Spectral Analysis of Parsec-Scale Jet in M87

Observational Constraint on the Magnetic Field Strengths in the Jet

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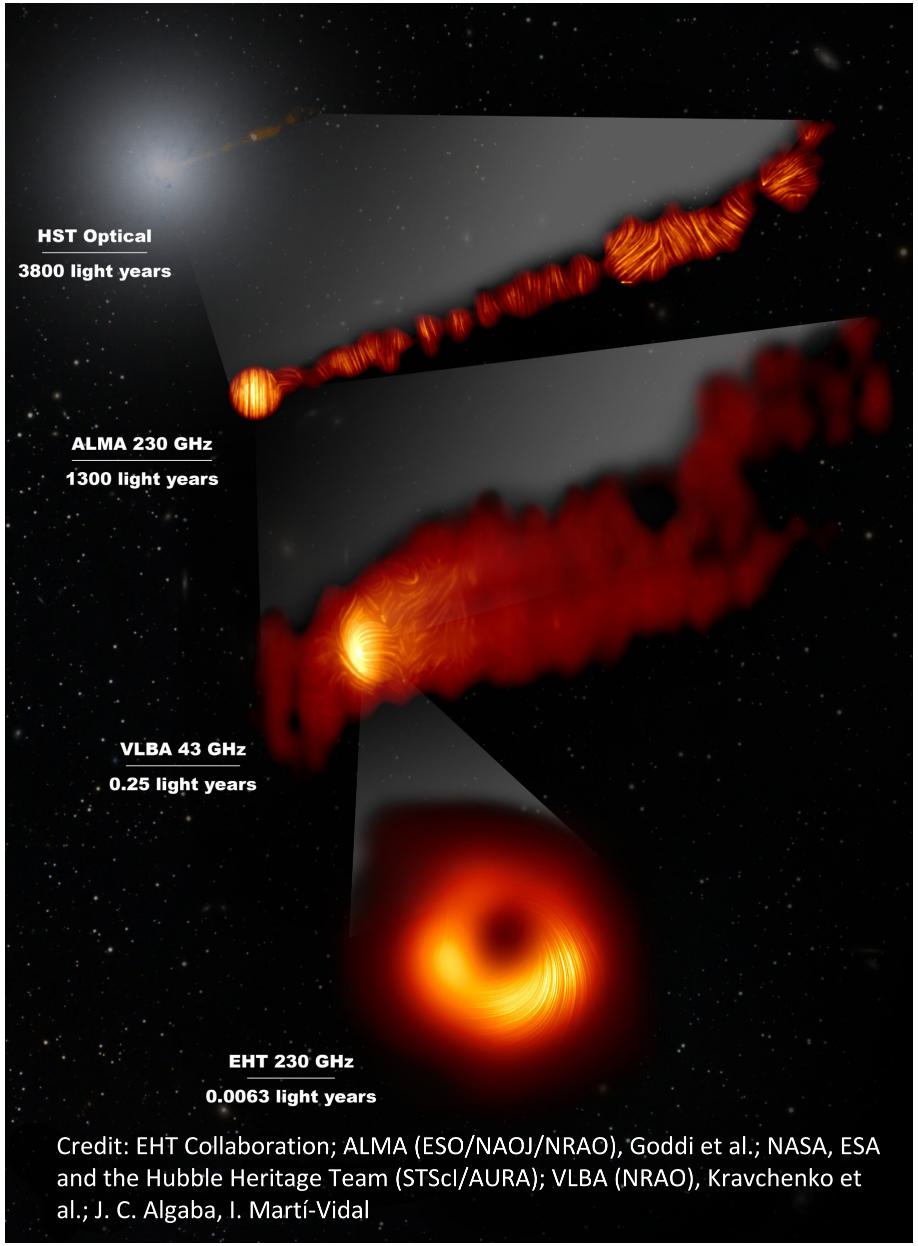
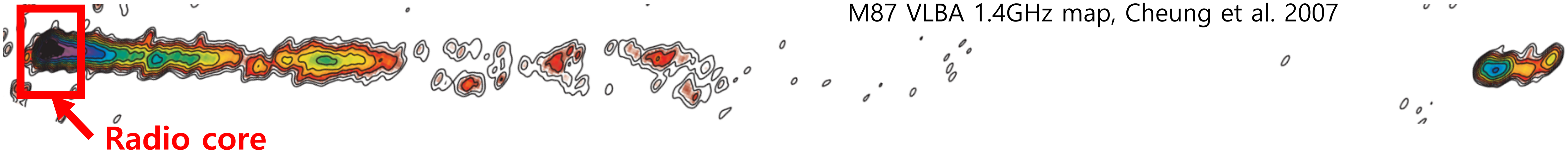
M87 jet

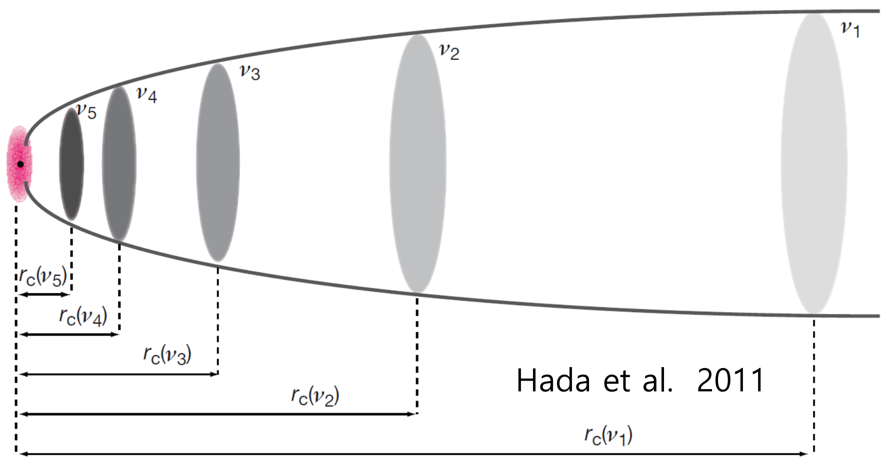


- 1mas ~ 130r_S (D_L = 16.7 Mpc, $M_{BH} = 6.5\times10^9\ M_\odot$)
- Jet width profile: $\boldsymbol{R(z) \propto z^{0.56}}$ (e.g., Hada et al. 2013)
- Velocity profile: $\boldsymbol{\Gamma(z) \propto z^{0.16}}$ (e.g., Park et al. 2019)
- **The magnetic field strength of the radio core** was estimated by various methods (e.g., Zamaninasab et al. 2014; Kino et al. 2015; EHT collaboration et al. 2019, 2021)
  - Core is highly magnetized (~100G at ~1r_S; Kino et al. 2015)

Observational constraints on jet magnetic field strengths



M87 VLBA 1.4GHz map, Cheung et al. 2007



Hada et al. 2011

- **Jet base (radio core; z $\lesssim 100 r_s$)**
  - **Size and flux measurement of core:** $B \propto \theta^4 \nu_m^5 S_m^{-2}$ (e.g., Kino et al. 2015)
  - **Core-shift :** $B \propto \left(\frac{\Delta r_{\mathrm{core},\nu_1,\nu_2}}{\nu_1^{-1} - \nu_2^{-1}}\right)^{\frac{3}{4}}$ (e.g., Zamaninasab et al. 2014)

Motivations and Question

M87 VLBA 1.4GHz map, Cheung et al. 2007

- Previous studies estimated the **magnetic field strengths of notable individual components (radio core, HST-1)**

Q: How to estimate the distribution of B field strengths of the jet?

In this study,

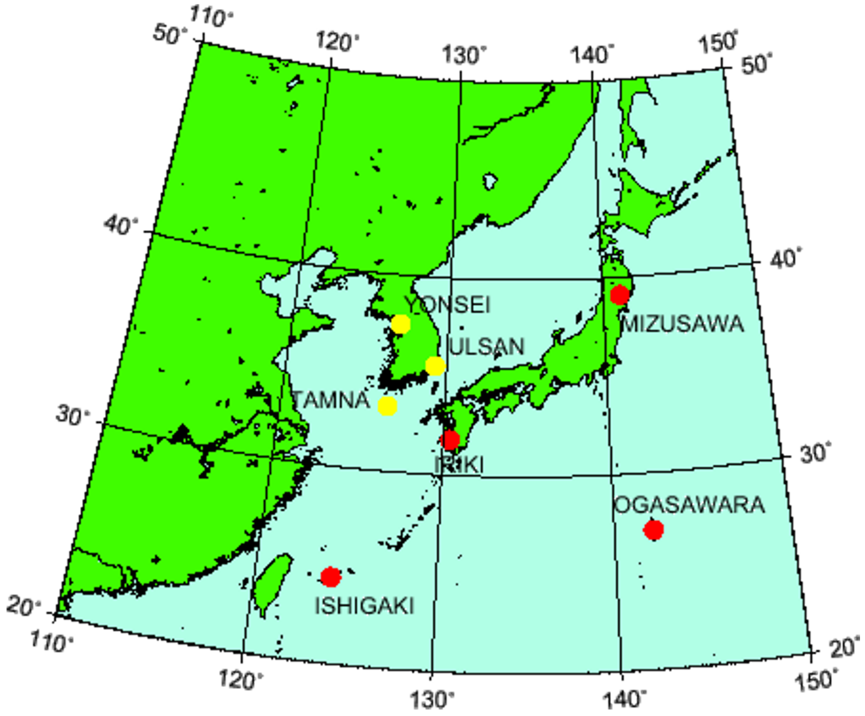
- **Analyze the spectral evolution along the jet** to constraint on **the magnetic field distribution and non-thermal electron injection of the jet on the scale of** $\gtrsim \mathbf{1000}r_s$

- **High quality spectral index maps of the M87 jet** are obtained by quasi-simultaneous **22GHz and 43GHz observations** using **KaVA** (KVN and VERA) large program and VLBA archival data

Observations

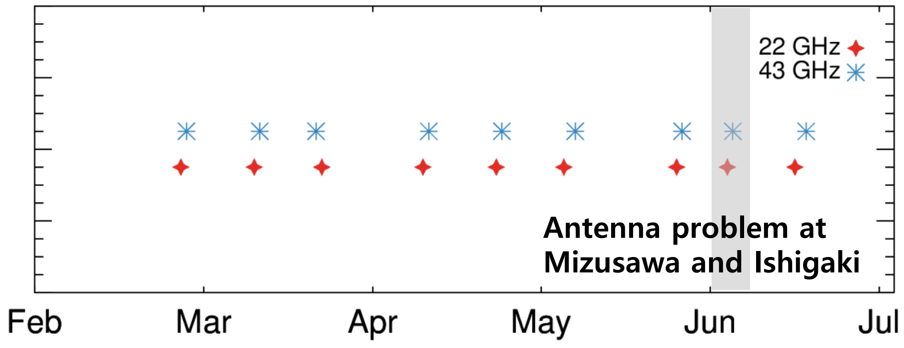
1. KaVA (KVN and VERA Array)

- Observation time: **2016 February – 2016 June**, **9 epochs** (~130 hours in total)
- Quasi-simultaneous observations: 22 and 43 GHz observations interval within 1-2 days
- Typical beam size: 1.2 mas (22GHz), 0.6 mas (43GHz)



2. VLBA archival data

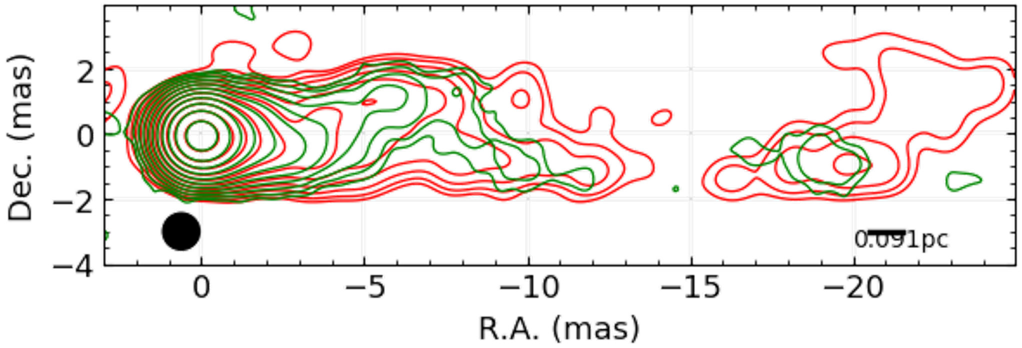
- A total of **five observations**: two in **2010 and** three in **2014**
- Simultaneous multi-frequency observations 22 and 43GHz
- Typical beam size: 0.8 mas (22GHz), 0.4 mas (43GHz)



9 epochs, quasi-simultaneous at 22/43 GHz observations in 2016

Making spectral index maps

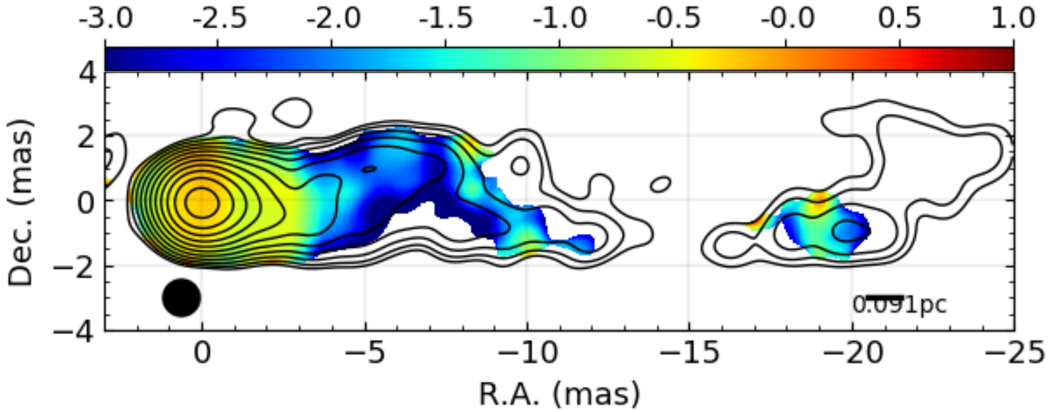
22GHz intensity contours
43GHz intensity contours (shifted)



Calculate spectral index of each pixel

$$\alpha_{22/43} = \frac{\log(S_{22}/S_{43})}{\log(22/43)}$$

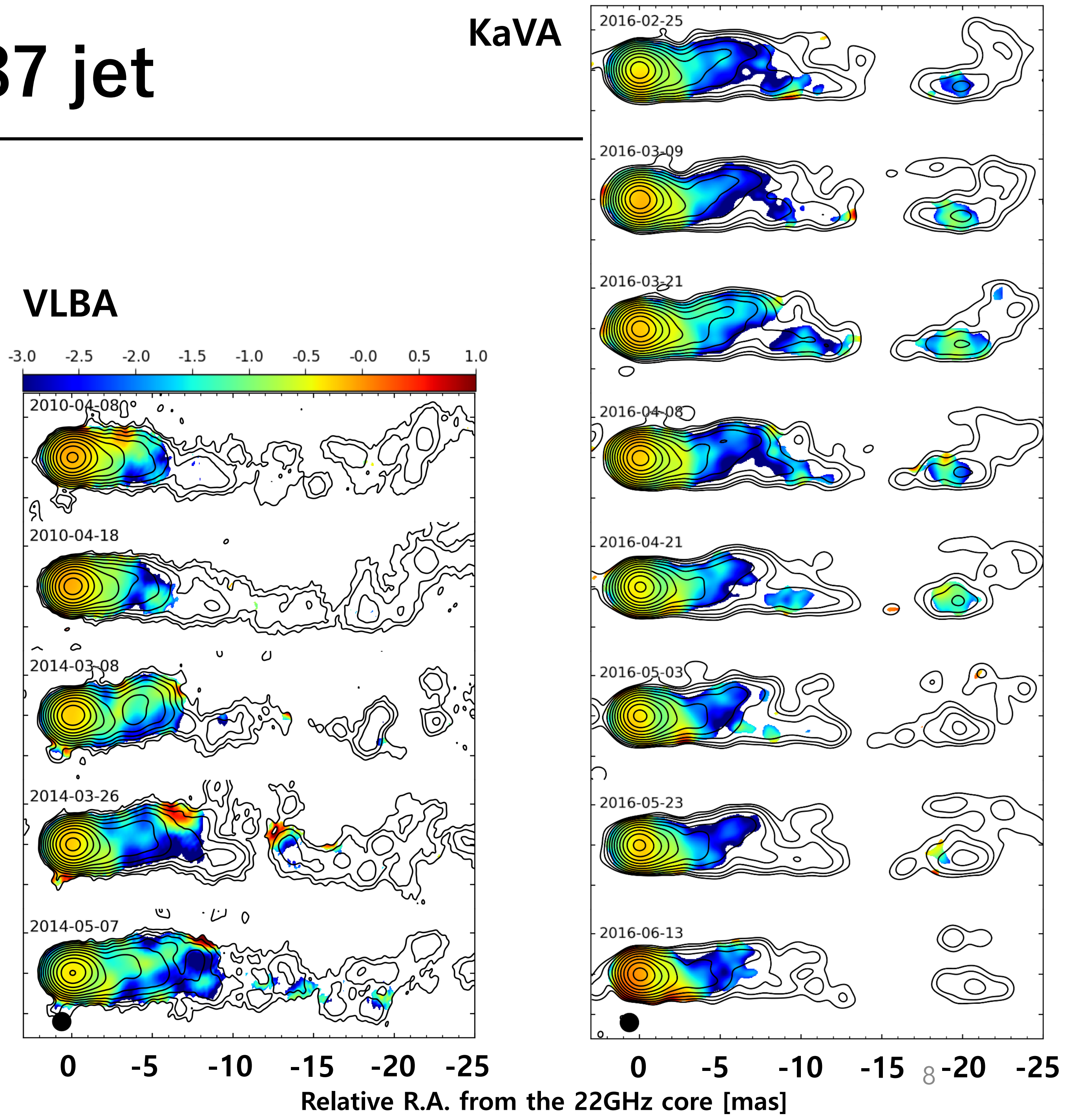
Spectrum index map (color map)



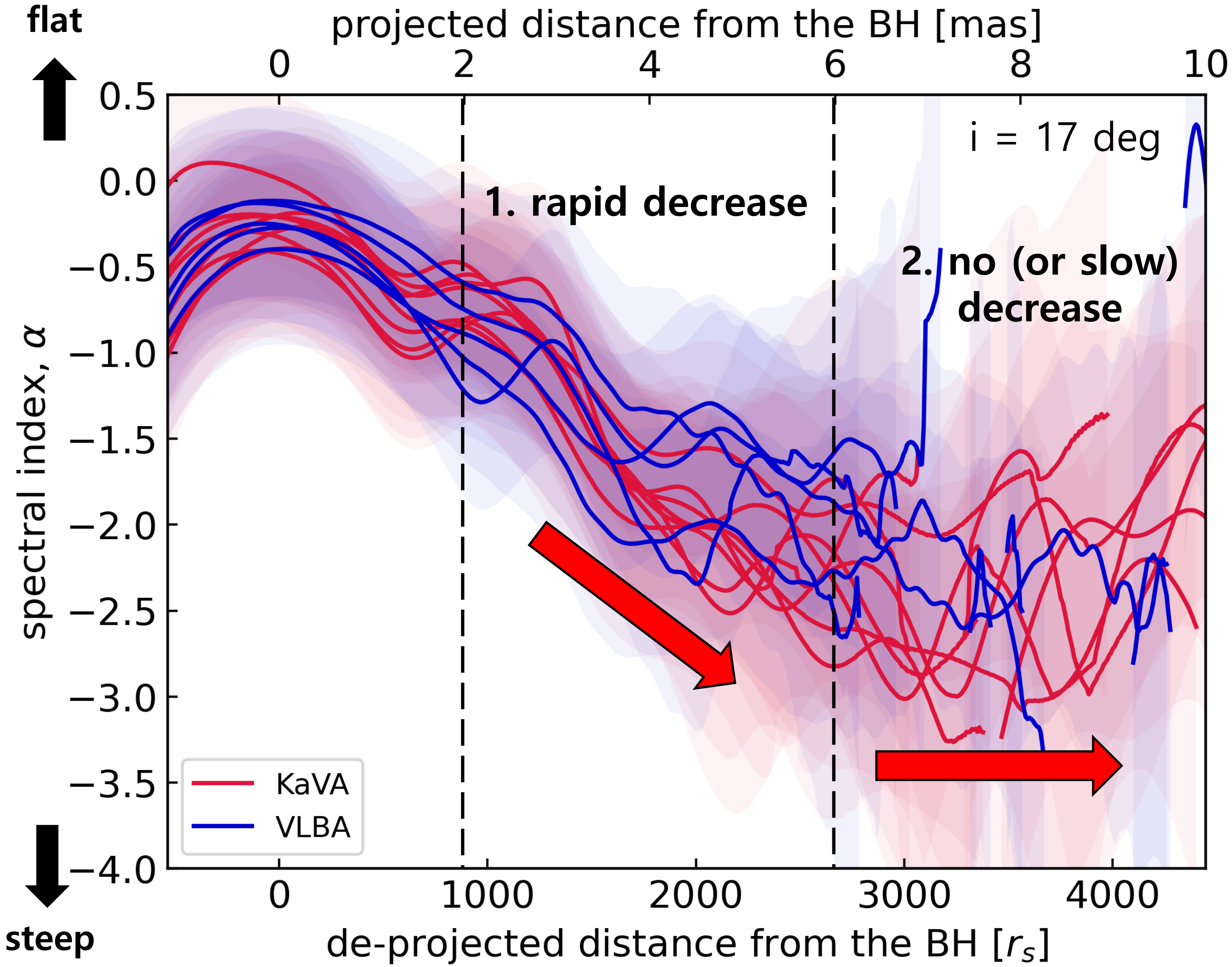
- Convolved beam size: **1.2mas circular beam**
- **Aligning images** at different frequencies
  - $r_{\rm core} \propto \nu^{-0.94}$ (Hada et al. 2011)
  - $\Delta r_{\rm core}(22-43\mathrm{GHz})$ ~ **0.036 mas**

Spectral index maps of M87 jet

- **Spectral indices** can be obtained **up to ~10 mas from the core**
  - **More than double than** had been **previously observed** (Ly et al. 2007; Niinuma et al. 2014; Kravchenko et al. 2020)



Spectral index distribution of M87 jet



Spectral index distributions of the M87 jet up to 10 mas (~4500 r_s)

Two interesting features in the **region further than ~2 mas**

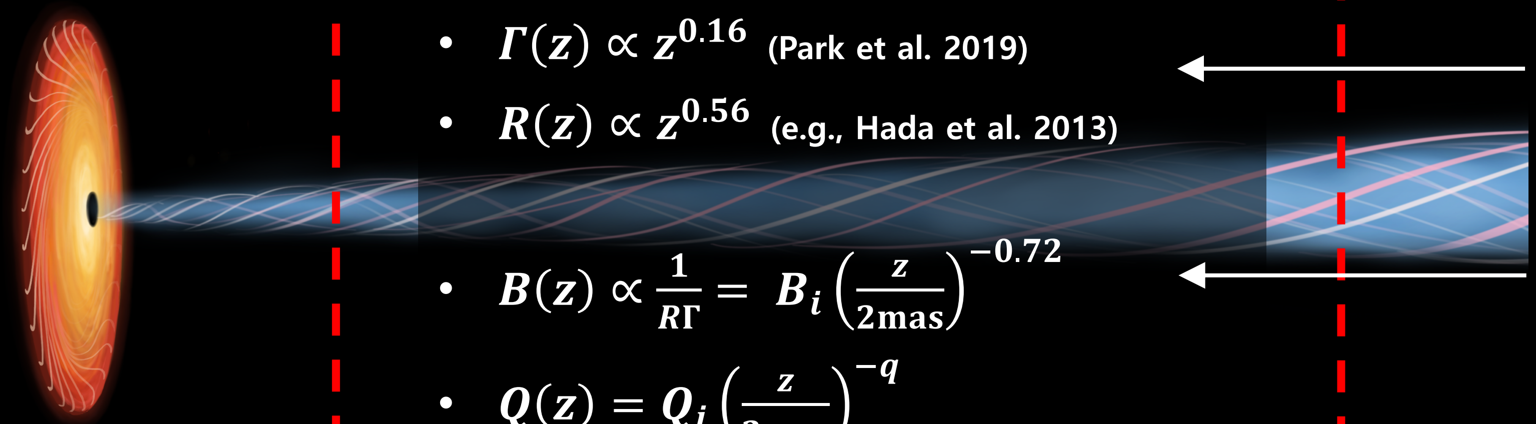
1. The spectral indices **decrease rapidly** with distance (from $\boldsymbol{\alpha \sim -0.7}$ **to** $\boldsymbol{\alpha \sim -2.5}$)

2. The spectral index seems to **stop declining at ~6 mas**

Spectral index distribution model

z_i=2mas (~900r$_s$, τ_i=0s)

z_f=10mas (~4500r$_s$, τ_f=2.2×10^{8}s)



- $\Gamma(z) \propto z^{0.16}$ (Park et al. 2019)
- $R(z) \propto z^{0.56}$ (e.g., Hada et al. 2013)
- $B(z) \propto \frac{1}{R\Gamma} = B_i\left(\frac{z}{2\mathrm{mas}}\right)^{-0.72}$
- $Q(z) = Q_i\left(\frac{z}{2\mathrm{mas}}\right)^{-q}$
  - $Q_i \propto \gamma^{-2.4}$ $\quad (10^1 < \gamma < 10^5)$

Bulk jet velocity and **Jet radius**

- travel time, adiabatic loss

Toroidal magnetic field

- magnetic flux is conserved
- B_i : the magnetic field strength at z_i

Non-thermal electron injection

- $q = 0$: **continuous injection** in the same amount as Q_i
- $q = \infty$: **no injection** after the initial injection
- $0 < q < \infty$: **continuous injection**, but the **amount of injection decreases with distance**

Transfer equation: evolution of $N(\gamma, \tau)$

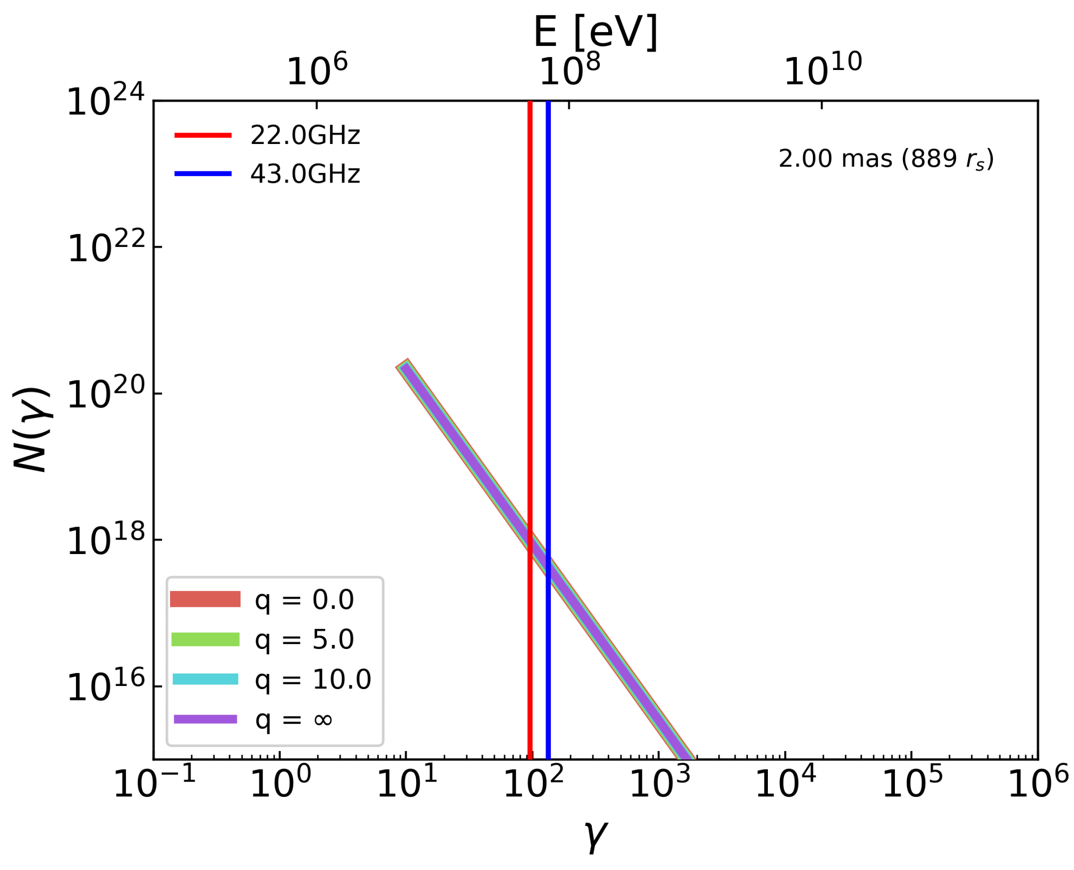
- $\frac{\partial N(\gamma,\tau)}{\partial \tau} + (\nabla \cdot v)N(\gamma,\tau) + \frac{\partial}{\partial \gamma}[b(\gamma,\tau)N(\gamma,\tau)] = Q(\gamma,\tau)$

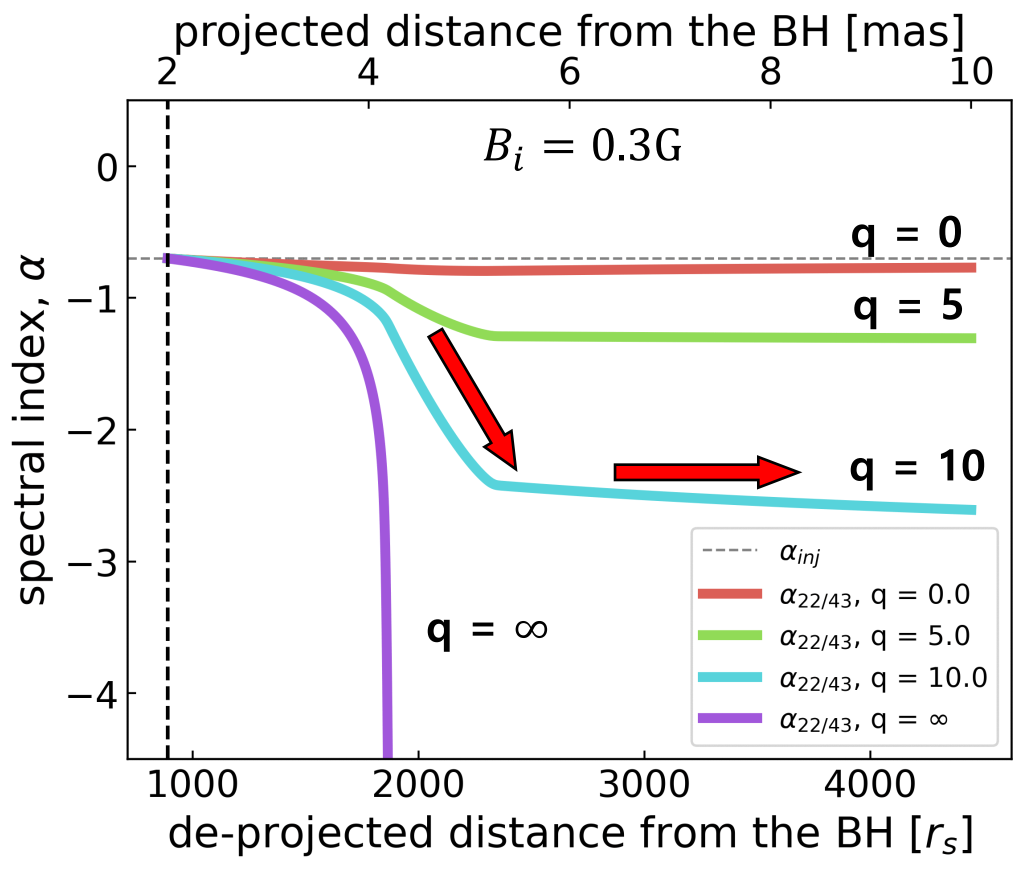
$$b(\gamma,\tau) = -\underbrace{\frac{1}{R}\frac{dR}{d\tau}\gamma}_{\text{adiabatic loss}} - \underbrace{\frac{4}{3}\frac{\sigma_T}{m_e c}\frac{B^2}{8\pi}\gamma^2}_{\text{synchrotron loss}}$$

- $\tau(z)$: travel time along the jet
- $\alpha = (p+1)/2 \quad$ (p : the slope of $N(\gamma)$)

How to explain the observed spectral index distribution?

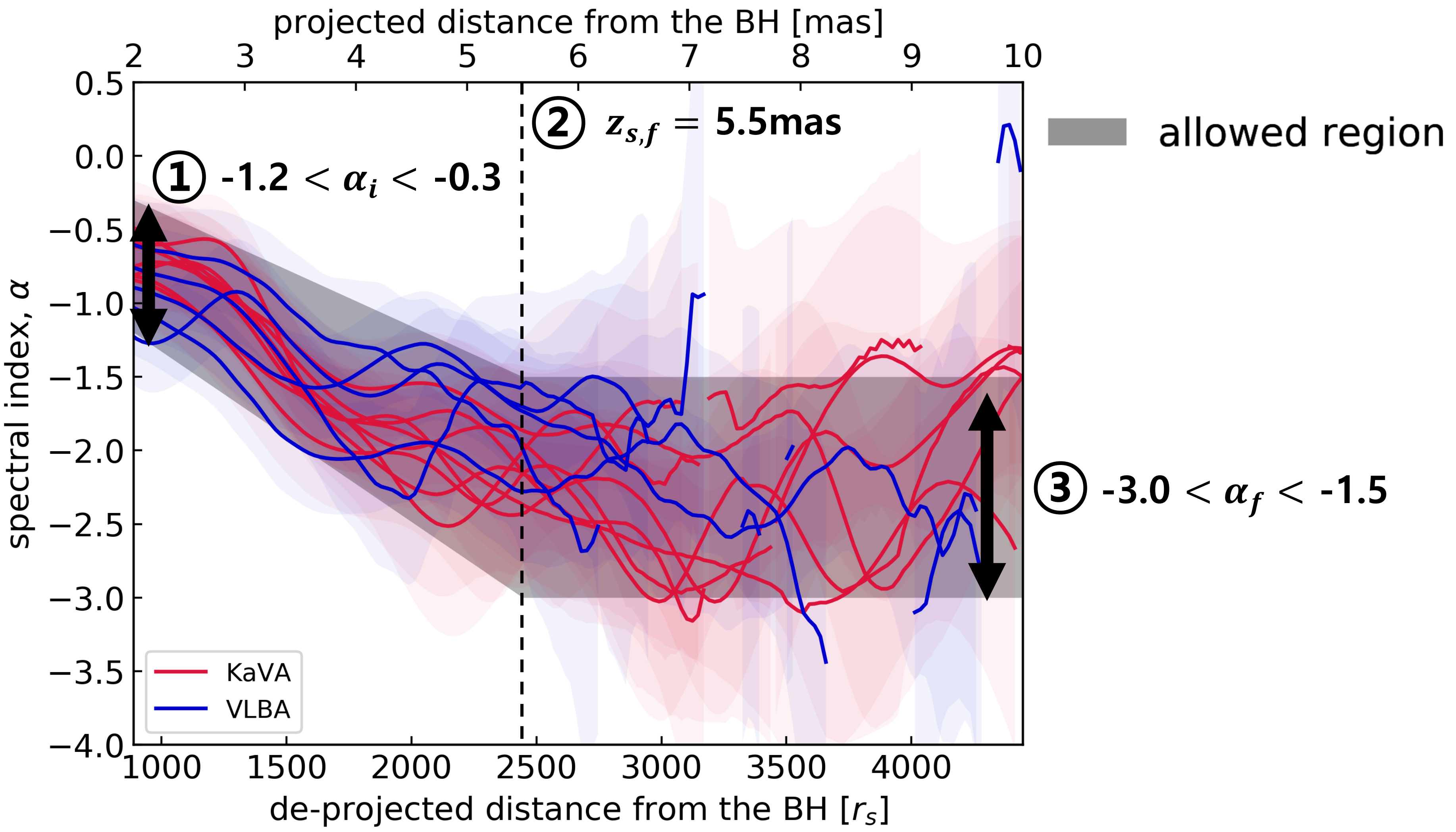
Spectral index models with different non-thermal electron injections



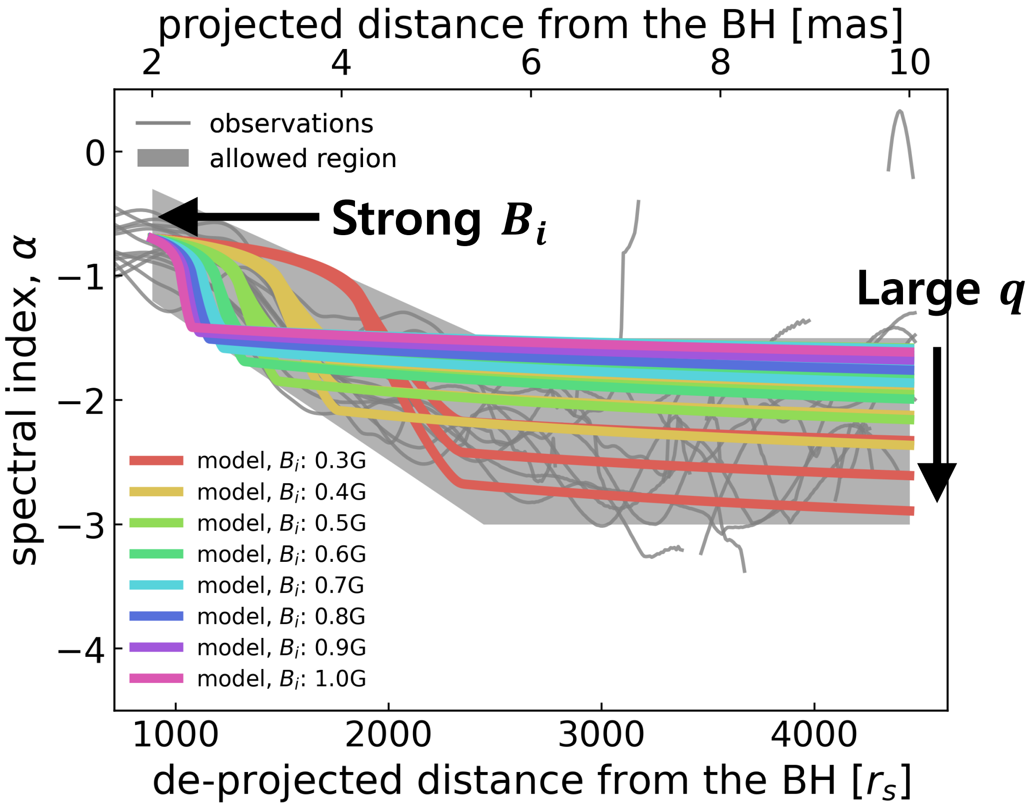


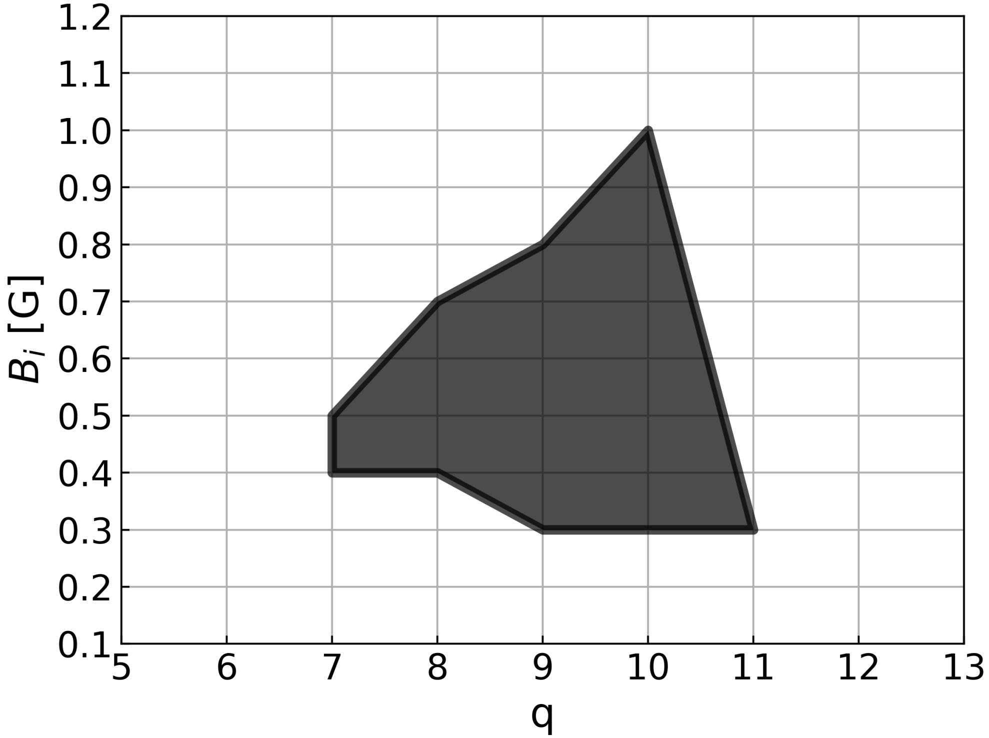
Models with 0 <q <∞ reproduce the observations

Constraining magnetic field strength



Constraining magnetic field strength: parameter space

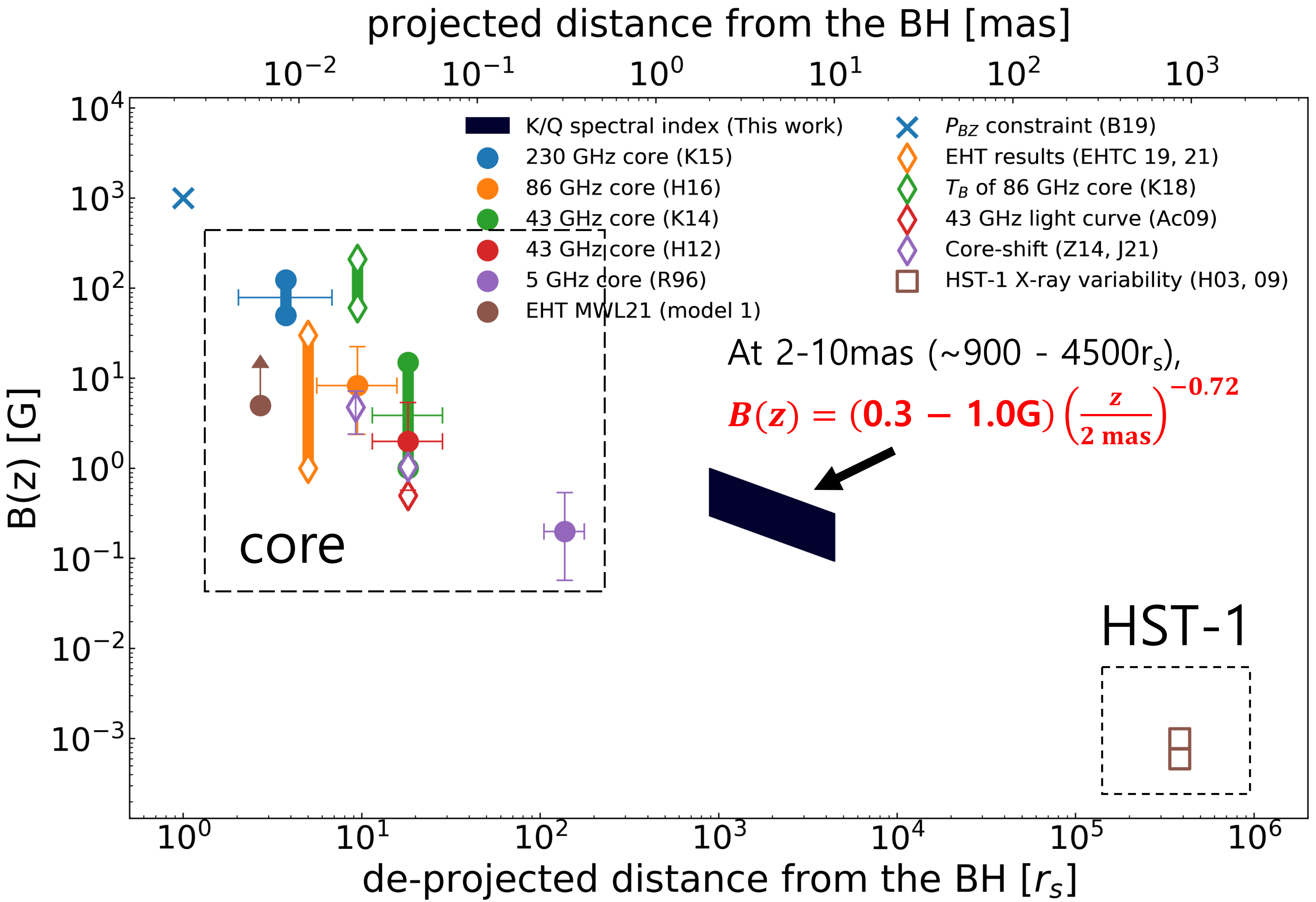




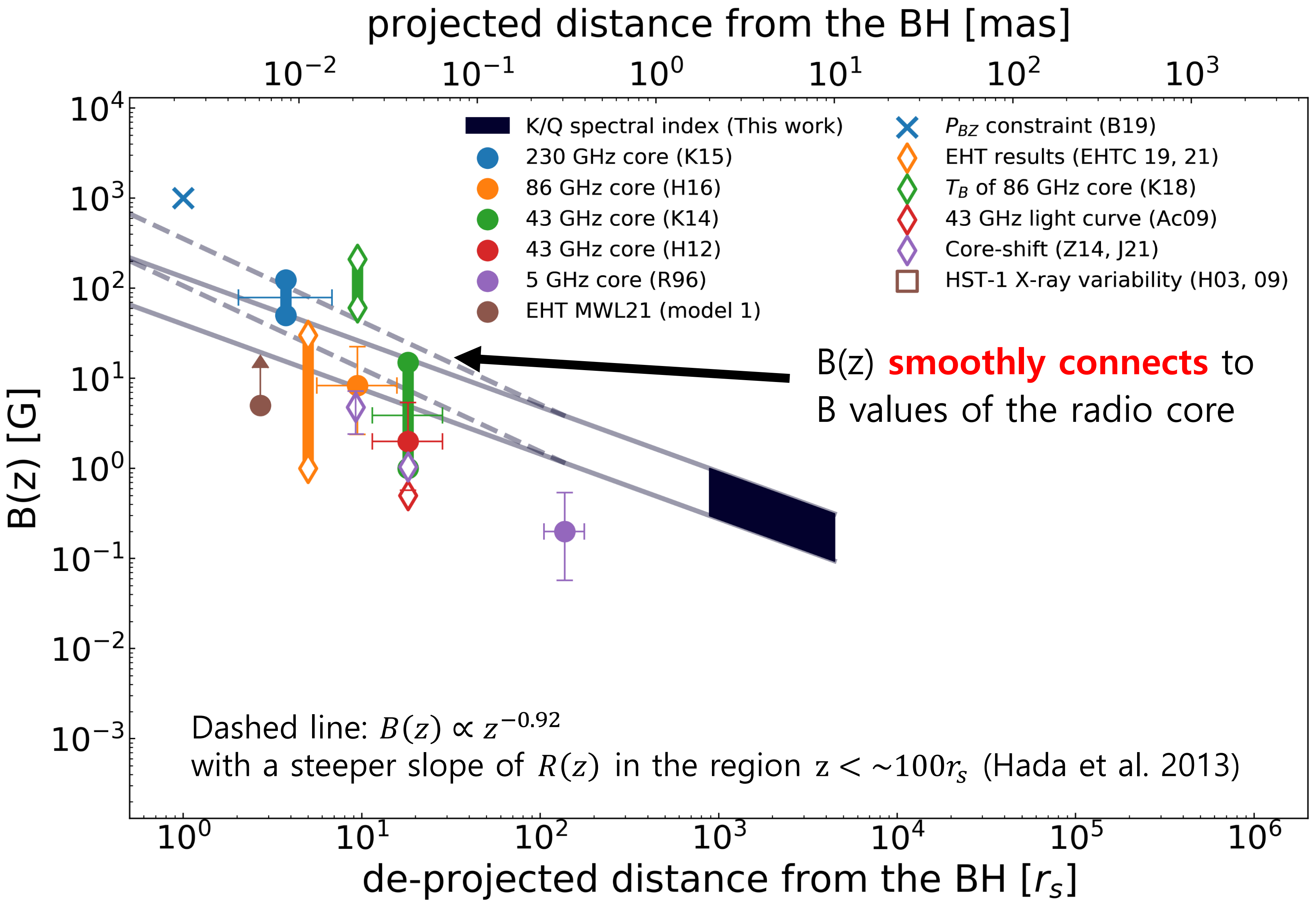
Allowed parameter space

$0.3\text{G} < B_i < 1.0\text{G}$ $\quad\quad$ $7 < q < 11$

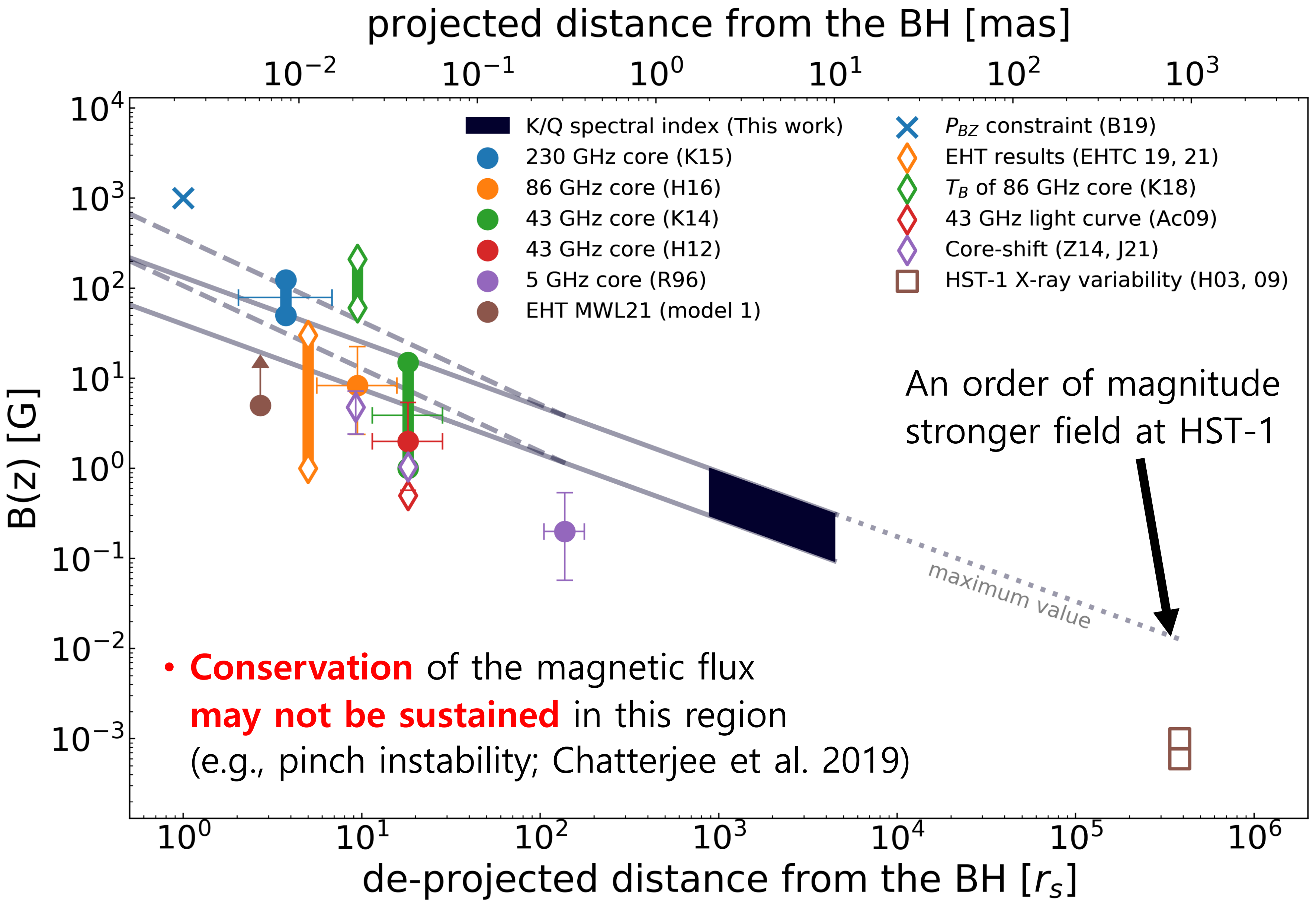
Magnetic field distribution of the M87 jet



Magnetic field distribution of the M87 jet



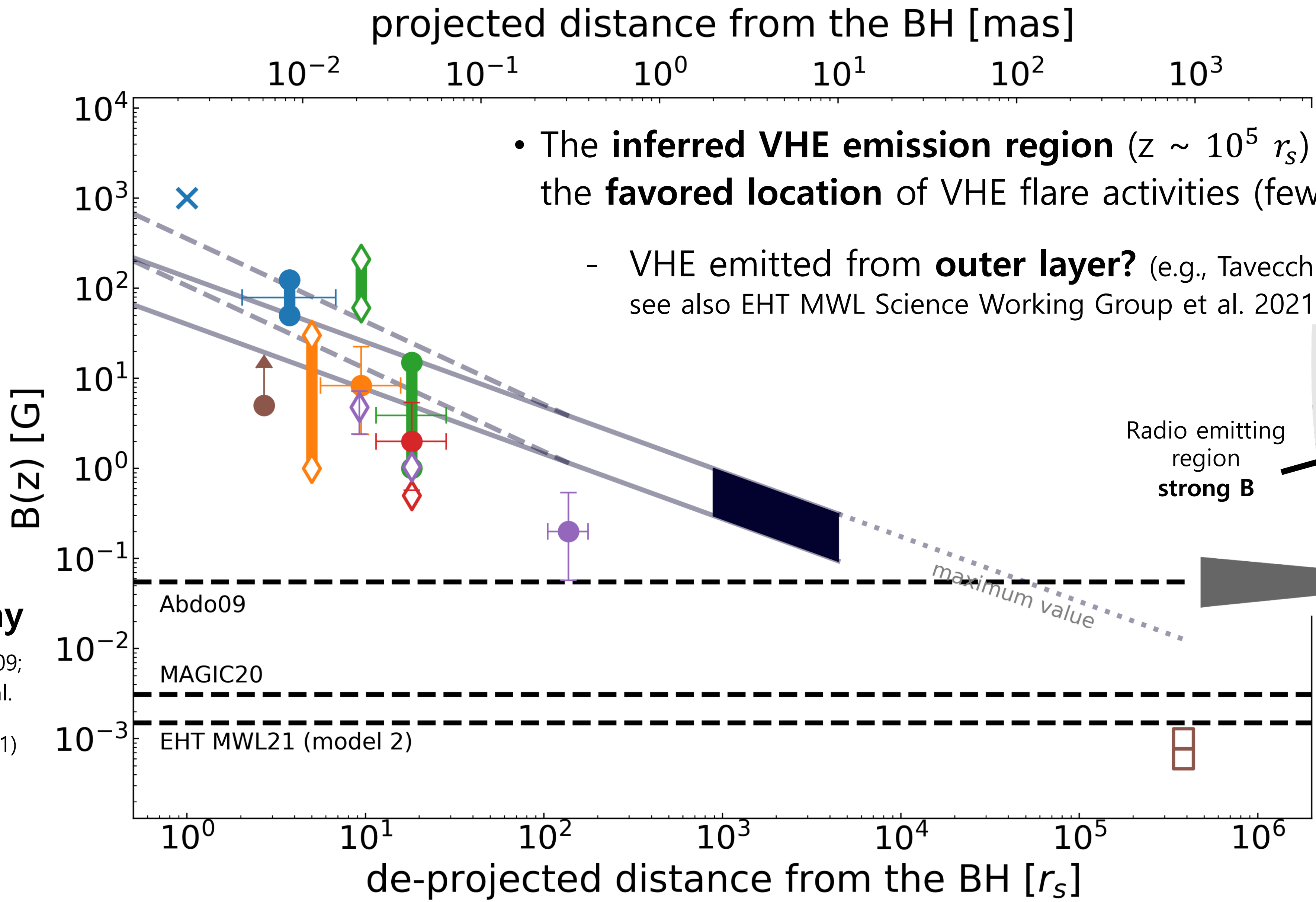
Magnetic field distribution of the M87 jet



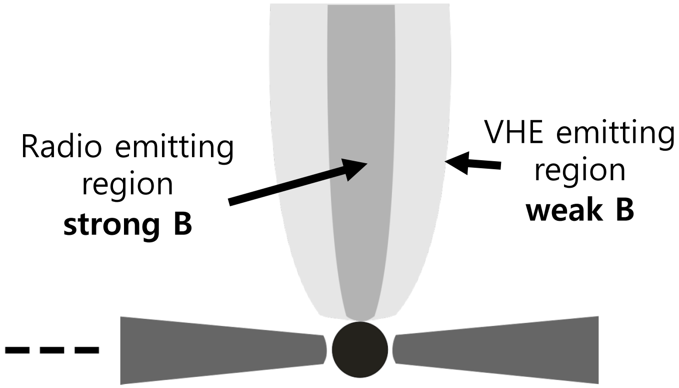
- **Conservation** of the magnetic flux **may not be sustained** in this region (e.g., pinch instability; Chatterjee et al. 2019)

Magnetic field distribution of the M87 jet

- The **inferred VHE emission region** (z ~ $10^5\ r_s$) **differs from** the **favored location** of VHE flare activities (few tens of r_s)
  - VHE emitted from **outer layer?** (e.g., Tavecchio & Ghisellini 2008; see also EHT MWL Science Working Group et al. 2021)



B values from **VHE gamma-ray** study (Abdo et al. 2009; MAGIC Collaboration et al. 2020; EHT MWL Science Working Group et al. 2021)



Rieger and Levinson 2018

Summary

1. The **spectral index distribution** of the M87 jet are investigated by KaVA and VLBA at 22-43GHz
   - The spectrum index **decreases rapidly** from $\alpha \sim -0.7$ to $\alpha \sim -2.5$ and **stops decreasing** at ~6mas
2. We **modeled** the spectral index distribution
   - If the amount of the electron injections **decreases with distance**, the observed distributions is well reproduced
   - Comparing the model with the observations, we conclude the **distribution of the B field strengths at 2 - 10 mas** (~ $900r_s$ - ~ $4500r_s$) to be

$$\boldsymbol{B(z) = (0.3 - 1.0\mathrm{G}) \left(\frac{z}{2\ \mathrm{mas}}\right)^{-0.72}}$$

3. We **compare** the B field strength distribution with previous studies
   - Our result is in good agreement with the estimates of the **radio core**, but an order of magnitude higher than that of **HST-1**