MASARYK UNIVERSITY

Studying radio-mechanical AGN feedback with X-ray cavities

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AGN feedback

quasar (wind) mode

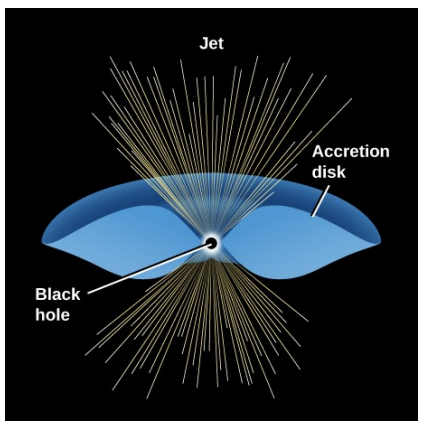
- geometrically thin disk
- optically thick
- radiatively efficient

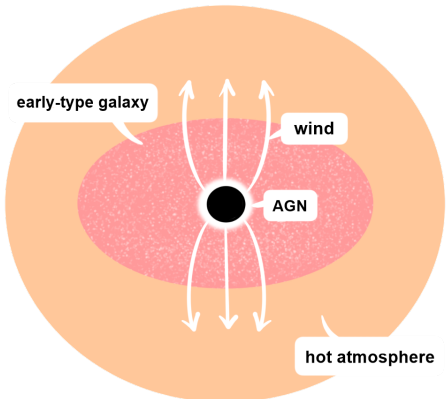
  $\rightarrow$ EM radiation
- all galaxy types

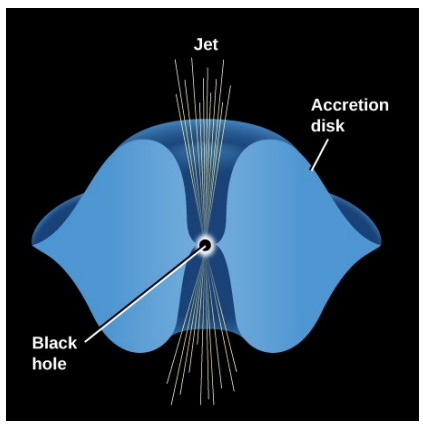
radio-mechanical mode

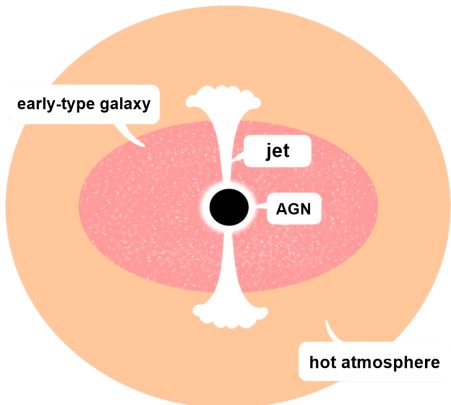
- geometrically thick torus
- optically thin
- radiatively inefficient (ADAF)

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









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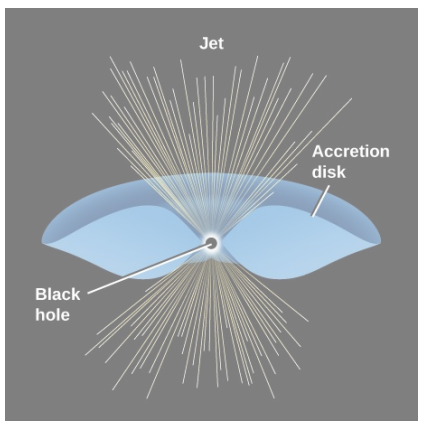
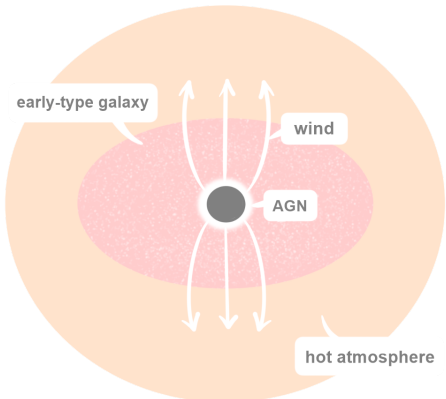
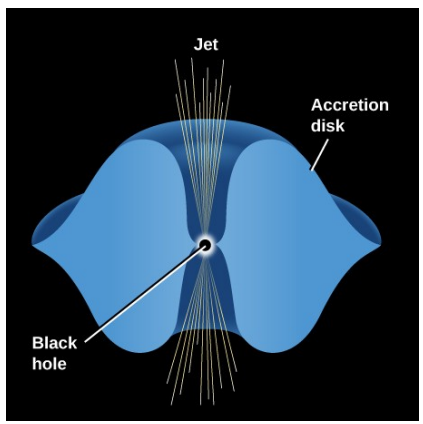
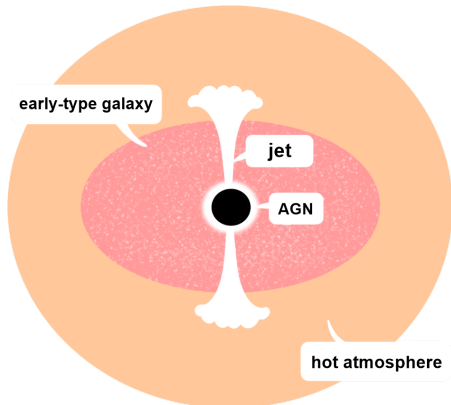




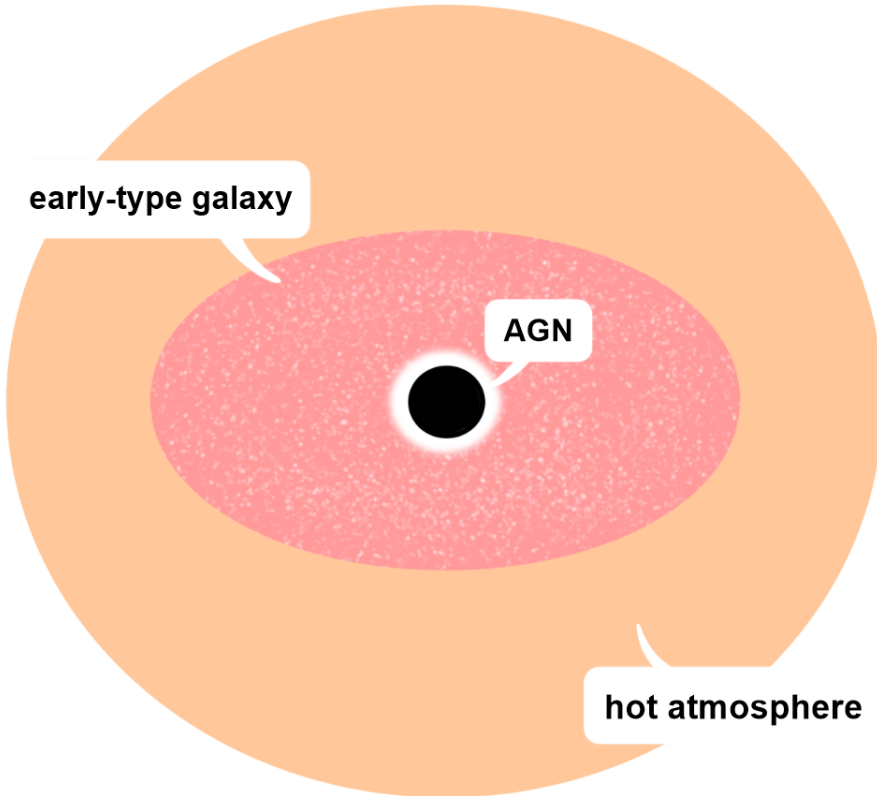




Early-type galaxies

- elliptical & lenticular galaxies
  - **red & dead** (SFR $\lesssim 1\,M_\odot yr^{-1}$)
  - total mass $> 10^{12} M_\odot$

  $\rightarrow$ hot atmospheres



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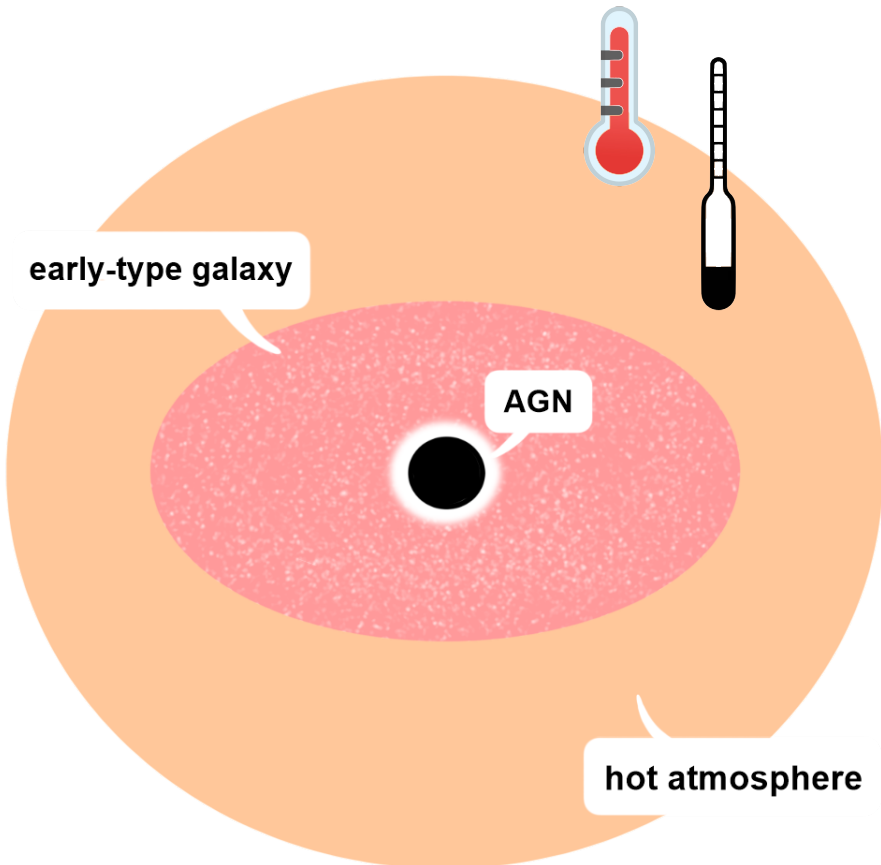
- hot & diffuse plasma
  - temperature $\approx 10^7$ K
  - electron density < 1 cm^{-3}

  $\sim$ 80% of all **baryons**



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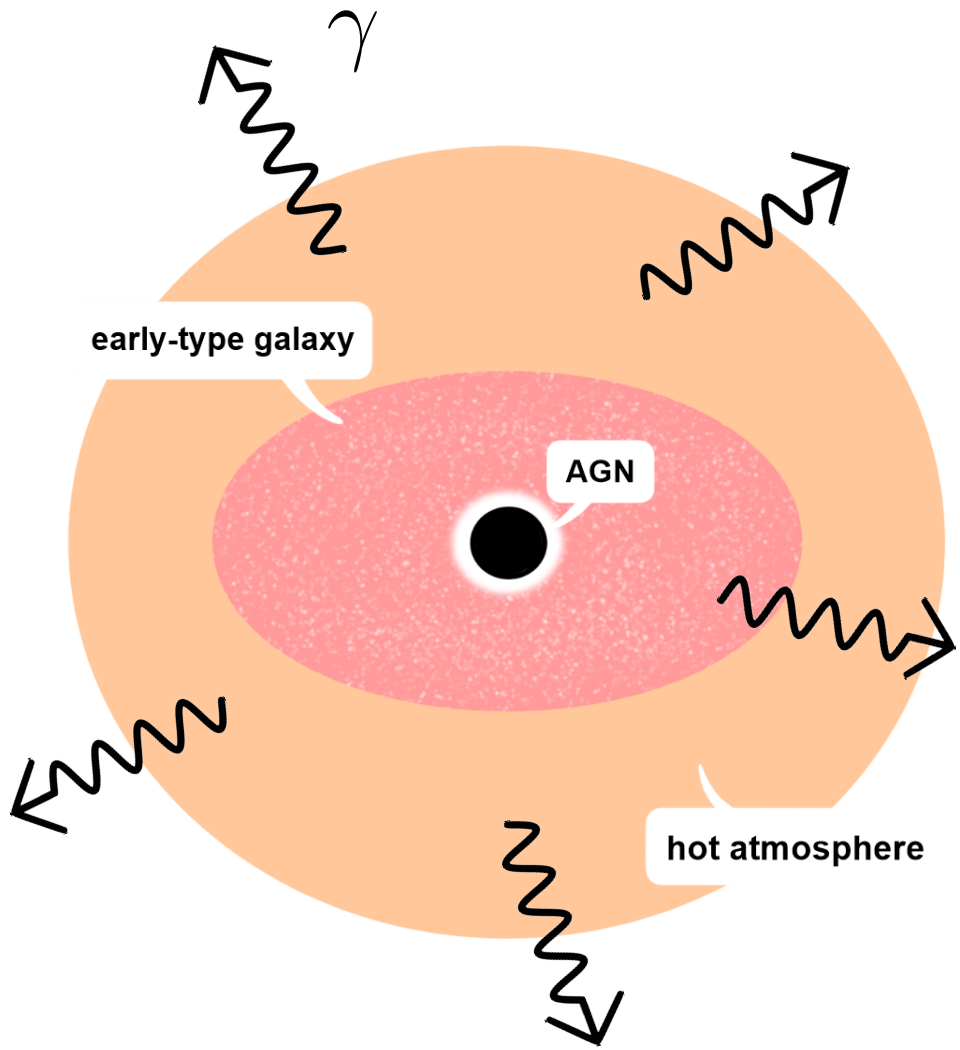

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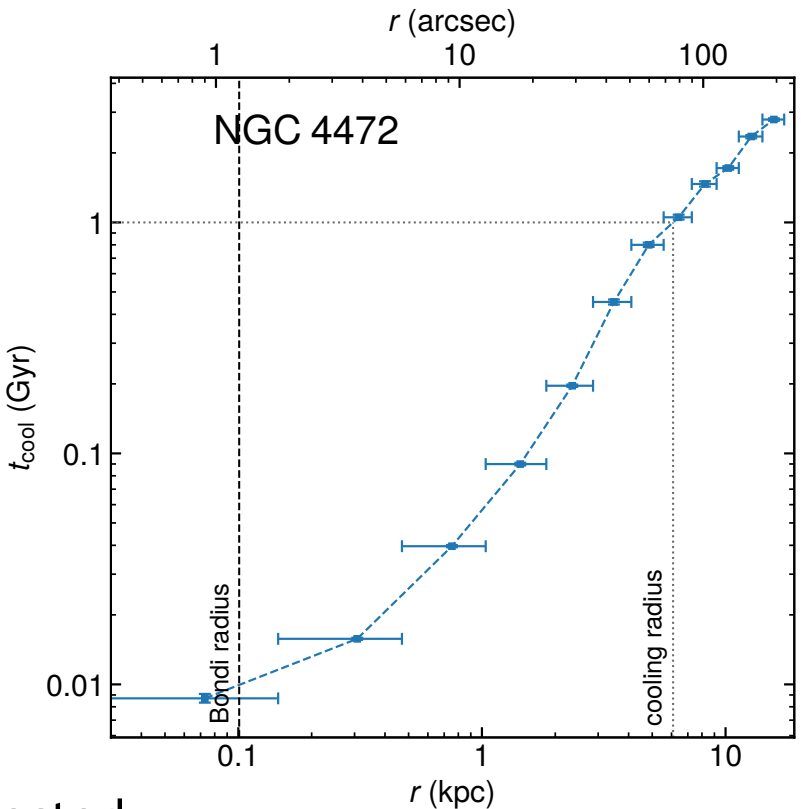
- hot $\rightarrow$ emit X-rays

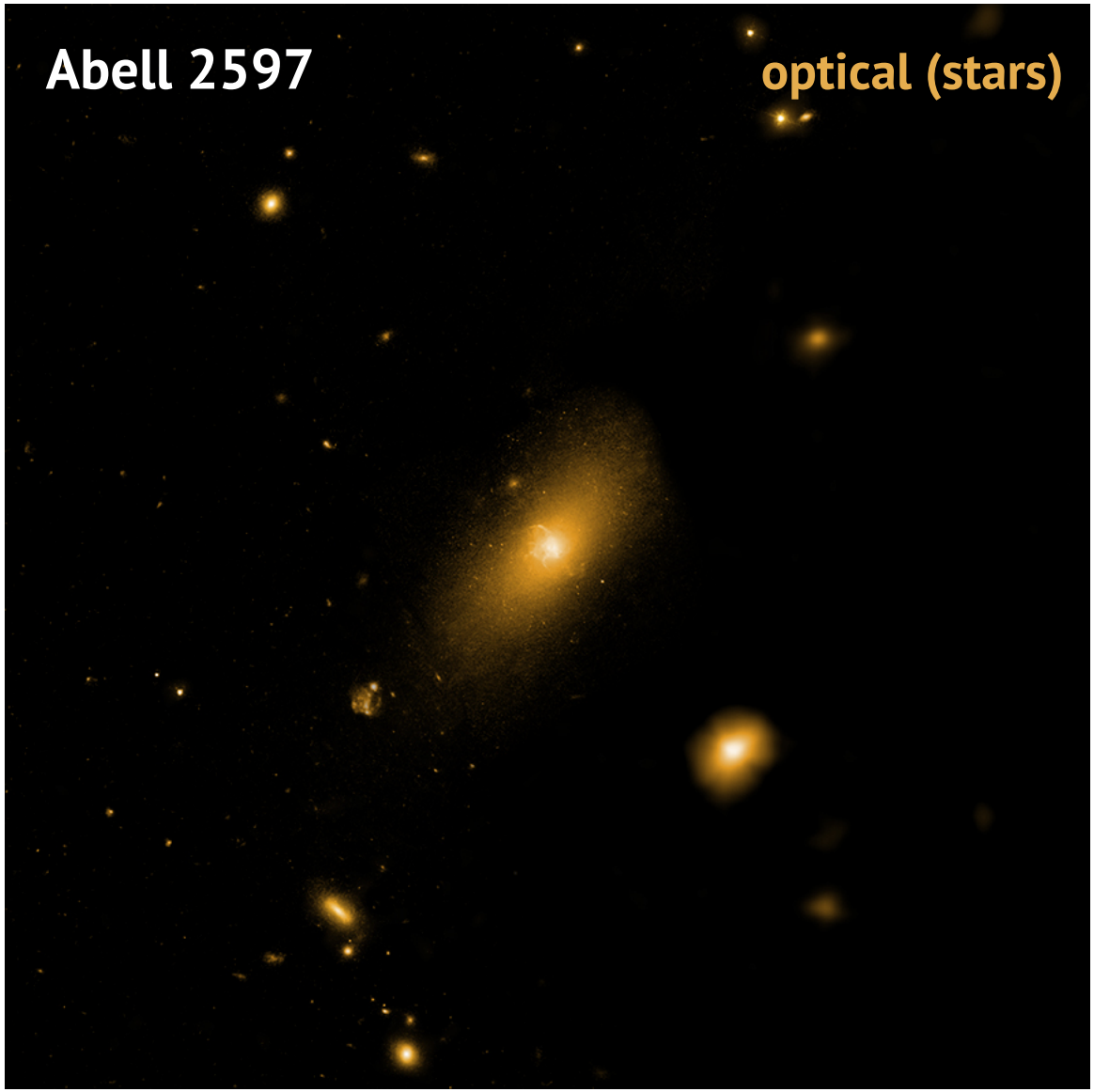
  $\rightarrow$ **cool radiatively** (t_{cool})

  $\rightarrow$ cold gas (Hα, CO) - less than expected

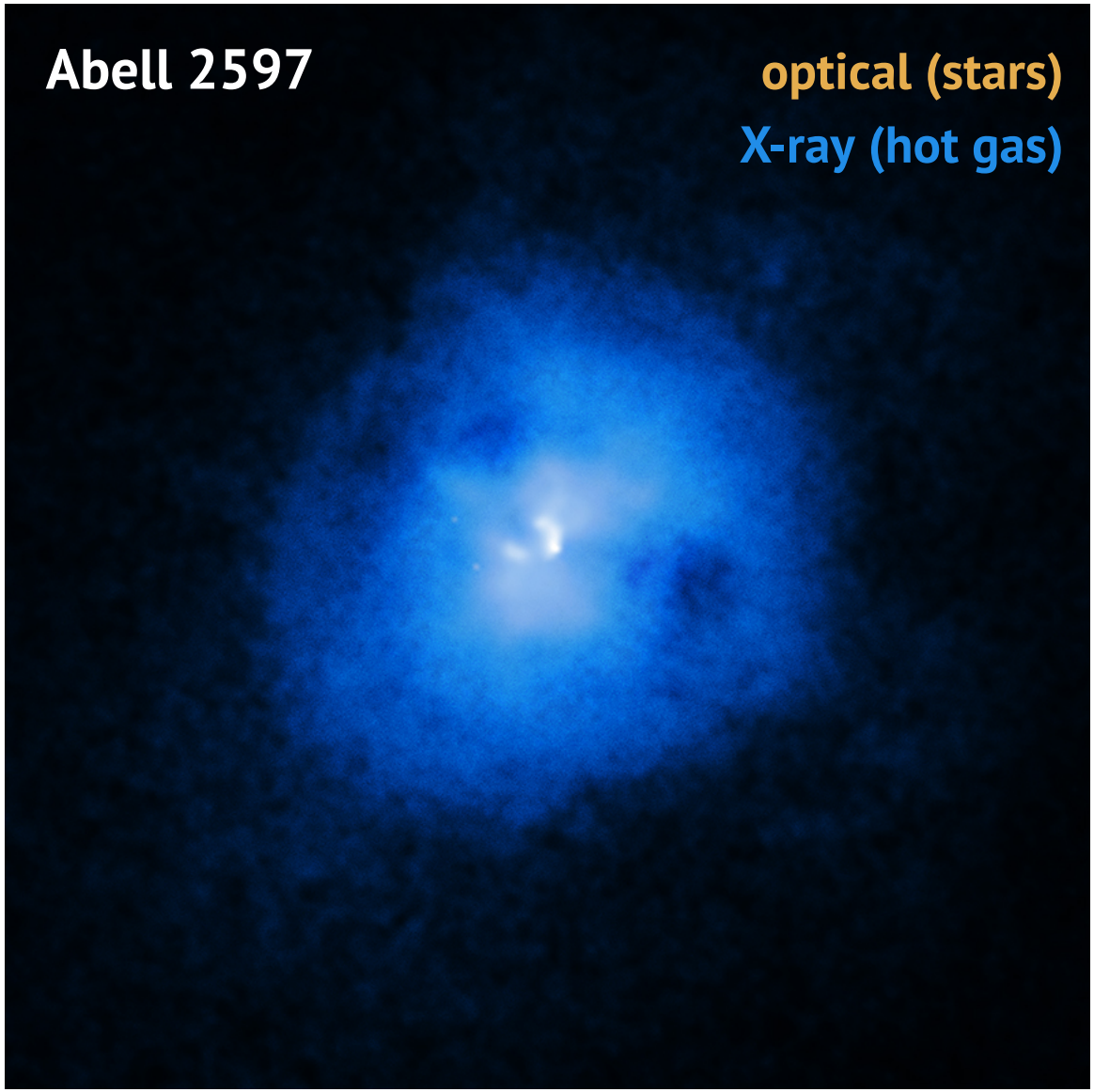
$$t_{cool} = \frac{\frac{3}{2}nkT}{L_X} \propto \frac{kT}{n}$$



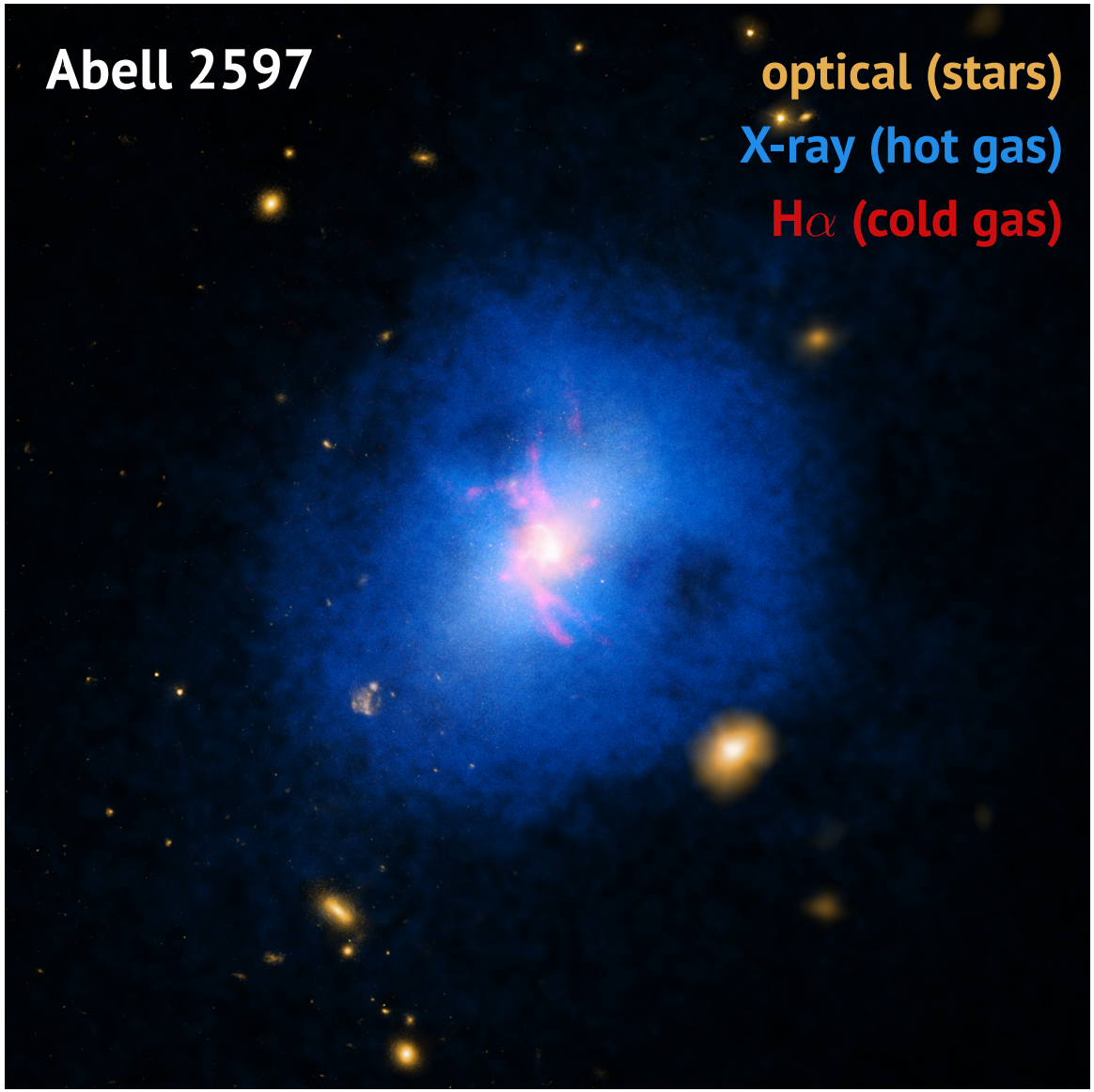
Early-type galaxies



Early-type galaxies



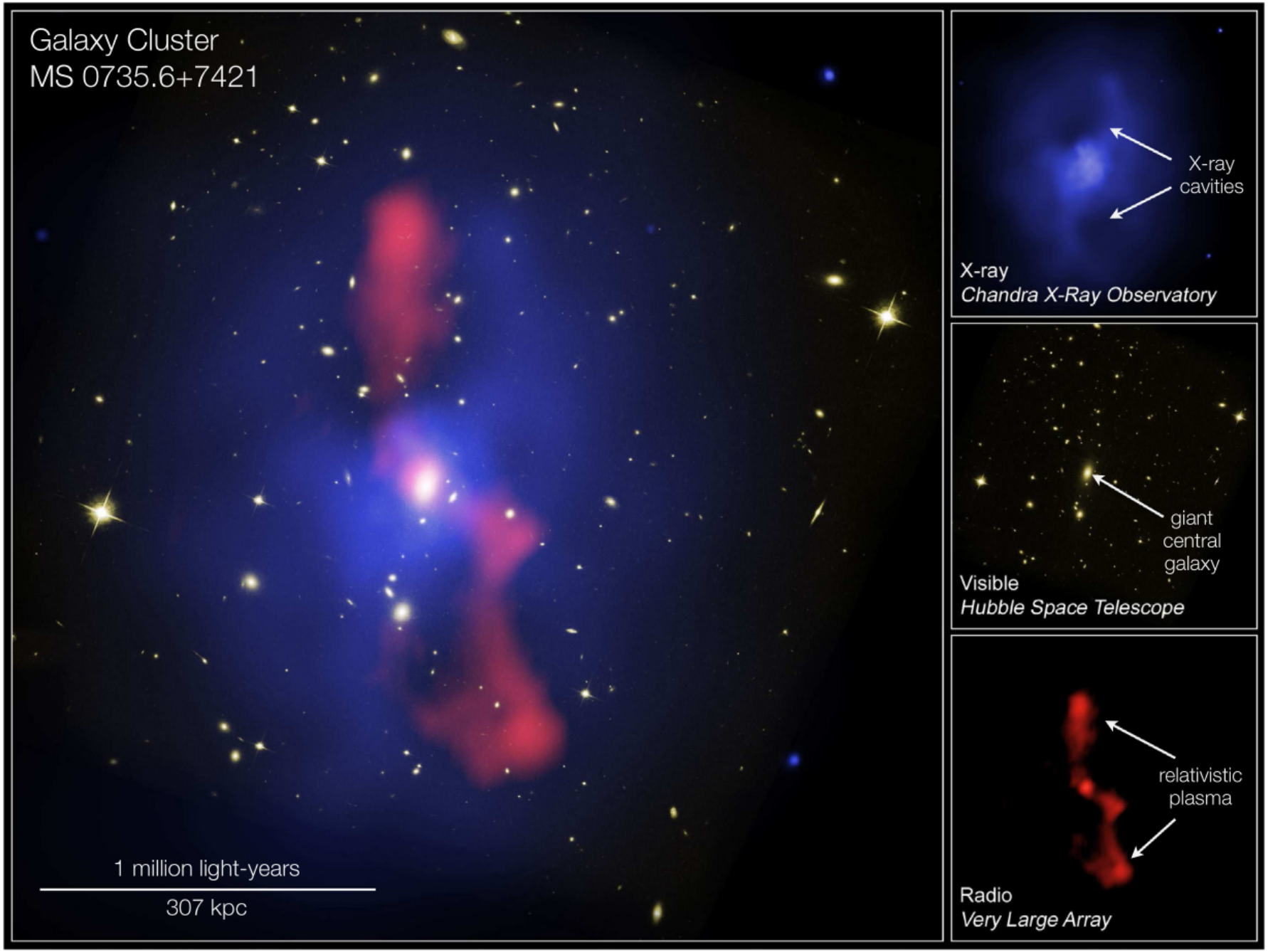
Early-type galaxies



Radio-mechanical AGN feedback

- relativistic jets $\rightarrow$ radio lobes
  - interact with hot gas

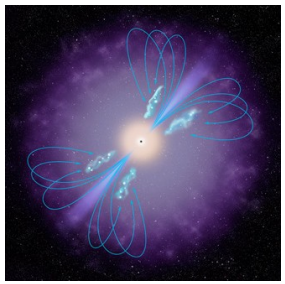
  $\rightarrow$ **X-ray cavities**

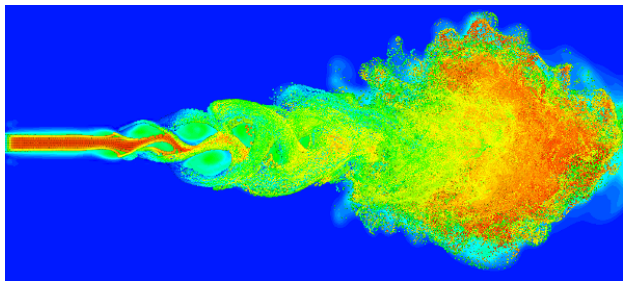

Galaxy Cluster
MS 0735.6+7421
1 million light-years
307 kpc
X-ray
cavities
X-ray
Chandra X-Ray Observatory
giant
central
galaxy
Visible
Hubble Space Telescope
relativistic
plasma
Radio
Very Large Array

Radio-mechanical AGN feedback

- relativistic jets $\rightarrow$ radio lobes
  - interact with hot gas

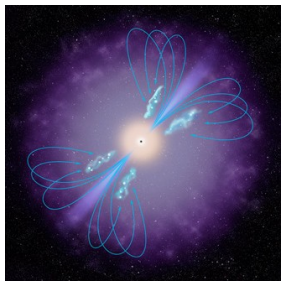
  $\rightarrow$ **X-ray cavities**
- uplifts low-entropy gas
  - **locally can trigger SF**
- deposits E on kpc—Mpc scale
  - turbulent flows, bulk motions
  - sound and shock waves

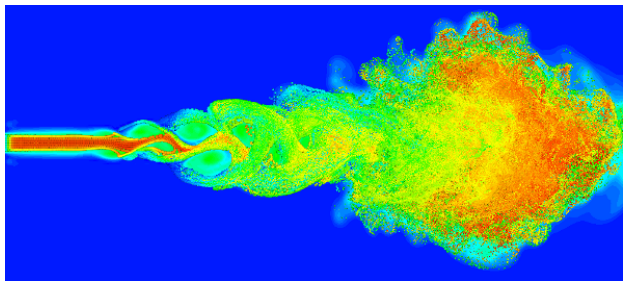


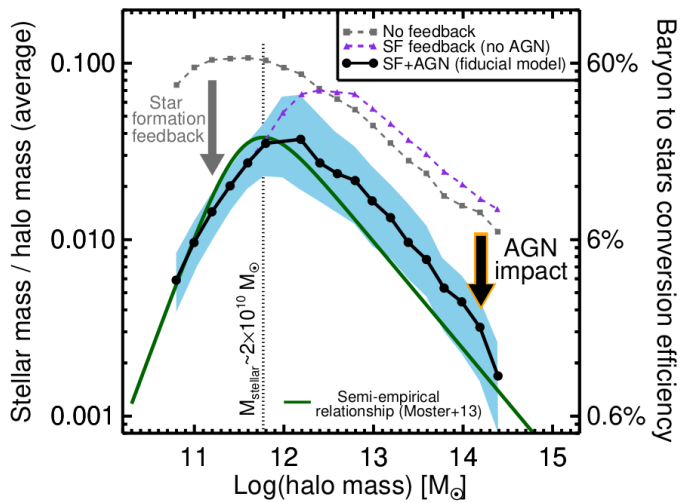


Radio-mechanical AGN feedback

- relativistic jets $\rightarrow$ radio lobes
  - interact with hot gas
  - $\rightarrow$ **X-ray cavities**
- uplifts low-entropy gas
  - **locally can trigger SF**
- deposits *E* on kpc—Mpc scale
  - turbulent flows, bulk motions
  - sound and shock waves
- heats the galactic atmosphere
  - **prevents star formation**
  - regulates further accretion

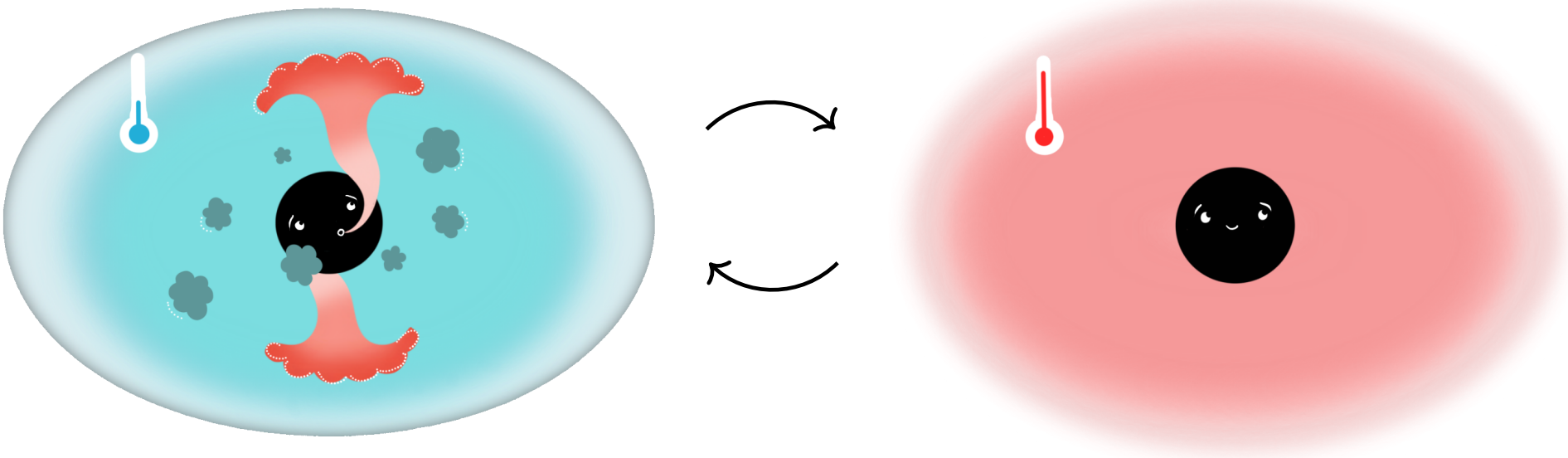






Radio-mechanical AGN feedback loop

gas cools



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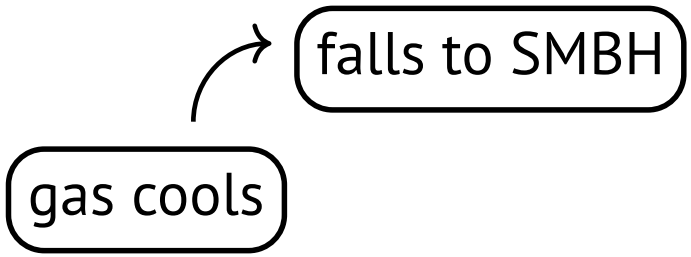
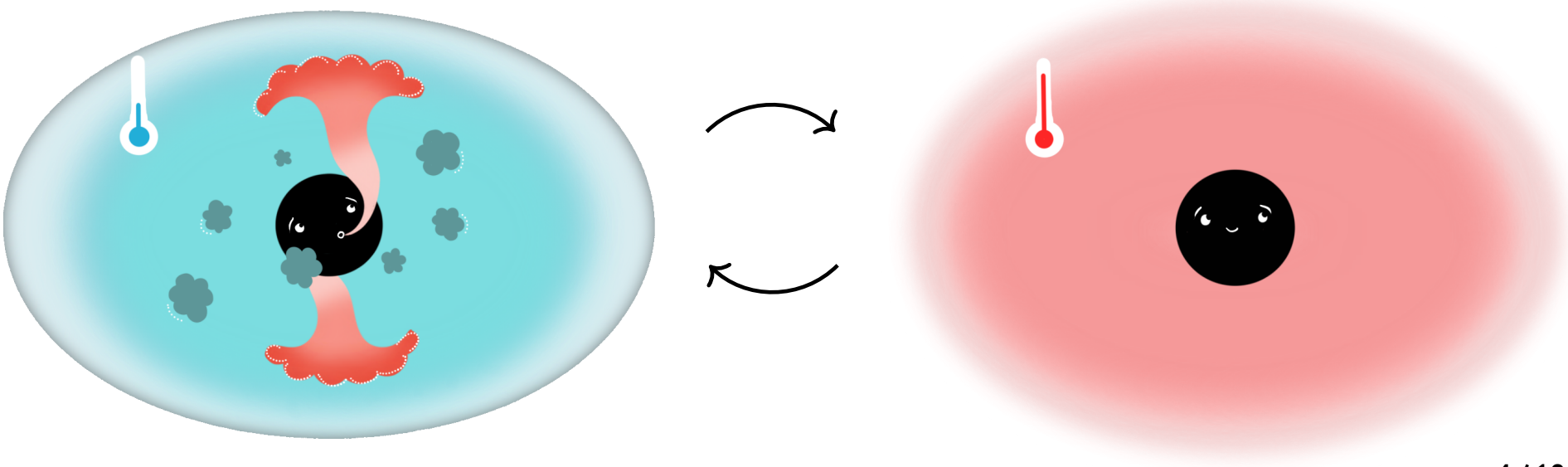
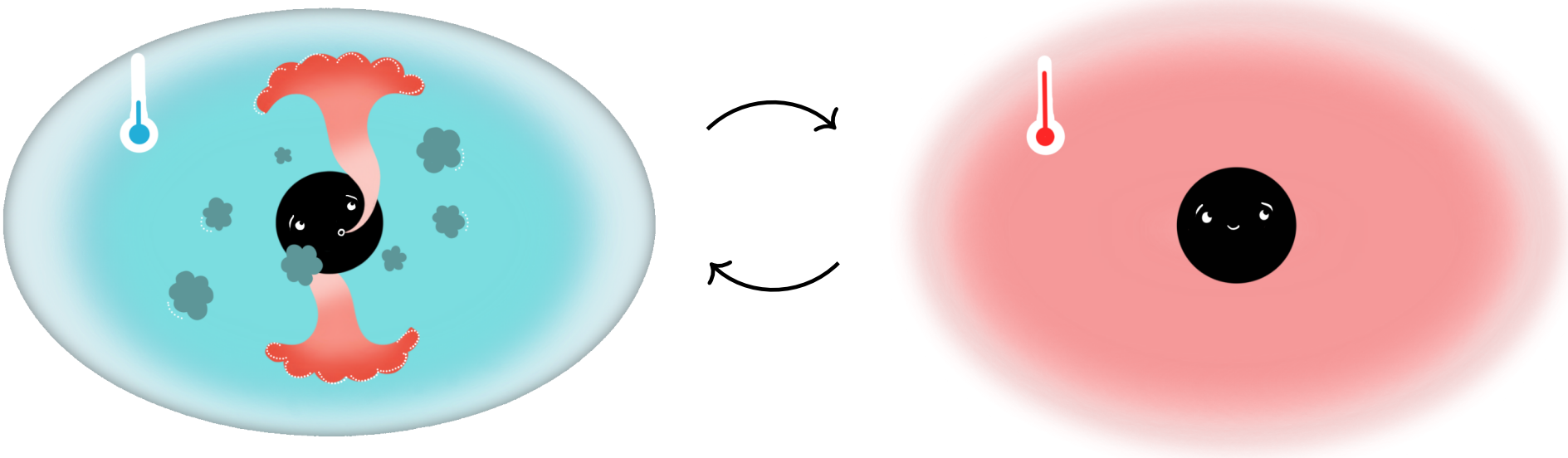




Radio-mechanical AGN feedback loop

gas cools → falls to SMBH → active jets



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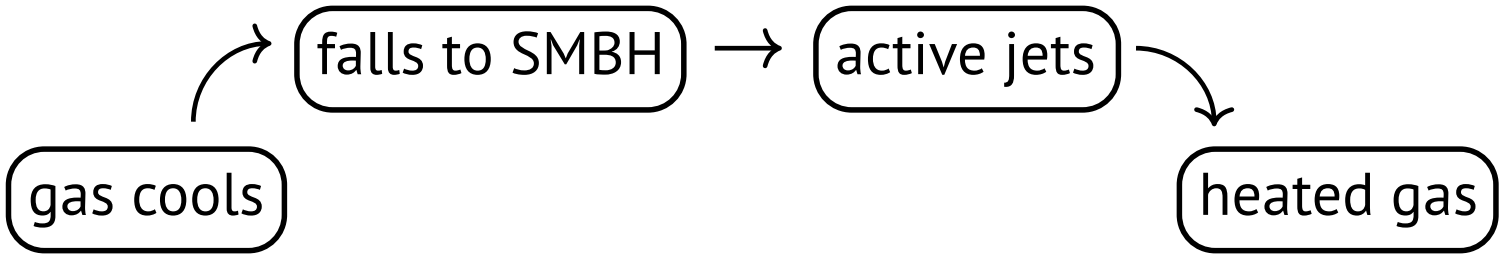

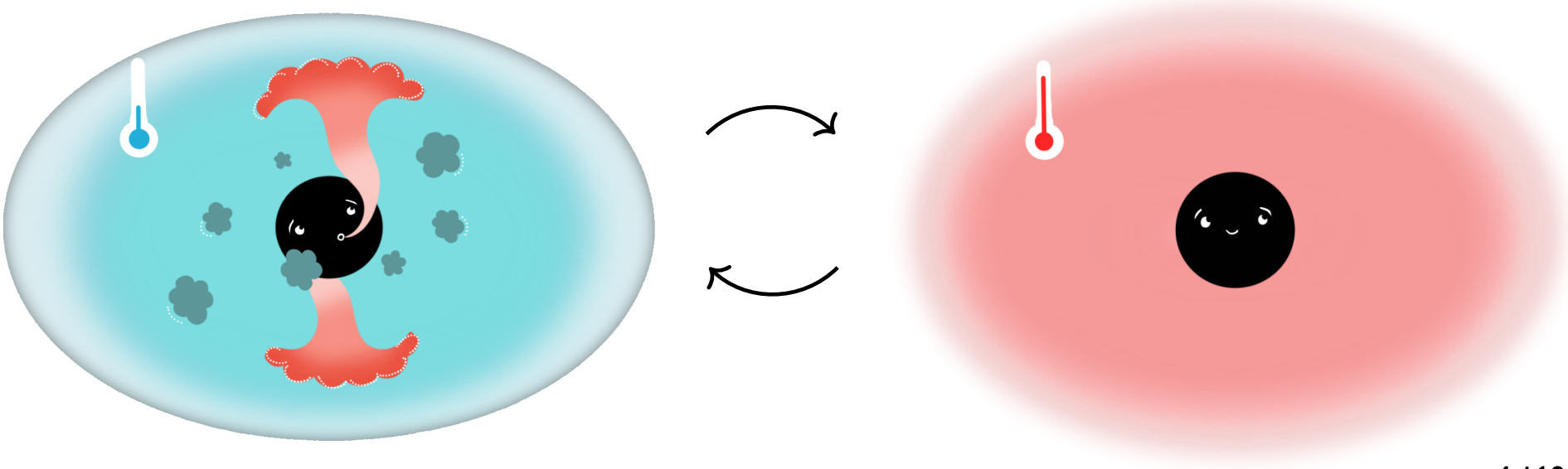

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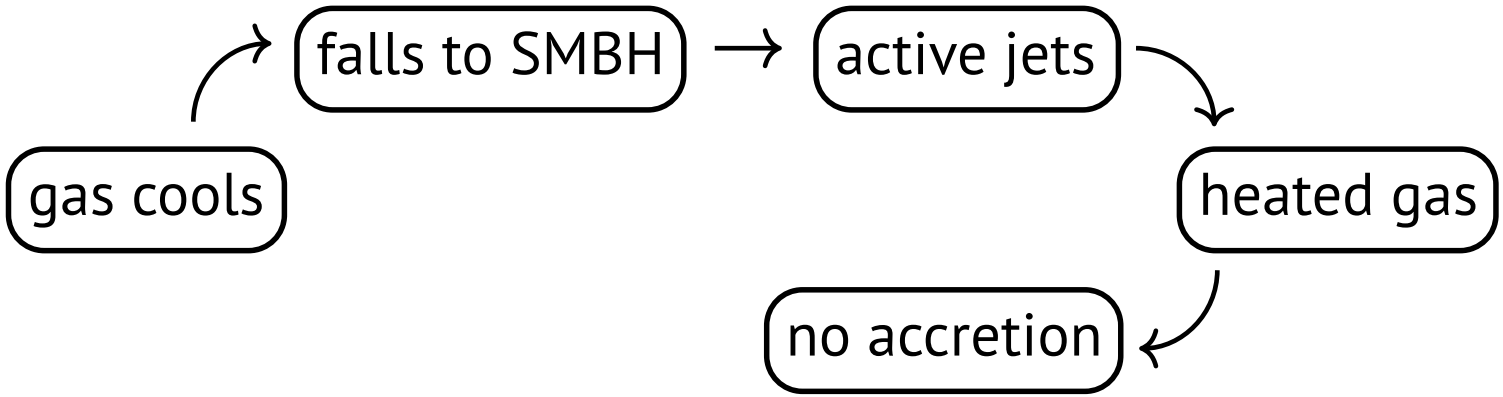

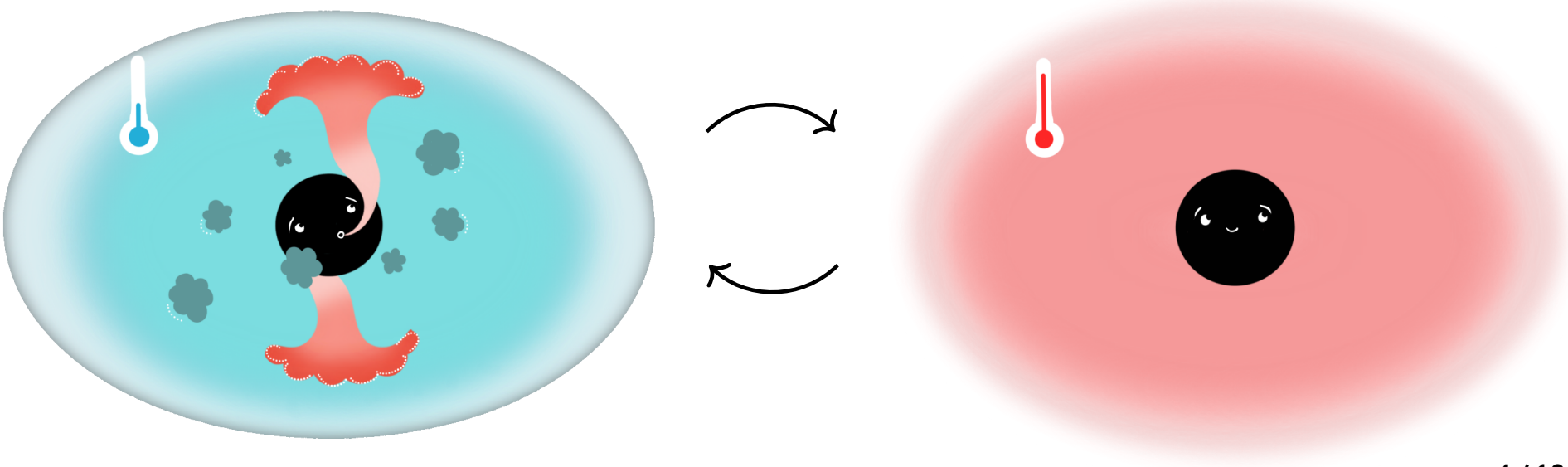

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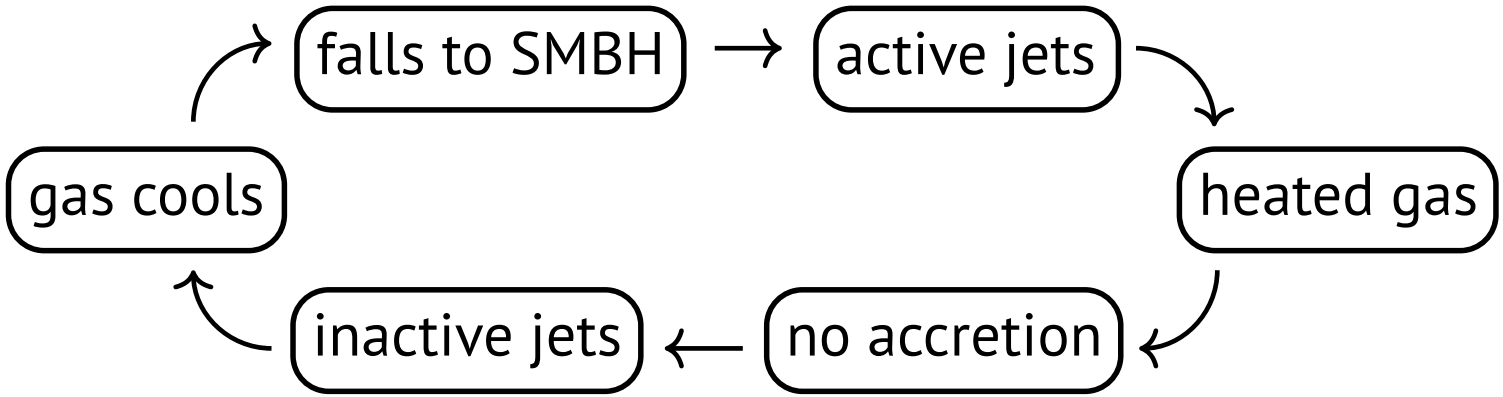
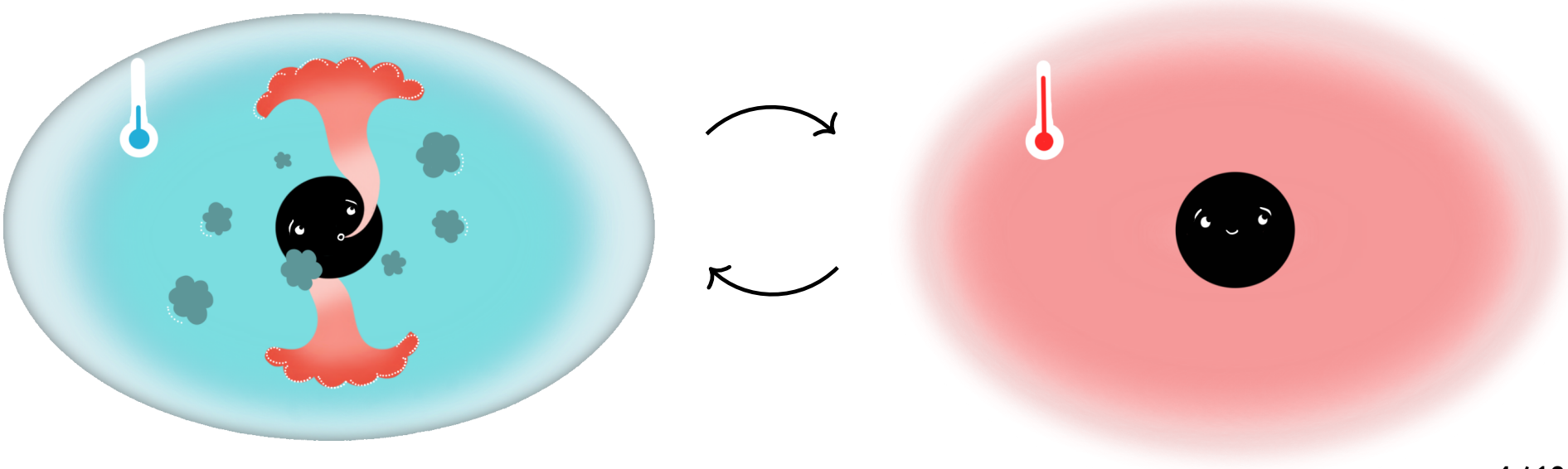
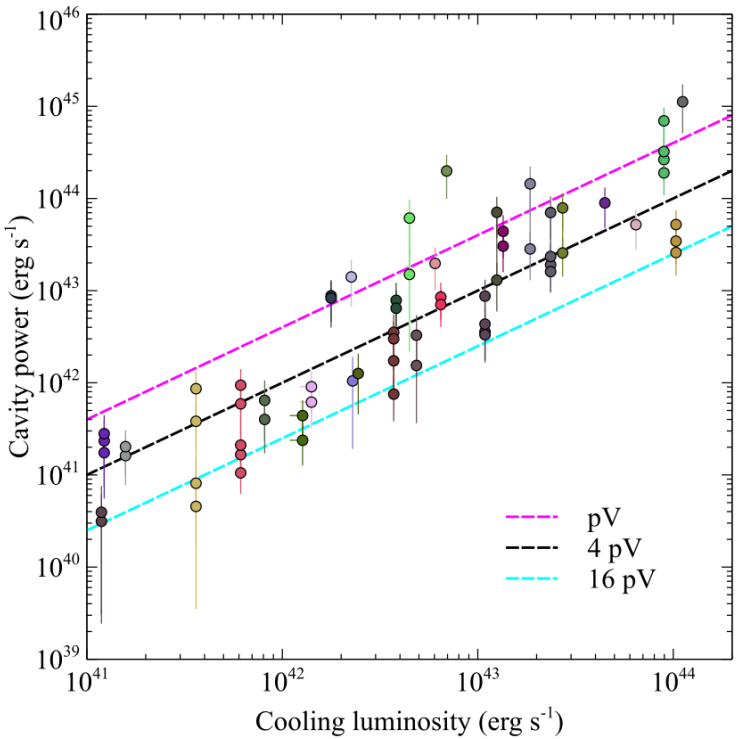




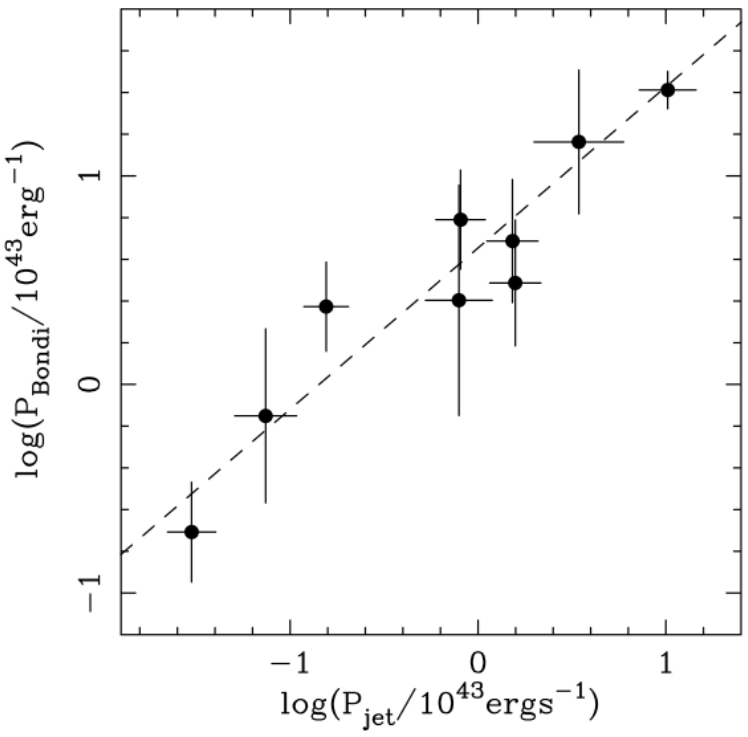
Radio-mechanical AGN feedback loop

hot atmosphere



Credit: Panagoulia et al. 2014

central engine



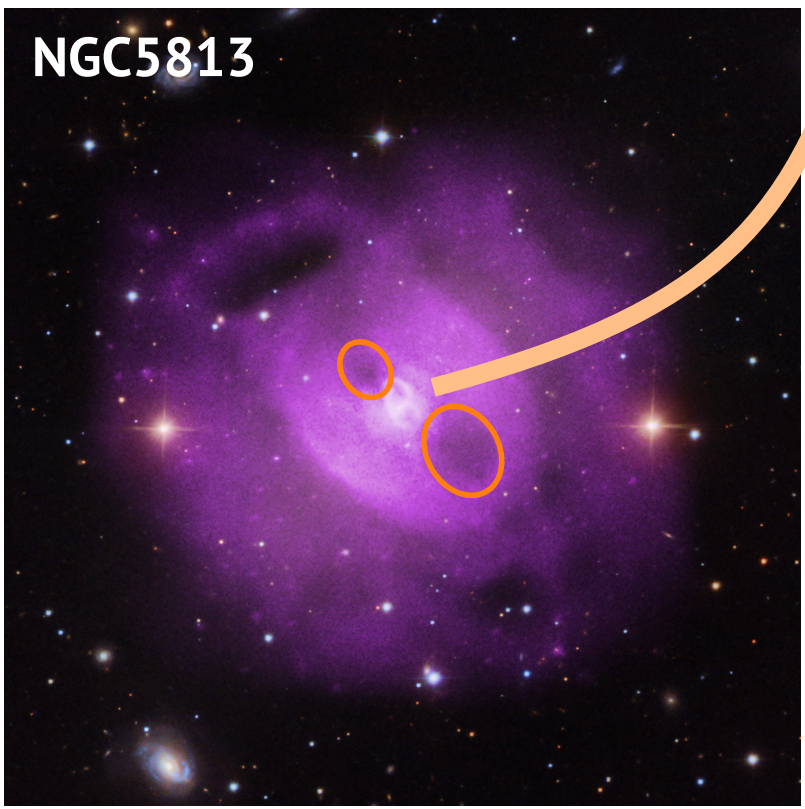
Credit: Allen et al. 2006

Studying AGN feedback with X-ray cavities

Credit: Randall et al. 2015

Studying AGN feedback with X-ray cavities

$$E \approx V \times p$$



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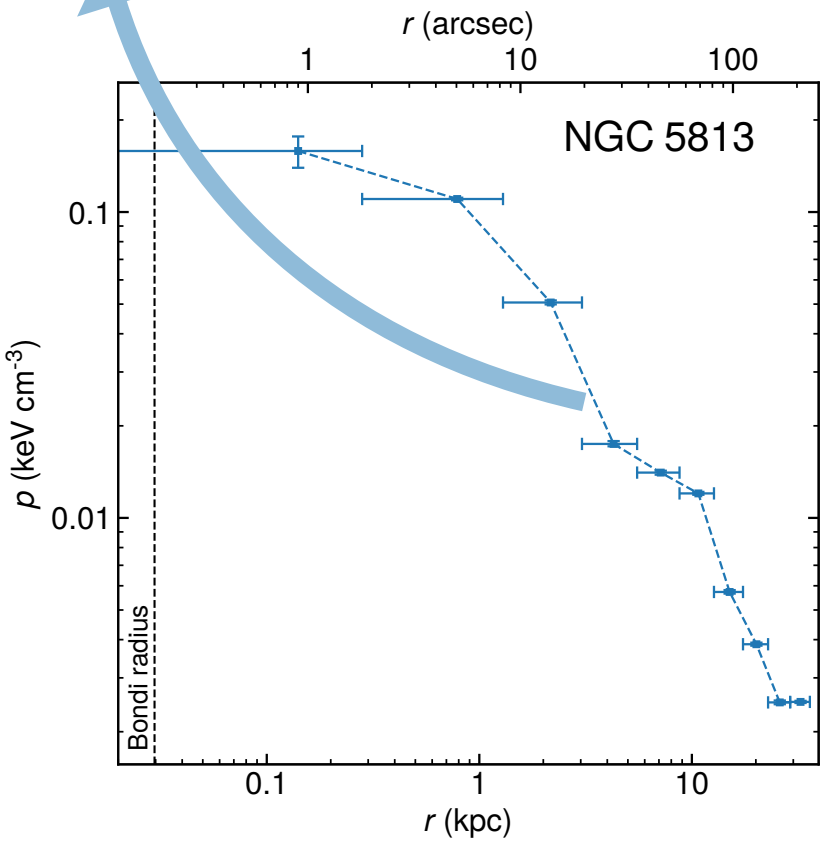
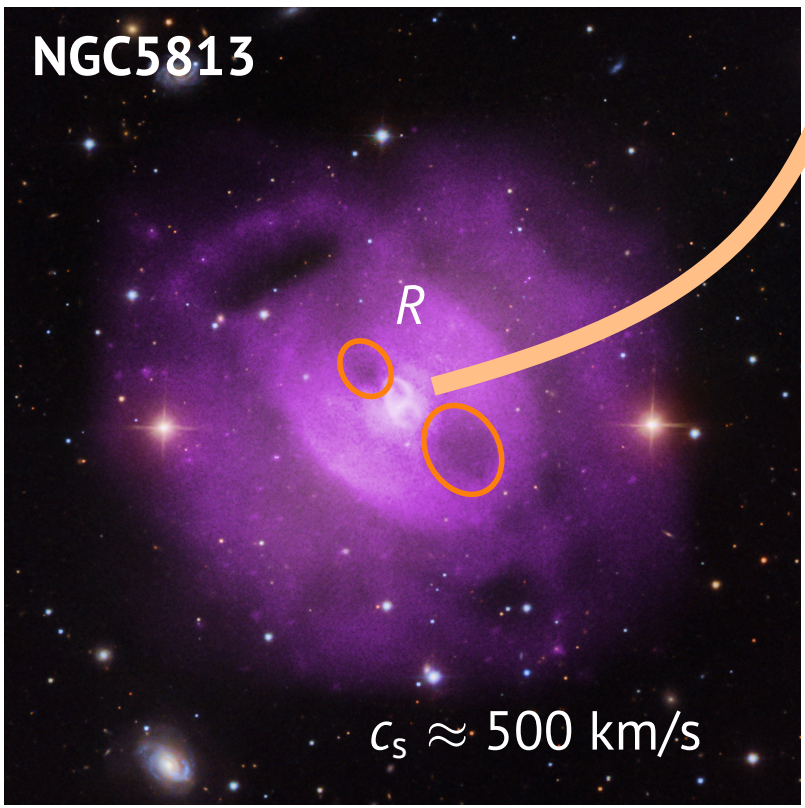


Credit: Plšek et al. 2022

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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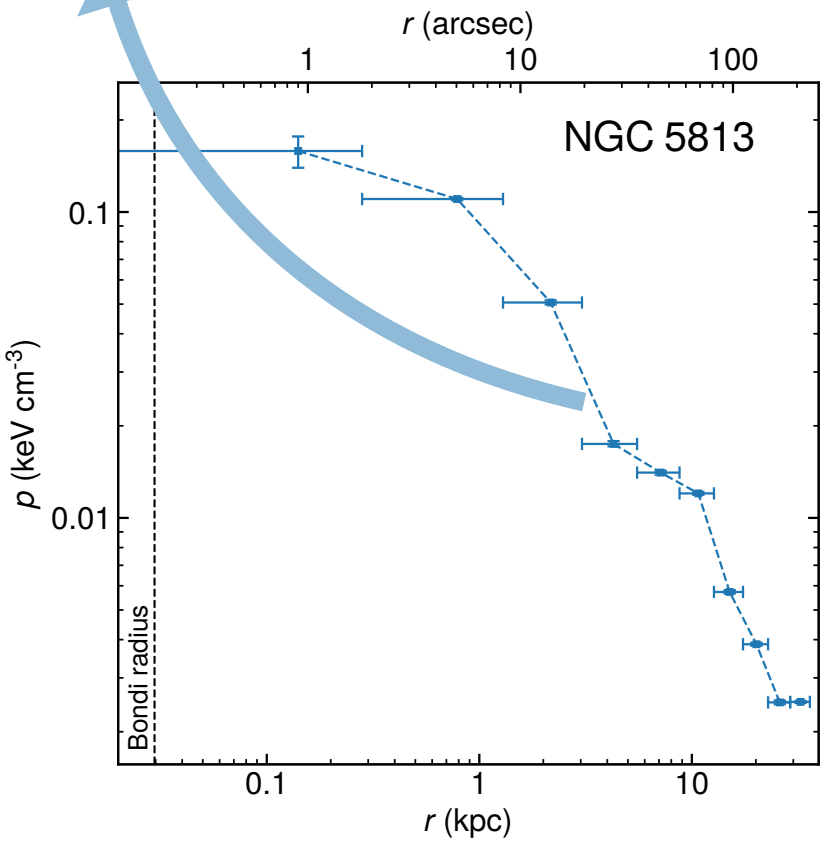


Credit: Plšek et al. 2022

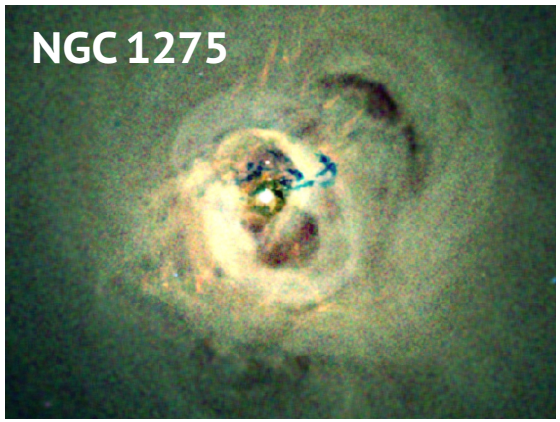
Broad range of jet powers

galaxies/groups

$R \approx 1$ kpc

$P_{\text{jet}} \approx 10^{42}$ erg/s

$M_{\text{displaced}} \approx 10^{8}$ $M_{\odot}$

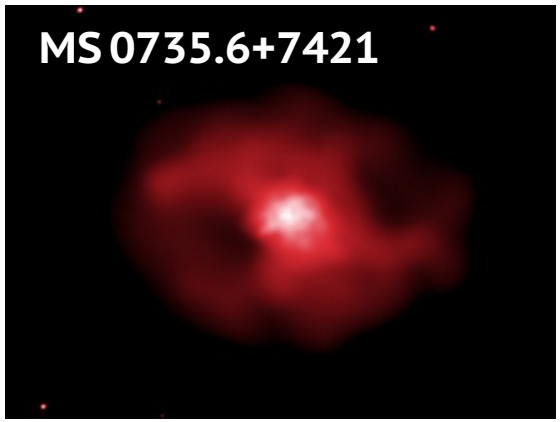


brightest cluster galaxies

$R \approx 10$ kpc

$P_{\text{jet}} \approx 10^{44}$ erg/s

$M_{\text{displaced}} \approx 10^{10}$ $M_{\odot}$



galaxy clusters

$R \approx 100$ kpc

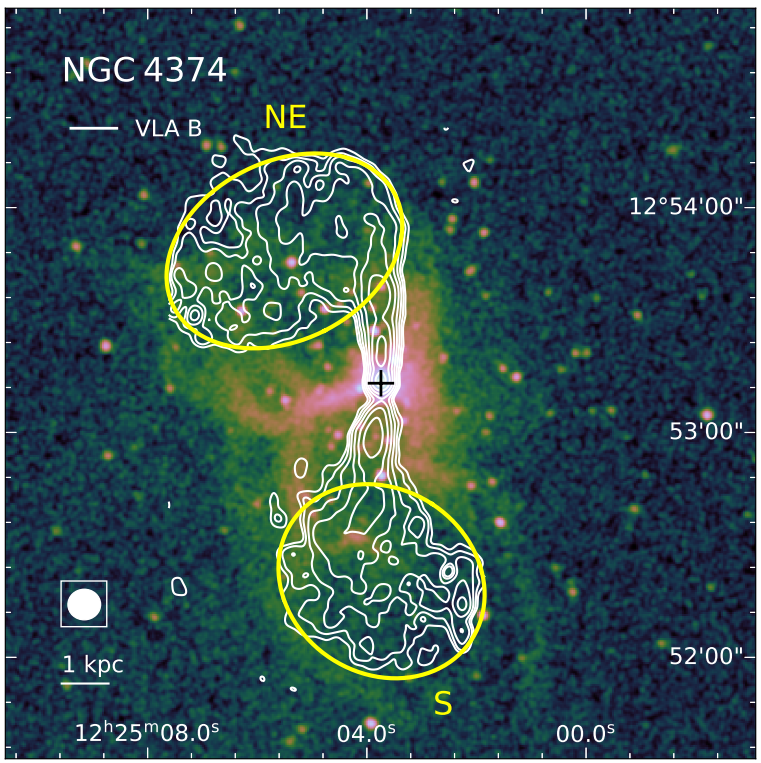
$P_{\text{jet}} \approx 10^{46}$ erg/s

$M_{\text{displaced}} \approx 10^{12}$ $M_{\odot}$

Correlation with Bondi accretion power

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

$$P_{\rm jet} \propto L_{\rm X}$$



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
NGC 4778	HCG 62	66.2	39.0	0.12
NGC 5044		32.2	10.0	0.065
NGC 6166	Abell 2199	125.0	63.0	0.1

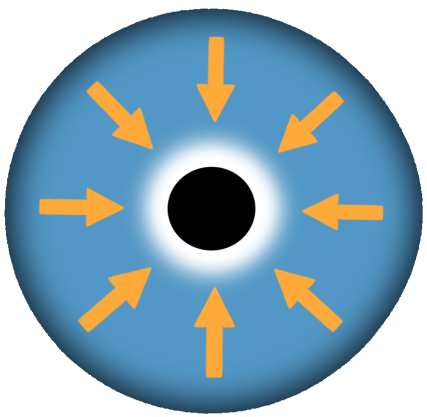
Correlation with Bondi accretion power

Bondi accretion

$$r_B = \frac{G M_\bullet}{c_s^2}$$

$$\dot{m}_B = \pi \rho c_s r_B^2$$

$$P_B \approx 0.1 \dot{m}_B c^2$$



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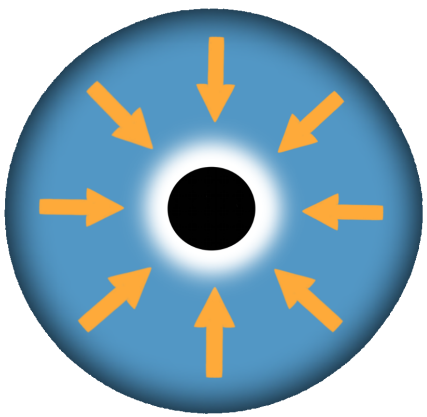

Chandra ≈ 0.5 arcsec

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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
NGC 4778	HCG 62	66.2	39.0	0.12
NGC 5044		32.2	10.0	0.065
NGC 6166	Abell 2199	125.0	63.0	0.1

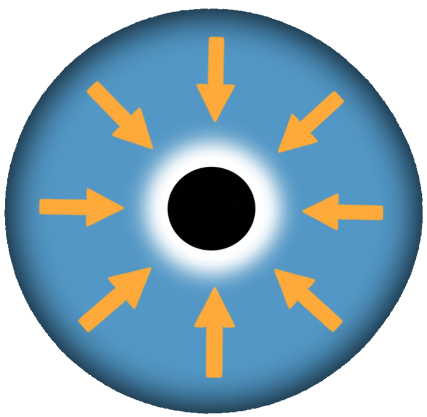
Correlation with Bondi accretion power

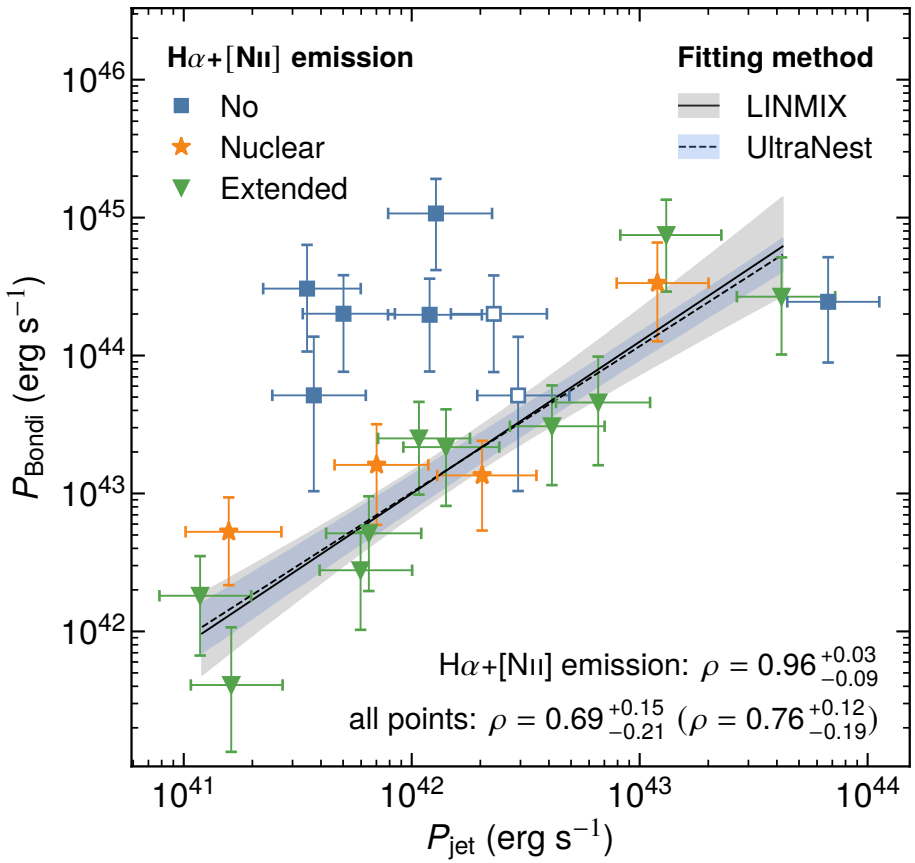
Bondi accretion

$$r_B = \frac{G M_\bullet}{c_s^2}$$

$$\dot{m}_B = \pi \rho c_s r_B^2$$

$$P_B \approx 0.1 \dot{m}_B c^2$$





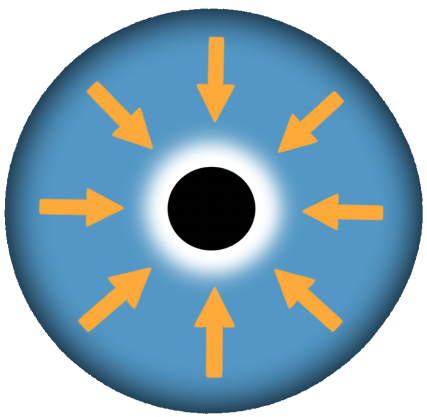
Correlation with Bondi accretion power

Bondi accretion

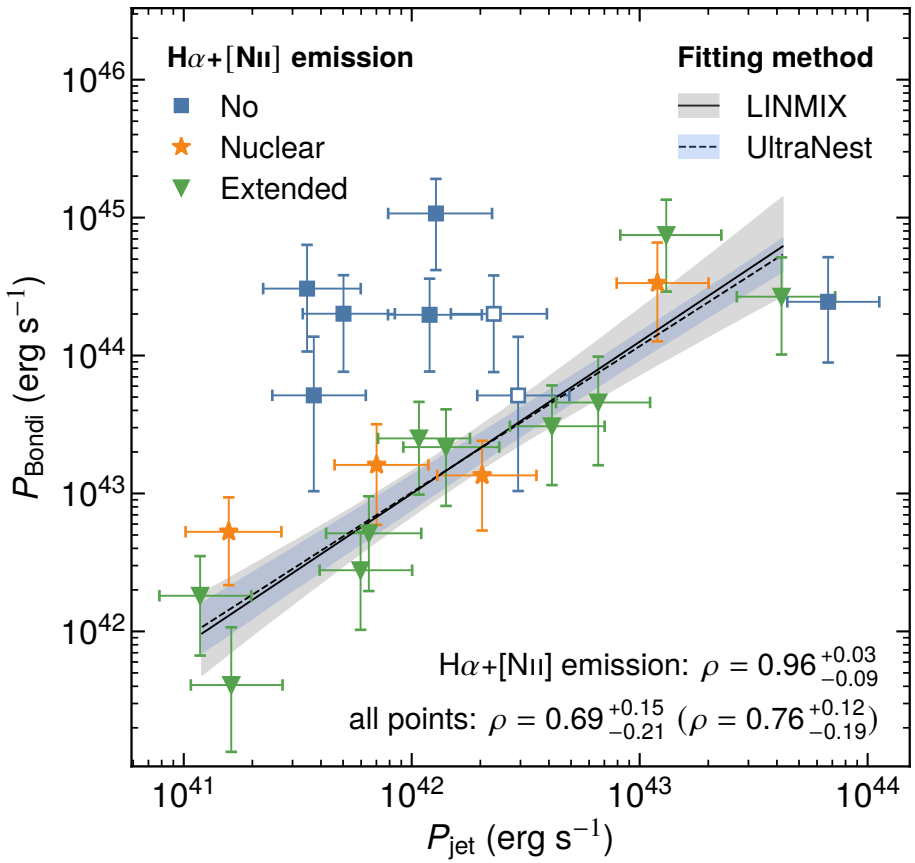
$$r_\mathrm{B} = \frac{G M_\bullet}{c_\mathrm{s}^2}$$

$$\dot{m}_\mathrm{B} = \pi \rho\, c_\mathrm{s} r_\mathrm{B}^2$$

$$P_\mathrm{B} \approx 0.1\, \dot{m}_\mathrm{B}\, c^2$$



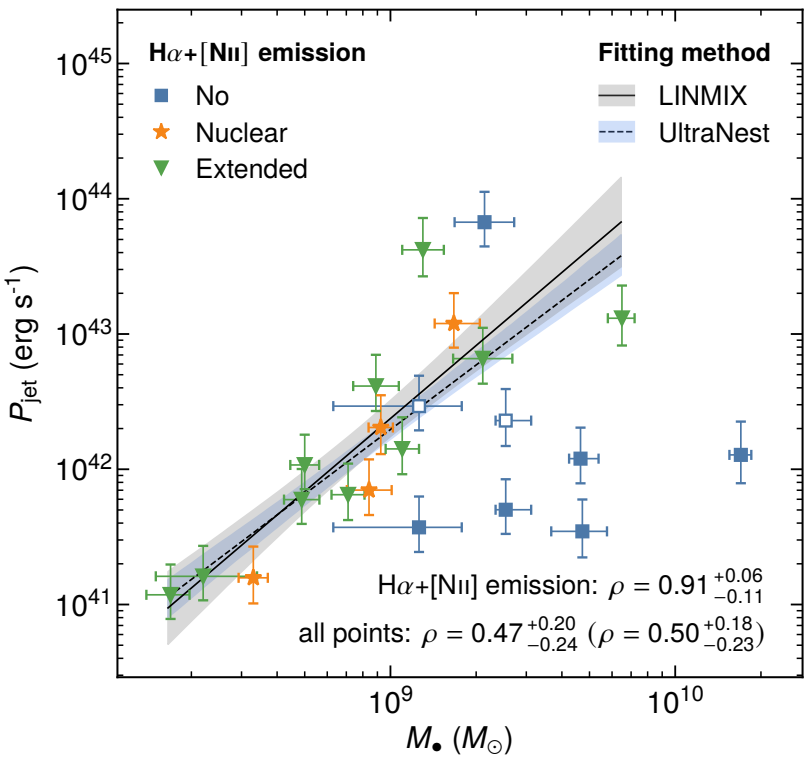
$$P_\mathrm{B} \propto P_\mathrm{jet}^{1.1\pm0.2} \qquad P_\mathrm{jet} \approx 0.01\, \dot{m}_\mathrm{B} c^2$$



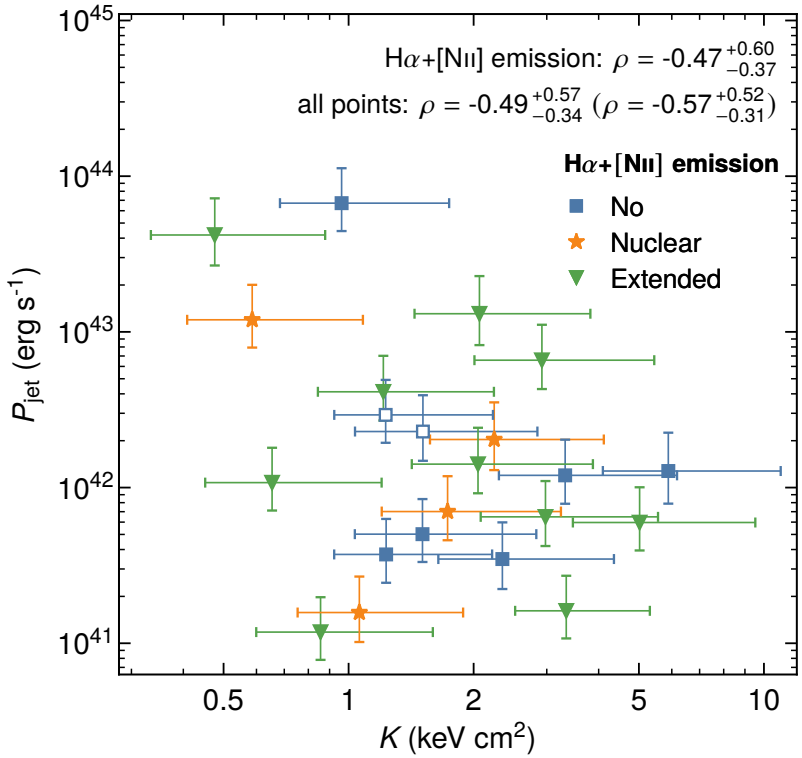
Underlying dependence on SMBH mass

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

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

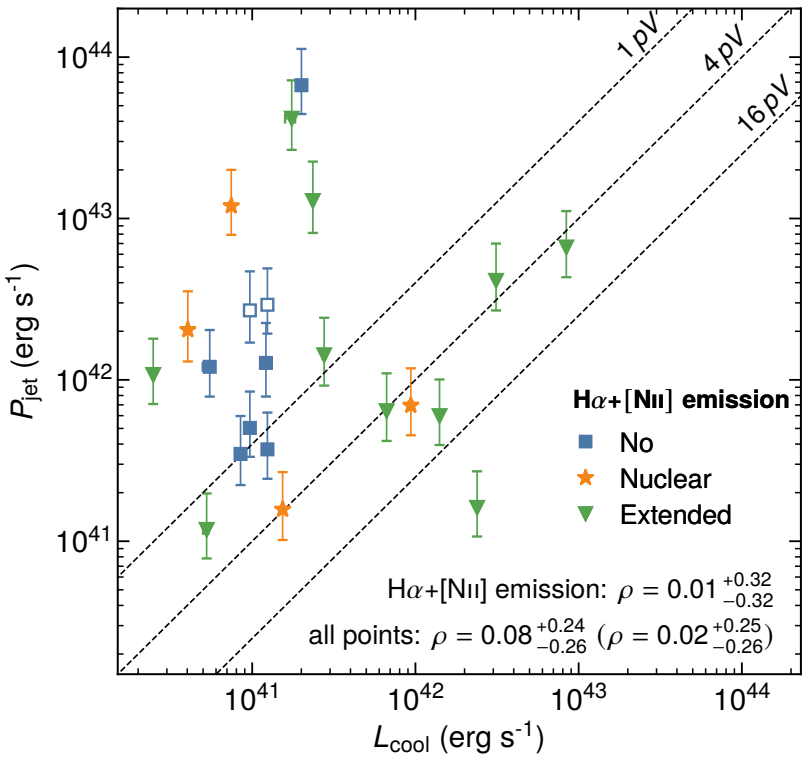


$$P_{\mathrm{jet}} \neq f(K)$$

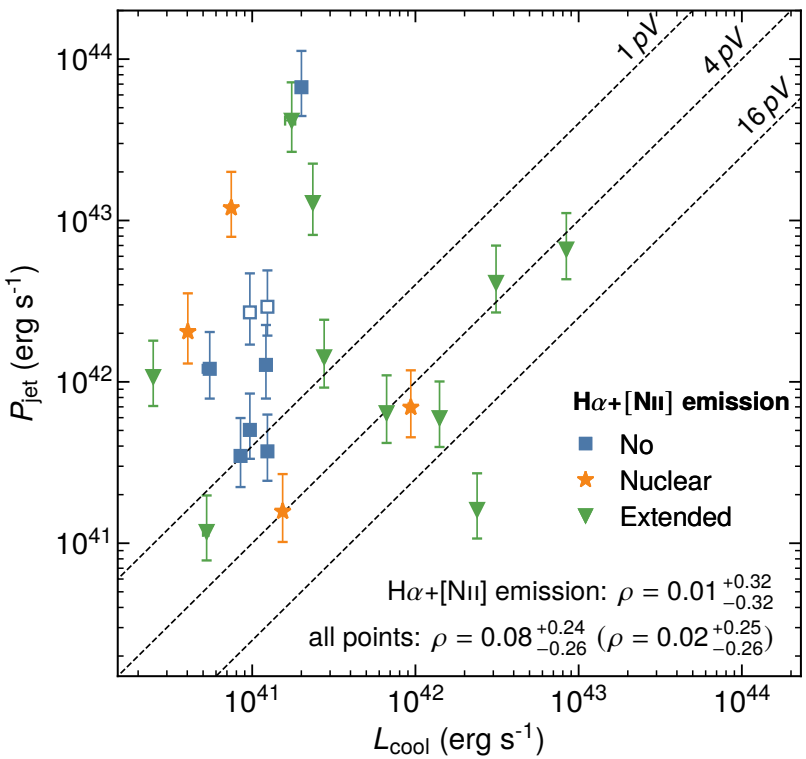


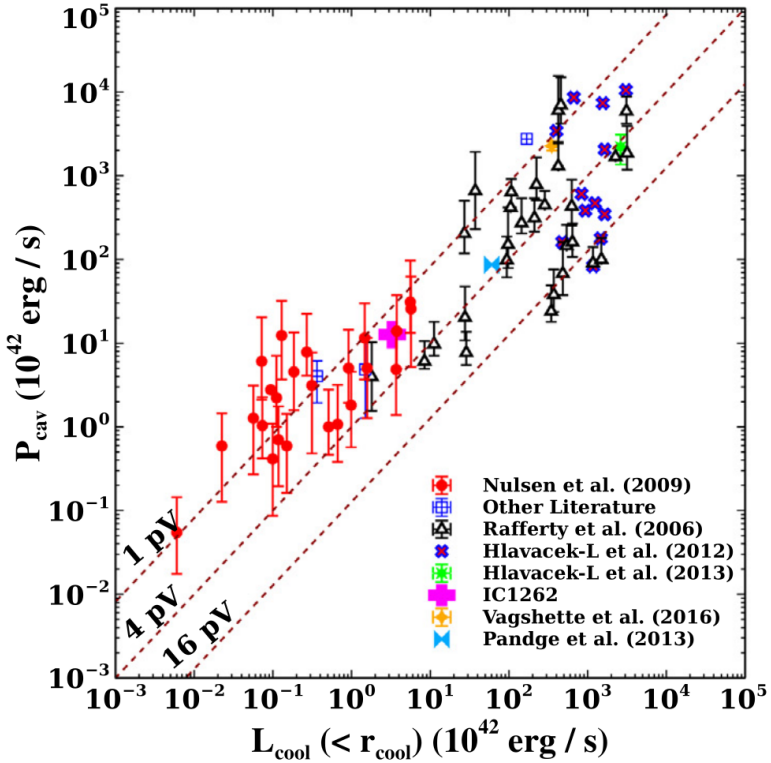
Plšek et al. 2022 (doi.org/10.1093/mnras/stac2770)

Lack of balance between heating and cooling?



Lack of balance between heating and cooling?



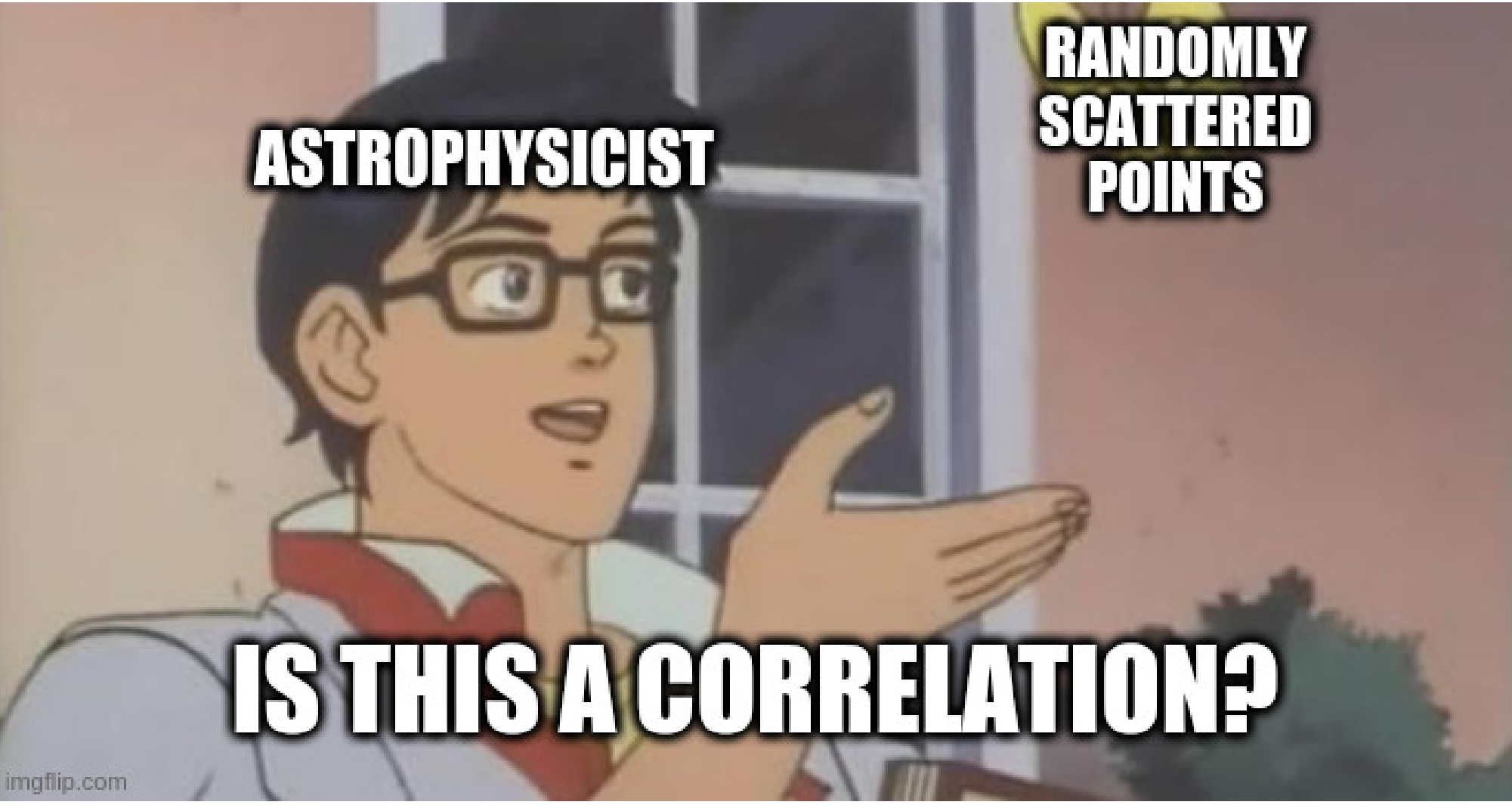


Conclusions

- correlation between P_{jet} and P_{Bondi}
  - caused by **underlying** $P_{\mathrm{jet}} - M_{\bullet}$ **correlation** ?

- SMBHs are fed from **thermally unstable** atmospheres
  - thermal state provides on/off switch
  - P_{jet} scales with $M_{\bullet}$

- hot atmospheres of early-type galaxies might be **overheated**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