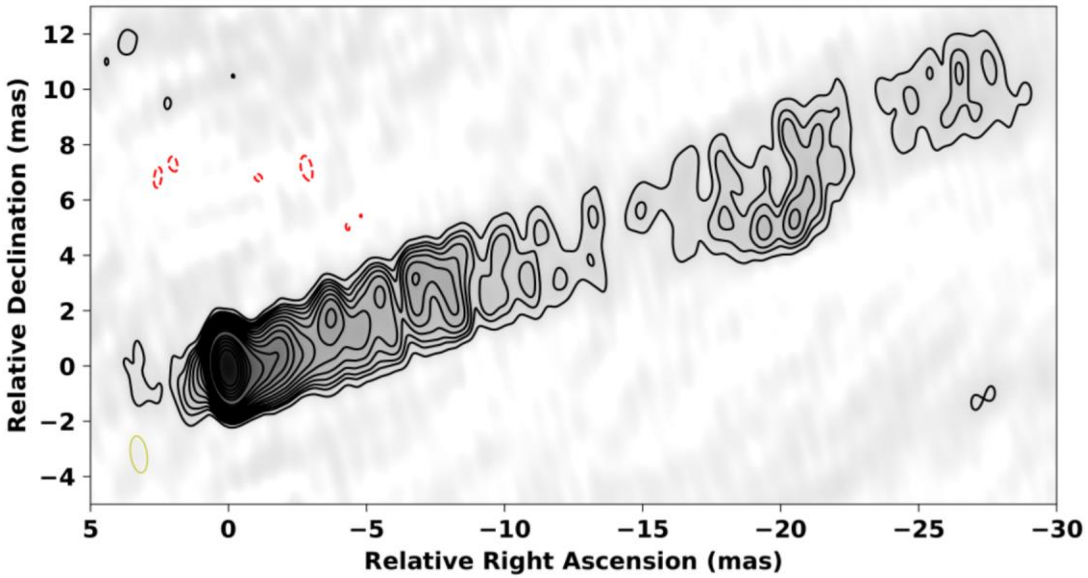
Spectral properties of M87 jet
revealed by multi-frequency VLBI observations

Hyunwook Ro (Yonsei Univ. / KASI)

Motoki Kino(Kogakuin Univ./NAOJ), Bong Won Sohn (KASI),
Masanori Nakamura (ASIAA), Kazuhiro Hada (NAOJ), Jongho Park (ASIAA)
and EAVN AGN SWG members

M87 jet



Hada 2018

- M87 is the best target to study AGN jet physics because of its proximity (D = 16.7Mpc) and large angular size of the black hole (M_{BH}~$6.5 \pm 0.7 \times 10^9 M_{sun}$; EHT collaboration 2019).
  - 1mas ~ $130r_s$ ($r_s = 2GM_{BH}/c^2$)
- According to the current leading scenario, **Magnetic field is the key** for launching and the accelerating the jet (e.g., Komissarov +07; McKinney+ 06; Tchekovskoy + 11)

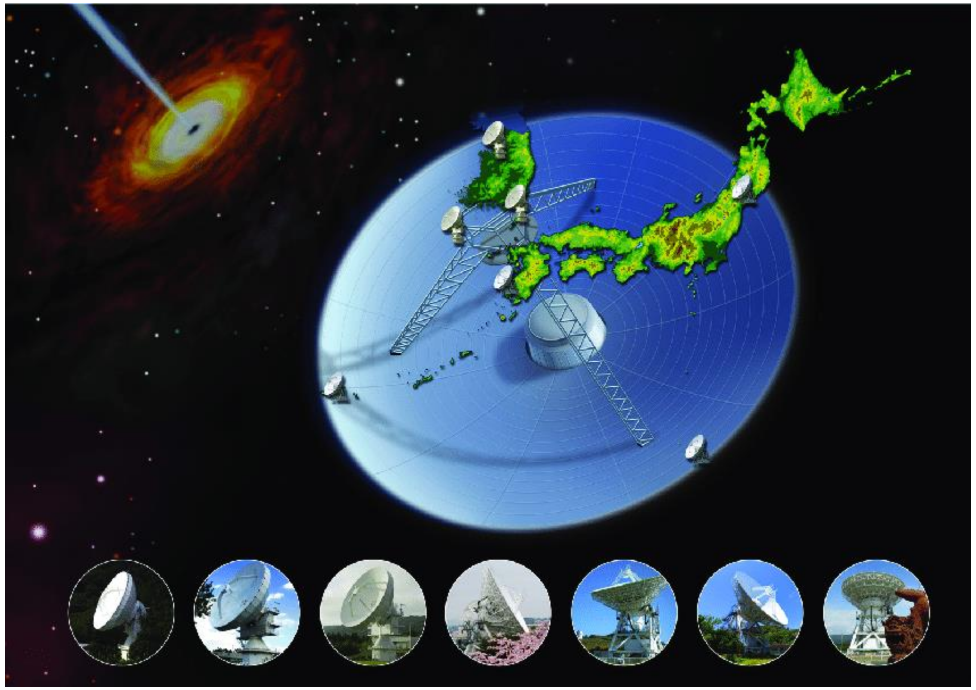
What's the issue?

- Some previous studies estimated the **magnetic field strength of the M87 jet base** using one-zone approximation (e.g., Hada+16; Kino+14; 15; Acciari+09; Abdo+09; MAGIC collaboration 20), but **little is known** about **the distribution of the magnetic field with distance.**

In this study…

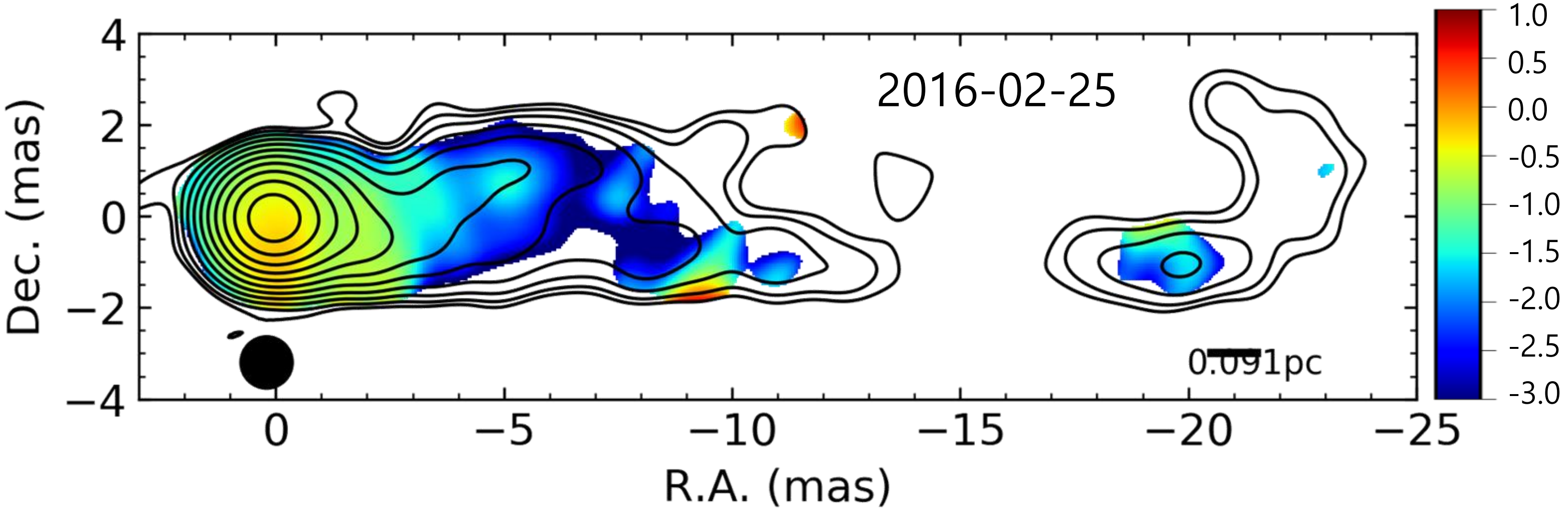
- High quality **spectral index maps** were obtained by quasi-simultaneous **22GHz (K band) and 43GHz (Q band) observations** using KaVA (KVN and VERA)'s large program
- We **compare** the **spectral index distribution** obtained from **observations with a theoretical model**, and place **limits on the distribution of magnetic field and non-thermal electron injection with distance**

KaVA Large program



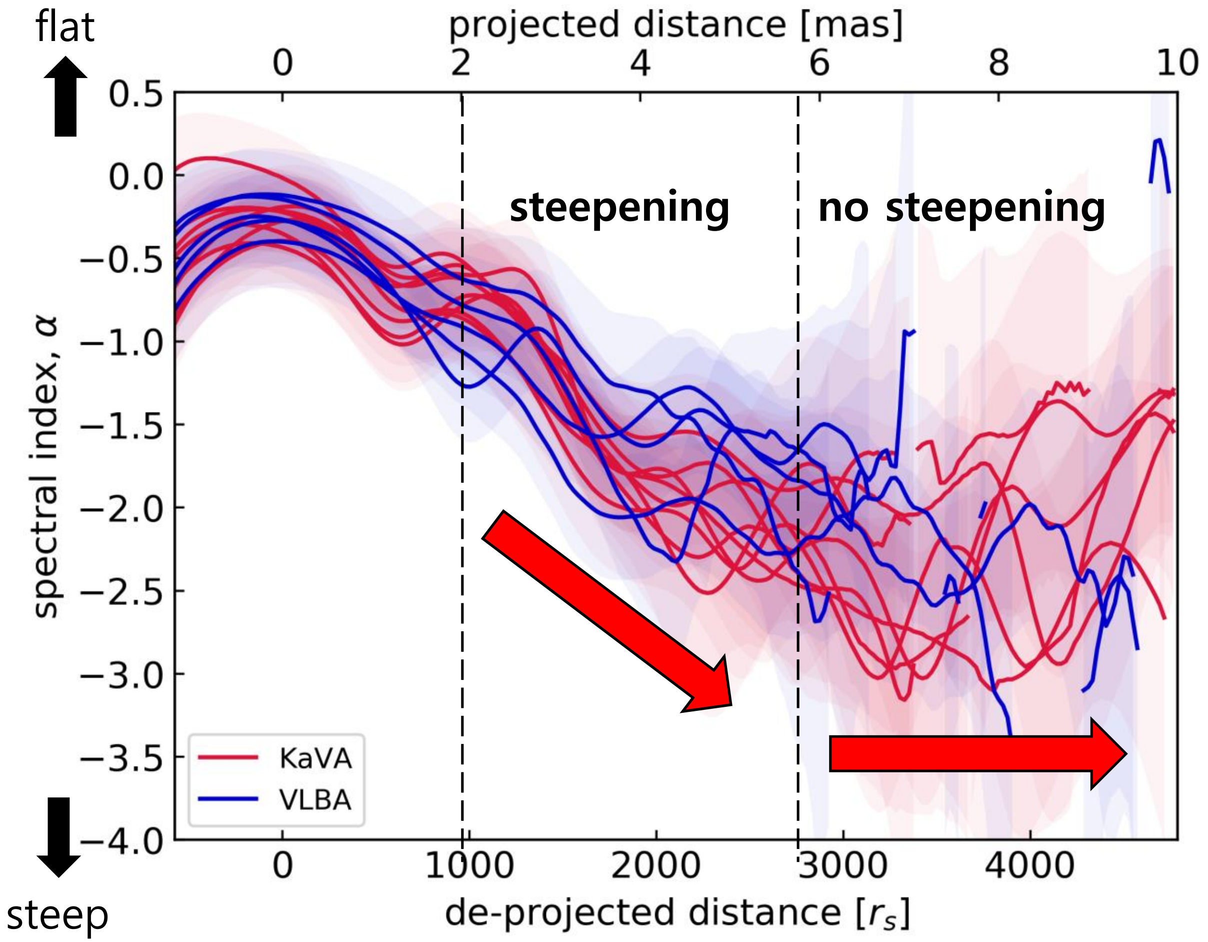
- KaVA (KVN and VERA Array)
- Observing frequency : 22, 43GHz
- Observation time : 2016 Feb. – 2016 Jun., 9 epochs (~130 hours in total)
- Compared to EHT and other high-frequency observations, **KaVA is able to explore the structure of M87 jet at a longer distance, by ~10mas.**

Spectral index maps of M87 jet



- Spectral index map between KaVA K/Q band images
  - Color : Spectral index α, ($I_\nu \propto \nu^{\alpha}$)
  - Contour : 22GHz map
  - Restoring beam : 1.2mas × 1.2mas (~$160 r_s$)
  - Uniform weighting
  - Common UV-coverage : 30 – 170 Mλ

Spectral index distribution of M87 jet as a function of distance



- The spectral index distributions with distance **look very similar from different telescopes at different times** (blue lines: VLBA K/Q archival data in 2010, 2014; Hada et al. 2011; 2016)
- From ~2mas, **the spectrum index decreases rapidly with distance** ($\alpha \sim -0.7$ to $\alpha \sim -2.5$), and **after ~6mas the spectrum index decrease stops**

Spectral index distribution model

- **We modeled the spectral index distribution between 2 – 10mas (~1000 – 5000r$_s$)**
- **The changes in spectrum index (α) with distance** is obtained **from the energy distribution of non-thermal electrons $N(\gamma)$.** The slope of the electron distribution (p) and the spectral index (α) is related by $\boldsymbol{\alpha = (p+1)/2}$ (Rybicki and Lightman 1979)**.**
- **The evolution of $N(\gamma)$ as a function of time (distance)** can be studied by a partial differential equation called **transfer equation.**
- **Transfer equation in co-moving frame** (Ginzburg 1964, Longair 2008, Blasi 2013)

$$\frac{\partial N(\gamma,\tau)}{\partial \tau} + (\nabla \cdot v)N(\gamma,\tau) + \frac{\partial}{\partial \gamma}\underbrace{[b(\gamma,\tau)N(\gamma,\tau)]}_{\text{Energy loss}} = \underbrace{Q(\gamma,\tau)}_{\text{Injection}}$$

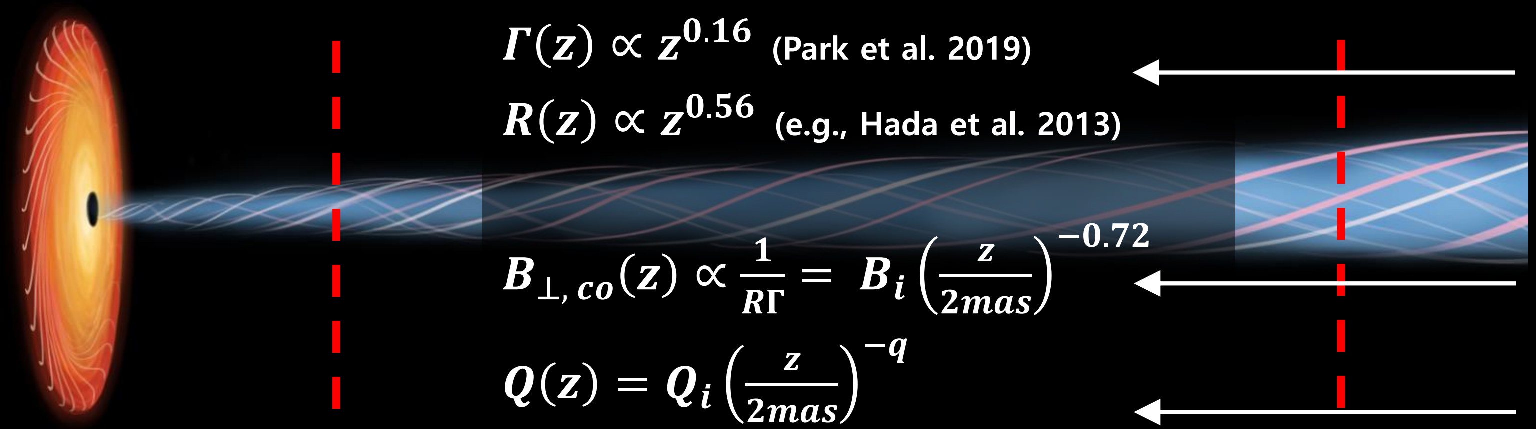
Energy loss $b(\gamma,\tau)$:

- **Adiabatic loss** : $\frac{1}{R}\frac{dR}{d\tau}\gamma$
- **Synchrotron loss** : $\frac{4}{3}\frac{\sigma_T}{m_e c}\frac{B^2}{8\pi}\gamma^2$

Spectral index distribution model

z_i=2mas (~1000r_s)

z_f=10mas (~5000r_s)



$\Gamma(z) \propto z^{0.16}$ (Park et al. 2019)

$R(z) \propto z^{0.56}$ (e.g., Hada et al. 2013)

Bulk velocity and radius as a function of distance are taken from previous observations.

$$B_{\perp,co}(z) \propto \frac{1}{R\Gamma} = B_i \left(\frac{z}{2mas}\right)^{-0.72}$$

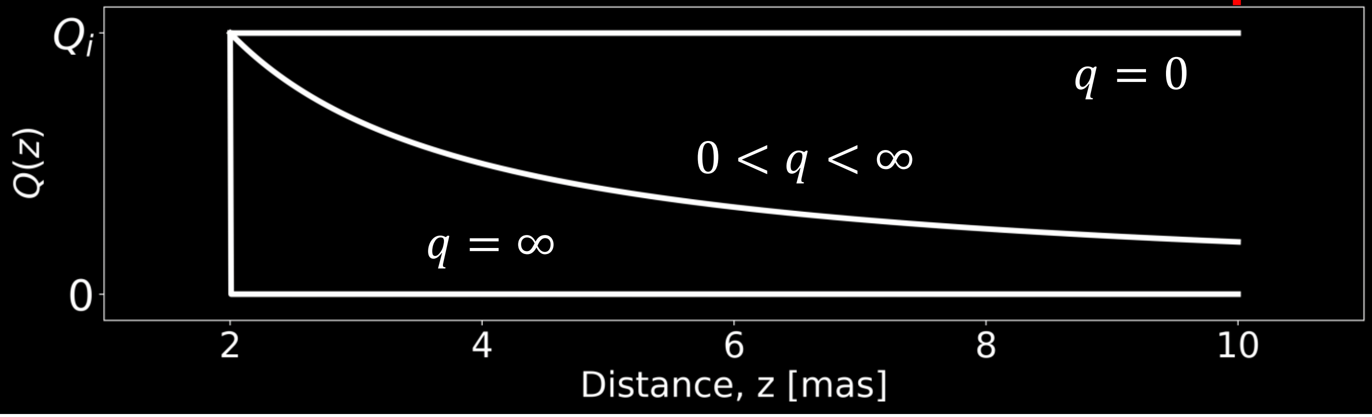
Magnetic field is dominated by **toroidal component** ($B \propto R^{-1}$)

$$Q(z) = Q_i \left(\frac{z}{2mas}\right)^{-q}$$

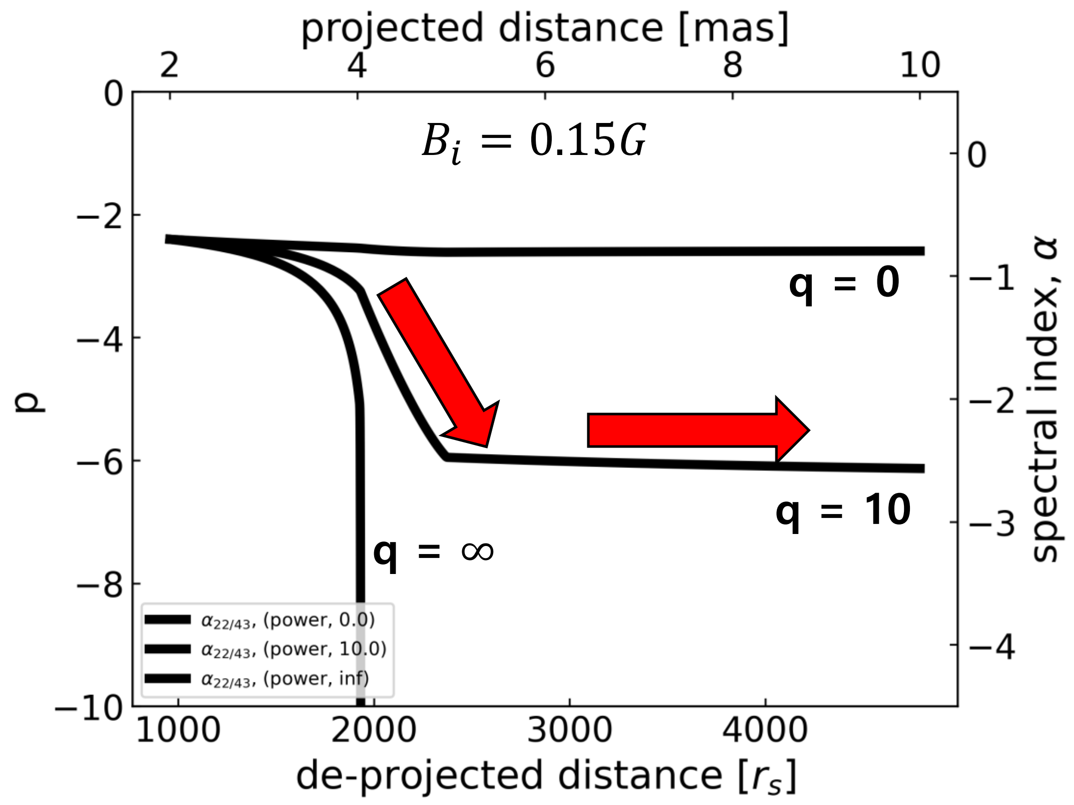
$$Q_i \propto \gamma^{-2.4} \quad (10^1 < \gamma < 10^4)$$

The electron **injection function depends on the distance**

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

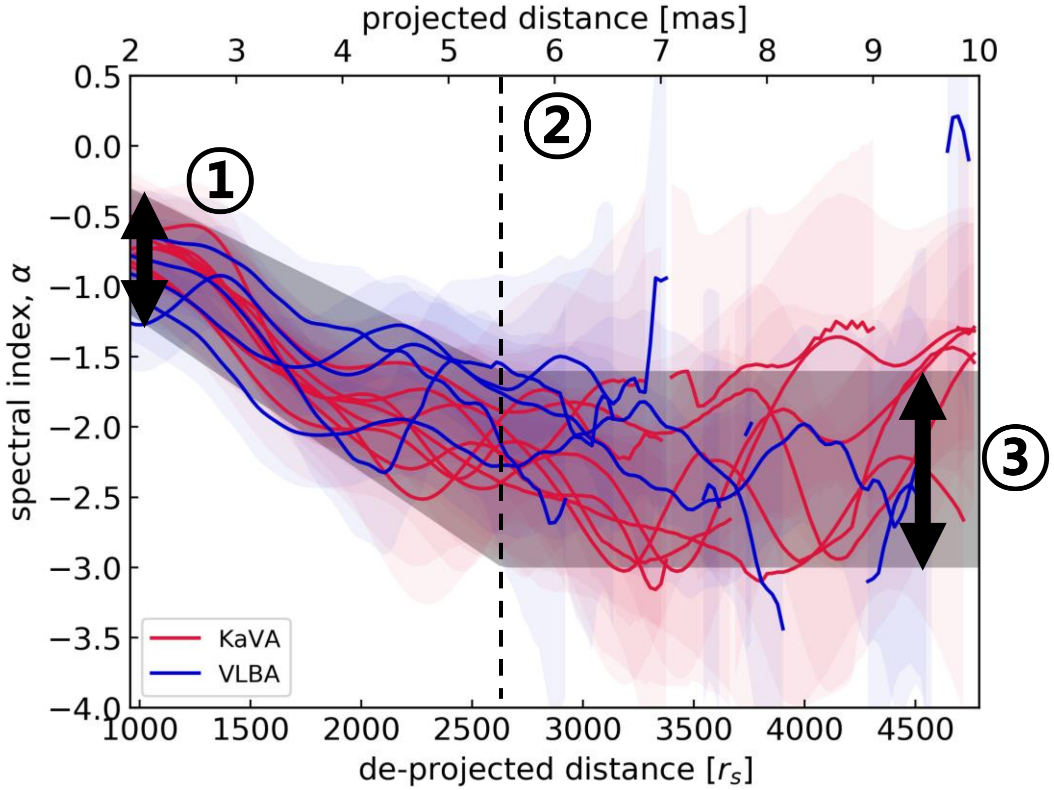


Importance of the particle injection to account for the observed spectral index distribution



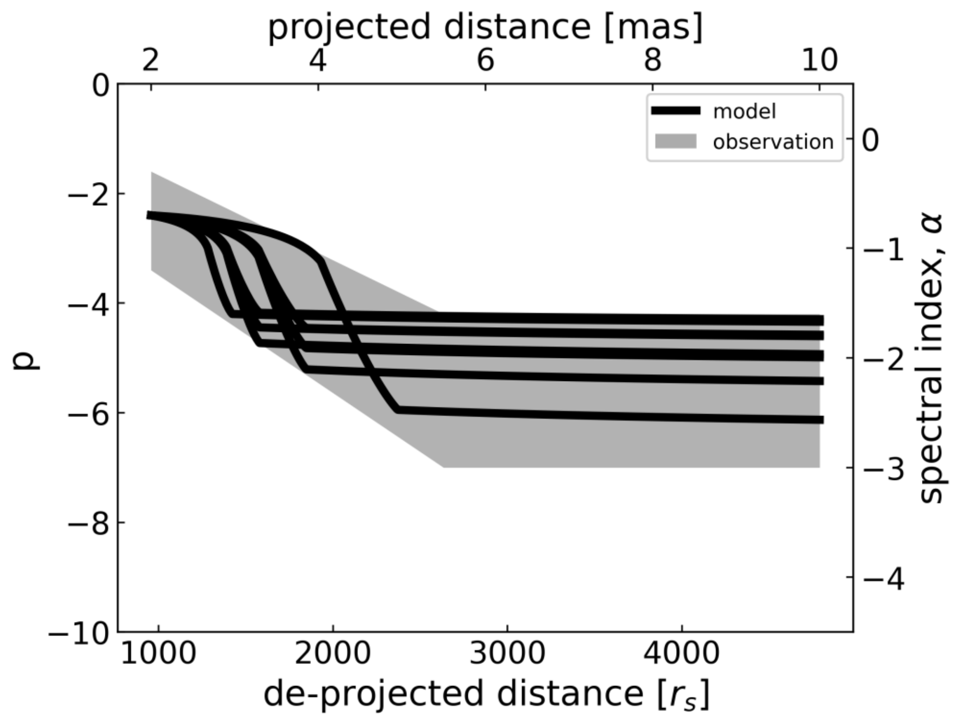
- The **model with constant injection (q = 0)** predicts that **the spectral index does not decrease significantly.**
- If there is **no injection after the initial injection (q = ∞)**, the **index will diverge due to synchrotron cooling**.
- If the **amount of particle injection decreases with distance (0 <q <∞)**, the **modeled distribution is similar to the observations** **(rapid decrease -> no decrease).**

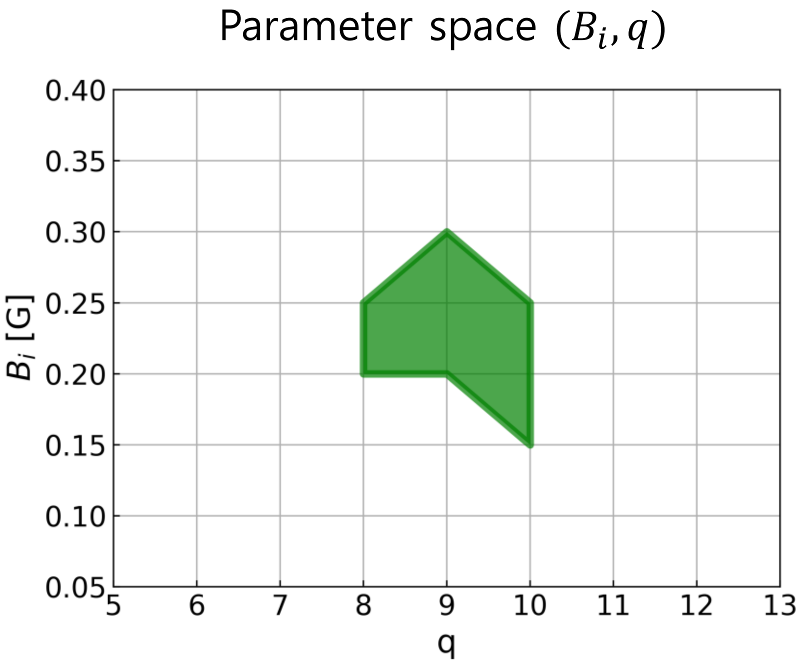
Constraining magnetic field distribution



- In order **to compare the modeled spectral index distributions with the observed ones**, we **limit the observed distribution to the following areas**:
  - ① Spectral index at 2mas : **-0.3 - -1.2**
  - ② End of the steepening region : **5.5mas**
  - ③ Spectral index after the steepening region : **-1.6 - -3.0**
- More than **90% of the observed distribution is within this area.**

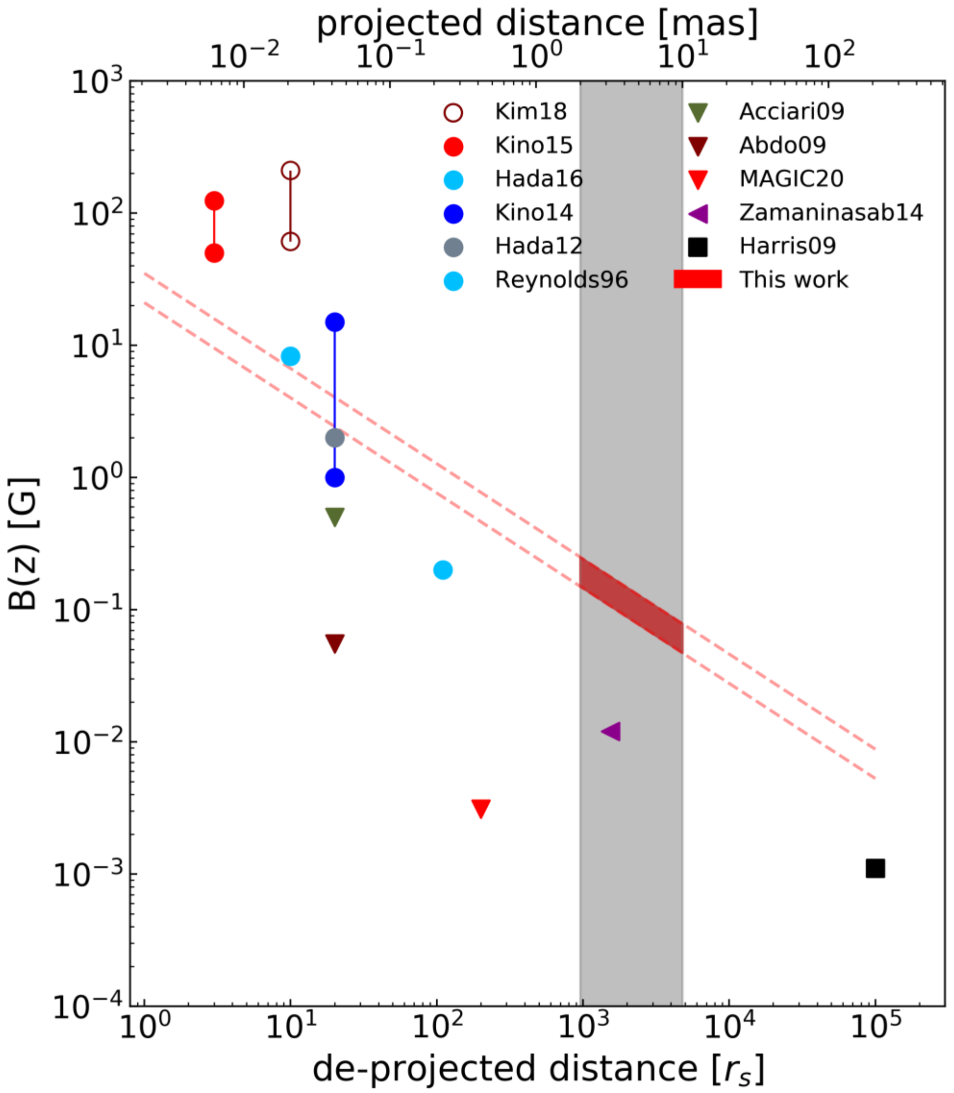
Constraining magnetic field distribution





- **Make a modeled spectral index distribution** using various **B field (B_i) and particle injections (q).** By comparison of observations and models, **we limit the parameters to 0.15G $< B_i <$ 0.30G and 8 $< q <$ 10.**

Magnetic field distribution of M87 jet



Circle : VLBI observations

- Kino et al. 2014, 2015; Hada et al. 2012, 2016; Reynold et al. 1996, Zamaninasab et al. 2014; Zdziarski et al. 2015, Kim et al. 2018

Triangle: High energy observations

- Acciari et al. 2009; Abdo et al. 2009, MAGIC collaboration et al. 2020

Square: HST-1

- Harris et al. 2003, 2009

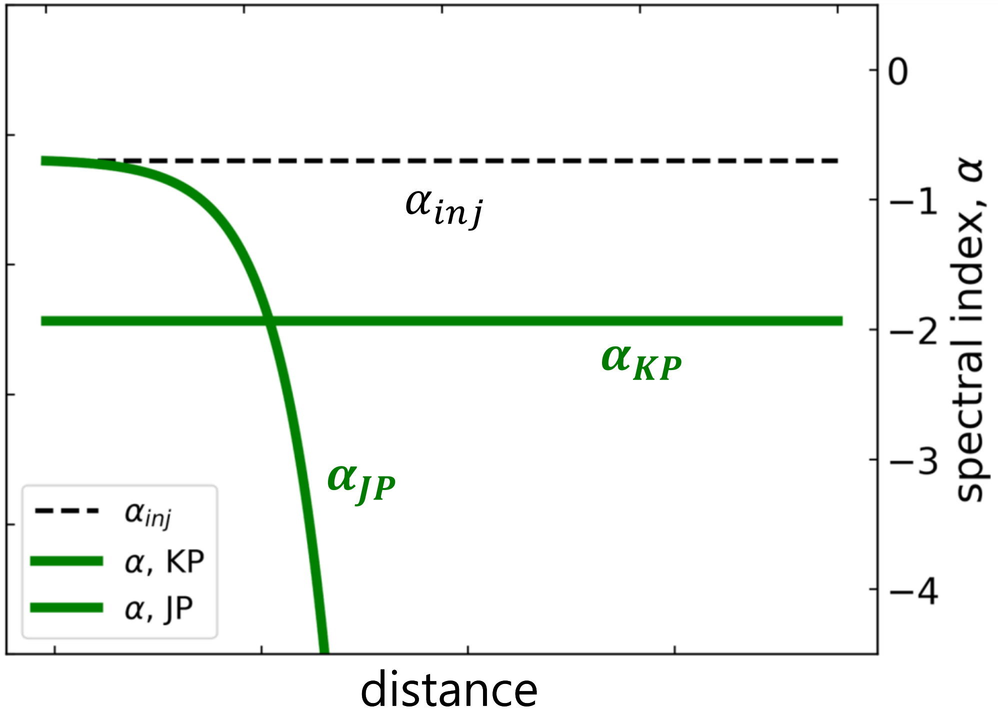
- From the spectral index observation, we obtained the **magnetic field distribution in 2-10mas (~1000-5000r$_s$) : $B_{\perp,co} = (0.15 - 0.30G)\left(\frac{z}{2mas}\right)^{-0.72}$**
- **Extrapolating our magnetic field distribution ($B_{\perp,co} \propto z^{-0.72}$)**, we can **compare with other observed magnetic field strengths.**
- **Our estimation seems to link with values obtained near the jet base from VLBI observations** and gives much stronger B fields compared to high energy studies.

Summary

1. The **spectral properties of M87 jet are investigated** through monitoring **observations at 22/43GHz with KaVA**
   - The **spectrum index decreases from $\alpha \sim -0.7$ to $\alpha \sim -2.5$ and stops decreasing at ~6mas**
2. **Constraint the magnetic field and electron injection at 2-10mas** by comparing the observed spectral index distribution to the theoretical model
   - Our model predicts that the **non-thermal electrons should be injected in a form that decreases with distance** to reproduce the observed spectral index distribution
   - **Models with B_i : 0.15 − 0.30G and q : 8 − 10** reproduce the observed spectral index distribution

Future work: Alternative explanation

Schematic diagram of the expected spectral index distribution in different emission models when the injection spectrum $\alpha_{inj} = 0.7$



- In our study, **we assumed the relation** of the electron distribution and the synchrotron spectrum by $\boldsymbol{\alpha = (p+1)/2}$ (Rybicki and Lightman1979).

- **However, for electrons whose energy is at the edge of the distribution** the **synchrotron spectrum can have a different shape depending on the synchrotron emission model we use (Kardashev 1962, Pacholczyk 1970; Jaffe and Perola 1973)**.

- Thus, **it is possible** to account for the observed spectrum index distribution **without electron injection** (e.g, Tribble 1993; Myers and Spangler 1985).

Thank you!