Radio Lobes of M87
in the view of MWA (and VLA)

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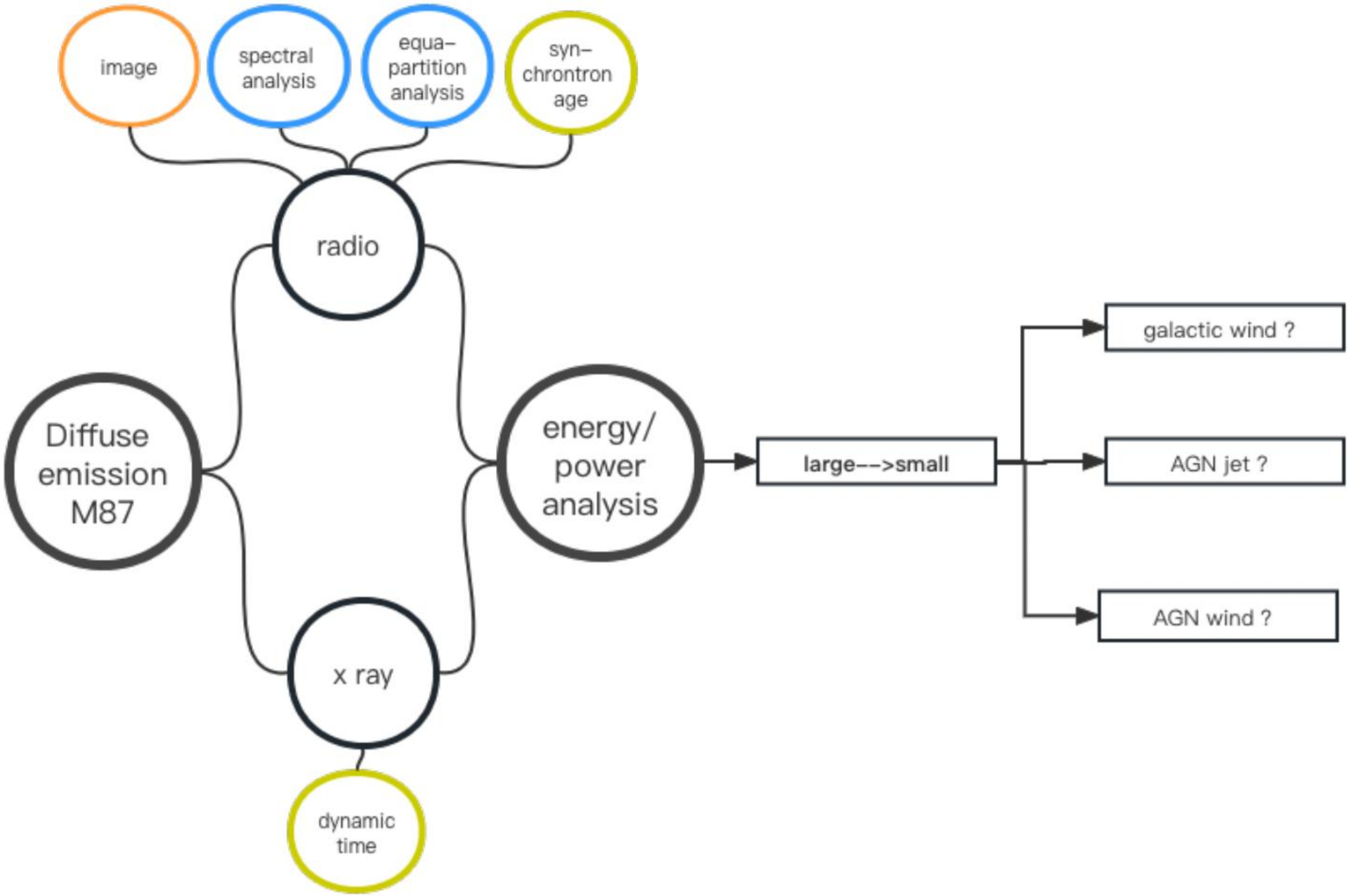
2023-07-25

Main idea



image

spectral analysis

equa–partition analysis

syn–chrontron age

radio

Diffuse emission M87

x ray

dynamic time

energy/ power analysis

large-->small

galactic wind ?

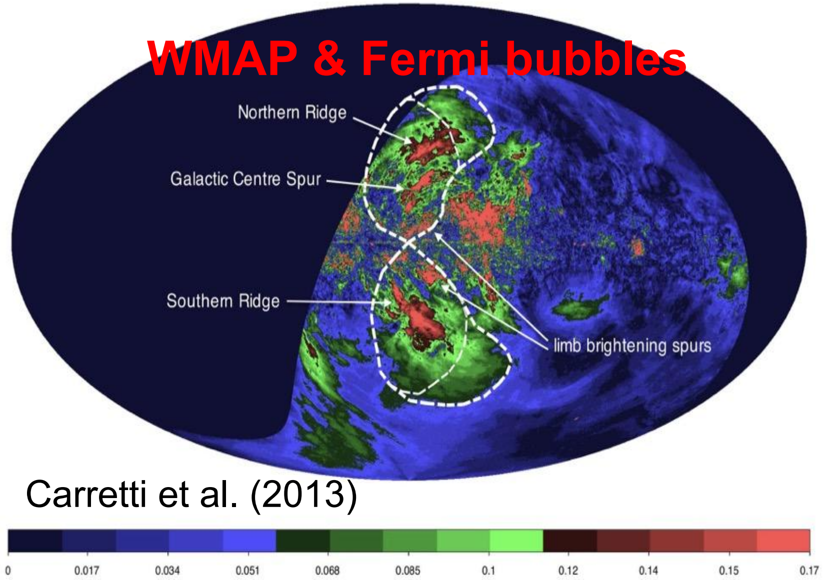
AGN jet ?

AGN wind ?

Content

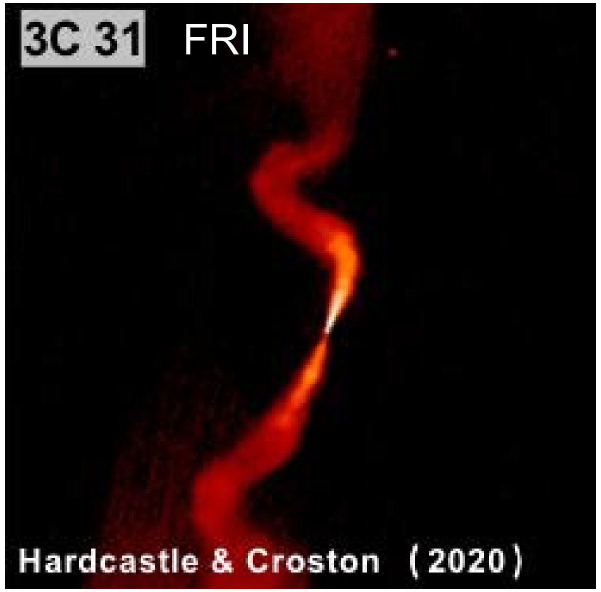
- Background
- Basic information and previous study of M87
- My results on the the diffuse radio emission in M87
- Conclusions

Background: Lobes and Bubbles



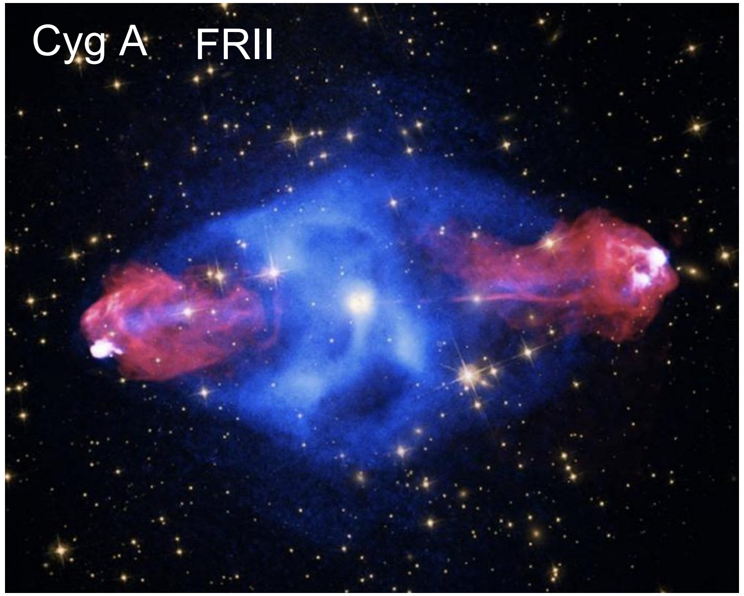
WMAP & Fermi bubbles

Carretti et al. (2013)

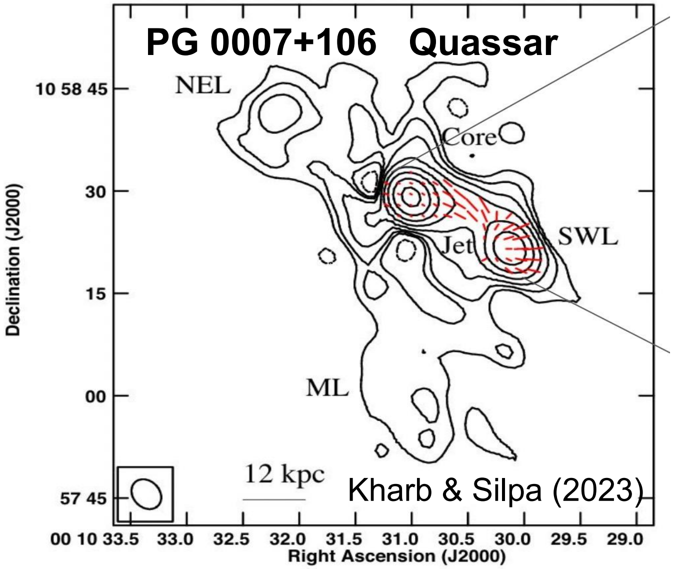


3C 31 FRI

Hardcastle & Croston (2020)

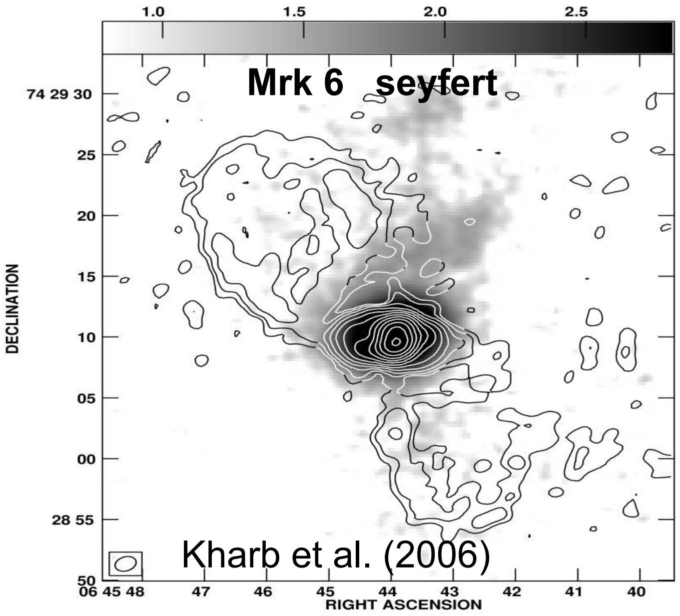


Cyg A FRII



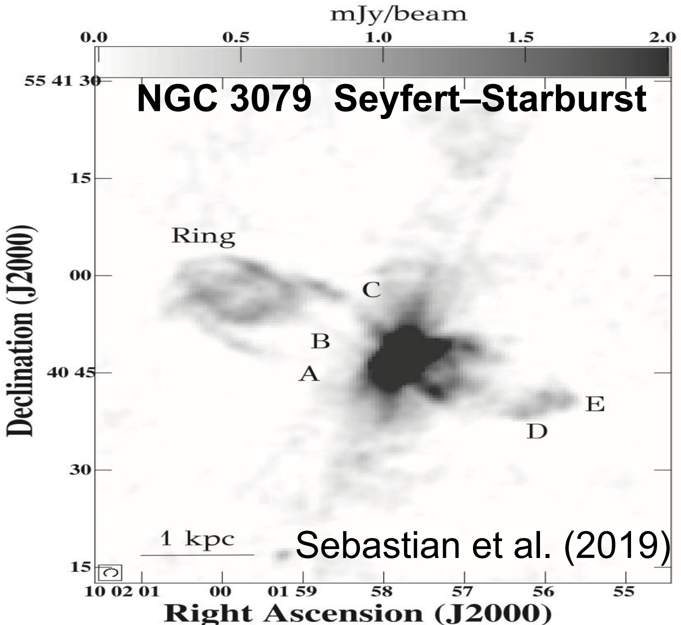
PG 0007+106 Quassar

Kharb & Silpa (2023)



Mrk 6 seyfert

Kharb et al. (2006)



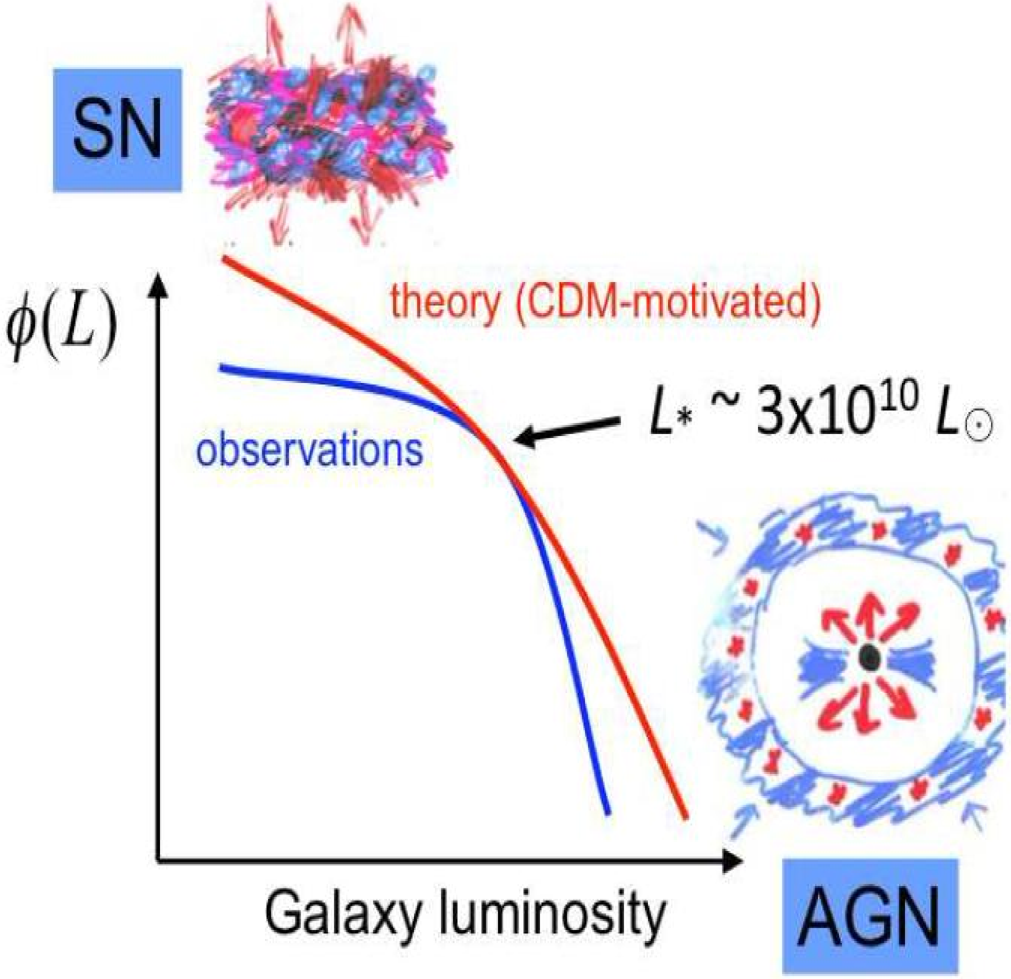
NGC 3079 Seyfert–Starburst

Sebastian et al. (2019)

Two mode feedback in galaxy

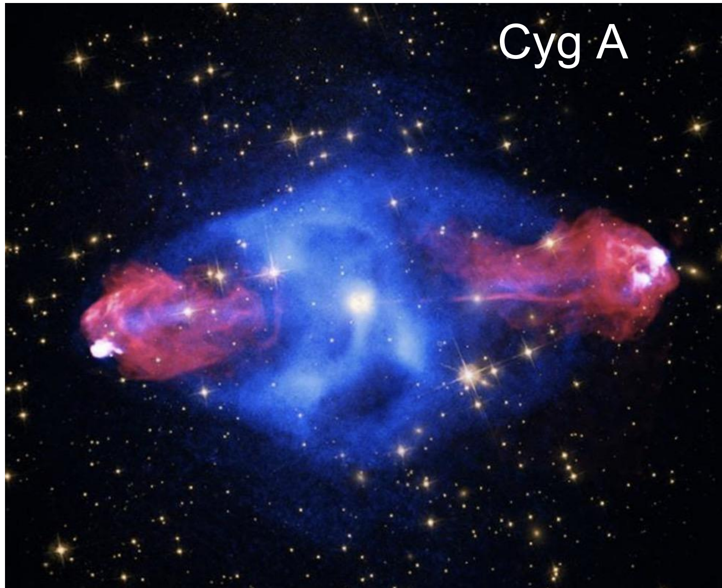
Star-forming (disk) galaxies
Early type

typical energy of 10^{51} erg per SN
starburst wind of
typical speed of 1000 km/s



Silk & Mamon 2012

Massive elliptical galaxies
Old type



BH accretion in AGN

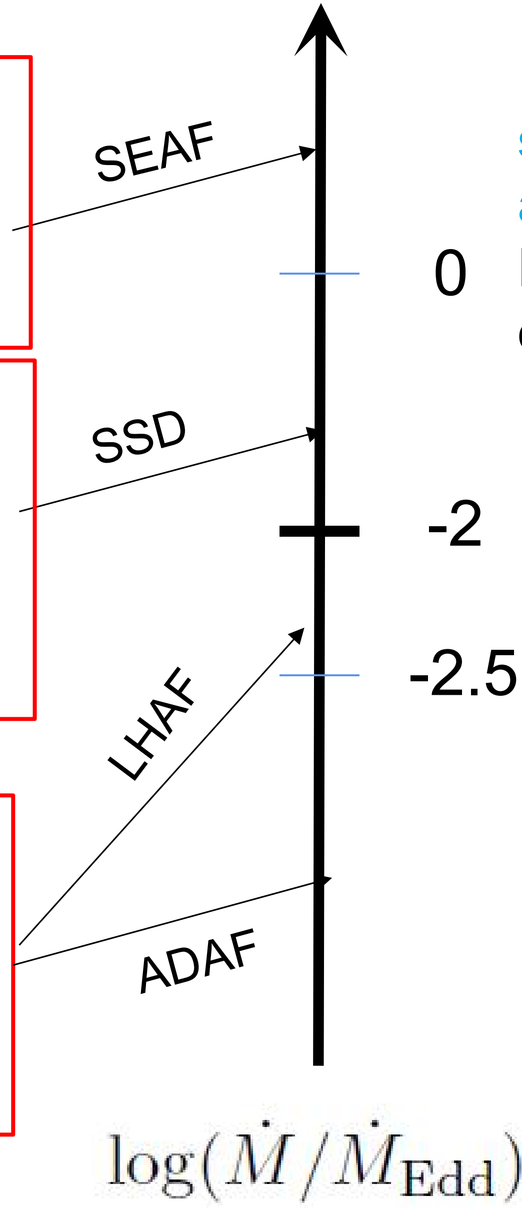
Cold mode

Super-Eddington accretion (slim disk)
(Abramowicz et al. 1989; Sadowski et al. 2014; Jiang et al. 2014)
TDEs, ULXs, SS433

Standard thin accretion disk
(Shakura-Sunyaev 1976; Pringle 1981, ARA&A)
Typical QSOs, Seyferts; XRBs in thermal soft state

Hot mode

Hot Accretion: ADAF(RIAF) & LHAF
(Narayan & Yi 94; Yuan 2001; Yuan & Narayan 2014, ARA&A)
LLAGN, BL Lac objects, Sgr A*, M87,XRBs in hard & quiescent states



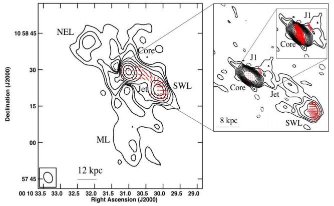
strong wind and radiation and weak/no jet
high power but short time
e.g., qussar, seyfert

weak wind and radiation and strong jet
low power but long time
e.g., our galaxy, radio galaxy
Still important !

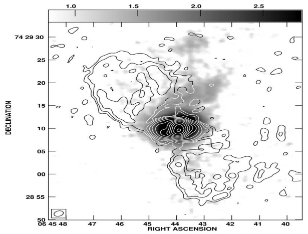
Copy from Yuan's ppt

Mechanisms in individual galaxies

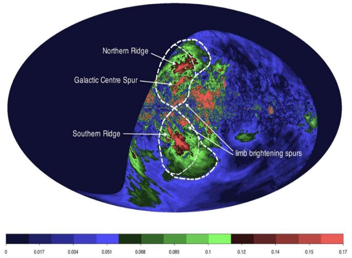
- **PG 0007+106 (quasar, high accretion)**
  Stratified radio outflow ("AGN jet + wind" or "spine + sheath" structure)
  (Kharb & Silpa 2023)



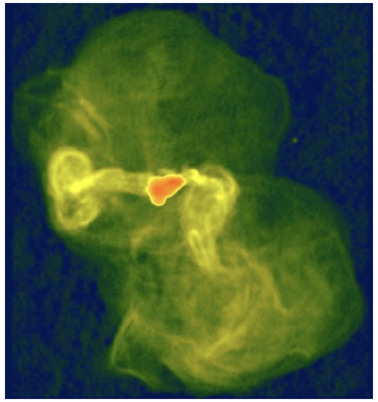
- **Mrk 6 (seyfert, high accretion)**
  Episodically powered precessing jet (dominated) and starburst (second)
  (Kharb et al. 2006)



- **our galaxy (low accretion)**
  Galactic winds from the Galactic Center (Crocker & Aharonian 2011)
  AGN Jet (Guo & Mathews 2012; Guo+ 2012; Guo 2017)
  as well as outflow model (AGN jet + wind)



- **Radio galaxy (low accretion)**
  dominated by jet
  while it can interact with wind and/or ISM
  (Bowman et al. 1996; Silpa et al. 2022; Kharb & Silpa 2023)



Recent simulation
Momentum flux: wind > jet
Power: wind ~ 1/10 jet
(Yuan et al. 2015; Yang, FY et al 2021)

Mechanisms in individual galaxies

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  stratified radio outflow ("AGN jet + wind" or "spine + sheath" structure)
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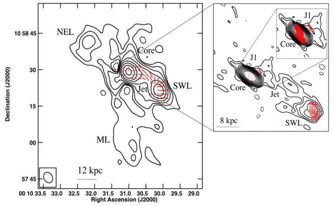

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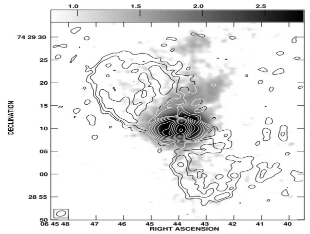

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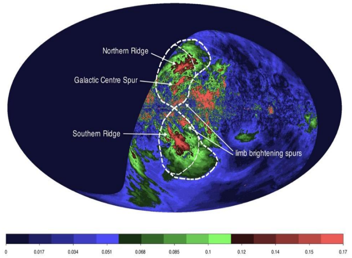

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  dominated by jet
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  (Bowman et al. 1996; Silpa et al. 2022; Kharb & Silpa 2023)

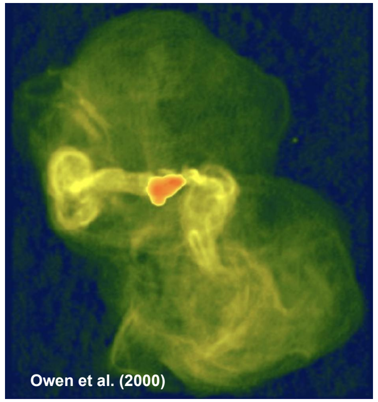
contribution: wind vs. jet?

Recent simulation

Momentum flux: wind > jet

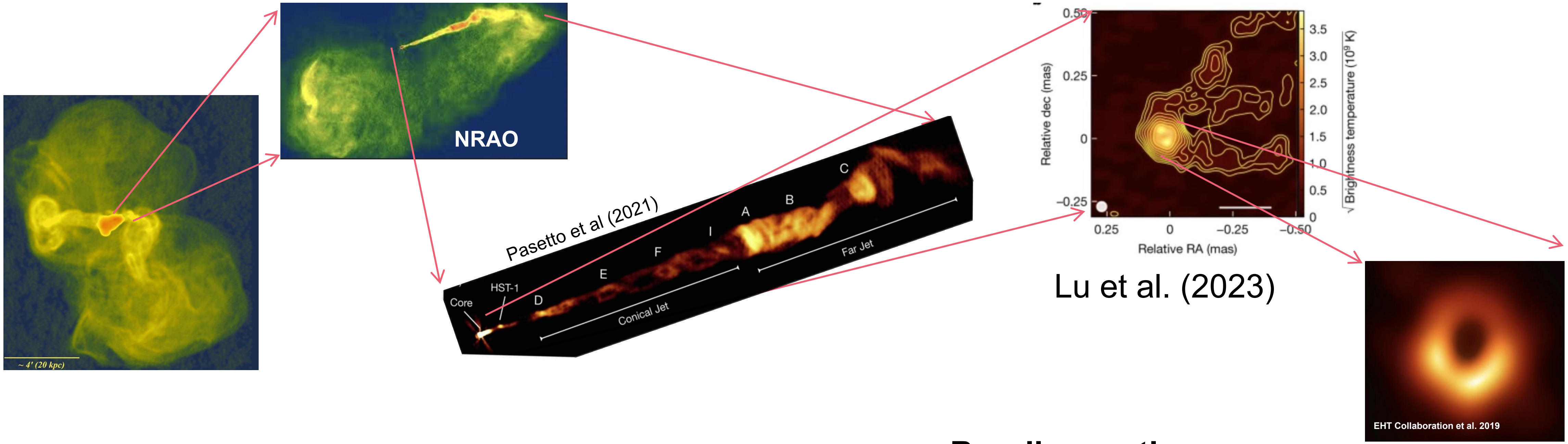
Power: wind ~ 1/10 jet

(Yuan et al. 2015; Yang, FY et al 2021)


Owen et al. (2000)

M87 is nearest radio galaxy which is very bright, idea source !

Basic information of M87



Lu et al. (2023)

Bright structures (40 kpc lobes)

minimum pressure:

Pj $\sim$ few $\times 10^{44}\mathrm{ergs}^{-1}$

equipartition + synchrotron age

assumed particle content

$P_\mathrm{j} \sim 6-10\times 10^{44}\mathrm{ergs}^{-1}$

(Owen et al. 2000; , de Gasperin et al. 2012)

Minimum energy (5 kpc)

$P_\mathrm{j,min} \sim 0.2\times 10^{44}\mathrm{ergs}^{-1}$

Bondi accretion

$M_B \sim 0.01 - 0.2 M_\odot$ /yr

Pout ~ $0.5 - 11 \times 10^{44}$erg/s

SED fitting (HST-1)

Pj $\sim 10^{43-44}\mathrm{ergs}^{-1}$

Accretion near SMBH

$(0.2-2)\times10^{-3} M_\odot$/yr

(Reynolds et al. 1996; Pasetto et al. 2021; Stawarz et al. 2006; Churazov et al. 2001; Di Matteo et al. 2003; EHT Collaboration et al. 2021; Kuo et al. 2014; Feng et al. 2016)

Previous study on M87

- **Large Scale bright structures**
  observation & simulation
  jet dominated (e.g., **Owen et al. 2000; de Gasperin et al. 2012; Churazov et al. 2001**)

- **Small Scale near SMBH**
  simulation for low luminous source
  Momentum flux: wind > jet; **Power: wind ~ 1/10 jet** (Yuan et al. 2015; Yang, FY et al 2021)
  simulation for M87 (MAD)
  Wind can explain the RM screen distribution of M87 (**Yuan et al. 2022**)

  Observation of M87
  edge-brightened and wider emission profile
  wind associated with the accretion flow and couple with jet (Lu et al 2023, Nature)

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  Observation of M87
  edge-brightened and wider emission profile
  wind associated with the accretion flow and couple with jet (Lu et al 2023, Nature)

Wind should play certain roles!
We also consider galactic wind .

Results

MWA 185/216 MHz
bandwidth： 30 MHz

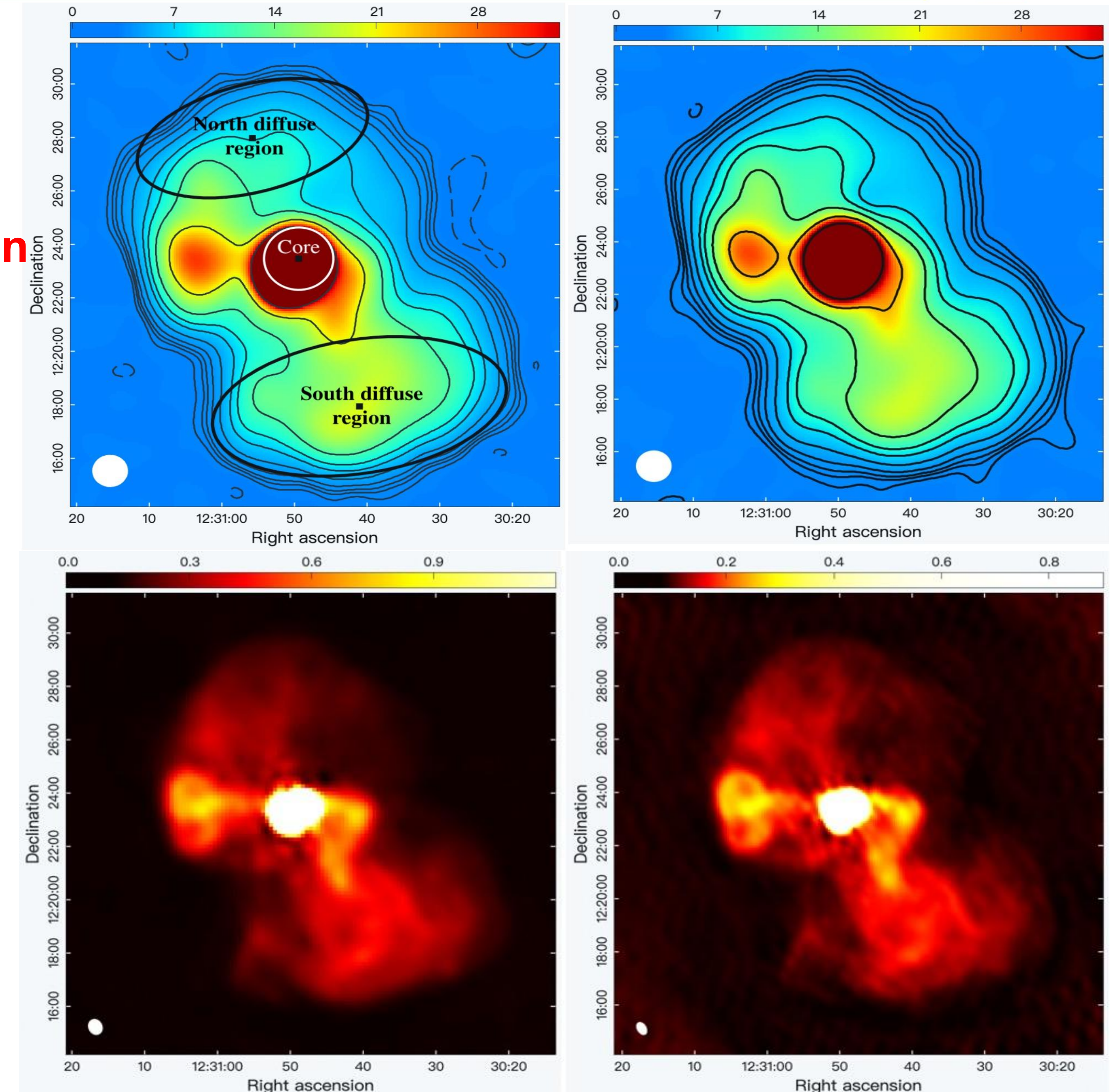
Mean intensity in diffuse lobe region
(Flux/N_B @ 185 MHz)
south: 7.6 Jy/beam
north: 3.8 Jy/beam

- ➢ **Total difussion flux： 610 Jy**

VLA 1.5/2.5 GHz
bandwidth: 1 GHz

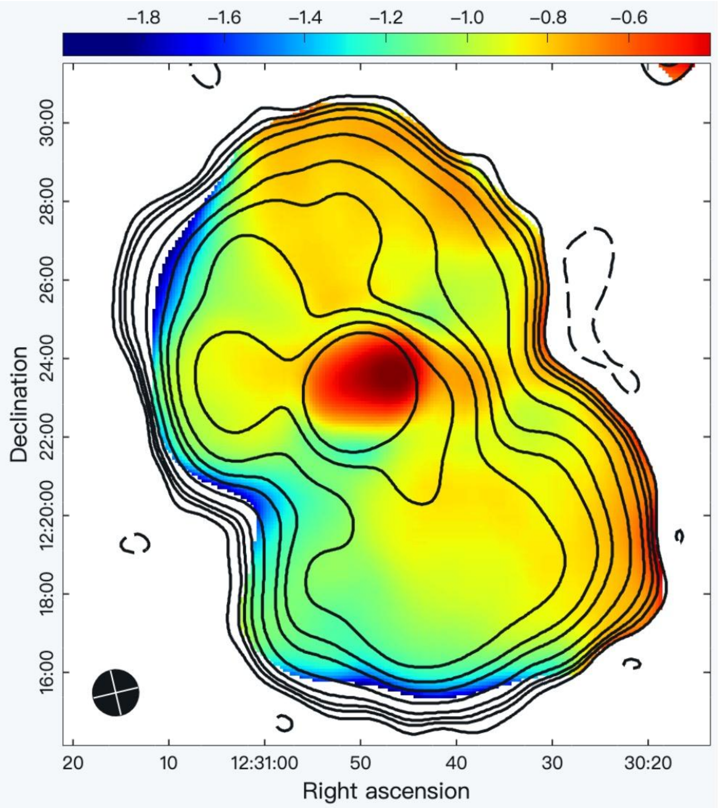
- ➢ **Filamentrary structures in lobes**

Turbulence



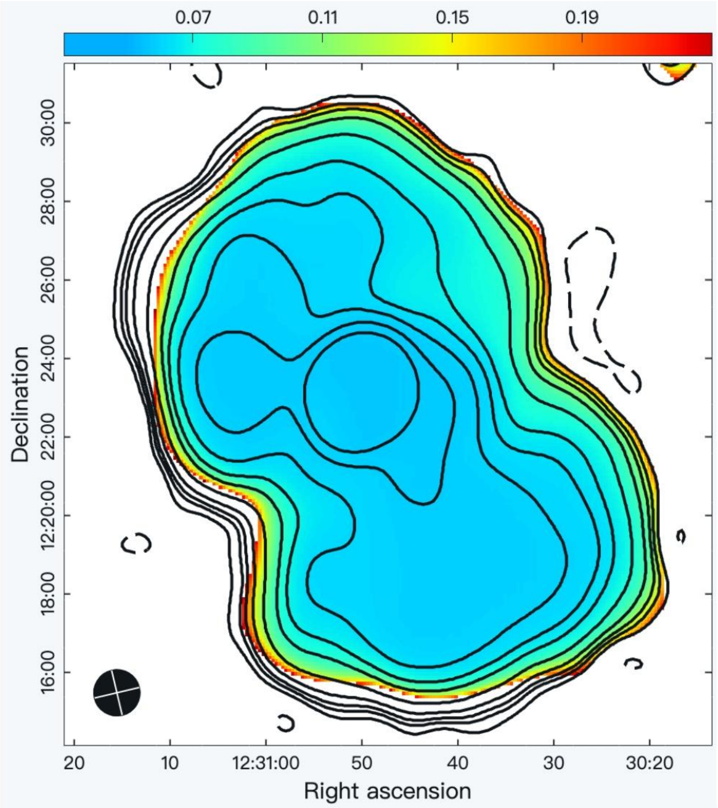
Spectral index

spectral index

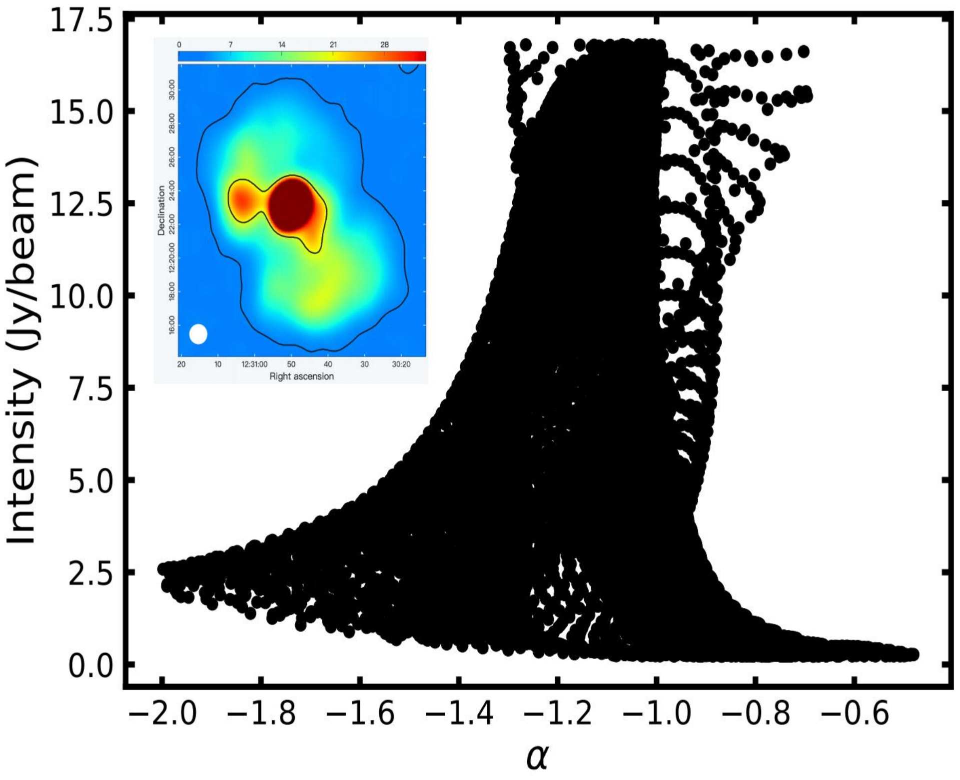


$S_\nu \sim \nu^{\alpha}$

error



distributiion in diffuse lobes



- **Core:~0.6; lobes: mean ~ -1.2, mostly in the range from -0.9~ -1.4**

Equipartition analysis

Equipartition magnetic field strength:
magnetic energy = relativistic particle energy
(Beck & Krause 2005)

$$B_{\mathrm{eq},\perp} = \left(\frac{4\pi(2\alpha-1)(K_0+1) I_\nu E_p^{1+2\alpha} \left(\frac{\nu}{2c_1}\right)^{-\alpha}}{(2\alpha+1) c_2(\alpha) l_{\mathrm{eff}}(i) \cdot c_4(i)} \right)^{\frac{1}{3-\alpha}}$$

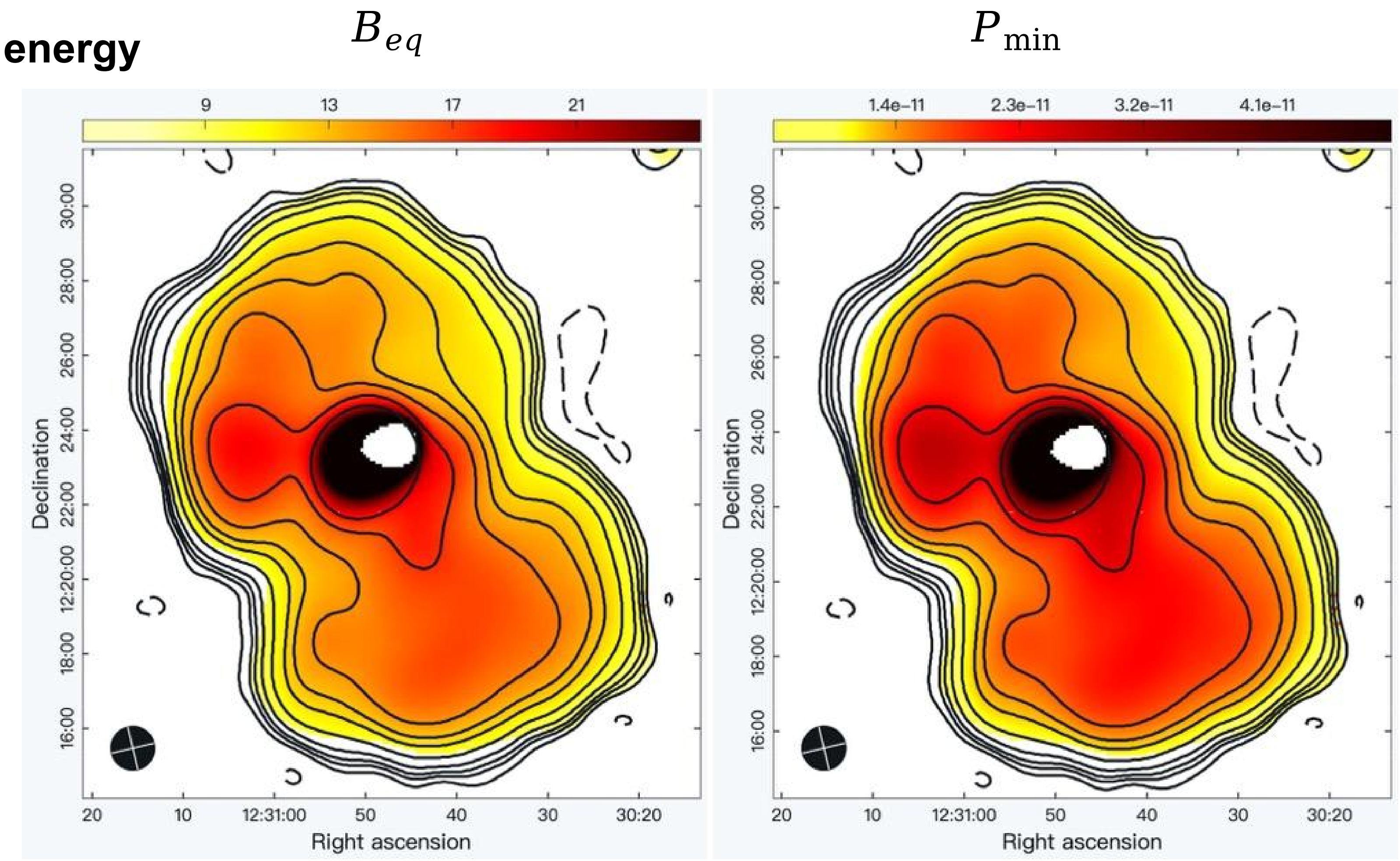
Assume isotropic magnetic fields

$$c_4 = \left(\frac{2}{3}\right)^{(1-\alpha)/2} .$$

set $l_{\mathrm{eff}} = 40$ kpc

Minimum pressure

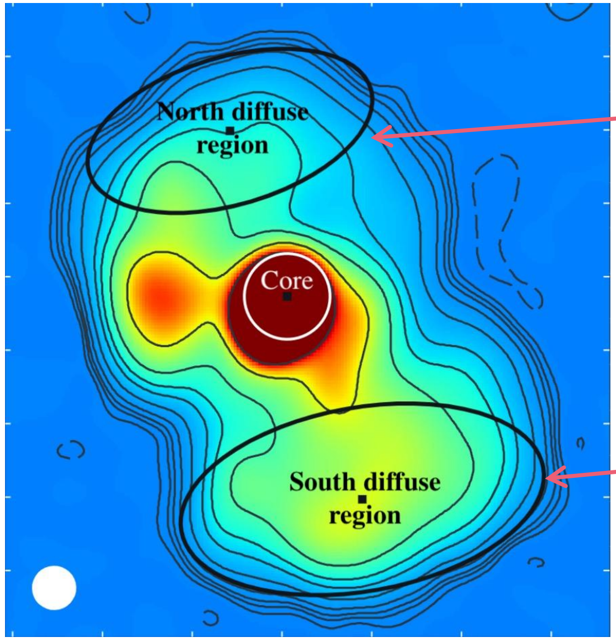
$$P_{\min} = \frac{B_{eq}^2}{8\pi}$$

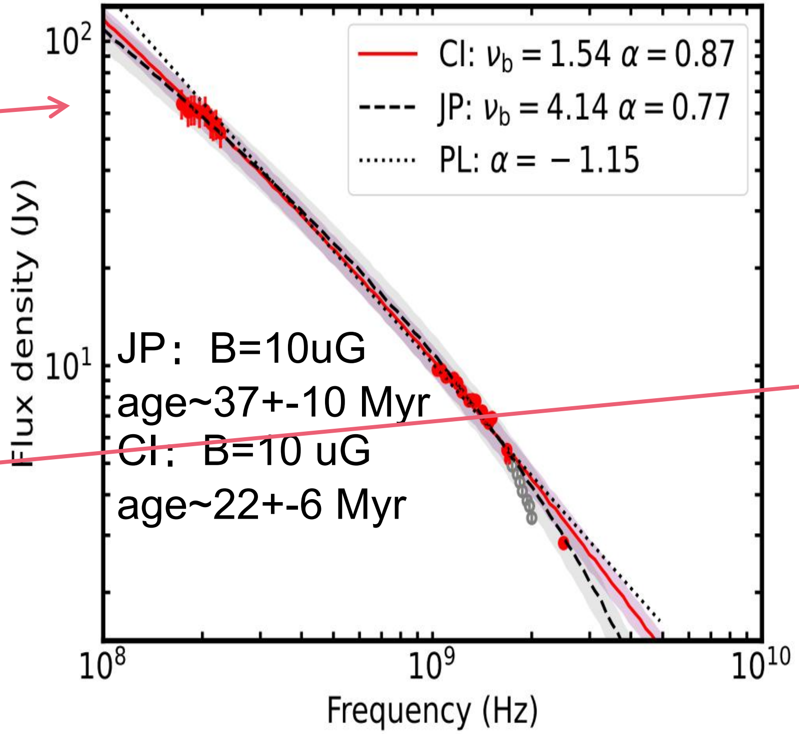


- ➢ $\boldsymbol{B_{eq}}$ **in lobes ~10 uG,** $\boldsymbol{P_{\min}}$ **at lobe edge ~** $\boldsymbol{10^{-11}}$ **dyn/cm^2**

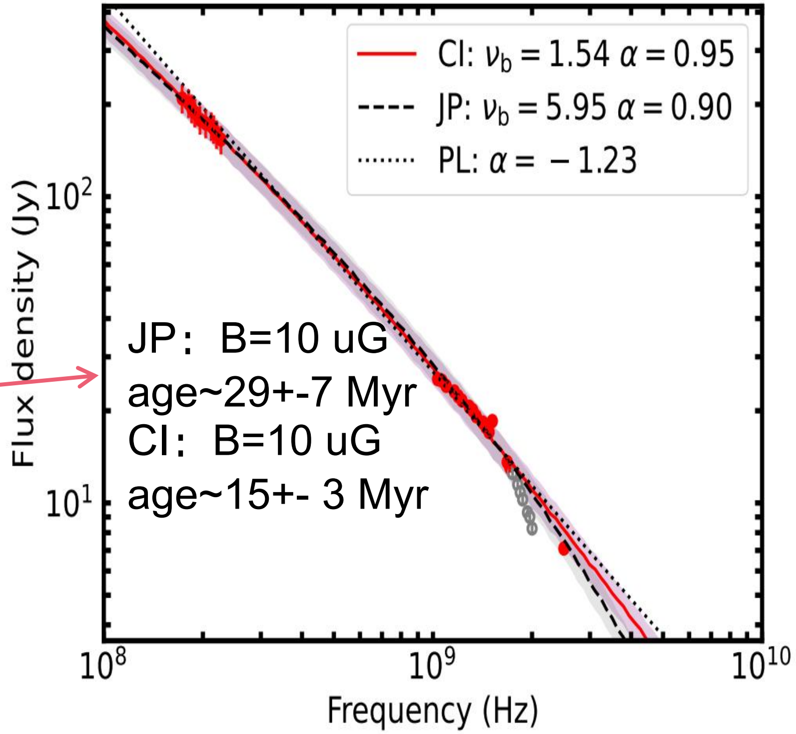
Spectral analysis

CI/JP model





JP： B=10uG
age~37+-10 Myr
CI： B=10 uG
age~22+-6 Myr



JP： B=10 uG
age~29+-7 Myr
CI： B=10 uG
age~15+- 3 Myr

Synchrotron age $t_s = 1590 \frac{B^{0.5}}{(B^2 + B_{IC}^2)\left[(1+z)\nu_b\right]^{0.5}} \mathrm{Myr},$

Energetics and Power from Radio

Total energy:

I. $\gamma = 4/3$, $E_{\rm min} = 4P_{\rm min}V \simeq 7.8\times 10^{58}{\rm erg}$

II. $\gamma \in (4/3, 5/3)$, $E_{\rm cav} = \gamma/(\gamma-1)P_{\rm th}V = (2.4 \sim 3.8)\times 10^{59}$ erg

Total radio luminosity (~ 1% of the total power):

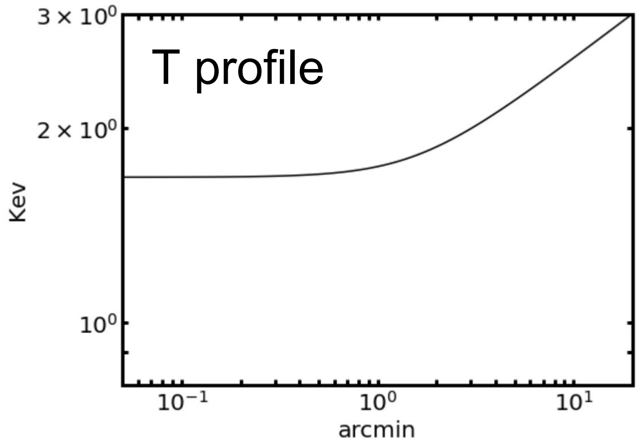
For diffuse region: $L_{\rm l,rad} \simeq 2.8\times 10^{41}{\rm erg/s}$

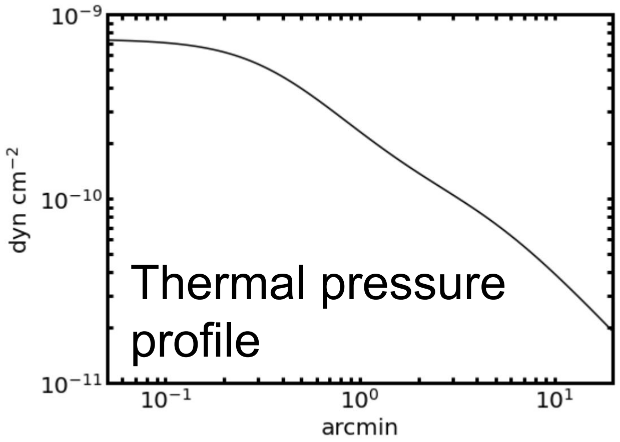
Whole region: $L_{\rm t,rad} = 2.8\times 2.8^{41}$**erg/s**

Kenetic power from $P_{\rm kin}$–L_{151} relation (Fan et al. 2018; Godfrey & Shabala 2013):

For diffuse region: $L_{\rm i,kin} = 1.1\times 2.8^{44}$ **erg/s**

For whole region: $L_{\rm i,kin} = 1.6\times 2.8^{44}$ **erg/s**





Dynamic time

Sound crossing time:

$$t_s = D_{\rm L}/c_s = D_{\rm L}\sqrt{\mu m_{\rm H}/\gamma kT}, \; c_s \equiv (P/\rho)^{1/2} = (\gamma kT/\mu m_{\rm H})^{1/2}$$

Set D_L~ 40 kpc, derive t_s~50 Myr

Excavation time of the lobes:

$$t_{\rm exc} = \frac{\gamma}{\gamma - 1}\frac{E_{\rm min;cav}}{P_{\rm out}}$$

γ = 4/3, $P_{\rm min}$, $t_{\rm exc} \sim 25/P_{44}$ Myr

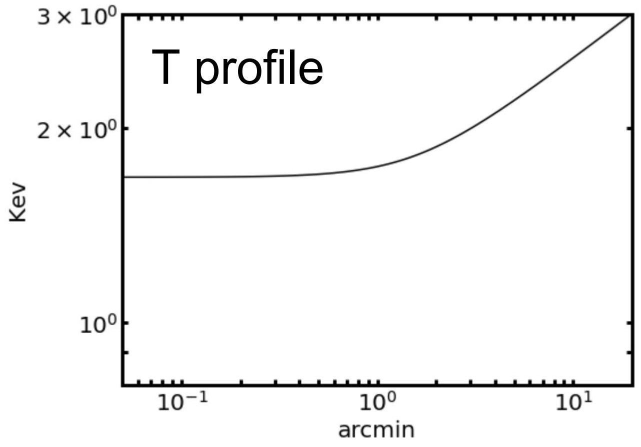
γ ∈ (4/3, 5/3), $P_{\rm th}$, $t_{\rm exc} \sim (76 - 124)/P_{44}$ Myr

Consistent with each other:

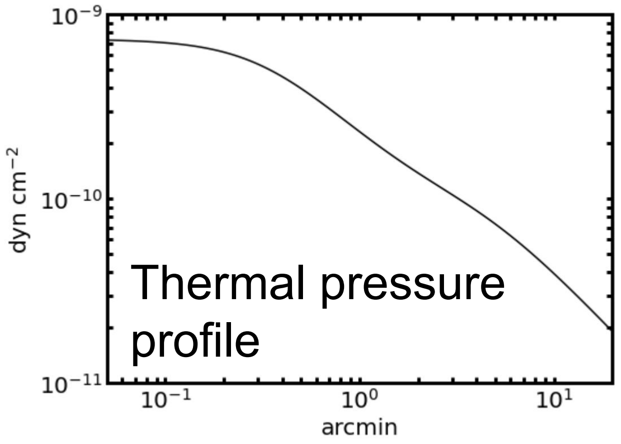
Then, for diffuse region: if $P_{\rm min}$, $P_{\rm out,}$ = 1.1×10^{44} erg/s

if $P_{\rm th}$, $P_{\rm out,}$ = $(1.5\sim2.5) \times 10^{44}$ erg/s

- **Power in the diffuse region: $(\mathbf{0.5\sim2.5}) \times \mathbf{10^{44}}$ erg/s**



T profile



Thermal pressure profile

Origin to produce diffuse emission

Stellar feedback? (Condon et al. 2002; Condon 1992)

In case of E_{cav}, SFR(M ≥ 0.1 $M_{\odot}$) ~ 600 − 1000 $M_{\odot}$/yr
In case of E_{min}, SFR(M ≥0.1 $M_{\odot}$) ~ 200 $M_{\odot}$/yr

While upper SFR ~0.081$M_{\odot}$/yr from far-infrared data of M87

Origin to produce diffuse emission

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AGN feedback?

AGN Jet

Jet power: P_j~ $10^{43\sim44}$ erg/s

Origin to produce diffuse emission

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AGN feedback?

AGN Jet **Absolutely**

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AGN feedback?

AGN Jet **primary, dorminant**

Jet power: P_j~ $10^{43\sim44}$ erg/s

AGN wind (Yuan et al. 2018; Yoon et al. 2018)

$\dot{M}_{\mathrm{tr}} - P_j$ relation: $\dot{M}_{\mathrm{tr}} \simeq 2\times10^{-3}\left(\frac{P_{\mathrm{W}}}{10^{43}\mathrm{erg/s}}\right)^{1/3}\dot{M}_{\mathrm{Edd}}$

With bondi accretion $\dot{m}_{\mathrm{B}} \equiv \frac{\dot{M}_{\mathrm{B}}}{\dot{M}_{\mathrm{Edd}}} \simeq (0.7-14)\times10^{-4}$

$$P_{\mathrm{W}} \simeq (5\times10^{38} - 4\times10^{42})\ \mathrm{erg/s}.$$

- Lower than the p**ower in the diffuse region !**

Origin to produce diffuse emission

Stellar feedback? (Condon et al. 2002; Condon 1992) X

In case of E_{cav}, SFR(M ≥ 0.1 $M_{\odot}$) ~ 600 − 1000 $M_{\odot}$/yr
In case of E_{min}, SFR(M ≥0.1 $M_{\odot}$) ~ 200 $M_{\odot}$/yr

While upper SFR ~0.081 $M_{\odot}$/yr from far-infrared data of M87

AGN feedback?

AGN Jet **primary, dorminant**

Jet power: $P_j \sim 10^{43 \sim 44}$ erg/s

AGN wind (Yuan et al. 2018; Yoon et al. 2018) **secondary**

$\dot{M}_{\mathrm{tr}} - P_j$ relation: $\dot{M}_{\mathrm{tr}} \simeq 2 \times 10^{-3} (\frac{P_{\mathrm{W}}}{10^{43} \mathrm{erg/s}})^{1/3} \dot{M}_{\mathrm{Edd}}$

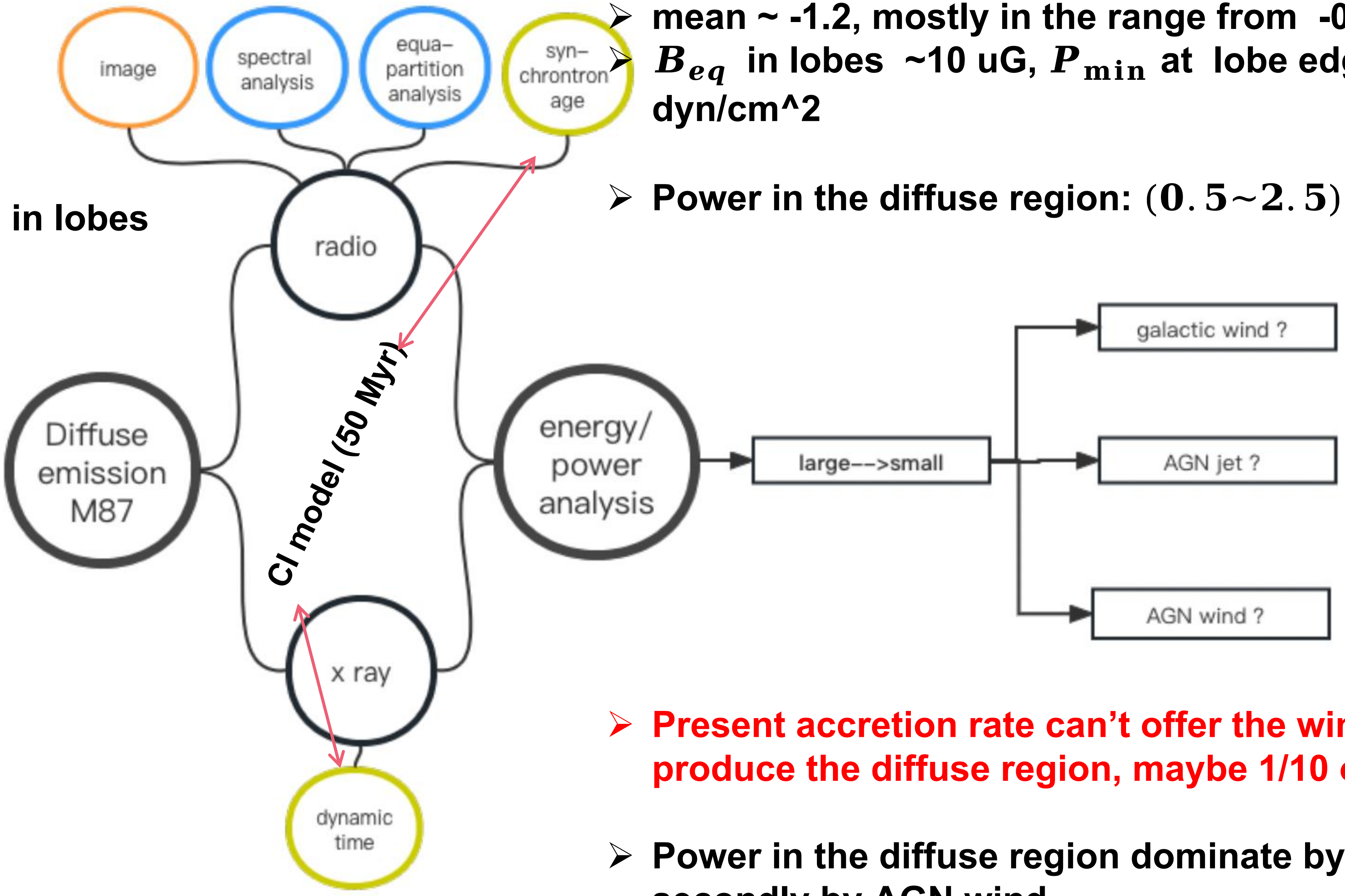
With 1/10 **power in the diffuse region**

$$\dot{M}_{\mathrm{tr}} \simeq (2.8 - 4.3) \times 10^{-3} \dot{M}_{\mathrm{Edd}}$$

- A little higher than present bondi accretion rate !

Conclusions

- ➢ Turbulence in lobes



- ➢ mean ~ -1.2, mostly in the range from -0.9~ -1.4
- ➢ B_{eq} in lobes ~10 uG, $P_{\min}$ at lobe edge ~ 10^{-11} dyn/cm^2

- ➢ Power in the diffuse region: $(0.5\sim2.5)\times10^{44}$ erg/s

- ➢ Present accretion rate can’t offer the wind power to produce the diffuse region, maybe 1/10 of it !

- ➢ Power in the diffuse region dominate by AGN jet, secondly by AGN wind.

Thank You!

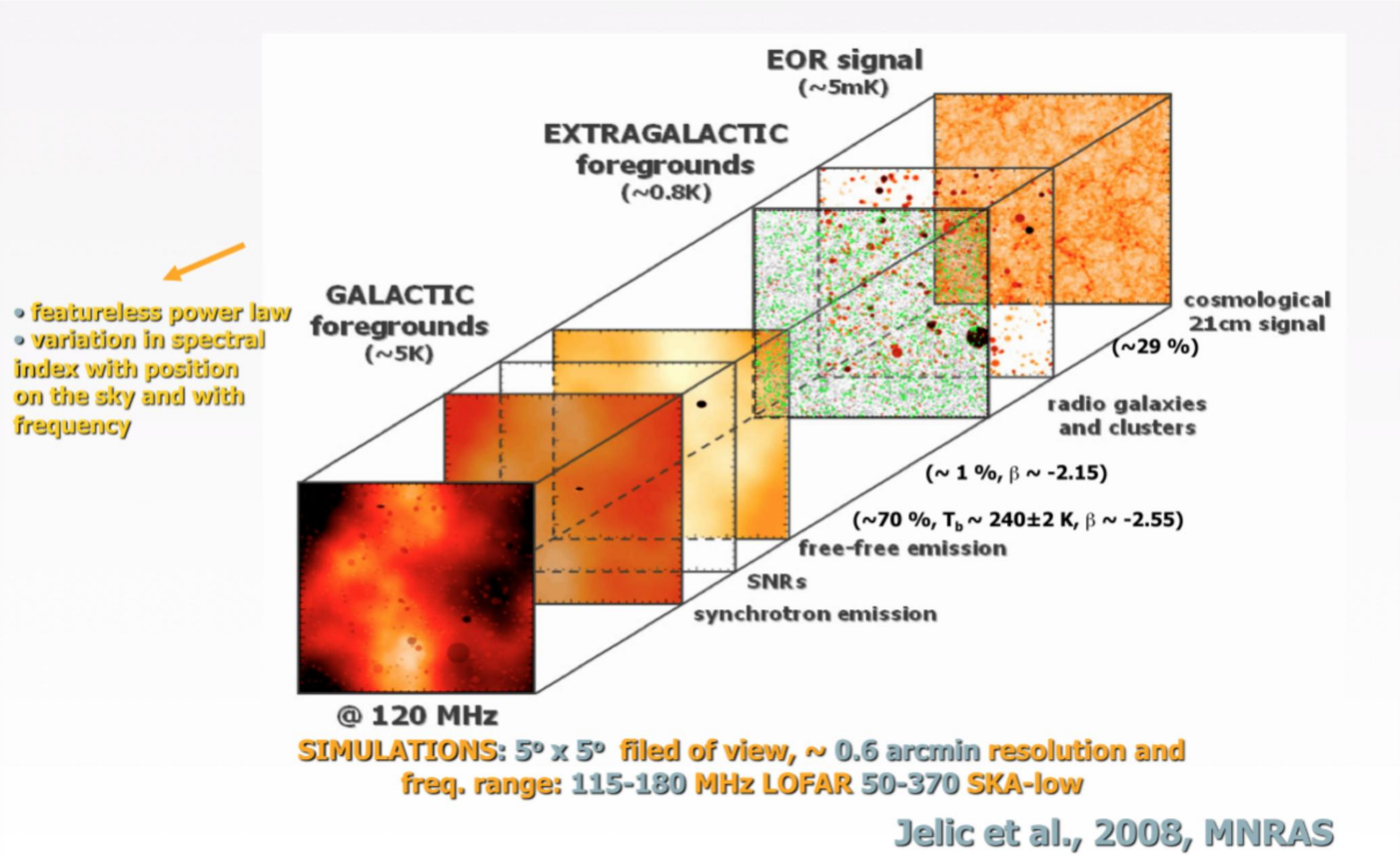
Background

Extragalactic foreground

- ➢ peeled in EoR detection

But

- ➢ We expore its physical properties, evolution history and feedback!



- featureless power law
- variation in spectral index with position on the sky and with frequency

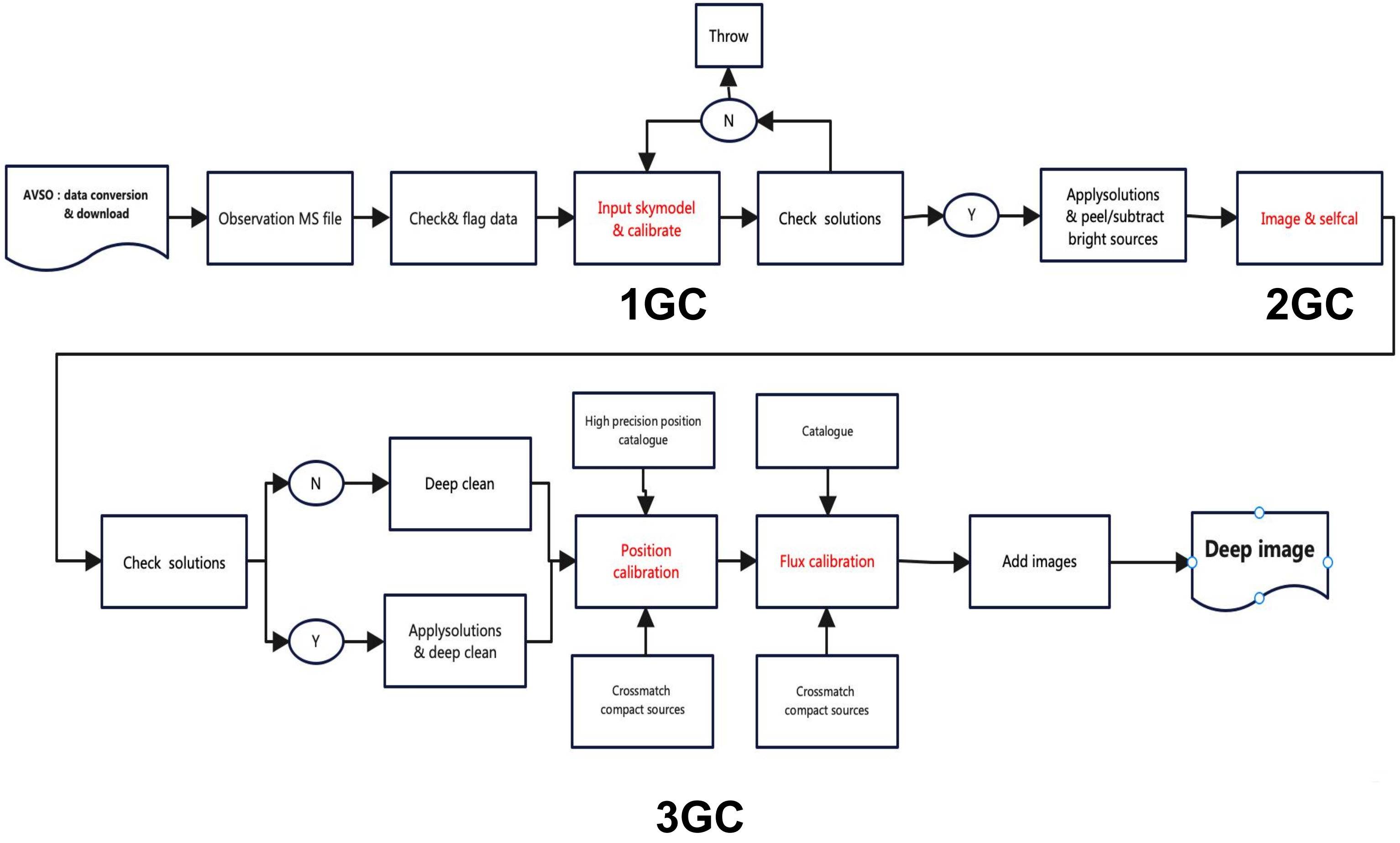
SIMULATIONS: 5° x 5° filed of view, ~ 0.6 arcmin resolution and freq. range: 115-180 MHz LOFAR 50-370 SKA-low

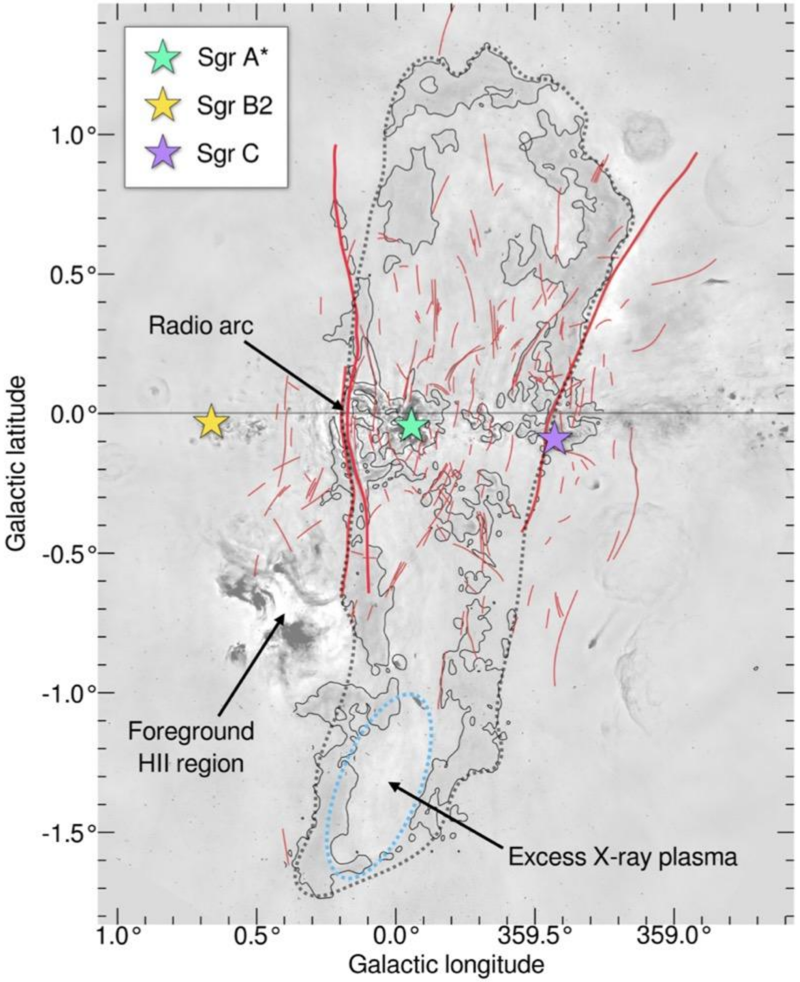
Jelic et al., 2008, MNRAS

Data processing

MWA pipeline: 1GC, 2GC, 3GC

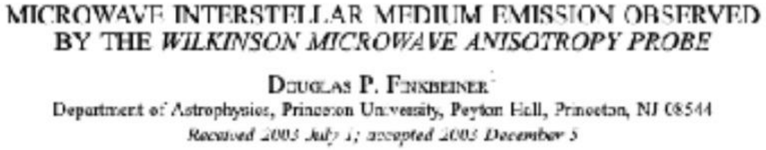
EVLA





Heywood et al. (2019)

WMAP Haze to Fermi Haze



MICROWAVE INTERSTELLAR MEDIUM EMISSION OBSERVED
BY THE *WILKINSON MICROWAVE ANISOTROPY PROBE*

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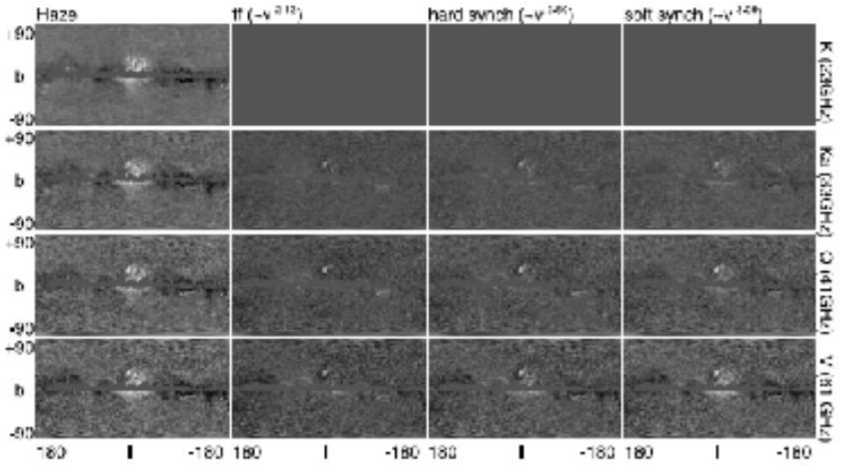

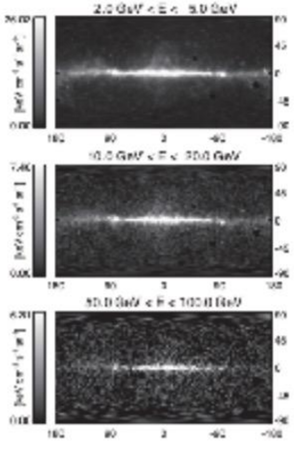

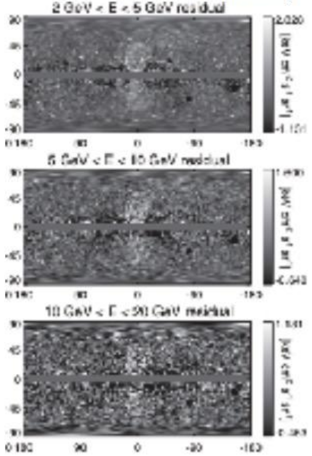

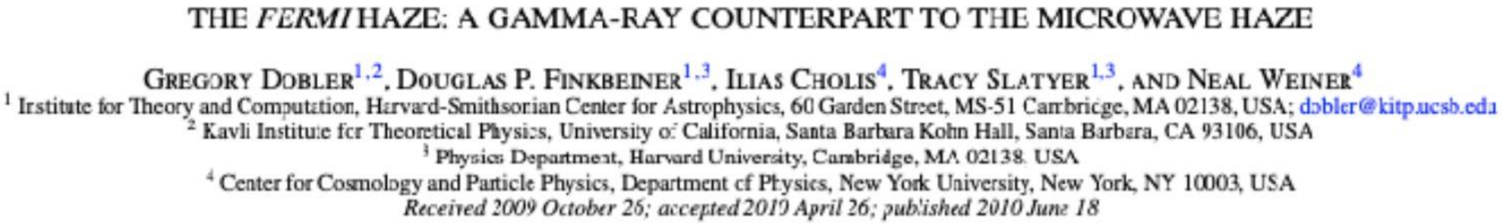

THE *FERMI* HAZE: A GAMMA-RAY COUNTERPART TO THE MICROWAVE HAZE

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