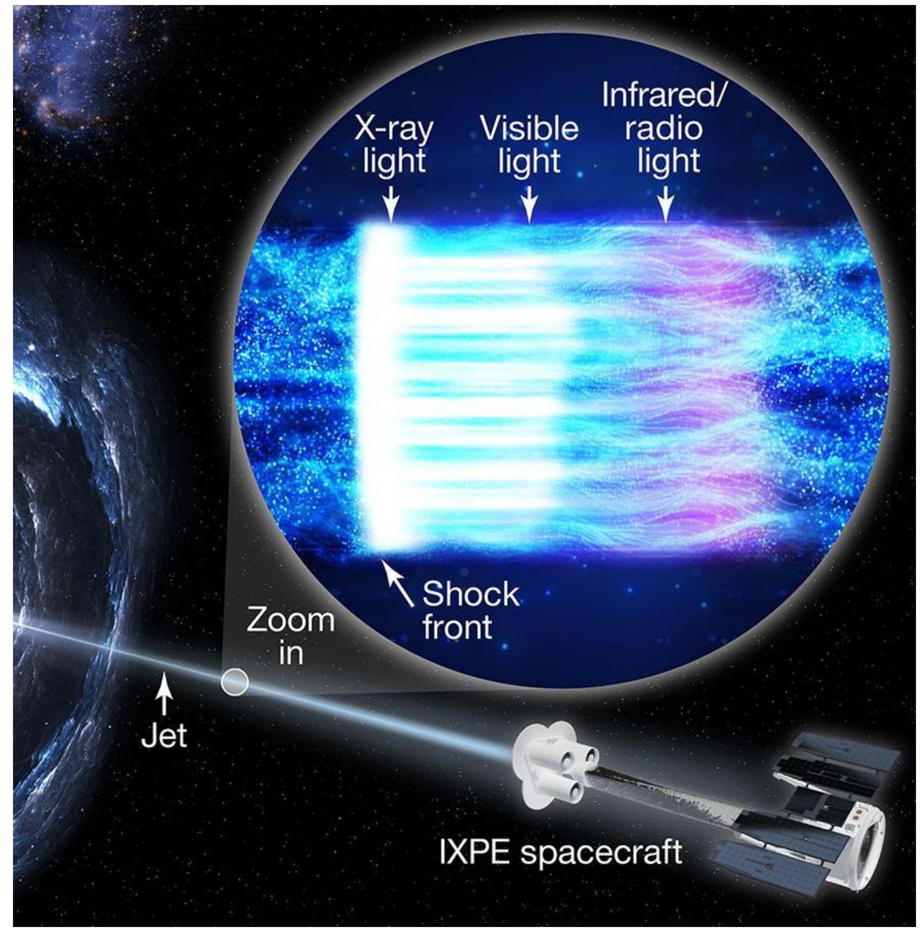
As expected for the scenario of X-rays produced by the synchrotron process!

Markarian 501 Liodakis, GM, et al., 2022

And, in many other BL Lac-type blazars!







Pablo Garcia (NASA/MSFC)

Kouch, … GM, … et al., 2024
arXiv:2406.01693

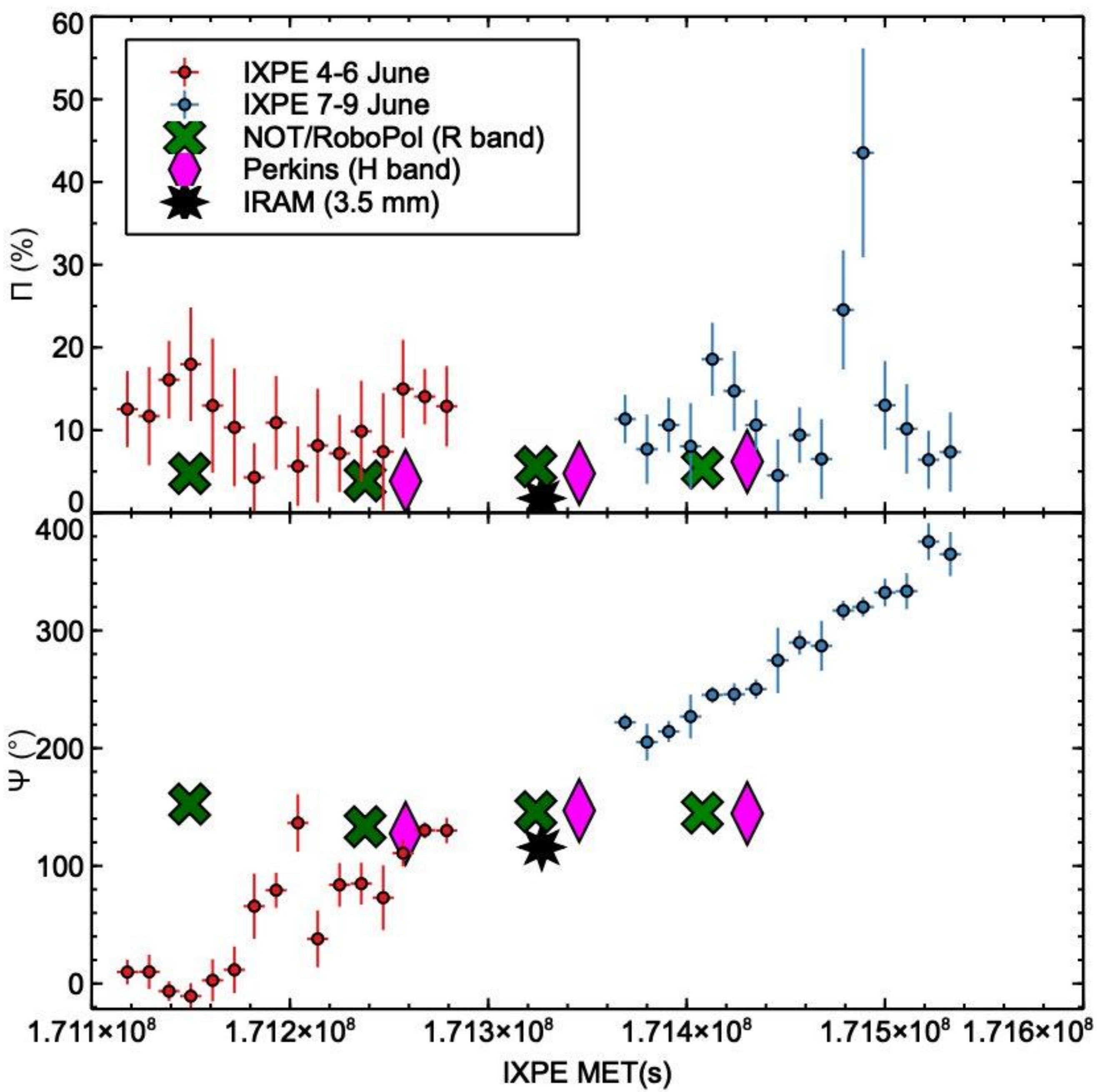
PKS 2155-304 and 1ES1959+65 were Berries favorites…

V. long observations of Mrk 421

First X-ray polarization angle rotation!

Implication: precessing jet?

Shocks moving in the jet?

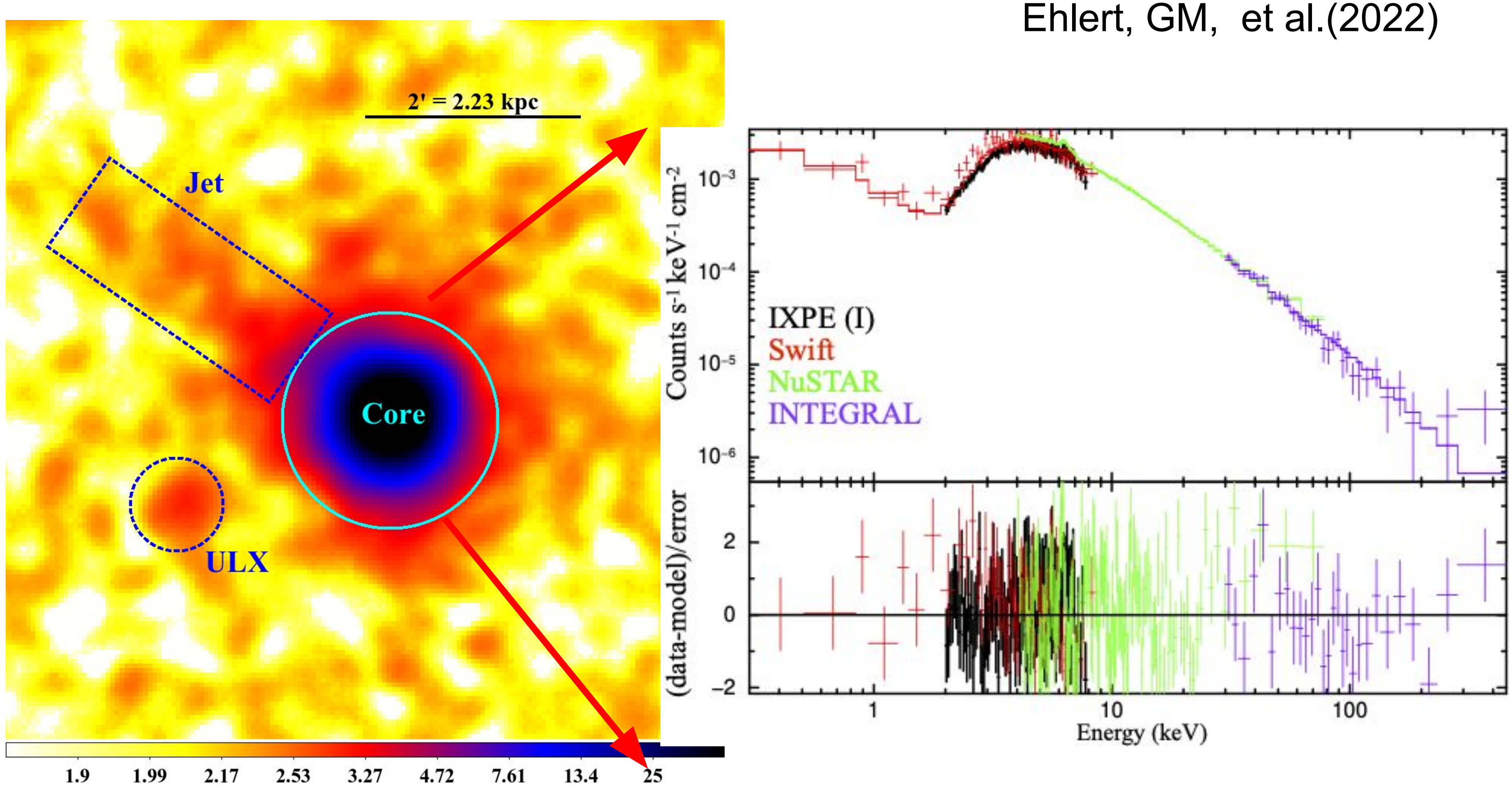


Di Gesu et al. (2023)

Nearby radio galaxy w/ a jet seen off-axis: Centaurus A

Spectral modelling suggests that X-ray originate from inverse Compton process rather than synchrotron process

Ehlert, GM, et al.(2022)

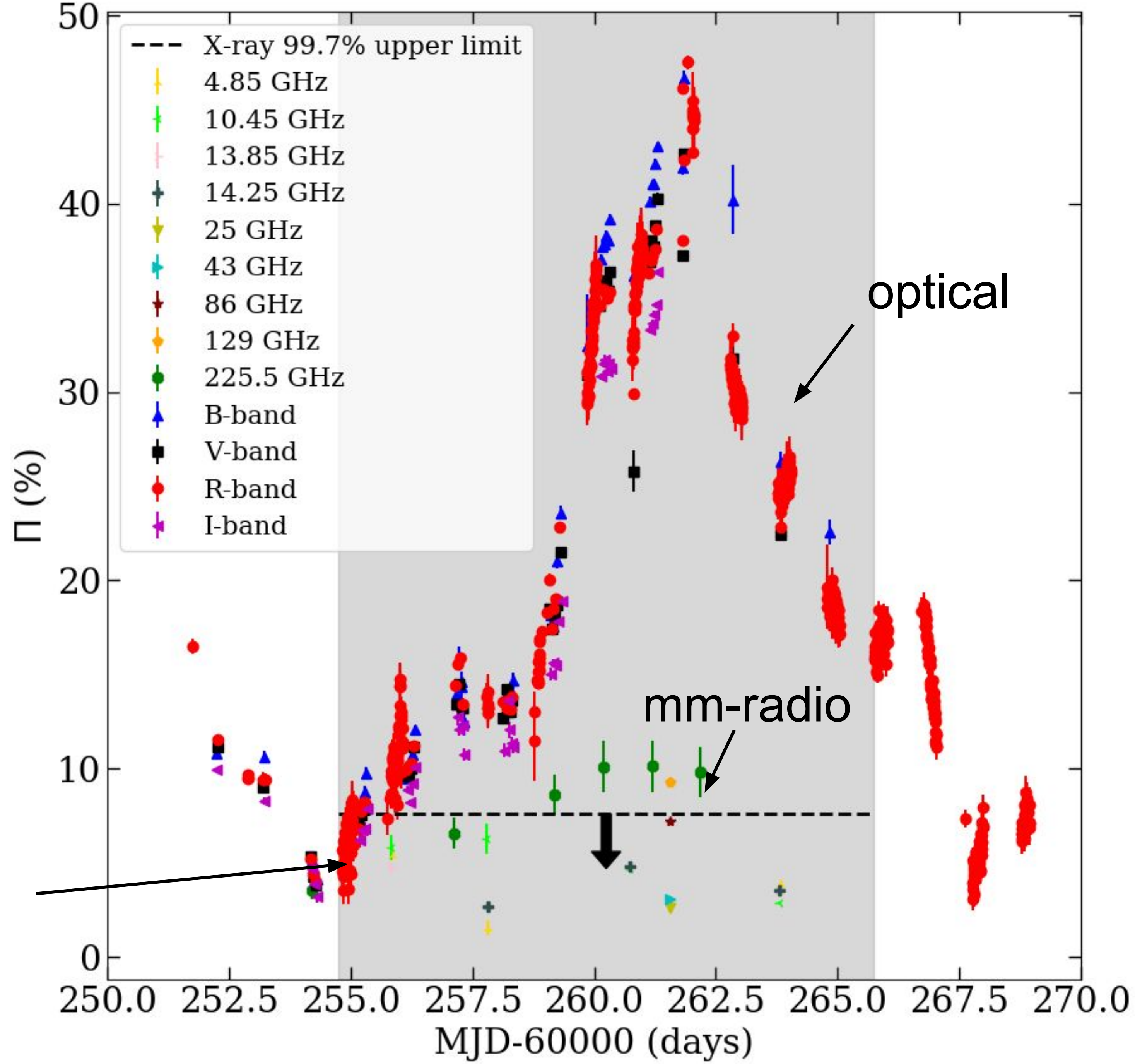


X-ray upper limit < 6.5-8% supports this!

Similar upper limits for FSRQ-type blazars

- support inverse Compton as origin of X-rays in high-luminosity blazars

BL Lac: upper limit on X-ray polarization suggests inverse Compton as the origin of X-rays



BL Lacertae is not a part of the BL Lac class?

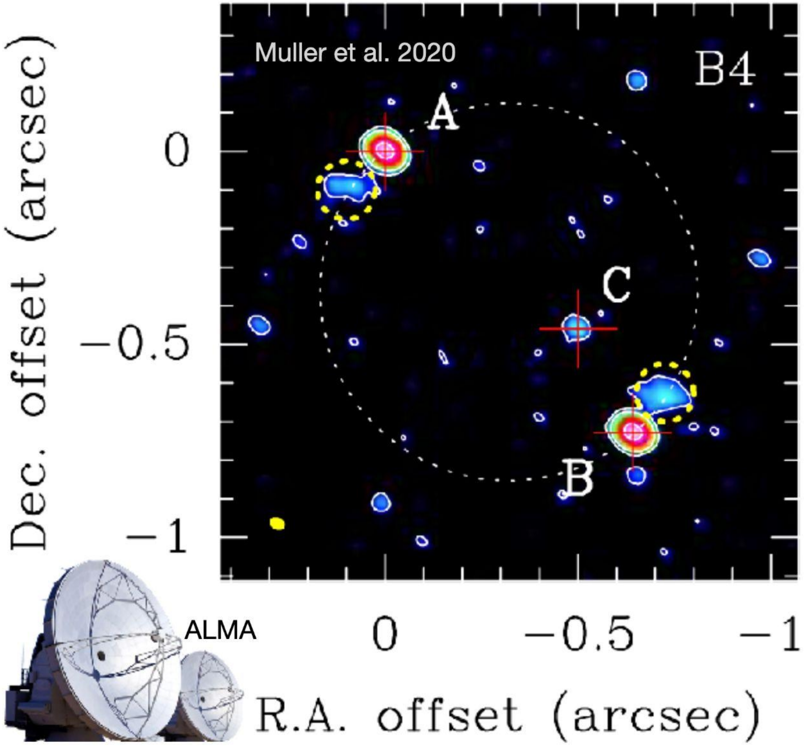
X-ray upper limit <7.4%

Agudo et al., submitted

Switching gears, back to Fermi blazars: gravitationally lensed sources!

- PhD thesis work of Sarah Wagner, PhD student at Wurzburg

- PKS 1830-211: one of two gravitationally-lensed blazars detected by Fermi
- Multiple images detected in radio, emission strongly variable
- Time - delay can be measured in radio using cross-correlation of light curves from multiple images is ~ 25 days
- Flux amplification by lensing permits excellent studies of this distant blazar!
- Generally, time-delays in general can be used to determine the Hubble constant



- FSRQ at z = 2.507 (Lidman et al. 1999)
- gravitationally lensed
  - two images (A & B) with core (red cross) and faint extension (yellow circle) separated by ~1 arcsec
  - much fainter third image (C) neglected here
- lens z = 0.88

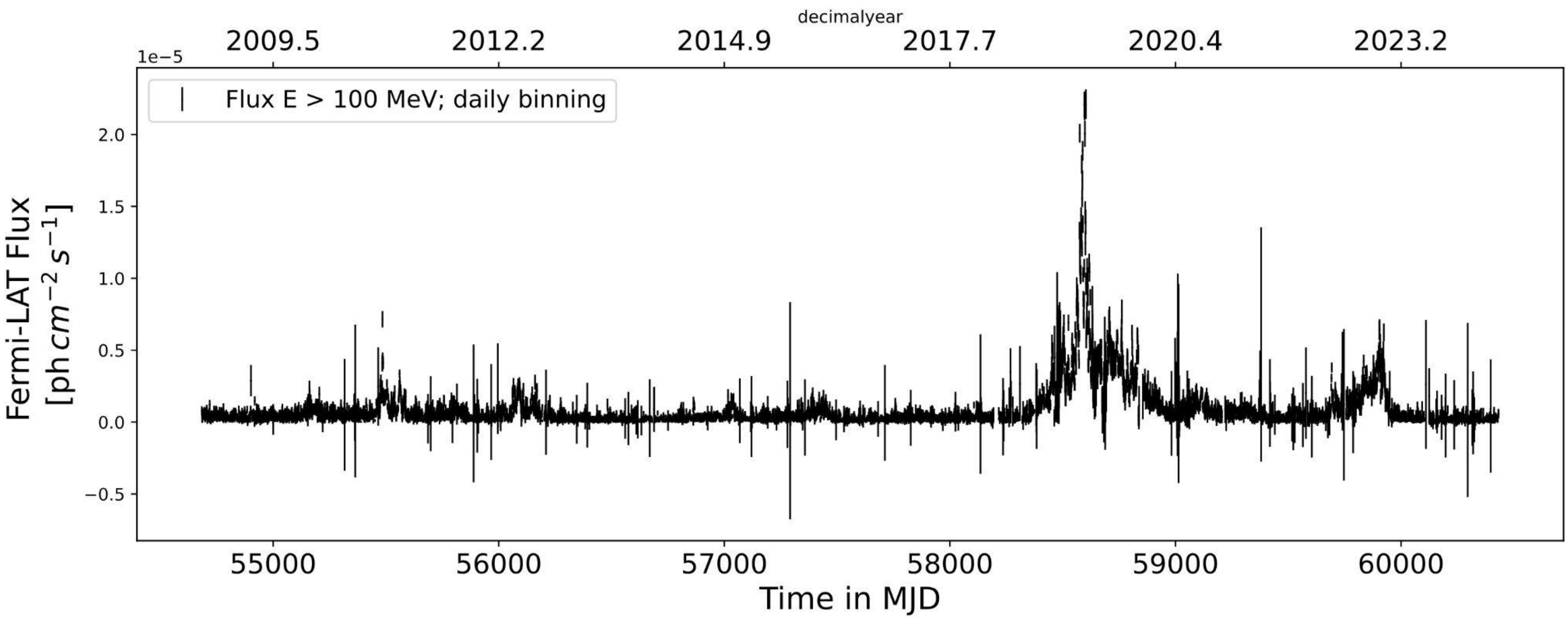
Paper posted on AstroPh: arXiv:2510.07220

Gravitationally lensed gamma-ray blazar PKS1830-211

Can we measure the time delay in the Fermi data?
Plus: excellent long-term measurements
Minus: cannot resolve the two images!
Invent an appropriate technique
If the technique works - can be applied to other data

Fermi observations:

standard, daily binned, 16 year light curve



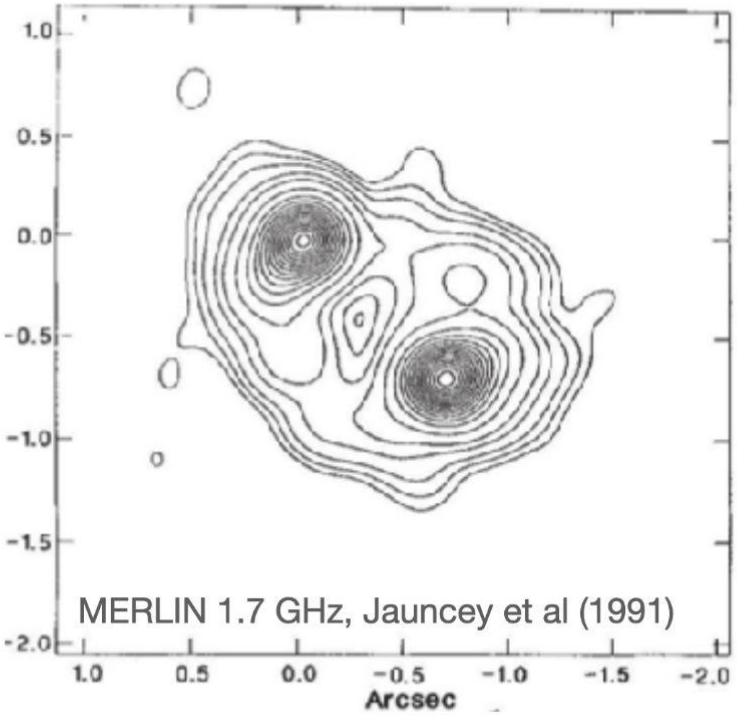
Lensed blazar PKS1830-211: what does Fermi see?

two unresolved images: $$y(t) = x(t) + a\, x(t - t_0)$$

magnification ratio and delay

= lens observables

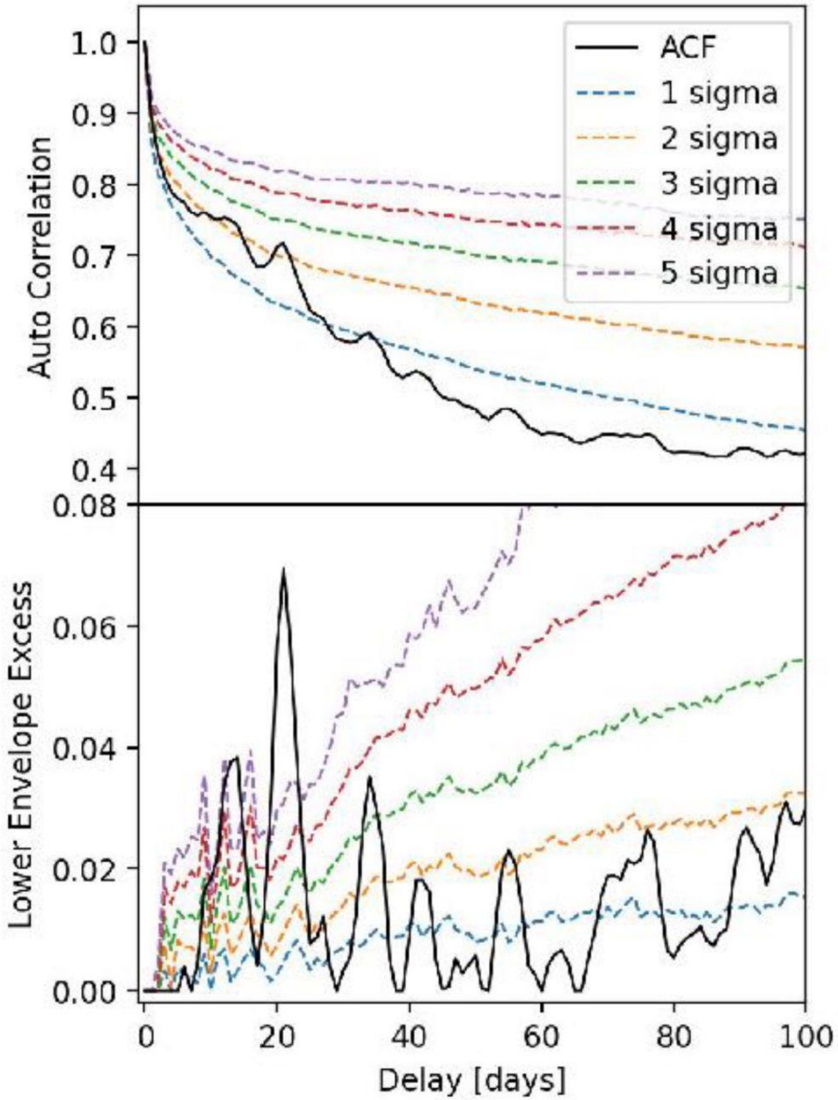
e.g. constrain jet geometry, determine Hubble constant



- When the multiple images are resolved - one can use cross-correlation techniques
- When the images are unresolved - one needs to use auto-correlation techniques

Gravitationally-lensed γ-ray emitting blazar PKS1830-211

Using auto-correlation function,
performing simulations to determine significance…



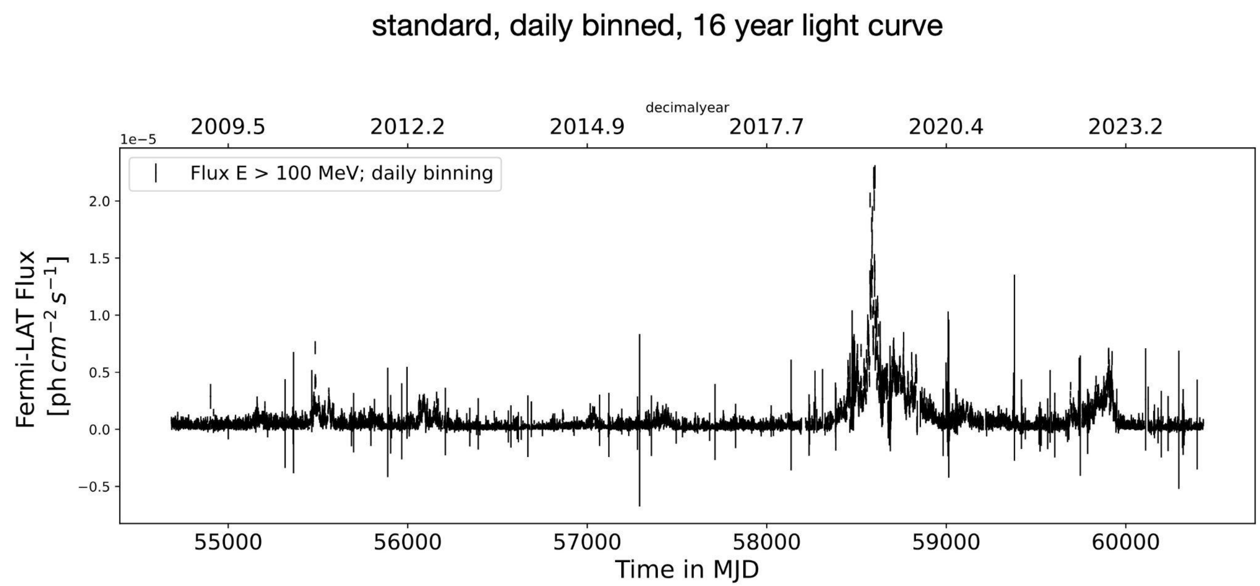
Novel method to

- asses degree of correlation on top of intrinsic noise behavior (lower envelope)
- exert magnification ratio form ACF

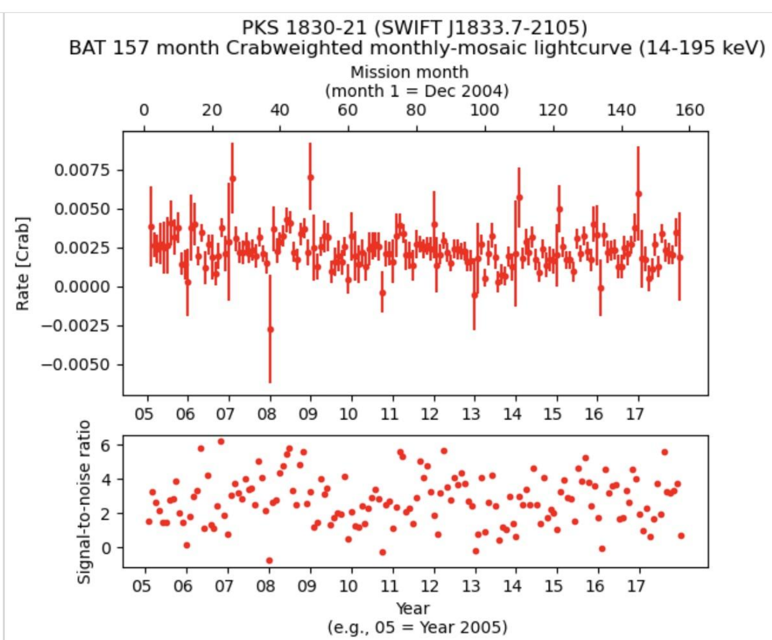
Delay: 21.1 ± 0.1 days at > 5 sigma signif.

Magn. ratio: 0.13 ± 0.01

X-ray variability is modest by comparison to the γ-ray variability



γ-ray variability



Lightcurve:

- Crab Weighted Monthly Mosaic LC
- Monthly Eight Band LC
- Eight Band Snapshot LC

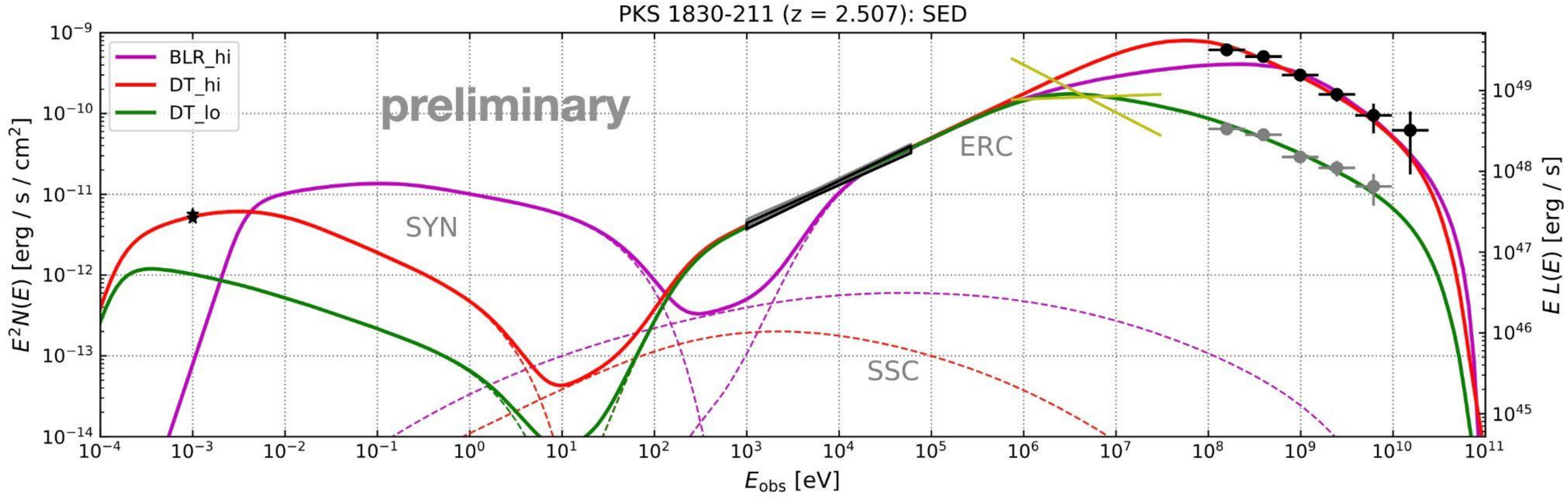
Crab Weighted Monthly Mosaic Lightcurve for SWIFT J1833.7-2105

X-ray variability

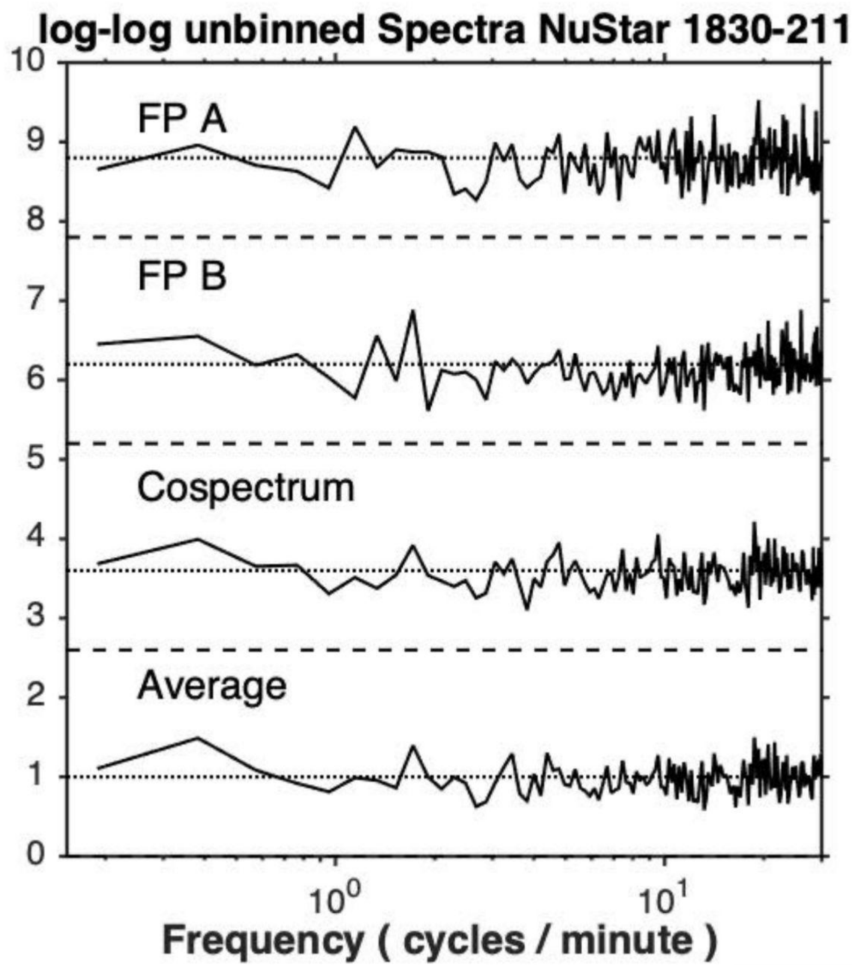
Modelling of the broad-band spectrum and variability of PKS 1830-211

- Rough analysis of the system (lens modelling, implies total flux magnification of ~ x10
- Modelling of two observations at very different gamma-ray states
- X-rays appear steady while γ-rays vary massively

- significant SSC contribution is incompatible with differing amplitudes
- focus on single ERC component (typical for FSRQ) with two distance scales:
  - r_BLR (magenta): cannot reproduce soft x-ray and gamma-rays
  - r_DT_hi (red): fits the high state data well
  - r_DT_lo (green): fits the low state data well (lower break in el distribution)



X-ray variability of active galactic nuclei: using a novel technique developed by Jeff Scargle



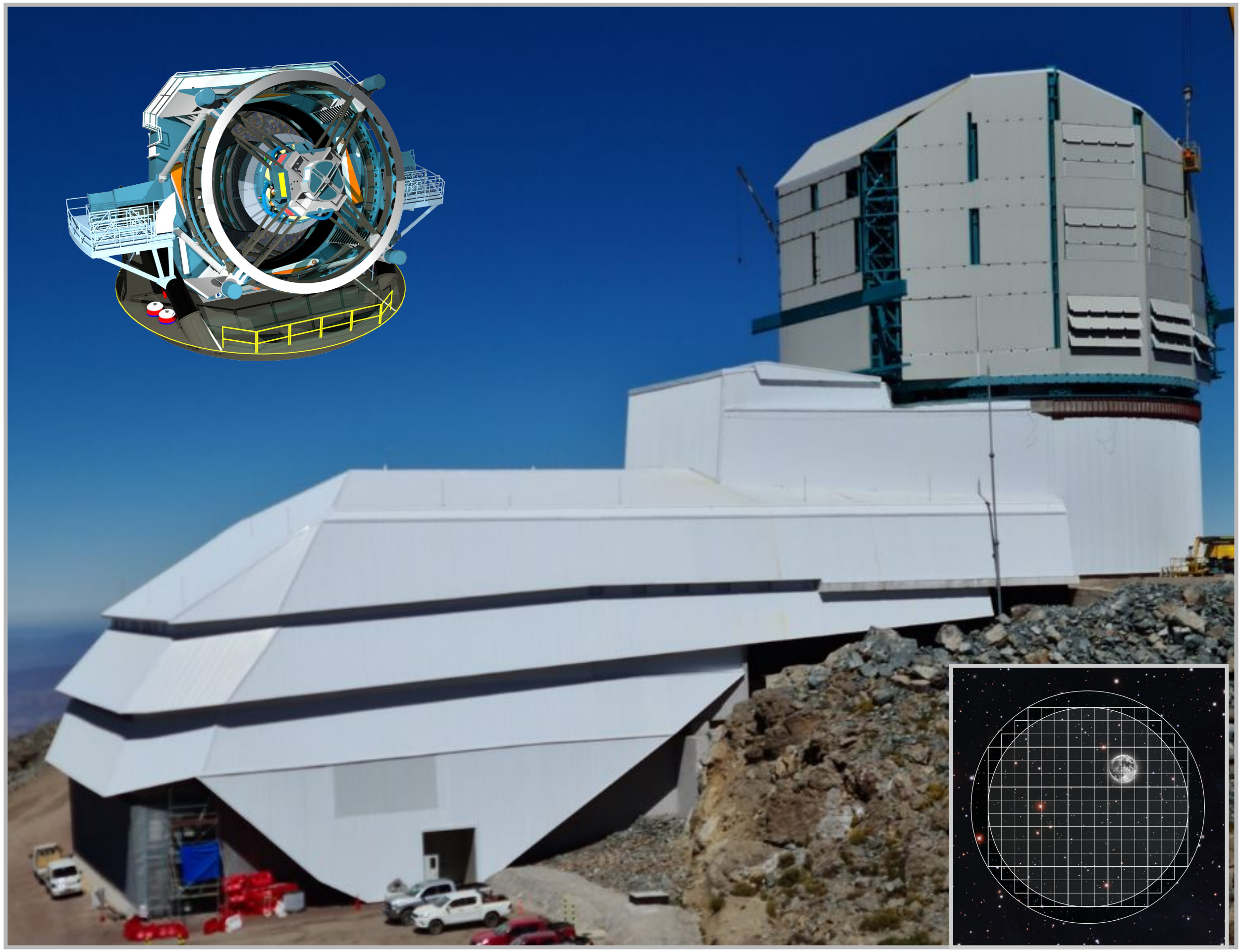
New method:

- un-binned, time-tagged photon spectrum
- co-spectrum is possible for two independent detectors (eg FPMA and FPMB in NuSTAR)
- intra-observation time (circa 10h) variability

very close to white noise —> no short term variability in NuSTAR data

Similar results for other blazars: do we see the timescale when variability disappears? Not certain yet - work in progress using the time-tagged photon data

The Vera C. Rubin Observatory

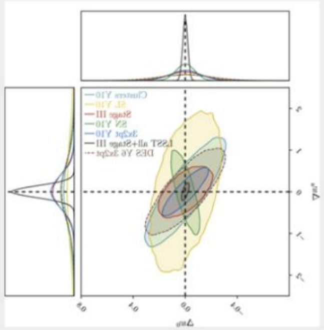
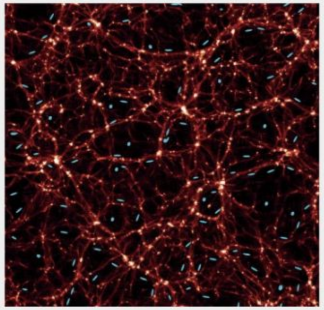


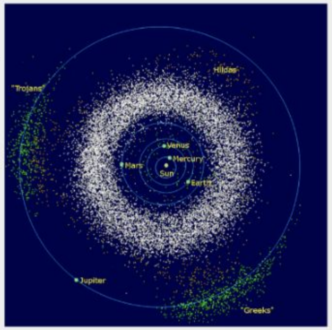
- The Vera C. Rubin Observatory is located on Cerro Pachón in Chile
- The Simonyi Survey Telescope's primary mirror has an 8.4 meter diameter
- Its camera features an 9.6 deg^2 field-of-view and six optical-NIR filters: *ugrizy*
- Very wide-field optical telescope: designed for surveys rather than single-source studies

Rubin Observatory/LSST "Science Pillars"

FOUR MAIN SCIENCE GOALS:

Probing dark energy and dark matter:
Weak and strong lensing
Baryon acoustic oscillations
Supernovae and quasars
Large scale structure

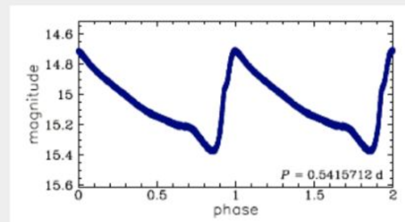



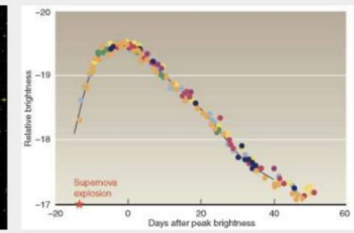
Taking an inventory of the solar system:
Near Earth objects. Potentially hazardous asteroids. Census of comets. Orbits of Trojan asteroids and Trans-Neptunian objects. Interstellar comets/asteroids.

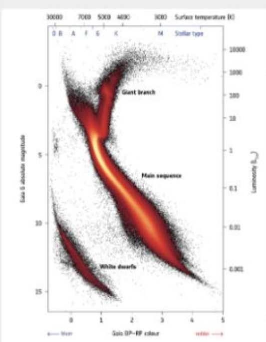
Rubin Observatory/LSST "Science Pillars"

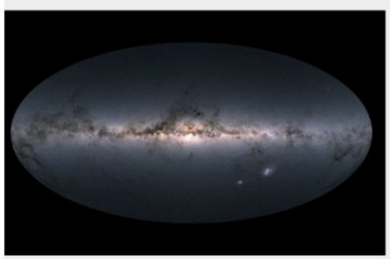
FOUR MAIN SCIENCE GOALS:

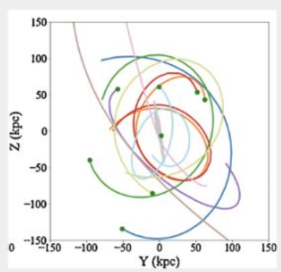
Exploring the transient optical sky:
Supernovae
Variable stars
Transiting exoplanets
Gravitational microlensing
AGNs and tidal disruption events





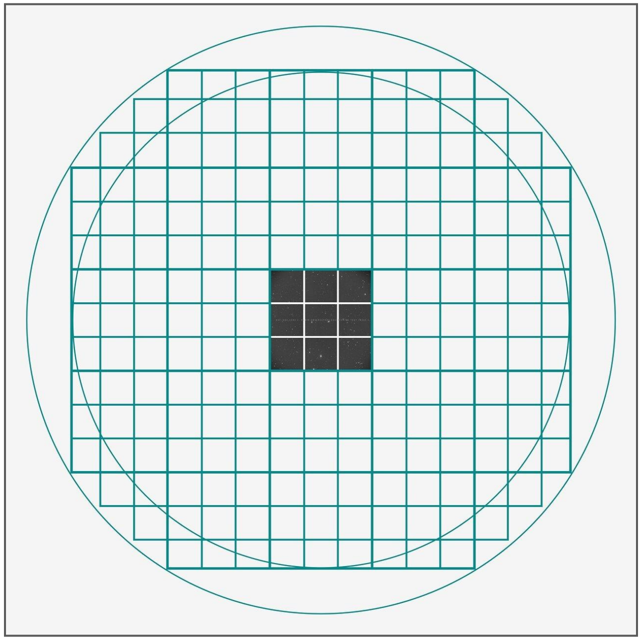






Mapping the Milky Way:
Structure and evolution of the bulge, disk, and halo. Census of dwarf galaxy satellites and tidal streams. Stellar evolution. Three-dimensional dust map. Hypervelocity stars.

First Rubin data were obtained with LSSTComCam



LSSTComCam
Commissioning Camera

A single "raft" of 9 CCDs.
(CCD = sensor = chip)

Oct 10 - Dec 11 2024:

- ~2 months
- 7 fields
- 6 filters

Not continuous observing but still substantial.

ComCam goals to commissiong of the telescope were successful.

THE FULL LSST CAMERA WAS INSTALLED IN THE RUBIN OBSERVATORY EARLIER IN 2025

LSSTComCam observations included in DP1

NES: north ecliptic spur

SCP: south celestial pole

WFD: wide fast deep

GP: galactic plane

MC: magellanic clouds

FOV: field of view

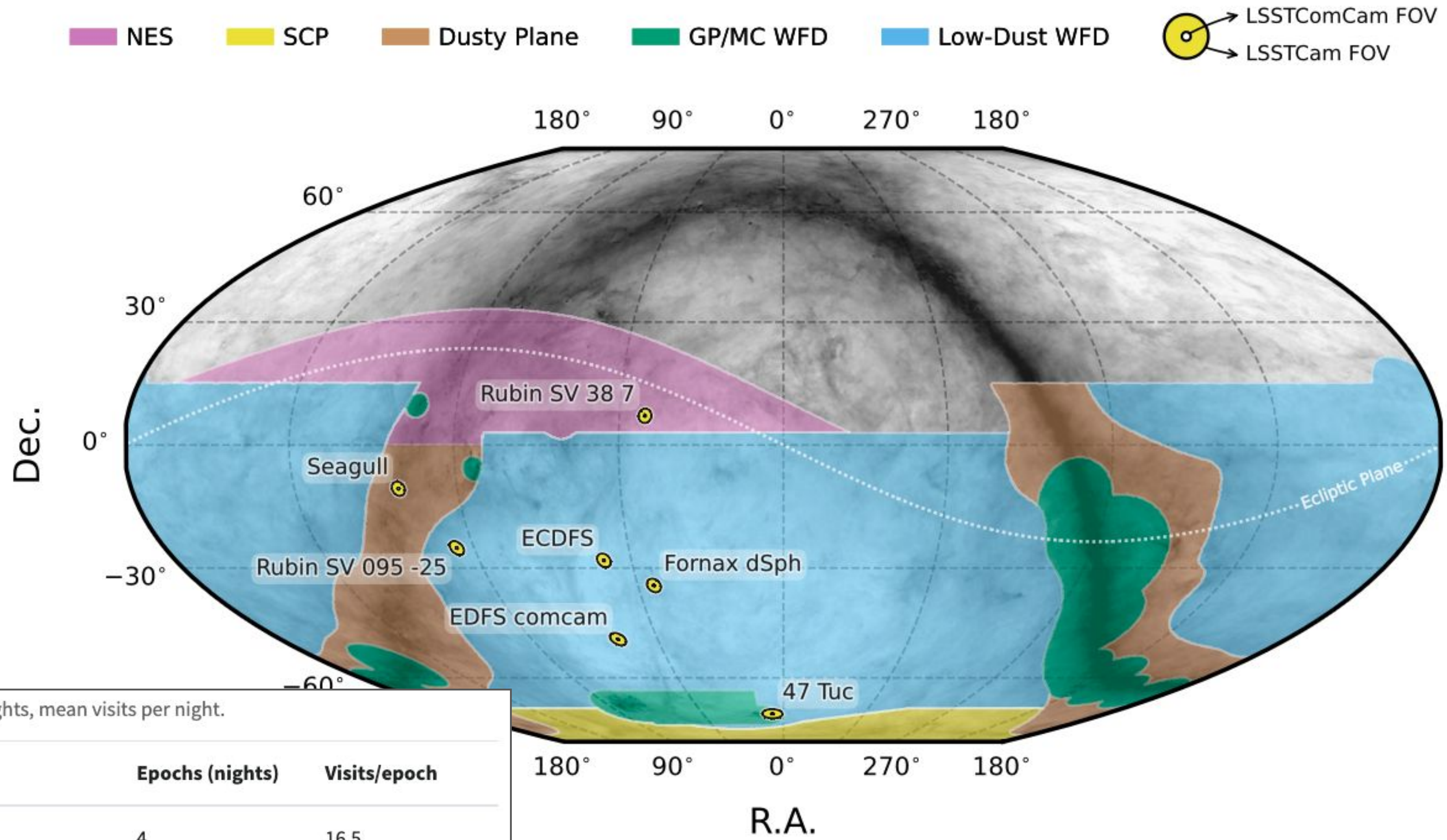
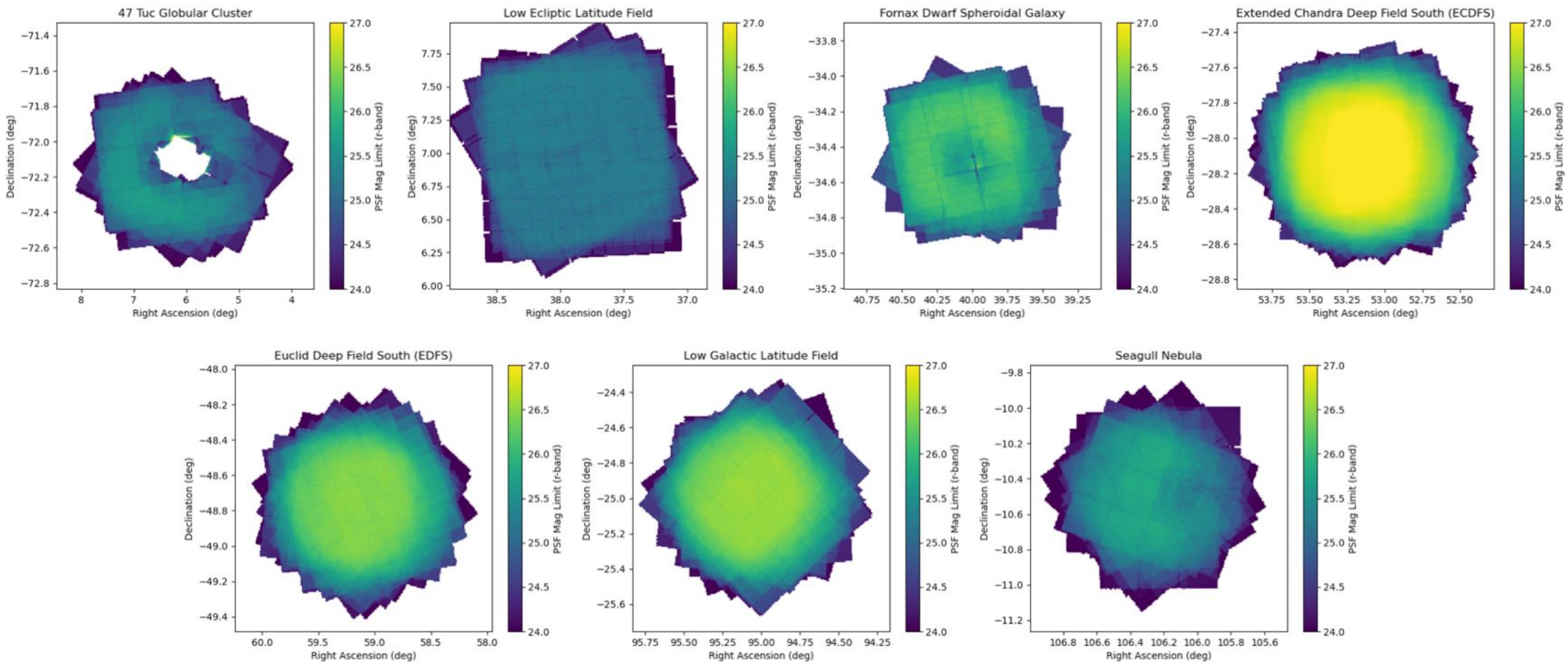


Table 3: Number of nights, mean visits per night.

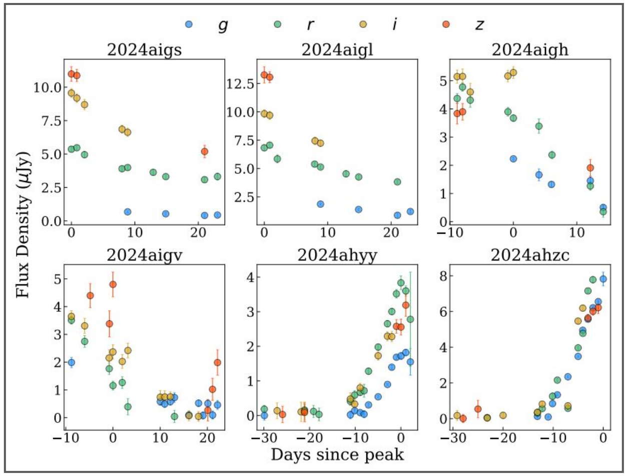
Field name	Epochs (nights)	Visits/epoch
47 Tuc Globular Cluster	4	16.5
Low Ecliptic Latitude Field	5	31.8
Fornax Dwarf Spheroidal Galaxy	2	21.0
Extended Chandra Deep Field South (ECDFS)	21	40.7
Euclid Deep Field South (EDFS)	9	30.2
Low Galactic Latitude Field	10	29.2
Seagull Nebula	4	25.0

LSSTComCam observations included in DP1

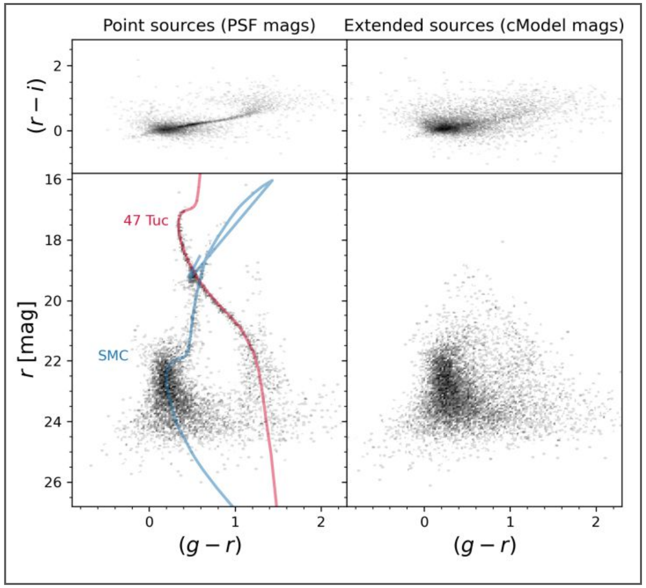


Maps of coadded depth in r-band

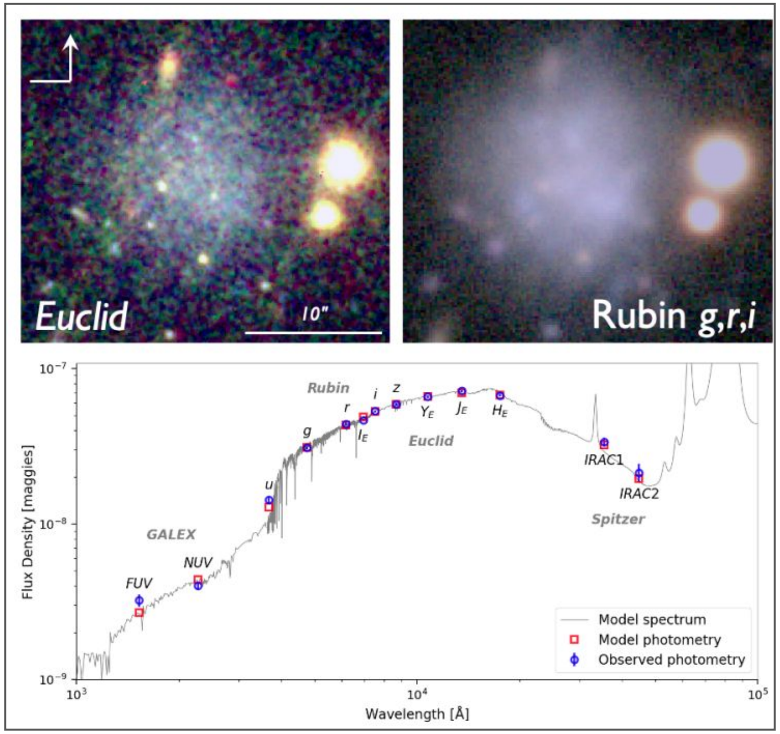
First results from Data Preview 1 from Rubin Observatory



Extragalactic transients in DP1.
Freeburn et al. 2025



Stellar isochrones for 47 Tuc.
Choi et al. 2025



Ultra-diffuse galaxy in Euclid+Rubin.
Romanowsky et al. 2025

Three example figures from the earliest DP1-based papers

A small preview of images from the Rubin LSST camera "full size", on the telescope now

This image is called the Cosmic Treasure Chest, focused on the southern region of the Virgo Cluster
The full image is about 25 square degrees

Rubin images of Southern part of the Virgo cluster, expanded

The most prominent feature is NGC 4261, the large elliptical galaxy in the top half of the image. In the bottom-left of the image is the lenticular galaxy NGC 4281.