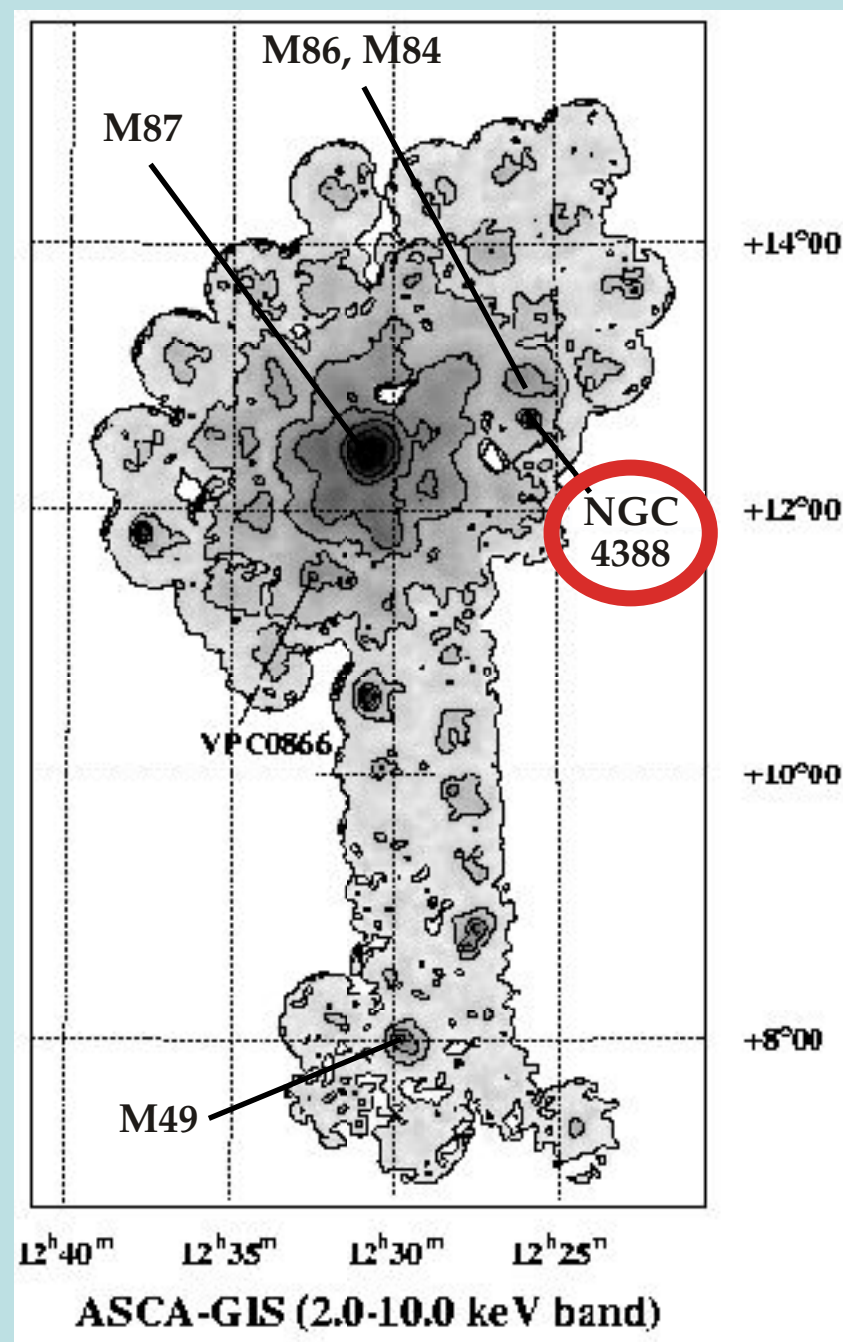


A Soft X-ray Arc from the Edge-on Spiral Galaxy NGC 4388 in the Virgo Cluster

Abstract

Recently, the very largely extended, ~ 35 kpc, H-alpha emission was first detected from NGC 4388 with Subaru (Yoshida et al. 2002). We analyzed the Chandra data of NGC 4388 paying attention to the extended emission. We found some X-ray gas clouds, 10-30 kpc away from the nucleus. In addition, a hint of an arc-like structure, "X-ray arc", connecting this region and the nucleus is seen. The distribution of the extended X-ray gas clouds roughly follows that of H-alpha, but is slightly shifted from that of H-alpha. The spectrum could be fitted with a thin thermal plasma model with a temperature of ~ 0.3 keV and a density with $\sim 8 \times 10^{-3} \text{ cm}^{-3}$. We tested several scenarios for the origin of the soft X-ray arc. We propose that the origin is most likely a gas stripped by the ram-pressure of the Virgo ICM.

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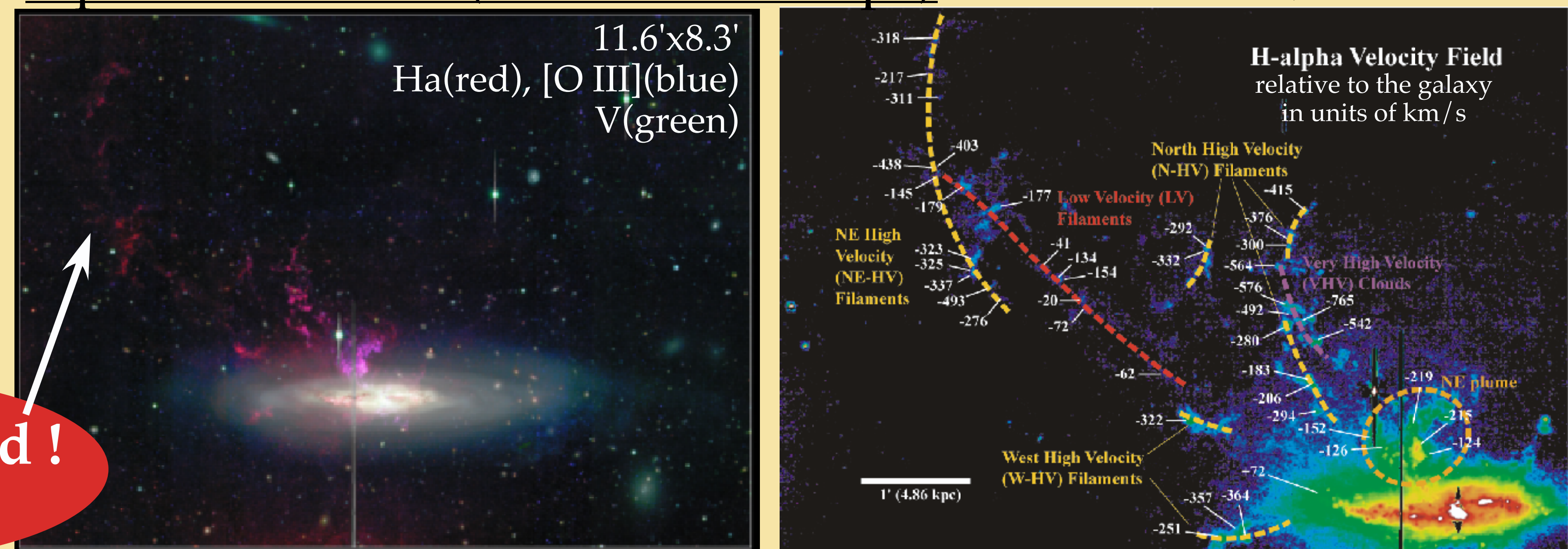
Properties of NGC 4388

- Adopted distance ~ 16.7 Mpc
- Edge-on spiral galaxy, Seyfert 2
- Member galaxy of Virgo cluster (~ 1 deg away from M87)
- Line of sight velocity ~ 1500 km/s, relative to the Virgo ICM

ASCA Virgo Map
Shibata et al. 2001

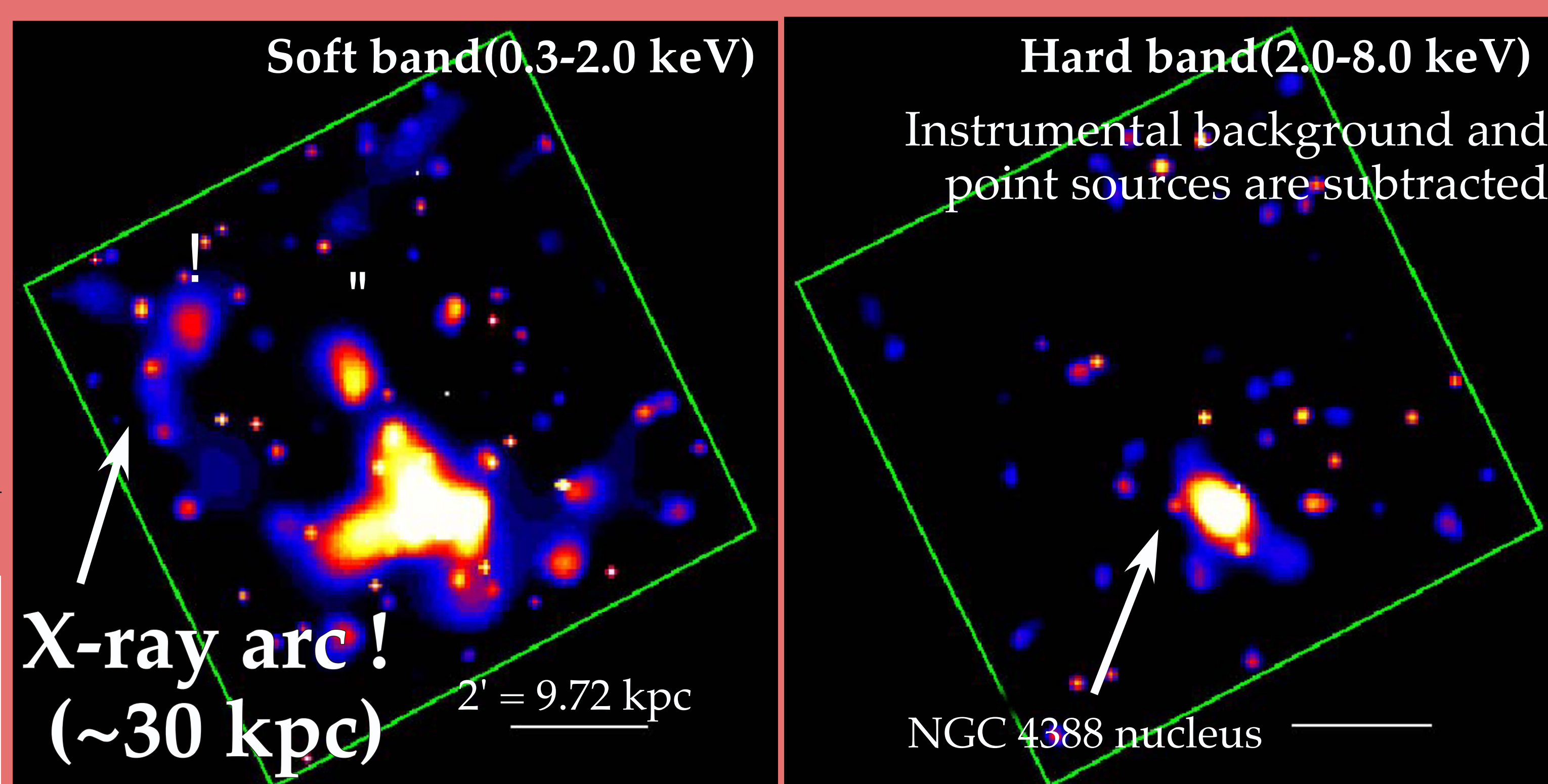
Very extended!
(~ 35 kpc)

Optical features (Subaru telescope) Yoshida et al. 2002, 2003



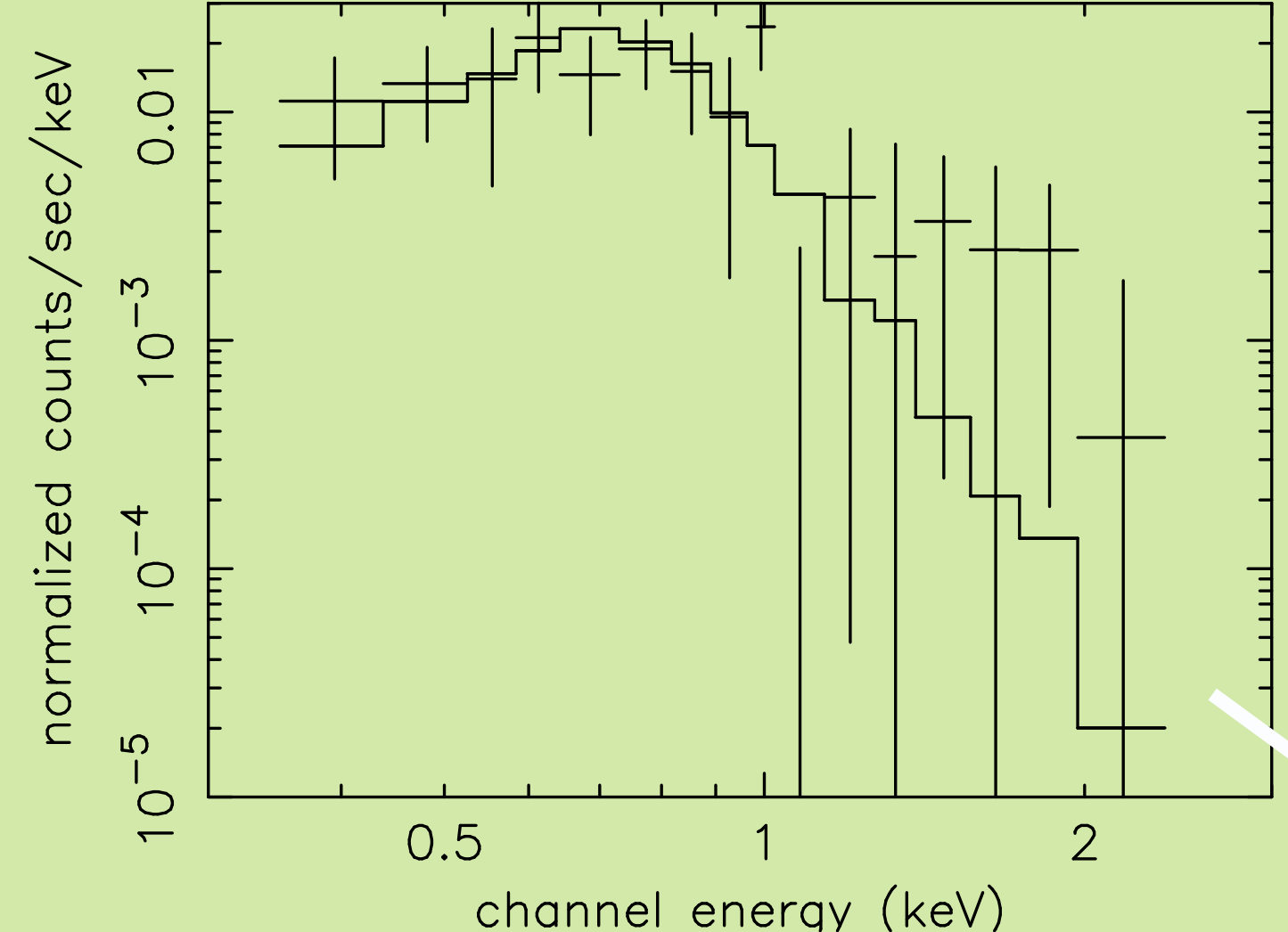
Chandra Observations

- 14 ksec, ACIS-S3
- Some X-ray gas clouds, 10-30 kpc away from the nucleus.
Region ! : ~ 4 sigma detection.
- A hint of an arc-like structure, "X-ray arc". The length ~ 30 kpc.
- The compact and bright emission (Region "). The size ~ 5 kpc.



- A very extended emission-line region (VEELR).
- The size is very large, ~ 35 kpc.
- The H-alpha recession velocities are blue-shifted relative to the systemic velocity of the galaxy.
- Grouping into Several streams : $\sim 100, 300, 500$ km/s.
- The emission-line ratios of VEELR are well explained by power-law photoionization models.

Soft X-ray arc spectrum (ICM emission subtracted)

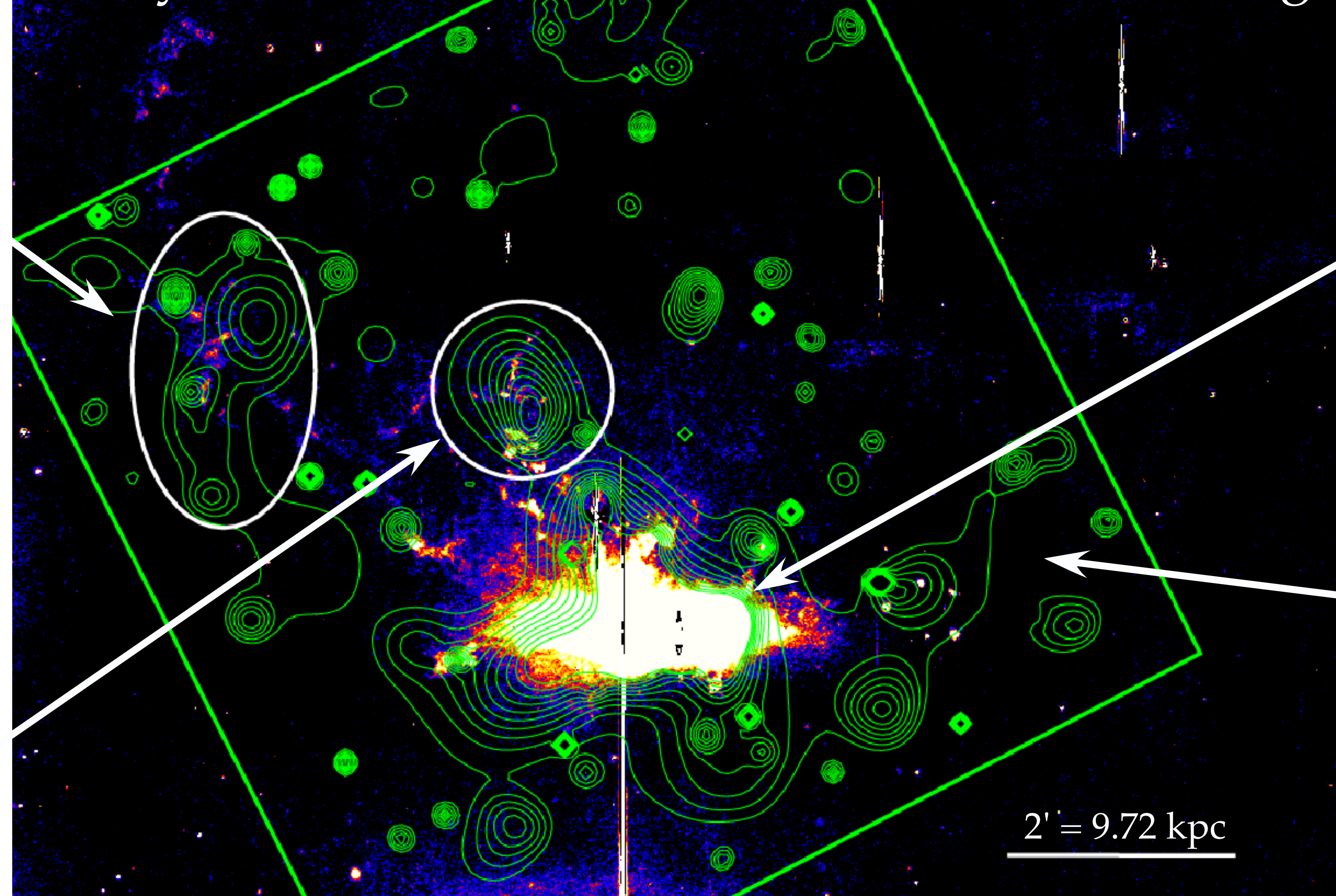


$N_H = 2.55 \times 10^{20} \text{ cm}^{-2}$ (Galactic fix)
Abundance = 0.12 (disk fix)
 $kT \sim 0.3$ keV (0.2 - 0.5)
 $L_x(0.5-2.5 \text{ keV}) \sim 1 \times 10^{39} \text{ erg/s}$

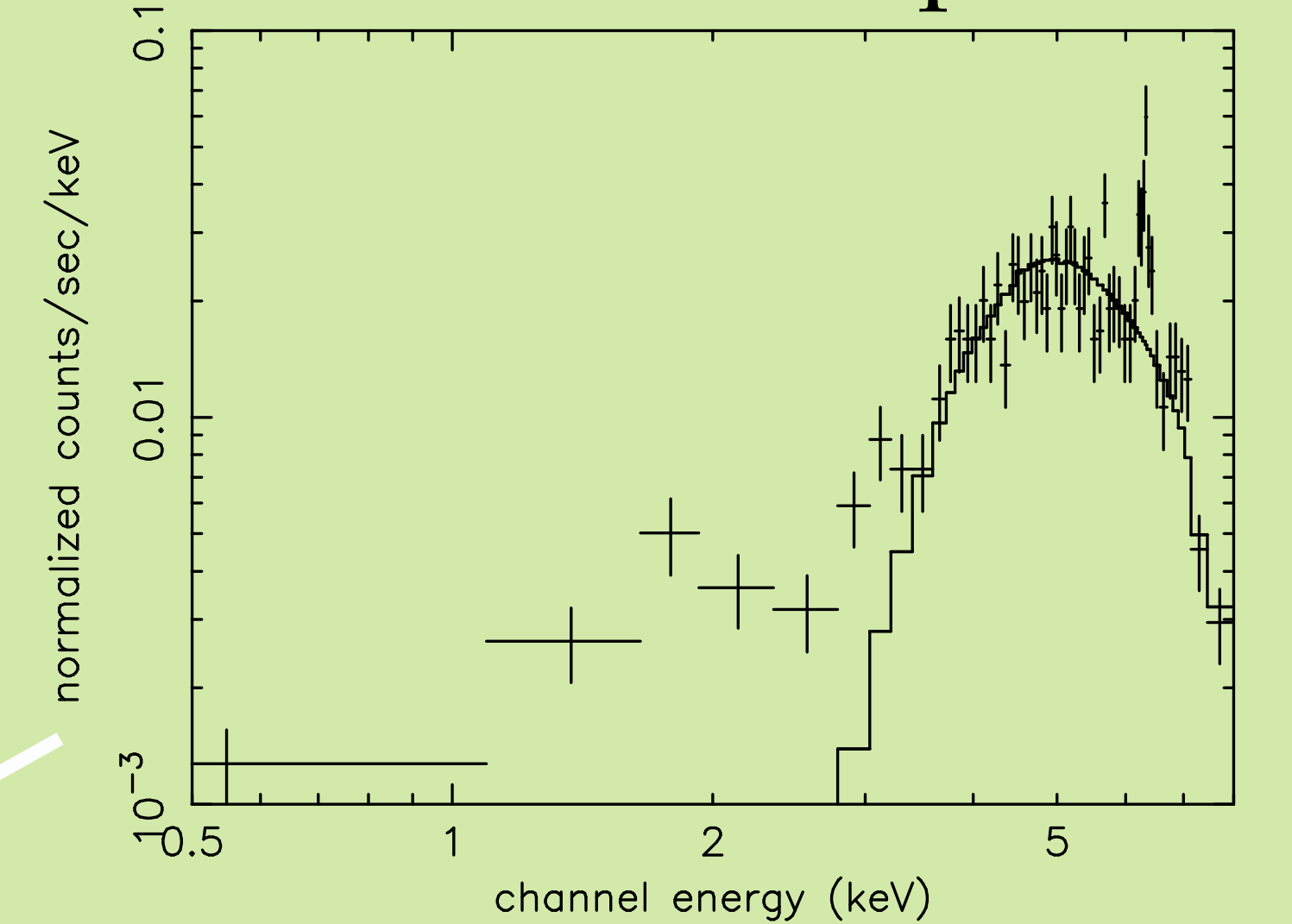
$n \sim 8 \times 10^{-3} \text{ cm}^{-3}$
 $V \sim 250 \text{ kpc}^3$
 $M \sim 5 \times 10^7 M_{\text{solar}}$

$kT \sim 0.3$ keV (0.2 - 0.7)
 $L_x(0.5-2.5 \text{ keV}) \sim 0.6 \times 10^{39} \text{ erg/s}$

X-ray contours (0.3-2.0 keV) overlaid on Ha image



NGC 4388 nucleus spectrum

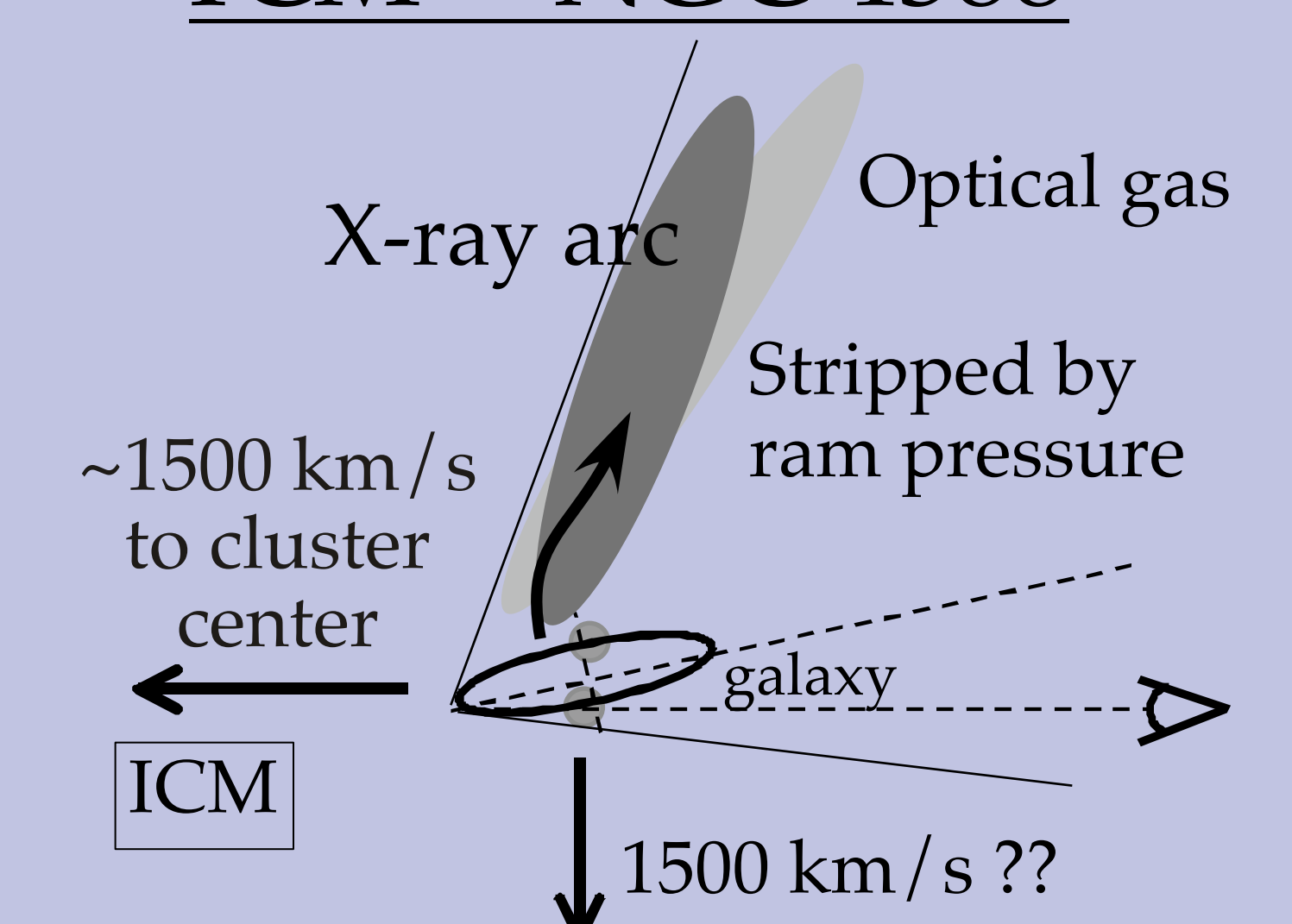


Photon index = 1.8 (fix)
 $N_H \sim 3.5 \times 10^{23} \text{ cm}^{-2}$
 $L_x(2-10 \text{ keV}) \sim 6 \times 10^{41} \text{ erg/s}$ (absorption corrected)
Iwasawa et al. 2003

Virgo ICM spectrum

$kT \sim 1$ keV (1.0 - 1.3)
 $n \sim 5 \times 10^{-4} \text{ cm}^{-3}$

Schematic view of ICM - NGC 4388



Reference

- Iwasawa et al. 2003, astro-ph, 0306139
- Shibata et al. 2001, ApJ, 549, 228
- Vollmer et al. 2001, ApJ, 561, 708
- Yoshida et al. 2002, ApJ, 576, 118
- Yoshida et al. 2003, in prep

Connection between X-ray and Ha

- The distribution of the X-ray roughly follows that of Ha, but is slightly shifted from Ha.
- The X-ray arc seems to be elongated to different direction from Ha.

Emission Mechanism of X-ray arc

× Photoionization by the nucleus

The input energy from AGN is not sufficient for the luminosity of X-ray arc.

Collisionally ionized gas

Moving gas clouds could be heated by the interaction with the Virgo ICM.

Origin of the X-ray arc

× AGN Wind

The observed size of radio jet is only ~ 1 kpc.

× Debris of Ancient Starburst

A starburst superwind should blow on both sides.

× Tidal Debris of a Past Minor Merger

The observed optical velocity should not exceed the infall velocity (~ 250 km/s).

Stripped Gas by Ram Pressure of Virgo ICM

The X-ray arc could be debris from the galaxy by ram pressure of Virgo ICM.

The relative speed between the ICM and X-ray arc (~ 1000 km/s) is high enough to heat ~ 0.3 keV. Numerical simulations predict the feature of observed two streams (Vollmer et al. 2001).