AGNジェットとSMBH近傍の高密度ガス雲との関係

～Physical relationship between AGN jets and high density gas clouds near SMBHs～

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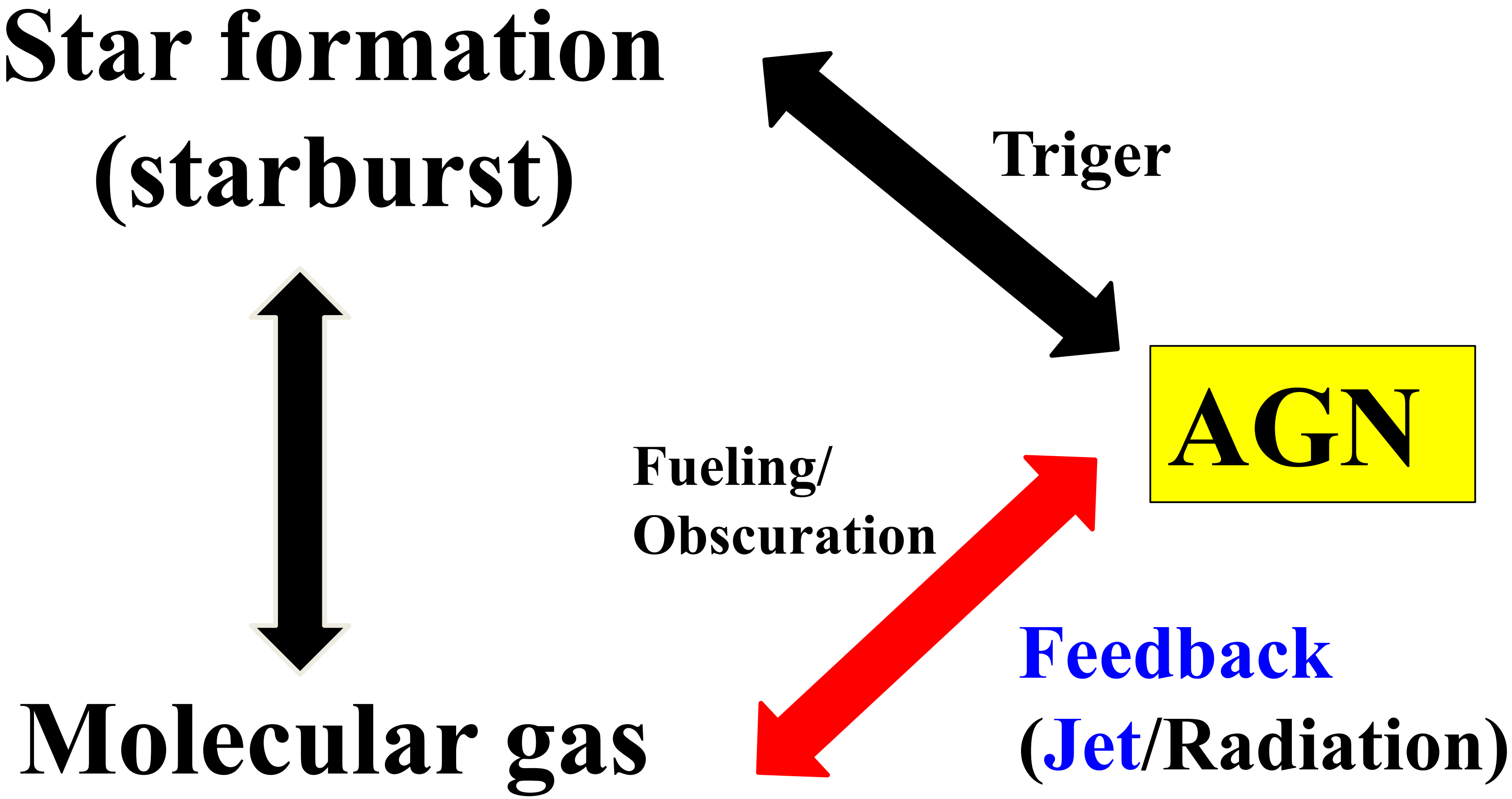
星形成と銀河構造における磁場の役割
（鹿児島大学　郡元キャンパス）2017.12.21

Key words in this WS

star formation,
molecular clouds,
magnetic fields

My interests

Active galactic nuclei; SMBH, AGN torus, jets



Star formation (starburst)

Triger

AGN

Fueling/ Obscuration

Feedback (Jet/Radiation)

Molecular gas

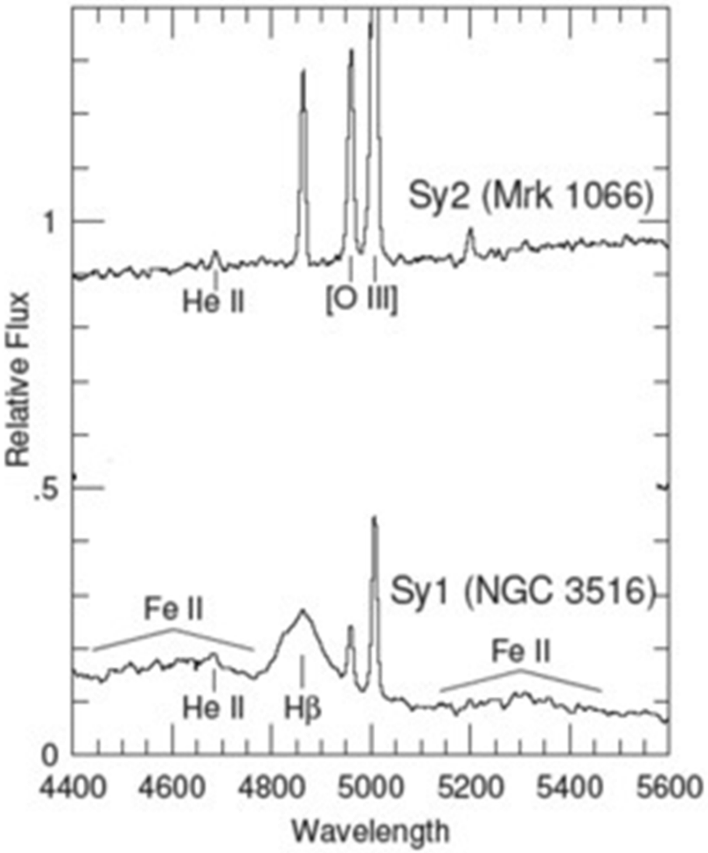
This talk

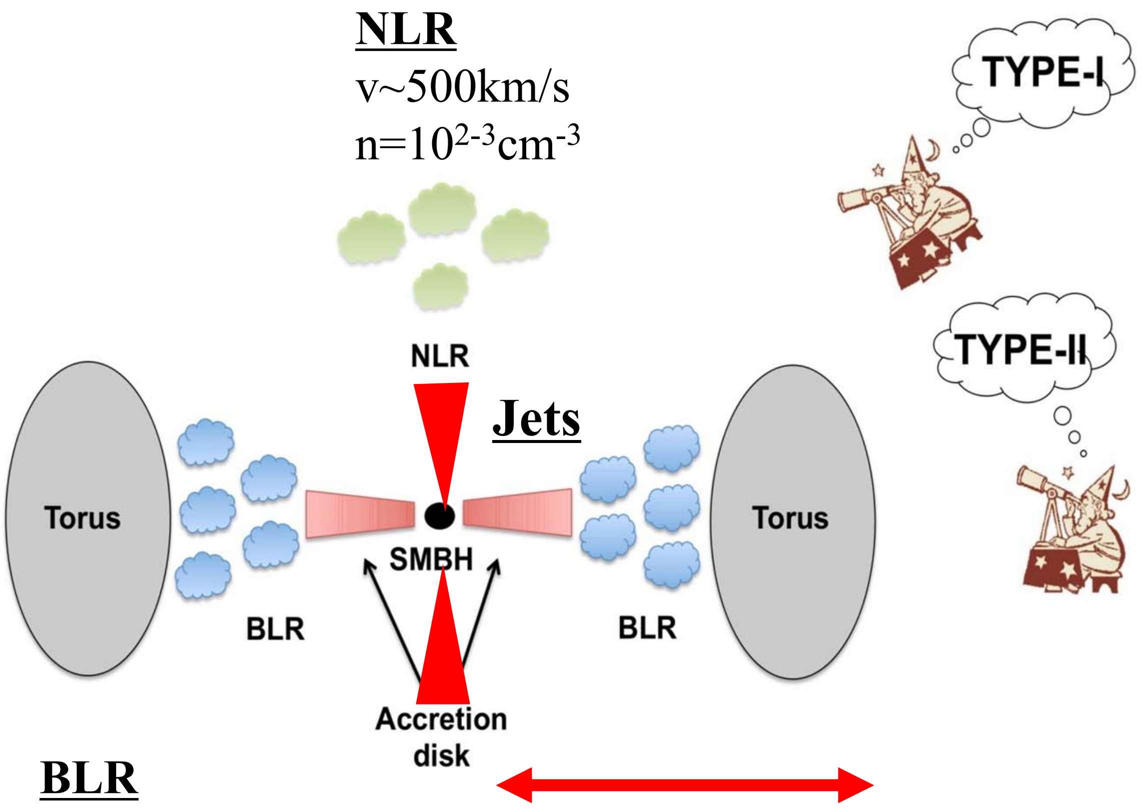
(1) High density clouds near SMBH (～1 pc)

(2) Interaction between AGN jets and clouds

Introduction

What are AGNs ?





NLR
$v \sim 500$km/s
$n = 10^{2-3}$cm^{-3}

BLR
$v = 2000\text{-}10{,}000$km/s
$n = 10^{10-12}$cm^{-3}

1-10pc

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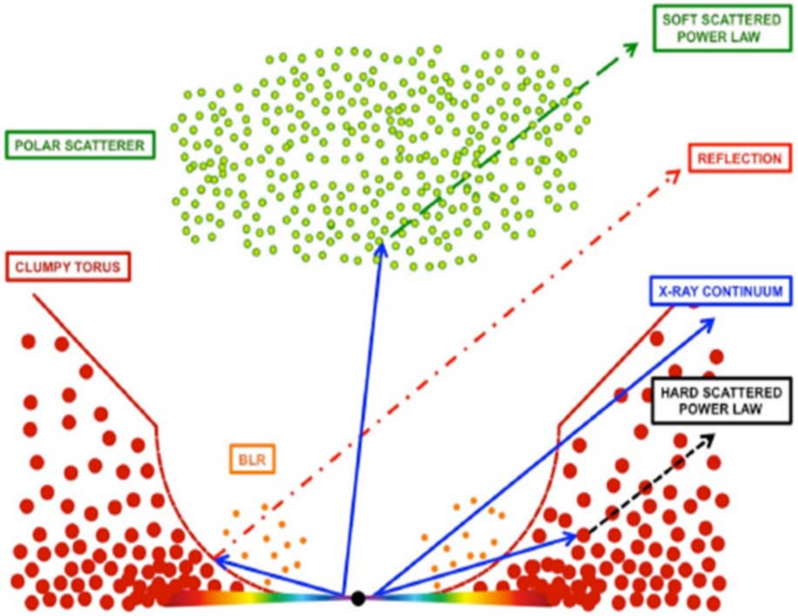
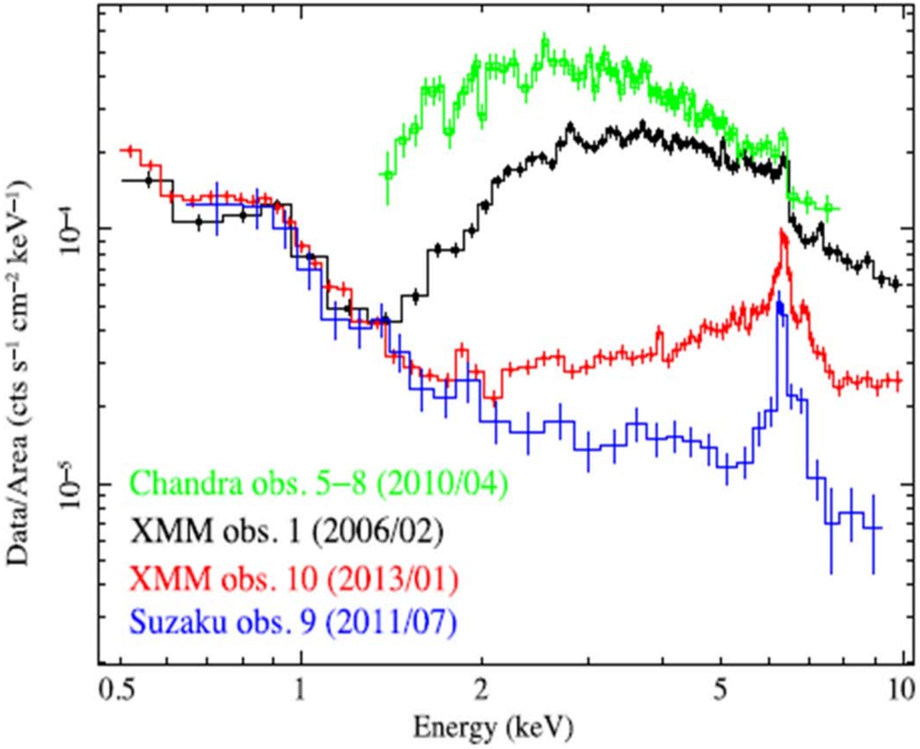
The circumnuclear matter distribution around AGNs are highly uncertain.

Time variability (X-ray)

Δt = a few months & years

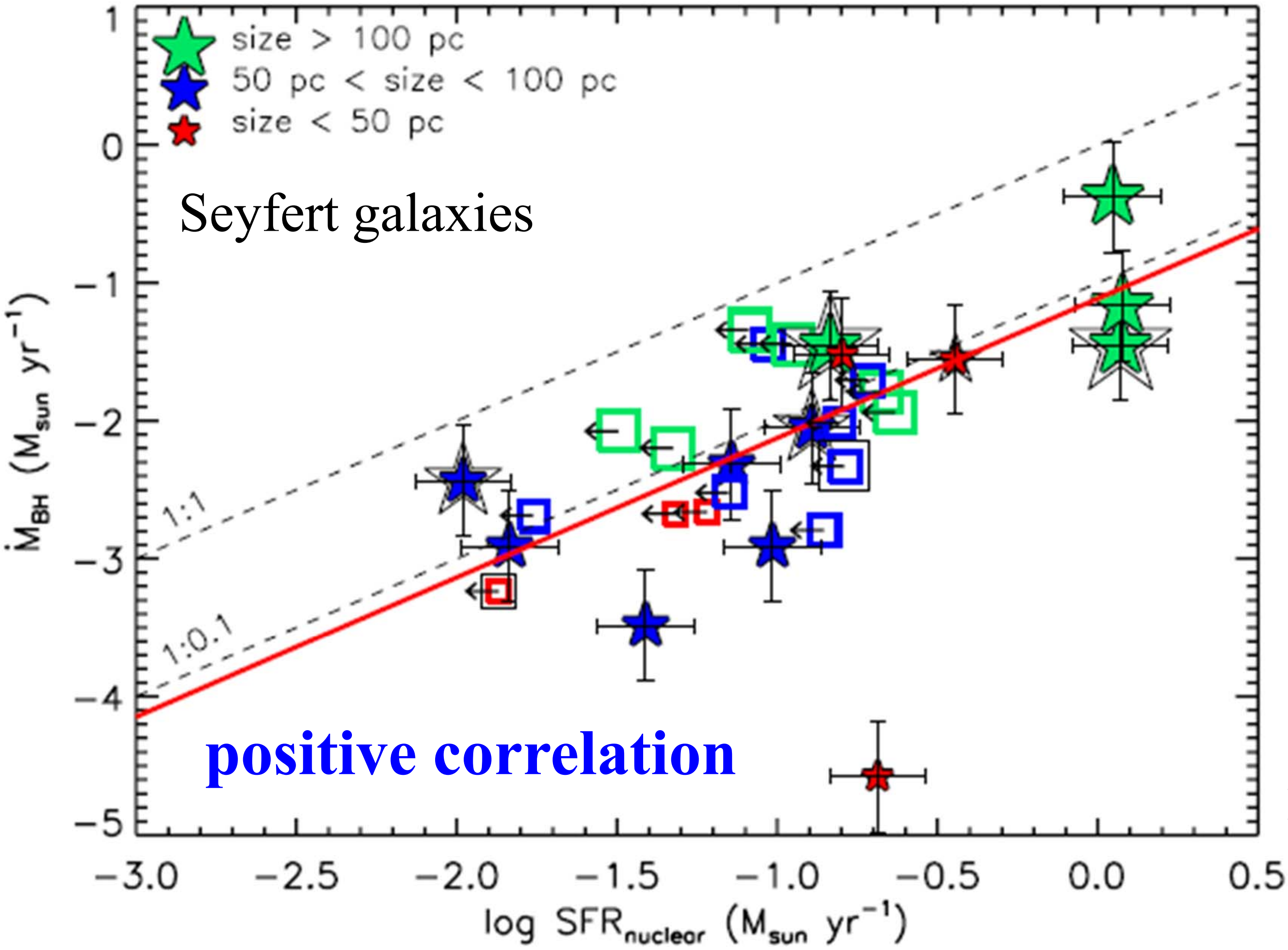
Highly non-uniform ISM such as clumps within 1pc





Miniutti et al. (2013)

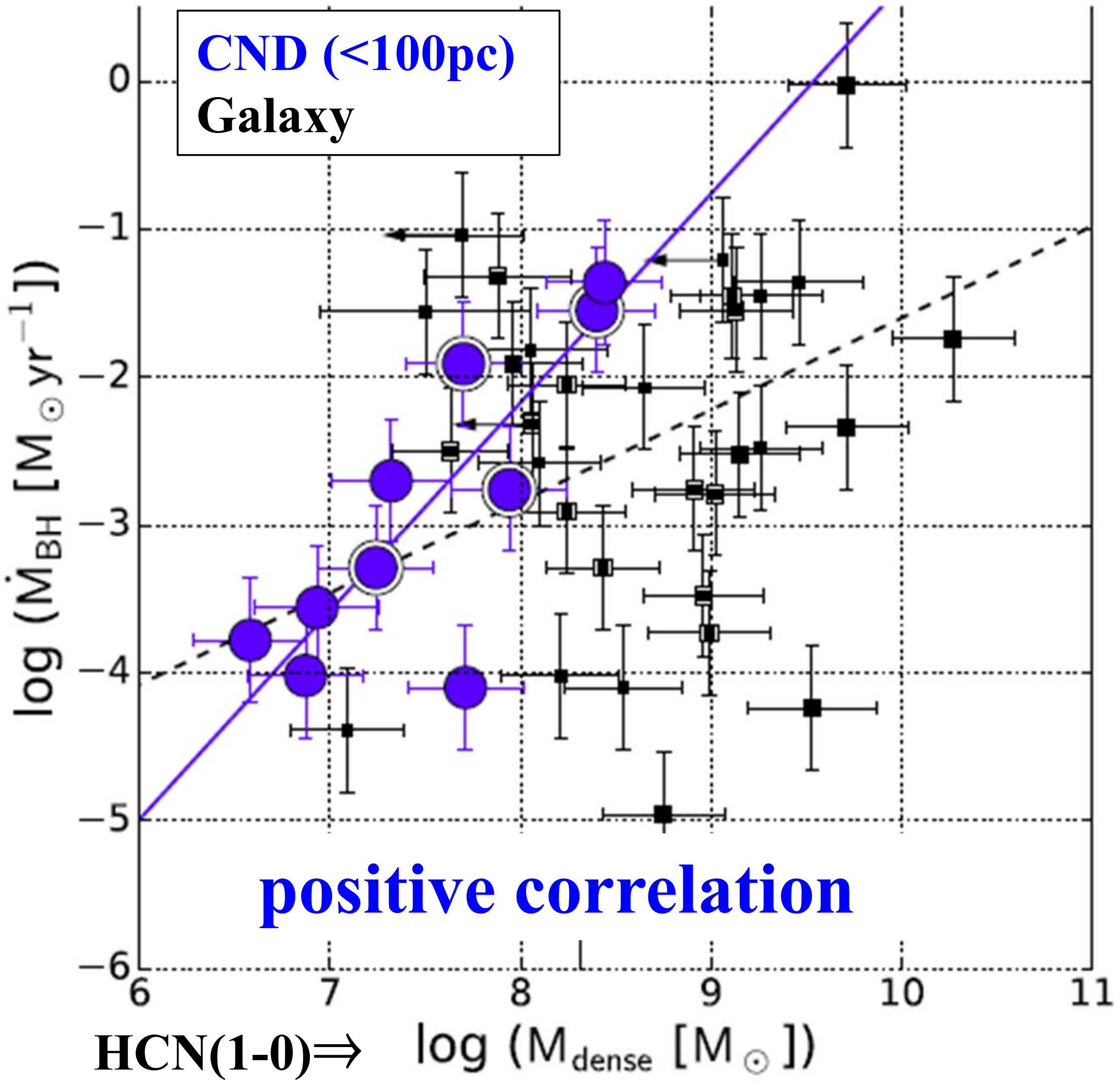
AGN-Nuclear starburst (< 100pc) relation



Esquej+2013

(see., Imanishi & Wada 2004; Imanishi+2011)

AGN-Dense molecular gas (< 100pc) relation



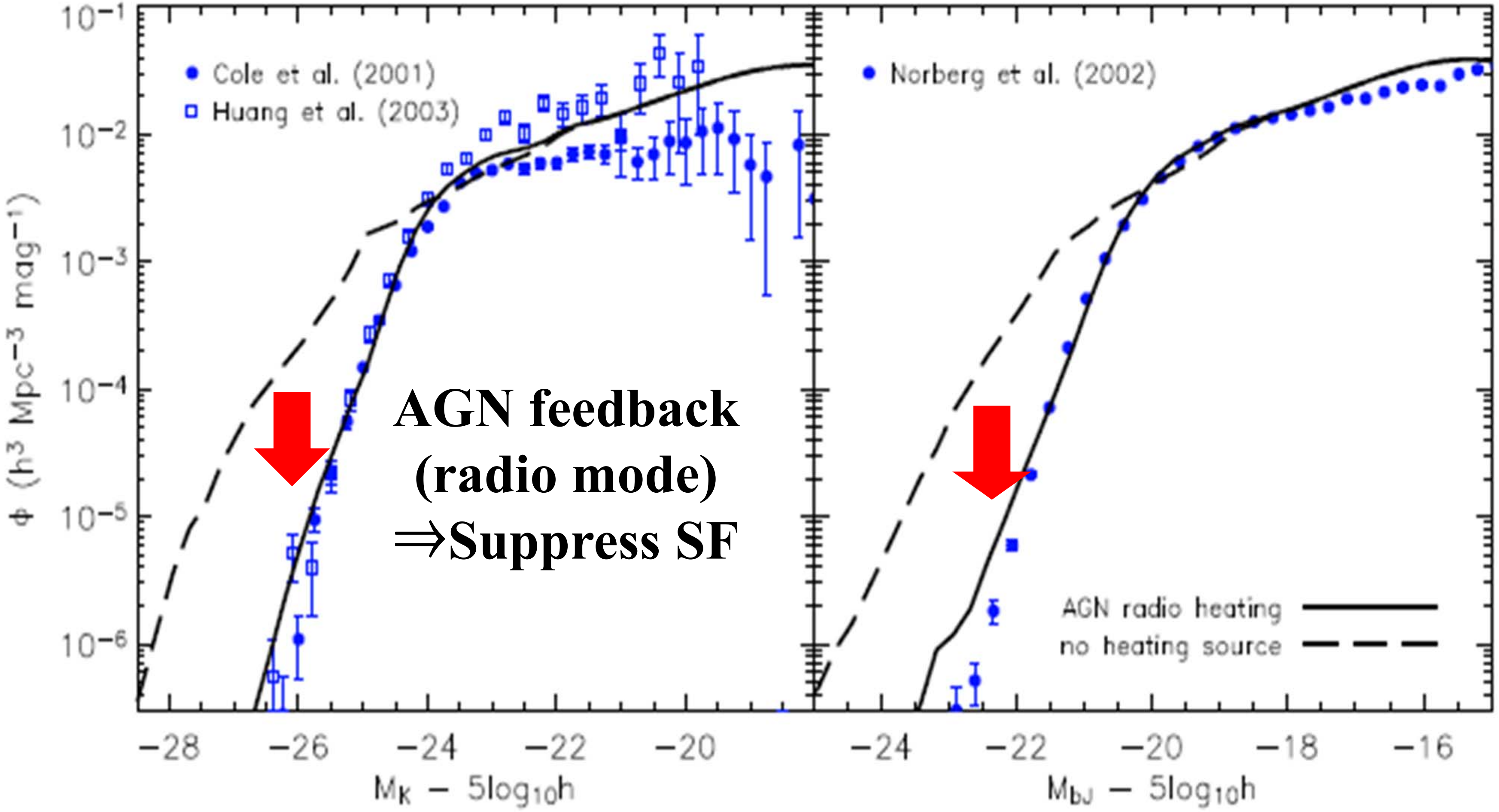
positive correlation

HCN(1-0)⇒

Izumi+2016

AGN feedback (e.g., Silk & Rees 1998)

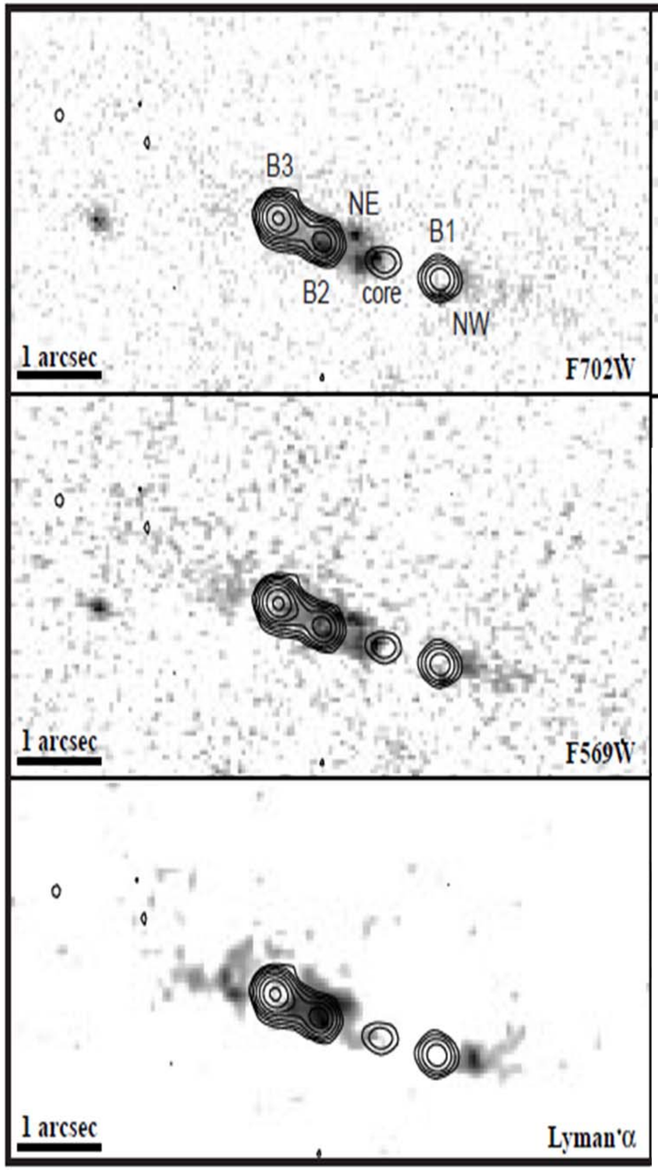
Luminosity function of galaxies

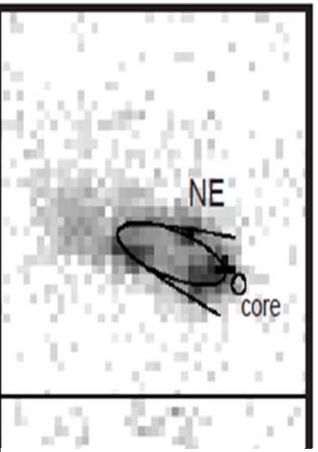


AGN feedback (radio mode)
⇒Suppress SF

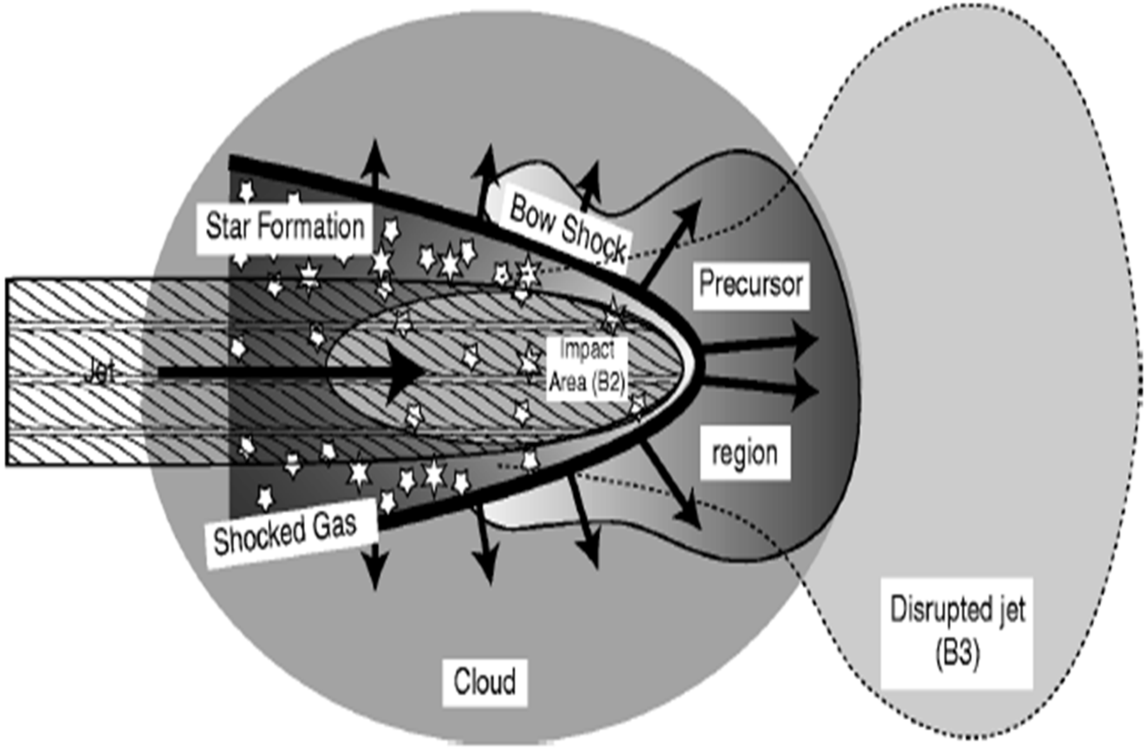
Croton et al. (2006)

Jet-induced star formation in high-z radio galaxies



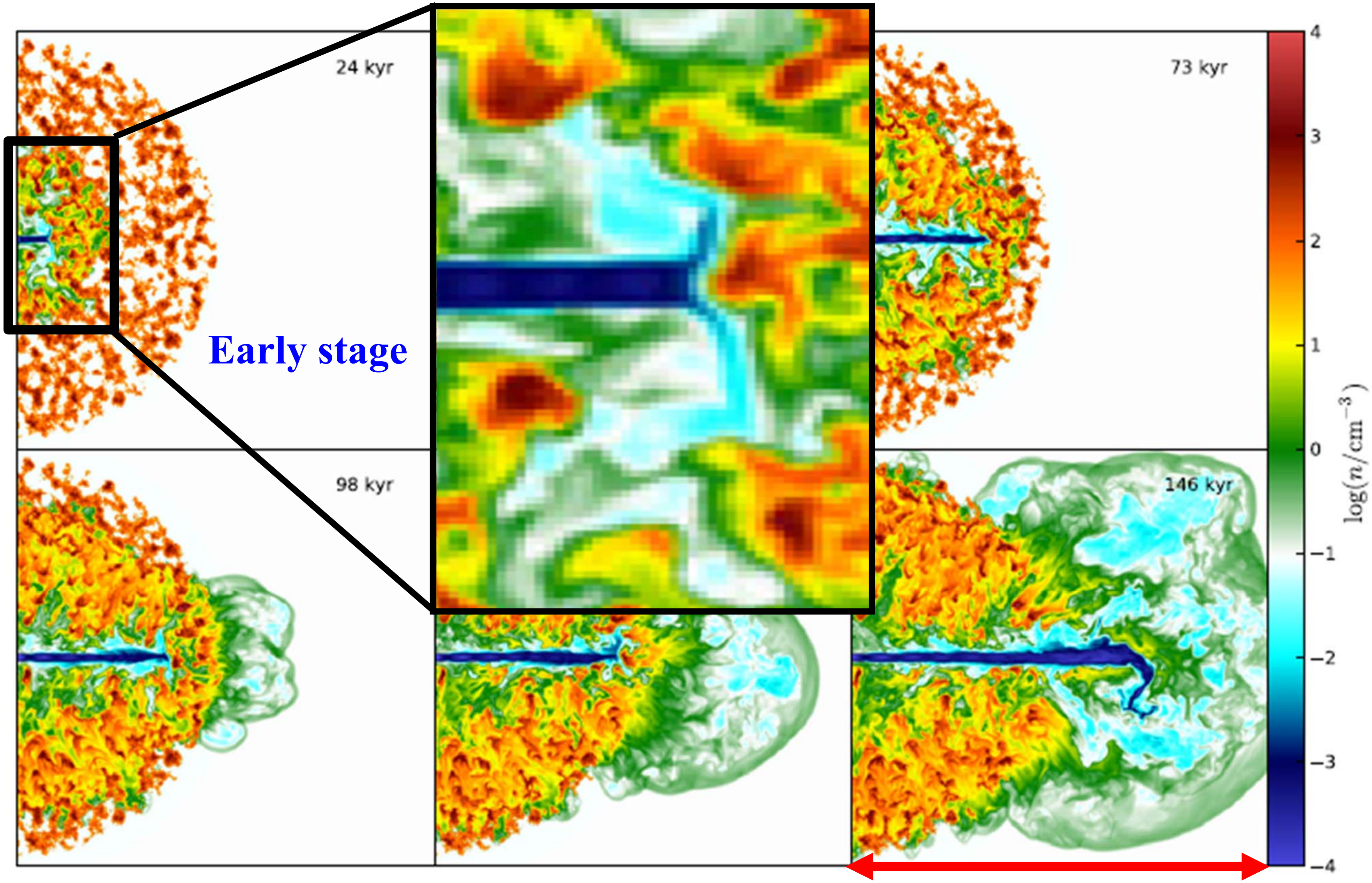


The direct association of the **radio components with both UV continuum and Lyα emission** strongly indicates the jet-induced star formation.



Bicknell +2000

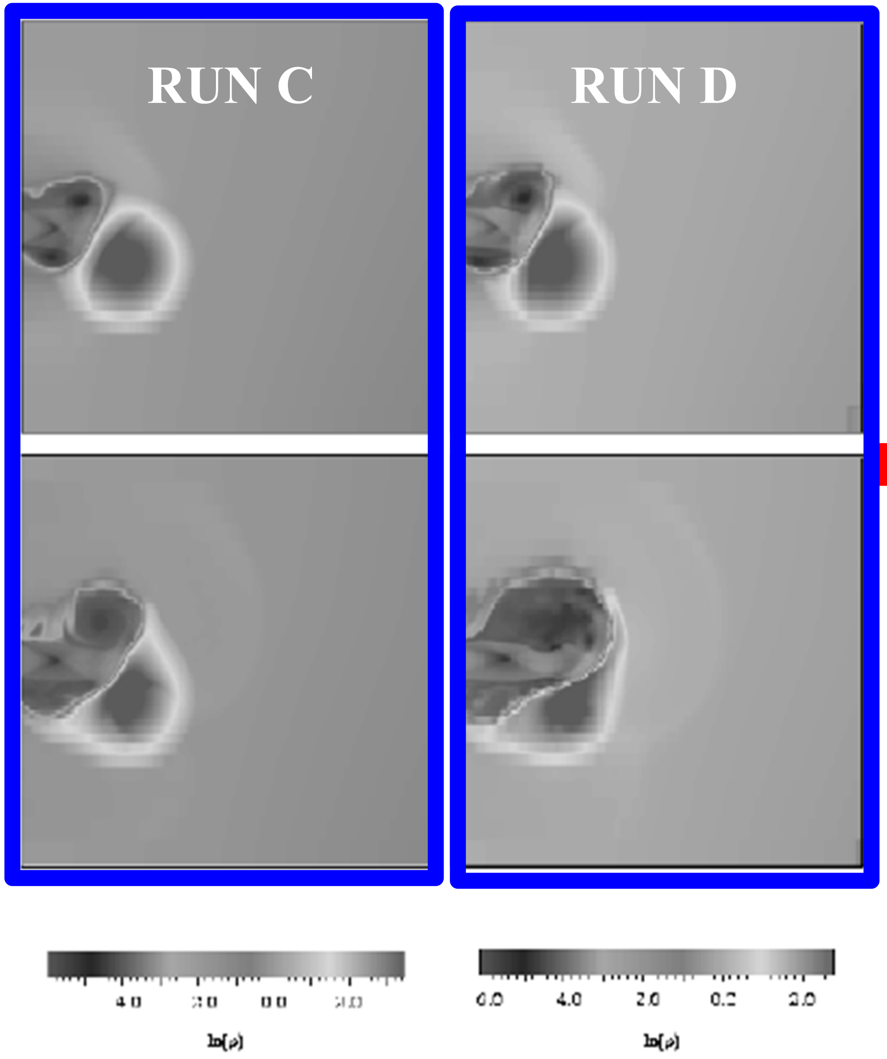
Simulations of AGN jets interacting with clouds

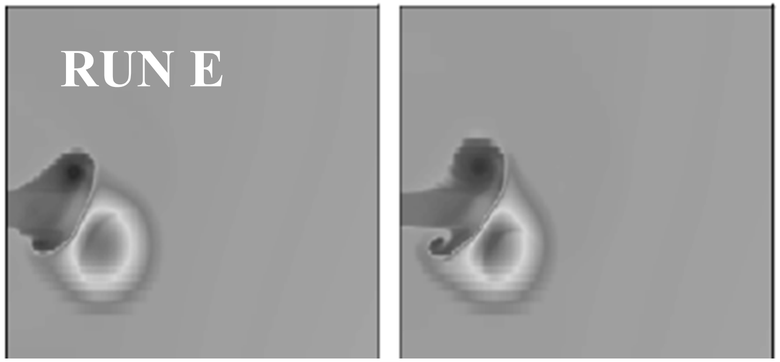


Wagner & Bicknell 2011

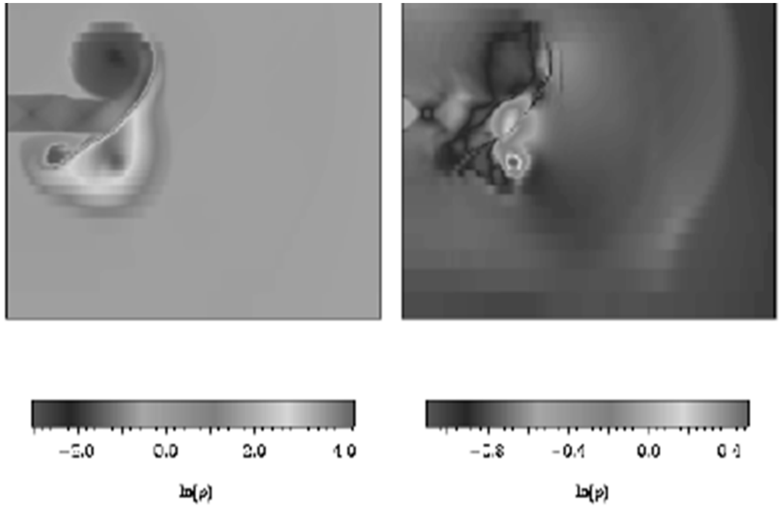
1 kpc

Simulations of AGN jets interacting with clouds





Denser and cold clouds
→ A bent jet can be formed!

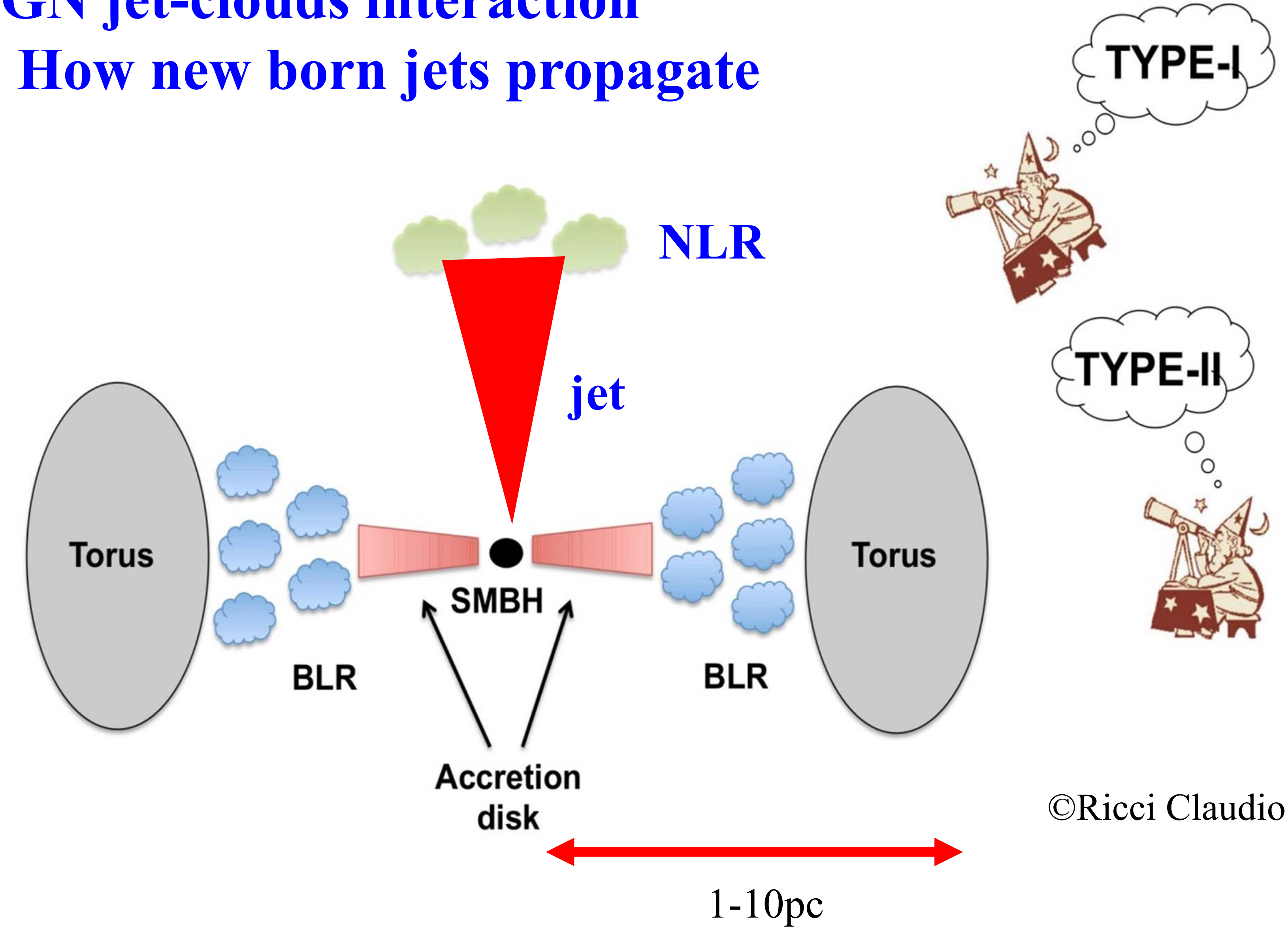


Wang et al. 2010

[Main goals]

- **Properties of gas clouds near SMBH**
- **AGN jet-clouds interaction**

⇒ How new born jets propagate



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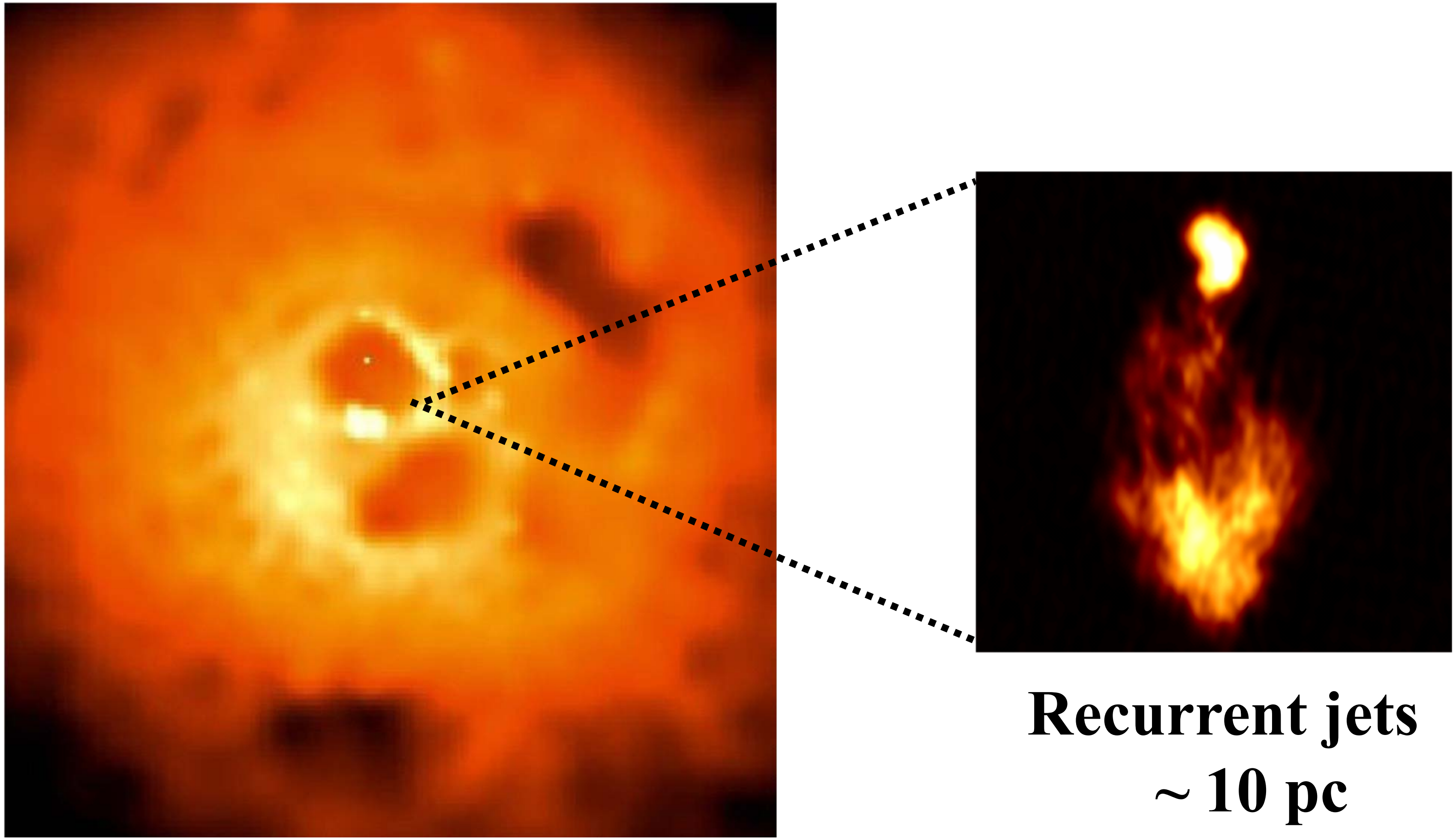
Target: 3C 84 (NGC 1275)



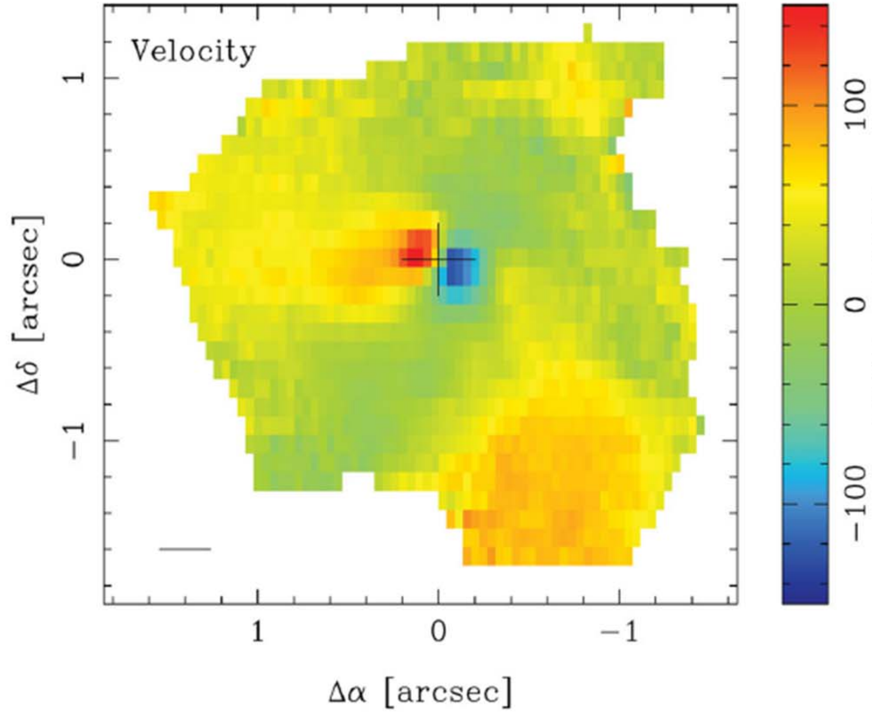
Recurrent jets
~ 10 pc

Asada et al. 2006

Core of Perseus cluster

Molecular hydrogen circumnuclear disk

Shock tracers: near infrared H2, [FeII] lines by NIFS Gemini (Scharwachter+13)



~50pc rotating disc

$$M_{\mathrm{H2}}(<50\,\mathrm{pc}) \sim 4\times10^{8}\,M_{\mathrm{sun}}$$

$$M_{\mathrm{BH}} \sim 8\times10^{8}\,M_{\mathrm{sun}}$$

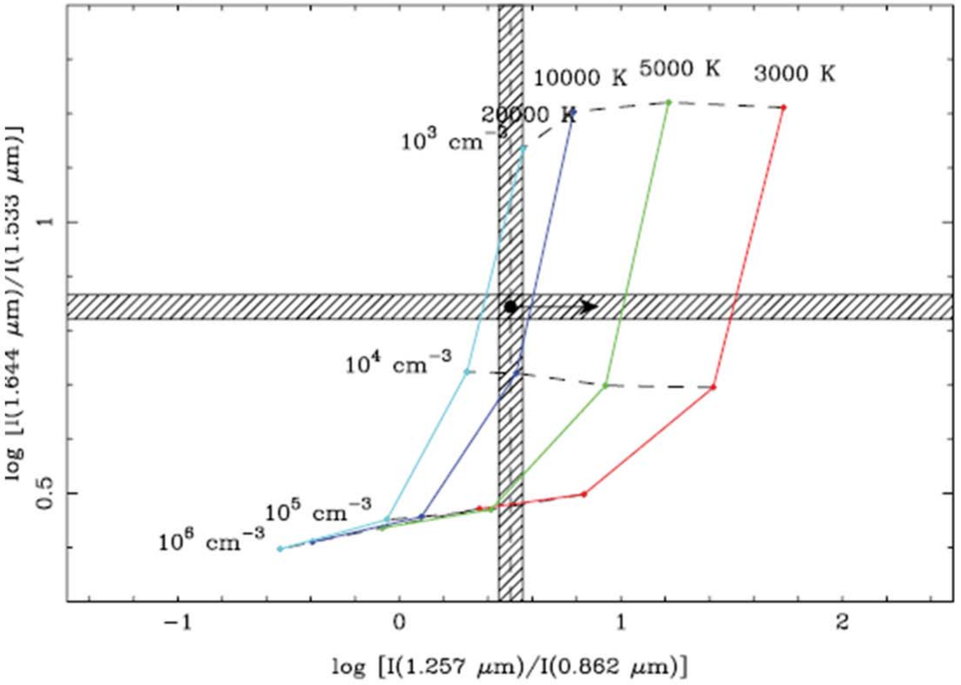
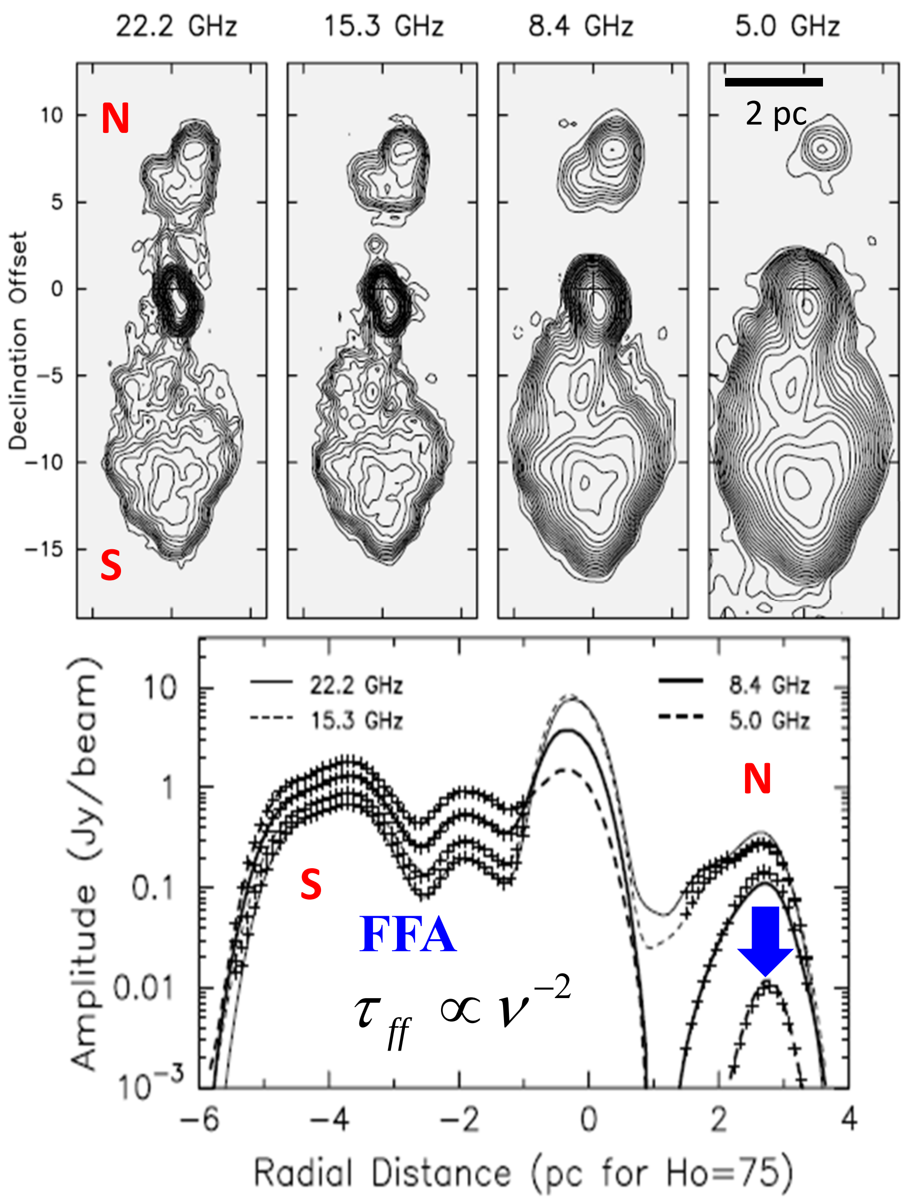


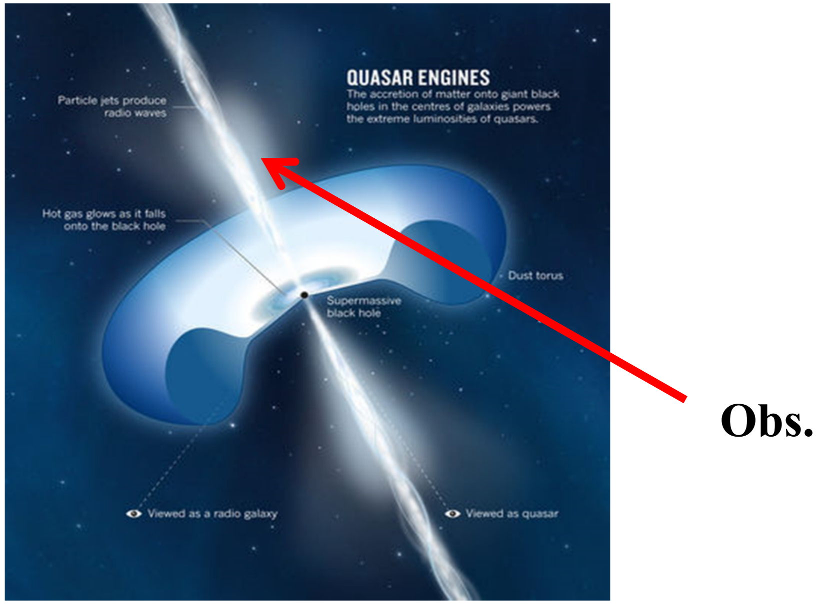
Figure 14. Theoretical [Fe II] emission-line ratios based on the $a^4P_{5/2}$–$a^4F_{9/2}$ 0.8617 μm transition. Models are computed for a range of electron temperatures and electron densities, as indicated. The horizontal shaded region corresponds to the measured 1.644 μm/1.533 μm ratio and its uncertainty in the integrated *H*-band spectrum of NGC 1275 (Fig. 1). The vertical dashed line and arrow correspond to the limit placed on the 1.257 μm/0.862 μm ratio from Riffel, Rodríguez-Ardila & Pastoriza (2006).

$$T \sim 1.5\times10^{4}\,\mathrm{K}, \quad n_e \sim 4\times10^{3}\,\mathrm{cm}^{-3}$$

10 pc-scale free-free-absorbed (FFA) plasma torus

Walker et al. 2000 Imaging @2.3, 5, 8.4, 15.4, 22, 43 GHz

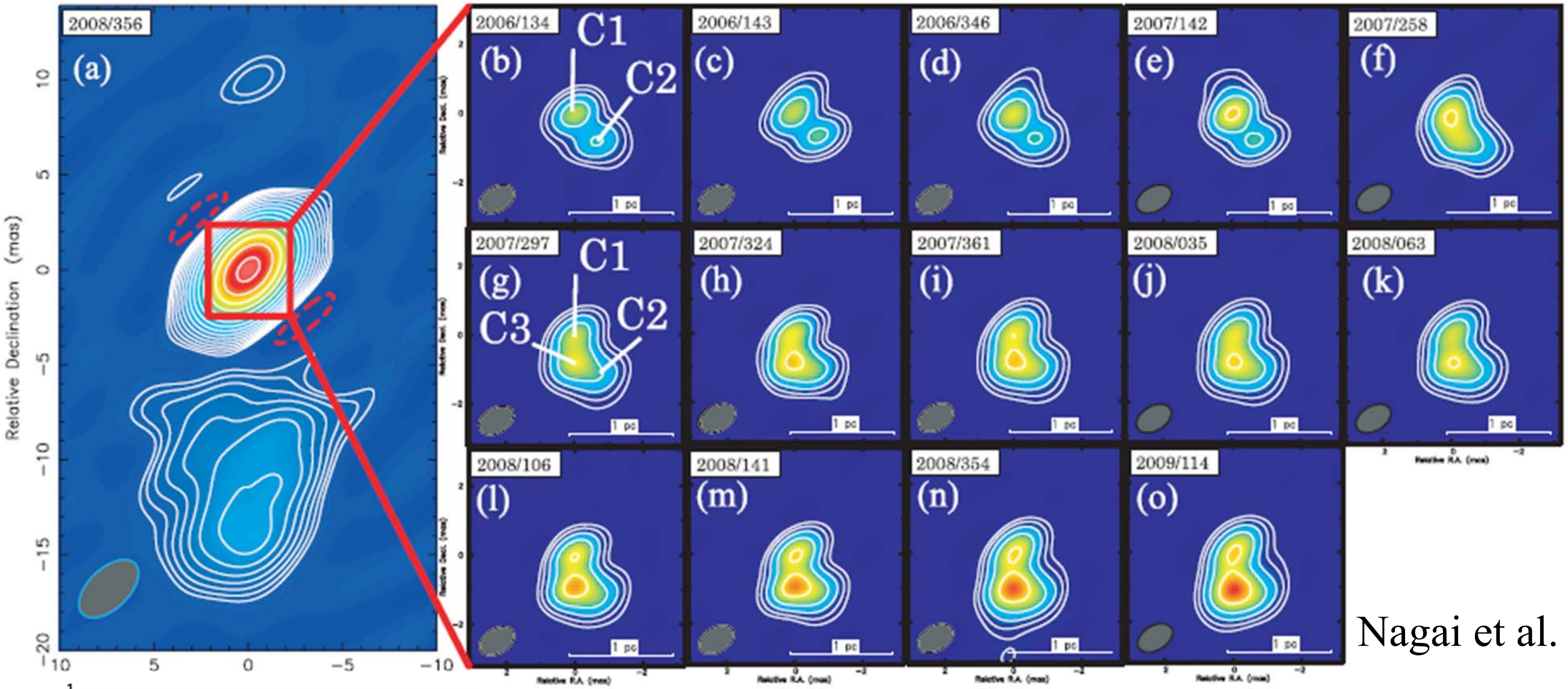




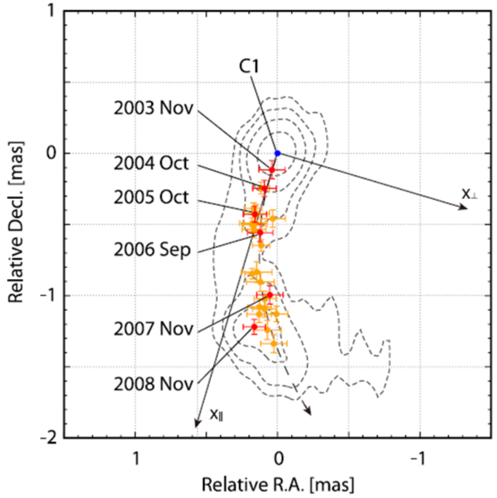
Walker found 10 pc uniform plasma torus (disk).

How about much smaller scale ?

Strong new born radio jet 3C 84 (~1pc)



Nagai et al. 2010



Suzuki et al. 2012

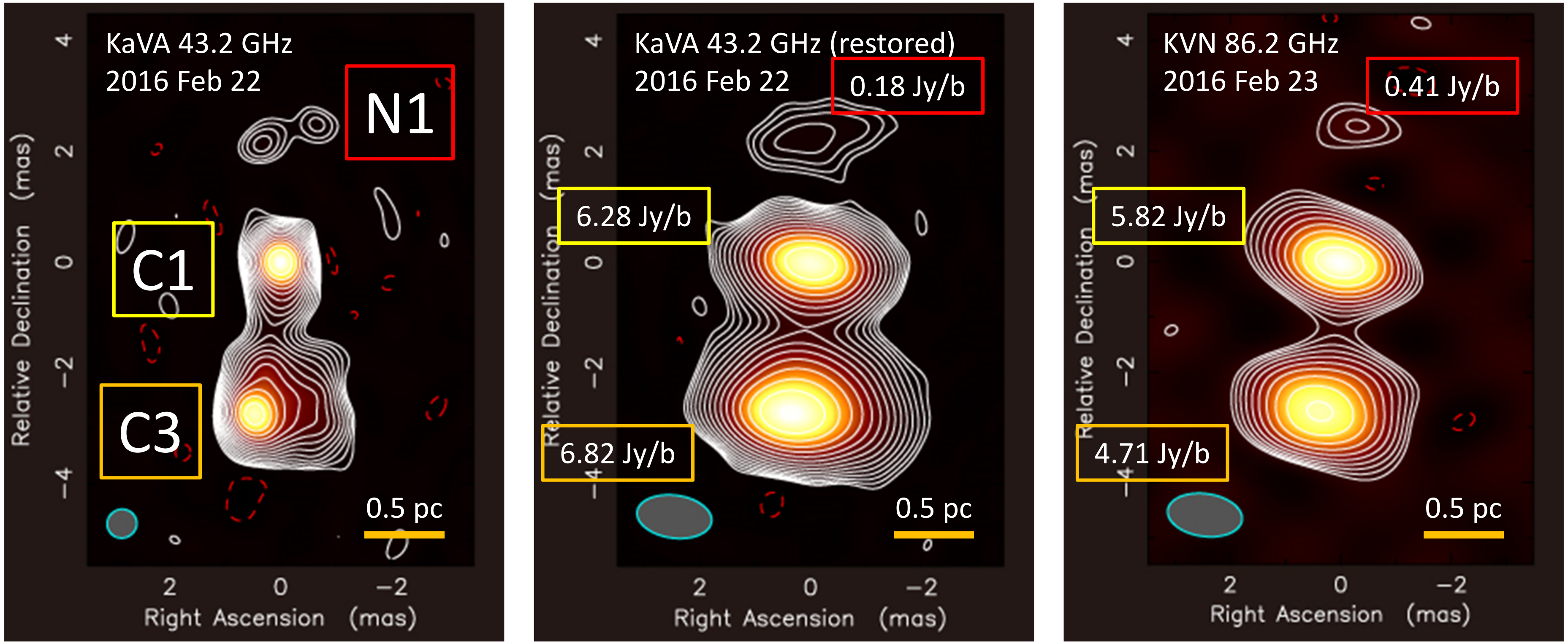
Jet –head advancing velocity

$$v_{\mathbf{h}} = 0.2 - 0.3c$$

We did not detect the counter jets so far.

New discovery of ~1 pc FFA plasma torus

KVN and VERA Array (KaVA) 43GHz, KVN 86GHz



Wajima, Kino, NK+

(cf. Fujita & Nagai 2017)

$$\frac{F(\mathrm{N1})}{F(\mathrm{C3})} = 0.025$$

$$\frac{F(\mathrm{N1})}{F(\mathrm{C3})} = 0.089$$

Optically thick spectrum of N1 component $S_\nu \propto \nu^{+1.2}$

→ Free-Free Absorption @ ~1pc

Physical properties of absorbing medium at pc scale

1. How about a parsec scale ? Uniform or clumpy ?

$$\begin{cases} \tau_{ff}(43\,\mathrm{GHz}) = \ln \dfrac{F(\mathrm{C3})_{\mathrm{obs}}}{F(\mathrm{N1})_{\mathrm{obs}}} \sim 3.63 \\ \tau_{ff}(86\,\mathrm{GHz}) = \ln \dfrac{F(\mathrm{C3})_{\mathrm{obs}}}{F(\mathrm{N1})_{\mathrm{obs}}} \sim 2.44 \end{cases}$$

$\tau_{ff} \propto \nu^{-0.57} [\Leftrightarrow \tau_{ff} \propto \nu^{-2}$: homogeneous]

$\Rightarrow$ **clumpy absorbing medium**

2. Number density of absorbers : FFA formula

$$\tau_{ff}(\nu) = 0.46\times10^{-6}\left(\frac{L}{1\mathrm{pc}}\right)\left(\frac{n_e}{1\mathrm{cm}^{-3}}\right)^2\left(\frac{T_e}{10^4 K}\right)^{-\frac{3}{2}}\left(\frac{\nu}{1\mathrm{GHz}}\right)^{-2.1}$$

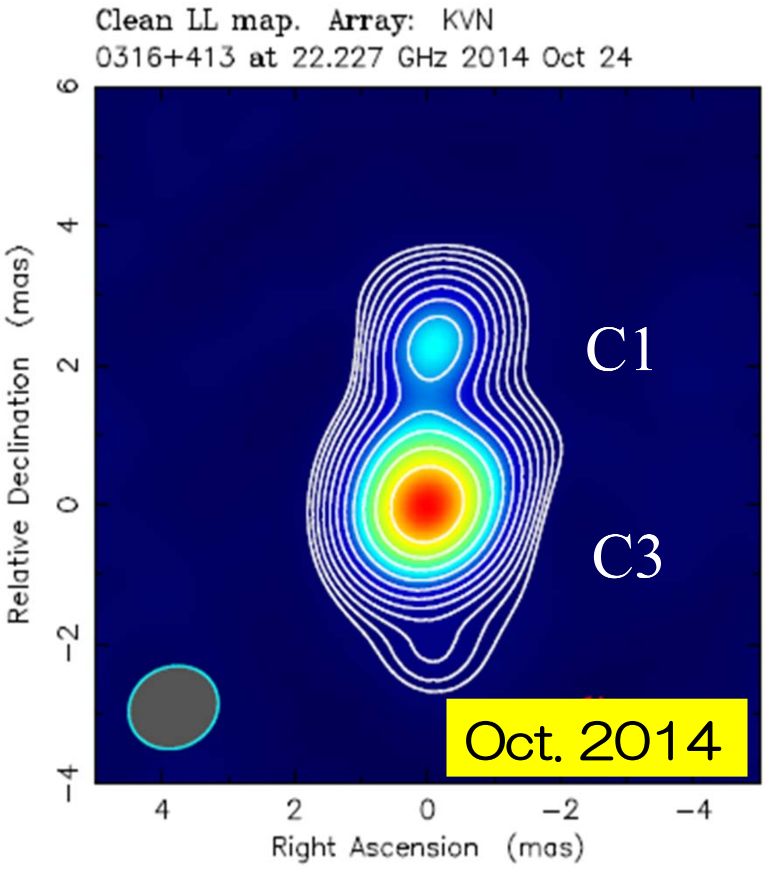
$$\Rightarrow \left(\frac{n_e}{1\mathrm{cm}^{-3}}\right)^2\left(\frac{T_e}{10^4 K}\right)^{-\frac{3}{2}} = 2.17\times10^6\left(\frac{L}{1\mathrm{pc}}\right)^{-1}\left(\frac{\nu}{1\mathrm{GHz}}\right)^{2.1}\tau_{ff}(\nu)$$

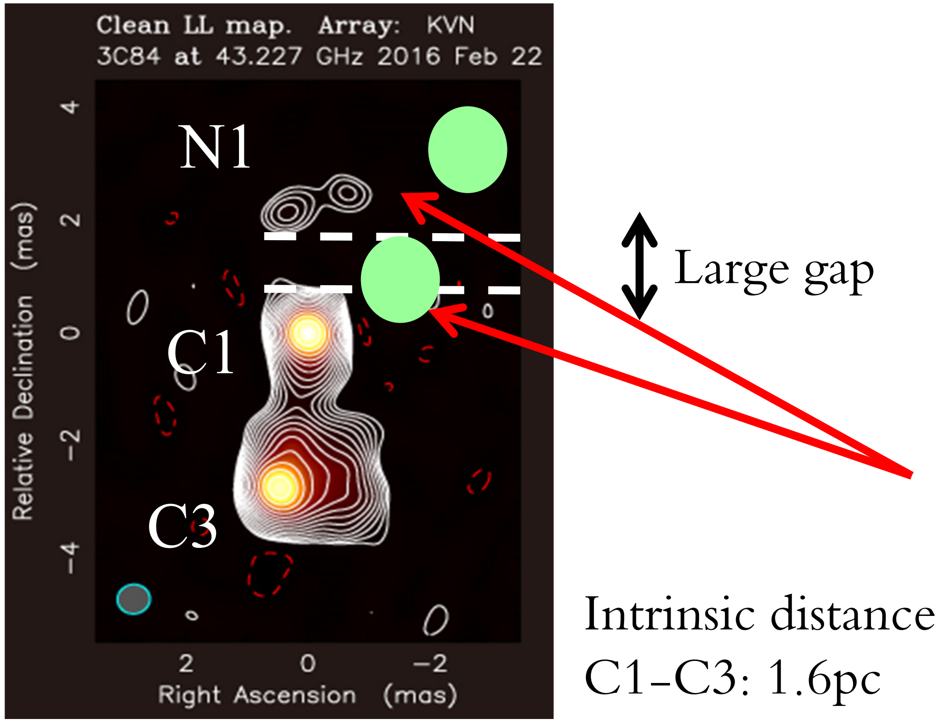
$$\boxed{\begin{cases} n_e \sim 1.4\times10^5\,\mathrm{cm}^{-3} \ @\,43\mathrm{GHz} \\ n_e \sim 2.5\times10^5\,\mathrm{cm}^{-3} \ @\,86\mathrm{GHz} \end{cases} \quad (if \quad T = 10^4 K, L = 1\mathrm{pc})}$$

Absorbing medium is clumpy？

2005～2015
N1 non-detection

2016 N1 first detection

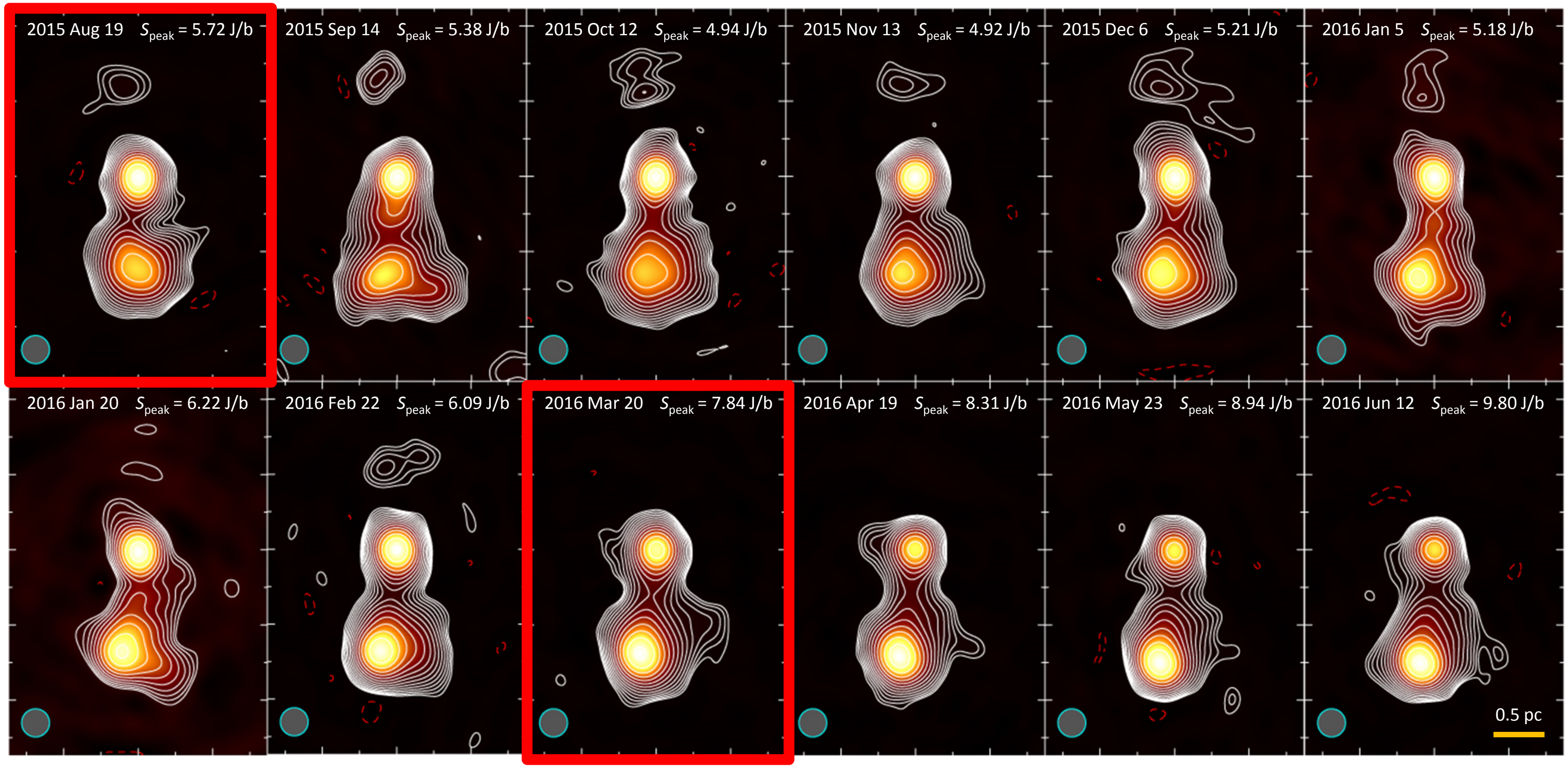




Intrinsic distance
C1–C3: 1.6pc
C1–N1: 1.4pc

τ (C1–N1) ≫ τ (N1) → ＜pc-scale clumpy dense gas clouds？

12-Epoch Images of 3C 84 at 43 GHz



Wajima, Kino, NK+

In March 2016, N1 disappears again.

→ Absorbing medium would change during ~6 month.

→ clumpy clouds pass though the line of sight ?

$$t_{\mathrm{cross}} = \frac{r_{\mathrm{clump}}}{v_h} \sim 0.6\mathrm{yr}\left(\frac{r_{\mathrm{clump}}}{0.03\mathrm{pc}}\right)\left(\frac{v_h}{0.1c}\right)^{-1}$$

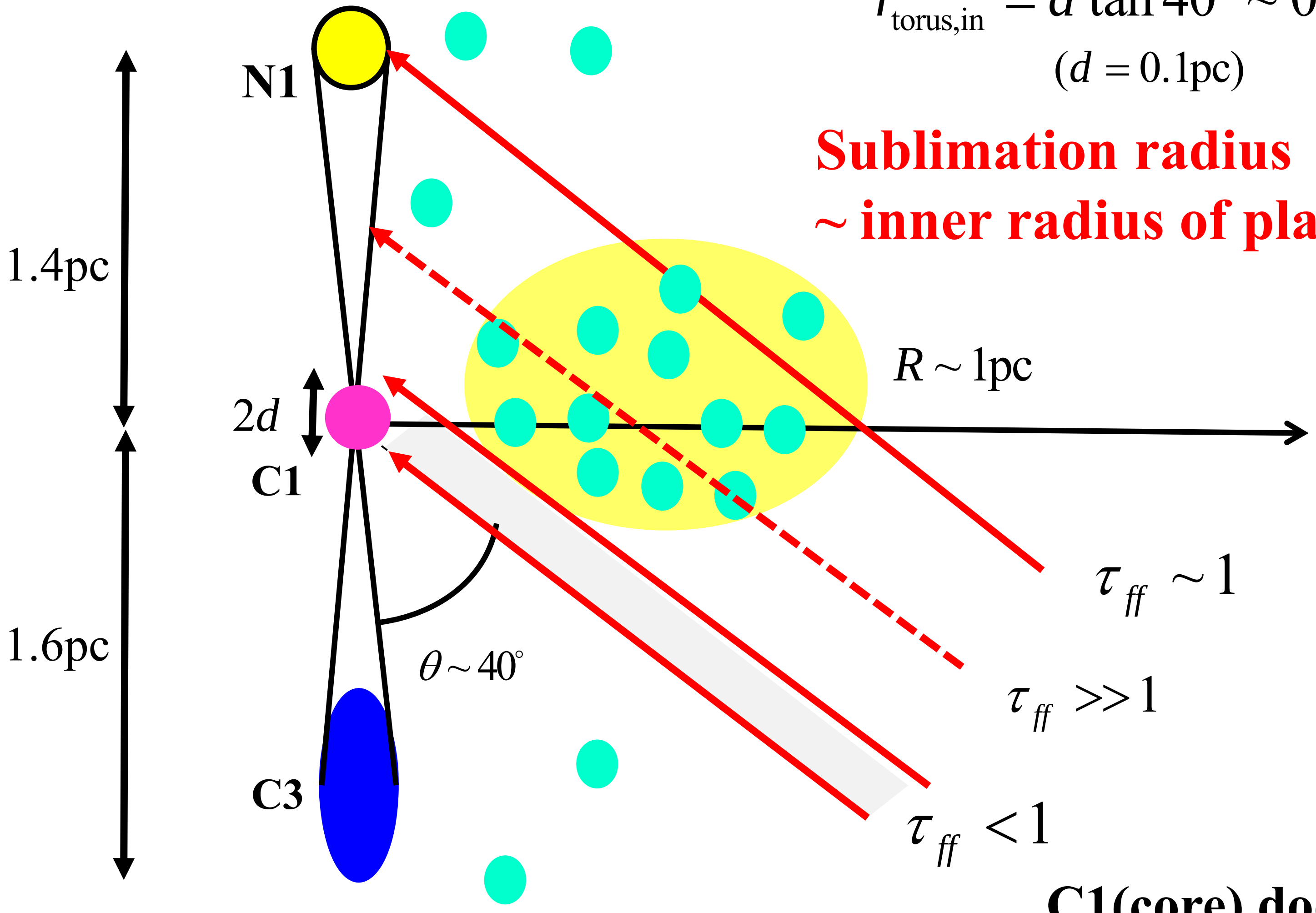
Schematic picture of 1pc clumpy plasma torus

Parsec-scale clumpy plasma torus

$$r_{\mathrm{torus,in}} = d \tan 40^\circ \sim 0.1\mathrm{pc} \sim r_{\mathrm{sub}}$$

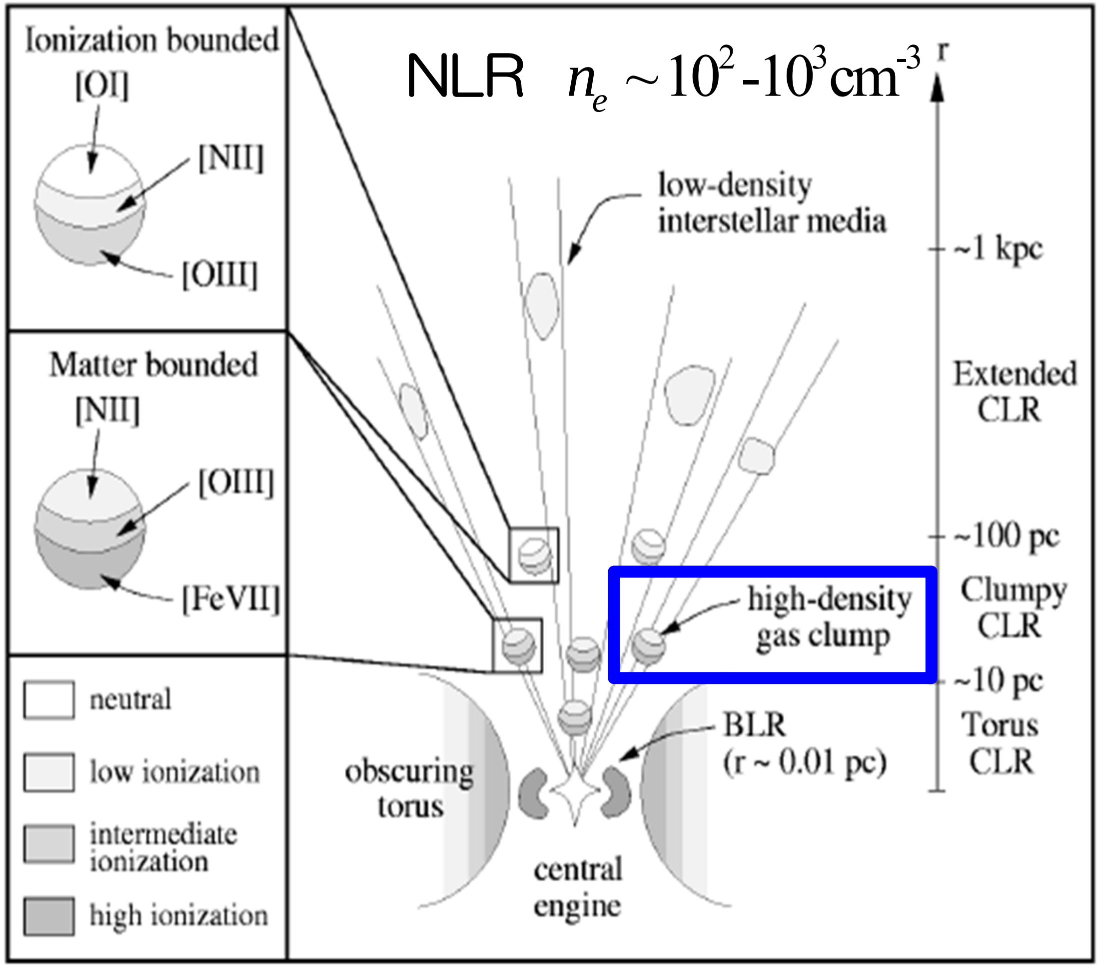
$$(d = 0.1\mathrm{pc})$$

Sublimation radius
~ inner radius of plasma torus



C1(core) does not obscure.

Have we observed the emission from ionized clumpy dense gas clouds ? Maybe yes.



Murayama & Taniguchi +98

AGN optical spectroscopy

Coronal line region clouds

$$n_e \sim 10^5\text{-}10^6 \mathrm{cm}^{-3}$$

$$r \sim 1\text{–}100 \mathrm{pc}$$

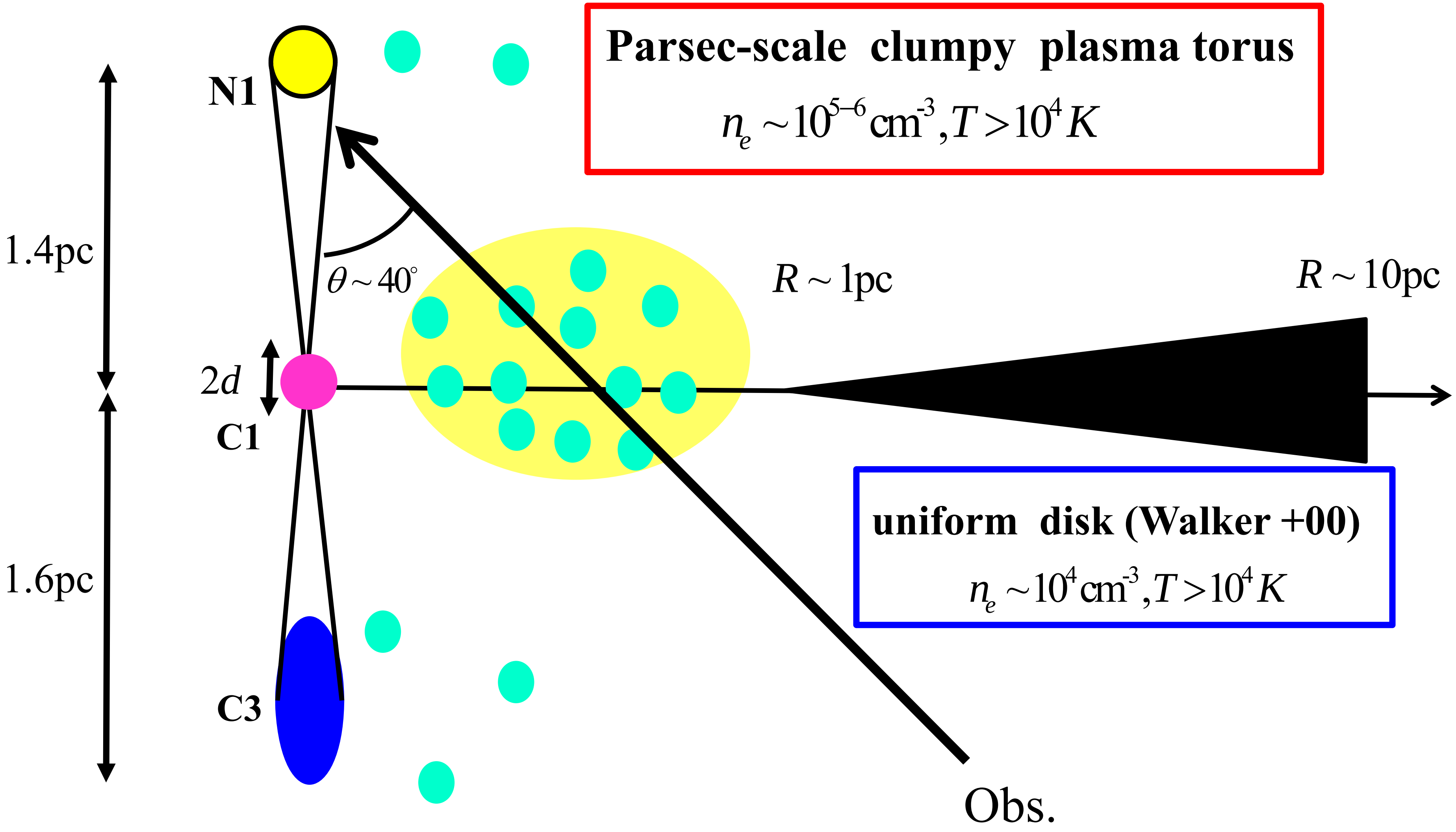
This work

$$n_e \sim 10^5 \mathrm{cm}^{-3}, T > 10^4 K$$

$$r \sim 1 \mathrm{pc}$$

Direct evidence of dense high-ionized gas clouds

Circum-nuclear structure of 3C 84 (< ~10 pc)



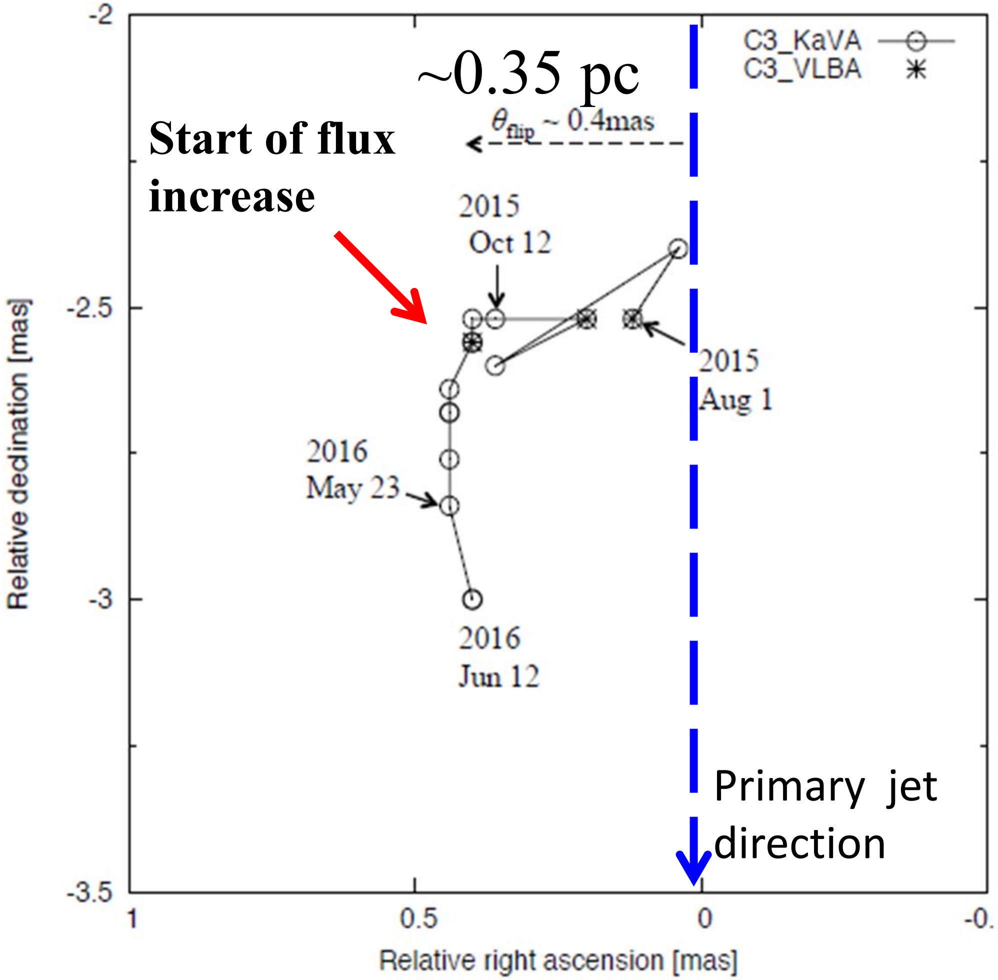
Parsec-scale clumpy plasma torus

$n_e \sim 10^{5-6}\mathrm{cm}^{-3}, T > 10^4 K$

uniform disk (Walker +00)

$n_e \sim 10^4\mathrm{cm}^{-3}, T > 10^4 K$

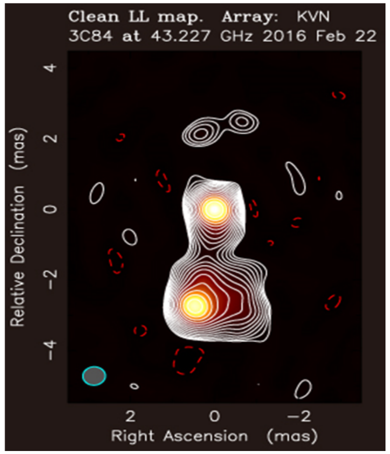
Flip of C3 peak position

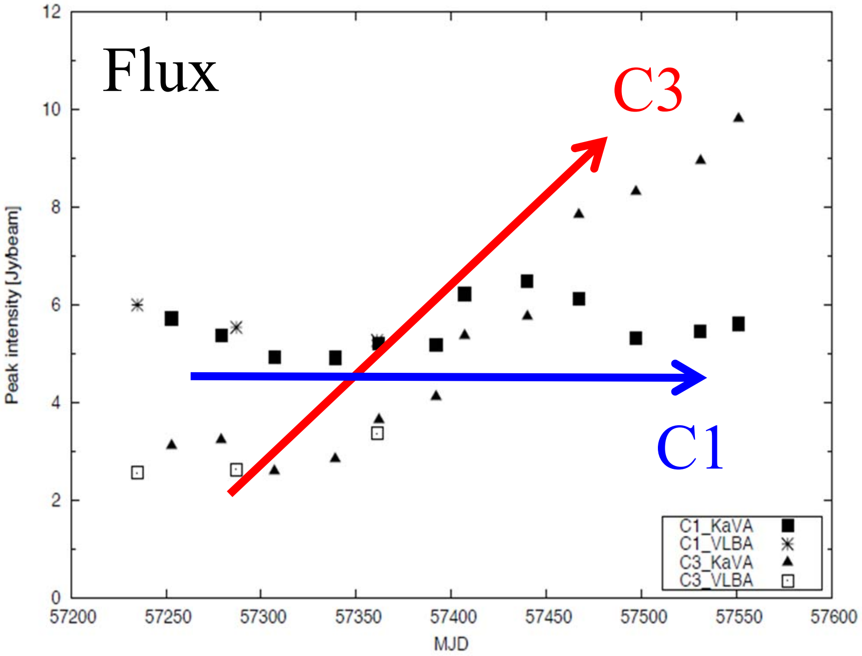


~0.35 pc

Start of flux increase

Primary jet direction





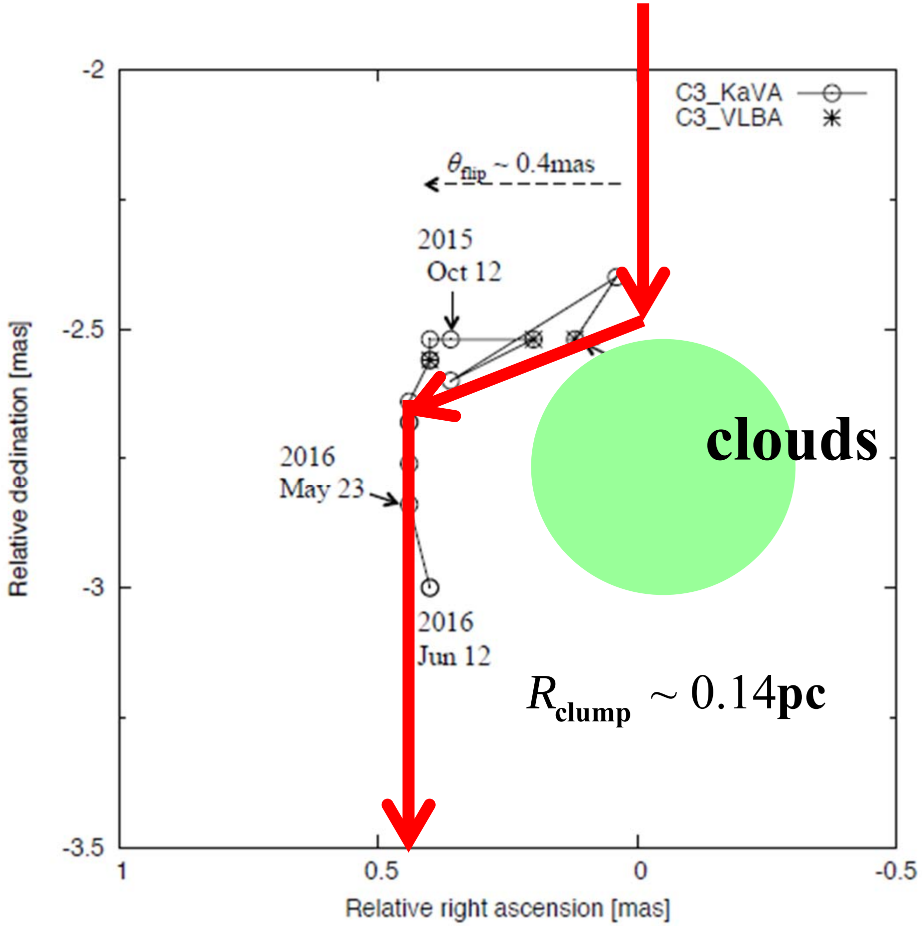
Flux

C3

C1

time

Direct evidence jet-cloud interaction



clouds

$R_{\rm clump} \sim 0.14$pc

Ram pressure balance

$$\frac{L_{\rm j}}{c} \approx \rho_{\rm cl} v_{\rm h}^2 A_{\rm cross},$$

$$0.2\ c \lesssim v_{\rm h} \lesssim 0.3\ c,$$

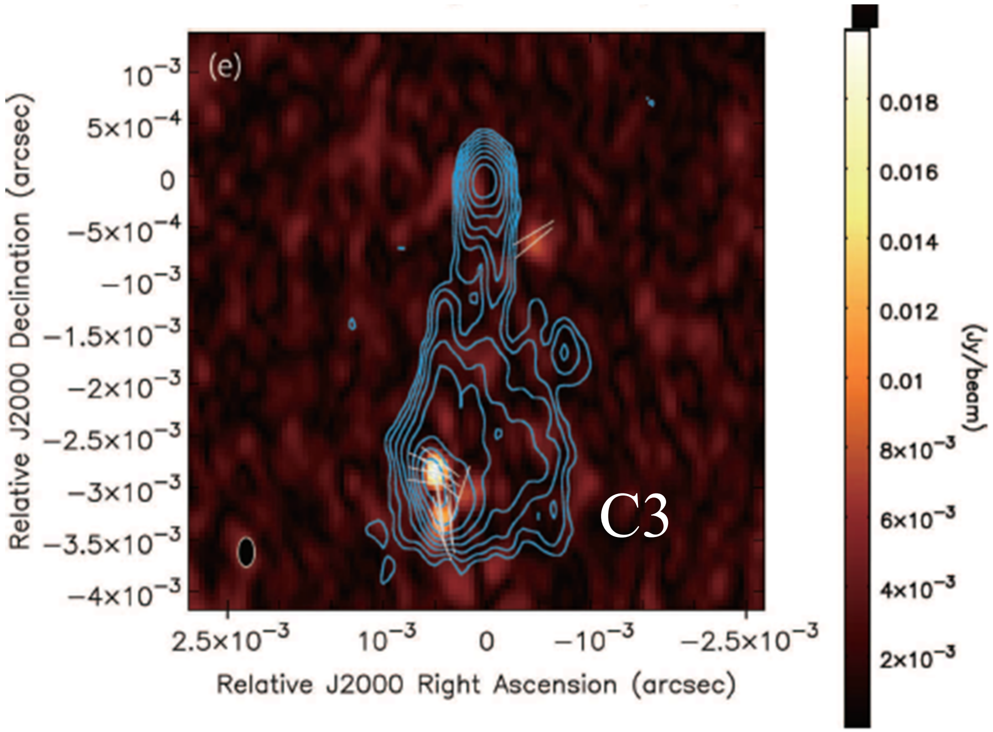
$$A_{\rm cross} \approx 2\pi \times 10^{35} \left(\frac{\theta_{\rm flip}}{0.4\ \rm mas}\right)^2\ \rm cm^{-2}$$

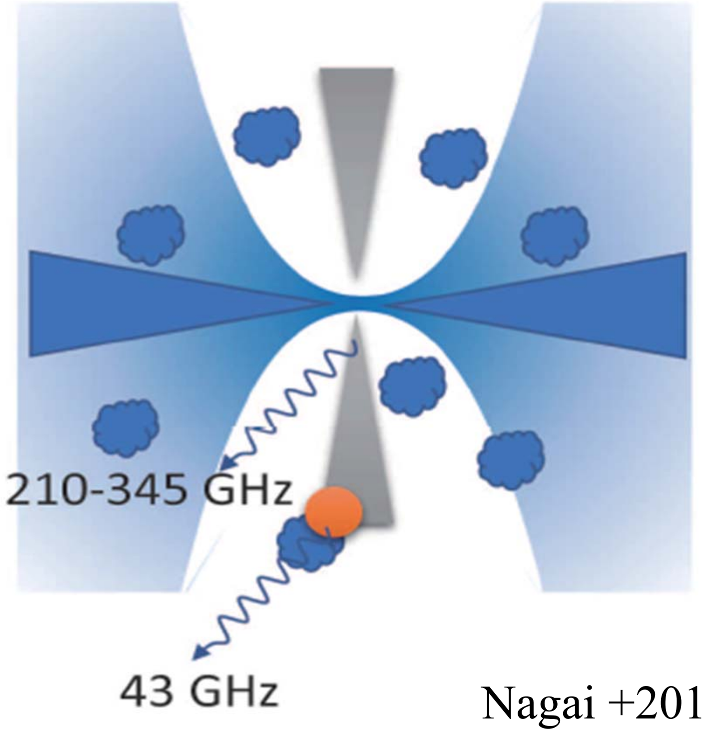
$$1 \times 10^{45}\ {\rm erg\ s} \lesssim L_{\rm j} \lesssim 2 \times 10^{47}\ {\rm erg\ s}$$

Number density of gas clouds

$$2 \times 10^4\ {\rm cm}^{-3} \lesssim n_{\rm cl} \lesssim 2 \times 10^5\ {\rm cm}^{-3}$$

Enhancement of linear polarization





Nagai +2017

$$RM_{\rm obs} = \left(6.3 \pm 1.9\right) \times 10^{5} [\mathrm{rad\ m}^{-2}]$$

Main component s in C3 is consistent with hot spot (terminal shock).

Clumpy medium interacting with jets is responsible for the observed rotation measure.

$$n_e \sim 10^4\,\mathrm{cm}^{-3}, R_{\rm clump} \sim 0.03\mathrm{pc}$$

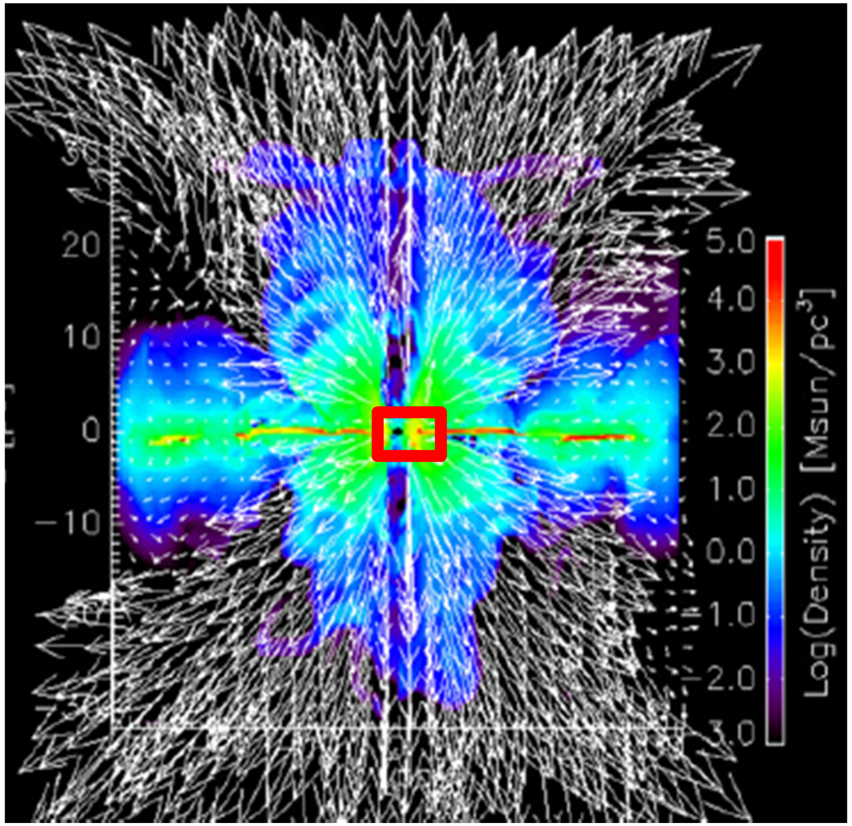
Origin of gas clouds

1. Ionized gas (T >10^4 K) clouds (NLR clouds)

$$2 \times 10^4 \ \mathrm{cm}^{-3} \lesssim n_{\rm cl} \lesssim 2 \times 10^5 \ \mathrm{cm}^{-3}$$

The clumpy clouds within ~1pc plasma torus

Clumpy clouds expected by FFA



The radiation feedback drives a "fountain," that is, a vertical circulation of gas in 1-10pc.

Ionized outflow interact with AGN jets ?

Radiation-driven fountain model (Wada +2012)

2. Self-gravitating cold gas clouds

$$M_{\mathrm{clump,obs}} = 3M_{\mathrm{sun}}\left(\frac{n_c}{10^4\,\mathrm{cm}^{-3}}\right)\left(\frac{R_{\mathrm{clump}}}{0.14\mathrm{pc}}\right)^3$$

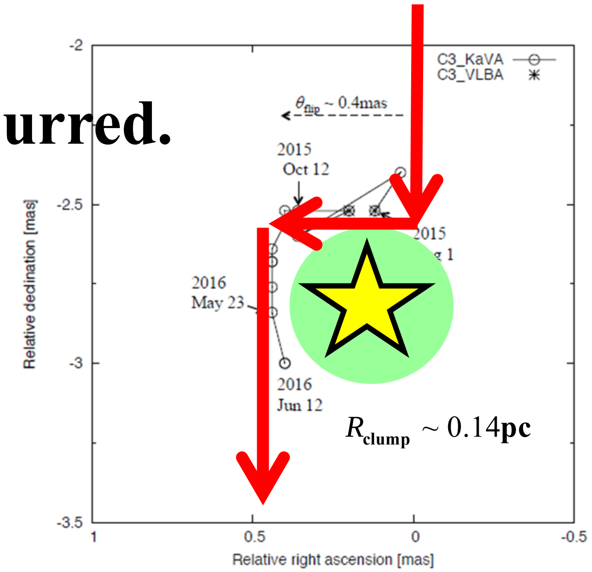
$$M_{\mathrm{clump,crit}} = \frac{\pi c_s^{\,2}}{3G} r_{\mathrm{clump}} = 0.2M_{\mathrm{sun}}\left(\frac{c_s}{1\mathrm{km/s}}\right)^3\left(\frac{r}{1\mathrm{pc}}\right)^{1.5}\left(\frac{M_{\mathrm{BH}}}{10^9 M_{\mathrm{sun}}}\right)^{-0.5}$$

$$M_{\mathrm{clump,crit}} < M_{\mathrm{clump,obs}}$$

Self-gravitating cloud if T$_{\mathrm{gas}}$ < 100K

The AGN jet-induced SF might be occurred.

It is essential to explore whether cold gas clouds coexist, together with hot/warm gas by ALMA.



Summary

- **FFA of new born AGN jets**

Discovery of ~ 1pc clumpy plasma torus
Consistent with X-ray/IR obscuration ?

- **Position flip of AGN jets**

Direct evidence of AGN jet-clump interaction
NLR clouds or self-gravitating clouds