

Studying radio-mechanical AGN feedback with X-ray cavities

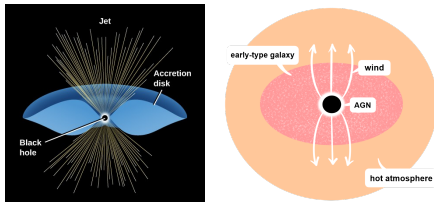
Tomáš Plšek

DTPA, Masaryk University, Brno, Czech Republic

AGN feedback

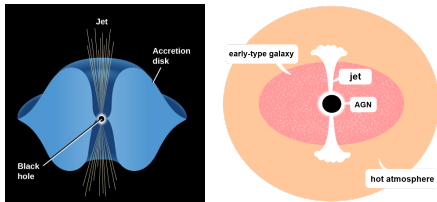
quasar mode

- geometrically thin disk
- optically thick, rad. efficient
 - EM radiation (wind)
- quasar, BL Lac, Seyfert I/II, ...
- all galaxy types



radio-mechanical mode

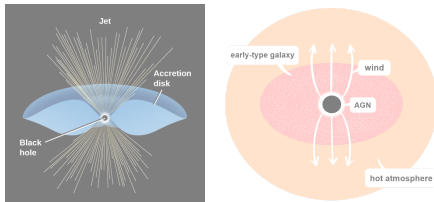
- geometrically thick torus
- optically thin, rad. inefficient
 - rel. particles (jets)
- radio galaxy (optically LINER)
- early-type galaxies



AGN feedback

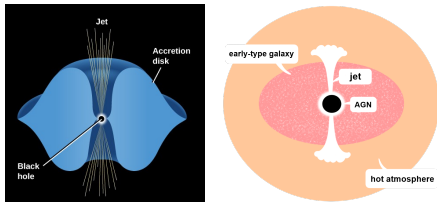
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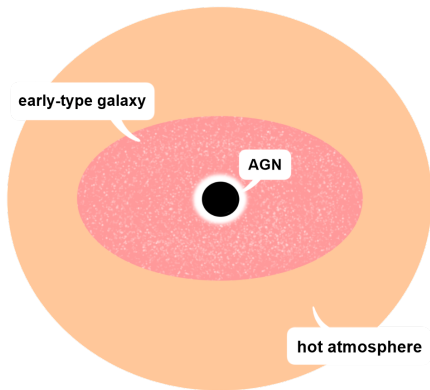
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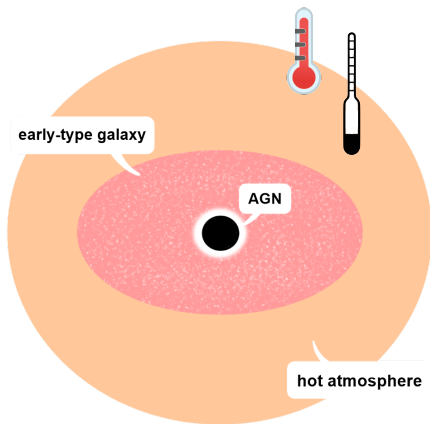
Early-type galaxies

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



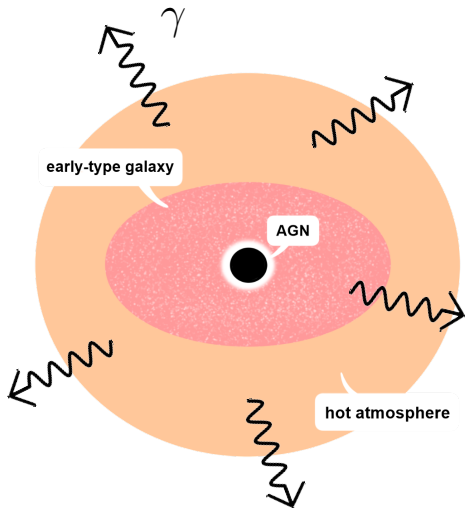
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- hot & diffuse plasma
 - temperature $\approx 10^7 \text{ K}$
 - electron density $< 1 \text{ cm}^{-3}$
 - $\sim 80\%$ of all **baryons**



Early-type galaxies

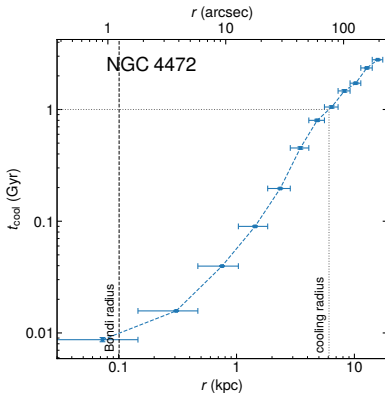
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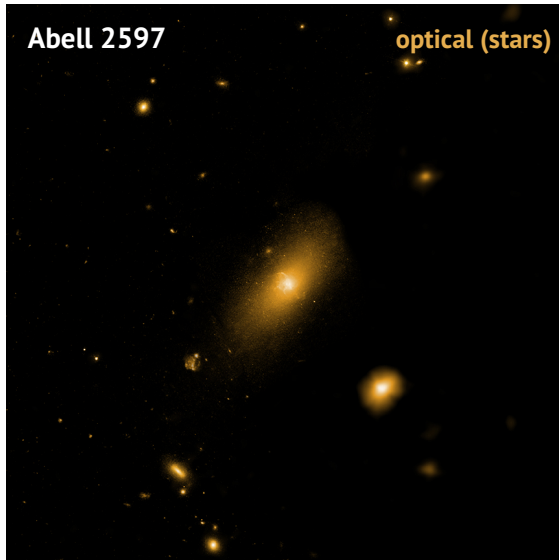
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- hot → emit X-rays
 - **cool radiatively** (t_{cool})
 - cold gas ($\text{H}\alpha$, CO) - less than expected

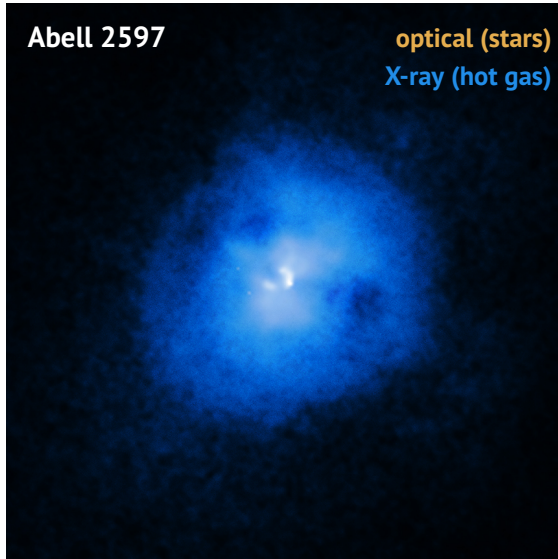
$$t_{\text{cool}} = \frac{\frac{3}{2}nkT}{L_X} \propto \frac{kT}{n}$$



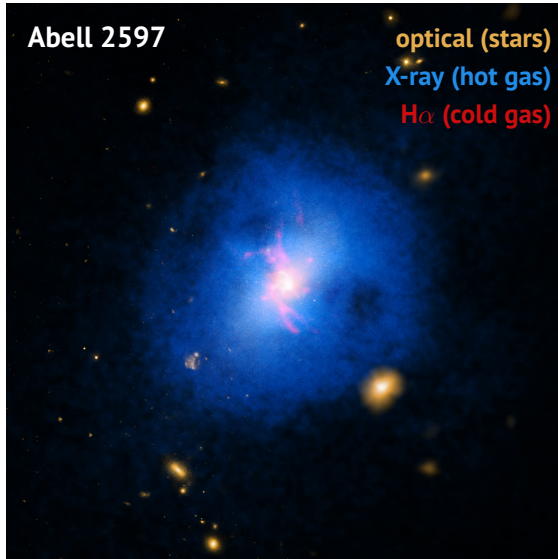
Early-type galaxies



Early-type galaxies



Early-type galaxies

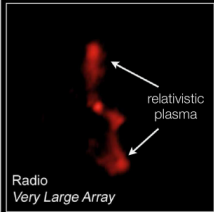
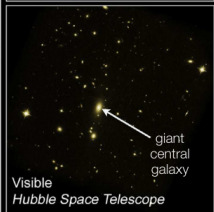
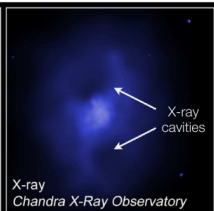
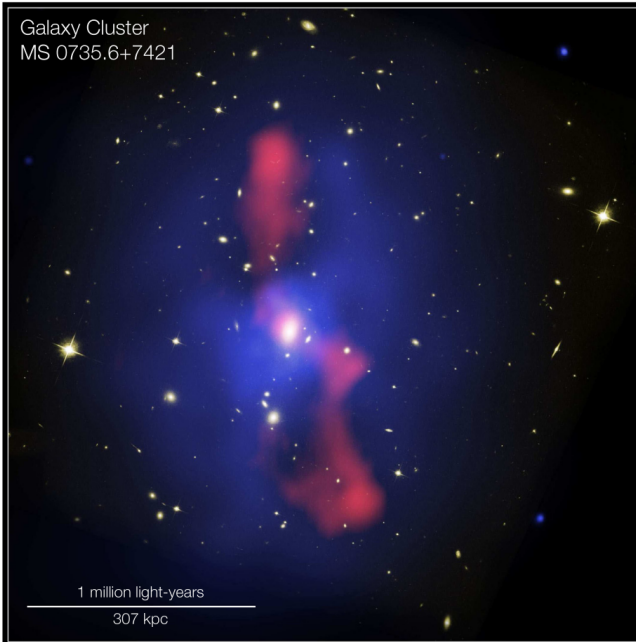


Radio-mechanical AGN feedback

- central SMBH accretes material
 - advection dominated acc. flow (ADAF)
 - relativistic jets $\rightarrow$ radio lobes
 - interact with hot gas $\rightarrow$ **X-ray cavities**

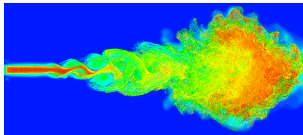
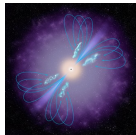


Galaxy Cluster
MS 0735.6+7421



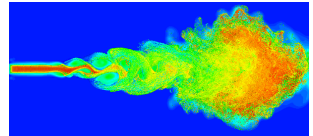
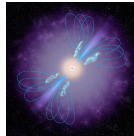
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- deposits E on kpc–Mpc scale
 - turbulent flows, bulk motions
 - sound and shock waves

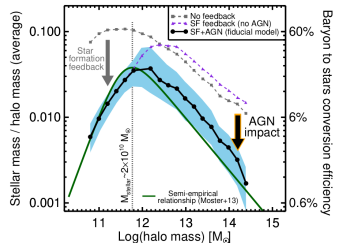


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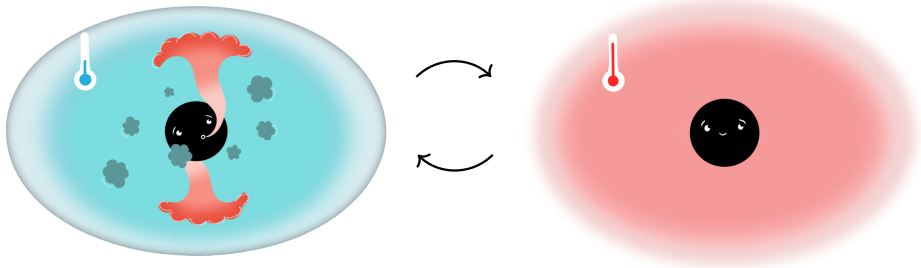


- deposits E on kpc–Mpc scale
 - turbulent flows, bulk motions
 - sound and shock waves
- heats the galactic atmosphere
 - prevents star formation
 - **regulates further accretion**

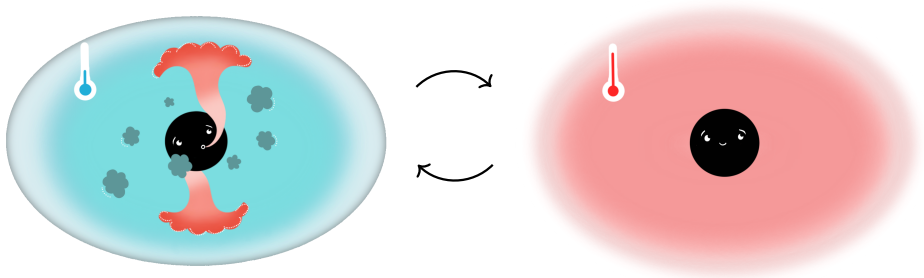
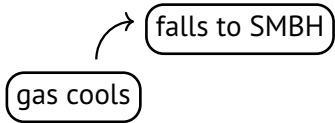


Radio-mechanical AGN feedback loop

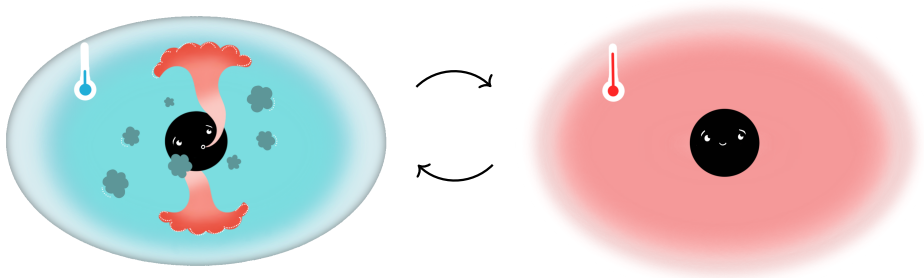
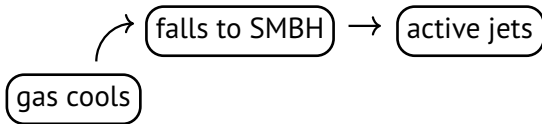
gas cools



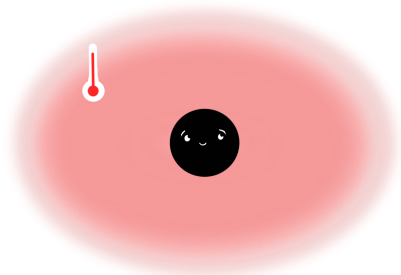
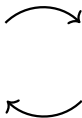
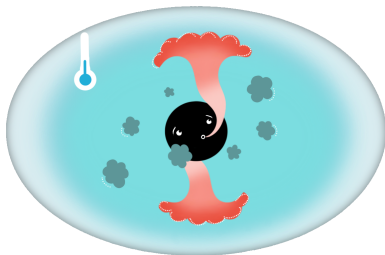
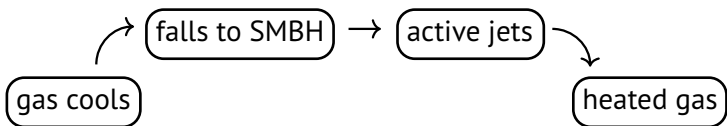
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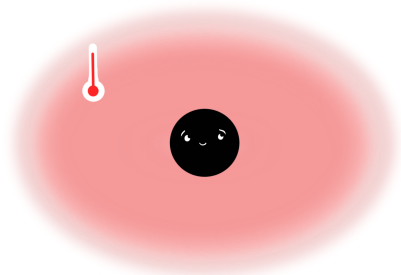
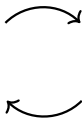
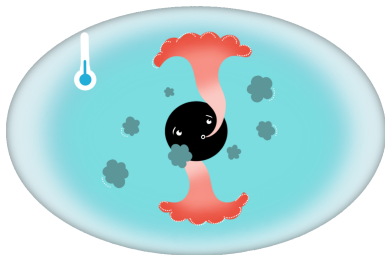
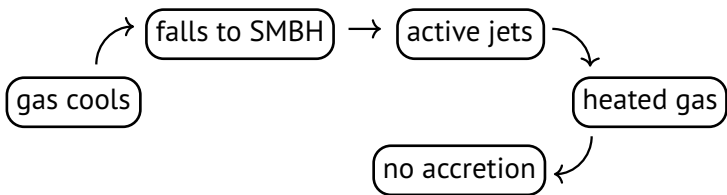
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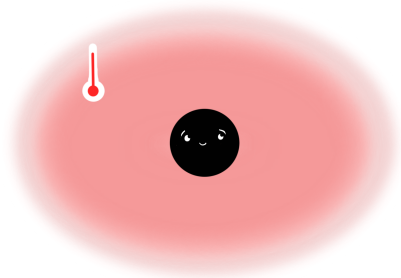
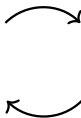
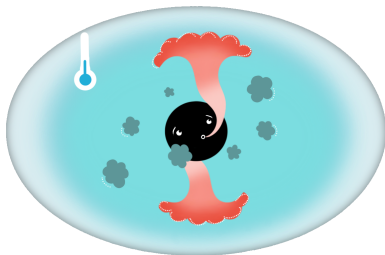
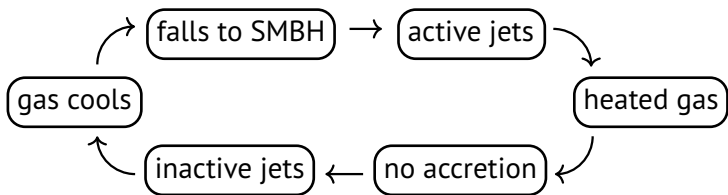
Radio-mechanical AGN feedback loop



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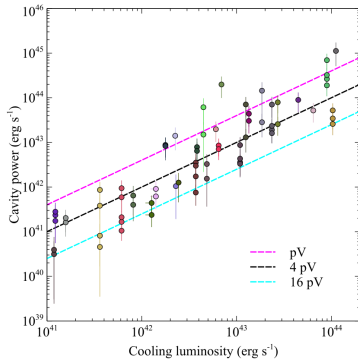


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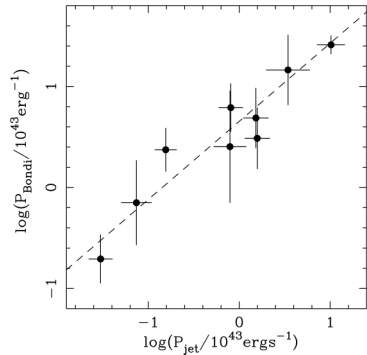
Radio-mechanical AGN feedback loop

hot atmosphere



Credit: Panagoulia et al. 2014

central engine



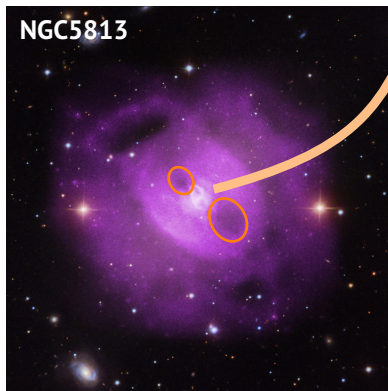
Credit: Allen et al. 2006

Studying AGN feedback with X-ray cavities

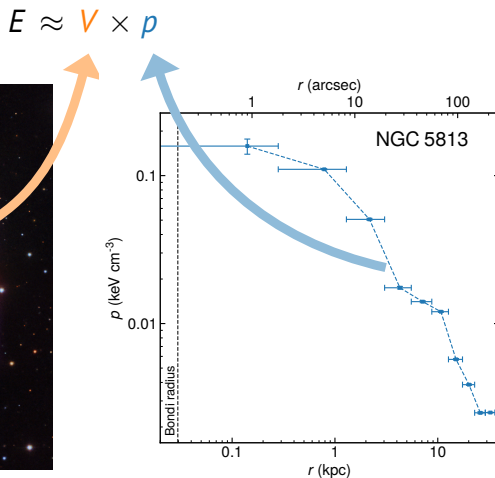


Credit: Randall et al. 2015

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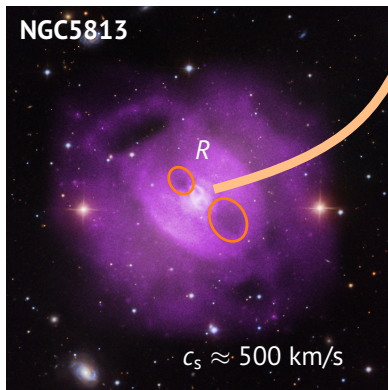
Credit: Plšek et al. 2022

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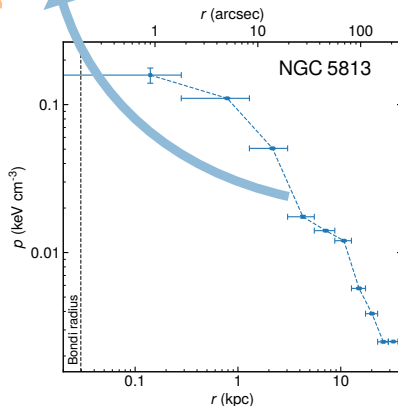
$$t_{\text{age}} = \frac{R}{c_s}$$

$$E \approx V \times p$$

$$P_{\text{jet}} = \frac{pV}{t_{\text{age}}}$$



Credit: Randall et al. 2015



Credit: Plšek et al. 2022

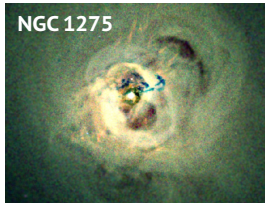
Broad range of jet powers



galaxies/groups

$$R \approx 1 \text{ kpc}$$

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



brightest cluster galaxies

$$R \approx 10 \text{ kpc}$$

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



galaxy clusters

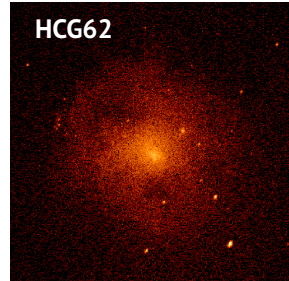
$$R \approx 100 \text{ kpc}$$

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

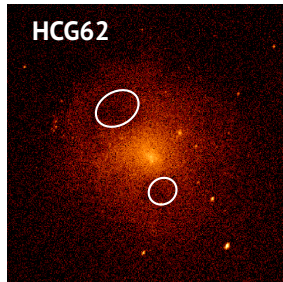
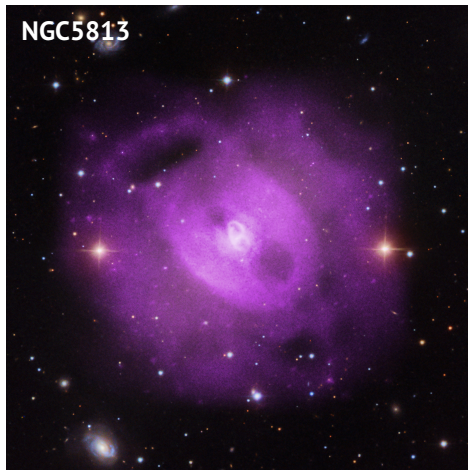
Pitfalls of visual detection



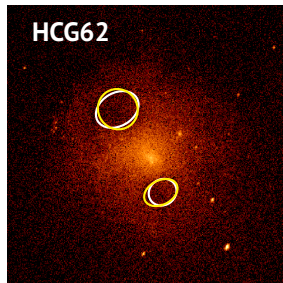
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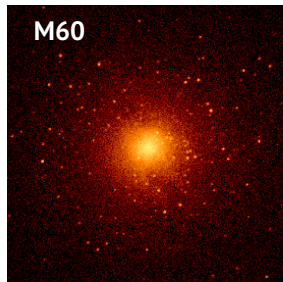
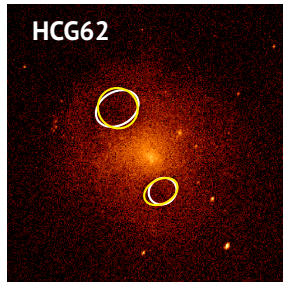
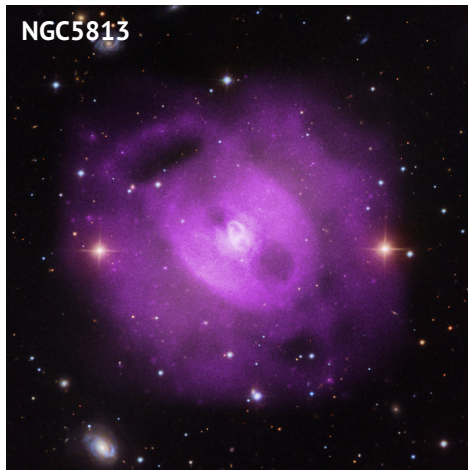
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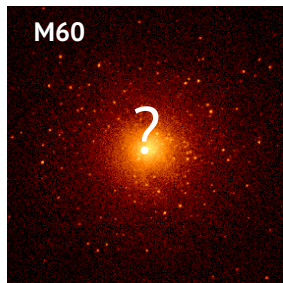
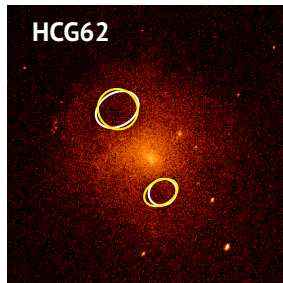
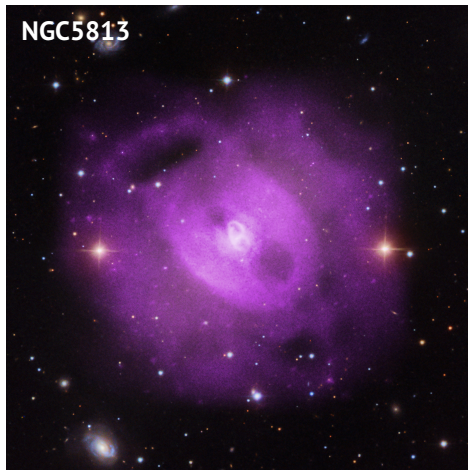
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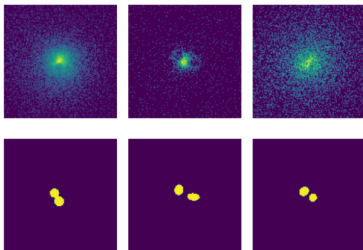
Pitfalls of visual detection



Cavity Detection Tool (CADET)

github.com/tomasplsek/CADET

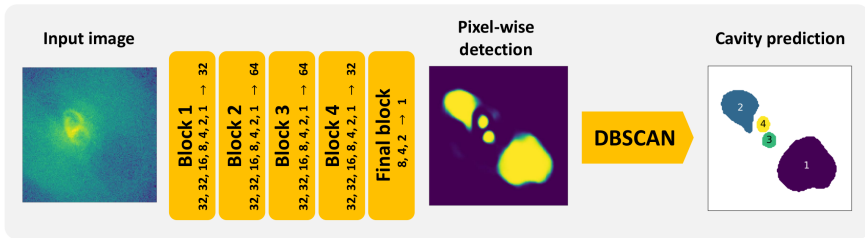
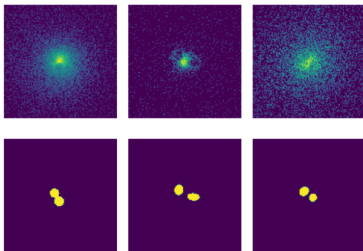
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 - surface brightness: β -model
 - ellipsoidal cavities (50% images)
 - 500k training images



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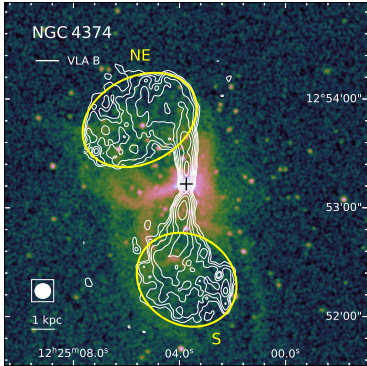
- mock training data
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 - 500k training images
- network architecture
 - CNN (Inception-like) + DBSCAN



Correlating the P_{jet} with other quantities

$$P_{\text{jet}} \propto \dot{m}_{\text{acc}}$$

$$P_{\text{jet}} \propto L_X$$



Galaxy	Alternative name	D (Mpc)	r_B (pc)	r_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

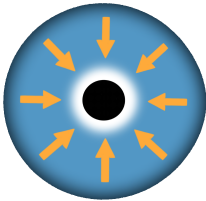
Correlating the P_{jet} with other quantities

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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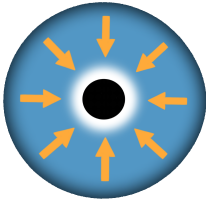
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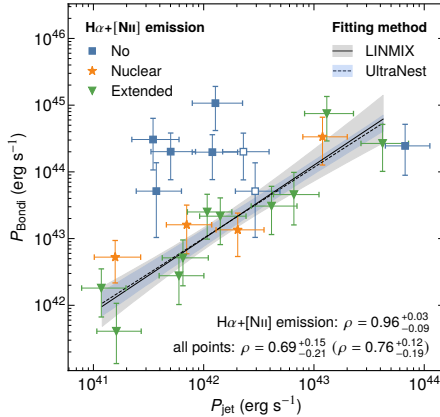


Chandra pixel size ≈ 0.5 arcsec

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Correlation with Bondi accretion power

$$P_B \propto P_{\text{jet}}^{1.1 \pm 0.2} \quad P_{\text{jet}} \approx 0.01 \dot{m}_{\text{BC}}^2$$

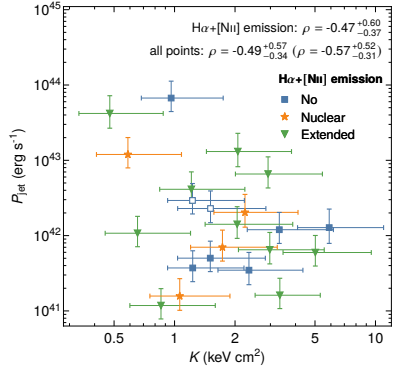
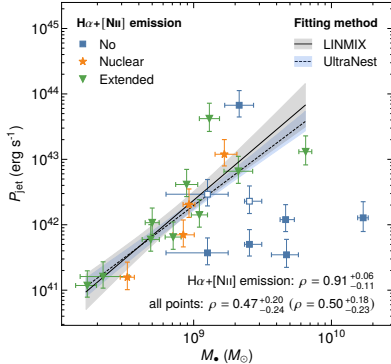


Underlying dependence on SMBH mass

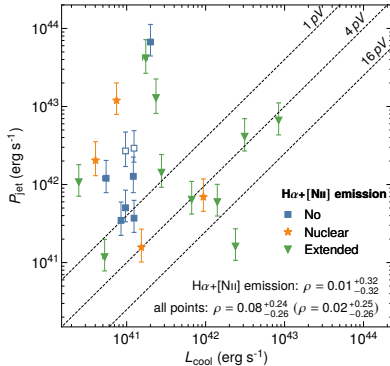
$$P_B \propto M_\bullet^2 \rho kT^{-3/2} \propto M_\bullet^2 K^{-2/3}$$

$$P_{\text{jet}} \propto M_\bullet^{1.80 \pm 0.36}$$

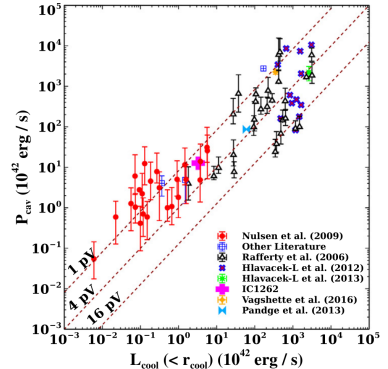
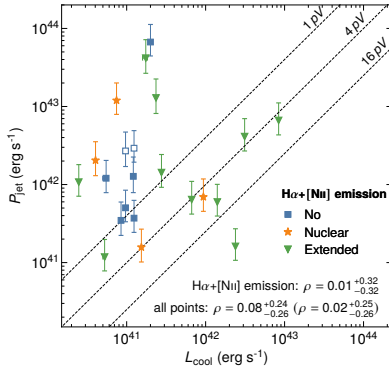
$$P_{\text{jet}} \neq f(K)$$



Lack of balance between heating and cooling?

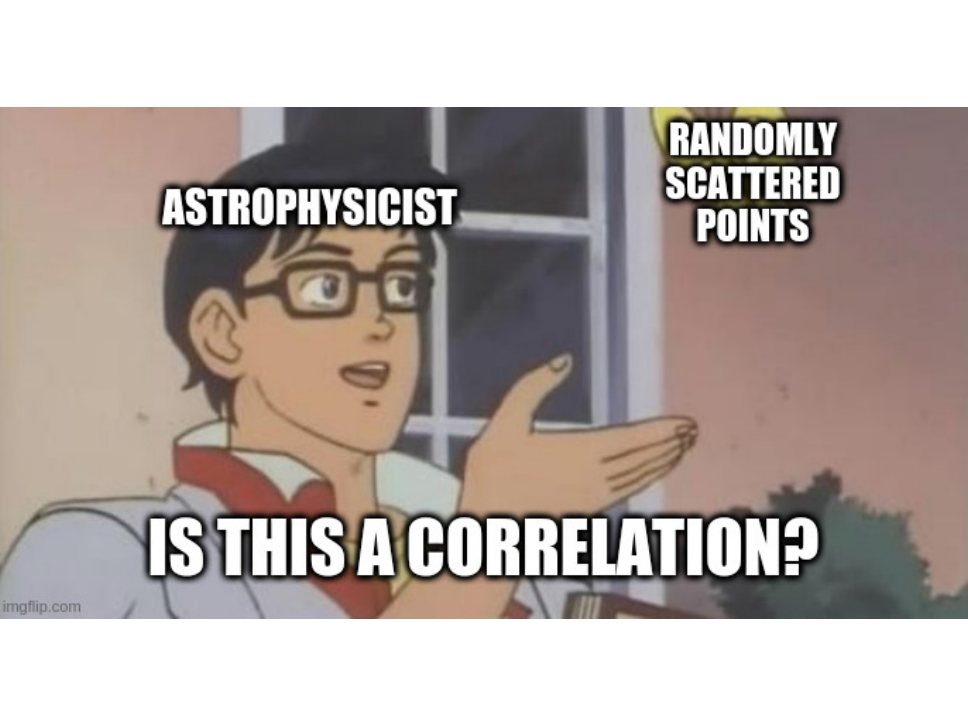


Lack of balance between heating and cooling?



Conclusions

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



ASTROPHYSICIST

**RANDOMLY
SCATTERED
POINTS**

IS THIS A CORRELATION?