A Chandra and ALMA Study of X-ray-irradiated Gas in the Central ~100 pc of the Circinus Galaxy

(Kawamuro et al. 2019a)

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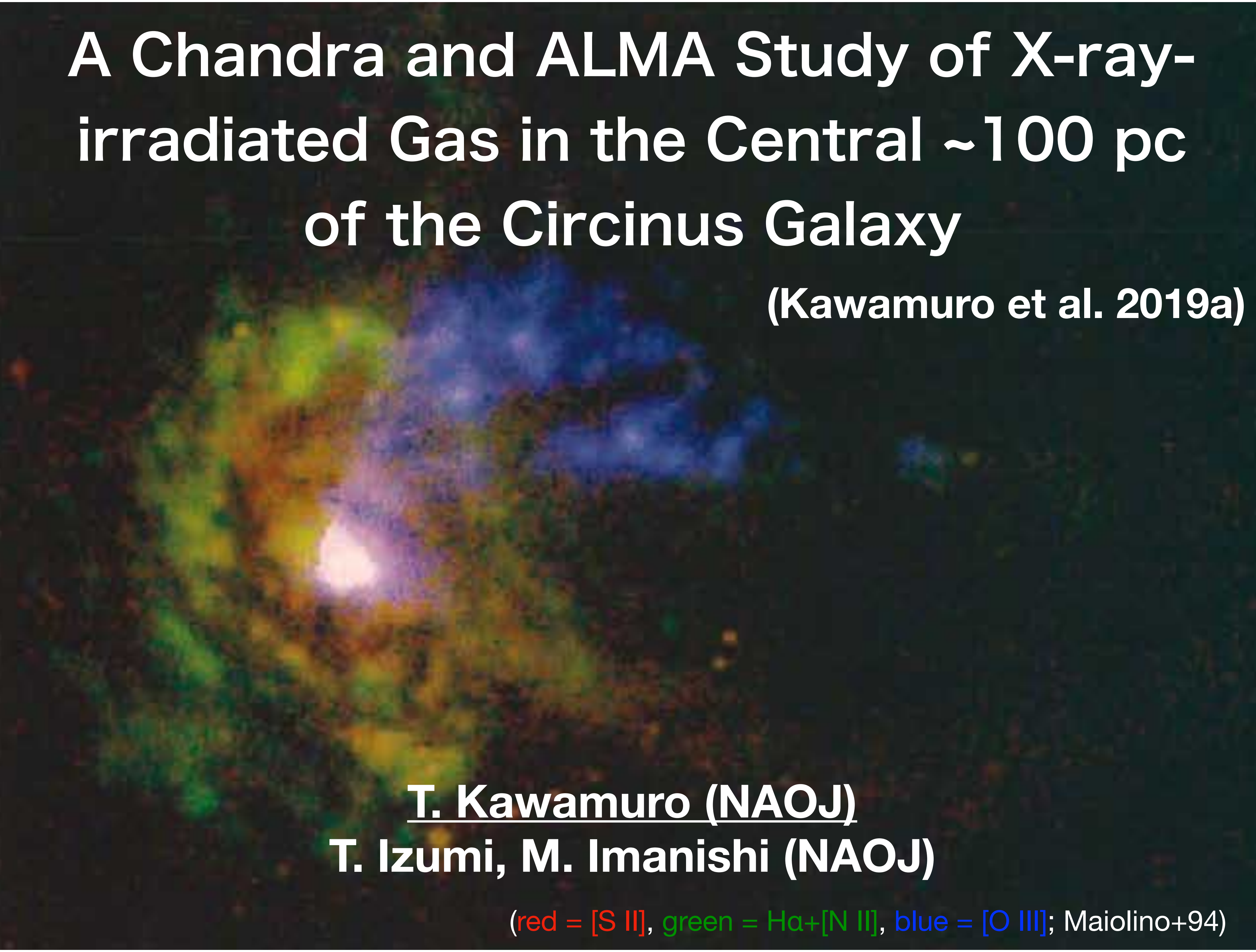
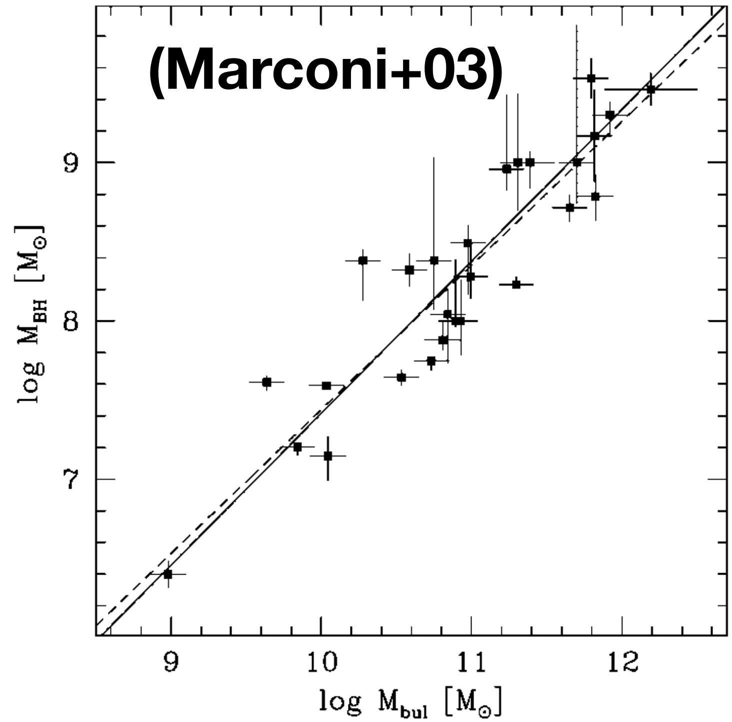


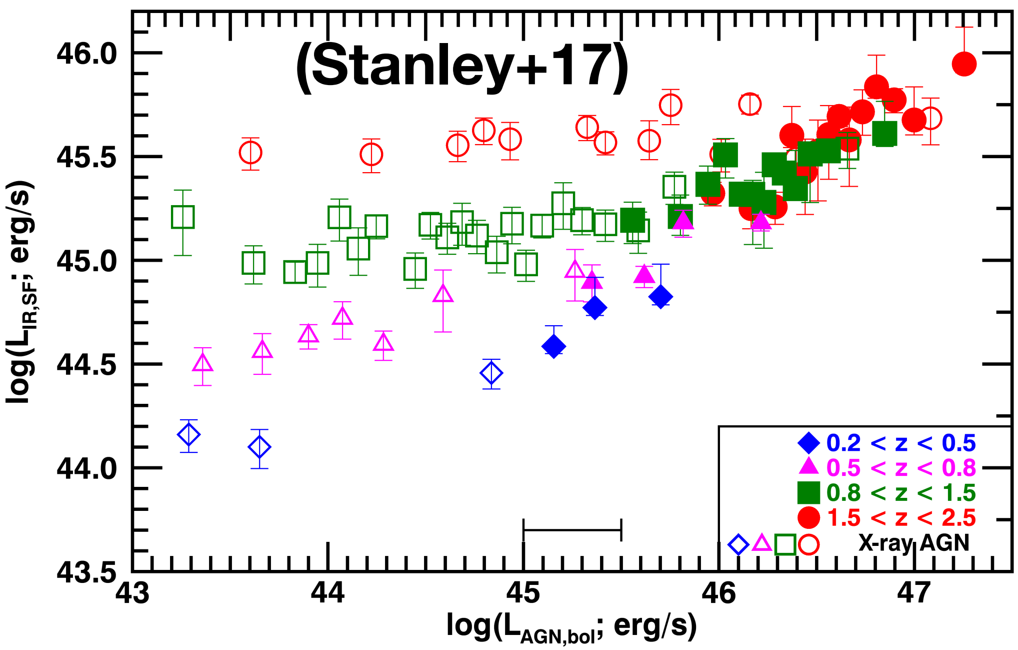
(red = [S II], green = Hα+[N II], blue = [O III]; Maiolino+94)

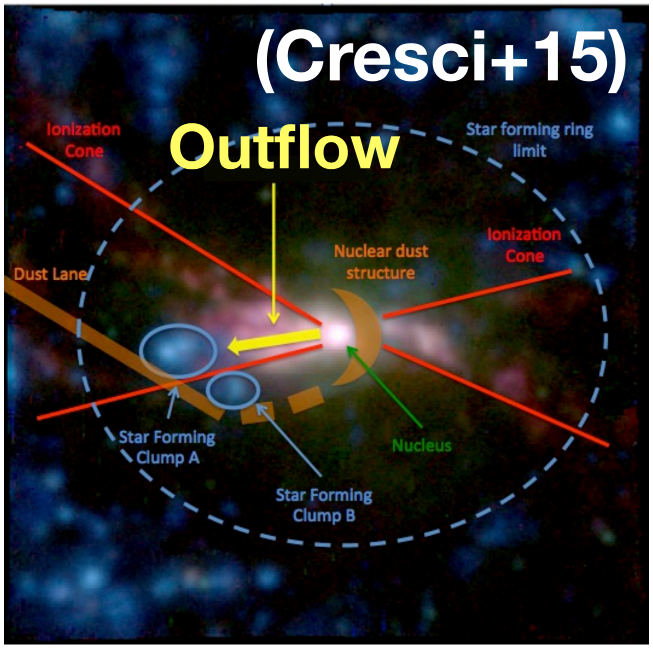
Co-evolution; AGN and SF relatoin

- **Understanding of the co-evolution b/w SMBHs and galaxies.**
  → Relation b/w AGN and SF activities.

- **Outflows by AGN.**
- **X-ray irradiation by AGN.**
  → This is an un-avoidable AGN effect on the host galaxy.







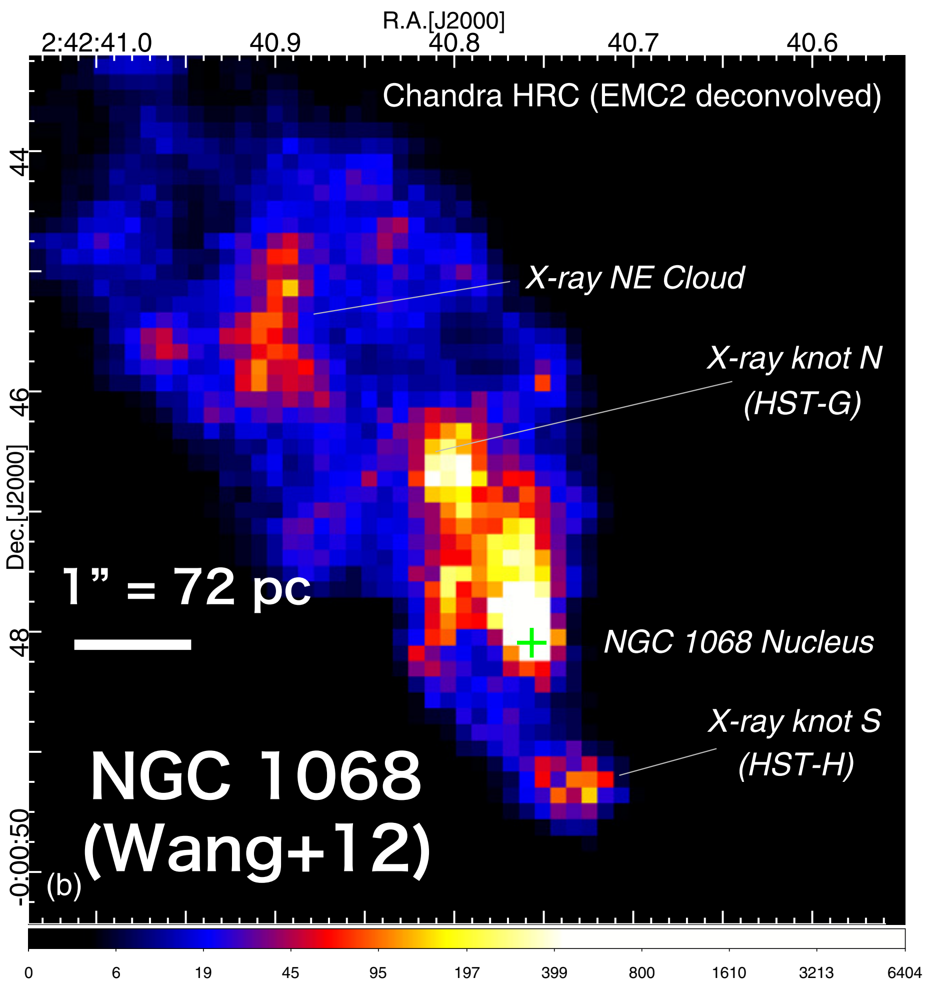
Extended X-ray emission

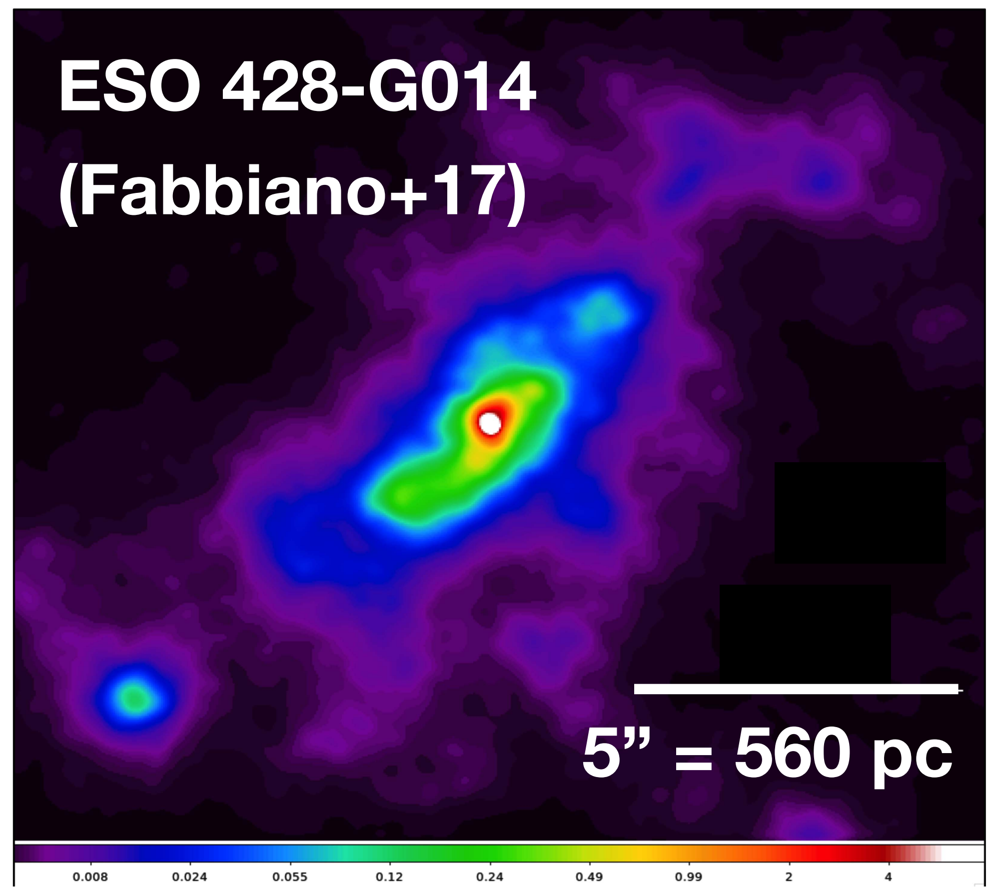
- **Chandra has revealed detailed spatial structures.**

(e.g., Tsunemi+01; Mori+01; Li+03,04)

- **Growing number of reports of extended X-ray emission**

(e.g., Wang+09; Marinucci+13,17; Feruglio+19)

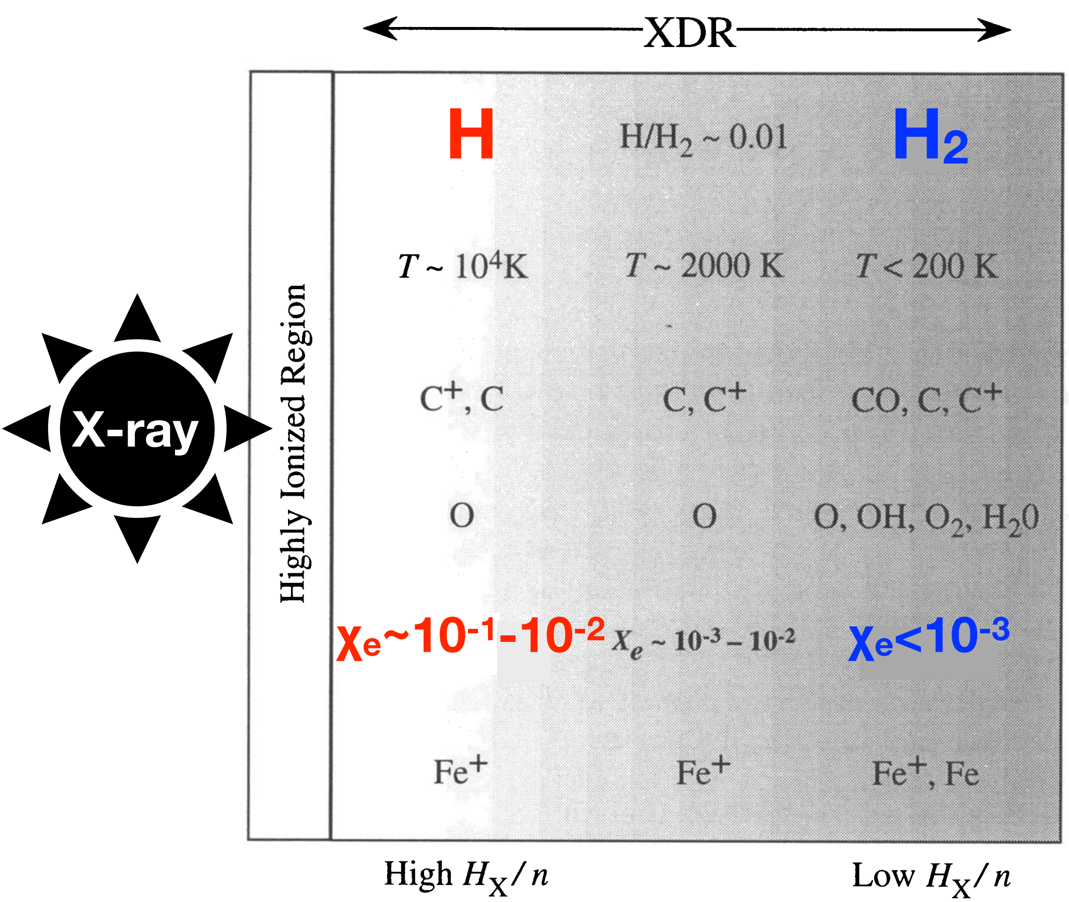




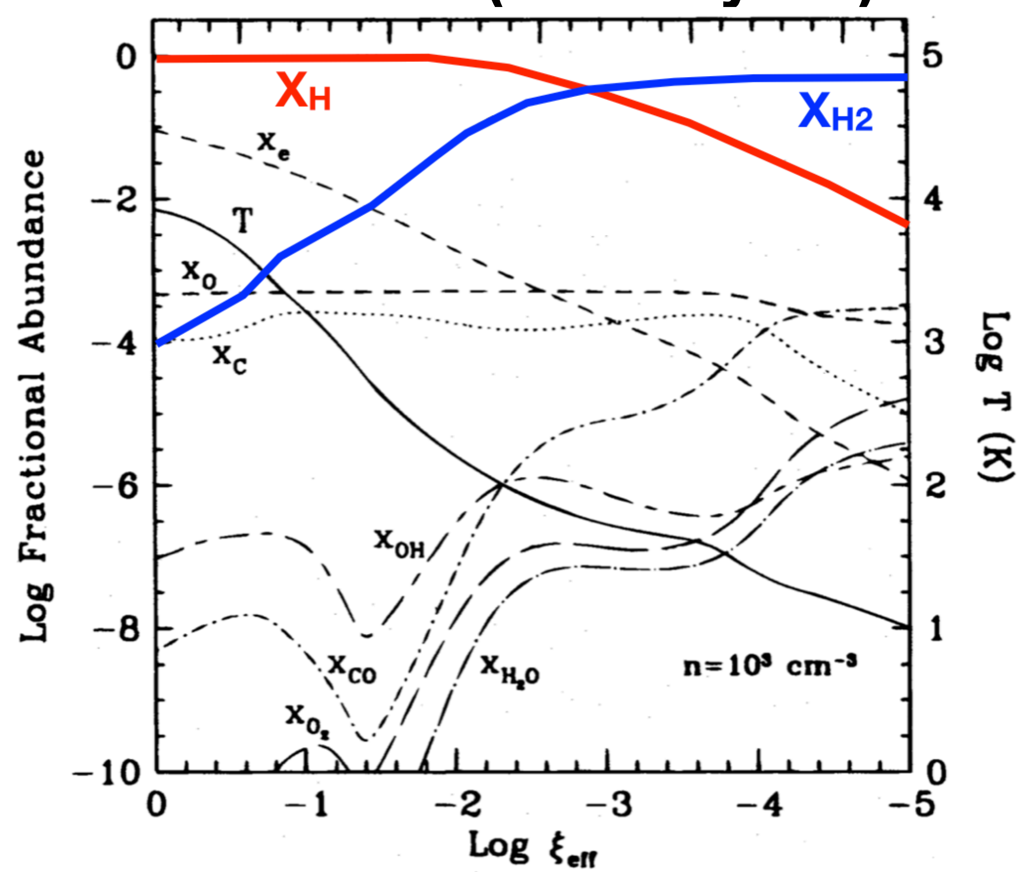
X-ray Irradiation of the ISM

- **X-ray irradiation causes a change of the chemical composition. → *X-ray Dominated Region (XDR)***
- **In the vicinity of an X-ray src, molecular dissociation is expected.**

$$\xi_{eff} = L_X / R^2 n_{H2} N^{1.1}_{att}$$



(Maloney+96)



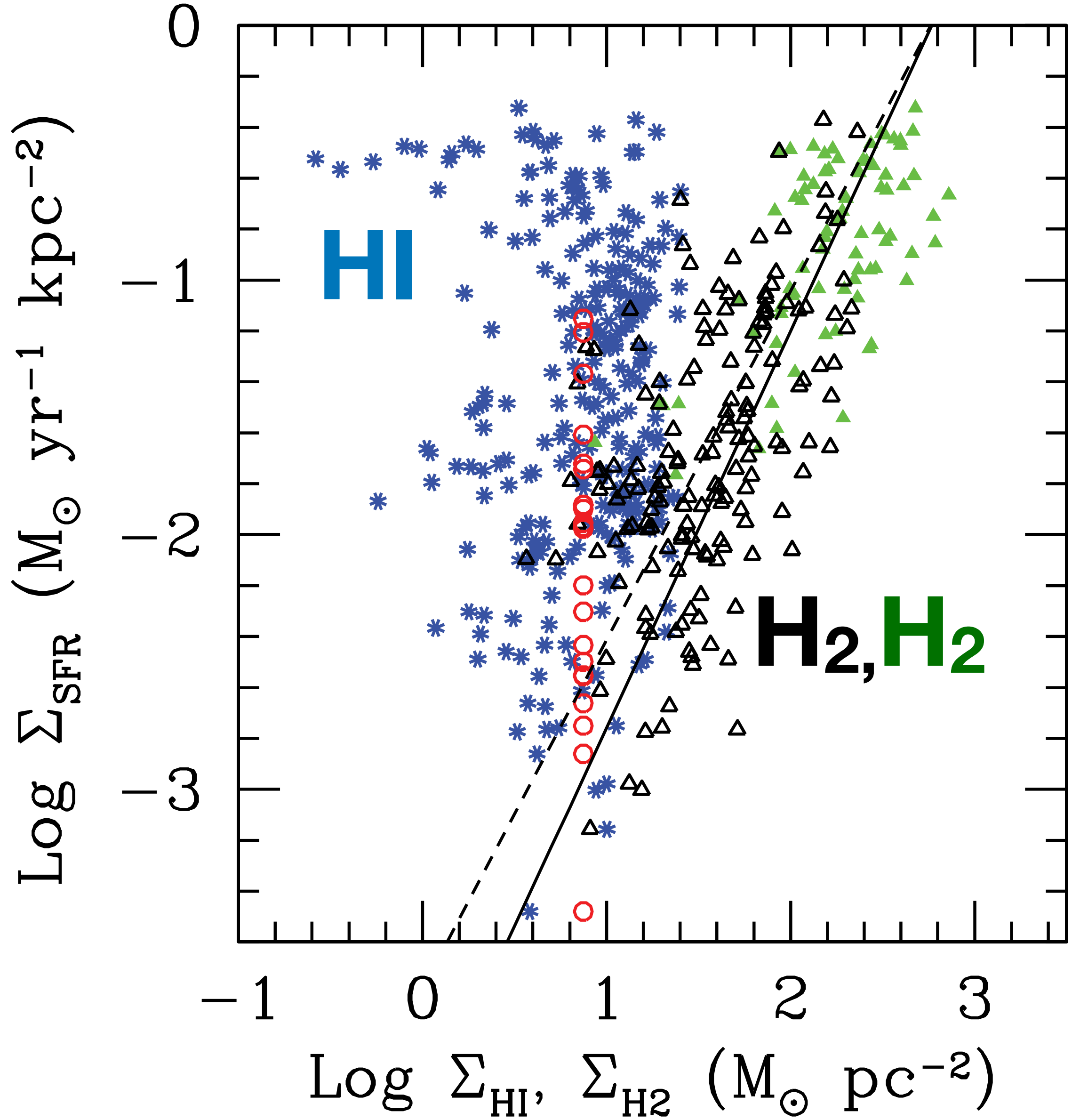
SF and Phases of Gas

- **Why do we care about the mol. gas dissociation?**

- **The positive correlation b/w Σmol and ΣSFR suggests a causal link b/w mol gas and the ability to form stars.**

- **A naive expectation is that X-ray emission can suppress SF by dissociating molecules.**

(Kennicutt+07)



Observational Test in the Circinus Galaxy

What we have done is to reveal an XDR around an AGN

Target: the Circinus galaxy

- D = 4.2 Mpc (1” ~ 20 pc).
- A Compton-thick AGN host.
  → Good for detecting faint, extended emission.

Obs.: Chandra & ALMA

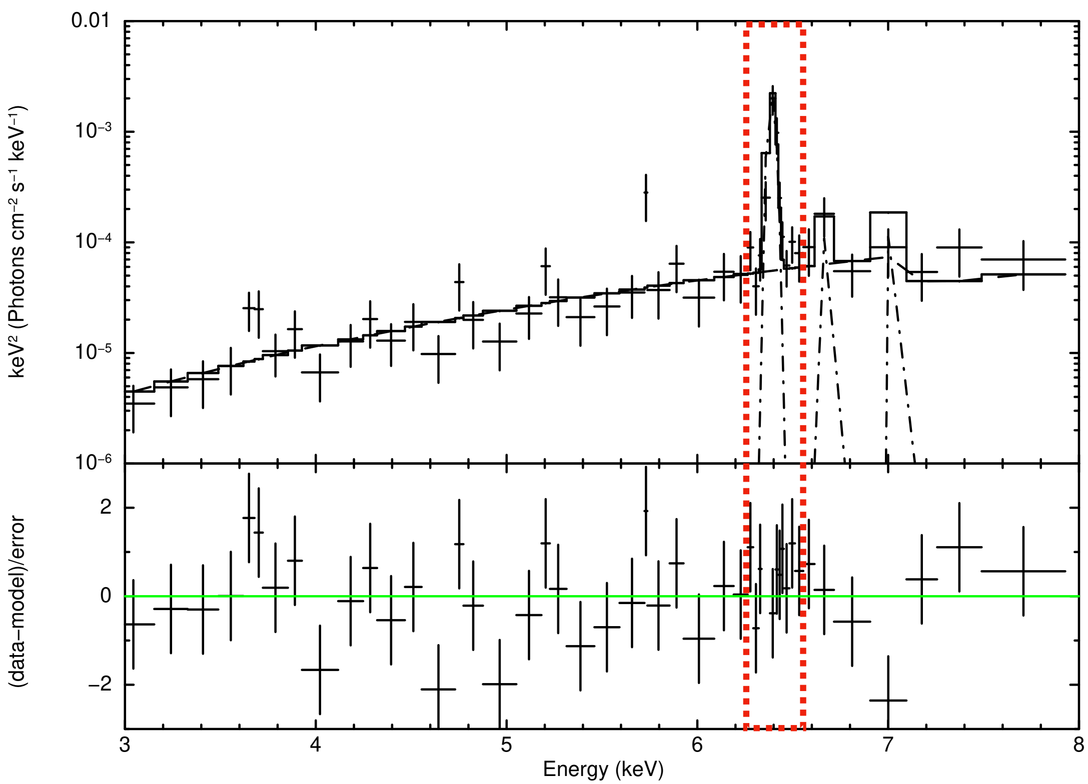
- high spatial res. (< 1”).
- high penetrating power of X-ray & submm/mm.
  → Good to study the dense nuclear region with the least bias.
- high S/N data.

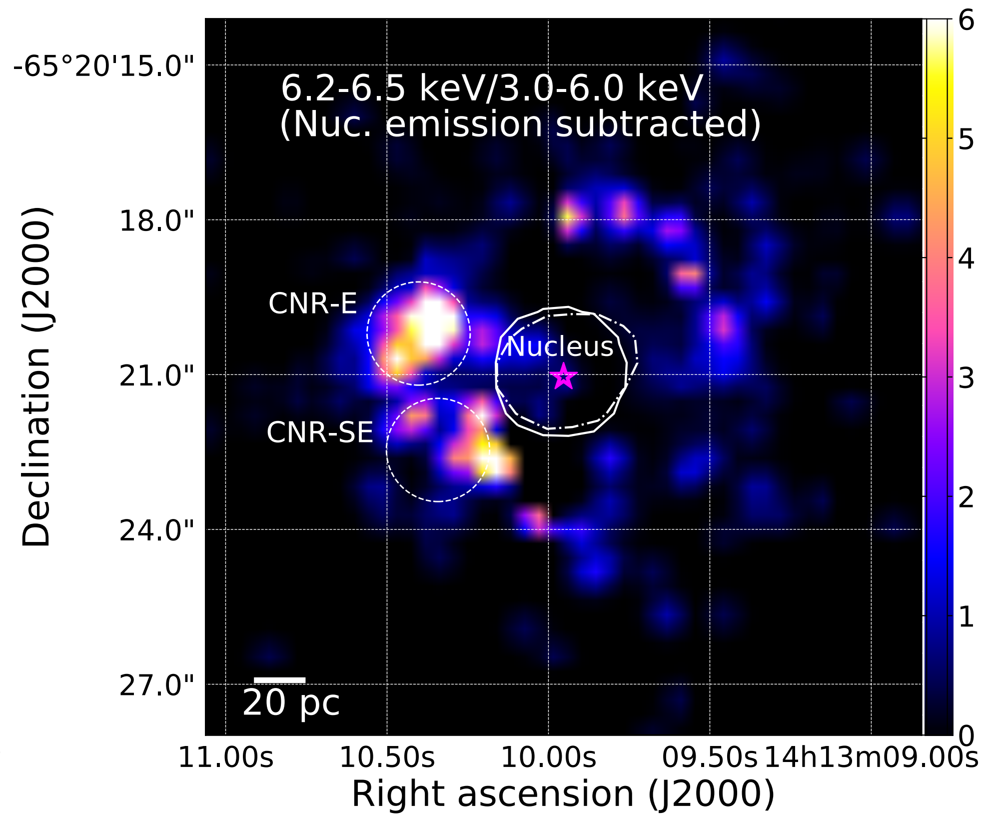
ObsID	Obs. date (UT)	Grating	Exp. (ksec)
(1)	(2)	(3)	(4)
12823	2010/12/17	NO	147
12824	2010/12/24	NO	38
62877	2000/06/16	YES	48
4770	2004/06/02	YES	48
4771	2004/11/28	YES	52

Project code	Obs. date (UT)	Molecules	Exp. (min)
(1)	(2)	(3)	(4)
#2015.1.01286.S (PI: F. Costagliola)	2015/12/31	HCO^+(J=4–3) HCN(J=4–3) CO(J=3–2)	3
#2015.1.01286.S (PI: F. Costagliola)	2015/12/31	HCO^+(J=3–2) HCN(J=3–2)	5
#2016.1.01613.S (PI: T. Izumi)	2016/11/24	HCO^+(J=4–3)	125

Fluorescent Iron-Kα Line as a Probe

- **The iron-Kα line probes X-ray irradiation regions.**
- **6.2-6.5 keV/3.0-6.0 keV ratios**
  → an proxy of the EW (Fe-Kα)
- **τ~1 for the X-ray w/ the edge energy when log N_H/cm^{-2} ~ 23.9**

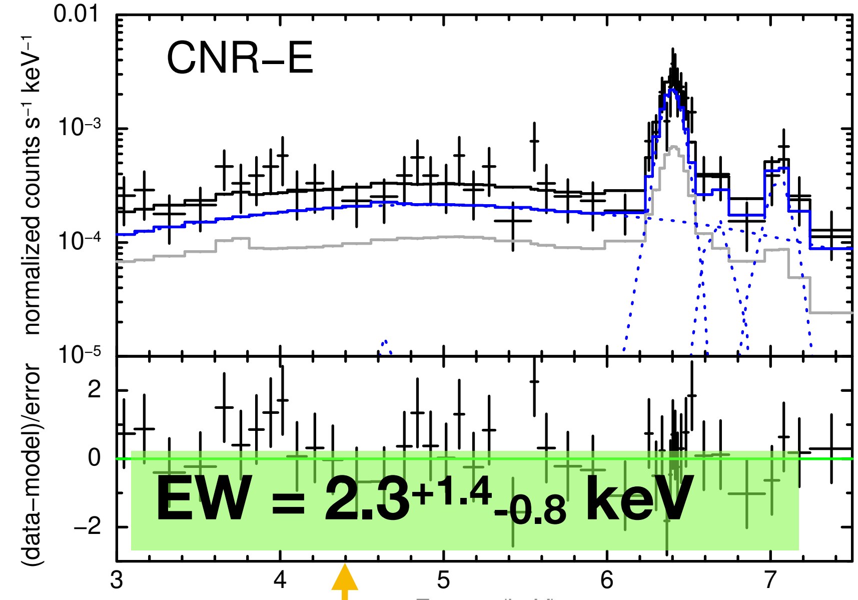


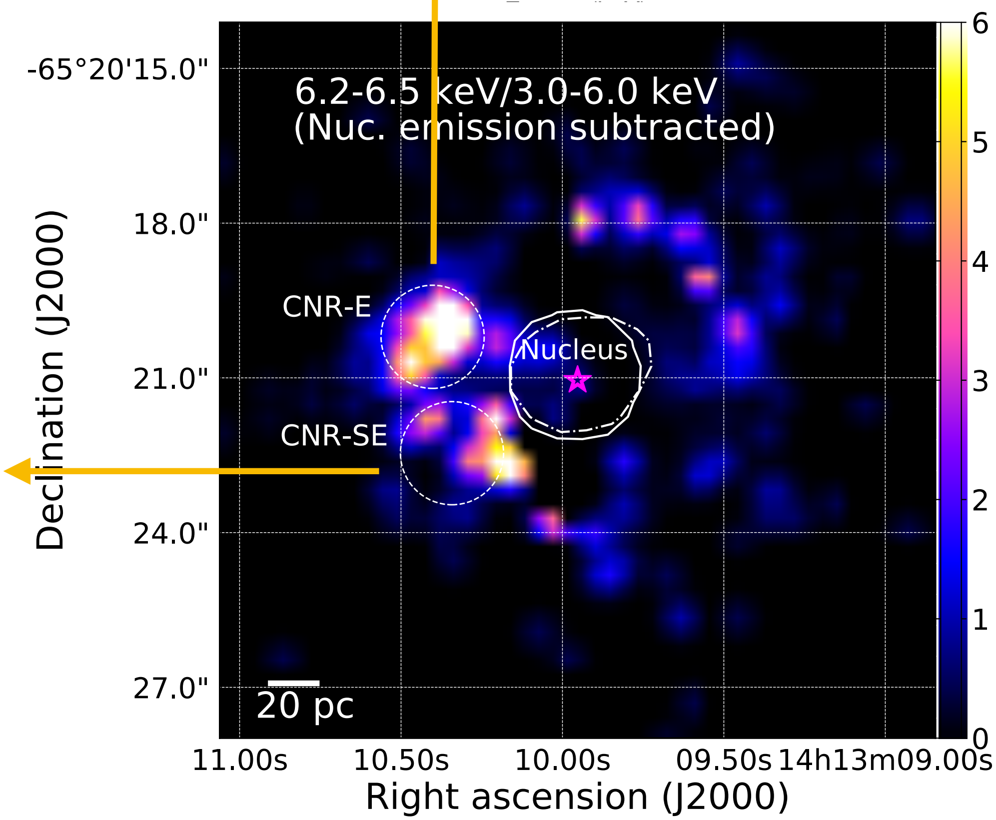


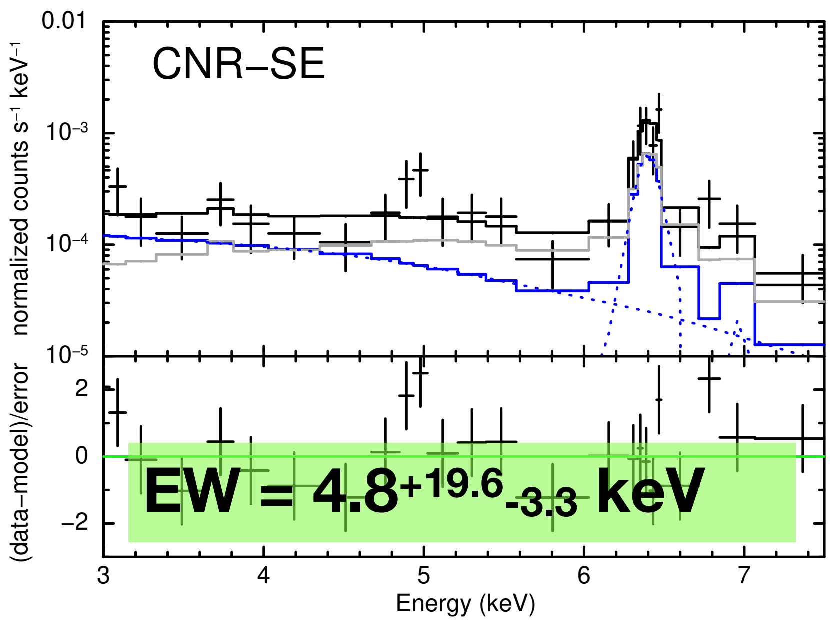
X-ray irradiation

- **Multiple regions w/ bright Kα emission**

- **High EWs (> 1 keV) are consistent w/ being irradiated by an X-ray src.**

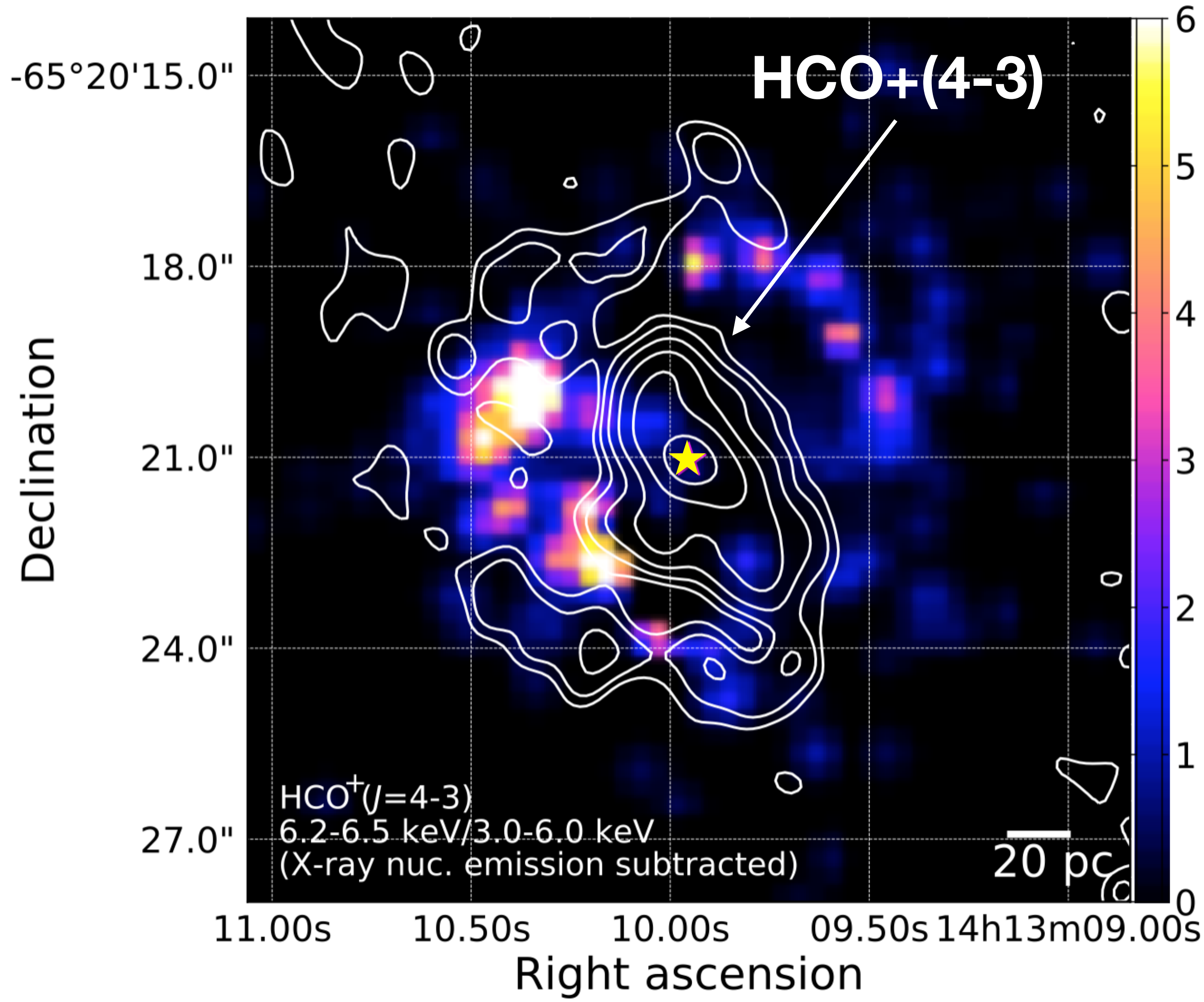






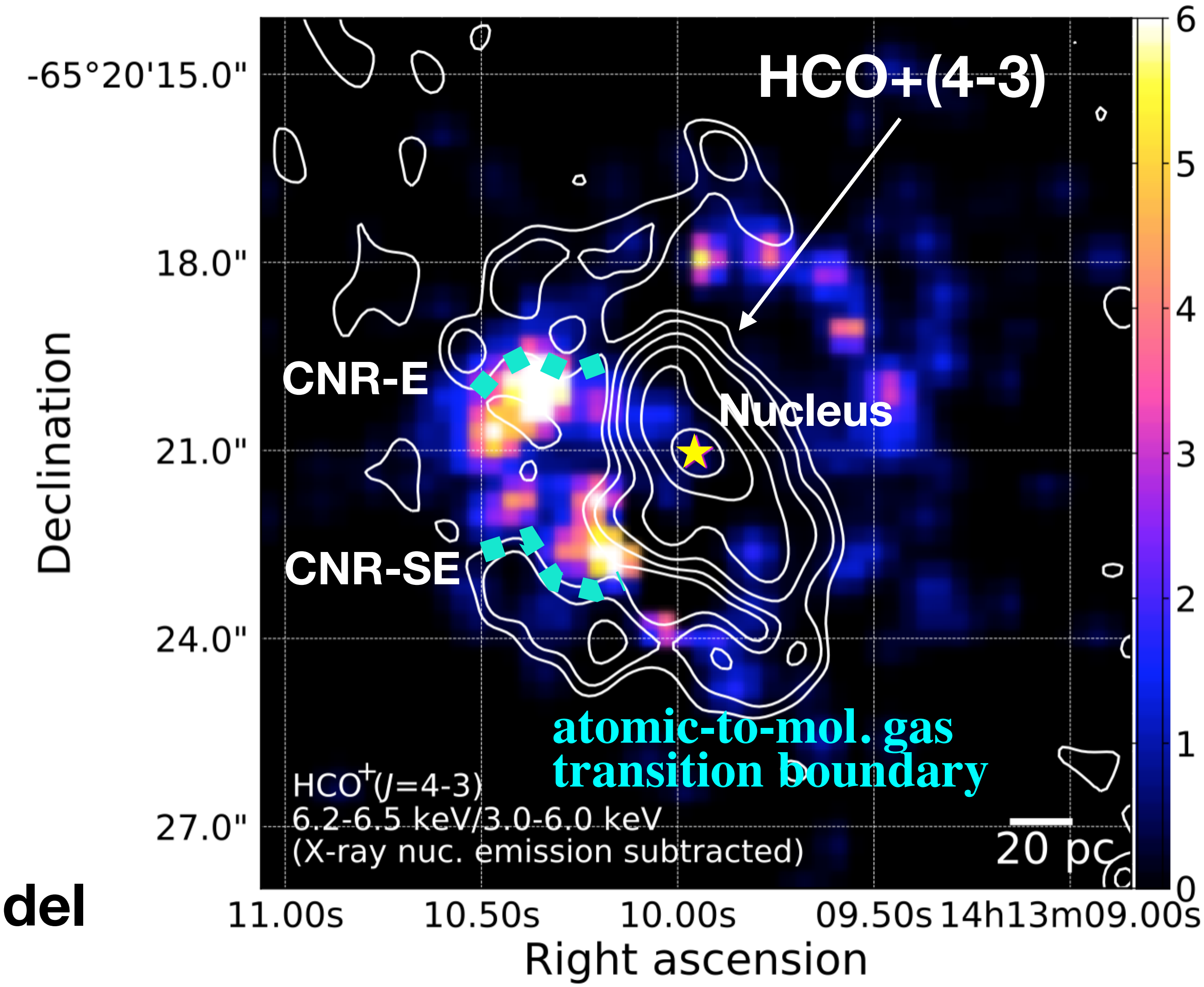
Spatial anti-correlation b/w mol. and iron lines

- **HCO+(4-3)**
  → **<u>Molecular gas</u>**
  → **high critical dens.**
  = dense gas tracer
- **Iron-Kα line**
  → **<u>gas irrespective of atomic/mol. phases</u>**



Spatial anti-correlation b/w mol. and iron lines

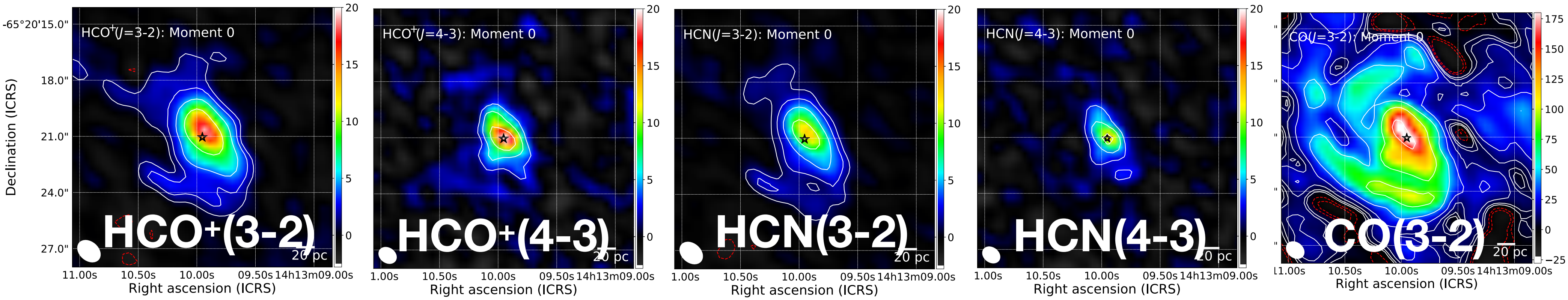
- HCO+(4-3)
  → Molecular gas
  → high critical dens.
  = dense gas tracer
- Iron-Kα line
  → gas irrespective of atomic/mol. phases
- Clear atomic-to-mol. transition boundaries
- Mol. dissociation ?
- Next is quantitative discussion w/ XDR model



$$\xi_{\rm eff} = L_X / R^2 n_{H2} N^{1.1}_{\rm att}$$

Physical state of the ISM

- **Multiple mol. line detections by ALMA**



- **Line ratios are compared w/ statistical equilibrium calculations involving collisional and radiative processes.**

(i.e., non-LTE code by van der Tak+07)

→ constrains on N_{H2}, n(H_2), T_k, [HCN]/[HCO^+]

	Nucleus	CNR-SE	CNR-E
log N_{H2} [cm^{-2}]	24.5 [25.0]	23.5 [24.5-25.0]	24.5 [20.0-25.0]
log n_{H2} [cm^{-3}]	**5.0 [4.5]**	**4.5 [3.0-4.0]**	**3.5 [3.0-5.0]**
T_k [K]	290 [190-400]	130 [80—400]	200 [50-330]
[HCN]/[HCO^+]	3 [-]	4 [2-5]	2 [3-4]

Is the X-ray powerful enough?

$\xi_{eff} = L_X / R^2 n_{H2} N^{\alpha}_{att}$

L_X ~ 1.3e+43 (1–100 keV)

(NuSTAR estimate by Arevalo+14)

R ~ 60 pc

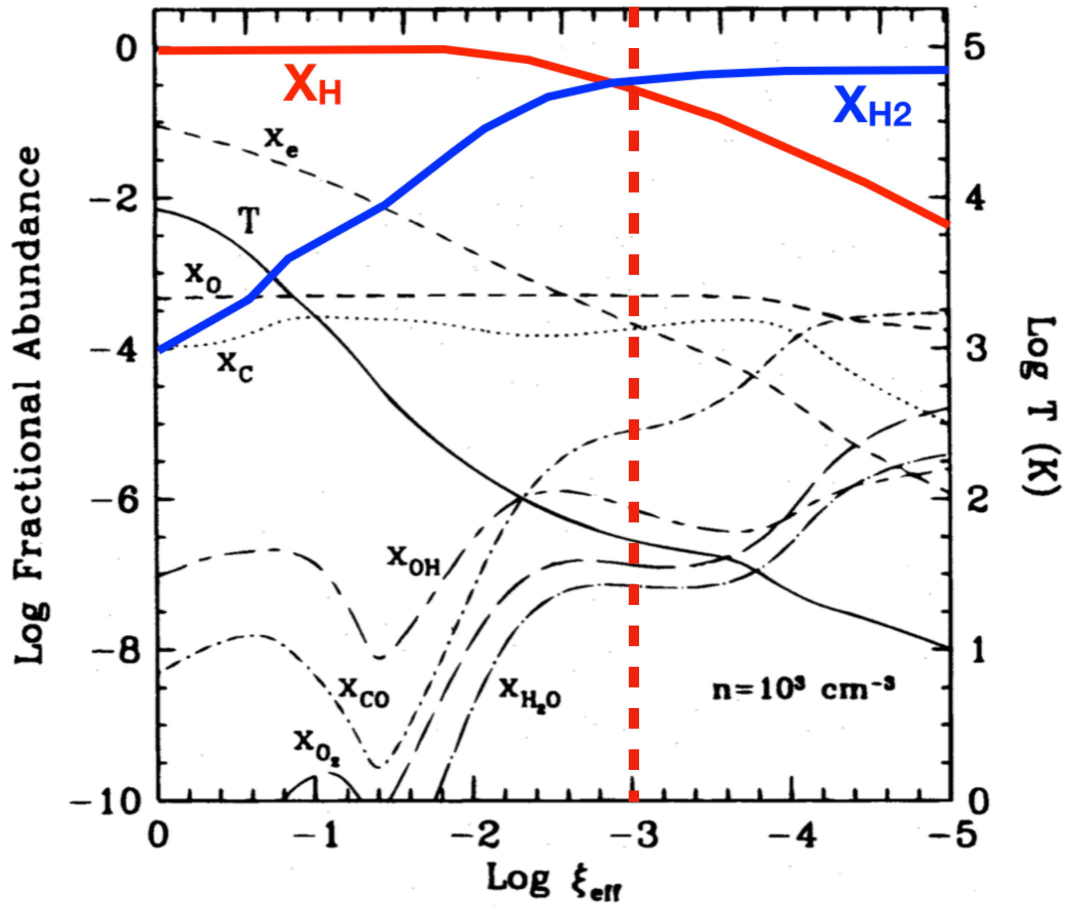
(spatially resolved map)

n_{H2} ~ 1e+3.0-5.0 cm^{-3}

(mol. line ratios fit by RADEX)

N_{att} ~ 1e+23.9 cm^{-2}

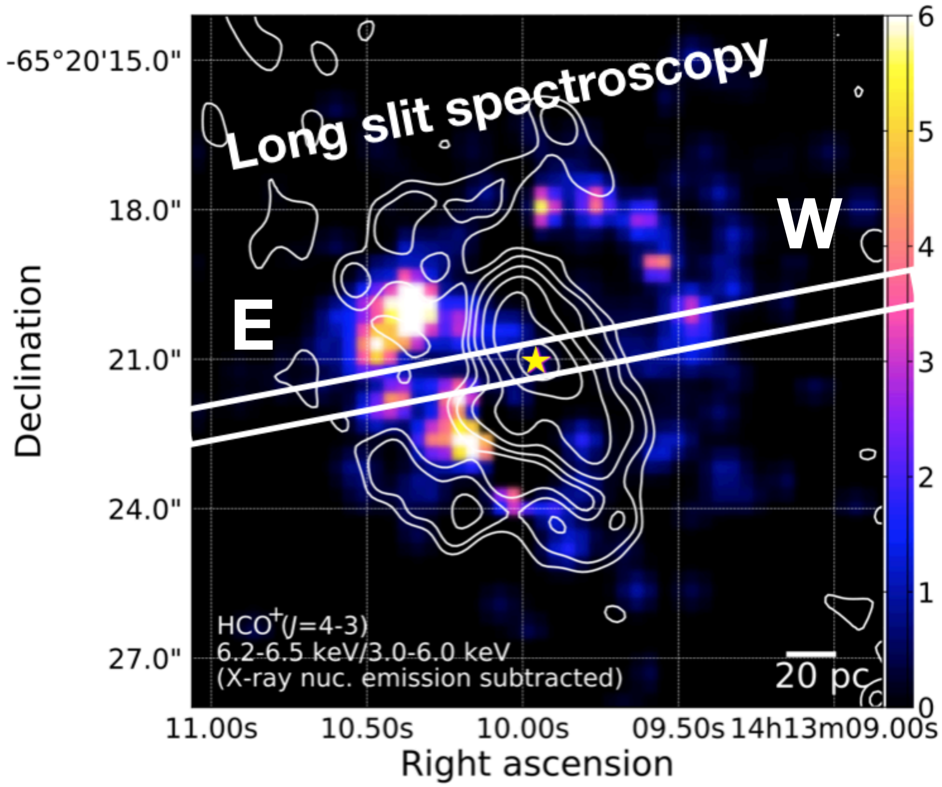
(τ~1 for the neutral iron)

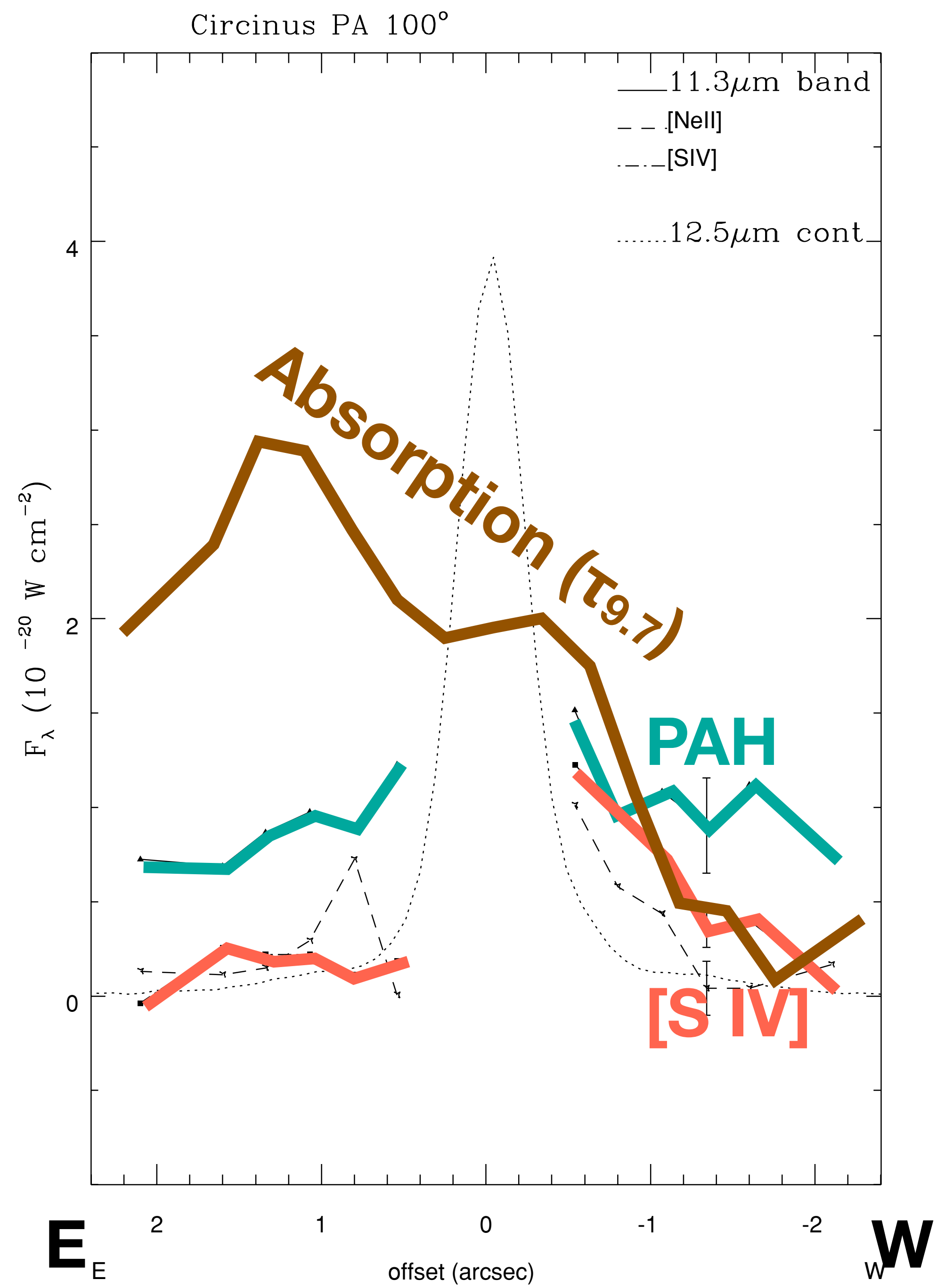


	Nucleus	CNR-SE	CNR-E
log ξ_{eff}	< -4.0	-4.6~-2.6	-4.0~-2.5

SF in the X-ray irradiated region

- **PAH emission study using Gemini-S/T-TeCS by Roche+06.**
- **Less extinct PAH emission in E**
  → SF in the foreground of the dust lanes
  → in-active SF in X-ray irradiate region





Summary

- **AGN usually emit X-rays, and therefore the X-ray irradiation is an un-avoidable effect on the host galaxy.**
- **Chandra and ALMA obs. have revealed the spatial anti-correlation b/w the molecular gas and iron-Kα line emission.**
- **Moderately high ionization parameters are consistent with molecules being dissociated by the X-ray emission.**
- **The high-spatial resolution study is important.**
  → We anticipate the future high spatial-resolution projects, such as MIXIM, AXIS, Lynx.