Particle Acceleration and Magnetic-field Amplification by Magnetic Turbulence in the West Hot Spot of Pictor A Revealed with Mid-to-Far Infrared Observations

- Isobe et al. 2017 ApJ, 850, 193
- Isobe et al. 2020 ApJ, 899, 17

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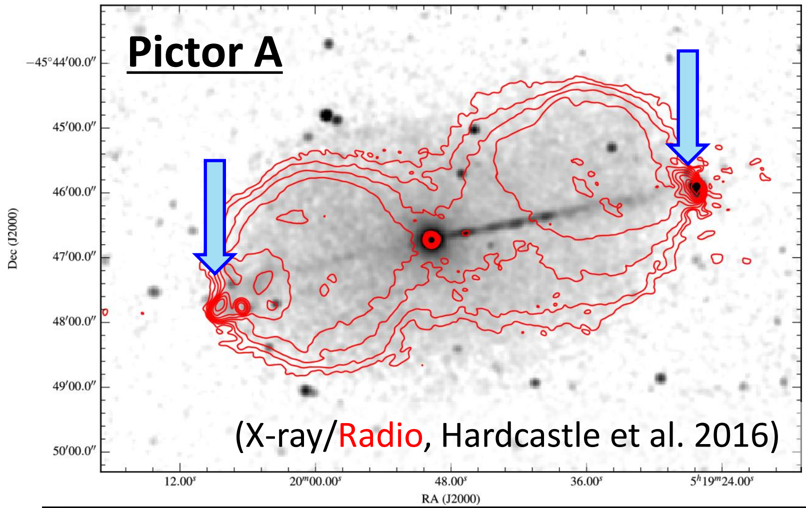
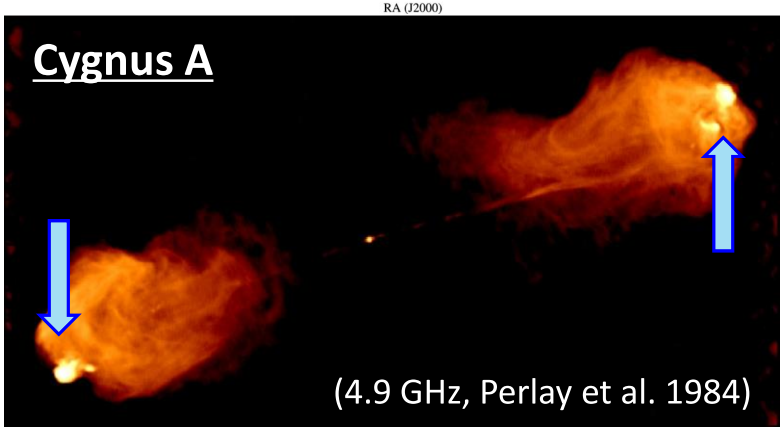
Hot Spots of Radio Galaxies



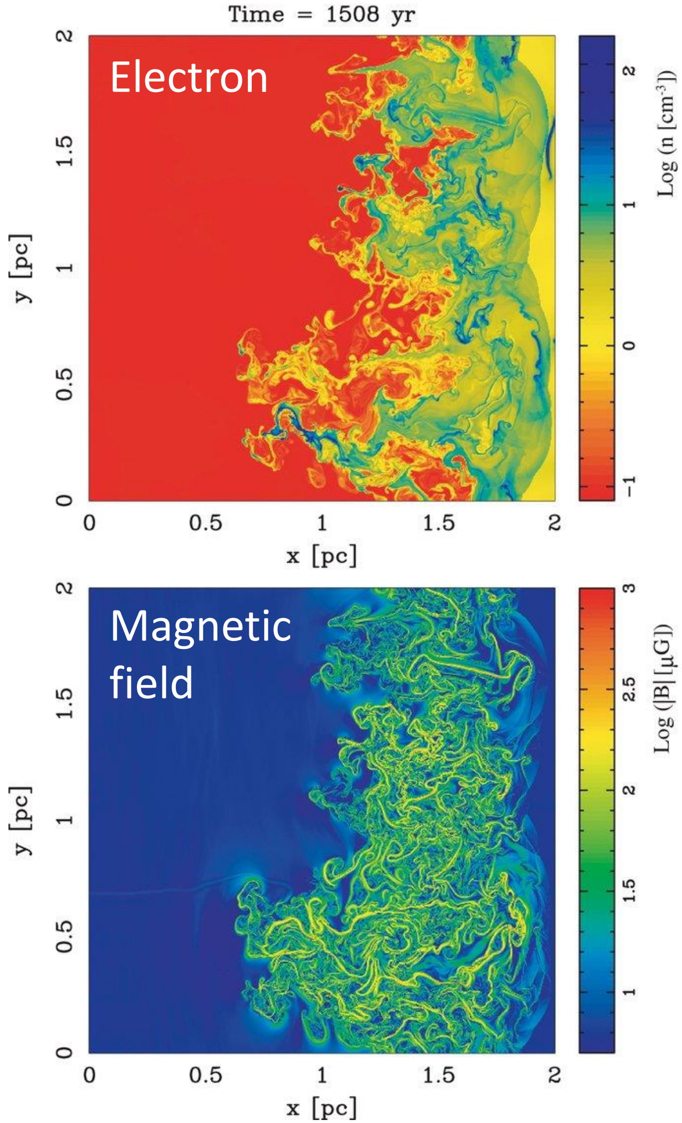
(X-ray/Radio, Hardcastle et al. 2016)



(4.9 GHz, Perlay et al. 1984)

- ✓Compact regions with a high radio flux at the end of the AGN jets
- ✓Strong jet-terminal shocks
- ✓Non-thermal emission from relativistic electrons
  - Synchrotron radio emission
  - Inverse-Compton X-ray emission
- ✓Standard picture
  - Diffusive shock acceleration (Fermi-I acceleration; Begelman et al. 1984)
- ✓One of the most promising candidates for ultra-high energy cosmic rays (E>10^{18} eV; Hillas 1984, Kotera & Olinto,2011)

MHD simulation for the turbulence behind the shock.



(Inoue et al. 2009)

Turbulence in Hot Spots

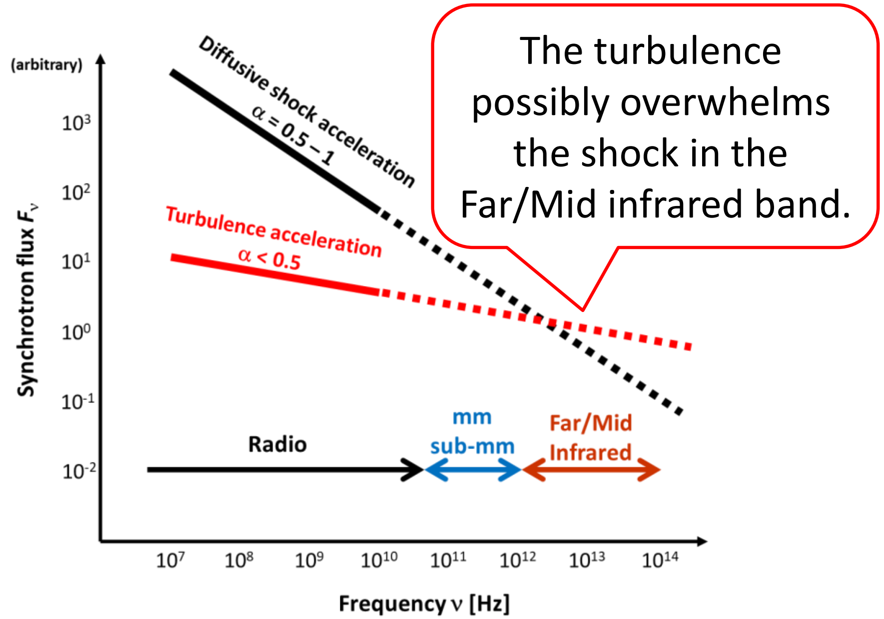
- ✓It is theoretically/numerically predicted that the shocks inevitably induce magnetic turbulence, due to plasma instabilities and/or inhomogeneities.
- ✓Possible roles of the turbulence.
  - ✓ Magnetic-field amplification (e.g., Inoue et al. 2009, 2011, Sano et al. 2012)
  - ✓ Particle acceleration (so-called stochastic acceleration or Fermi-II; Schlickeiser1984)
- ✓The magnetic-field amplification by the turbulence is invoked to explain the strong magnetic field in the X-ray shell/rim of supernova remnants
  - ✓ ~100μG (Bamba et al.2003;Vink & Laming2003)
- ✓No concrete observational evidence has not yet obtained for the turbulence acceleration in the hot spots
  - ✓ except for a few observational indications (Orienti et al. 2017) and theoretical applications (e.g., Asano et al. 2009, 2014, 2015, 2018)

Impotence of Infrared Observation to Search for Turbulence Acceleration

✓The turbulence acceleration is expected to be a slow process.
- Its synchrotron flux negligible in the radio band.

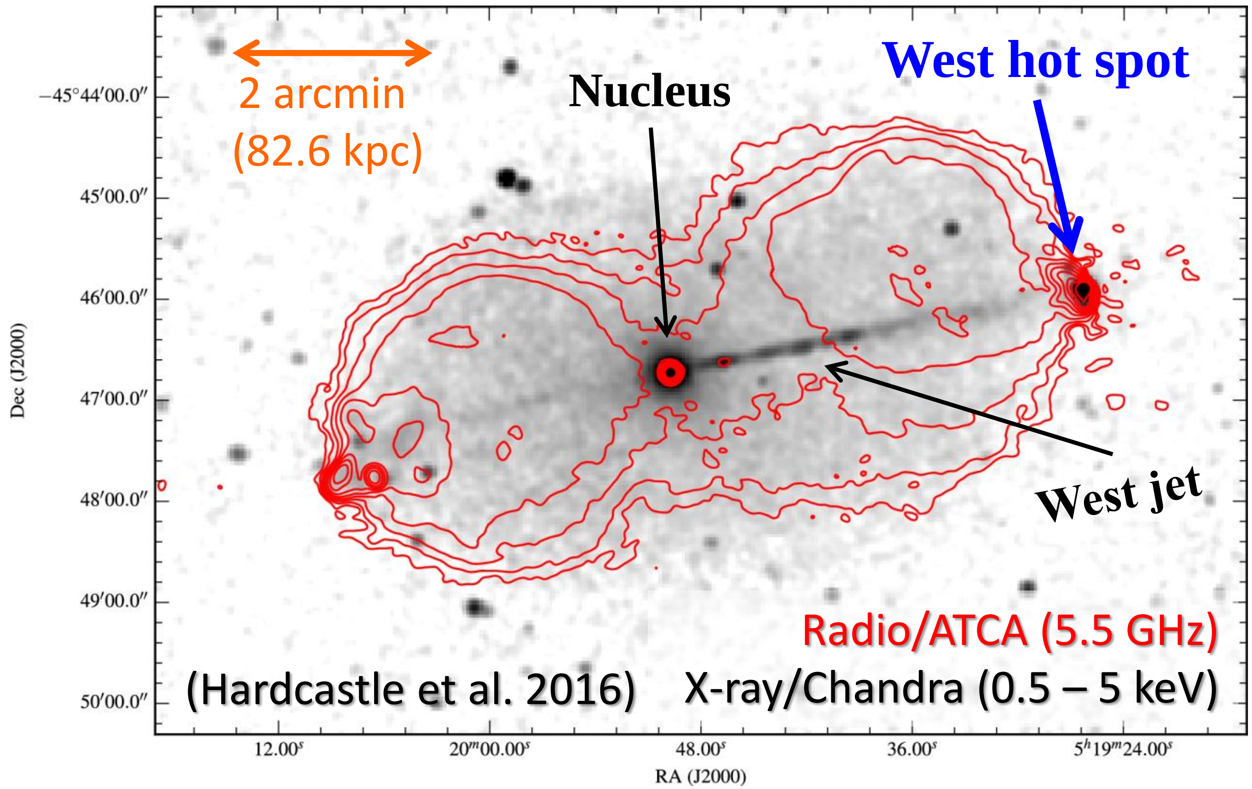
✓The spectrum of the turbulence acceleration is significantly harder than that of the diffusive shock acceleration.
- Spectrum of magnetic turbulences
  - ✓ $|\delta B^2|_k \propto k^{-q}$ $(1 < q < 2)$
  - ✓ k: Wave number of turbulences
- Electron spectrum
  - ✓ $N(\varepsilon_e) \propto {\varepsilon_e}^{-p} \propto \gamma^{-p}$
  - ✓ $p = q - 1$
- Synchrotron spectrum
  - ✓ $F_\nu \propto \nu^{-\alpha}$
  - ✓ Energy index: $\alpha = \frac{p-1}{2}$

(e.g., Asano et al. 2014)

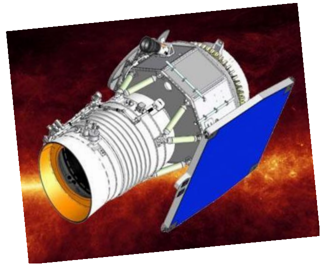


	Turbulence		Strong shock
	Kolmogorov	Hard sphere	
Turbulence q	$5/3$	2	–
Electron p	$2/3$	1	2
Synchrotron α	$-1/6$	0	0.5

The West Hot Spot of the Radio Galaxy Pictor A



Herschel (Far infrared)

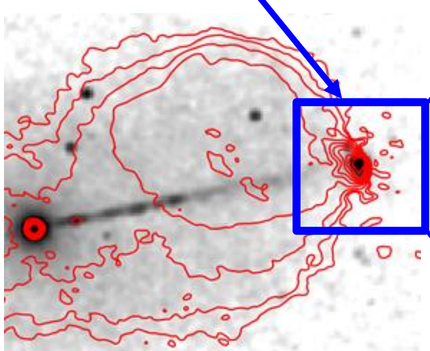


WISE (Mid infrared)

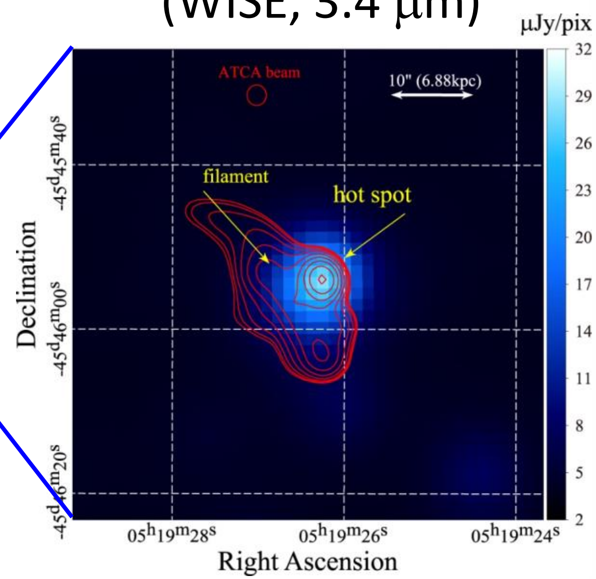
- One of the brightest and most extensively studied hot spots, thanks to its proximity ($z = 0.035$, $D_L = 151.9$ Mpc)
- Optical emission is detected (e.g., Thomson et al.1995)

Far/Mid Infrared Observation of the Pictor A West Hot Spot

West hot spot

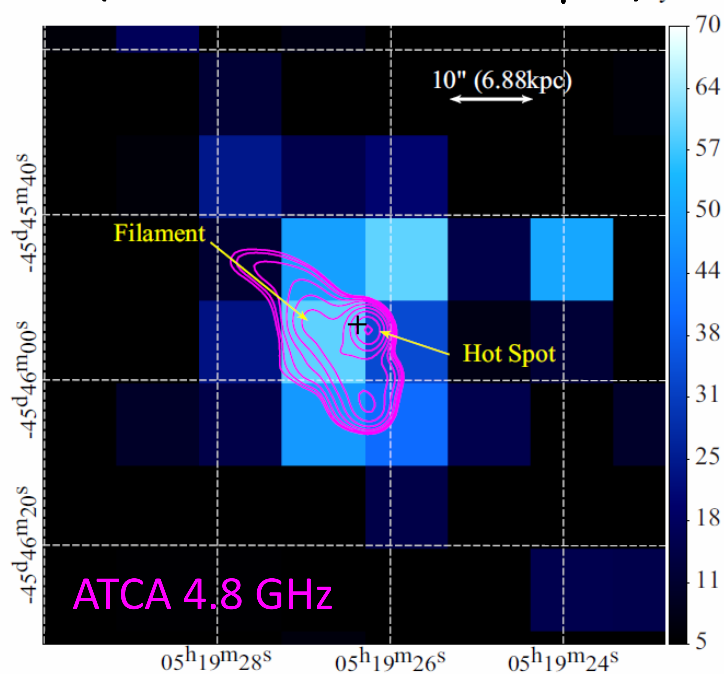


Mid infrared image
(WISE, 3.4 μm)



(Isobe et al. 2017)

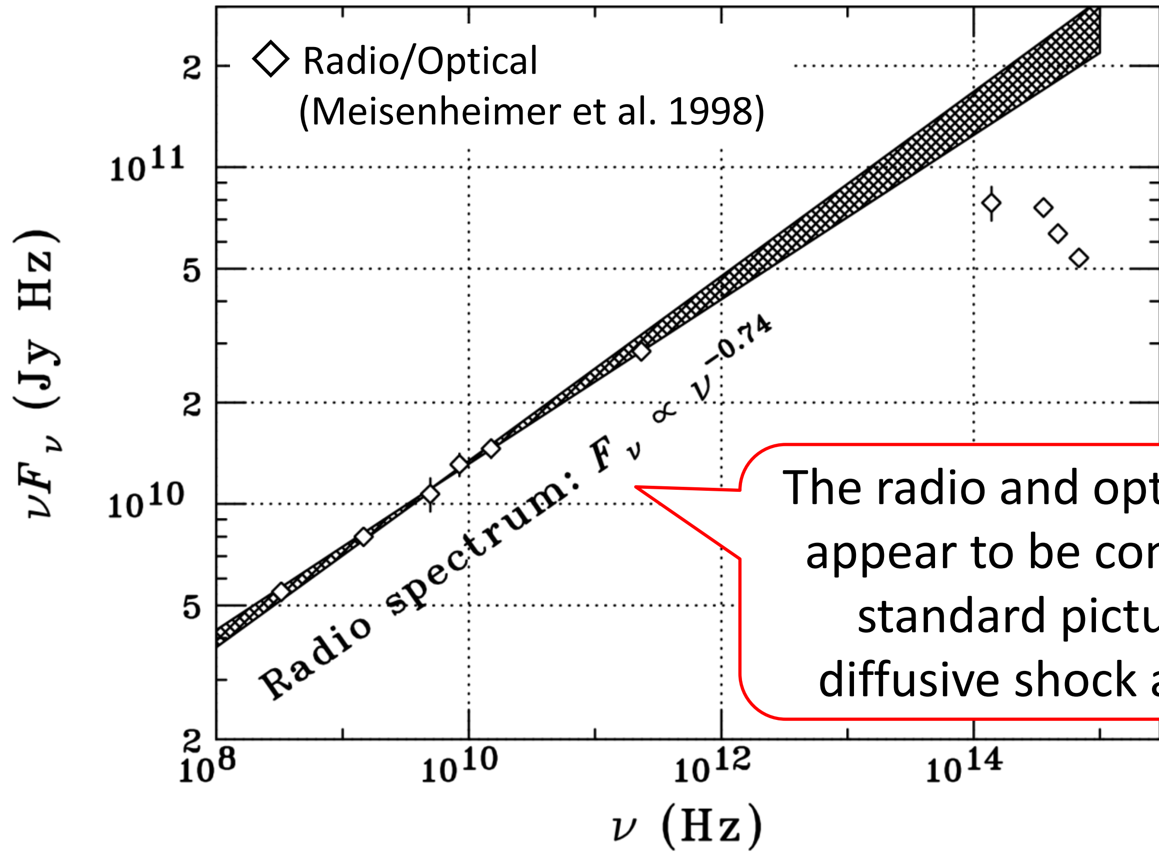
Far infrared image
(Herschel/SPIRE, 350 μm)



(Isobe et al. 2020)

(ATCA data kindly provided by Dr. Lenc)

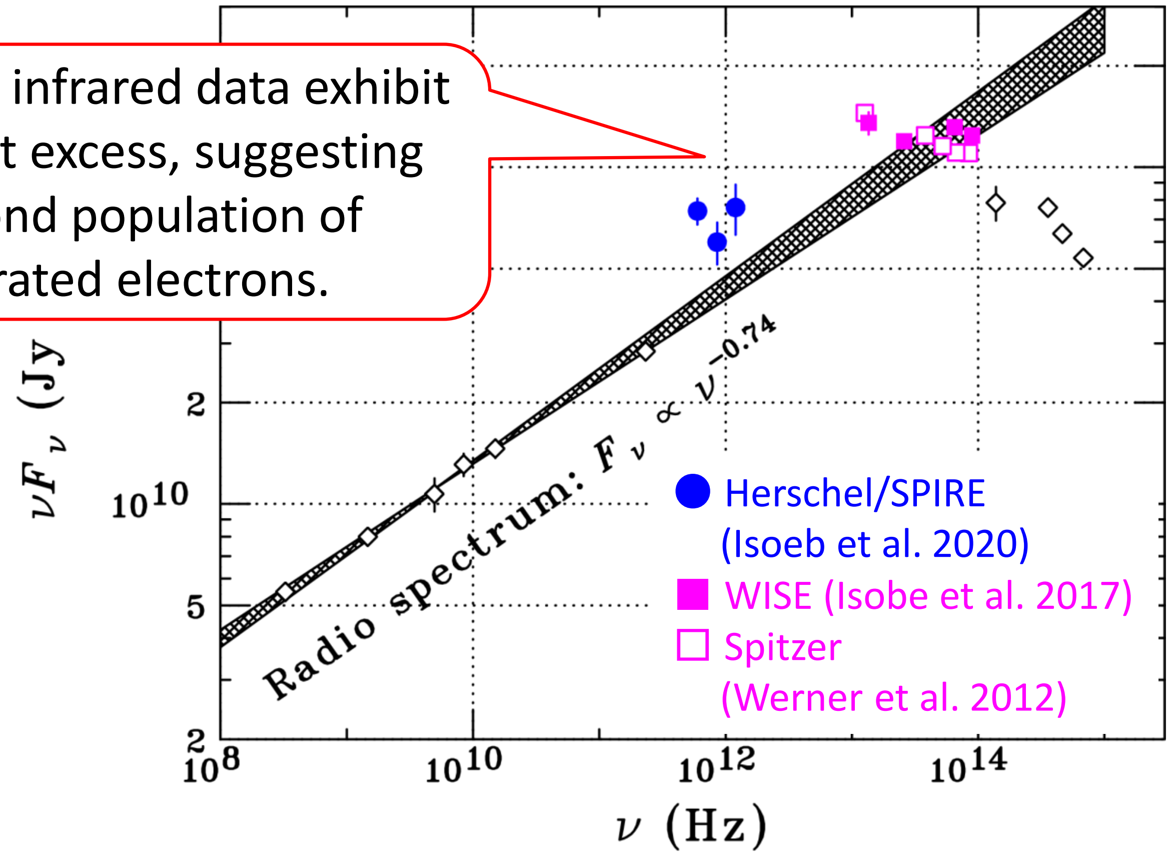
Spectral energy distribution of the Pictor A west hot spot



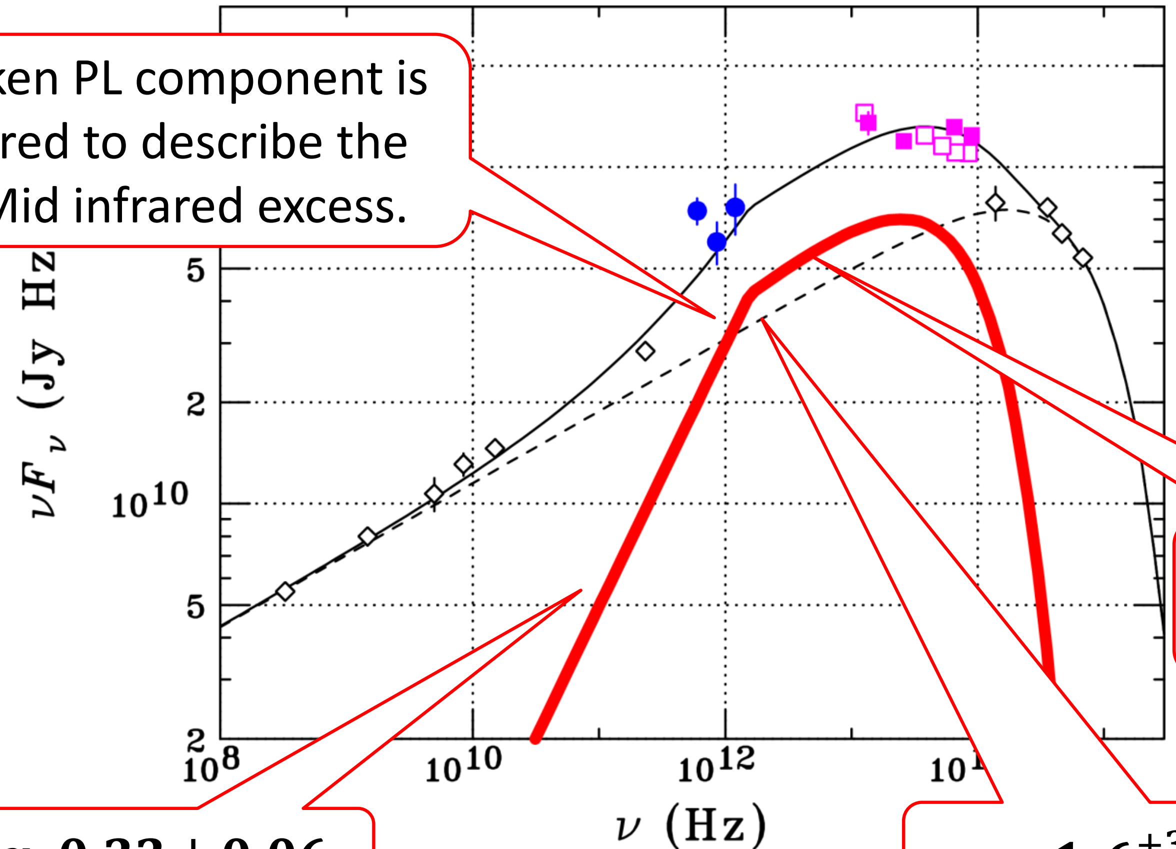
The radio and optical data alone appear to be consistent to the standard picture (i.e., the diffusive shock acceleration).

Discovery of the Far/Mid infrared excess

The Far/Mid infrared data exhibit a significant excess, suggesting the second population of accelerated electrons.

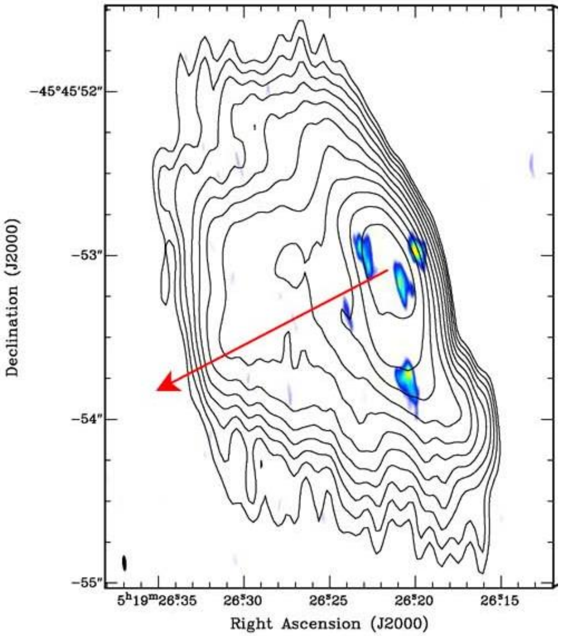


Discovery of the Far/Mid infrared excess

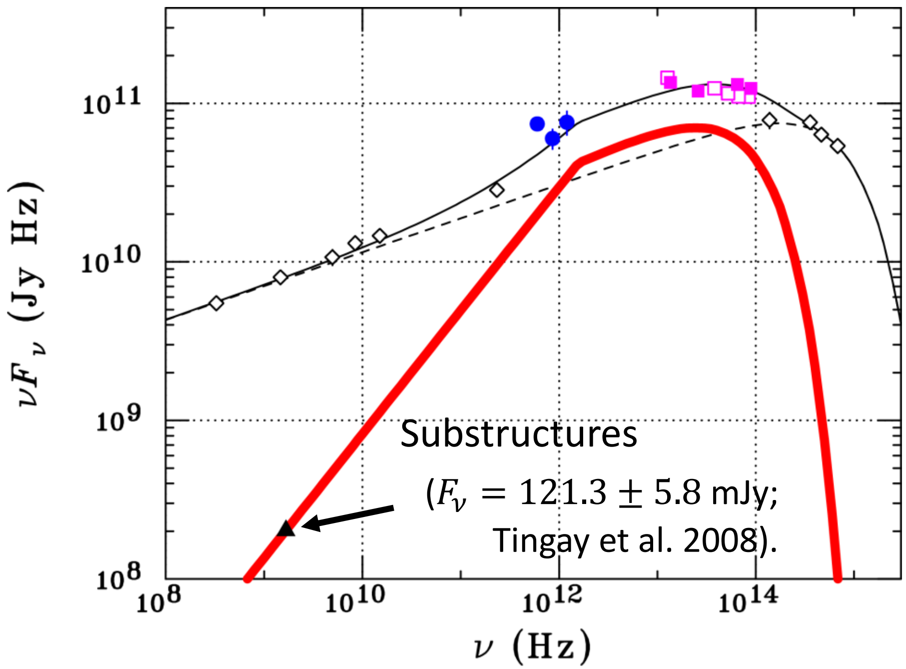


Origin
of the Far/Mid Infrared excess

Substructures within the Pictor A west hot spot



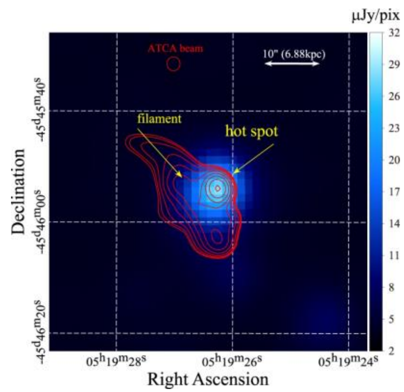
1.67 GHz VLBA (color)
15 GHz VLA (contour)
(Tingay et al. 2008)

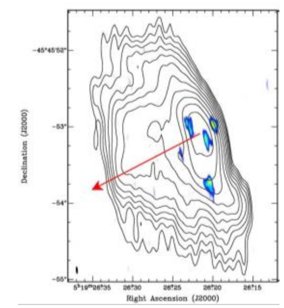


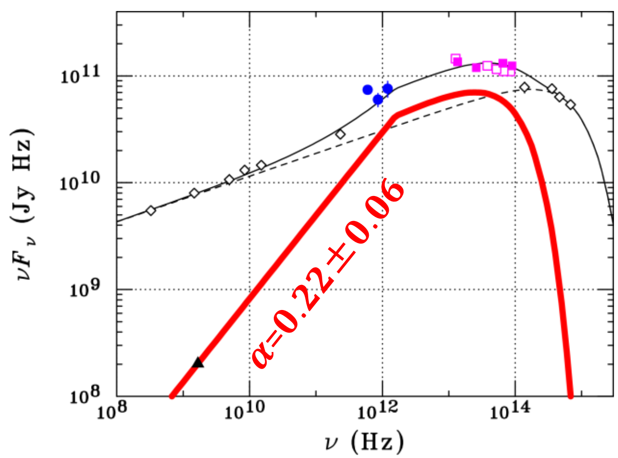
The Far/Mid excess is indicated to originate in the substructures.

Acceleration process for the Far/Mid Infrared excess

- ✓The spectrum of the Far/Mid IR excess is difficult to be explained by the diffusive shock acceleration in the hot spots.
  - ✓$\alpha = 0.22 \pm 0.06$ for the Far/Mid IR excess below the break
  - ✓$\alpha > 0.5$ for the diffusive shock acceleration.
- ✓The turbulence acceleration is a promising process for generating a hard spectrum.
  - ✓The spectrum of the Far/Mid IR excess is slightly softer than that of the turbulence acceleration
    - ✓ $\alpha = 0$ for the hard sphere limit (i.e., the softest case).
  - ✓The spectral softening by such as particle escape is required.







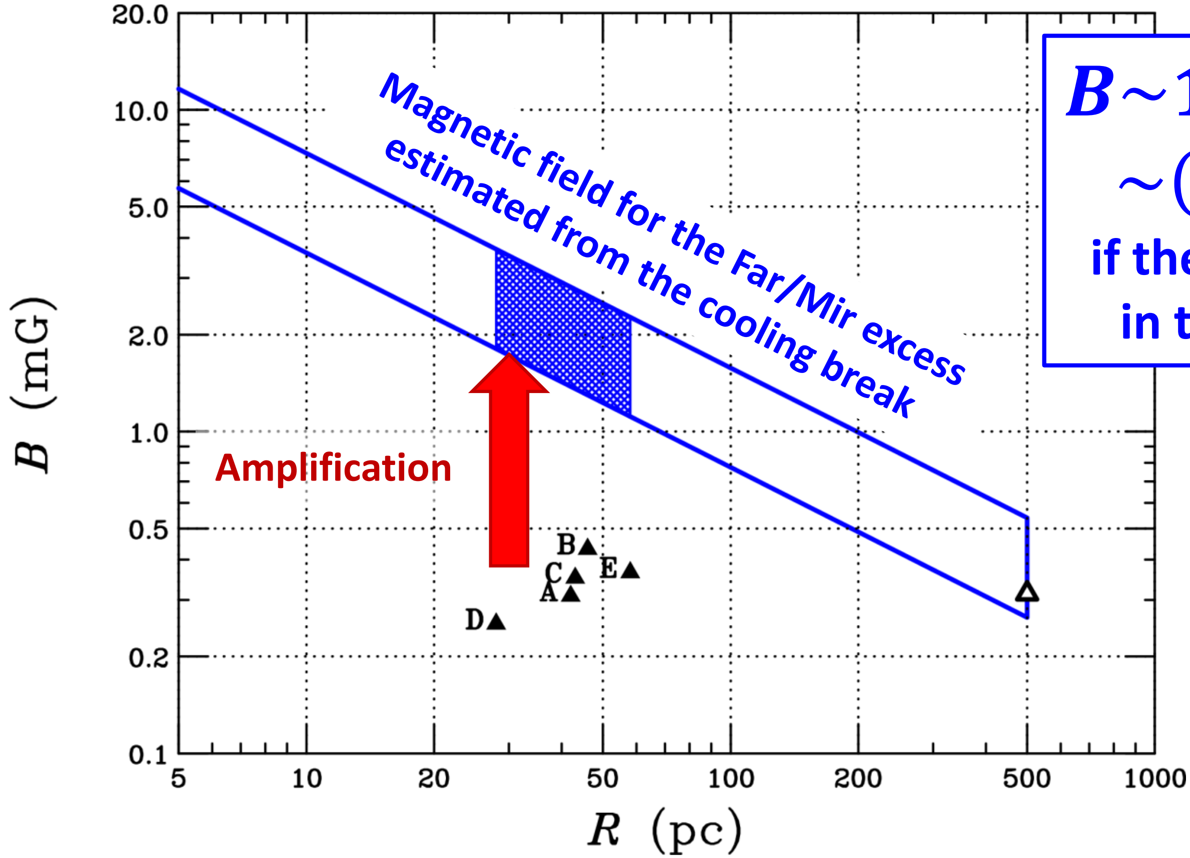
The origin of the Far/Mid infrared excess is the substructures within the hot spot where the electrons are energized via the turbulence acceleration.

Estimation of the magnetic field

- ✓The broken PL model for the Far/Mid excess satisfies **the radiative cooling break under the continuous energy injection.**
  - ✓$\Delta\alpha = 0.5$ (e.g., Carilli et al. 1991)
- ✓Electron Lorentz factor at **the cooling break**: $\gamma_b = \frac{6\pi v m_e c^2}{\sigma_T B^2 R}$ (1)
  - ✓ $t_{\mathrm{rad}} = t_{\mathrm{ad}}$ (e.g., Inoue and Takahara 1996)
    - ✓ Radiative cooling timescale: $t_{\mathrm{rad}} = \frac{3 m_e c}{4 u_B \sigma_T \gamma}$ (neglecting the inverse Compton cooling)
    - ✓ Adiabatic loss time scale: $t_{\mathrm{ad}} = \frac{R}{v}$
- ✓Synchrotron critical frequency at the break: $\nu_{\mathrm{b}} = \frac{3 {\gamma_{\mathrm{b}}}^2 eB \sin\theta}{4\pi m_e c}$ (2)
- ✓**Magnetic field** estimated from the cooling break
  - ✓$B^3 \backsimeq \frac{27\pi e m_e v^2 c}{{\sigma_T}^2} R^{-2} {\nu_{\mathrm{b}}}^{-1}$ (3)
    - ✓ R: region size (Adopting the size of the substructures)
    - ✓ v: downstream flow velocity ($v = 0.3c$ is assumed; e.g., Kino & Takahara 2004)

$\boldsymbol{\nu_{\mathrm{b}} = 1.6^{+3.0}_{-1.0} \times 10^{12}}$ **Hz**

Estimation of the magnetic field



$B \sim 1 - 4$ mG $\sim (3 - 10)\, B_{\mathrm{me}}$
if the excess originates in the substructures

Minimum-energy magnetic field B_{me} (Miley 1980)

▲ Substructures

△ West Hot Spot

Consistent to the picture of magnetic field amplification by the turbulence.

Summary and conclusion

- ✓Far/Mid infrared observations are a possible probe for the turbulence acceleration in the hot spots of radio galaxies.
  - ✓Thanks to the spectral hardness of the turbulence acceleration, its synchrotron spectrum is possible dominates that of the diffusive shock acceleration, in the Far/Mid infrared band.
- ✓By making most of the Herschel and WISE data, we searched for the signature of the turbulence acceleration in the west hot spot of Pictor A.
- ✓ The Far/Mid infrared excess synchrotron emission is detected over the radio and optical synchrotron spectrum from the west hot spot of Pictor A.
- ✓The Far/Mid excess is successfully described by a broken PL model.
  - ✓The radio flux is consistent to that of the substructures within this hot spot.
  - ✓The spectrum below the break ($\alpha = 0.22 \pm 0.06$) is harder than that of the diffusive shock acceleration ($\alpha > 0.5$) .
- ✓The Far/Mid excess is suggested to originate in the 10-pc scale substructures within the hot spot, where the magnetic turbulence plays two important roles.
  - ✓In order to interpret the hard spectrum of the Far/Mid infrared excess, the turbulence acceleration is required.
  - ✓The strong magnetic field of the excess estimated from the cooling break condition is consistent to the magnetic-field amplification due to the turbulence.