MAD in Action in M87

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Outline

- "VLBI study of AGN Jets" during the last decade
  - Lesson from M87 to others: Acc. & Colli. zone (ACZ: Marscher+ 2008) as "Pipeline" (Marscher & Gear 1985) and Jet Collimation Break (JCB: Asada & MN 2012), providing a physical extent of ACZ (Park's talk)
  - Thrilling results with EHT, but the horizon-scale jet in M87 is still unknown (or has no strong constraints)
- Any unique usage of EAVN facilities to understand the fundamental physics in AGN jets?

Global Structure of AGN Jets: ACZ + JCB

M87 + NGC 6251 + NGC 315 + FSRQs + BLOs

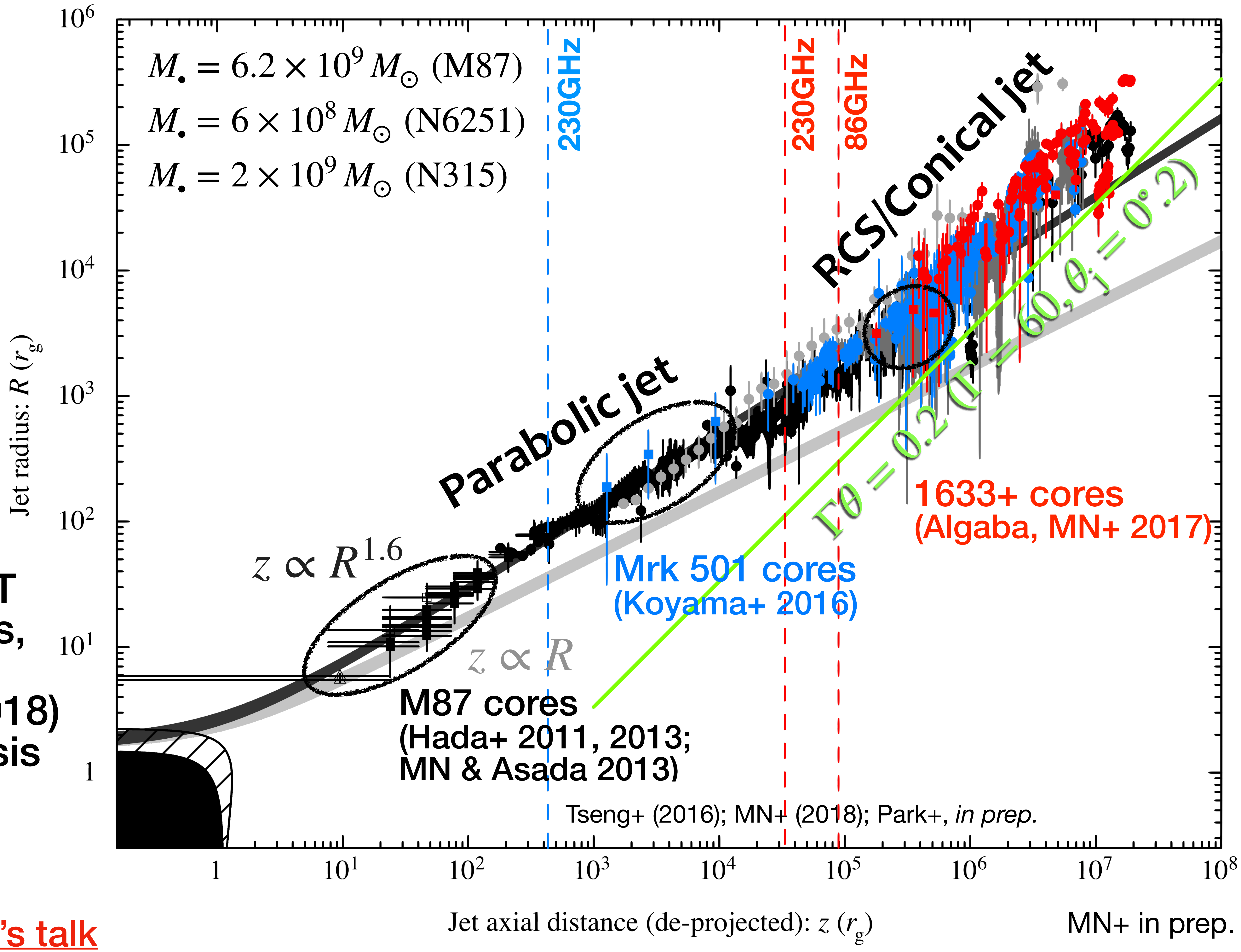
1633+382 1928+738 2201+315 Mrk 501 Mrk 421 3C 371	• Nearby or • Massive $M_{\rm BH}$ or • Large $\theta_{\rm v}$

- Blandford & Königl (1979)
  ➡Revisiting "conical" jet model

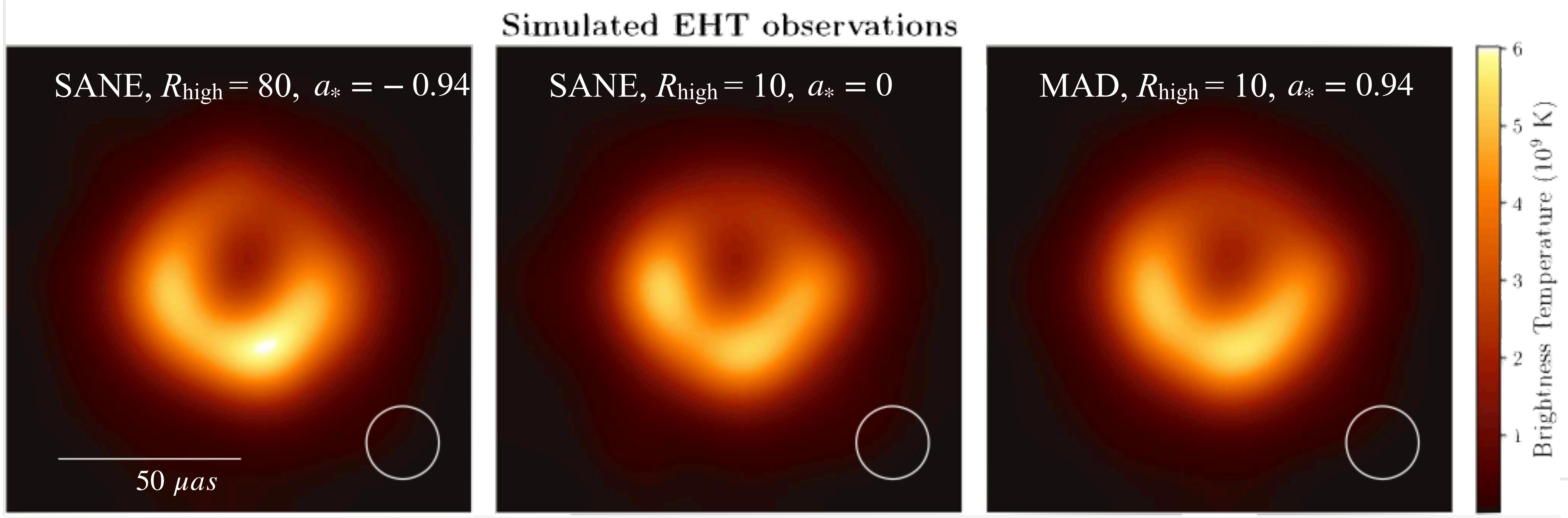
- Blandford & Znajek (1977)
  Blandford & Payne (1982)
  ➡BP82 (disk-driven) wind may NOT produce limb-brightened features, while BZ77 does play a role (Takahashi, Toma+ 2018; MN+ 2018)
  ➡Revisiting spine-sheath hypothesis

- Blandford & Begelman (1999)
  ➡ADIOS as a confining material

ACZ & JCB in a FSRQ: *See*, Lee (SNU)'s talk



MN+ in prep.

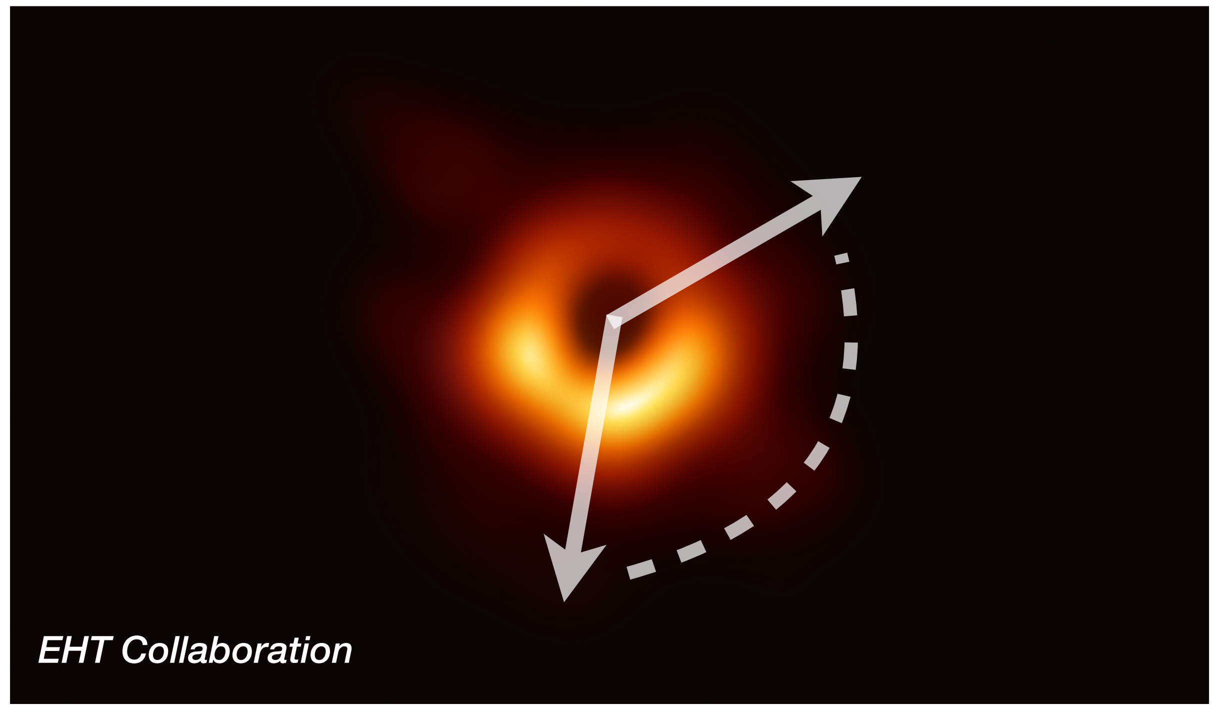


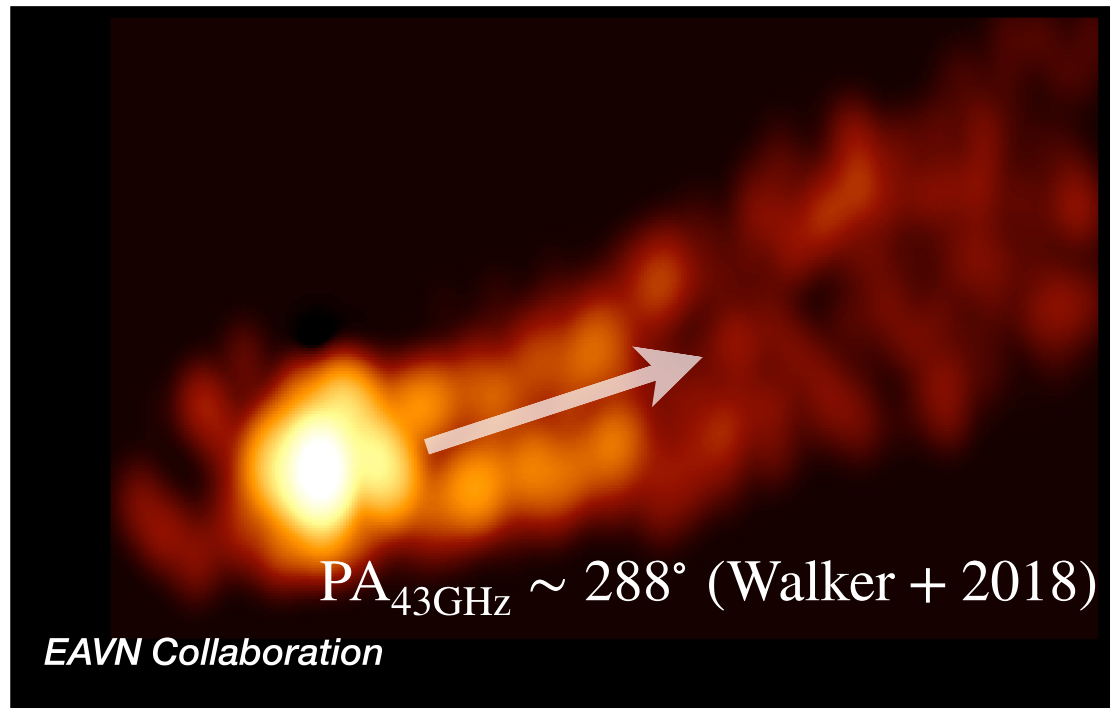
from paper I (EHTC 2019a)

- **Synthesized emission: the funnel wall and/or accretion flow with $\sigma < 1$: $\Gamma_\infty \to 1$**

  σ: Poynting flux per unit matter energy flux

- **Connection with the extended jet (relativistic outflow: $\Gamma_\infty \gg 1$) is unknown**





- **BH mass:**
  $M_\bullet = (6.5 \pm 0.7) \times 10^9 \, M_\odot$
- **Mass accretion rate:**
  $\dot{m} \left(\equiv \dot{M}/\dot{M}_{\rm Edd}\right) \simeq 5 \times 10^{-7} - 3 \times 10^{-4}$
- **Jet power:**
  $10^{42}\ \mathrm{erg\,s^{-1}} < P_{\rm jet}\ (\lesssim 10^{43}\ \mathrm{erg\,s^{-1}})$
- **BH spin** (*a*=0 can't do >10^{42} erg/s):
  $|a| \leq 0.94$
- **Magnetic flux:**
  $\phi = 3.6 - 56.5$ (units of $\sqrt{\dot{M} R_g^2 c}$)
  SANE MAD
- **Electron temperature:**
  $T_e \simeq T_i/(10 - 160)$
- **$\mathrm{PA}_{\rm GRMHD}$ (forward jet):**
  $235^\circ \pm 65^\circ$ (Apr 5 – 11)

Event Horizon Telescope

Magnetically Arrested Disk (MAD)

$$\Phi \equiv \int 2\pi \mathcal{B}_p r\,dr$$

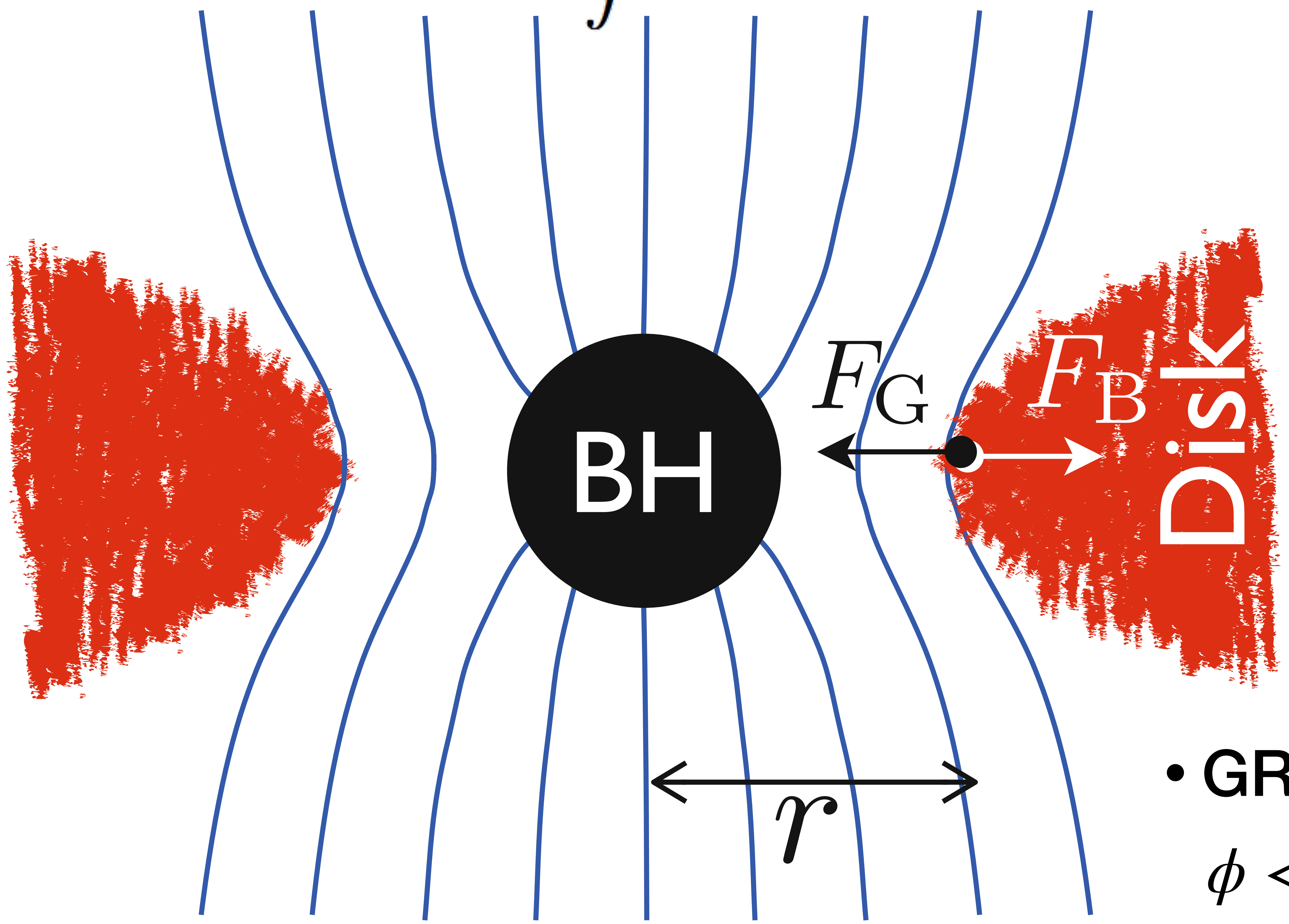


Image courtesy : A. Tchekhovskoy

- **Poloidal magnetic field supports the accreting gas against the BH gravity** (Narayan+ 2003; Igmenshchev 2008)

$$\frac{\mathcal{B}_p^2}{8\pi} \simeq \frac{GM\rho}{R_g} = \rho c^2$$

$$\begin{aligned} \Phi &= \phi\sqrt{\dot{M} R_g^2 c} \\ &\simeq 10^{33}\phi\,\dot{m}^{1/2} m_9^{3/2}\ \mathrm{Mx}\ (\mathrm{G\,cm^2}) \end{aligned}$$

$$\dot{m} \lesssim 0.01\ (\mathrm{RGs,\ BL\,Lacs})$$

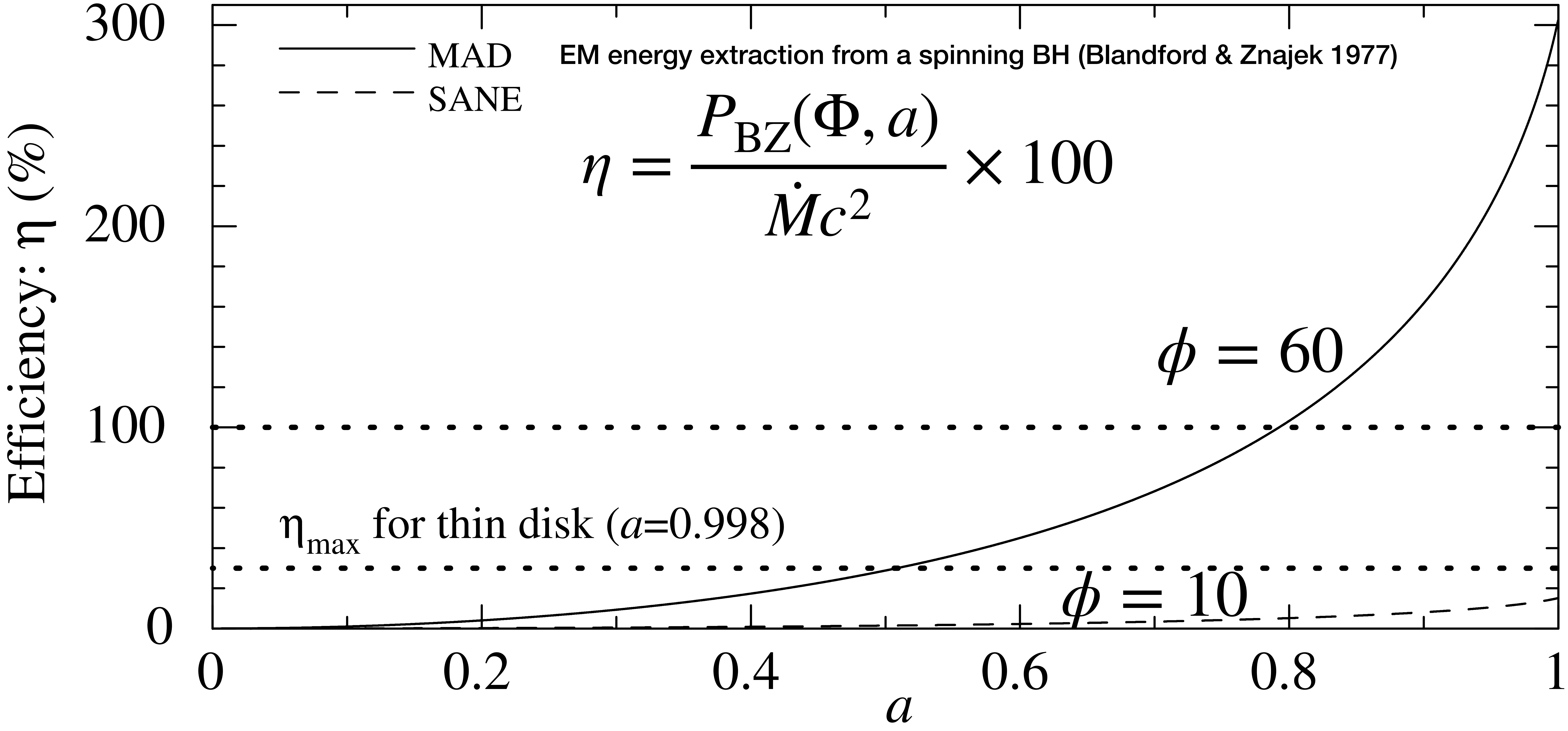
- **GRMHD Simulations:**

  $\phi < 10$ (SANE), $\phi \sim 40 - 80$ (MAD) (Narayan+ 2012; Sadowski+ 2013)

- **Supporting MAD in observations:**

  $\Phi_{\rm jet} = 10^{31} - 10^{35}$ Mx (Zamaninsab+ 2014) $P_{\rm jet} \gtrsim \dot{M}c^2$ (Ghisellini+ 2014)

MAD Can Make $P_{\rm jet} > \dot{M}c^2$

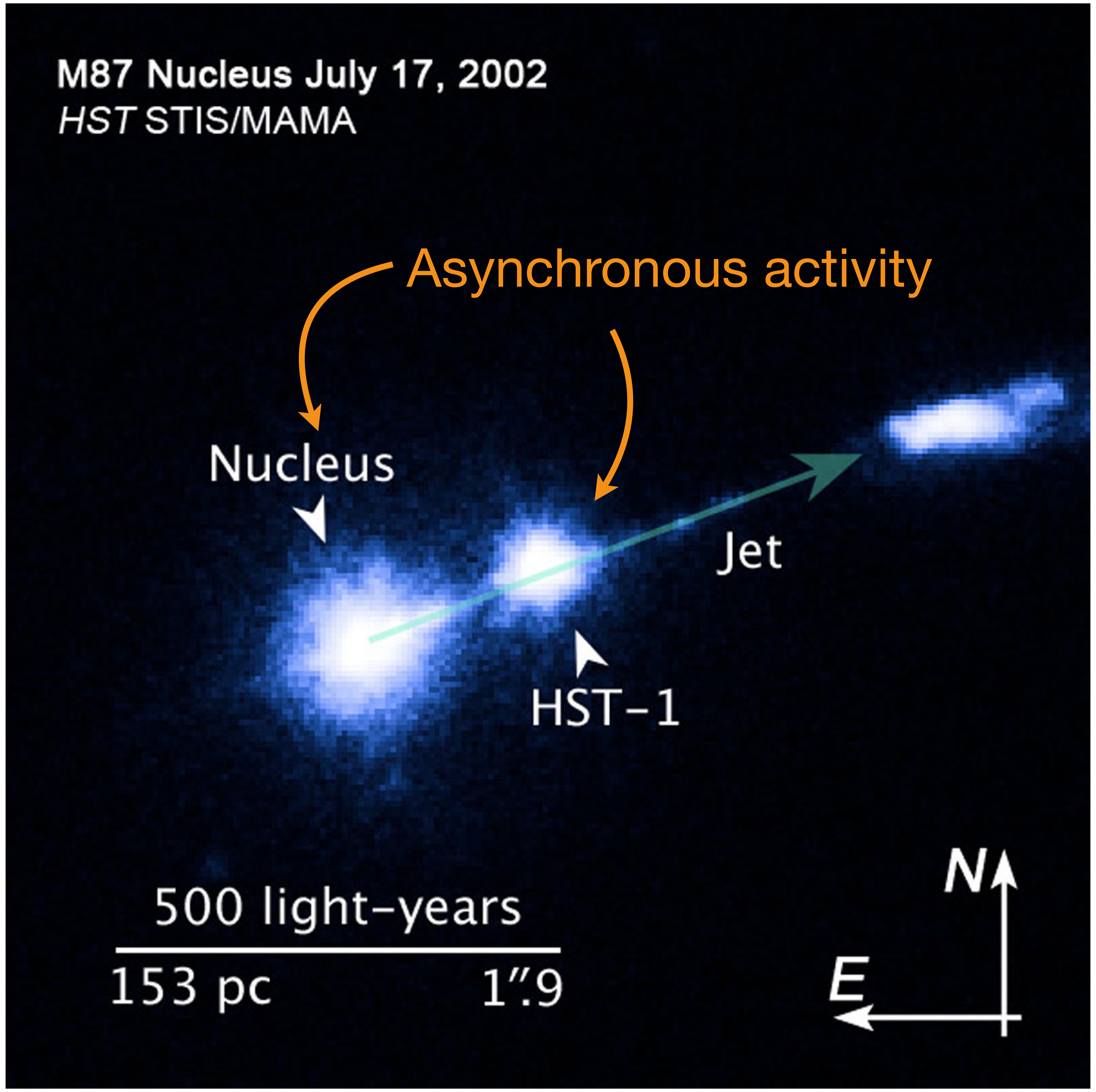


Motivations

6.3. Jet Power

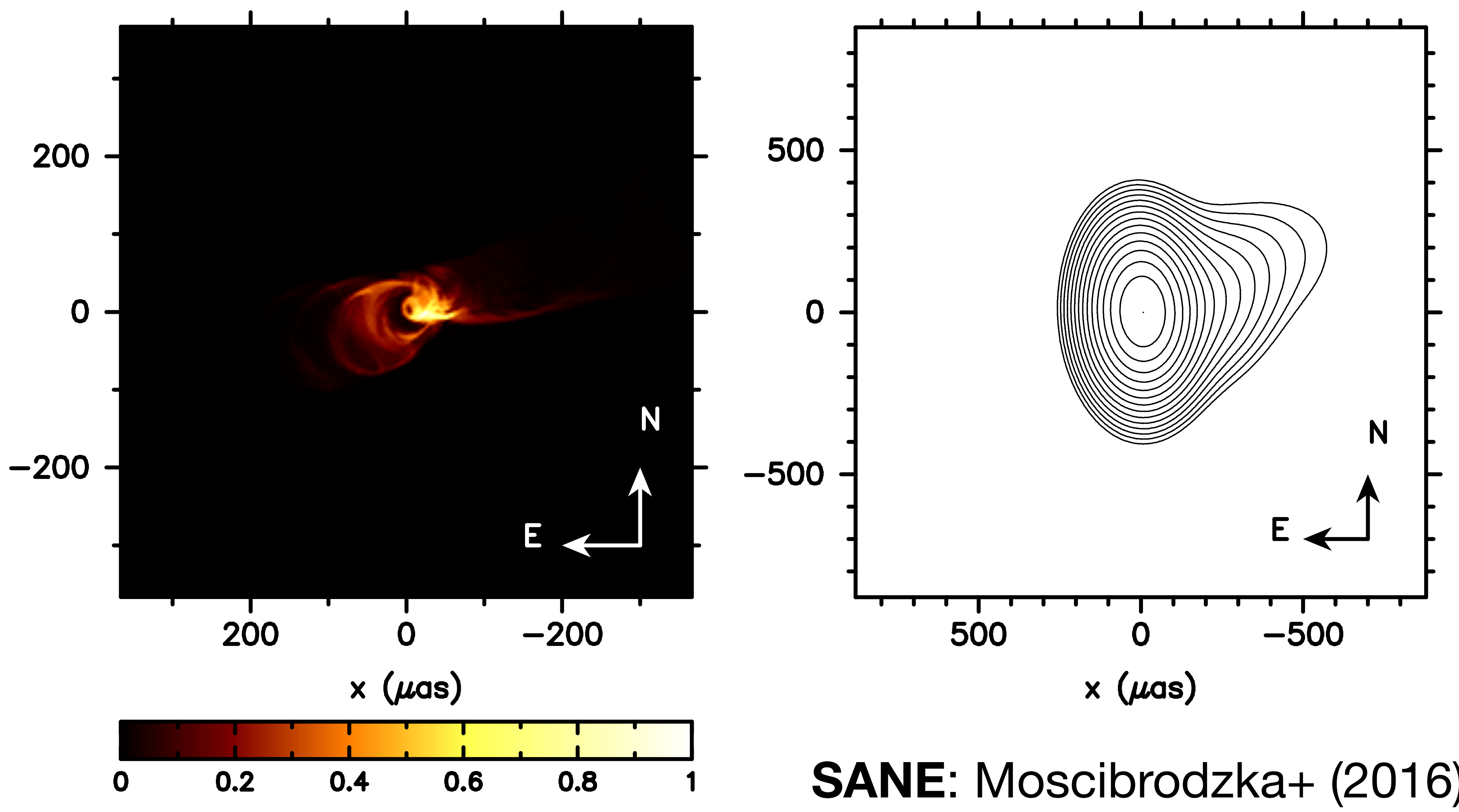
Estimates of M87's jet power ($P_{\rm jet}$) have been reviewed in Reynolds et al. (1996), Li et al. (2009), de Gasperin et al. (2012), Broderick et al. (2015), and Prieto et al. (2016). The estimates range from 10^{42} to 10^{45} erg s^{-1}. This wide range is a consequence of both physical uncertainties in the models used to estimate $P_{\rm jet}$ and the wide range in length and timescales probed by the observations. Some estimates may sample a different epoch and thus provide little information on the state of the central engine during EHT2017. Nevertheless, observations of *HST*-1 yield $P_{\rm jet} \sim 10^{44}$ erg s^{-1} (e.g., Stawarz et al. 2006). *HST*-1 is within ∼70 pc of the central engine and, taking account of relativistic time foreshortening, may be sampling the central engine $P_{\rm jet}$ over the last few decades. Furthermore, the 1.3 mm light curve of M87 as observed by SMA shows $\lesssim$50% variability over decade timescales (Bower et al. 2015). Based on these considerations it seems reasonable to adopt a very conservative lower limit on jet power $\equiv P_{\rm jet,min} = 10^{42}$ erg s^{-1}.

from paper V (EHTC 2019e)



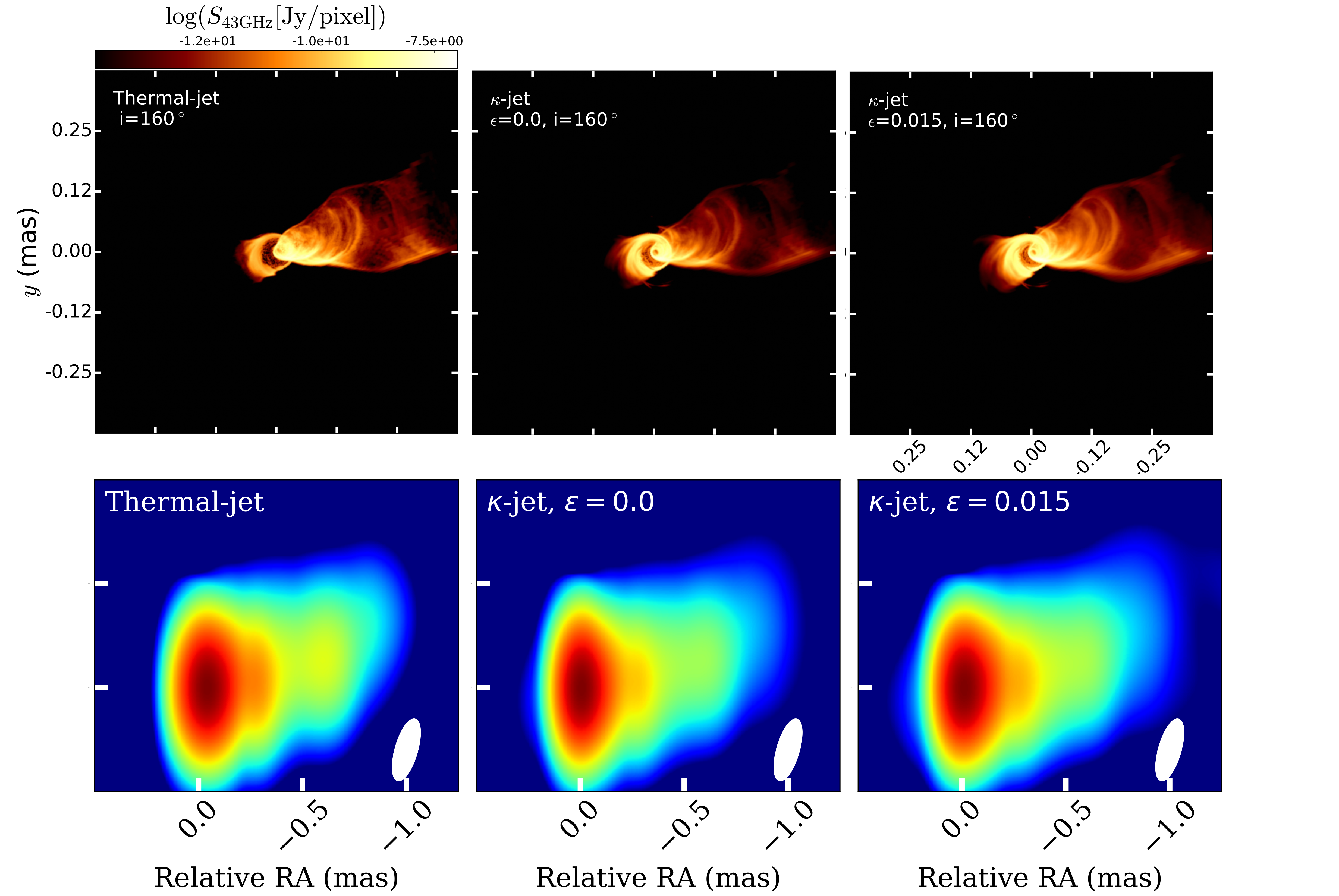
- **Current jet power needs be examined with further inner regions (mm/cm VLBI)**

Motivations

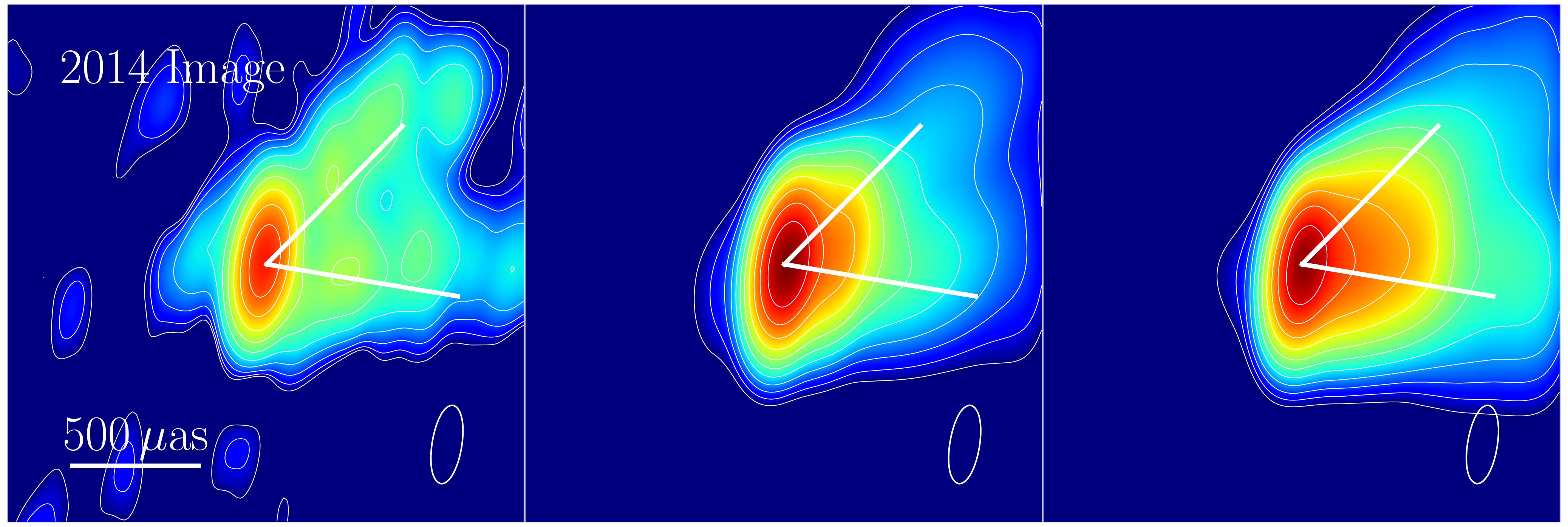


SANE: Moscibrodzka+ (2016)

$P_j = (4 - 30) \times 10^{42}$ erg s^{-1}



43GHz imaging with **SANE**: Davelaar+ (2019) $P_j \sim 10^{43}$ erg s^{-1}



86GHz imaging with **MAD**: Chael+ (2019)

$P_j = (6.6 - 13.0) \times 10^{42}$ erg s^{-1}

- None of models (SANE/MAD, (non-)Thermal eDF) can reproduce the morphology; Limb-brightened (L-B) feature
- Punsly (2019) argue both SANE and MAD jets (M16, C19) are narrower than real jet at 43/86GHz (Hada+ 2013, 2016)

M87

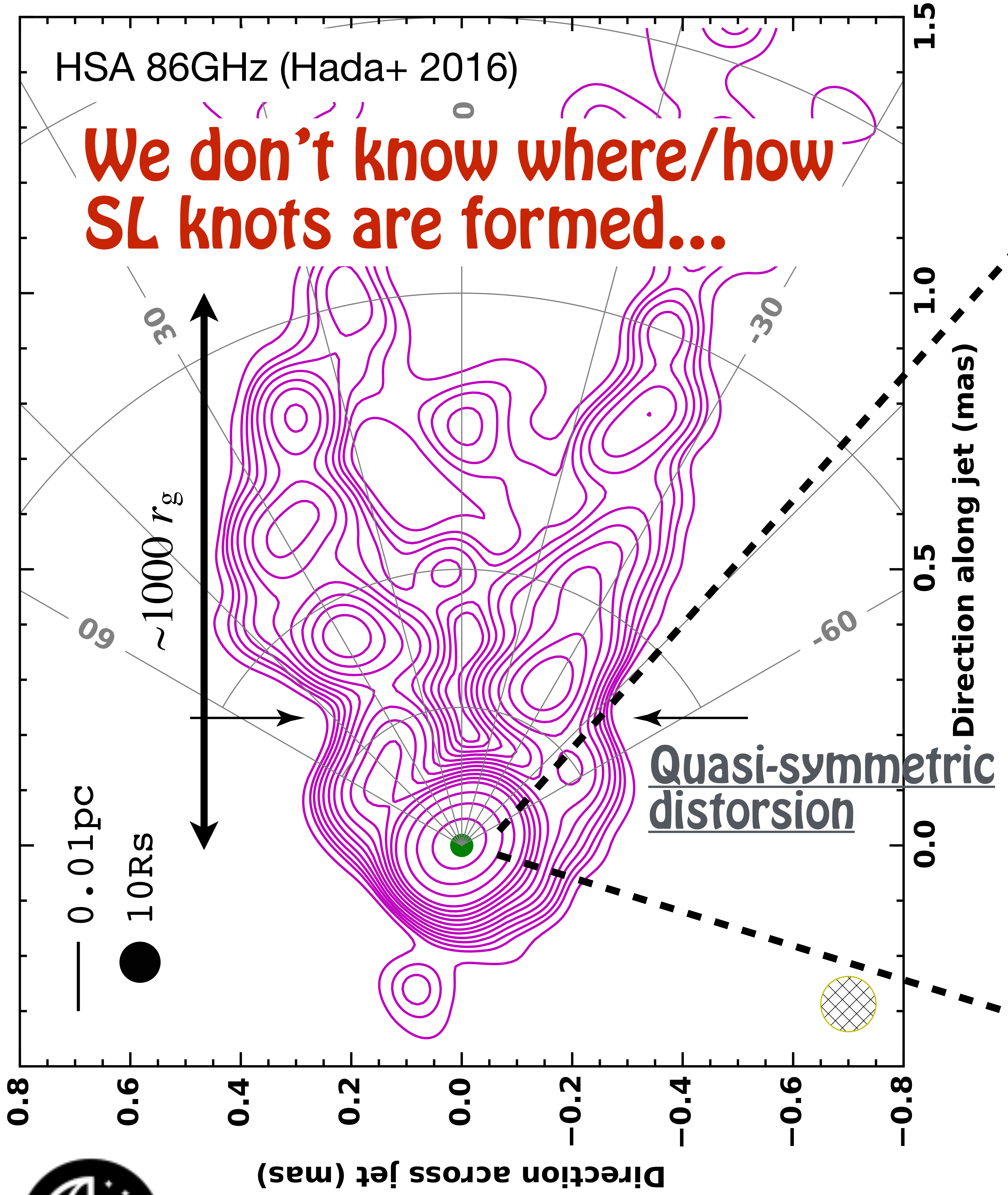
GRMHD sim. →

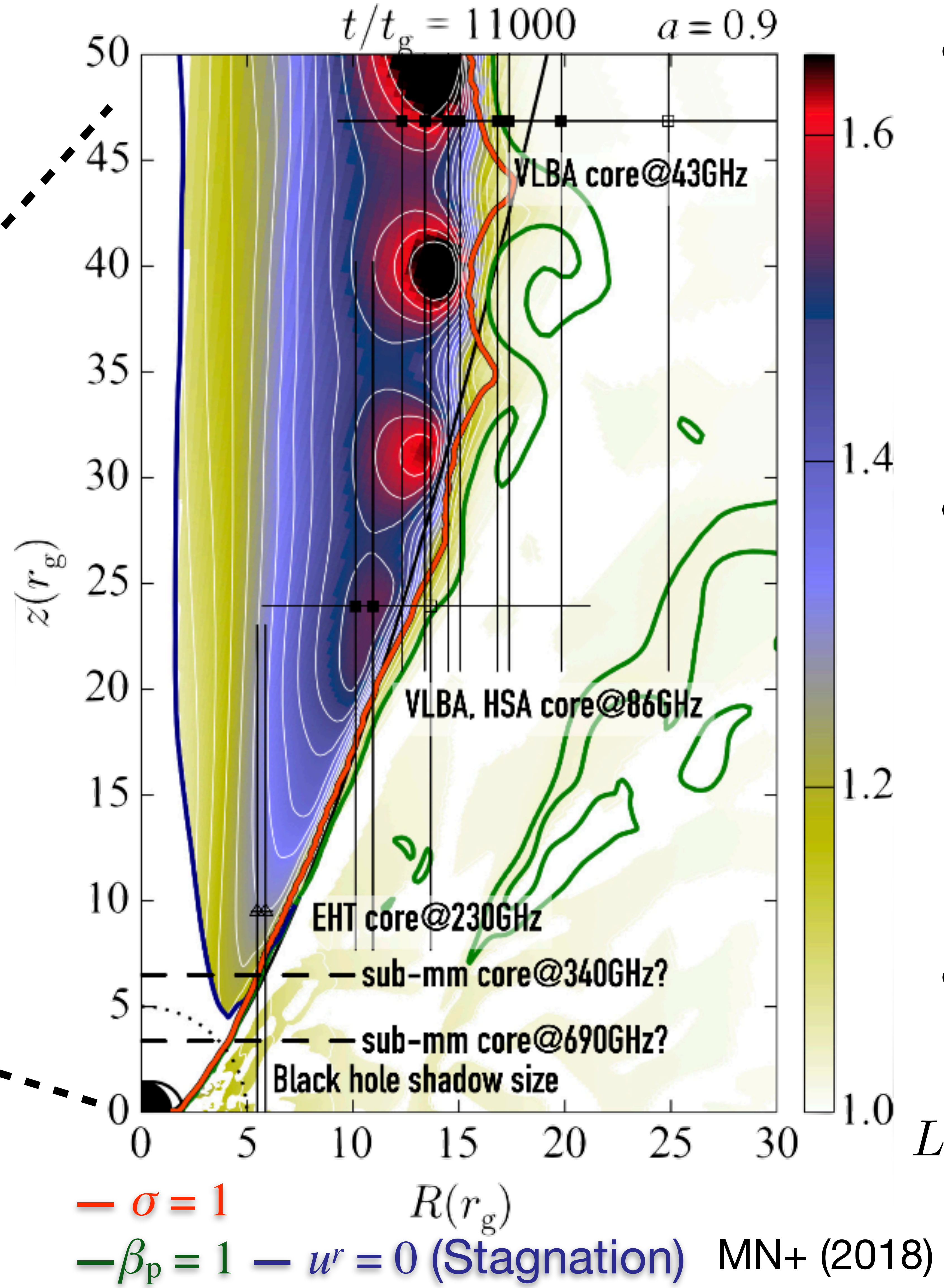
$$\phi = \frac{\Phi}{\sqrt{\dot{M} R_{\rm g}^2 c}}$$

VLBI core obs.

Pol. / X-ray obs.

Innermost Structure of the M87 Jet





MN+ (2018)

- **SSA thick VLBI cores → $|\boldsymbol{B}|$ ($z < 50\, r_g$)**

  Hada+ (2012, 2016); Kino+ (2014, 2015)

  $$\Phi_{43-230\,\mathrm{GHz}} \simeq (1-2)\times 10^{33}\ \mathrm{Mx}\,(\mathrm{G\,cm^2})$$

- **Enclosed current $I(\Phi)$**

  e.g. Mestel (1969); Okamoto (1978); Beskin (1997); Narayan+ (2007)

  $$I(\Phi) = \frac{c}{2} R B_\phi \approx -\frac{\Omega_F \Phi}{2\pi} \simeq (1.5-3)\times 10^{17}\ \mathrm{A}$$

  $(a = 0.9)$

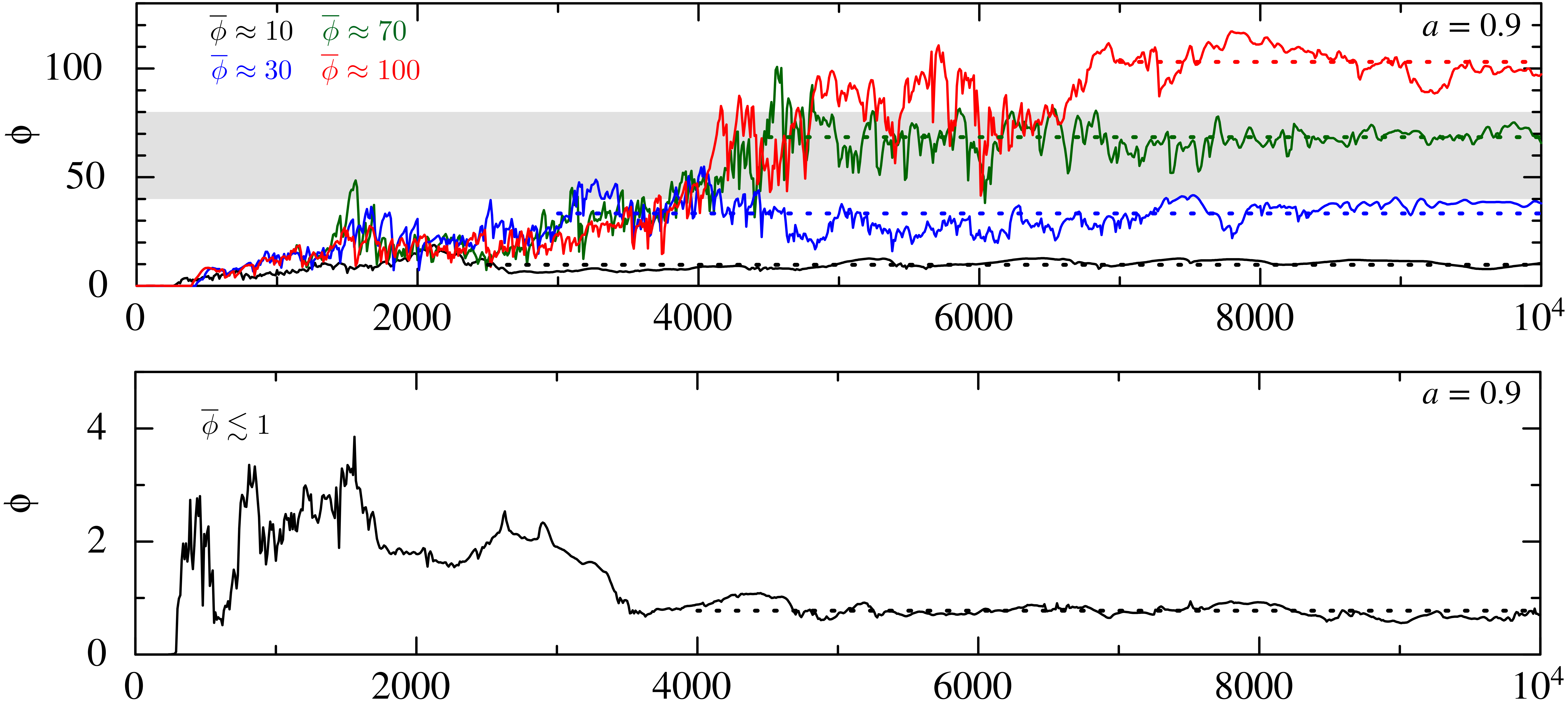
- **Electromagnetic (Poynting) luminousity**

  $$L_{\mathrm{EM}} = I^2 z \simeq (4-15)\times 10^{43}\ \mathrm{erg\ s^{-1}}$$

  $(z \sim 160\,\Omega,\ a = 0.9)$

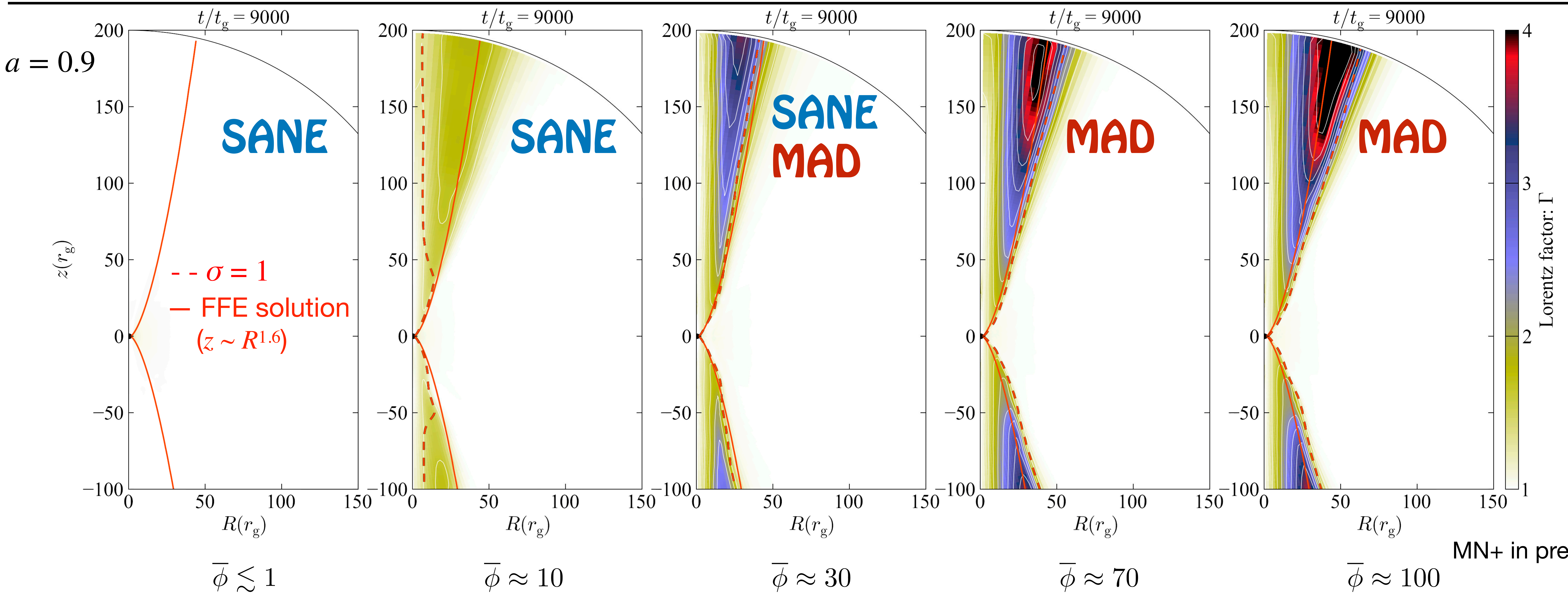
Event Horizon Telescope

Axisymmetric 2D GRMHD Survey



MN+ in prep.

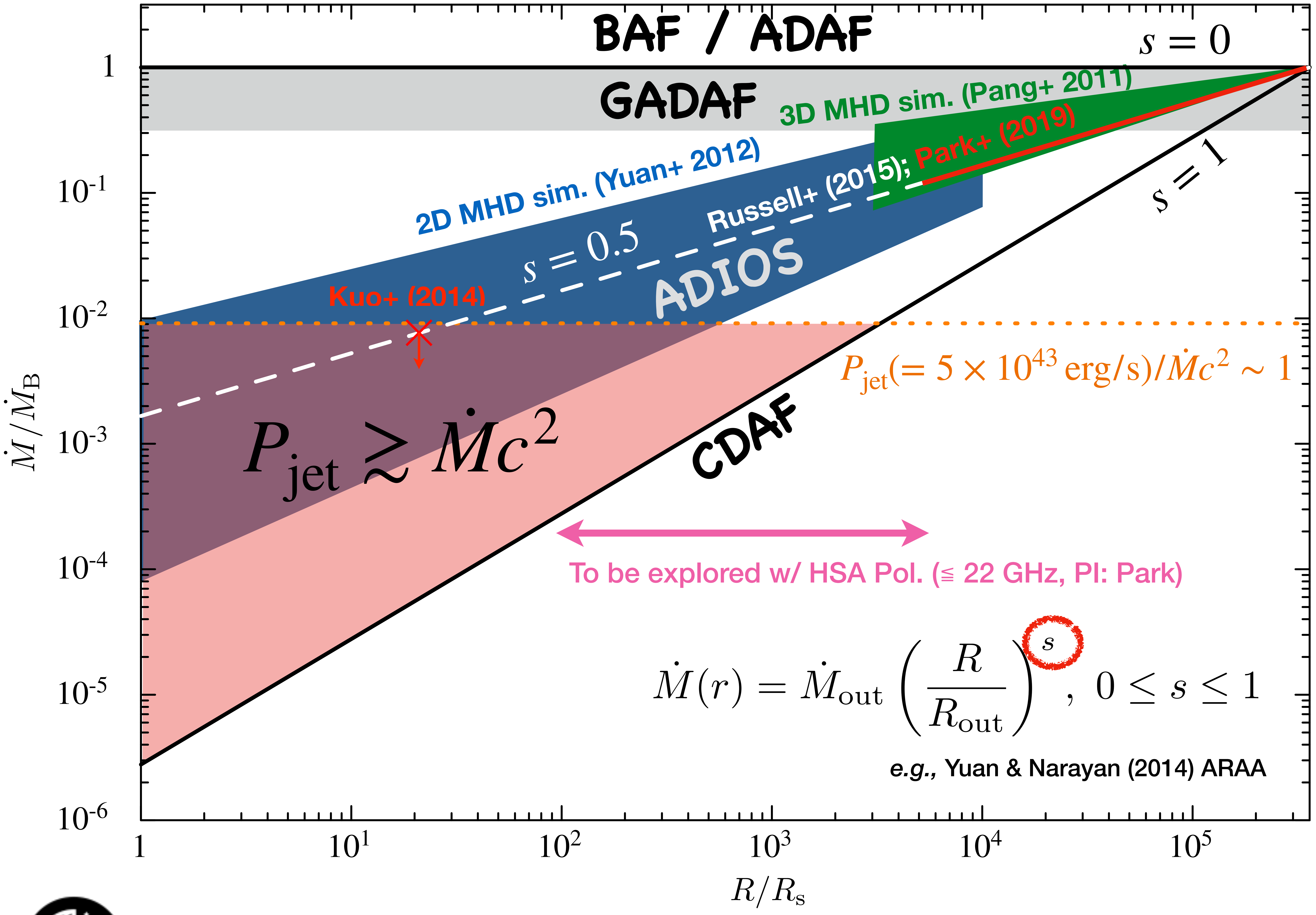
Lateral Expansion & Acceleration



MN+ in prep.

- Bulk acceleration takes place in the funnel where $\sigma > 1$
- Large ϕ causes a lateral expansion (effective magnetic nozzle); limb-brightened → MAD?
- $\phi = 30 - 70$ can be matched with the parabolic shape of $\sigma \sim 1$ → VLBI obs.?

Event Horizon Telescope



X-ray obs.

$$R_{\rm B} \simeq 210\ {\rm pc}\left(\frac{kT_{\rm B}}{0.9\,{\rm keV}}\right)^{-1}\left(\frac{M_\bullet}{6.2\times10^9\,M_\odot}\right) \simeq 3.6\times10^5\ R_{\rm s}$$

$$\dot{M}_{\rm B} \simeq 0.2\,M_\odot\ {\rm yr}^{-1}\left(\frac{n_{\rm e,B}}{0.3\,{\rm cm}^{-3}}\right)\left(\frac{kT_{\rm B}}{0.9\,{\rm keV}}\right)^{-3/2}\left(\frac{M_\bullet}{6.2\times10^9\,M_\odot}\right)^2$$

Di Mateo+ (2003); Rafferty+ (2006); Russell+ (2015)

$$\dot{M}_{\rm Edd} = 136.4\ M_\odot\,{\rm yr}^{-1}\left(\frac{\epsilon_{\rm acc}}{0.1}\right)^{-1}\left(\frac{M_\bullet}{6.2\times10^9\,M_\odot}\right)$$

X-ray / Pol. obs.

$n_{\rm e} \propto R^{-1}\ (R \gtrsim 5000\,R_{\rm s})$: $s \simeq 0.5$

Russell+ (2015) - X-ray

Park+ (2019) - VLBA Pol. (≦ 5 GHz)

$\dot{M} \lesssim 9.2\times10^{-4}\ M_\odot\,{\rm yr}^{-1}(R \simeq 20\,R_{\rm s})$

Kuo+ (2014) - SMA Pol.

$\dot{M}|_{R=10\,R_{\rm s}} \simeq 5.3\times10^{-4}\ M_\odot\,{\rm yr}^{-1}$

$\dot{m} \simeq 3.9\times10^{-6}$

$\dot{M}c^2 \simeq 3.0\times10^{43}\ {\rm erg\,s^{-1}}$

M87

$$\simeq (1-2)\times 10^{33}$$

VLBI core obs.

Hada+ (2012, 2016);
Kino+ (2014, 2015)

GRMHD sim. & VLBI obs.

$$\phi = \frac{\Phi}{\sqrt{\dot{M} R_{\rm g}^2 c}} \simeq 30 - 70$$

$$\simeq 3 \times 10^{31}$$

Pol. / X-ray obs.

Russell+ (2015); Park+ (2019)

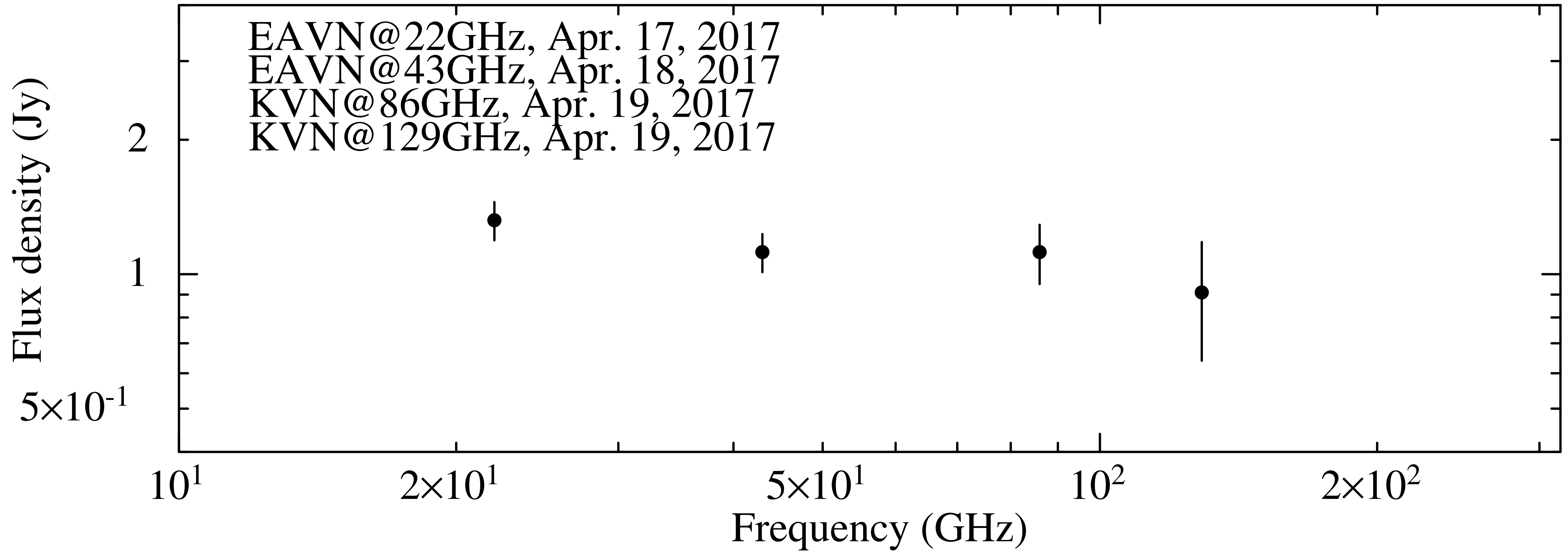
Quasi-simultaneous Monitoring of VLBI Core

- Past efforts w/ KVN 22-129GHz (2012-2016; Kim, Lee+ 2018)
  - Spectral steeping, but limited (*u*, *v*) coverage and/or structure blending?
  - True spectrum of the jet base can be flat up to 129 GHz

- Partially SSA-thick at 230GHz? (Kino 2015+)

- Assuming the poloidal flux conservation in the funnel, $\Phi_{\rm EH}$ can be extracted from VLBI core at mm-cm bands ($\geq 43\,{\rm GHz}$) where the SSA-thick core exists $({\rm Hada+2011};\, r \lesssim 50\, r_{\rm g})$

Measurement within a $0.5 \times 0.5{\rm mas}^2$ box around the peak

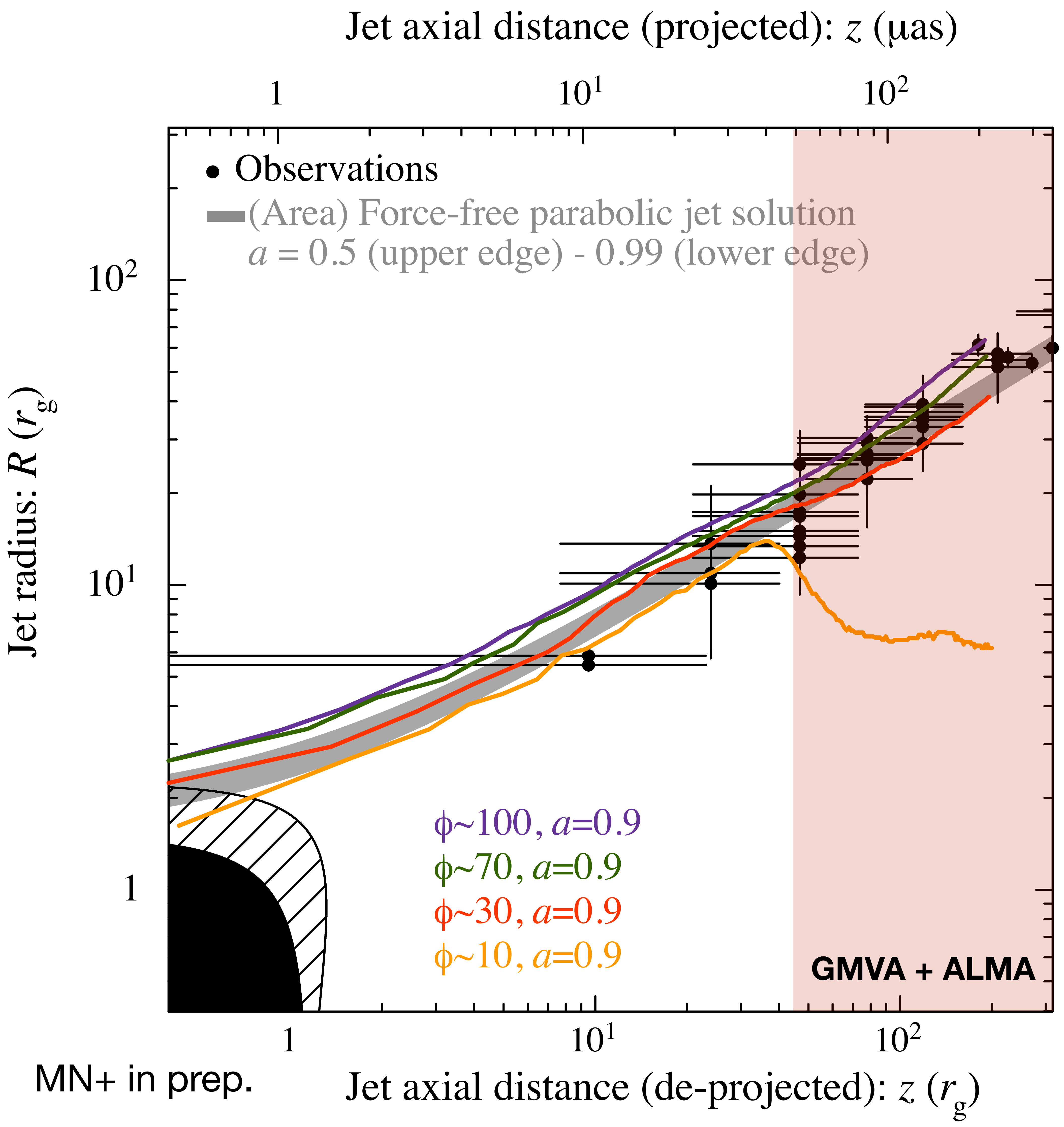


Data from paper IV (EHTC 2019d)

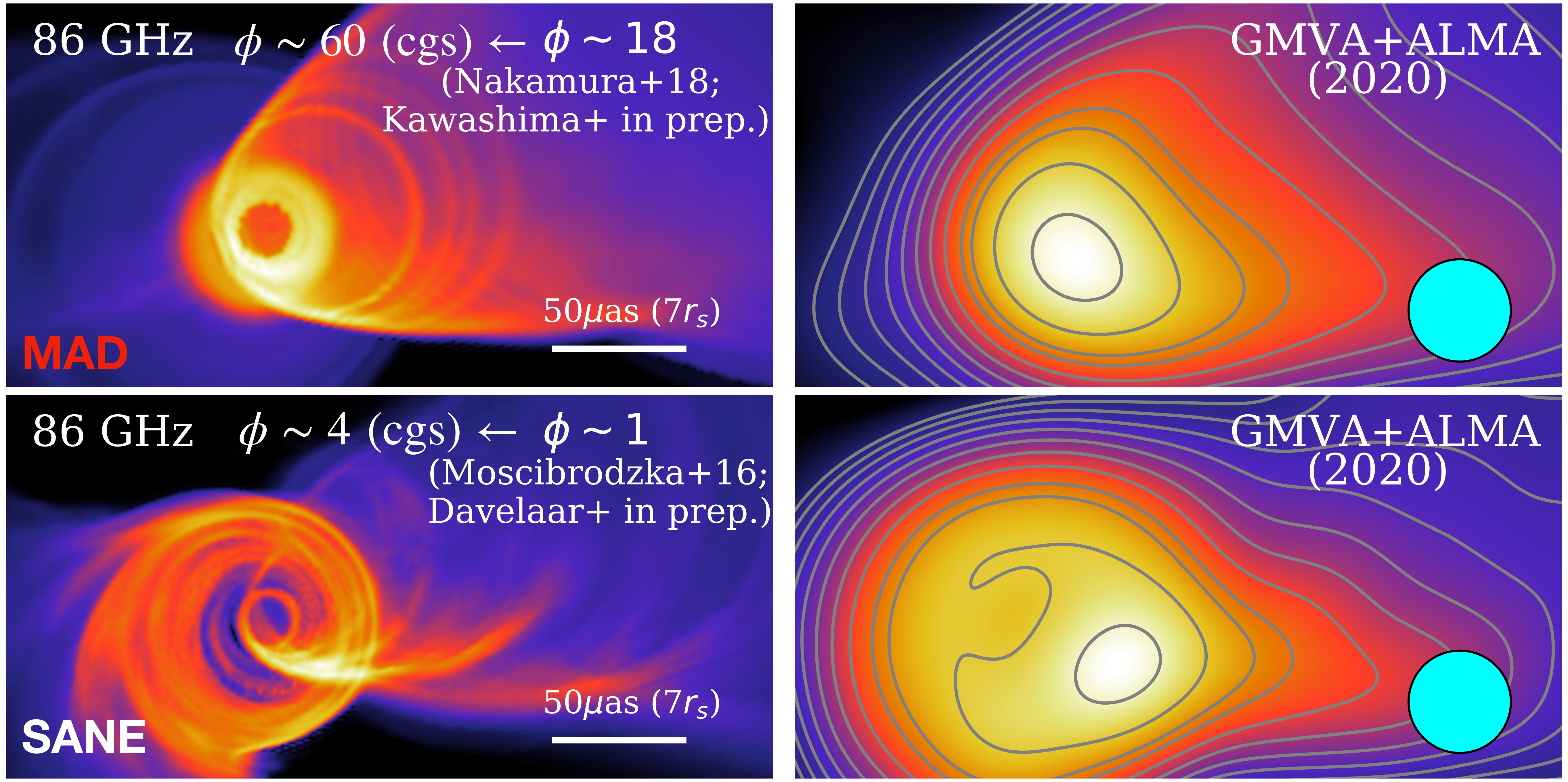
- Measuring core size & flux at ≤ 86 GHz (GMVA+ALMA / EAVN)
- Monitoring VLBI core flux at 22-129 GHz (KVN+EAVN hybrid mode)

➡ Estimations of $\Phi_{\rm EH}$ & $L_{\rm EM}$ during EHT2020

GMVA+ALMA 2020 (PI: J. Kim)
submitted to **EAVN2020A** (PI: Y. Cui)



MN+ in prep.



from GMVA+ALMA Cy 7 proposal (PI: Kim, J.)

- Adequate jet expansion in the lateral direction in MAD
  - Γ increases due to the magnetic nozzle effect
  - <u>Unexpected counter jet emission</u> is suppressed
  - <u>Quasi-symmetric limb-brightens feature</u> may appears in the approaching jet side ($\lesssim 100\,\mu$as)

- **Let's see imaging the jet w/ EHT@230GHz / GMVA@86GHz in 2020**

Summary

- MWL data (< 230 GHz) is useful to nail down the horizon-scale parameters $(\Phi_{\rm EH}, L_{\rm EM}, \dot{M})$ in M87
- EHT2020: Simultaneous obs. with EAVN/KVN (22/43/86/129GHz) and GMVA+ALMA towards VLBI cores
- Presumably, MAD in action in M87:
    - $\phi \simeq 30 - 70$
    - $\Phi_{\rm EH} \simeq 10^{33}\,(\phi/60)\,(\dot{m}/4\times10^{-6})^{1/2}\,(M/6.5\times10^{9}\,M_{\odot})^{3/2}\ {\rm Mx}$
    - $L_{\rm EM} \simeq (4-15)\times10^{43}\,{\rm erg\,s^{-1}}(a=0.9)$
    - Limb-brightened feature is one of key observables

Jan 31, 2020: Deadline for registrations / abstract submission

http://eaagn2020.csp.escience.cn/dct/page/1