A first view at the core of A1668: offset cooling and AGN feedback

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Bologna, January 2021

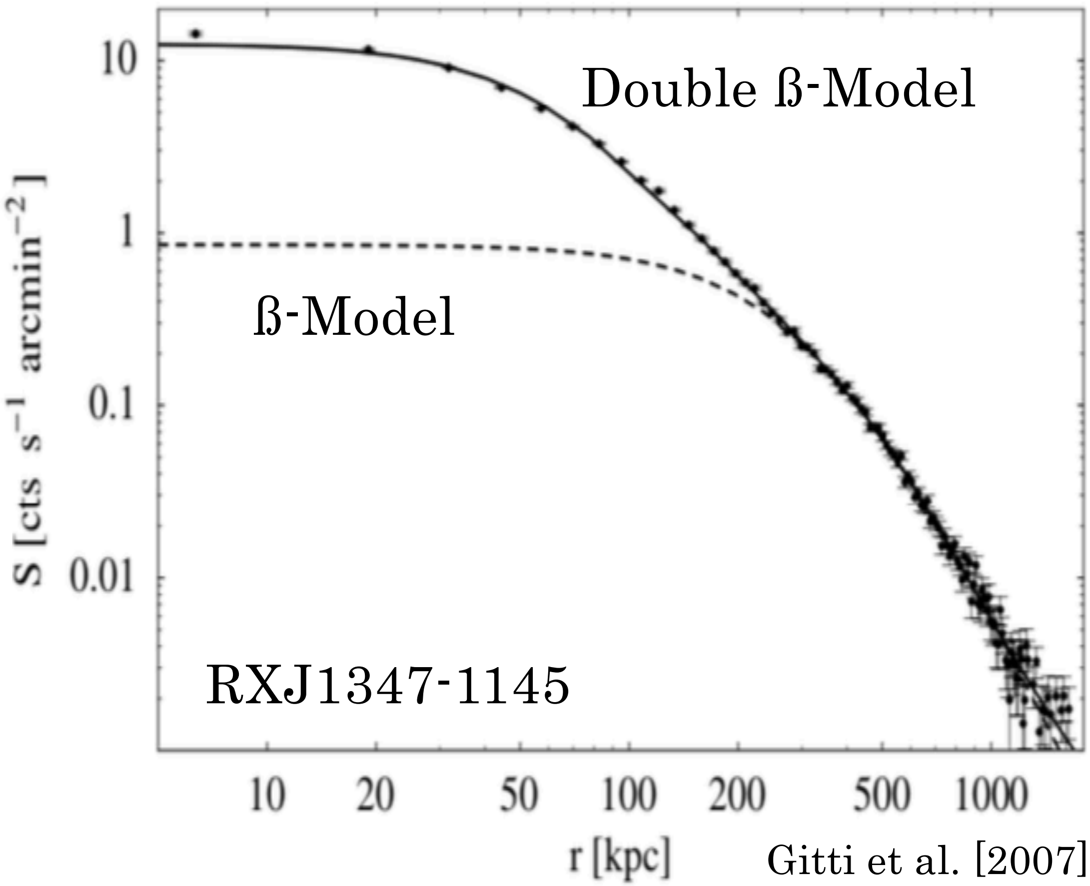
Outline of the talk

- Introduction on cool-core clusters, cooling flow problem and AGN feedback;
- The cool-core cluster A1668: radio analysis;
- X-ray analysis: surface brightness and thermodynamical profiles;
- Multi-wavelength analysis with Hα data;
- Putative cavities in A1668;
- What is happening in the core of A1668?;
- Conclusions.

What is a cool-core cluster?

- Surface brightness peaks in the central region
- Surface brightness profile usually modeled through a double ß-Model [Mohr et al. 1999, LaRoque et al. 2006]:

$$\Sigma_X(r) = \sum \Sigma_{X,i}(0) \left[1 + \left(\frac{r}{r_{c,i}}\right)^2\right]^{\frac{1}{2}-3\beta}$$



Gitti et al. [2007]

Cooling Flows

The hot (~10^7 K) ICM is cooling through Bremsstrahlung and line emission:

$$t_{cool} = \frac{5}{2}\frac{kT(r)}{\mu X n_e(r)\Lambda(T)}$$

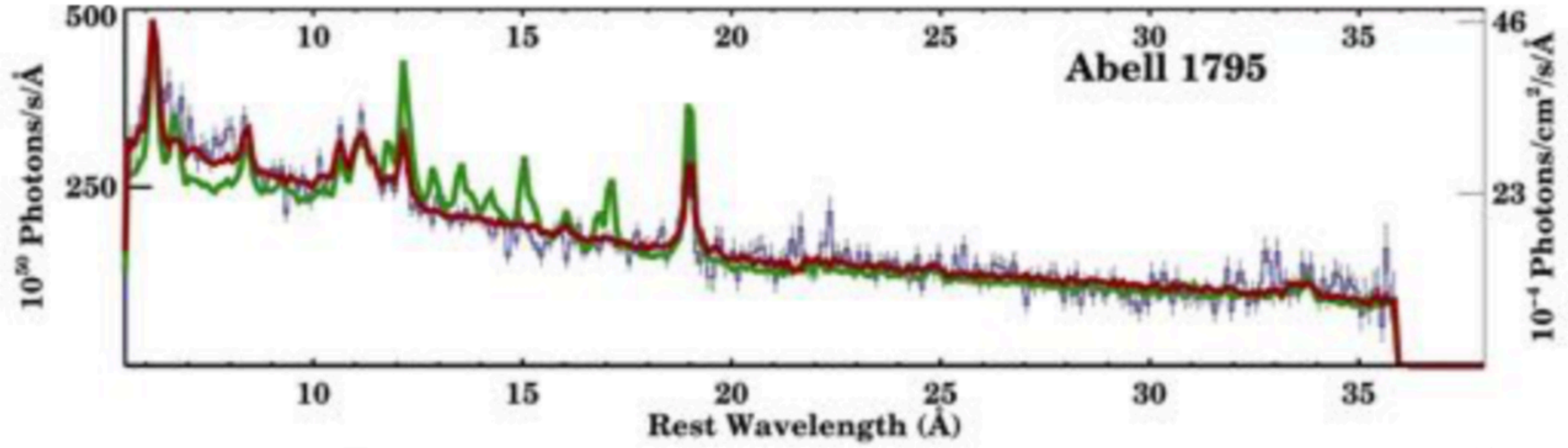
$$\Downarrow$$

Central regions cool faster due to higher density: we expect a 'flow' of cool gas moving towards the cluster core and depositing a mass:

$$\dot{M}_{cool} = \frac{2}{5}\frac{\mu m_p}{kT}L_X$$

Cooling Flow Problem

- The signatures of the cooling flow (e.g., SFR, line emission) are tipically detected only at ~1-10% of the expected rates



Peterson & Fabian [2006]

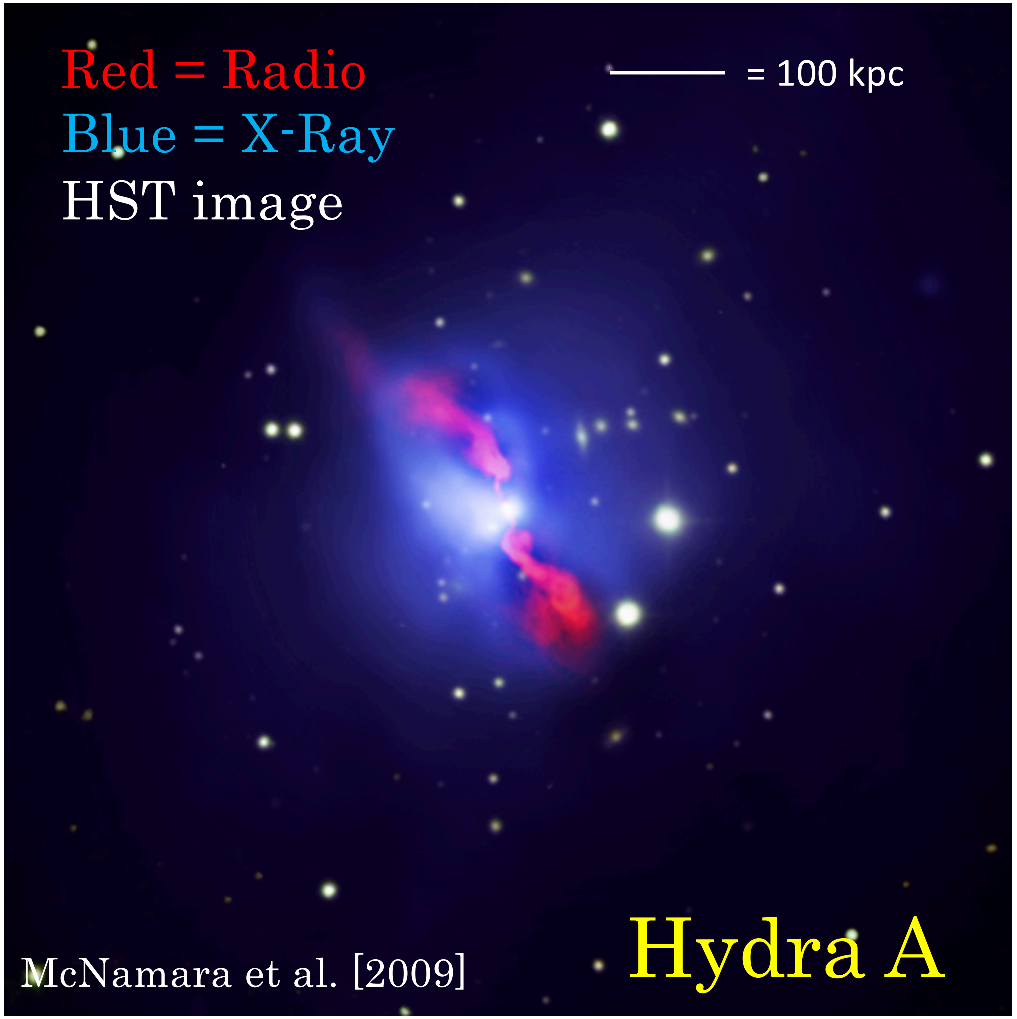
Cooling Flow Model

Observed Cooling Flow

Solution

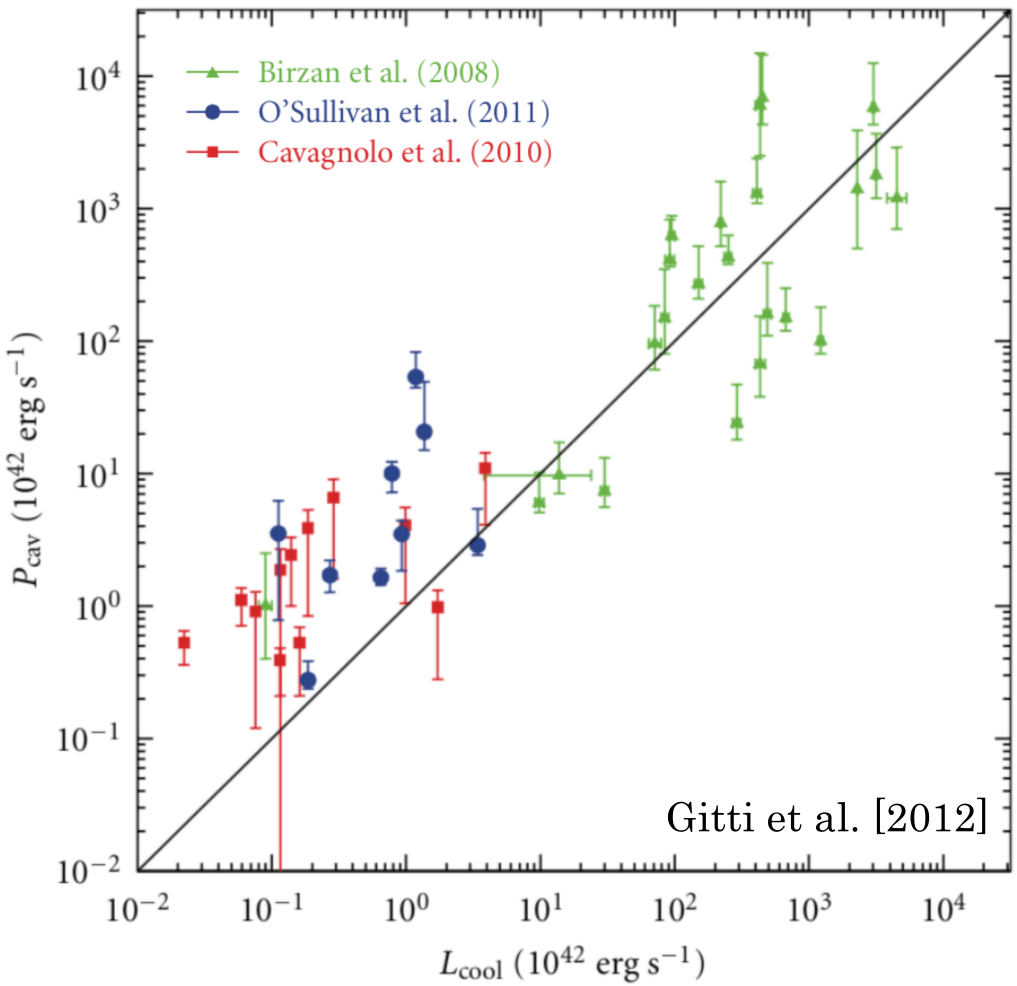
There is an heating source that is able to quench the cooling of the ICM

<u>AGN FEEDBACK</u>



AGN feedback signatures: ICM cavities

- Mechanical feedback from the AGN produces bubbles in the ICM
- These so-called cavities are usually filled with radio-emitting plasma;
- The measured power of such cavities is comparable to the luminosity emitted by the cooling region of the cluster.



Gitti et al. [2012]

A1668 [Pasini et al., submitted to ApJ, $z = 0.06355$]

2 EVLA Datasets (P.I. Gitti):

- 1 C-Band (5 GHz)
  t_{exp} = 4h, Array B
- 1 L-Band (1.4 GHz)
  t_{exp} = 3 h, Array A

1 *Chandra* Dataset (P.I. Gitti):

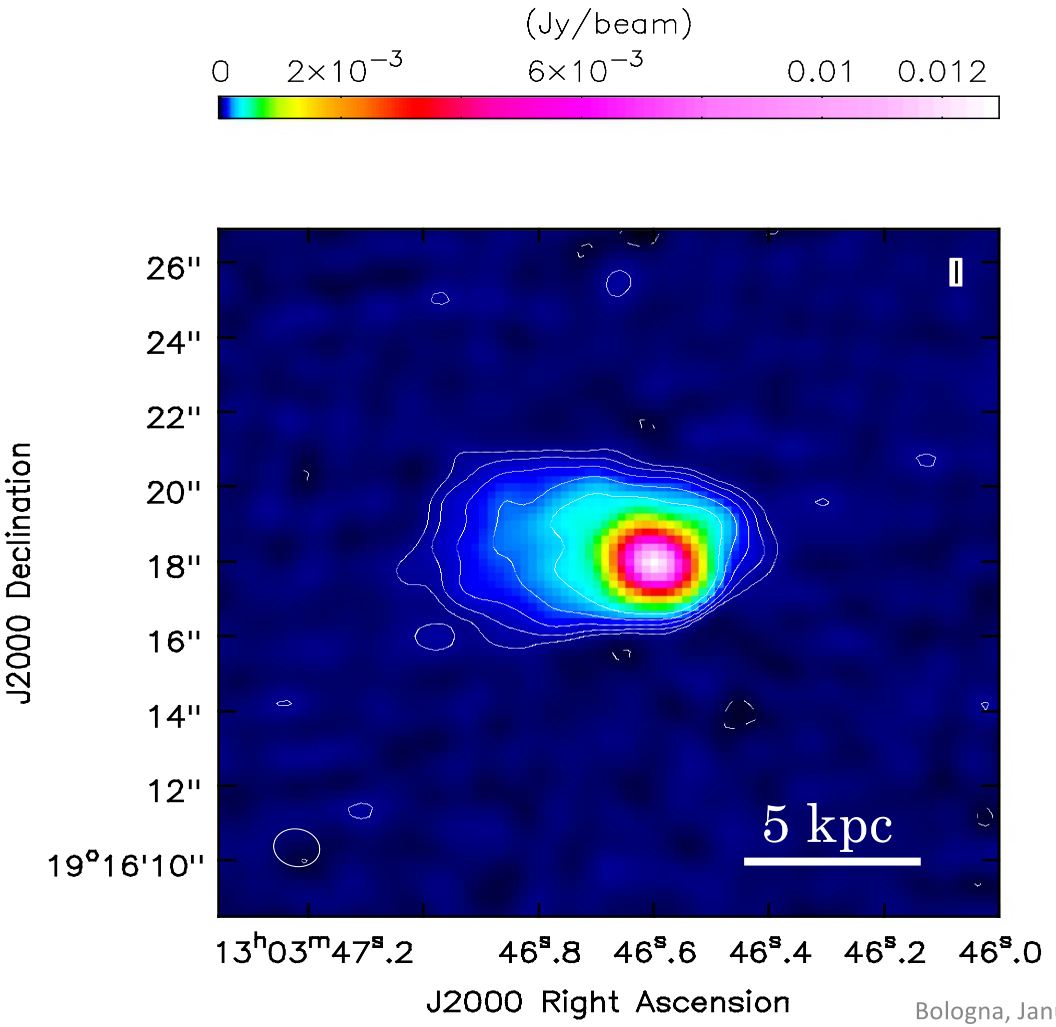
- 10 ks observation
- First X-ray observation

+ Hα (VIMOS) data

Frequency	Number of spw	Channels	Bandwith	Array	Total exposure time
5 GHz (C BAND)	2 (4832 MHz - 4960 MHz)	64	128 MHz	B	3h59m21s
1.4 GHz (L BAND)	2 (1264 MHz - 1392 MHz)	64	128 MHz	A	2h59m28s

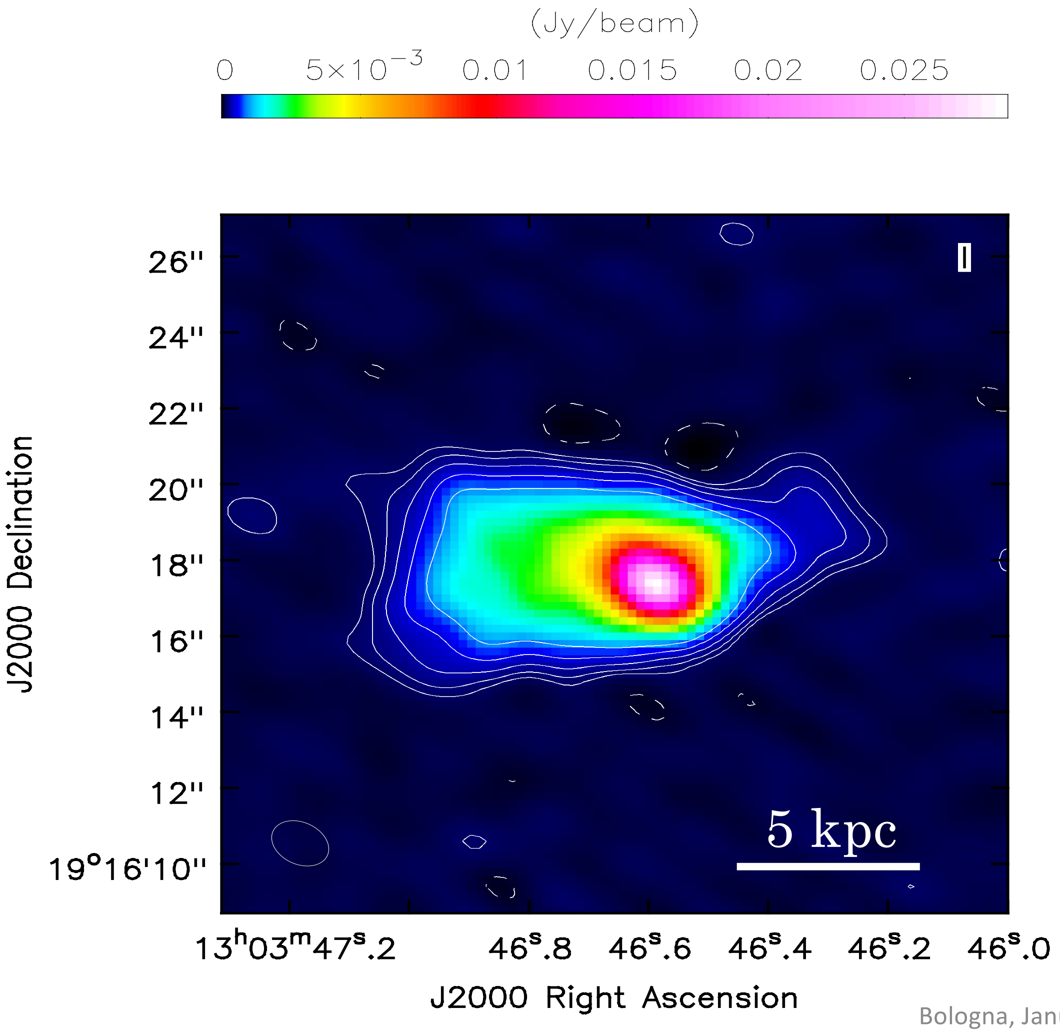
Table 1. Radio observations properties (project code SC0143, P.I. M. Gitti).

A1668: 5 GHz map



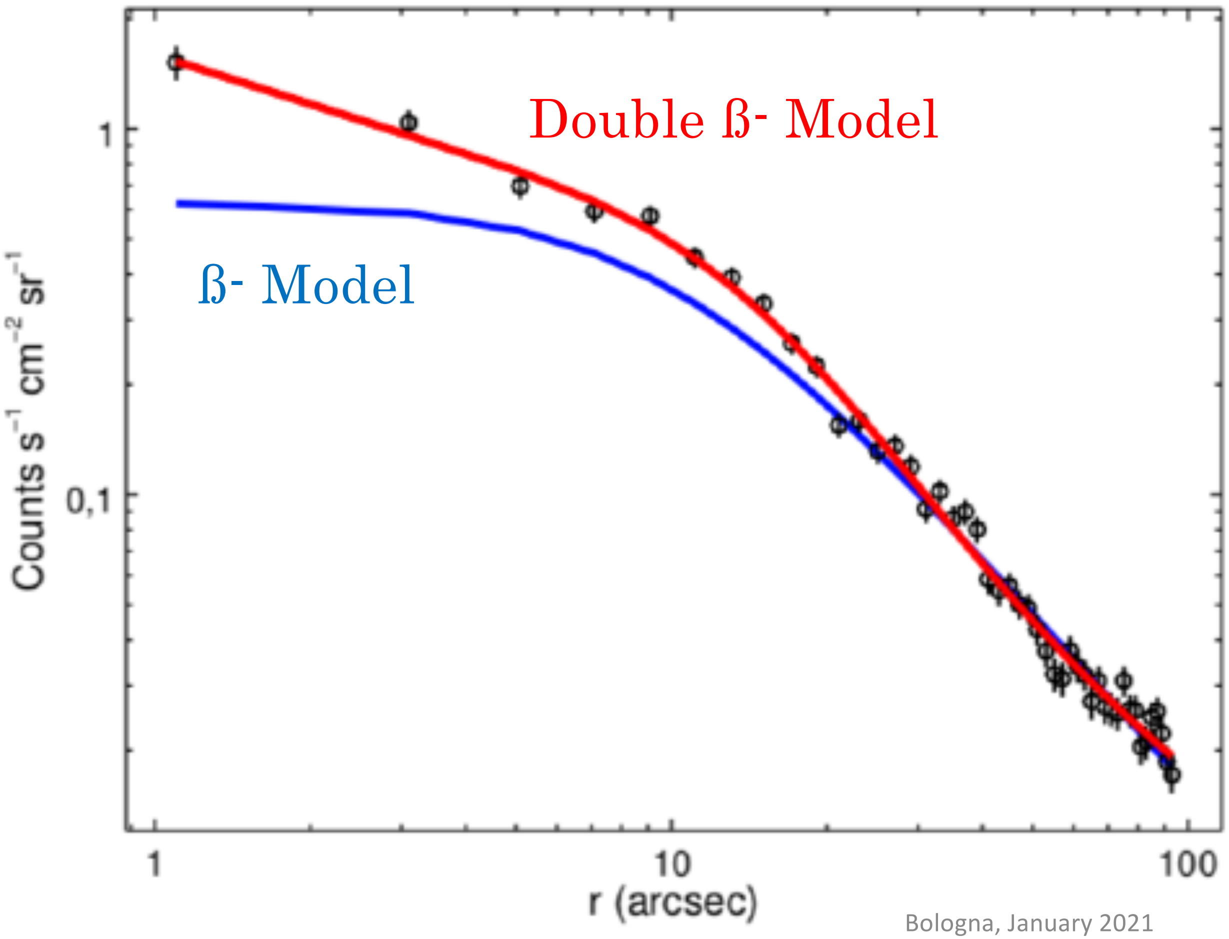
- Flux density = 19.9 ± 1.0 mJy
- RMS = 6 μ Jy/beam
- Beam = 1.14 x 1.00 arcsec
- $L_{1.4GHz} \sim 1.8 \cdot 10^{23}$ W/Hz

A1668: 1.4 GHz map



- Flux density = 70.2 ± 3.5 mJy
- RMS = 17 μ Jy/beam
- Beam = 1.44 x 1.08 arcsec
- $L_{1.4GHz} \sim 6.3 \cdot 10^{23}$ W/Hz

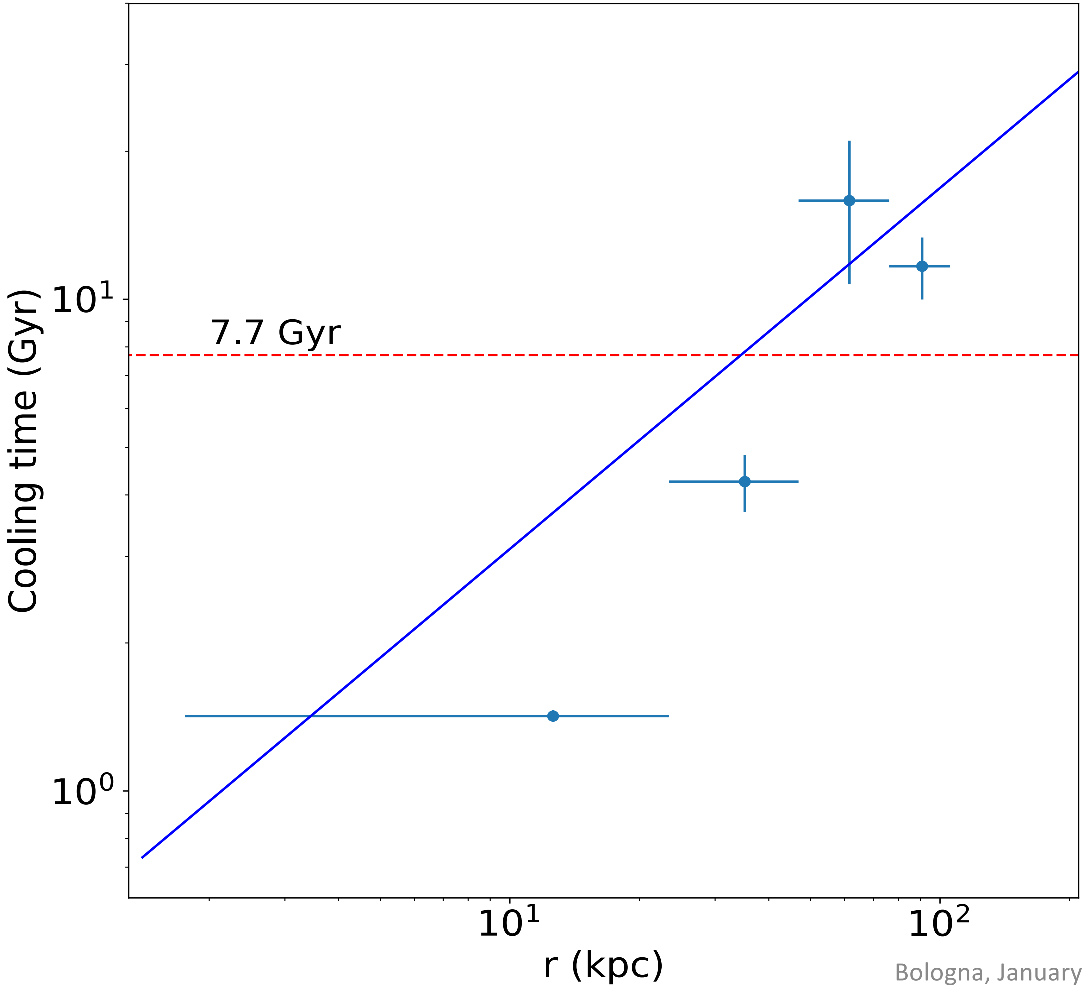
X-ray analysis: surface brightness profile



r_c= 10".0 $\pm^{0.7}_{0.4}$
ß= 0.43 ± $\pm^{0.4}_{0.2}$
χ^2/Dof ~ 1.71

r_{c1}= 0".64 $\pm^{0.32}_{0.76}$
$ß_1$= 0.42 $\pm^{0.02}_{0.01}$
r_{c2}= 15".6 $\pm^{4.2}_{2.7}$
$ß_2$= 0.67 $\pm^{0.14}_{0.08}$
χ^2/Dof ~ 1.49

Cooling time profile



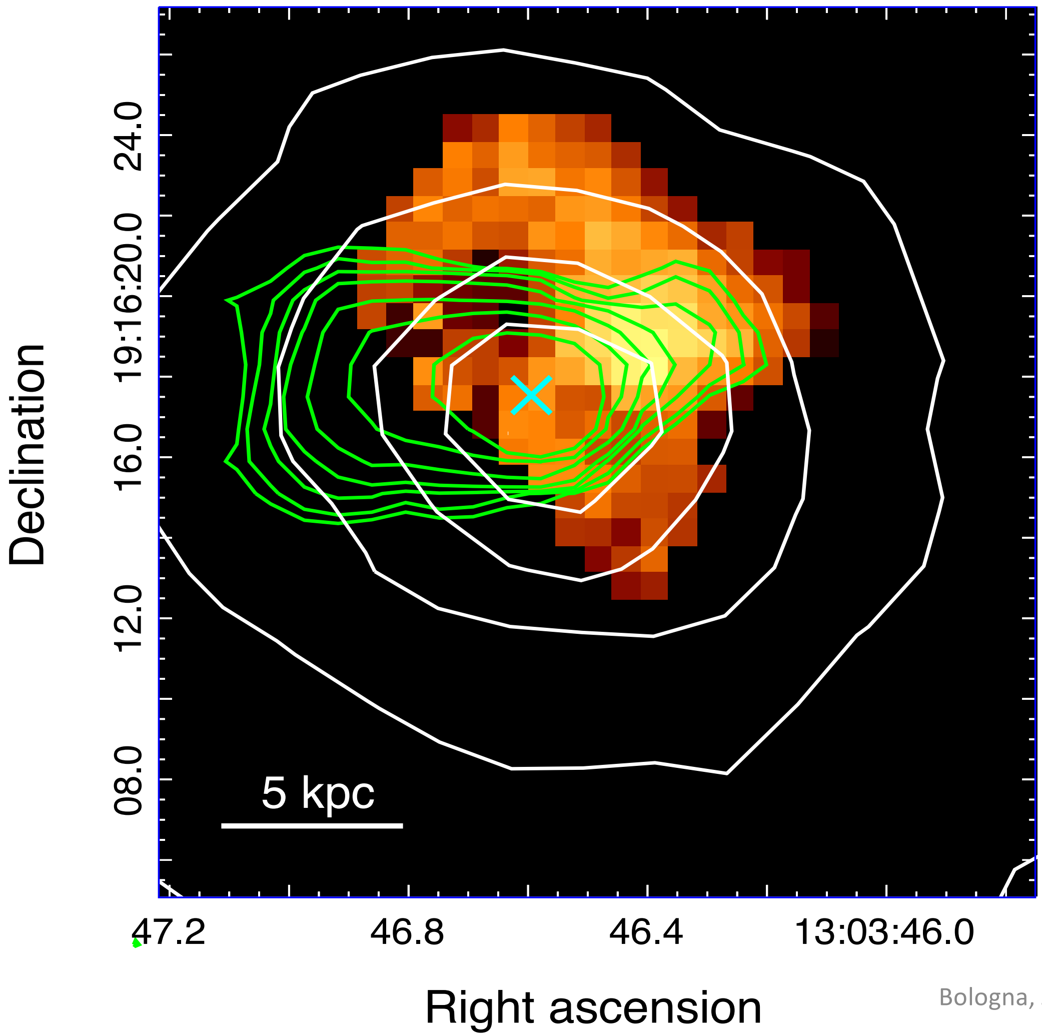
7.7 Gyr

Cooling time best fit

- $r_{cool} \simeq 40$ kpc
- Fit of the cooling region with projct*phabs*apec:

$$L_{cool} \simeq 1.9 \cdot 10^{43} \text{ erg/s}$$

Hα line emission analysis

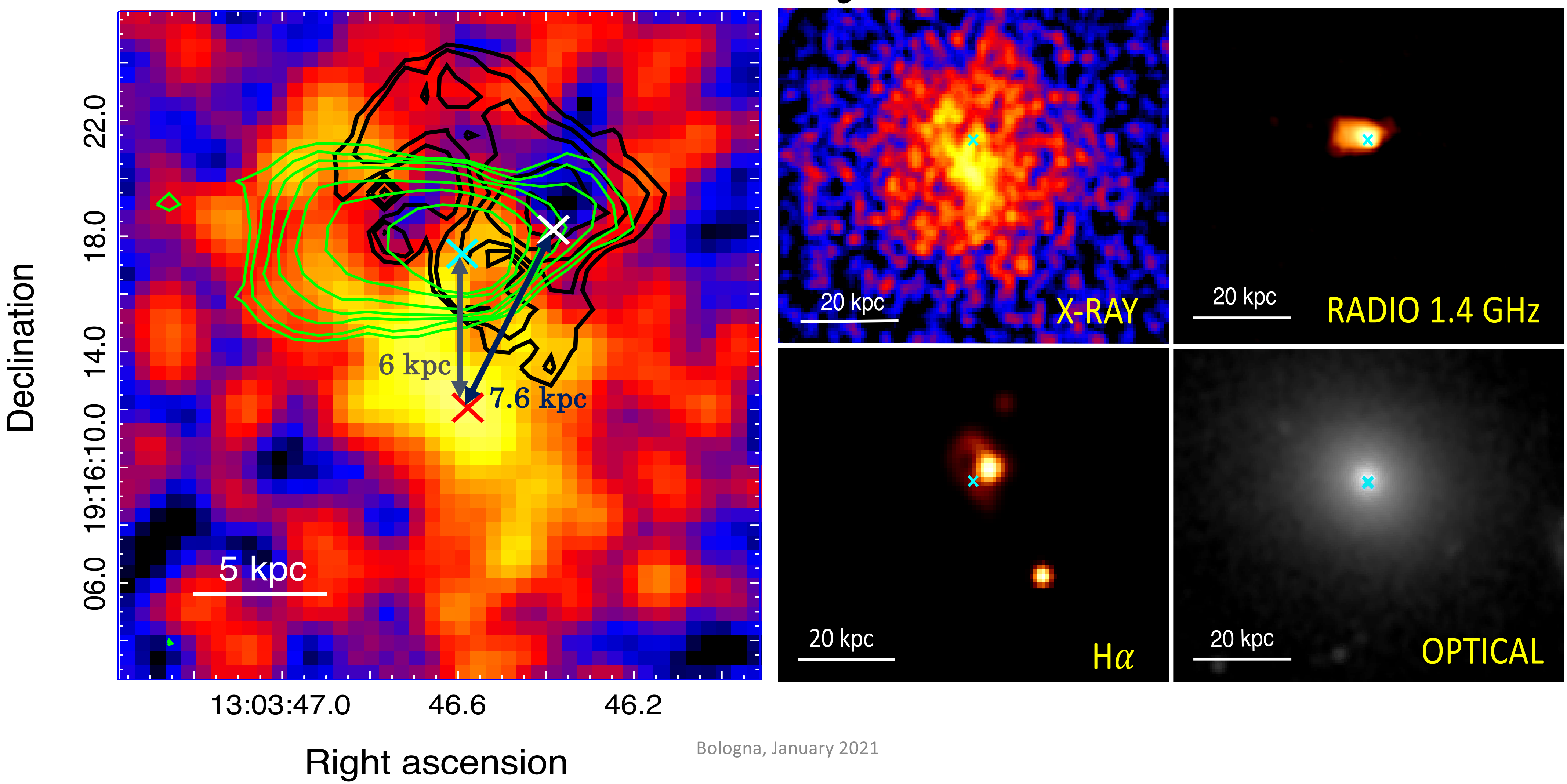


- VIMOS IFU observation
- Published in Hamer et al. (2016)
- Three sets of 600s exposures
- $L_{H\alpha} = (3.85 \pm 0.30)\times10^{40}$ erg/s
- $M_{H\alpha} = (2.4 \pm 0.2) \times 10^{6}\ M_{\odot}$ estimated through:

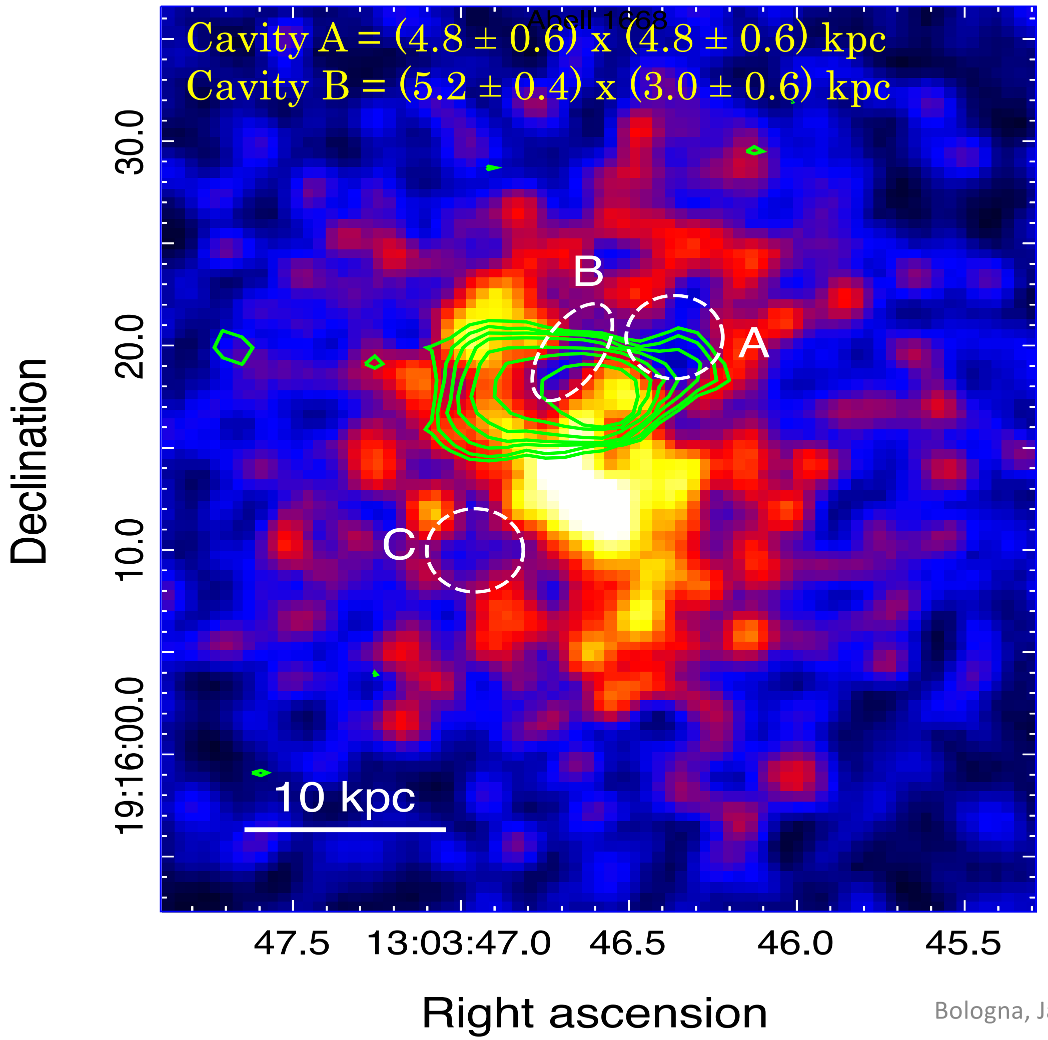
$$M_{\mathrm{H}\alpha} \simeq L_{\mathrm{H}\alpha} \frac{\mu m_p}{n_{\mathrm{H}\alpha}\, \epsilon_{\mathrm{H}\alpha}},$$

with $n_{\mathrm{H}\alpha} T_{\mathrm{H}\alpha} \simeq n_{\mathrm{ICM}} T_{\mathrm{ICM}}$.

Combined analysis: offsets



ICM Cavities



- Uncertain due to short observation;
- Axes 'measured' by estimating the significance:

$$\mathbf{N_M\text{-}N_C/\sqrt{N_M + N_C}},$$

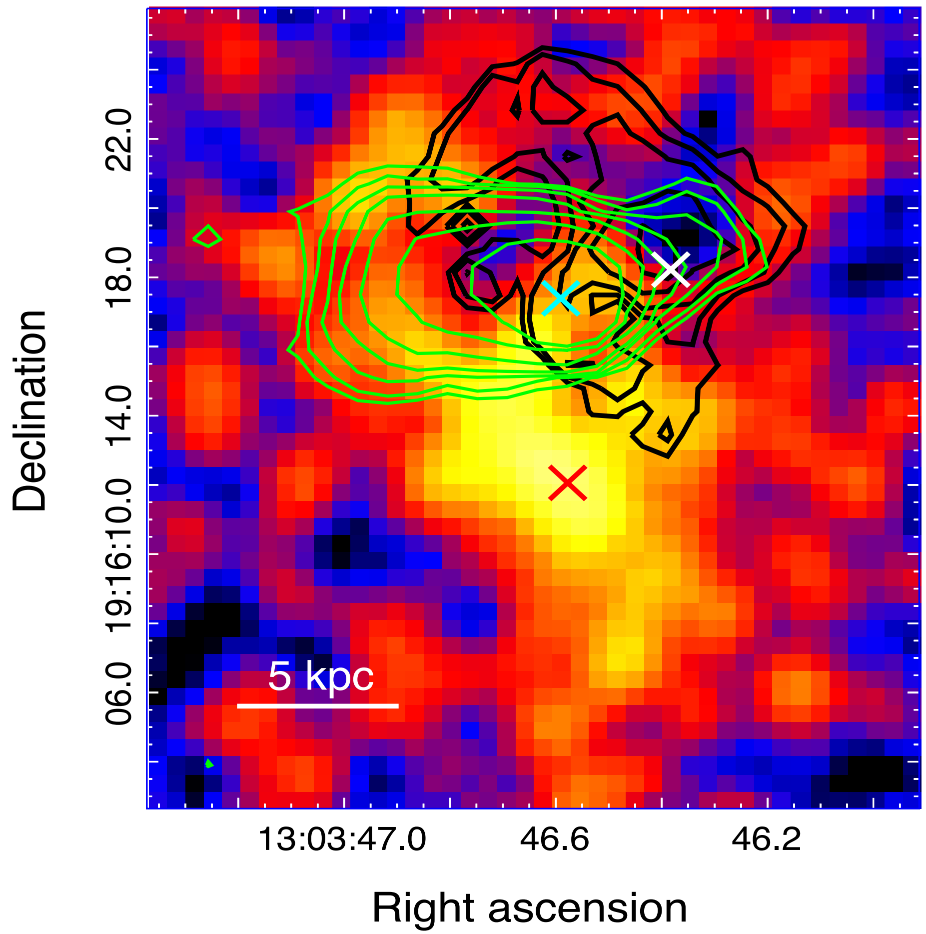
with N_M and N_C being the number of counts in a region close to the putative cavity and in the cavity, respectively;

- Sizes corresponding to 2σ and 3σ are the limits for the axes;
- Energetics: $E_{cav} = \frac{\gamma}{\gamma - 1} pV = 4pV$
- Power: $P_{cav} = \frac{4pV}{t_{cav}}$ with $t_{cav} = \frac{R}{v}$
- $t_{cav} = 5.2 \pm 0.7$ Myr
- $P_{cav,A} = (5.1 \pm 2.6) \times 10^{42}$ erg/s
- $P_{cav,B} = (3.8 \pm 1.4) \times 10^{42}$ erg/s

Connecting the dots: what is happening in A1668?

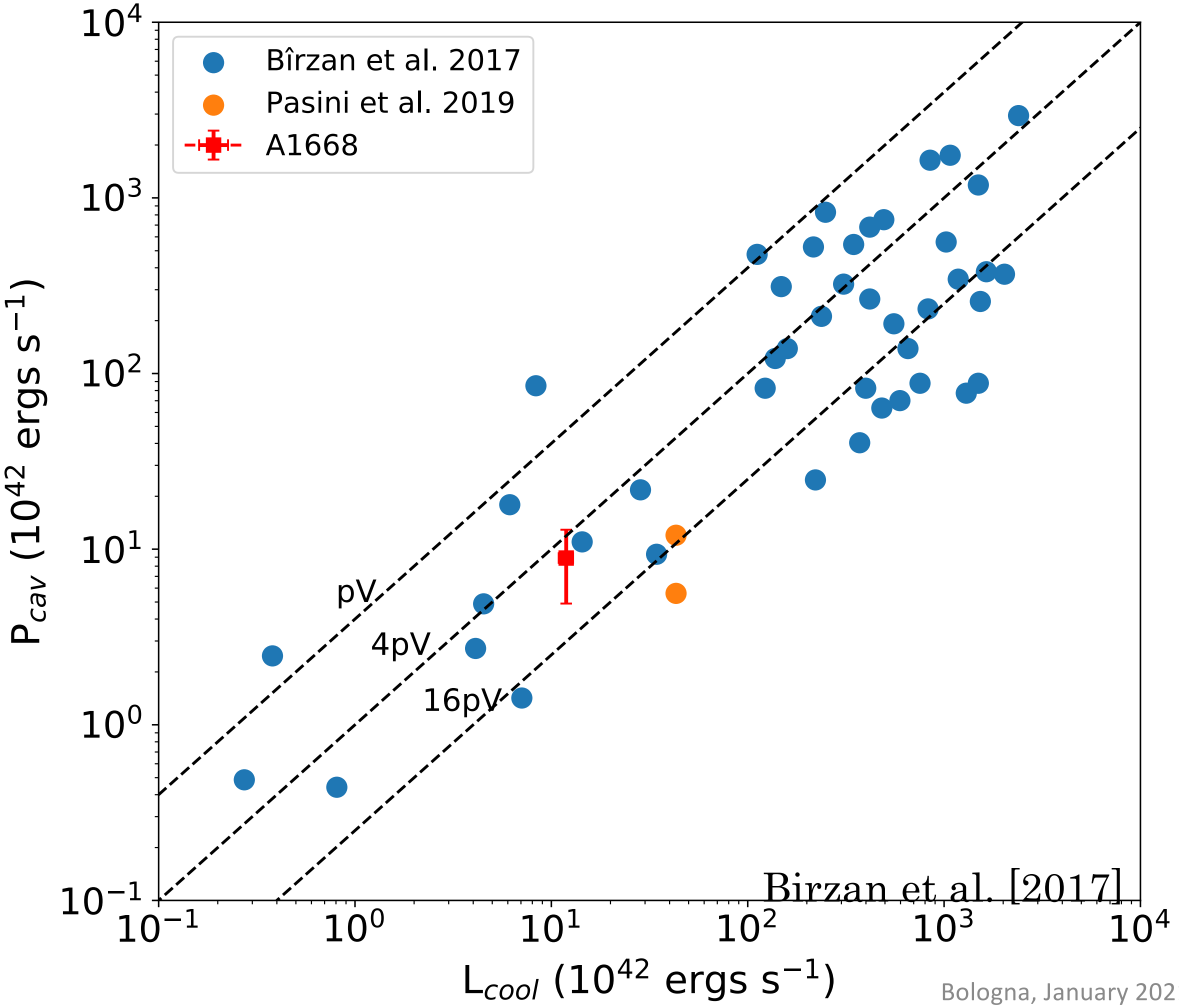
1. Initial stage: relaxed cluster with cool core;
2. Cooling centered on the (previous) X-ray peak produced the Hα nebula;
3. Minor merger triggered sloshing;
4. The accreting SMBH produced the jets/lobes (~5 Myr ago);
5. The expansion of the lobes pushed aside the Hα gas and hotter ICM;
6. Production of the cavities;
7. Radio lobes not affected by sloshing (t_{slosh} >> t_{exp}).

~500 Myr ~ Myr



'Predictions' of this scenario: nested cold fronts, cavities correlated with radio jets and lobes, filamentary Hα nebula.

Are offsets breaking the feedback cycle?



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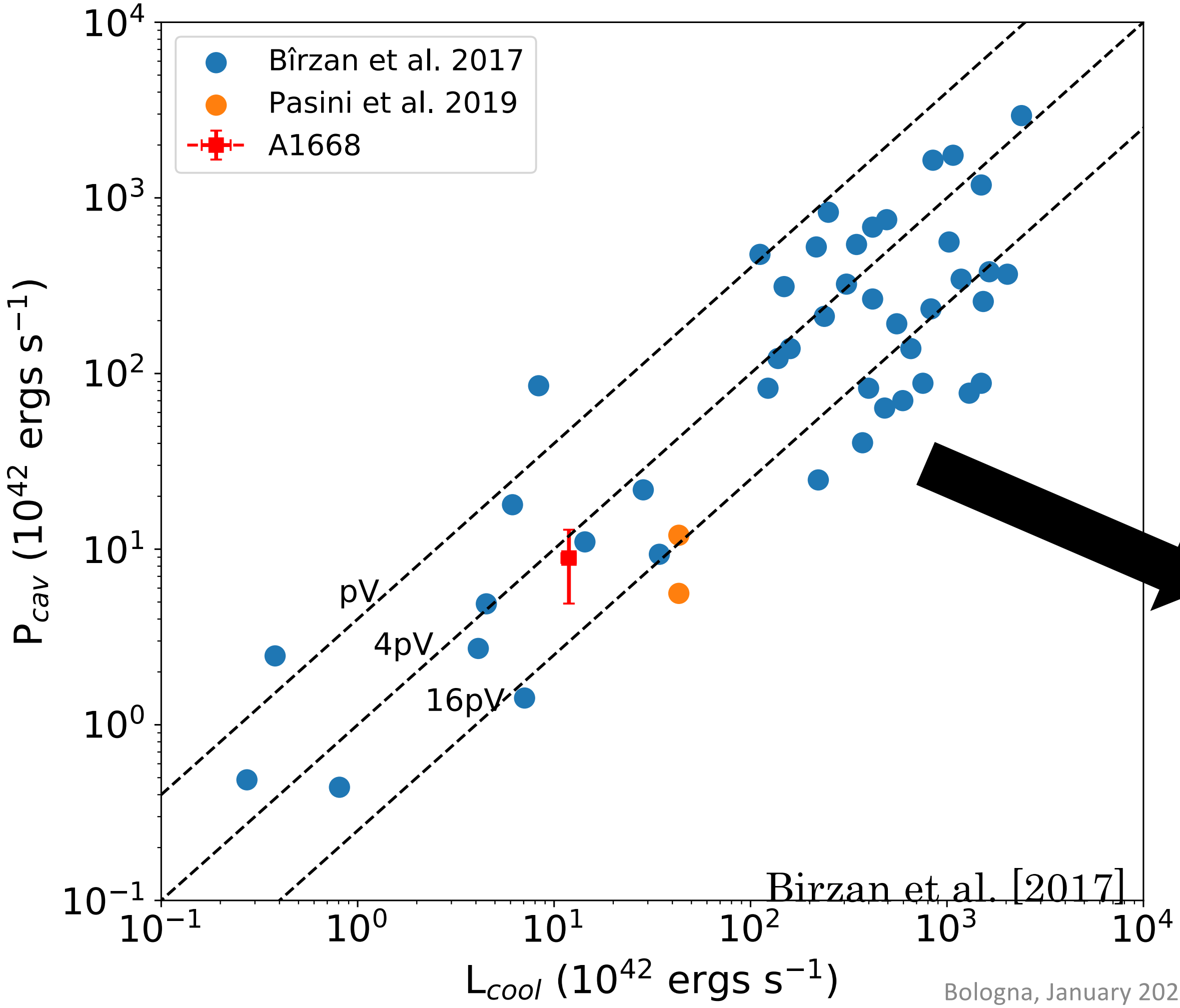


<u>Sloshing is not interrupting or preventing the feedback cycle</u>

The environment of A1668: takeaway messages

- Small (~14 kpc) radio galaxy hosted in the BCG with low (~6 x 10^{23} W/Hz at 1.4 GHz) luminosity;
- ~6 kpc offset between radio and X-ray emission, and ~7.6 kpc offset between X-ray and Hα emission;
- Two putative cavities with age ~ 5.2 Myr;
- Gas motions and the expansion of the lobes likely produced the observed environment.

The environment of A1668: (next) future

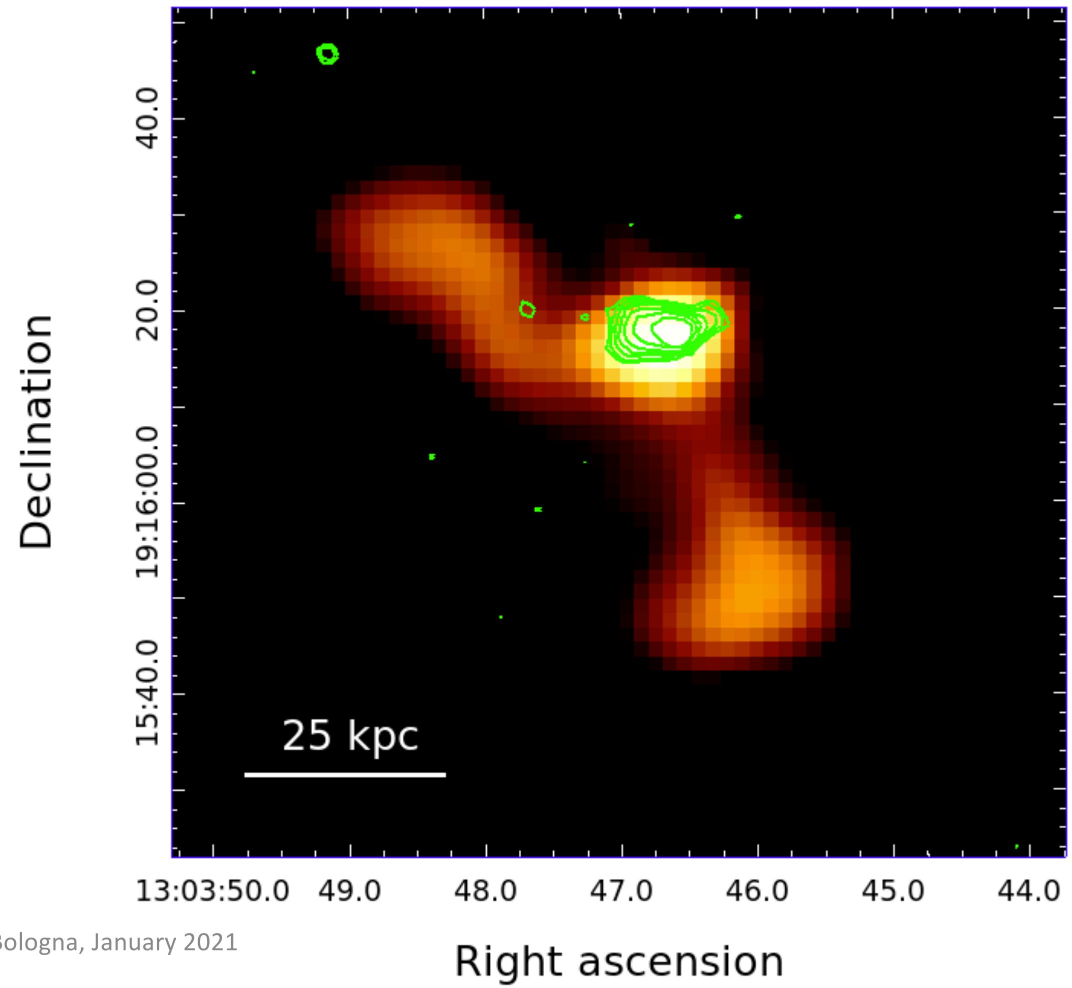
- X-ray band: request deeper Chandra observation (next cycle) to:

  - Investigate possible cold fronts (signature of sloshing);
  - Confirm the presence of ICM cavities;
  - Study the feedback cycle by better determining the cavities and ICM properties.

- Radio band: look at other bands (e.g. LOFAR) to perform a thorough spectral analysis;

The environment of A1668: (next) future

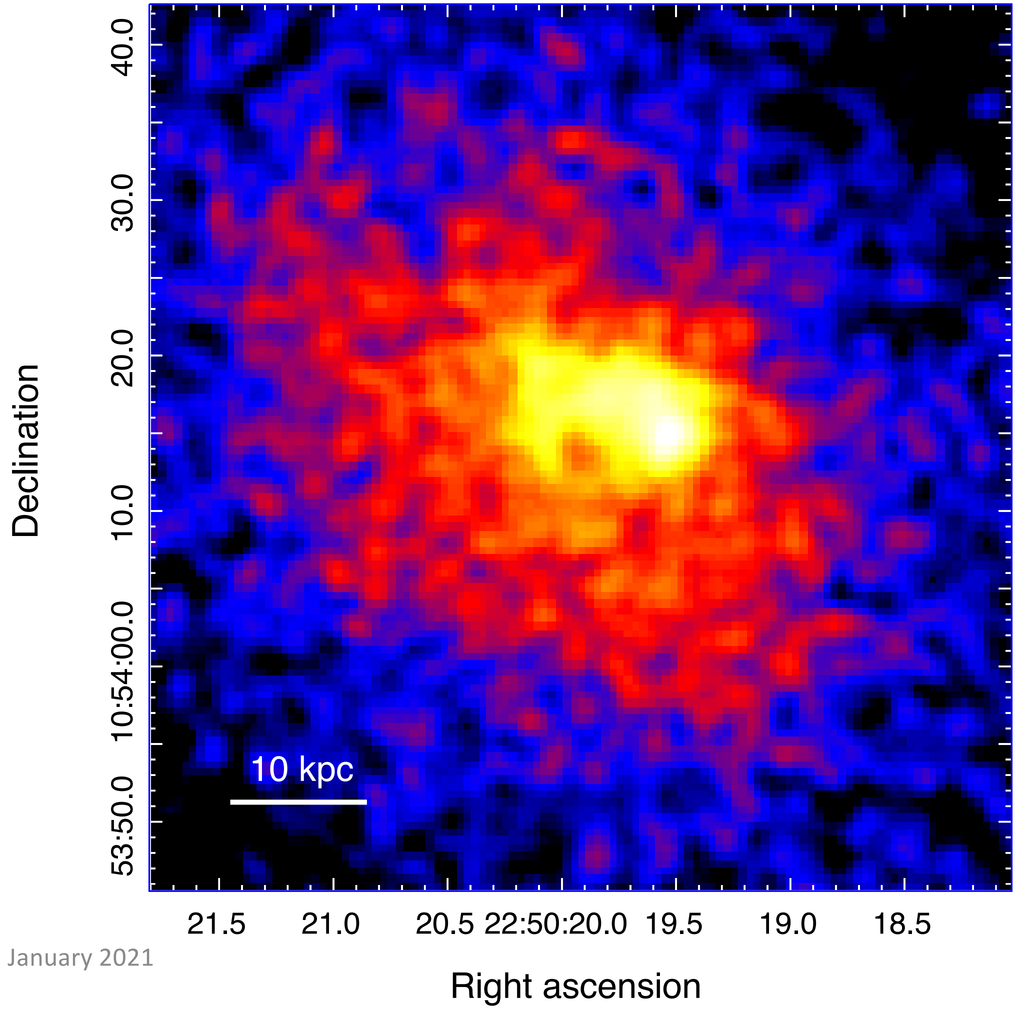
- Already available LOFAR observations of A1668, showing elongated and bented jets at 150 MHz (Pasini et al, in prep.).



A ‘twin’ cluster: next future for A2495

- Already obtained ~130 ks Chandra follow-up for A2495 (Pasini et al. 2019); currently under analysis by master student of M. Gitti.

- Already obtained LOFAR 150 MHz observation of A2495, showing interesting features (mini-halo?)



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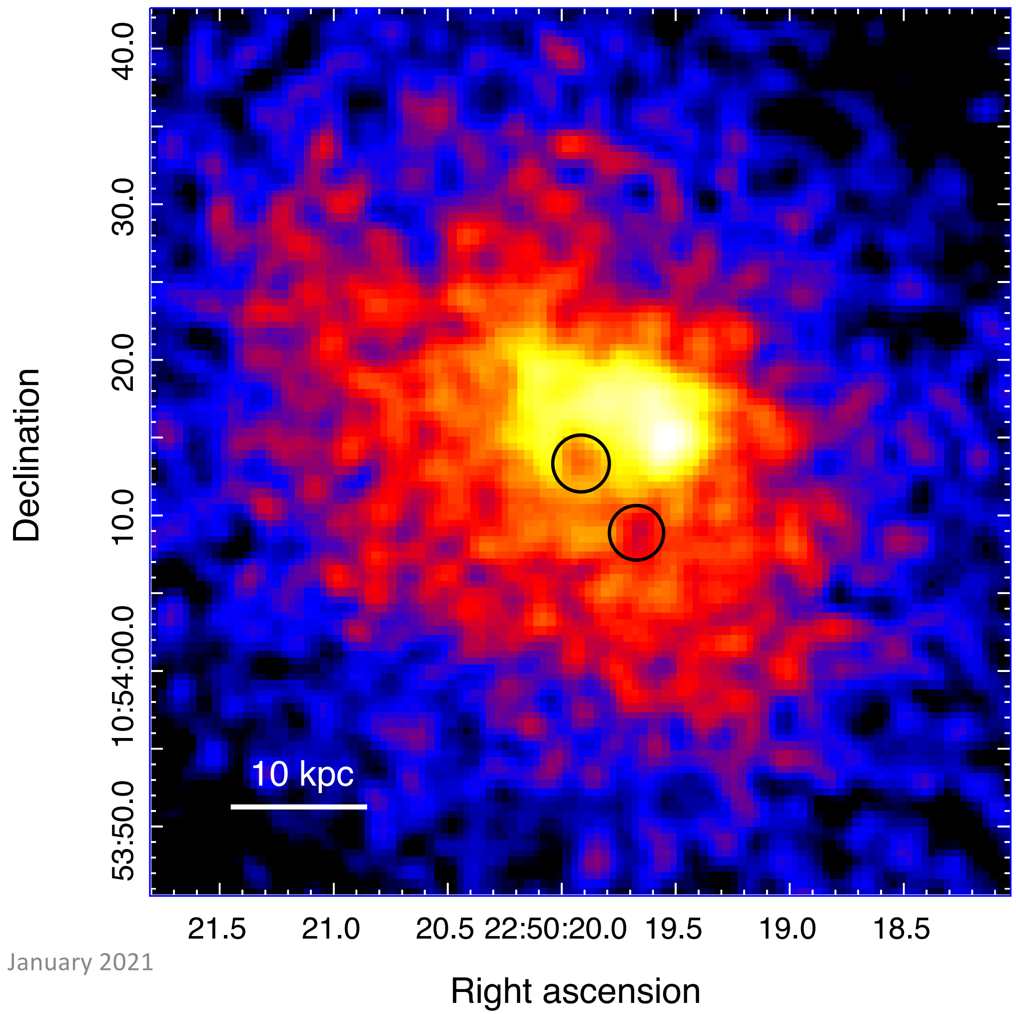

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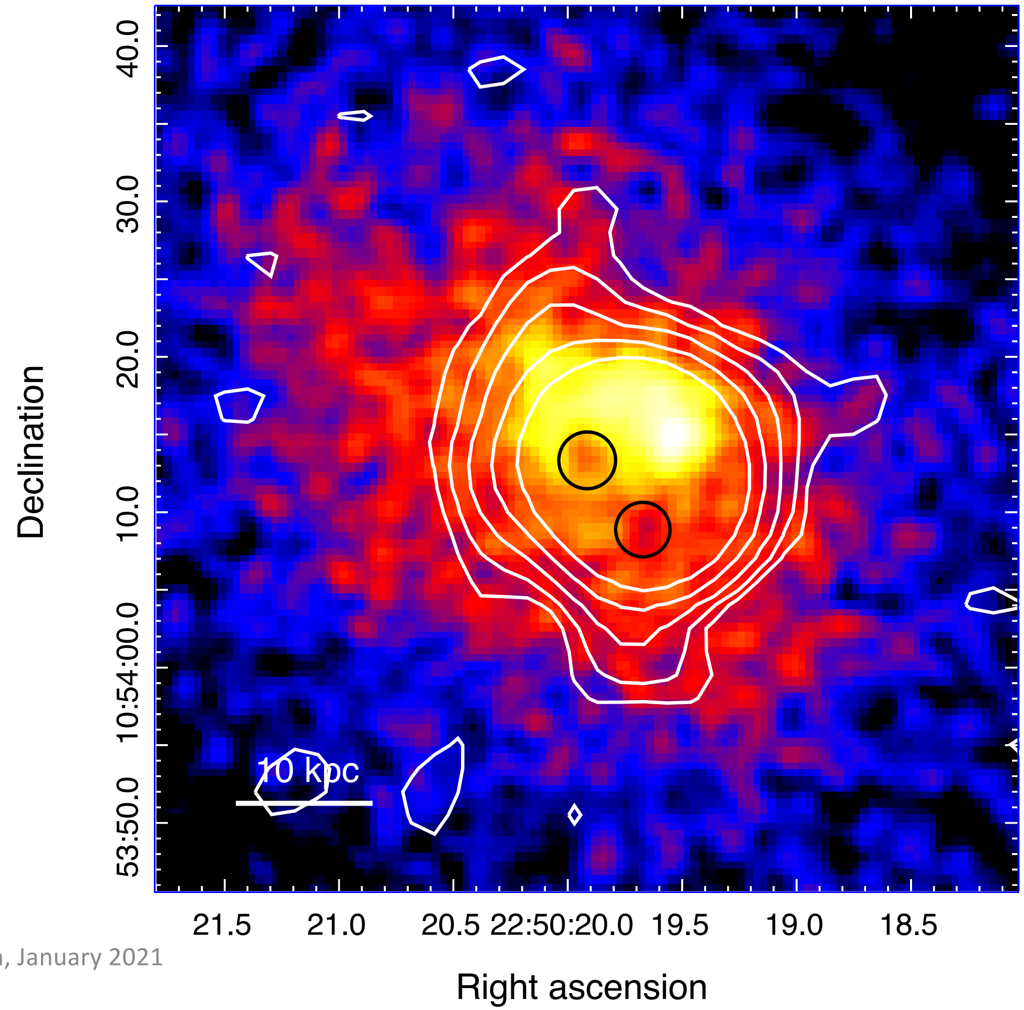

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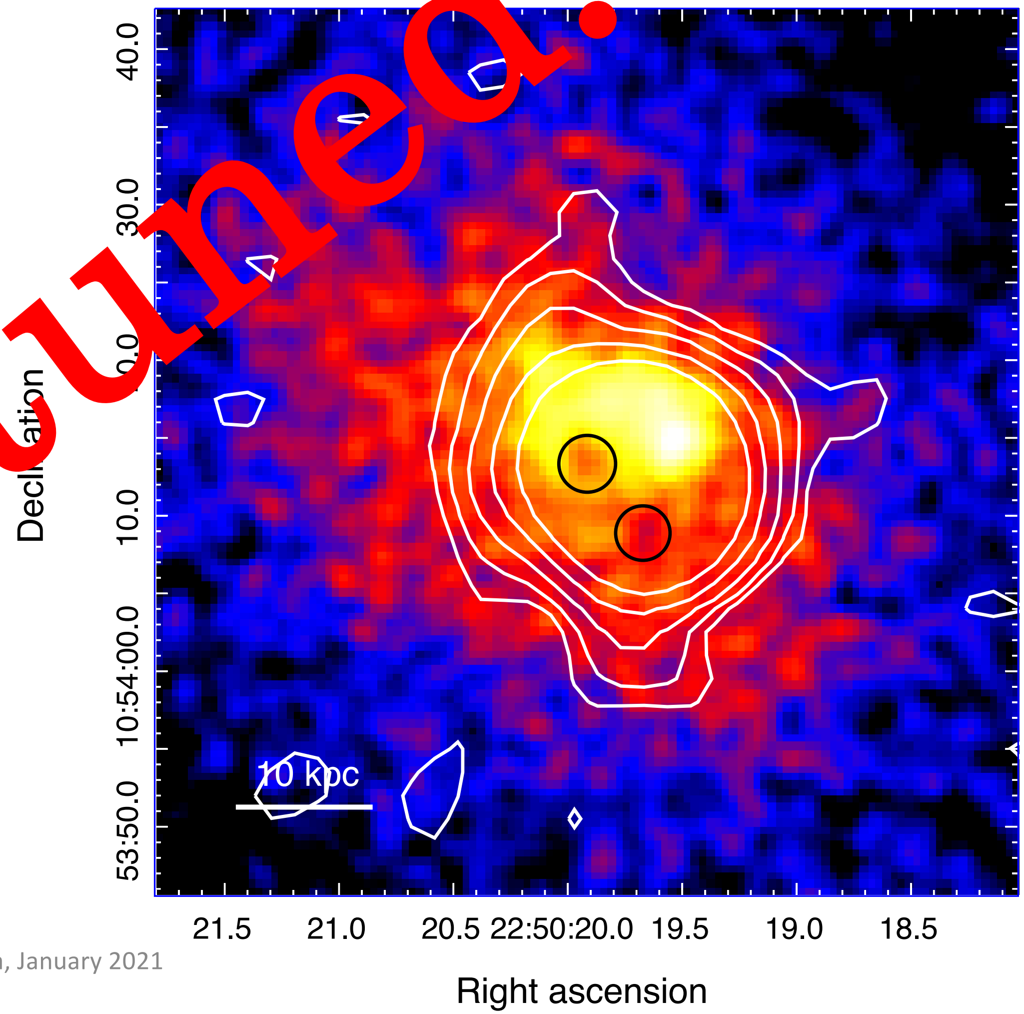
Stay tuned!



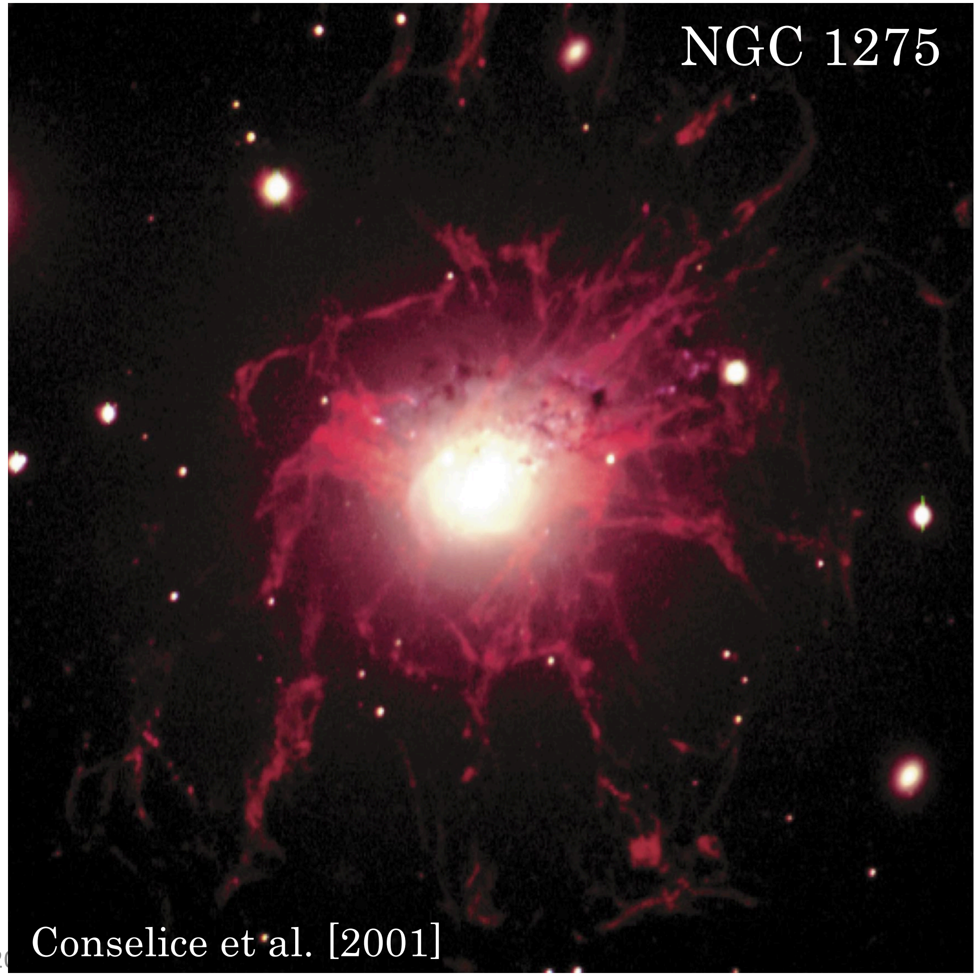

Thank you!
Questions?
Bologna, January 2021

Cooling signatures in BCGs

- Brightest Cluster Galaxies are the most massive and luminous galaxies usually found at the center of galaxy clusters.

- We find signatures of past and ongoing cooling in BCGs:

a) SFR;
b) Hα emission;
c) Molecular gas (e.g., CO).

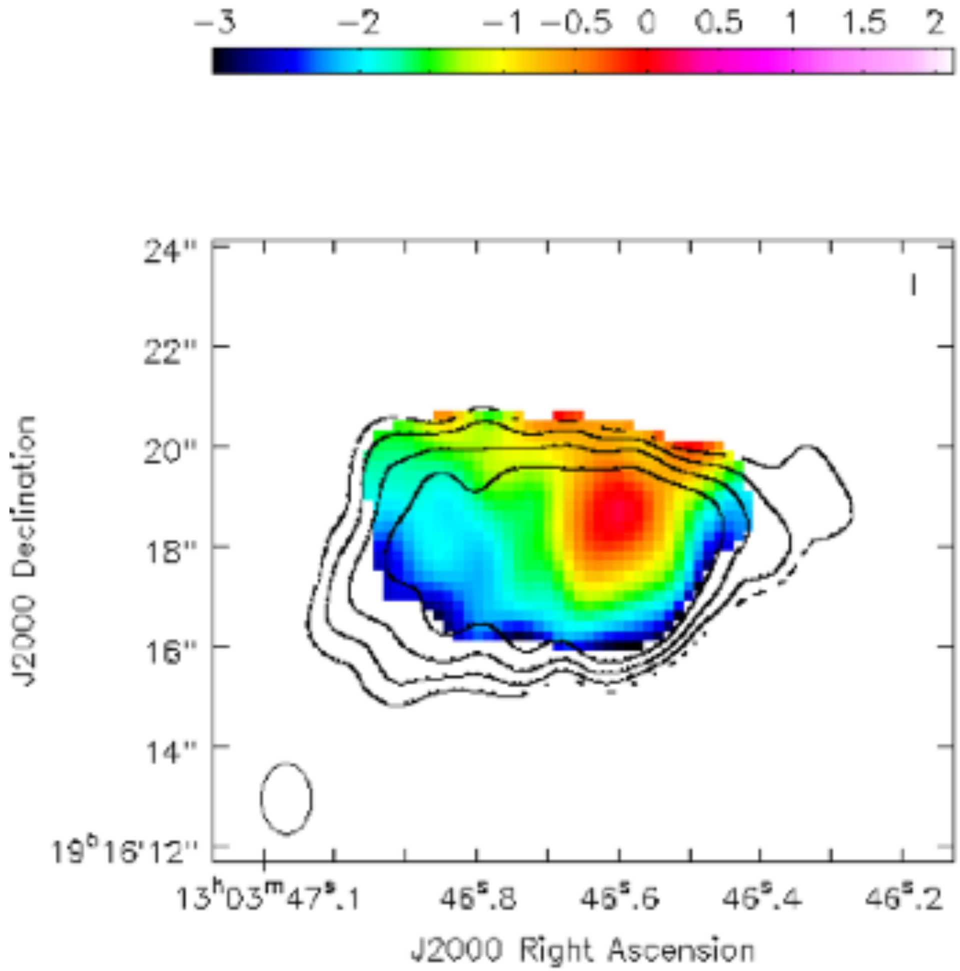


Selection criteria

- $F_X > 10^{-11}$ erg cm^{-2} s^{-1} [BCS Sample, Ebeling 1998]

- $L_{H\alpha} > 10^{40}$ erg s^{-1} [Crawford et al. 1999]

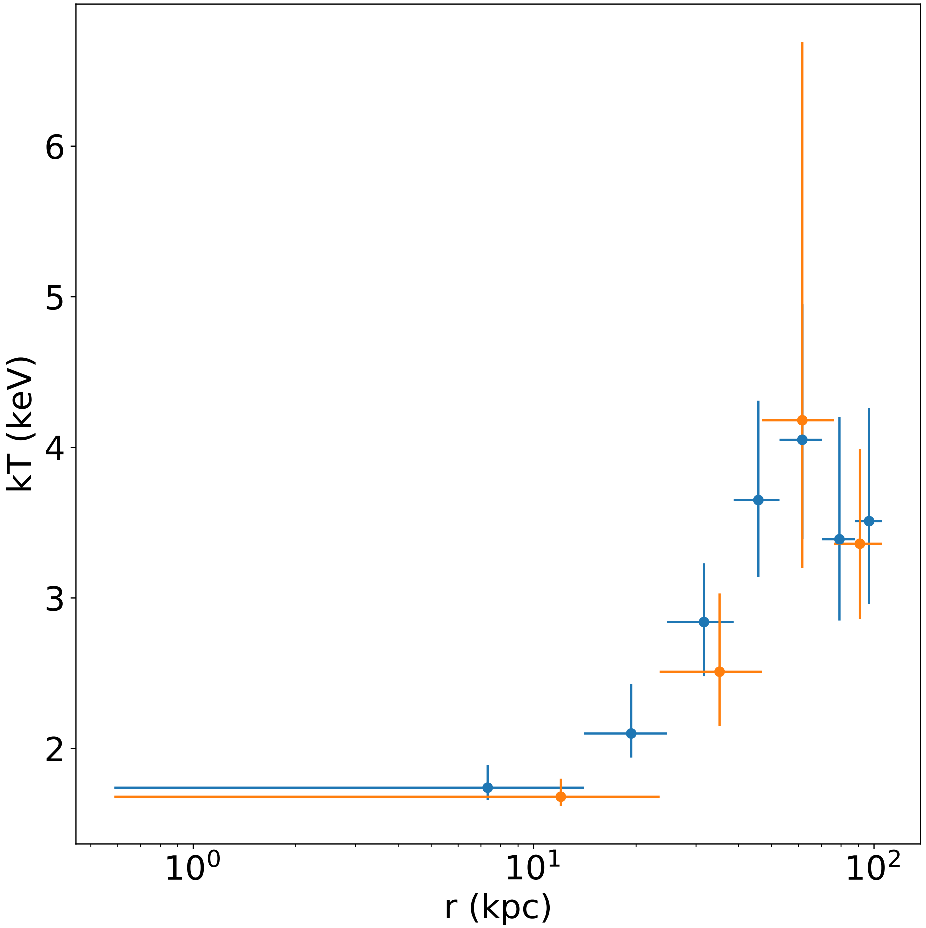
A1668: Spectral index map

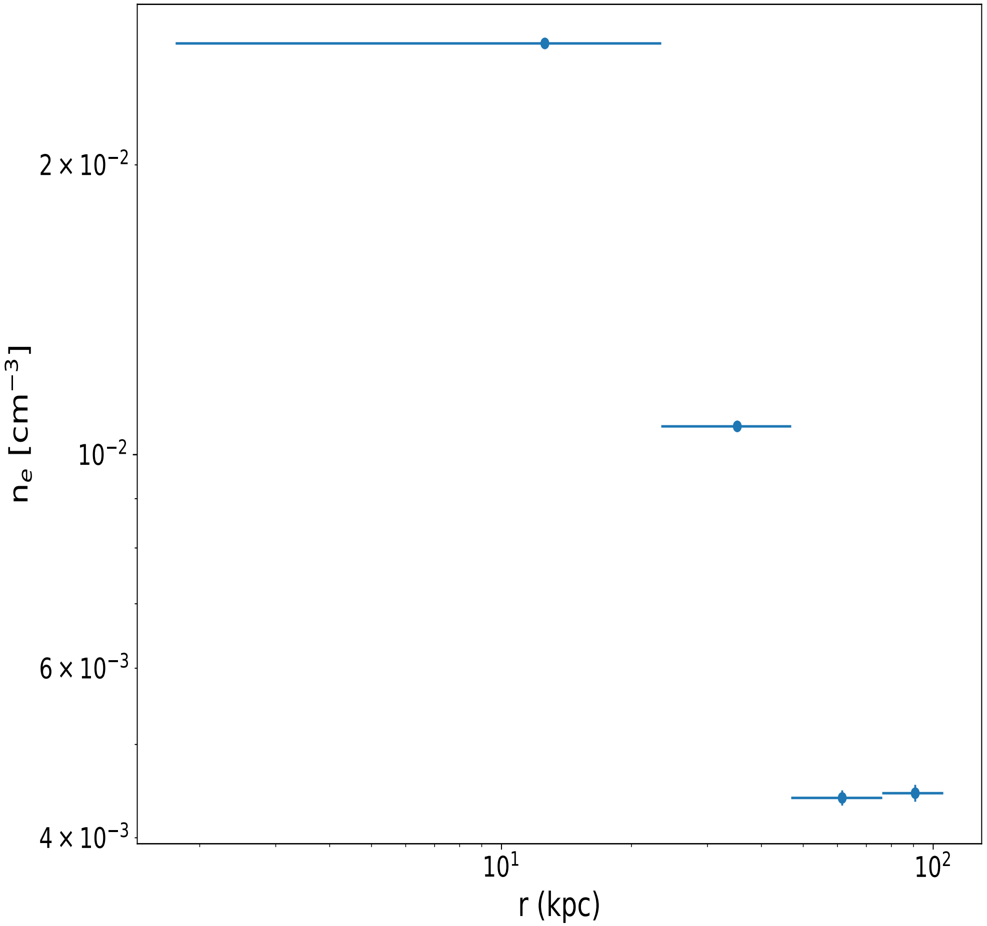


- $S_\nu \propto \nu^\alpha$
- Produced with CASA setting weighting=uniform, same resolution (1.4" x 1.0") and UVRANGE = 6.5 - 152 for both frequencies;

Region	$S_C \pm \Delta S_C$ [mJy]	$S_L \pm \Delta S_L$ [mJy]	$\alpha \pm \Delta\alpha$
Peak	7.5 ± 0.4	17.6 ± 0.9	-0.67 ± 0.06
Extended	12.4± 0.6	52.6 ± 2.6	-1.13 ±0.05
Total	19.9 ± 1.0	70.2 ± 3.5	-0.99 ± 0.06

X-ray analysis: thermodynamical profiles





Cooling time radial profile

- Cooling time due to Bremsstrahlung and line emission;

- Two different methods:

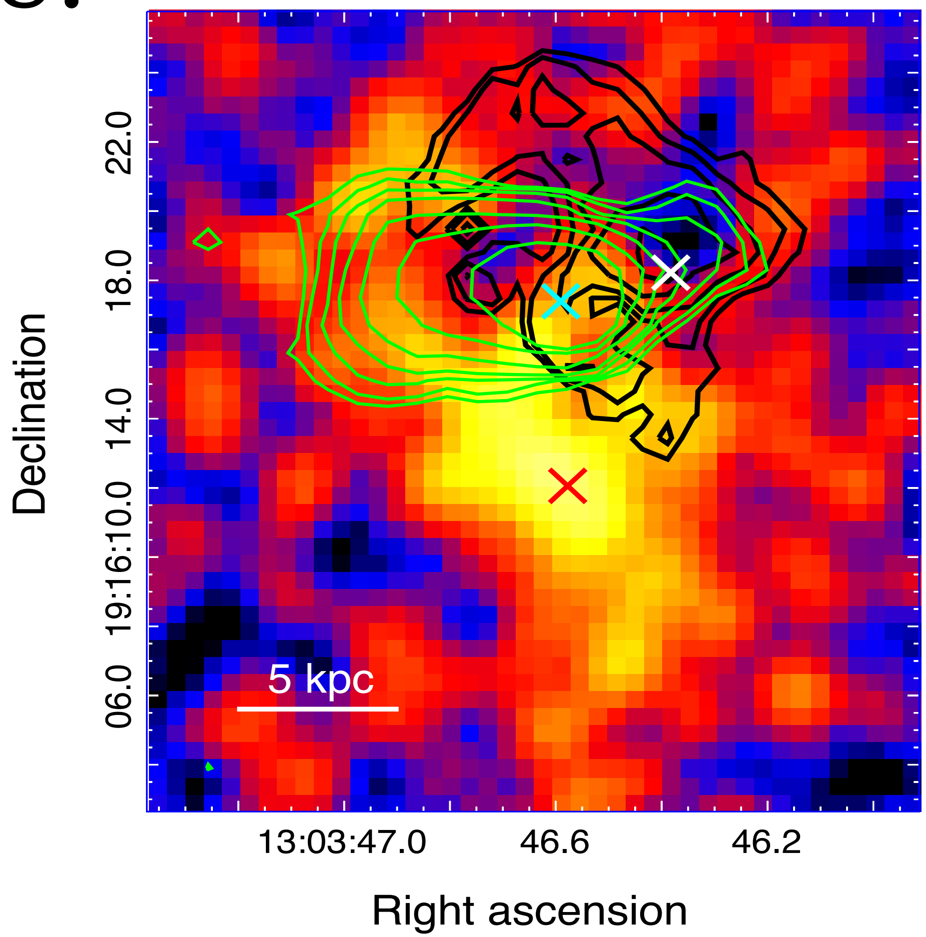
➢ Classical formula: $t_{cool} = \frac{H}{\Lambda(T) n_e n_p} = \frac{\gamma}{\gamma - 1} \frac{kT(r)}{\mu X n_e(r) \Lambda(T)}$

➢ Cooling function approximation: $t_{cool} = 8.5 \cdot 10^{10}\ yr \left(\frac{n_e}{10^{-3}\ cm^{-3}} \right)^{-1} \left(\frac{T}{10^8\ K} \right)^{\frac{1}{2}}$
[Sarazin, 1988]

Connecting the dots: what is happening in A1668?

<u>**Proposed alternative scenarios:**</u>

- Chaotic Cold Accretion (CCA);
- Cavity uplift;
- ISM remnant of gas-rich galaxy after merger;
- BCG Stellar mass loss.



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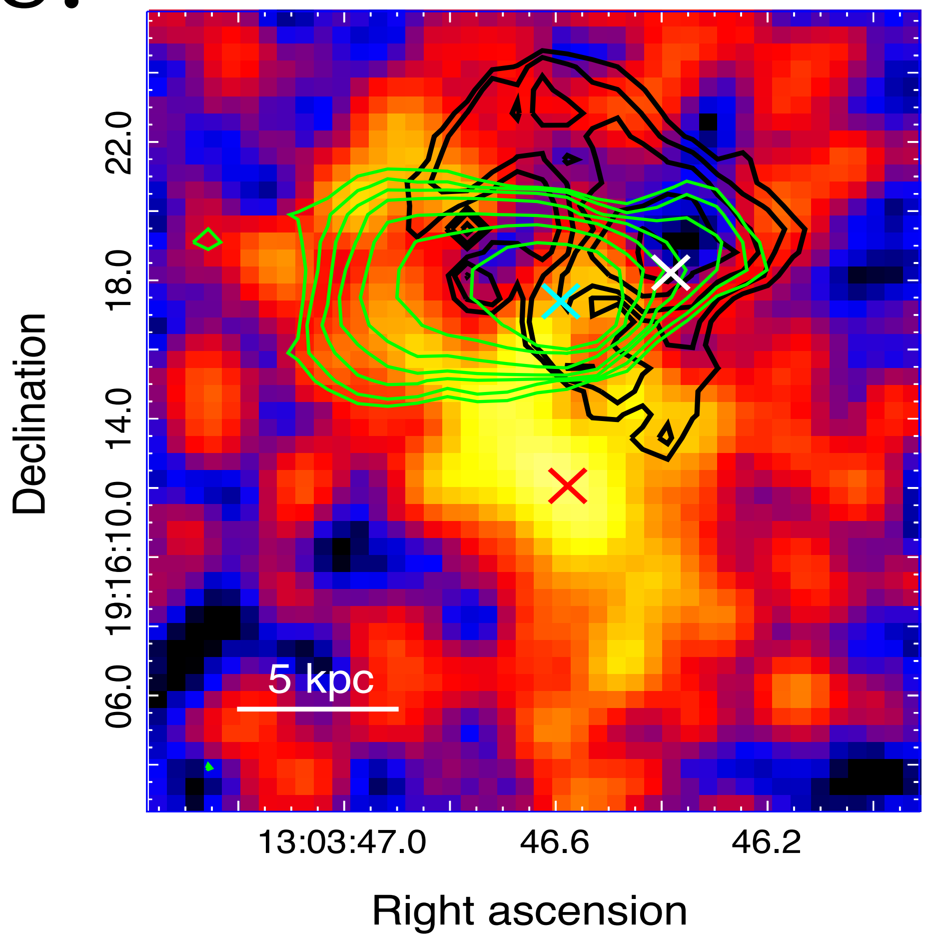

How to estimate the sloshing timescale?

$$t_{slosh} = \frac{2\pi}{\omega} \longrightarrow \omega = \Omega_k \sqrt{\frac{1}{\gamma}\frac{d\ln S}{d\ln r}} \; and \; \Omega_k = \sqrt{GM/r^3}$$

$$\text{Assuming } t_{ff} = r/\sigma_* \longrightarrow \omega = \frac{1}{tff}\sqrt{\frac{6}{5}\frac{d\ln S}{d\ln r}}$$

$$\left.\begin{array}{l} d\ln S/d\ln r \sim 0.67 \text{ (Hogan et al. 2017)} \\ \sigma_* = 226 \pm 7 \text{ km/s (Pulido et al. 2018)} \\ \text{X-ray trail length} \sim 16 \text{ kpc} \end{array}\right\} t_{slosh} \sim 7tff \sim 490 \text{ Myr}$$