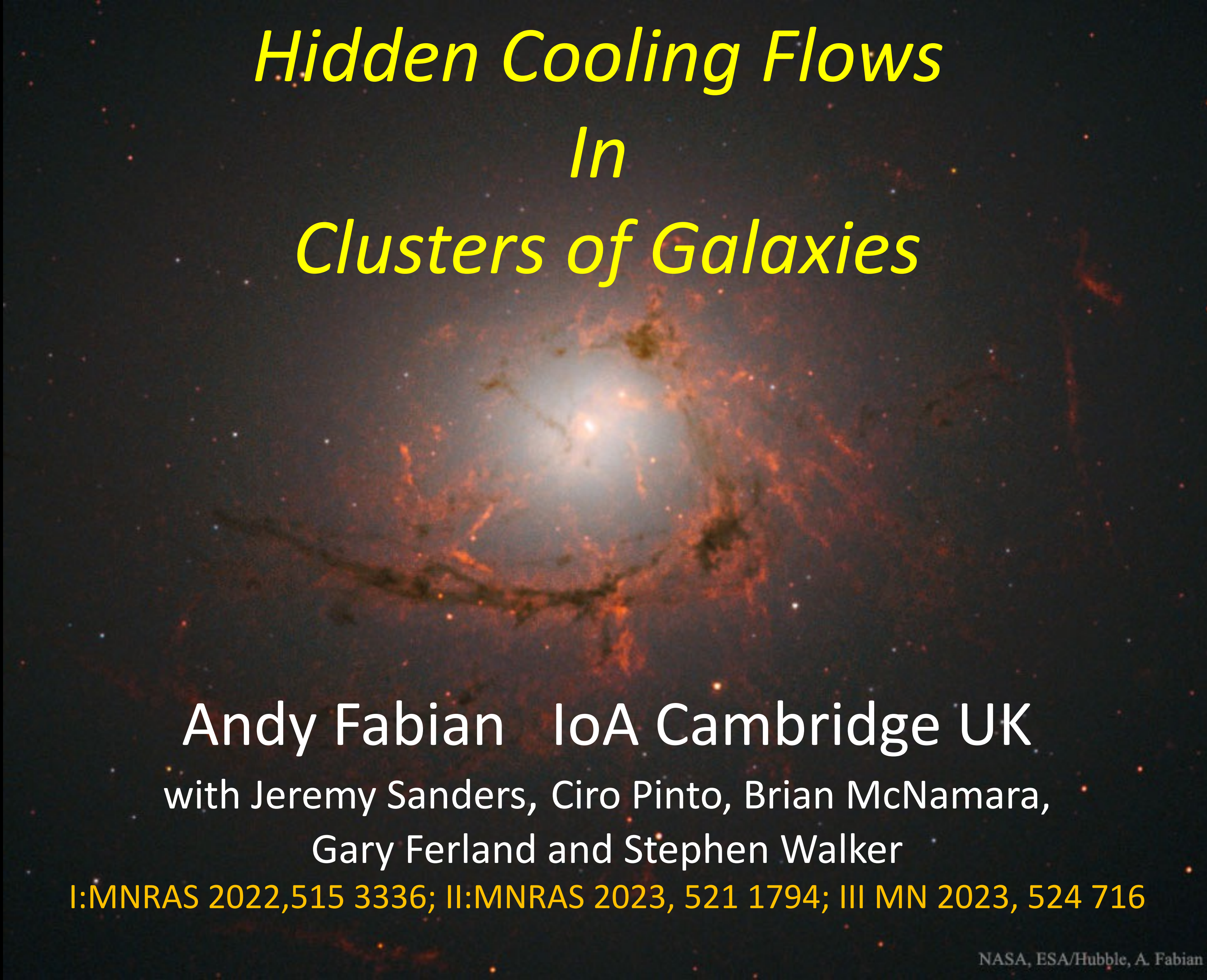
# *Hidden Cooling Flows In Clusters of Galaxies*

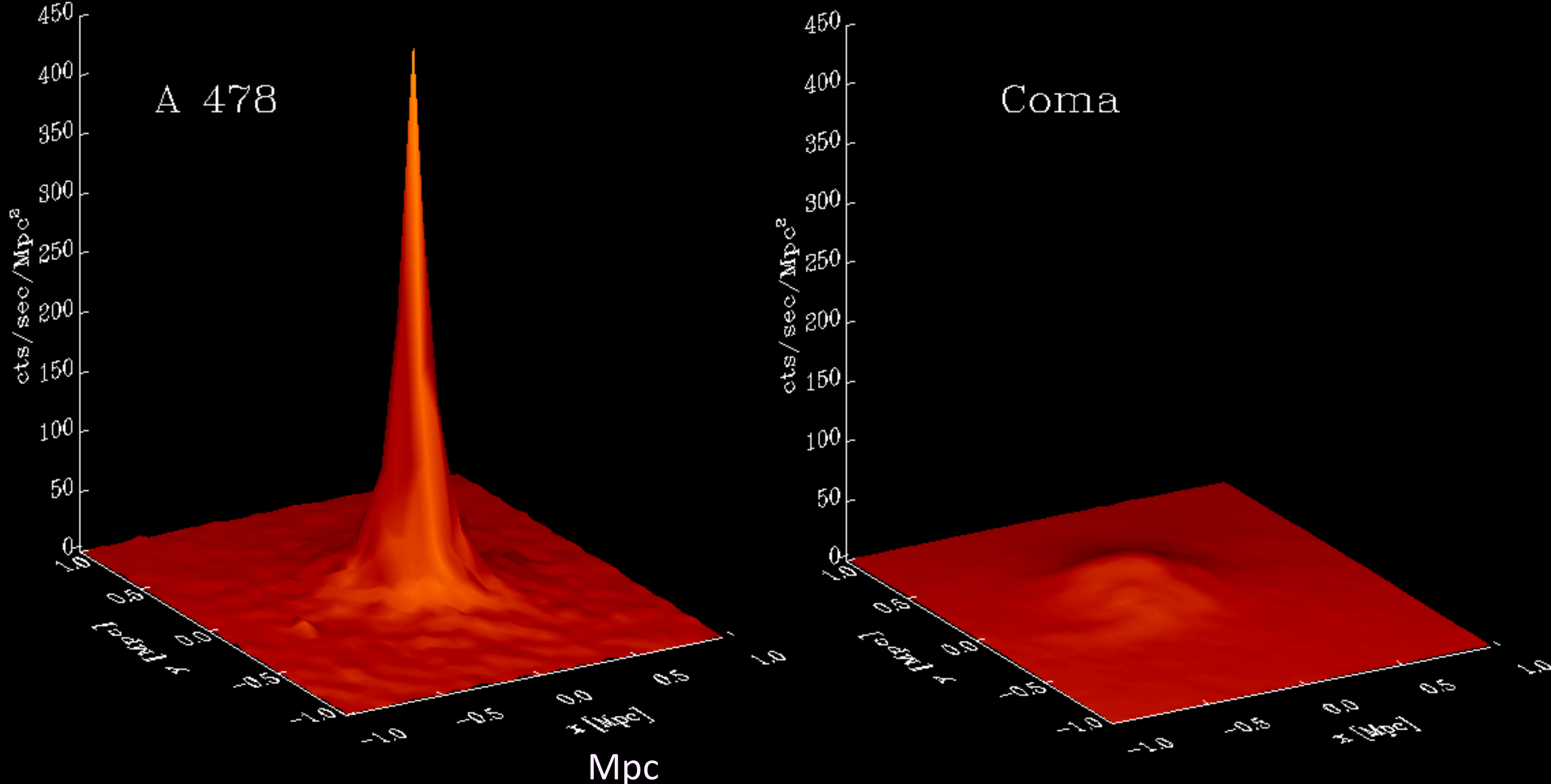

Andy Fabian IoA Cambridge UK

with Jeremy Sanders, Ciro Pinto, Brian McNamara, Gary Ferland and Stephen Walker


I:MNRAS 2022,515 3336; II:MNRAS 2023, 521 1794; III MN 2023, 524 716

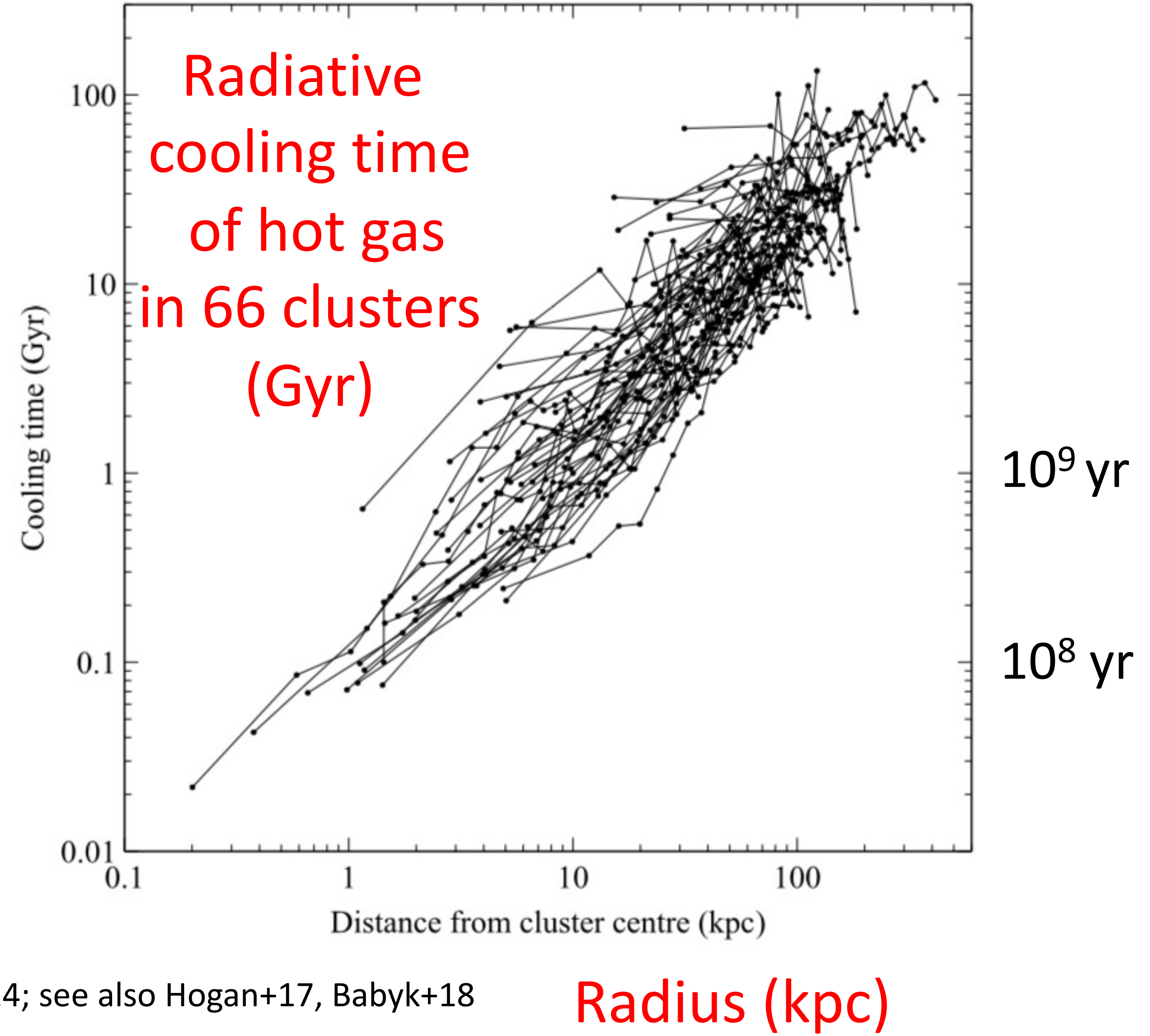


# X-ray surface brightness of typical clusters of galaxies



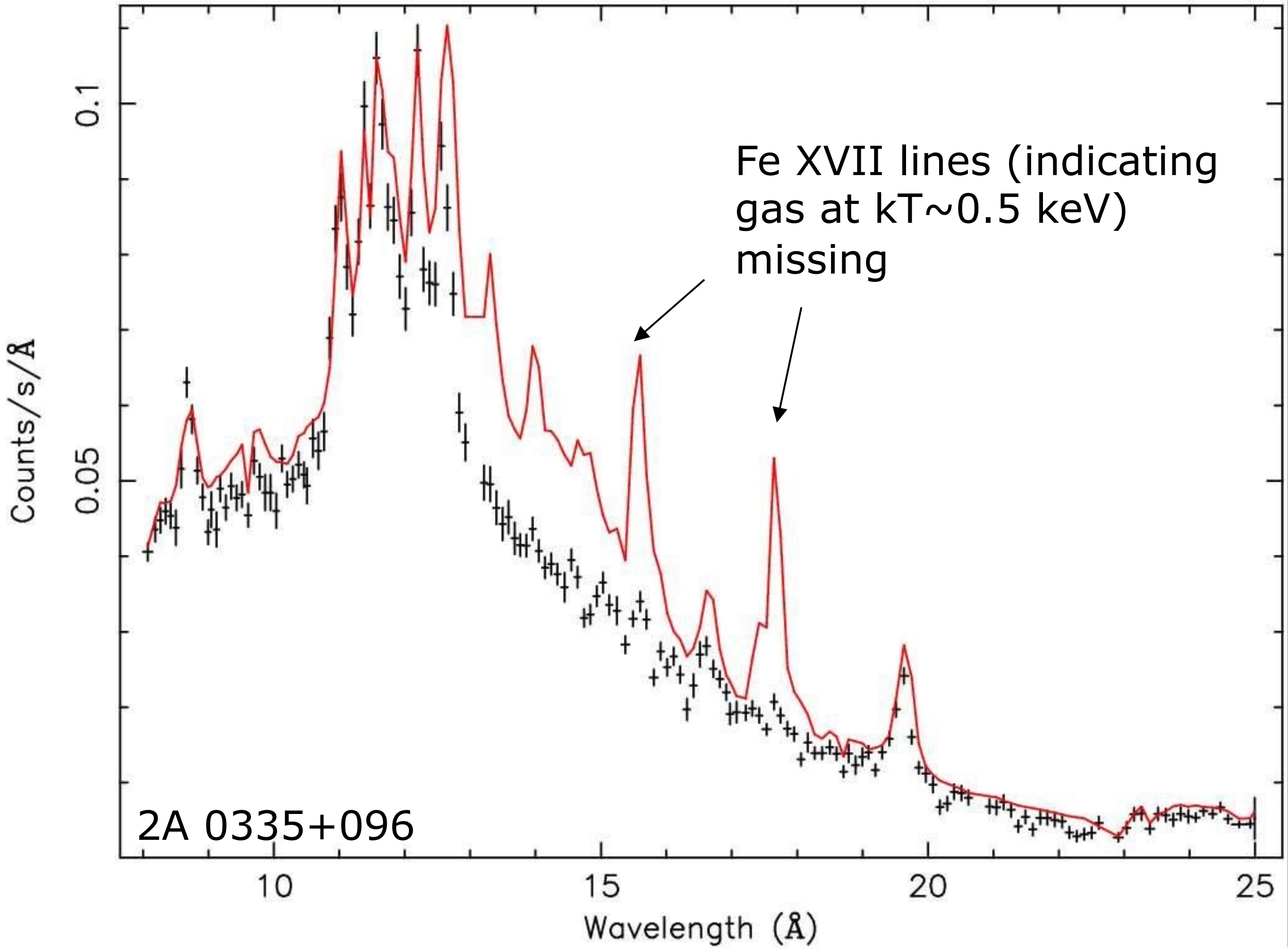

Cool Core

Non Cool Core




Panagoulia+14; see also Hogan+17, Babyk+18

# Lack of cool X-ray emitting gas




Slow cooling in the core of the galaxy cluster 2A 0335+096

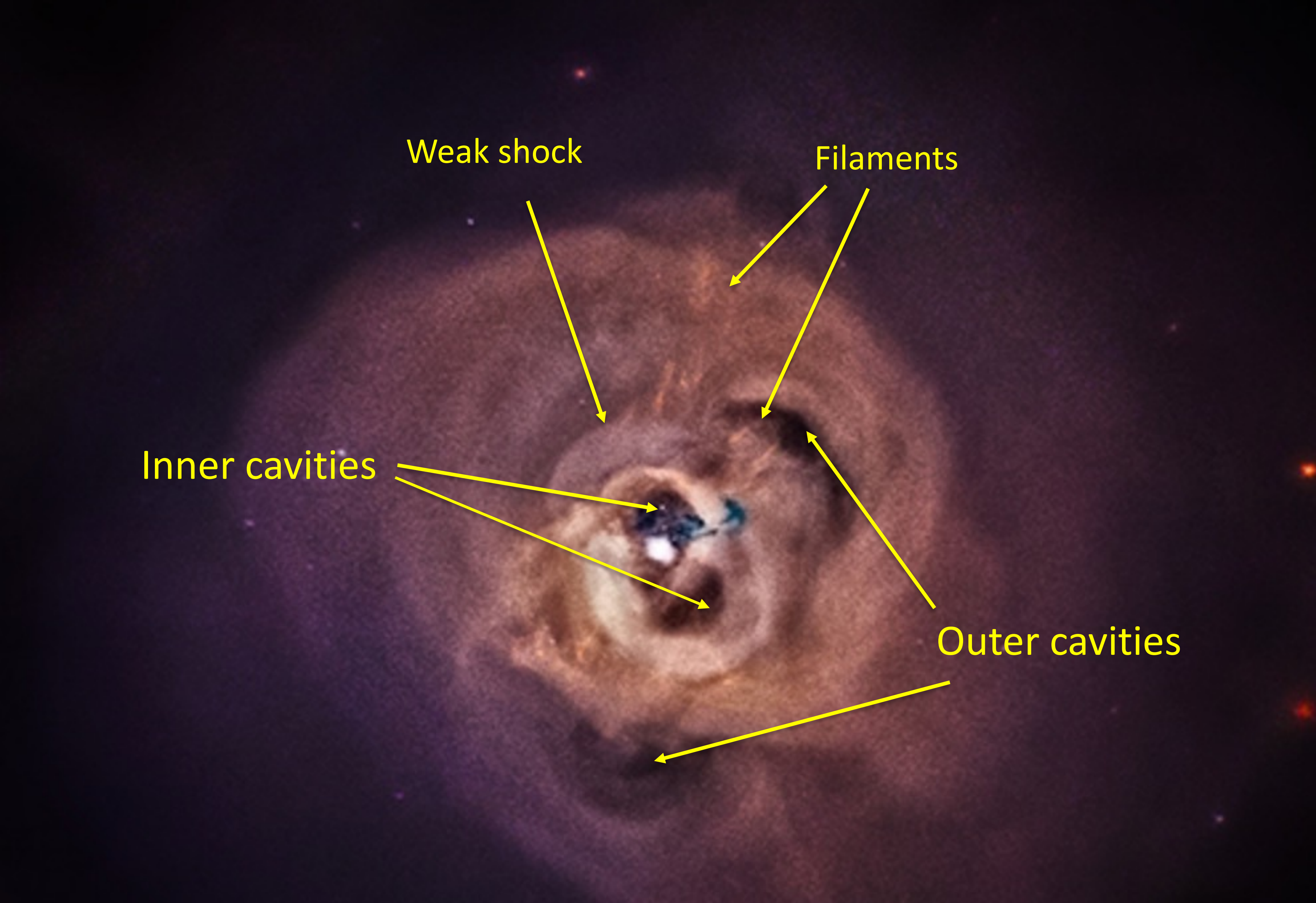
Image courtesy of Jelle de Plaa, SRON, NL.

European Space Agency

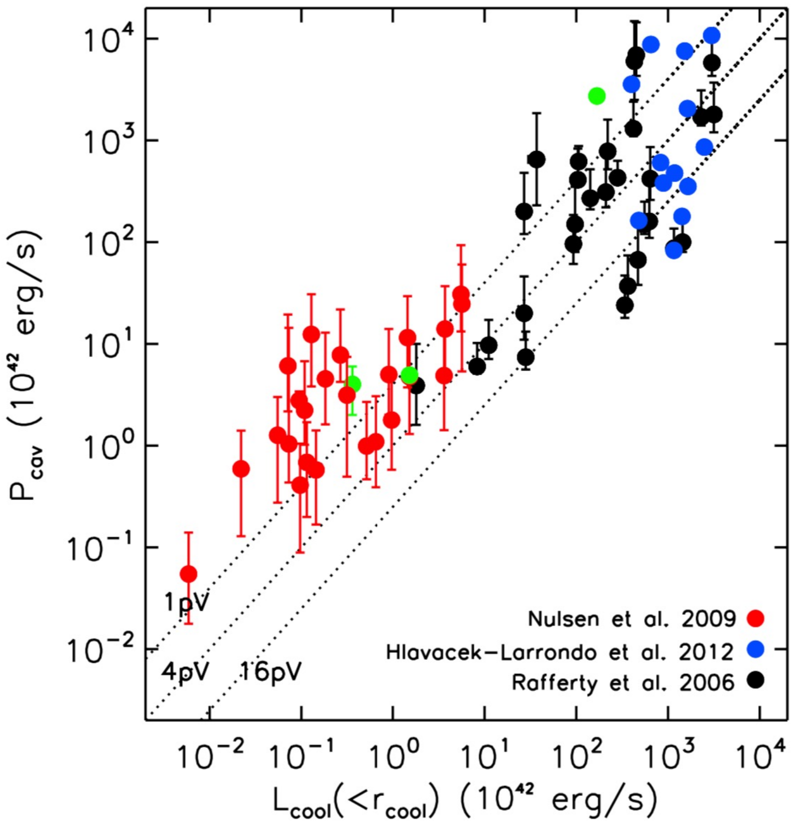
Spectra imply less than 10% of imaging cooling rates

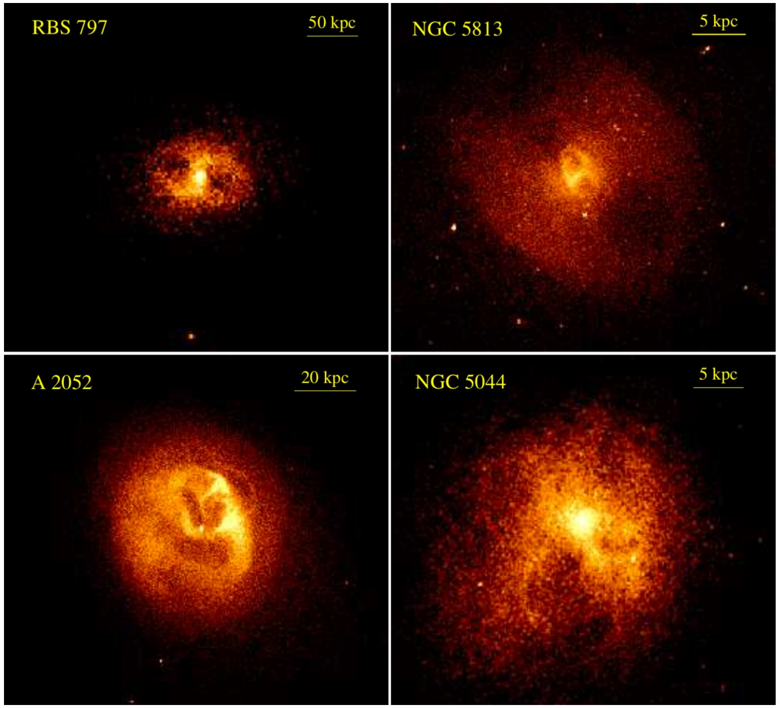
Typical temperature drops to 1/2 to 1/3 of outer temperature

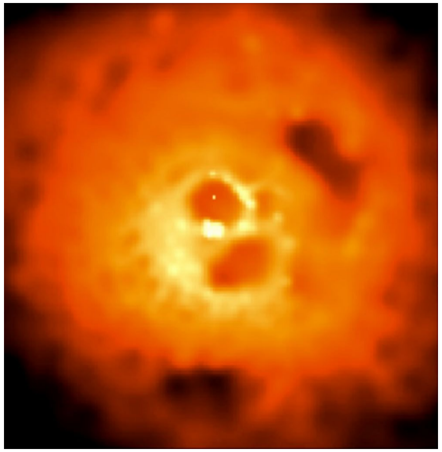
XMM RGS SPECTRUM




Perseus Cluster A426 NGC1275



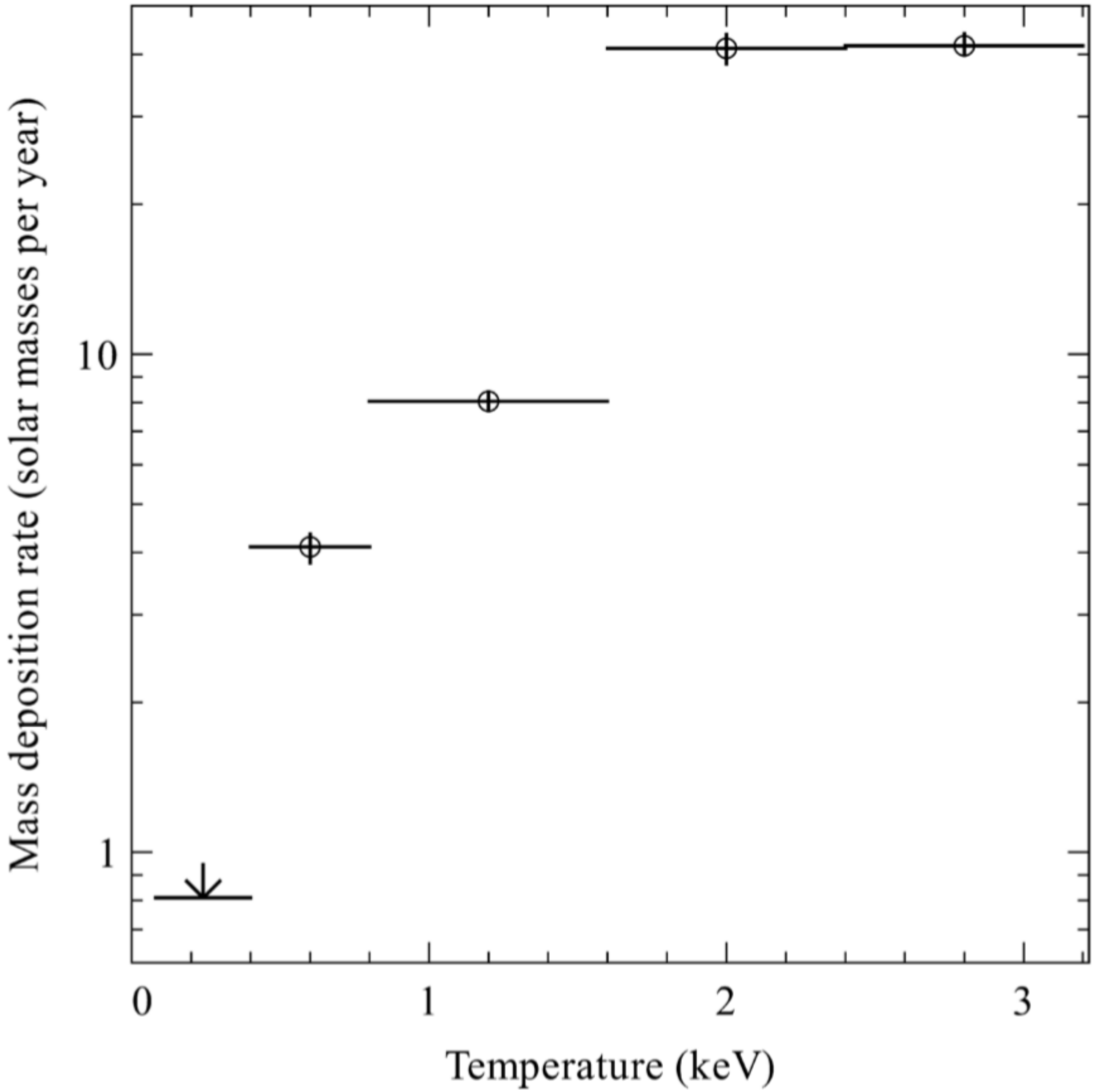



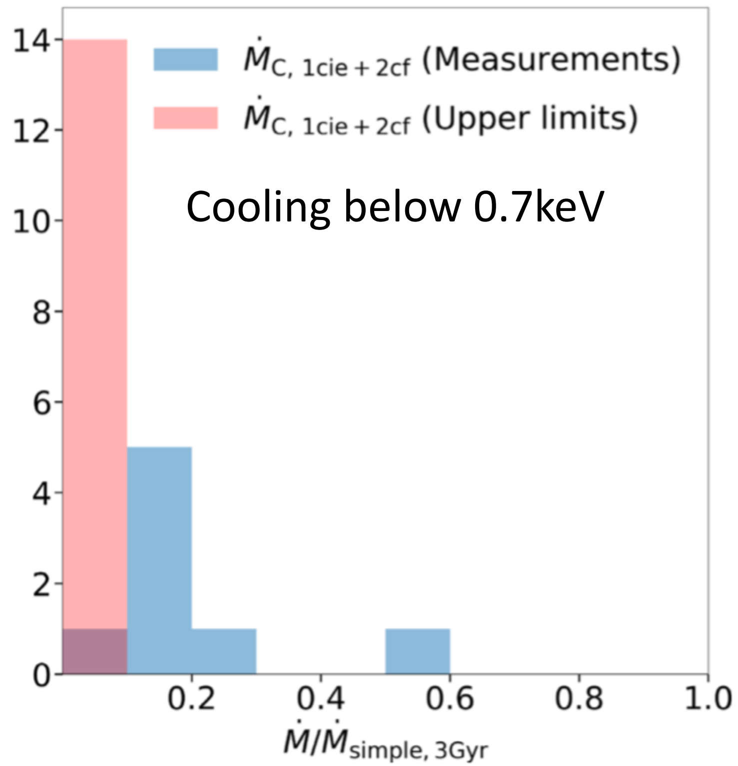
Much of cooling
in core balanced
by heating via bubbles?
AGN Feedback
REVIEWS in
Fabian12; McNamara&Nulsen12

*J. S. Sanders et al.* 08 Centaurus

Mass Cooling Rate



XMM RGS Spectroscopy




Liu, Fabian+19

Little cooling obvious in RGS spectra of cool cores

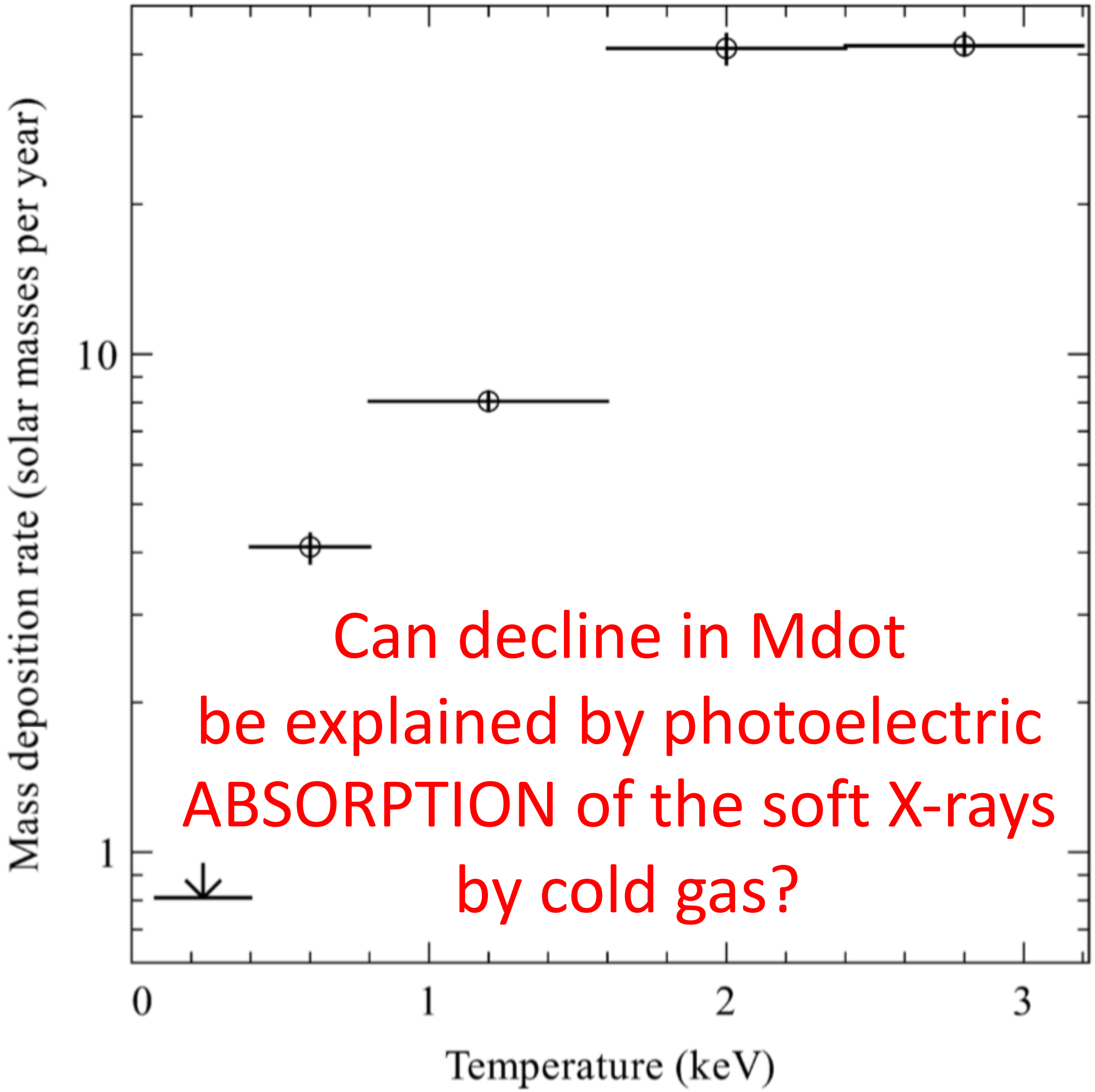
$Mdot_{simple} = M_{gas}(<r)/t_{cool}$ within radius r where $t_{cool}$=3Gyr

AGN feedback in clusters and groups appears continuous and gentle

Reduction of Mdot at small radii and below 1 keV seems like fine tuning?

# *J. S. Sanders et al.* 08 Centaurus

Mass
Cooling
Rate
(Mdot)




Can decline in Mdot
be explained by photoelectric
ABSORPTION of the soft X-rays
by cold gas?

*Mon. Not. R. astr. Soc.* (1991) **252,** 72–81

1991

# The discovery of large amounts of cold, X-ray absorbing matter in cooling flows

D. A. White,[1] A. C. Fabian,[1] R. M. Johnstone,[1] R. F. Mushotzky[2] and K. A. Arnaud[2, 3]

Mon. Not. R. Astron. Soc. **286,** 583–603 (1997)

1997

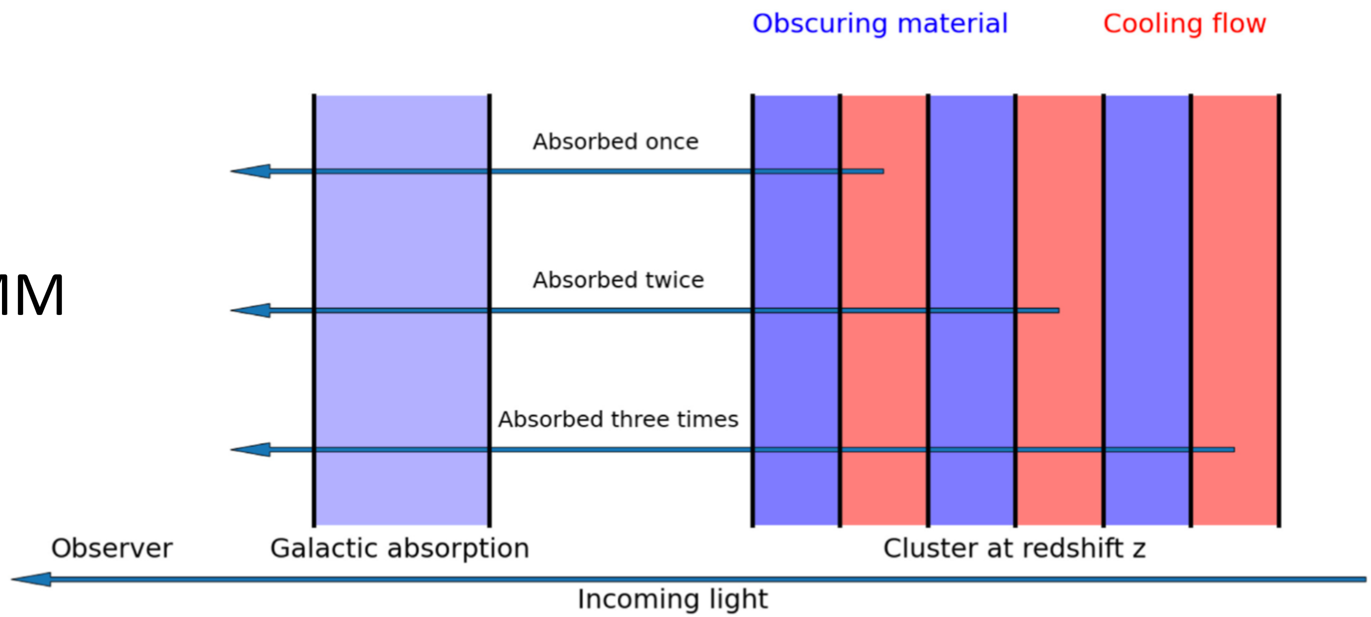
# The spatial distributions of cooling gas and intrinsic X-ray-absorbing material in cooling flows

S. W. Allen and A. C. Fabian
*Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

# Hidden Cooling Flows?

- Include absorption of soft X-rays by cold gas…
- …which occupies same region as cooling gas
- Use multilayer intrinsic absorption model first used on ROSAT PSPC data by Allen&Fabian97
- Energy from gas cooling below 1 keV ultimately emitted by dust and gas in FIR + UVOIR

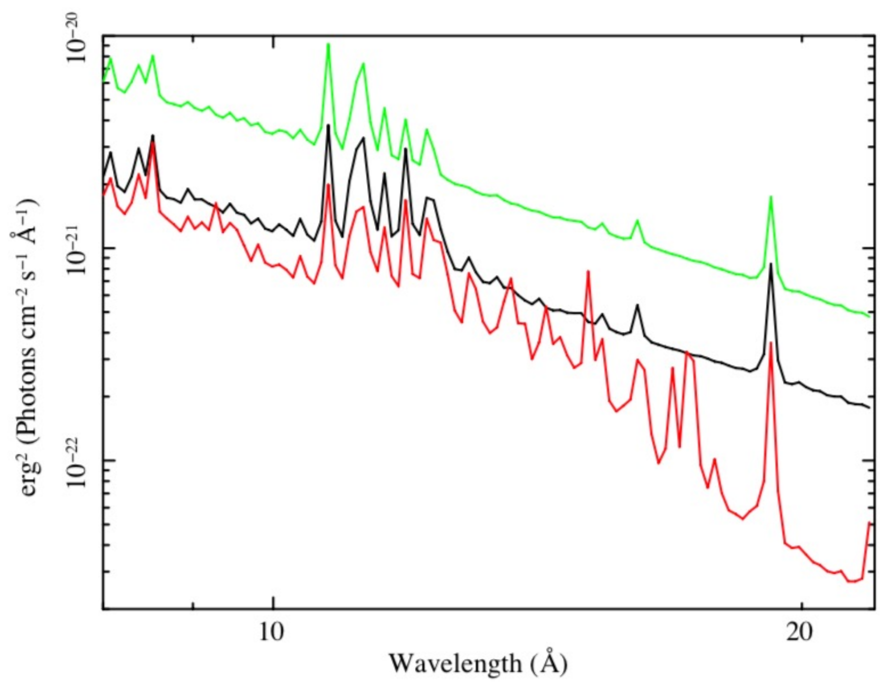
XMM




$$F_t = \frac{F_e(1 - e^{-\sigma N_t})}{\sigma N_t}$$

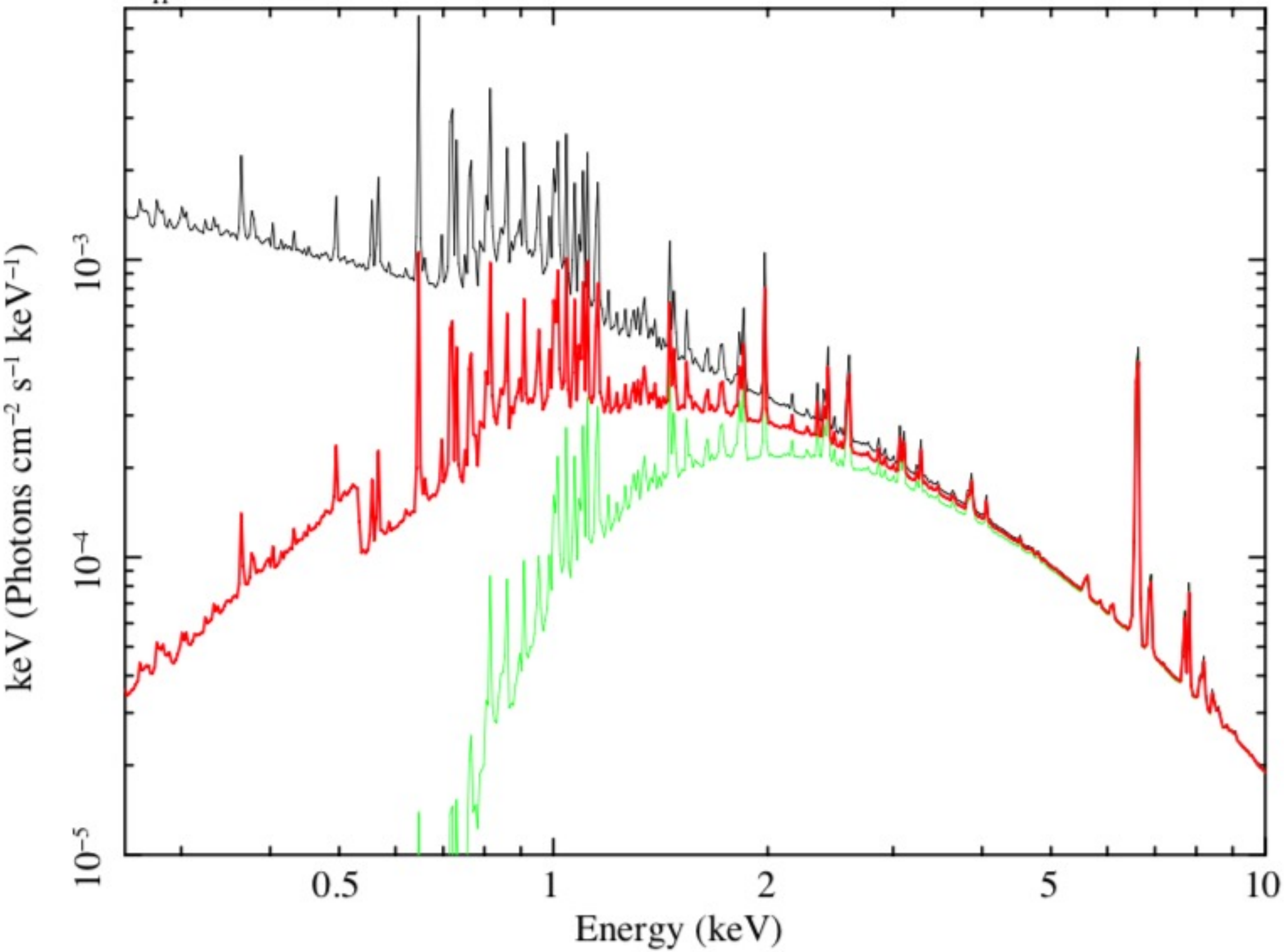
Crawford & Fabian 1992
Allen & Fabian 97 ROSAT
Allen 00,01 ASCA
Liu, Fabian+22 XMM
Also Werner+13, Walker+15

No, Truncated and Hidden Cooling Flow



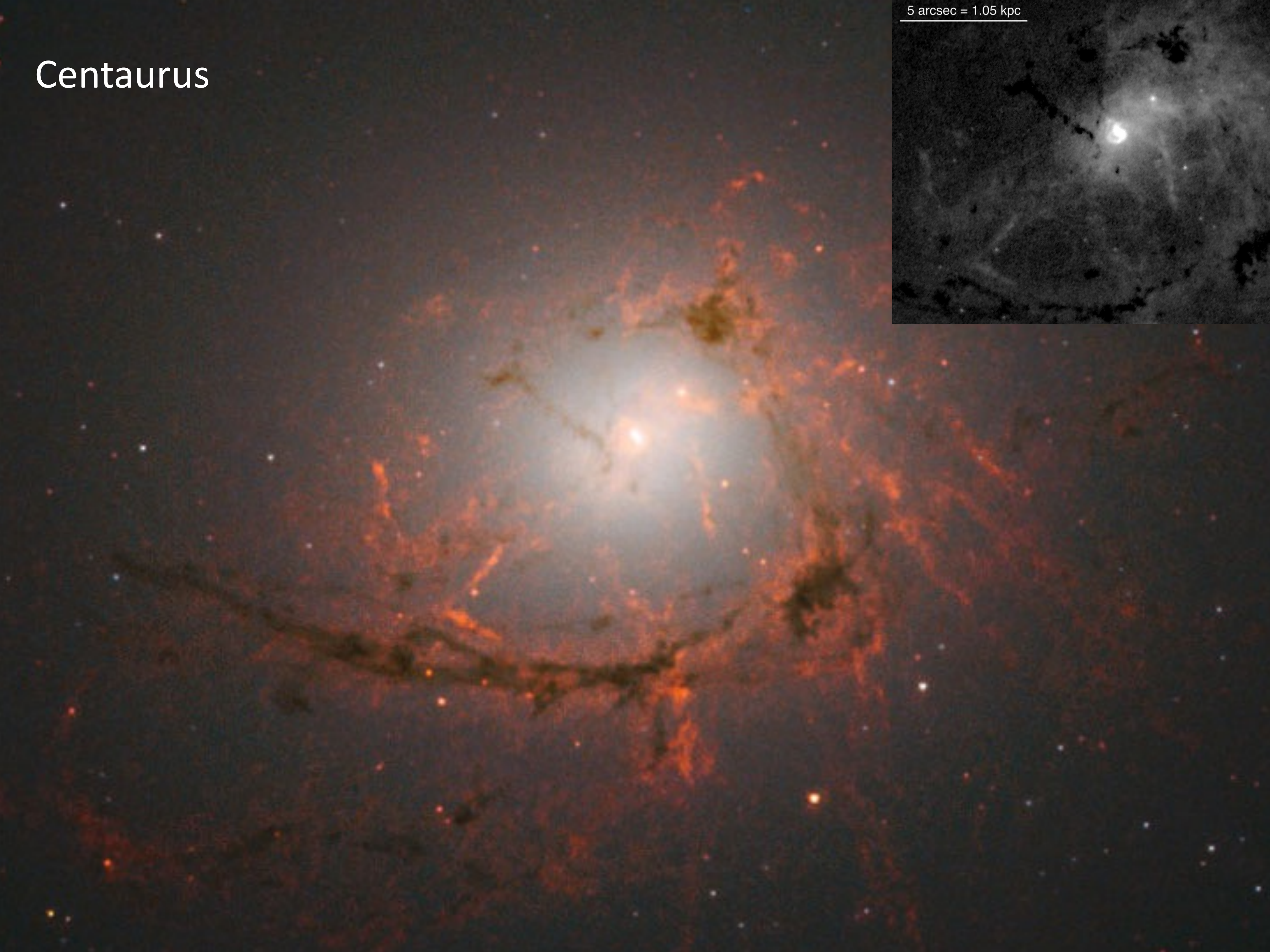
No (black), intrinsic (red) and full (green) absorption

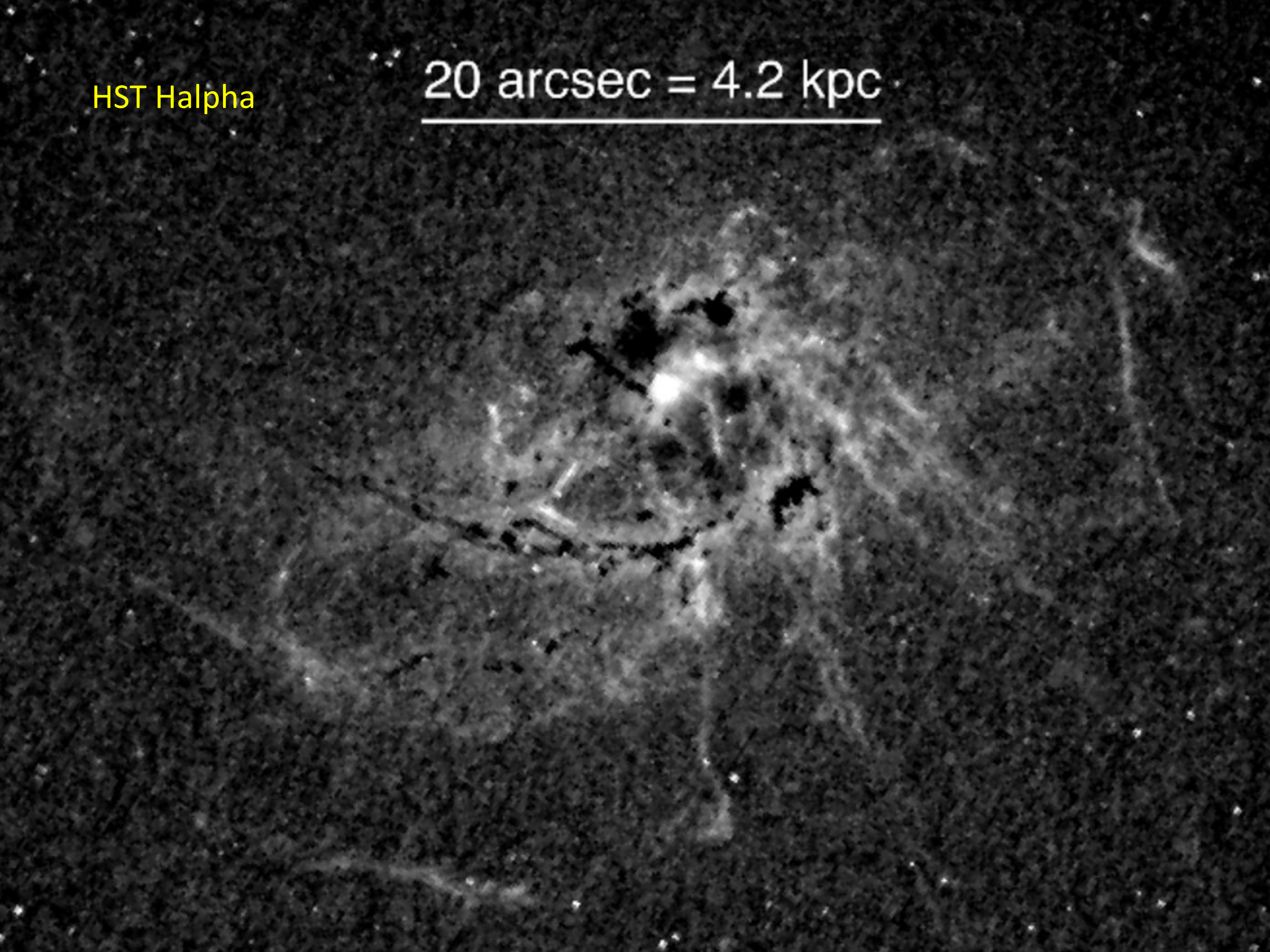
$N_H=10^{22}$ cm$^{-2}$



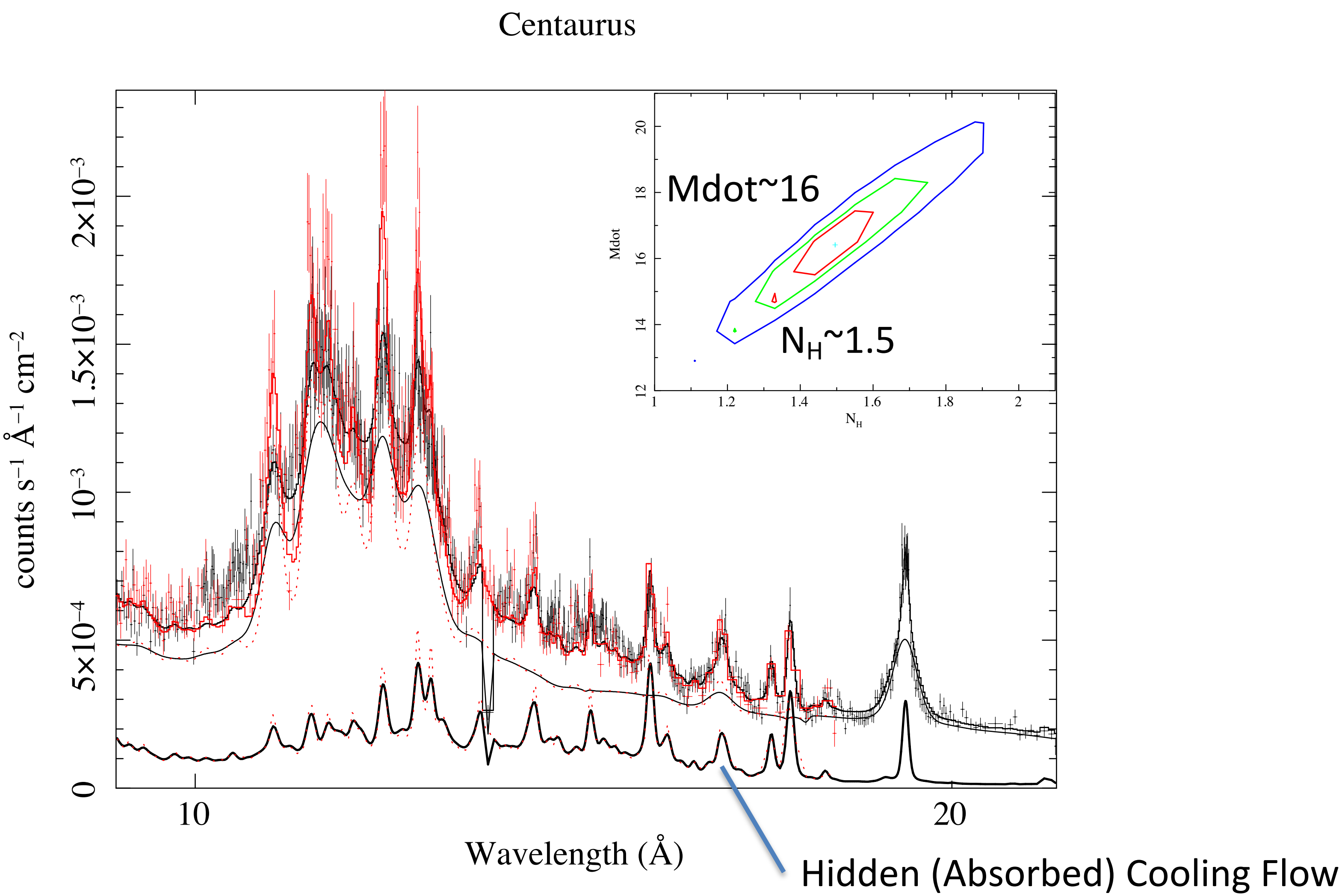
# Centaurus in X-rays (Chandra – Sanders+16)

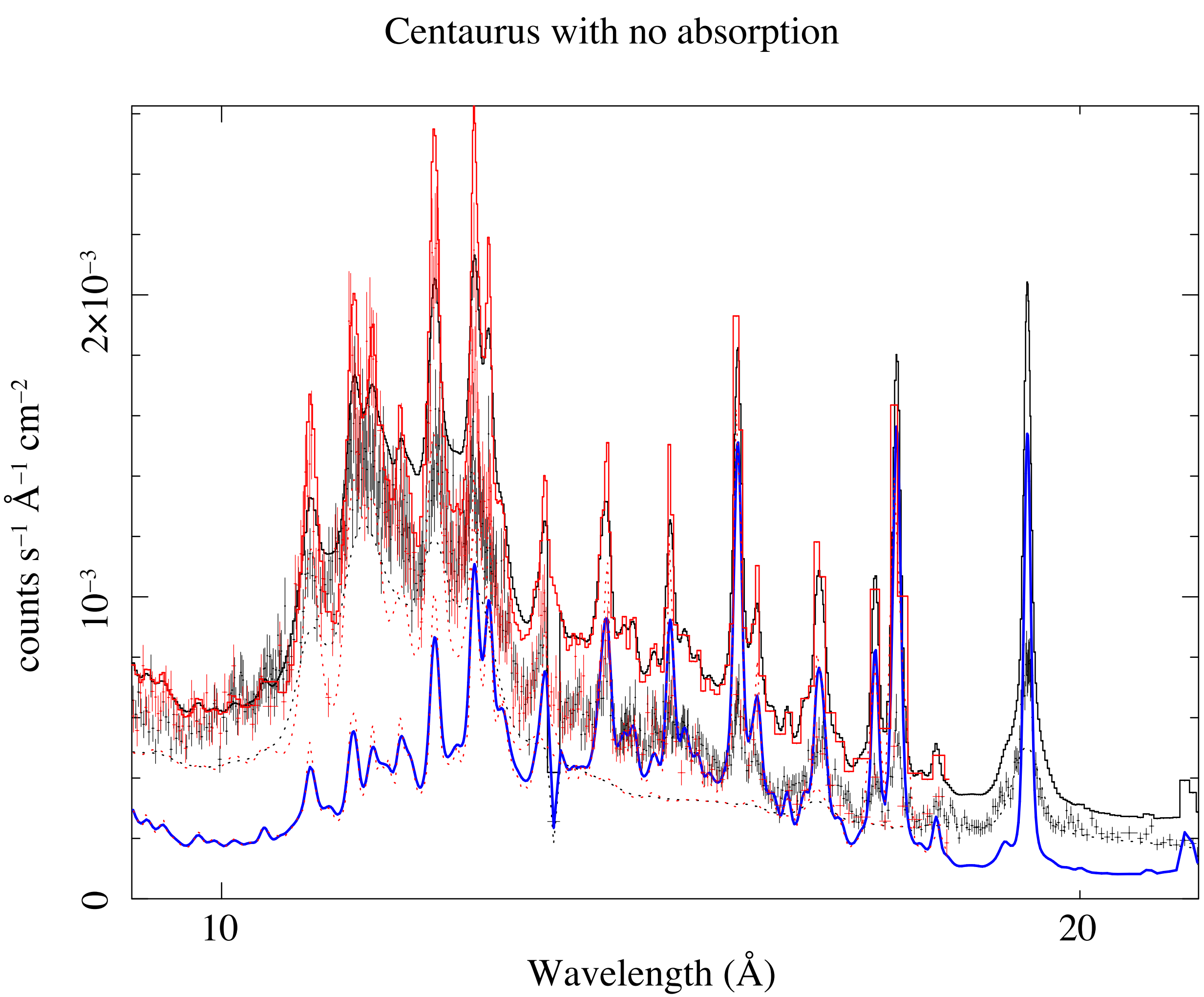
# Centaurus



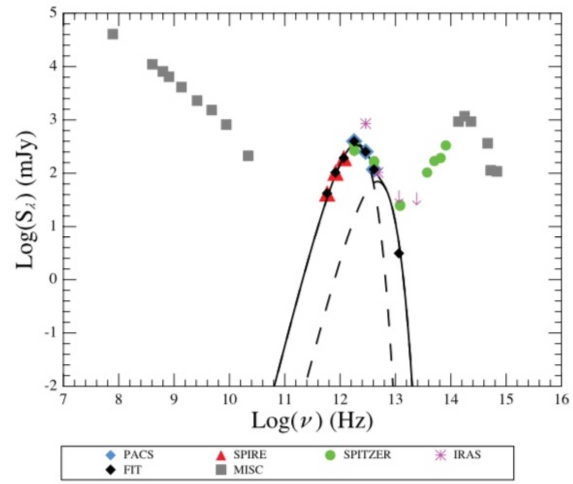

HST Halpha
20 arcsec = 4.2 kpc

XMM RGS

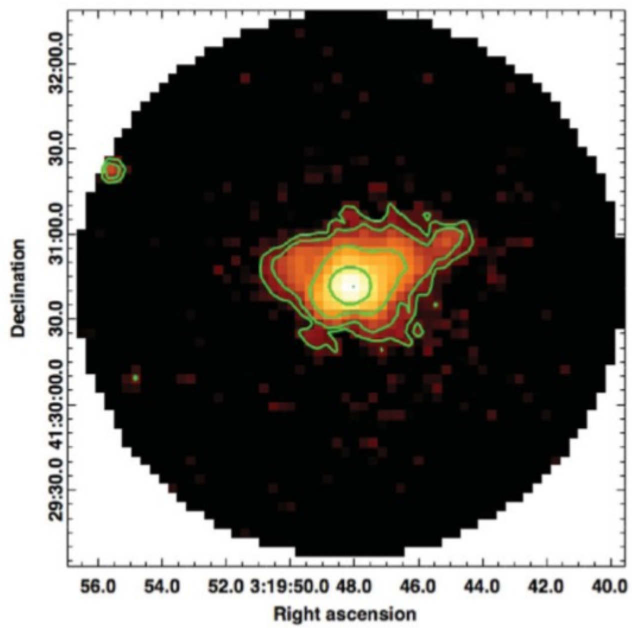

Centaurus
counts s$^{-1}$ Å$^{-1}$ cm$^{-2}$
0
5×10$^{-4}$
10$^{-3}$
1.5×10$^{-3}$
2×10$^{-3}$
10
20
Wavelength (Å)
Mdot
NH
Mdot~16
N$_H$~1.5
Hidden (Absorbed) Cooling Flow


Centaurus with no absorption
counts s$^{-1}$ Å$^{-1}$ cm$^{-2}$
2×10$^{-3}$
10$^{-3}$
0
10
20
Wavelength (Å)

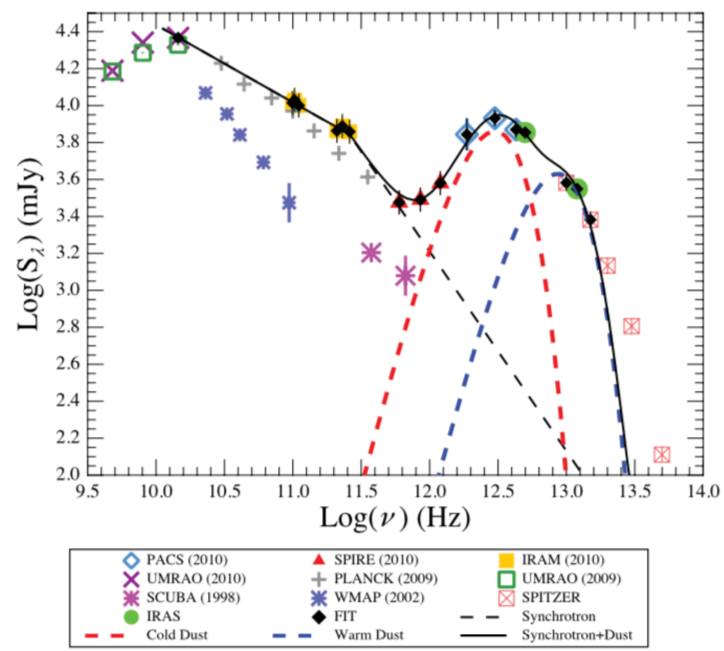
*Herschel observations of the Centaurus cluster*




Far Infrared Mittal+11,12

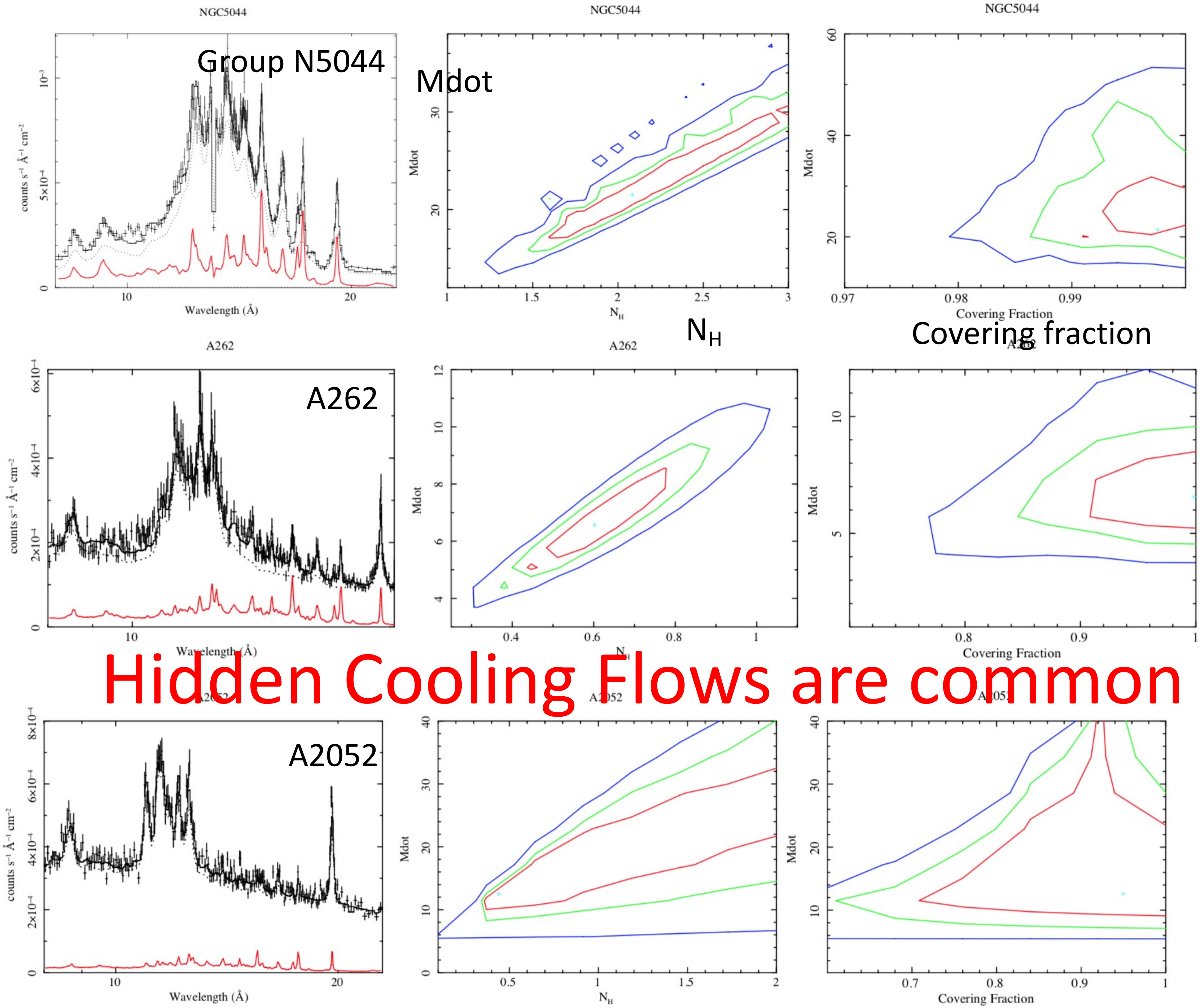


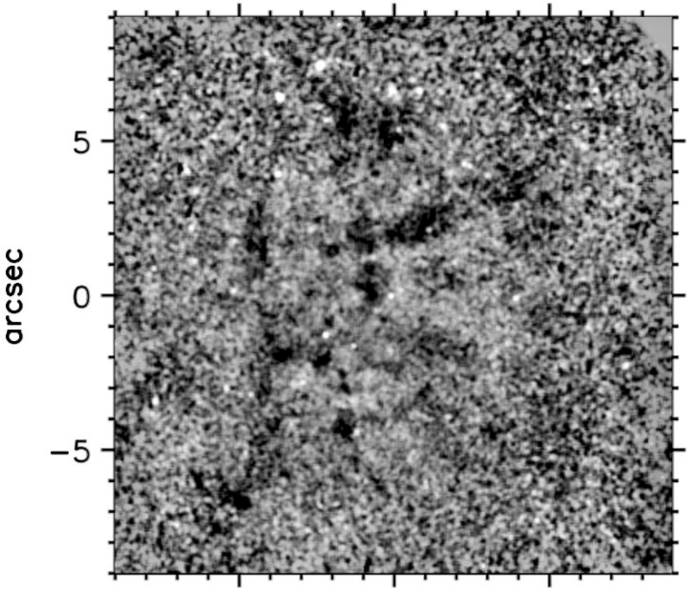

Perseus



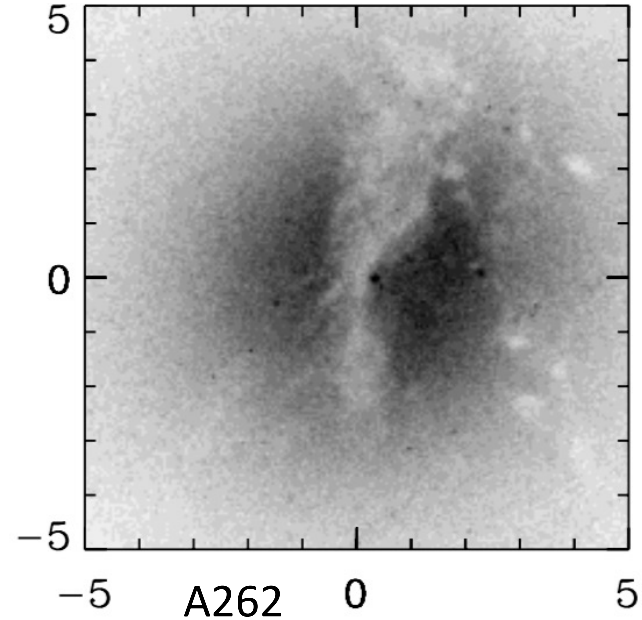
# Will too much gas accumulate?

- Maybe (In 1 Gyr, ~$10^{10}$Msun in Cen, ~$10^{11}$ in Per)
- What is too much?
- There is much cold gas observed in many CC ($10^{8}$-$10^{11}$Msun)
- Speculate: perhaps most in ultracold clouds (<5K?)
- Bubble shocks destroy clouds and drag gas outward, regulating cooled gas mass
- Low mass star formation? High gas pressure lowers Jeans mass: Jura 1977; Fabian+82; Ferland+94… Bottom-heavy IMF van Dokkum+10, Oldham+Auger18 (M87)


Group N5044
Mdot
$N_H$
Covering fraction
A262
A2052
Hidden Cooling Flows are common
NGC5044
A262
A2052
counts s$^{-1}$ Å$^{-1}$ cm$^{-2}$
Wavelength (Å)
Mdot
$N_H$
Covering Fraction



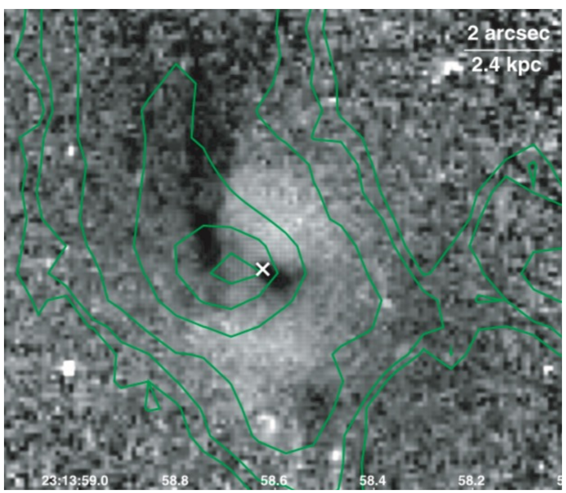

NGC5044



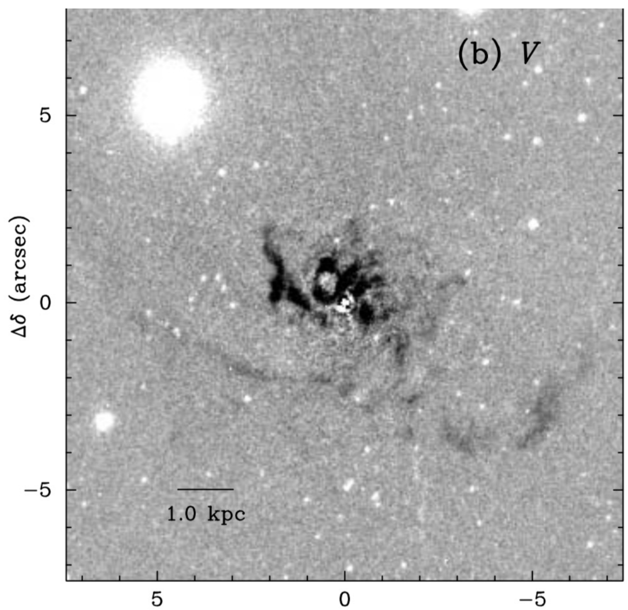

A262

HST images of CCs

note patchy extinction commonly seen

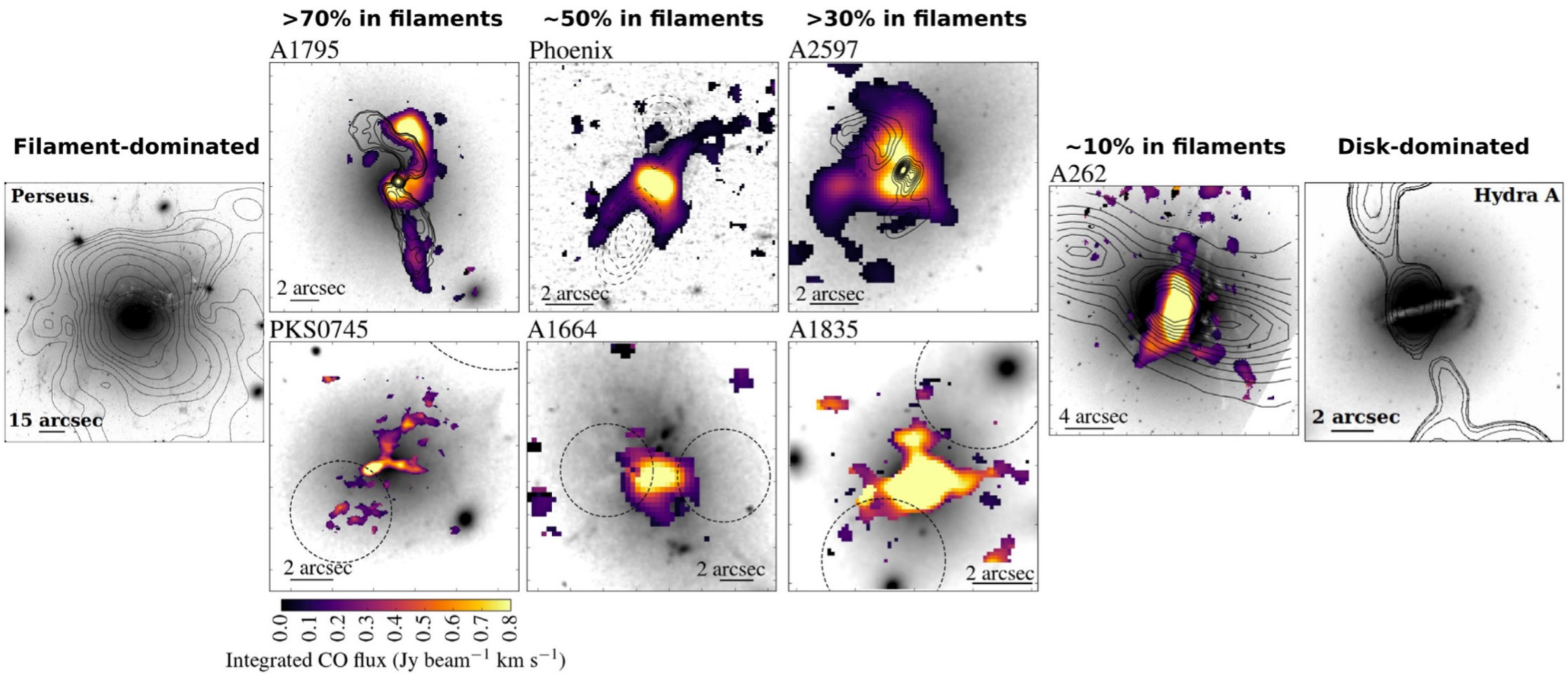



SERSIC 159

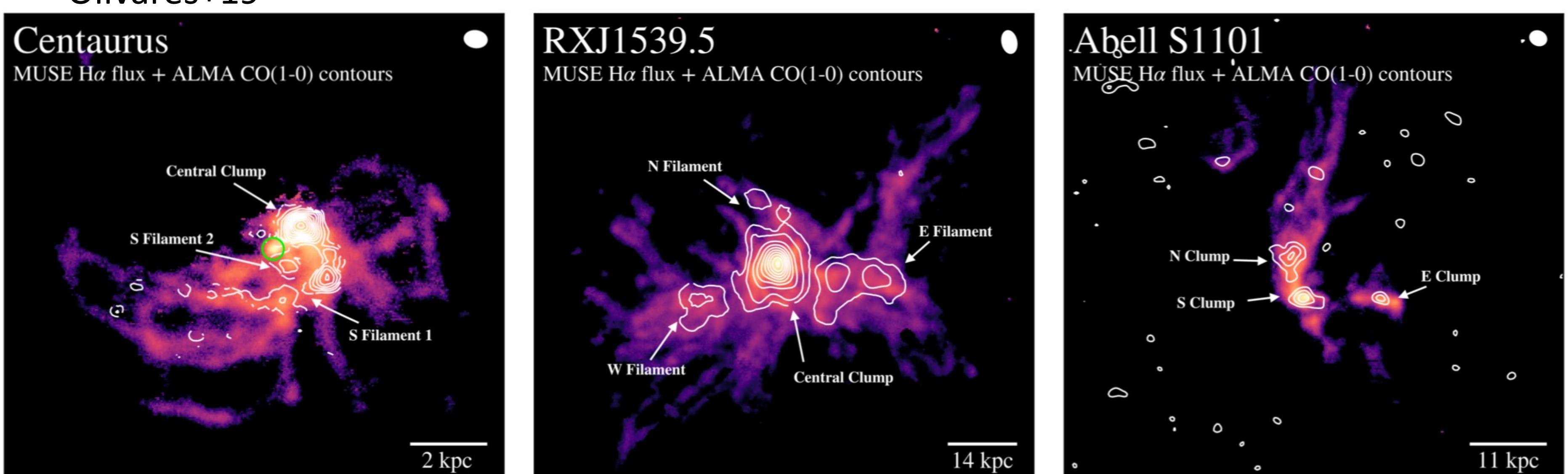


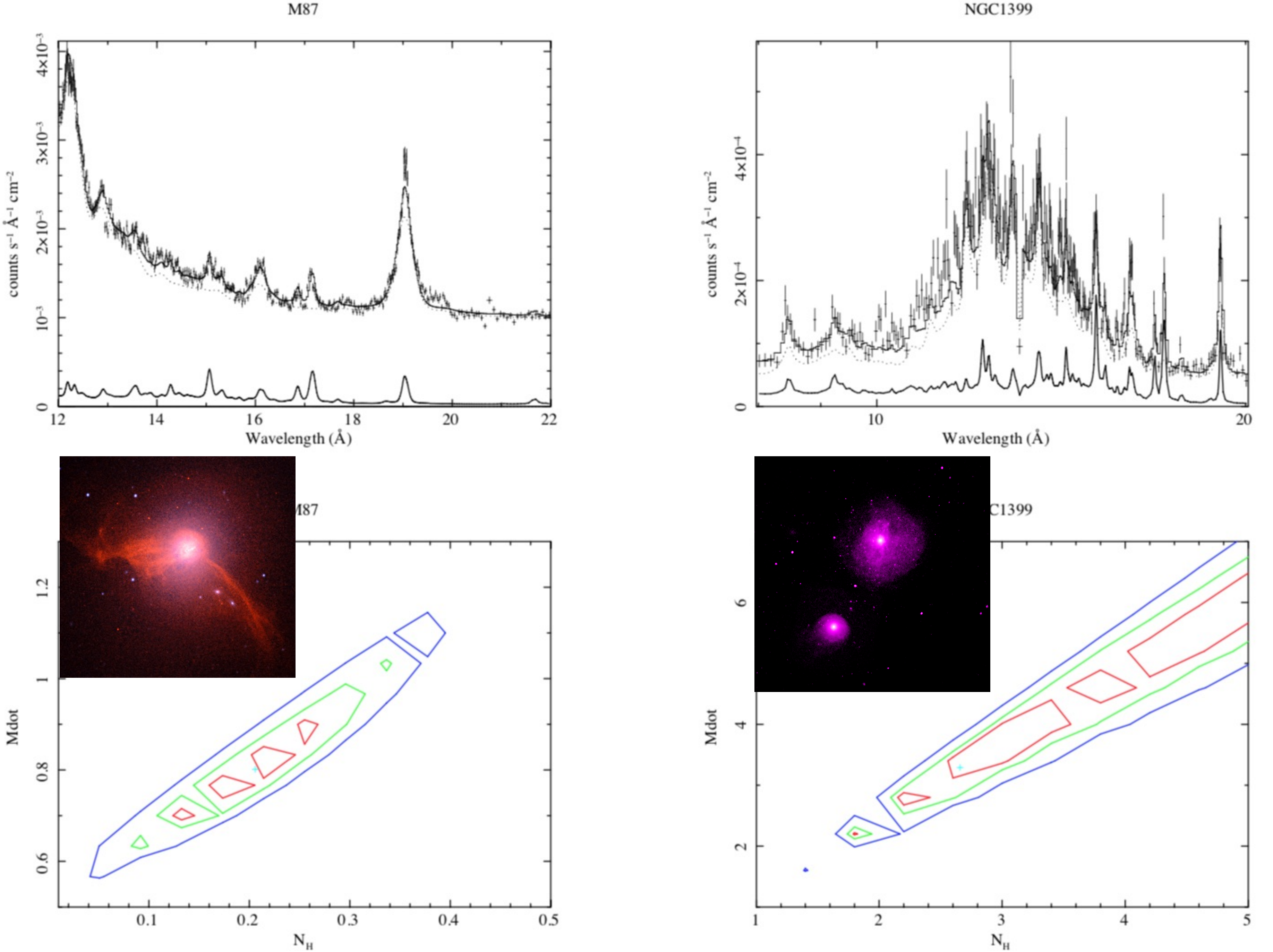

A2052

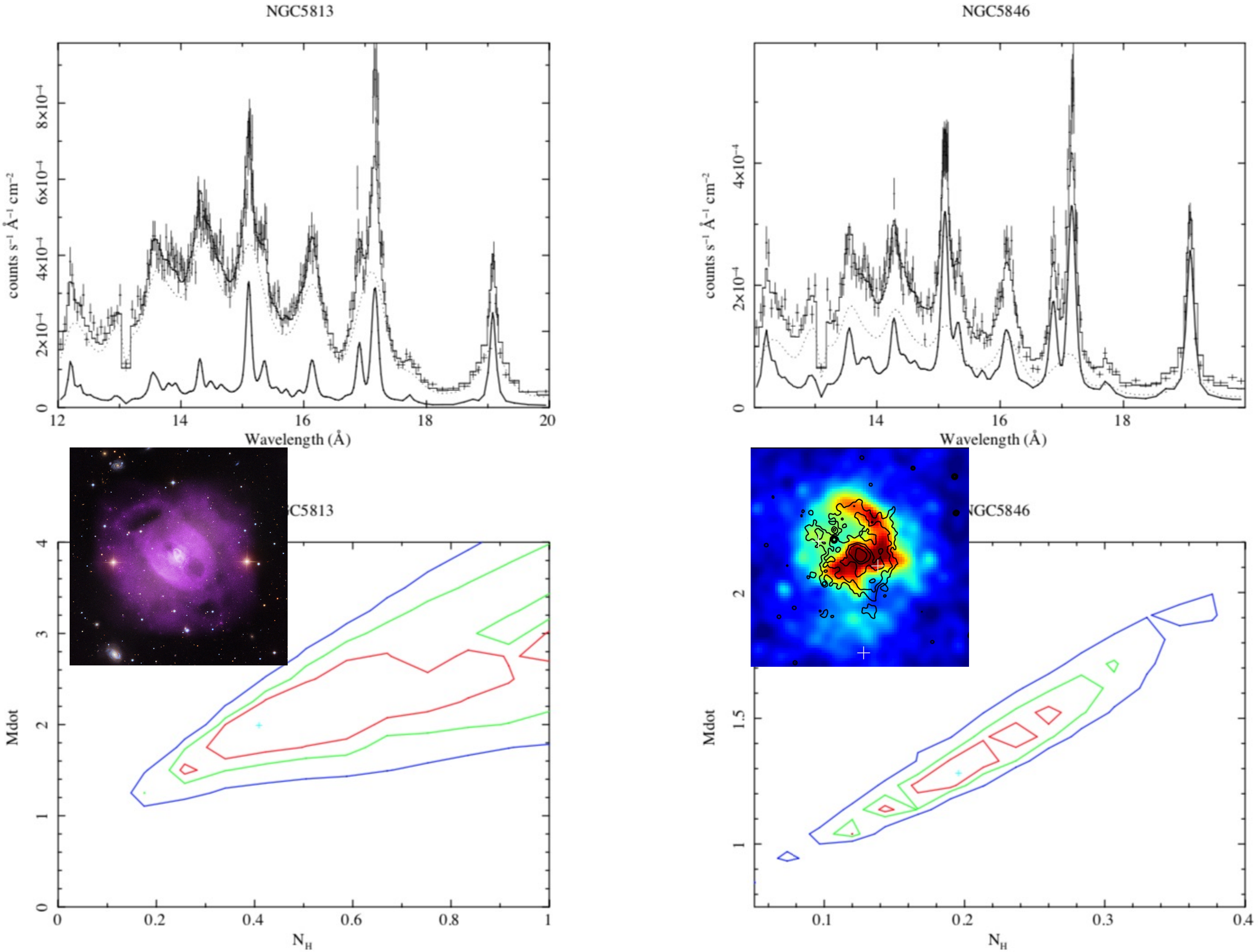
3028 *H. R. Russell et al.* 19




Olivares+19




M87
NGC1399
counts s⁻¹ Å⁻¹ cm⁻²
Wavelength (Å)
M87
C1399
Mdot
N_H

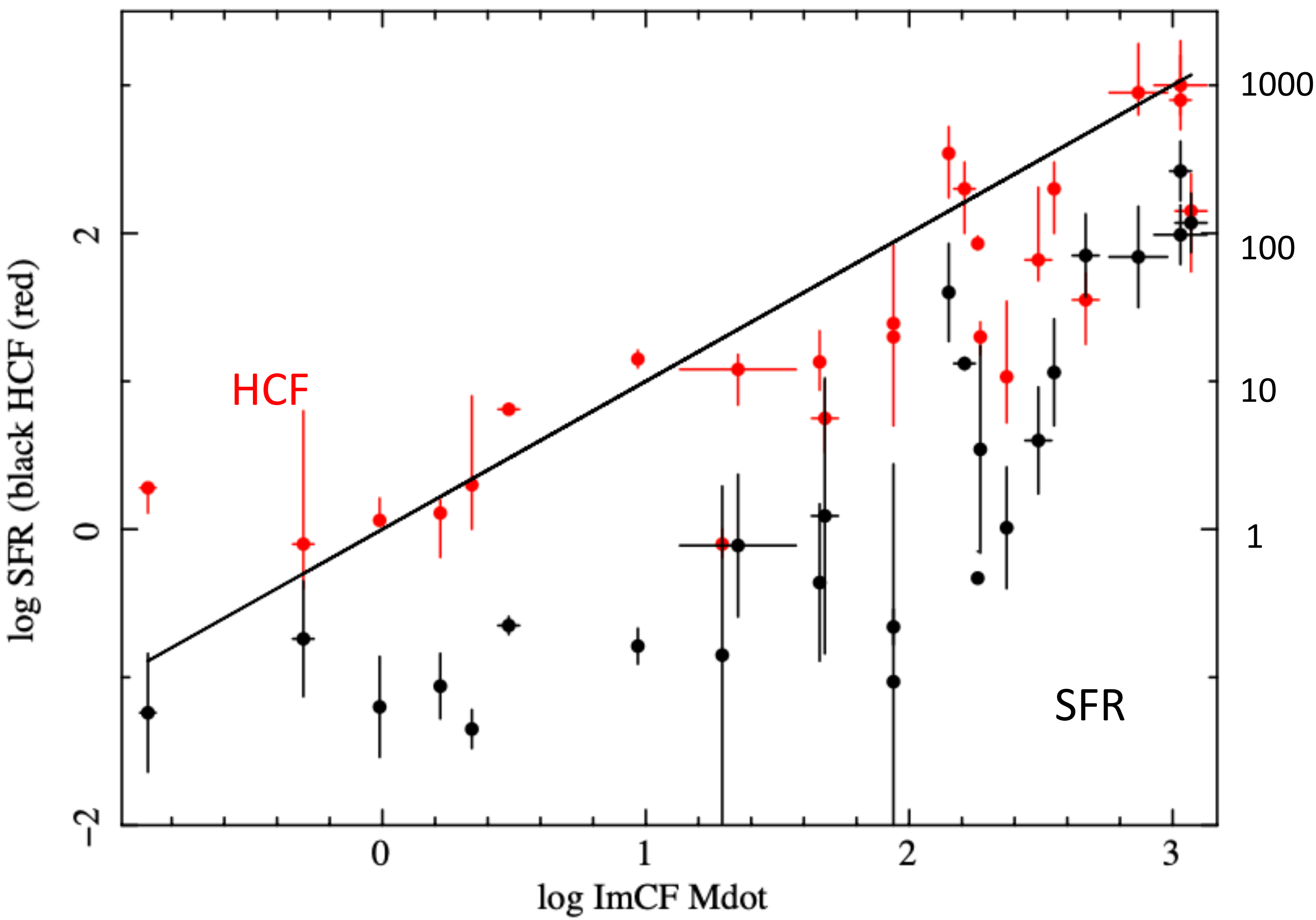


NGC5813
NGC5846
counts s⁻¹ Å⁻¹ cm⁻²
8×10⁻⁴
6×10⁻⁴
4×10⁻⁴
2×10⁻⁴
0
12
14
16
18
20
Wavelength (Å)
Mdot
N_H
0
0.2
0.4
0.6
0.8
1
2
3
4
1.5
0.1
0.3

# $L_a$ is absorbed luminosity

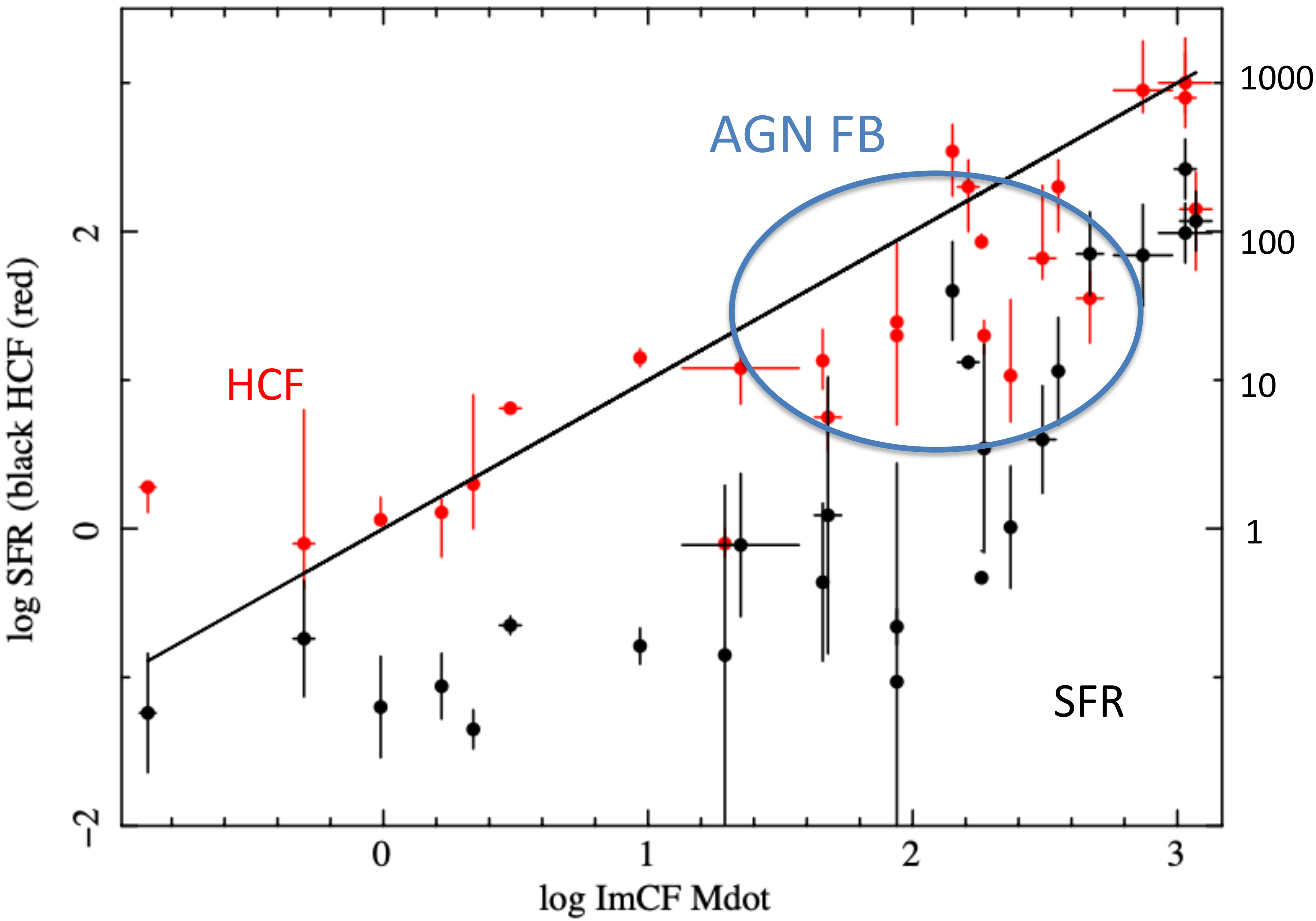
| Cluster | $L$(FIR) | $L_a$ | $\dot{M}$ | $L$(H$\alpha$) | $M_{CO}$ | $M_{BH}$ |
|---|---|---|---|---|---|---|
| | erg s$^{-1}$ | erg s$^{-1}$ | M$_\odot$ yr$^{-1}$ | erg s$^{-1}$ | M$_\odot$ | M$_\odot$ |
| 2A0335 | 4e43 | 2.1e43 | 86 | 8e41 | 1.1e9 | - |
| A85 | 2.8e43 | 9.9e42 | 23 | - | - | 4e10 |
| A496 | - | 9.6e42 | 23 | 5e40 | - | - |
| A2597 | 6.5e43 | 2.1e43 | 67 | 3e42 | 2.3e9 | - |
| A2199 | - | 1.5e42 | 5.6 | 3.5e40 | - | 4e9 |
| M87 | 5.0e41 | 1.6e41 | 0.8 | 1.9e40 | - | 6.5e9 |
| NGC1399 | - | 7.4e41 | 3.3 | 1e39 | | 1$e$9 |
| NGC720 | - | 1.5e41 | 1.0 | - | 1.1e7 | - |
| NGC1550 | - | 8.7e41 | 1.5 | - | - | 4.5e9 |
| NGC1600 | - | 1.3e41 | 0.8 | 4e39 | - | 1.7e10 |
| NGC3091 | - | 1.6e42 | 8.5 | - | - | 3.6e9 |
| NGC5813 | 1.1e42 | 5.9e41 | 2.0 | 1.6e40 | - | - |
| NGC5846 | 6.2e41 | 2.0e41 | 1.3 | 2.5e40 | 2e6 | - |
| MRK1216 | - | 1.3e41 | 9.7 | - | - | 4.9e9 |
| ZW3146 | 1.0e45 | 6.3e44 | 1570 | 6e42 | 5e10 | - |
| NGC5044 | 3.0e42 | 3.6e42 | 20 | 7.0e40 | 1.5e8 | |
| Sersic 159 | 7.3e42 | 2.5e42 | 10 | 2.0e41 | 1.1e9 | |
| A262 | 8.0e42 | 2.1e42 | 7 | 9.4e40 | 4.0e8 | |
| A2052 | 8.3e42 | 4.4e42 | 15 | 6e40 | 2.8e8 | |
| RXJ0821 | 4.5e44 | 7.8e42 | 40 | 3.0e41 | 3.9e10 | |
| RXJ1532 | 2.3e45 | 2.0e44 | 1000 | 3e42 | 8.7e10 | |
| MACS1931 | 5.6e45 | 4.6e44 | 1000 | 2e42 | 9.0e10 | |
| Phoenix Cluster | 3.7e46 | 3.3e44 | 2000 | 8.5e43 | 2e10 | |
| M84 | 1.0e42 | 3.3e41 | 2.0 | 4.0e39 | <1.8e7 | |
| M49 | 1.2e42 | 2.0e41 | 1.0 | 5.8e39 | <1.4e7 | |
| Centaurus | 3.2e42 | 3.6e42 | 15 | 1.7e40 | 1.0e8 | |
| Perseus | 5.6e44 | 5.8e42 | 50 | 3.2e42 | 2.0e10 | |
| A1835 | 3.2e45 | 5.2e43 | 400 | 4.4e42 | 5.0e10 | |
| RXJ1504 | - | 1.9e44 | 520 | 3.2e43 | 1.9e10 | |

ImCF and SFR from McDonald+18




Mdot from Chandra imaging

ImCF and SFR from McDonald+18




Mdot from Chandra imaging

# Other Evidence of Cooling Gas

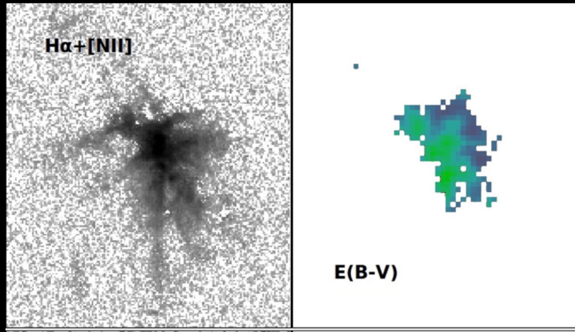
- OVI emission from gas at $T \sim 10^{5.5}$ K detected by FUSE in A2597 (Oegerle+2001). Confirmed by Bregman+ in 2006 who also found OVI in Perseus and A1795.

- EUV emission spectrum from HCF consistent with optical line ratios in Cool Cores (Polles+2021).

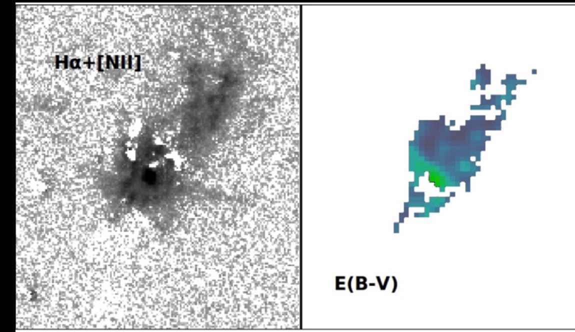
- Chandra X-ray spectrum of filaments in Perseus and Centaurus consistent with HCF spectrum (HCF1).

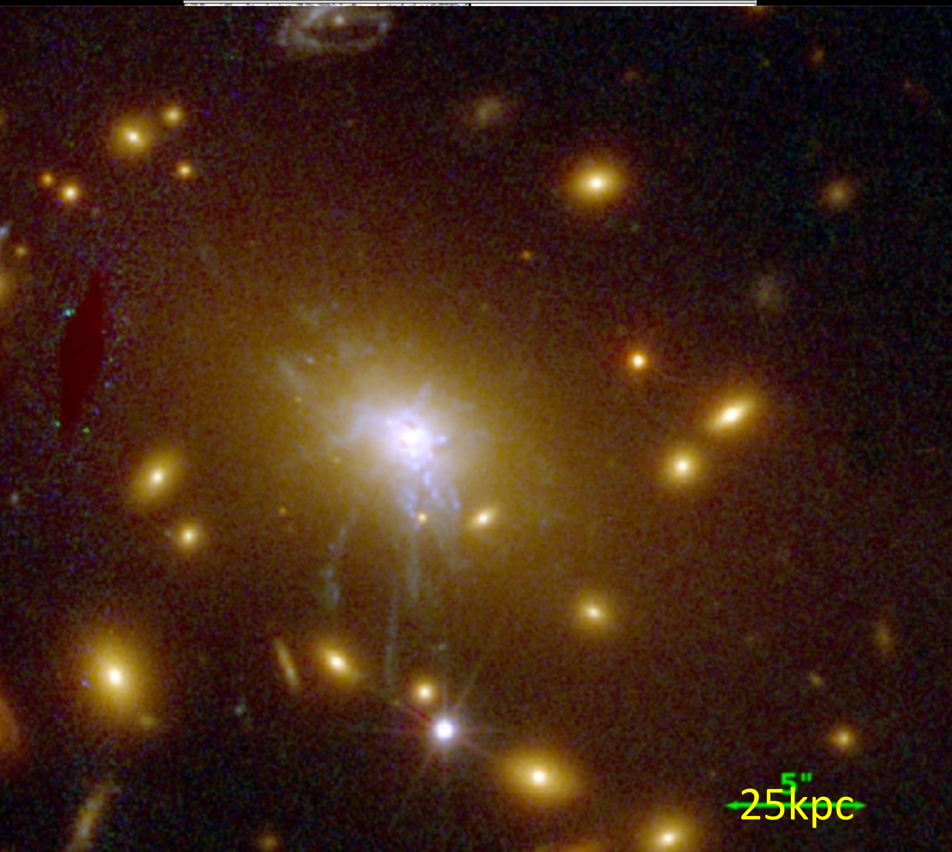
# Growth of Central Black Hole

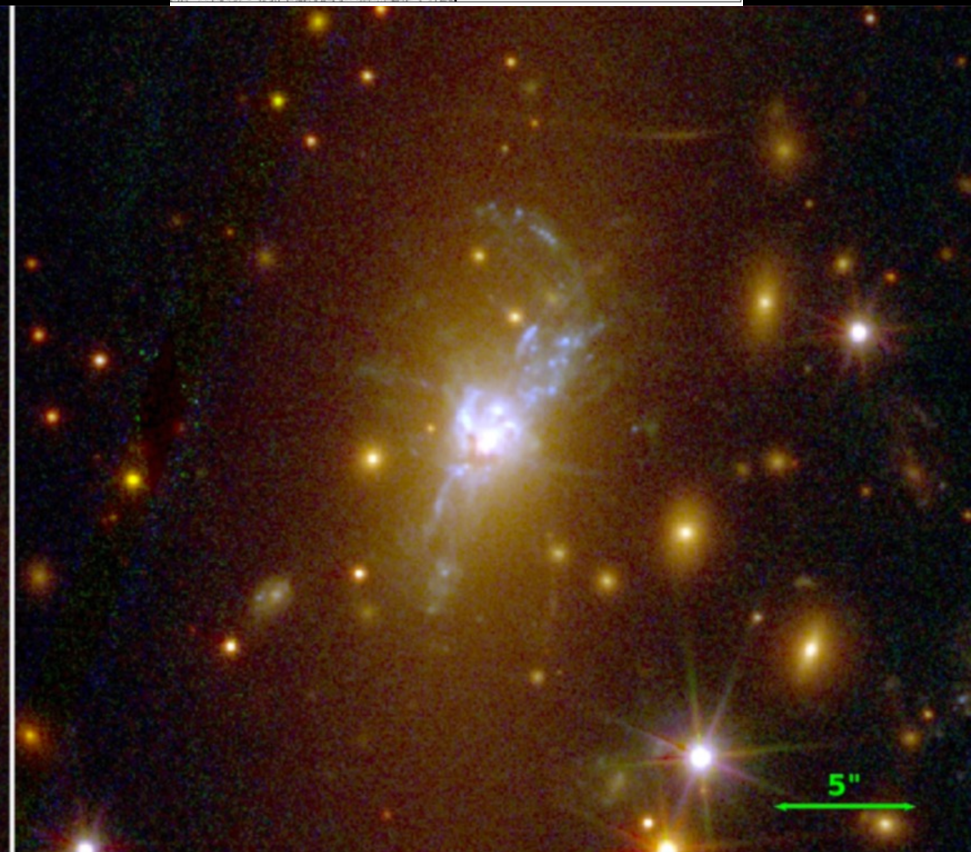
- How much accretes into central black hole?
- Gravitational torques act on substellar objects collapsed from very cold clouds, then swallowed whole, i.e invisibly.
- Explains why so many of the most massive BH at centres of clusters?
- e.g. Holm 15A in A85 of $4x10^{10}M_{sun}$ (Mehrgan+19)
- Farrah, Shankar+2023 $M_{BH}$ in ellipticals has increased since z=1




Mdot > 1000



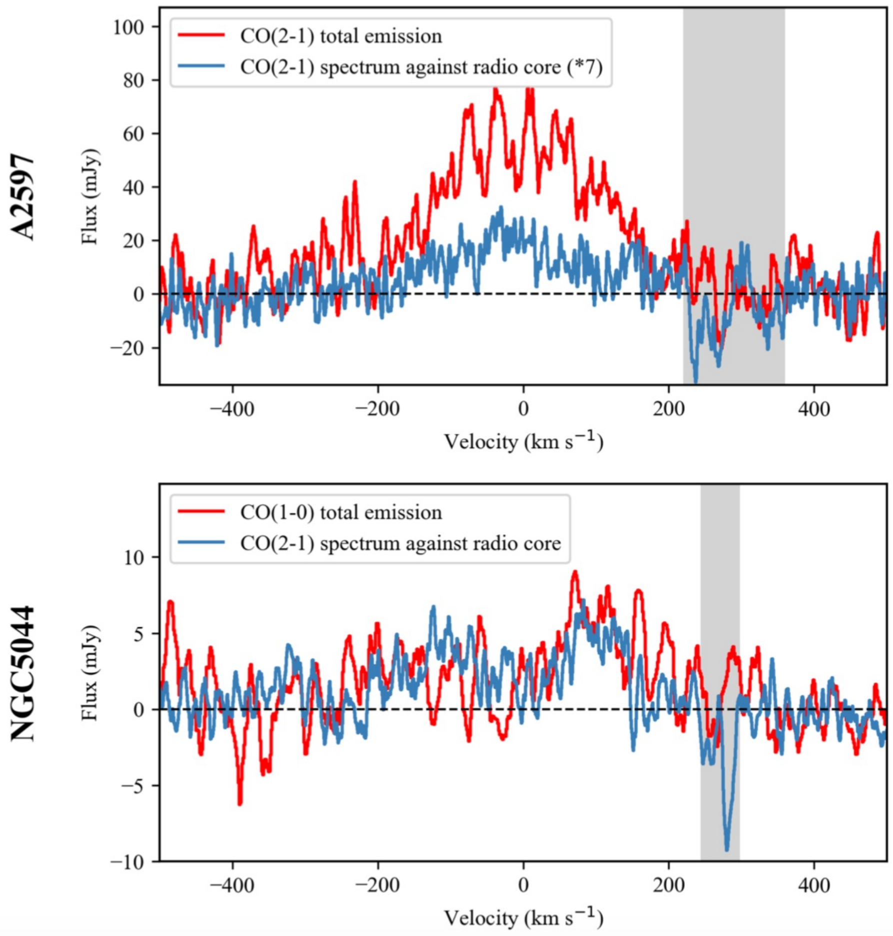

RXJ1532 z=0.35

RXJ1931 z=0.36

Fogarty+15

# Absorption of nucleus by cold clouds

Redshifted molecular absorption of CO seen against nucleus in some cool cores (Rose+23).




Many cool core nuclei either intrinsically weak or absorbed in X-rays (Hlavacek-Larrondo+11, Yang+18).

# Summary

- ICM is cooling below 10 million K, mostly hidden by intrinsic absorption
- Mass cooling rates several times > unabsorbed estimates
- Most of absorbed energy emerges in FIR
- Ultracold clouds exist? + High pressure low mass star/brown dwarf formation?
- Inner few kpc of cool cores v complex and multiphase
- Large range of densities and sizes challenges numerical simulations (most assume no absorption)
- Some substellar objects may be swallowed whole by central BH
- Cooling flows are at the heart of AGN Feedback in ellipticals

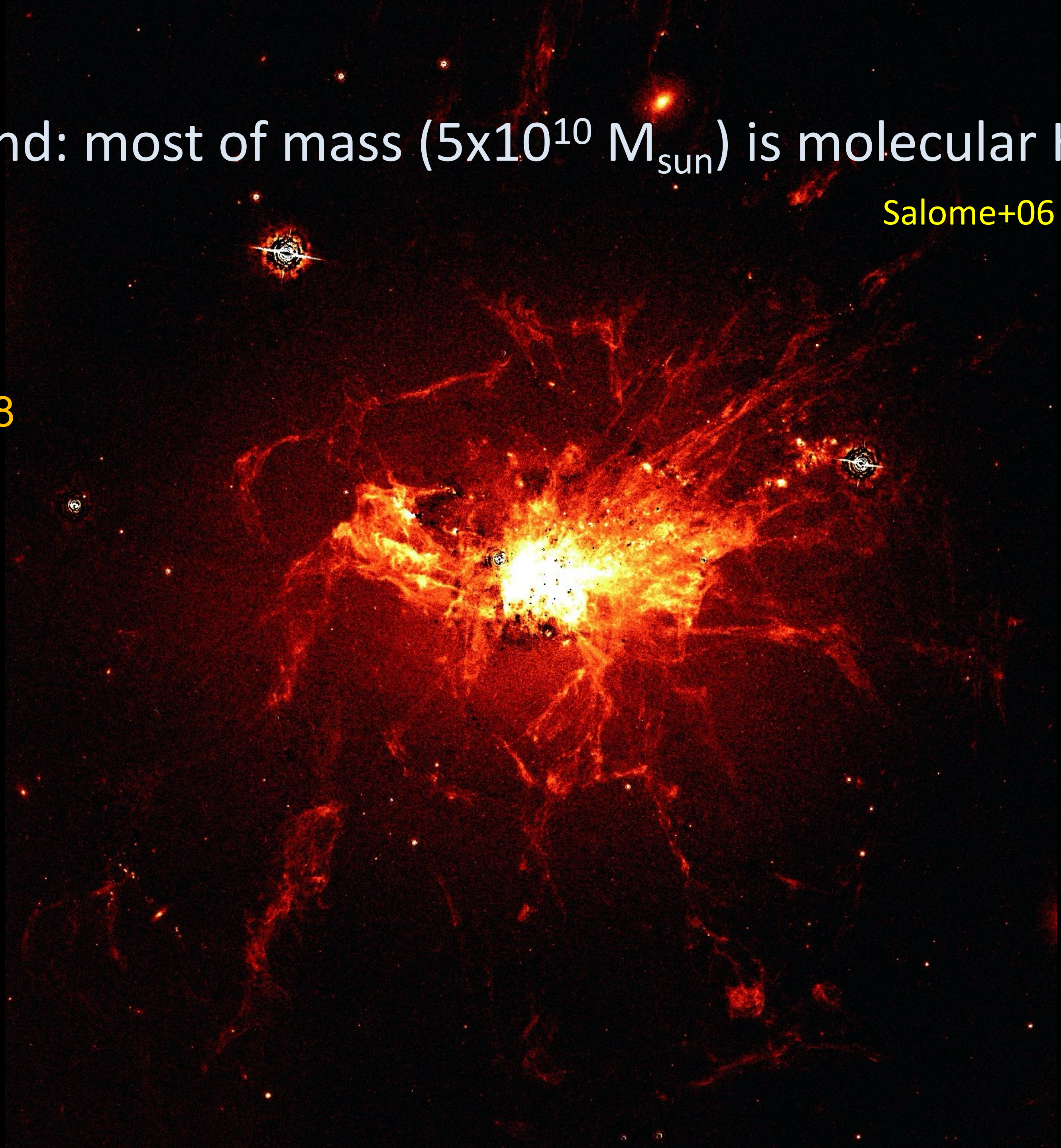
All models and interpretation require cold absorption!

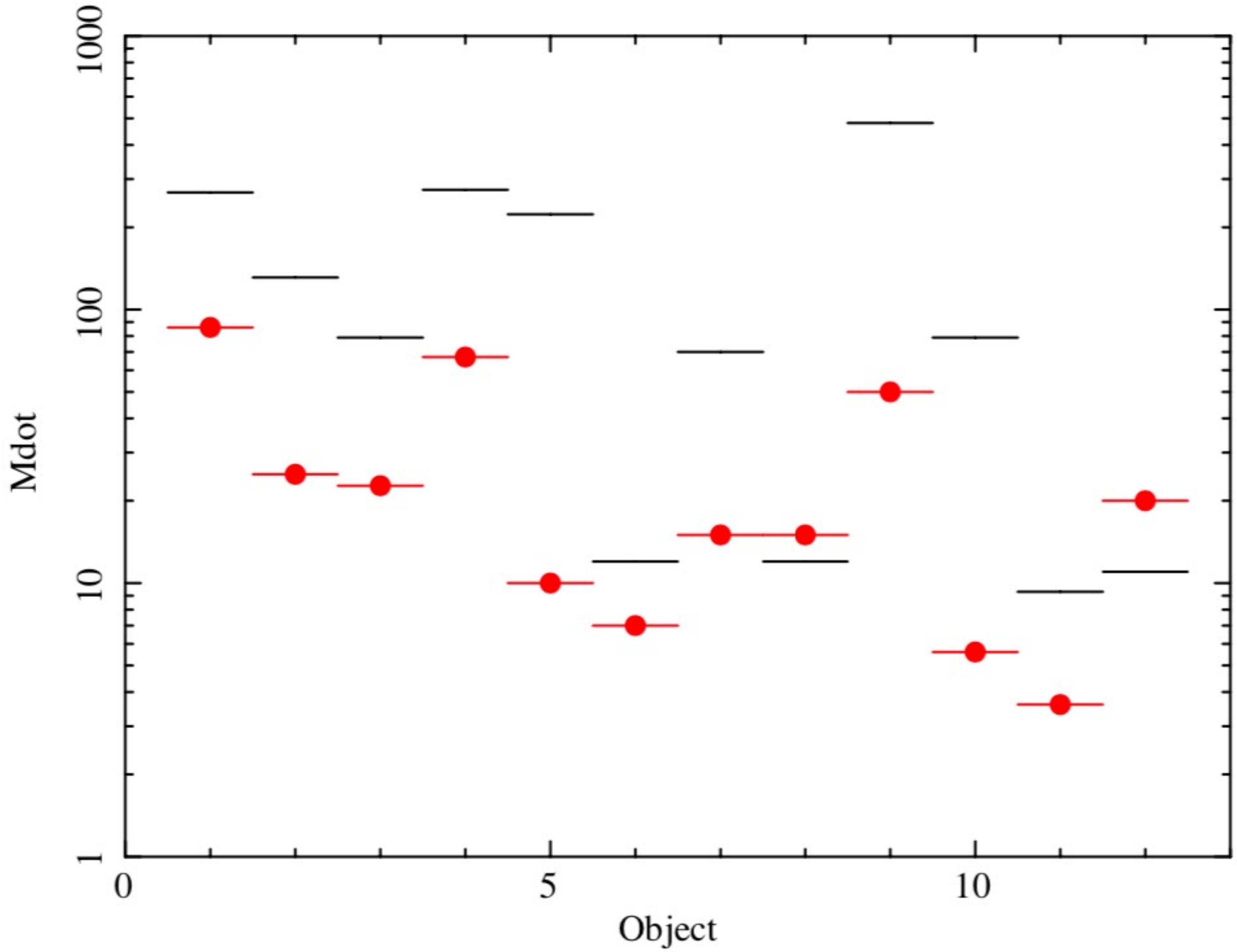
# Hα band: most of mass ($5x10^{10}$ $M_{sun}$) is molecular $H_2$

Salome+06

HST

Fabian+08



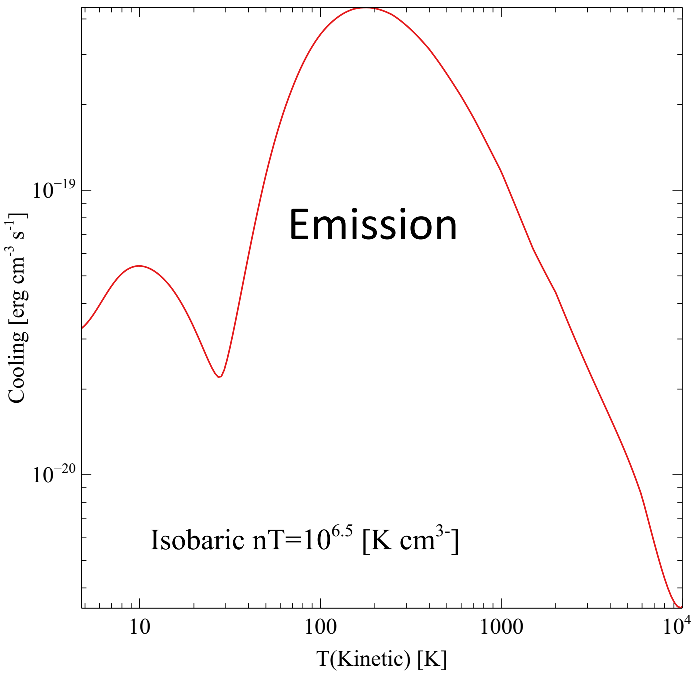



Black – Classical Imaging

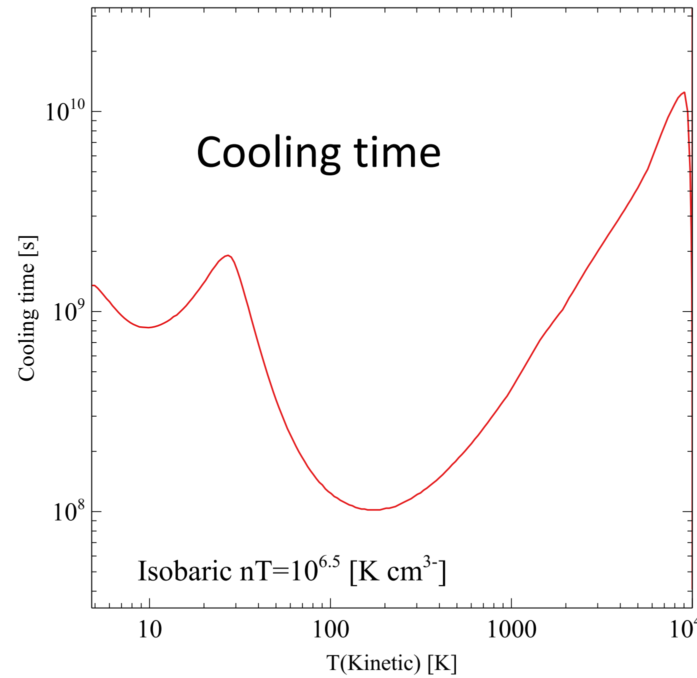
Red – HCF RGS

Bubbling AGN Feedback reduces Mdot by factor of 2 or more

**Figure 3.** Mass cooling rates, classical imaging rate from (Hudson et al. 2010) (black), if available, and spectroscopic HCF rate (red). Objects: 1) 2A0335; 2) A85; 3) A496; 4) A2597; 5) S159, 6) A262, 7) A2052; 8) Cen; 9) Per, 10) A2199 11) NGC1550 and 12) NGC5044. The average ratio of red (HCF) to black (classical) is 0.45.



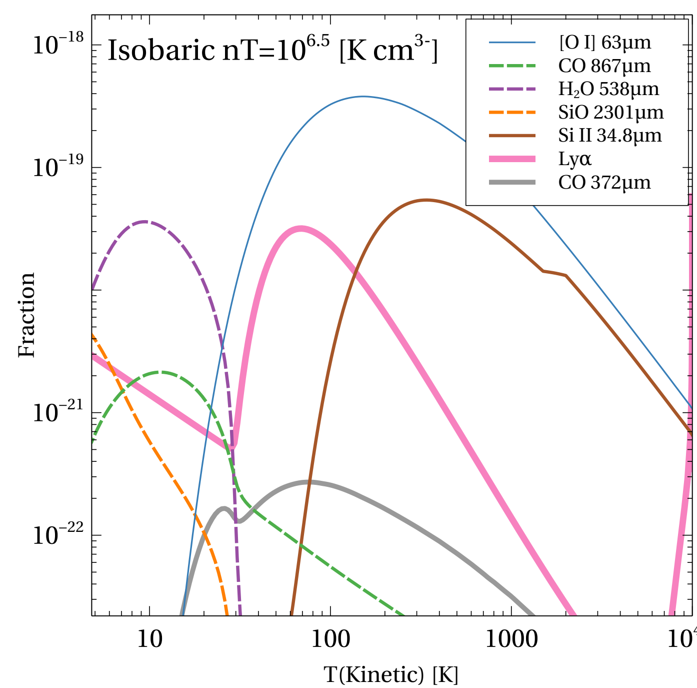

30 yr




Clouds cool fast.

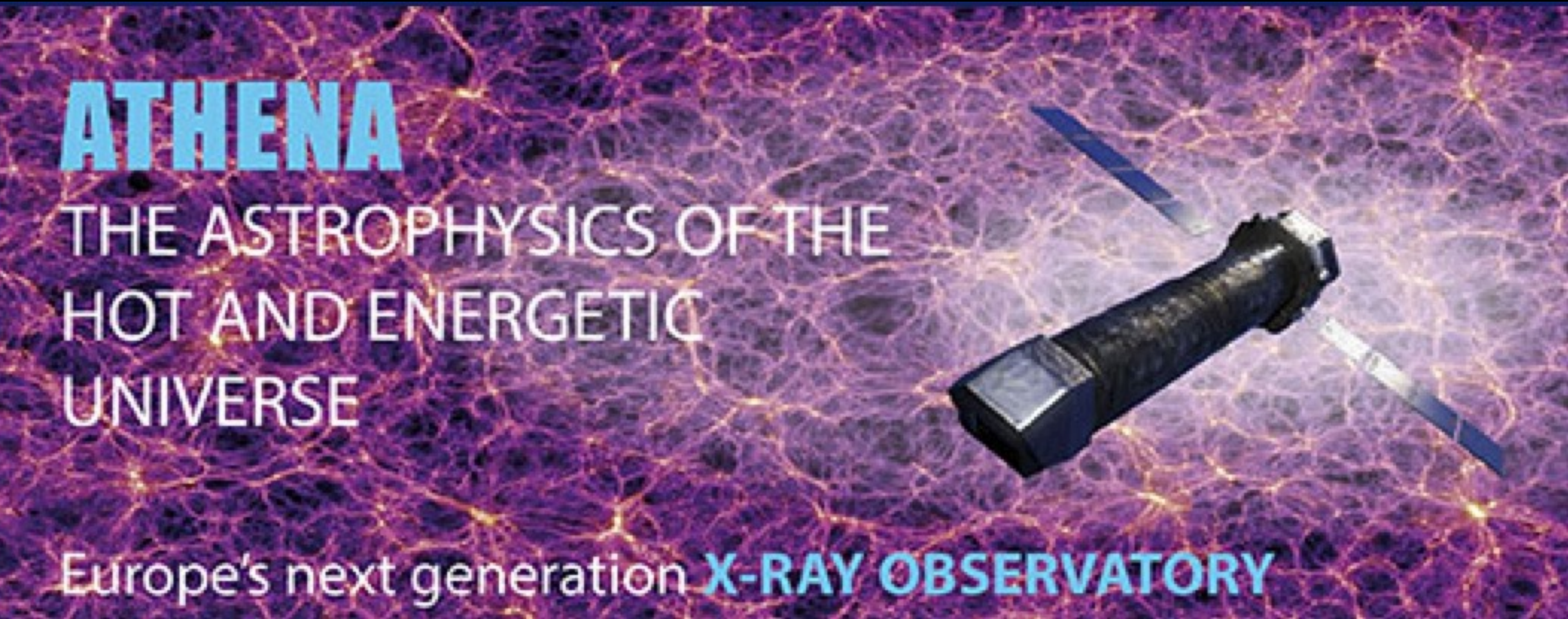
How cold can clouds go?

3K?

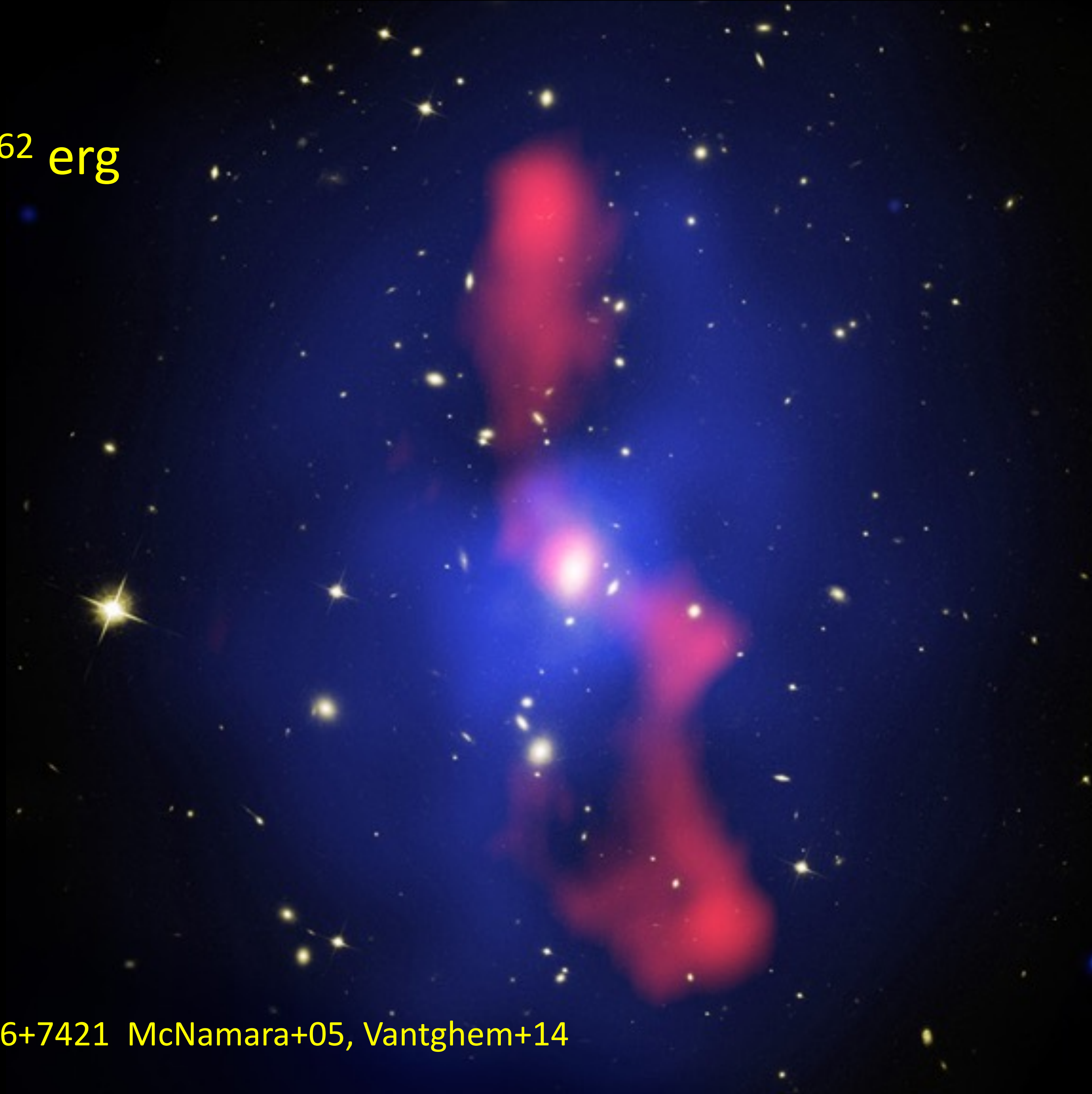



G Ferland

Future  is XRISM then



~$10^{62}$ erg



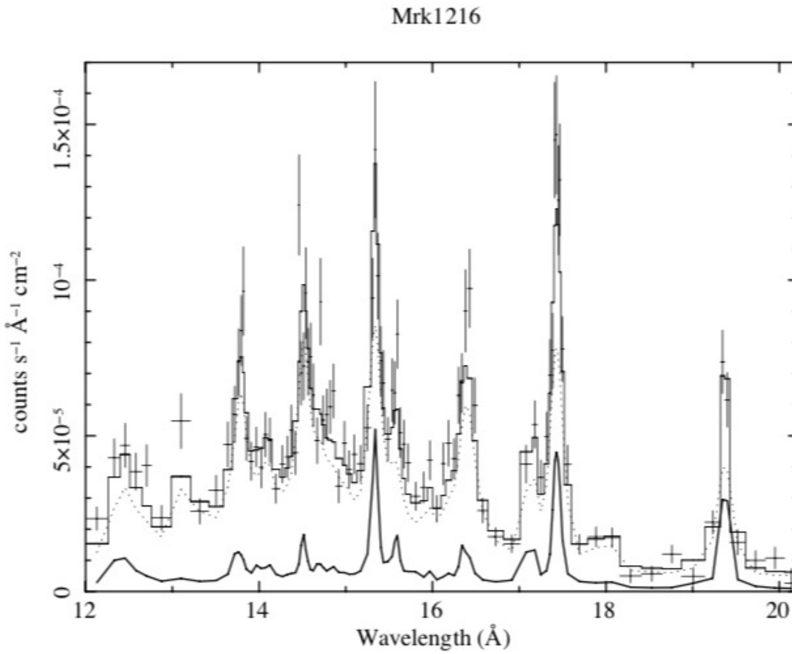
700kpc

MS0735.6+7421  McNamara+05, Vantghem+14

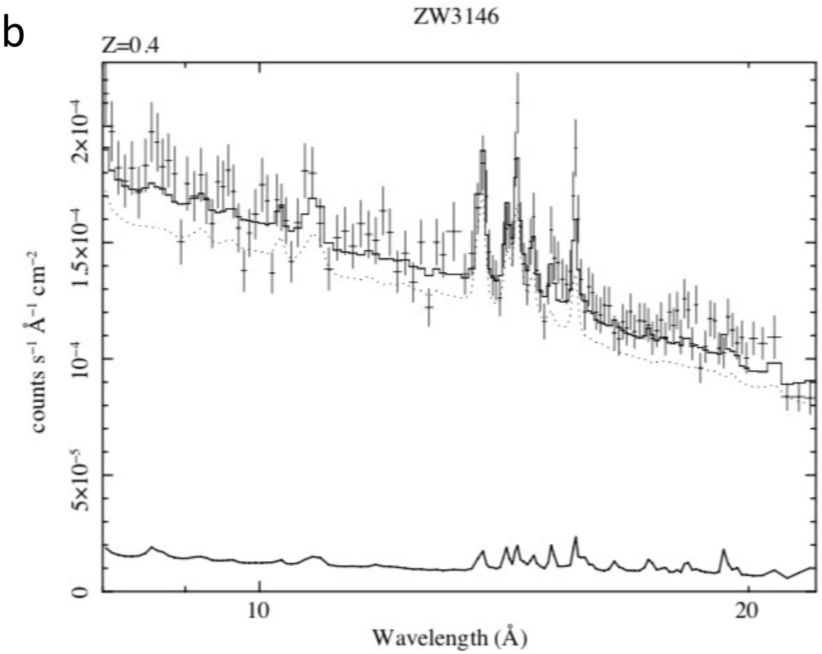
# Cooling Flow Phase in Galaxy Formation?

- Core of galaxy forms from densest gas that cools on the inflow time
- Next phase involves a cooling flow from less dense gas
- Mergers and cold flows add further dense gas
- Some galaxies, either in dense clusters (e.g. NGC1277) or in the field (eg Mrk1216) are fossils of the early phases.

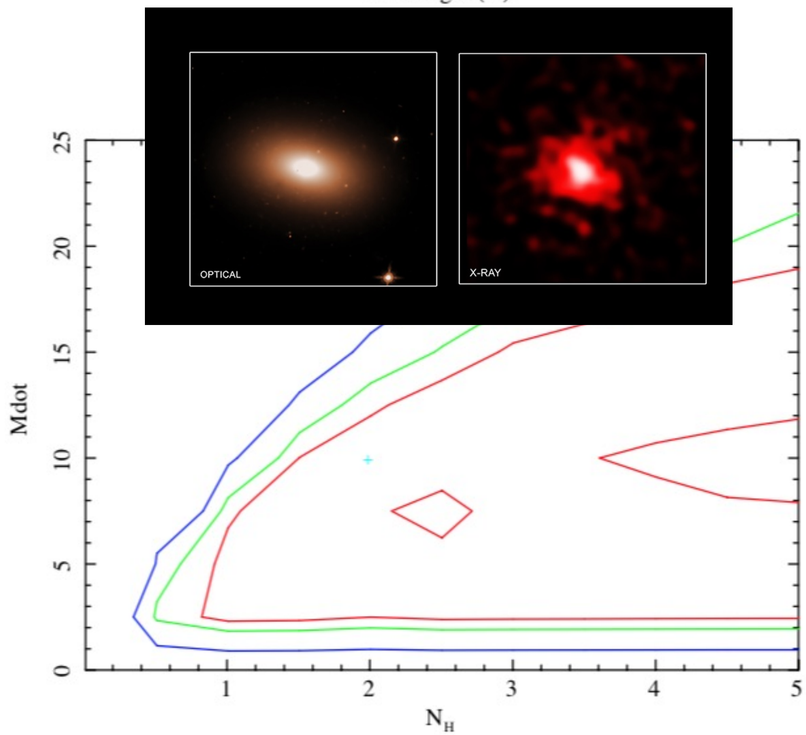
Fabian+23b



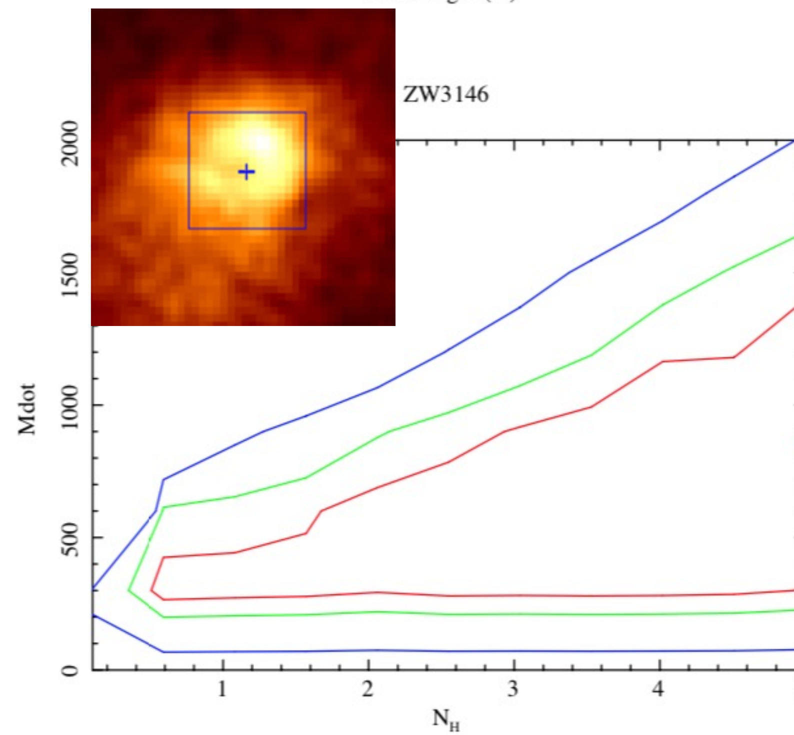
Mrk1216
counts s⁻¹ Å⁻¹ cm⁻²
1.5×10⁻⁴
10⁻⁴
5×10⁻⁵
0
12
14
16
18
20
Wavelength (Å)

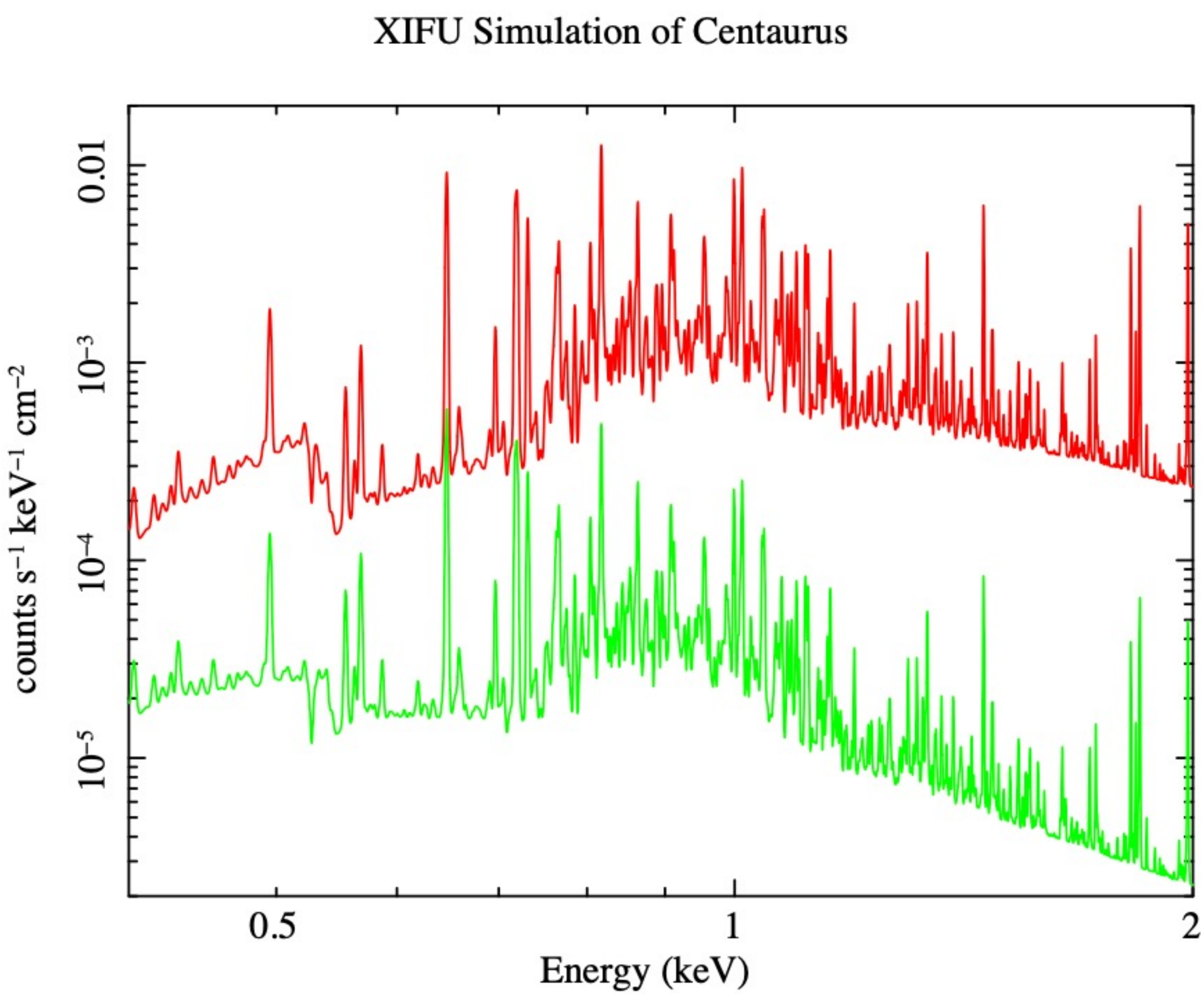
ZW3146
Z=0.4
counts s⁻¹ Å⁻¹ cm⁻²
2×10⁻⁴
1.5×10⁻⁴
10⁻⁴
5×10⁻⁵
0
10
20
Wavelength (Å)

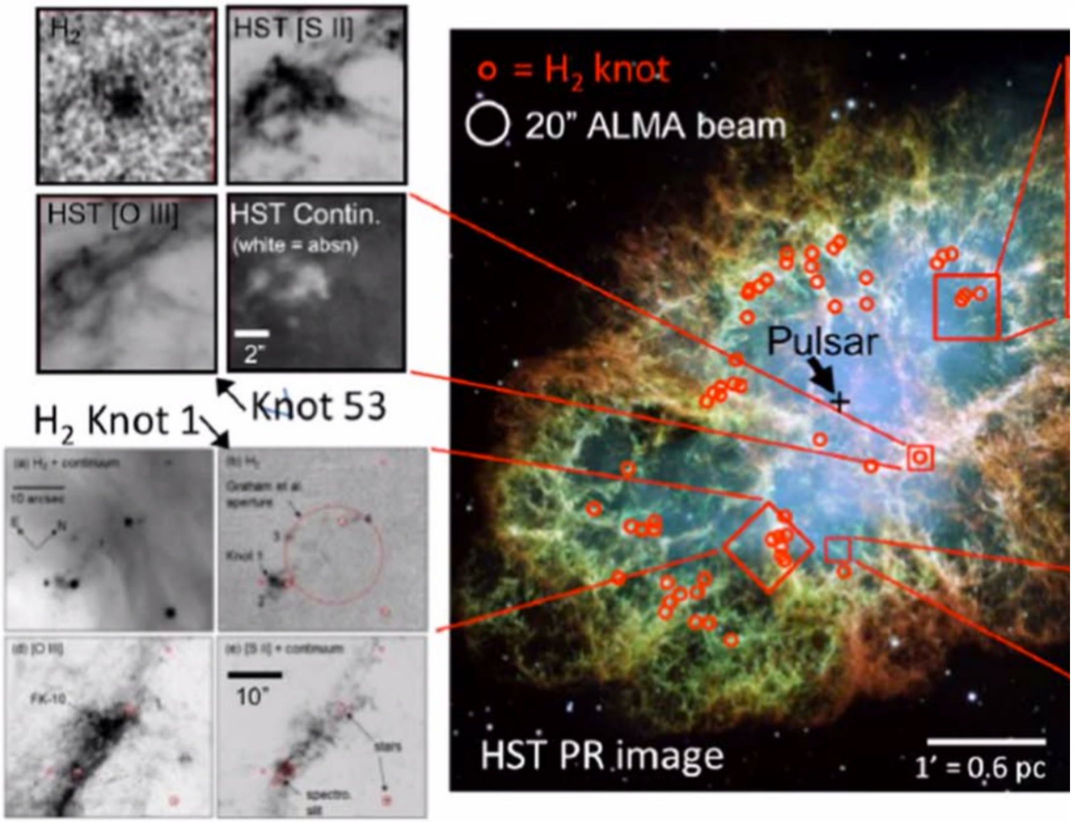
OPTICAL
X-RAY
Mdot
25
20
15
10
5
0
1
2
3
4
5
N_H

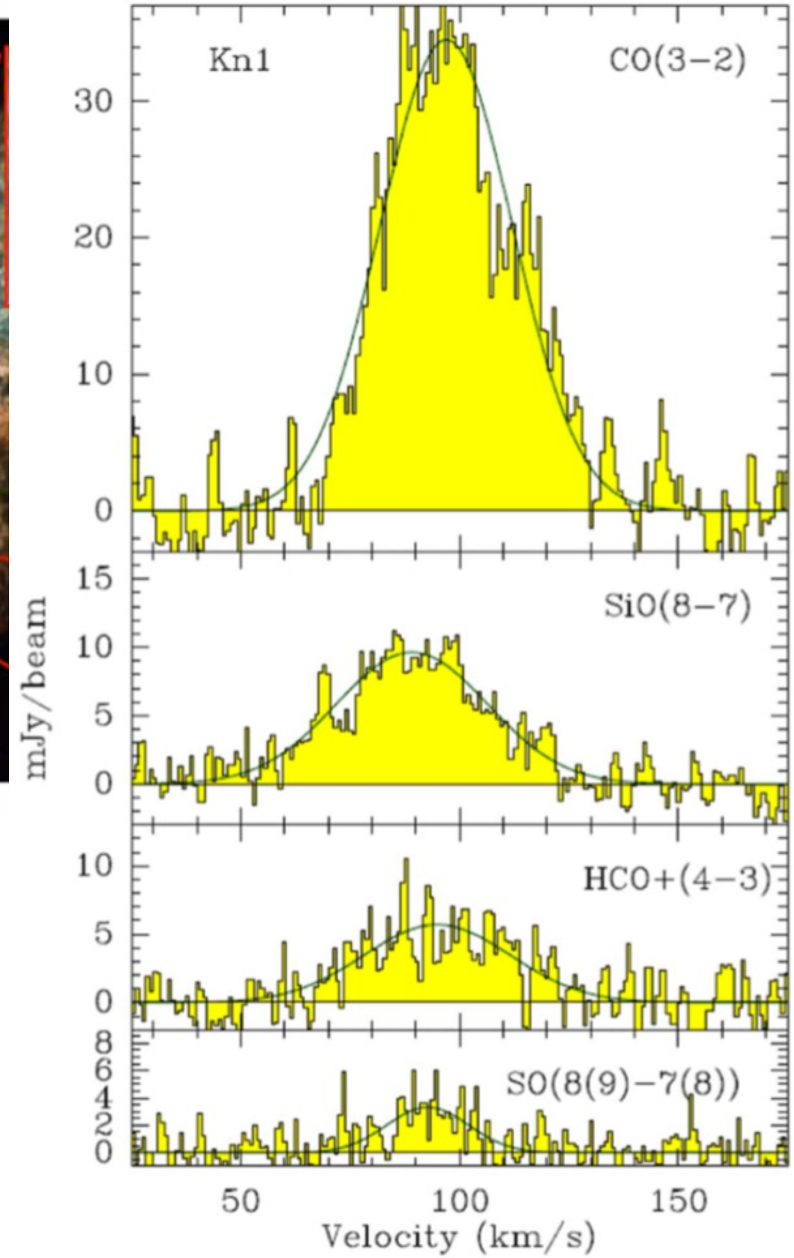



ZW3146
Mdot
2000
1500
1000
500
0
1
2
3
4
5
N_H




Hidden CF of 14 Msun/yr and unabsorbed CF of 0.1 Msun/yr



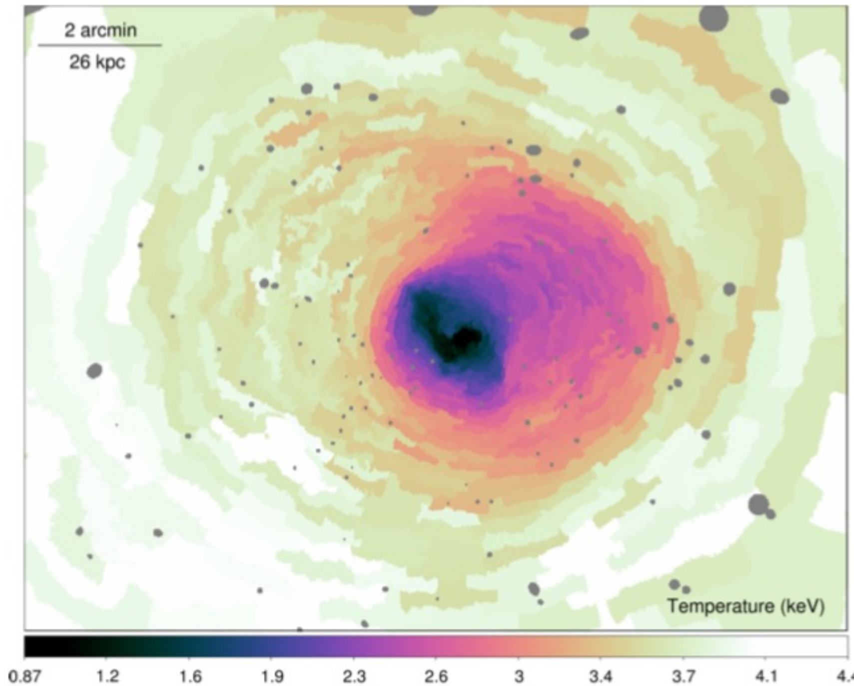




Crab Nebula

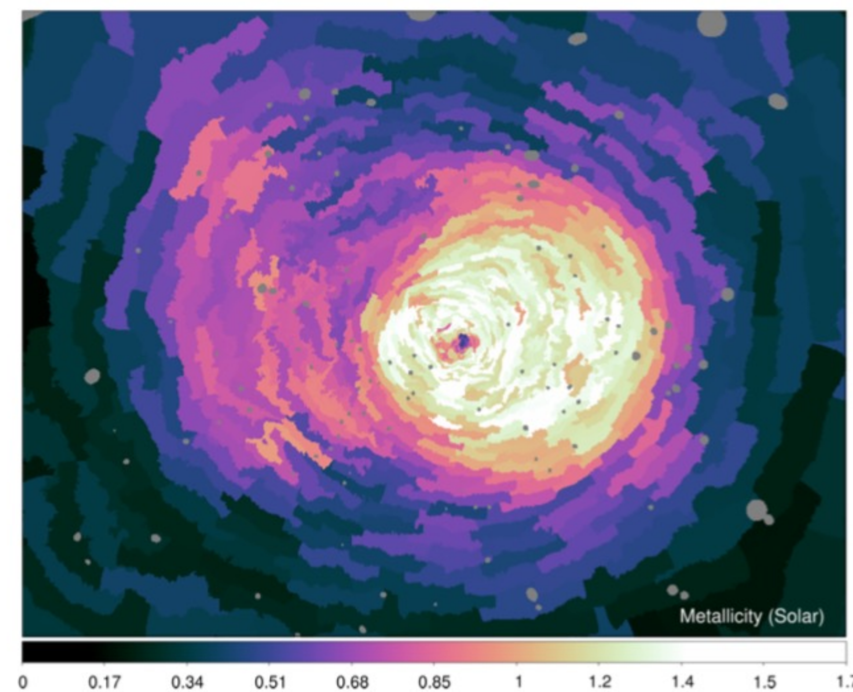
Pressure $nT=10^{6.5}$ $cm^{-3}$ K

Similar to cool cores in galaxy clusters

Centaurus cluster
Chandra X-ray
Sanders+16



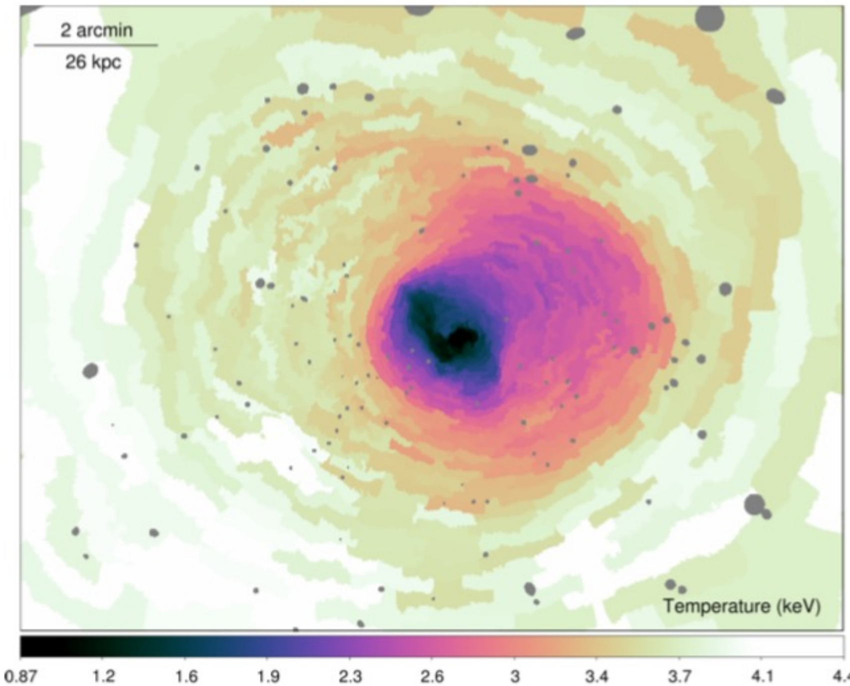

kT




Z

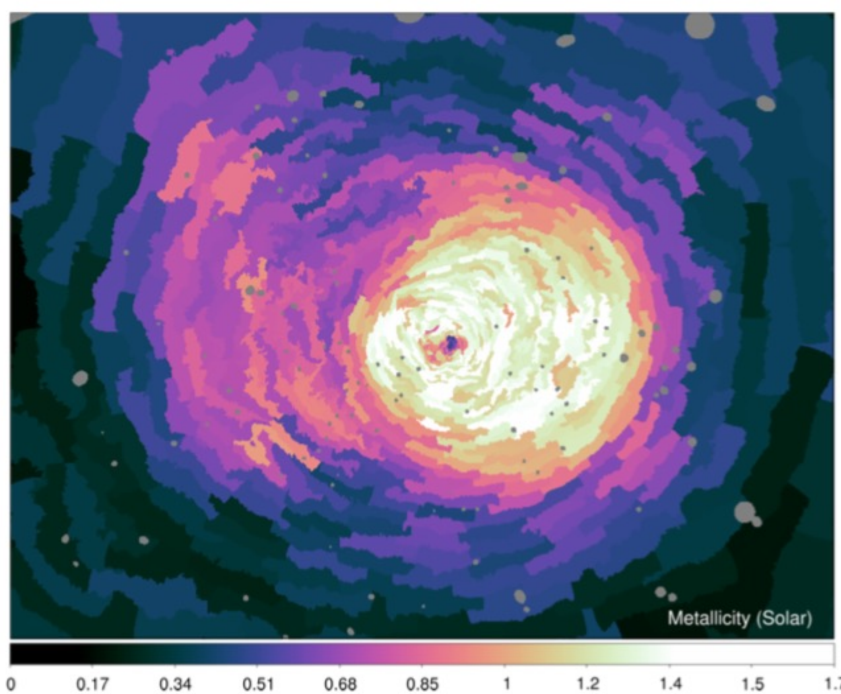
Centaurus

Centaurus cluster
Chandra X-ray
Sanders+16




kT

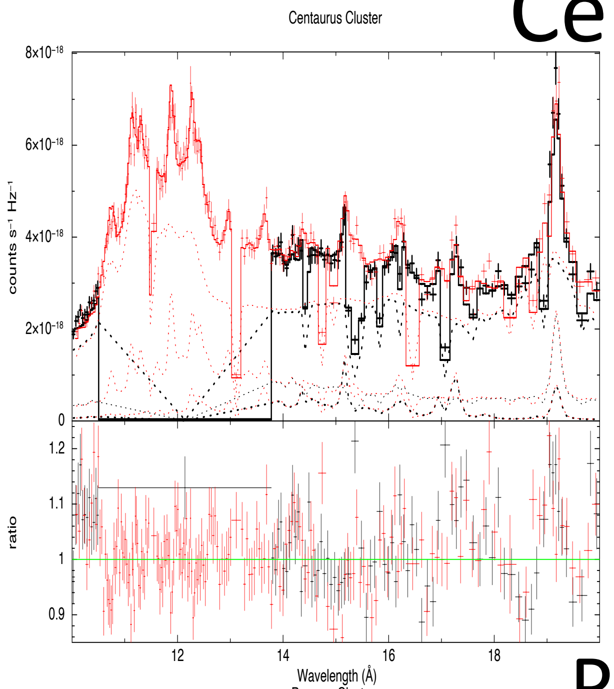
Central abundance drop shows feedback transporting gas to outskirts?

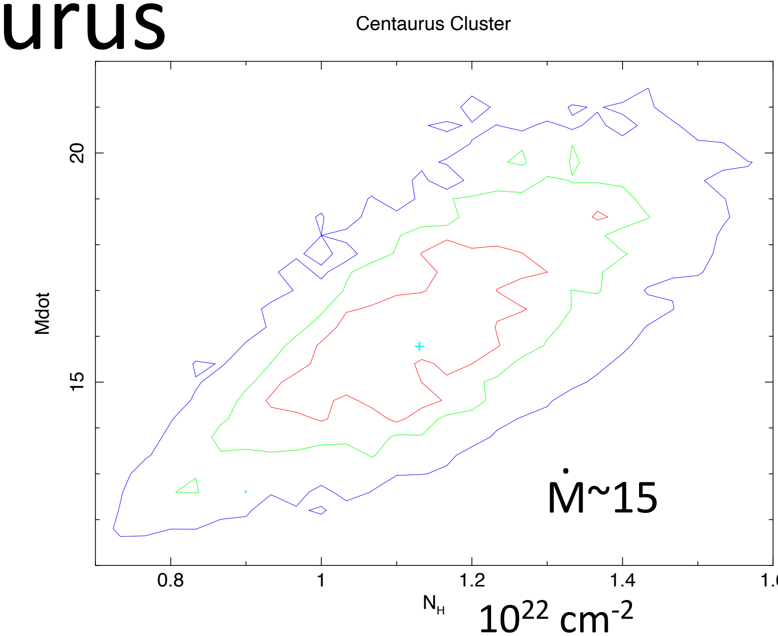



Z

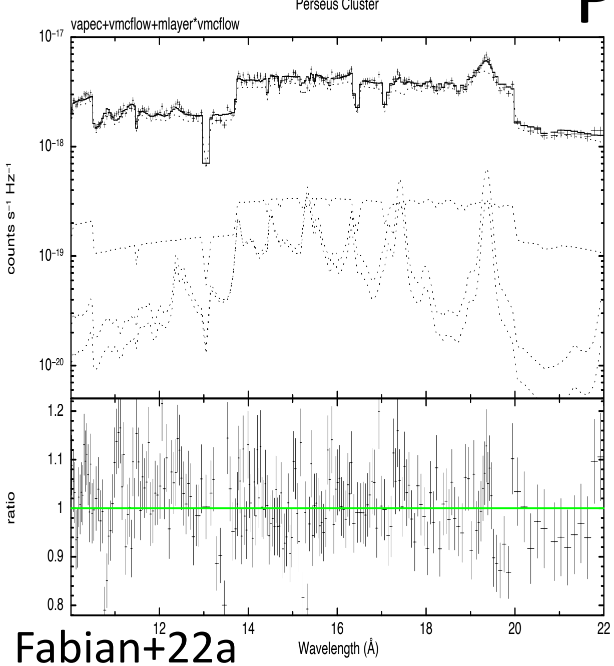
Centaurus

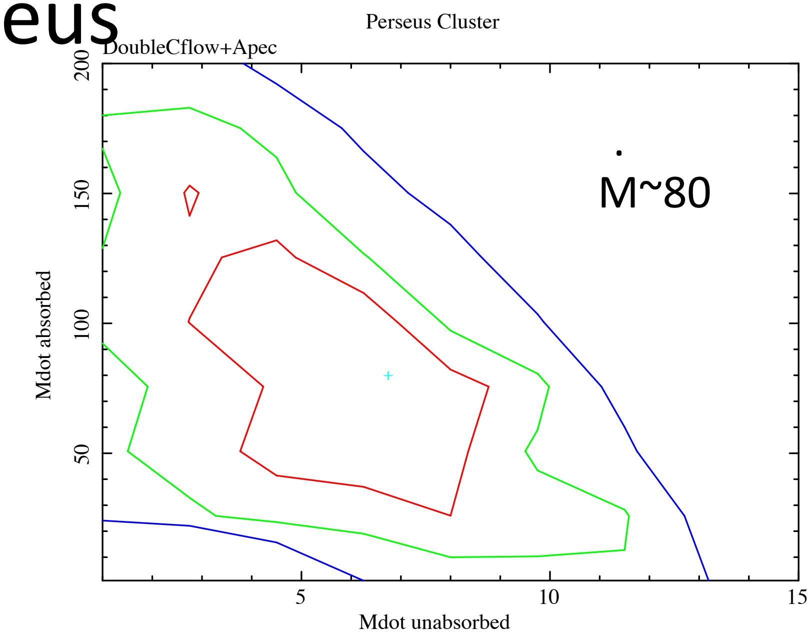
# Centaurus




# Perseus




HCFI Fabian+22a