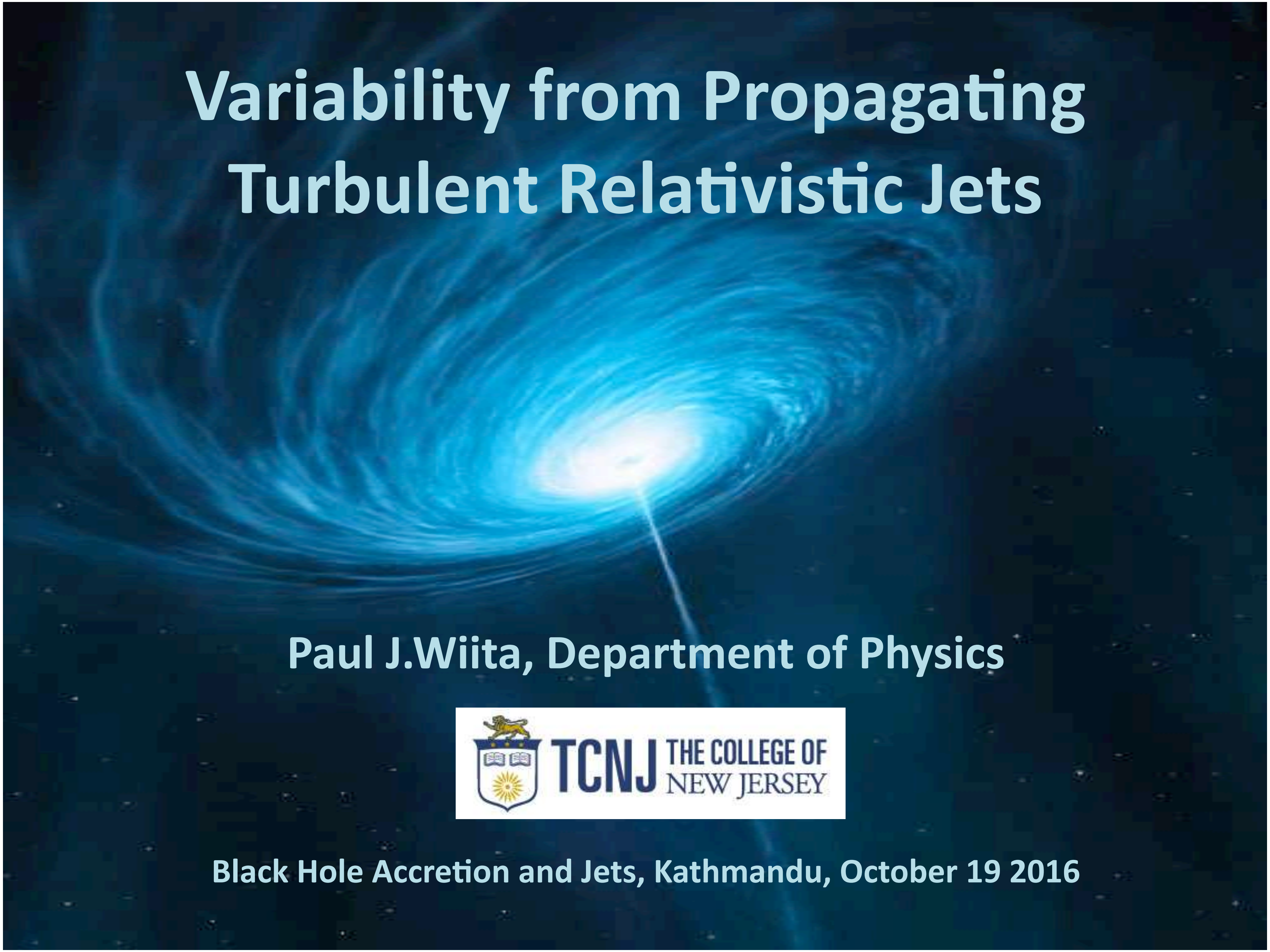

Variability from Propagating Turbulent Relativistic Jets

Paul J.Wiita, Department of Physics

TCNJ THE COLLEGE OF NEW JERSEY

Black Hole Accretion and Jets, Kathmandu, October 19 2016

Outline

- Quick Review of Some Properties of Blazars
- Light Curves from the Kepler Satellite
- Models of Variability: Turbulence and Bulk Changes

Main Collaborators in these projects:

Ann Wehrle (Space Science Institute), Stephen Unwin (NASA/Jet Propulsion Lab), Michael Carini (Western Kentucky U.)

Mitchell Revalski (Georgia State), Victoria Calafut (Cornell), Maxwell Pollack (Wisconsin), Paolo DiLorenzo (UNM), David Pauls, Dawid Nowak, Daniel Silano, Daniel Sprague (UNC): all were/are TCNJ students

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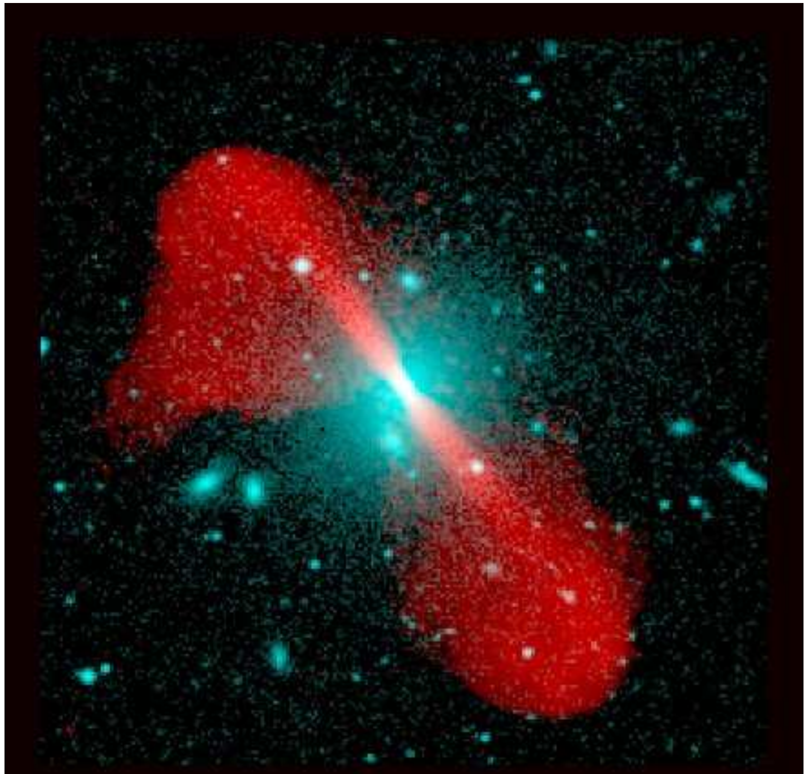
RADIO GALAXIES

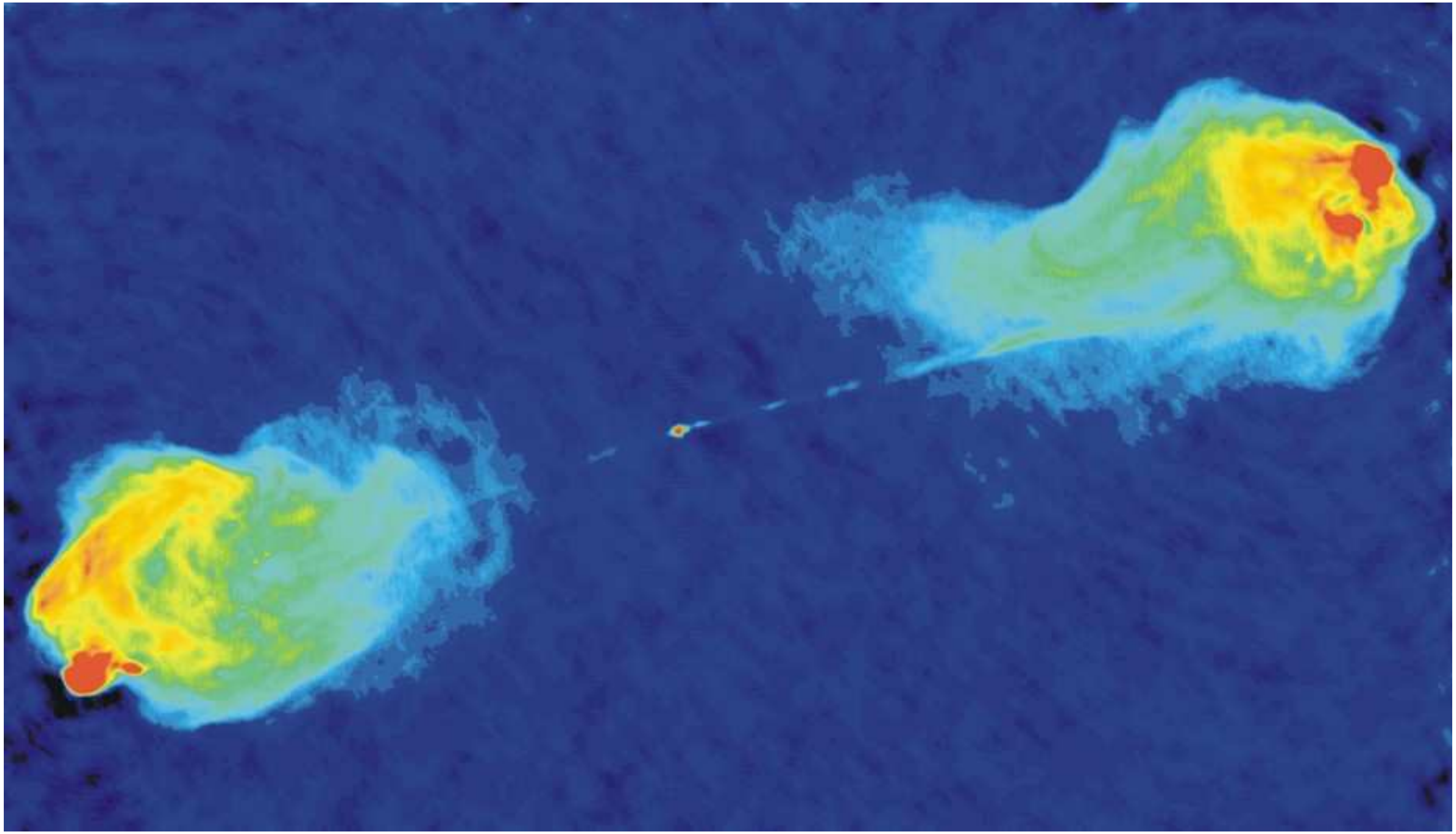
Biggest Connected Objects in the Universe

- Sizes: up to Mpc
- Powers: up to ~10^{46}erg/s
- Lifetimes: up to ~10^{8} yr
- Relativistic jets carry very hot plasma over huge distances
- ~10% of Quasars are also RGs



Radio Galaxy 3C296
Radio/optical superposition

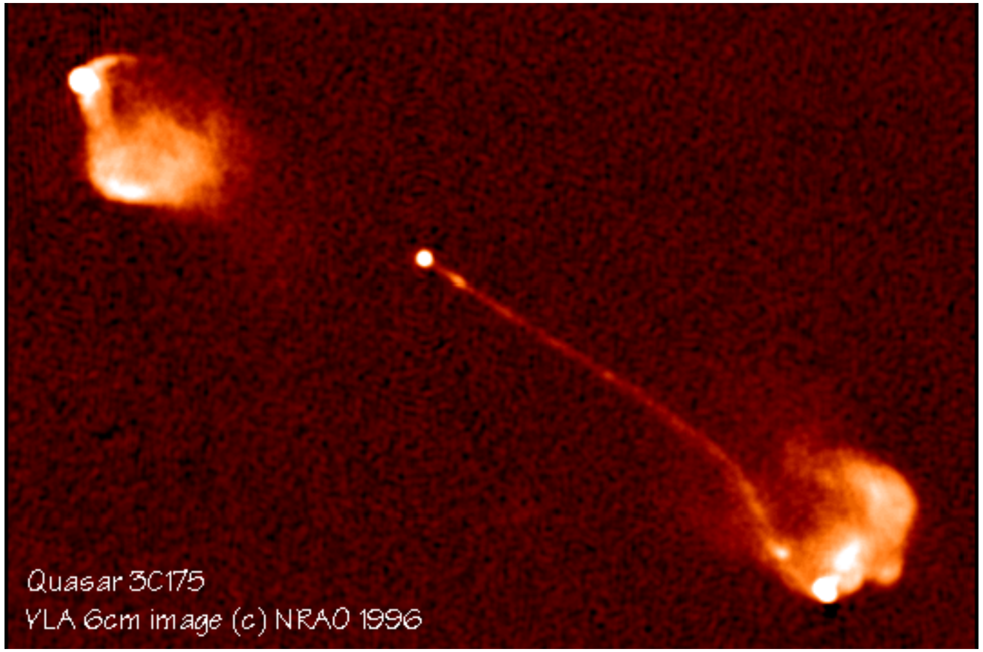
Canonical Powerful RG: Cygnus A



Powerful RGs: most emission from lobes at outer parts at ends of stable jets

Radio Loud Quasar: 3C 175

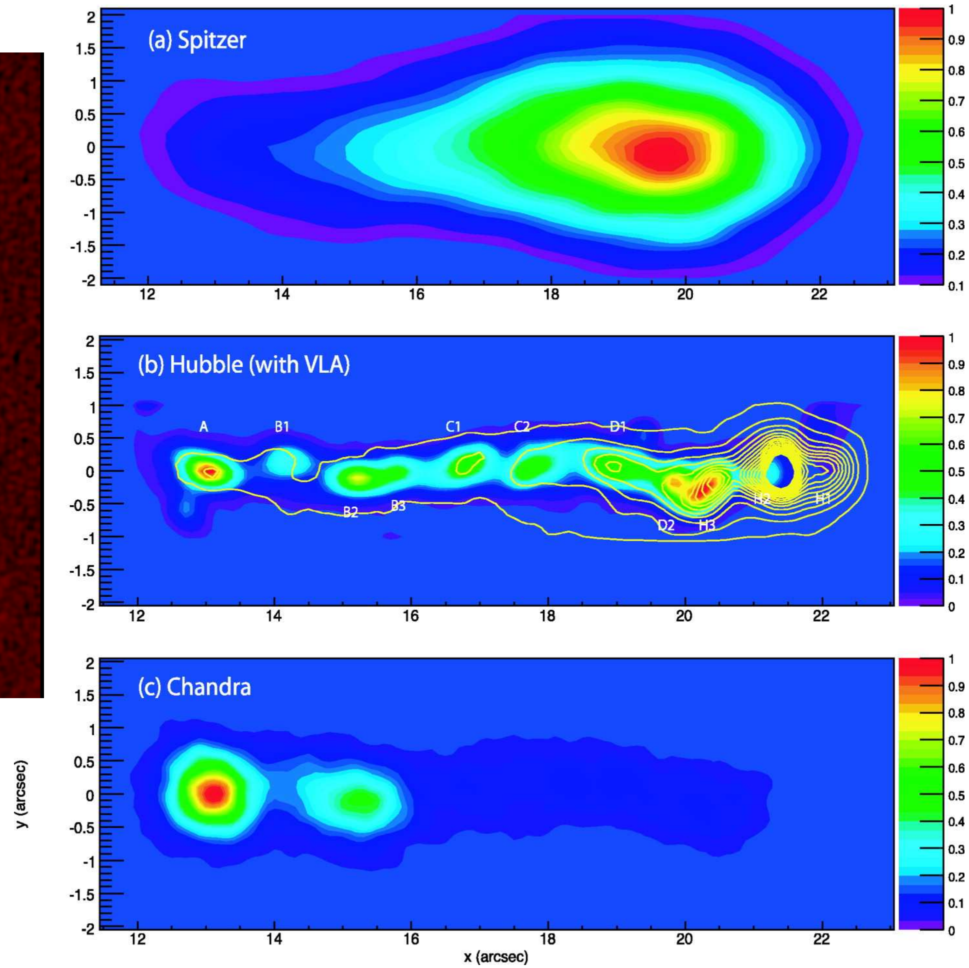
Only 1 jet seen; core relatively more prominent than in RGs



Jet of Quasar 3C 273

(Uchiyama et al. 2006)

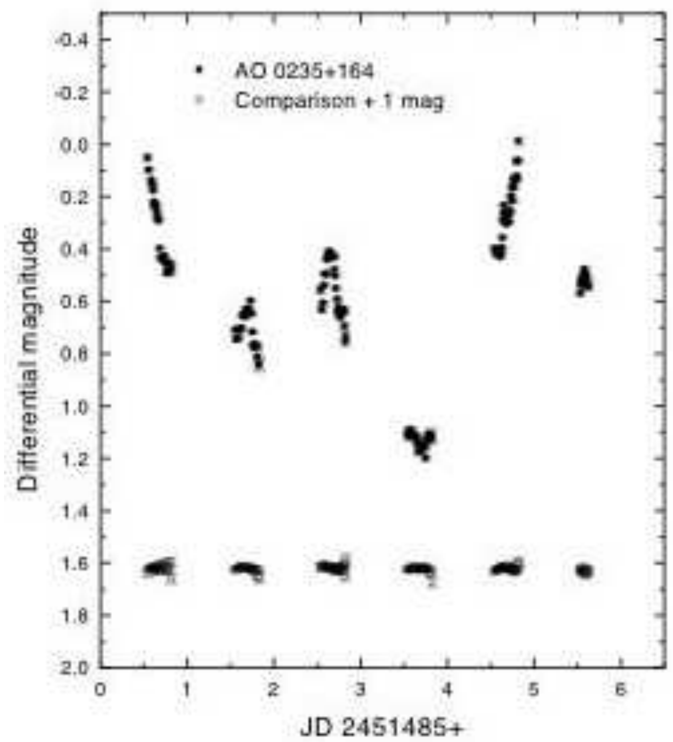
in IR, radio + optical & X-ray



BL Lacertae Objects and Blazars

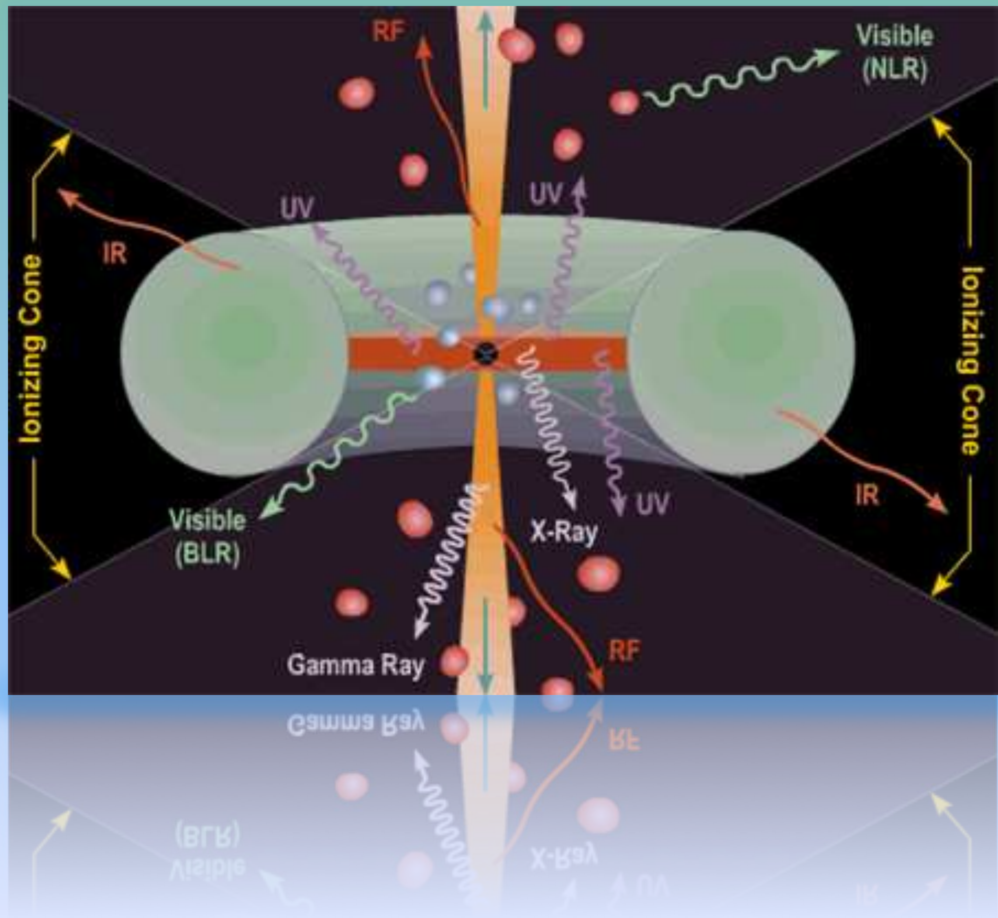
- NON-THERMAL SPECTRUM: Radio through X-ray (and gamma-ray)
- Radiation strongly POLARIZED
- HIGHLY VARIABLE in ALL BANDS

- But (when discovered) very weak emission lines, so no measured redshifts, so distances unknown
- Later, surrounding elliptical galaxies found
- CONCLUSION: greatly enhanced emission from the AGN due to RELATIVISTIC BOOSTING of a JET pointing very close to us.
- **BL Lacs + OPTICALLY VIOLENTLY VARIABLE QUASARS (or FLAT SPECTRUM RADIO QUASARS) are usually clubbed together as BLAZARS**



The Central Engine

- Even for regular quasars, variability time scales of ~1 yr → sizes < 1 pc
- Total powers up to 10^{48} erg/s → high efficiency
- Hence accretion onto SMBH only viable mechanism
- Accretion disk and corona yield continuum
- Gas clouds ionized by continuum produce broad and narrow line regions
- A fraction eject relativistic jets emitting synchrotron continuum
- Doppler boosting explain rapid variability
- Also explains superluminal VLBI knots



Our Observations of Blazars and Quasars

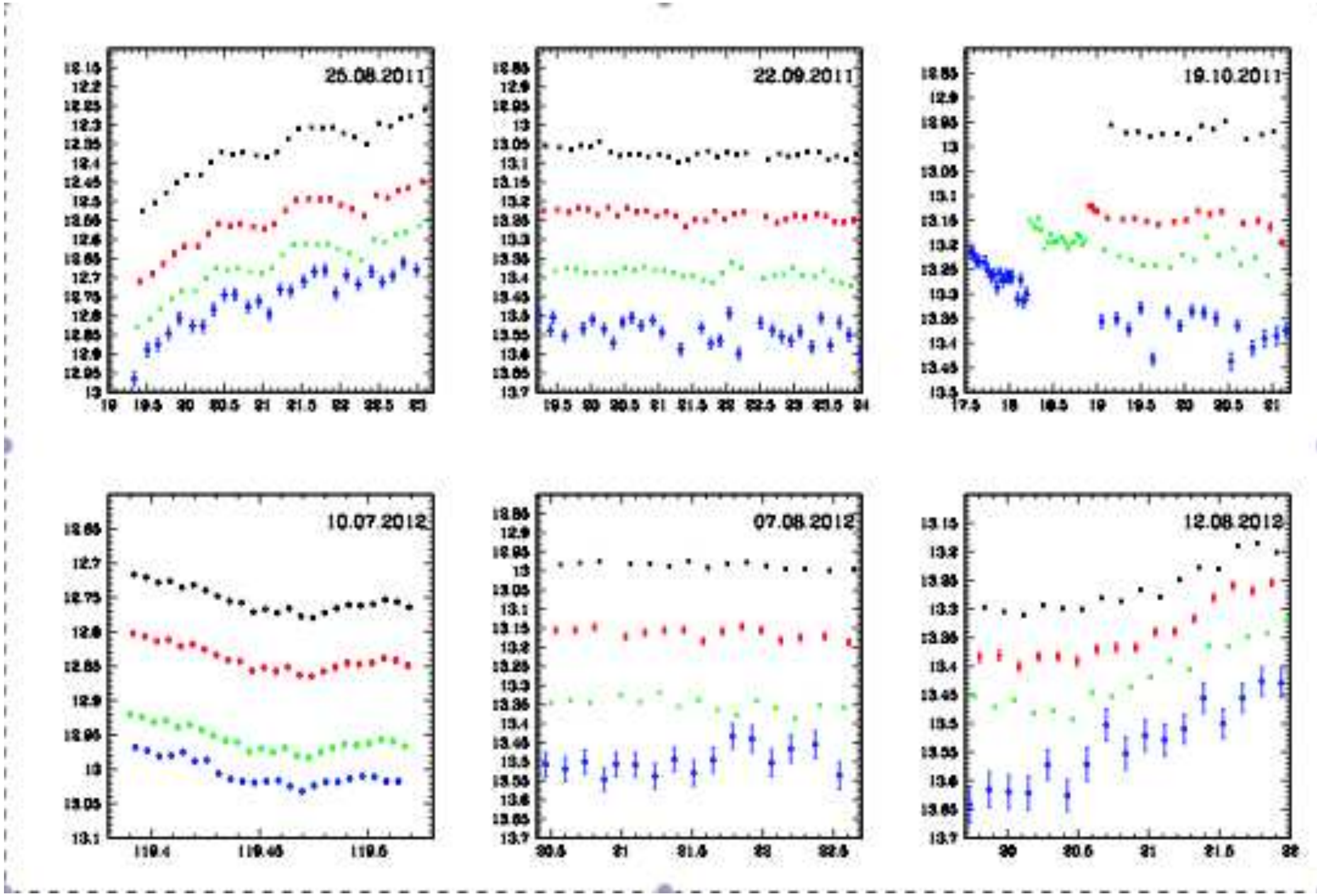
For 25 years, from the ground, with optical and radio telescopes in India, Bulgaria, Japan, Greece, USA

For 8 years, from space, with X-ray (XMM-Newton, RXTE – won't discuss) and optical (Kepler) telescopes

XMM-Newton preparation

European Space Agency

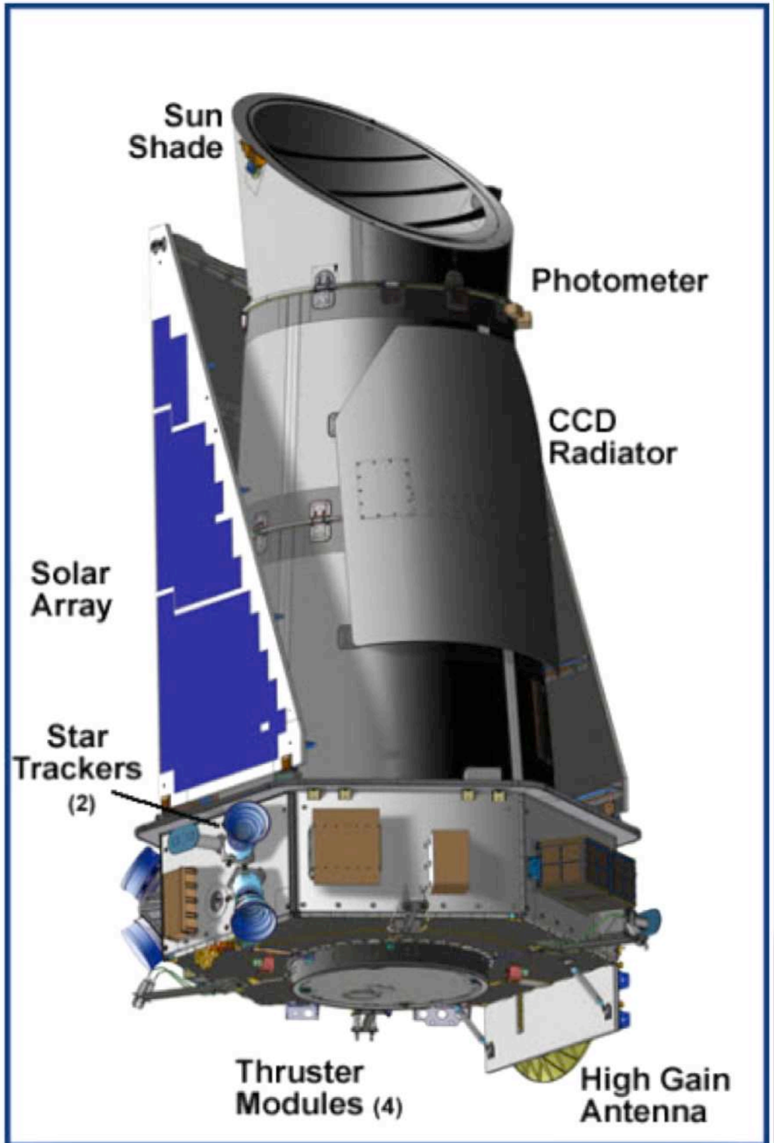
Ground Based Blazar Observations



- BL Lac in 2011 and 2012 in B,V,R,I (Gaur et al. 2015, MNRAS, 452, 4263)

From Space, with Kepler

- NASA Satellite: 0.95 m
- Earth-Trailing Orbit
- High Precision Photometric Data ($<10^{-5}$ for 10^{th} mag)
- Designed to search for earth-sized Exoplanets



Kepler Spacecraft and Photometer

How We Use Kepler and K2

- First: study the few suspected blazars in its original field for 2.75 years
- Now: look at many AGN (> 10 blazars) for 80 days
- Data Downloaded each Quarter
- Advantages:
  - High Precision CCD Cameras
  - Above Earth's Distorting Atmosphere
  - Continuous Data Sets: Long (30 min) and Short (1 min) Cadence Data

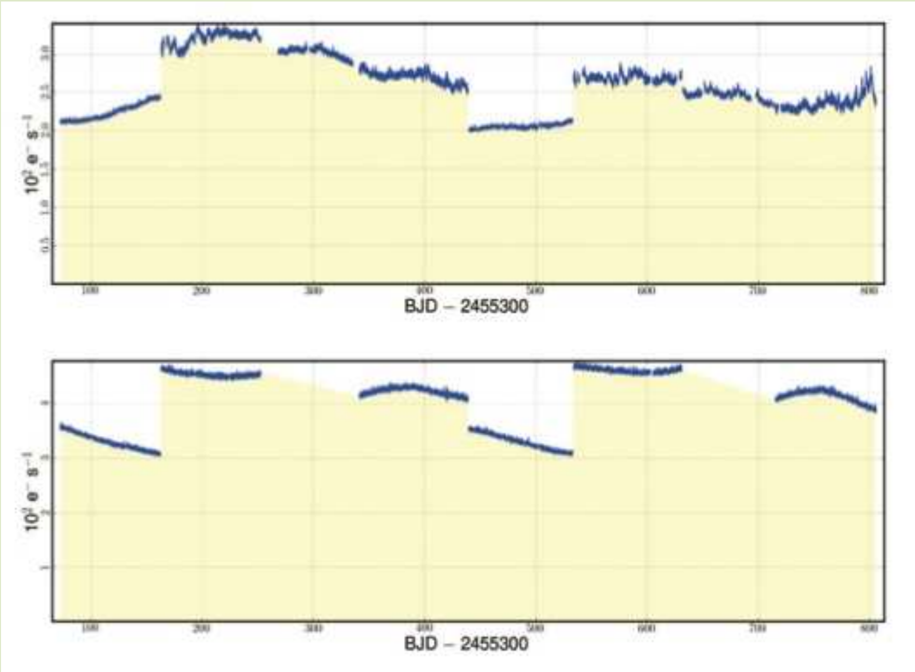
Table 1. Kepler AGN Monitoring Target List

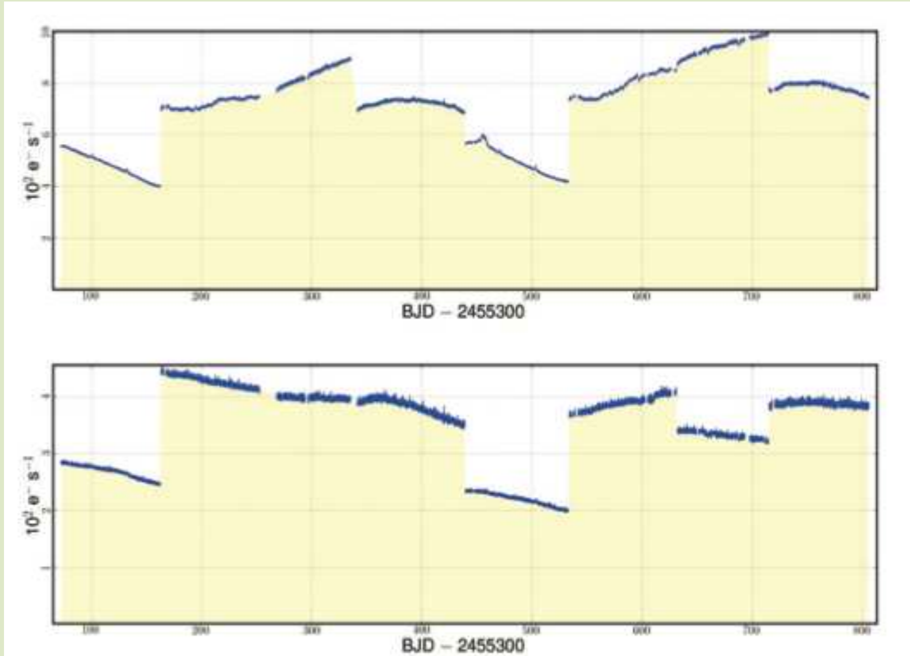
Object Designation	Name	Kepler Input Catalog Number	Right Ascension (hh:mm:ss.s)	Declination (dd:mm:ss)	Kepler Input Catalog Magnitude	Redshift	Radio Spectral Index[a]
A	MG4 J192325+4754	10663134	19:23:27.24	47:54:17.0	18.6	1.520	0.32
B	MG4 J190945+4833	11021406	19:09:46.51	48:34:31.9	18.0	0.513	0.75
C	CGRaBS J1918+4937[b]	11606854	19:18:45.62	49:37:55.1	17.8	0.926	0.00
D	[HB89] 1924+507	12208602	19:26:06.31	50:52:57.1	18.4	1.098	0.19

[a]Radio spectral index obtained from VLBA Calibrator website, defined between 2.3 and 8.3 GHz or 2.3 and 8.6 GHz with $S \propto \nu^{-\alpha}$

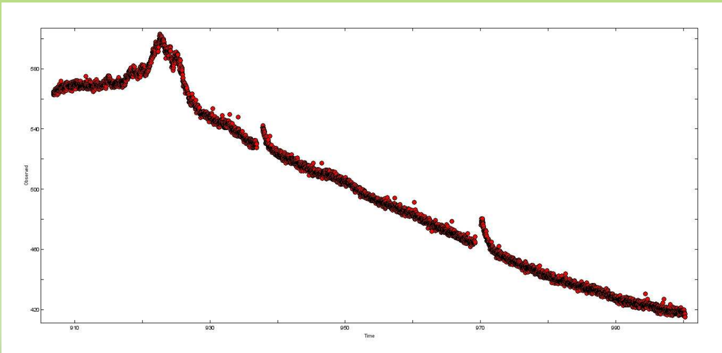
[b]Kepler Input Catalog incorrectly indicates that this target is a star with contamination 0.73, but we have verified it is an isolated quasar.

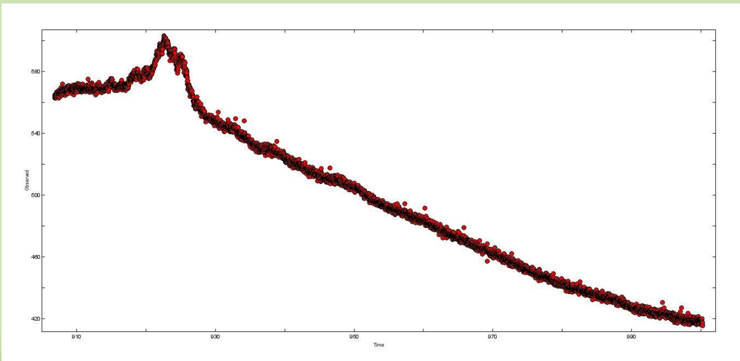
Kepler Light Curves: Quarters 6-13



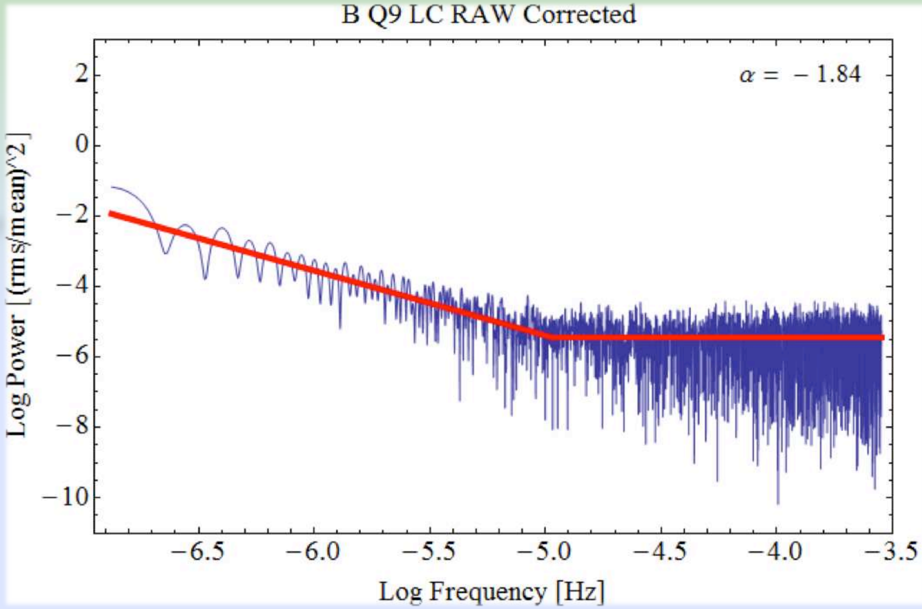


Before and After Corrections (Object C, Q 10)





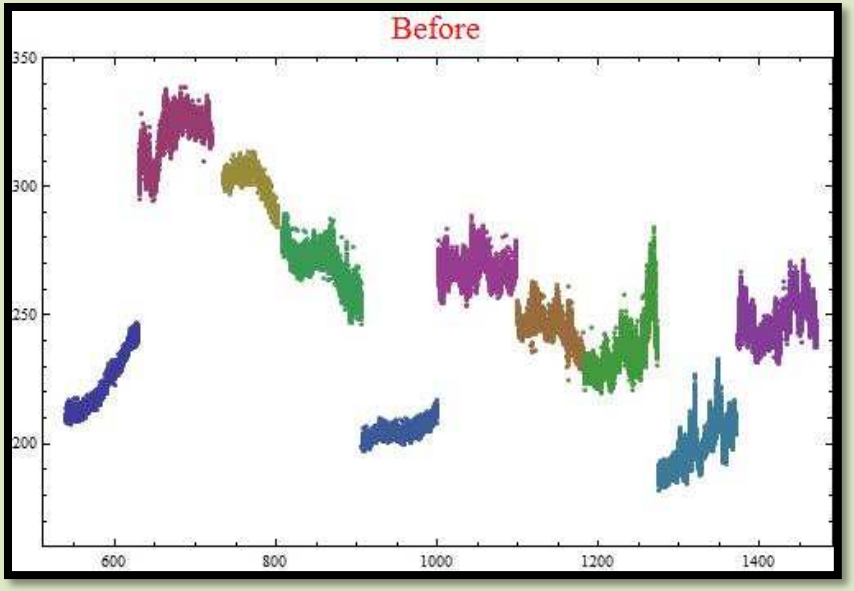
Single Quarter PSD (Object B, Q 9)

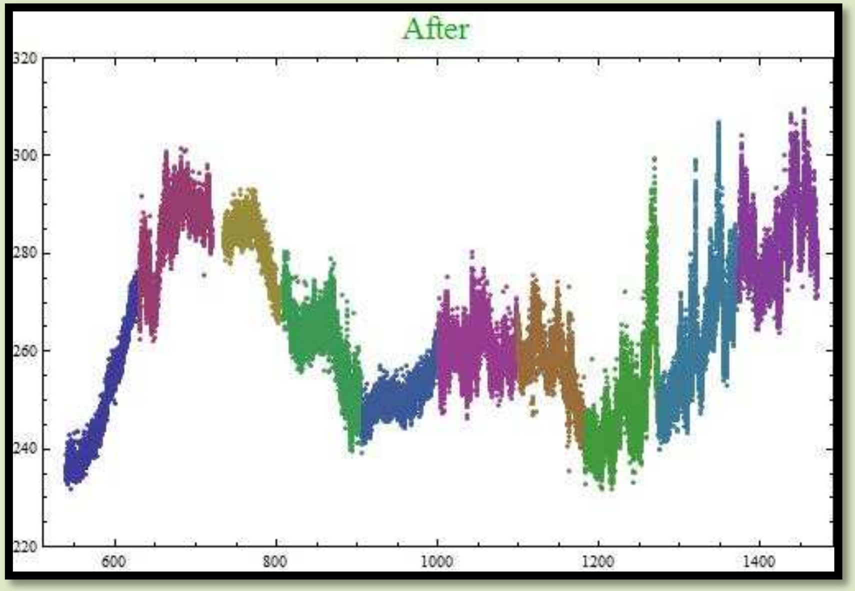


Log (f) of 6.9 to -5.9 = 90 to 9 d,
-5.9 to -4.9 = 9 to .9, -4.9 to -3.9 = .9 to .09 d

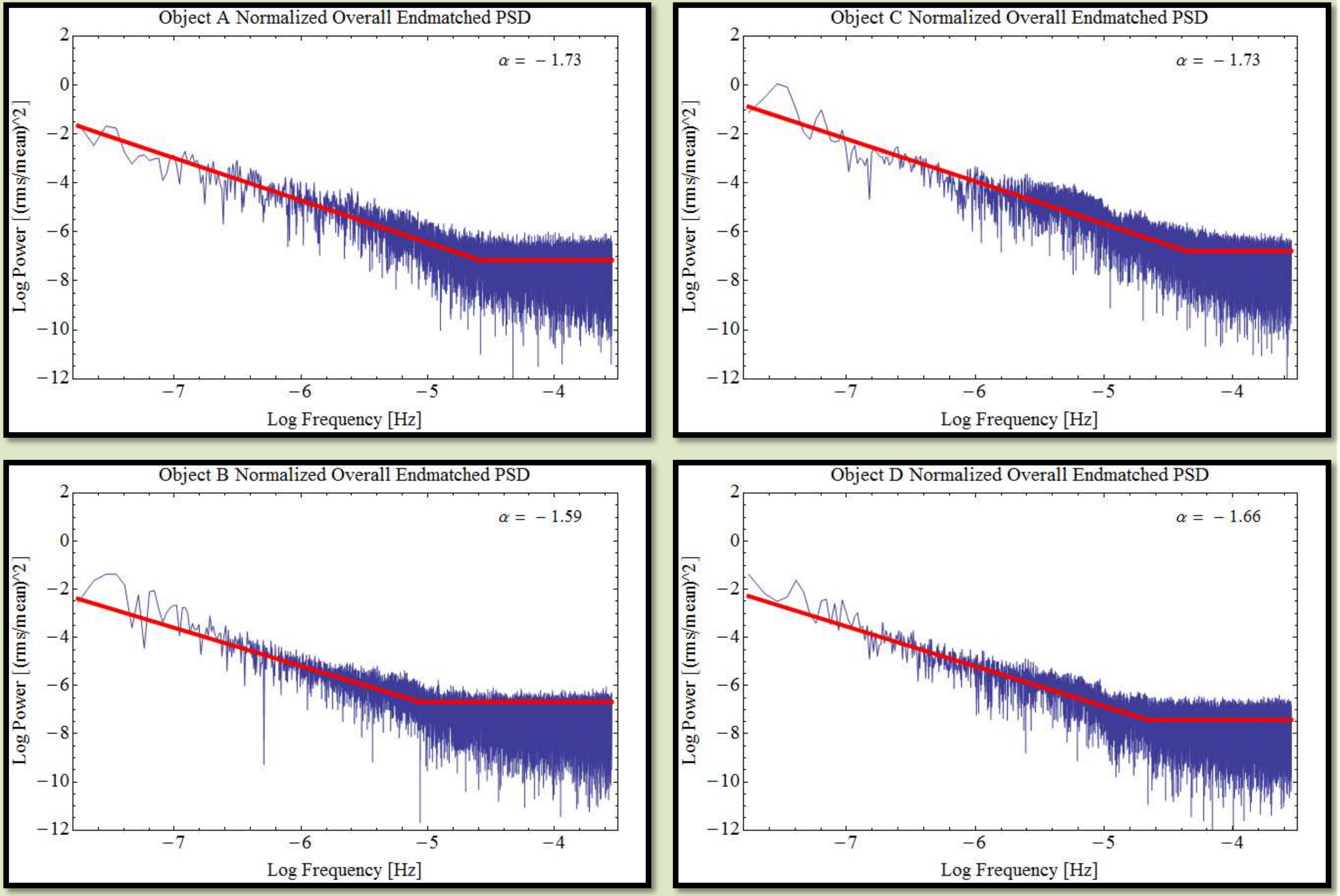
Quarter Stitching

multiplicative and additive scaling to match data across different CCDs;
allows probing of lower frequencies





Combined Kepler Power Spectral Densities



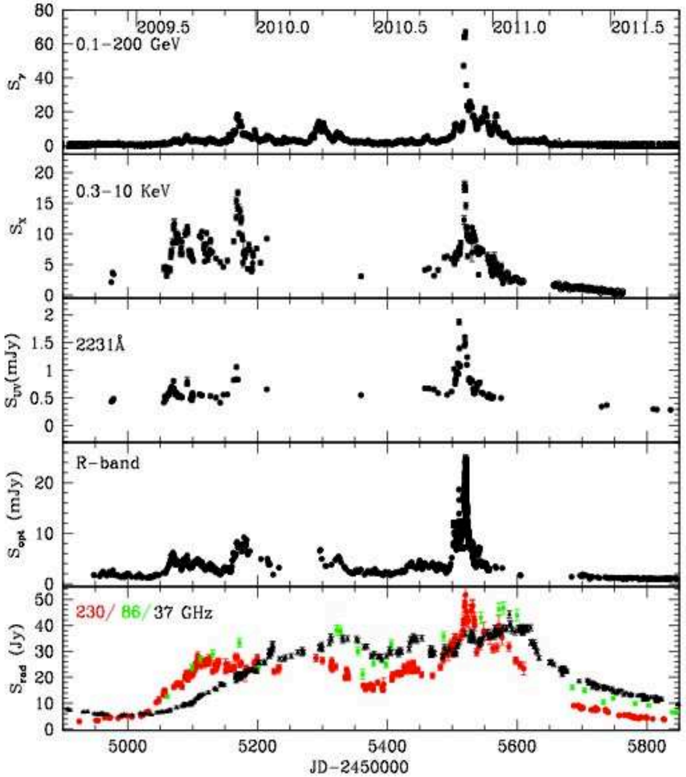
Kepler Conclusions

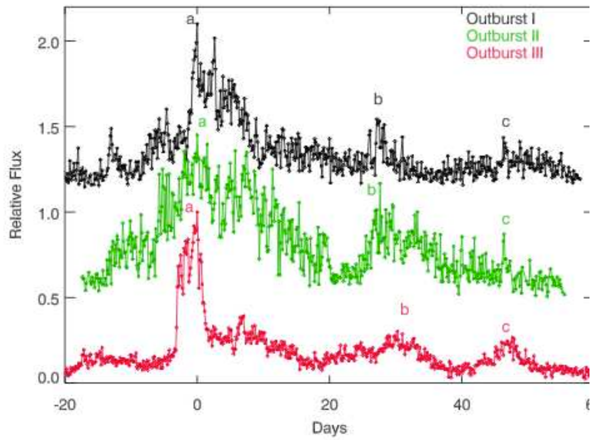
- Best sampled, high quality photometry available to date for active galaxy research
- Allows for probing of lower frequencies than possible from the ground
- We obtain quasar PSDs with reasonable red-noise slopes, comparable to those of ground based optical observations and to X-ray observations of Seyferts
- Our methods appear to be appropriately combining the individual data sets
- No (quasi-)periodicities detected, unsurprisingly
- Three of our four objects were in low activity states

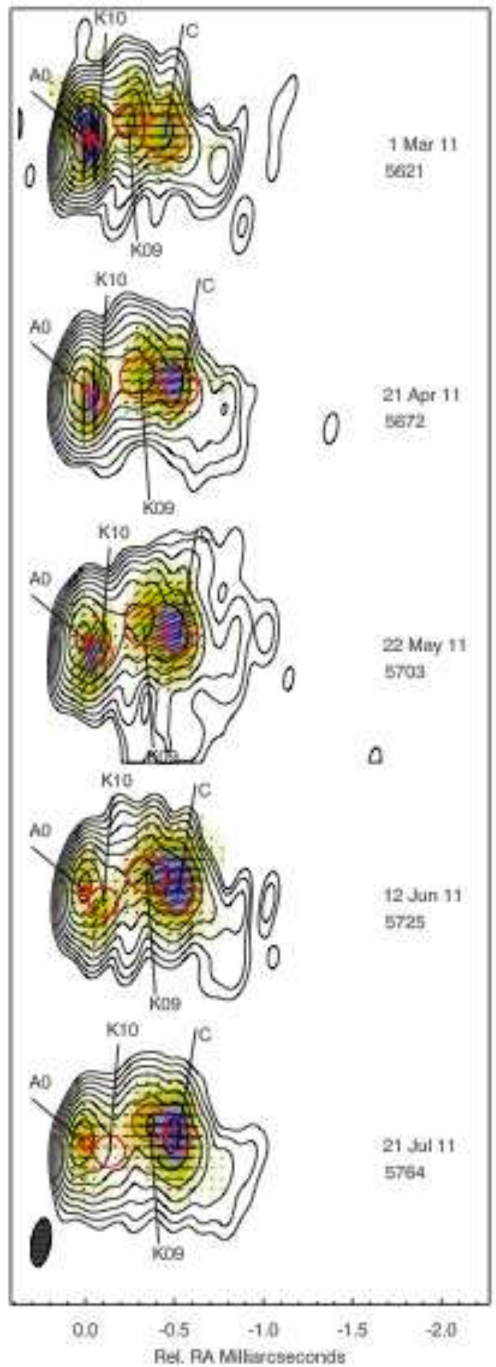
Ongoing Kepler Work

- We are performing a similar analysis on new targets: collecting data for several hundred AGN
- But only for 80 days each, in the current Kepler/K2 fields and more instrumental artifacts need to be carefully removed
- Developed programs allow for quicker processing of K2 data
- Paper on results for Q6-13: Wehrle, Wiita, Unwin, Di Lorenzo, Revalski, Silano & Sprague Ap J, 773, 89 (2013)
- Paper on Q14-16 and data stitching: Revalski, Nowak, Wiita, Wehrle & Unwin, Ap J, 785, 60 (2014)

Turbulence in Relativistic Jets: 3C454.3 flares (Jorstad et al. 2013)

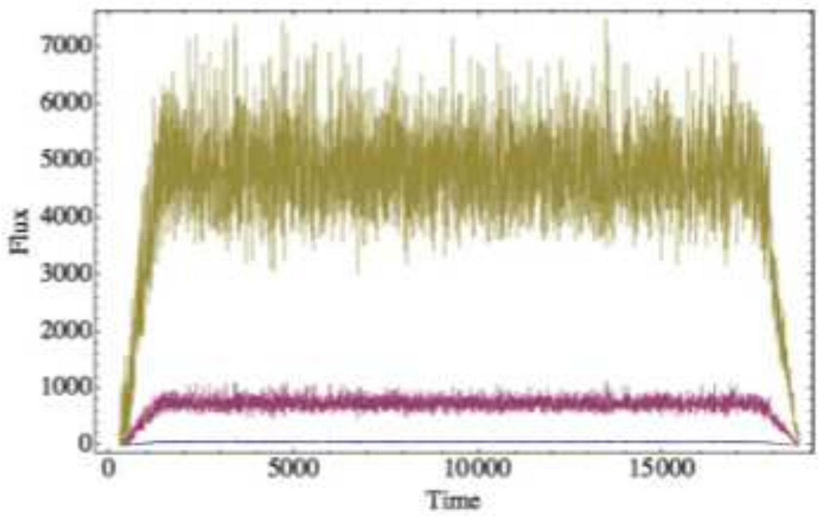


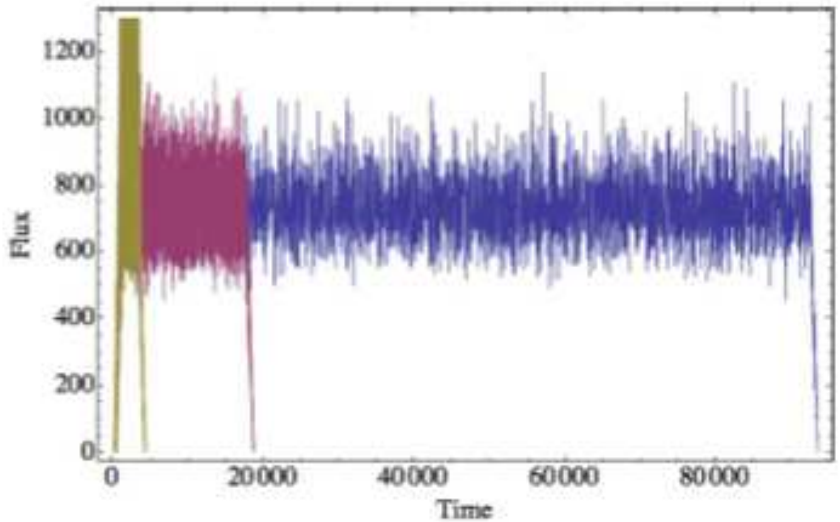




Multiband, and scaled gamma-ray LCs
VLBI maps show shock propagating through helical region with turbulence very likely.

Modeling Variability with Turbulent Relativistic Jets



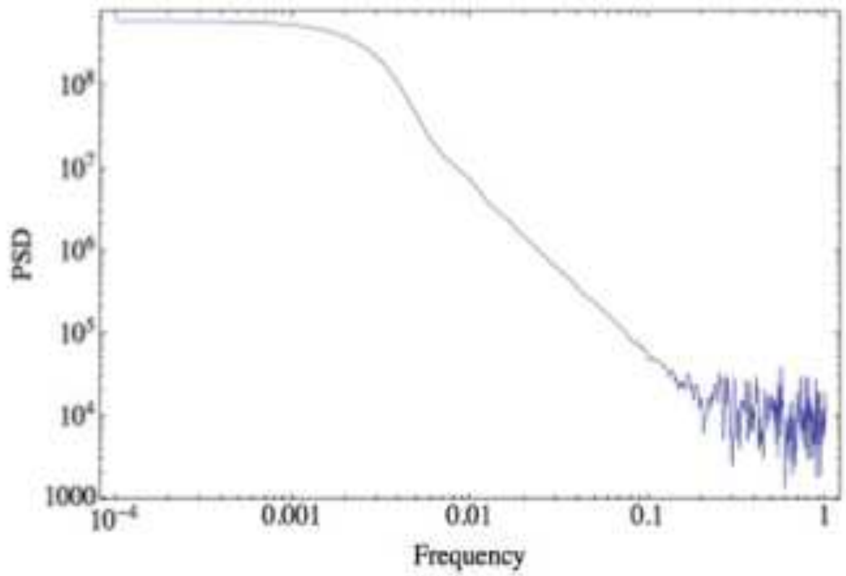


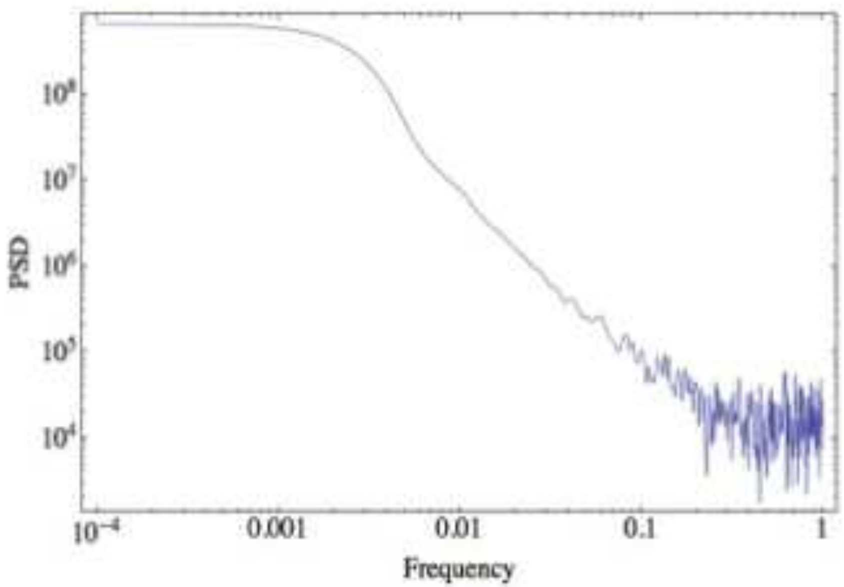
Calafut & Wiita (2015): relativistic turbulent spectrum (Zrake & MacFadyen 2013) compared with usual Kolmogorov. Modeled using 9 levels of embedded cells.

Top: V_b = .99c, V_t = 0.3c, θ = 3°, 10°, 30° (top to bottom)

Bottom: V_b = .99c, θ = 10° for V_t = 0.9c, 0.3c, 0.1c (L to R) V_t > 0.6c ⇒ unrealistic light curves

Power Spectra of Static Turbulent Jets





Both for $V_b = 0.99c$ and $\theta = 10^o$ all for the relativistic turbulence spectrum.

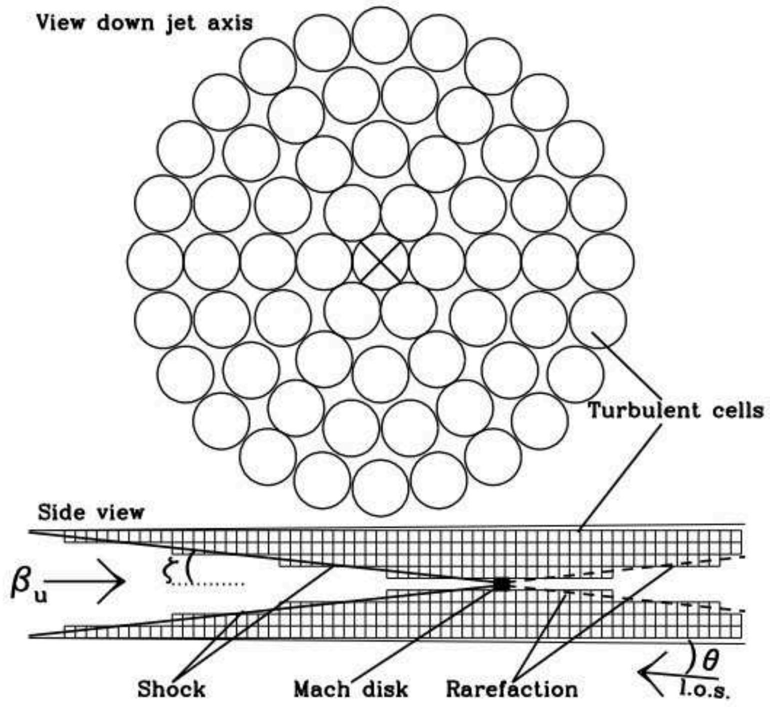
Top: $V_t = 0.1c$: red-noise slope, $\alpha = -2.15$

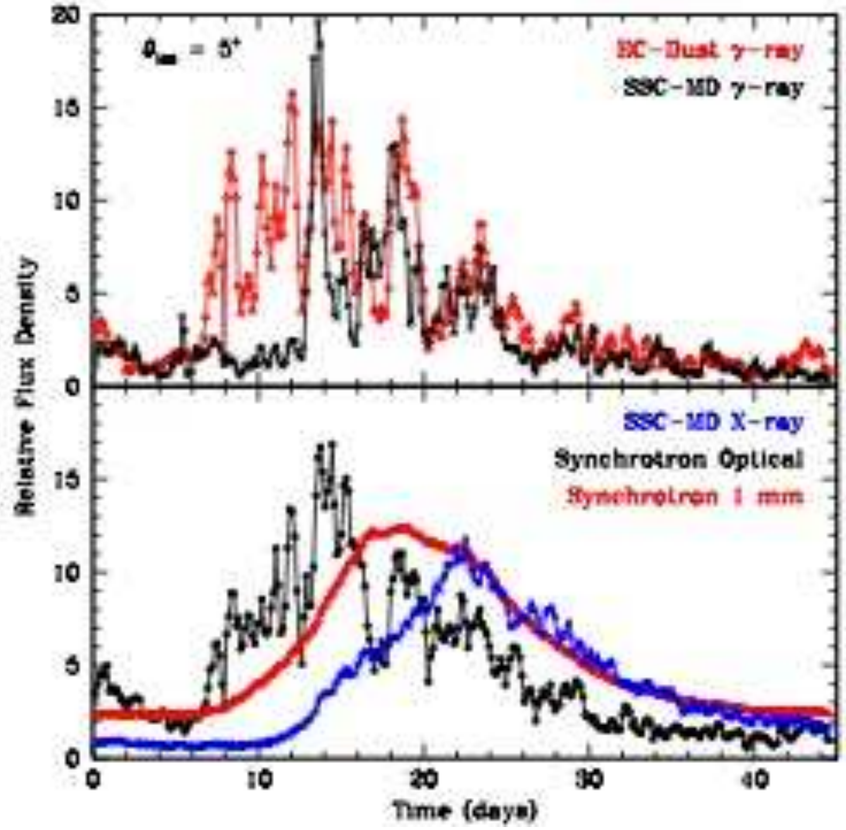
Bottom: $V_t = 0.3c$: $\alpha = -2.05$

Reasonable agreement with data, but red-noise covers only 2 decades in frequency.

Calafut & Wiita, J. Astrophys & Astron, 36, 255 (2015)

Turbulent Extreme Multi-Zone Model
(Marscher 2014)

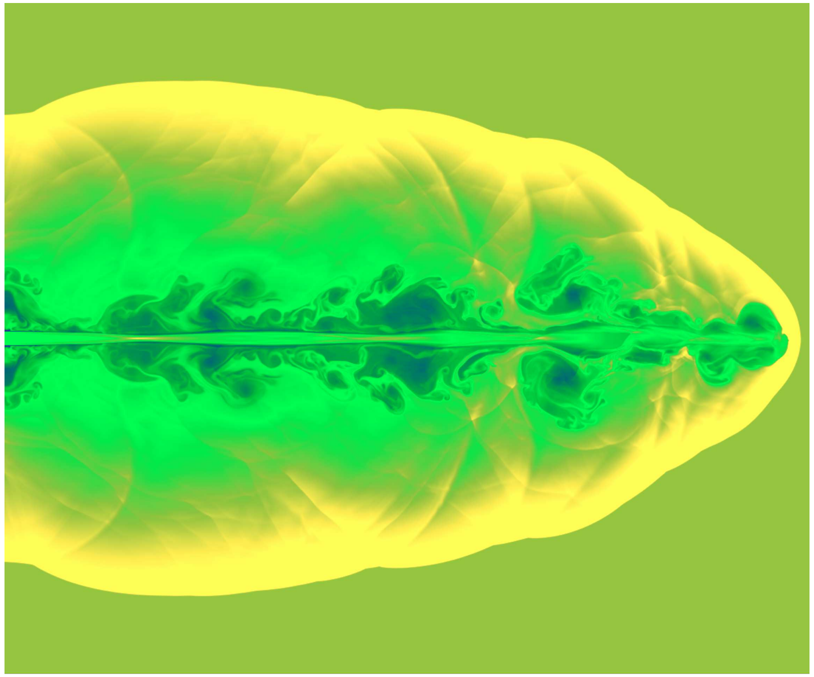


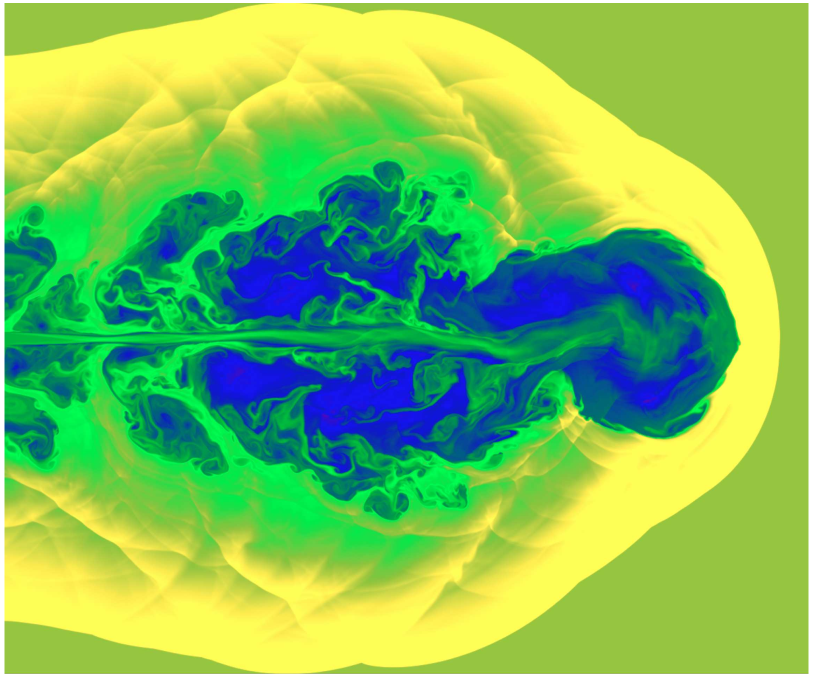


Multiband light curves and polarization predictions from bolus of plasma entering a turbulent region close to shock zone.
Includes SSC and EC options.

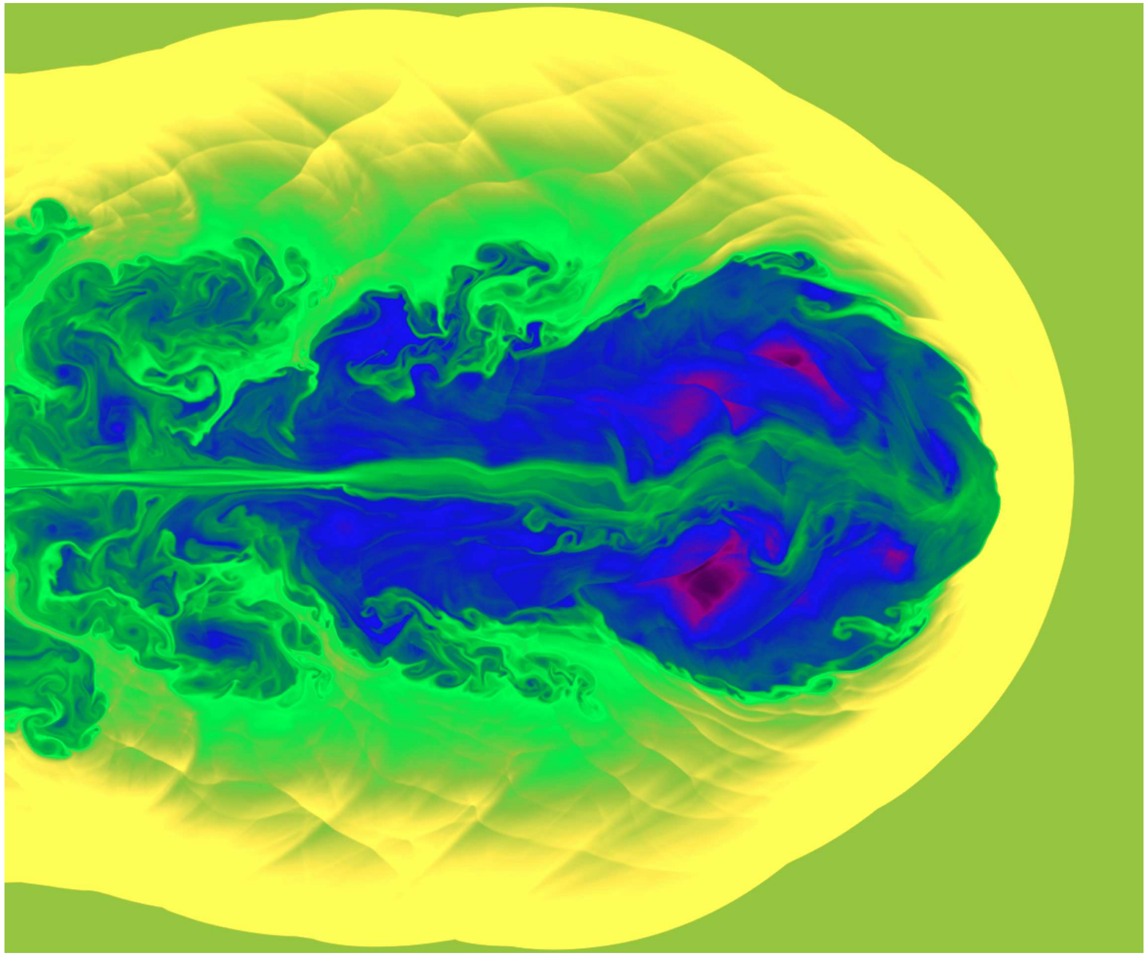
Modeling Turbulence in Propagating Jets

- We use the Athena relativistic magnetohydrodynamics code in its hydro mode and inject a relativistic jet into a constant density ambient medium (Pollack, Pauls & Wiita, 2016).
- Jet density ranges from 0.1 to 0.001 of ambient,and V_b from 0.9c to 0.998c, similar to radio jets in active galaxies.
- Plots show densities on log scale: yellow to violet





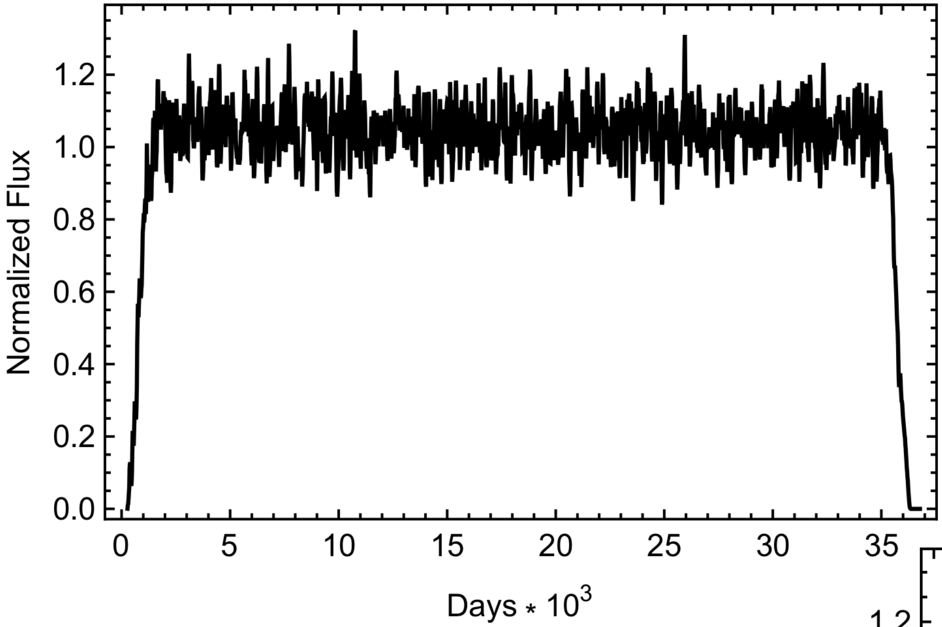
Variations from bulk Doppler changes in region behind confinement shock + turbulence



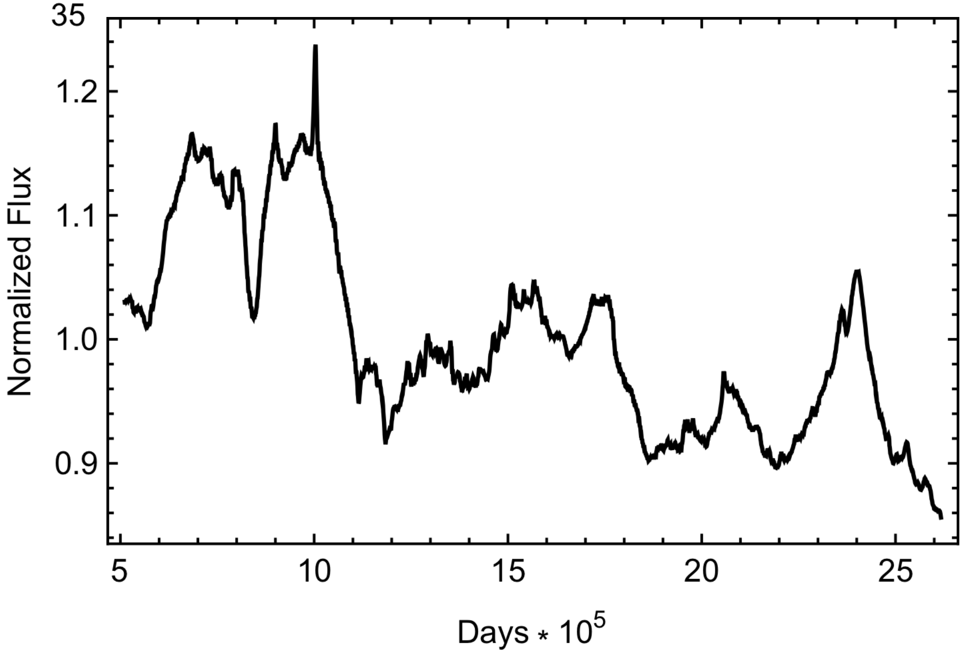
Bulk velocity = 0.995c, η=0.01:
Stable, like powerful radio quasars

V_b=0.9c and η=0.0316:
Unstable, like weaker BL Lacertae radio blazars

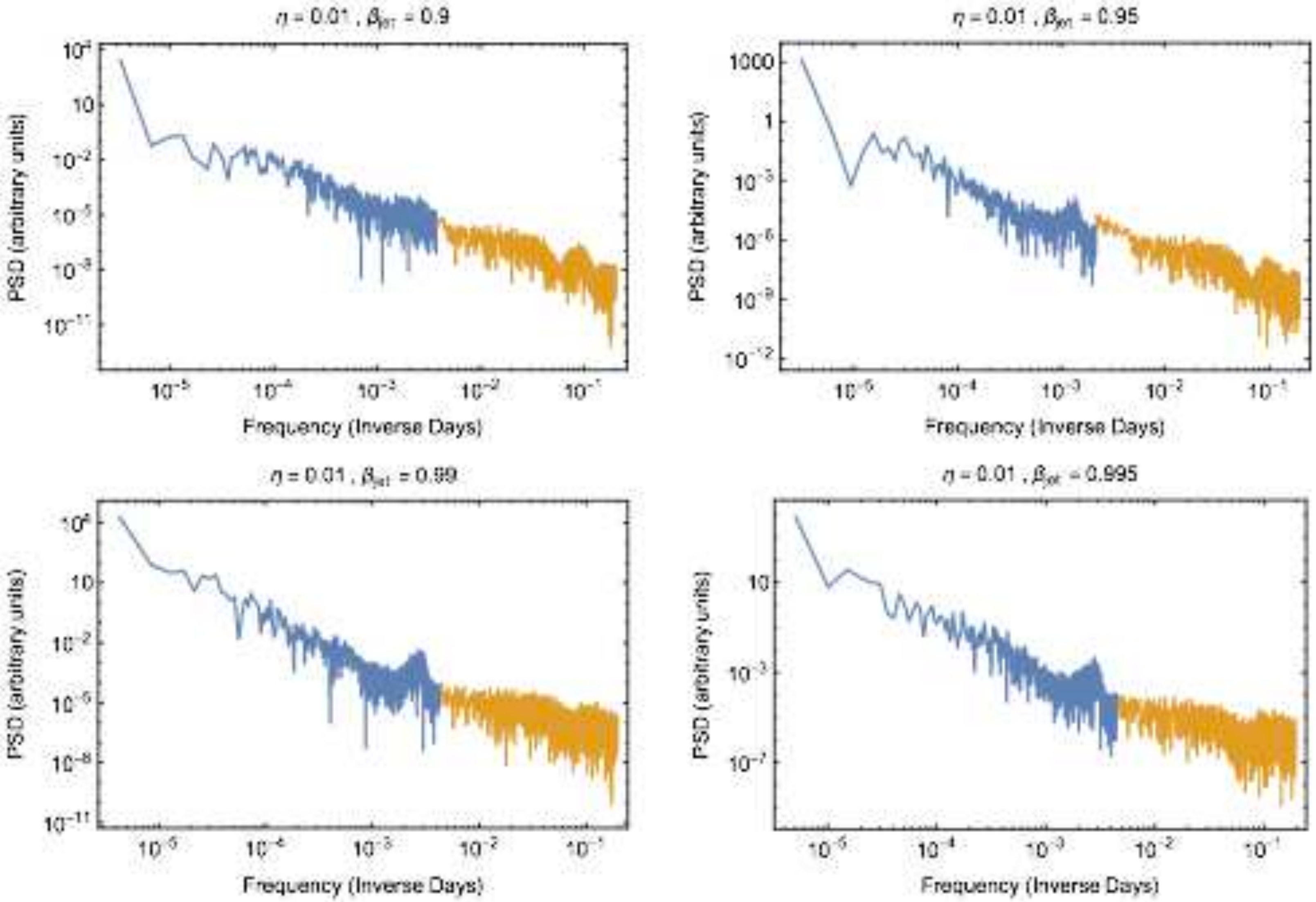
Light Curves: Turbulent and Bulk Variability



Pollack, Pauls & Wiita,
Astrophys. J. 820, 12 (2016)



Combined Power Spectra



PSD slopes: -2.1 to -2.4 for bulk flucuations and -1.8 to -2.3 for turbulent

Conclusions from Modeling

- Turbulence behind strong jet shocks is expected.
- Reasonable turbulent spectra and jet parameters can provide LCs and PSDs that look like observations over shorter times.
- Jets change as they propagate: slight changes in the direction or speed of bulk velocities yield substantial observed variations over longer time scales.
- Together these can provide good fits to LCs and PSDs over 5 decades (hours to years).