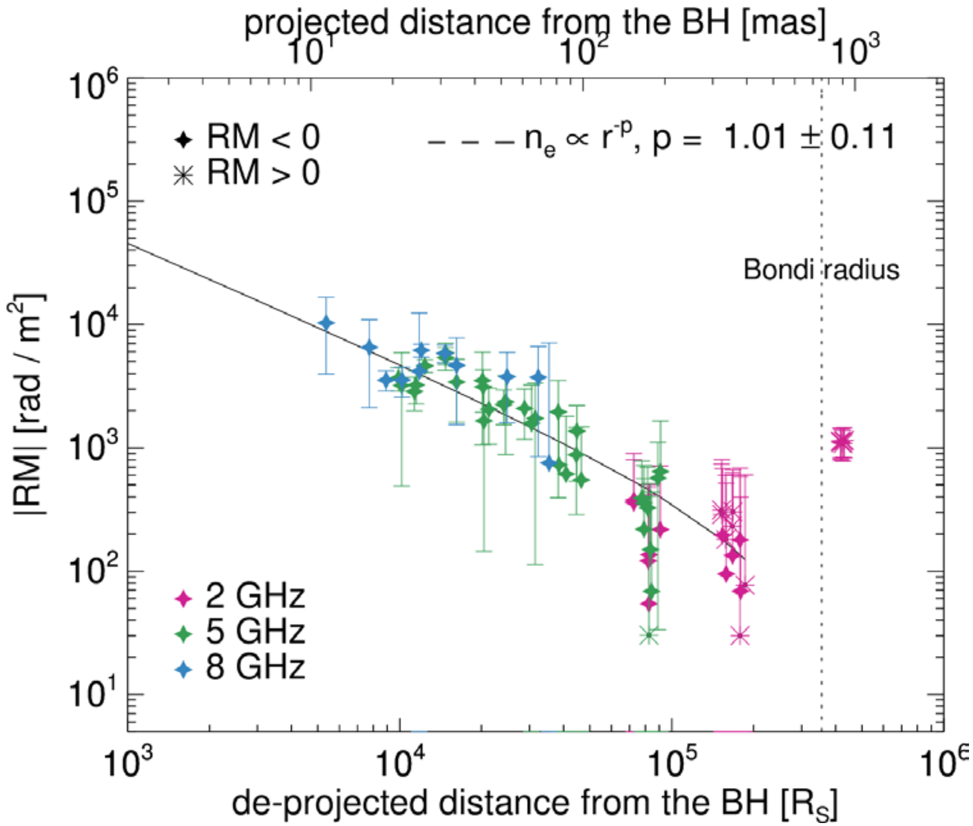
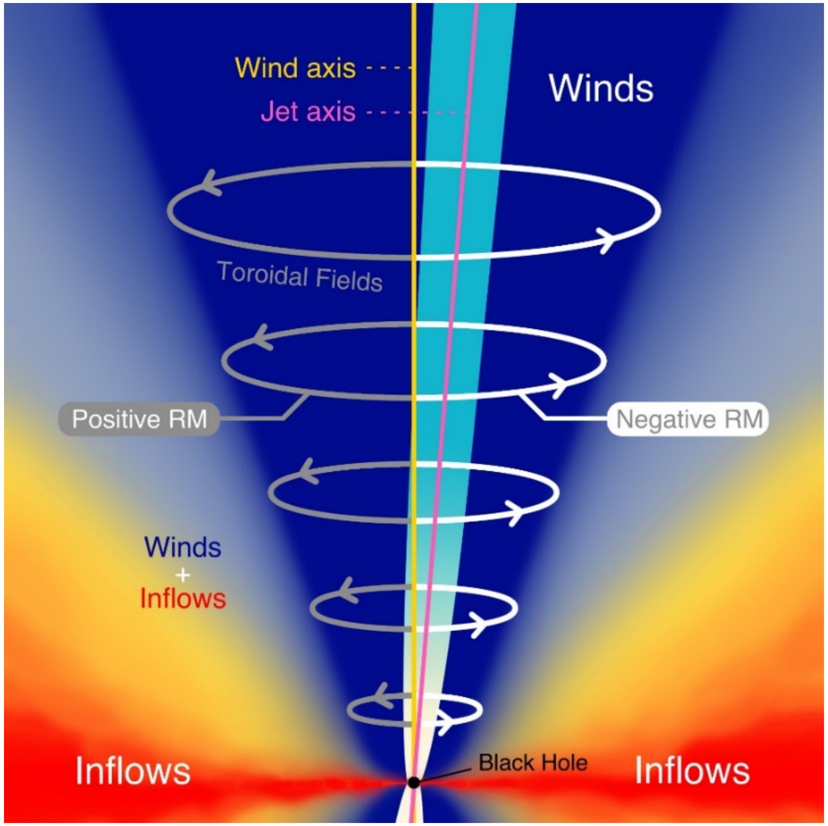
Substantial winds from the accreting supermassive black hole in M87 revealed by Faraday rotation observations

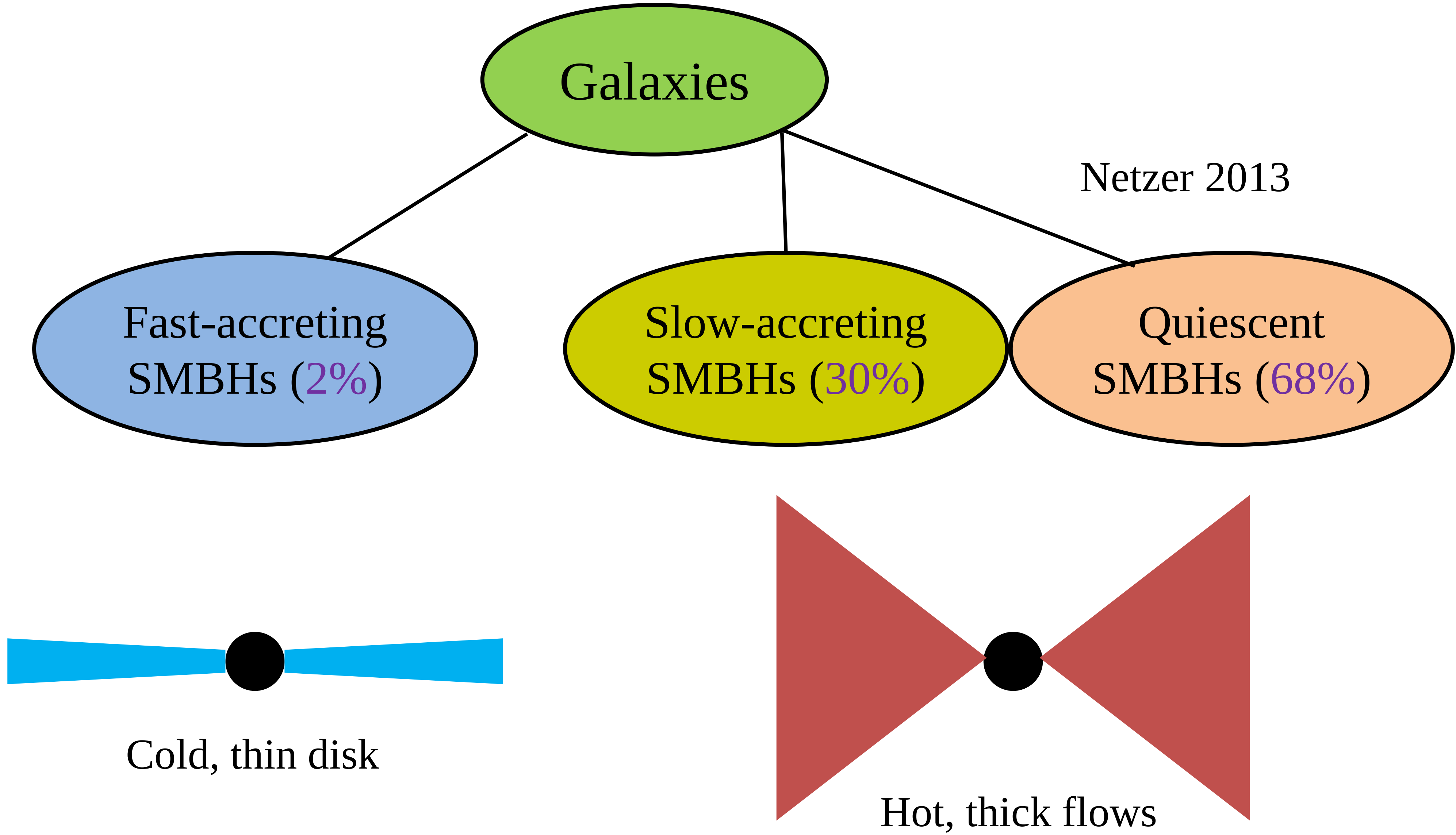




Presenter : Jongho Park (Seoul National University)

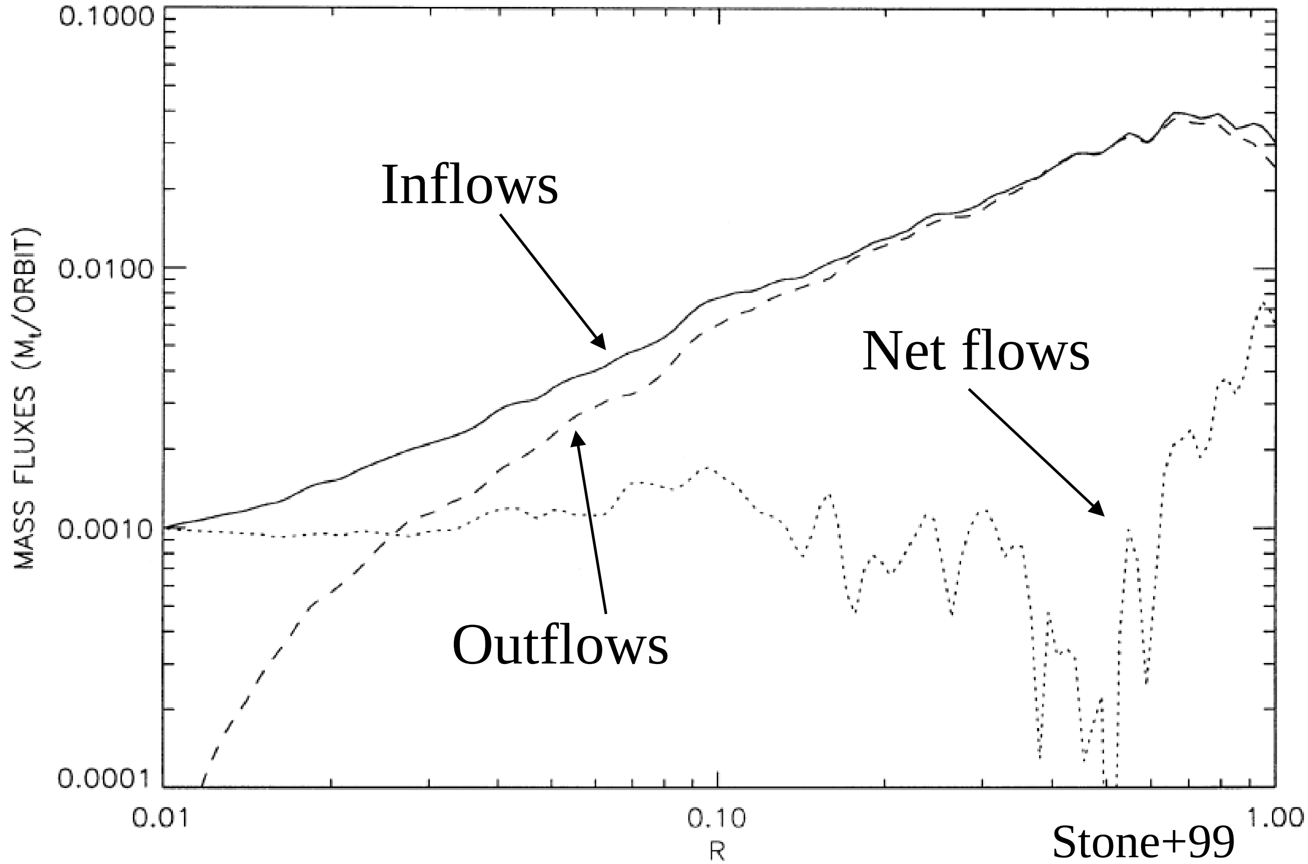
Co-I : Kazuhiro Hada (Mizusawa obs), Motoki Kino (Kogakuin Univ. / NAOJ), Masanori Nakamura (ASIAA), Hyunwook Ro (Yonsei Univ.), Sascha Trippe (SNU)

Hot accretion flows prevalent in low luminosity AGNs (LLAGNs)



— Understanding hot accretion flows is very important because it might govern the evolution of most of the galaxies in the universe.

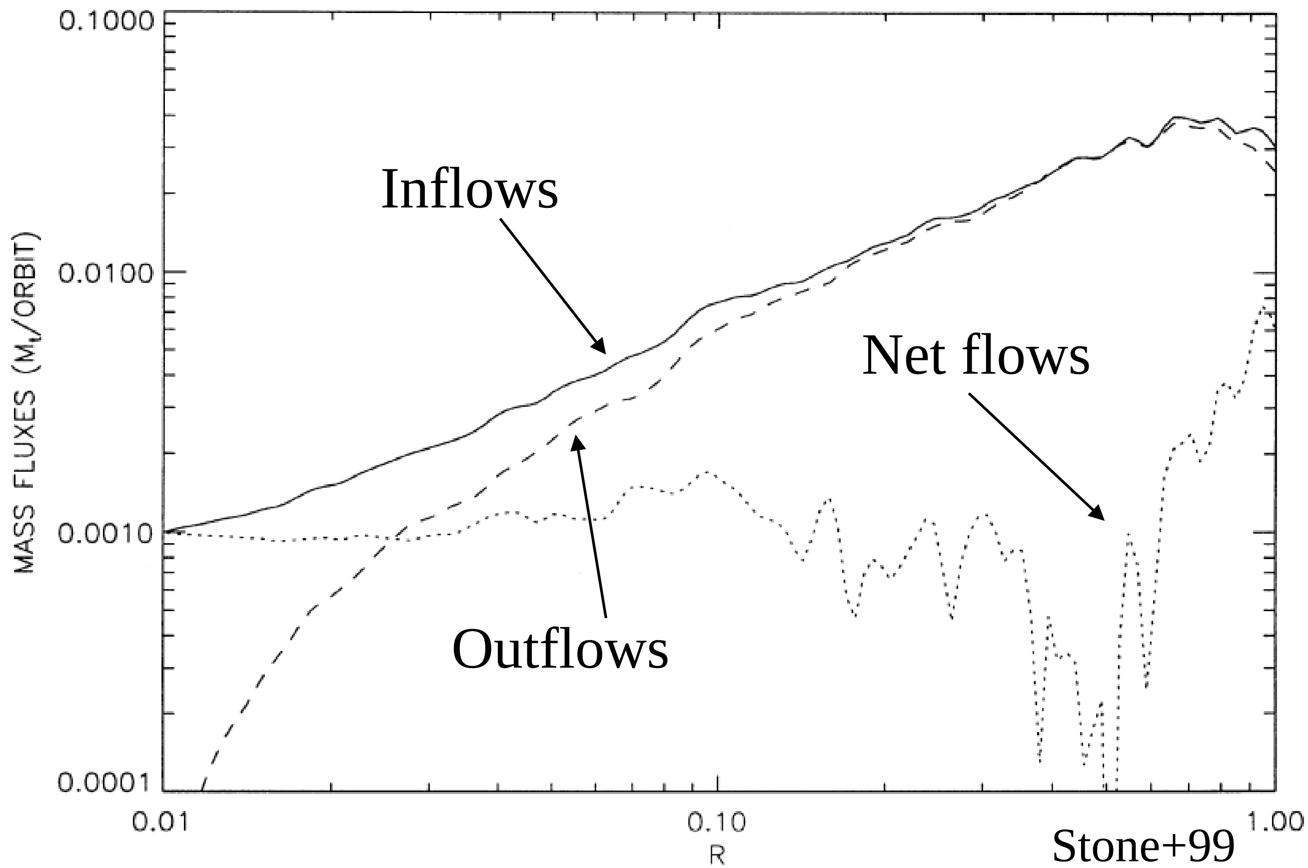
Winds in hot accretion flows



$$\dot{M} \propto r^s \qquad \rho \propto r^{-p},\ p = 1.5 - s$$

s = 0, p = 1.5 ADAFs : pure inflows	0 < s < 1, 0.5 < p < 1.5 ADIOS : inflows/outflows	s = 1, p = 0.5 CDAFs : convection
Narayan & Yi (1994)	Blandford & Begelman (1999)	Igumenshchev & Abramowicz (1999)

Winds in hot accretion flows



Stone+99

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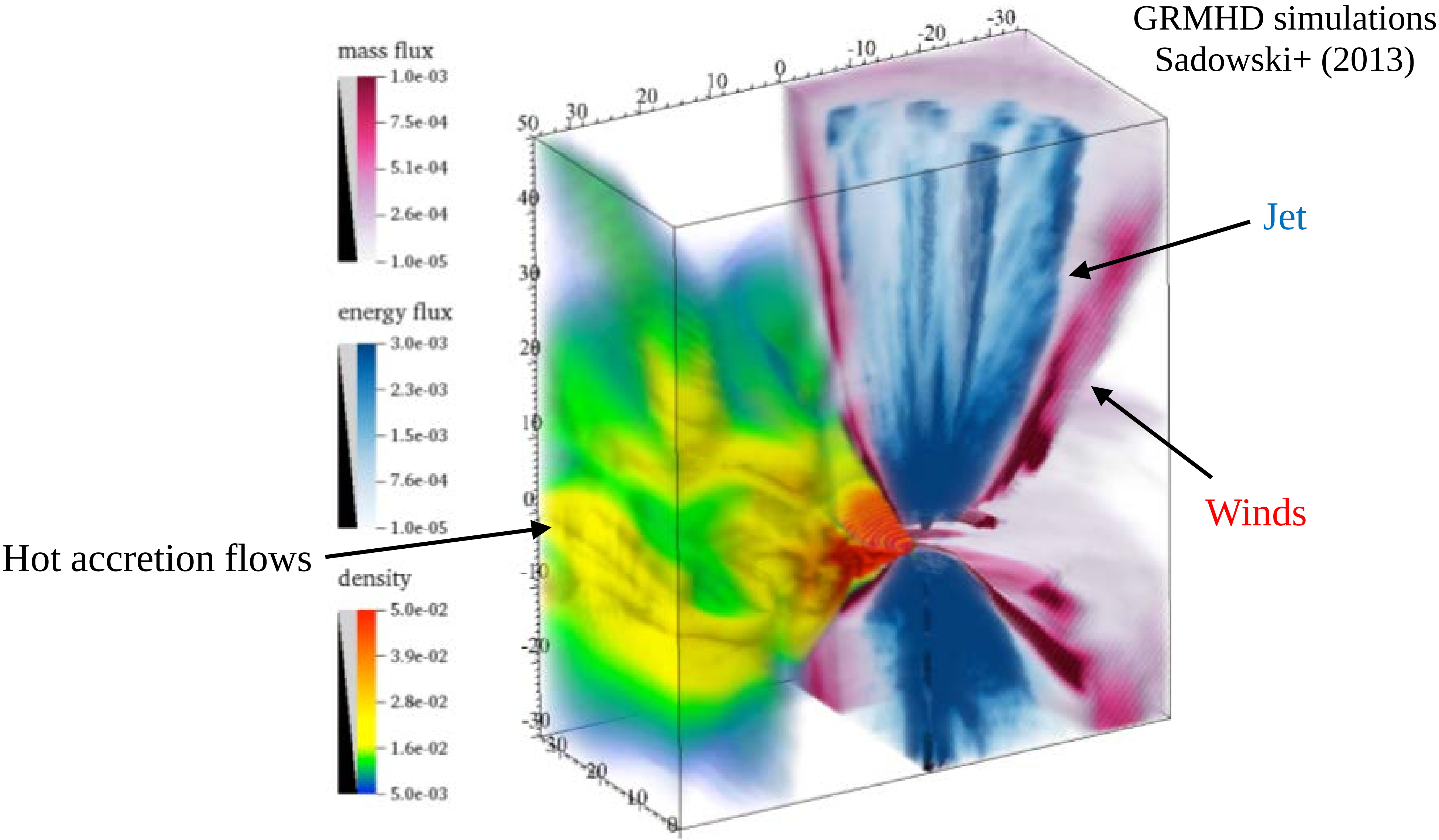
Numerical Simulations

Winds in hot accretion flows



Winds : (i) un-collimated, (ii) moderately magnetized, and (iii) non-relativistic gas outflows launched from the accretion flows.

Jets : (i) collimated, (ii) highly magnetized, and (iii) relativistic gas outflows.

Jets collimated by winds?

– AGN jets cannot be self confined $\rightarrow$ must be confined by an external medium.

Begelman & Li (1994)

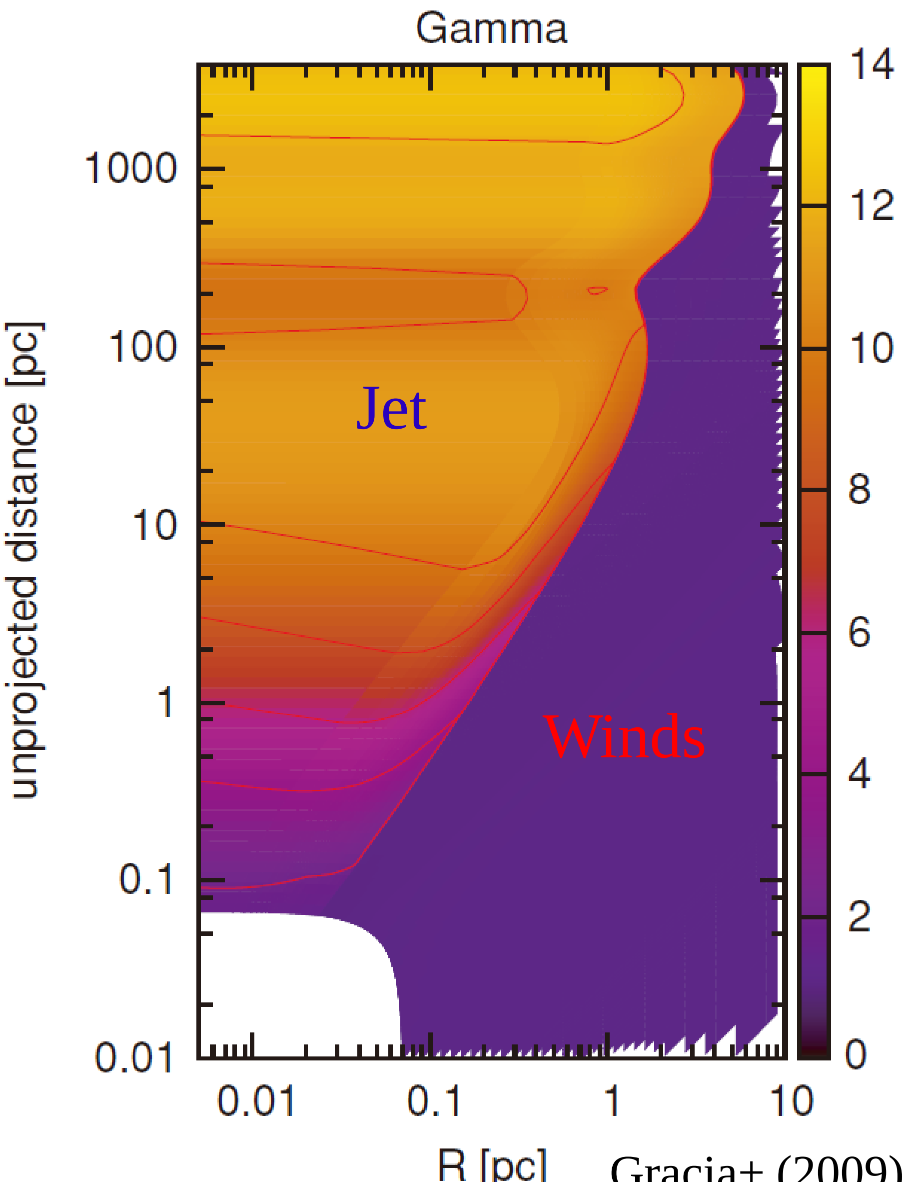
$$p_{\rm ext} = p_{\rm ext,lc}(z/z_{\rm lc})^{-\alpha} \qquad z \propto r^a$$

Komissarov+ (2009)

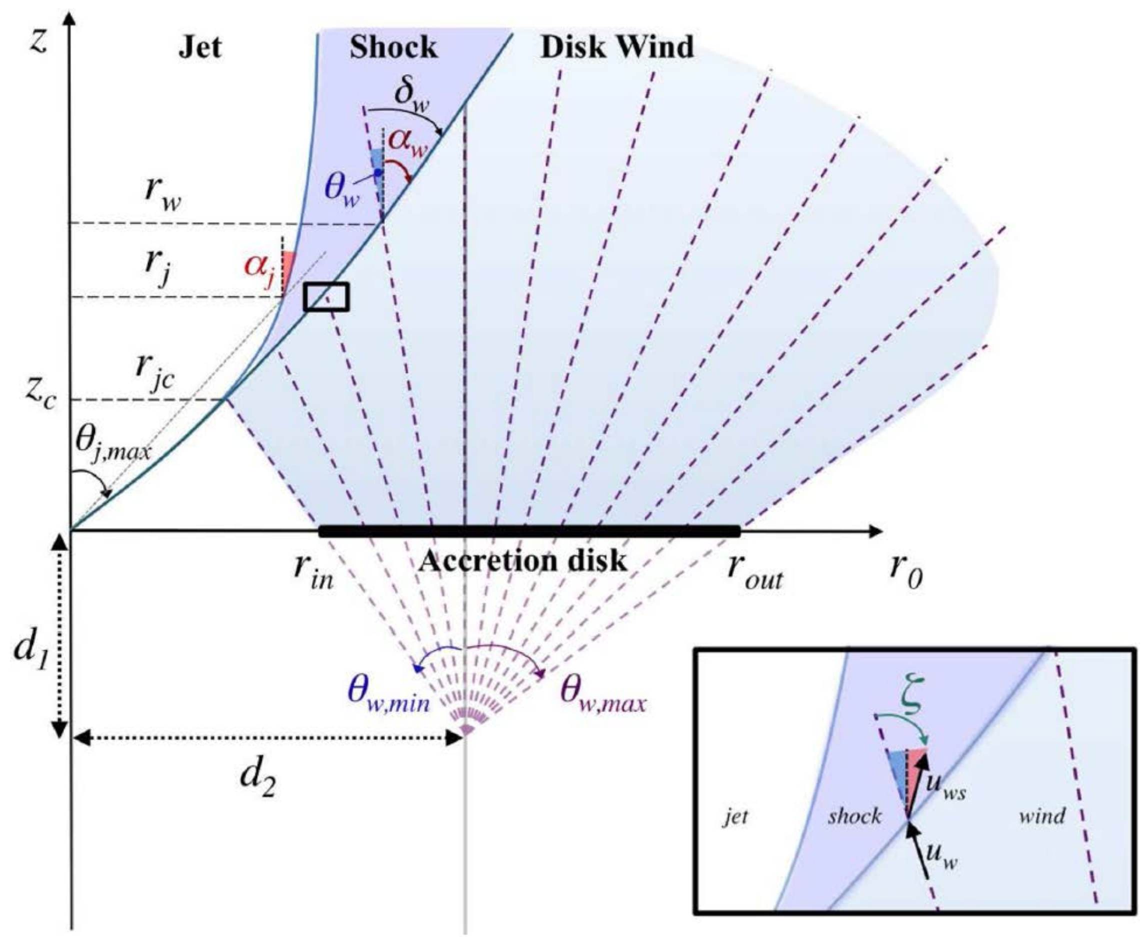
(i) $\alpha < 2 \Leftrightarrow a = 4/\alpha > 2$,
(ii) $\alpha = 2 \Leftrightarrow 1 < a \leq 2$, $\longrightarrow$ Parabolic jet shape (collimation)
(iii) $\alpha > 2 \Leftrightarrow a = 1$. $\longrightarrow$ Conical jet shape (free expansion)

– To have a parabolic jet shape, $\alpha \leq 2$ is needed (external-confinement).

Jets collimated by **winds?**



Gracia+ (2009)

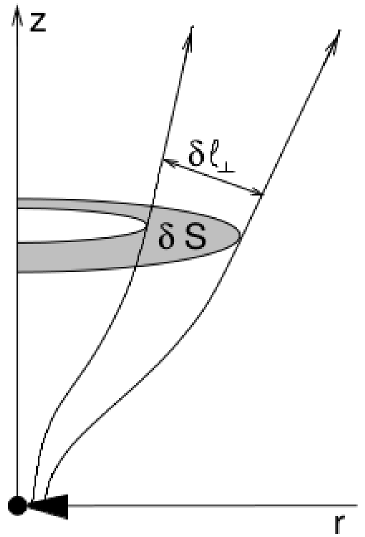


Globus & Levinson (2016)

Strongly magnetized winds

Weakly magnetized winds

☞ component of the momentum equation



$$\gamma\rho_0(\boldsymbol{V}\cdot\nabla)(\gamma\xi\boldsymbol{V}) = -\nabla p + J^0\boldsymbol{E} + \boldsymbol{J}\times\boldsymbol{B}$$

along the flow (wind equation): $\gamma \approx \mu - \mathcal{F}$

where $\mathcal{F} \propto \varpi^2 B_p$

Lorentz factor

Total energy (conserved)

since $B_p \delta S = \text{const}$,

$\mathcal{F} \propto \varpi^2/\delta S \propto \varpi/\delta\ell_\perp$

acceleration requires the separation between streamlines to increase faster than the cylindrical radius

the collimation-acceleration paradigm:

$\mathcal{F}\downarrow$ through stronger collimation of the inner streamlines relative to the outer ones (differential collimation)

— Jet collimation and acceleration are intimately related.

Taken from Vlahakis' lecture note

The fundamental questions we want to answer are:

1. **Winds exist in hot accretion flows?**
   → Not all the hot gas captured by the black hole's gravity is actually accreted.

2. **AGN jets are collimated by winds?**
   → This collimation can result in gradual acceleration of the jets to relativistic speeds (by converting EM energy into kinetic energy).

How to probe hot accretion flows and winds?

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Emission or absorption lines ✖ Fully ionized

How to probe hot accretion flows and winds?

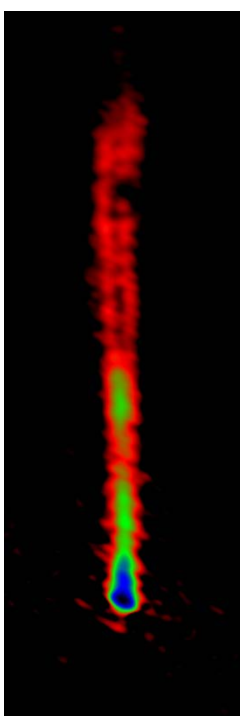
Emission or absorption lines	✖ Fully ionized
Measuring density profiles with X-ray observations	✖ Limited resolution

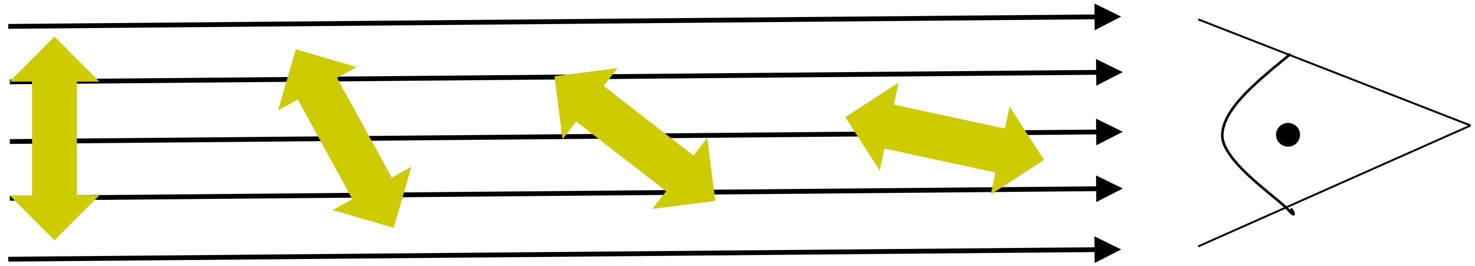
How to probe hot accretion flows and winds?

Emission or absorption lines — ✗ Fully ionized

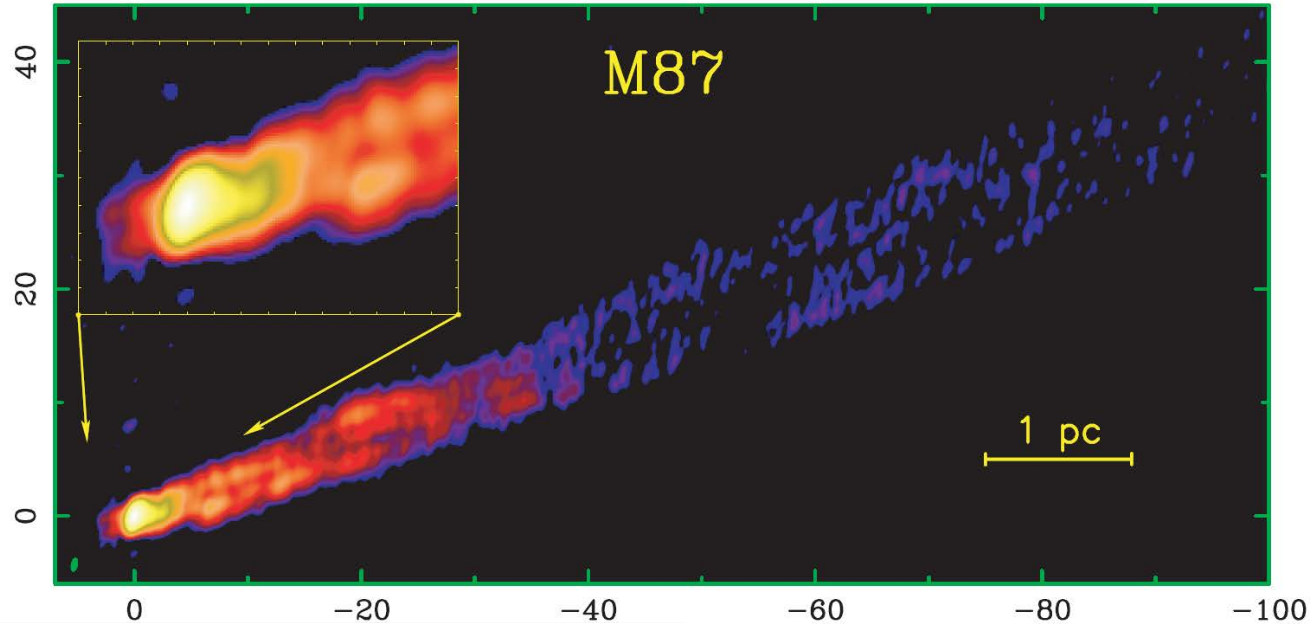
Measuring density profiles with X-ray observations — ✗ Limited resolution

Faraday rotation with VLBI — ○ the medium between the jet and the observer

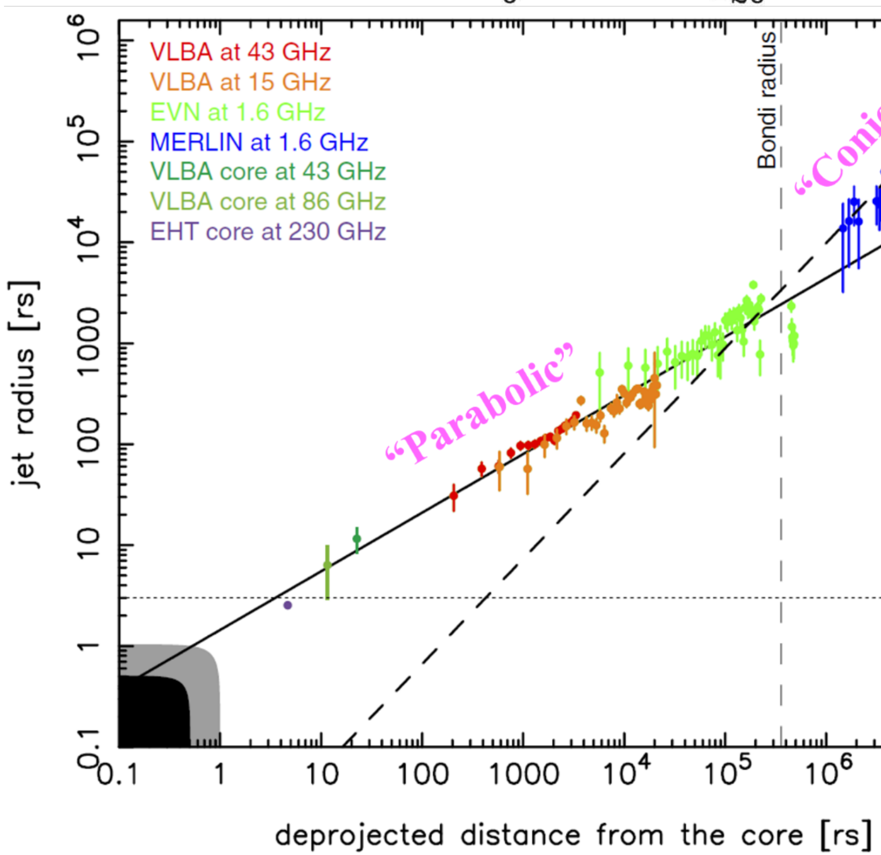




M87 : a good laboratory for studying jets and winds



Kovalev+ (2007)



Nakamura & Asada (2013)

M87 has

(i) Hot accretion flows

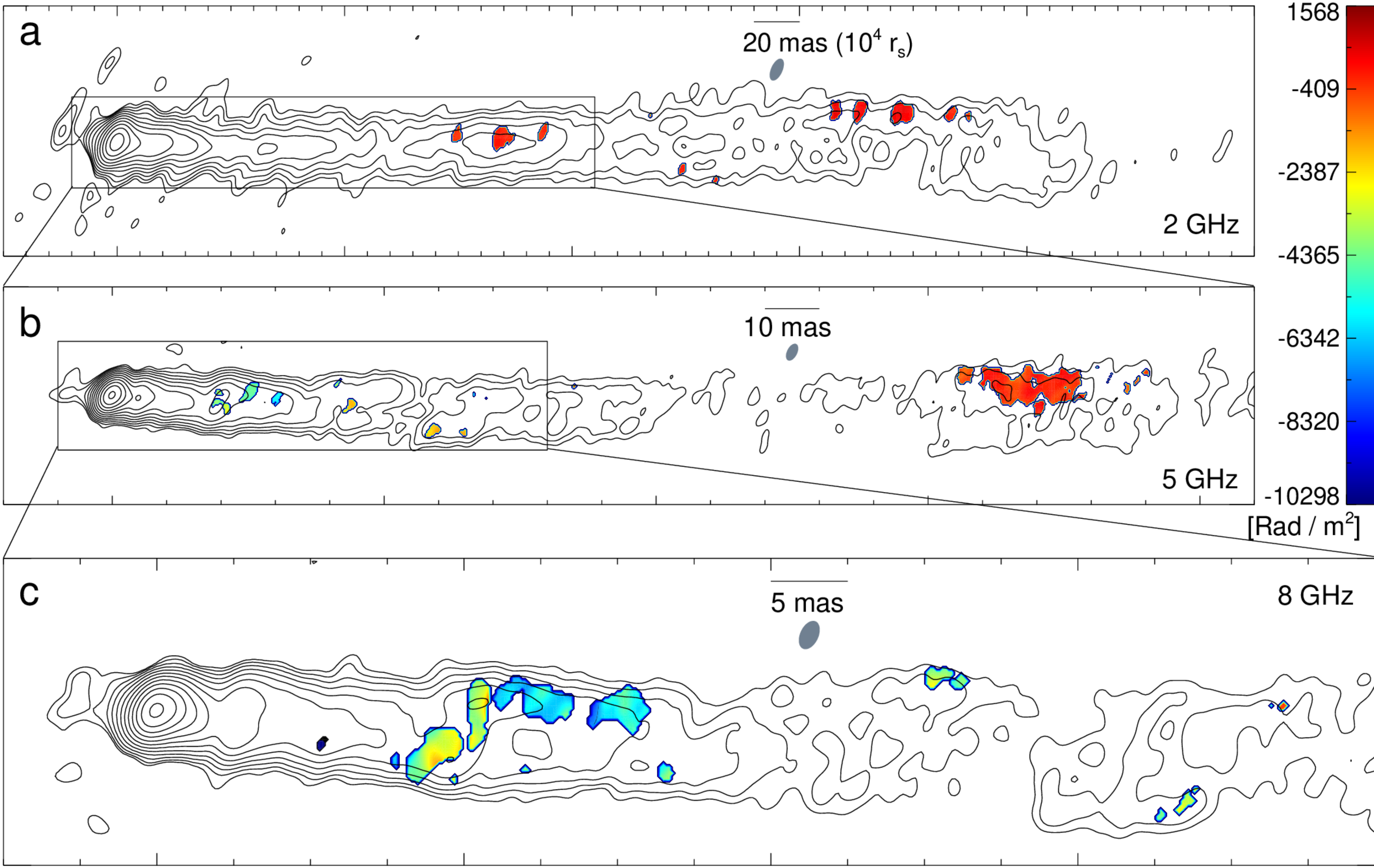
(ii) Polarized Jets

(iii) Evidence for gradual collimation inside the Bondi radius

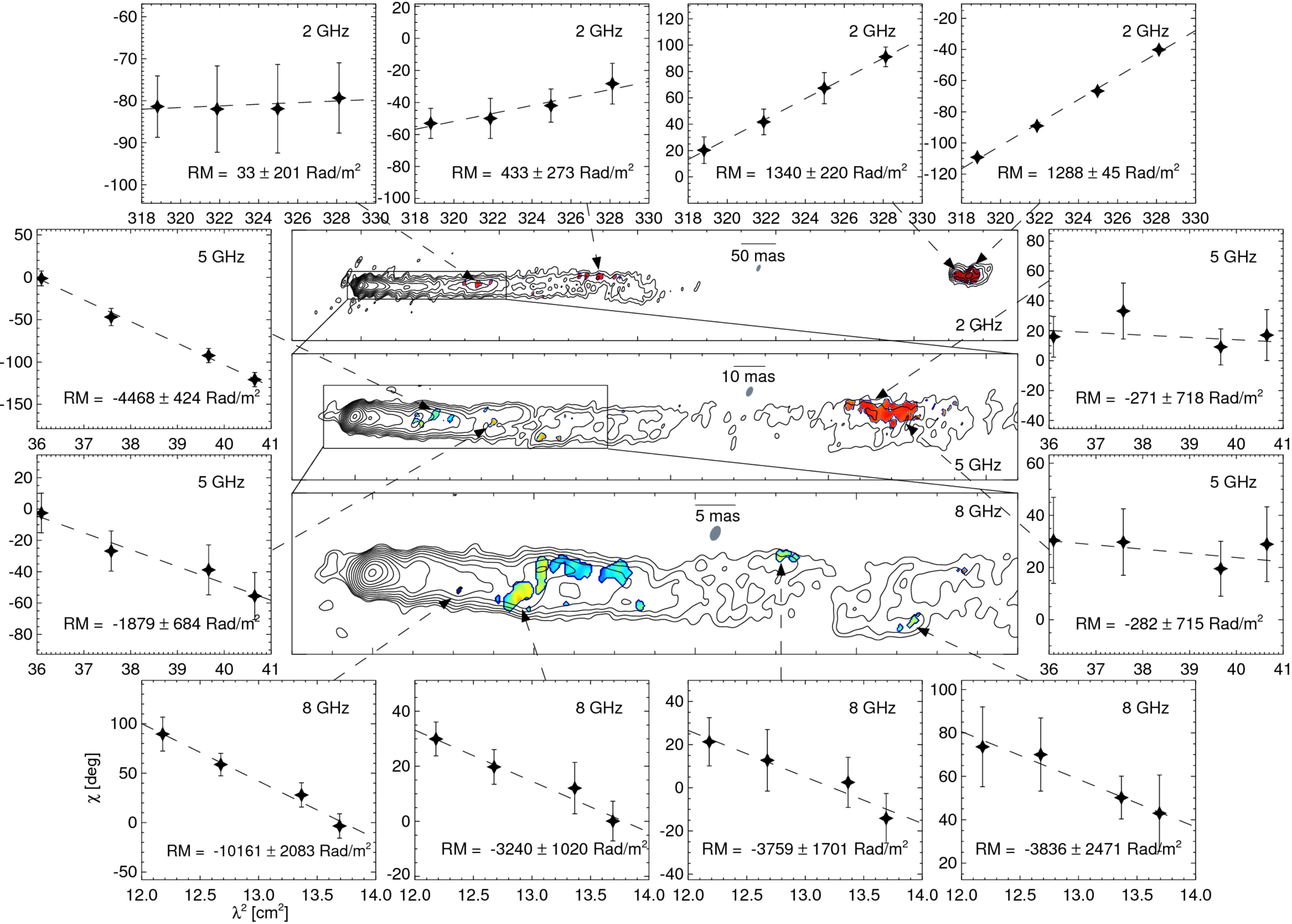
VLBA archive data analysis

– We analyzed the VLBA archive data at 1.7, 5, 8.3 GHz.
– We obtained EVPA rotation as a function of λ^2 ‘within the bands’ (across different baseband channels).

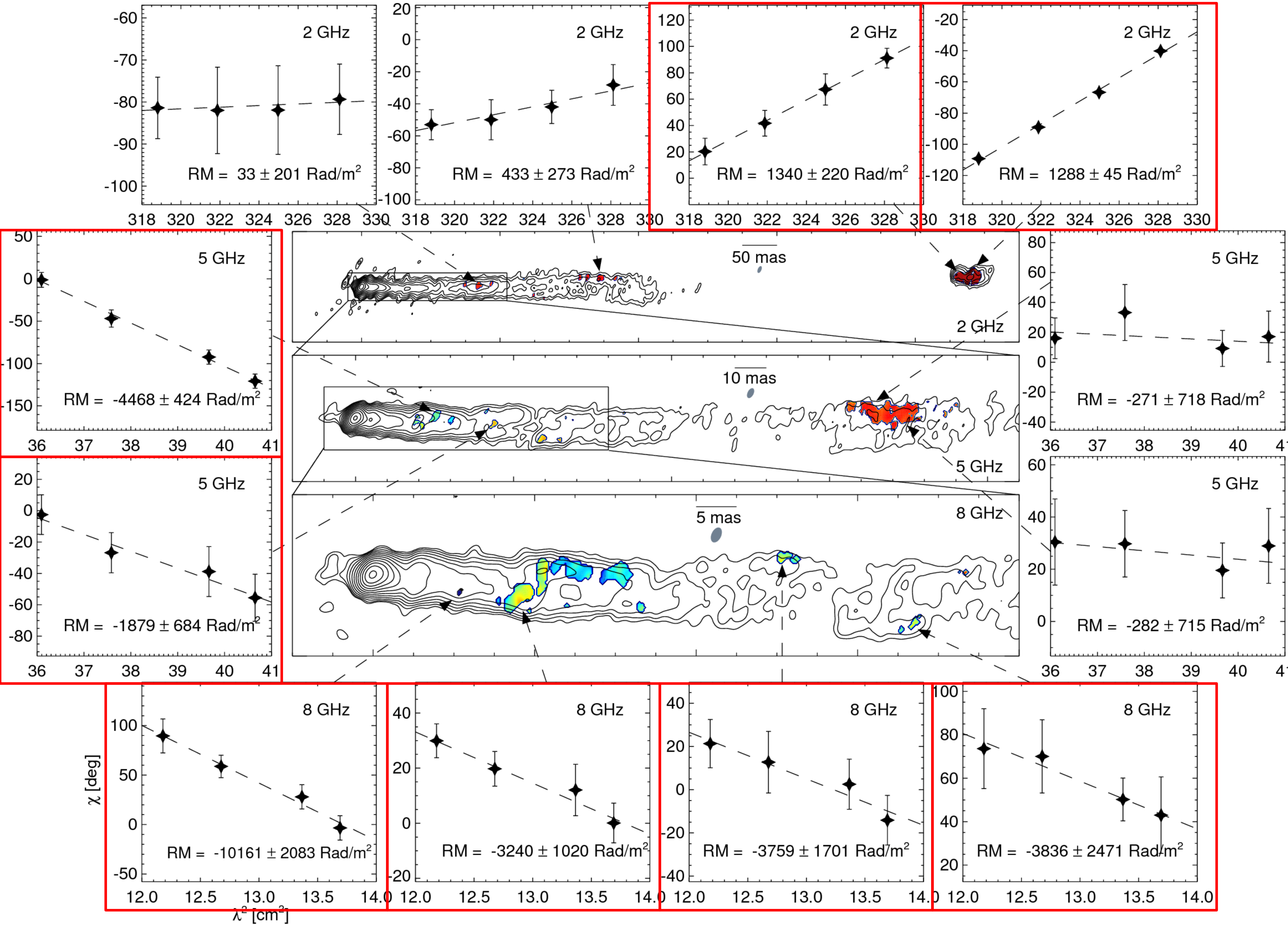
Project Code	Epoch	Frequency
BJ020A	1995 Nov 22	8.11, 8.20, 8.42, 8.59 GHz
BJ020B	1995 Dec 09	4.71, 4.76, 4.89, 4.99 GHz
BC210B	2013 Mar 09	4.85, 4.88, 4.92, 4.95, 4.98, 5.01, 5.04, 5.08 GHz
BC210C	2014 Jan 29	4.85, 4.88, 4.92, 4.95, 4.98, 5.01, 5.04, 5.08 GHz
BC210D	2014 Jul 14	4.85, 4.88, 4.92, 4.95, 4.98, 5.01, 5.04, 5.08 GHz
BH135F	2006 Jun 30	1.65, 1.66, 1.67, 1.68 GHz
BC167C	2007 May 28	1.65, 1.66, 1.67, 1.68 GHz
BC167E	2007 Aug 20	1.65, 1.66, 1.67, 1.68 GHz



a
20 mas (10^4 r_s)
2 GHz
b
10 mas
5 GHz
c
5 mas
8 GHz
1568
-409
-2387
-4365
-6342
-8320
-10298
[Rad / m^2]



2 GHz
RM = 33 ± 201 Rad/m²
2 GHz
RM = 433 ± 273 Rad/m²
2 GHz
RM = 1340 ± 220 Rad/m²
2 GHz
RM = 1288 ± 45 Rad/m²
5 GHz
RM = -4468 ± 424 Rad/m²
50 mas
2 GHz
5 GHz
RM = -271 ± 718 Rad/m²
10 mas
5 GHz
5 GHz
RM = -1879 ± 684 Rad/m²
5 mas
8 GHz
5 GHz
RM = -282 ± 715 Rad/m²
8 GHz
RM = -10161 ± 2083 Rad/m²
8 GHz
RM = -3240 ± 1020 Rad/m²
8 GHz
RM = -3759 ± 1701 Rad/m²
8 GHz
RM = -3836 ± 2471 Rad/m²
χ [deg]
λ² [cm²]



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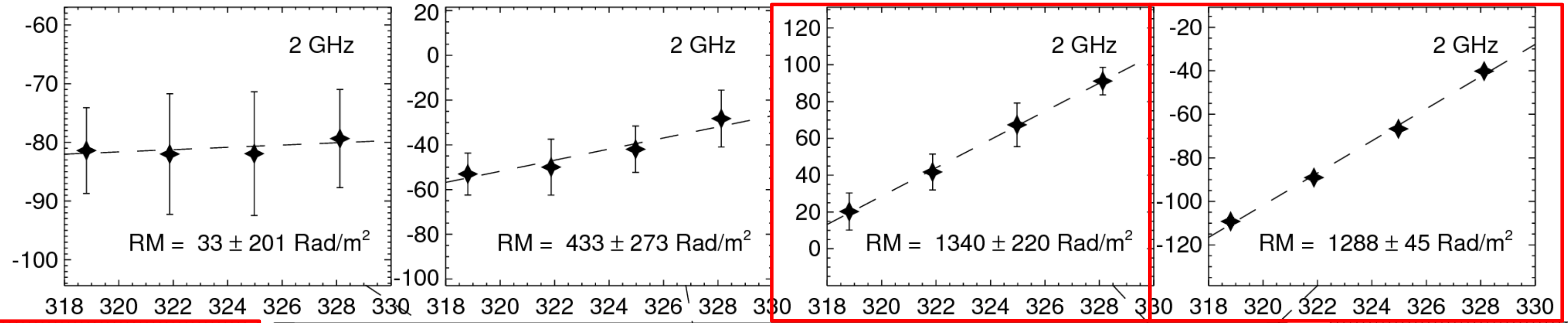
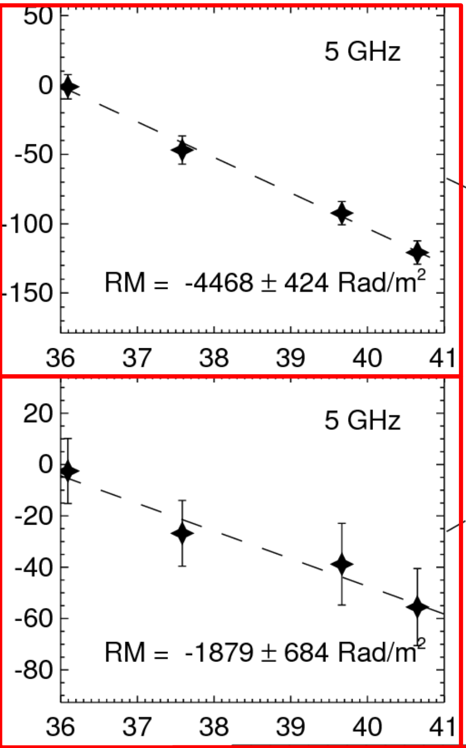
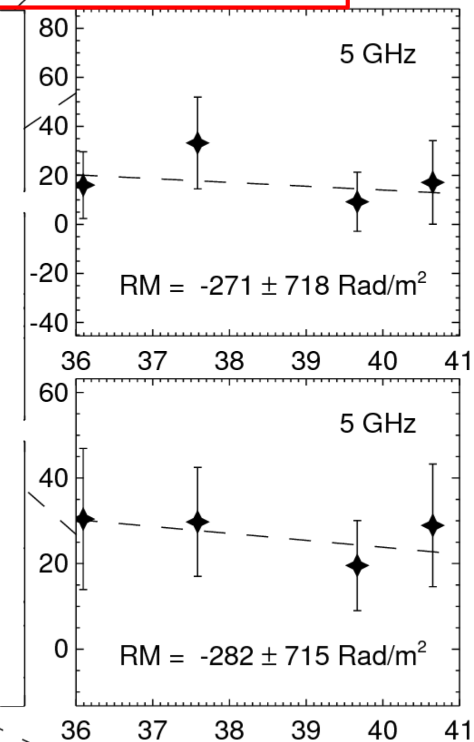


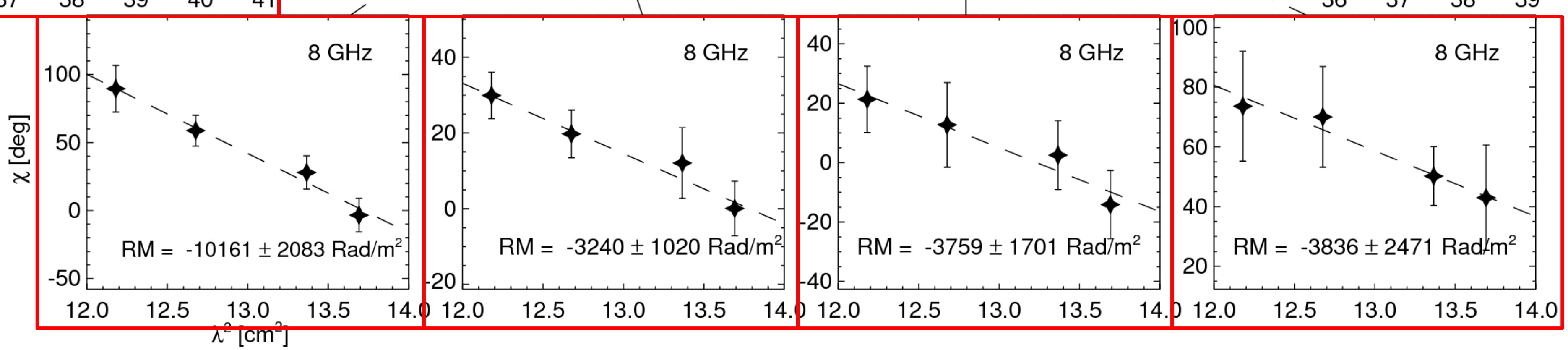


Internal Faraday rotation : no EVPA rotation larger than 45 degrees (Burn 1966)

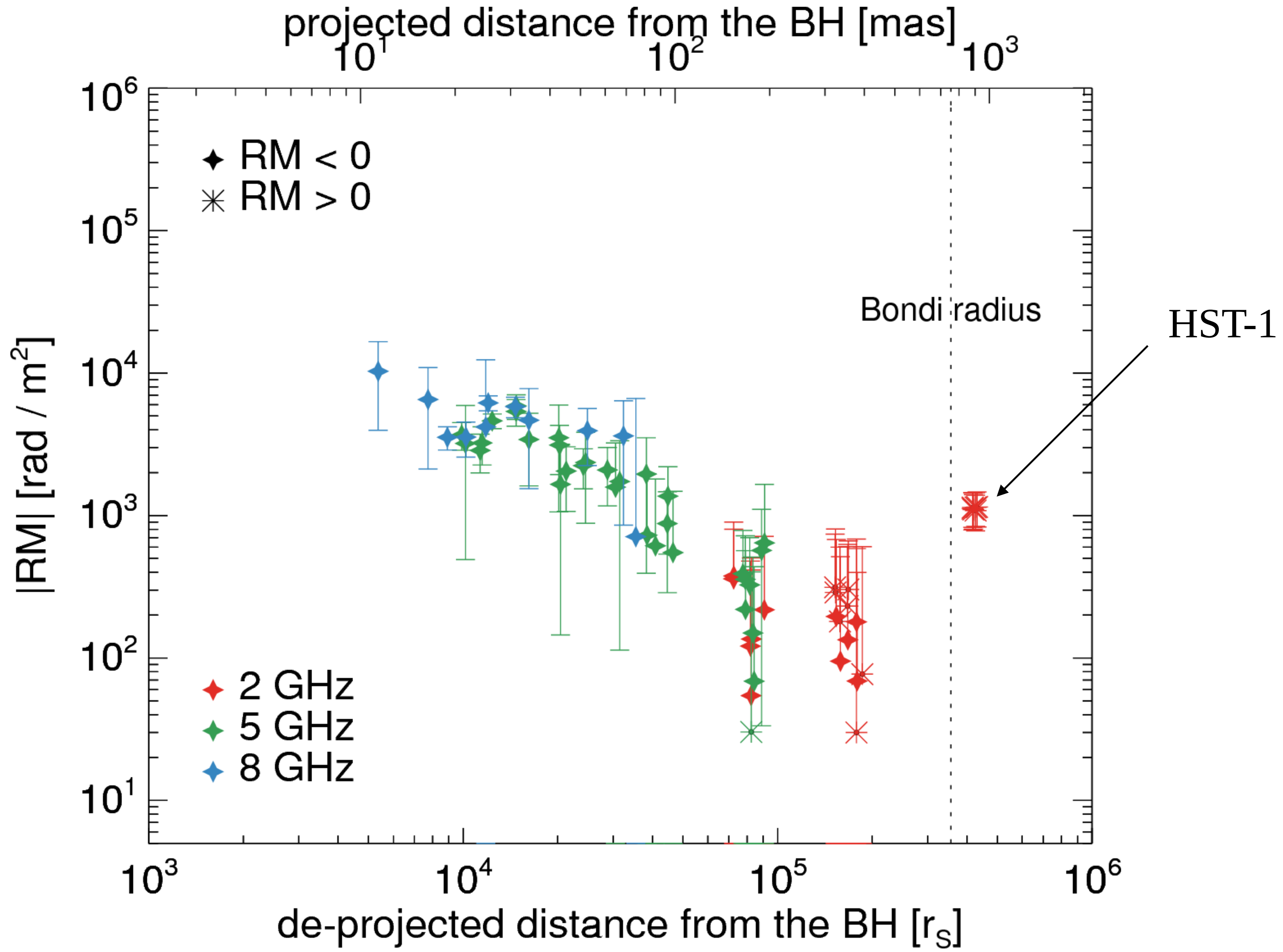
→ The Faraday screen is external to the jet.

(Hot accretion flows)





RM distribution as a function of distance



Applying the hot accretion flows model to the data

$$\mathrm{RM} = 8.1 \times 10^5 \int n_e B dl$$

$$n_e = n_{\mathrm{out}} \left(\frac{r}{r_{\mathrm{out}}} \right)^{-p} \qquad B(r) = B_{\mathrm{out}} \left(\frac{r}{r_{\mathrm{out}}} \right)^{-1}$$

$$\mathrm{RM} = 8.1 \times 10^5 n_{\mathrm{out}} B_{\mathrm{out}} r_{\mathrm{out}}^{(p+1)} \int_{r_{\mathrm{in}}}^{r_{\mathrm{out}}} r^{-(p+1)} dl$$

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from the model of hot accretion flows

$$\rho(r) \propto r^{-p} \qquad \dot{M}(r) \propto r^s \qquad p = 1.5 - s$$

Yuan & Narayan (2014)

Applying the hot accretion flows model to the data

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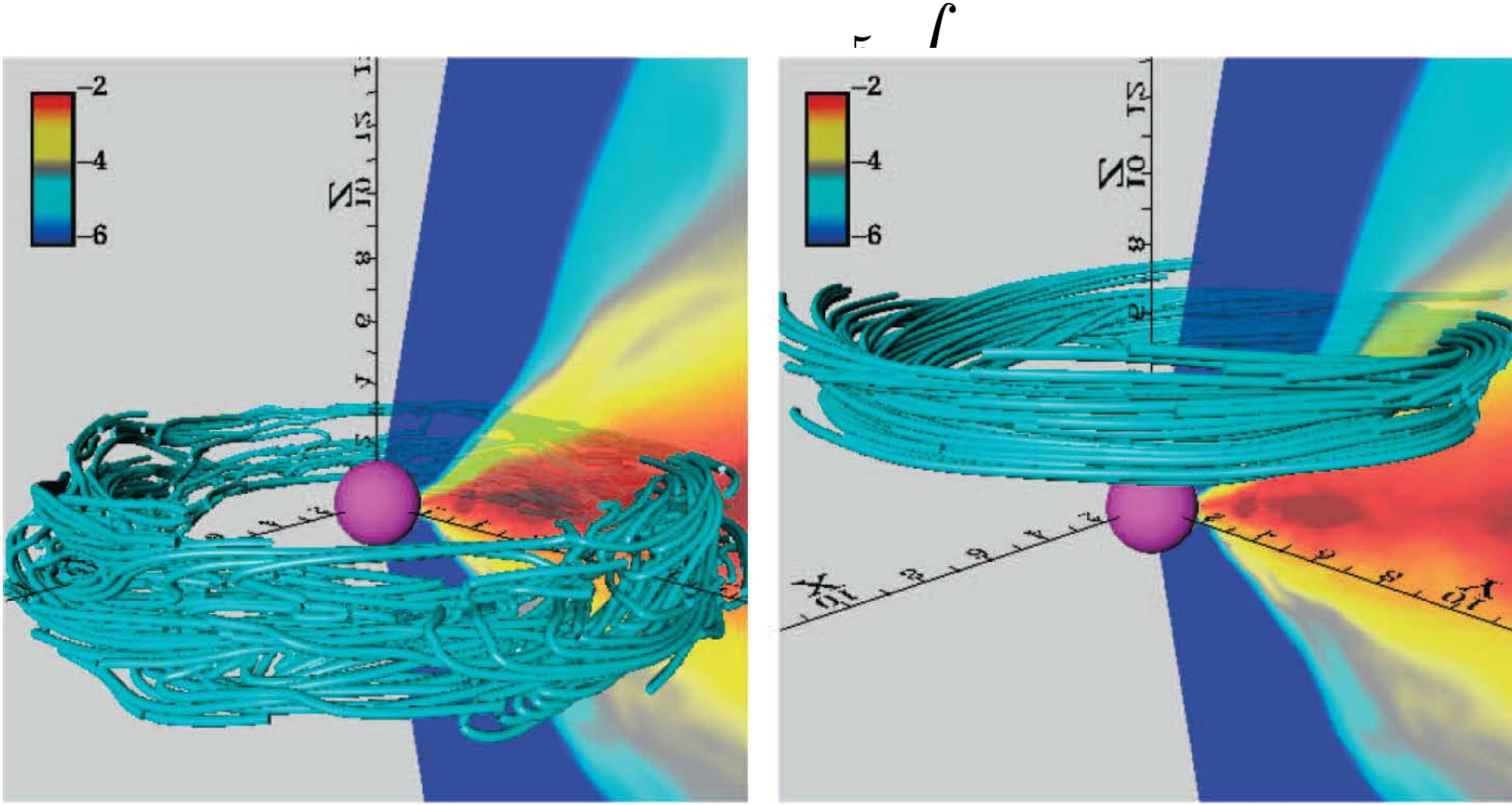
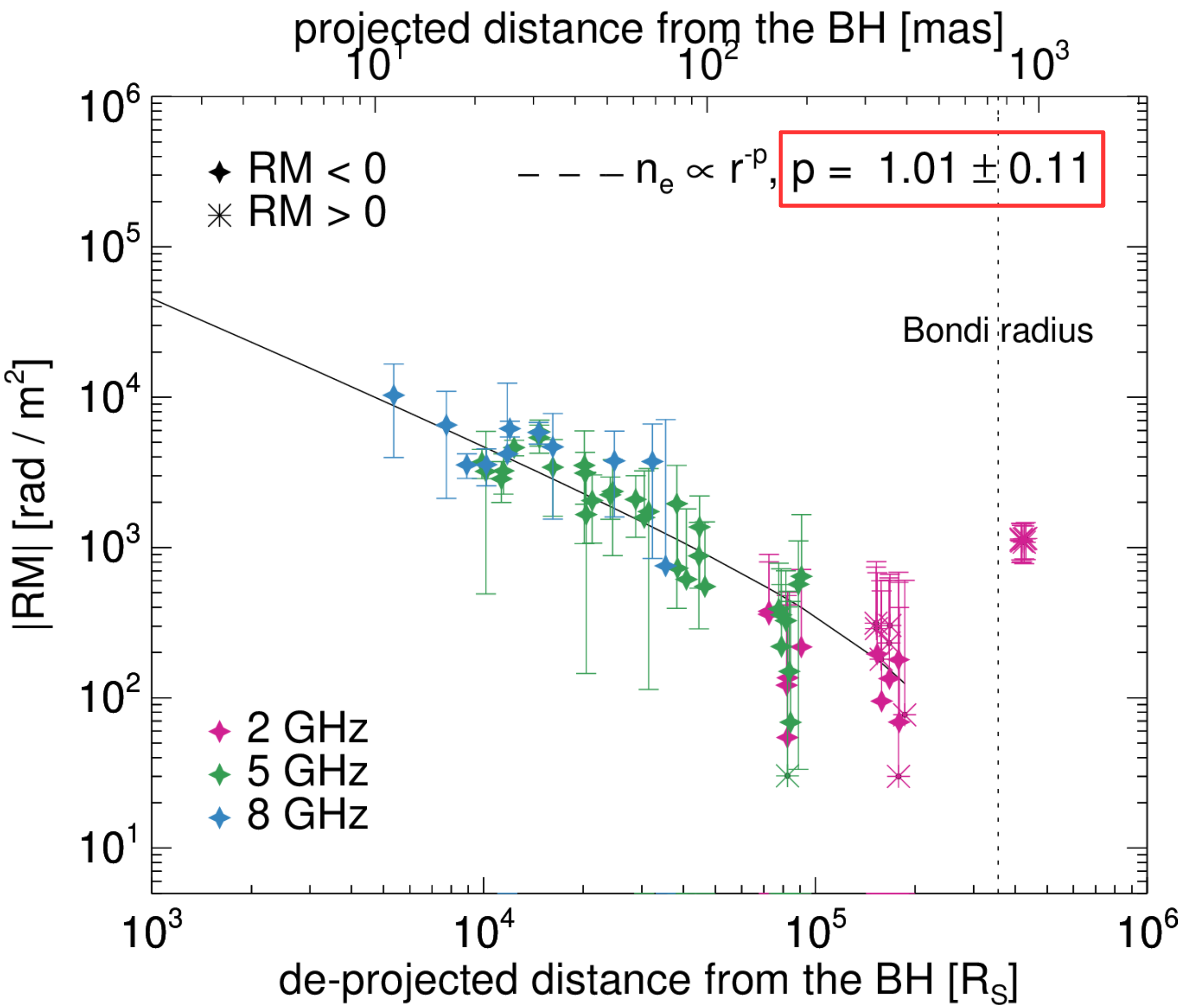


Hirose+ (2004)

The radial RM profile



– We obtained p ~ 1. ⟶ $\rho \propto r^{-1}$: Support ADIOS (p ~ 1) $n_e = n_{\rm out}\left(\frac{r}{r_{\rm out}}\right)^{-p}$

p = 1.5 : classical ADAF

0.5 < p < 1.5 : ADAF with mass outflows, ADIOS

p = 0.5 : convection dominated accretion flows, CDAF

→ **Winds do exist in M87!**

Jet collimation

– AGN jets cannot be self confined → must be confined by an external medium.

$$p_{\rm ext} = p_{\rm ext,lc}(z/z_{\rm lc})^{-\alpha} \qquad\qquad z \propto r^{a}$$

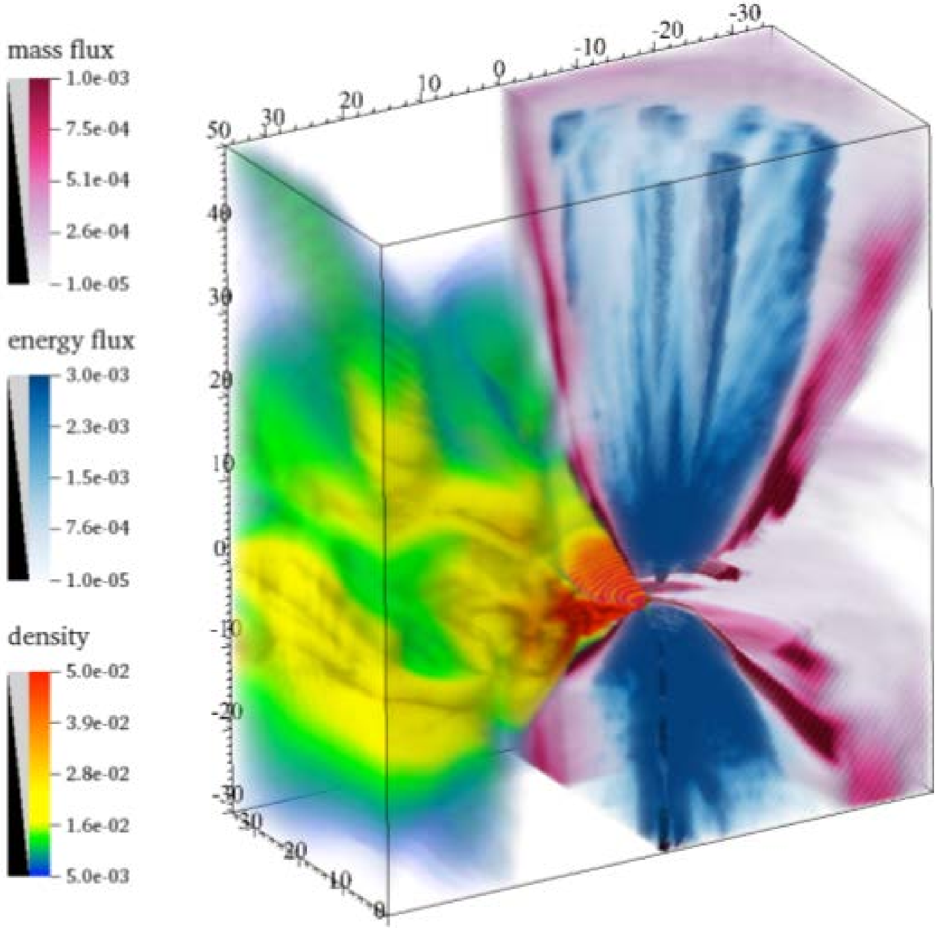
Komissarov+ (2009)

(i) $\alpha < 2 \Leftrightarrow a = 4/\alpha > 2\,,$
(ii) $\alpha = 2 \Leftrightarrow 1 < a \leq 2\,,$
→ Parabolic jet shape (collimation)

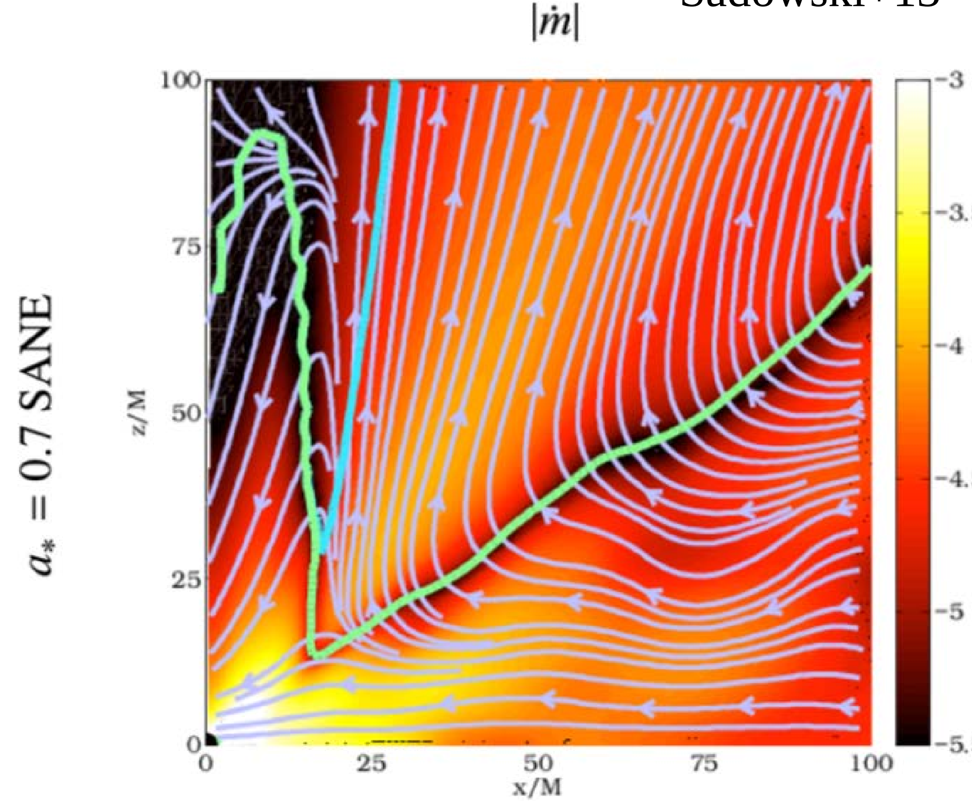
(iii) $\alpha > 2 \Leftrightarrow a = 1.$ → Conical jet shape (free expansion)

– To have a parabolic jet shape, $\alpha \leq 2$ is needed (external-confinement).

– GRMHD simulations found that winds are surrounding the highly magnetized jets.



Sadowski+13

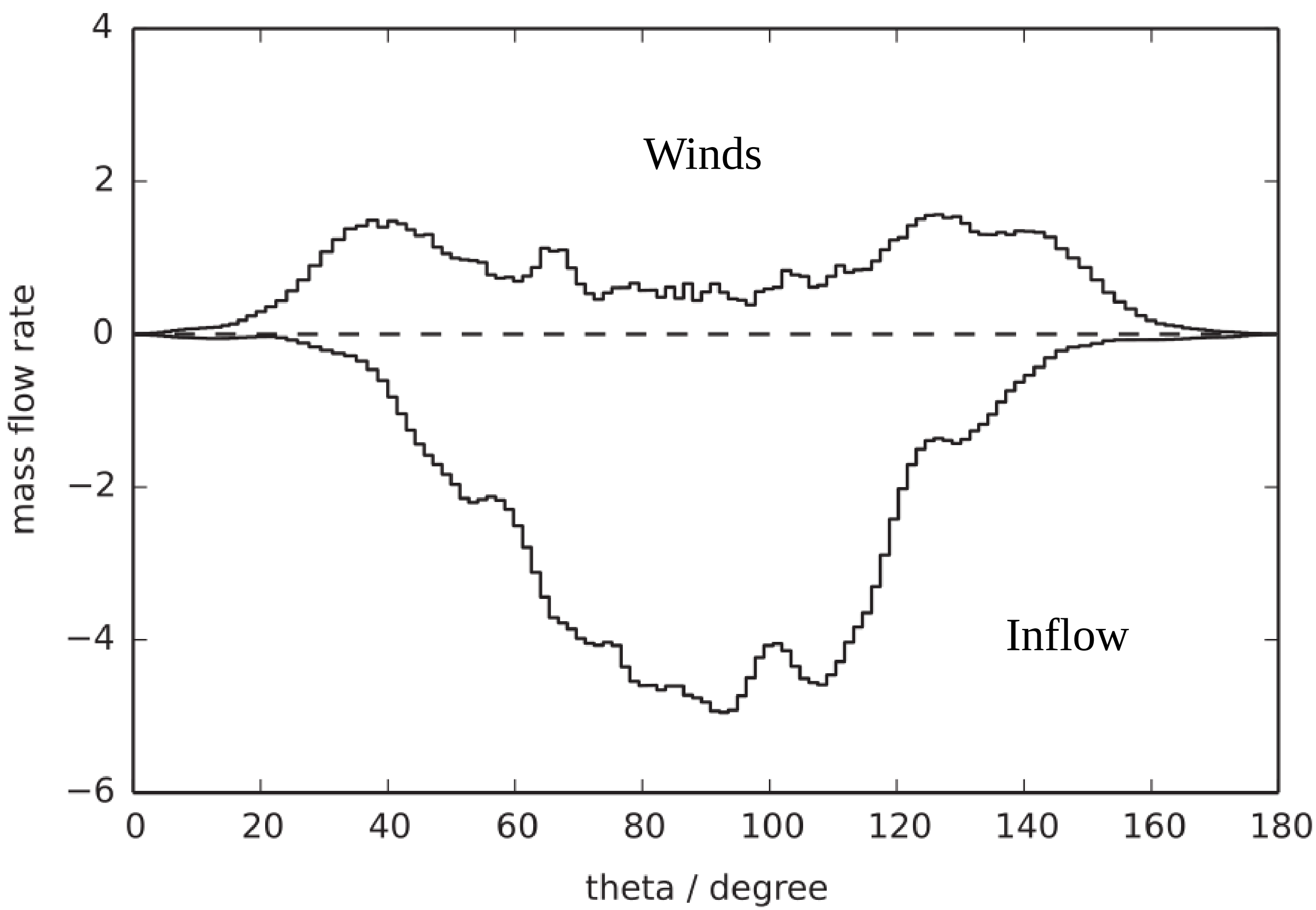


Blue line : dividing line between jet/wind
Green line : dividing line between wind/inflow

– “It is clear that the strong energy flux region is surrounded by the region where the mass-loss is most efficient.” (Sadowski+ 2013)

Jet collimation

— GRMHD simulations found that winds are surrounding the highly magnetized jets.



Yuan+15

— Winds are likely the source of Faraday rotation, given the small jet viewing angle (~17 deg, Mertens et al. 2016).

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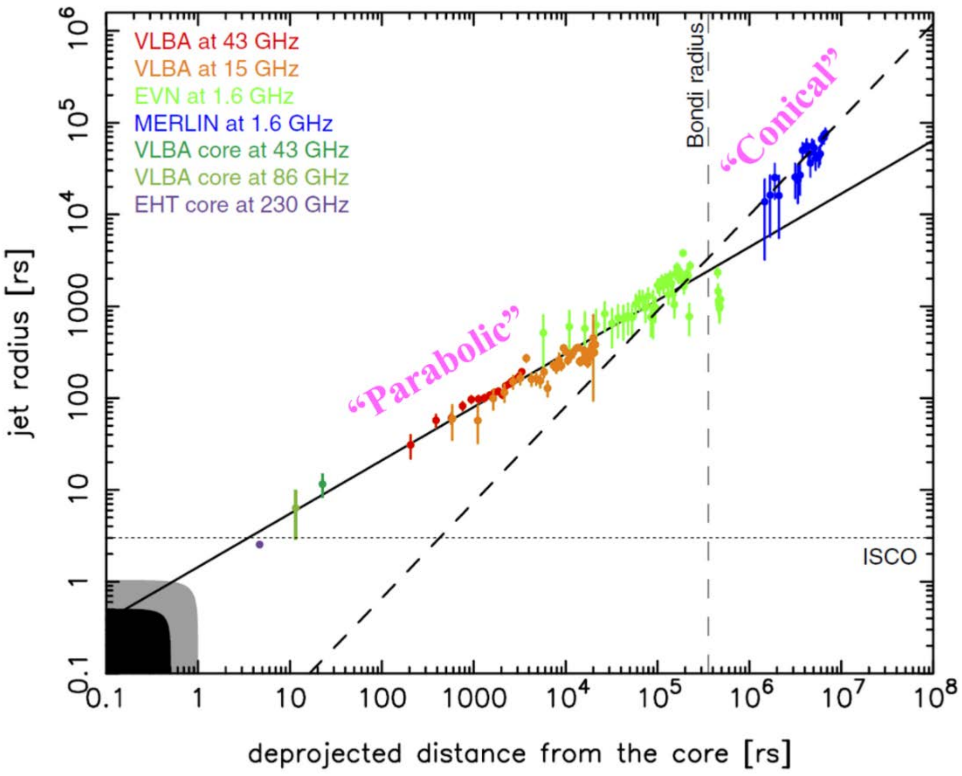
– To have a parabolic jet shape, $\alpha \leq 2$ is needed (external-confinement).

$$\rho \propto r^{-1} \qquad P_{\rm gas} \propto \rho^{\gamma} \propto r^{-1.67}$$

$$\gamma = 5/3$$

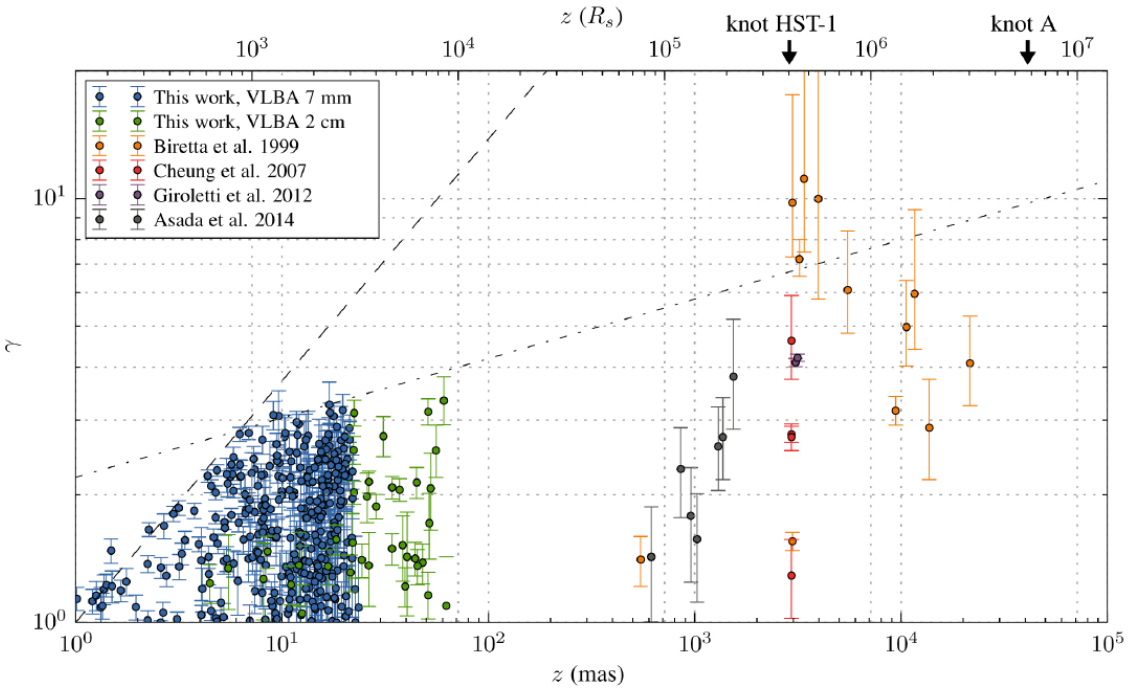
$$P_{\rm gas} \propto r^{-1.67}$$

Jet collimation & acceleration



Nakamura & Asada (2013)

Jet collimation

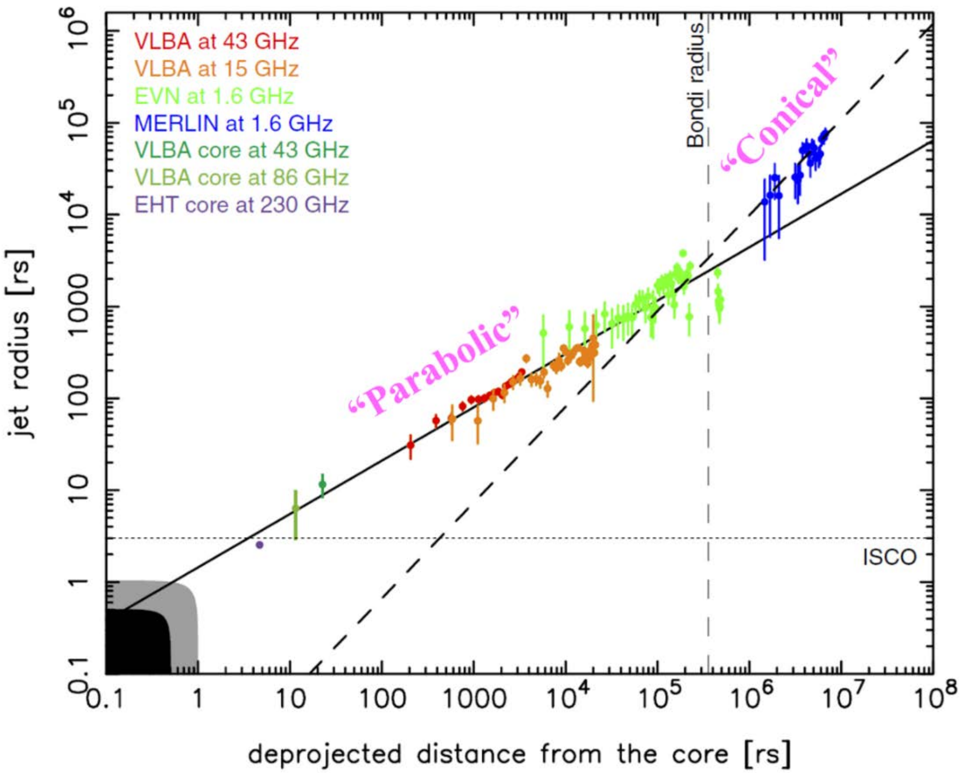


Mertens+ (2016)

Jet acceleration

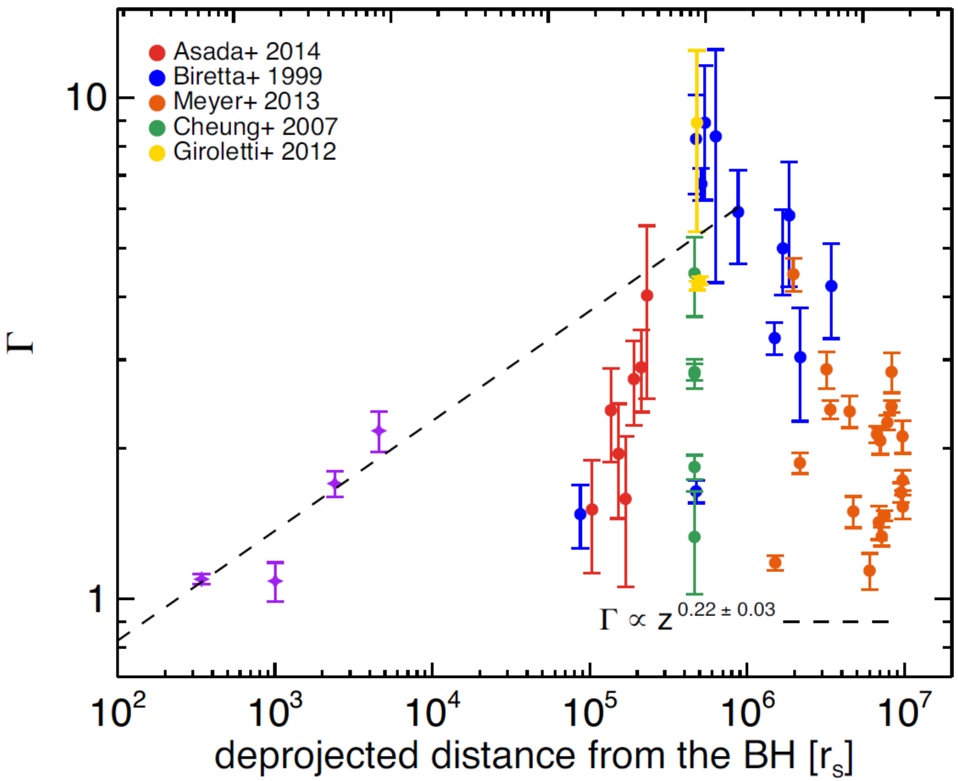
Confinement of the jet by the winds ⟶ collimation ⟶ acceleration

Jet collimation & acceleration



Nakamura & Asada (2013)

Jet collimation



Hada+ (2017)

Jet acceleration

Confinement of the jet by the winds ⟶ collimation ⟶ acceleration

Mass accretion rate

– We obtained $\rho \propto r^{-1}$
– If the radial self-similarity holds, then

$$\longrightarrow \dot{M}(r) \propto r^{0.5} \longrightarrow \dot{M}_{\rm BH} = 1.58 \times 10^{-4} M_\odot \ {\rm yr}^{-1}$$

$\dot{M}_{\rm Bondi} = 0.1 M_\odot {\rm yr}^{-1}$ from X-ray observations
(with a few assumptions…)

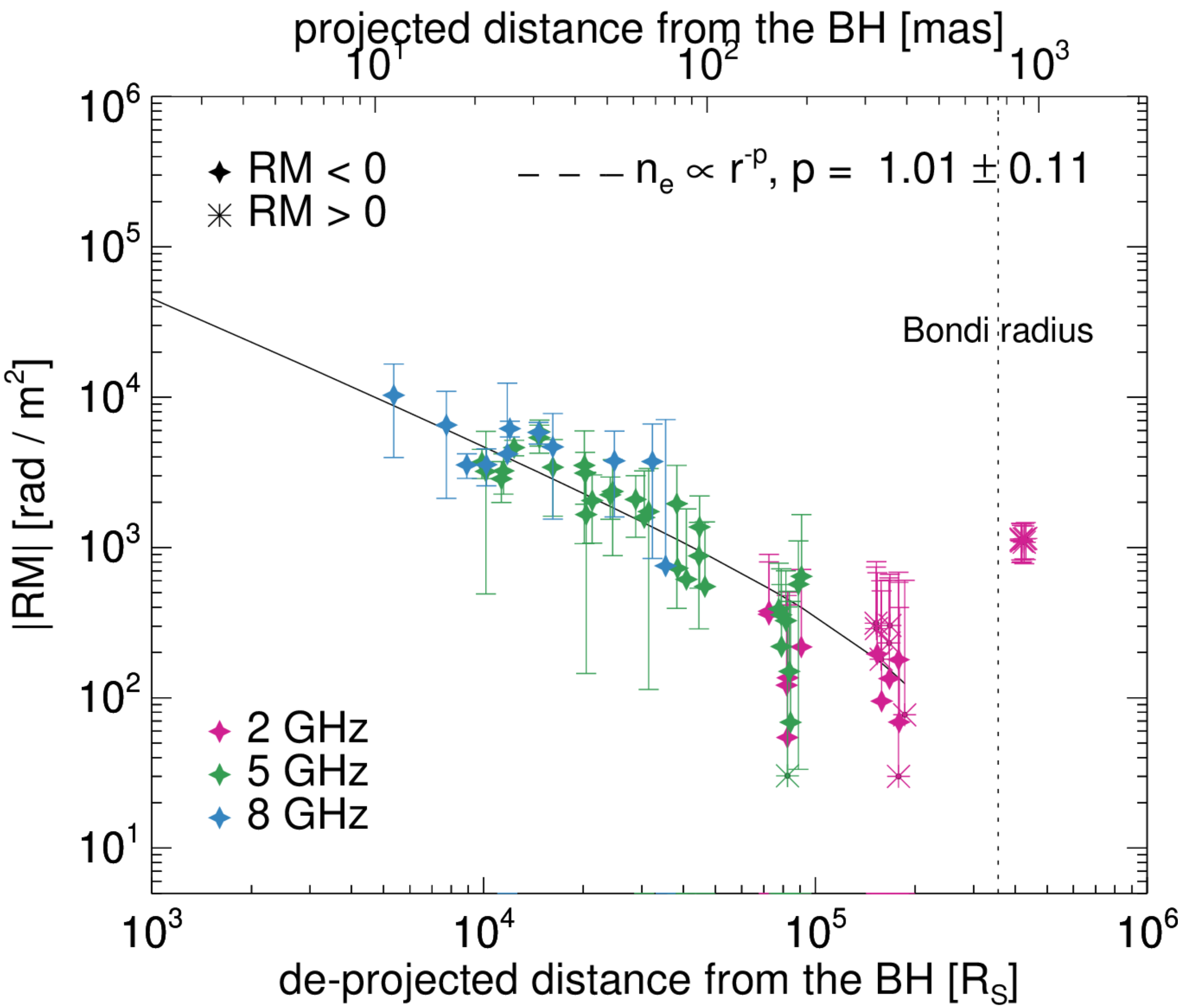
$$\longrightarrow \epsilon \equiv L_{\rm disk}/\dot{M}_{\rm BH}c^2 \approx 3.8\%$$

The radiative efficiency of hot accretion flows might not be as small as usually assumed. The faintness of LLAGNs is due to the reduced mass accretion rate via winds.

$$\longrightarrow \eta \equiv P_{\rm jet}/\dot{M}_{\rm BH}c^2 \gtrsim 110\%, \ \ P_{\rm jet} \gtrsim 10^{43} \ {\rm erg \ s^{-1}}$$

Blandford-Znajek process operating in a MAD state (Tchekhovskoy et al. 2011).

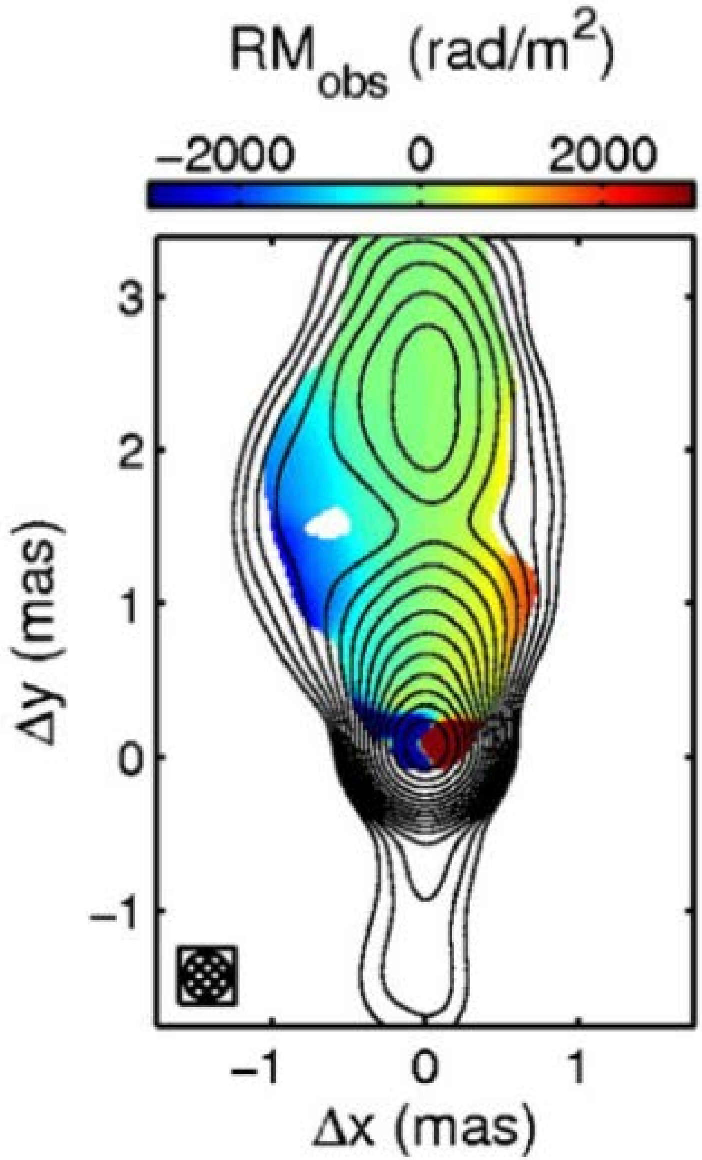
Mis-alignment between the jet axis and the wind axis

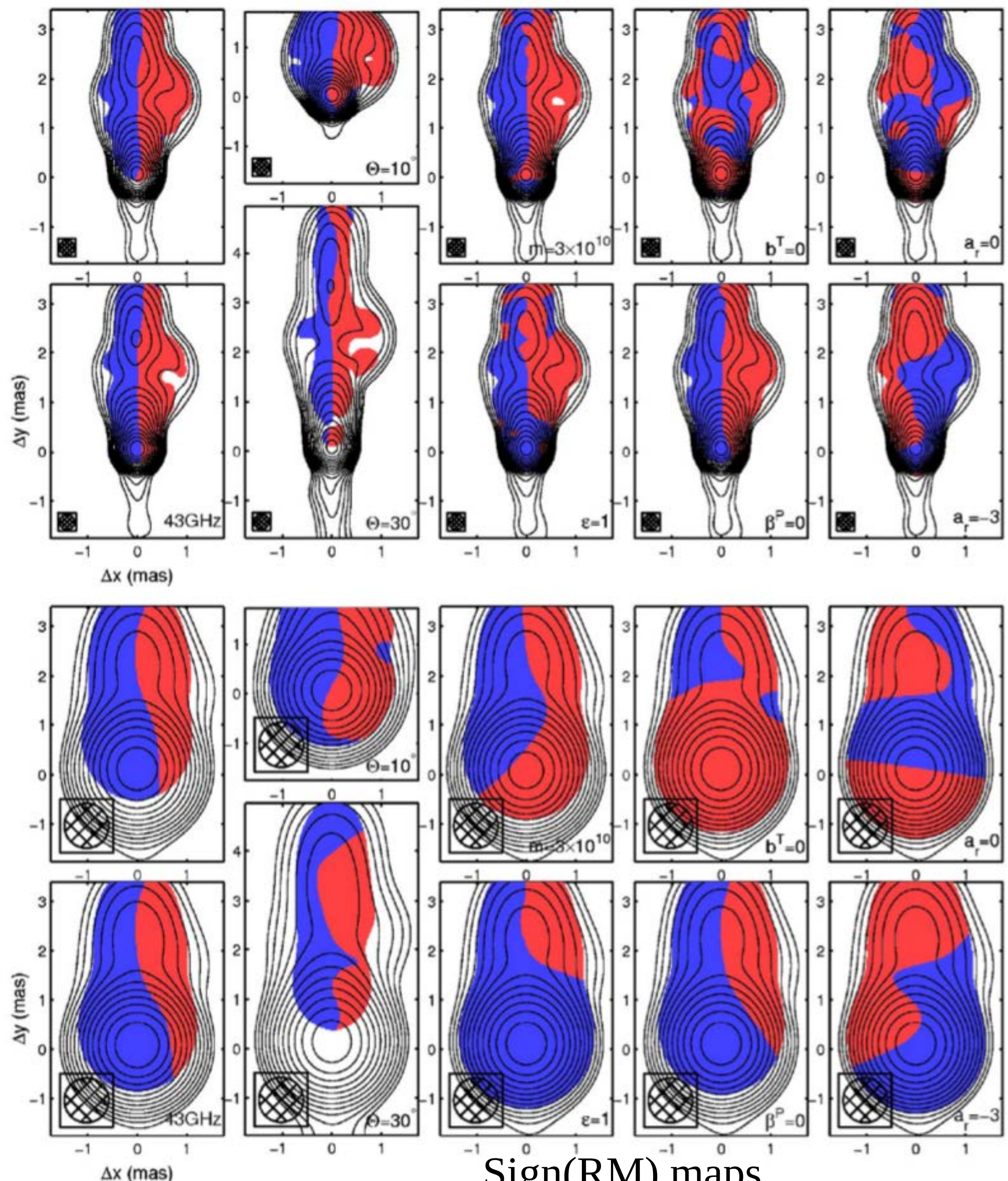


– RM sign is negative in almost all distance ranges.

Mis-alignment between the jet axis and the wind axis

Broderick & McKinney (2010)



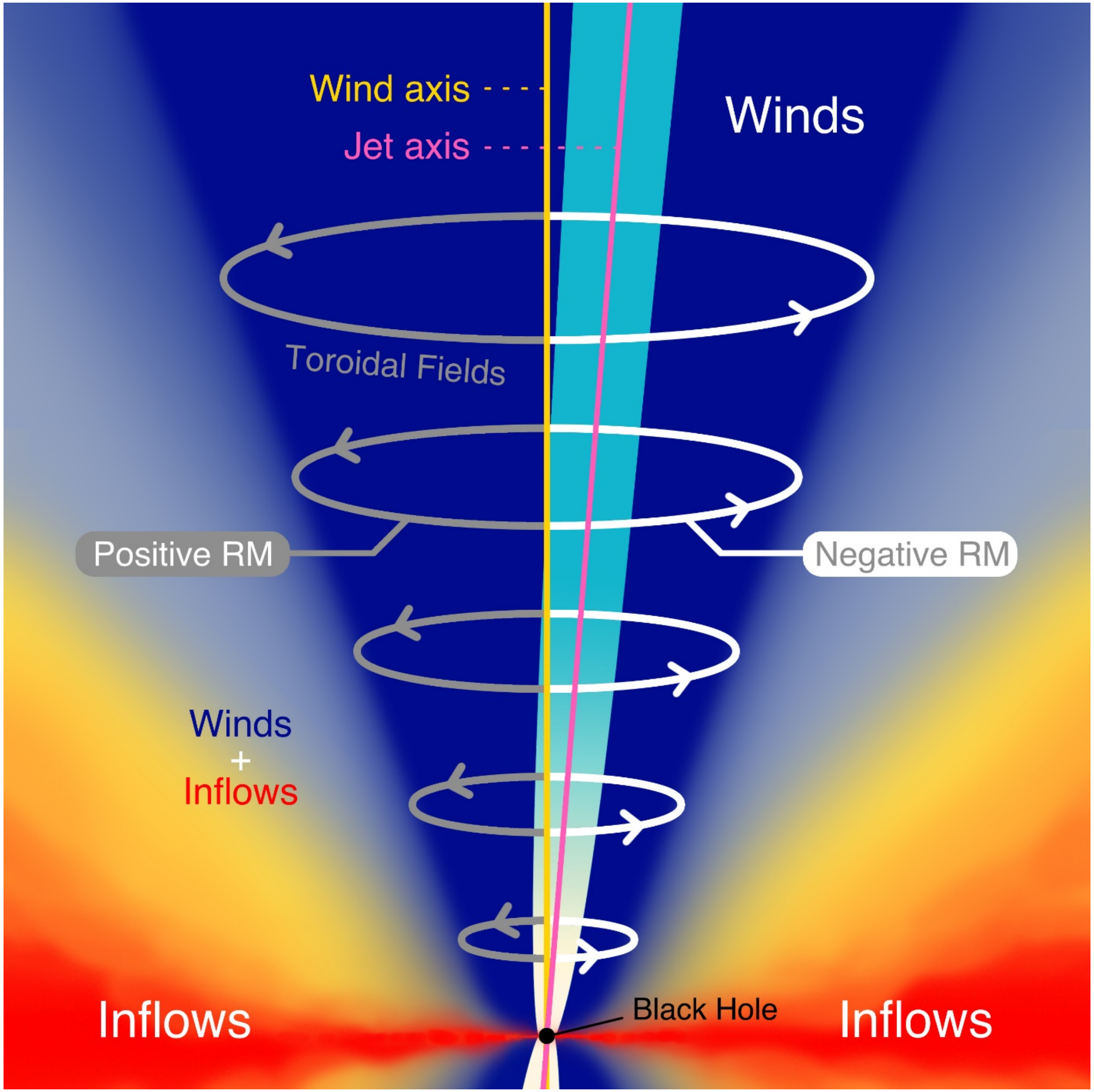


Sign(RM) maps

If the Faraday screen is very close to the jet, e.g., a jet sheath, then

→ Different RM signs on different jet sides with respect to the axis.

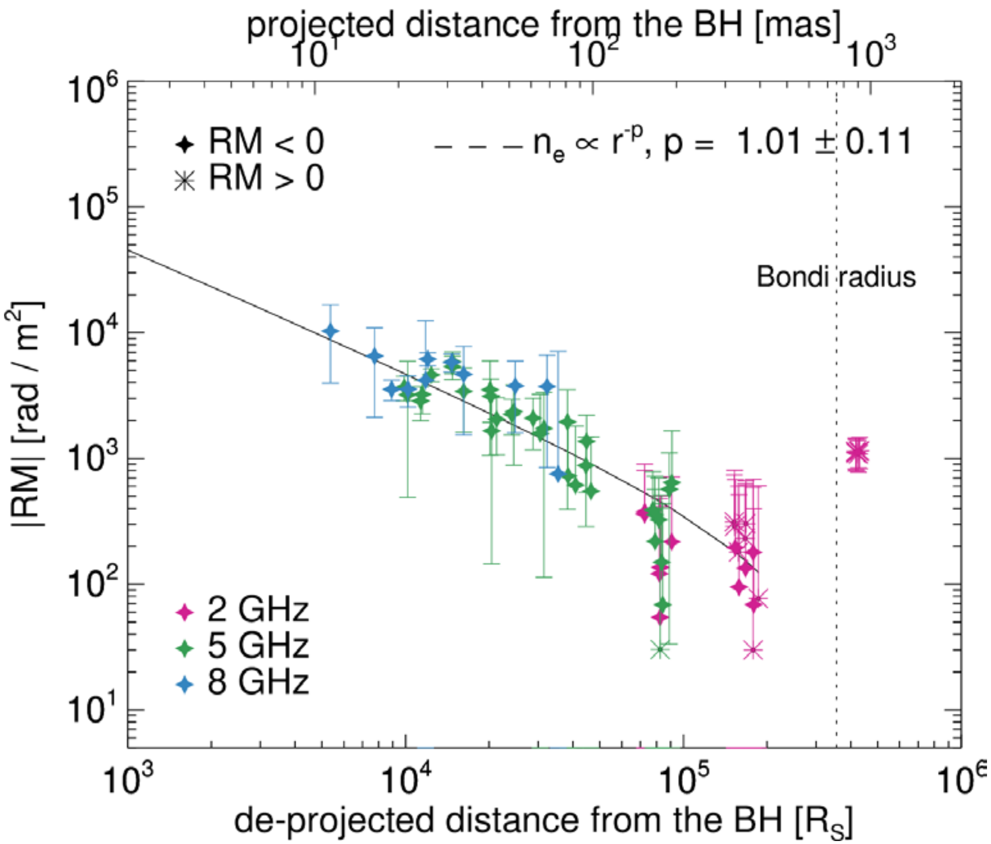
Mis-alignment between the jet axis and the wind axis

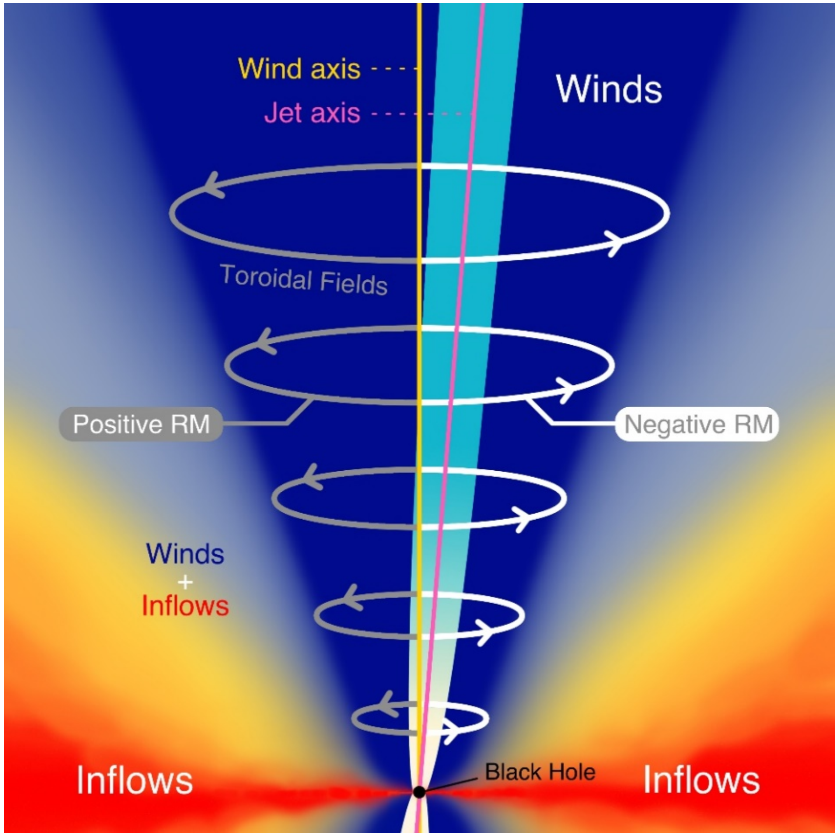


The background light source exposes only one side of the toroidal magnetic loops.

→ Mis-alignment between the jet axis and the accretion axis.

Summary





We studied Faraday rotation in the jet of M87 inside the Bondi radius. The data are consistent with:

1. the presence of substantial winds from hot accretion flows
2. collimation of the jet by the winds with relatively flat pressure profile
3. mis-alignment between the jet and the wind axis.

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