Linear Disk—Jet coupling following the tidal disruption of a star by a super-massive black hole

Dheeraj Pasham (DJ)
MIT

Einstein Symposium, 12 October 2017
Pasham & van Velzen (2017), submitted
arXiv:1709.02882

Punch line:

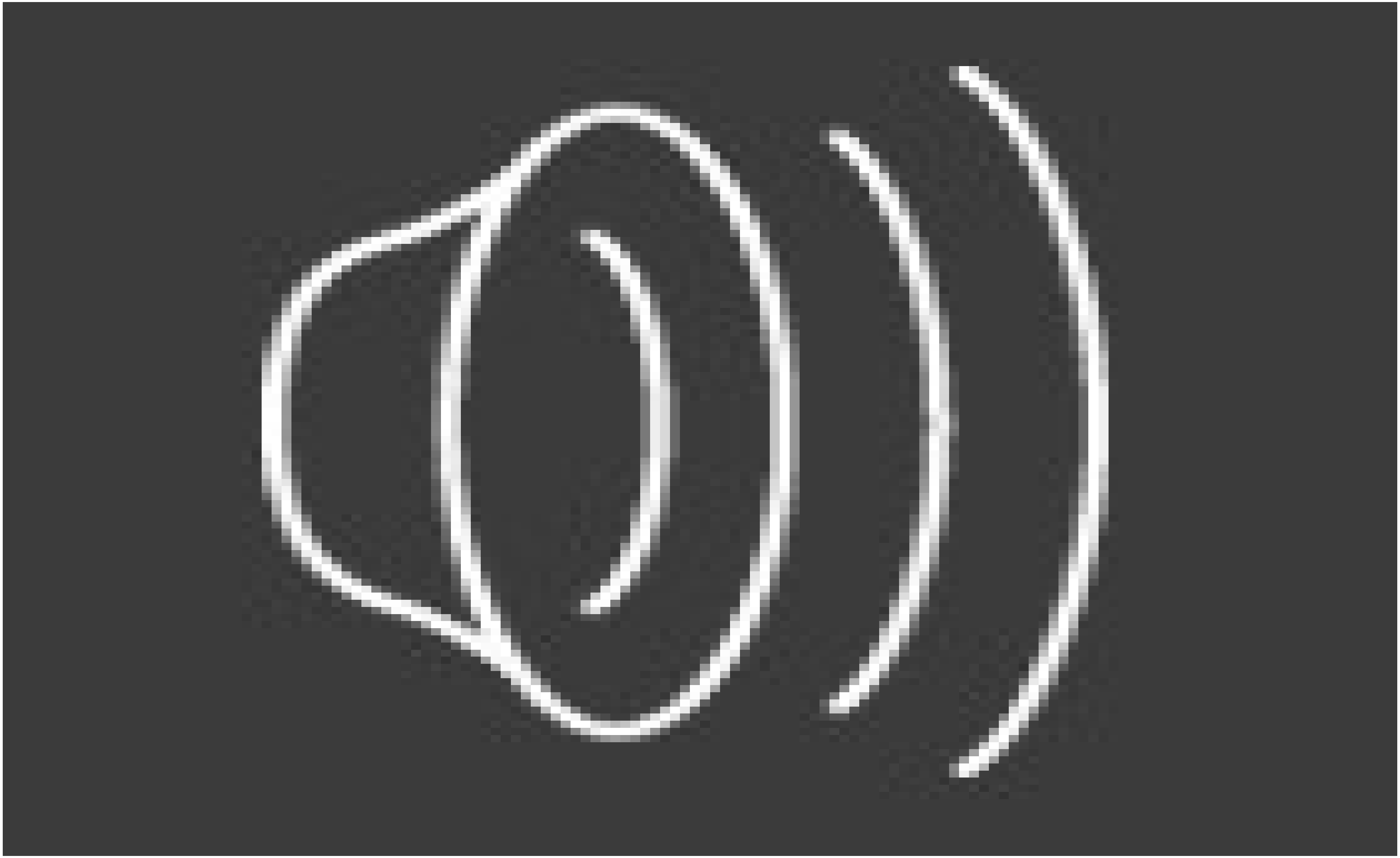
1) ASASSN-14li’s entire radio flux is correlated with X-ray emission

2) The radio lags X-rays by 13 days

3) Physical mechanism responsible for this disk—jet coupling is very efficient

What is a Tidal Disruption Event?

What is a Tidal Disruption Event?



They form accretion disks and jets:

Ideal to probe the
Interplay between
accretion and ejection of matter
near a black hole

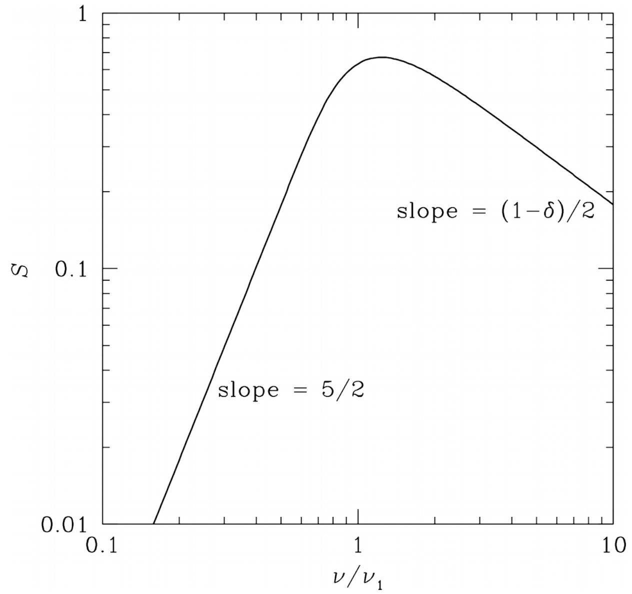
ASASSN-14li: A TDE Poster Child

- Why a TDE?
  - Spatial position
  - 5/3 power law decline
  - Blue optical spectra with broad Hα and He emission lines
  - A constant optical color unlike Sne
- A flare that shined in X-ray, UV, optical and radio: a true multi-wavelength TDF

Holoien et al. (2016); Miller et al. (2015); van Velzen et al. (2016); Krolik et al. (2016); Alexander et al. (2016), Arcavi et al. (2014), etc

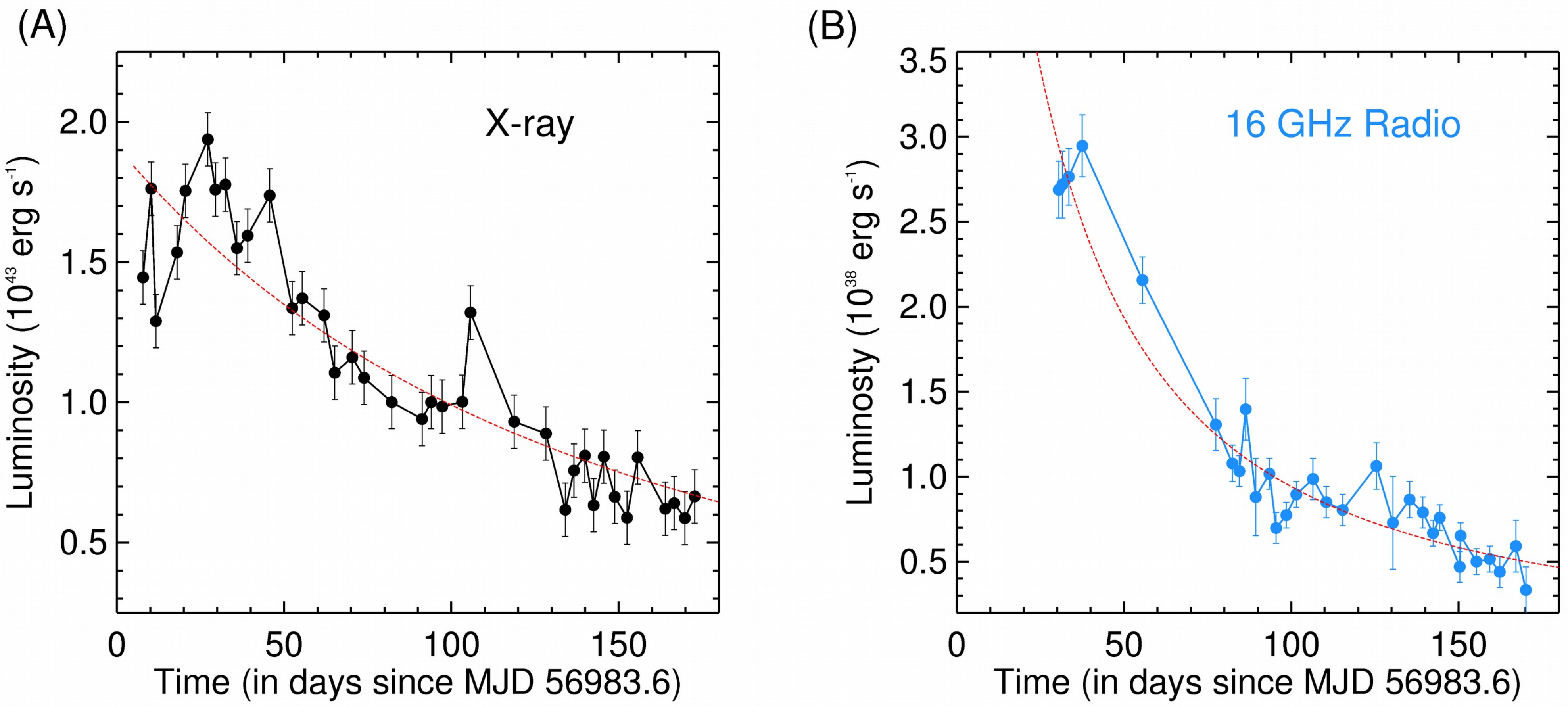
ASASSN-14li: Ideal to study Disk-Jet Interplay

- Thermal X-rays (pure disk)
- Synchrotron radio flare
    - Accelerated electrons (jet?)



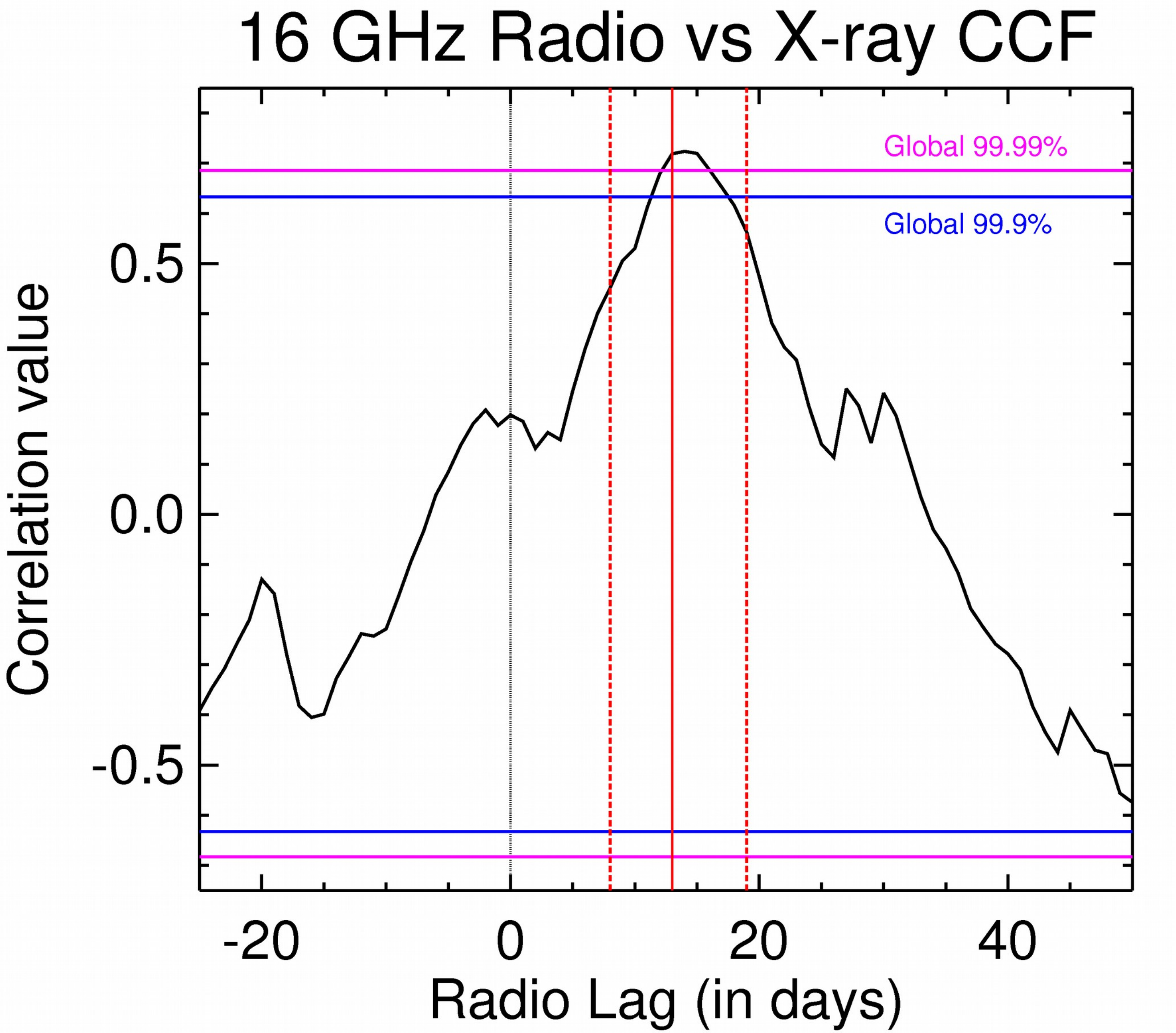
Analysis

X-ray and Radio monitoring



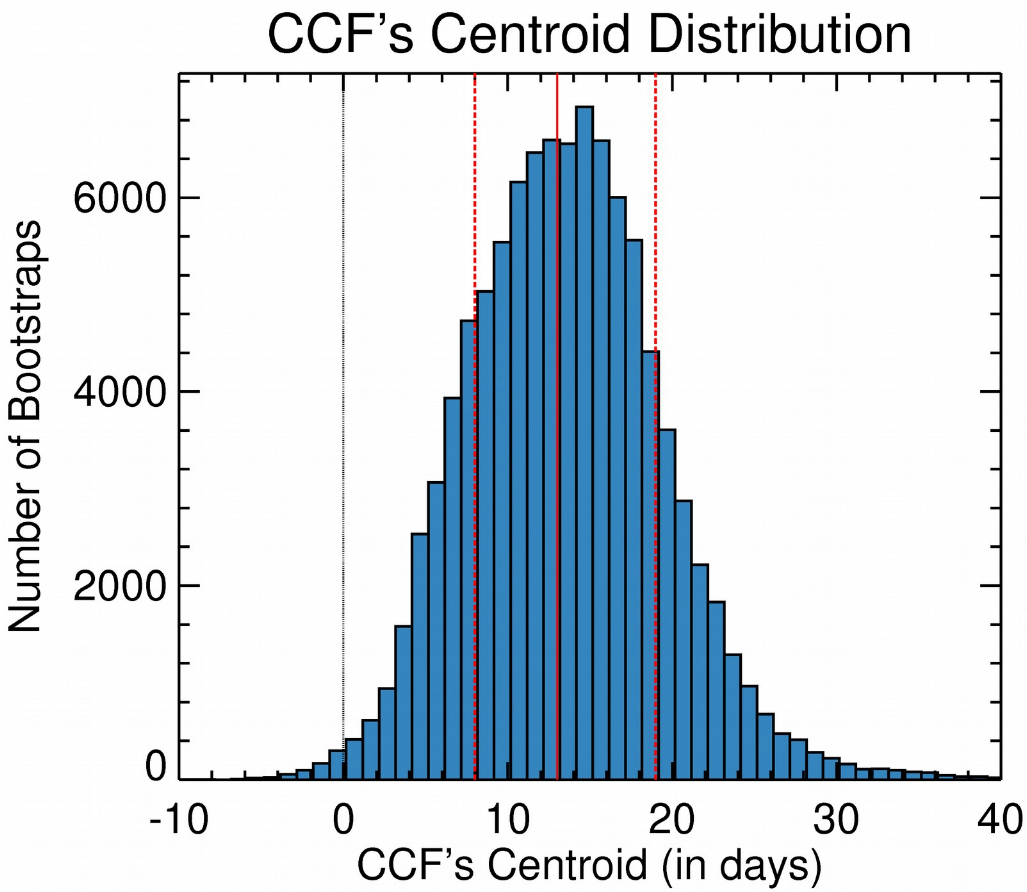
Pasham & van Velzen (2017), *Submitte*

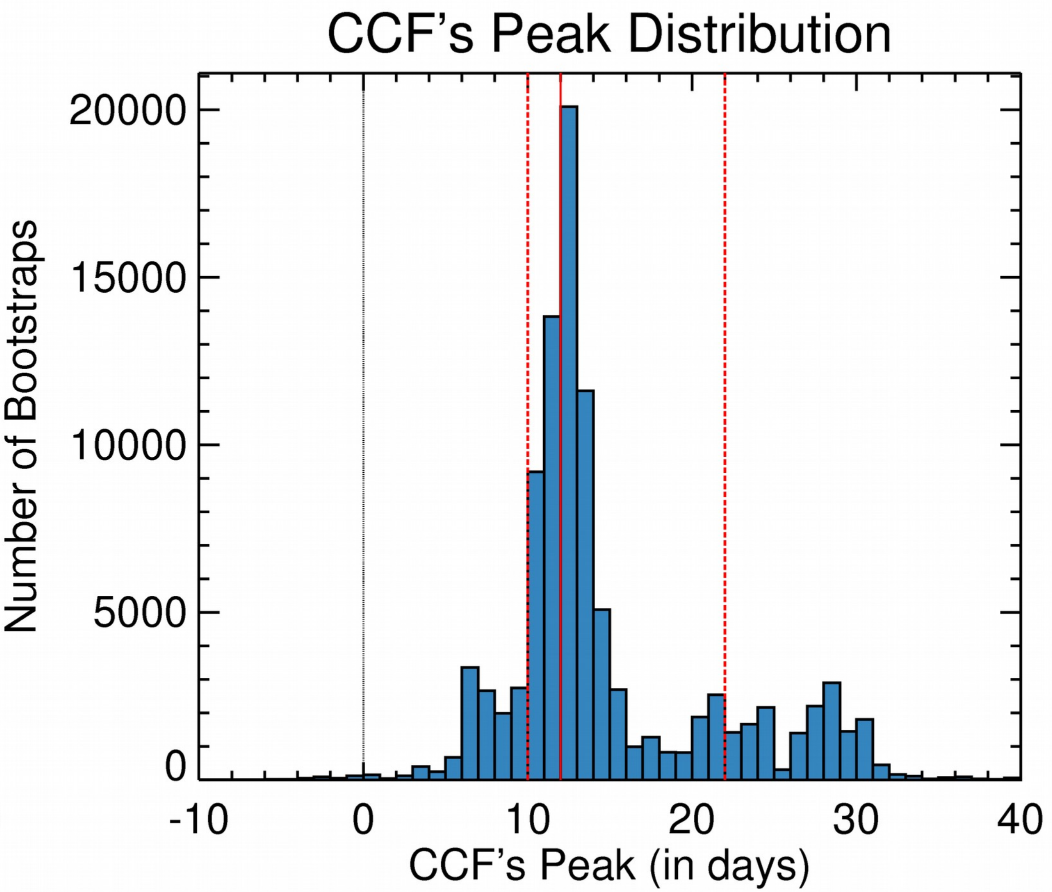
X-ray vs Radio Cross-Correlation



Radio changes “lag” the X-rays by ≈ 13 d

Estimate error on the lag

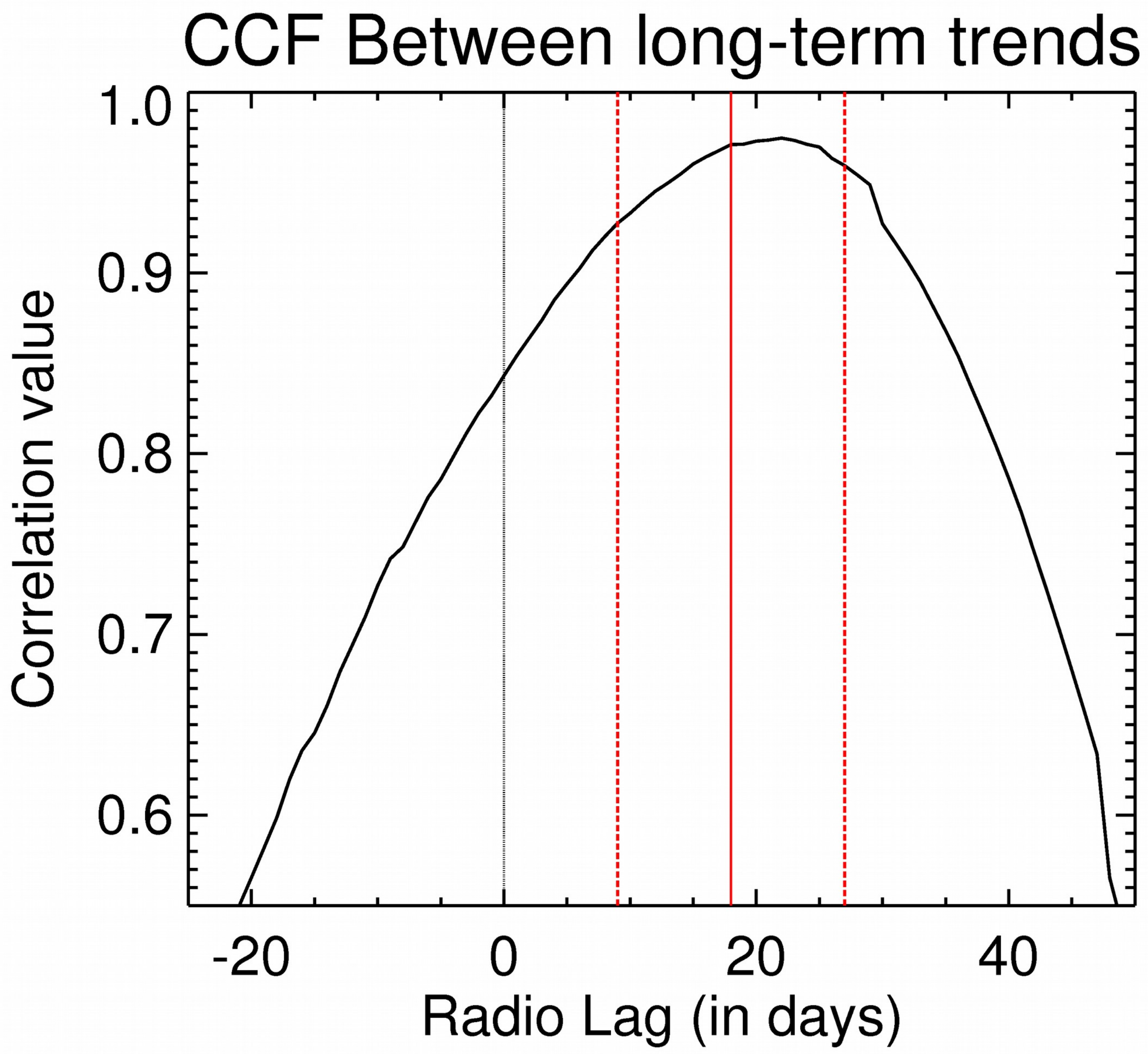




These errors account for both the sampling and measurement uncertainties of both X-ray and radio light curves

Radio tracks the X-rays!

Entire Radio Emission tracks X-rays!



So what does that mean?

We know X-rays are very likely coming from an inner accretion disk.

But, where does the radio originate from?

Radio: 3 models proposed so far …

1. A blast wave shocking with the circumnuclear medium (Similar to GRBs)
2. Interaction of the unbound stellar debris with the circumnuclear medium
3. A transient jet ejection ramming into the external medium

Alexander et al. (2016), Krolik (2016), van Velzen et al. (2016)

Radio: 3 models proposed so far ...

1. A blast wave shocking with the circumnuclear medium (Similar to GRBs)
2. Interaction of the unbound stellar debris with the circumnuclear medium
3. A transient jet ejection ramming into the external medium

All previous models have two commonalities:
(1) e^-s accelerated via external interactions
(2) radio originates from a single ejection of energy

Alexander et al. (2016), Krolik (2016), van Velzen et al. (2016)

Radio: 3 models proposed so far ...

1. A blast wave shocking with the circumnuclear medium (Similar to GRBs)
2. ~~Interaction of the unbound stellar debris with the circumnuclear medium~~
3. A transient jet ejection ramming into the external medium

All previous models have two commonalities:
(1) e^-s accelerated via external interactions
(2) radio originates from a single ejection of energy

Alexander et al. (2016), Krolik (2016), van Velzen et al. (2016)

Radio: 3 models proposed so far ...

1. ~~A blast wave shocking with the circumnuclear medium (Similar to GRBs)~~
2. ~~Interaction of the unbound stellar debris with the circumnuclear medium~~
3. ~~A transient jet ejection ramming into the external medium~~

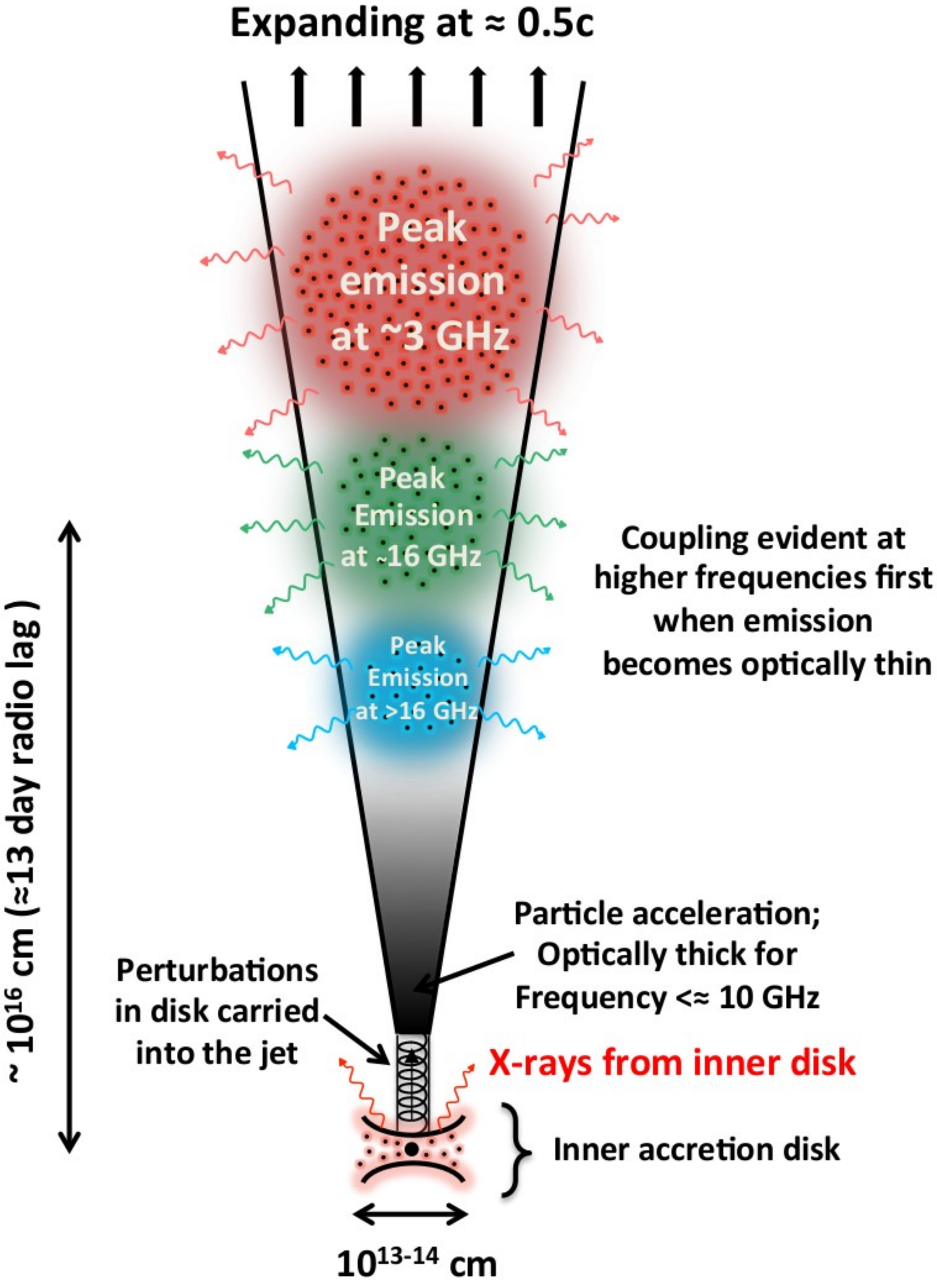
All previous models have two commonalities:
(1) e^-s accelerated via external interactions
(2) radio originates from a single ejection of energy

Alexander et al. (2016), Krolik (2016), van Velzen et al. (2016)

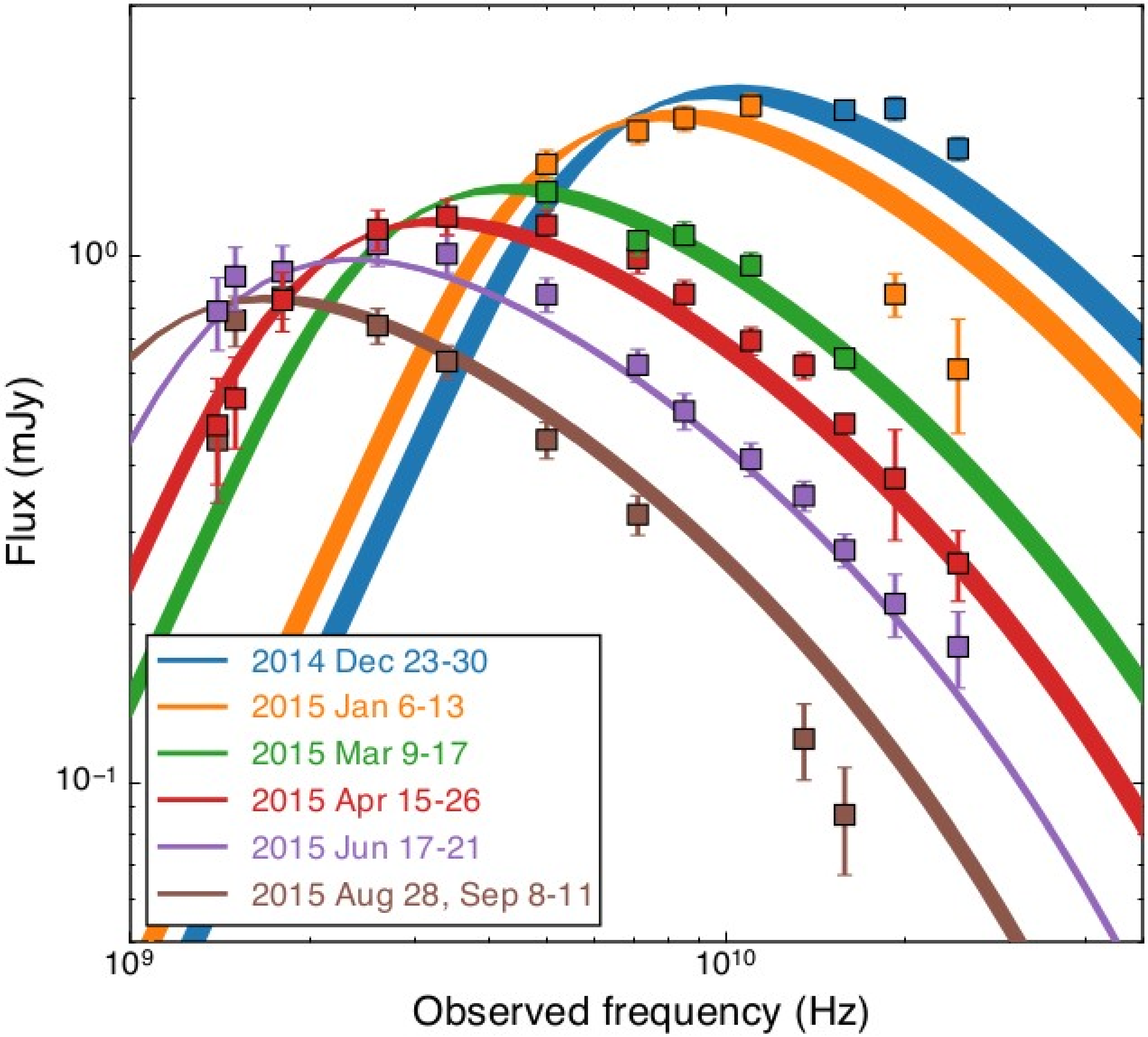
Radio originates from a jet regulated by disk

A mechanism that naturally facilitates a medium to propagate information about the accretion rate to the radio-emitting region is a jet launched from the black hole’s accretion disk.

We propose …


Expanding at ≈ 0.5c
Peak emission at ~3 GHz
Peak Emission at ~16 GHz
Peak Emission at >16 GHz
Coupling evident at higher frequencies first when emission becomes optically thin
~ 10^16 cm (≈13 day radio lag)
Particle acceleration; Optically thick for Frequency <≈ 10 GHz
Perturbations in disk carried into the jet
X-rays from inner disk
Inner accretion disk
10^13-14 cm

Radio spectra tell us how the jet evolves!



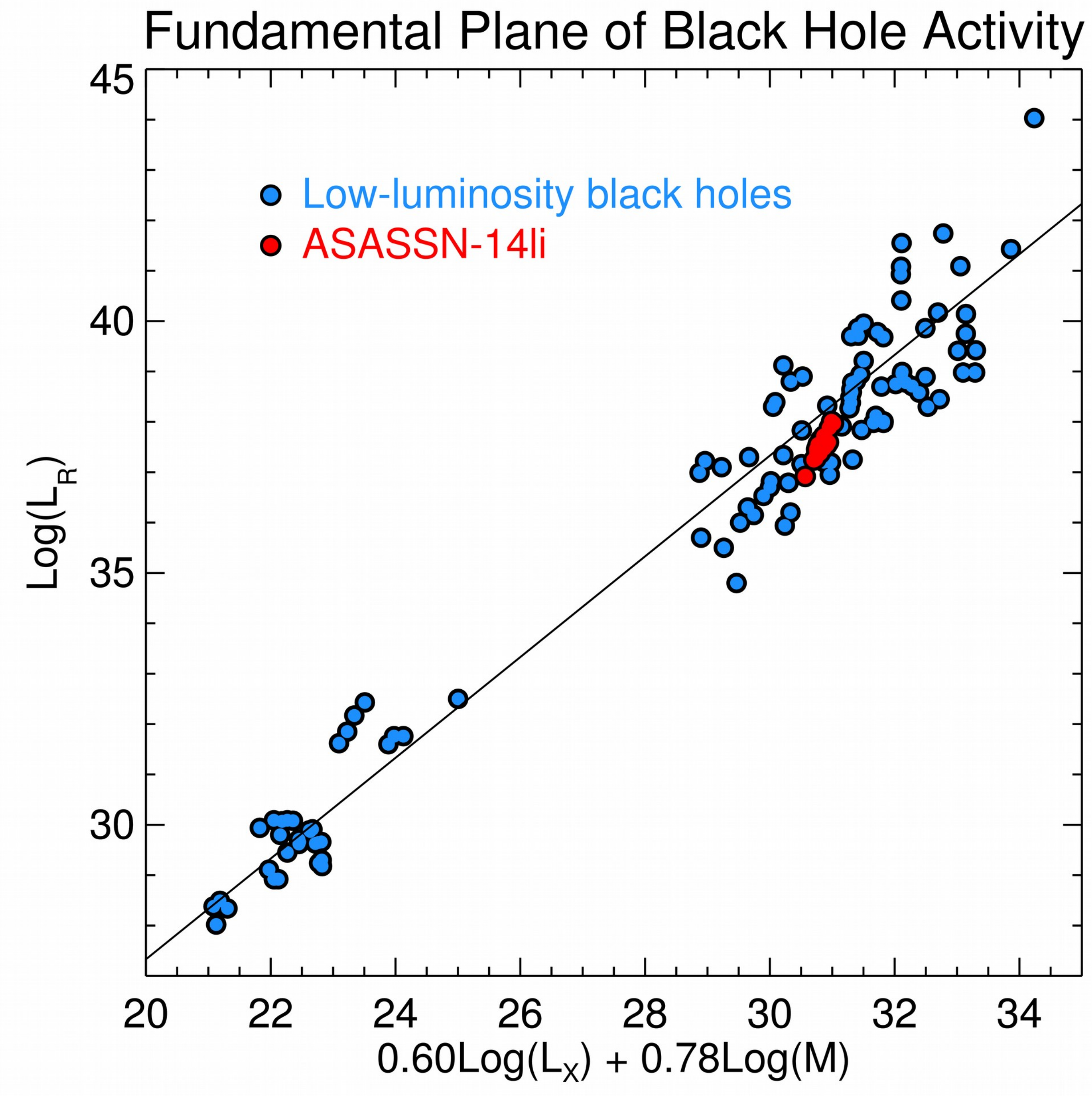
- B ~ z^{-1} scaling of a jet (classical prediction)

- By extrapolating the jet evolution backwards we estimate jet was launched in the 1st week of October 2014

Conclusions

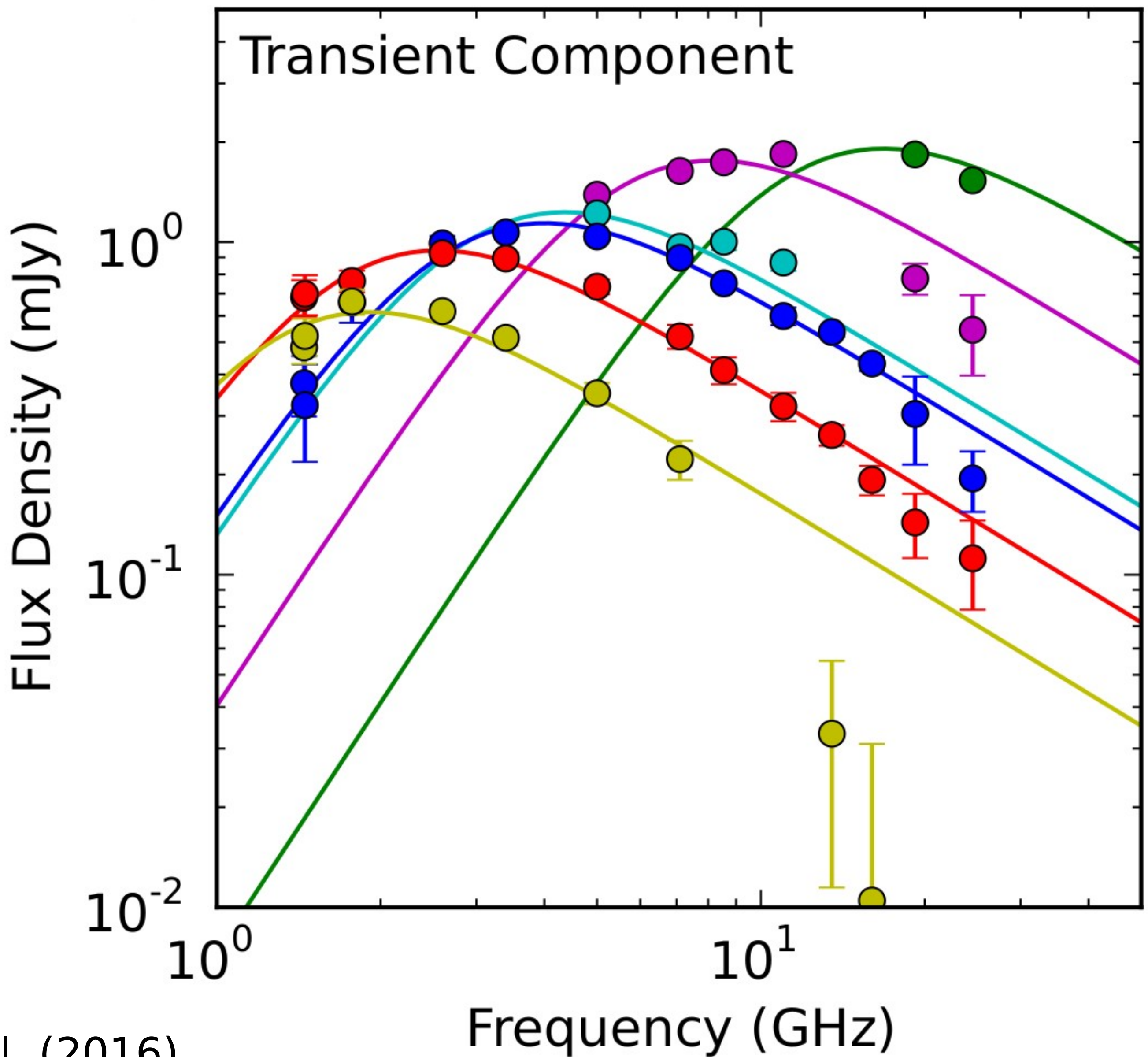
1. We have discovered the 1st disk—jet coupling in a tidal disruption flare!
2. This has the potential to understand how jets evolve in their earliest stages
3. The evolution of radio SEDs will NOT probe the circumnuclear medium, instead reveal properties internal to the jet!

Interesting to see it lie right on the fundamental plane



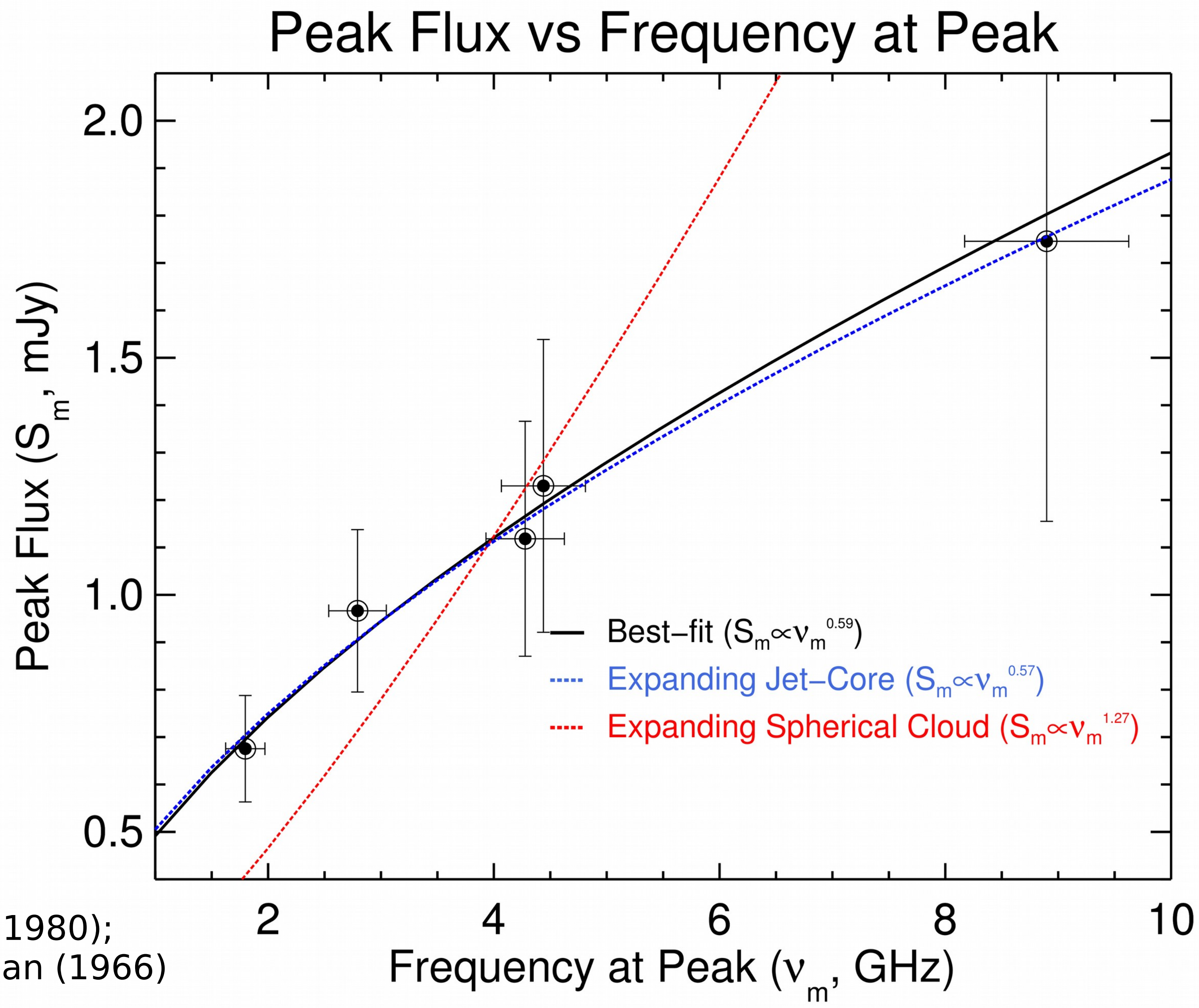
Merloni (2004);
Falcke et al. (2004)

Radio spectral evolution: hint of a jet!



Alexander et al. (2016)

Radio spectral evolution: hint of a jet!



Marscher (1980);
van der Laan (1966)

Using eq. (7) of Heinz & Sunyaev (2003) it can be seen straightaway that the optically thin synchrotron emissivity, j_ν, at a given radio frequency (ν) for a power-law distribution of electrons with index p is given as,

$$j_\nu = J_p K B^{\frac{\mathrm{p}+1}{2}} \nu^{-\frac{\mathrm{p}-1}{2}} \tag{14}$$

where J_p is a constant weakly dependent on p, and B is the magnetic field strength, and K is defined as before (see 4.2).

Thus, at a given radio frequency

$$j_\nu \propto L_{\mathrm{radio}} \propto K B^{\frac{\mathrm{p}+1}{2}} \tag{15}$$

where L_{radio} is the radio luminosity at ν. The jet power scales with the magnetic field strength as $Q_j \propto B^2$ and, under the assumption of equipartition $K \propto B^2$. Combining these two relations, we find (Heinz & Sunyaev 2003, their Eq. 16)

$$L_{\mathrm{radio}} \propto Q_j^{1+\frac{\mathrm{p}+1}{4}} \tag{16}$$

For, $2 < \mathrm{p} < 3$ the index is 1.875 ± 0.125.

From the observed X-ray and radio luminosities, we have $L_{\mathrm{radio}} \propto L_{\mathrm{x-ray}}^{2.2\pm0.2}$. Combining these into Eq. 16 results in

$$Q_j \propto \dot{m}^{1.2\pm0.1} \tag{17}$$

4.4. *Coupling between Accretion Rate and Jet Power*

Under the assumption of a constant expansion velocity, our estimate of the jet power scaling obtained in the previous subsection can be translated to a scaling of the jet power with time. Along the jet-axis, $Q_j \propto z^{1.2\pm0.4}$. Under the assumption of a constant expansion velocity, we thus obtain $Q_j \propto t^{-1.2\pm0.4}$. Interestingly, this relation is consistent with the slope of the observed X-ray flux decay, $L_{\mathrm{X-ray}} \propto (t - t_0)^{-1.7\pm0.1}$ (here we fixed the time normalization, t_0, to our estimate of the time when the jet was launched). This X-ray flux decay index is also close to the expected fallback rate of the stellar debris, $t^{-5/3}$ (Phinney 1989). Because the thermal X-ray energy spectrum suggests an efficient accretion disk we expect the X-ray luminosity, $L_{\mathrm{X-ray}} \propto \dot{m}$ (mass accretion rate). We thus find evidence for a linear coupling between the accretion rate and jet power.

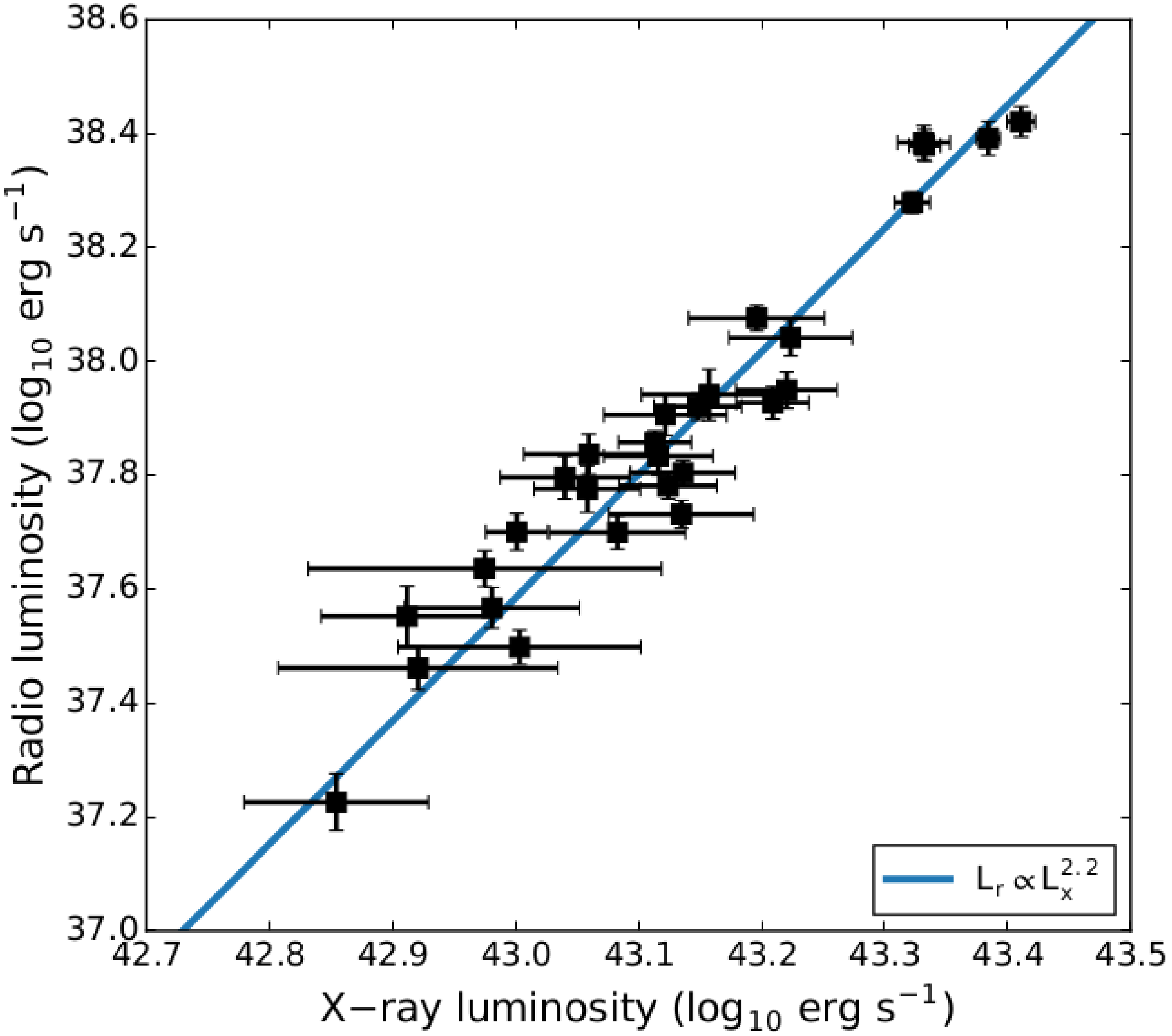


FIG. 5.— X-ray and radio luminosity. Here we show the lead-corrected X-ray luminosity and the 16 GHz radio luminosity (after subtracting the non-transient flux). The correlation between the luminosity in these two wavelengths can be described as $L_{\rm radio} \propto L_{\rm X-ray}^{2.2\pm0.2}$. The reduced χ^2 of the best-fit power-law relation is 0.96. This index suggests that ASASSN-14li's accretion and jet power are linearly coupled (see Sec. 4.4).

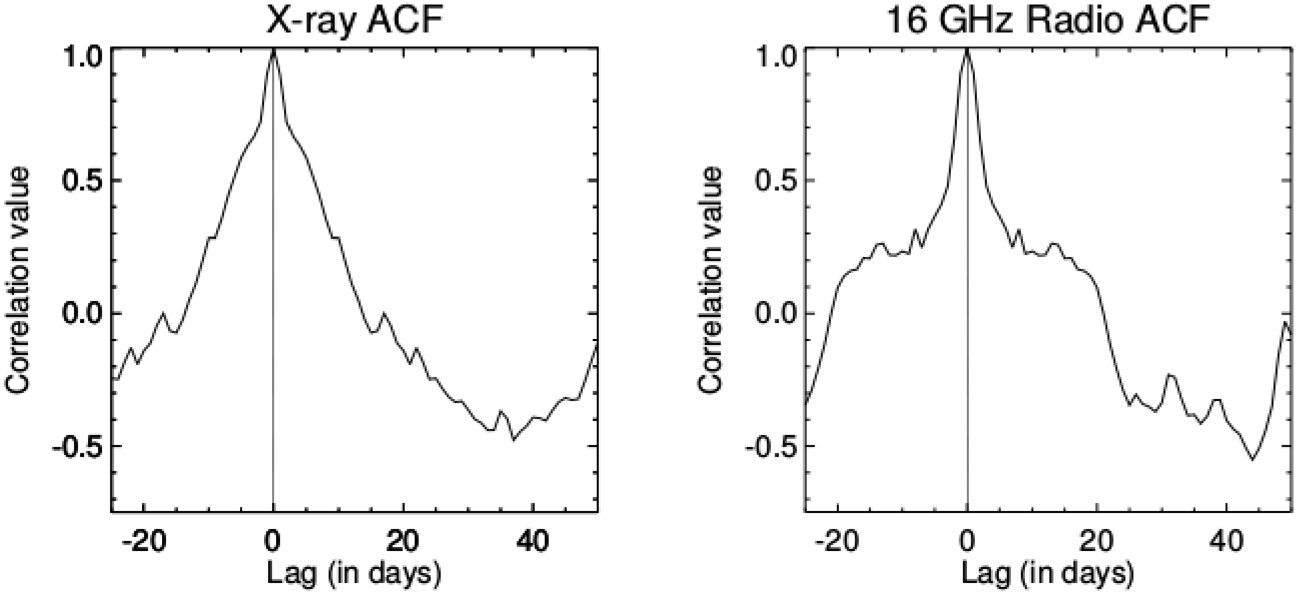


FIG. 4.— X-ray and radio auto-correlation functions (ACFs). The ACF of the X-ray and the radio light curves are shown in the left and the right panels, respectively. Both are obtained using the same CCF parameters as in Fig. 2. The difference in the two ACF shapes is only an artifact of the difference in the sampling of their respective light curves (see Sec. 3.5).