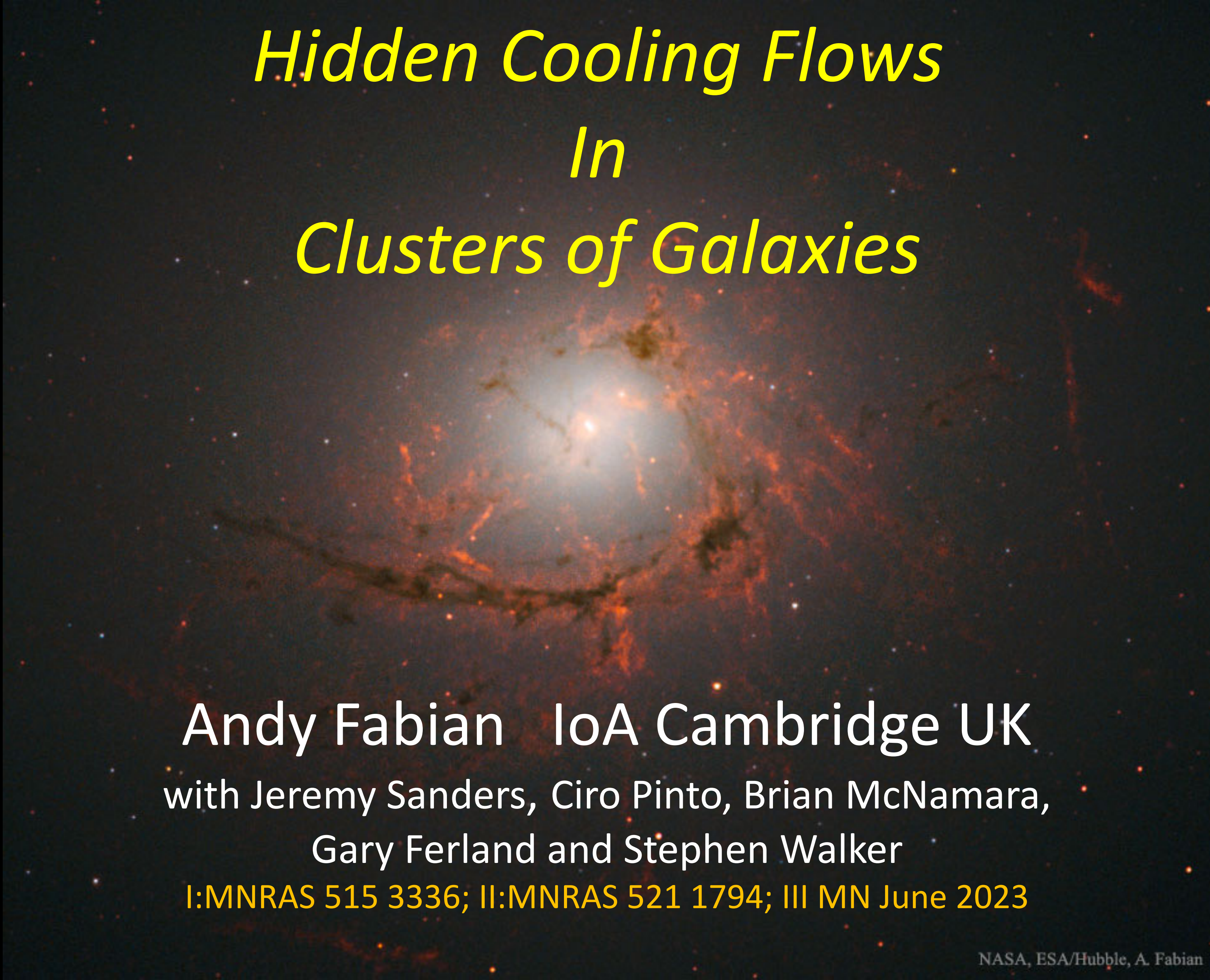
Hidden Cooling Flows In Clusters of Galaxies

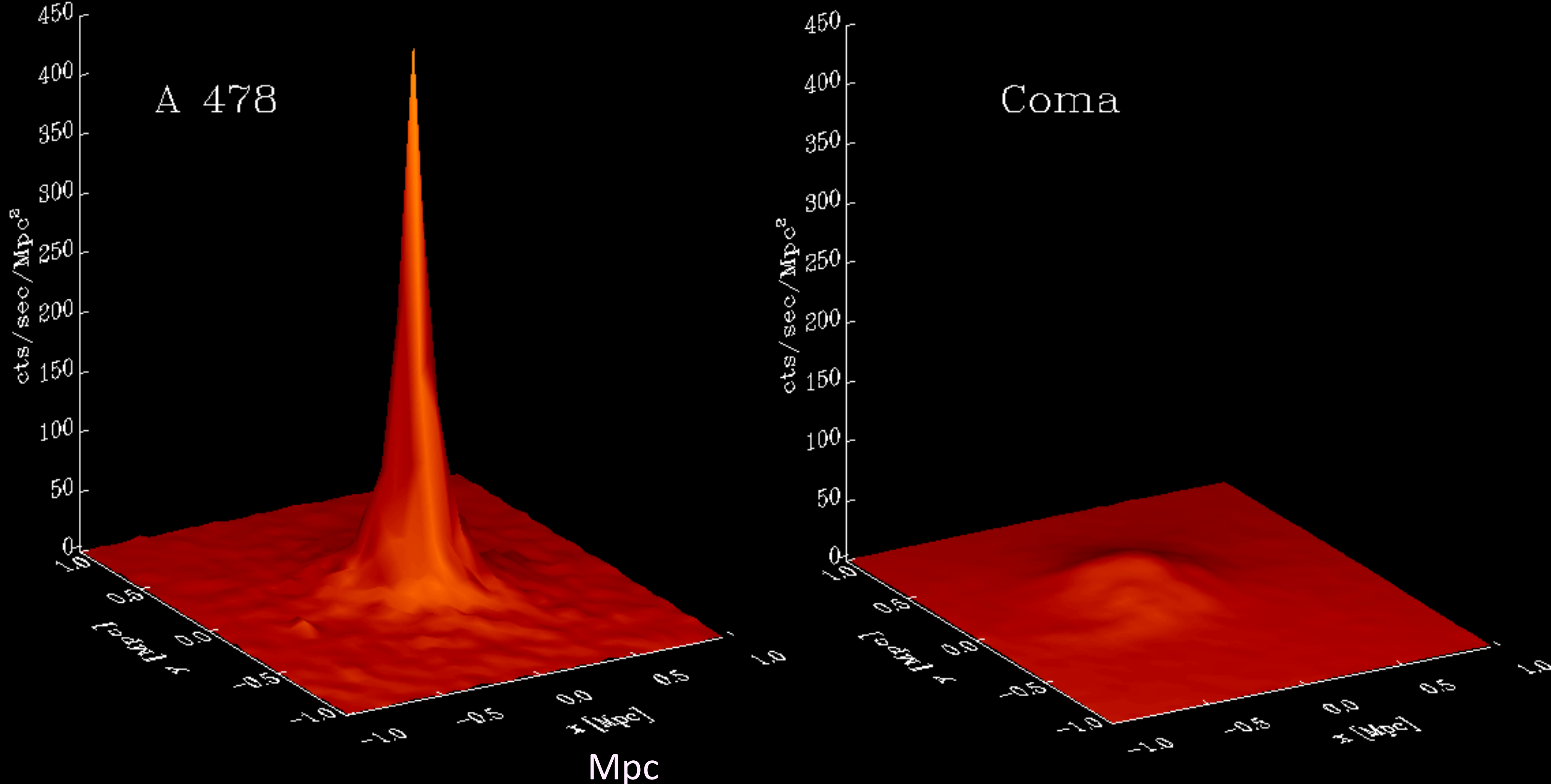
Andy Fabian IoA Cambridge UK

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

I:MNRAS 515 3336; II:MNRAS 521 1794; III MN June 2023

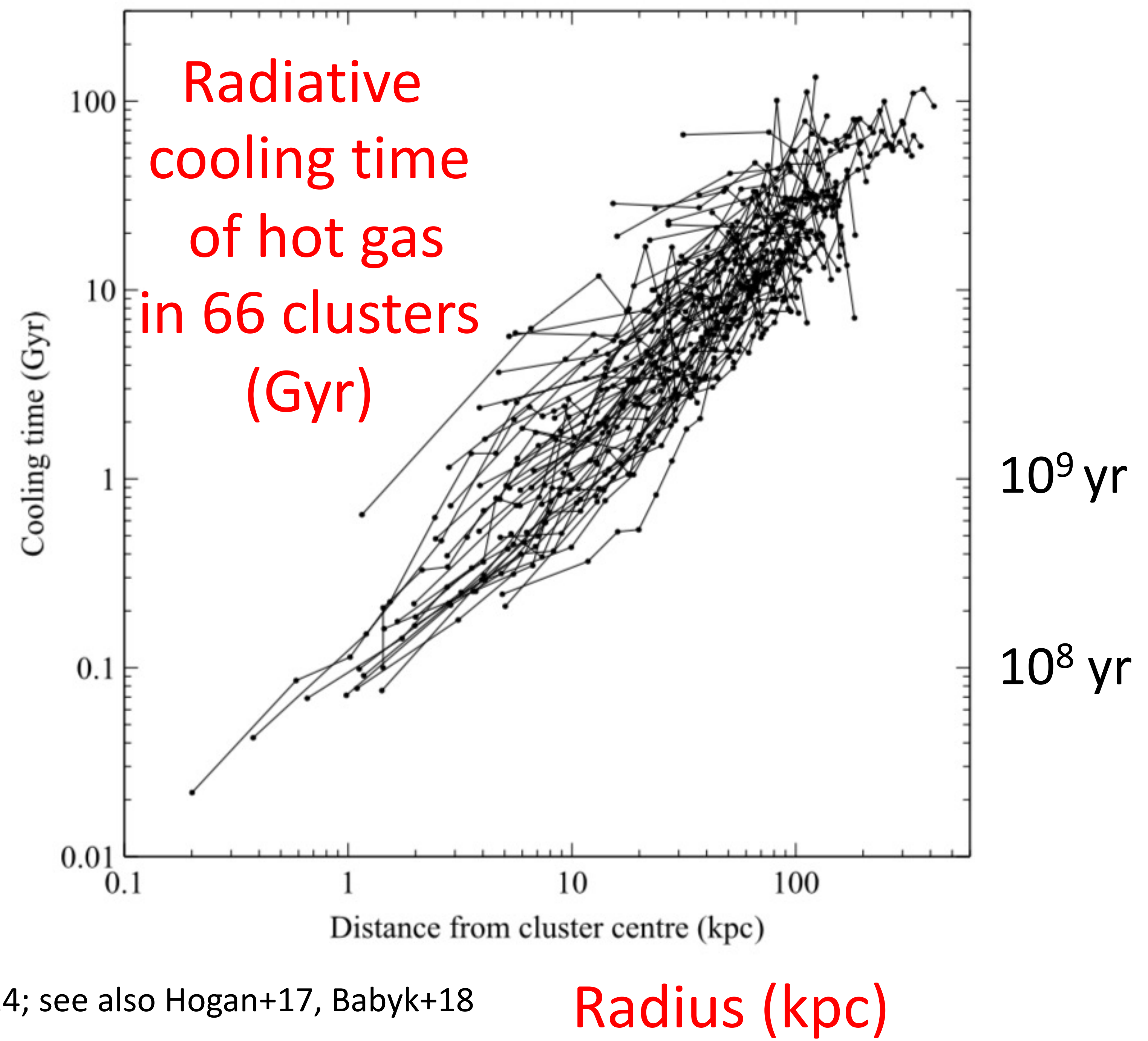


X-ray surface brightness of typical clusters of galaxies



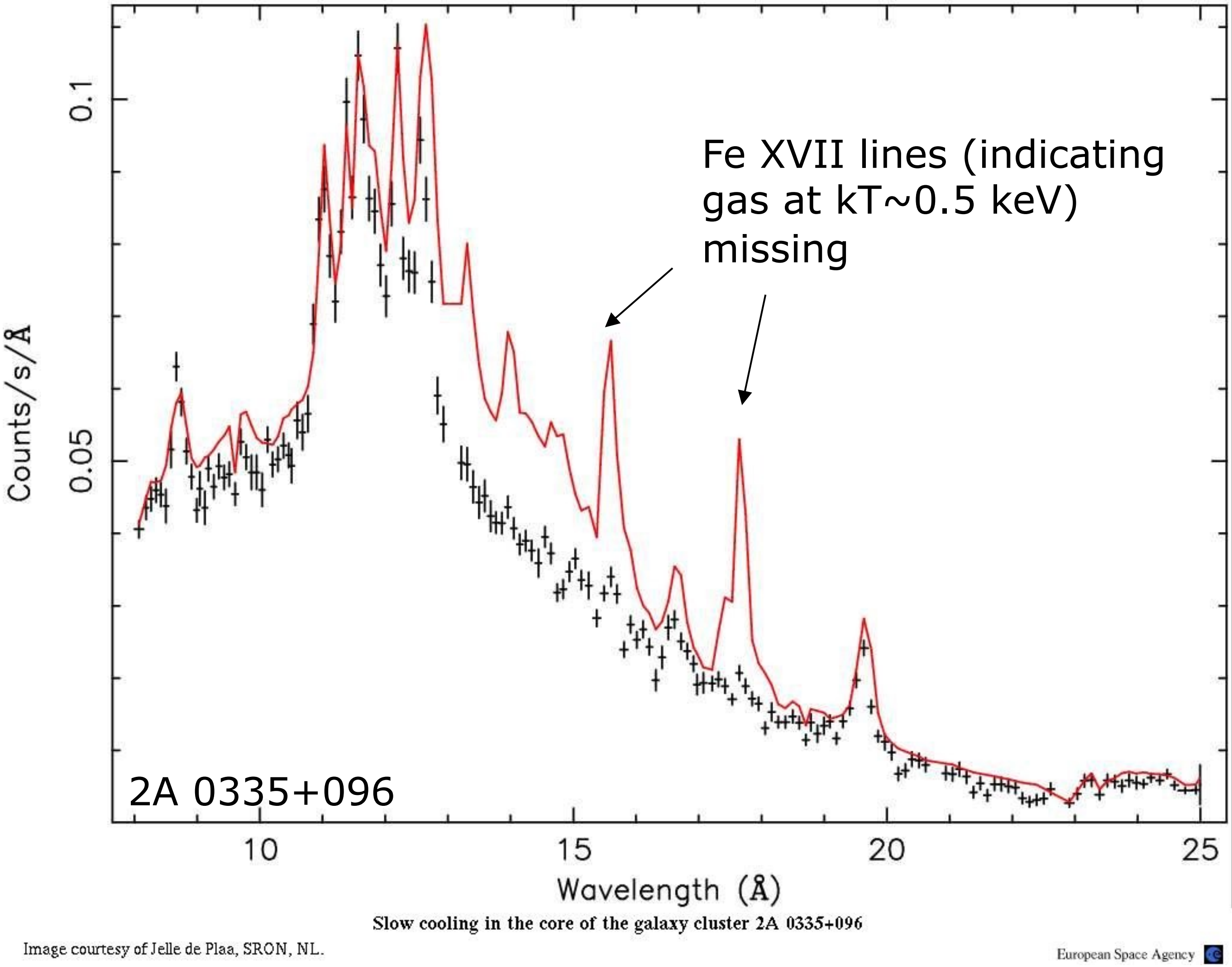
Cool Core

Non Cool Core



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

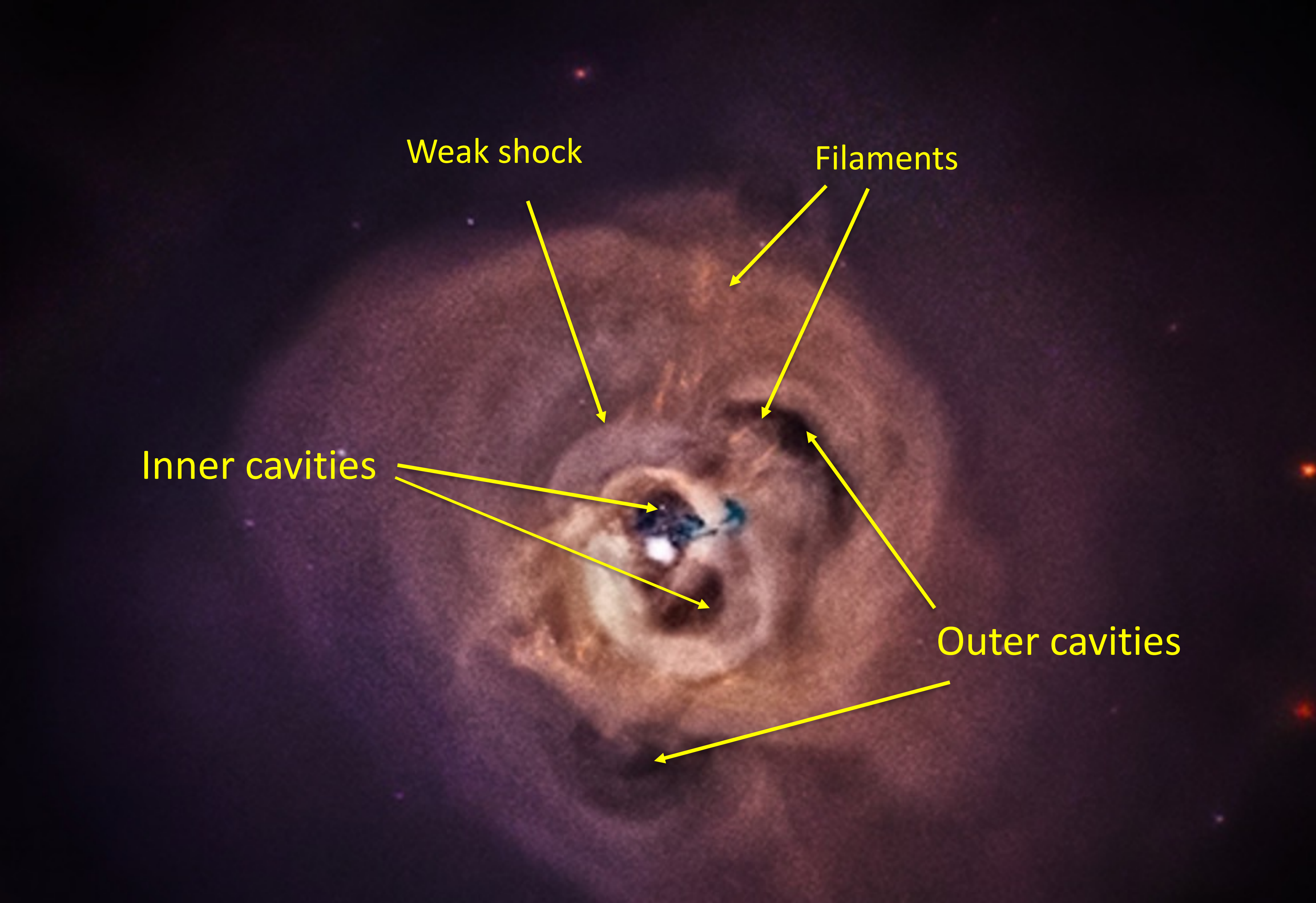
Lack of cool X-ray emitting gas



Spectra imply less than 10% of imaging cooling rates

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

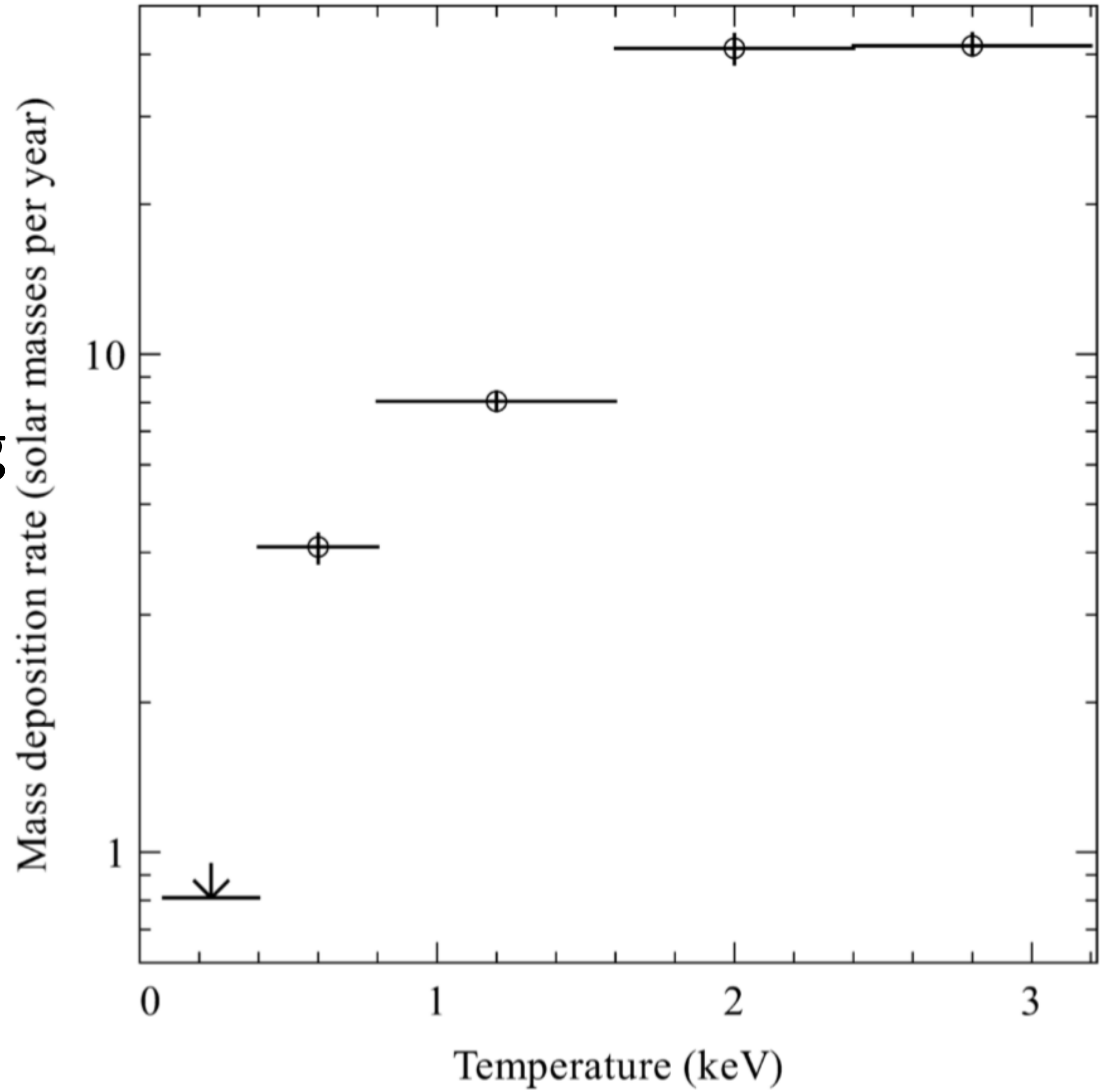
XMM RGS SPECTRUM



Perseus Cluster A426 NGC1275

J. S. Sanders et al. 08 Centaurus

Mass Cooling Rate

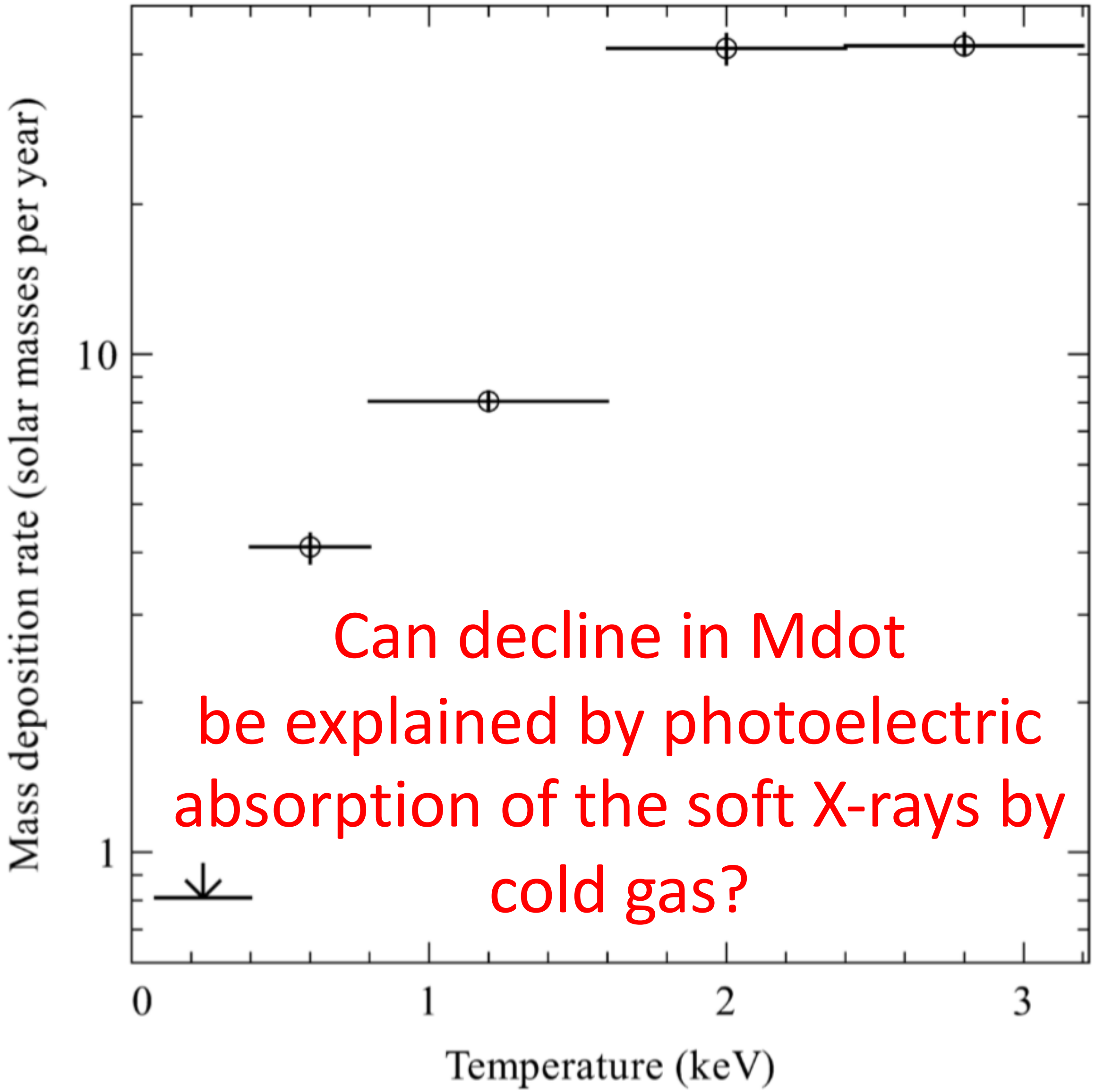


AGN feedback in clusters and groups appears continuous and gentle

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)



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

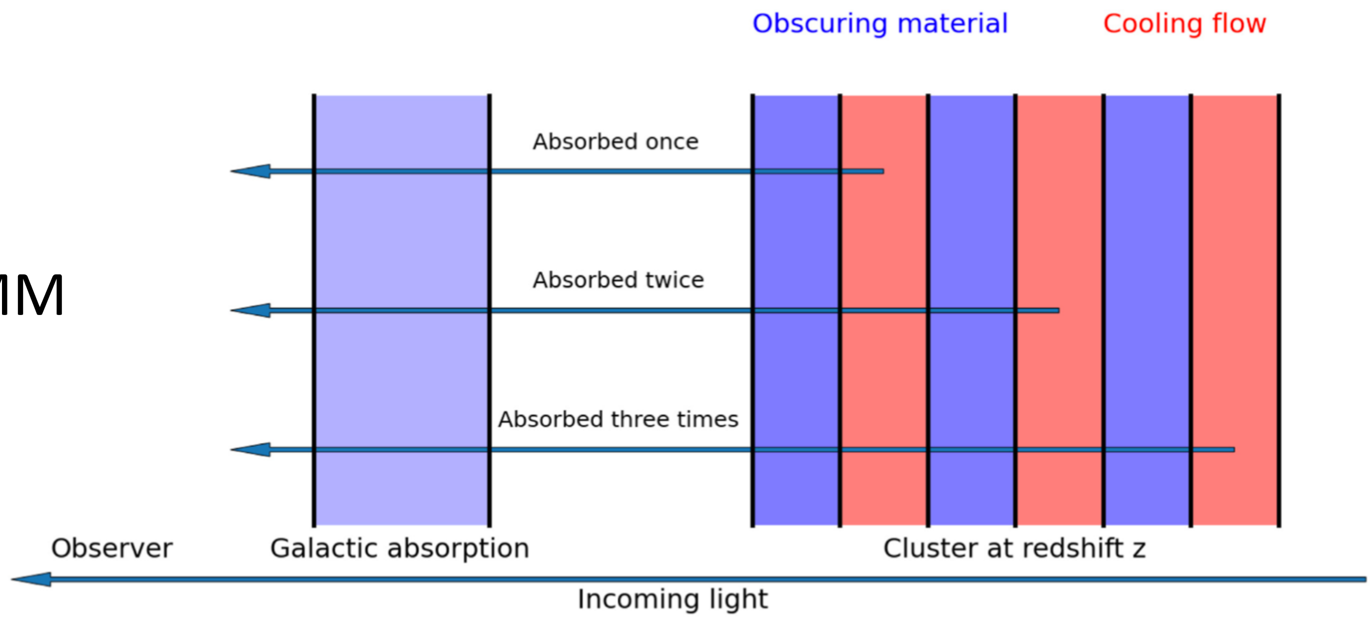
The spatial distributions of cooling gas and intrinsic X-ray-absorbing material in cooling flows

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

Hidden Cooling Flows?

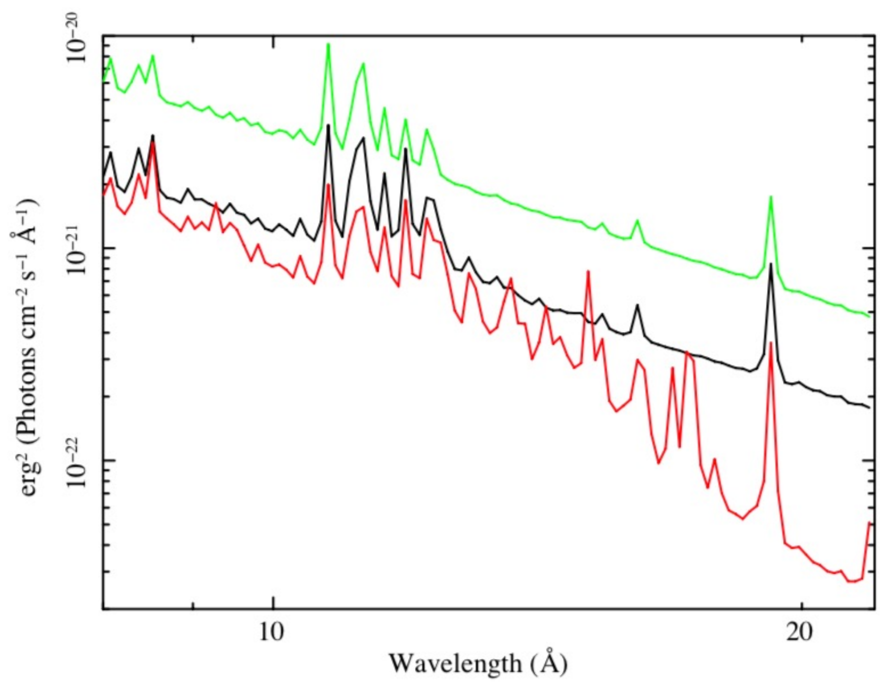
- Include absorption of soft X-rays by cold gas…
- …which occupies same region as cooling gas
- Use multilayer intrinsic absorption model first used on ROSAT PSPC data by Allen&Fabian97
- Energy from gas cooling below 1 keV ultimately emitted by dust and gas in FIR + UVOIR

XMM



$$F_{\mathrm{t}} = \frac{F_{\mathrm{e}}(1 - e^{-\sigma N_{\mathrm{t}}})}{\sigma N_{\mathrm{t}}}$$

No, Truncated and Hidden Cooling Flow

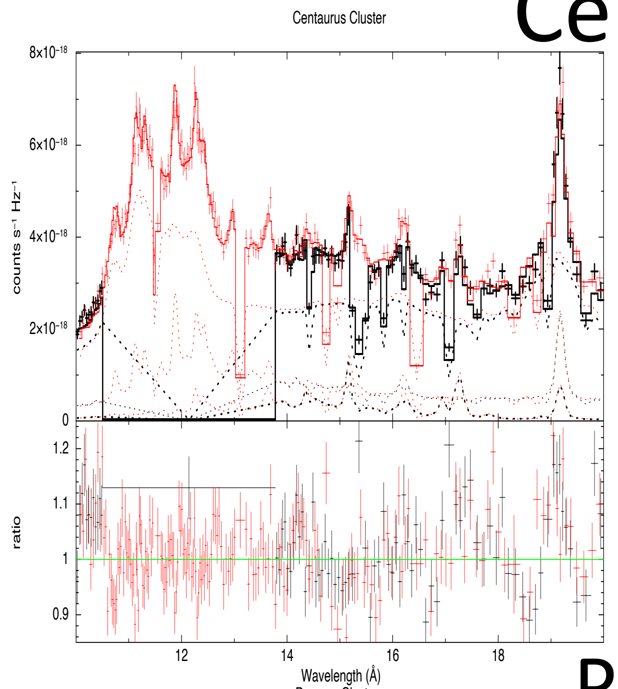


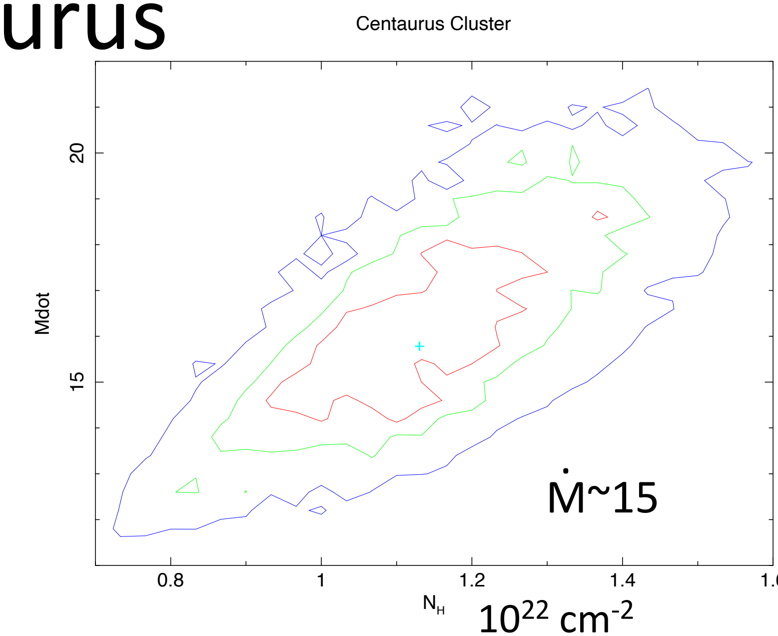
Crawford & Fabian 1992

Allen & Fabian 97	ROSAT
Allen 00	ASCA
Liu, Fabian+22	XMM

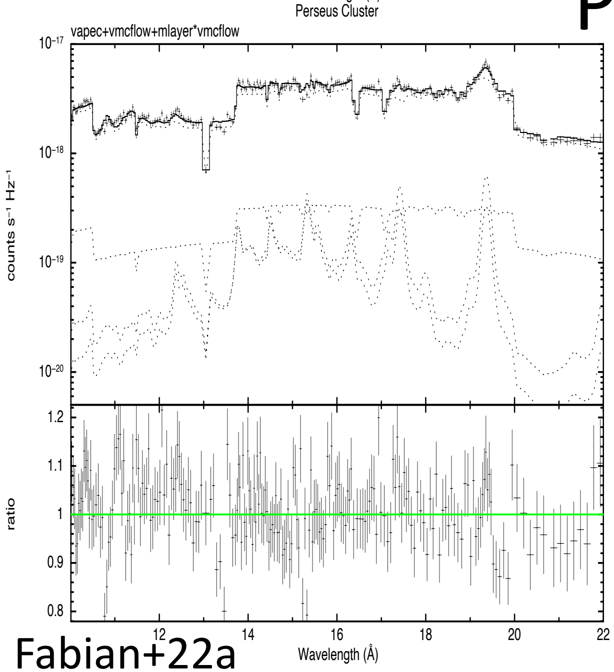
Also Werner+13, Walker+15

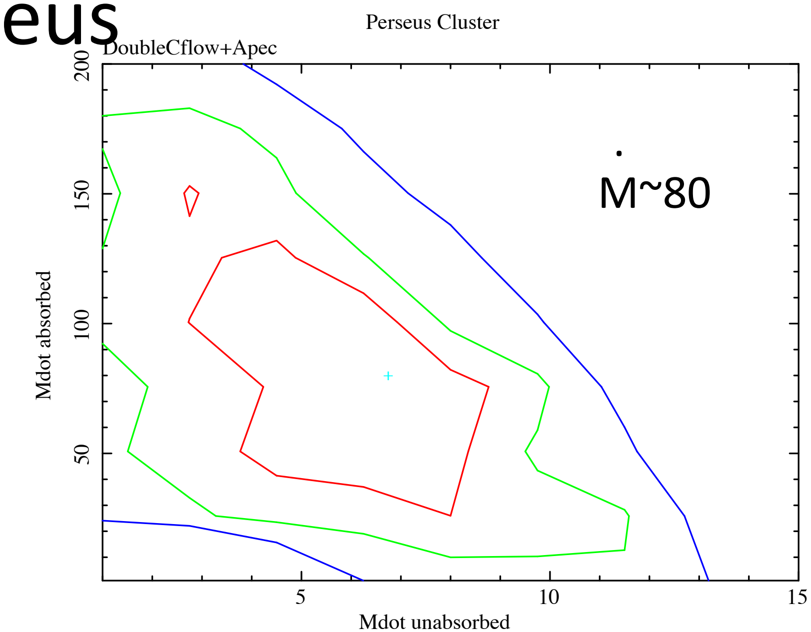
Centaurus





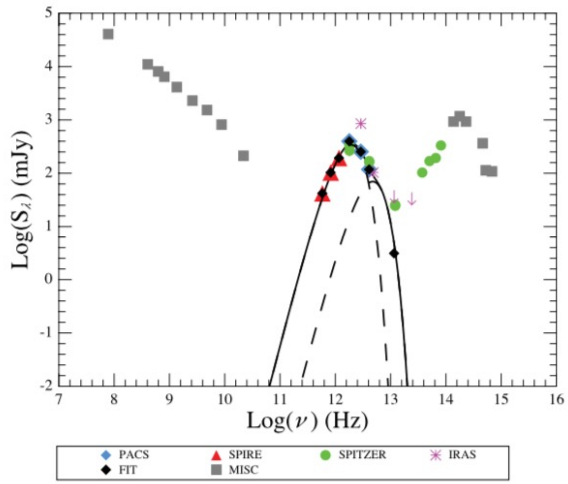
Perseus



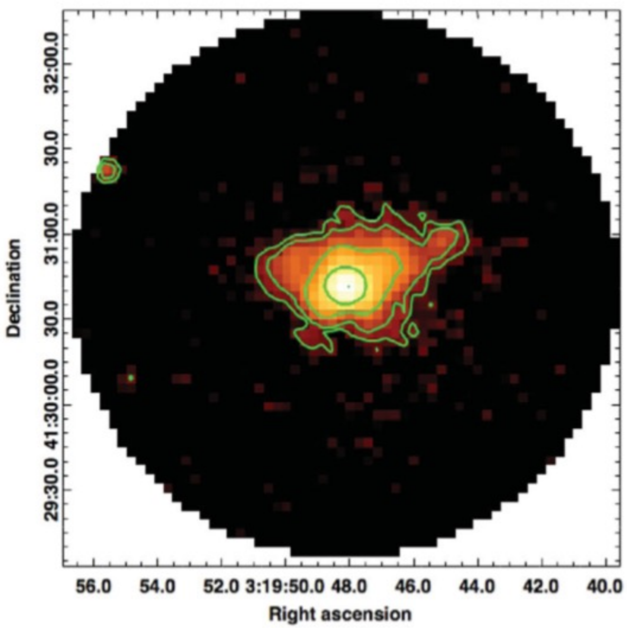


HCFI Fabian+22a

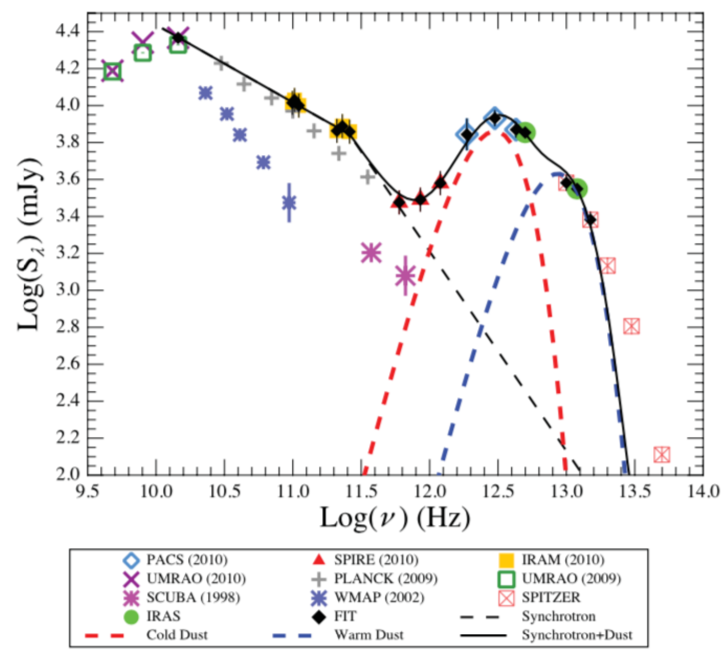
Herschel observations of the Centaurus cluster



Far Infrared Mittal+11,12



Perseus



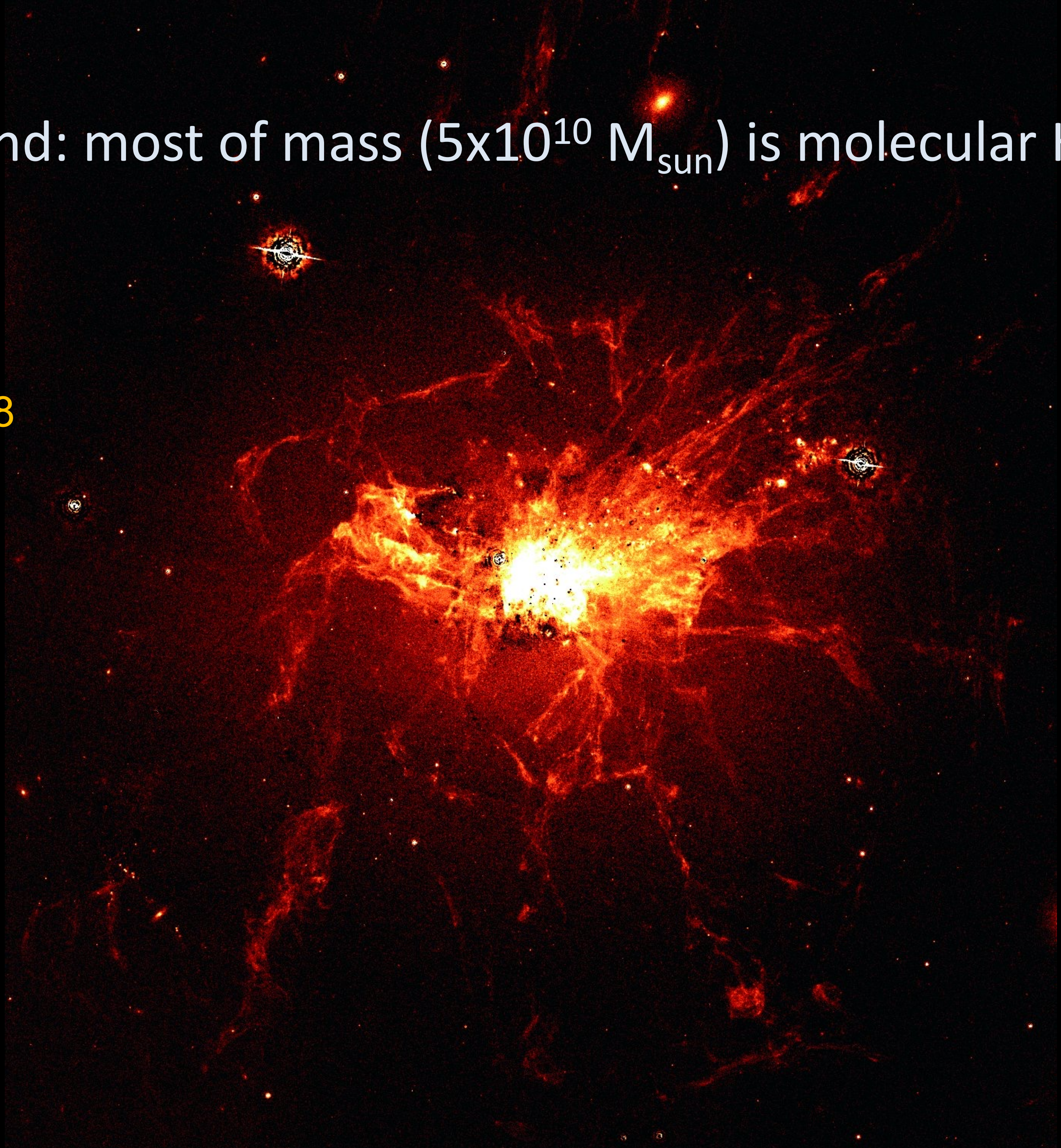
Will too much gas accumulate?

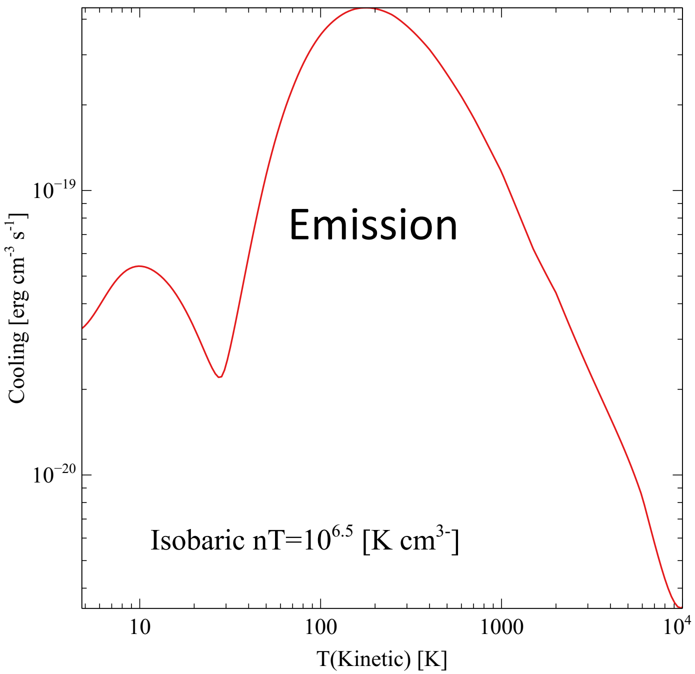
- Maybe (In 1 Gyr, ~10^{10}Msun in Cen, ~10^{11} in Per)
- What is too much?
- There is much cold gas observed in many CC (10^8-10^{11}Msun)
- Speculate: perhaps most in ultracold clouds (<5K?)
- Bubble shocks destroy clouds and drag gas outward, regulating cooled gas mass
- Low mass star formation?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

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

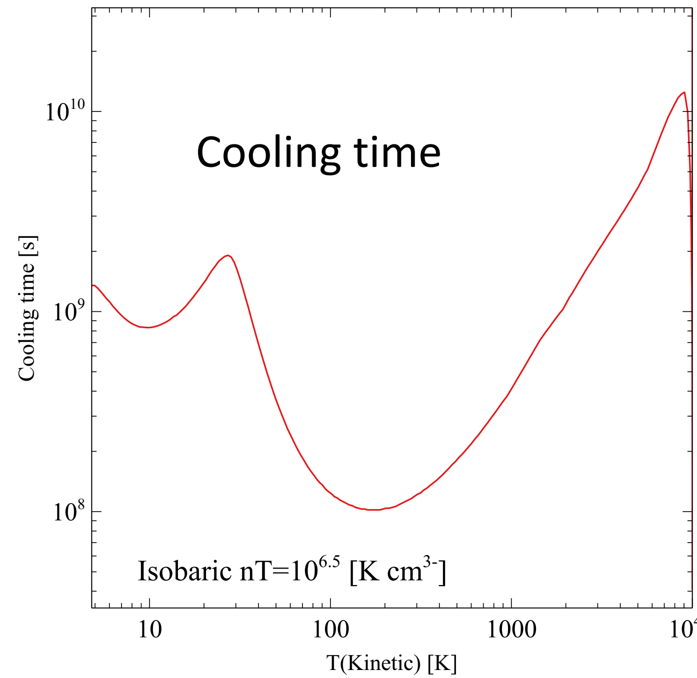
HST

Fabian+08

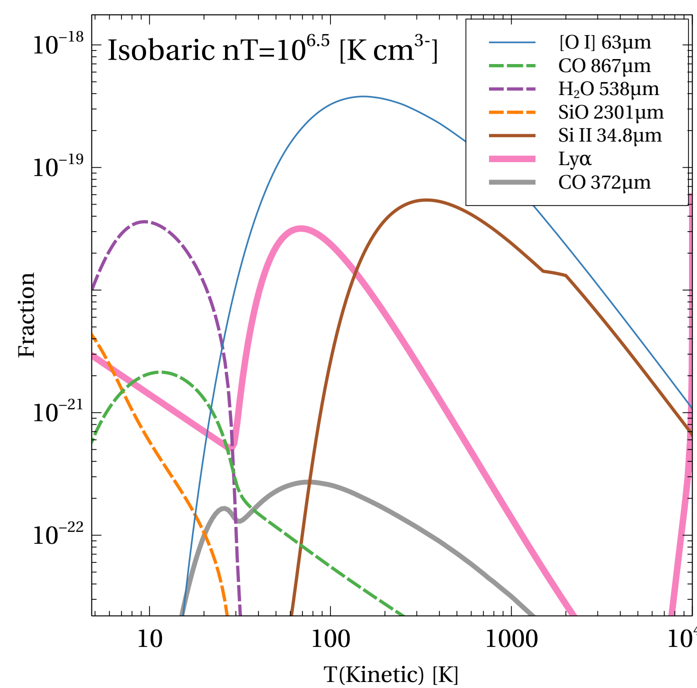




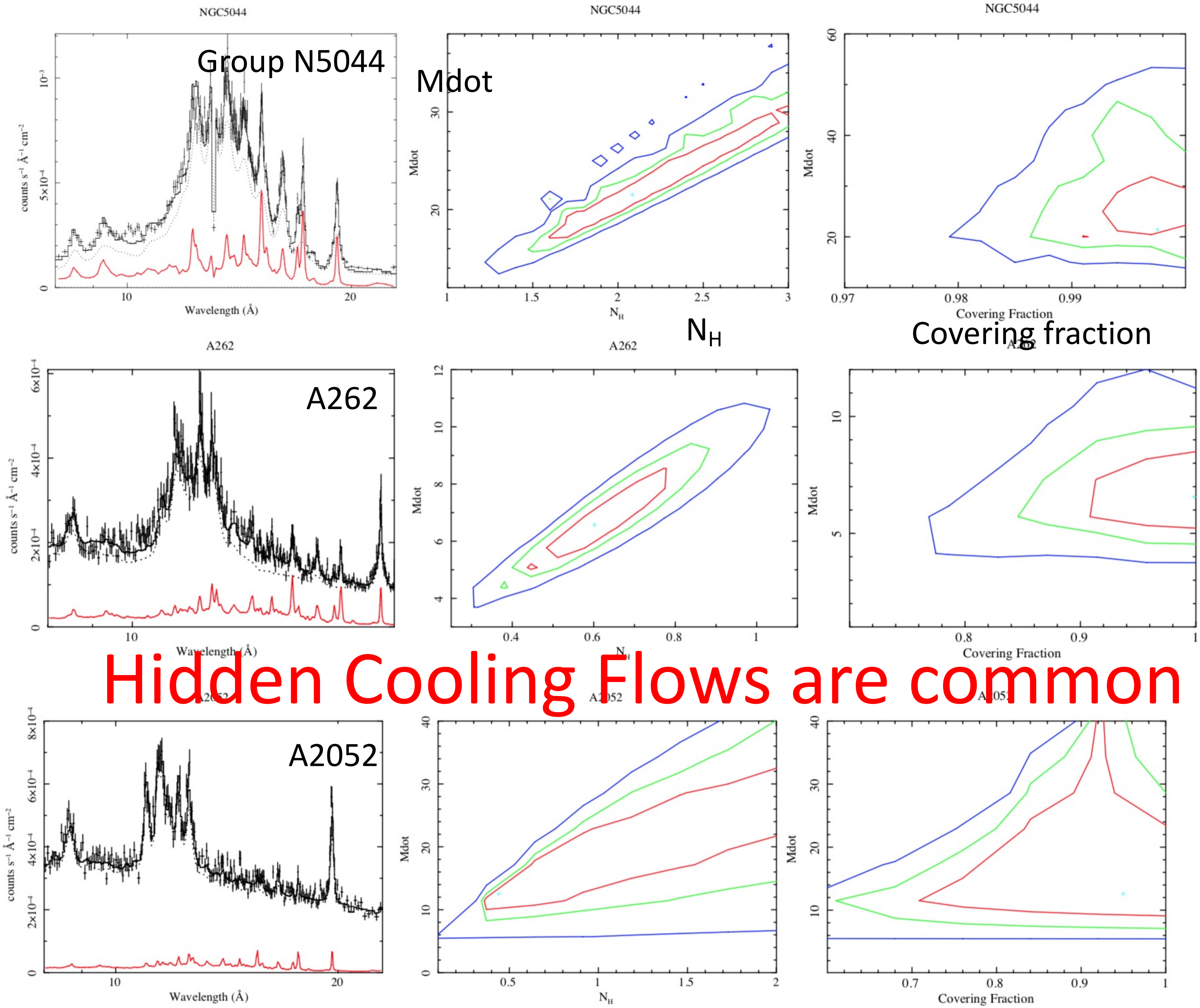
30 yr



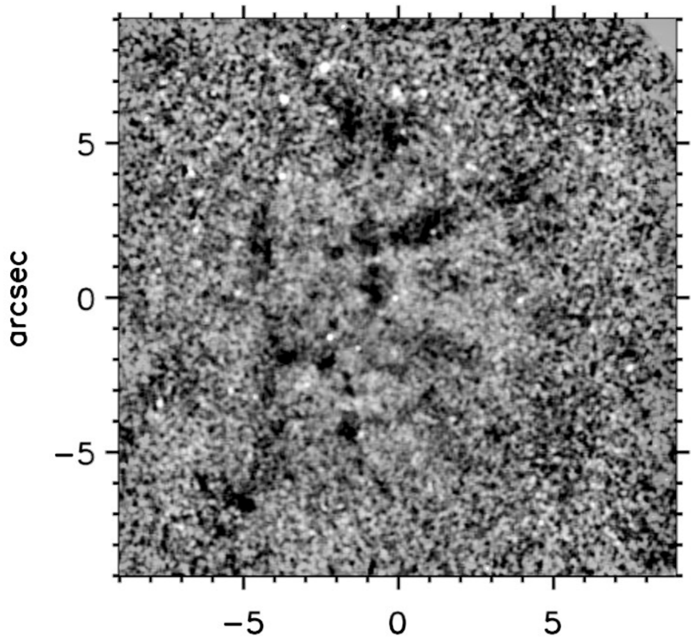
Clouds cool fast.
How cold can clouds go?
3K?



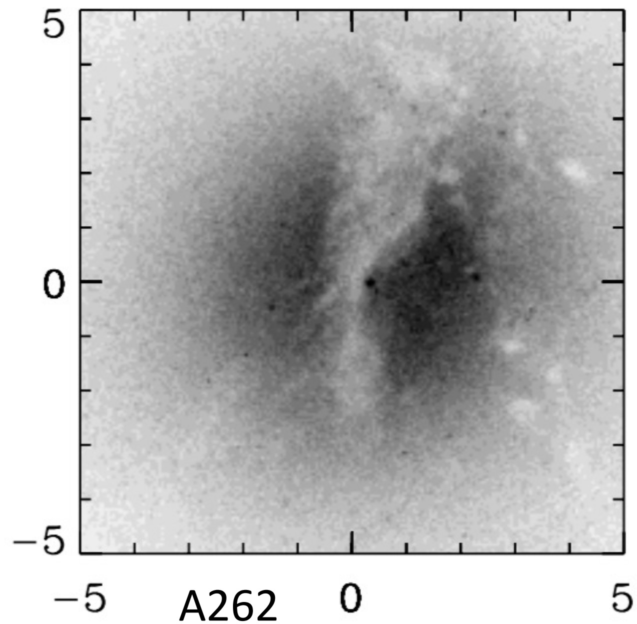
G Ferland



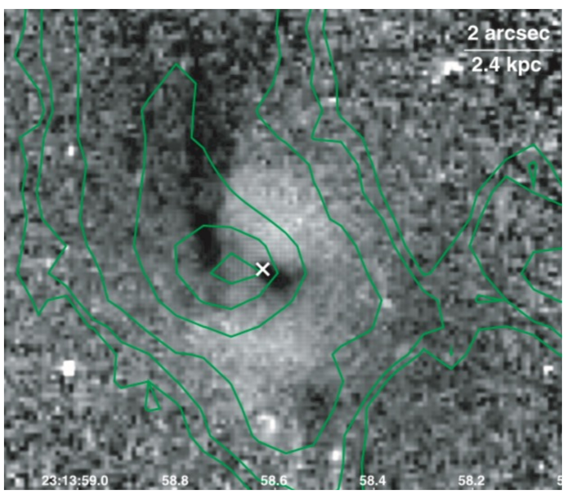
Hidden Cooling Flows are common
NGC5044
Group N5044
Mdot
N_H
Covering fraction
A262
A2052
counts s⁻¹ Å⁻¹ cm⁻²
Wavelength (Å)
Covering Fraction



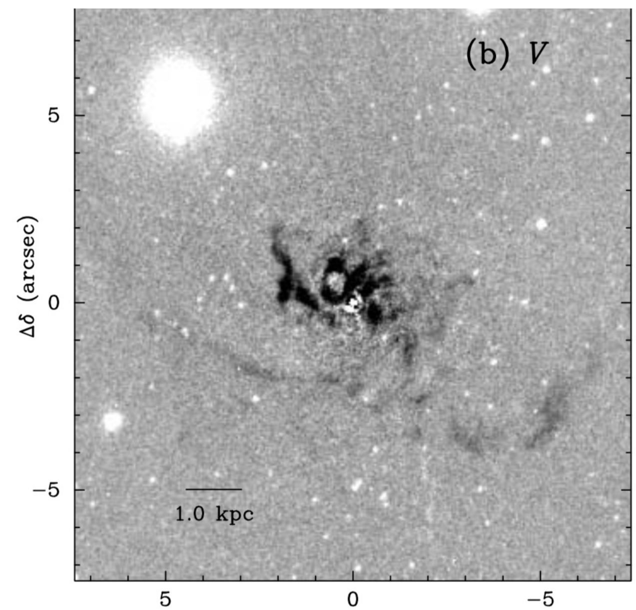
NGC5044



A262



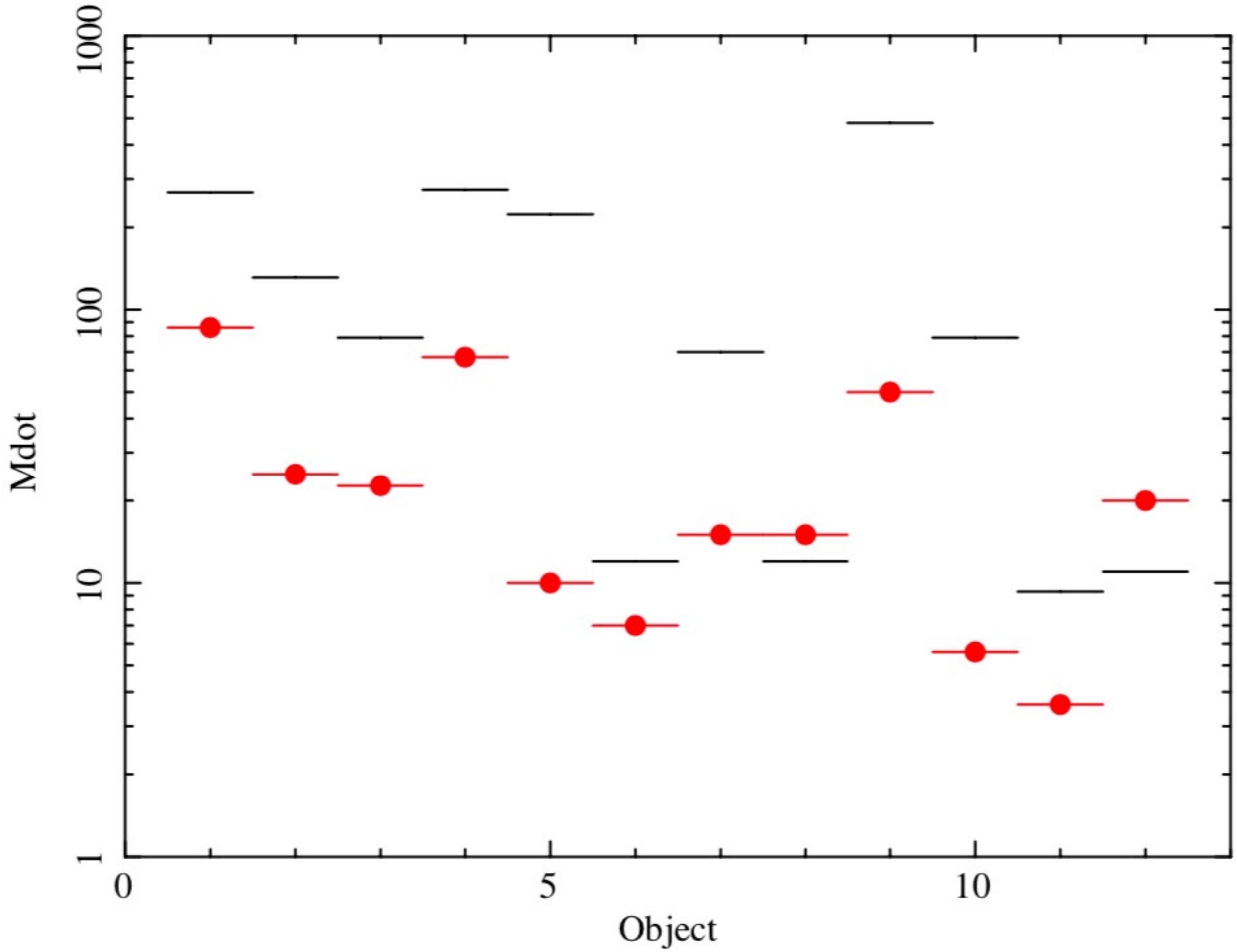
SERSIC 159



A2052

HST images of CCs

note patchy extinction commonly seen



Black – Classical Imaging

Red – HCF RGS

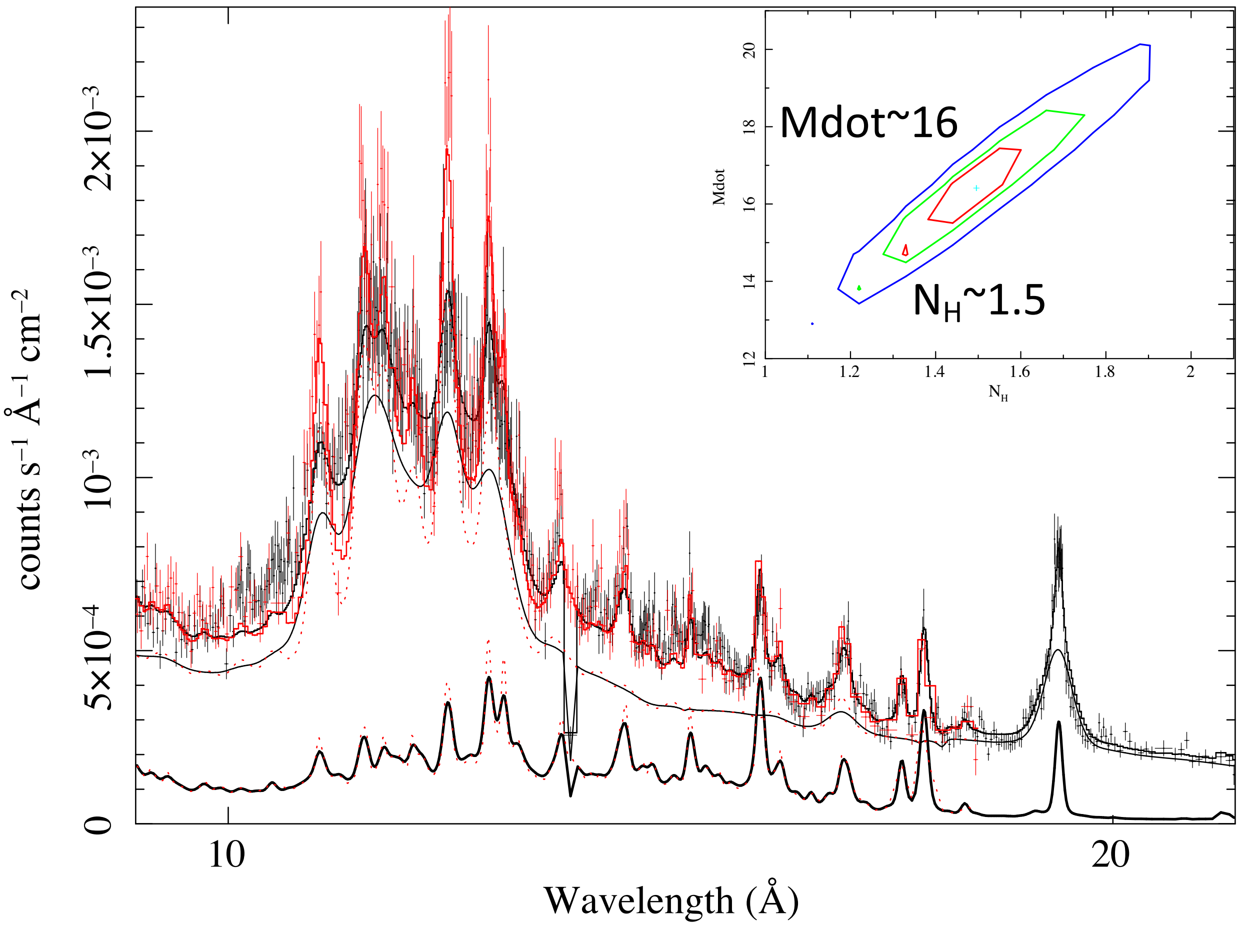
Bubbling AGN Feedback reduces Mdot by factor of 2 or more

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.

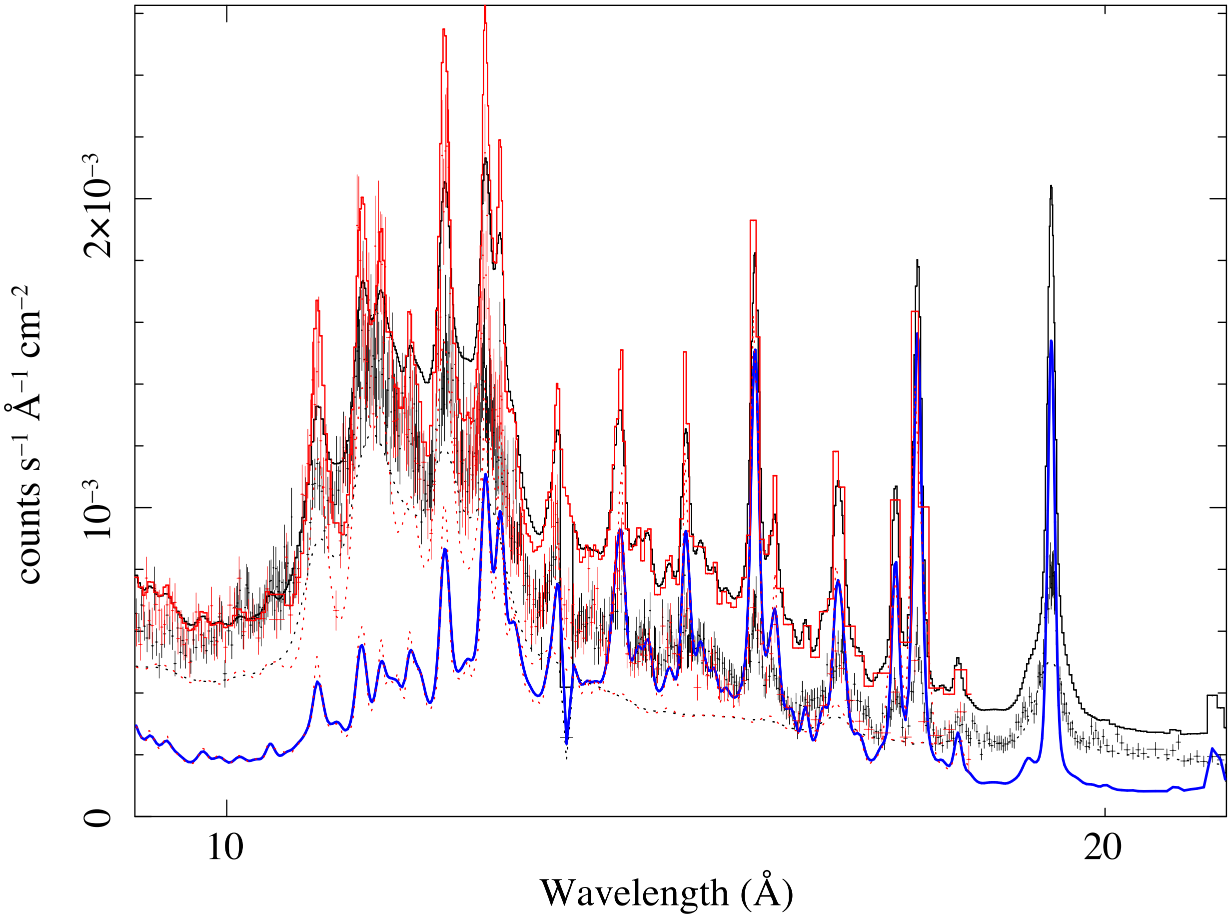
Growth of Central Black Hole

- 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)

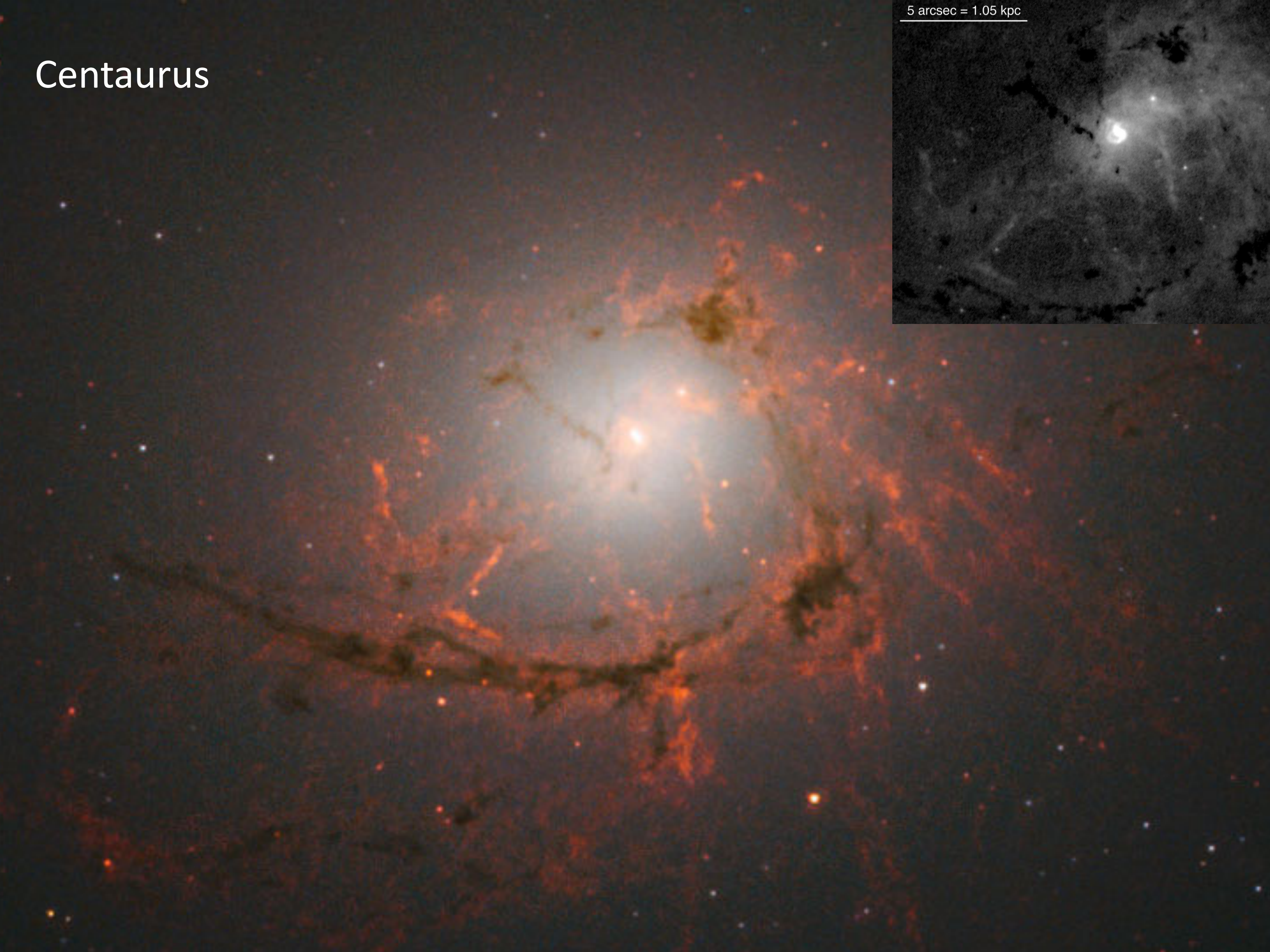
Centaurus

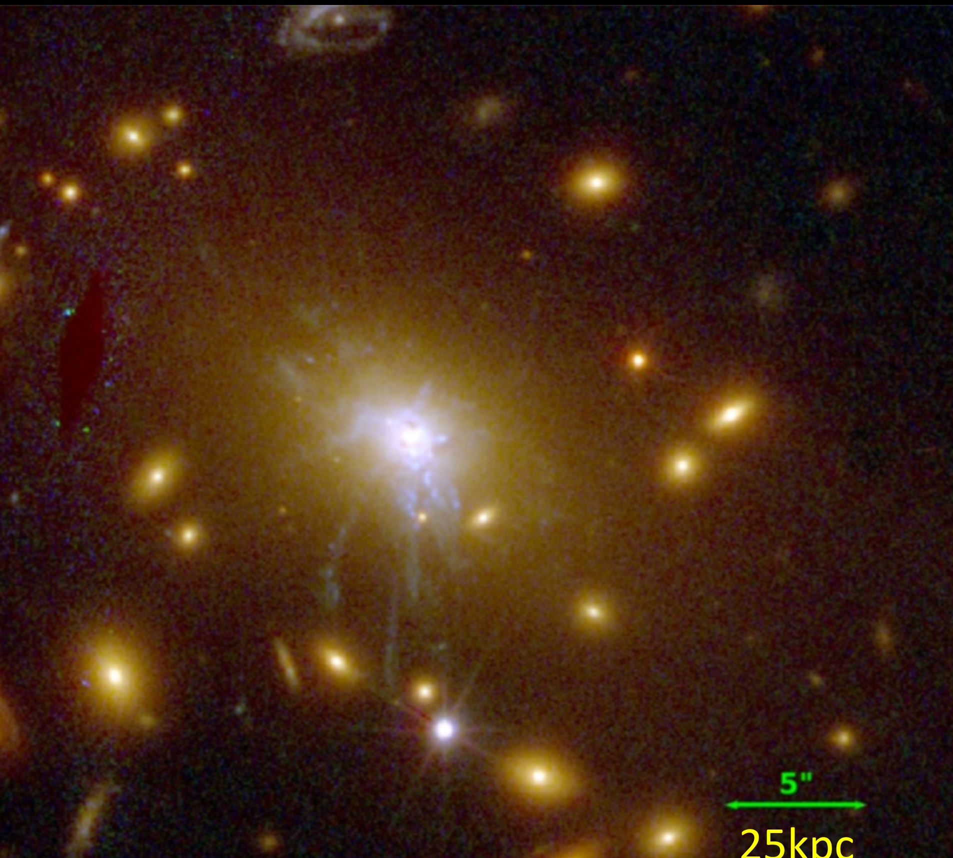


Centaurus with no absorption

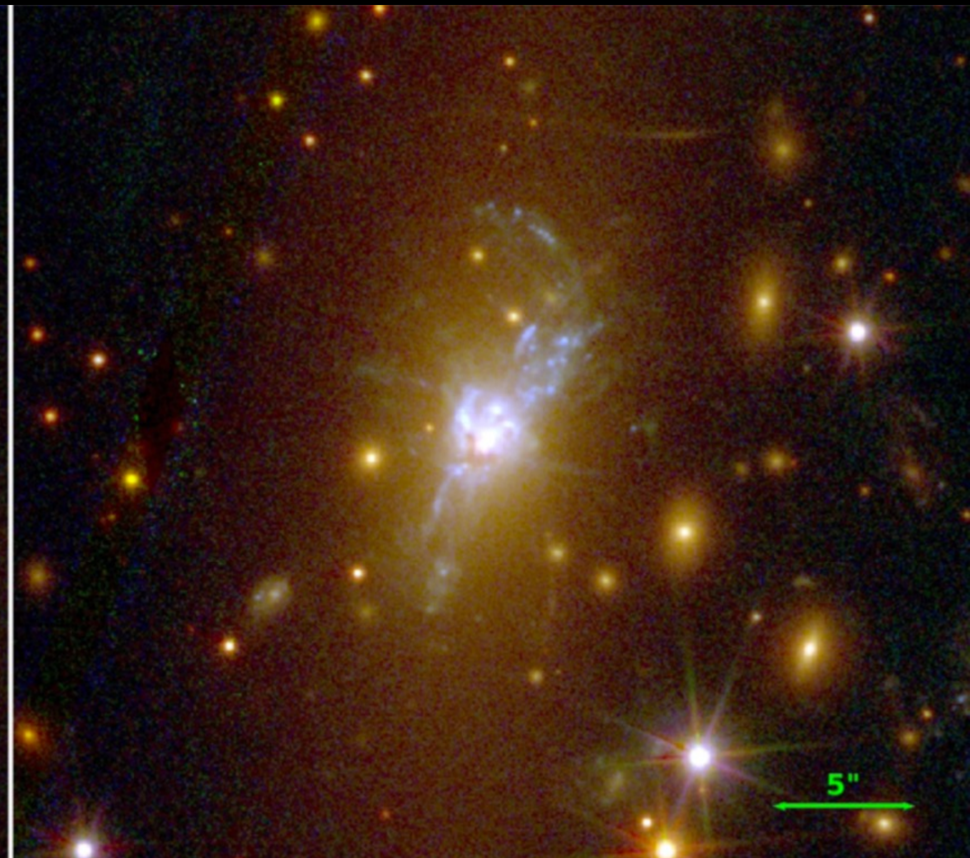


Centaurus





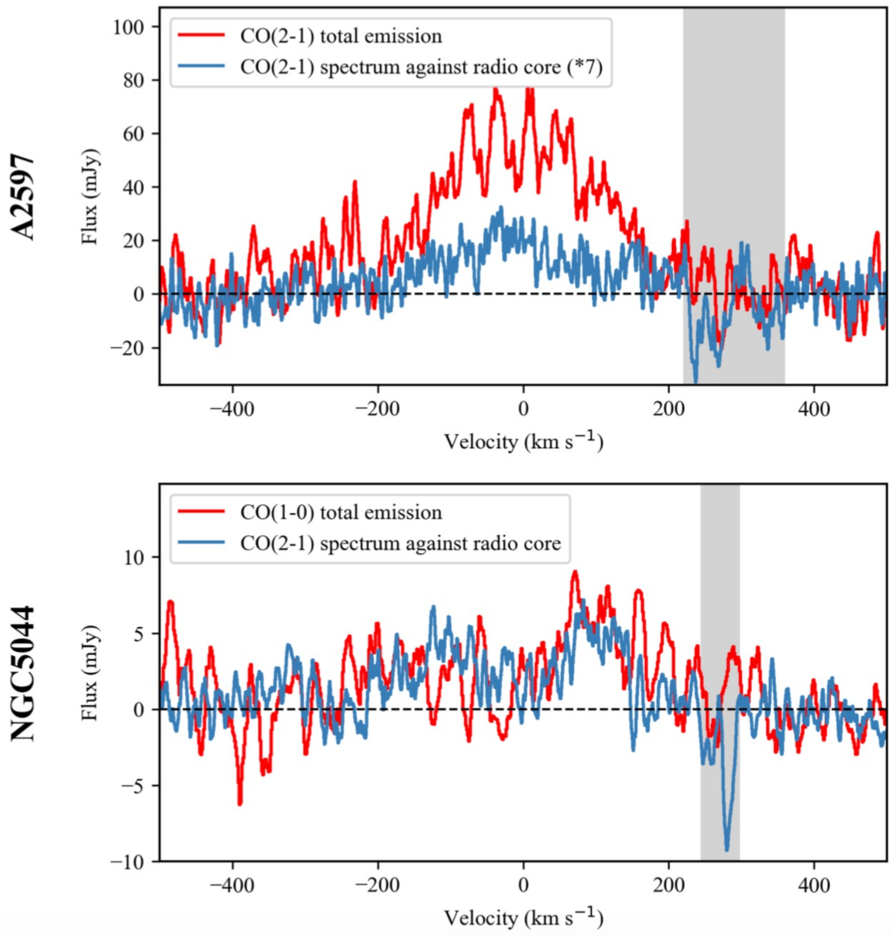
RXJ1532 z=0.35



RXJ1931 z=0.36

Absorption of nucleus by cold clouds

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



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

Future is XRISM (launch later this month) then

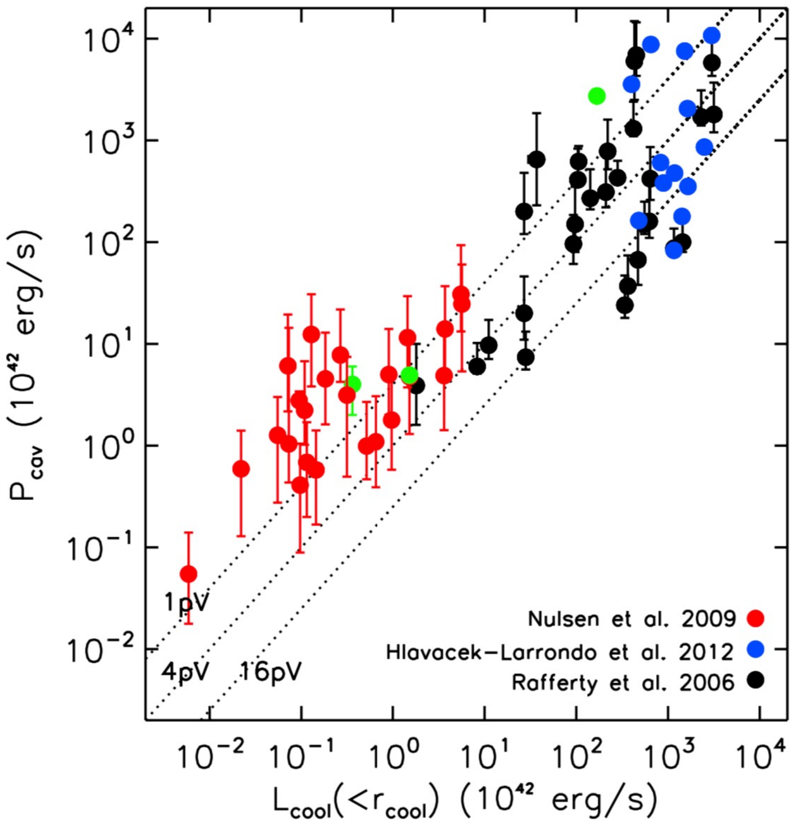
Waiting for Probes

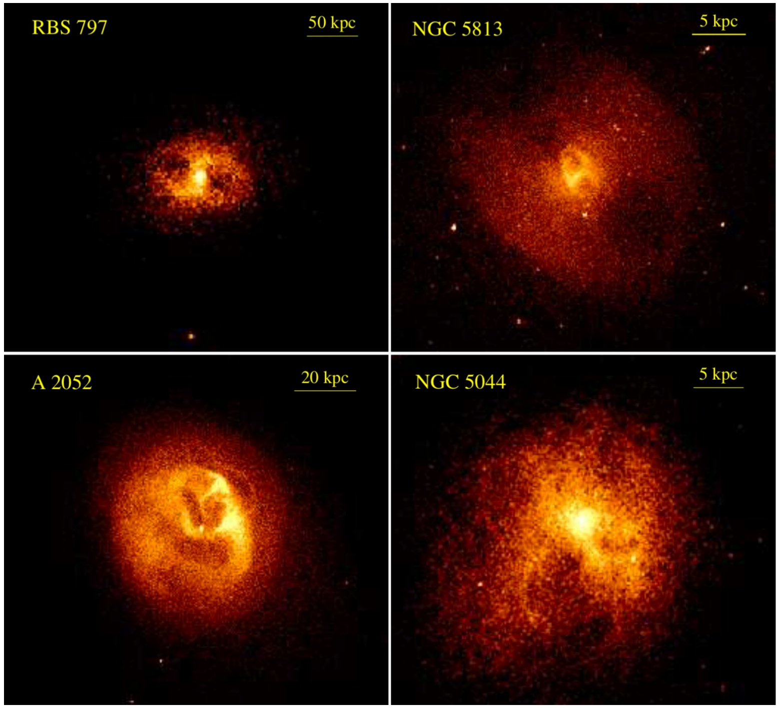
Centaurus in X-rays (Chandra)

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? + 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

All models and interpretation require cold absorption!



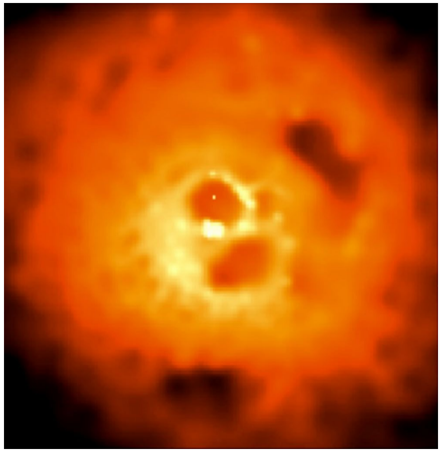


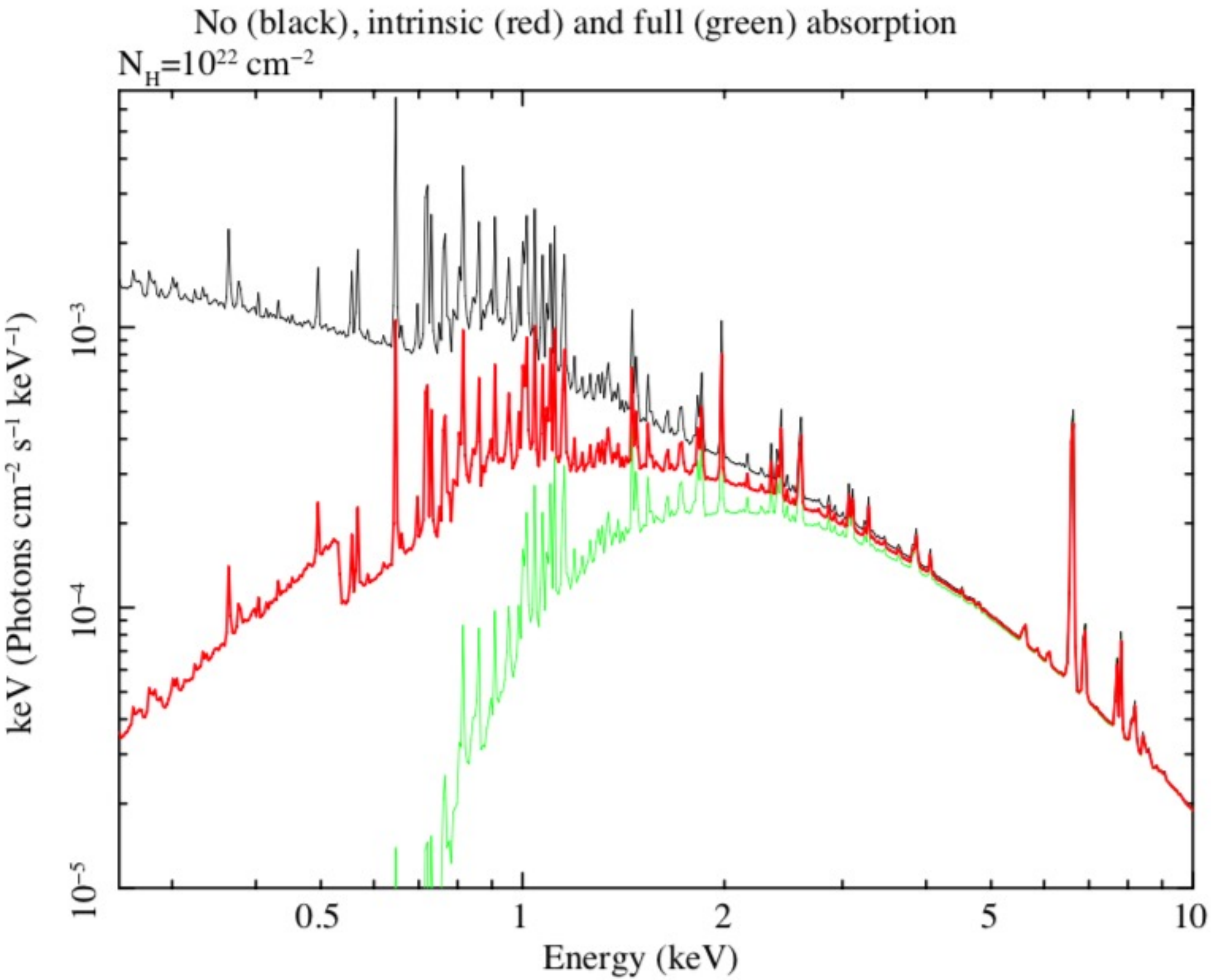
Much of cooling
in core balanced
by heating via bubbles?

AGN Feedback

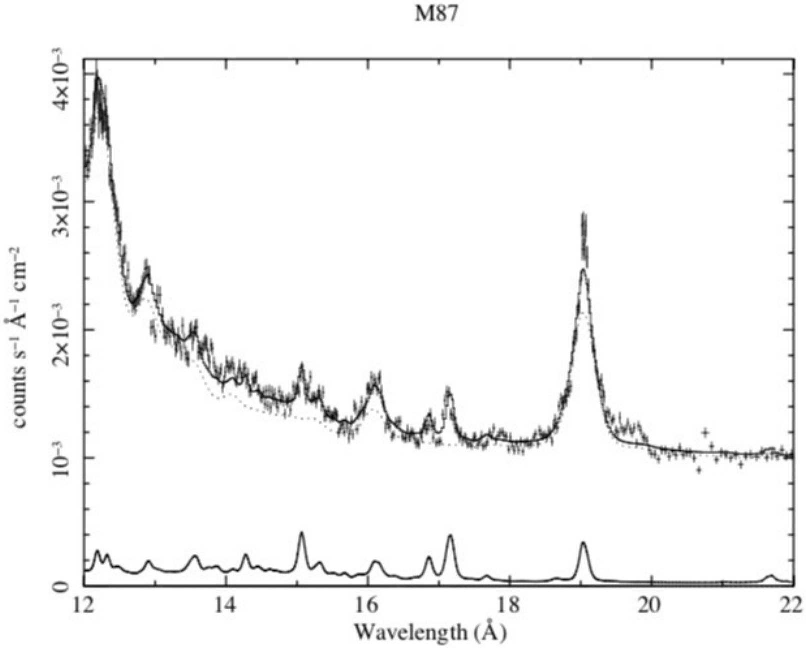
REVIEWS in

Fabian12; McNamara&Nulsen12

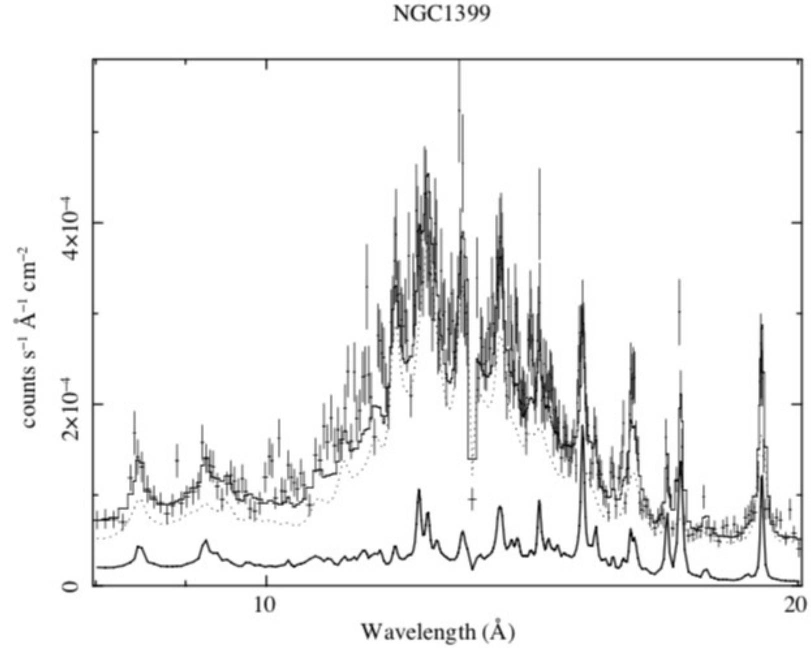




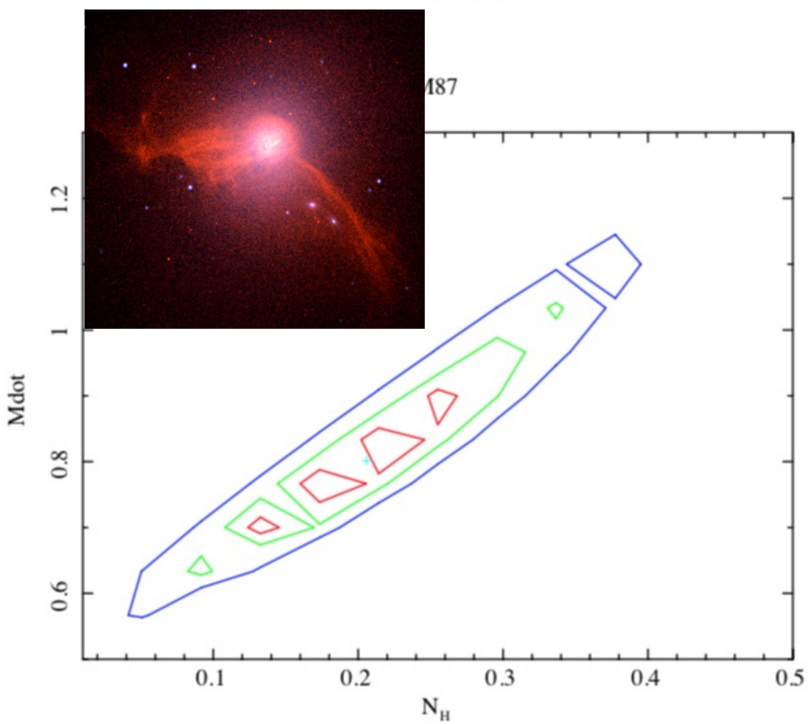
No (black), intrinsic (red) and full (green) absorption
$N_H = 10^{22}$ cm^{-2}
keV (Photons cm^{-2} s^{-1} keV^{-1})
10^{-3}
10^{-4}
10^{-5}
0.5
1
2
5
10
Energy (keV)



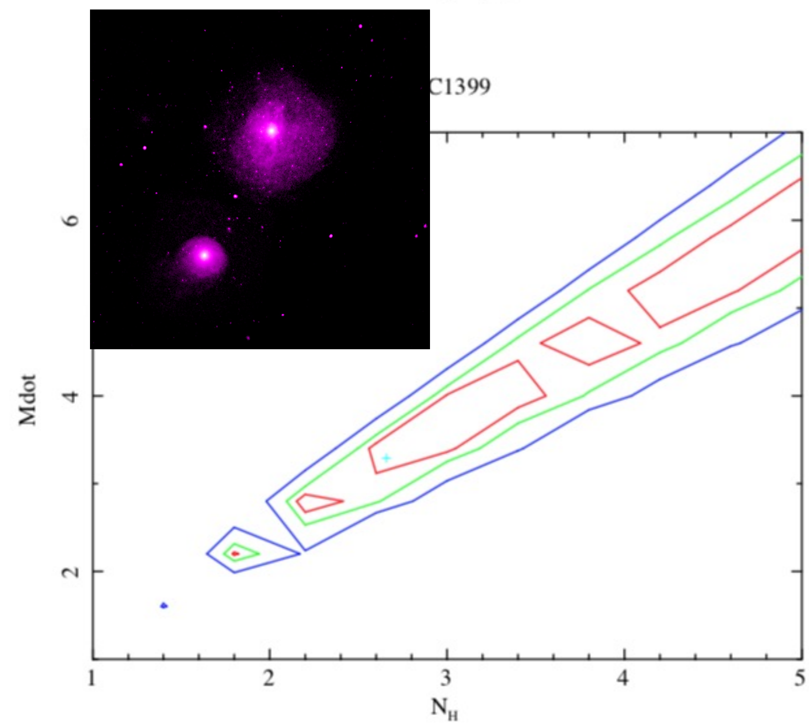
M87
counts s⁻¹ Å⁻¹ cm⁻²
Wavelength (Å)
0
10⁻³
2×10⁻³
3×10⁻³
4×10⁻³
12
14
16
18
20
22



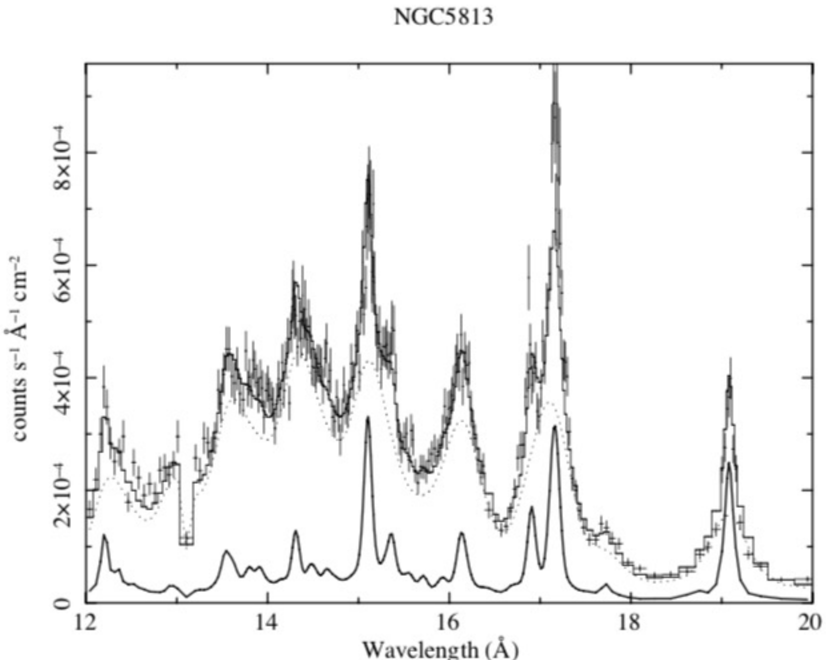
NGC1399
counts s⁻¹ Å⁻¹ cm⁻²
Wavelength (Å)
0
2×10⁻⁴
4×10⁻⁴
10
20

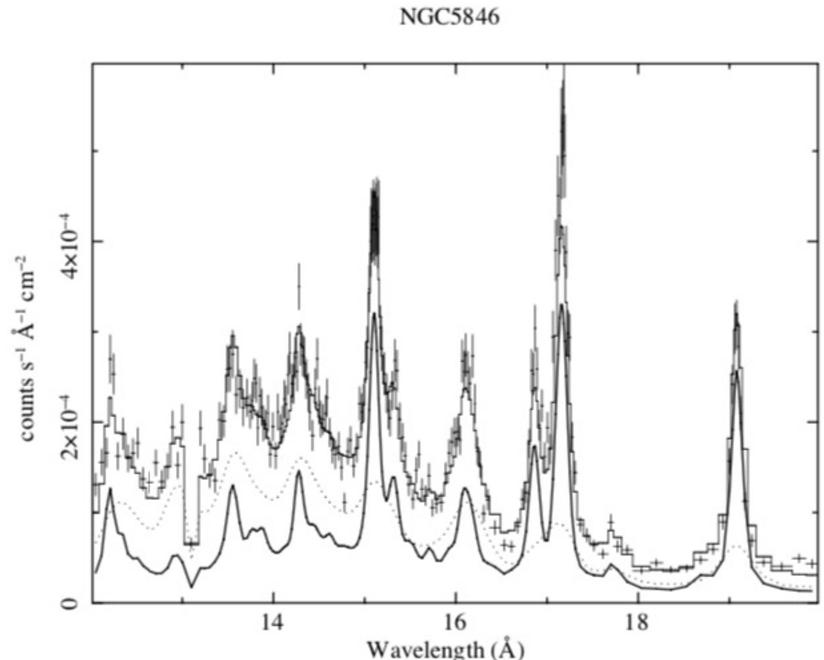


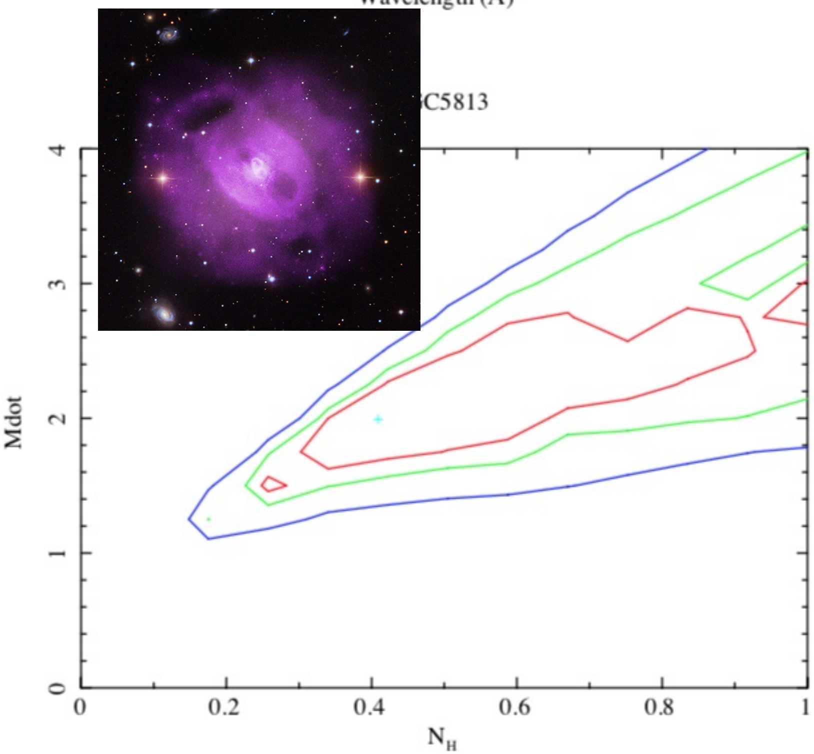
M87
Mdot
N_H
0.6
0.8
1
1.2
0.1
0.2
0.3
0.4
0.5

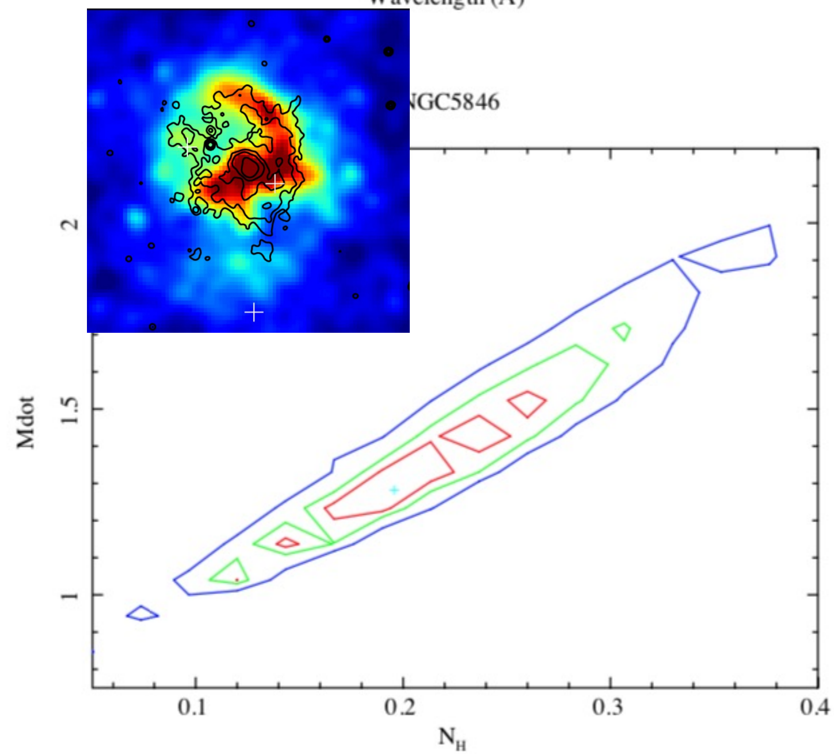


C1399
Mdot
N_H
2
4
6
1
2
3
4
5

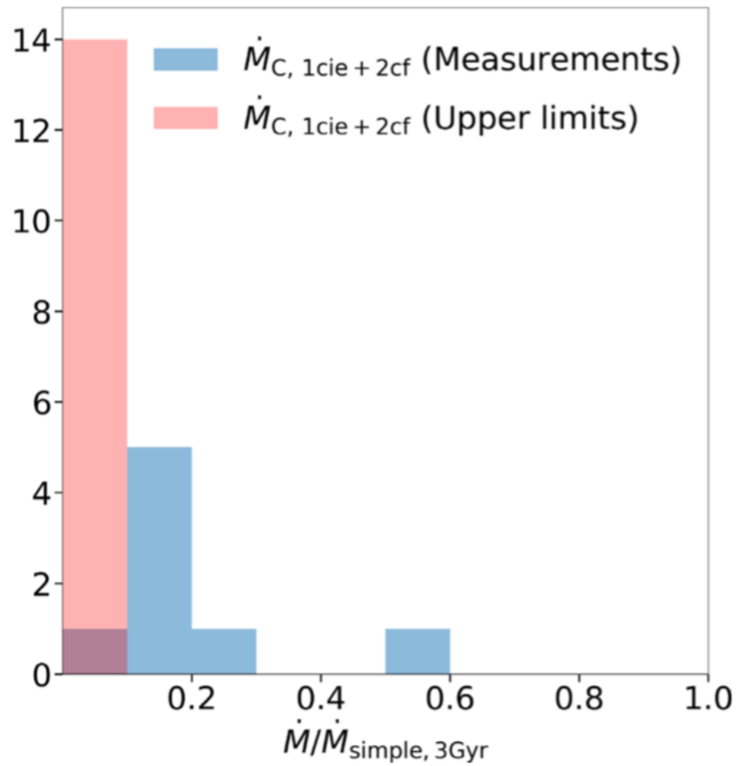

NGC5813
counts s⁻¹ Å⁻¹ cm⁻²
0
2×10⁻⁴
4×10⁻⁴
6×10⁻⁴
8×10⁻⁴
12
14
16
18
20
Wavelength (Å)


NGC5846
counts s⁻¹ Å⁻¹ cm⁻²
0
2×10⁻⁴
4×10⁻⁴
14
16
18
Wavelength (Å)


NGC5813
Mdot
0
1
2
3
4
0
0.2
0.4
0.6
0.8
1
N_H


NGC5846
Mdot
1
1.5
2
0.1
0.2
0.3
0.4
N_H

XMM RGS Spectroscopy

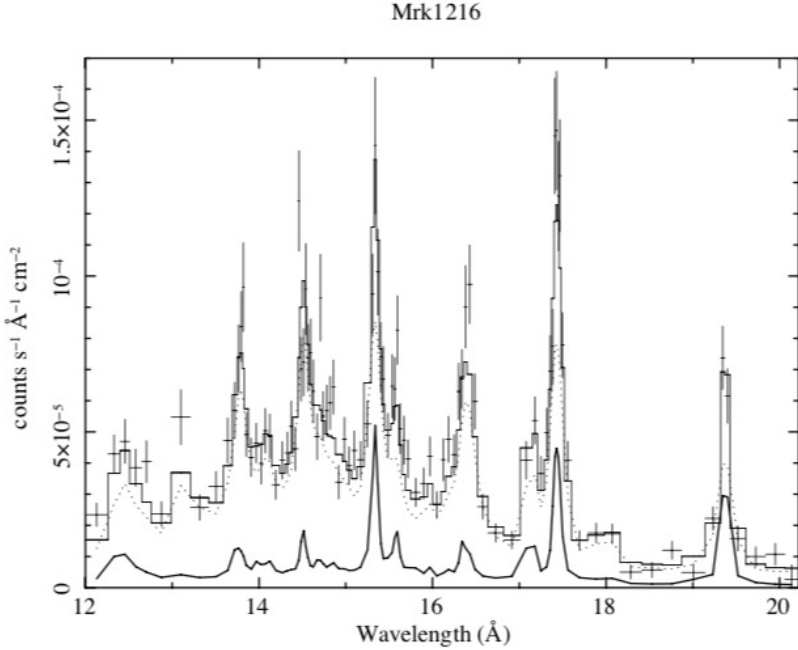


Liu, Fabian+19

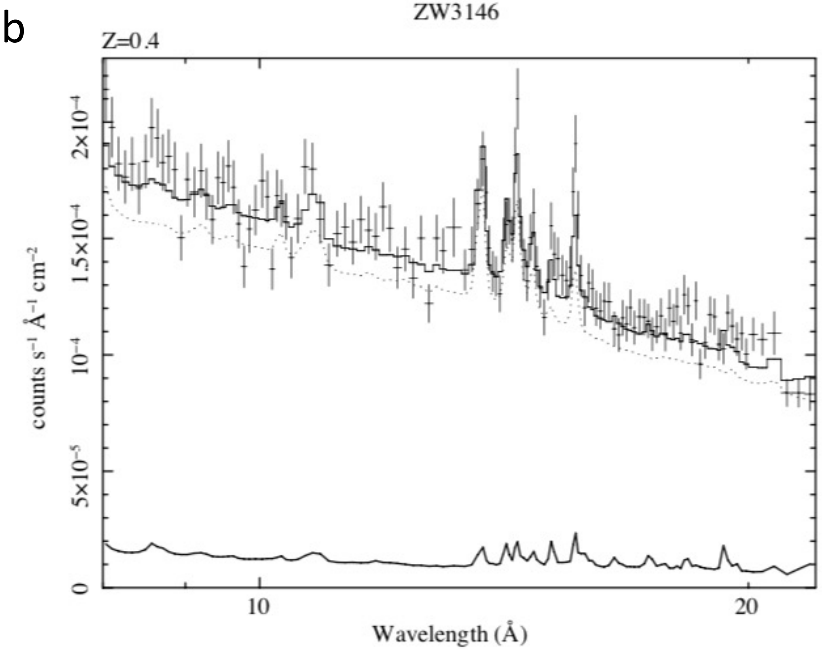
Little cooling obvious in RGS spectra of cool cores

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

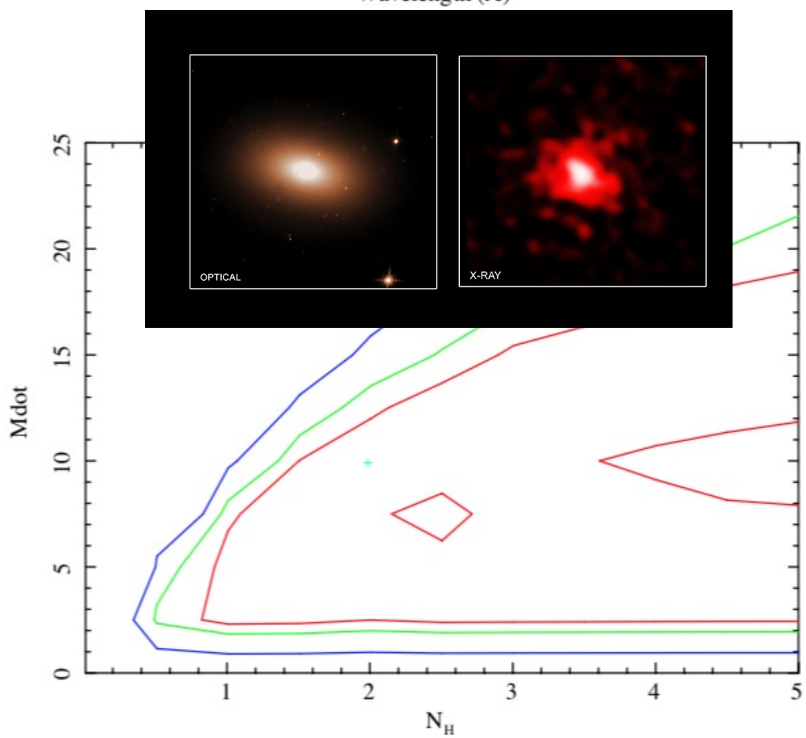
Fabian+23b



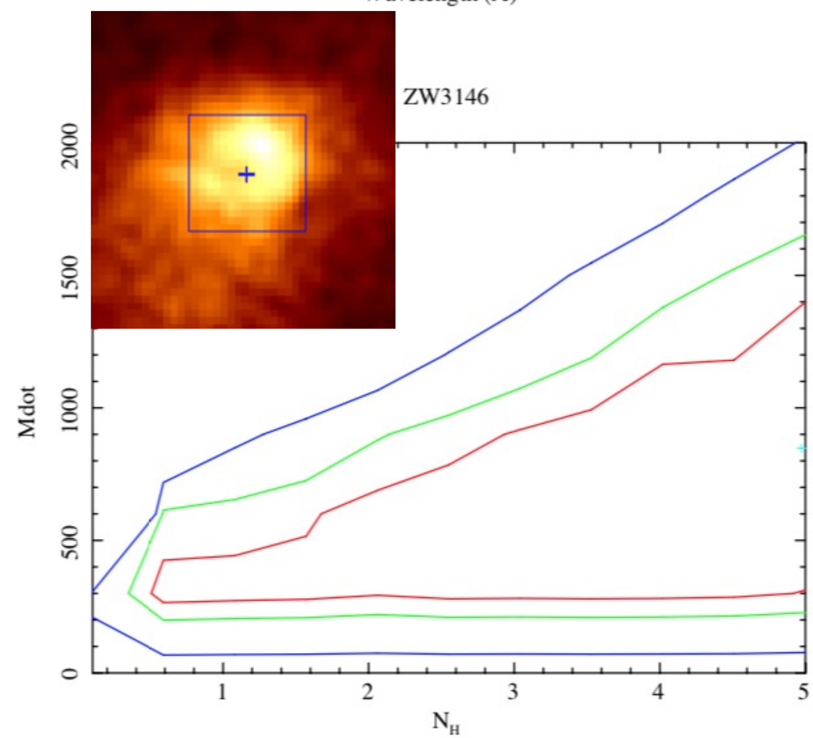
Mrk1216
counts s⁻¹ Å⁻¹ cm⁻²
Wavelength (Å)



ZW3146
Z=0.4
counts s⁻¹ Å⁻¹ cm⁻²
Wavelength (Å)

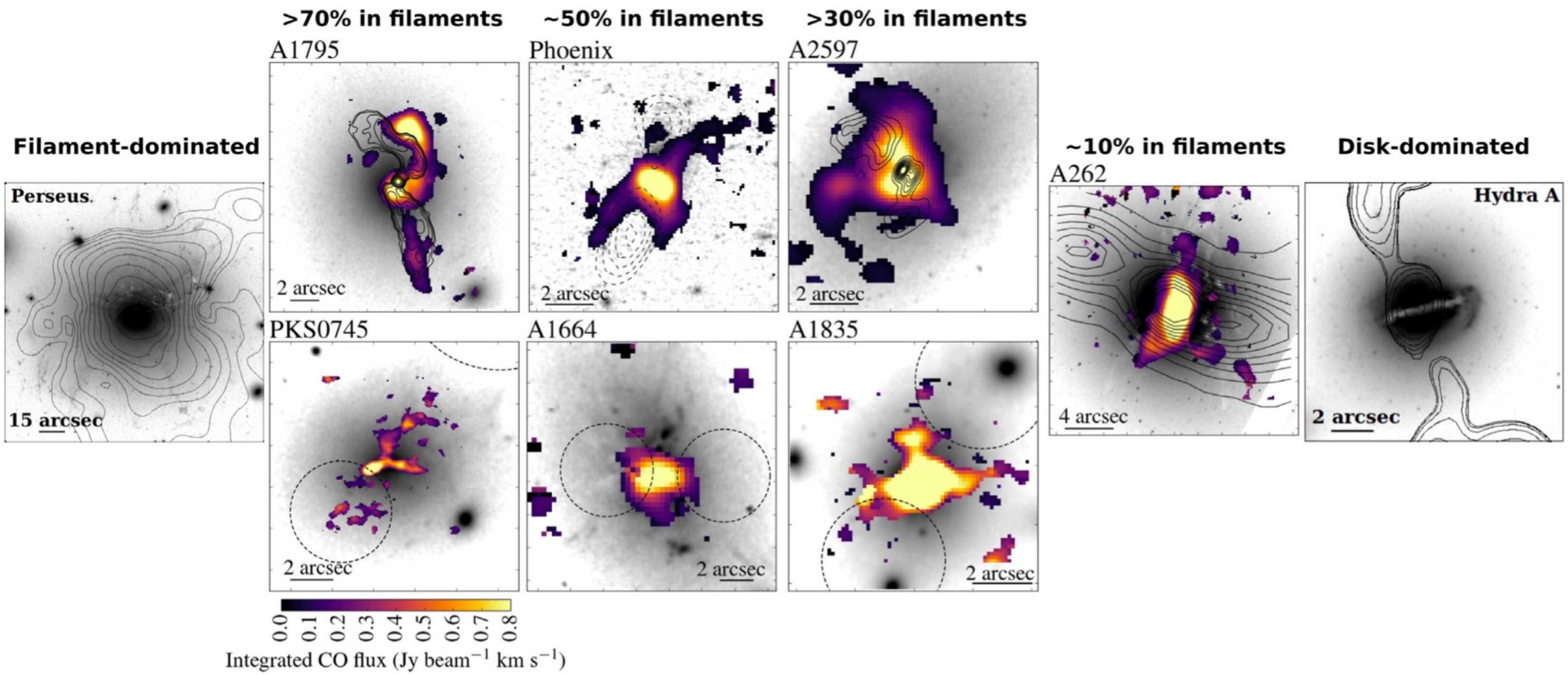


OPTICAL
X-RAY
Mdot
N_H

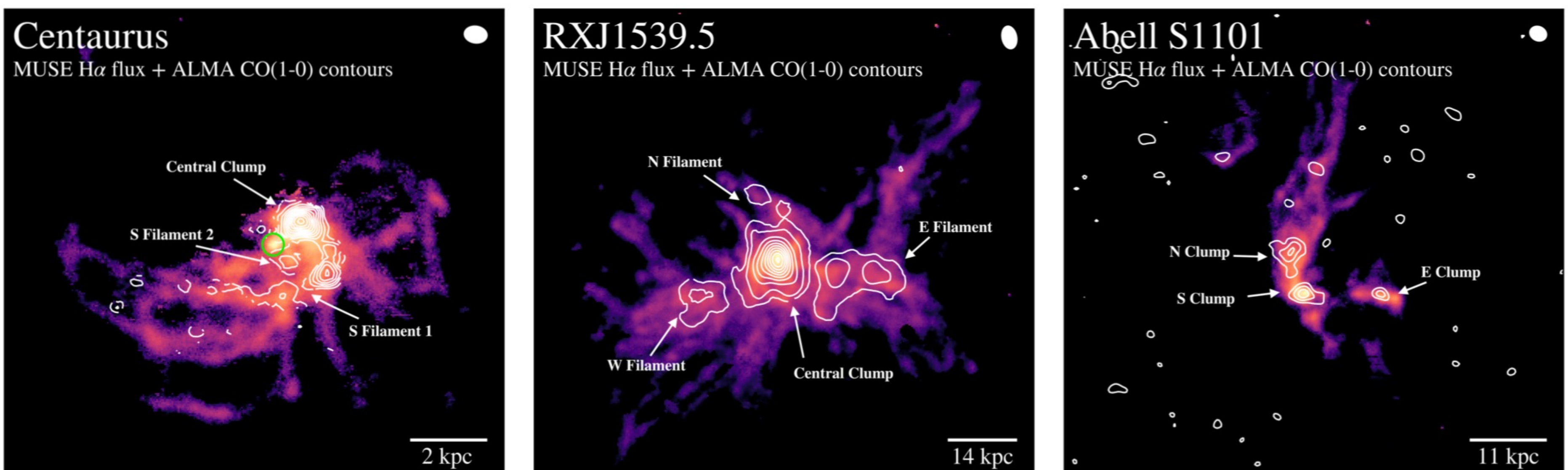


ZW3146
Mdot
N_H

 19

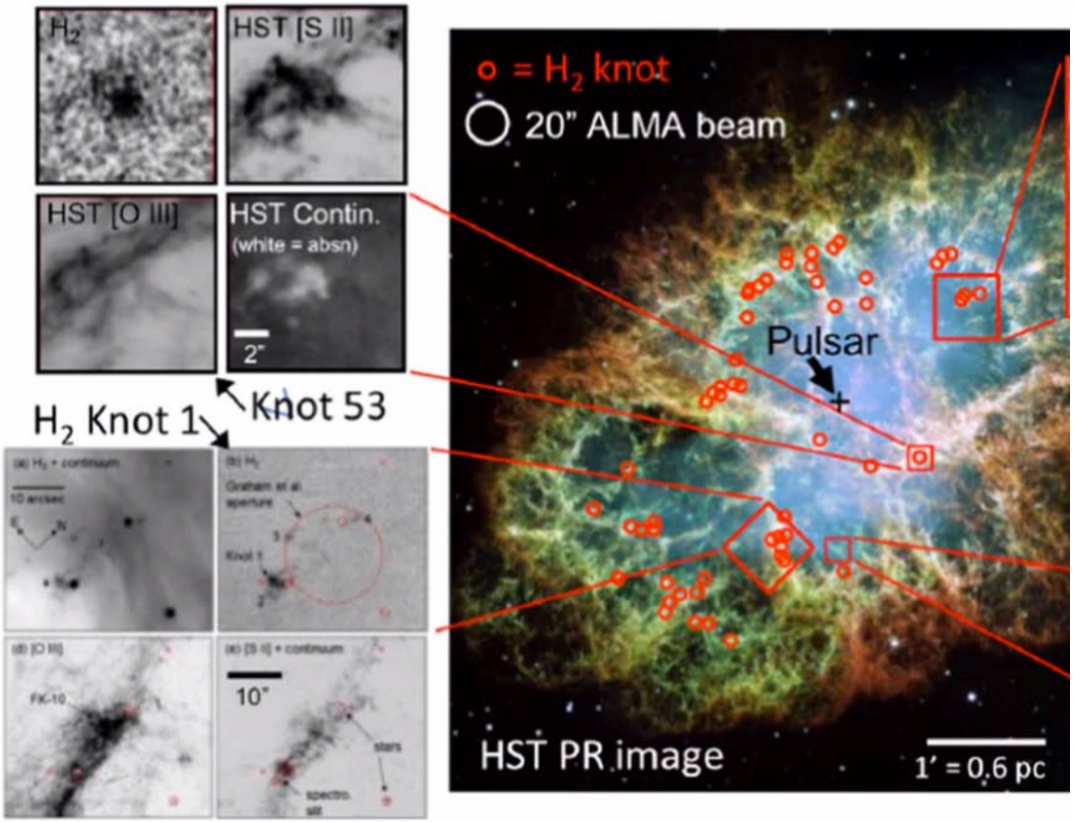


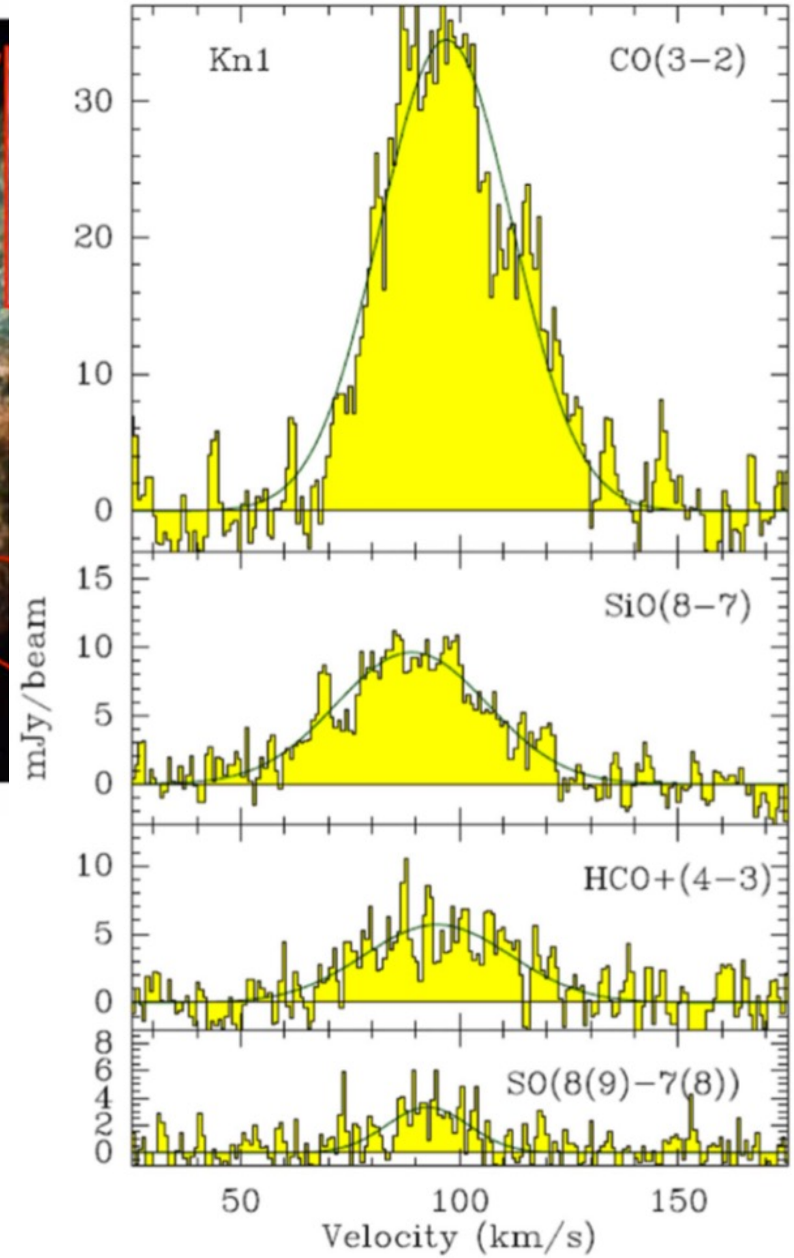
Olivares+19



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		1e9
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	



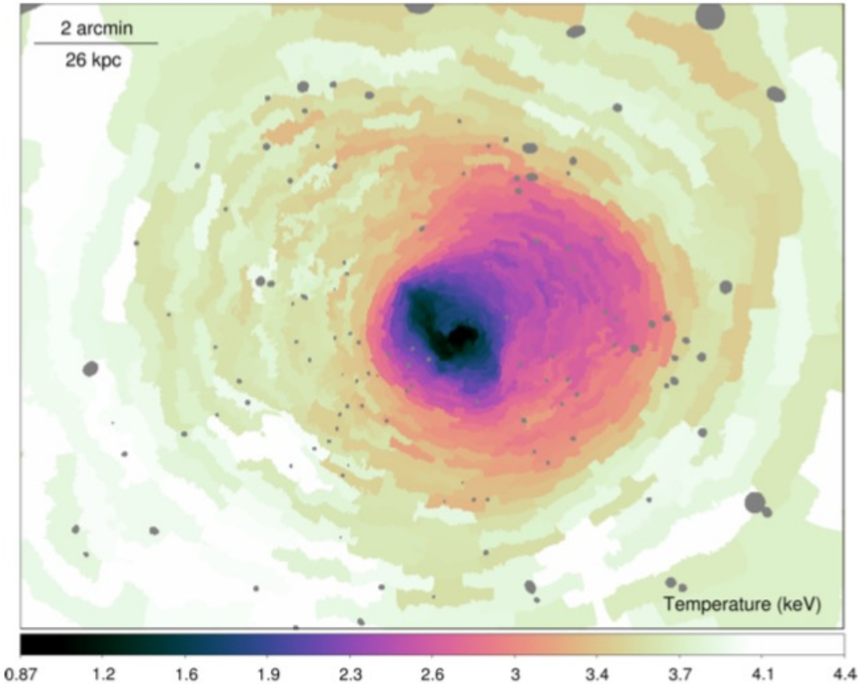


Crab Nebula

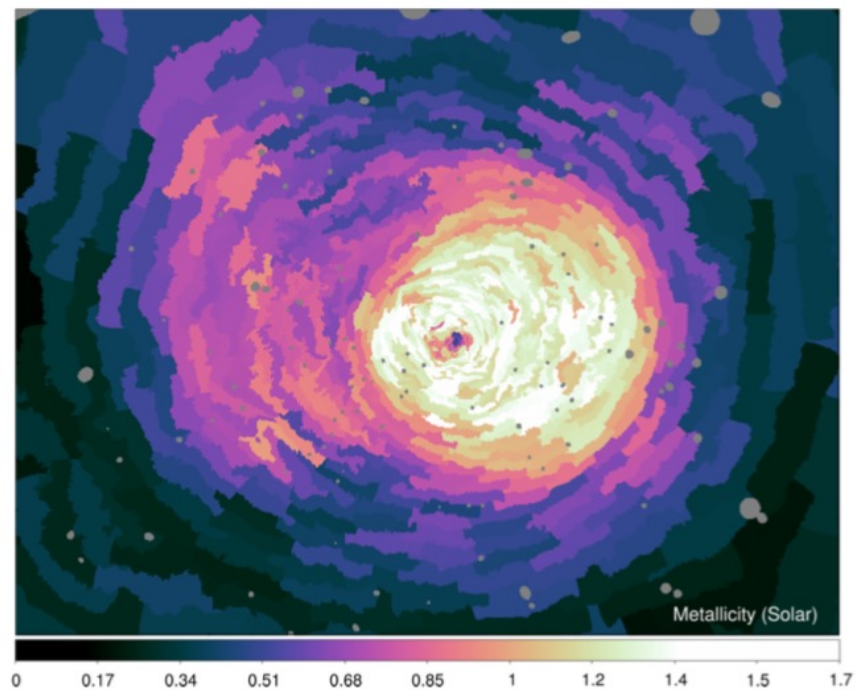
Pressure $nT=10^{6.5}$ cm^{-3} K

Similar to cool cores

Centaurus cluster
Chandra X-ray
Sanders+16



kT



Z

Centaurus