MASARYK UNIVERSITY

Studying radio-mechanical AGN feedback with X-ray cavities

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AGN feedback

quasar mode

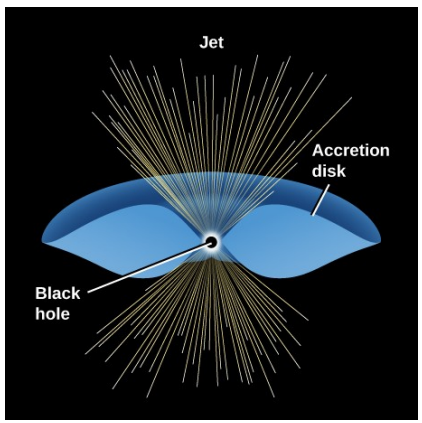
- geometrically thin disk
- optically thick
- radiatively efficient

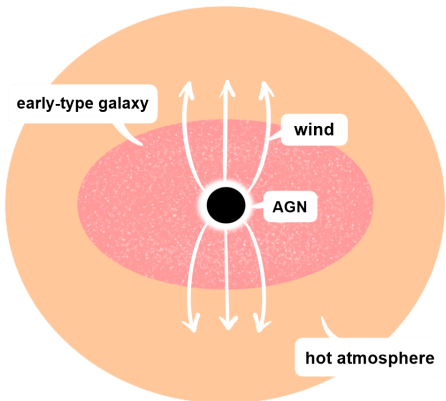
  $\rightarrow$ EM radiation
- all galaxy types

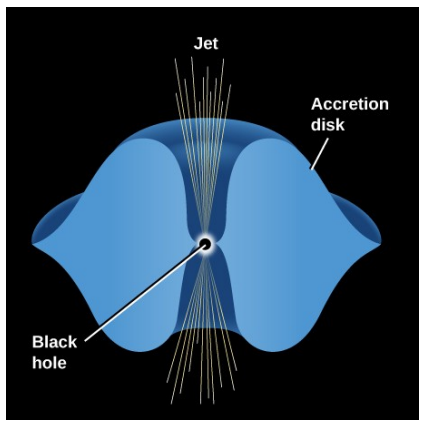
radio-mechanical mode

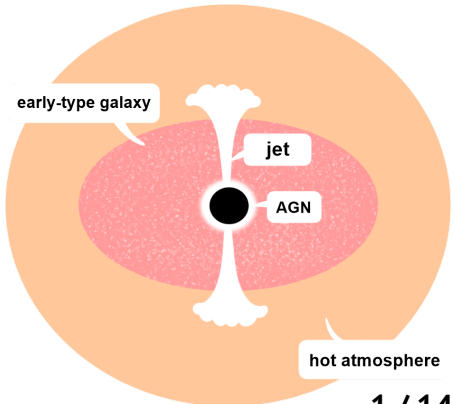
- geometrically thick torus
- optically thin
- radiatively inefficient (ADAF)

  $\rightarrow$ relativistic particles (jets)
- early-type galaxies









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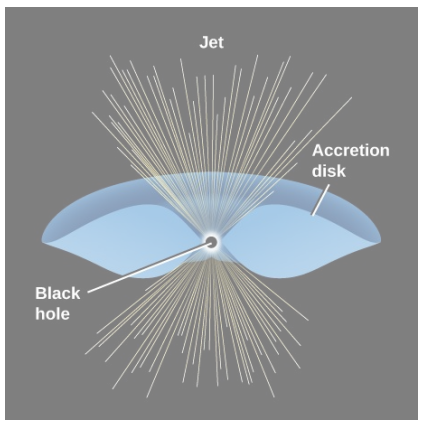
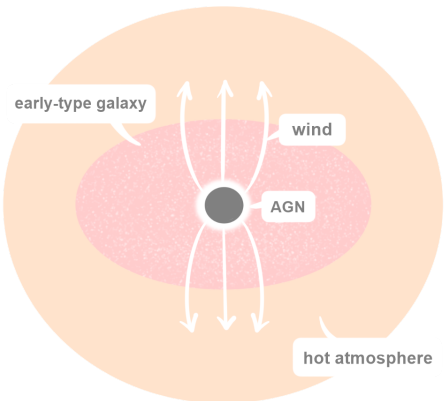
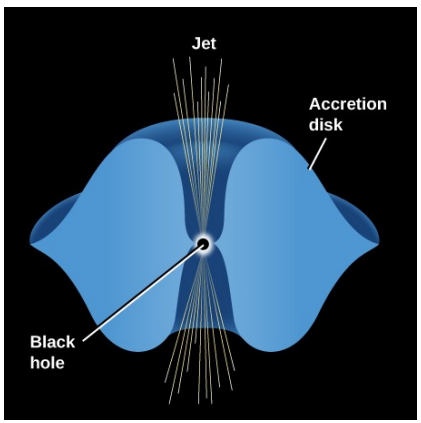
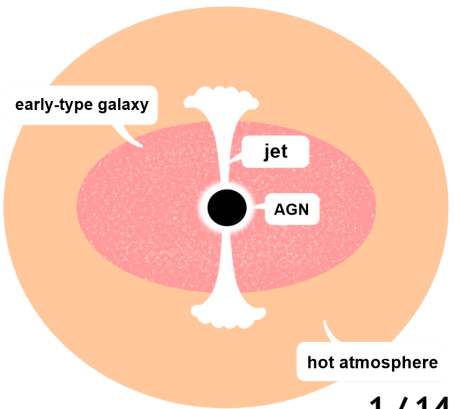




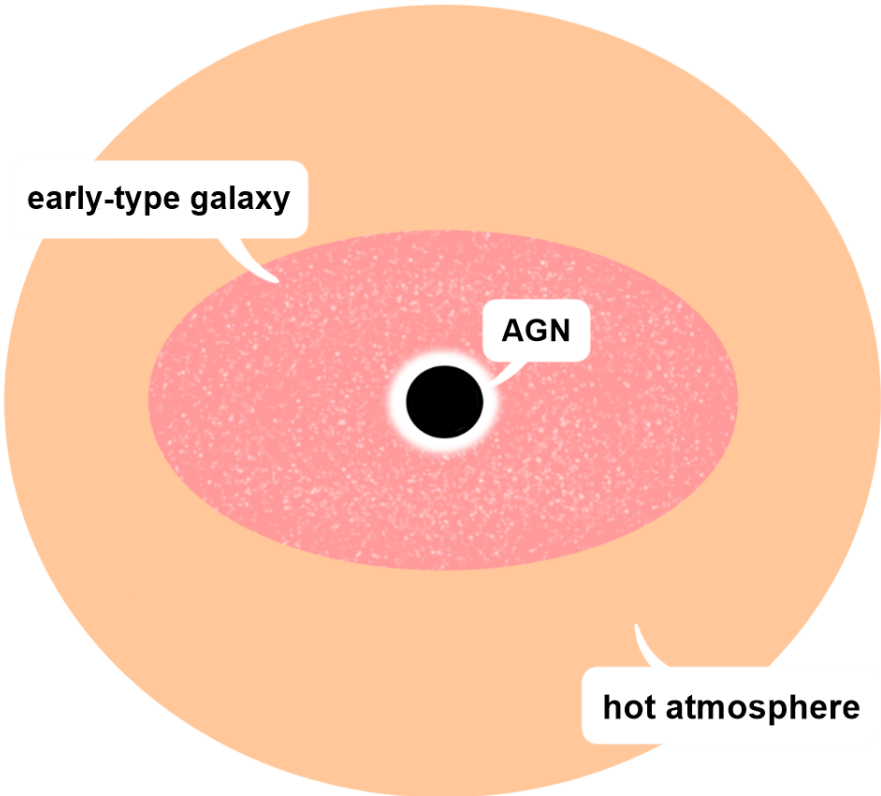




Early-type galaxies

- elliptical & lenticular galaxies
  - total mass $> 10^{12} M_{\odot}$

  $\rightarrow$ hot atmospheres



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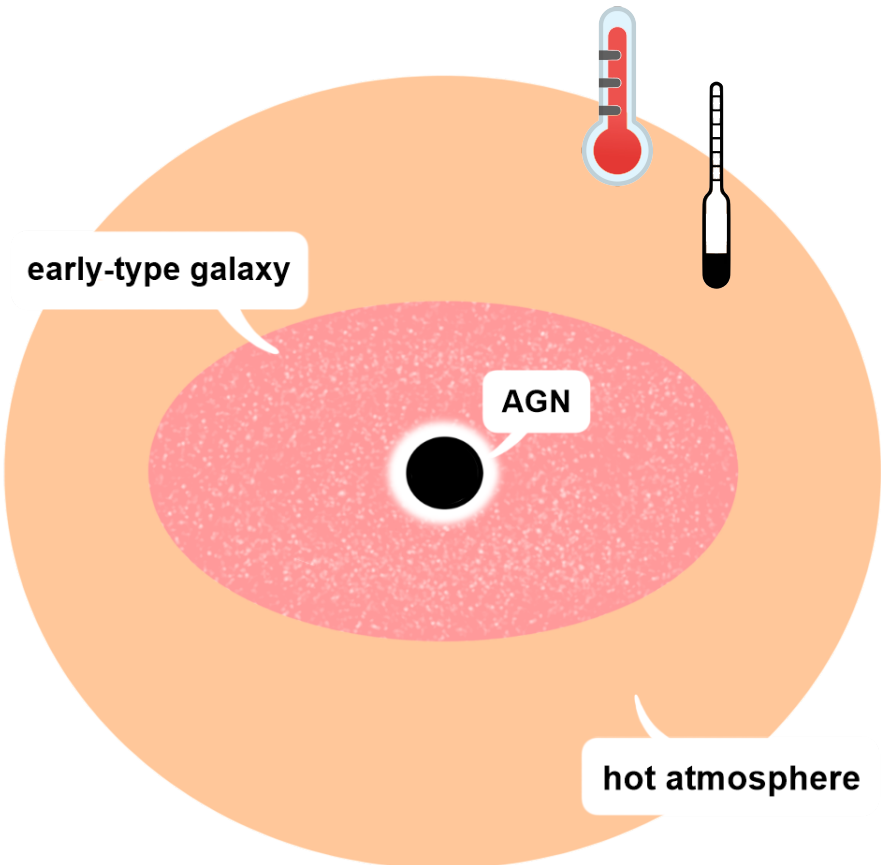
  - $n \approx 10^{-5} - 1\ \mathrm{cm}^{-3}$
  - $T \approx 10^6 - 10^8\ \mathrm{K}$



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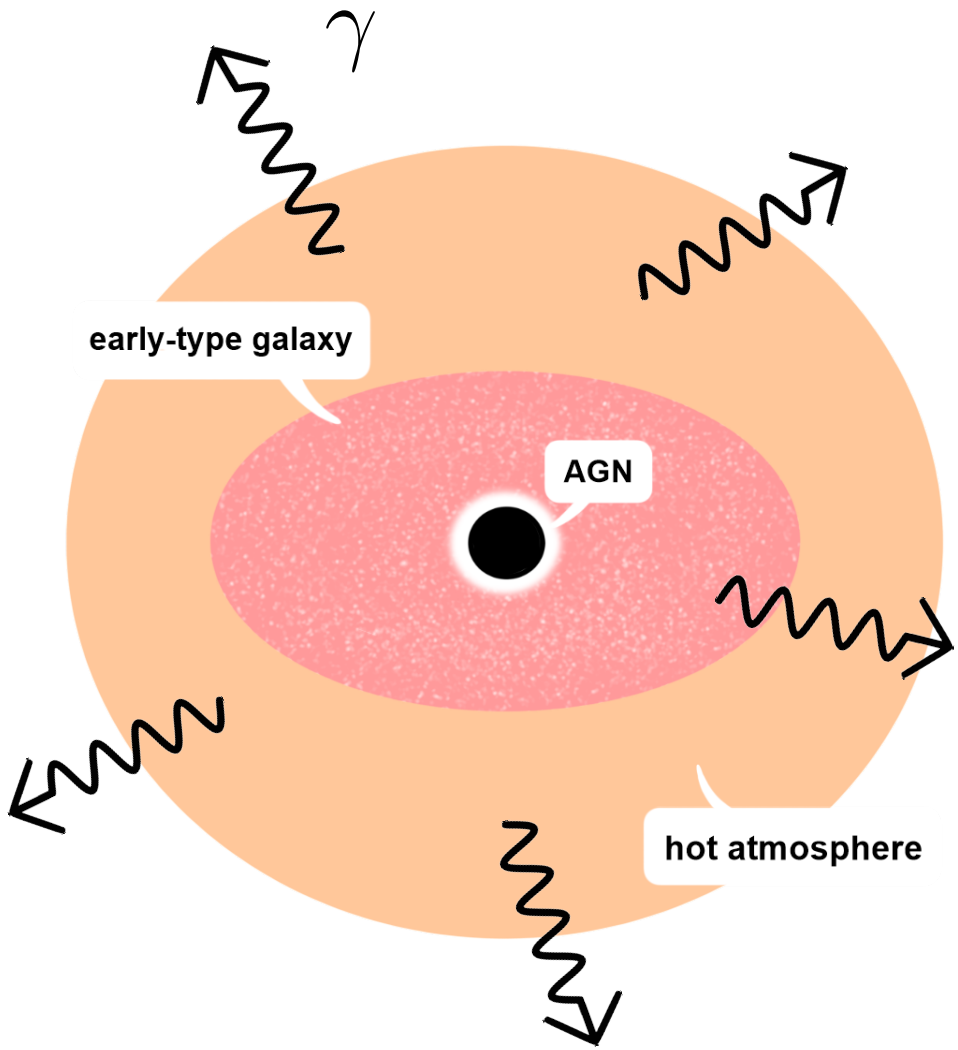

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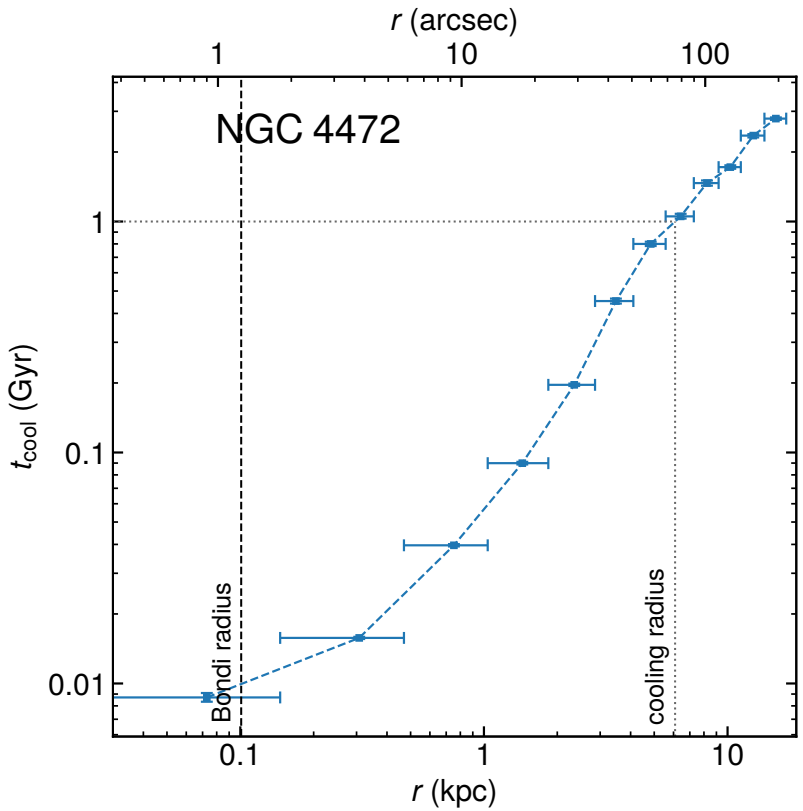
- hot $\rightarrow$ emit X-rays
  - optically thin

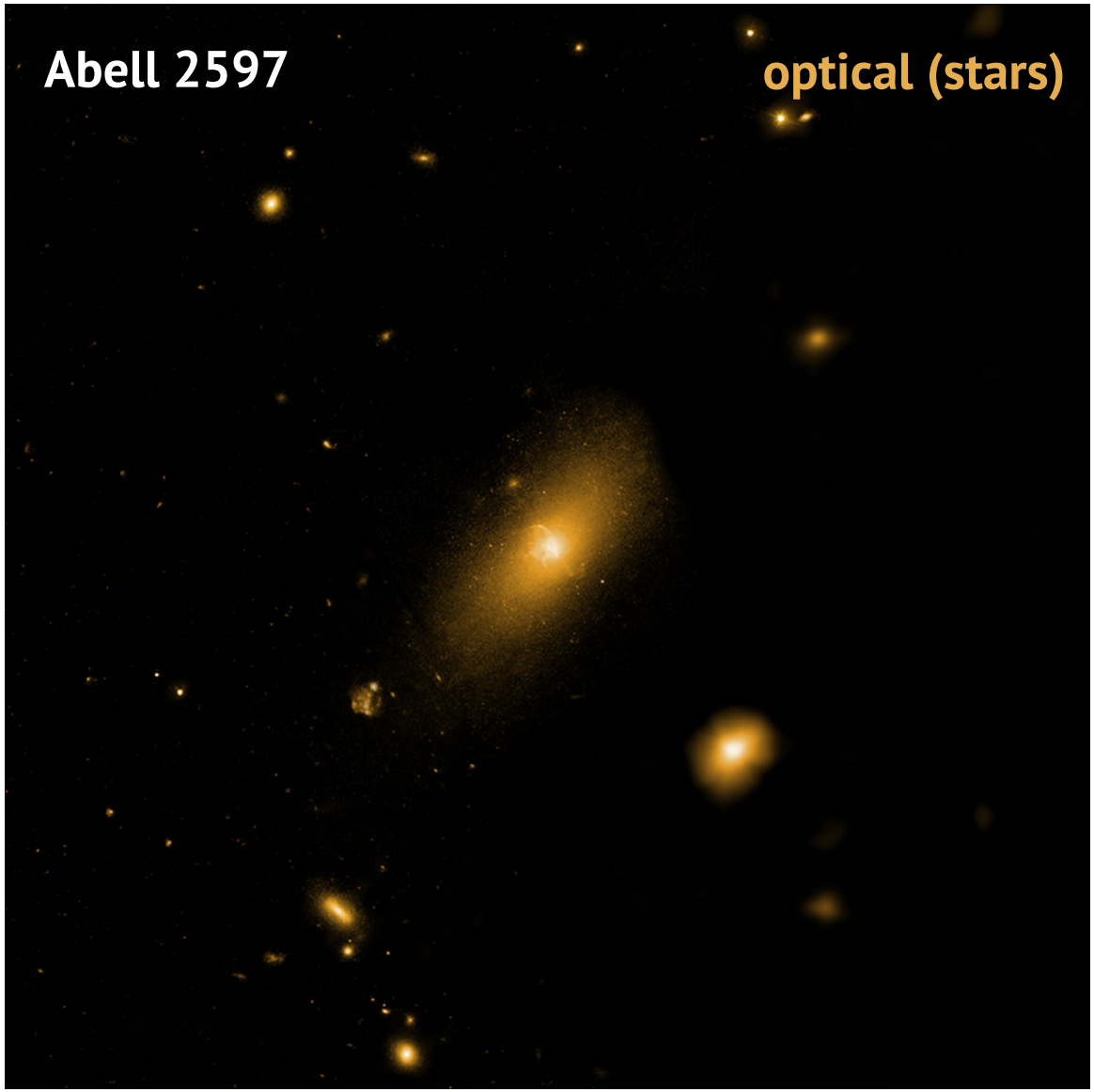
  $\rightarrow$ cool radiatively ($t_{\rm cool}$)

  $\rightarrow$ cold gas (Hα+[NII], CO)

$$t_{\rm cool} = \frac{\frac{3}{2} nkT}{L_{\rm X}} \propto \frac{kT}{n}$$



Early-type galaxies



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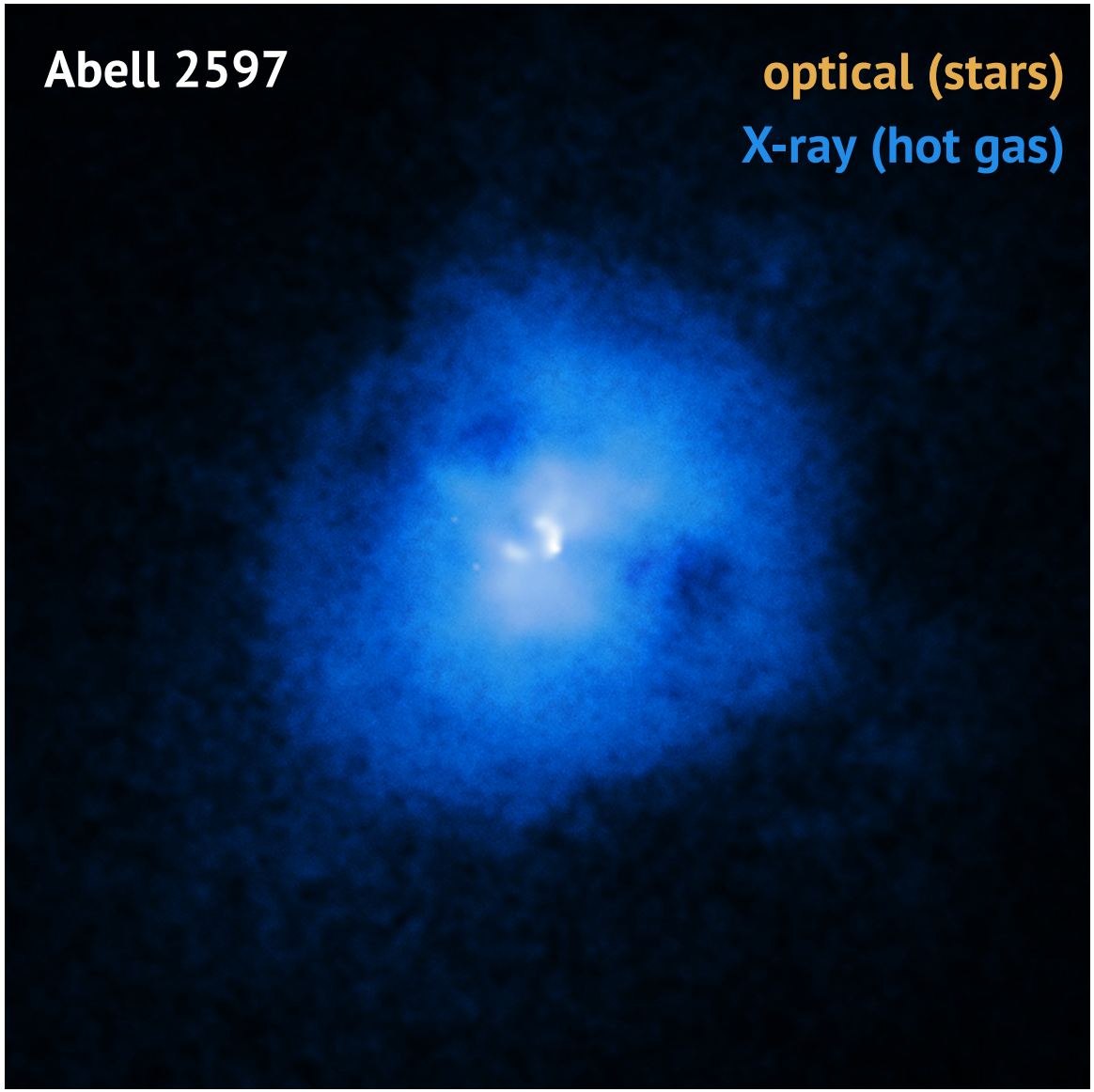
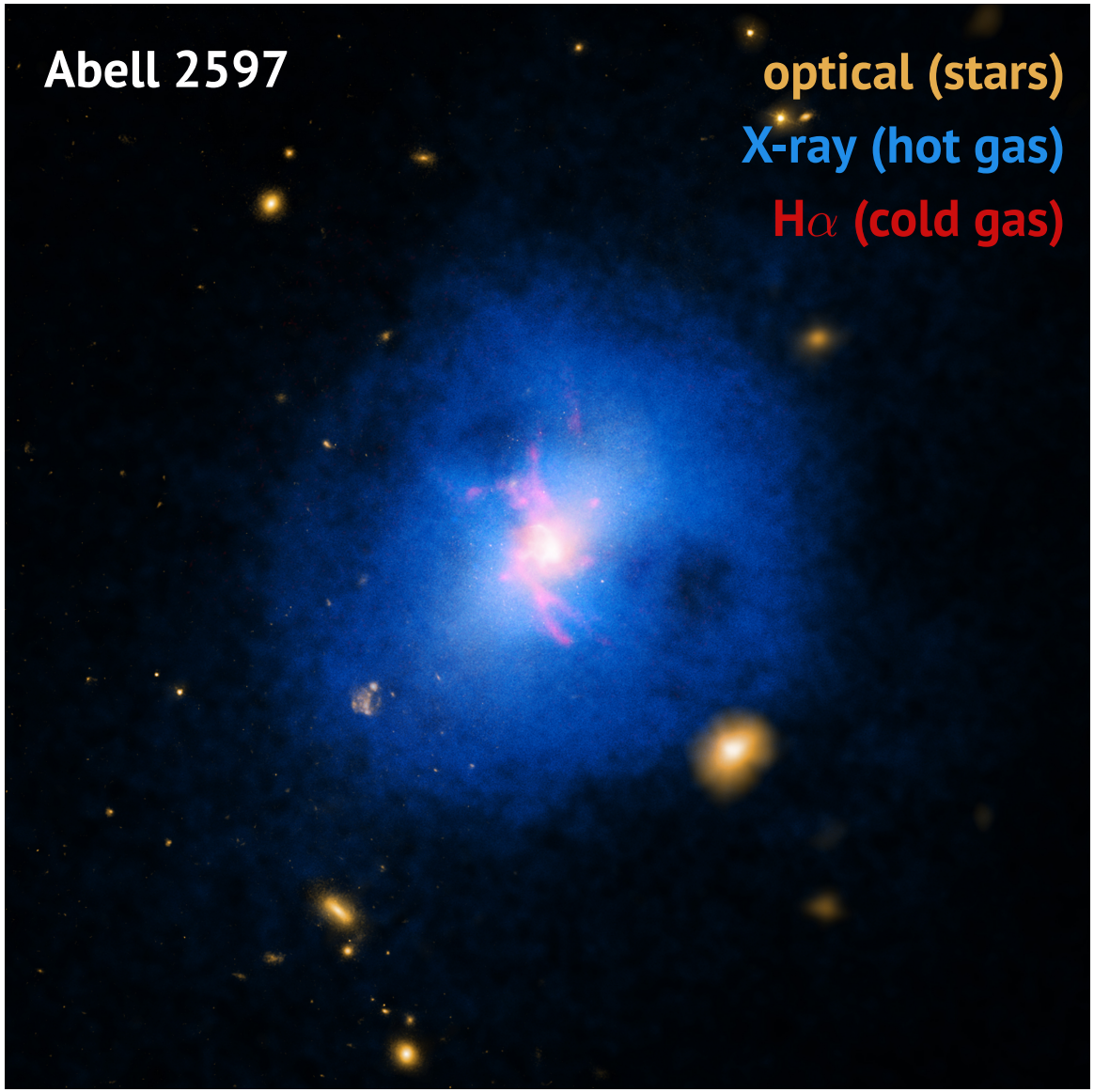
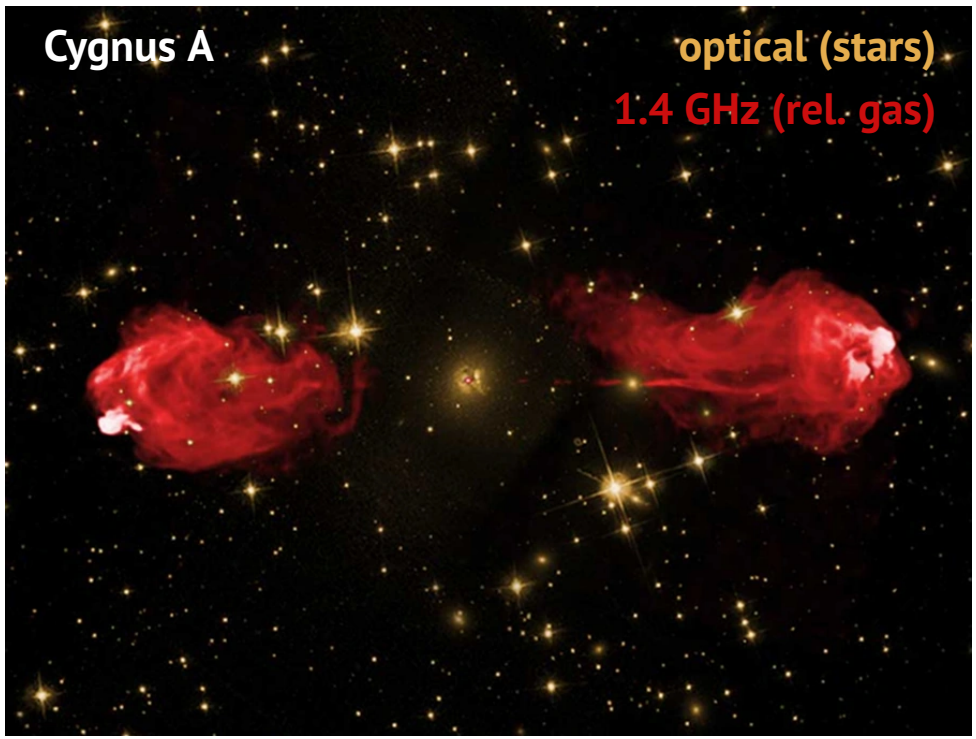


Early-type galaxies



Radio-mechanical AGN feedback

- relativistic jets $\rightarrow$ radio lobes
  - interact with hot gas
  - inflate X-ray cavities



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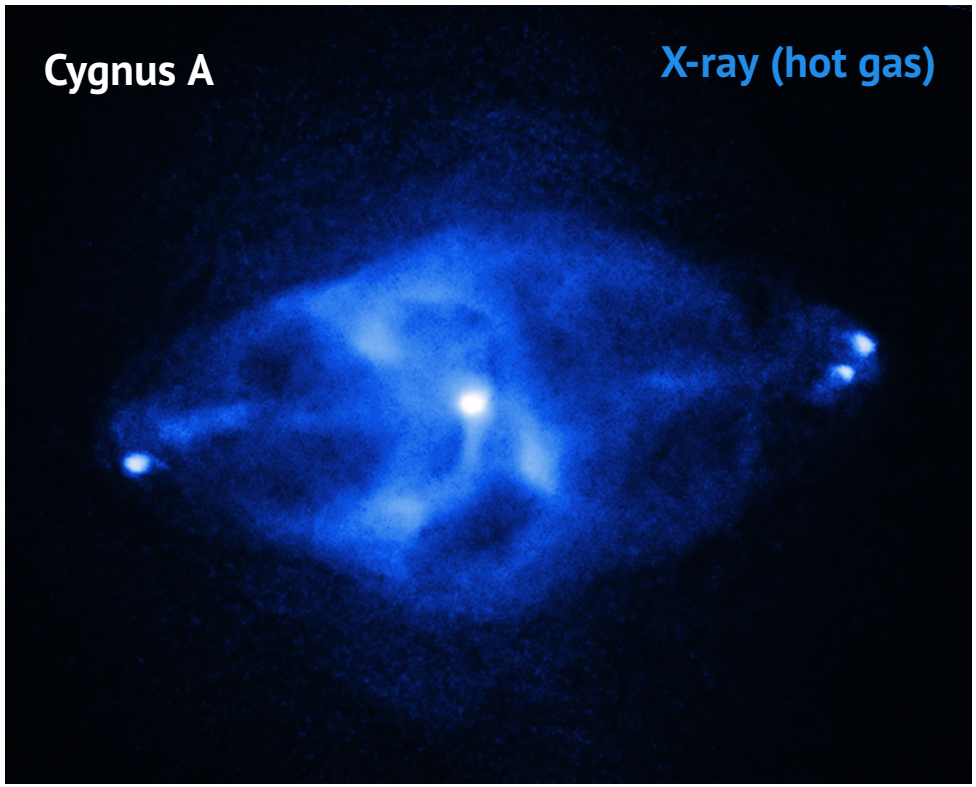

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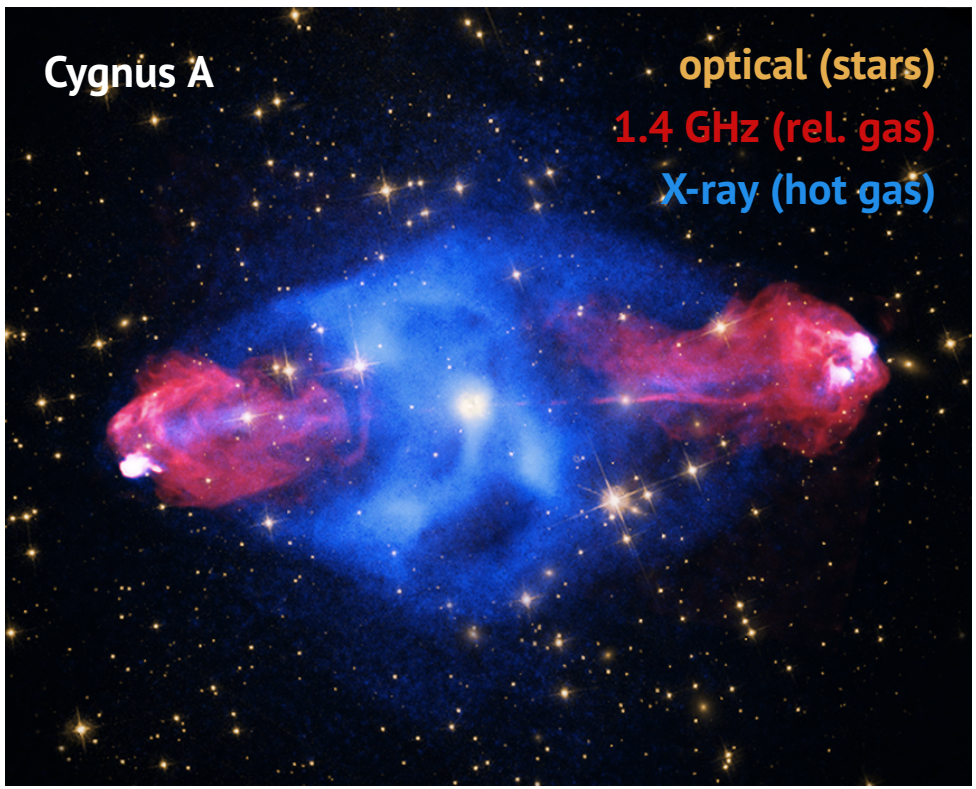

Radio-mechanical AGN feedback

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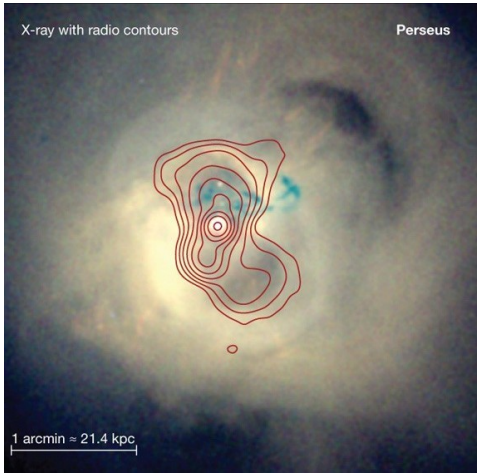
- for older no radio counterpart
  = ghost cavities



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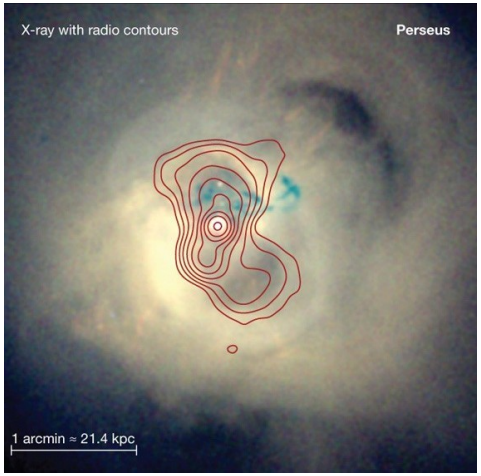
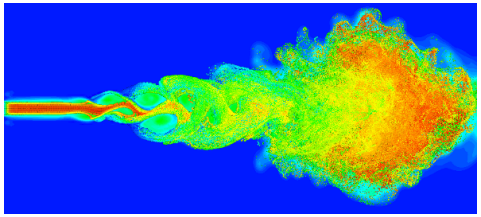
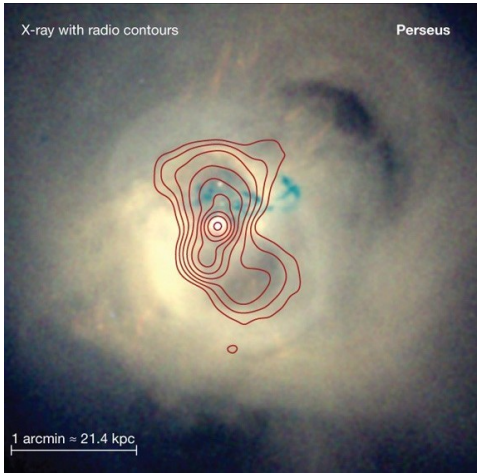
  - turbulent flows, bulk motions
  - sound and shock waves

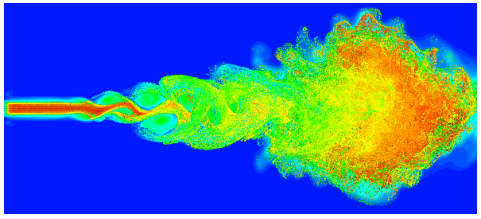


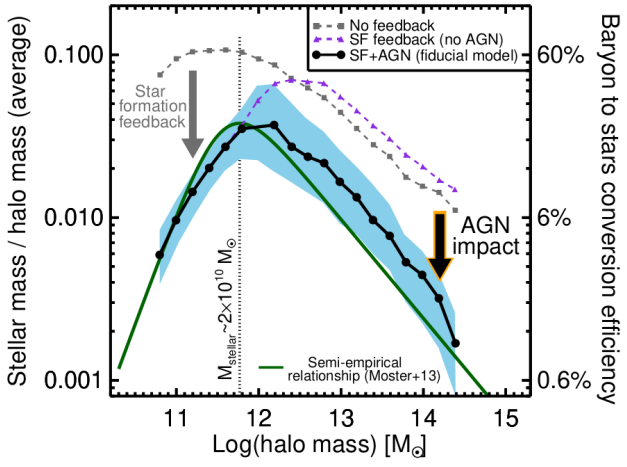


Radio-mechanical AGN feedback

- relativistic jets $\rightarrow$ radio lobes
  - interact with hot gas
  - inflate X-ray cavities
- for older no radio counterpart
  = ghost cavities
- deposits *E* on kpc—Mpc scale
  - turbulent flows, bulk motions
  - sound and shock waves
- heats the galactic atmosphere
  - prevents star formation
  - regulates further accretion

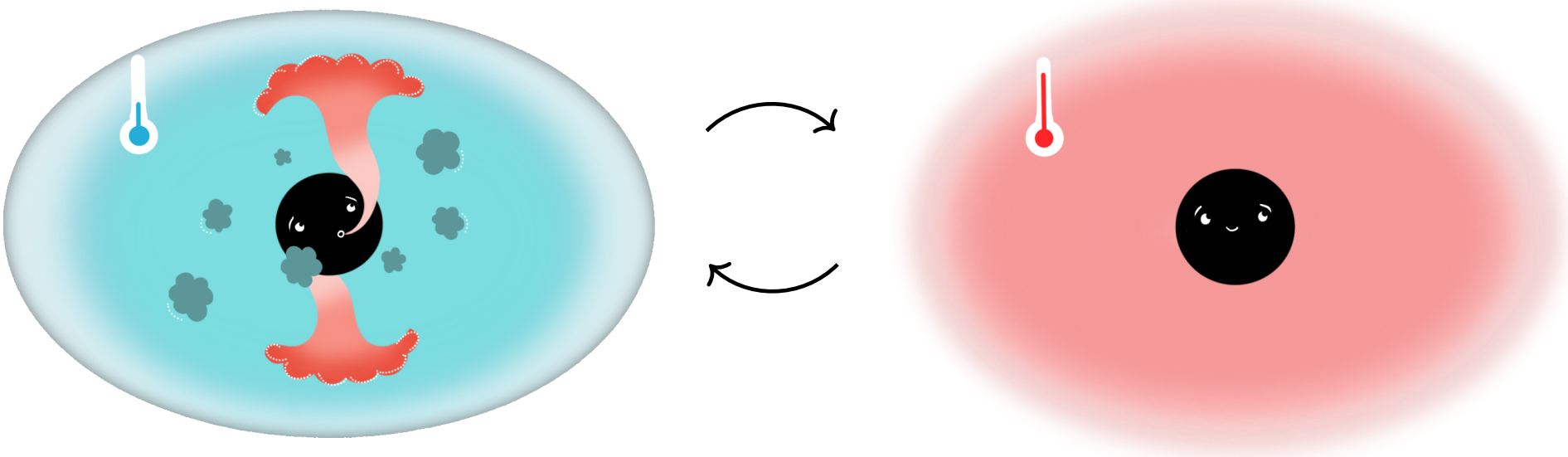






Radio-mechanical AGN feedback loop

gas cools



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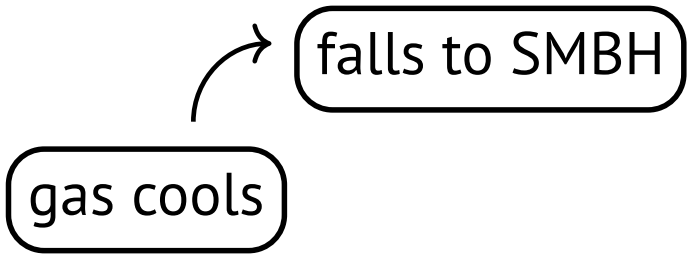

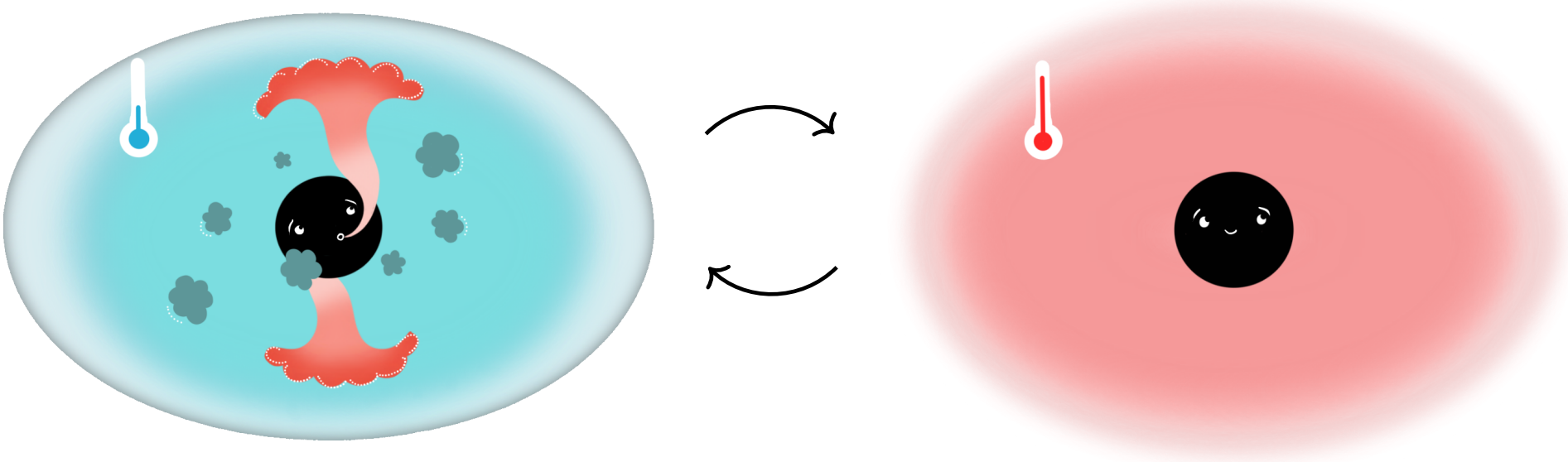

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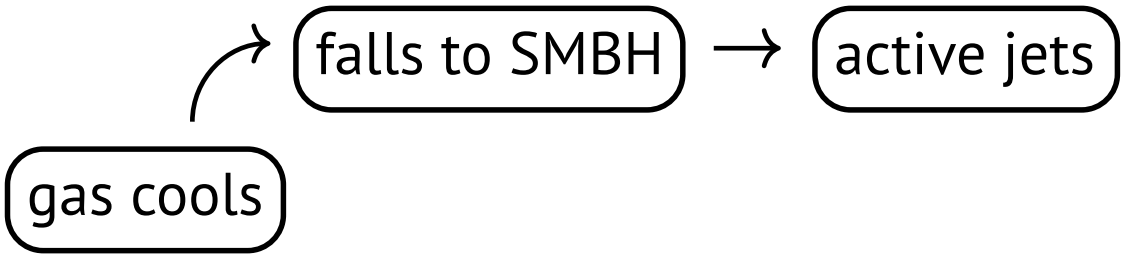

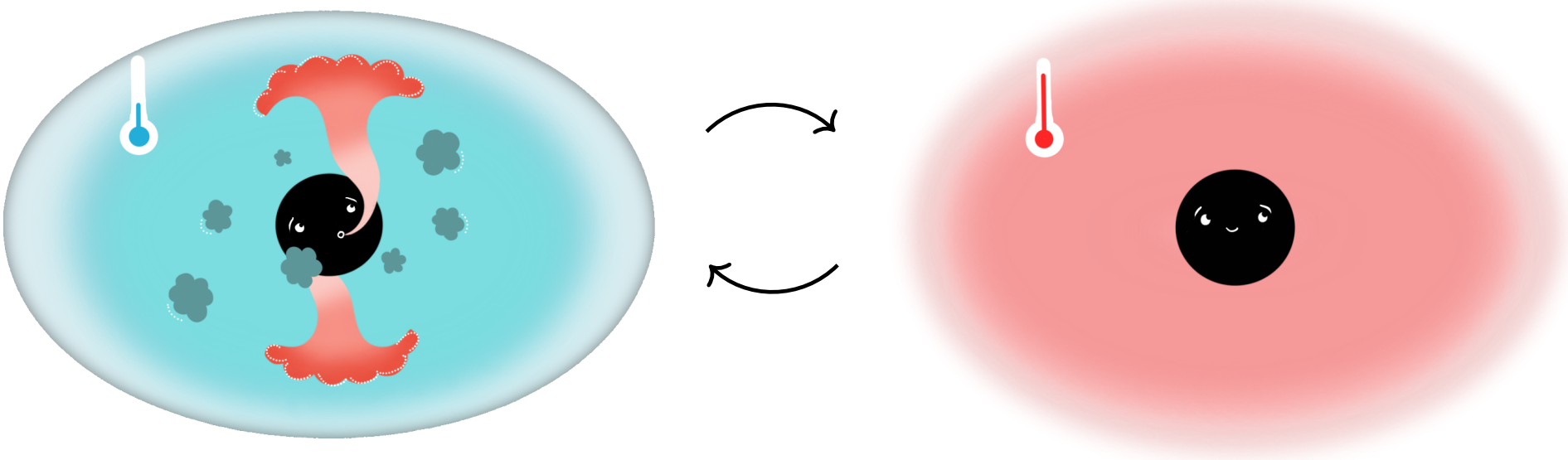

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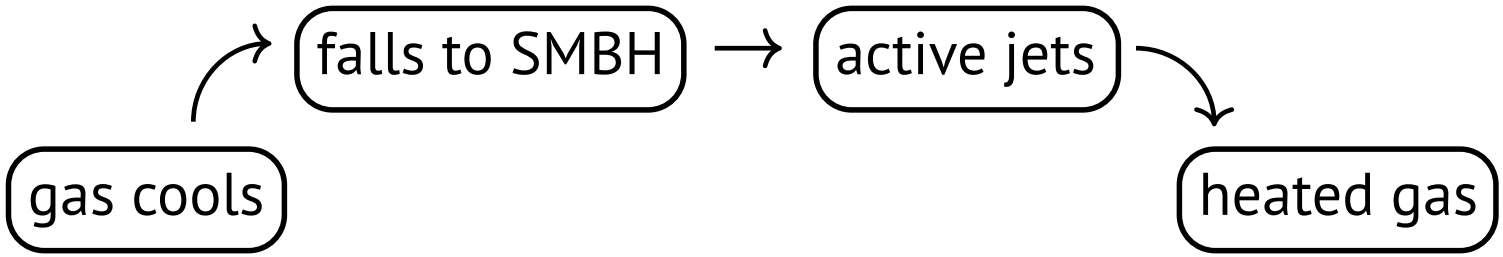

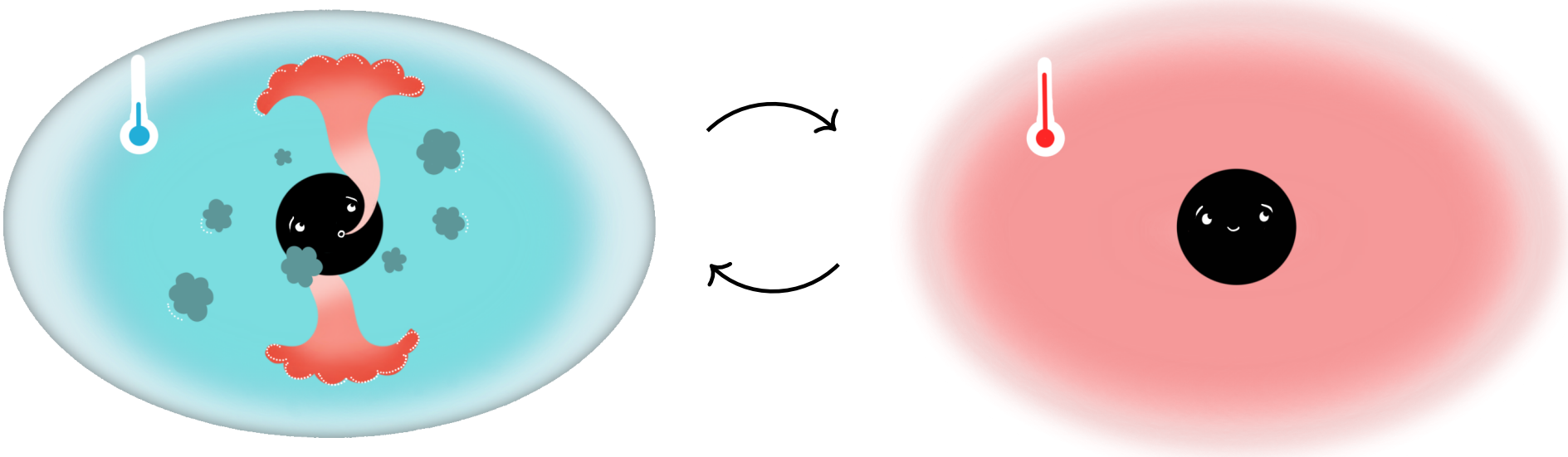

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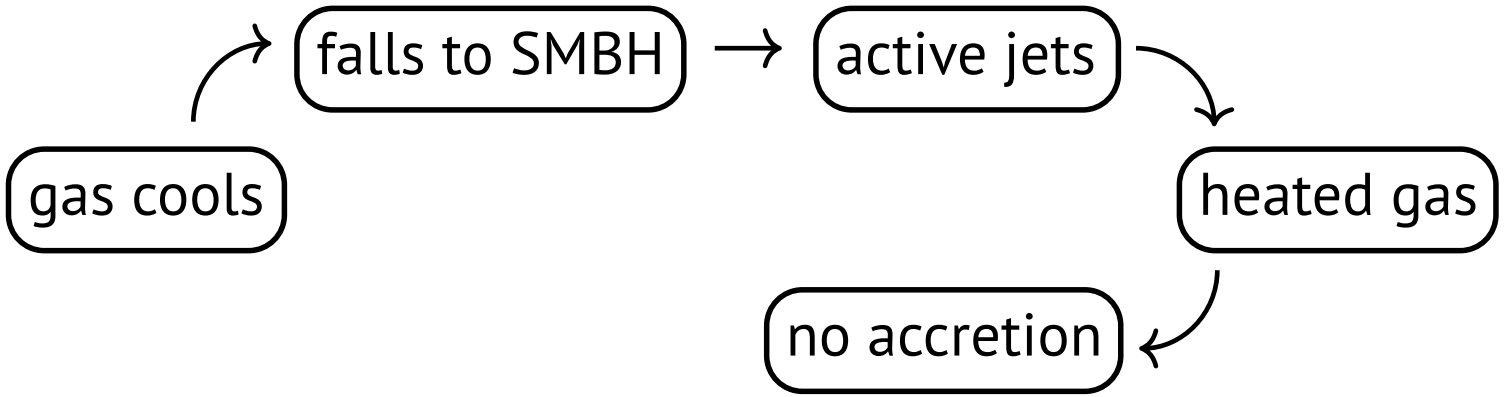

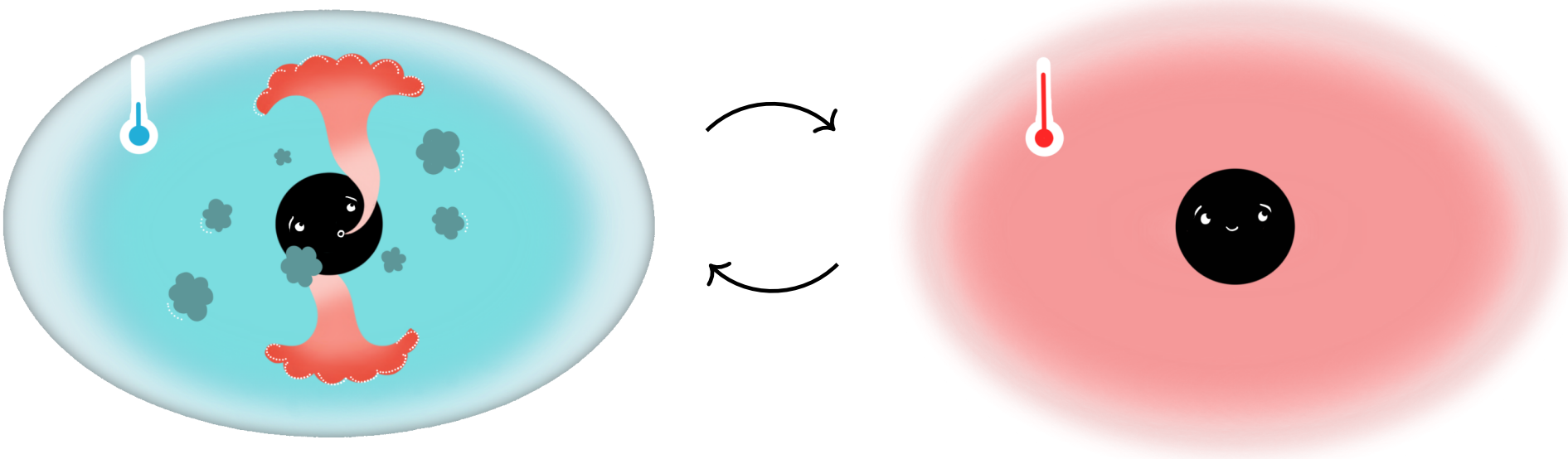

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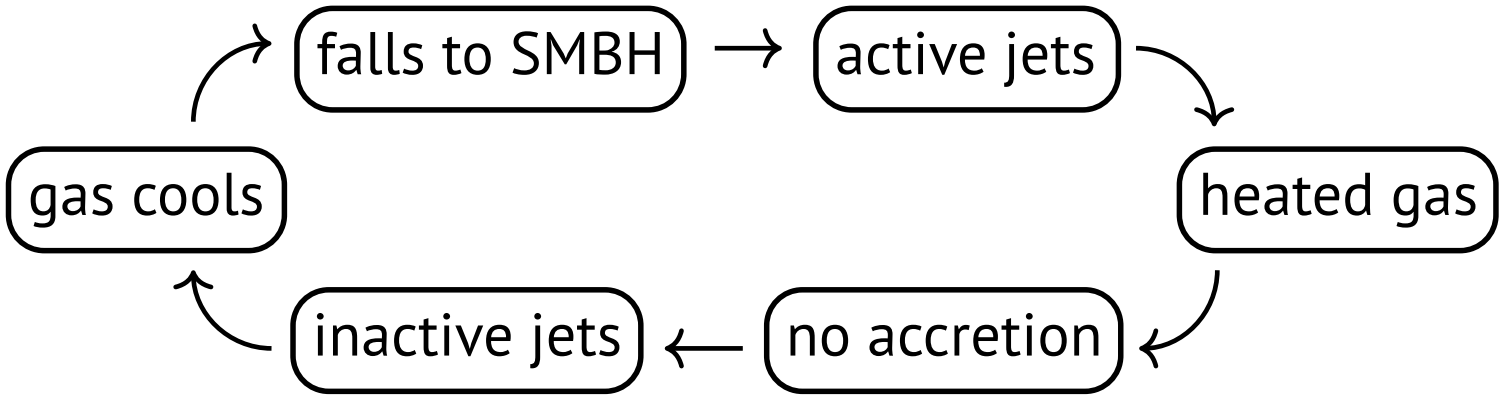
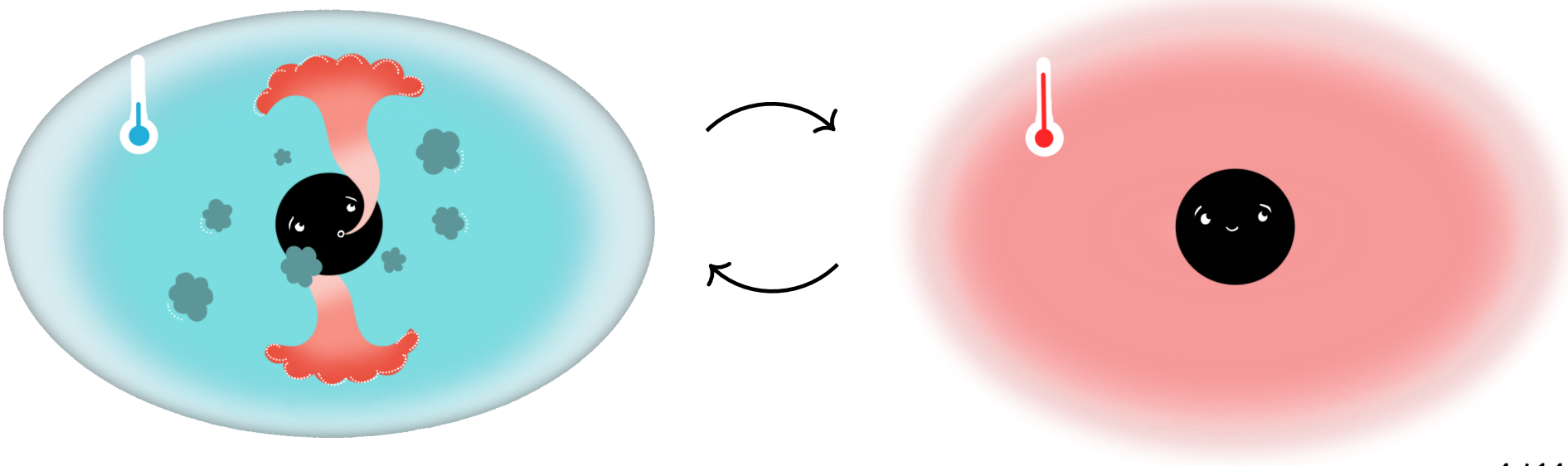
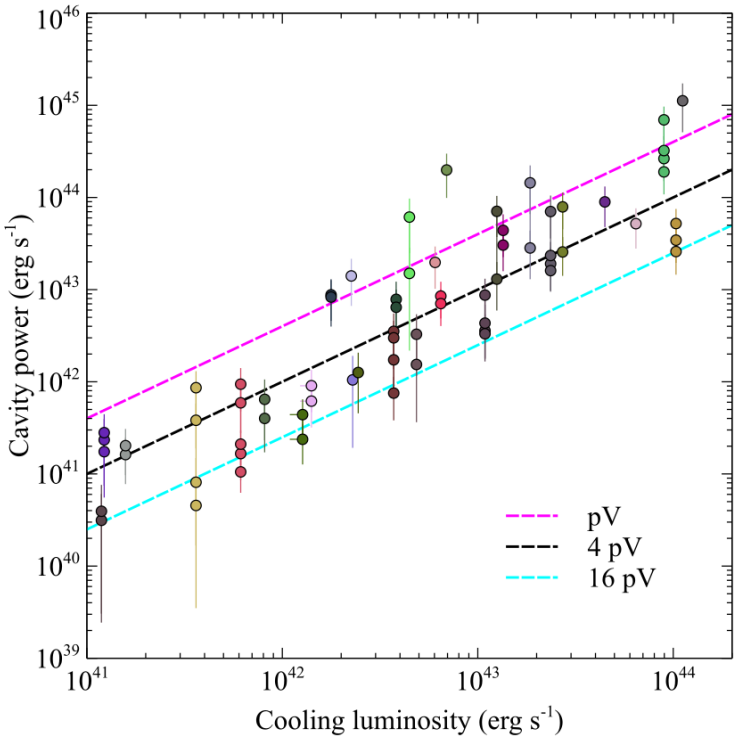




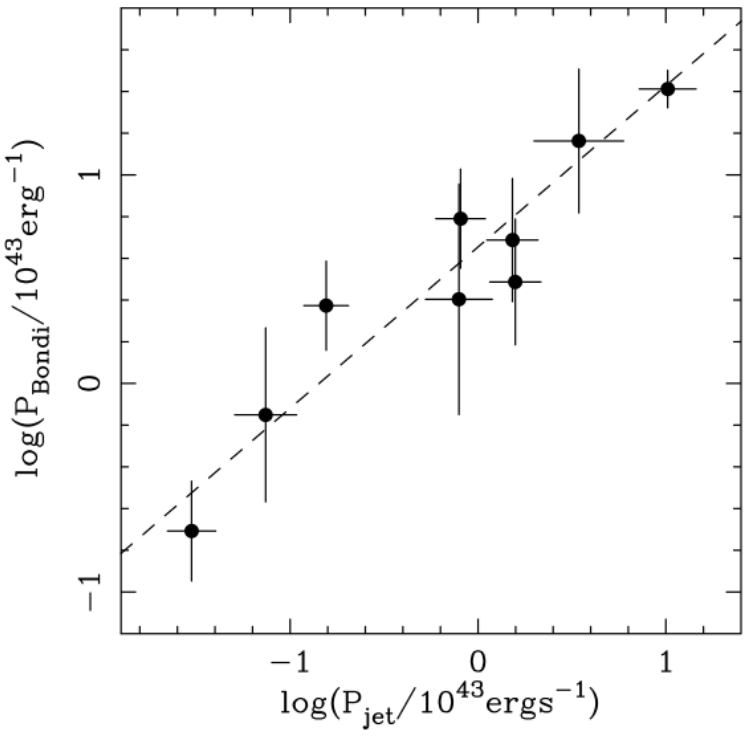
Radio-mechanical AGN feedback loop

hot atmosphere



Credit: Panagoulia et al. 2014

central engine



Credit: Allen et al. 2006

Studying AGN feedback with X-ray cavities

Credit: Randall et al. 2015

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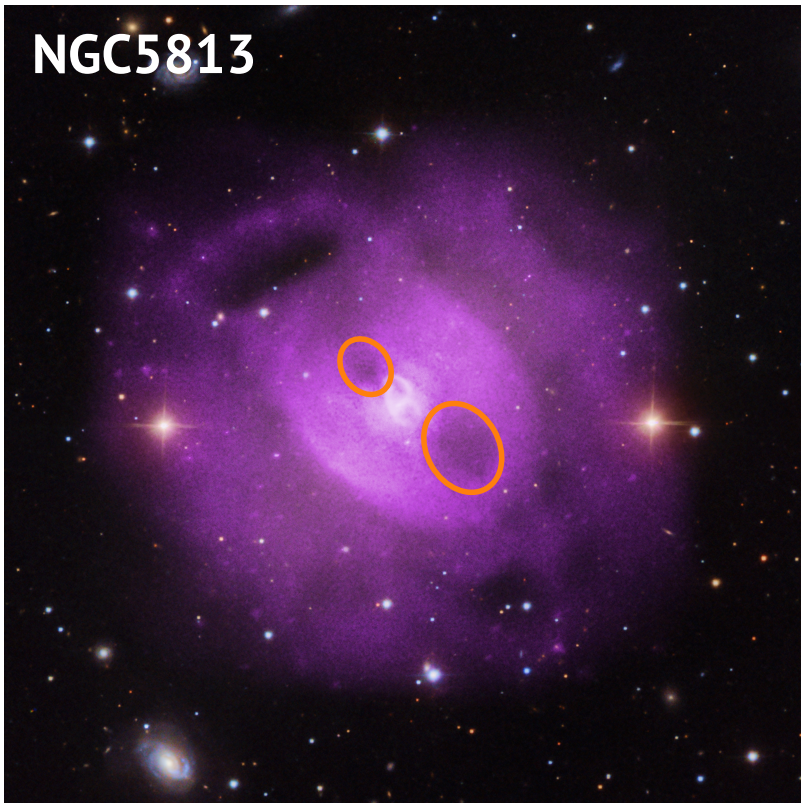

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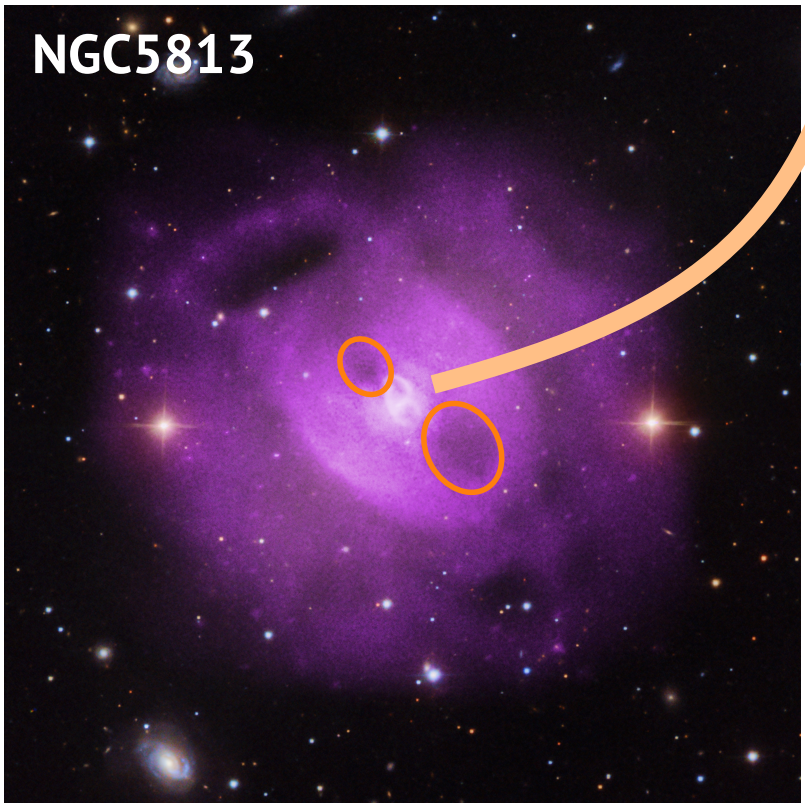
Studying AGN feedback with X-ray cavities

$$E \approx V \times p$$



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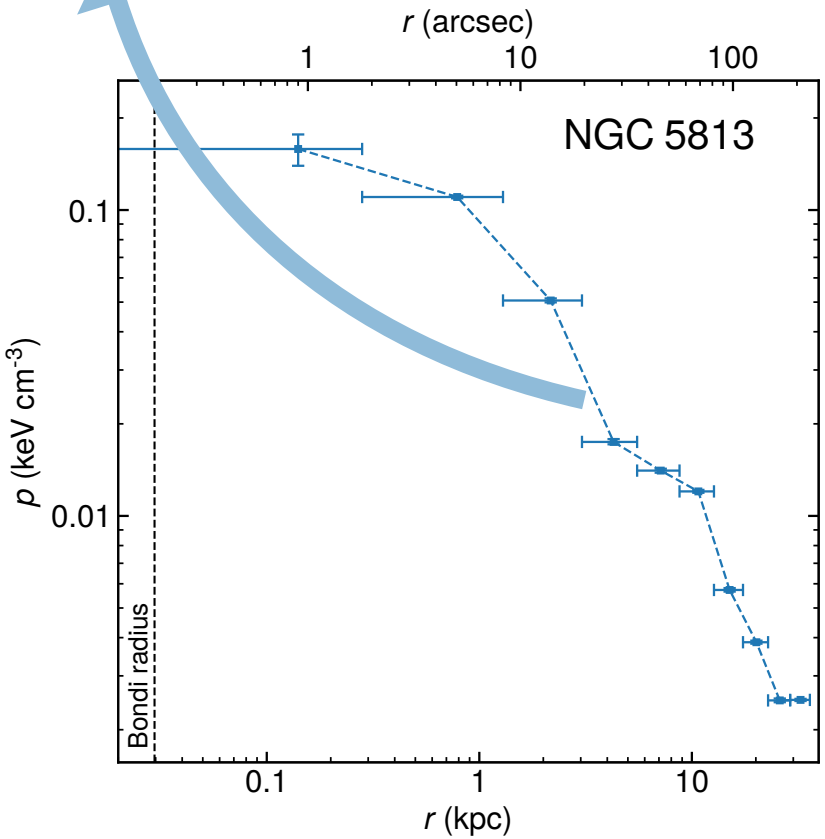
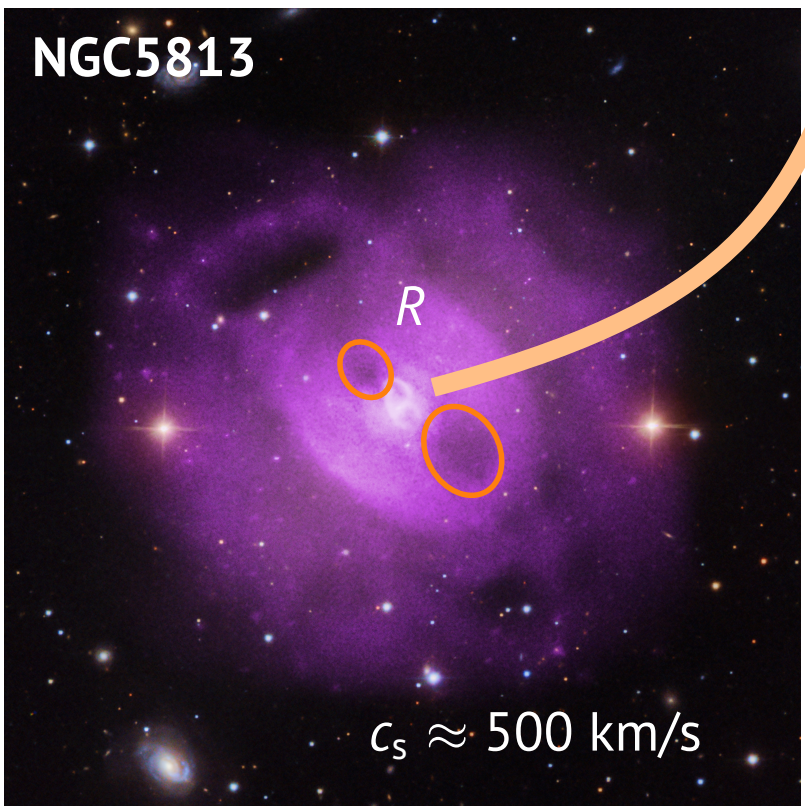


Credit: Plšek et al. 2022

Studying AGN feedback with X-ray cavities

$$t_{\text{age}} = \frac{R}{c_s} \qquad E \approx V \times p \qquad P_{\text{jet}} = \frac{pV}{t_{\text{age}}}$$



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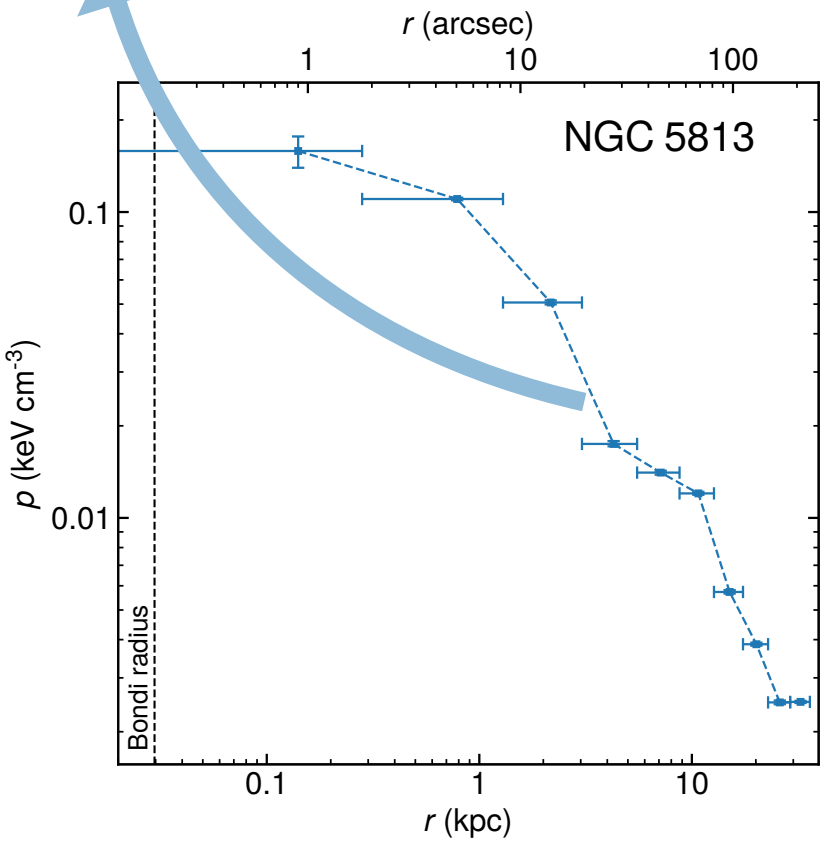


Credit: Plšek et al. 2022

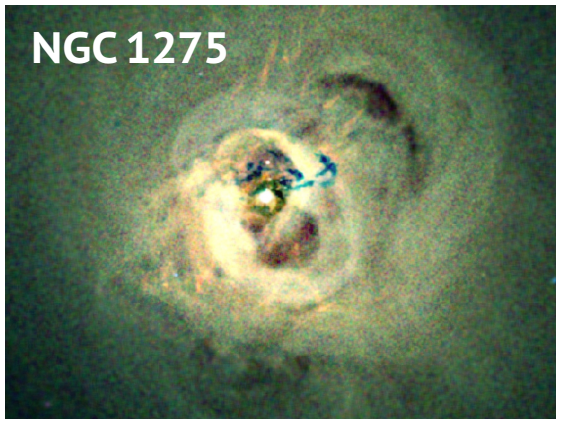
Broad range of jet powers

galaxies/groups

$R \approx 1$ kpc

$E \approx 10^{56}$ erg

$P_{\rm jet} = 10^{41} - 10^{43}$ erg/s

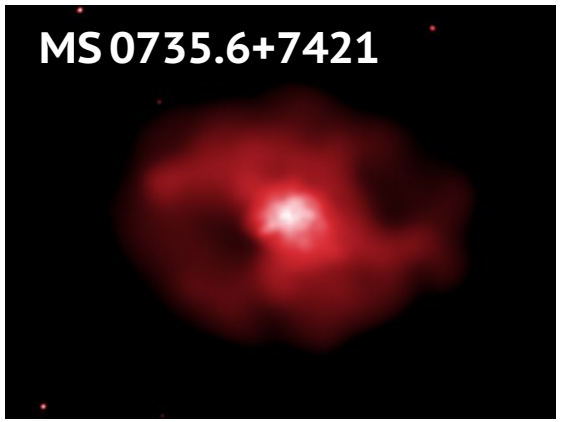


brightest cluster galaxies

$R \approx 10$ kpc

$E \approx 10^{59}$ erg

$P_{\rm jet} = 10^{43} - 10^{45}$ erg/s



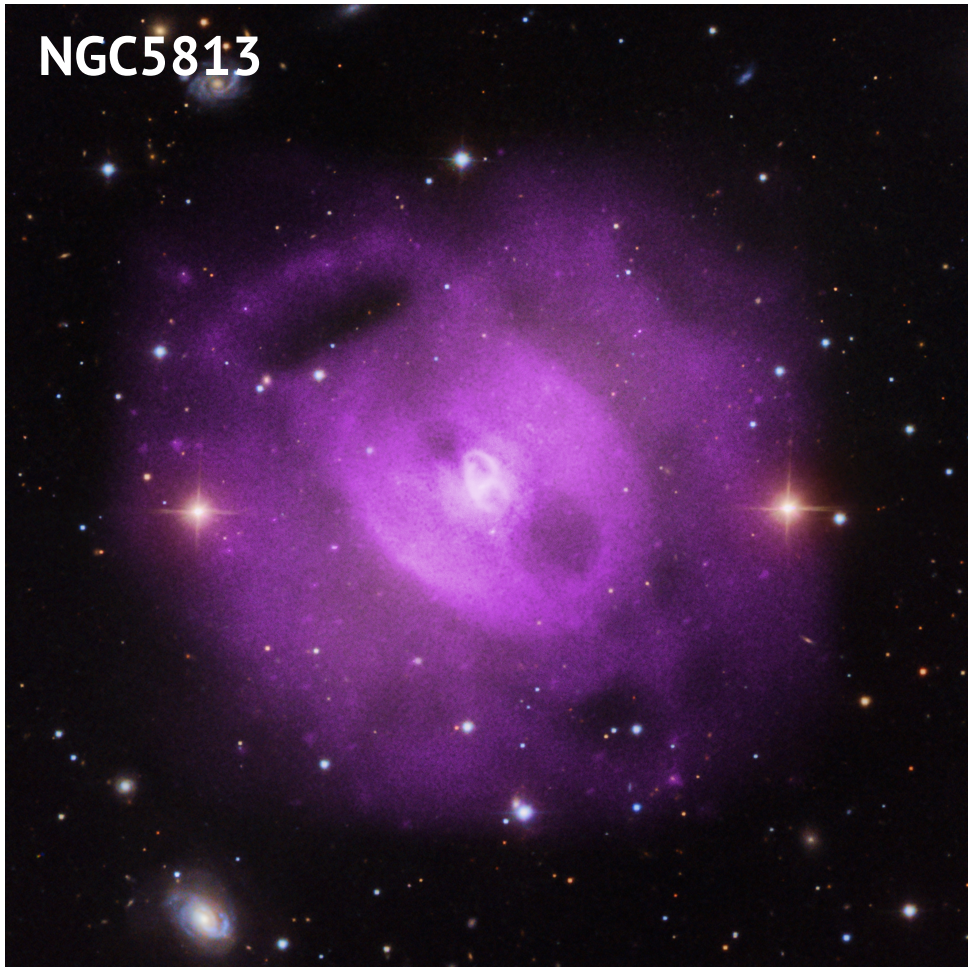
galaxy clusters

$R \approx 100$ kpc

$E \approx 10^{62}$ erg

$P_{\rm jet} = 10^{45} - 10^{46}$ erg/s

Pitfalls of visual detection



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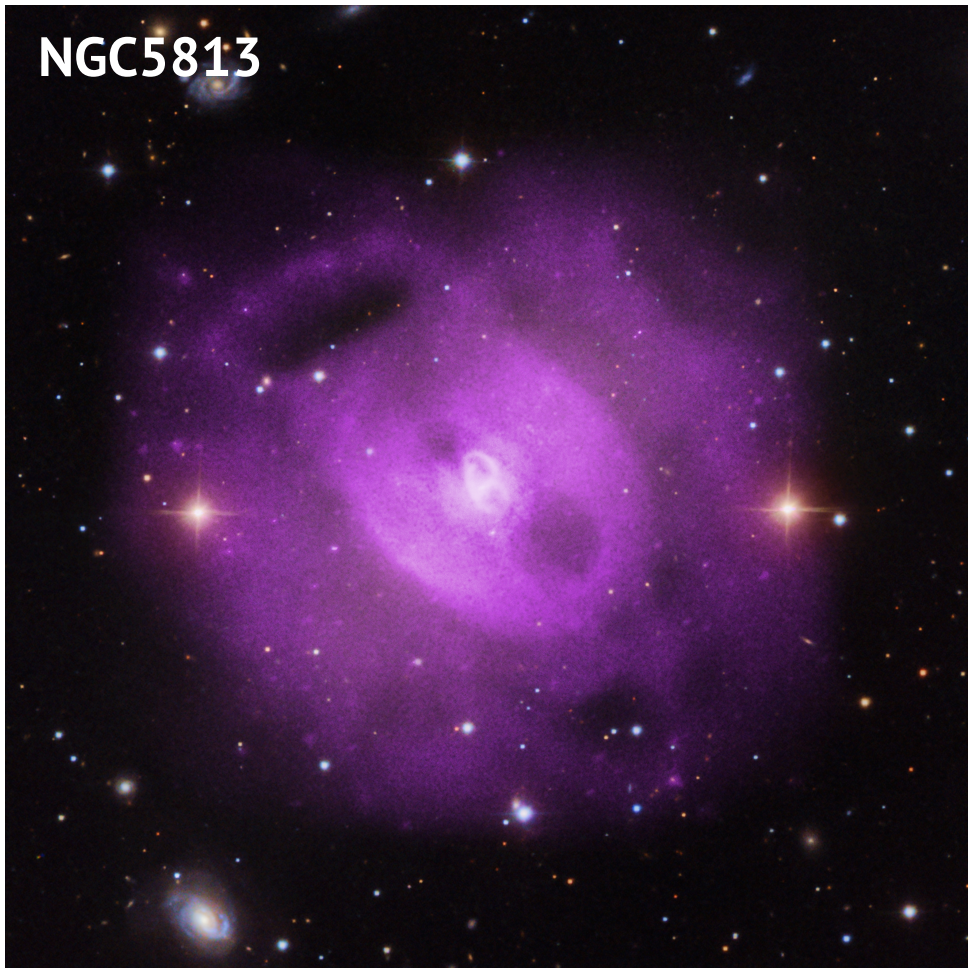

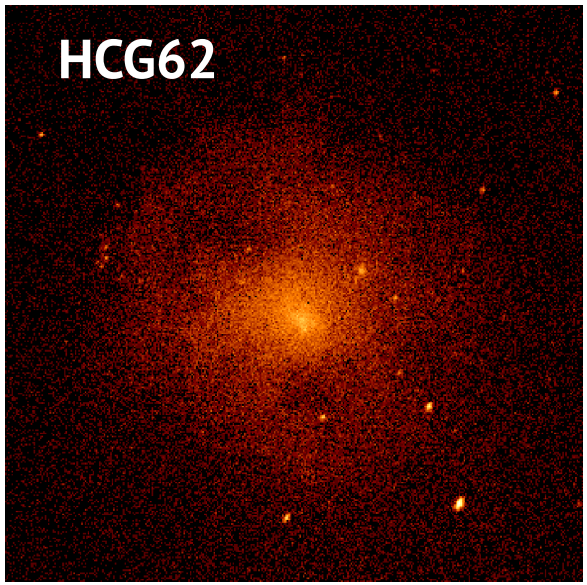

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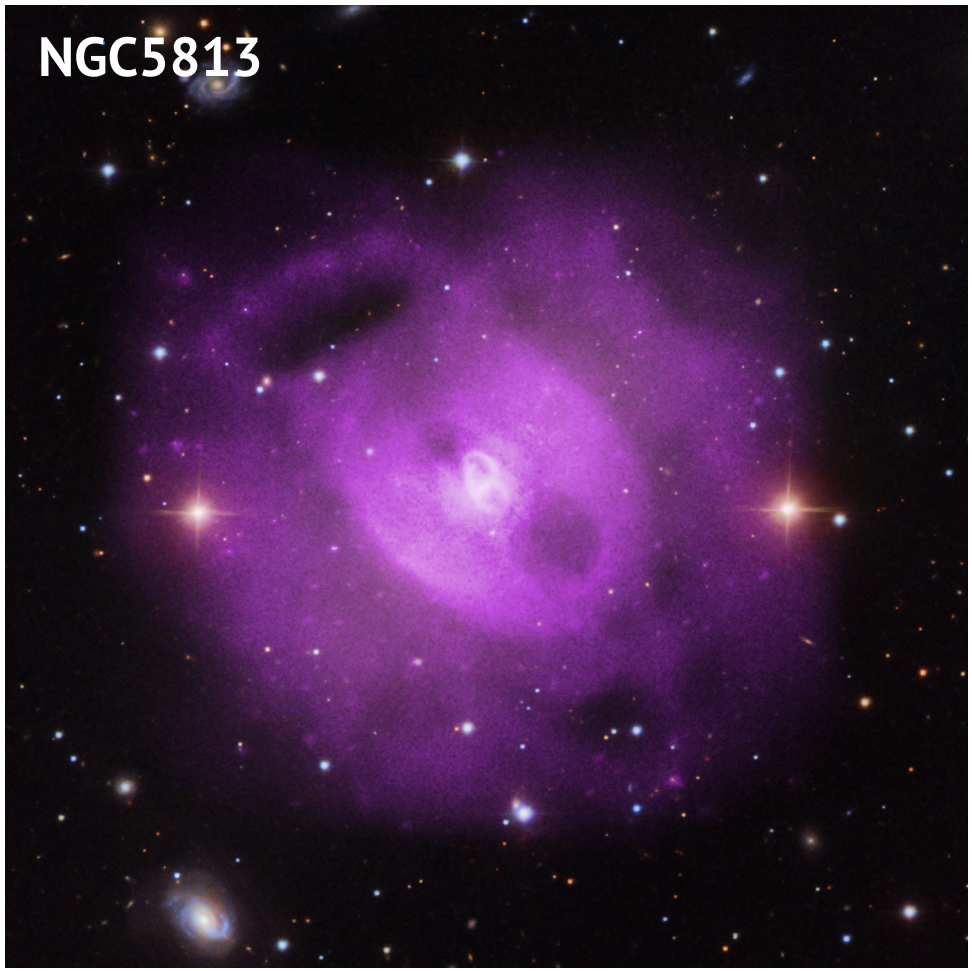

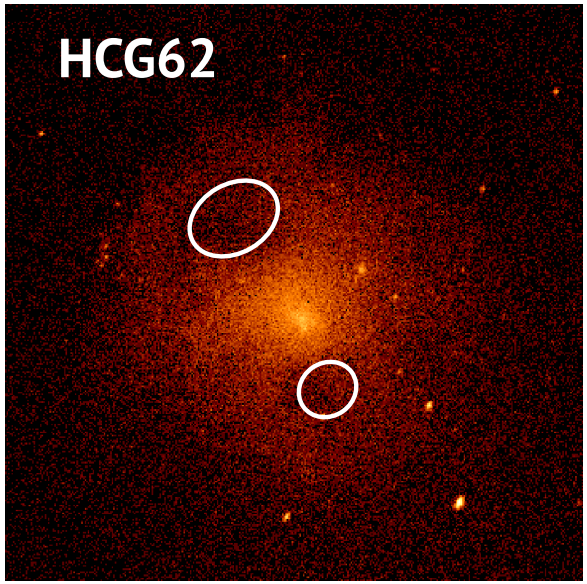

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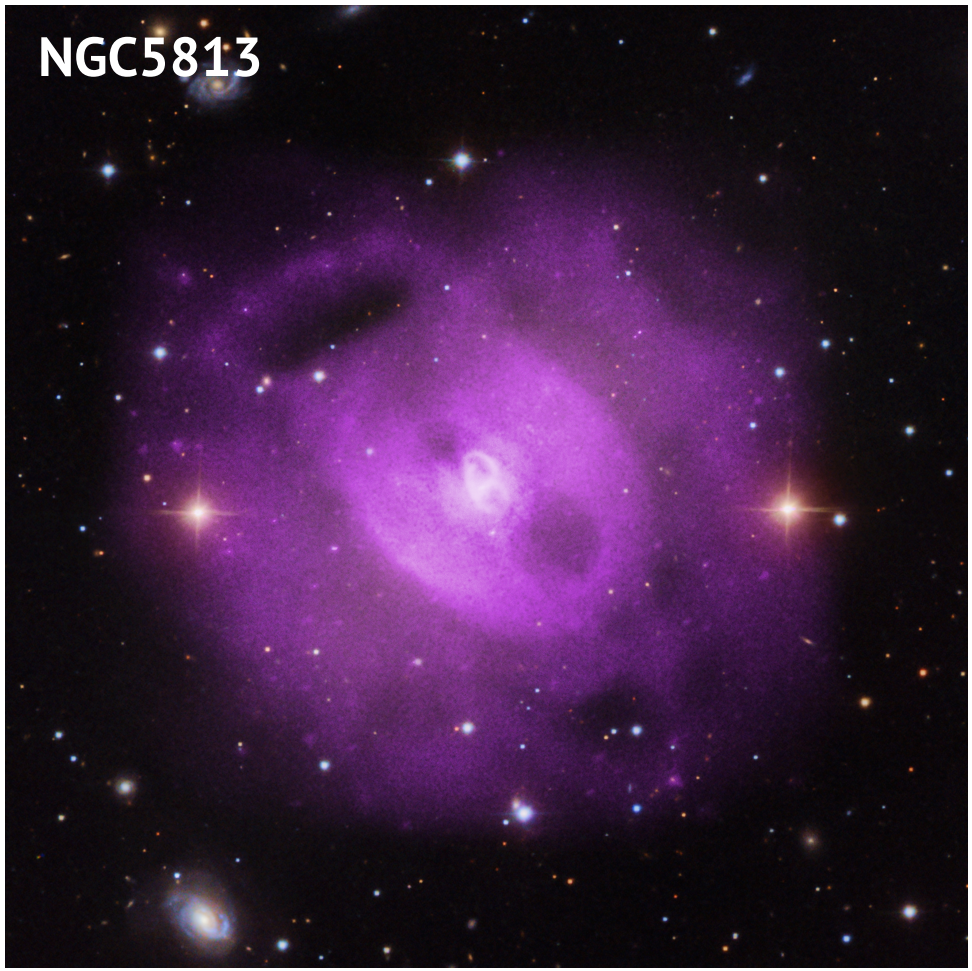

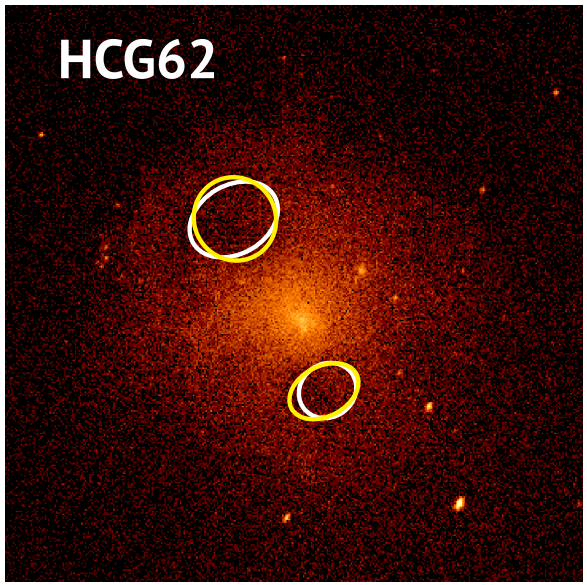

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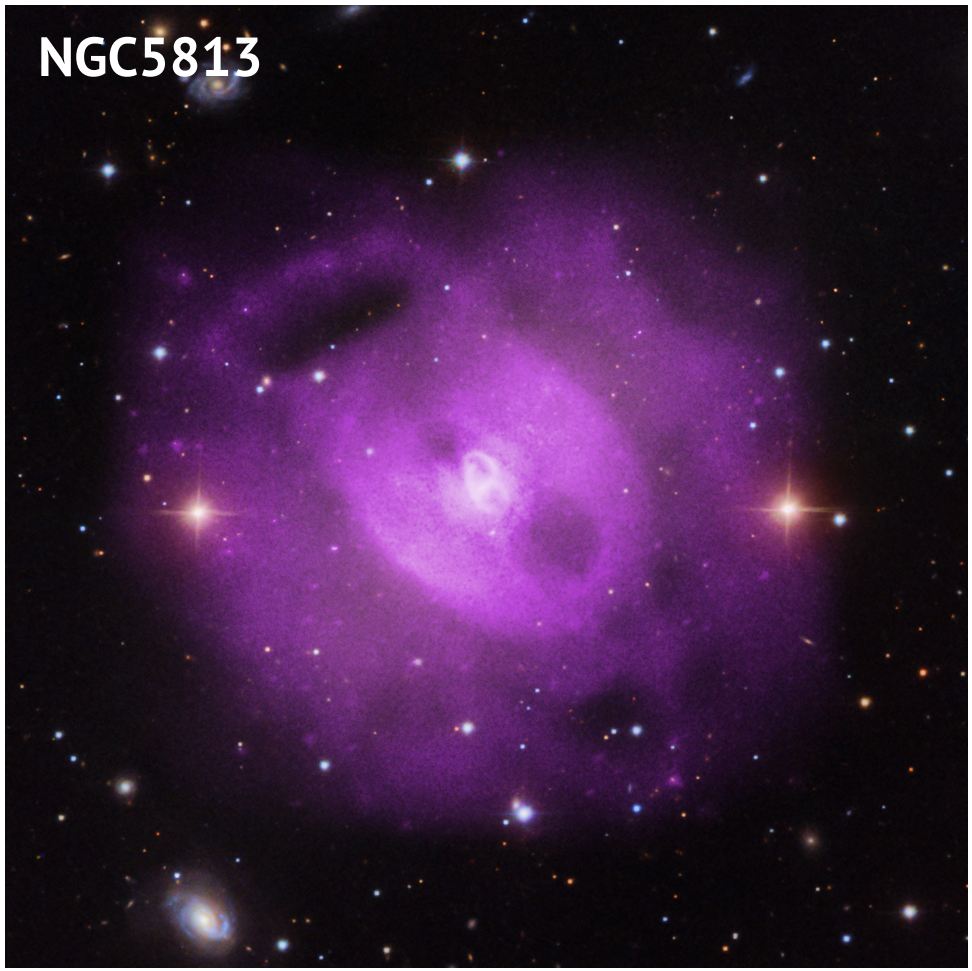

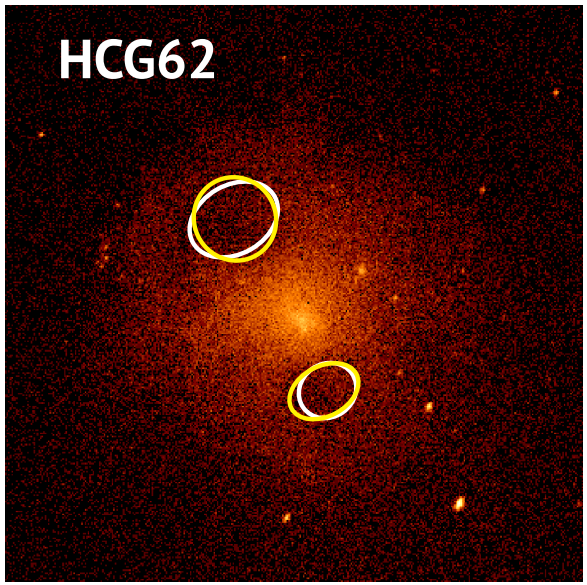

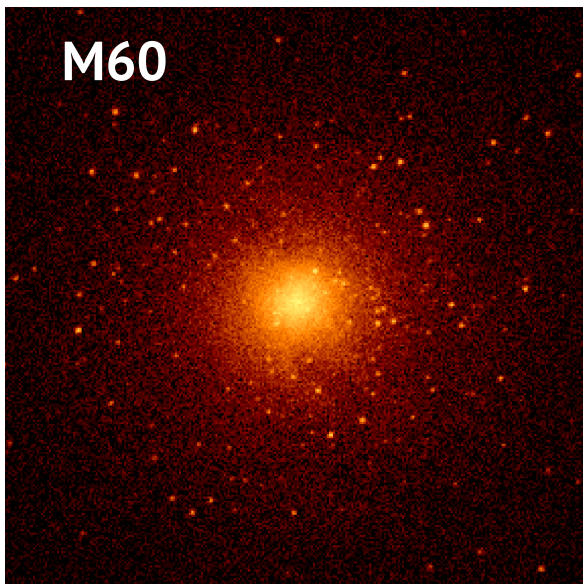

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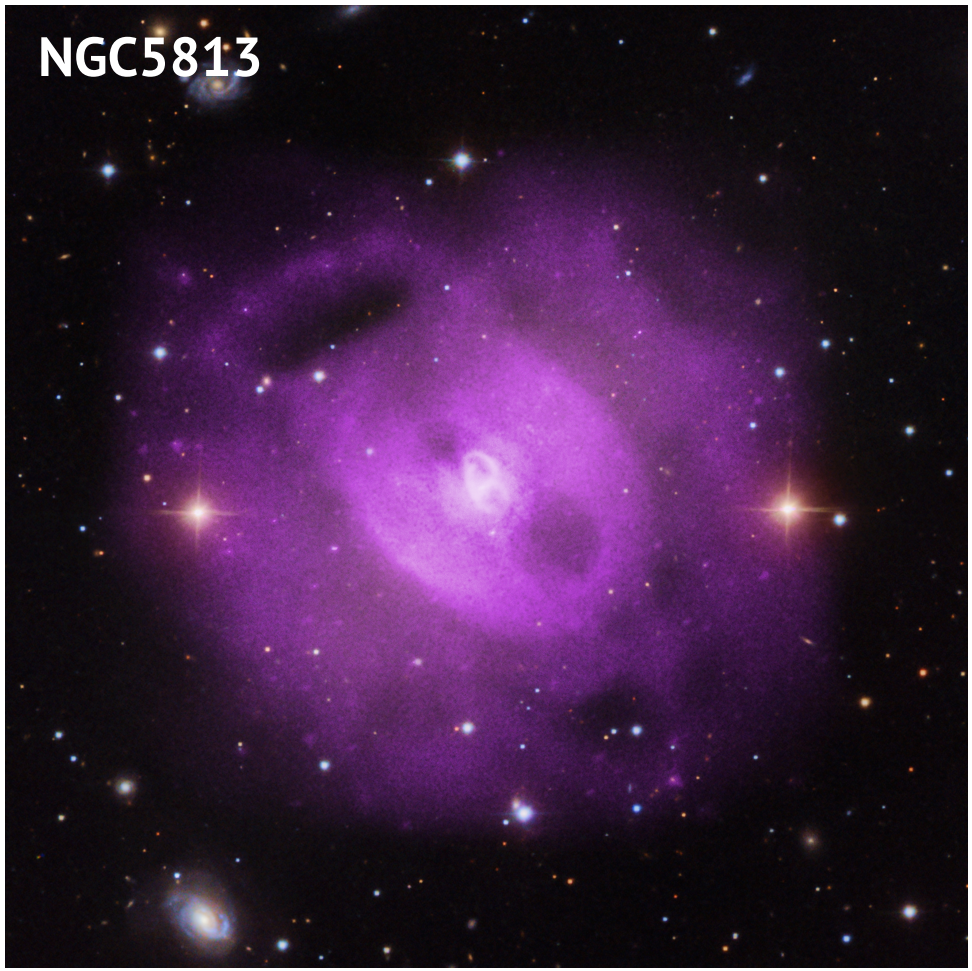
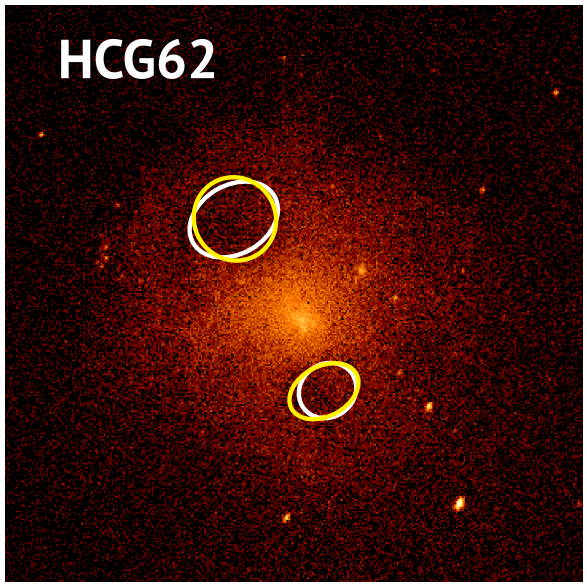
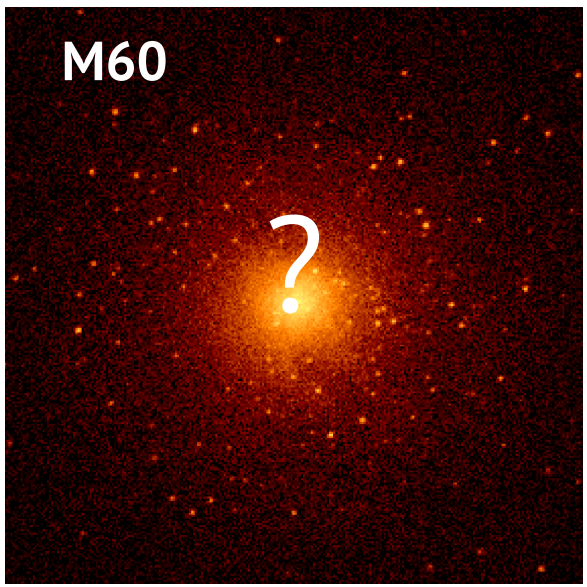


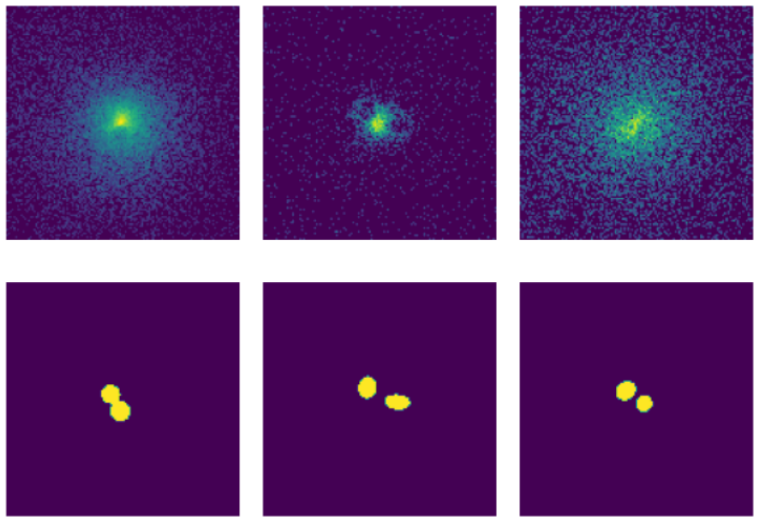




Cavity Detection Tool (CADET)

`github.com/tomasplsek/CADET`

- mock training data
  - 3D β-models
  - ellipsoidal cavities (50%)
  - 500k training images



Cavity Detection Tool (CADET)

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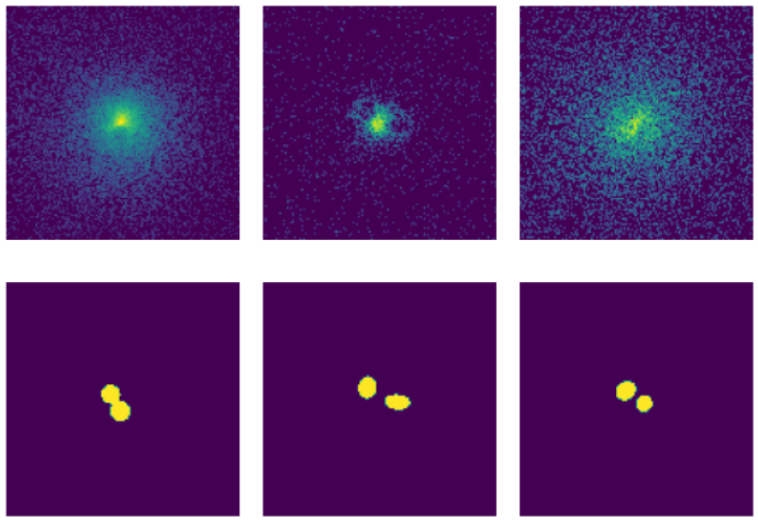
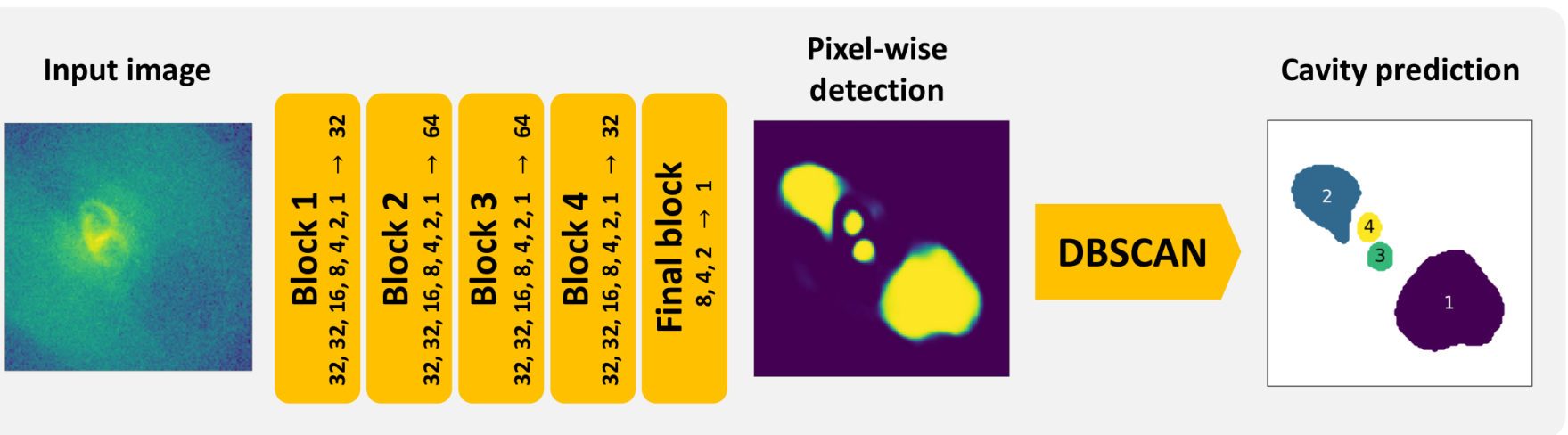
  - 500k training images
- convolutional neural network

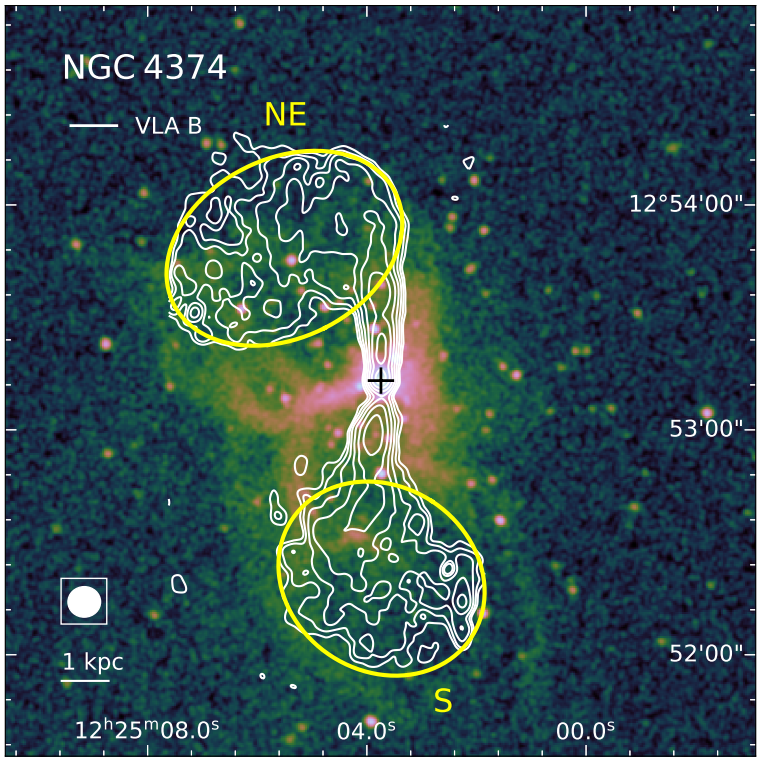
  $\rightarrow$ image segmentation





Correlation with Bondi accretion power

$$P_{\rm jet} \overset{?}{\propto} P_{\rm B}$$



Galaxy	Alternative name	D (Mpc)	$r_{\rm B}$ (pc)	$r_{\rm B}$ ($''$)
IC 4296	Abell 3565	49.0	70.0	0.29
NGC 1399	Fornax c.	21.1	38.0	0.24
NGC 1407		25.1	164.0	1.3
NGC 1600		63.7	539.0	1.7
NGC 4261		32.4	81.0	0.52
NGC 4472	M49	16.5	106.0	1.3
NGC 4486	M87	16.5	208.0	2.6
NGC 4636		14.7	35.0	0.49
NGC 4649	M60	16.5	122.0	1.5
NGC 5813		32.2	40.0	0.26
NGC 5846		24.9	48.0	0.35
NGC 507		64.6	86.0	0.28
NGC 708	Abell 262	62.8	17.0	0.056
NGC 1316	Fornax A	22.7	8.0	0.077
NGC 4374	M84	16.5	62.0	0.77
NGC 4552	M89	16.5	14.0	0.18
NGC 4696	Centaurus c.	42.5	36.0	0.17
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NGC 5044		32.2	10.0	0.065
NGC 6166	Abell 2199	125.0	63.0	0.1

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$$r_{\mathrm{B}} = \frac{G M_\bullet}{c_{\mathrm{s}}^2}$$

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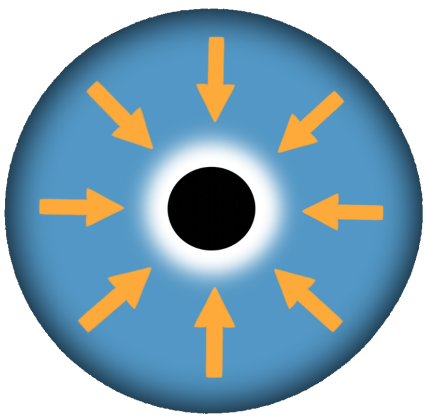

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Plšek et al. 2022 (doi.org/10.1093/mnras/stac2770)

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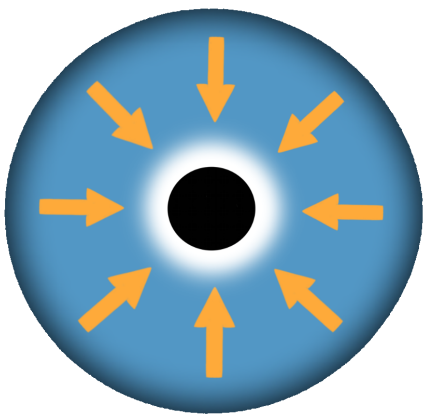

Chandra ≈ 0.5 arcsec

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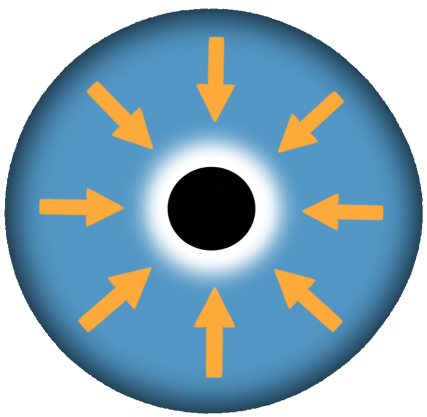

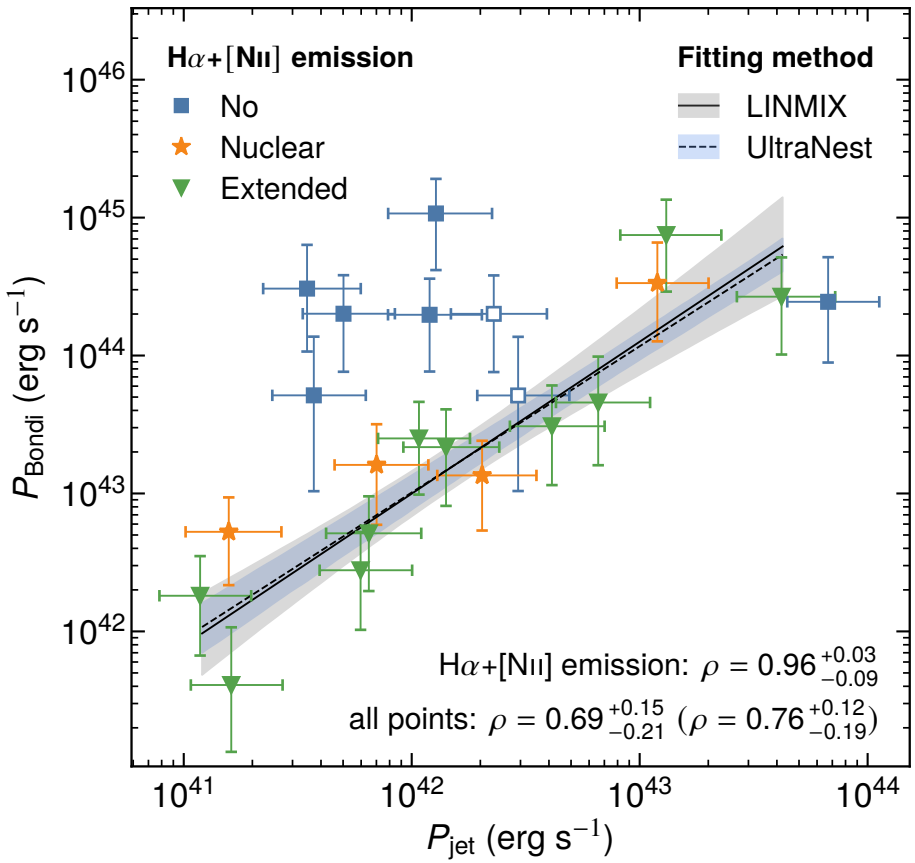

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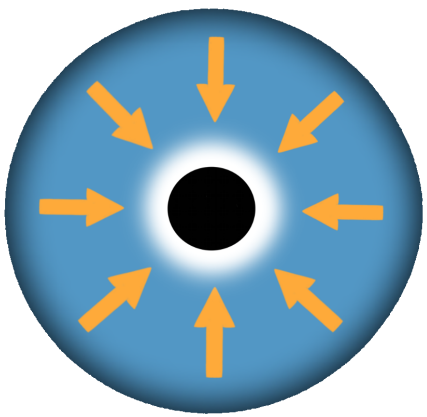
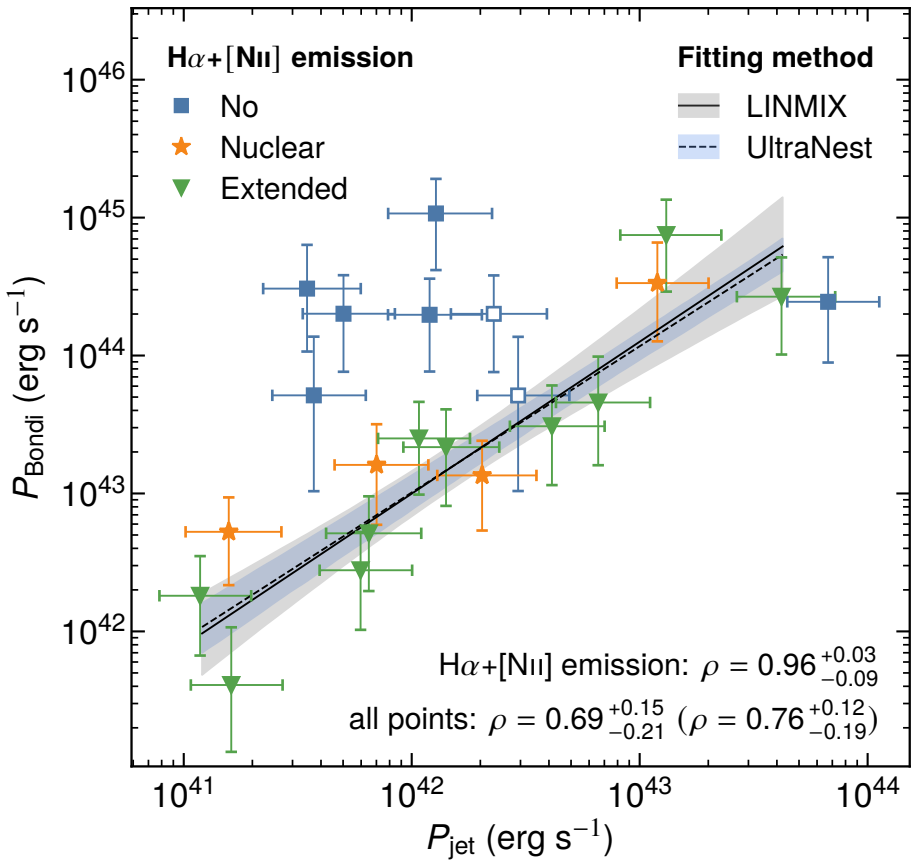


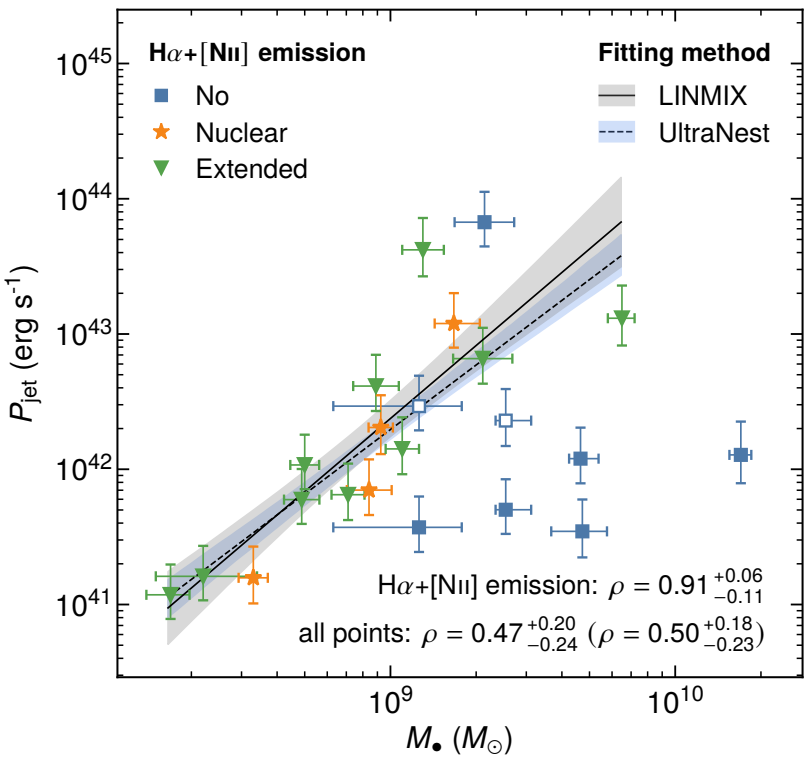
$$P_\mathrm{B} \propto P_\mathrm{jet}^{1.1\pm0.2} \qquad P_\mathrm{jet} \approx 0.01 \dot{m}_\mathrm{B} c^2$$



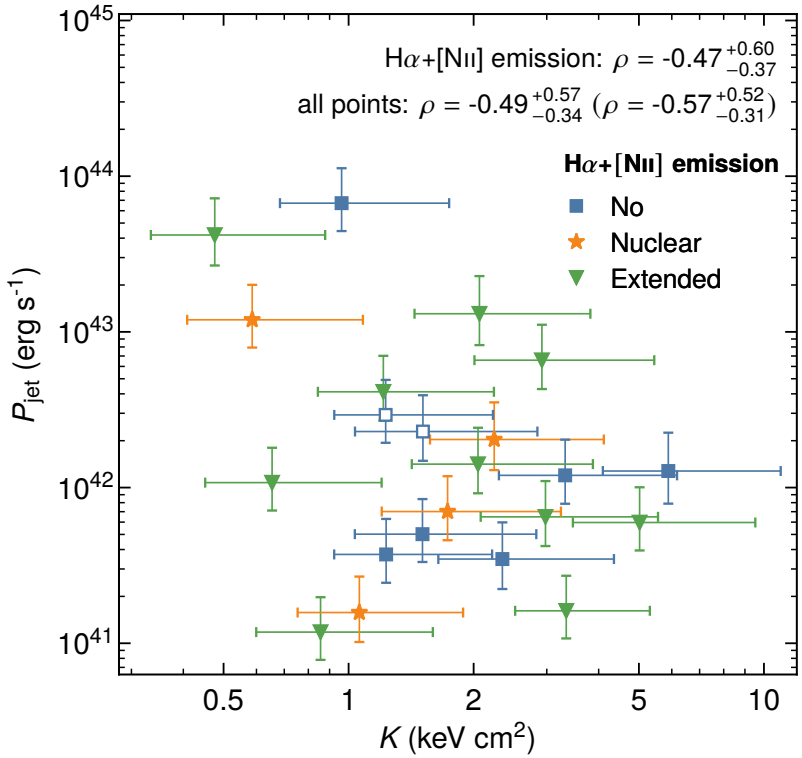
Underlying dependence on SMBH mass

$$P_{\rm B} \propto M_\bullet^2\, \rho\, kT^{-3/2} \propto M_\bullet^2\, K^{-2/3}$$

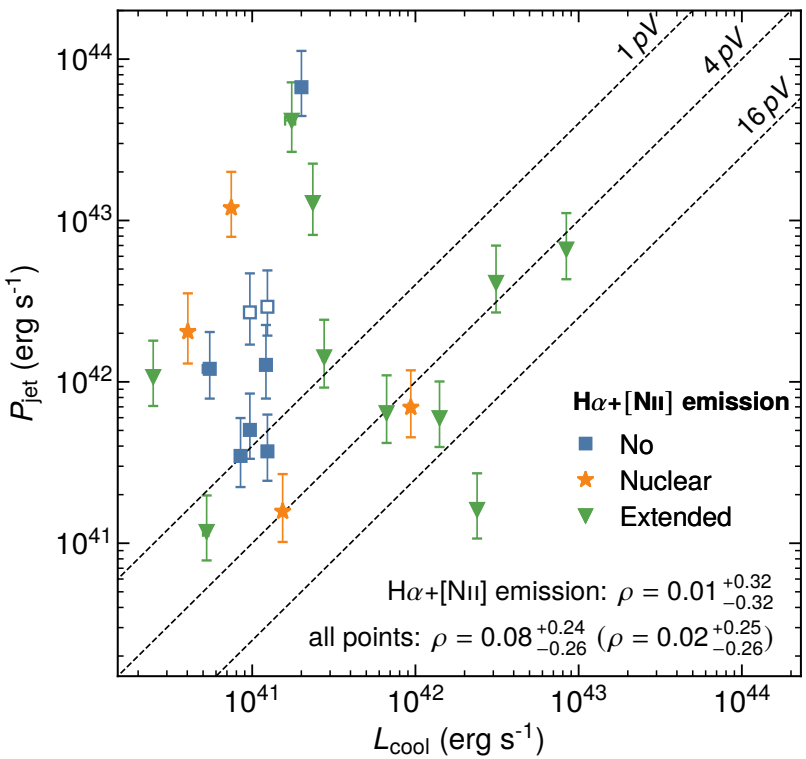
$$P_{\rm jet} \propto M_\bullet^{1.80\pm0.36}$$



$$P_{\rm jet} \neq f(K)$$



Lack of balance between heating and cooling?



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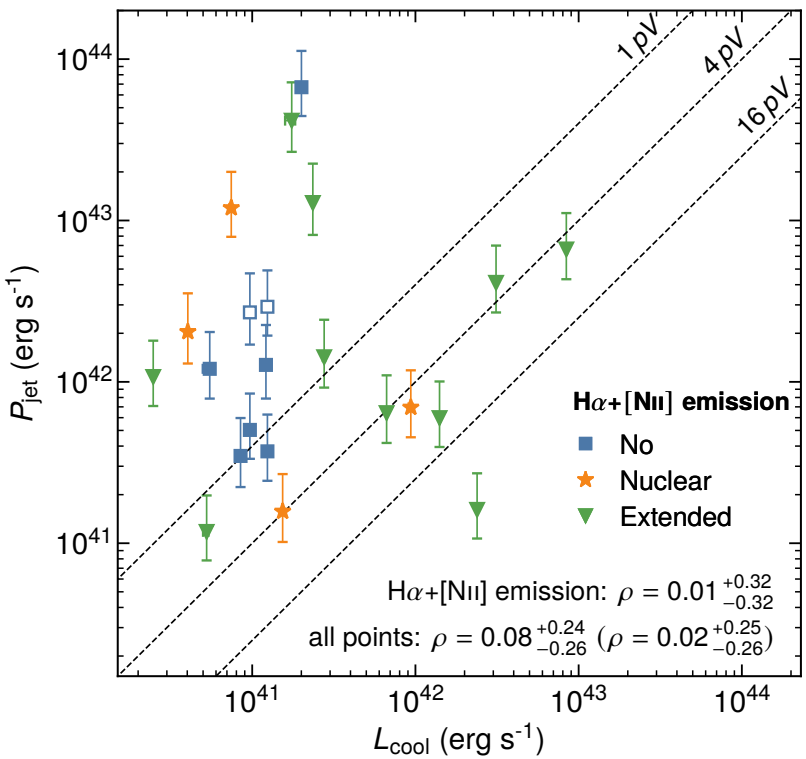
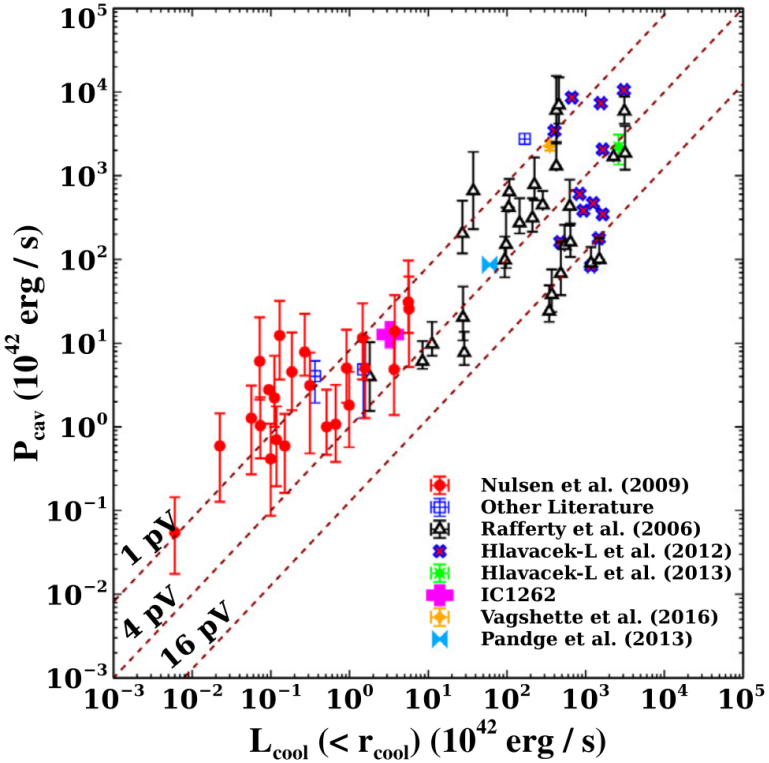




Extending the sample

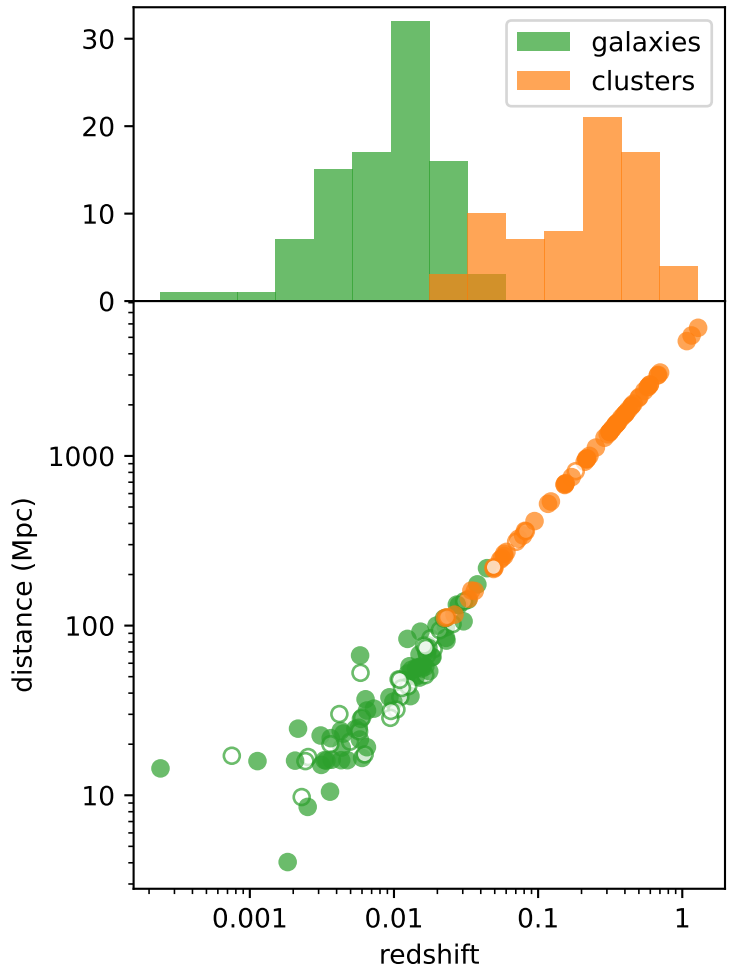
- archival *Chandra* data
- objects with known cavities
  - no strict selection criteria
  - not a duty cycle study
- planned:
  - 100 early-type galaxies

  \+ 60 galaxy clusters
- currently analyzed:

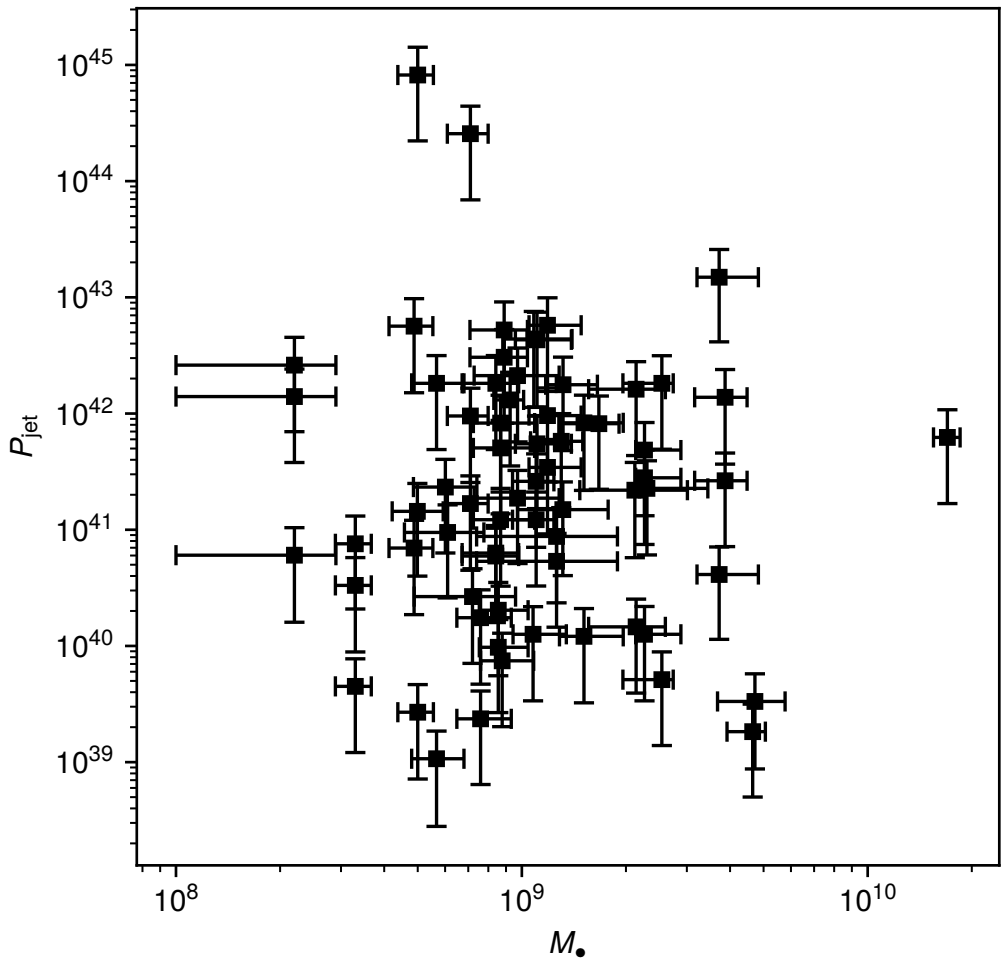
  $\approx$ 50 early-type galaxies

  $\rightarrow$ 80 X-ray cavities (CADET)

  \+ thermodynamic profiles



Preliminary results



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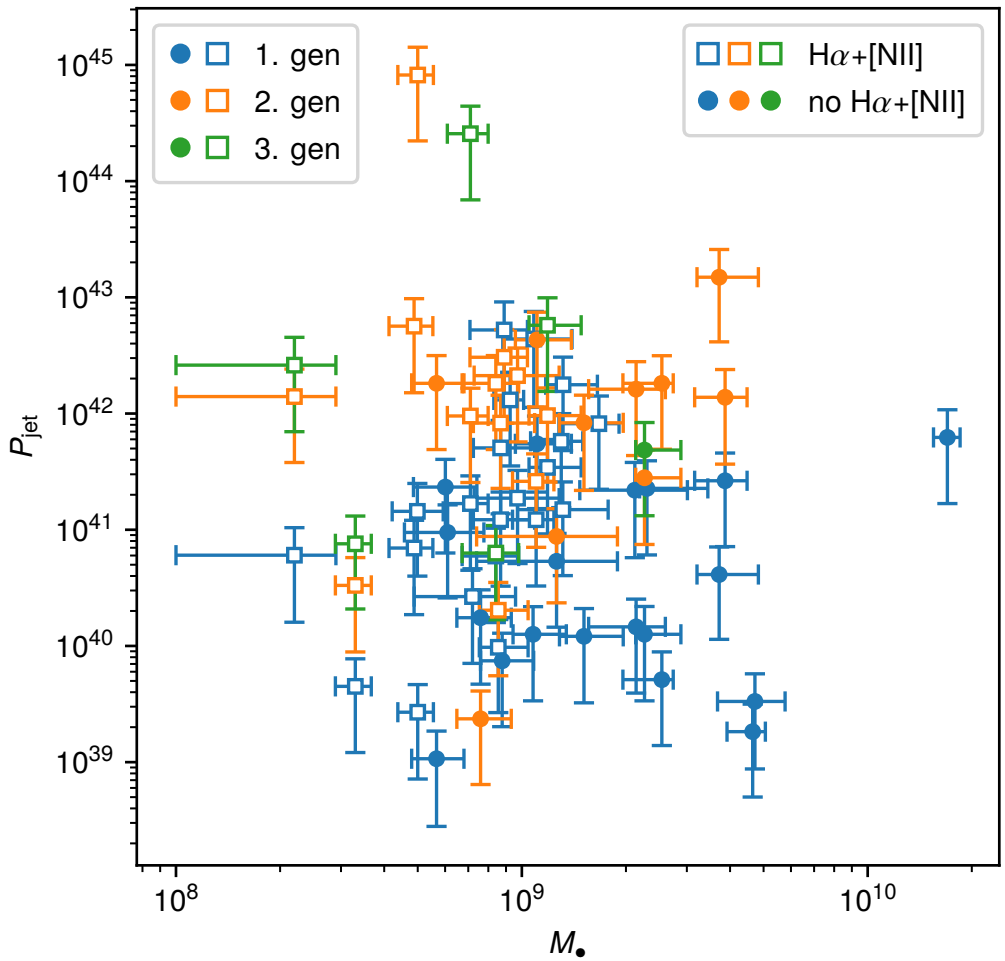

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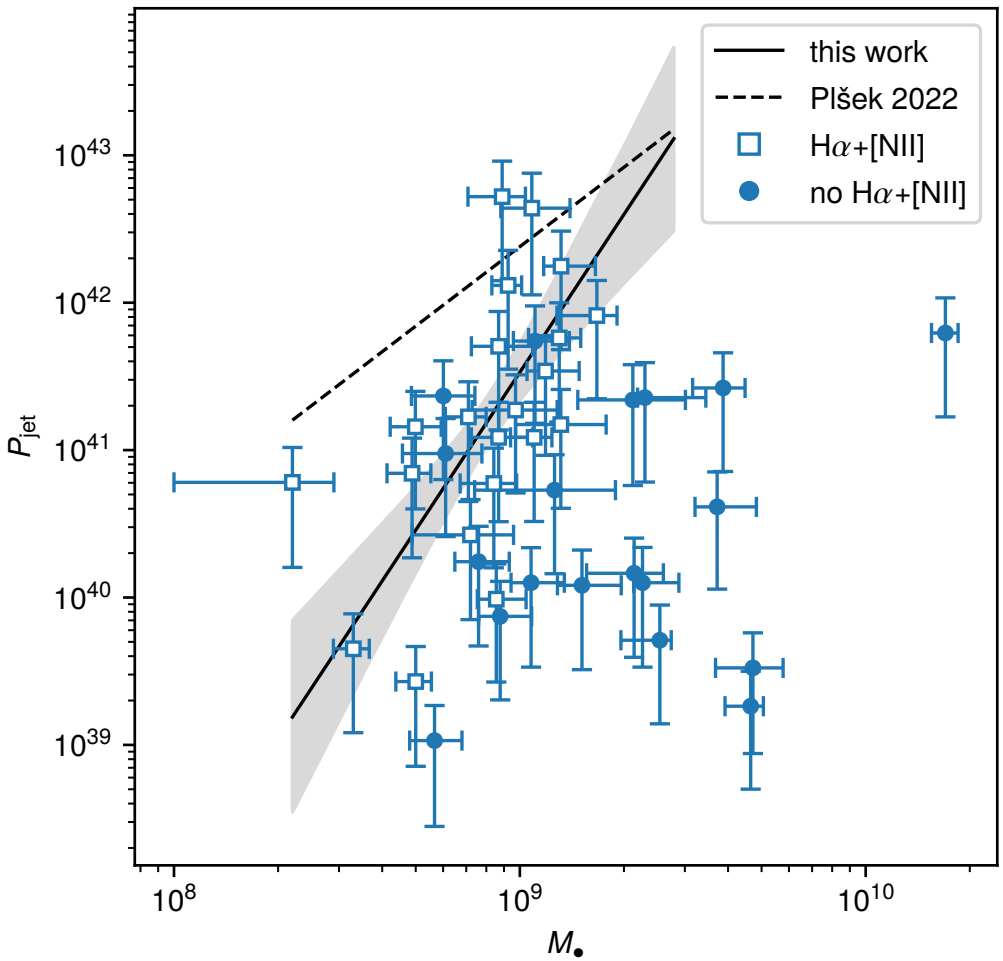
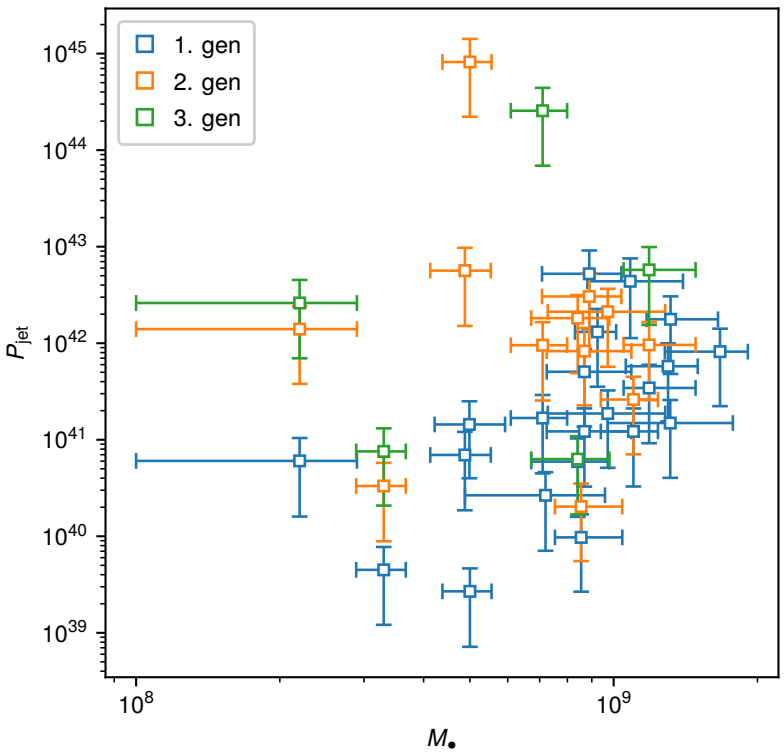
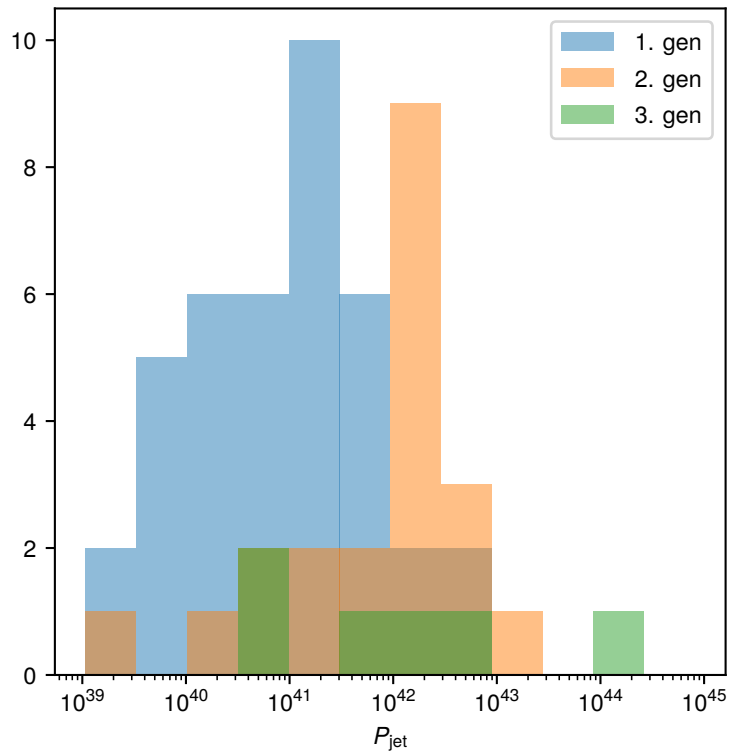


Preliminary results

projection effects?





Future work

- enlarge the sample ($\gtrsim$ 160 sources)
  - suggestions or cavity candidates?
- probe other properties
  - kT, M_{500}, L_X, K, thermal state of atmosphere (Hα)
  - L_{AGN}, galaxy morphology?
- large X-ray cavity sample statistics
  - general characteristics
  - cavity flattening, positional/rotational angles
  - jet precession (on big timescales)?