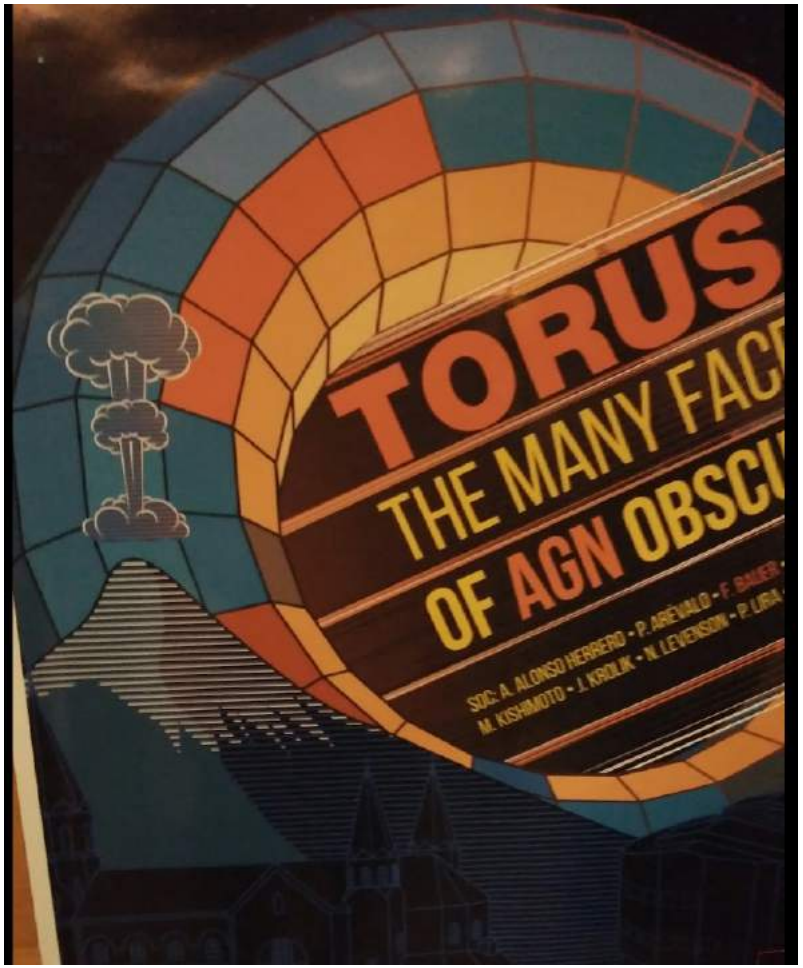
# Dynamical pictures of tori and observations of the multi-phase ISM




**WADA Keiichi**

Kagoshima university, Japan

Ryosuke Fukushige
Kensuke Yonekura
Marc Schartmann (MPE)
Takuma Izumi (NAOJ)
Tohru Nagao (Ehime)
Rowin Meijerink (Leiden)

**Radiation-driven Fountain and Origin of Torus around Active Galactic Nuclei** Wada (2012)

radiation hydro model

**Multi-phase Nature of a Radiation-driven Fountain with Nuclear Starburst in a Low-mass Active Galactic Nucleus**

KW, Schartmann, & Meijerink (2016)

SED fitting for Circinus

## Multi-phase Gas in the Circinus Galaxy

I. Non-LTE Calculations of **CO Lines**

X-factor, line ratios

KW, Fukushige, Izumi, & Tomisaka (2016) ApJ 852, 88

II. A Novel View of the **Molecular and Atomic Obscuring Structures** Revealed with ALMA

CO(3-2), [CI]

Izumi, KW, Fukushige, Hamamura & Kohno, ApJ in press

III. Structures of the Nuclear **Ionized Gas**

NLRs: [OIII], [NII],…

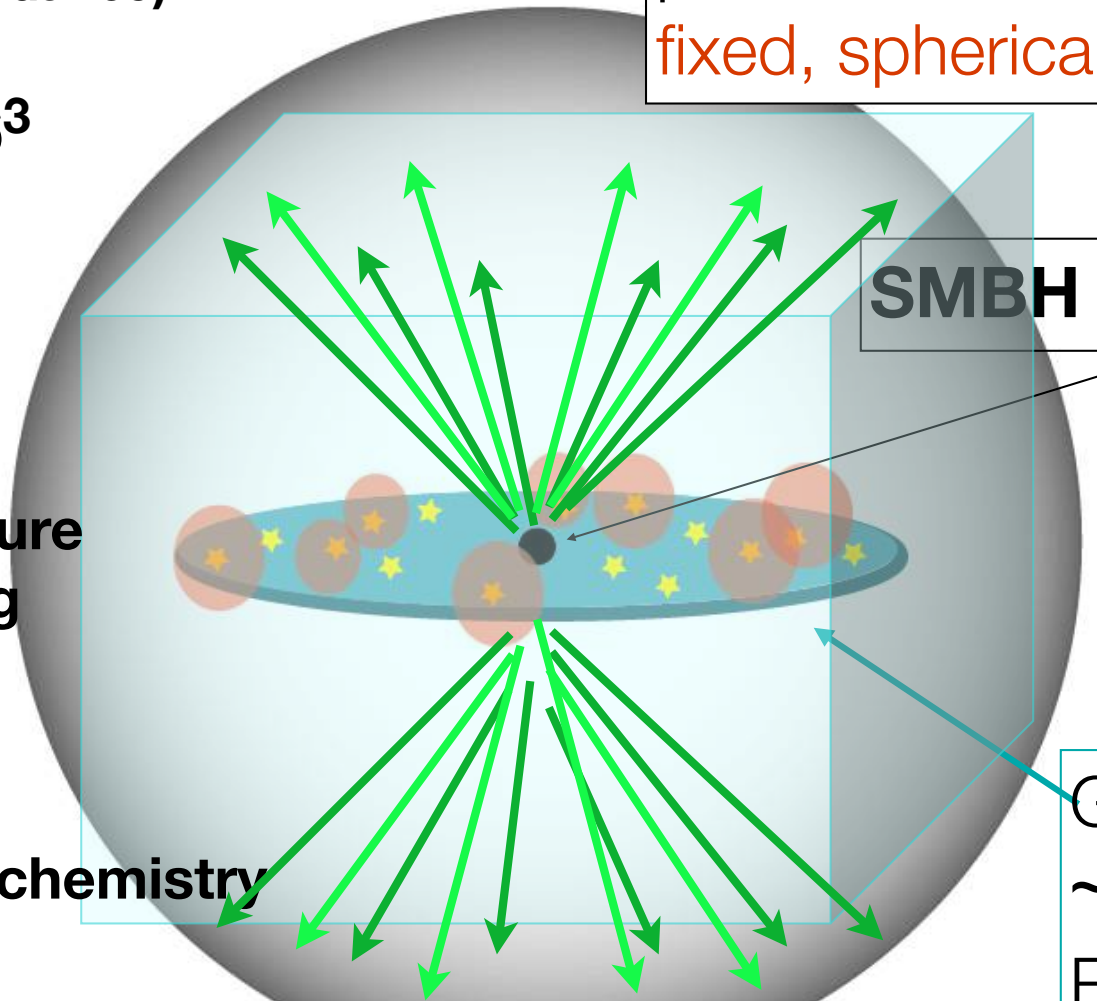
KW, Yonekura & Nagao, ApJ in press

# 3-D Radiative Hydrodynamics of a gas disk around a SMBH

**Code: RHD.*(Wada12) ,**
**based on HD.* (Wada+09)**

***Uniform grid $256^3$**
***Ray tracing**
**($256^3$ rays),**

- **Self-gravity**
- **Radiation pressure**
- **Radiative cooling**
- **X-ray heating**
- **uniform FUV**
- **SNe feedback**
- **non-equilibrium chemistry**



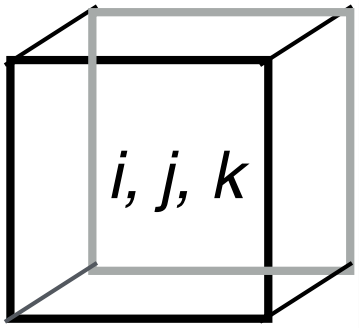
potential:
fixed, spherically symmetric

**SMBH $10^{6\text{-}9}$ $M_{sun}$**

Gas disk
~0.1-1.0 $M_{BH}$
R=16-32 pc

$$L_{UV}(\theta) \propto \cos\theta(1+2\cos\theta)$$

# *Chemo*-Radiation Hydrodynamics



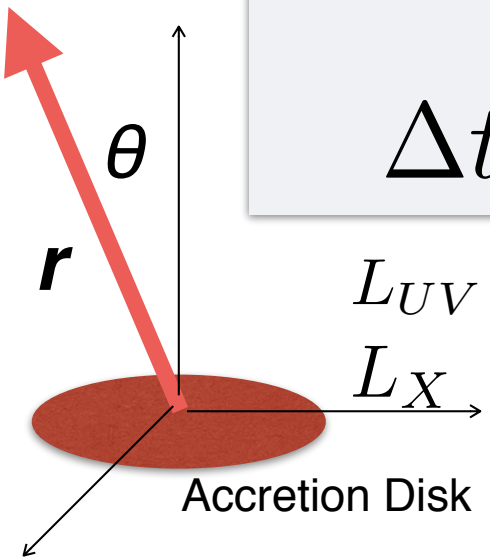

$$T_{gas,i,j,k}$$

$$T_{dust,i,j,k}$$

$$n_{i,j,k}$$

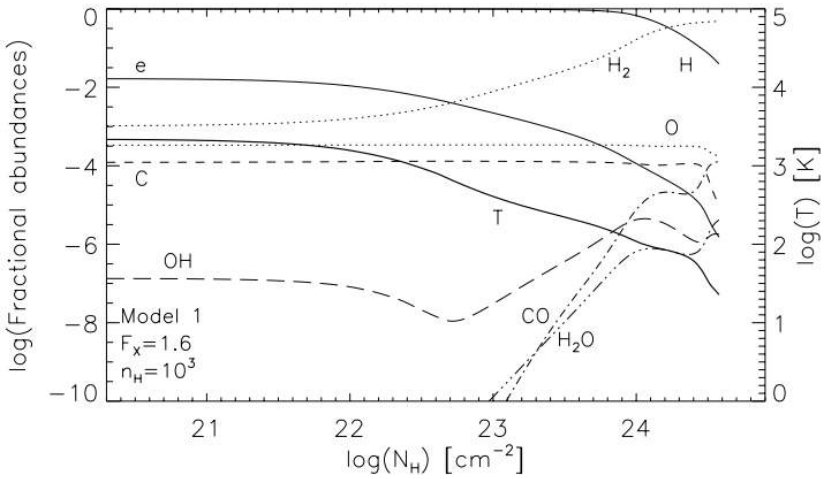
$$\xi_{ijk} = \frac{L_X}{r_{ijk}^2 n_{ijk}} e^{-\tau_{ijk}}$$

$$\Delta t$$




$$L_{UV}(\theta) \propto \cos\theta(1 + 2\cos\theta)$$

$L_X$ spherical




Non-equilibrium chemistr
for 25 species

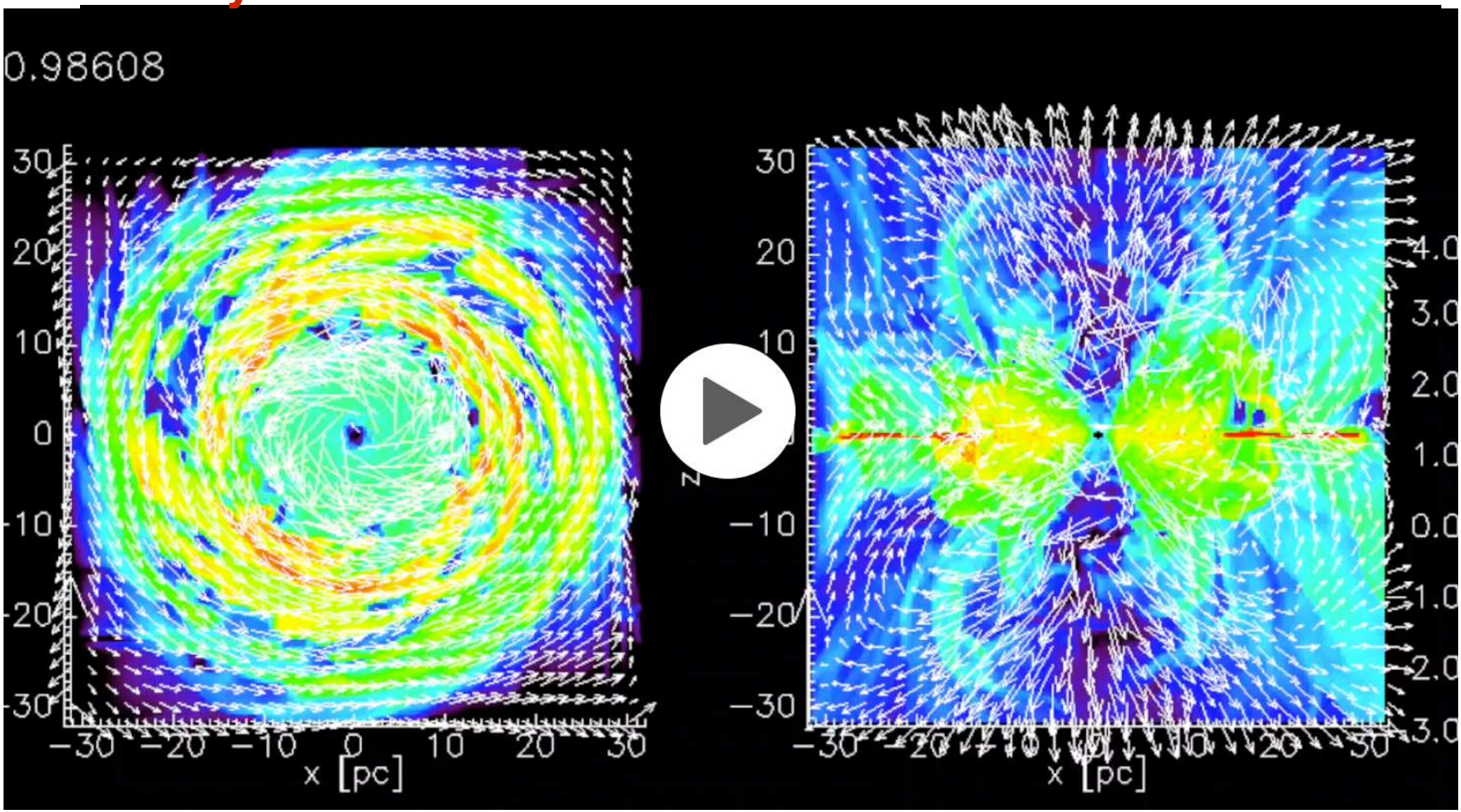
Ádámkovics, Glassgold, Meijerink (2011)

Meijerink , Spaans (2005)

H, H2, H+, H2+, H3+, H-, e-, O, O+, O2, O2+, O2H+, OH, OH+, H2O, H2O+, H3O+, C, C+, CO, Na, Na+, He, He+

# An example of fountain flow and formation of a “torus-like” structure

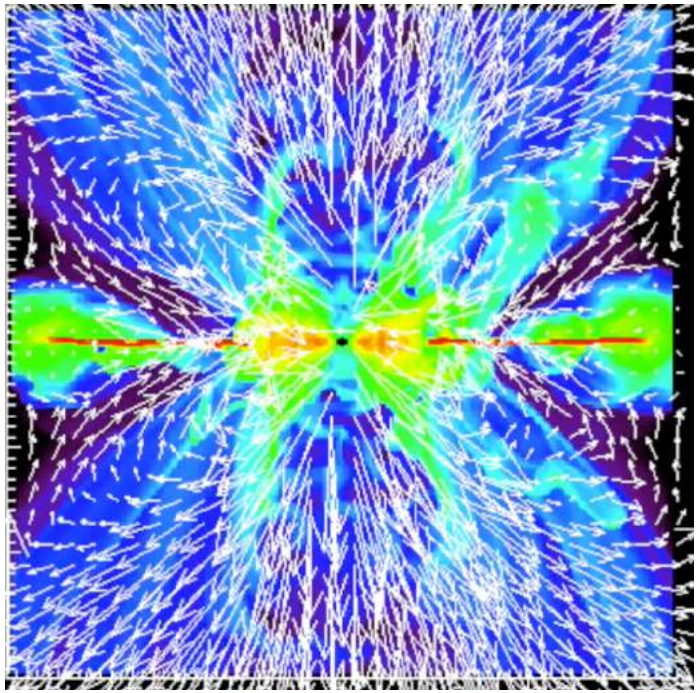
**density**



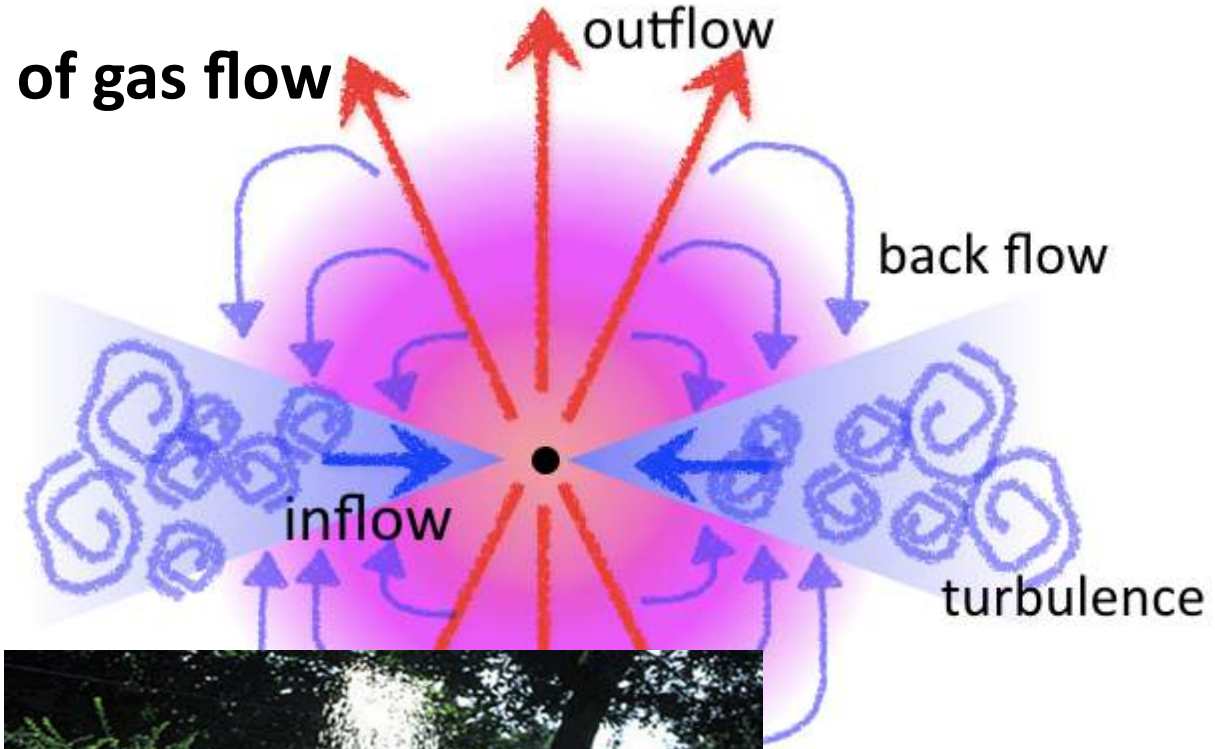

Wada (2012)

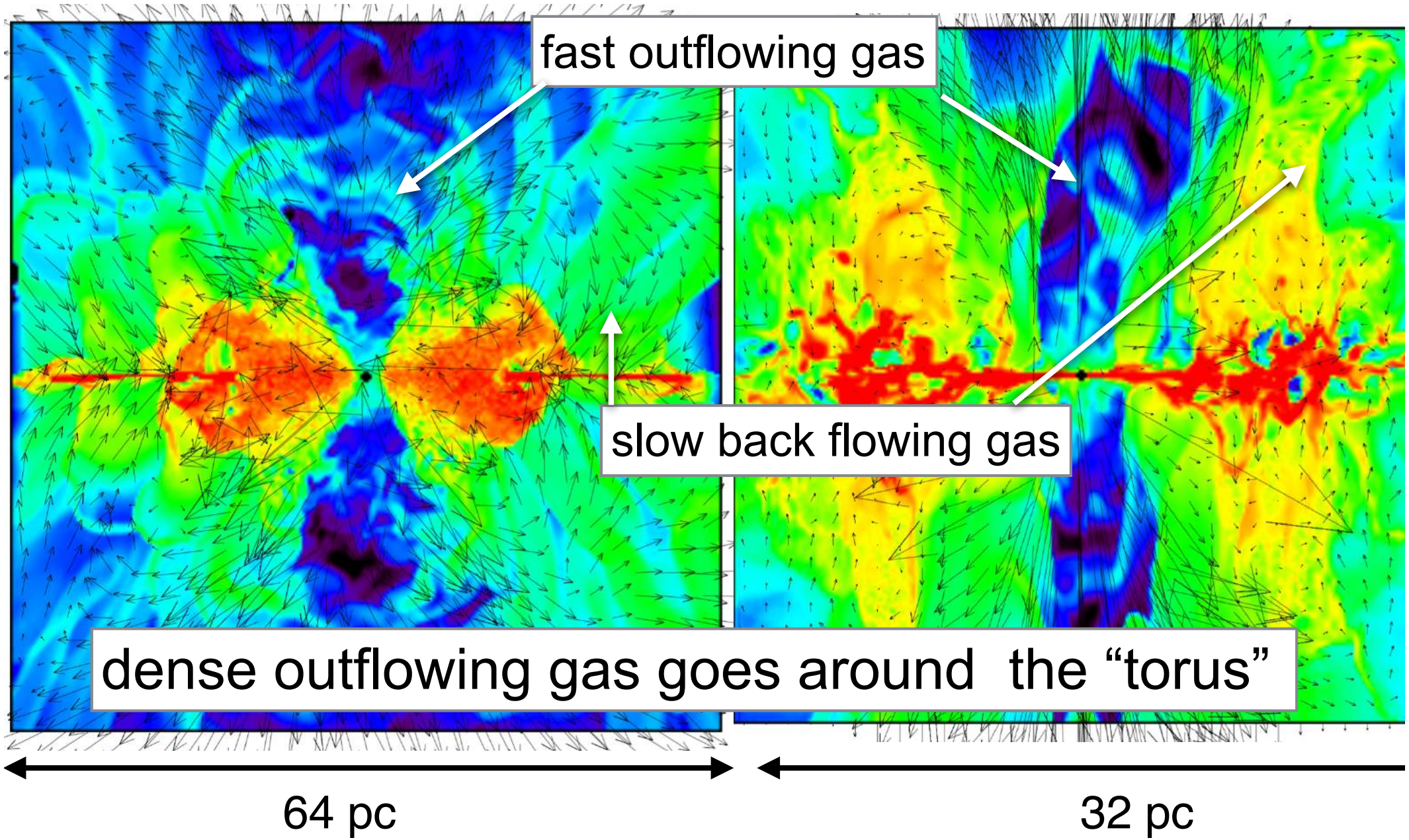
# Radiation-driven fountain

- outflow, “thick disk”, and “thin disk” are not independent, not static
- A quasi-steady circulation of gas flow

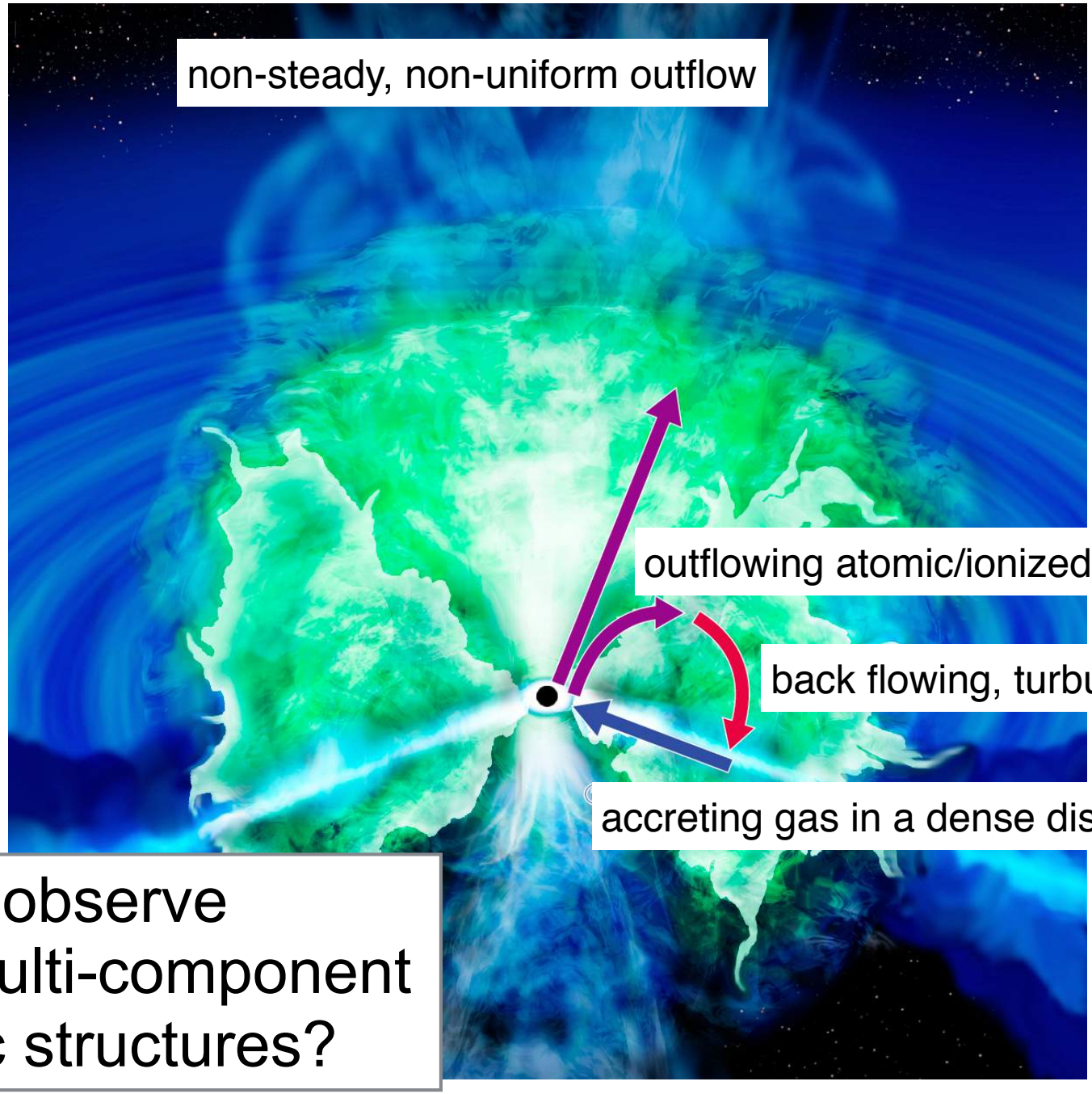


Wada (2012)





M_BH = 10^7 Msun
w/o supernova feedback
M_BH = 10^6 Msun
with supernova feedback
fast outflowing gas
slow back flowing gas
dense outflowing gas goes around the “torus”
64 pc
32 pc

# A “torus” is formed as a part of a radiation-driven fountain flow



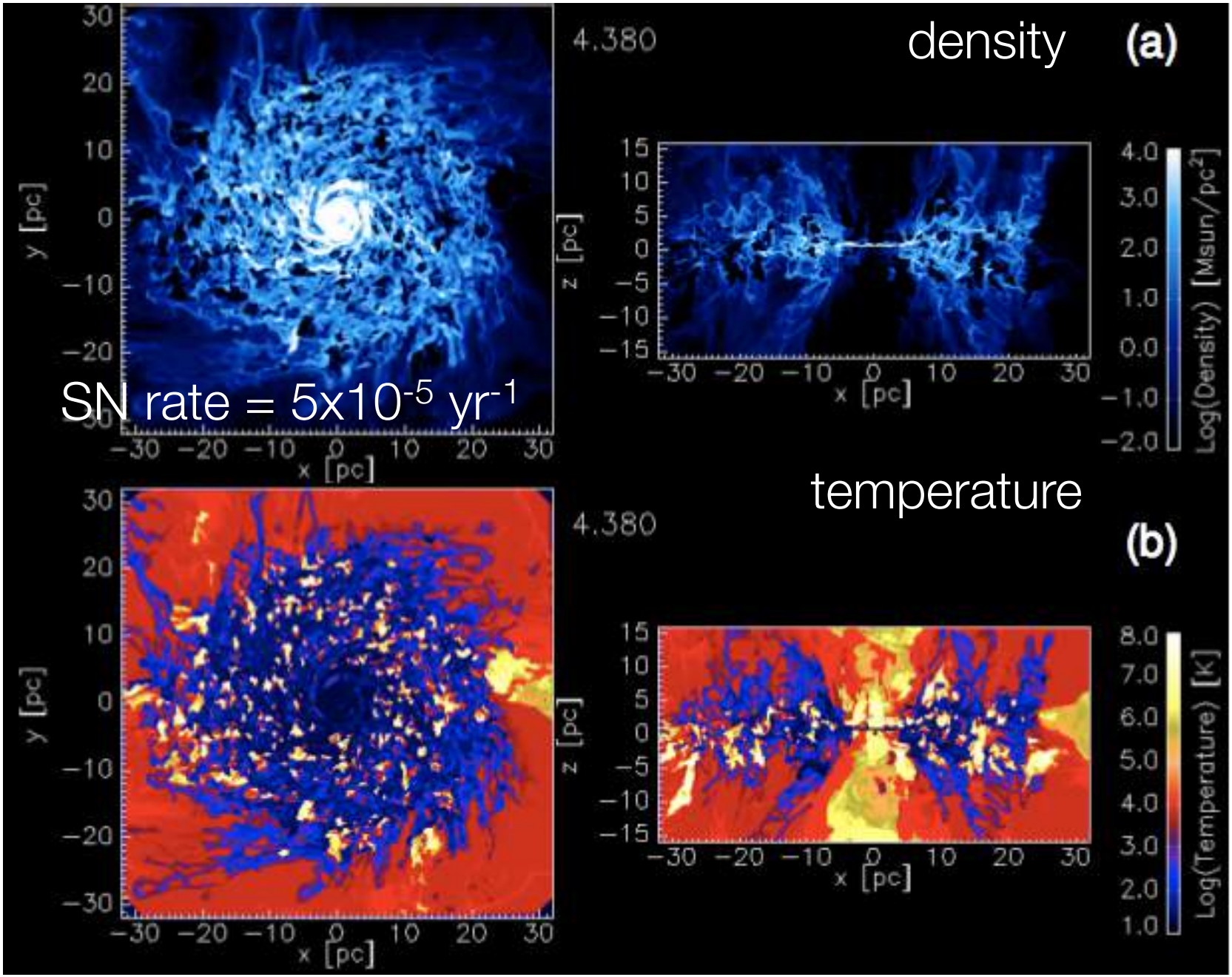

Can we observe these multi-component dynamic structures?

# Feedback on pc-10 pc scale: Supernova

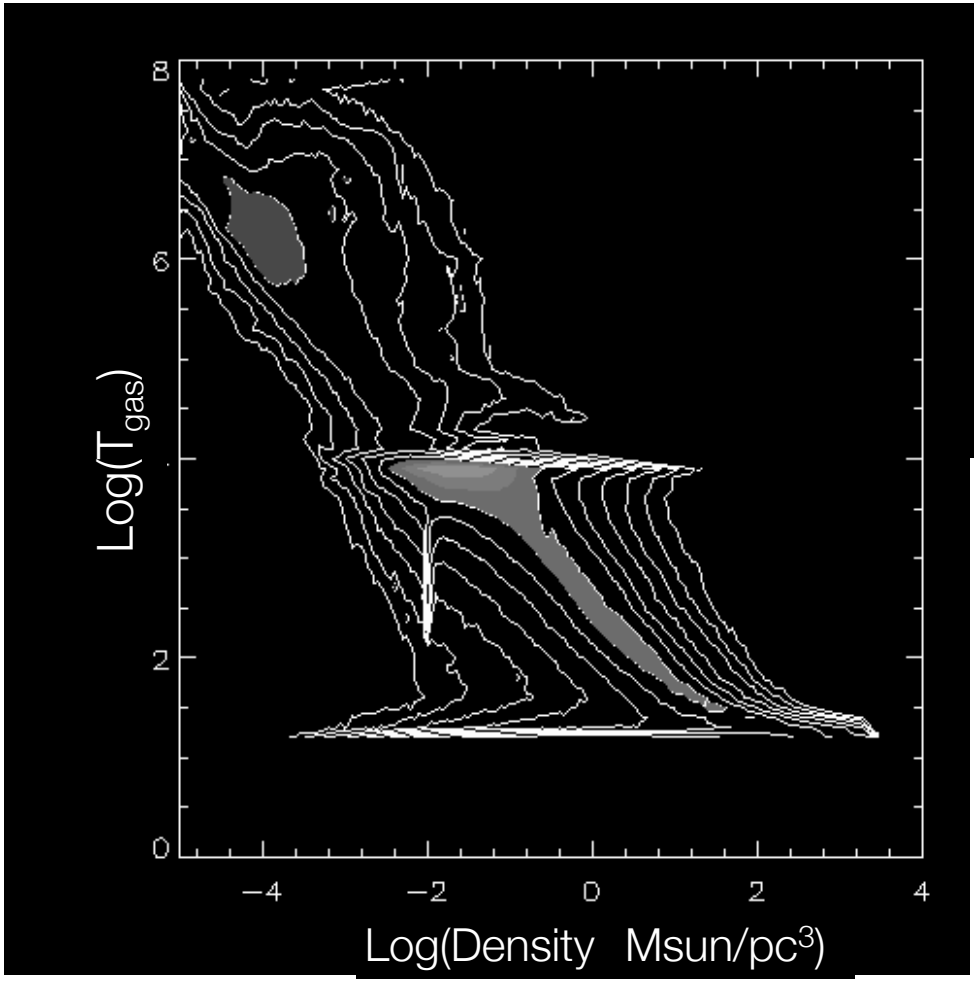
KW, Papadopoulos, Spaans (2009)

$M_{BH} = 1.3 \times 10^7\ M_{sun}$

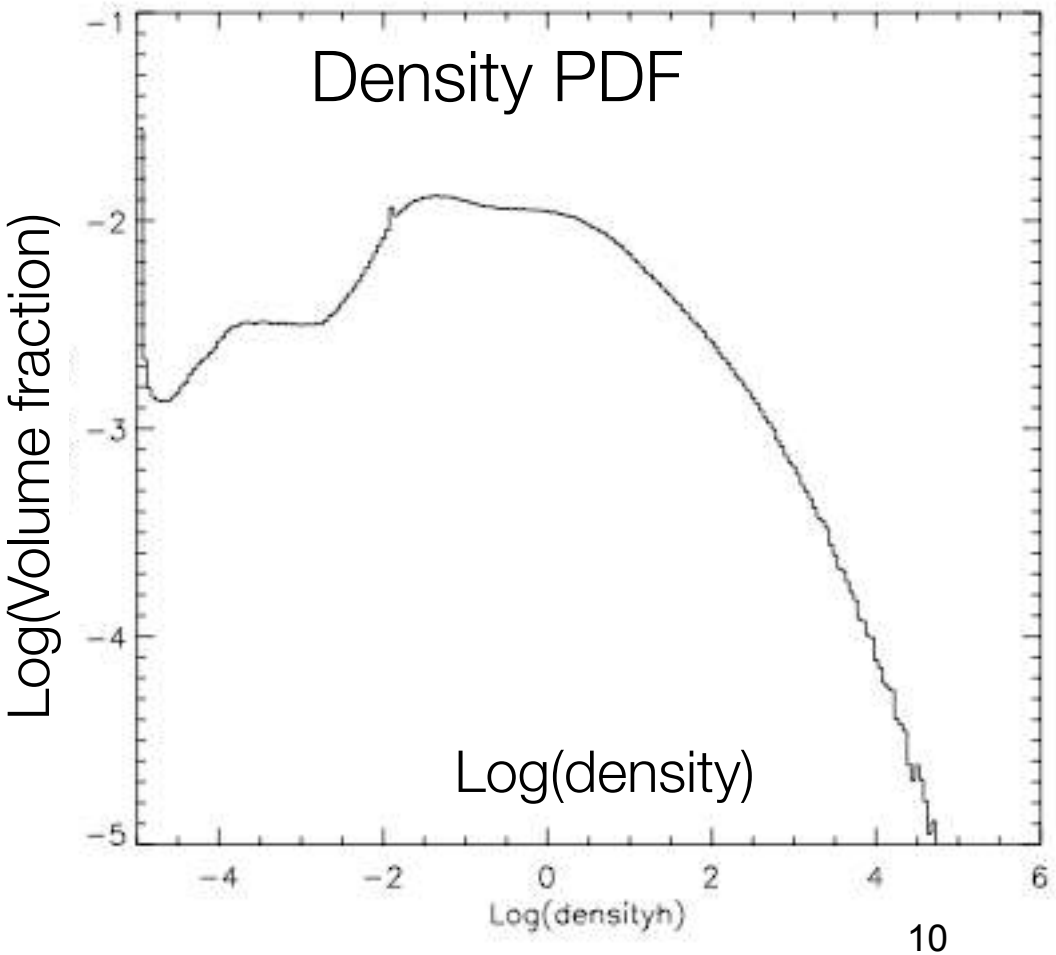
$M_{gas} = 6 \times 10^6\ M_{sun}$



# ISM on 10s pc scale: Inhomogeneous and multi-phase. Log-normal PDF in high density gas




- high & low density gases are NOT independent
- "clumpy torus" model



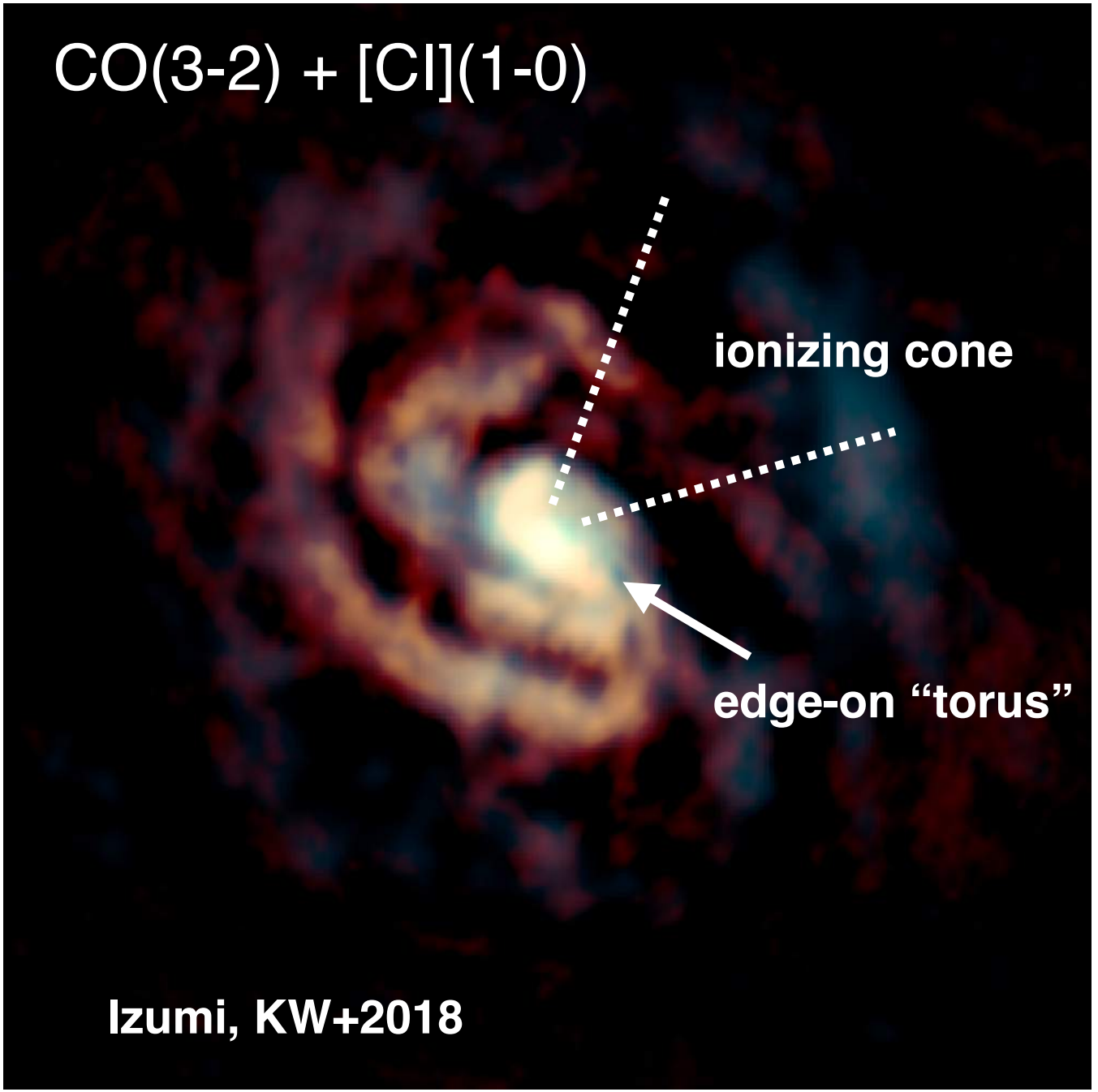
# Circinus galaxy (Sy2 at 4Mpc)

**The Circinus Galaxy**
**Credit:** Andrew S. Wilson (U. Maryland) et al., WFPC2, HST, NASA

yellow: i-band
red: Hα

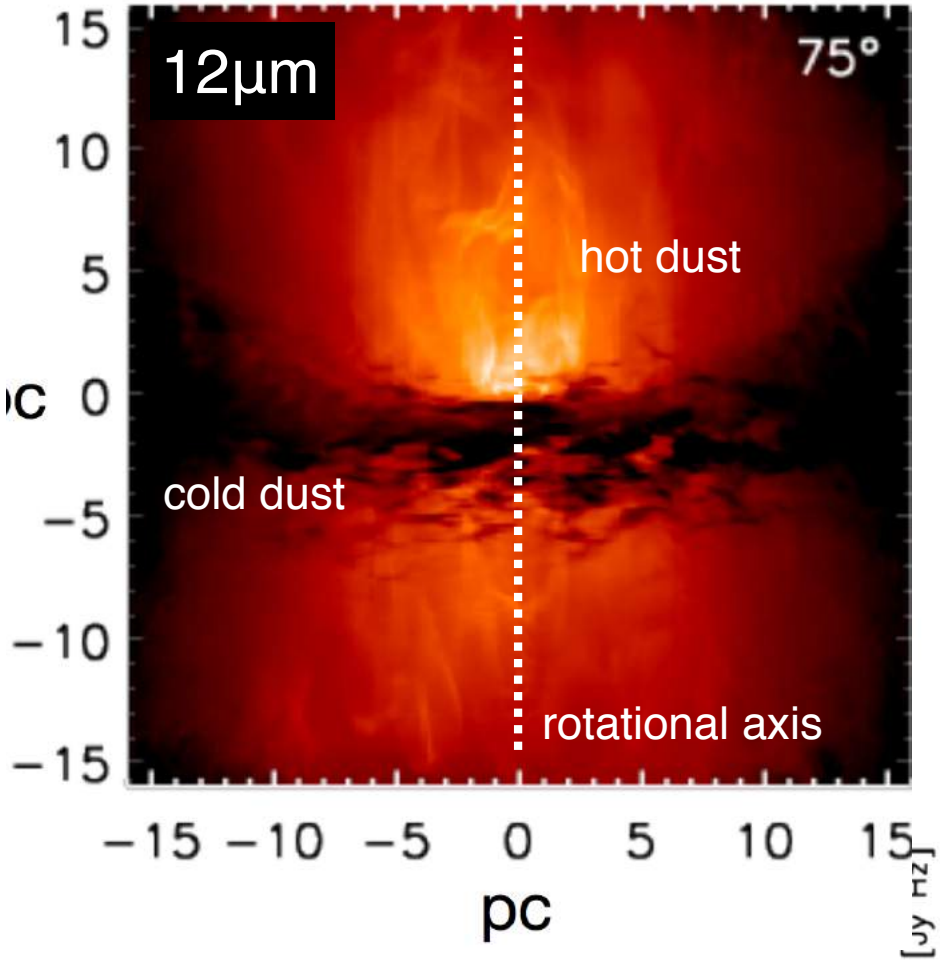
# What we observed by ALMA is edge-on disk + spiral





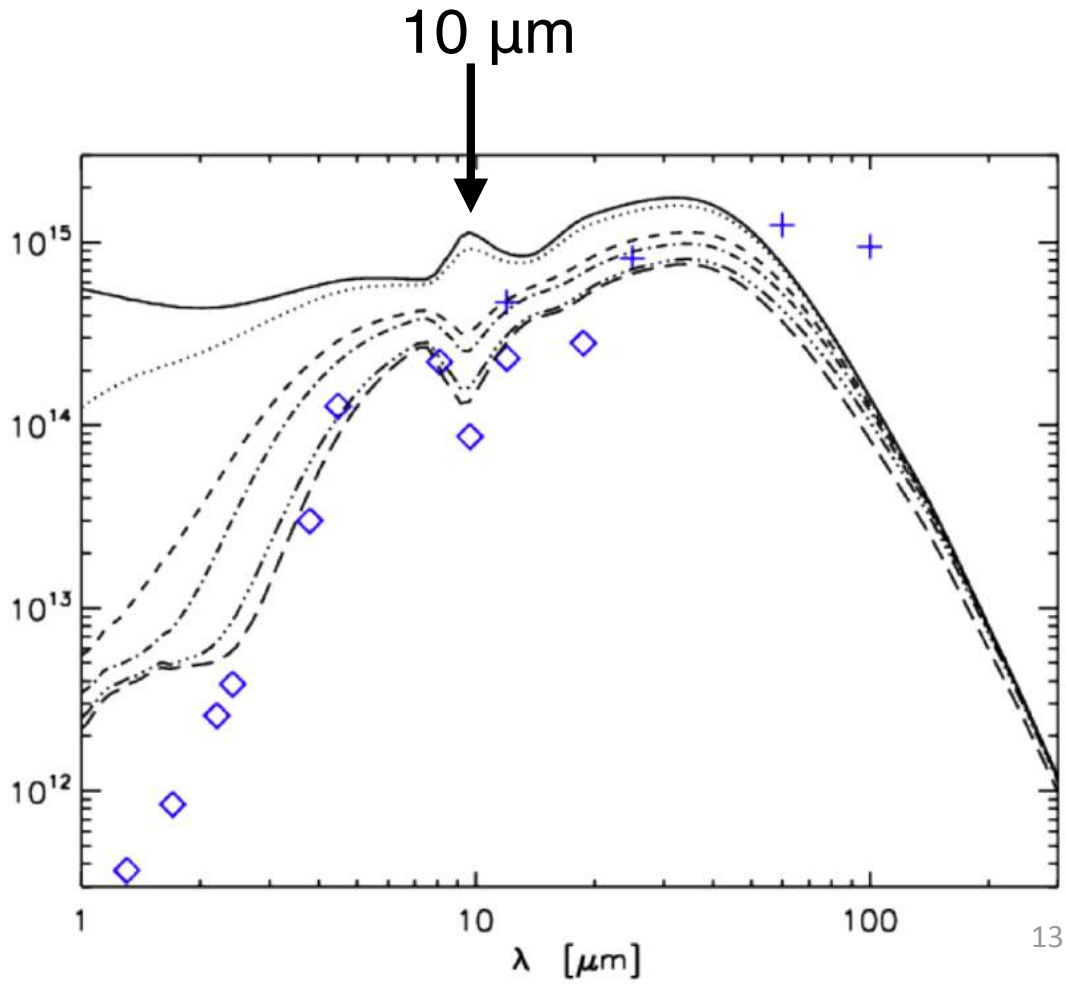
# Case study: Circinus galaxy

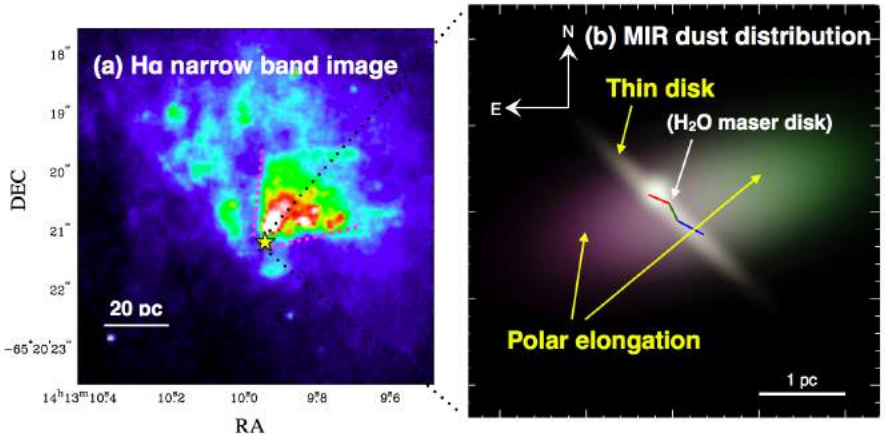
**KW, Schartmann, & Meijerink (2016)**




SED and 10 μm absorption are reproduced for **viewing angle > 75deg**

**Nuclear disk should be close to edge-on!**



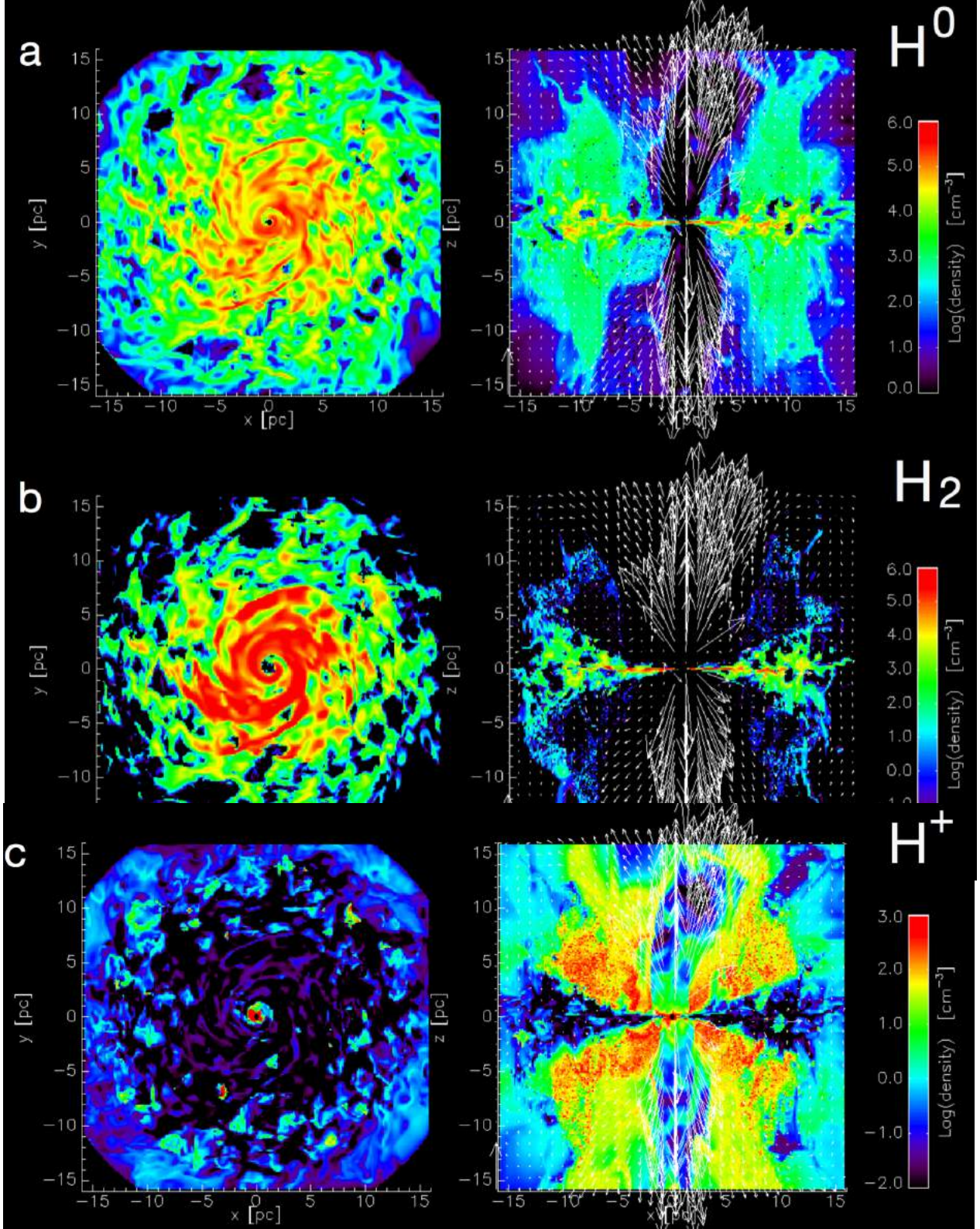



# Three phases of hydrogen

Model for
Circus galaxy

**XDR chemistry is included**

KW, Schartmann,
Meijerink (2016)



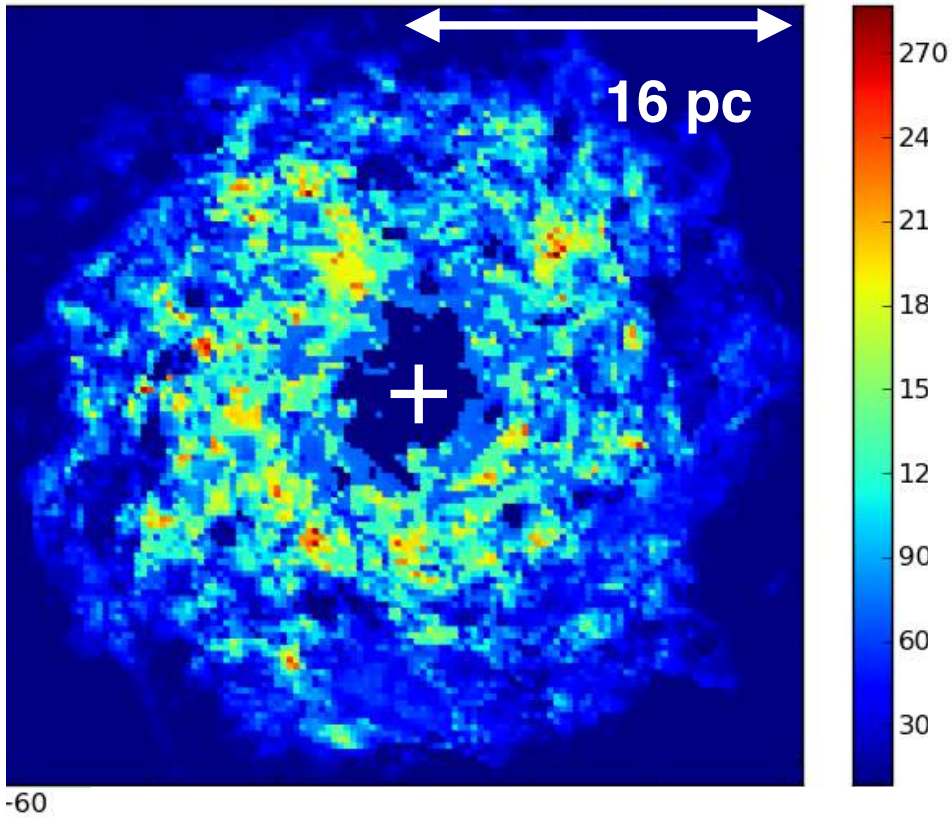
# cold molecular gas in Circinus

**KW, Fukushige, Izumi, Tomisaka (2018)**

## **3D non-LTE radiative transfer** for CO, CI, …,

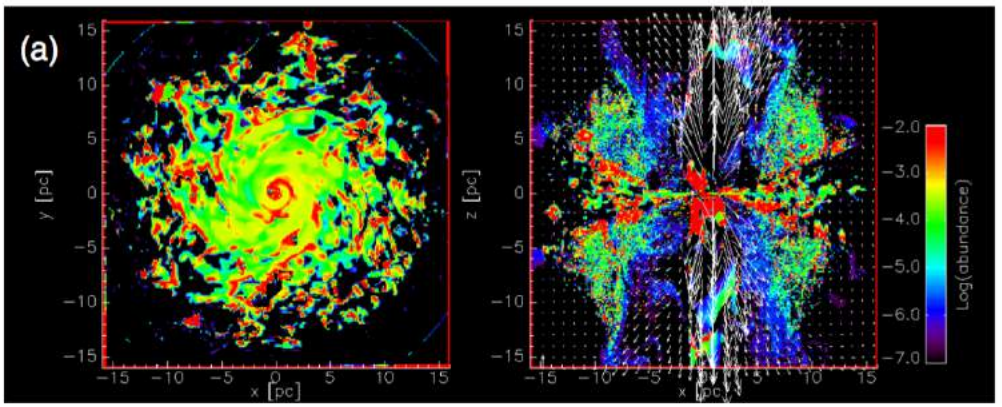
based on Wada & Tomisaka (2005): Monte Carlo based code

## **CO (3-2) integrated intensity map**, face-on

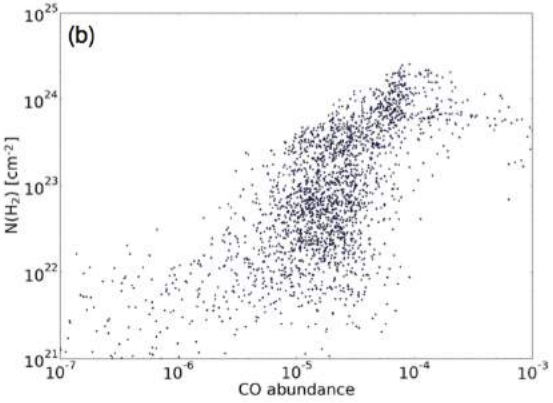



**resolution: 0.25 pc**

**CO abundance**




**density**



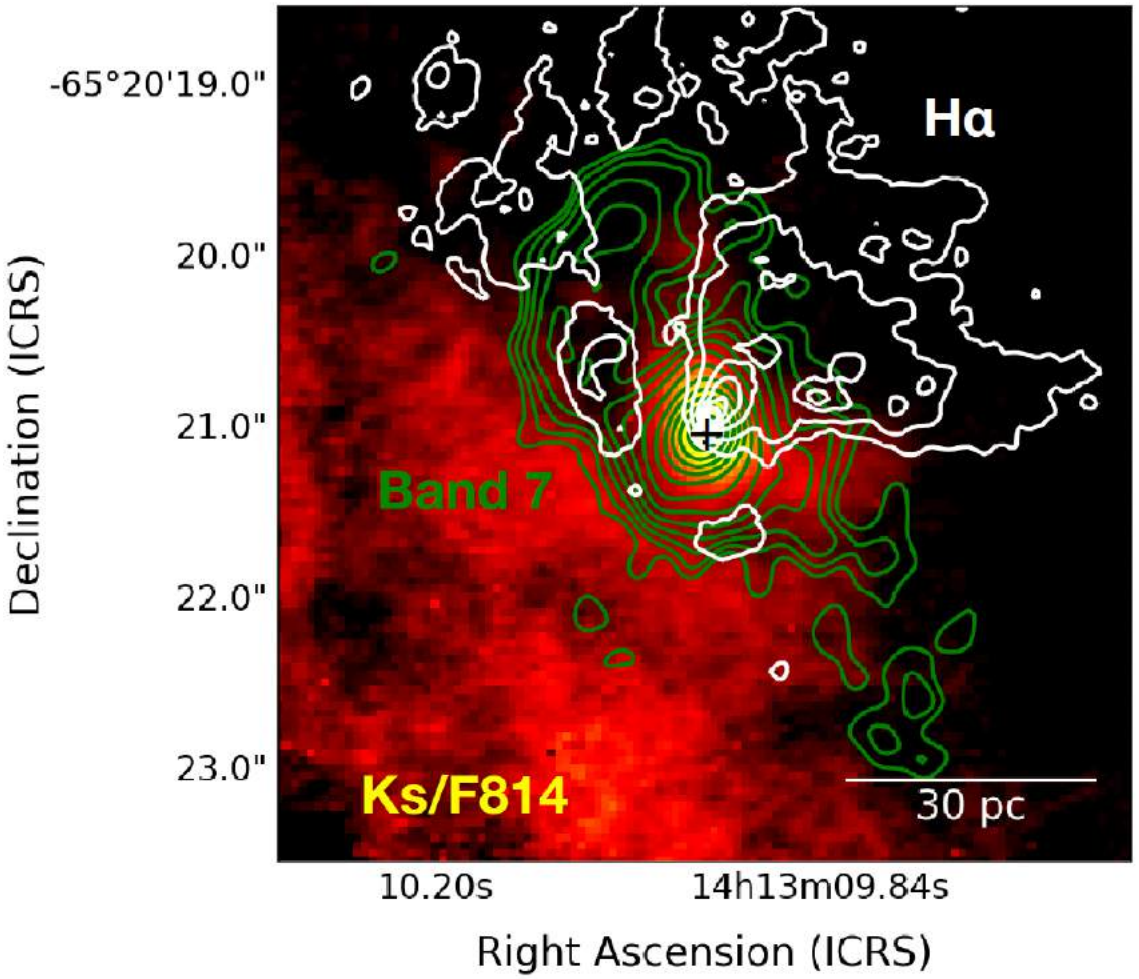

**CO abundance**

# Origin of NLR in AGN

Circinus torus? + funnel of ionized gas on 10 pc

extinction map (K/I-band) + [OIII]

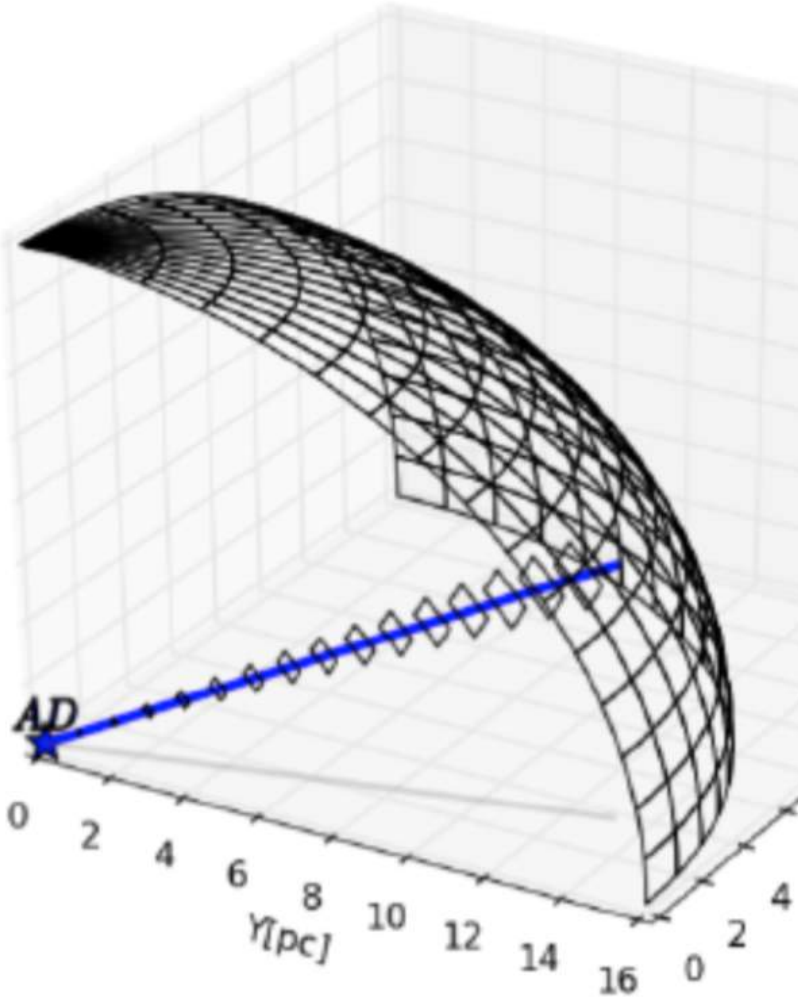
brighter regions,
higher dust absorption




The Circinus Galaxy
Credit: Andrew S. Wilson (U. Maryland) et al., WFPC2, HST, NASA

Mezcua+2016

**pseudo-3D radiative transfer** for emissions from ionized gas (i.e. only radial propagation is solved with **CLOUDY (Ferland 2017)**)



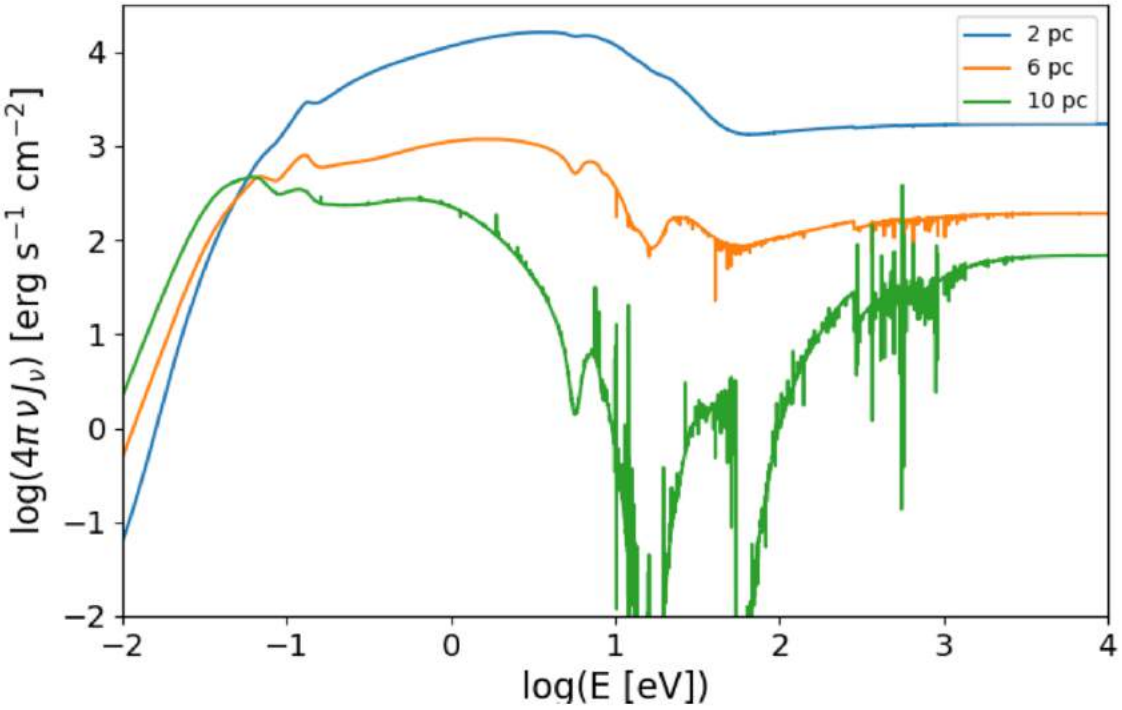
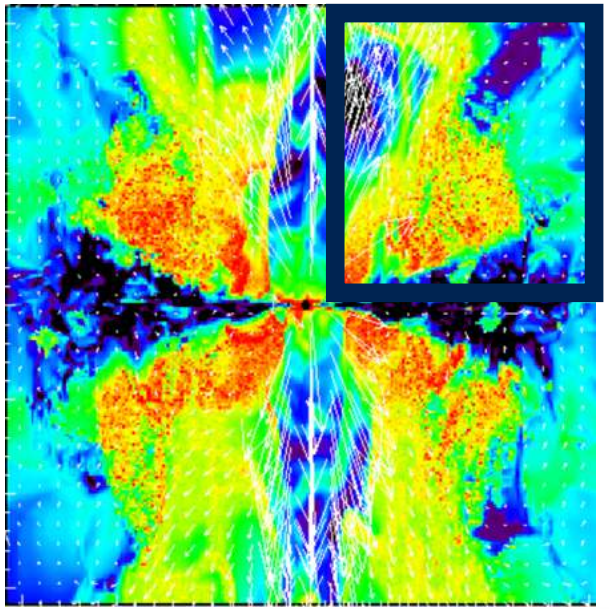




**Figure 5.** Radial change of SEDs at $r = 2, 6$, and 10 pc from the center along a ray of $\theta = 40°$ from the rotational axis.

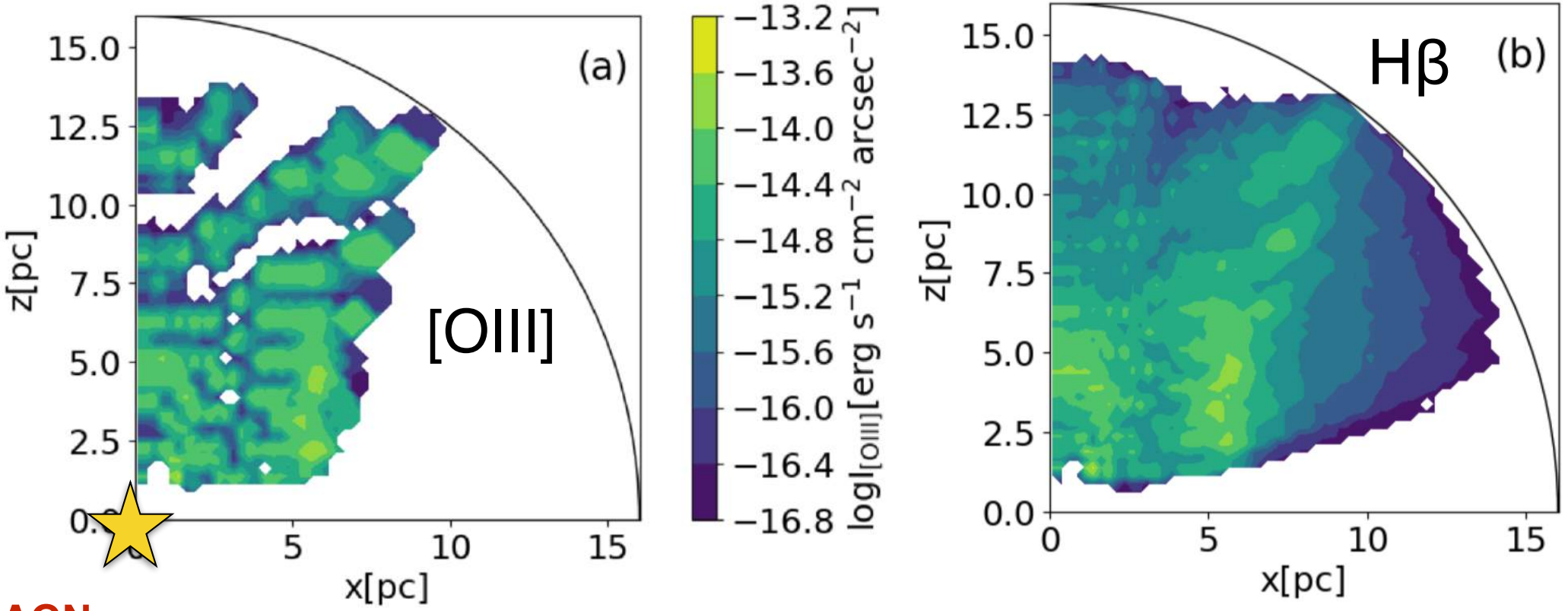
# Origin of NLR?
# outflowing ionized gas ?

***Fountain model*** *+ multi-dimensional RT using* ***Cloudy (Ferland 2017)***

H+



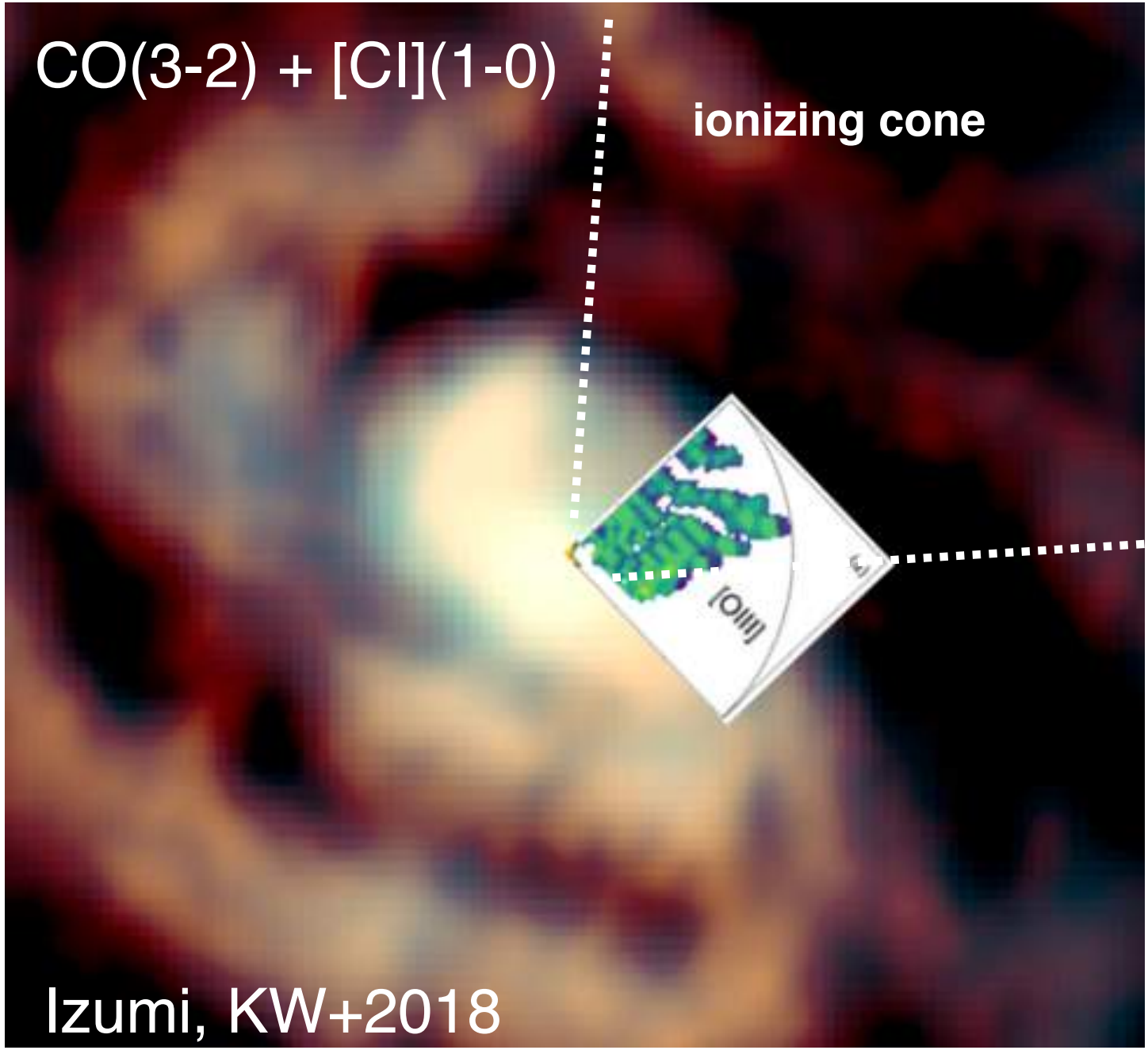
**Edge-on view**

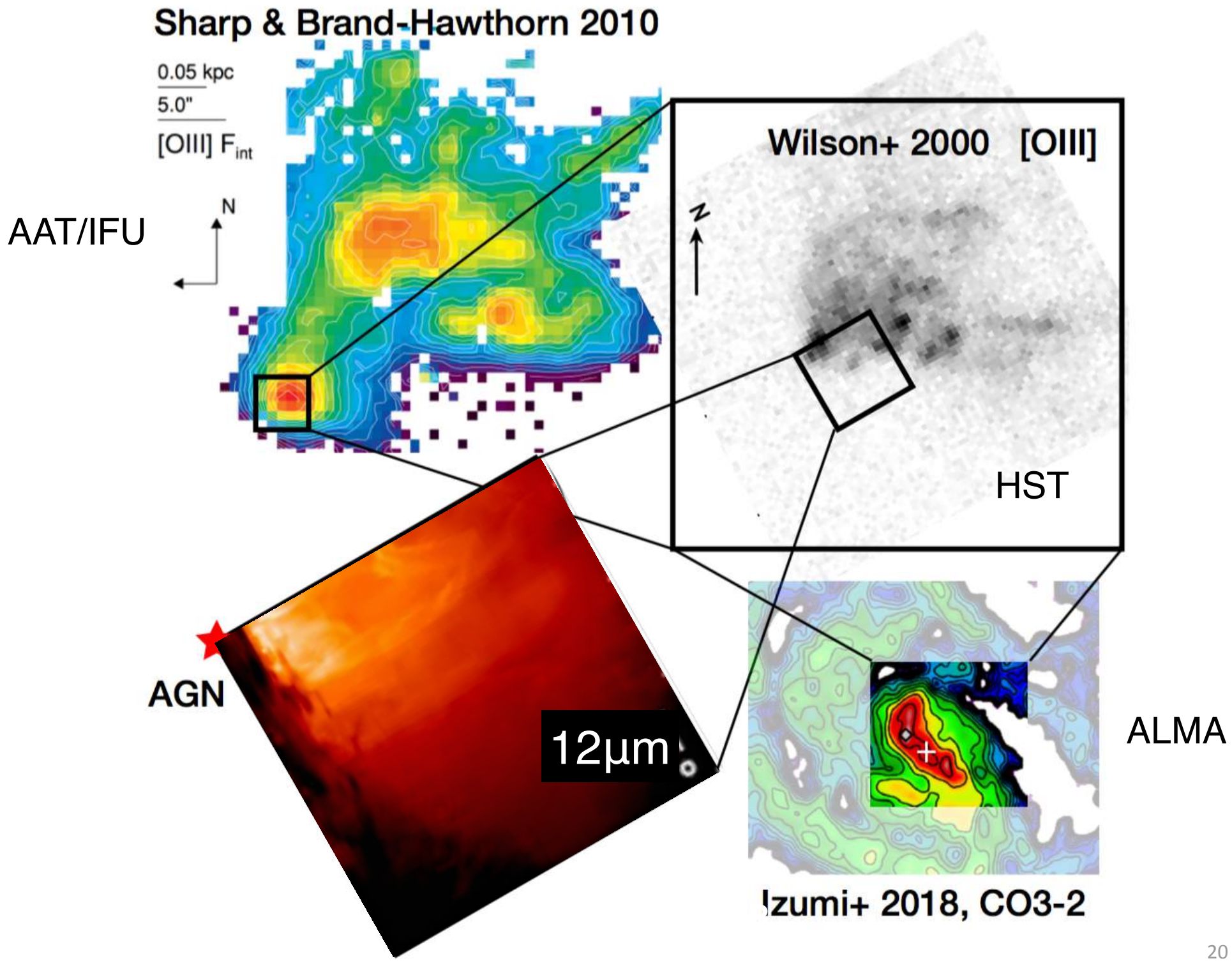



**AGN**

**KW, Yonekura, Nagao (2018)**

# Multi-phase gas in central ~ 100 pc

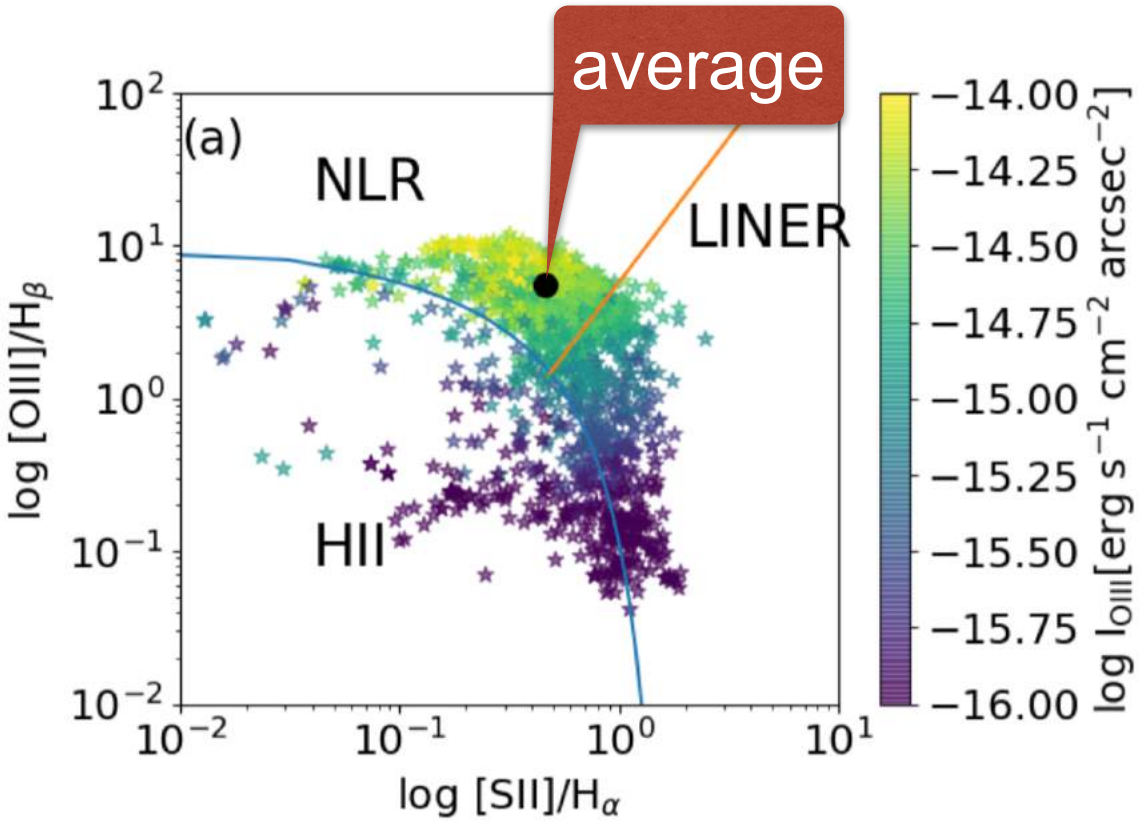



Sharp & Brand-Hawthorn 2010
0.05 kpc
5.0"
[OIII] $F_{int}$
N
AAT/IFU
Wilson+ 2000 [OIII]
N
HST
AGN
12μm
ALMA
Izumi+ 2018, CO3-2

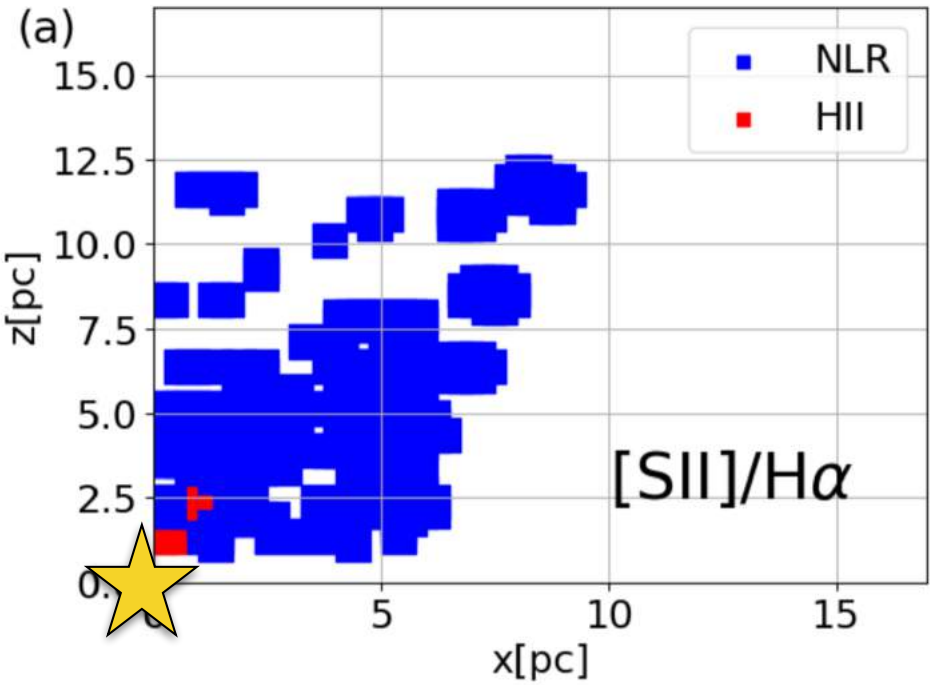
# NLR = outflowing ionized gas

KW, Yonekura, Nagao (2018)

**BPT diagram (Baldwin, Philips, Terlevich diagram)**



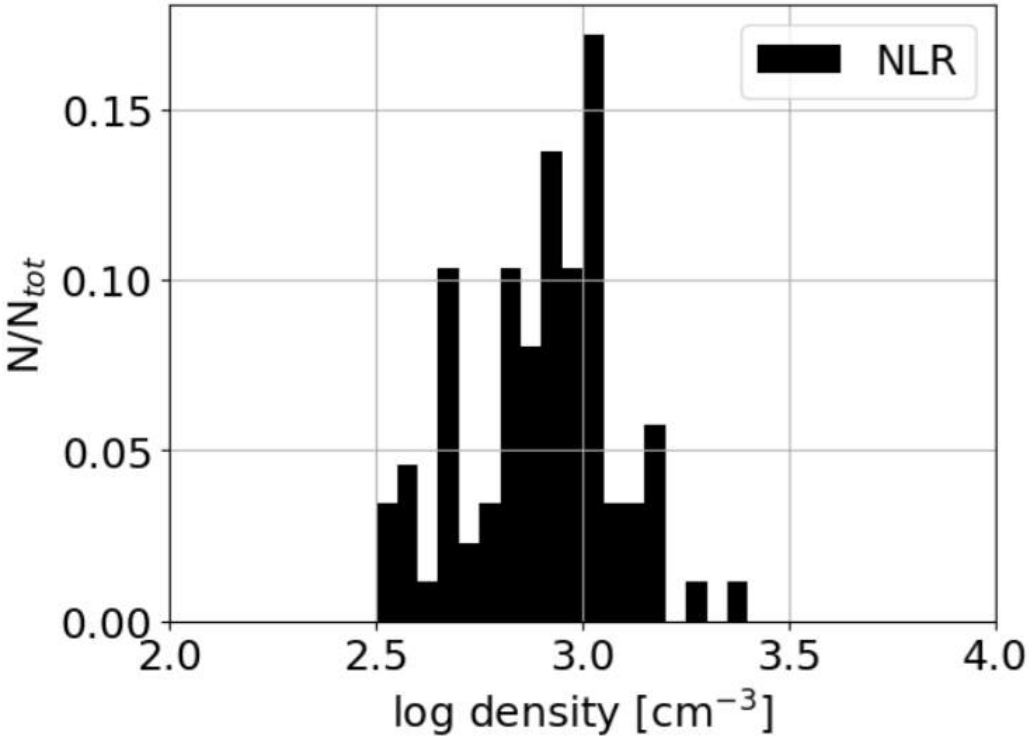

**Fountain flows + central radiation = NLRs**

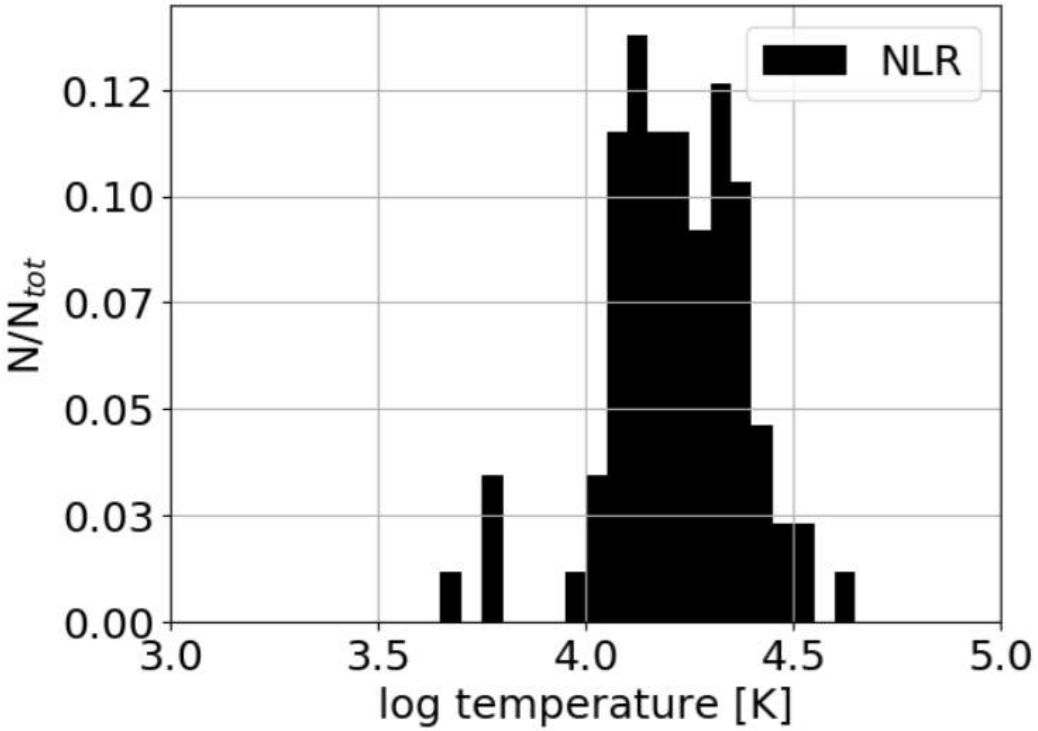



**AGN**

KW, Yonekura, Nagao (2018)

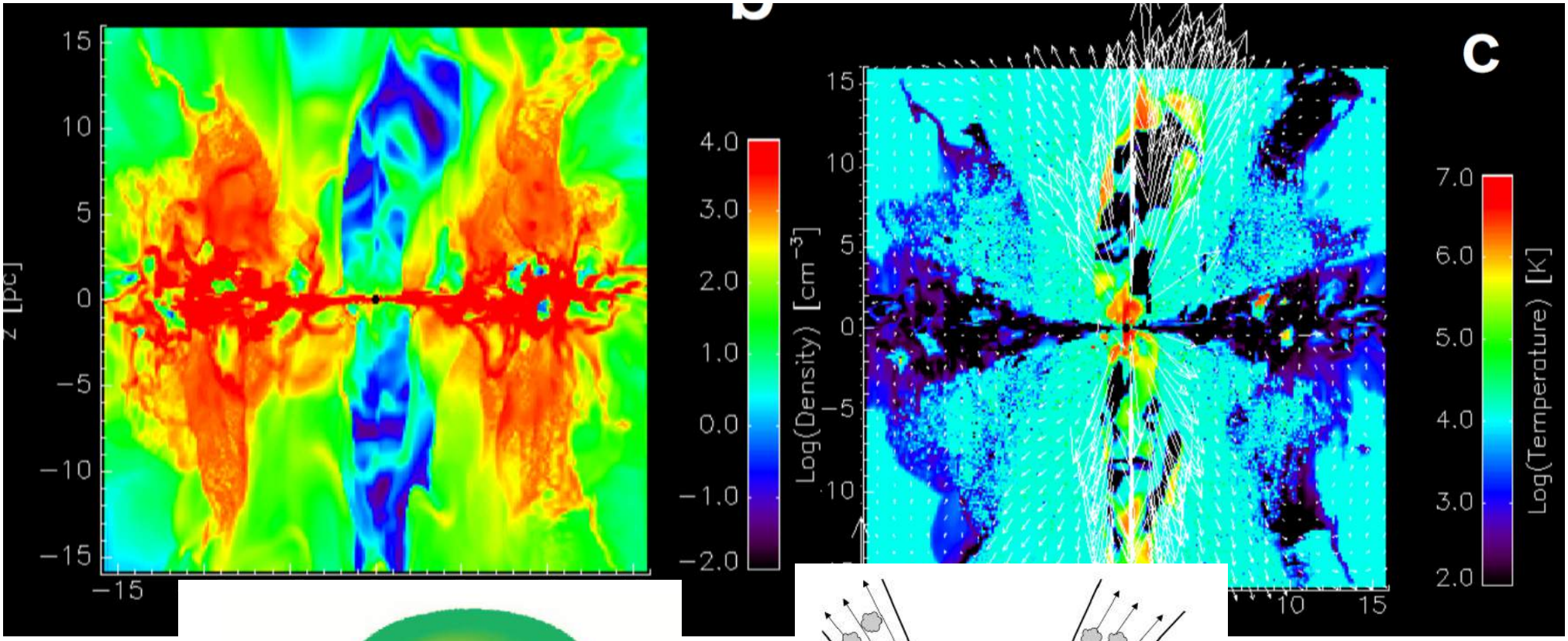
# Physical properties of “NLR” gas




**The gases observed as “NLR” have**
**$n \sim 10^{2.5\text{-}3}$ cm$^{-3}$, $T \sim 10^{4\text{-}4.5}$ K**

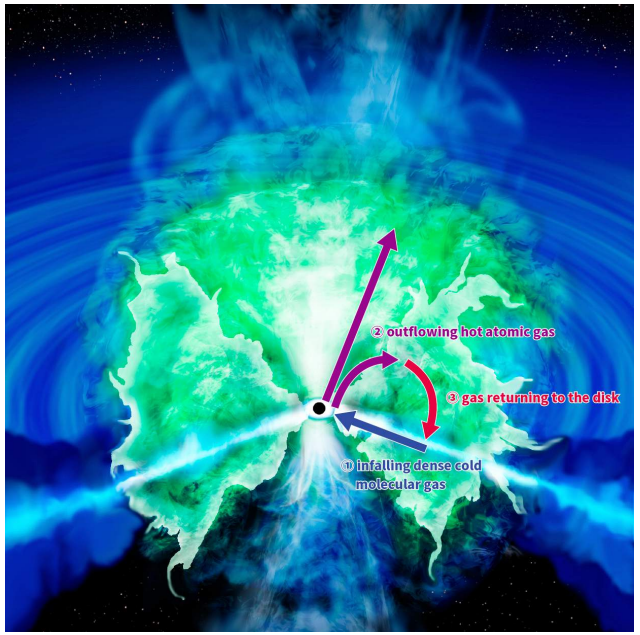
“NLR” gases are located at **the inner surface** of the thick disk




Das+2006

# summary

**1) "Tori" should not be static, rather dynamic, and the radiation-driven fountain shapes a torus.** KW 2012, 2015




**2) Multi-wavelength obs. in the Circinus galaxy are consistent with the fountain model.**

- **IR SED** KW, Schartmann,Meijerink 2016
- **cold molecular & atomic gas by ALMA** Izumi, KW, Fukushige, Hamamu 2018
- **ionized gas, NLR** KW, Yonekura, Nagao 2018
- **X-ray SED** Buchner+2018