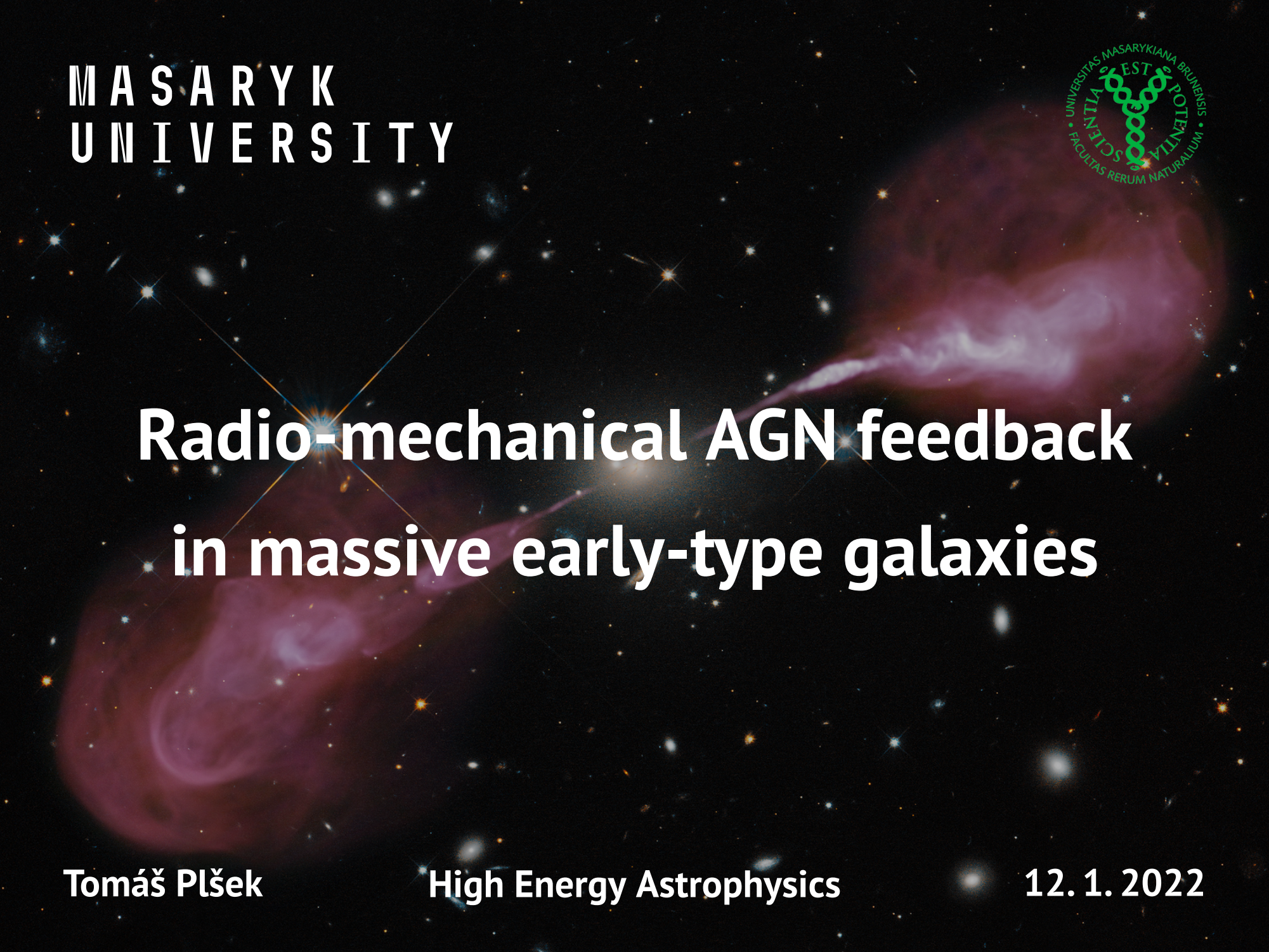


MASARYK UNIVERSITY

Radio-mechanical AGN feedback in massive early-type galaxies

Tomáš Plšek

High Energy Astrophysics

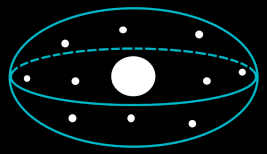
12. 1. 2022

Content

- Early-type galaxies
- Active galactic nuclei (AGN)
- AGN feedback
- How to study radio-mechanical AGN feedback?
- Homework

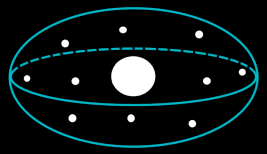
Content

- Early-type galaxies

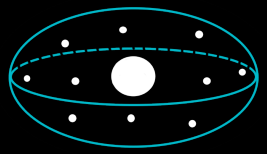


- Active galactic nuclei (AGN)
- AGN feedback
- How to study radio-mechanical AGN feedback?
- Homework

Content

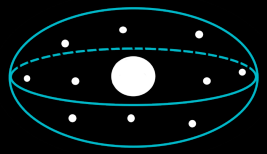


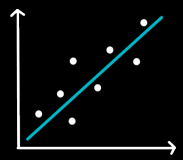
Content



- Early-type galaxies
- Active galactic nuclei (AGN)
- AGN feedback
- How to study radio-mechanical AGN feedback?
- Homework

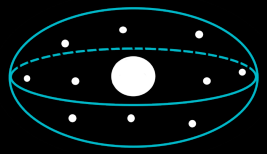
Content

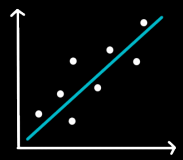


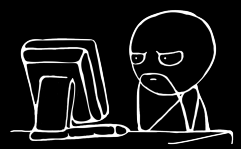


Content

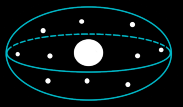
- Early-type galaxies
- Active galactic nuclei (AGN)
- AGN feedback
- How to study radio-mechanical AGN feedback?
- Homework





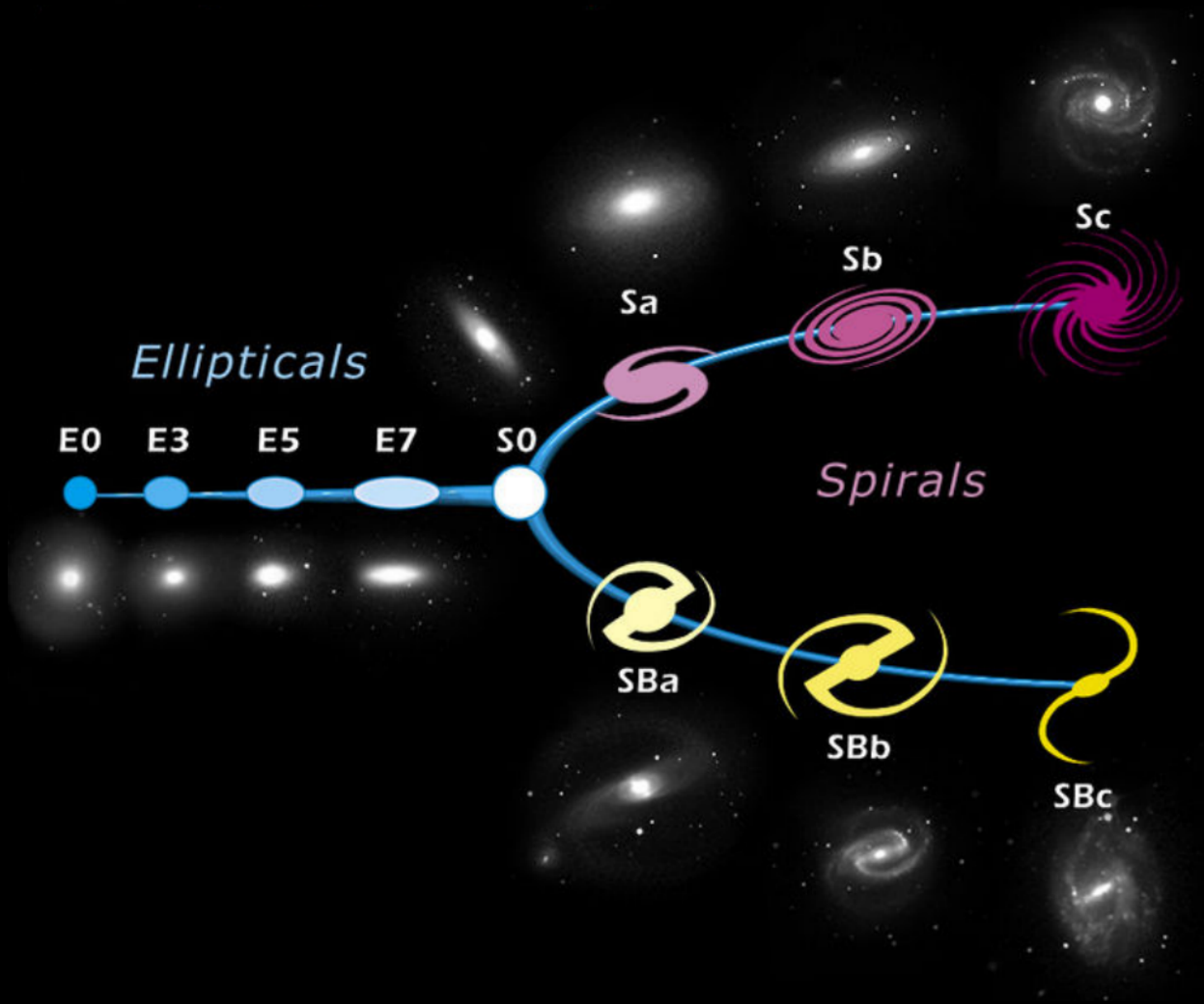


Galaxy classification

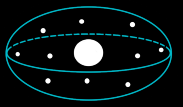


Early-type

Late-type

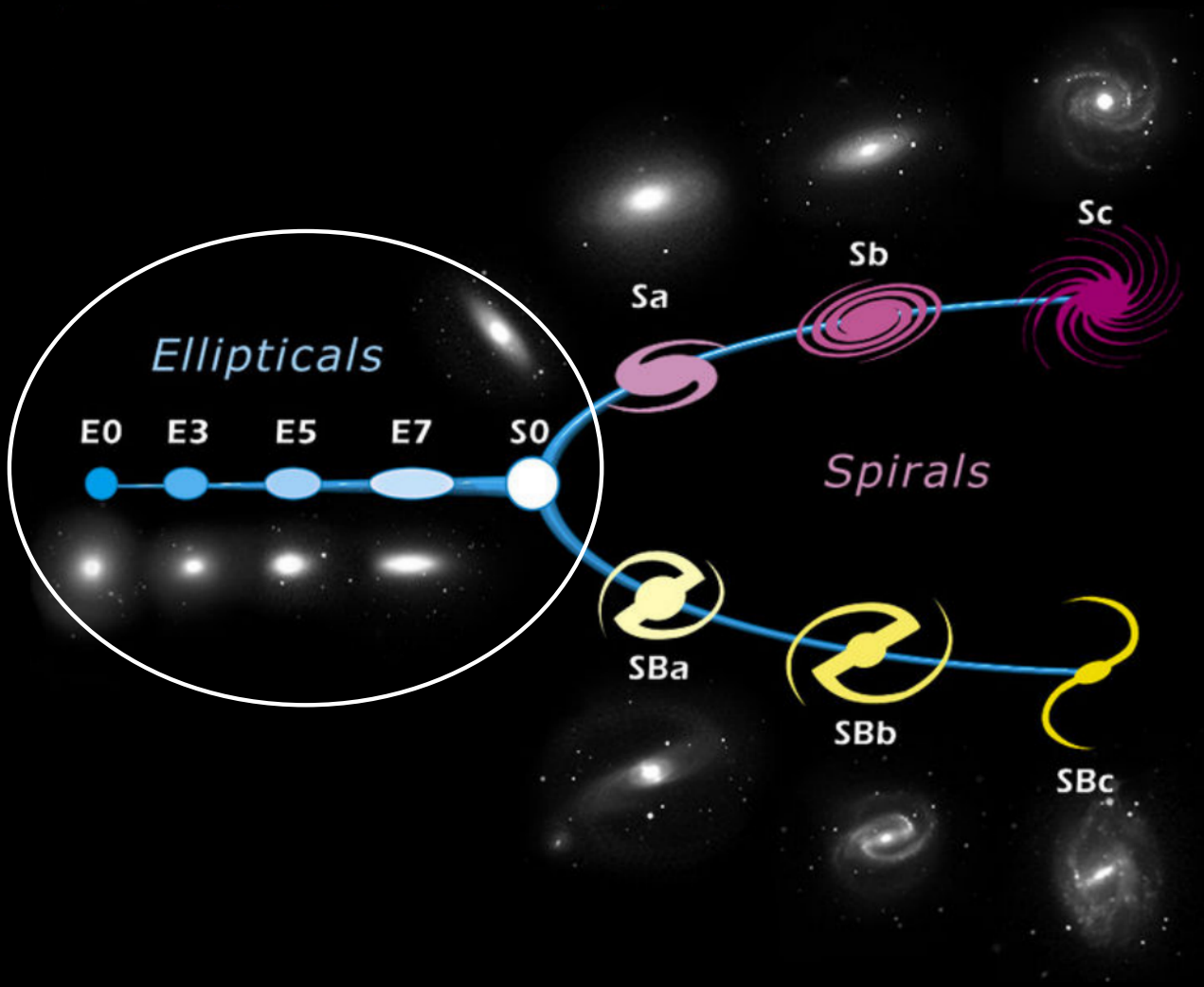


Galaxy classification

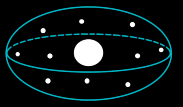


Early-type

Late-type



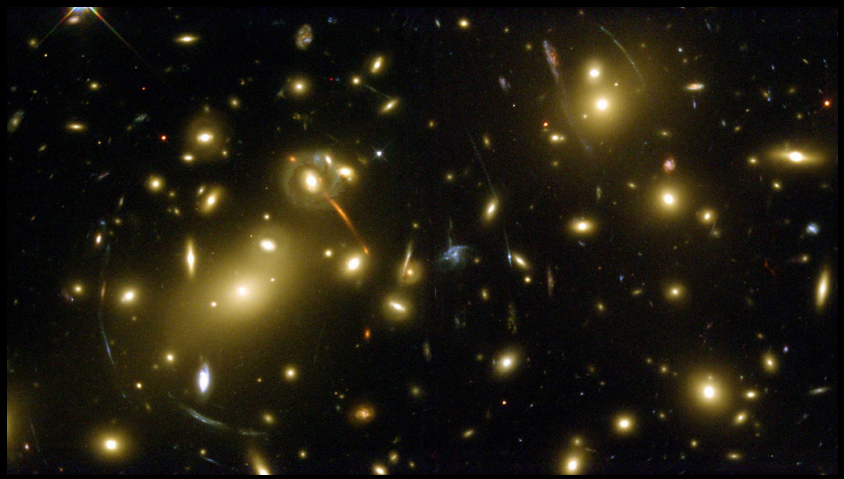
Early-type galaxies



= ellipticals and lenticulars

- red & dead
  - old stellar population
  - low star formation ($< 1\,M_\odot/\mathrm{yr}$)
- in galaxy groups and clusters

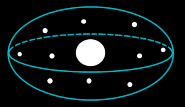
elliptical galaxy



galaxy cluster

lenticular galaxy

Early-type galaxies

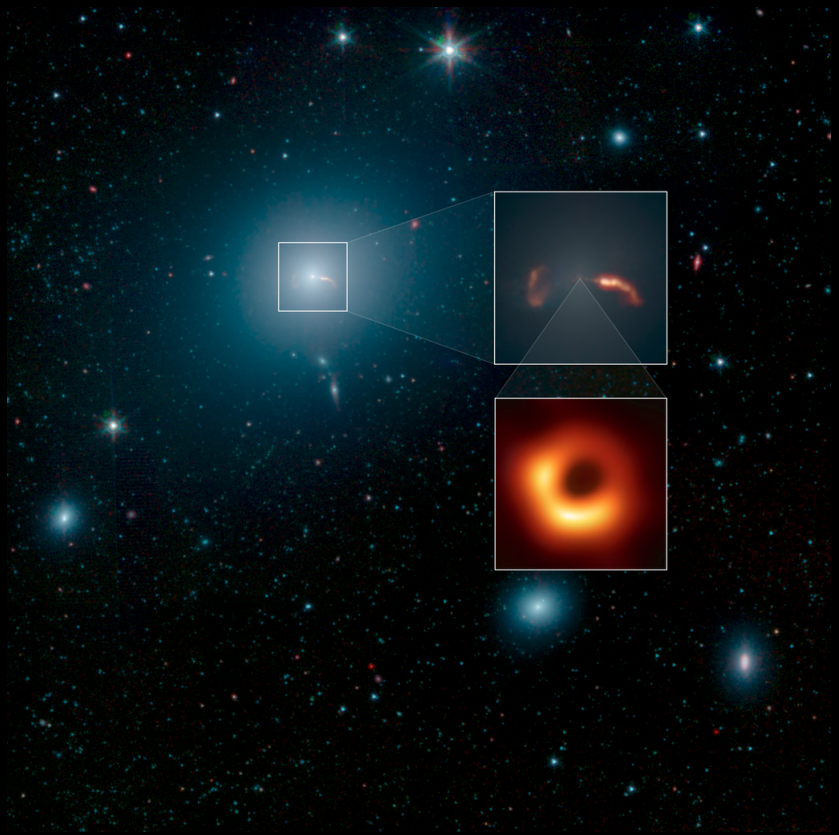


= ellipticals and lenticulars

- red & dead
  - old stellar population
  - low star formation ($< 1\,M_\odot/\mathrm{yr}$)
- in galaxy groups and clusters
- massive systems ($> 10^{12}\ M_\odot$)
  - hot atmospheres
  - supermassive black holes

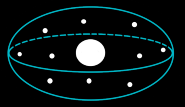
    $\approx 10^6 - 10^{10}\ M_\odot$

    = Active Galactic Nucleus (AGN)



M87, Credit: EHT Collaboration

Early-type galaxies

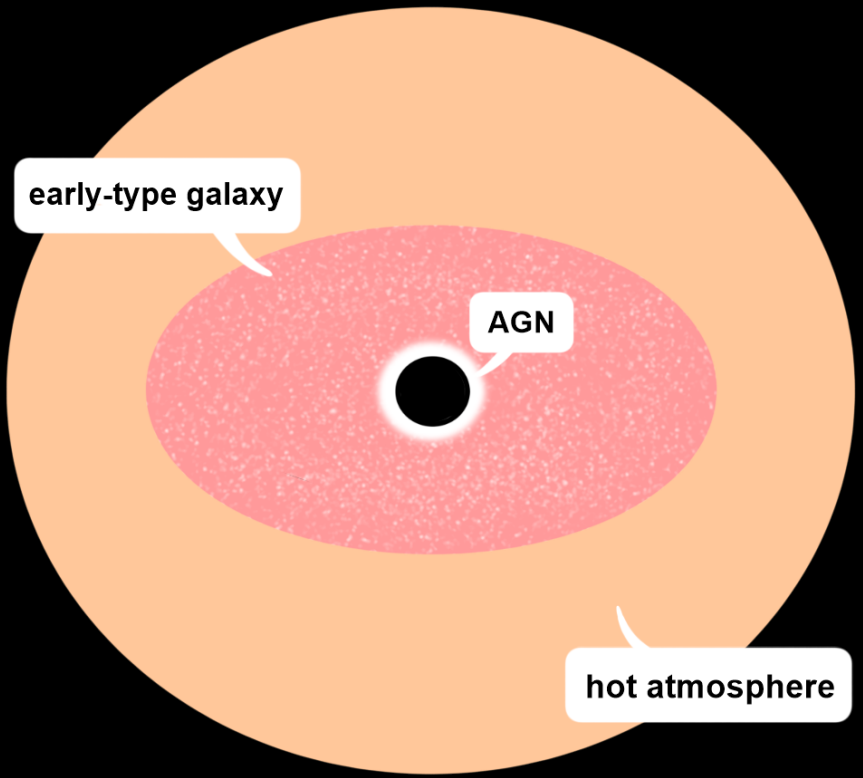


= ellipticals and lenticulars

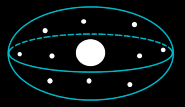
- red & dead
  - old stellar population
  - low star formation ($< 1\,M_\odot/\mathrm{yr}$)
- in galaxy groups and clusters
- massive systems ($> 10^{12}\ M_\odot$)
  - hot atmospheres
  - supermassive black holes

    $\approx 10^6 - 10^{10}\ M_\odot$

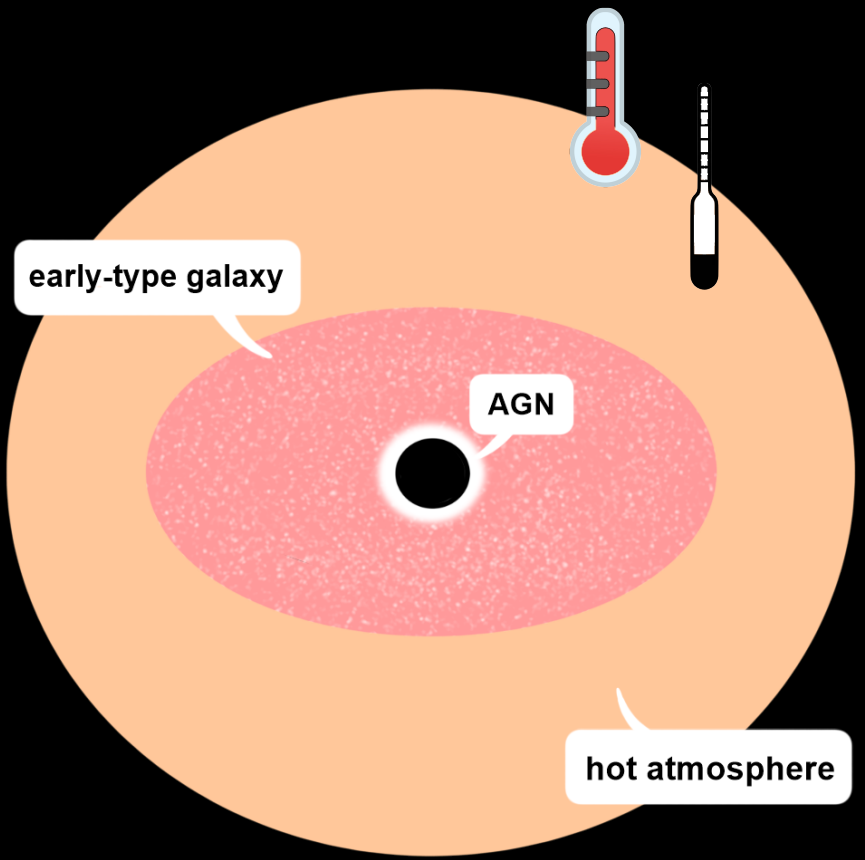
    = Active Galactic Nucleus (AGN)



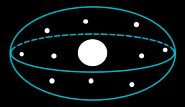
Hot atmospheres



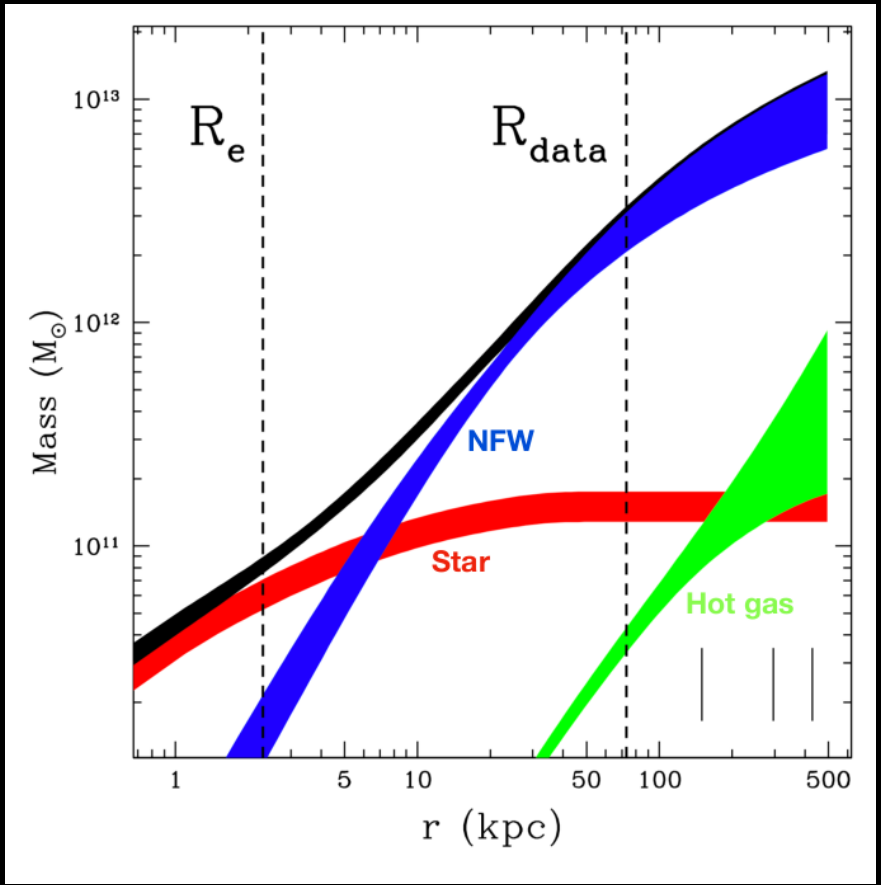
- hot diffuse plasma
  - $n \approx 10^{-5} - 1$ cm^{-3}
  - $T \approx 10^{6} - 10^{8}$ K



Hot atmospheres

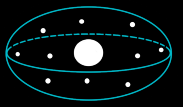


- hot diffuse plasma
  - $n \approx 10^{-5} - 1$ cm^{-3}
  - $T \approx 10^{6} - 10^{8}$ K
- most of the baryonic matter
  - halo > 80 %
  - stars ~ 10 %
  - cold gas & dust < 1 %

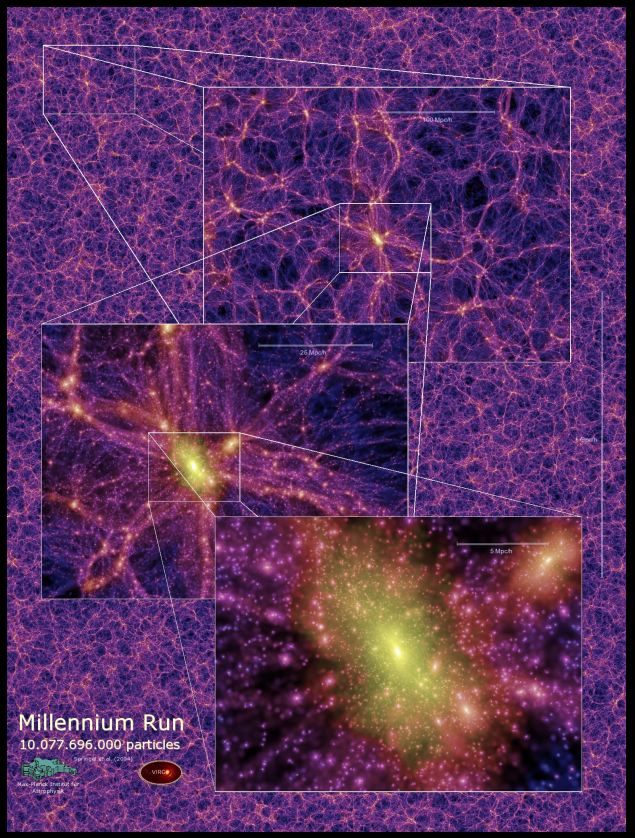


Credit: Buote & Barth 2018

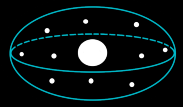
Hot atmospheres



- hot diffuse plasma
  - $n \approx 10^{-5} - 1$ cm^{-3}
  - $T \approx 10^{6} - 10^{8}$ K
- most of the baryonic matter
  - halo > 80 %
  - stars ~ 10 %
  - cold gas & dust < 1 %
- origin of atmospheres
  - accretion from filaments
  - stellar wind & supernovae

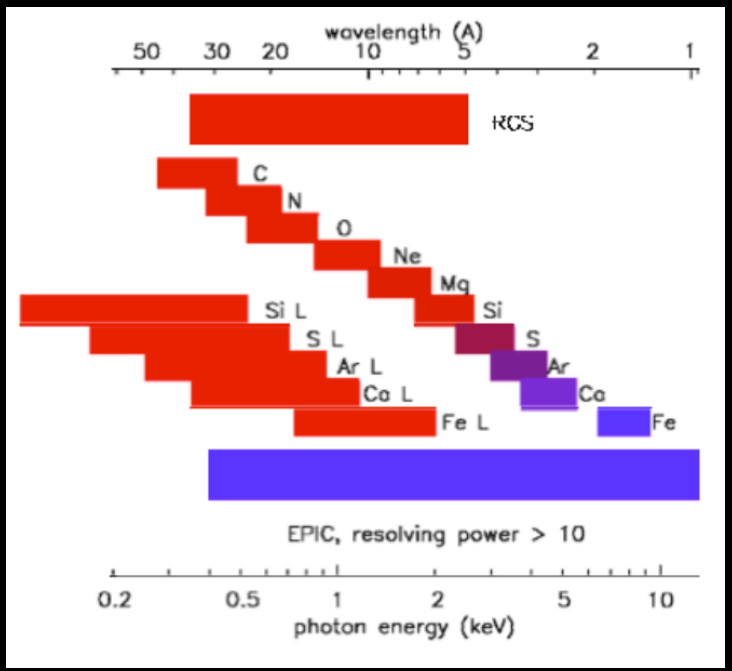


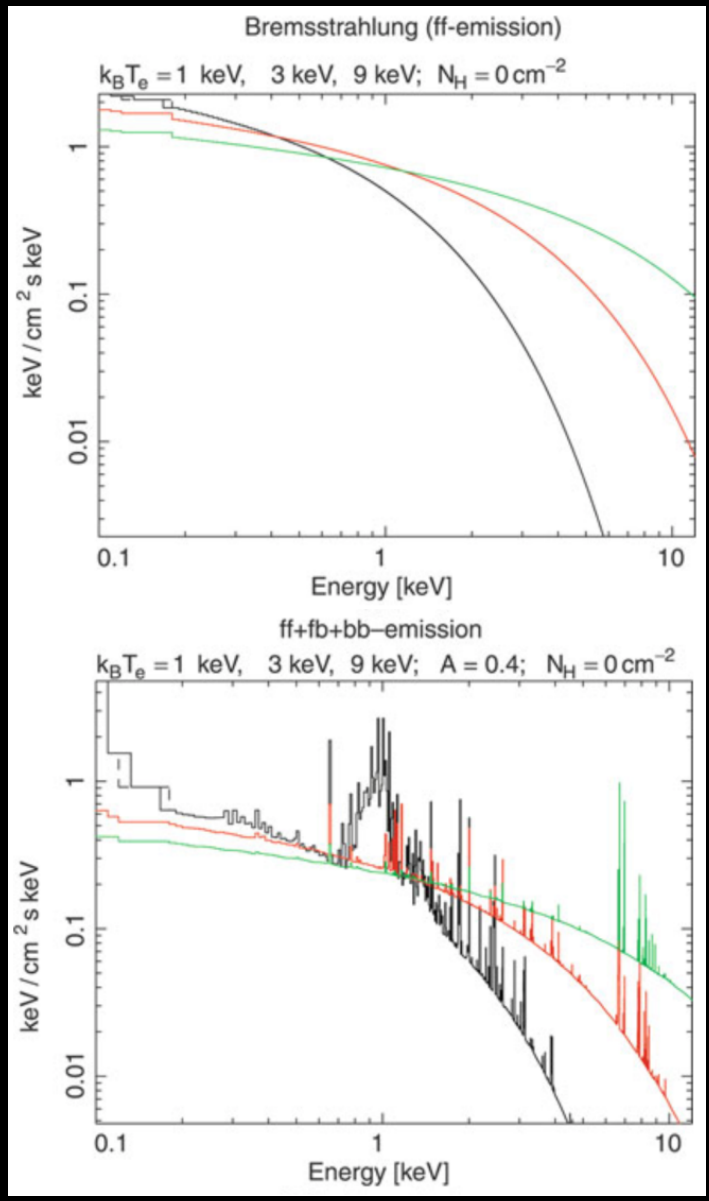
Hot atmospheres in X-rays



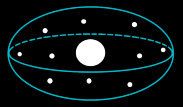
- emit X-ray photons
  - bremsstrahlung (ff)
  - line emission (bb)

  Fe, Si, S, Mg, Ca, O, Ne,...



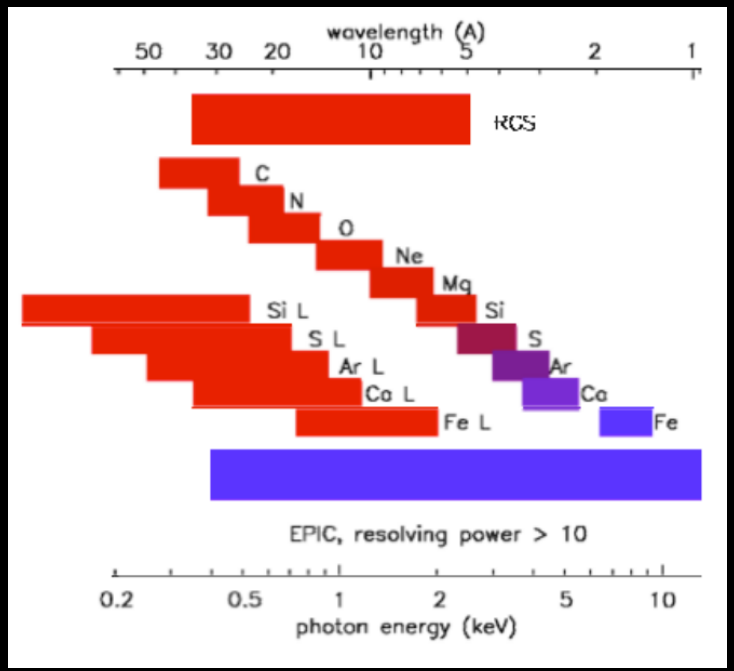


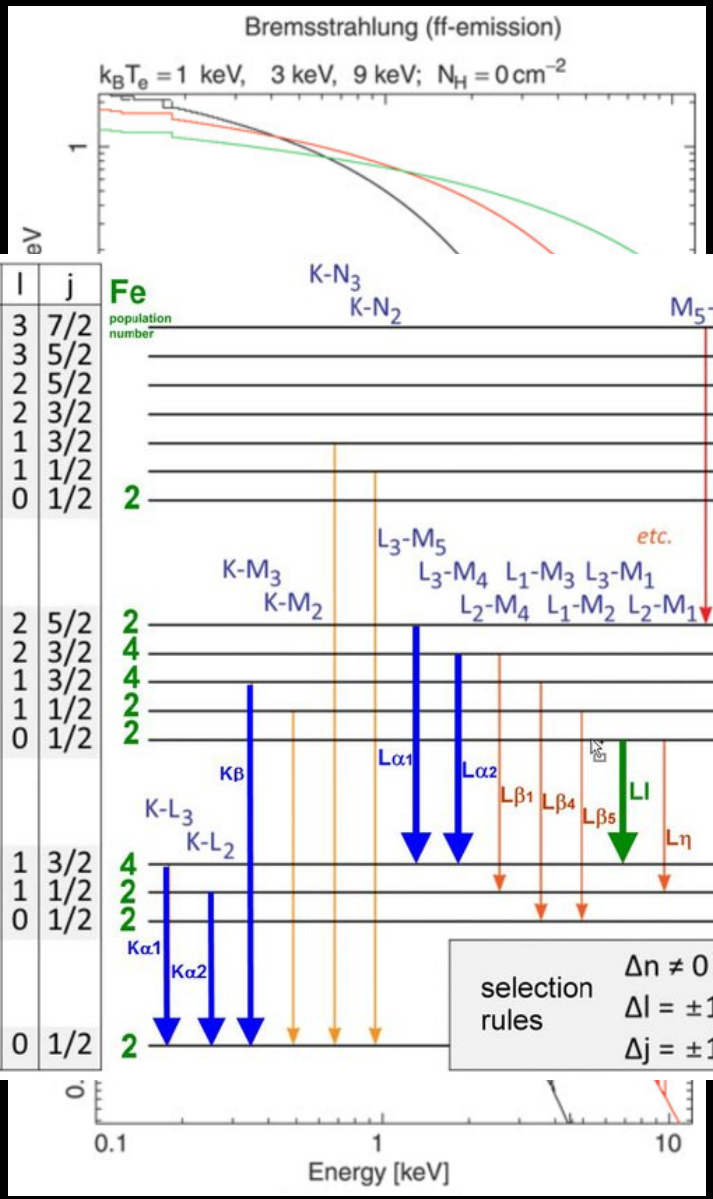
Hot atmospheres in X-rays



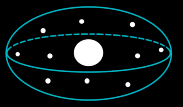
- emit X-ray photons
  - bremsstrahlung (ff)
  - line emission (bb)

  Fe, Si, S, Mg, Ca, O, Ne,...

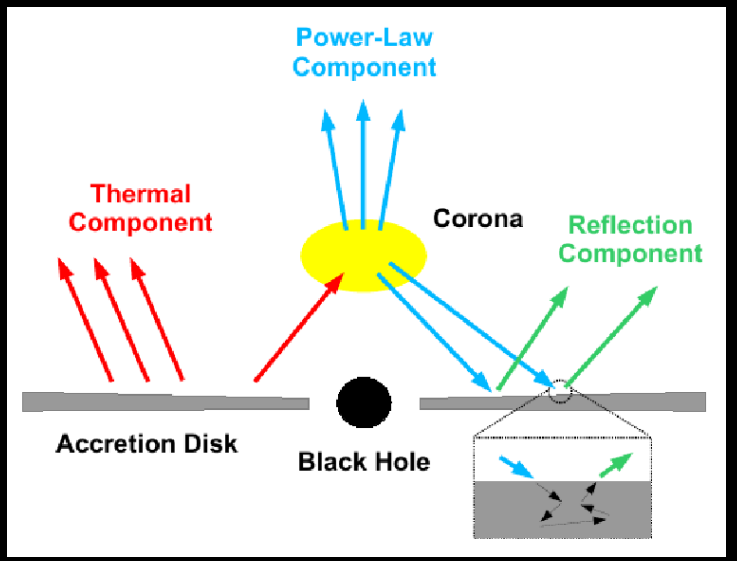


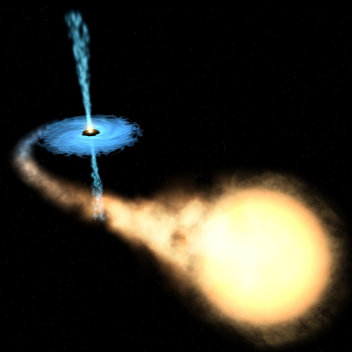


Hot atmospheres in X-rays



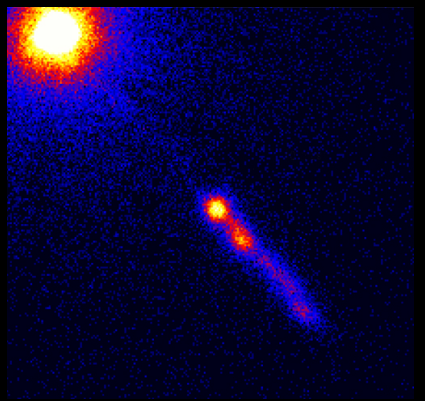
- emit X-ray photons
  - bremsstrahlung (ff)
  - line emission (bb)
- other X-ray emitters
  - central AGN (IC)
  - AGN jets (IC / synchrotron ?)
  - LMXBs, CVs, CABs





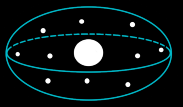
low-mass X-ray binary

Pictor A



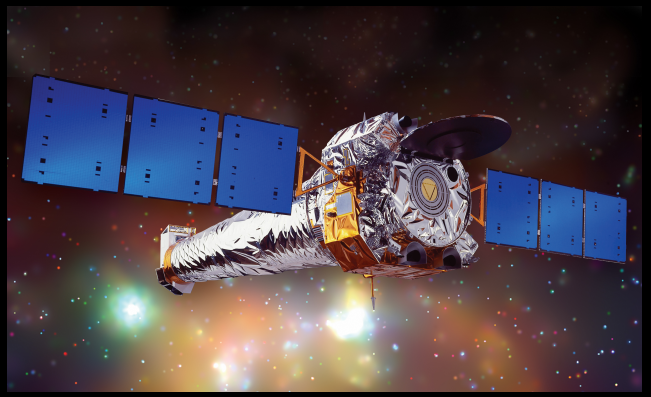
3C 273

Hot atmospheres in X-rays



XMM-Newton, ESA, 1999

Chandra, NASA, 1999

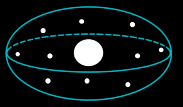


Suzaku, JAXA, 2005

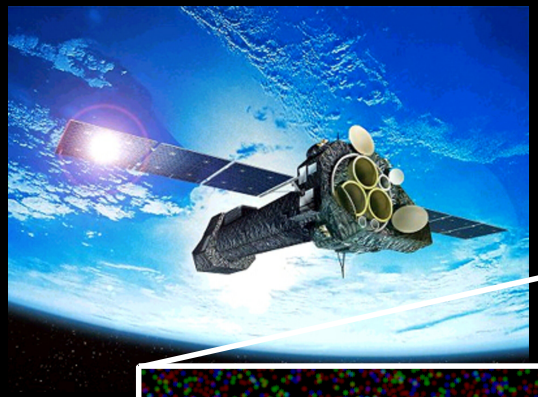
XRISM, JAXA, 2023?

Athena, ESA, 2030s

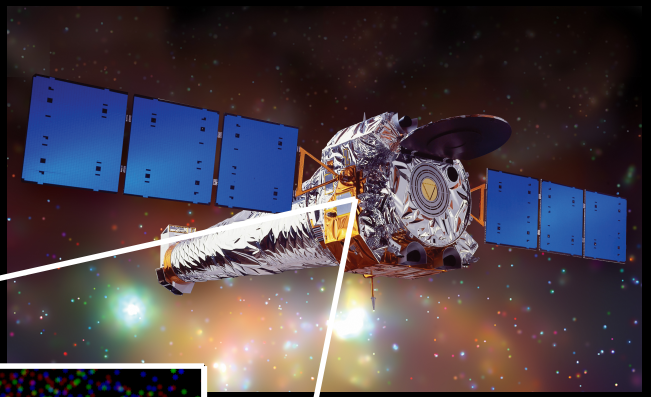
Hot atmospheres in X-rays



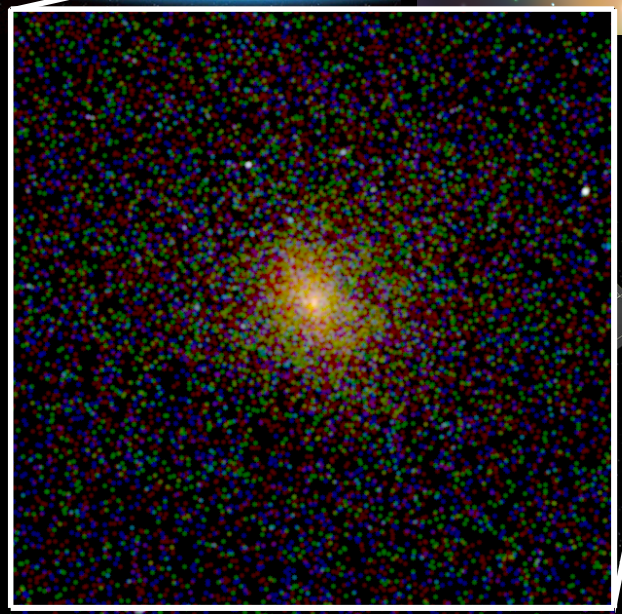
XMM-Newton, ESA, 1999



Chandra, NASA, 1999

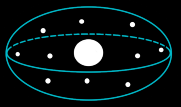


Suzaku, JAXA, 2005

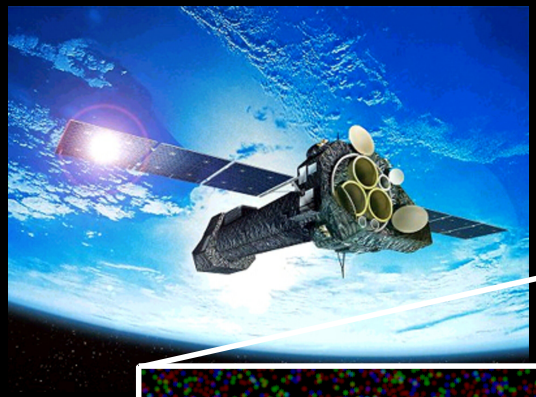


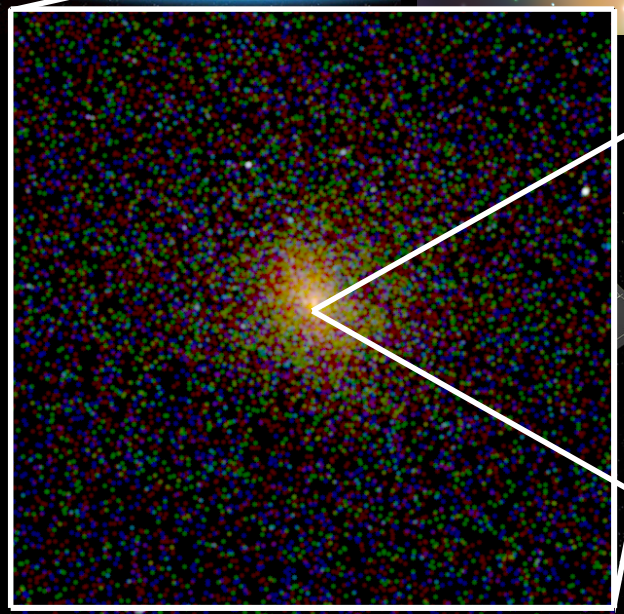
Athena, ESA, 2030s

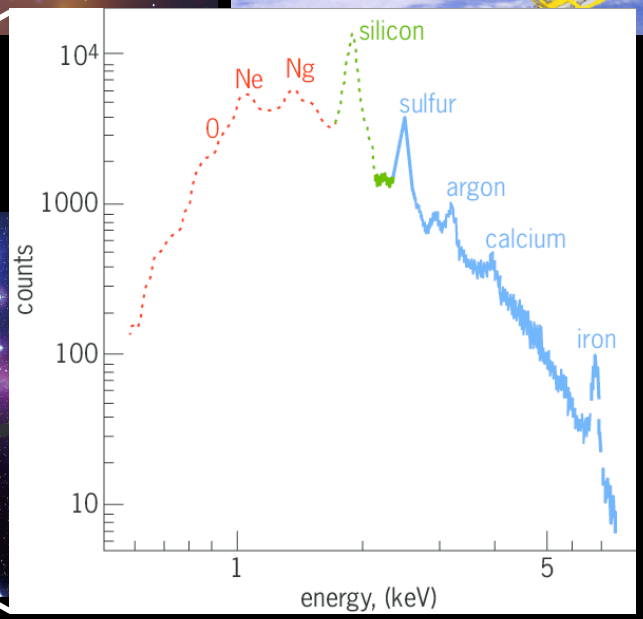
Hot atmospheres in X-rays



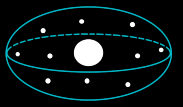
XMM-Newton, ESA, 1999 Chandra, NASA, 1999 Suzaku, JAXA, 2005

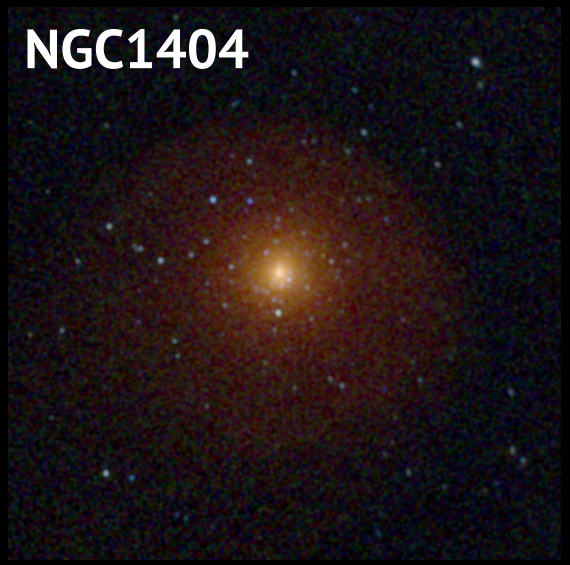


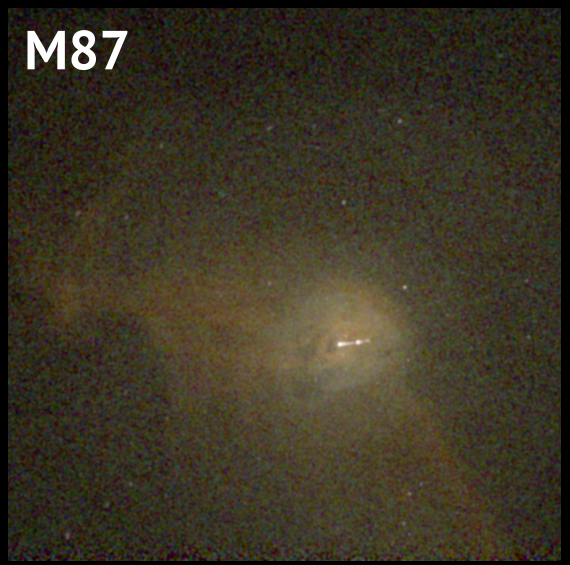


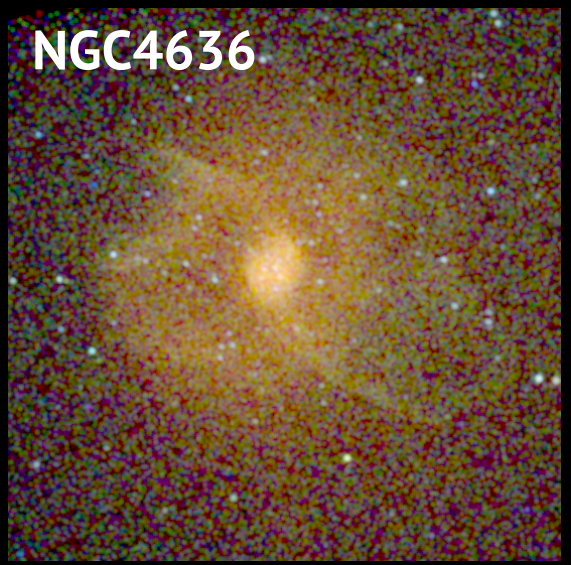


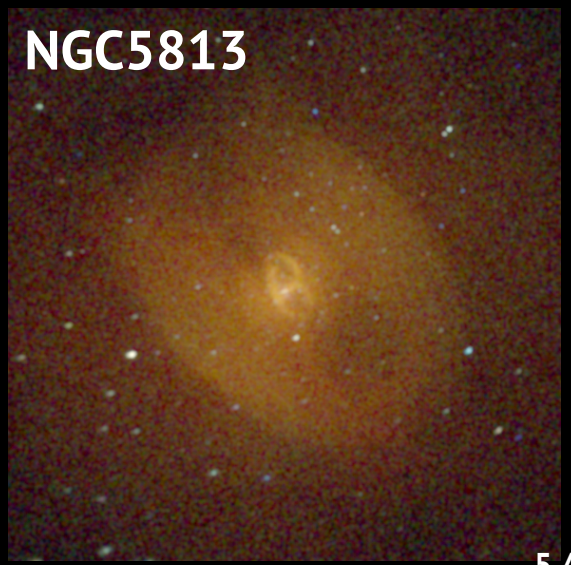
Hot atmospheres in X-rays



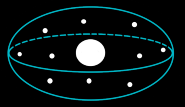








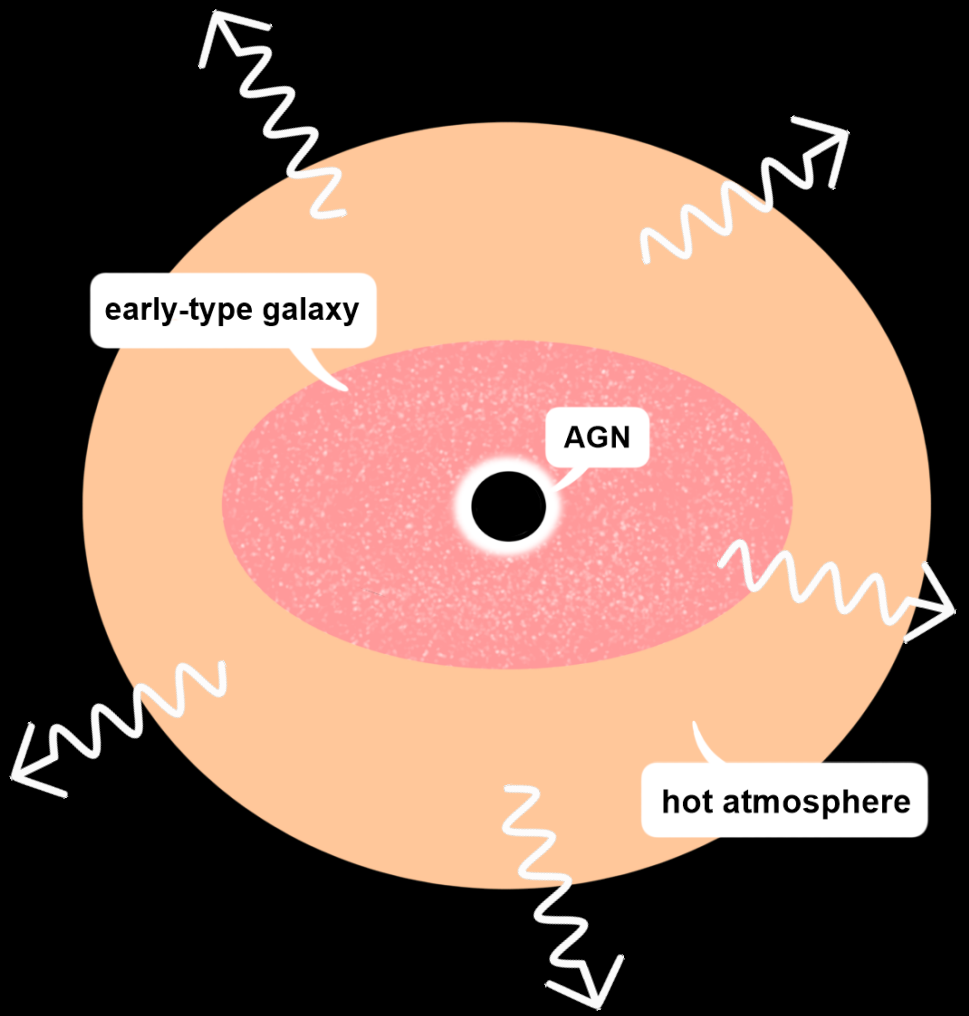
Cooling atmospheres



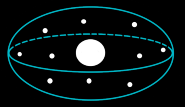
- atmospheres emit X-rays
  - optically thin

  $\Rightarrow$ no γ are absorbed

  $\Rightarrow$ cool radiatively



Cooling atmospheres



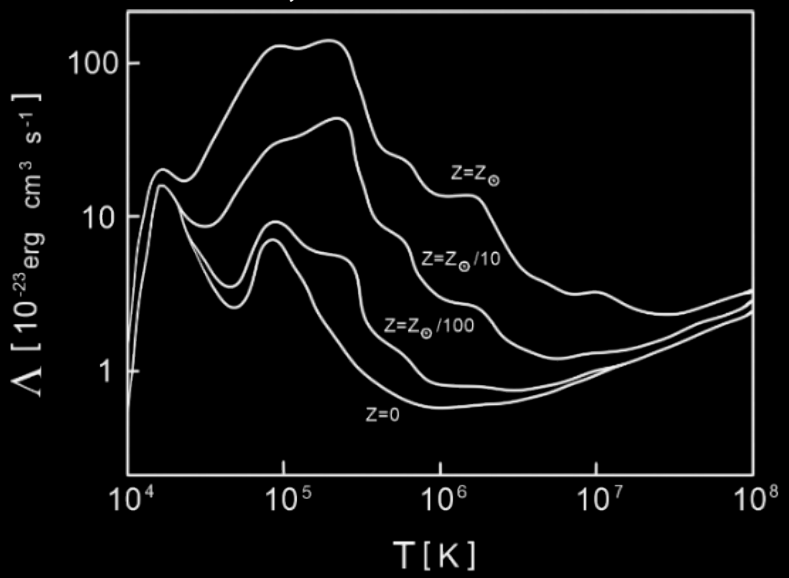
- atmospheres emit X-rays
  - optically thin

  $\Rightarrow$ no γ are absorbed

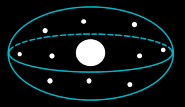
  $\Rightarrow$ cool radiatively
- cooling time

$$t_{\mathrm{cool}} = \frac{\frac{3}{2} nkT}{L_{\mathrm{X}}} = \frac{\frac{3}{2} nkT}{n_{\mathrm{i}}\, n_{\mathrm{e}}\, \Lambda(Z,T)}$$

Mo, Bosch & White 2010



Cooling atmospheres



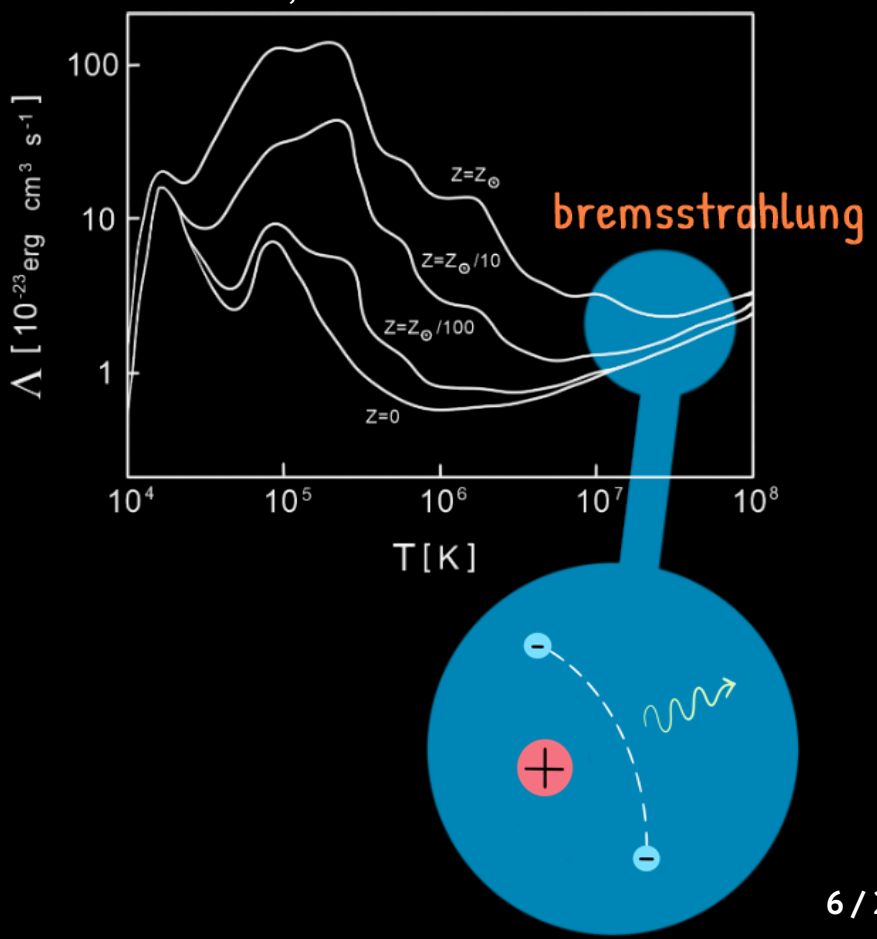
- atmospheres emit X-rays
  - optically thin

  $\Rightarrow$ no γ are absorbed

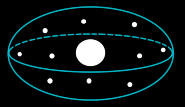
  $\Rightarrow$ cool radiatively
- cooling time

$$t_{\mathrm{cool}} = \frac{\frac{3}{2} nkT}{L_{\mathrm{X}}} = \frac{\frac{3}{2} nkT}{n_{\mathrm{i}}\, n_{\mathrm{e}}\, \Lambda(Z,T)}$$

Mo, Bosch & White 2010



Cooling atmospheres

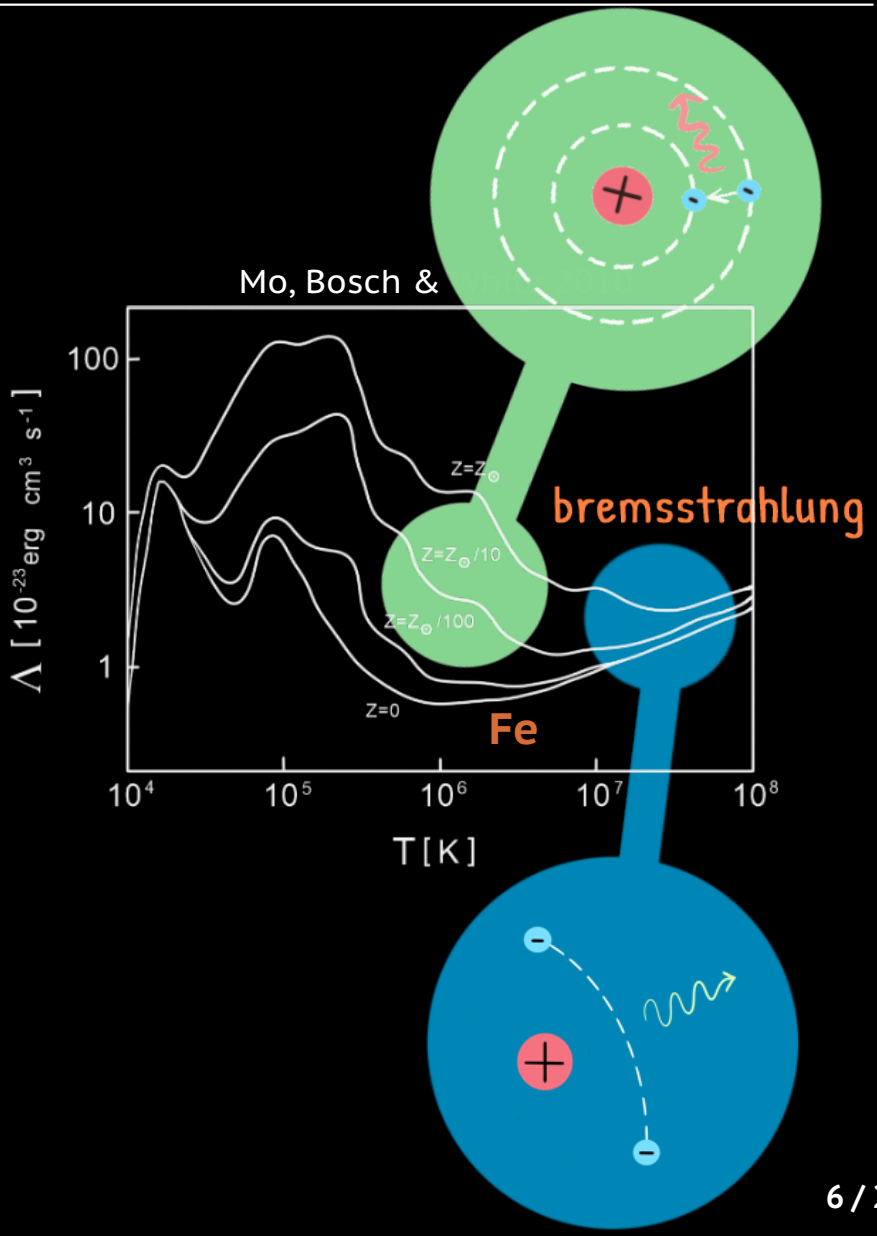


- atmospheres emit X-rays
  - optically thin

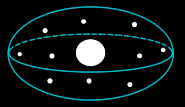
  $\Rightarrow$ no γ are absorbed

  $\Rightarrow$ cool radiatively
- cooling time

$$t_{\rm cool} = \frac{\frac{3}{2} nkT}{L_{\rm X}} = \frac{\frac{3}{2} nkT}{n_{\rm i}\, n_{\rm e}\, \Lambda(Z,T)}$$



Cooling atmospheres

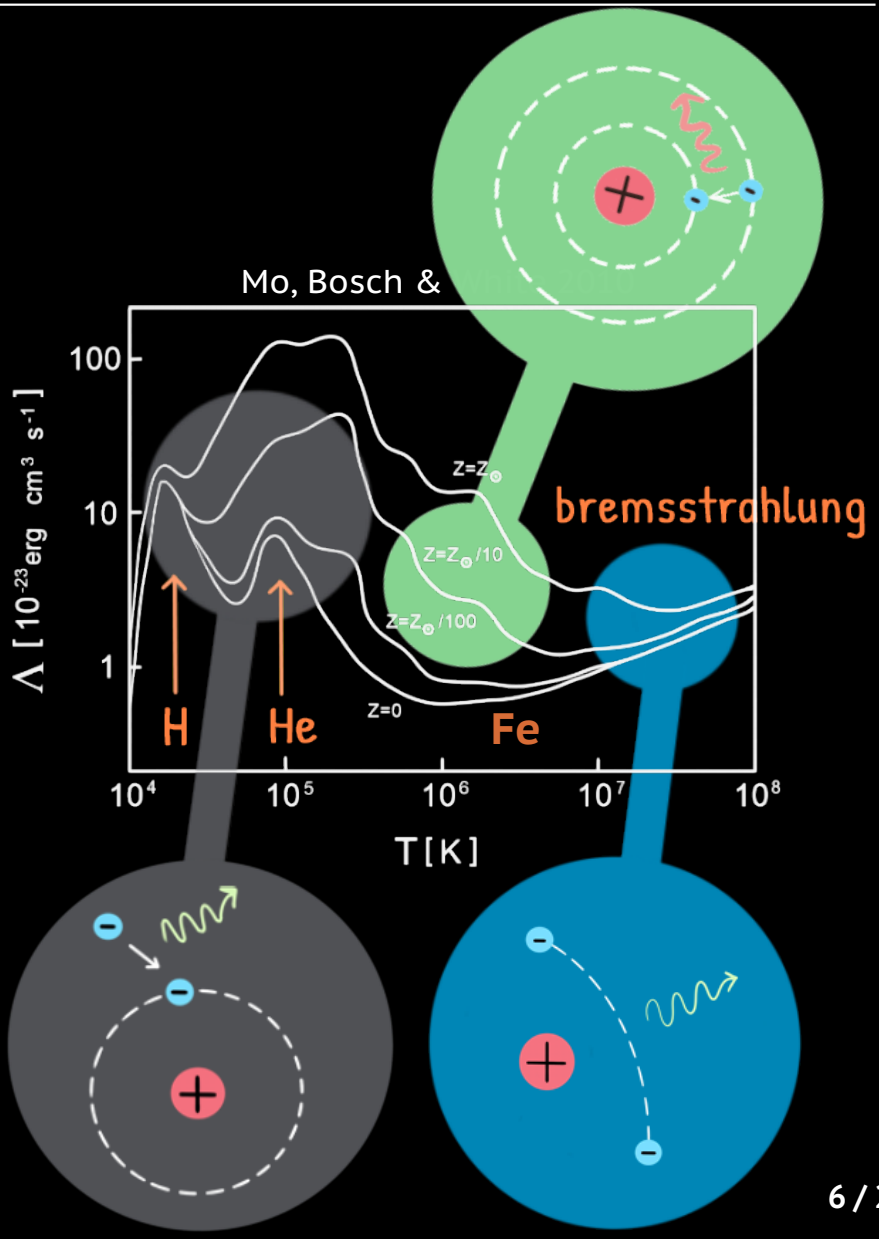


- atmospheres emit X-rays
  - optically thin

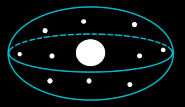
  $\Rightarrow$ no γ are absorbed

  $\Rightarrow$ cool radiatively
- cooling time

$$t_{\rm cool} = \frac{\frac{3}{2} nkT}{L_{\rm X}} = \frac{\frac{3}{2} nkT}{n_{\rm i}\, n_{\rm e}\, \Lambda(Z,T)}$$



Cooling atmospheres



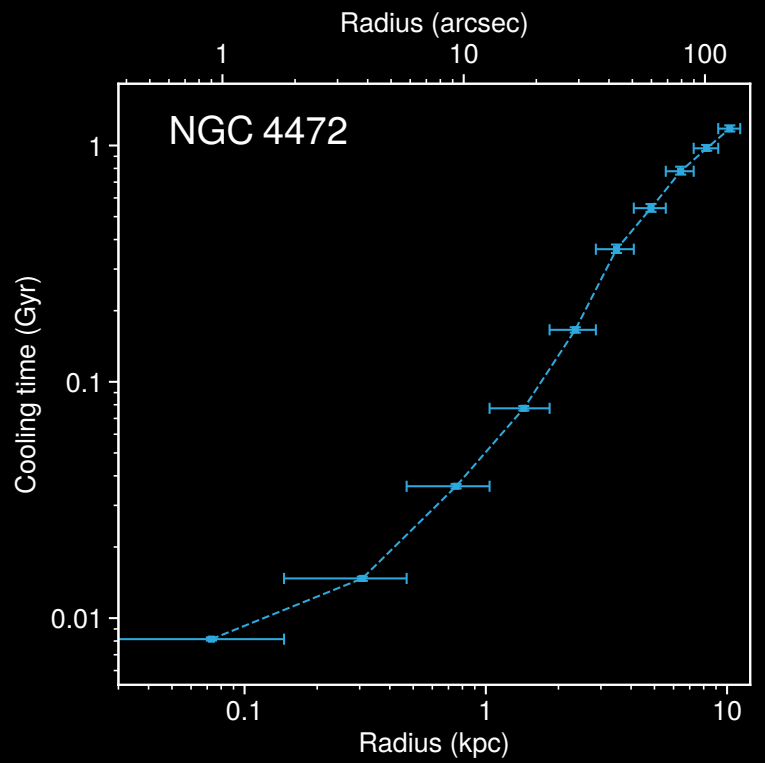
- atmospheres emit X-rays
  - optically thin

  $\Rightarrow$ no γ are absorbed

  $\Rightarrow$ cool radiatively
- cooling time

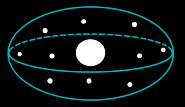
$$t_{\mathrm{cool}} = \frac{\frac{3}{2} nkT}{L_{\mathrm{X}}} = \frac{\frac{3}{2} nkT}{n_{\mathrm{i}}\, n_{\mathrm{e}}\, \Lambda(Z,T)}$$

$$t_{\mathrm{cool}} \propto \frac{kT}{\rho}$$



Credit: Plšek et al. 2022

Cooling atmospheres



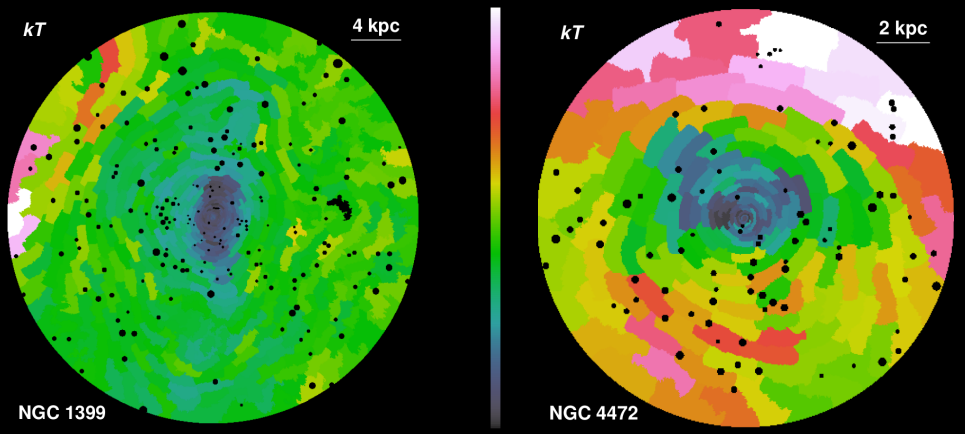
- atmospheres emit X-rays
  - optically thin

  $\Rightarrow$ no γ are absorbed

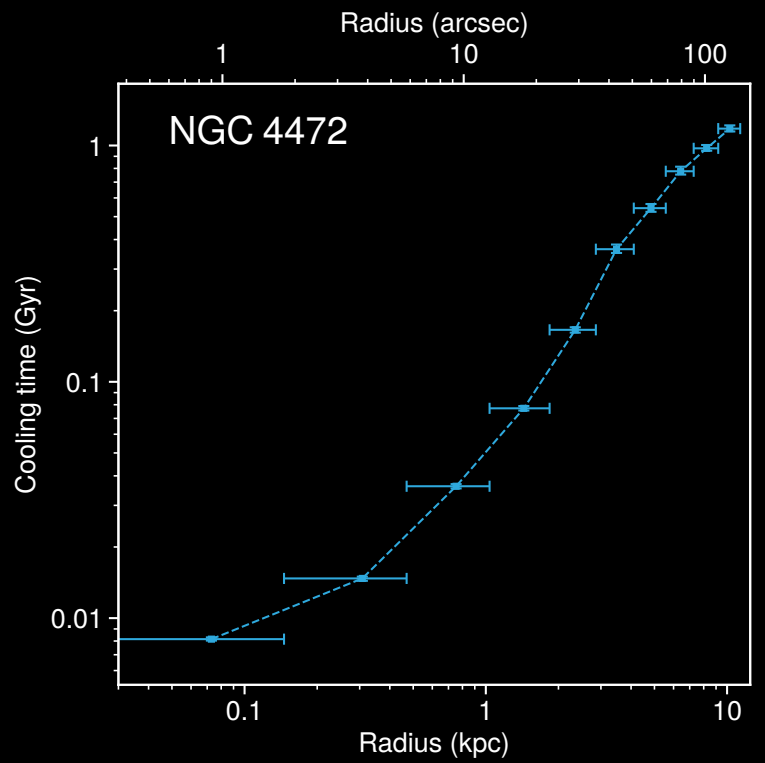
  $\Rightarrow$ cool radiatively
- cooling time

$$t_{\mathrm{cool}} = \frac{\frac{3}{2} nkT}{L_{\mathrm{X}}} = \frac{\frac{3}{2} nkT}{n_{\mathrm{i}}\, n_{\mathrm{e}}\, \Lambda(Z,T)}$$

$$t_{\mathrm{cool}} \propto \frac{kT}{\rho}$$

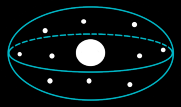


Credit: Werner et al. 2012



Credit: Plšek et al. 2022

Cooling atmospheres



- atmospheres emit X-rays
  - optically thin
  - $\Rightarrow$ no γ are absorbed
  - $\Rightarrow$ cool radiatively
- cooling time

$$t_{\mathrm{cool}} = \frac{\frac{3}{2} nkT}{L_{\mathrm{X}}} = \frac{\frac{3}{2} nkT}{n_{\mathrm{i}}\, n_{\mathrm{e}}\, \Lambda(Z,T)}$$

NGC 5044

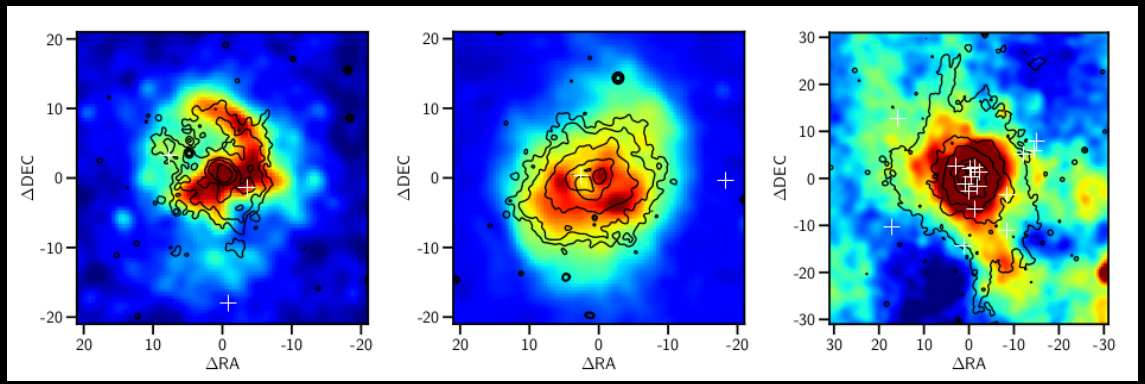
Credit: Werner 2014

Perseus cluster

Credit: NASA, ESA

- multiphase gas
  - hot X-ray gas
  - Hα filaments
  - molecular clouds (CO)

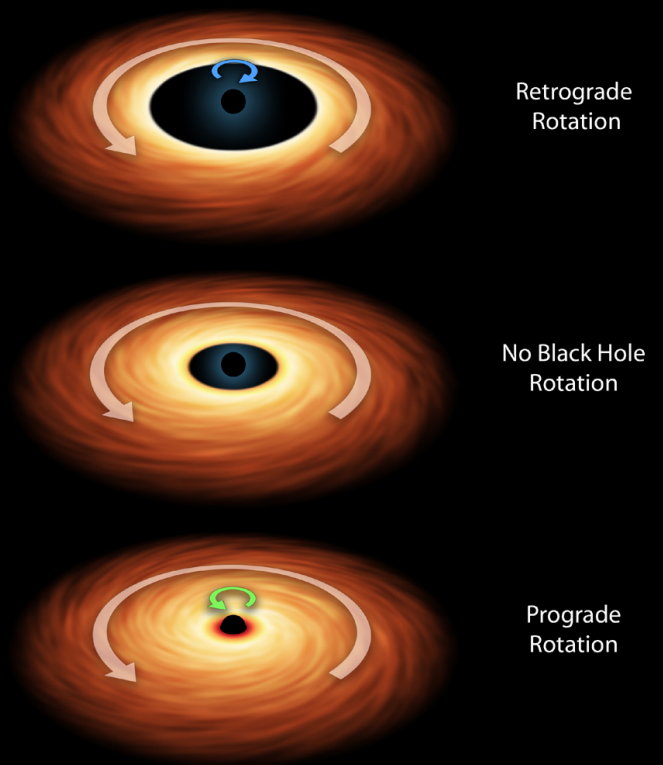
NGC 5846 NGC 4636 NGC 5044



Credit: Temi et al. 2018

Active galactic nuclei (AGN)

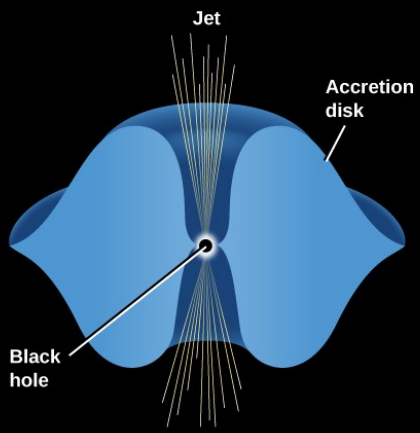
- supermassive black hole
  - accretes ambient material
  - rest mass $\rightarrow$ energy $\rightarrow$ EM/jets
- efficiency depends on spin
  - non-rotating 6 %
  - maximally rotating 40 %
  - geometry of accretion flow



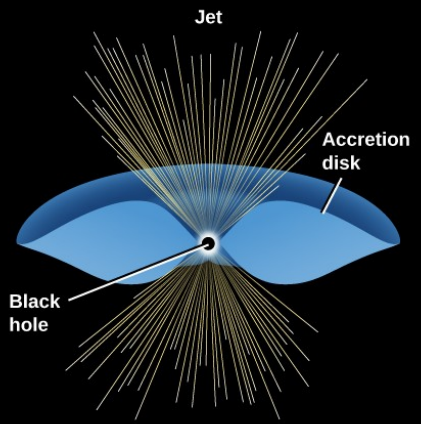
Active galactic nuclei (AGN)

- supermassive black hole
  - accretes ambient material
  - rest mass $\rightarrow$ energy $\rightarrow$ EM/jets
- efficiency depends on spin
  - non-rotating 6 %
  - maximally rotating 40 %
  - geometry of accretion flow

thick disk / torus



thin disk



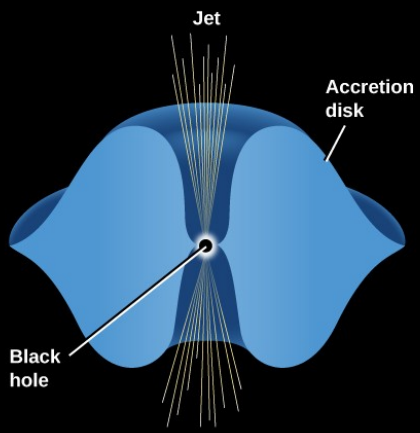
Active galactic nuclei (AGN)

- supermassive black hole
  - accretes ambient material
  - rest mass $\rightarrow$ energy $\rightarrow$ EM/jets
- efficiency depends on spin
  - non-rotating 6 %
  - maximally rotating 40 %
  - geometry of accretion flow

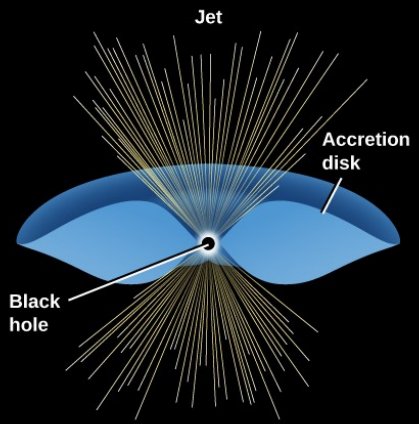
$$r_{\mathrm{Bondi}} = \frac{GM_{\mathrm{BH}}}{c_s^2}$$

$$\dot{m}_{\mathrm{Bondi}} = \pi \lambda \rho r_{\mathrm{Bondi}}^2 c_s$$

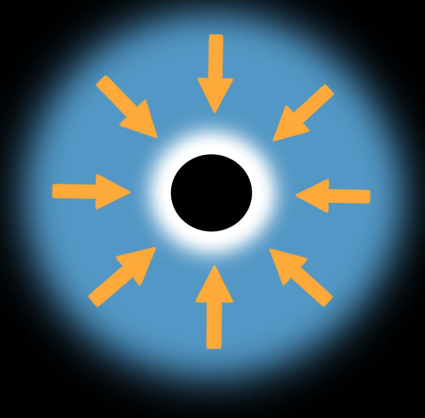
thick disk / torus



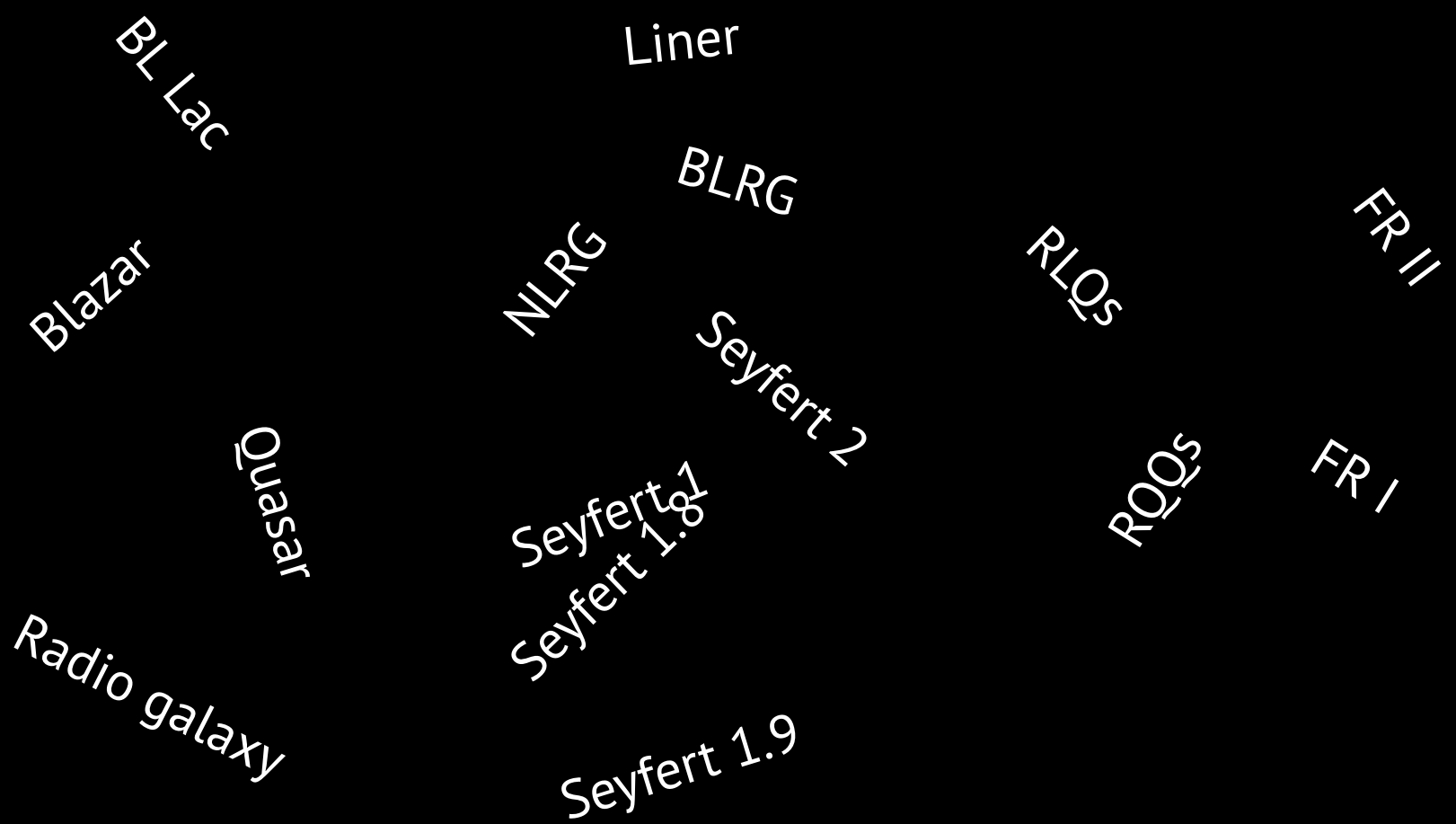
thin disk



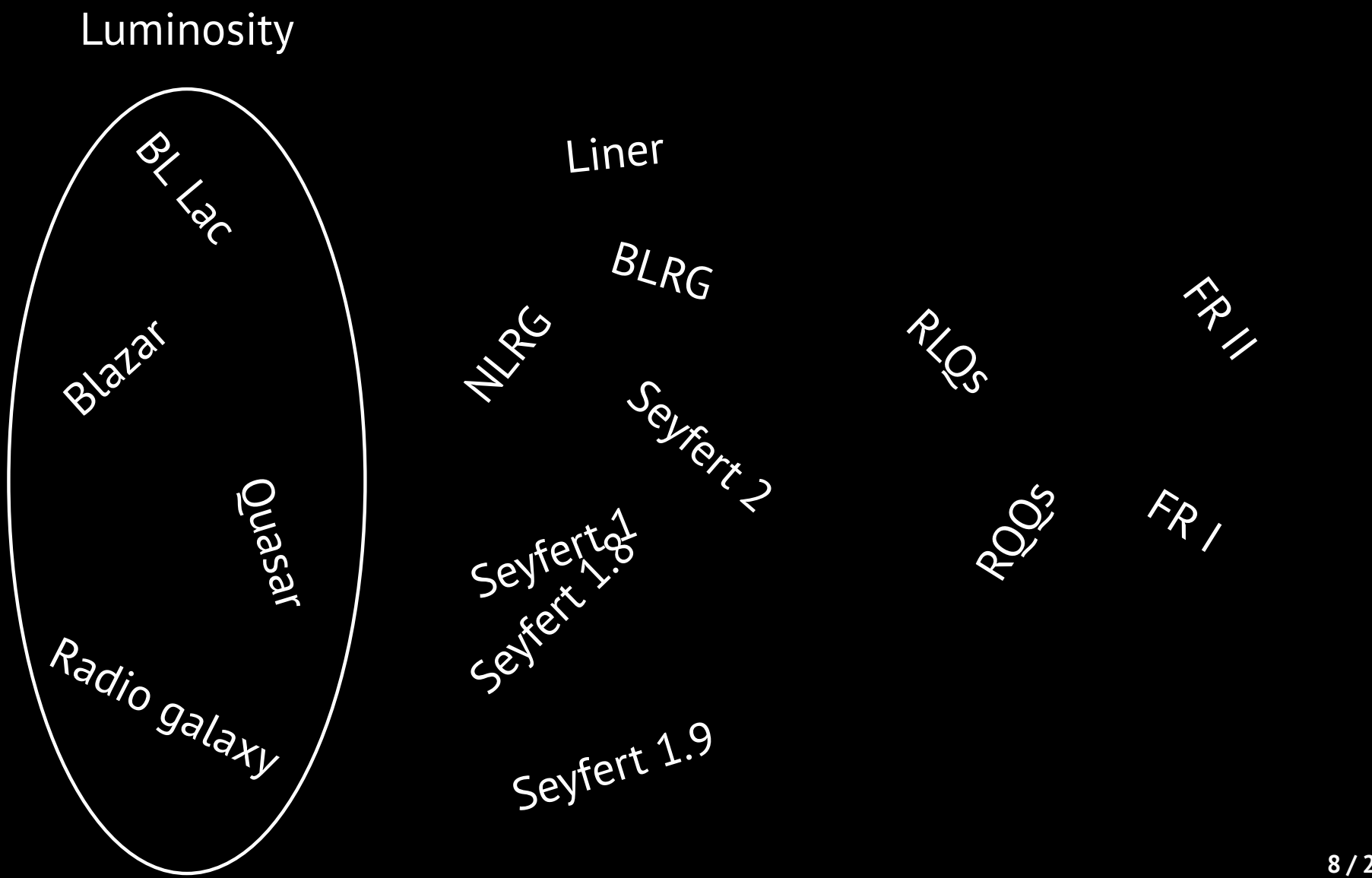
spherical accretion



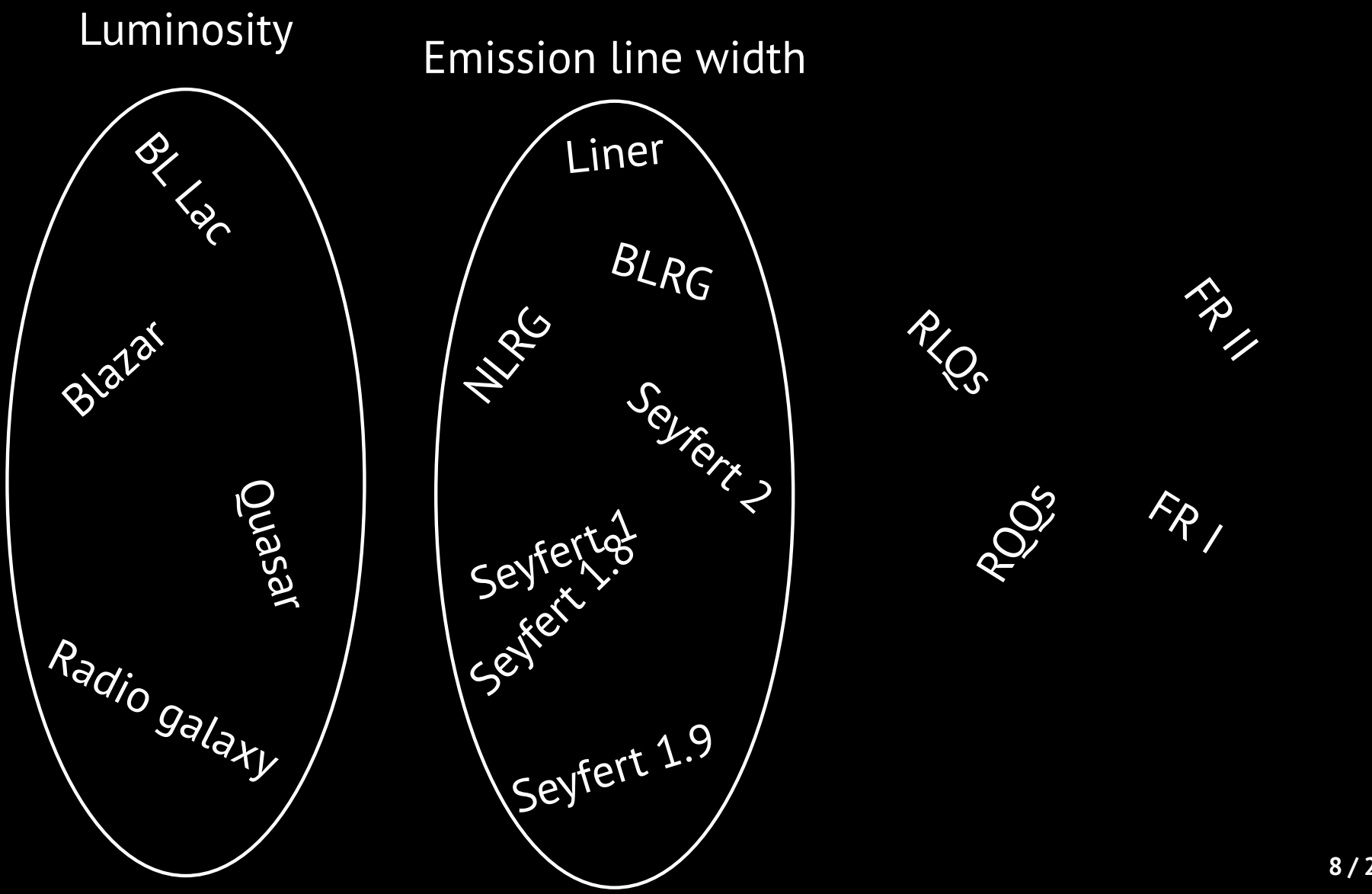
AGN unification scheme



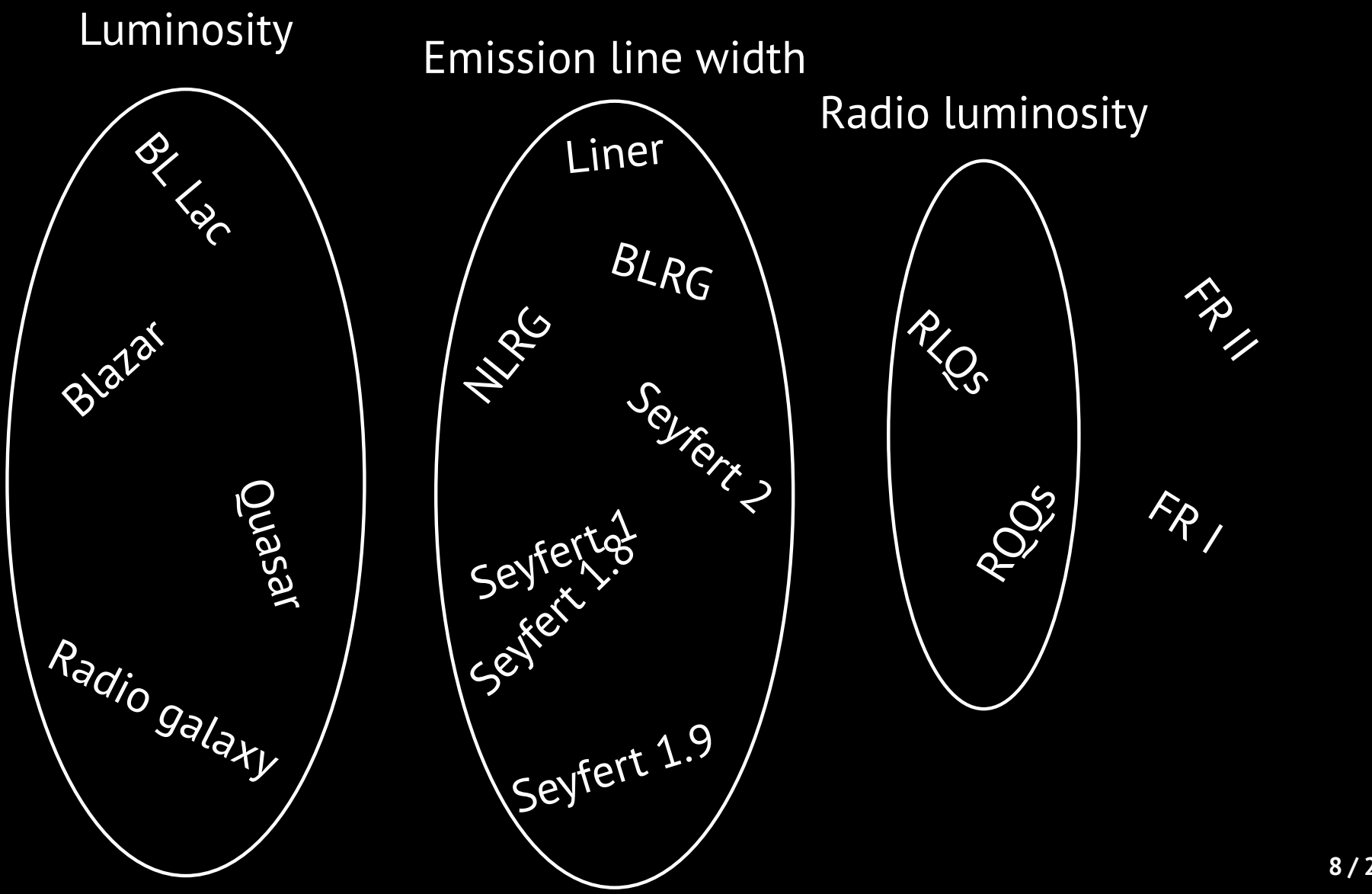
AGN unification scheme



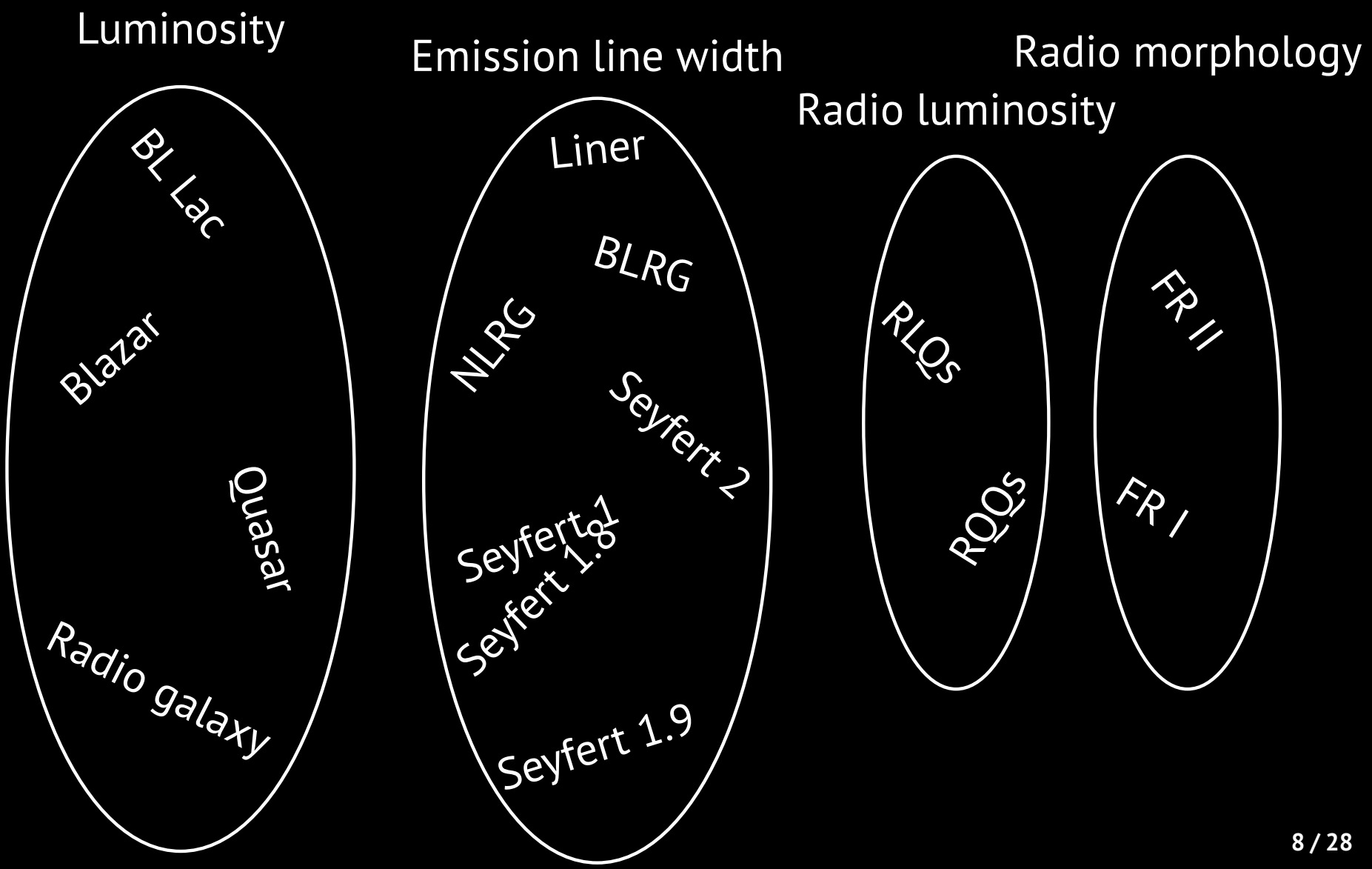
AGN unification scheme



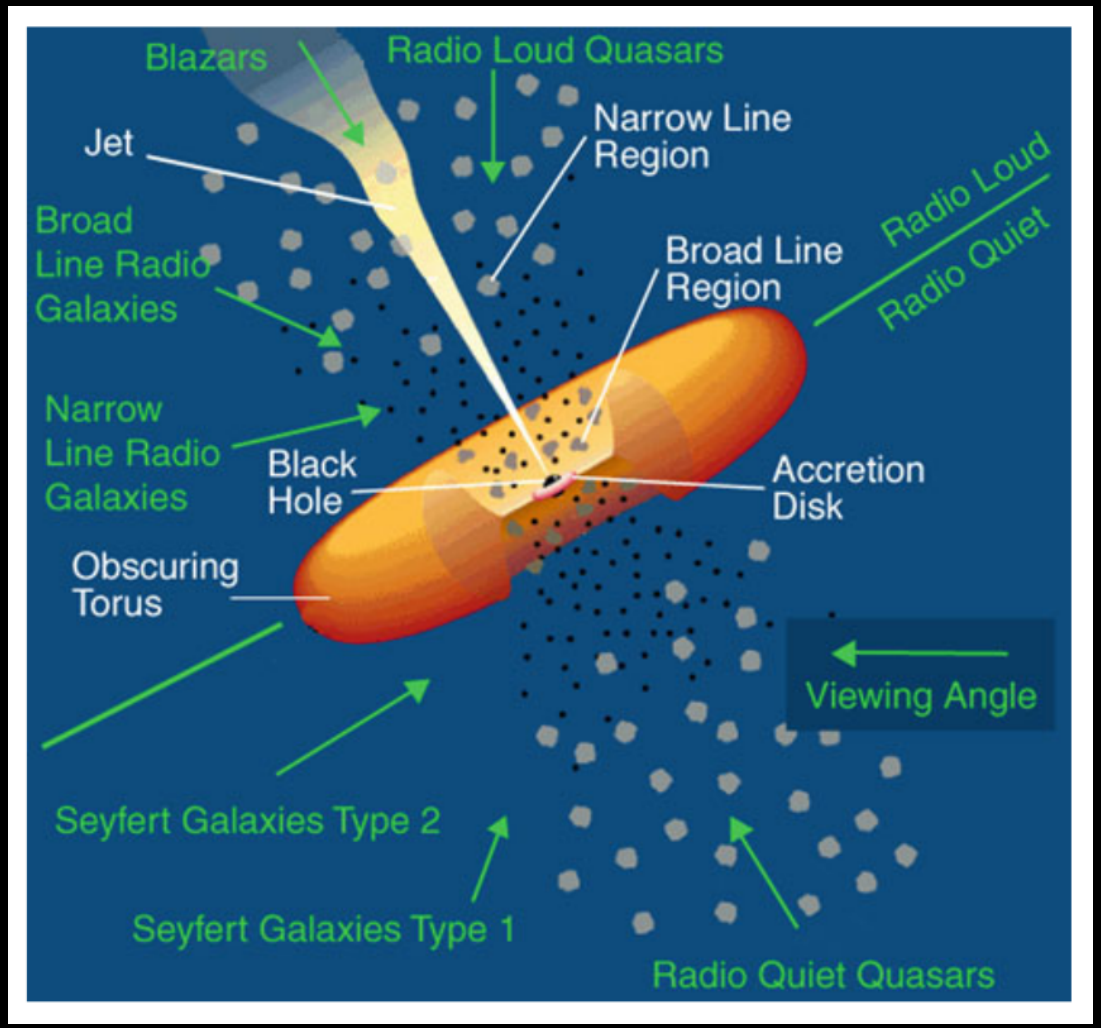
AGN unification scheme



AGN unification scheme

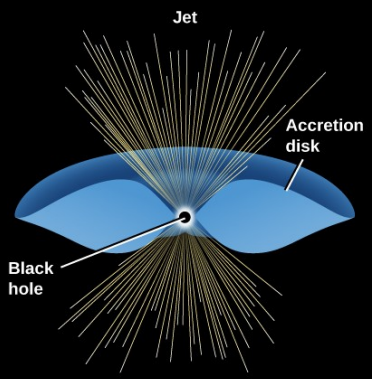


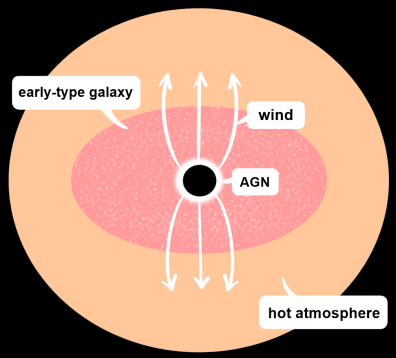
AGN unification scheme



Quasar vs Radio galaxy

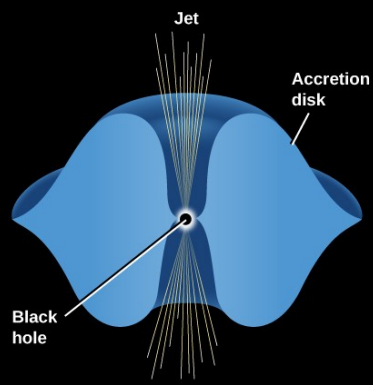
Quasar

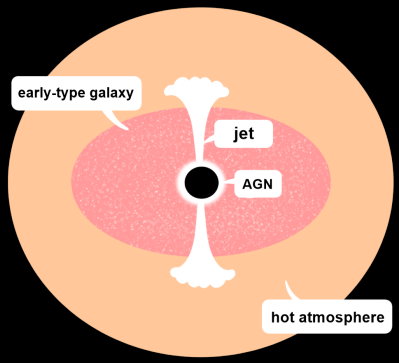




- optically thick disk
- radiatively efficient
- EM radiation
- radio quiet (loud)
- $L_{\mathrm{bol}} = 10^{45} - 10^{48}$ erg/s
- all galaxy types

Radio galaxy





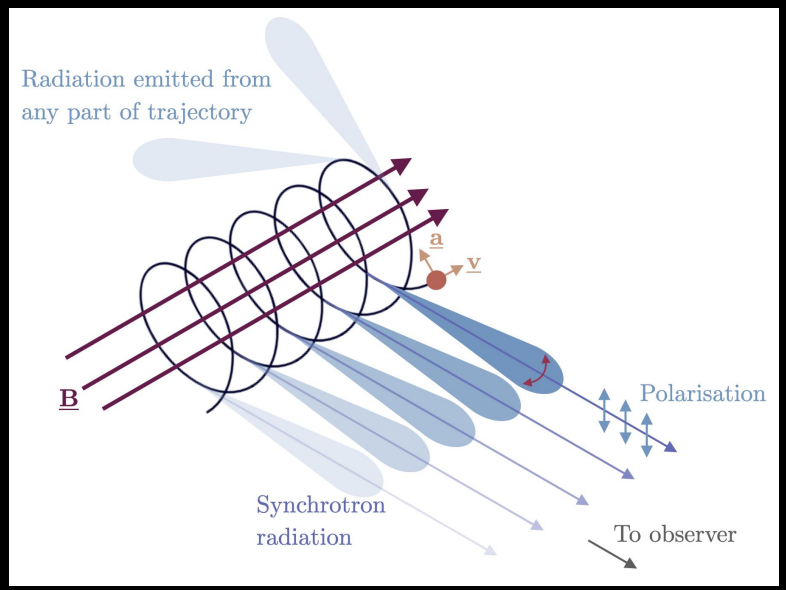
- optically thin torus
- radiatively inefficient
- relativistic jets
- radio loud
- $P_{\mathrm{jet}} = 10^{41} - 10^{46}$ erg/s
- early-type galaxies

Radio galaxies

- relativistic particles (e^-, e^+) in magnetic field (**B**)

  $\Rightarrow$ synchrotron emission $\Rightarrow$ powerlaw spectrum

$$\nu_c = \frac{3\gamma eB}{4\pi m_e c} \approx 4 \times 10^6 \gamma^2 \left(\frac{B}{1\mathrm{G}}\right) \mathrm{Hz} \qquad B \approx 10^{-4}\,\mathrm{G}$$



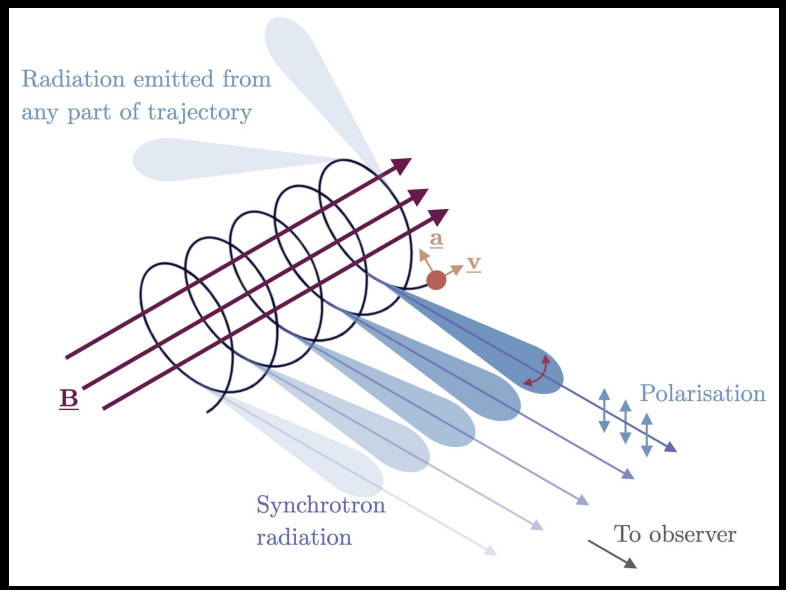
Radio galaxies

- relativistic particles (e^-, e^+) in magnetic field (**B**)

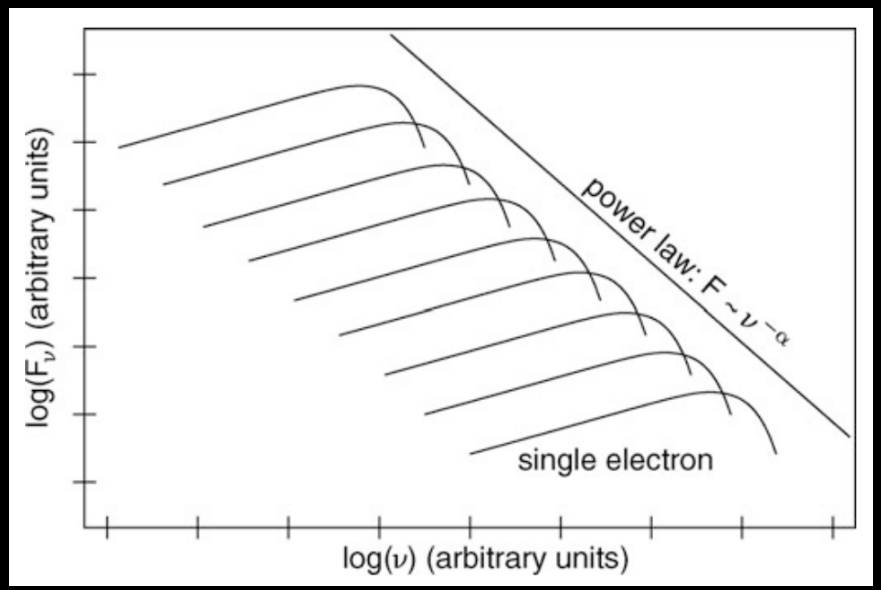
  $\Rightarrow$ synchrotron emission $\Rightarrow$ powerlaw spectrum

$$\nu_c = \frac{3\gamma eB}{4\pi m_e c} \approx 4 \times 10^6 \gamma^2 \left(\frac{B}{1\,\mathrm{G}}\right) \mathrm{Hz} \qquad B \approx 10^{-4}\,\mathrm{G}$$

$$N(E)dE \propto E^{-s}dE \qquad \alpha = (s-1)/2 \qquad F_\nu \propto \nu^{-\alpha}$$



$\Rightarrow$



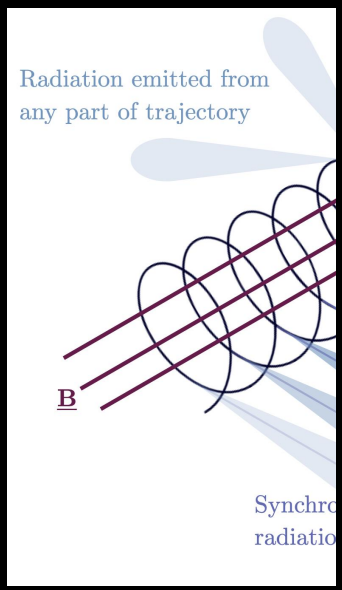
Radio galaxies

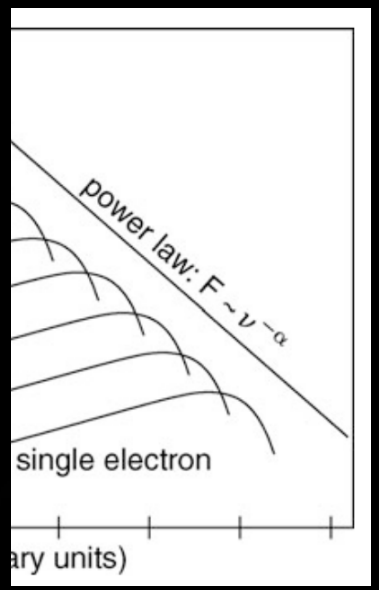
- relativistic particles (e^-, e^+) in magnetic field (**B**)

  $\Rightarrow$ synchrotron emission $\Rightarrow$ powerlaw spectrum

$$\nu_c = \frac{3\gamma eB}{4\pi m_e c} \approx 4 \times 10^6 \gamma^2 \left(\frac{B}{1\mathrm{G}}\right) \mathrm{Hz} \qquad B \approx 10^{-4}\,\mathrm{G}$$

$$N(E)dE \propto E^{-s}dE \qquad \alpha = (s-1)/2 \qquad F_\nu \propto \nu^{-\alpha}$$





Radio galaxies - observations

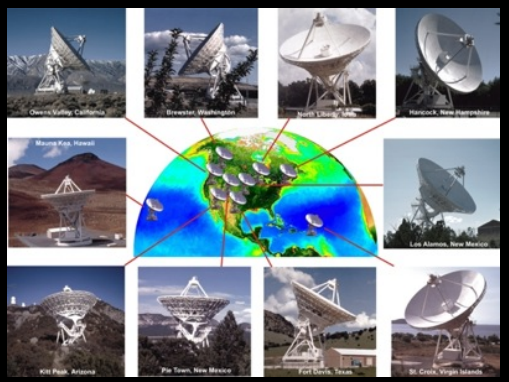
LOFAR (10 — 240 MHz)

GMRT (50 MHz — 1.5 GHz)

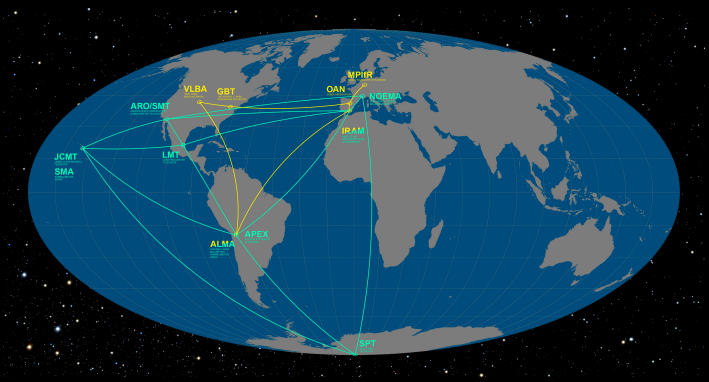
VLA (74 MHz — 50 GHz)

ALMA (31 — 1000 GHz)

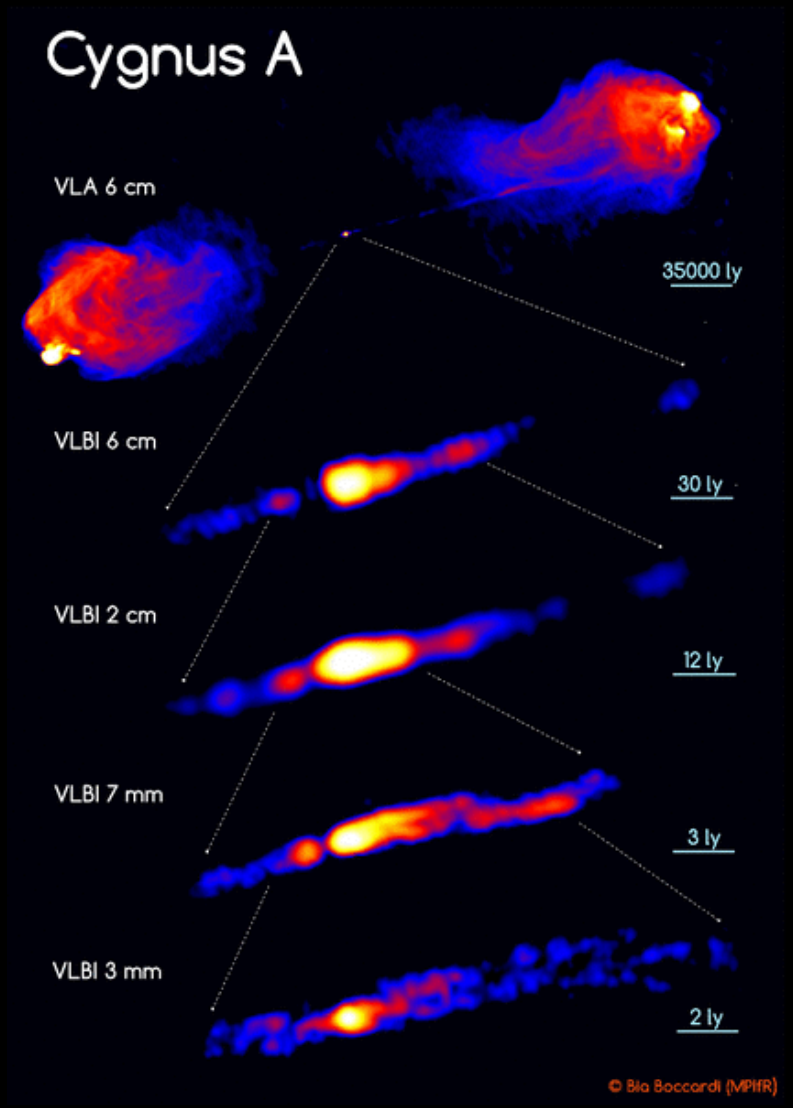
VLBA (0.3 — 96 GHz)



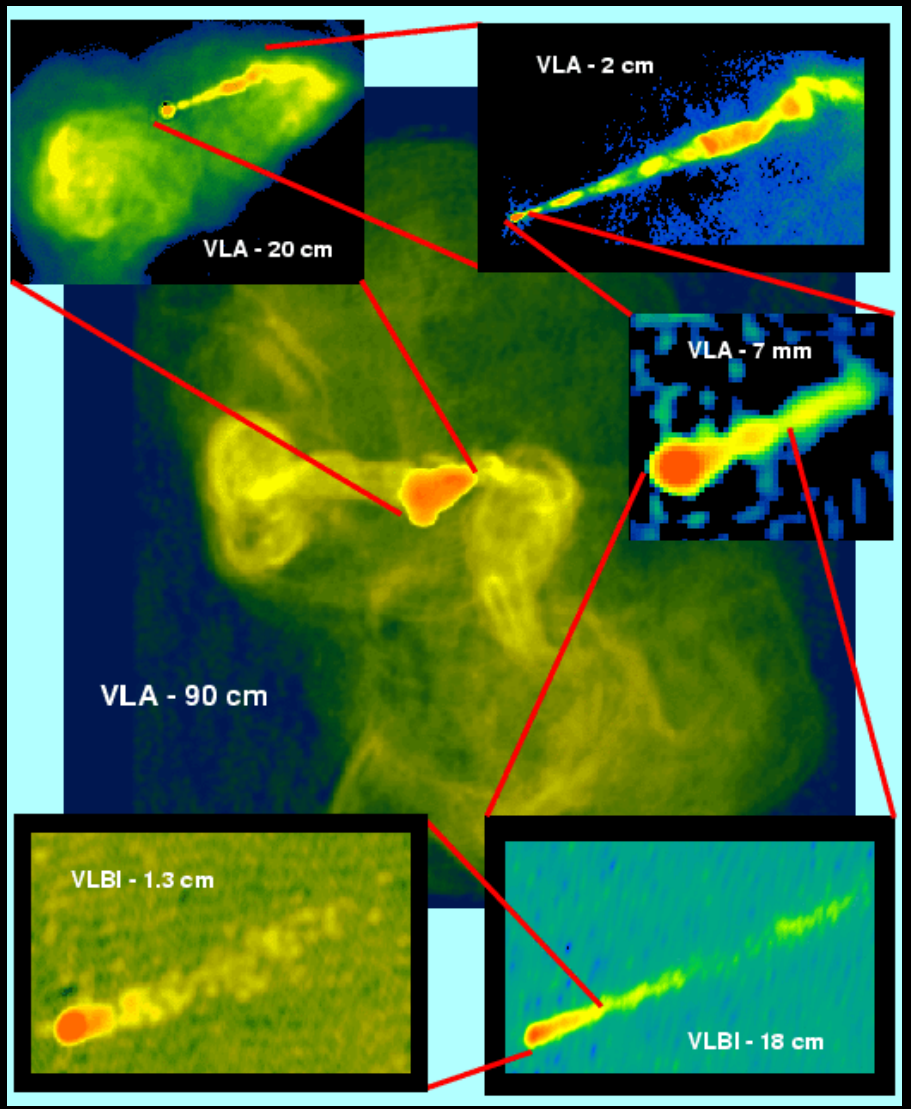
EHT (230 — 450 GHz)

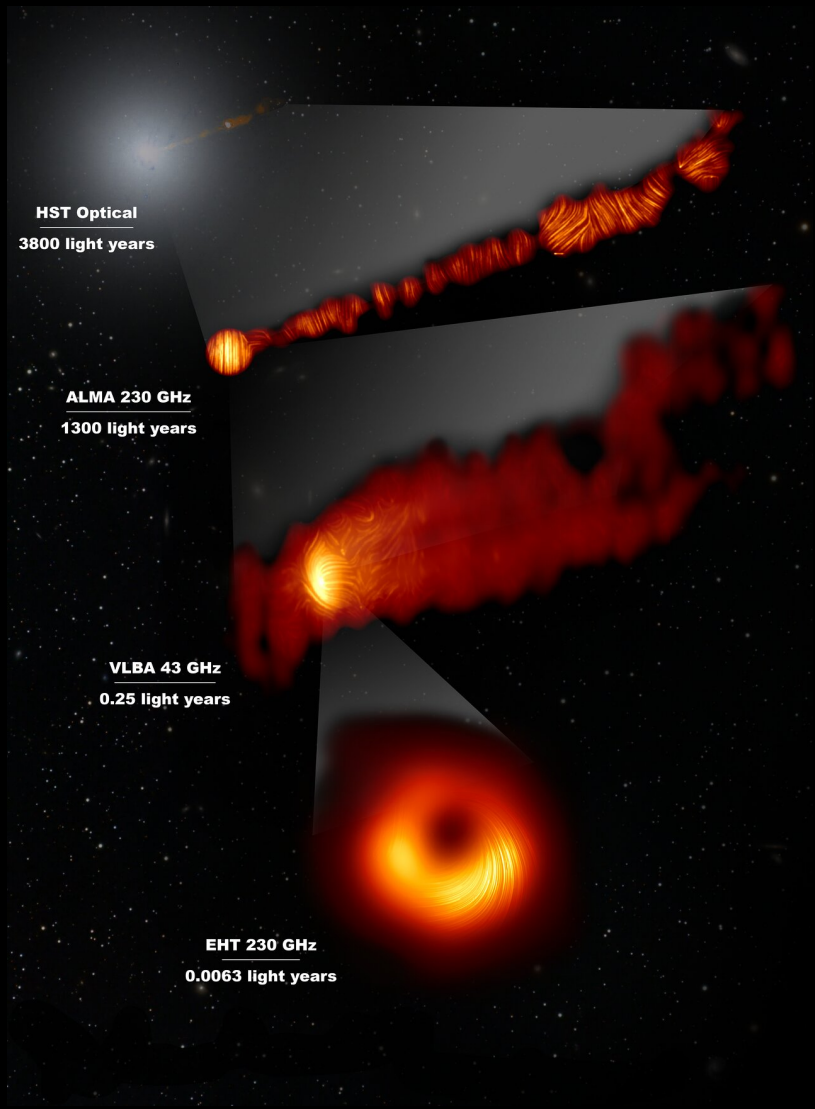


Radio galaxies - observations

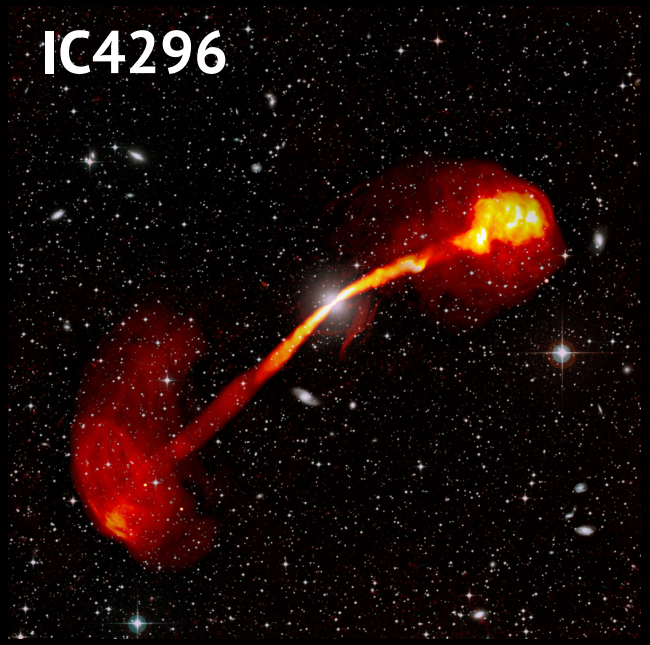


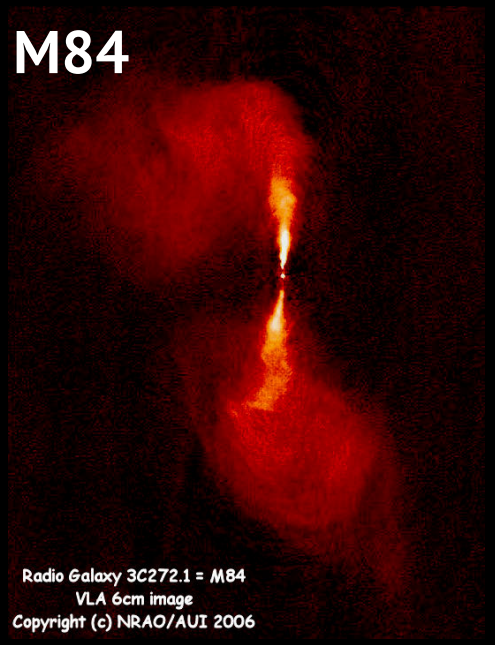
Radio galaxies - observations

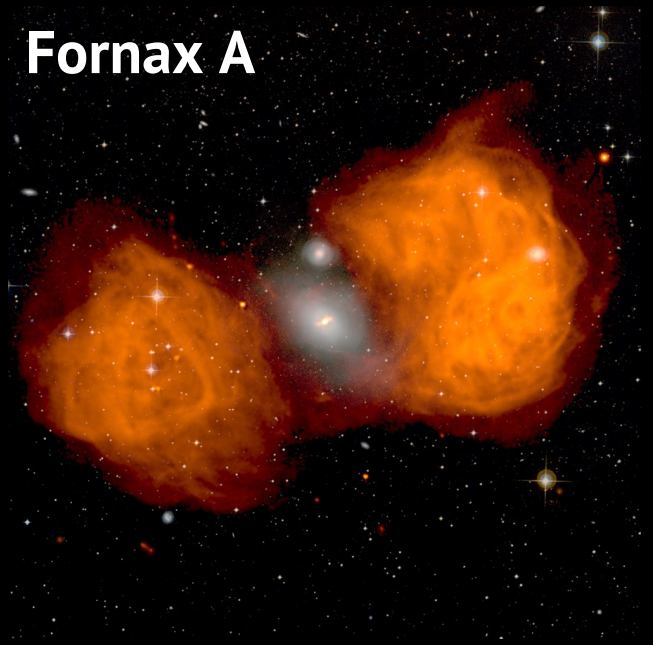


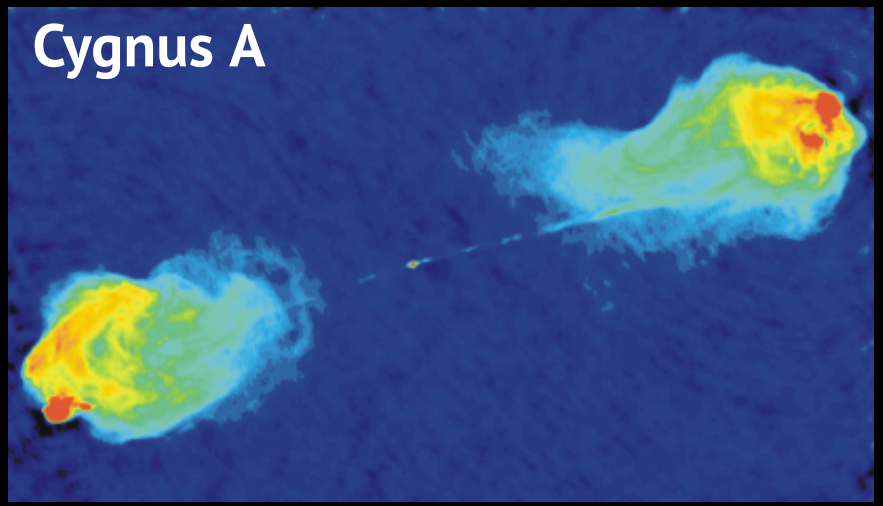


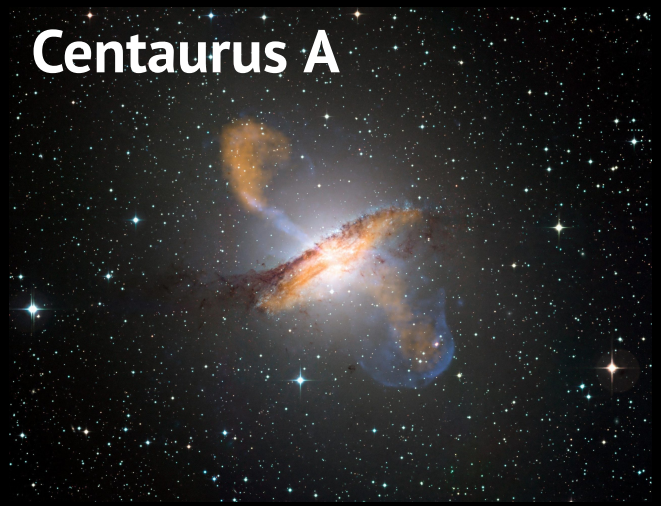
Radio galaxies - observations







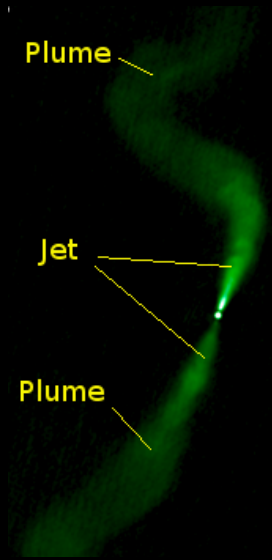


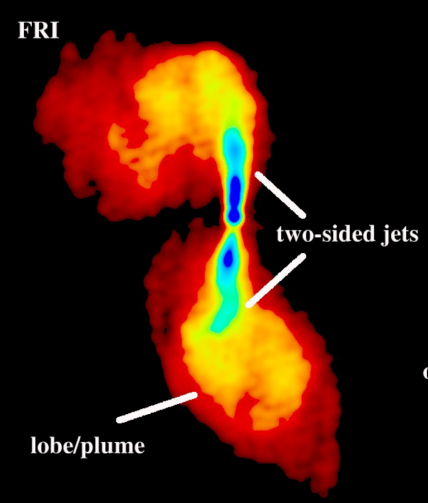


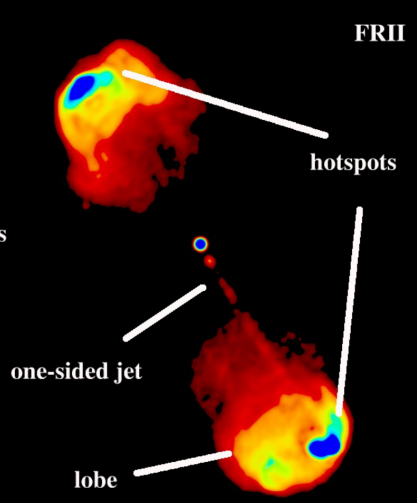
Radio galaxies - observations

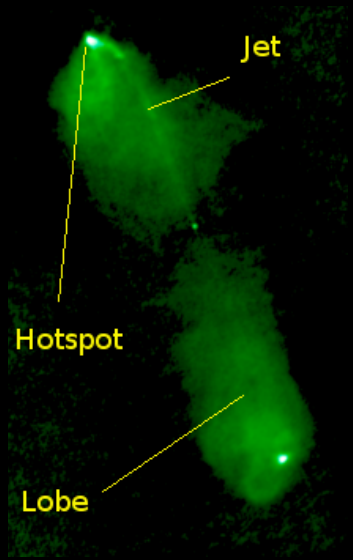
Fanaroff–Riley classification

FR I





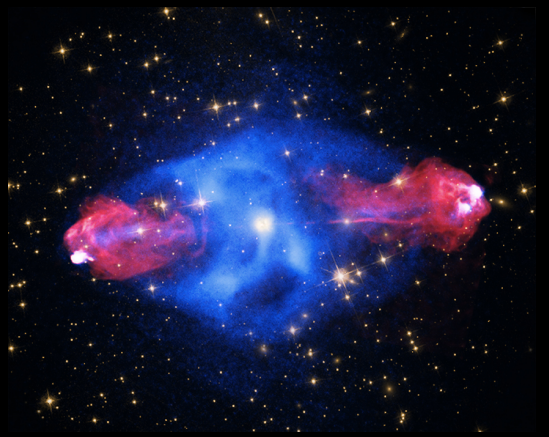




FR II

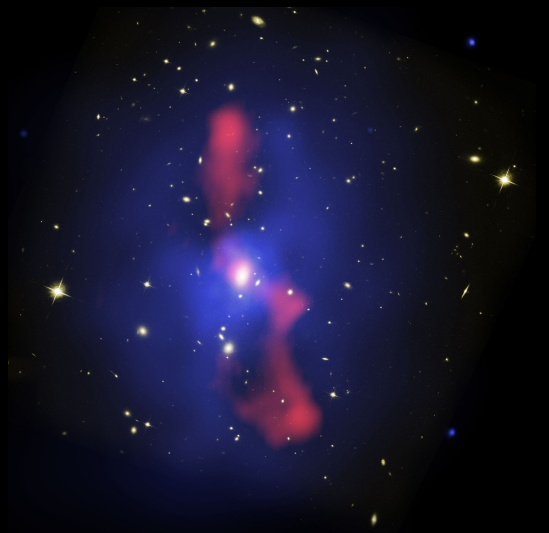
AGN feedback

- radio-mechanical mode:
  - jets interact with hot gas
  - create radio lobes
  - inflate X-ray cavities



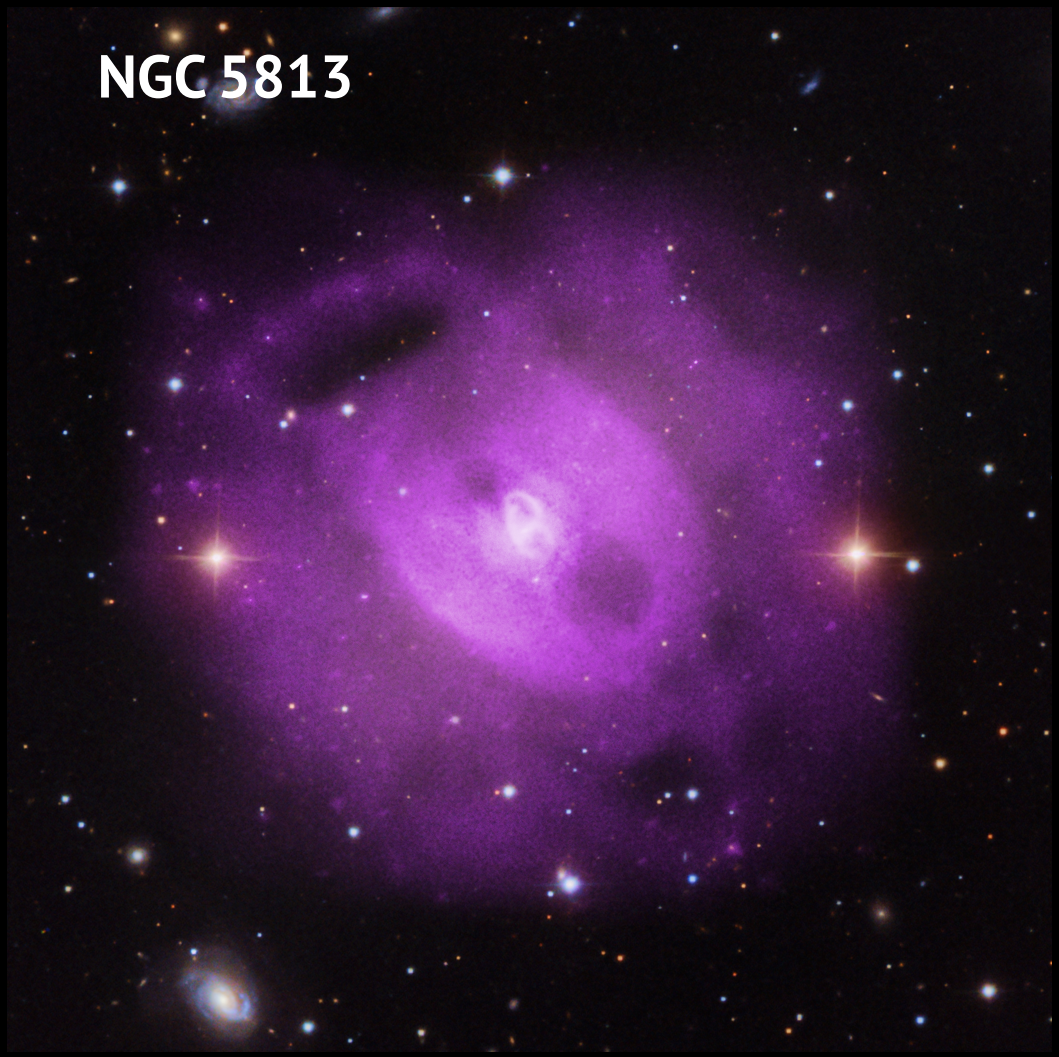
Cygnus A, Credit: NASA/NRAO

Hydra A, Credit: NASA/NRAO/DSS



MS 0735, Credit: NRAO

X-ray cavities

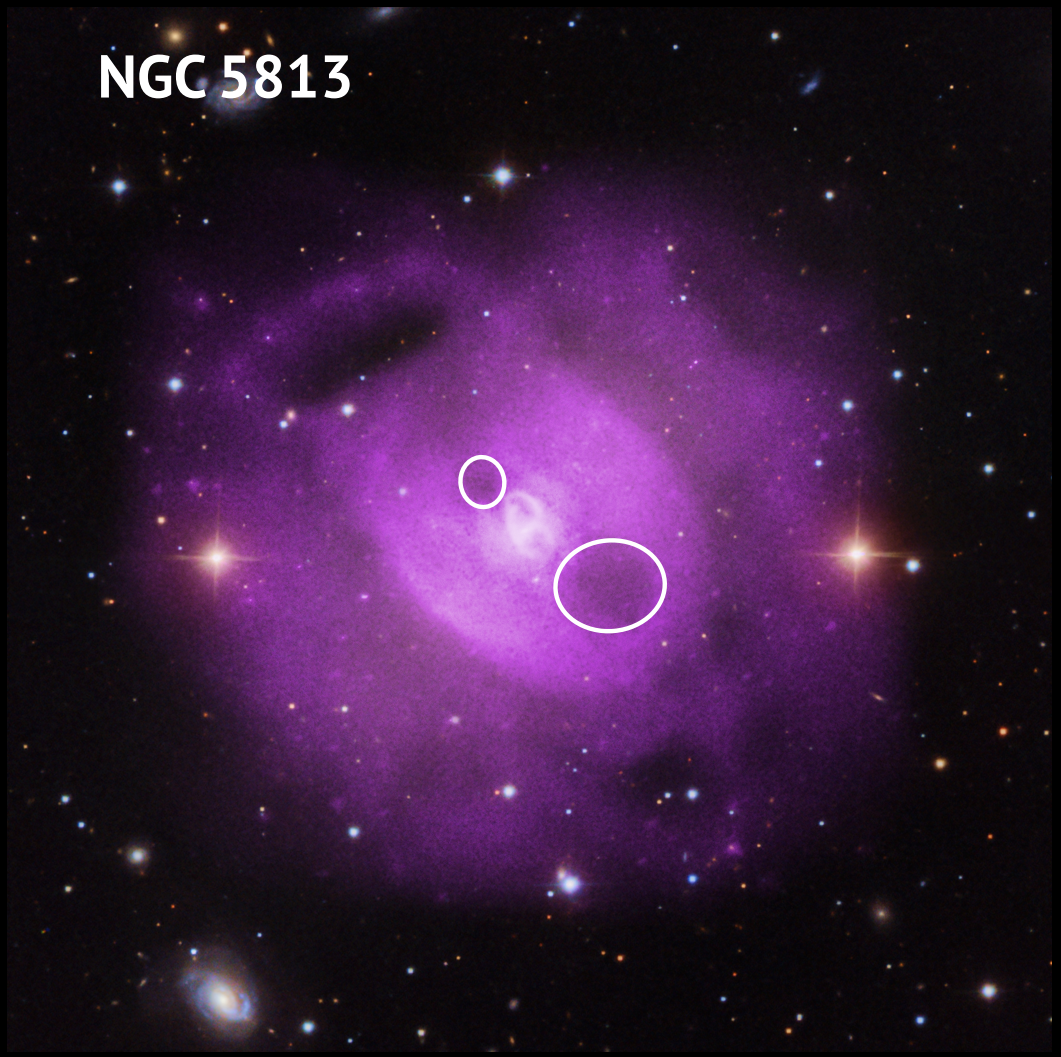


$$H = \frac{pV}{\gamma - 1} + pV$$

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

$$P_{\text{jet}} = \frac{H}{t_{\text{age}}} = \frac{4pV}{t_{\text{age}}}$$

X-ray cavities



$$H = \frac{pV}{\gamma - 1} + pV$$

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

$$P_{\text{jet}} = \frac{H}{t_{\text{age}}} = \frac{4pV}{t_{\text{age}}}$$

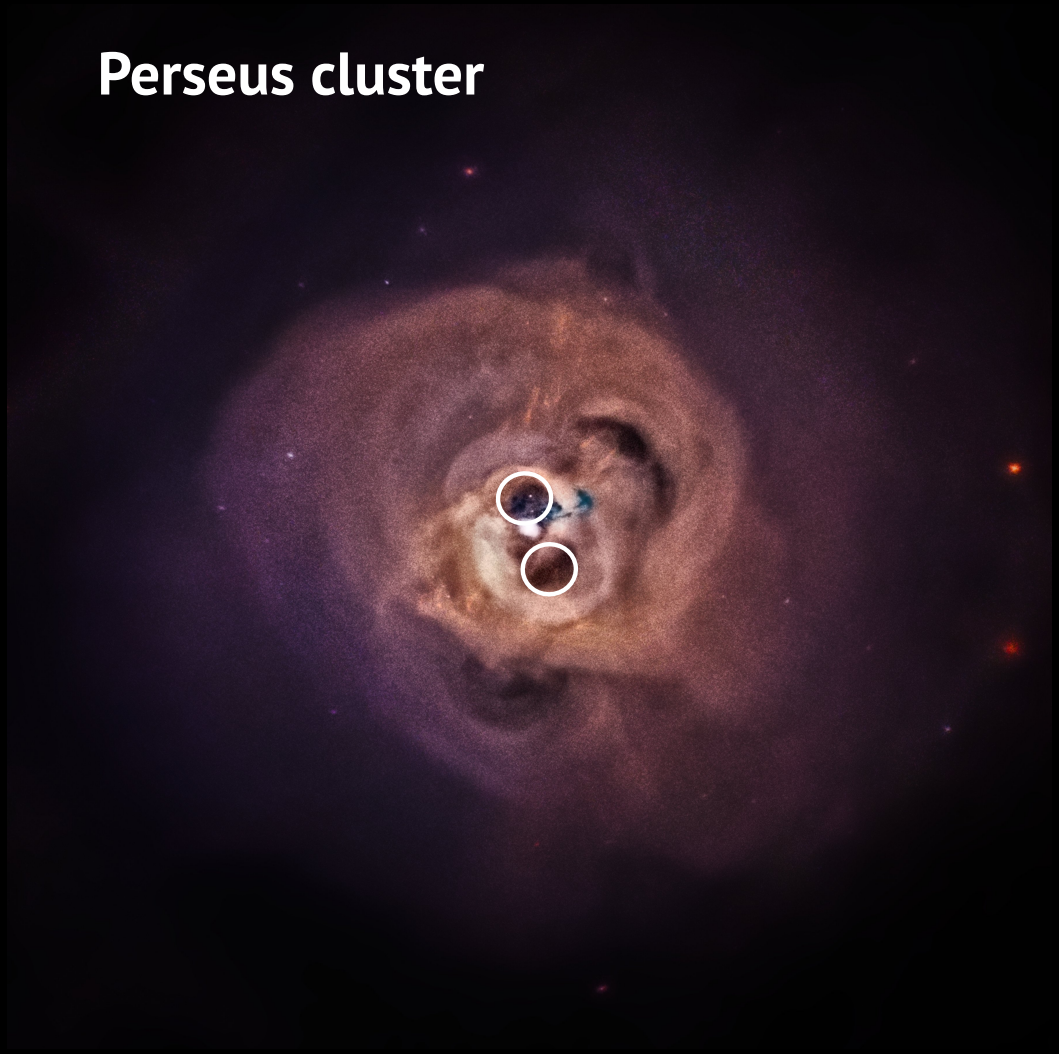
$z = 0.0065$

$R = 1$ kpc

$E = 10^{56}$ erg

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

X-ray cavities



$$H = \frac{pV}{\gamma - 1} + pV$$

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

$$P_{\text{jet}} = \frac{H}{t_{\text{age}}} = \frac{4pV}{t_{\text{age}}}$$

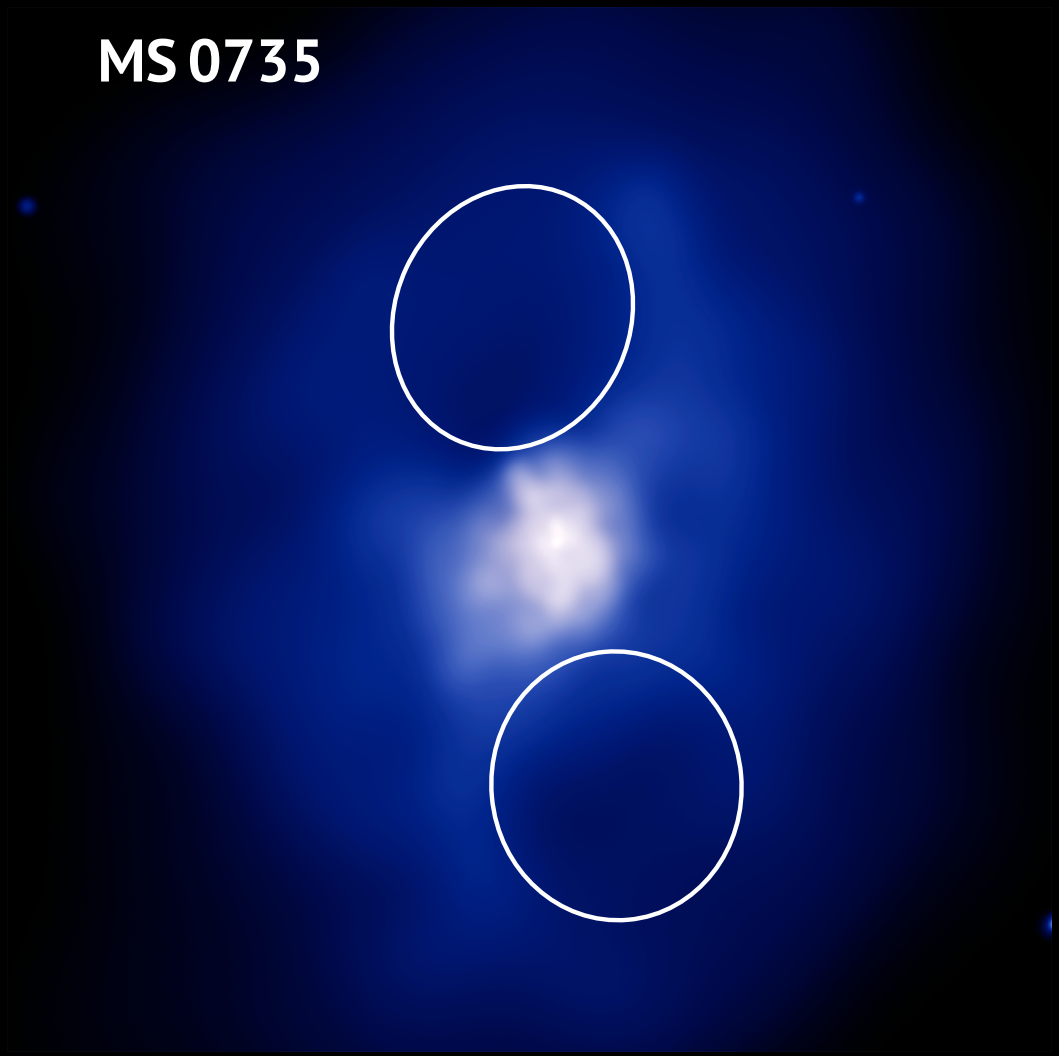
$z = 0.018$

$R = 10$ kpc

$E = 10^{59}$ erg

$P_{\text{jet}} = 10^{45}$ erg / s

X-ray cavities



$$H = \frac{pV}{\gamma - 1} + pV$$

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

$$P_{\text{jet}} = \frac{H}{t_{\text{age}}} = \frac{4pV}{t_{\text{age}}}$$

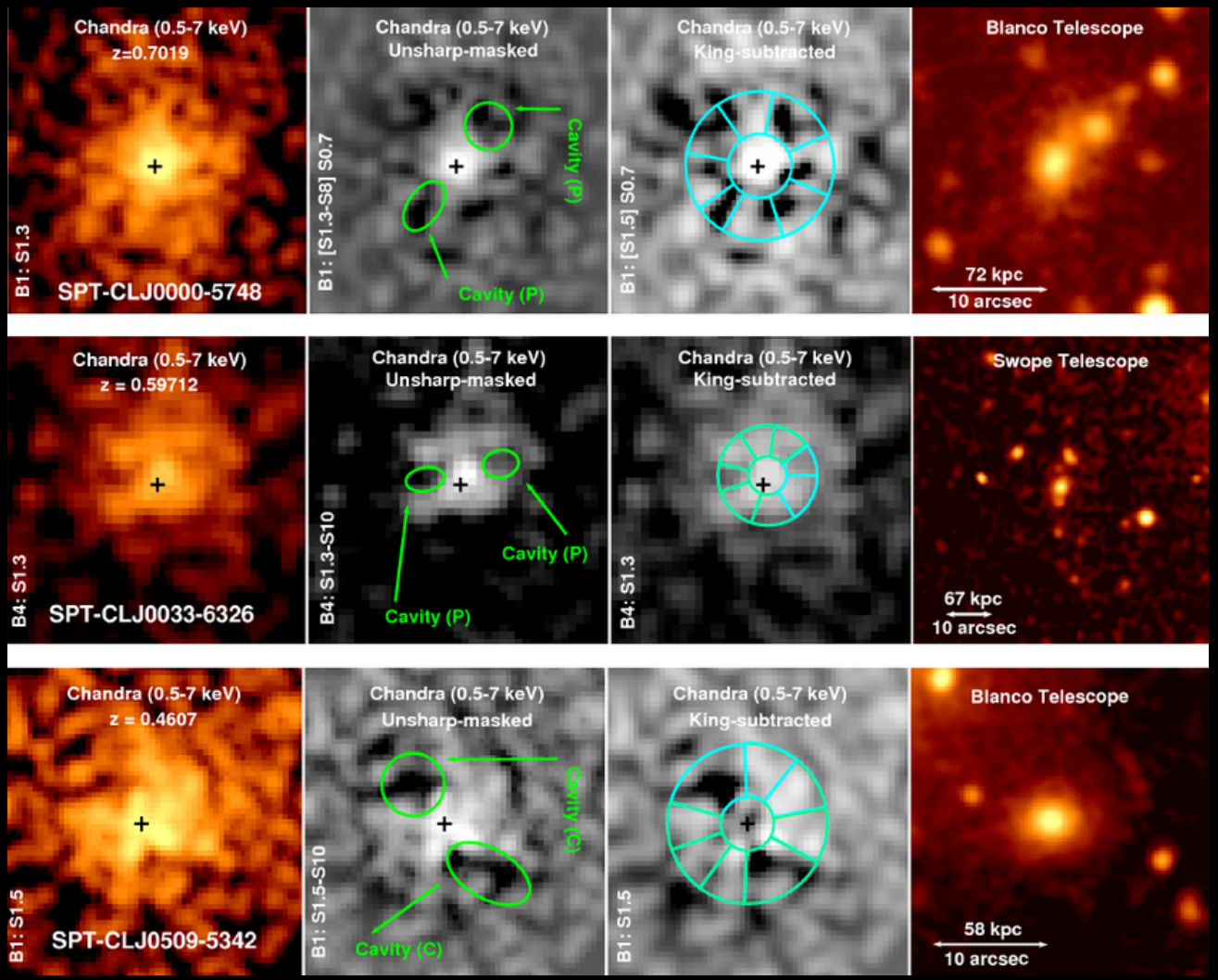
$z = 0.216$

$R = 100$ kpc

$E = 10^{62}$ erg

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

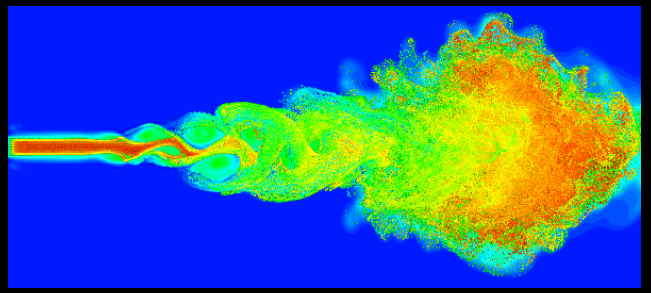
X-ray cavities

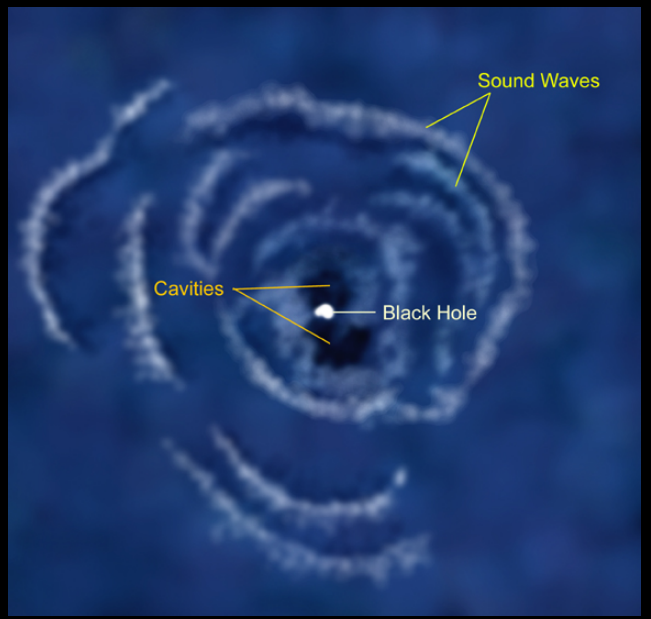


Credit: Hlavacek-Larrondo et al. 2015

Energy dissipation

- cavities deposit E on kpc—Mpc scales
  - turbulent flows
  - sound and shock waves
- heats the atmosphere
  - prevents star formation
  - regulates accretion

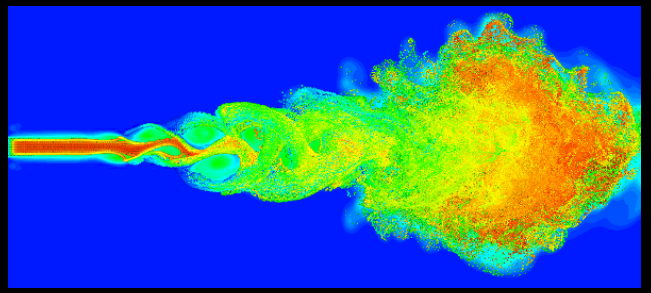


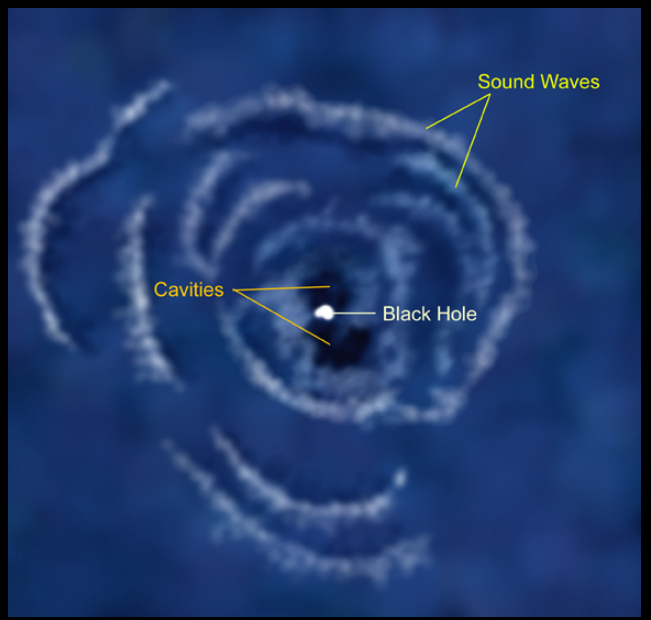


Perseus (sound waves), Credit: M.Weiss

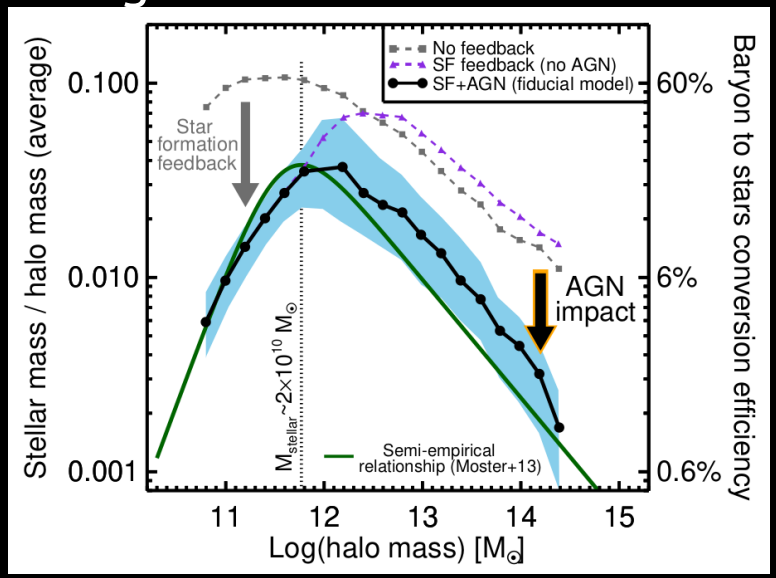
Energy dissipation

- cavities deposit *E* on kpc—Mpc scales
  - turbulent flows
  - sound and shock waves
- heats the atmosphere
  - prevents star formation
  - regulates accretion





Perseus (sound waves), Credit: M.Weiss

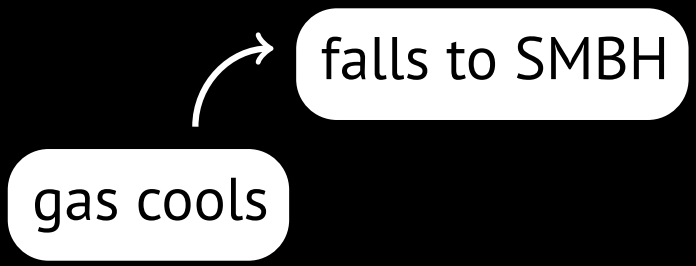


Credit: Harrison et al. 2017

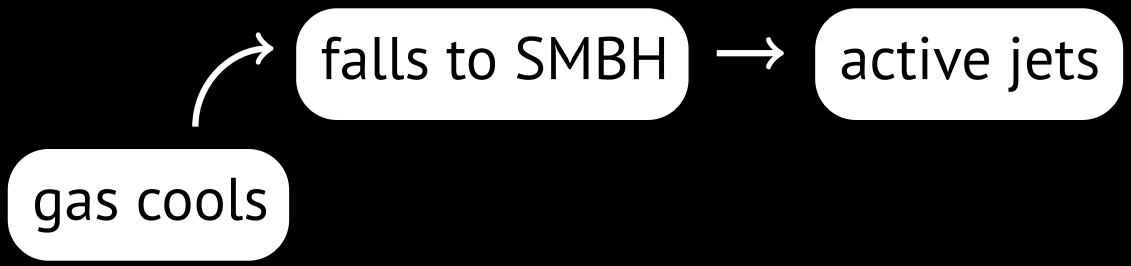
AGN feedback loop

gas cools

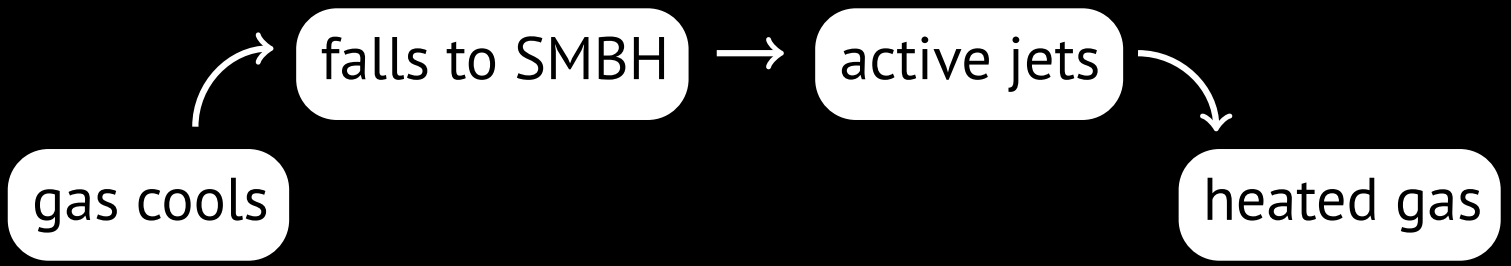
AGN feedback loop



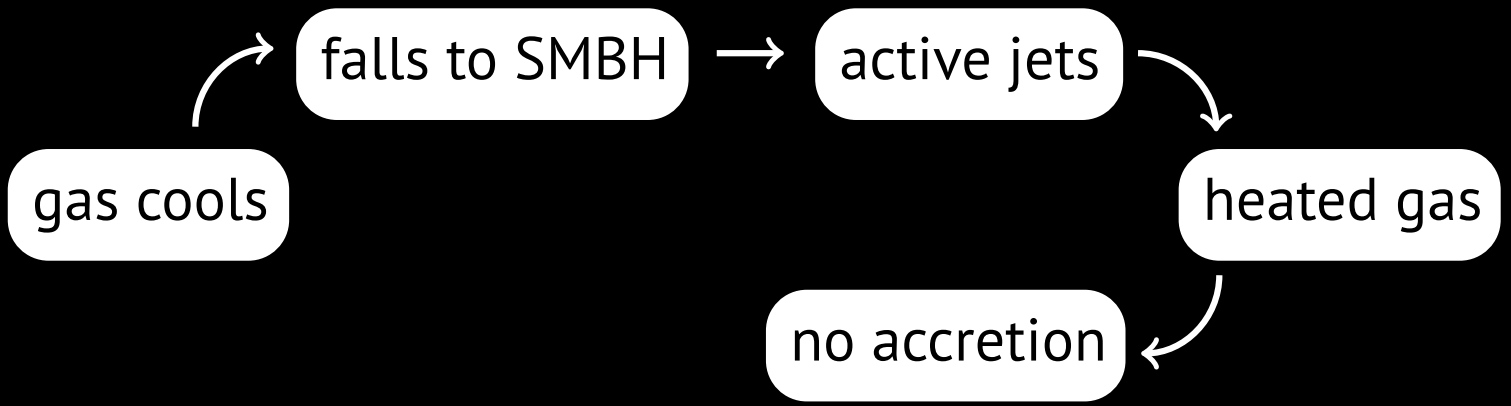
AGN feedback loop



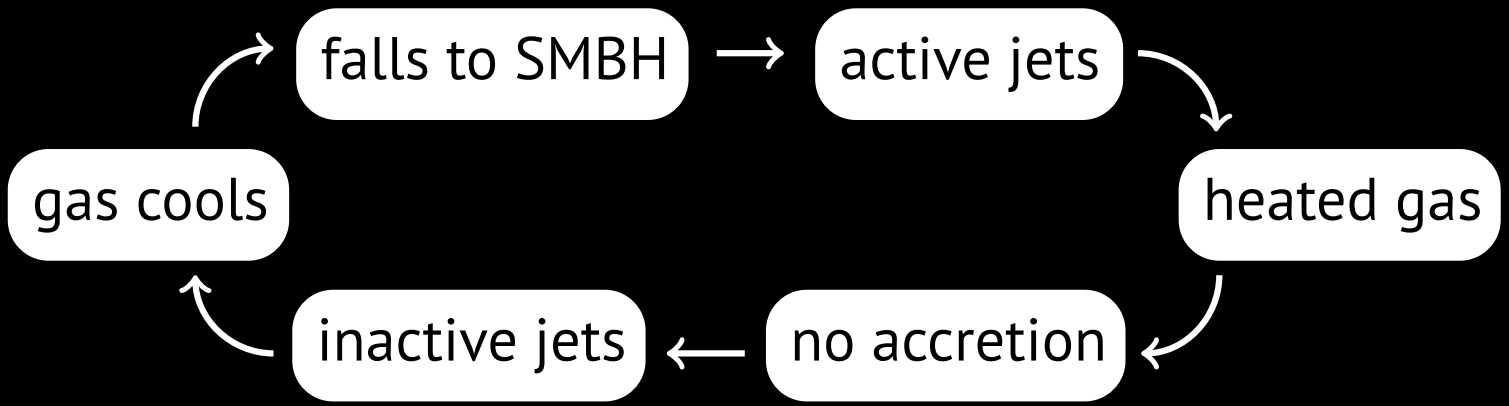
AGN feedback loop



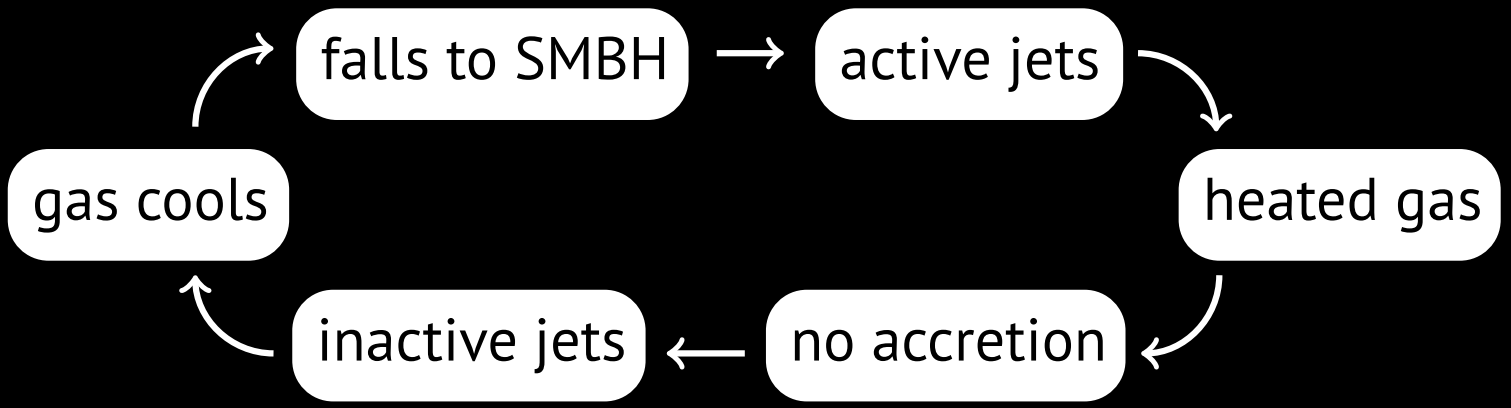
AGN feedback loop

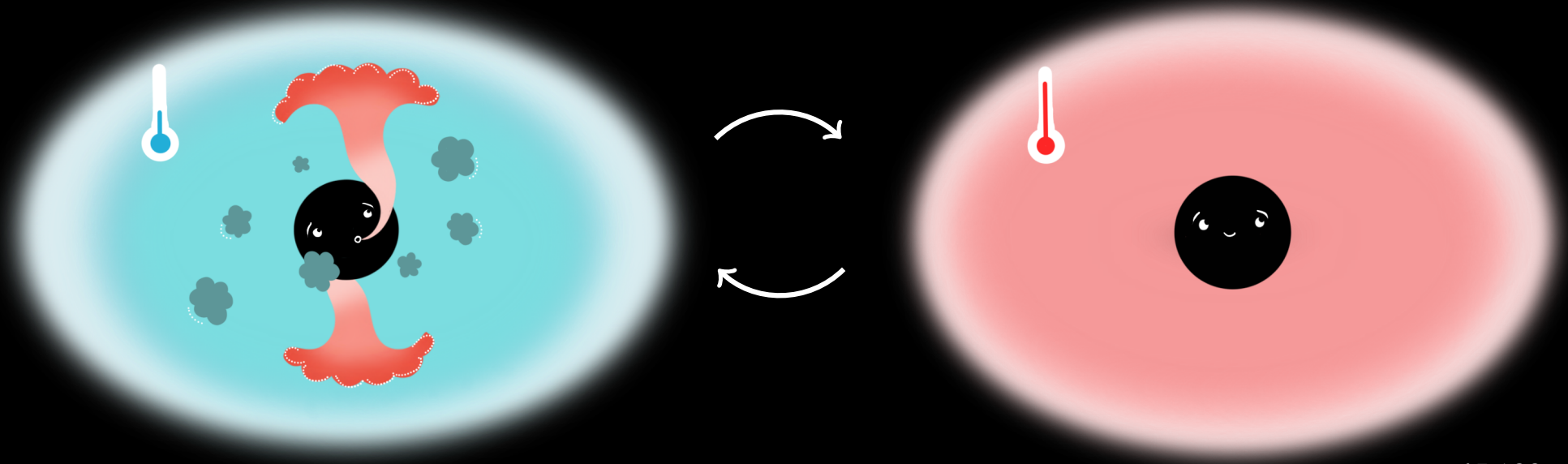


AGN feedback loop



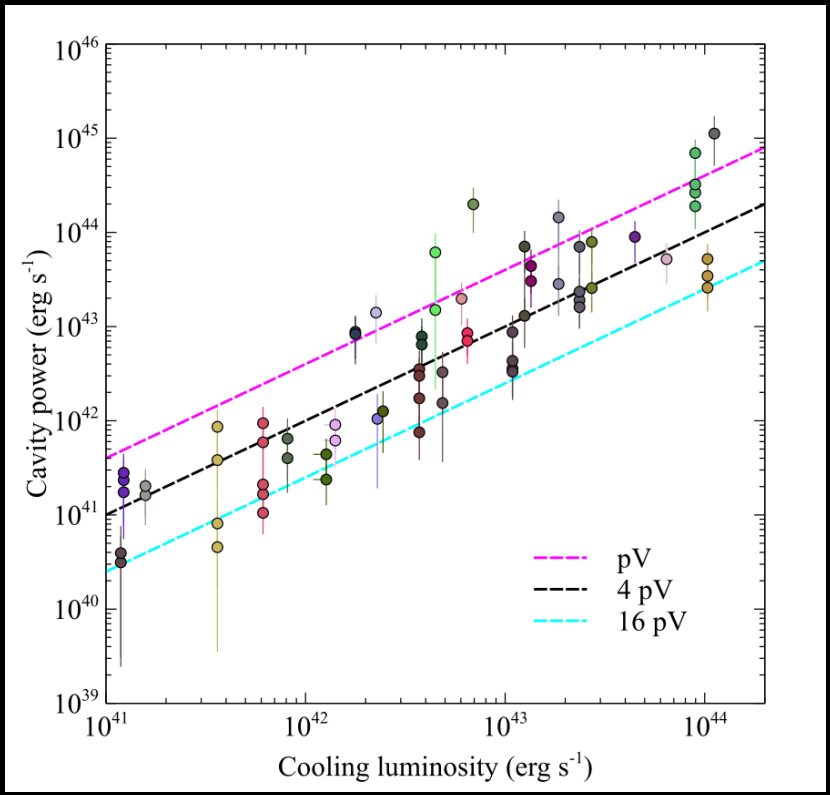
AGN feedback loop





AGN feedback loop

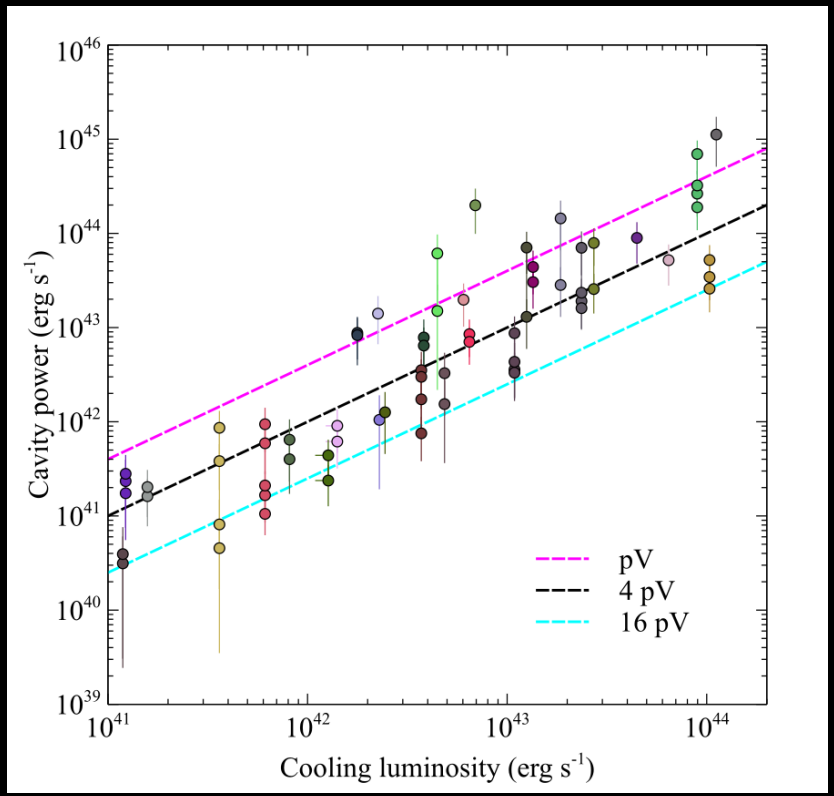
expelled $E \approx$ obtained E



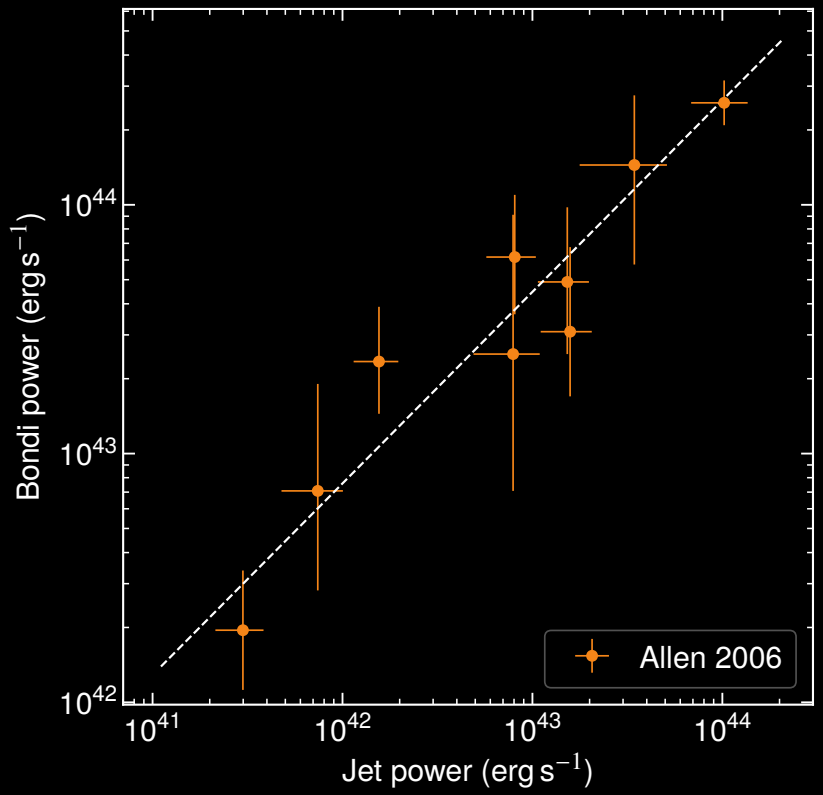
Credit: Panagoulia et al. 2014

AGN feedback loop

expelled $E \approx$ obtained E

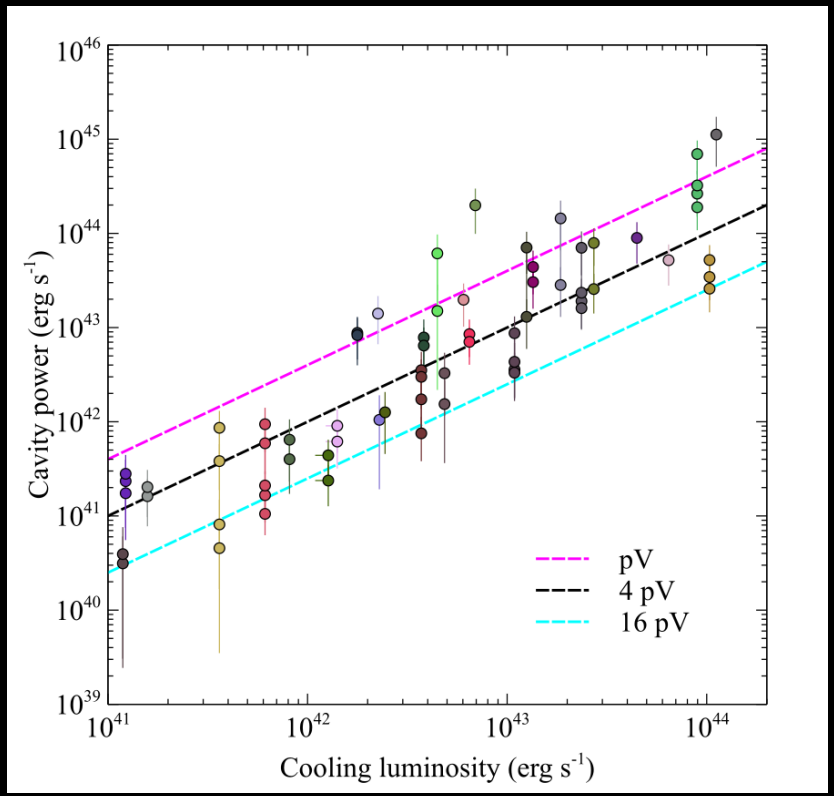


Credit: Panagoulia et al. 2014

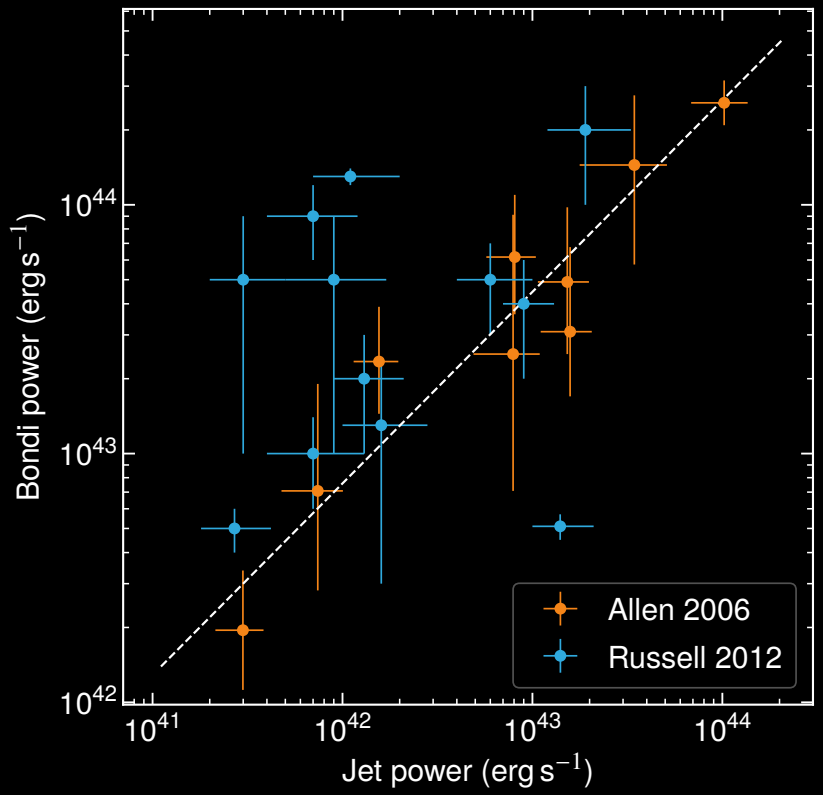


AGN feedback loop

expelled $E \approx$ obtained E



Credit: Panagoulia et al. 2014

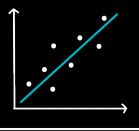


Spectral analysis

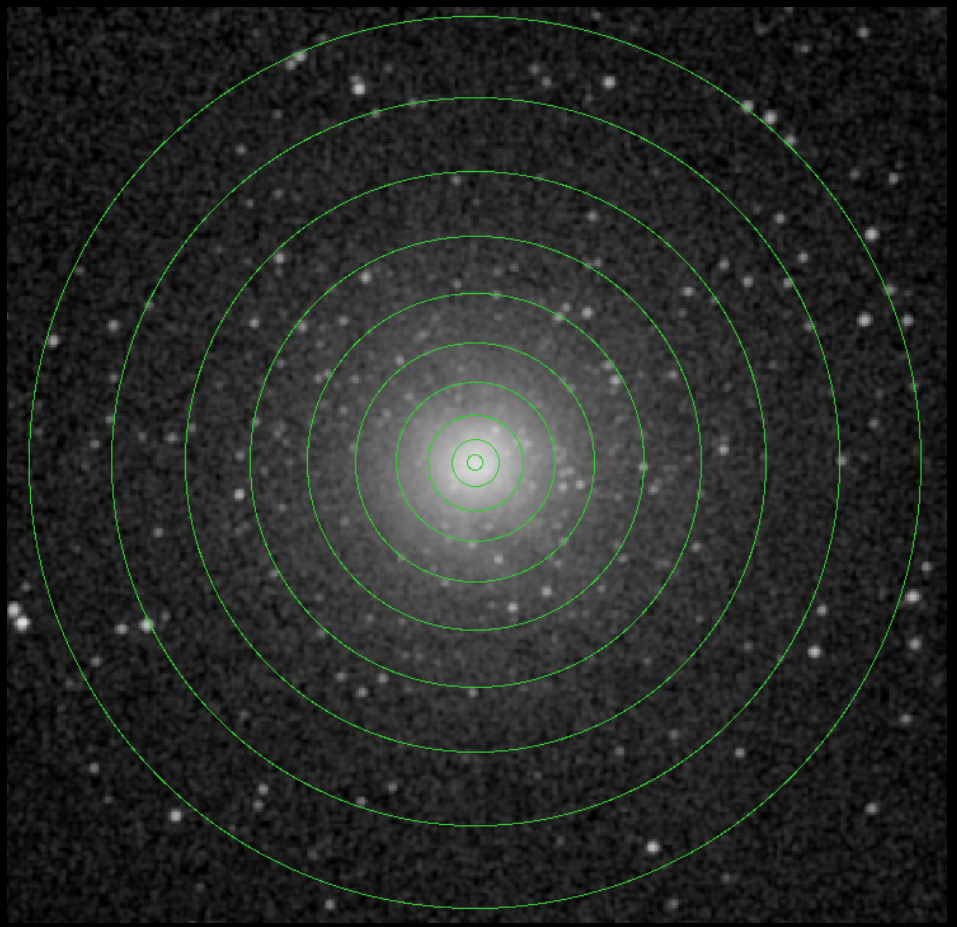
- 20 galaxies
  - Bondi radius
  - radio lobes (VLA)

$$r_{\text{Bondi}} = \frac{2GM}{c_s^2}$$

Spectral analysis

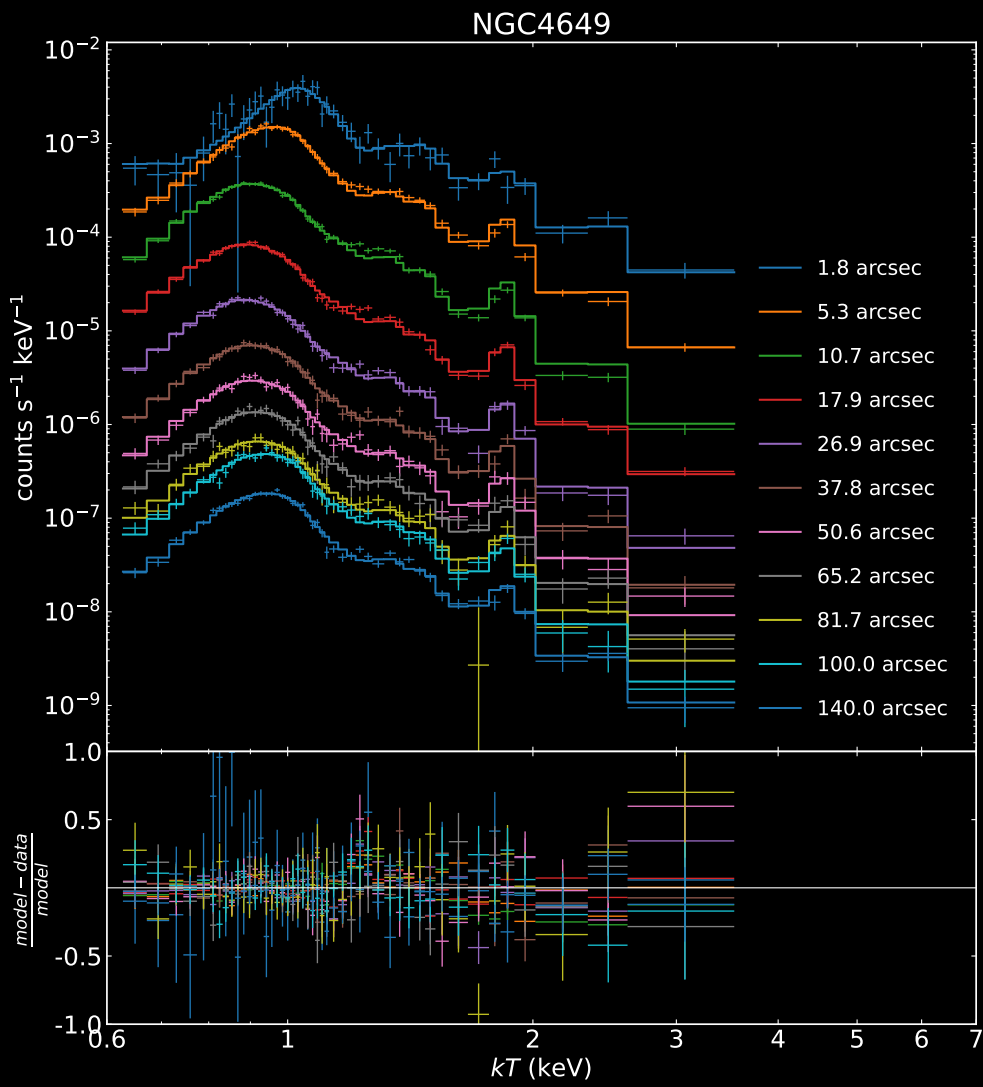


- 20 galaxies
  - Bondi radius
  - radio lobes (VLA)
- deprojected spectra

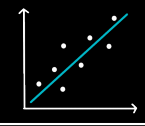


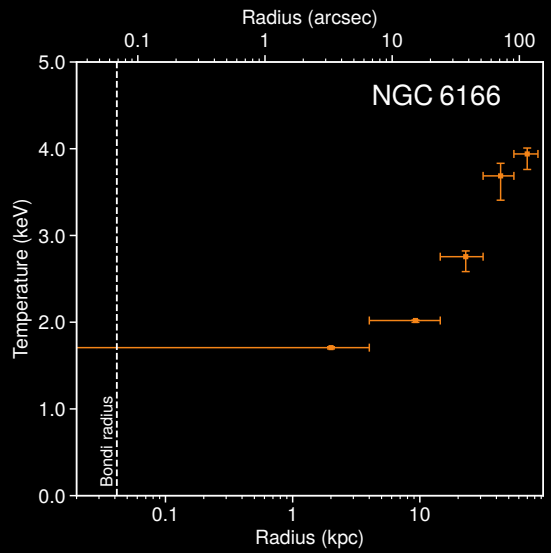
Spectral analysis

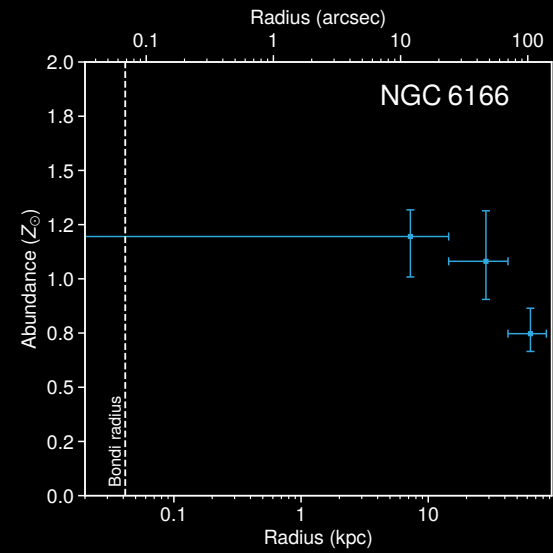
- 20 galaxies
  - Bondi radius
  - radio lobes (VLA)
- deprojected spectra
- spectral models (*Xspec*)
  - `apec` - hot plasma
    - kT, n_e, Z
  - `powerlaw` - AGN
    - $\Gamma \approx 1.9$
  - `bremss` - point sources
    - $kT \approx 7.3$ keV

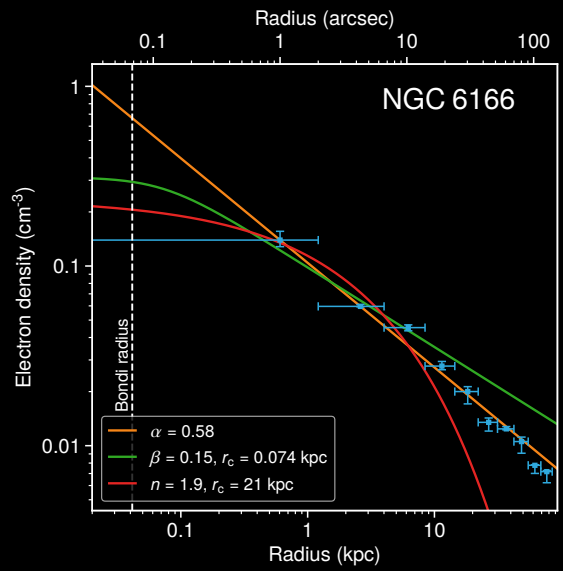


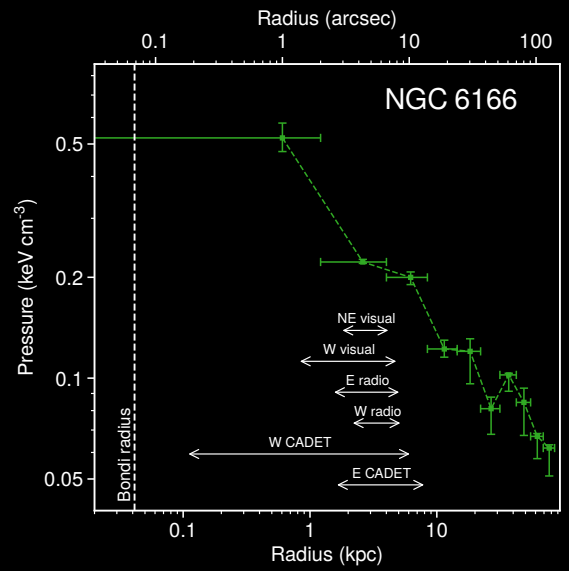
Spectral analysis - profiles



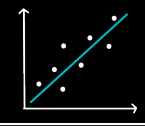








Spectral analysis - profiles

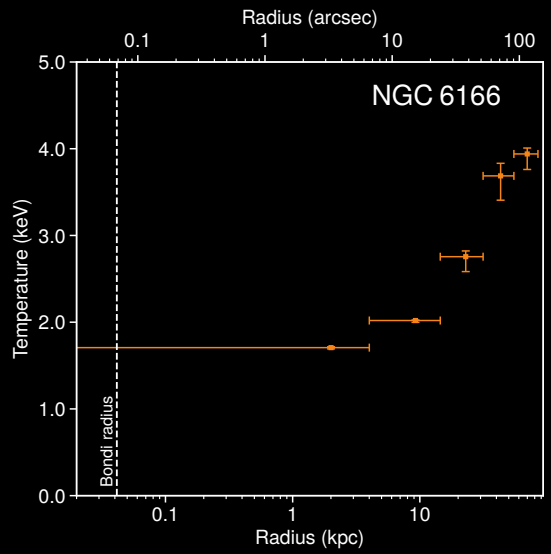


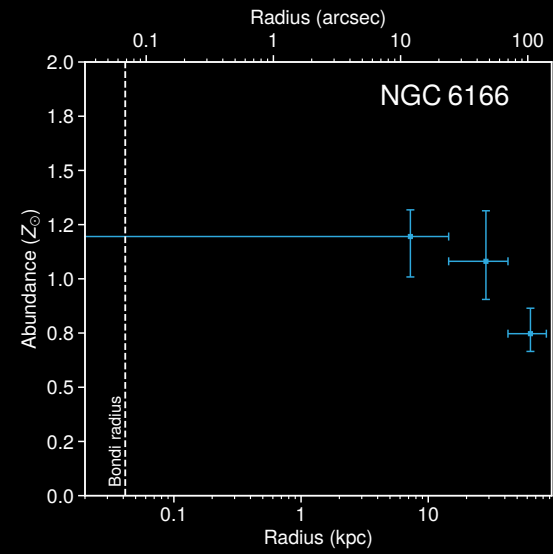
- density profile

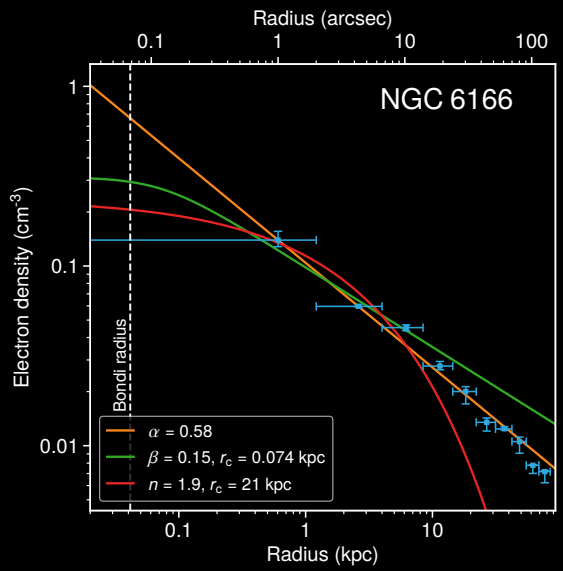
$$n_e(r) = \beta \cdot r^{\alpha}$$

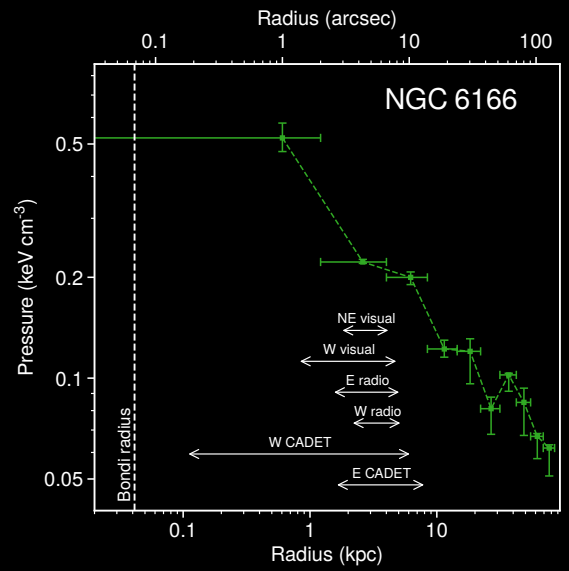
$$n_e(r) = n_{e,0}\left(1 + \frac{r^2}{r_c^2}\right)^{-\frac{3}{2}\beta}$$

$$n_e(r) = n_{e,0} e^{-b_n\left(\frac{r}{r_c}\right)^{\frac{1}{n}}}$$

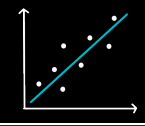








Spectral analysis - profiles



- density profile

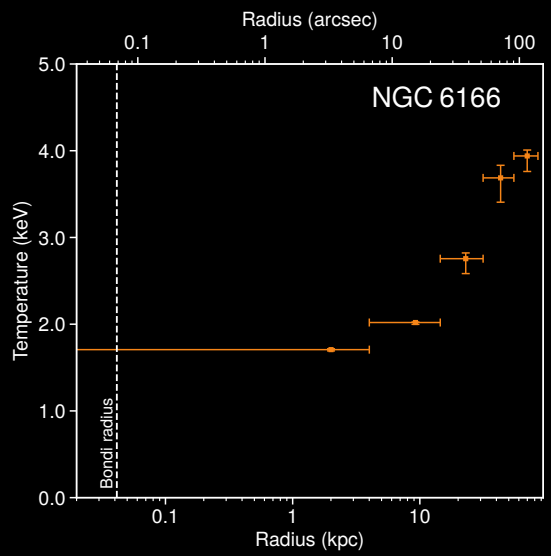
$$n_e(r) = \beta \cdot r^{\alpha}$$

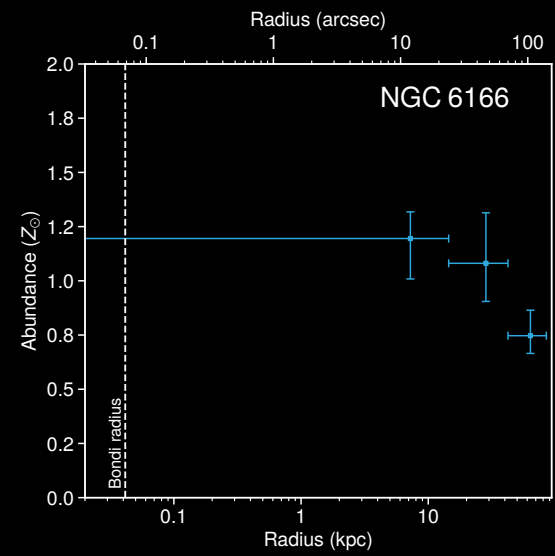
$$n_e(r) = n_{e,0}\left(1 + \frac{r^2}{r_c^2}\right)^{-\frac{3}{2}\beta}$$

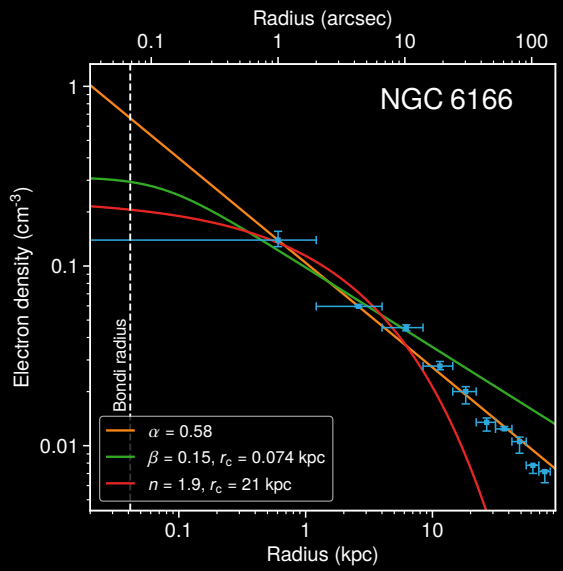
$$n_e(r) = n_{e,0} e^{-b_n\left(\frac{r}{r_c}\right)^{\frac{1}{n}}}$$

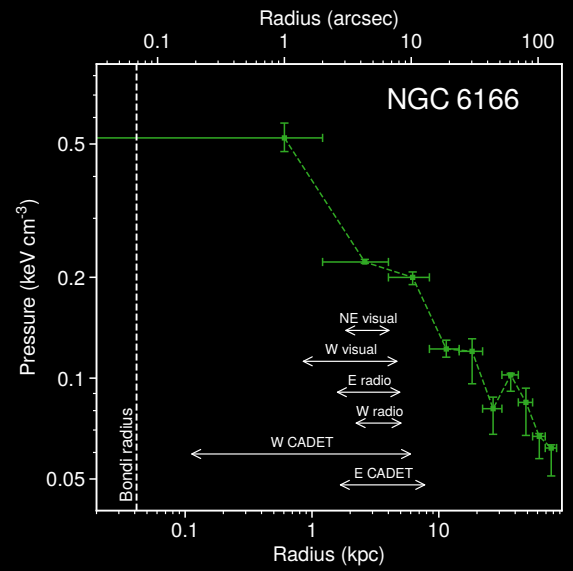
- Bondi accretion

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



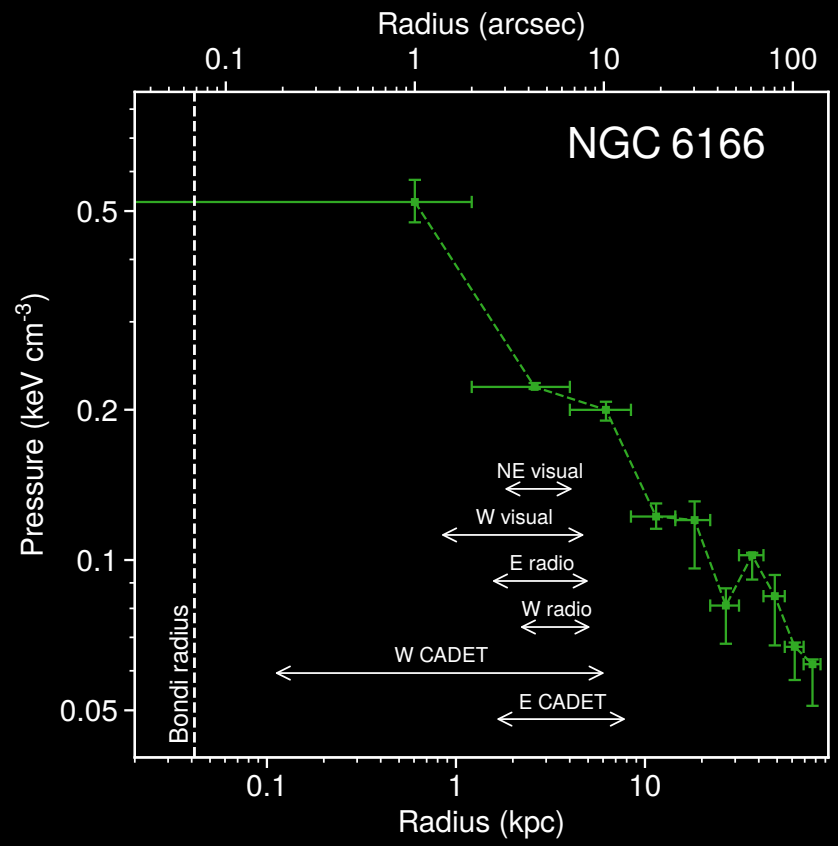


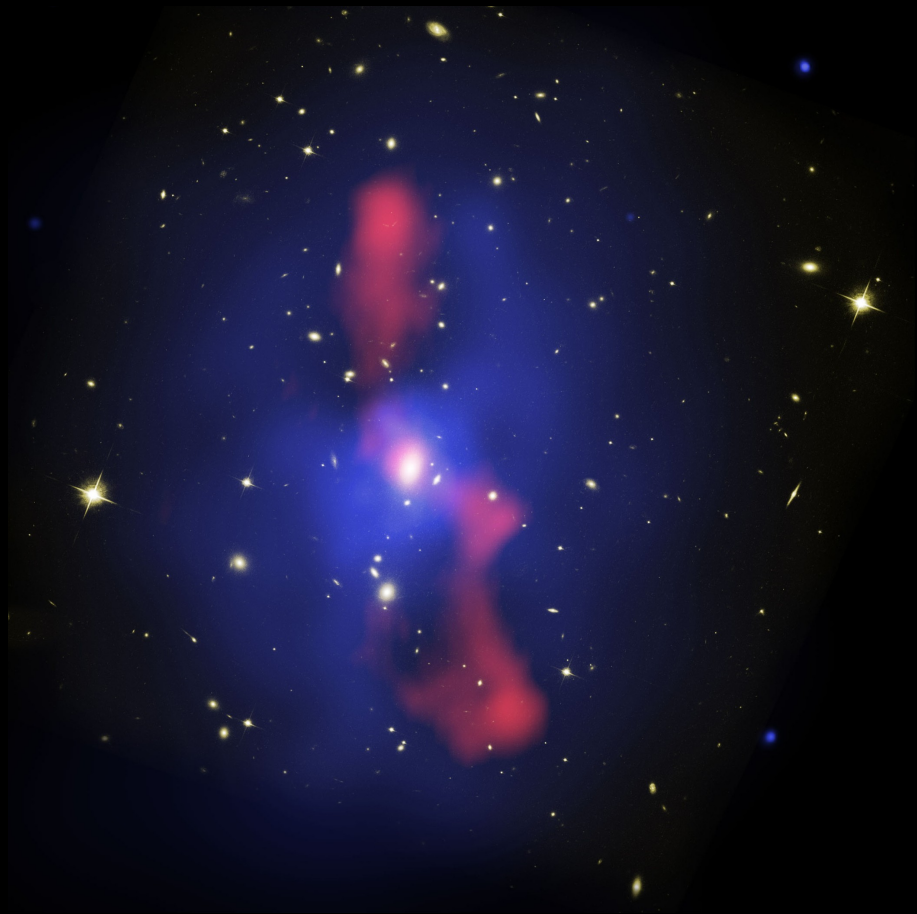




Jet power estimation

$$P_{\text{jet}} = \frac{4pV}{t_{\text{age}}} \qquad t_{\text{age}} = \frac{R}{c_s}$$

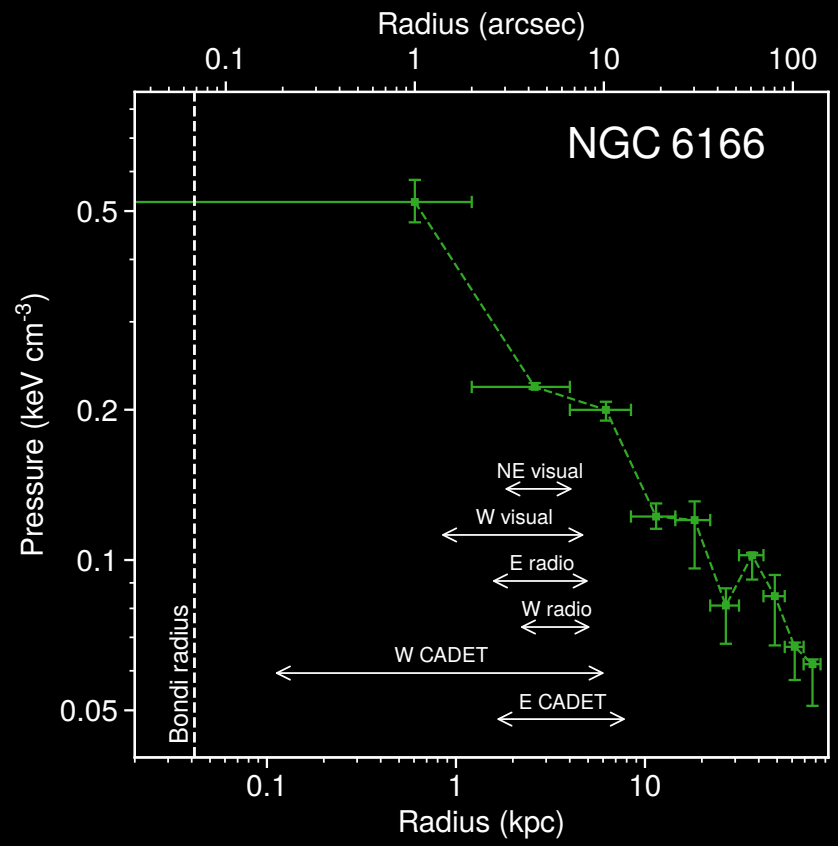


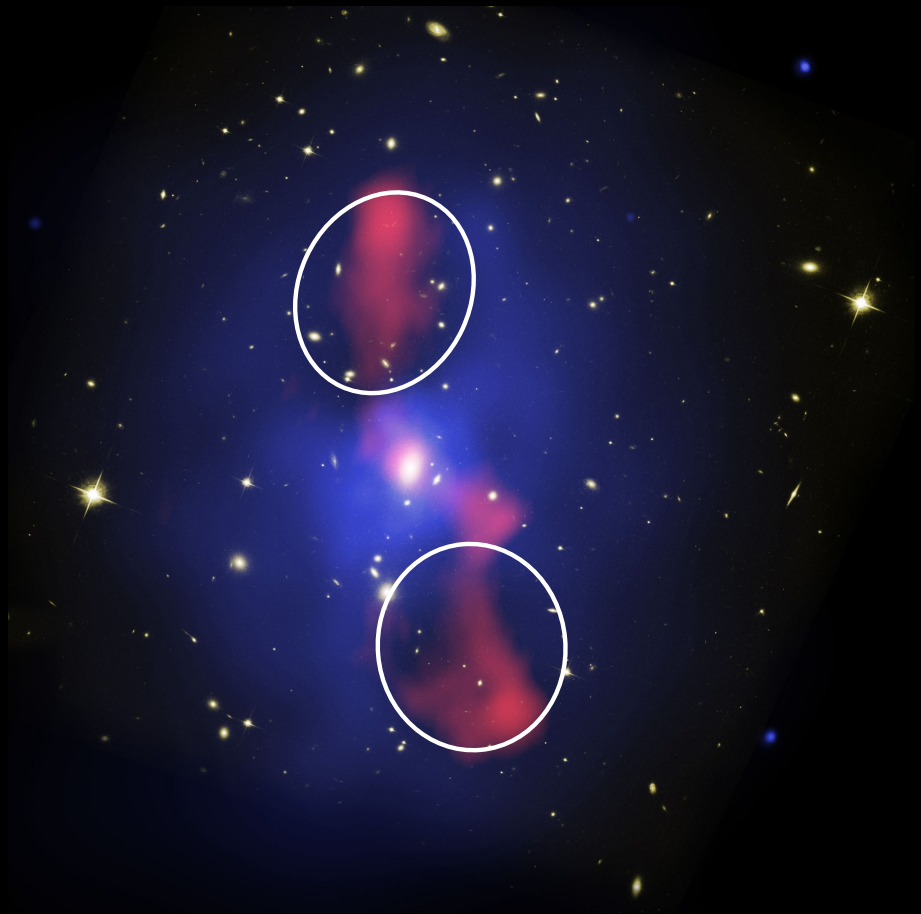


MS0735, Credit: NRAO

Jet power estimation

$$P_{\text{jet}} = \frac{4pV}{t_{\text{age}}} \qquad t_{\text{age}} = \frac{R}{c_s}$$



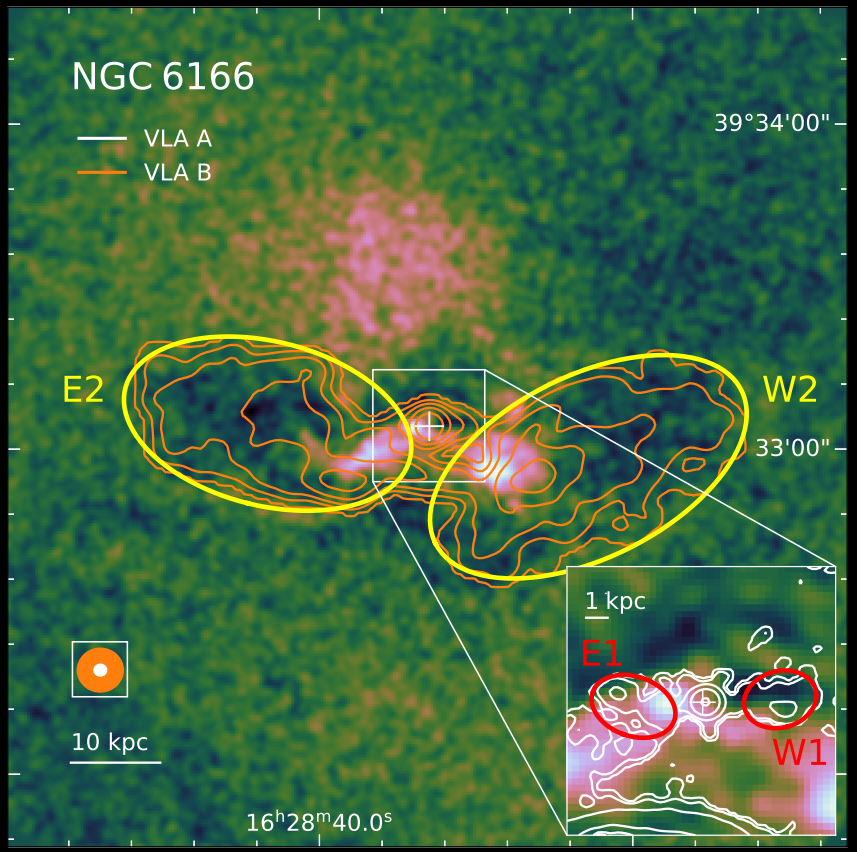


MS0735, Credit: NRAO

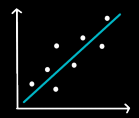
Jet power estimation

$$P_{\text{jet}} = \frac{4pV}{t_{\text{age}}} \qquad t_{\text{age}} = \frac{R}{c_s}$$

- Radio lobes
  - VLA contours (1.4 GHz)

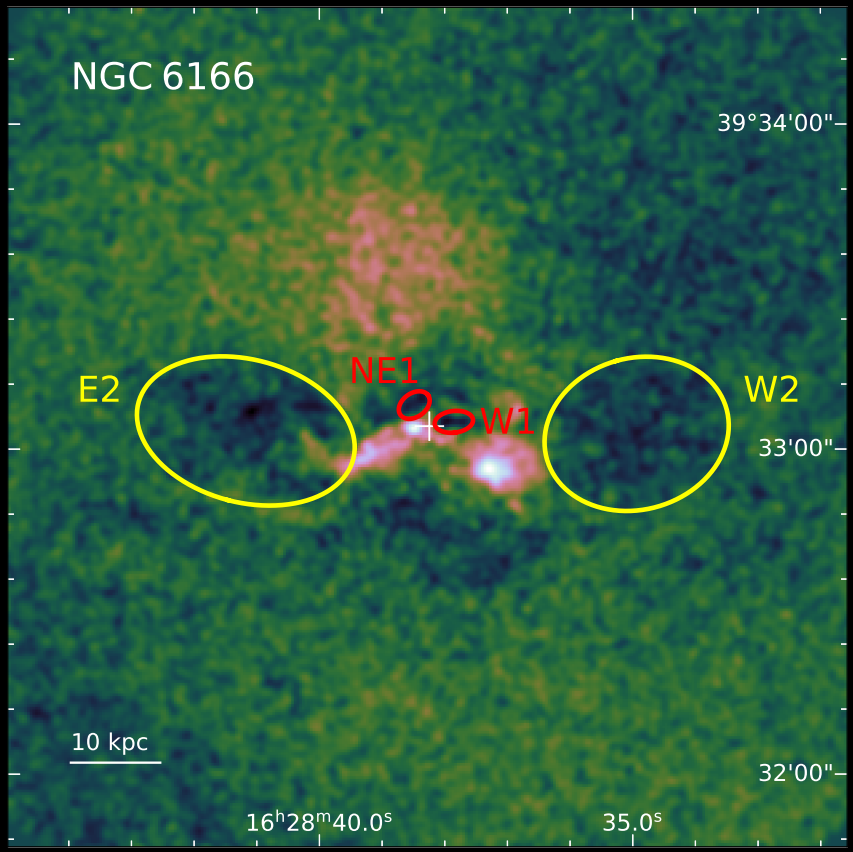


Jet power estimation



$$P_{\text{jet}} = \frac{4pV}{t_{\text{age}}} \qquad t_{\text{age}} = \frac{R}{c_s}$$

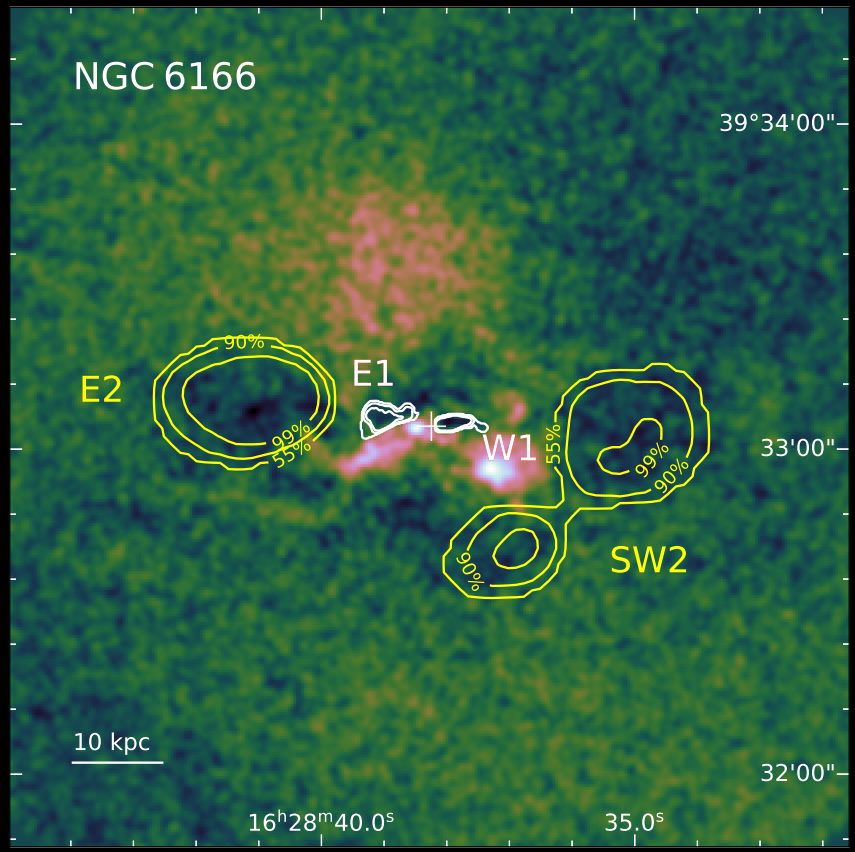
- Radio lobes
  - VLA contours (1.4 GHz)
- Residual X-ray images
  - β-modeling of *Chandra* data
  - estimated manually



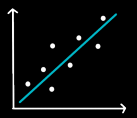
Jet power estimation

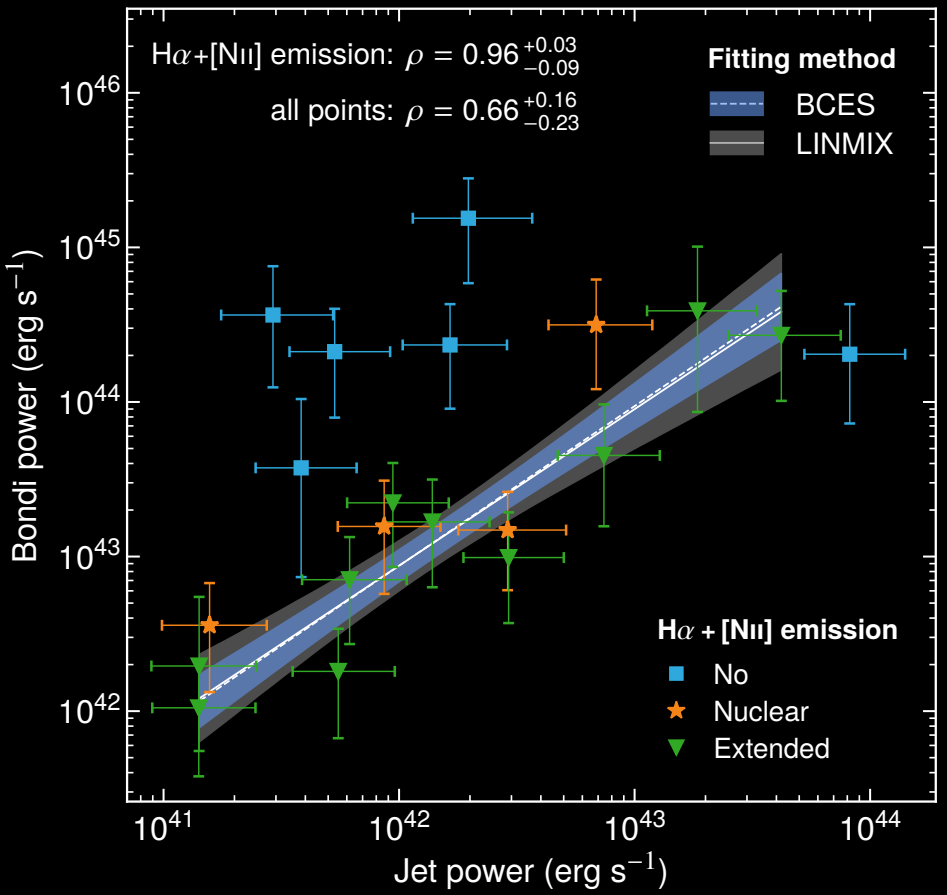
$$P_{\text{jet}} = \frac{4pV}{t_{\text{age}}} \qquad t_{\text{age}} = \frac{R}{c_s}$$

- Radio lobes
  - VLA contours (1.4 GHz)
- Residual X-ray images
  - β-modeling of *Chandra* data
  - estimated manually
- Neural network (CADET)
  - raw X-ray images



Apparent Bondi to jet power correlation

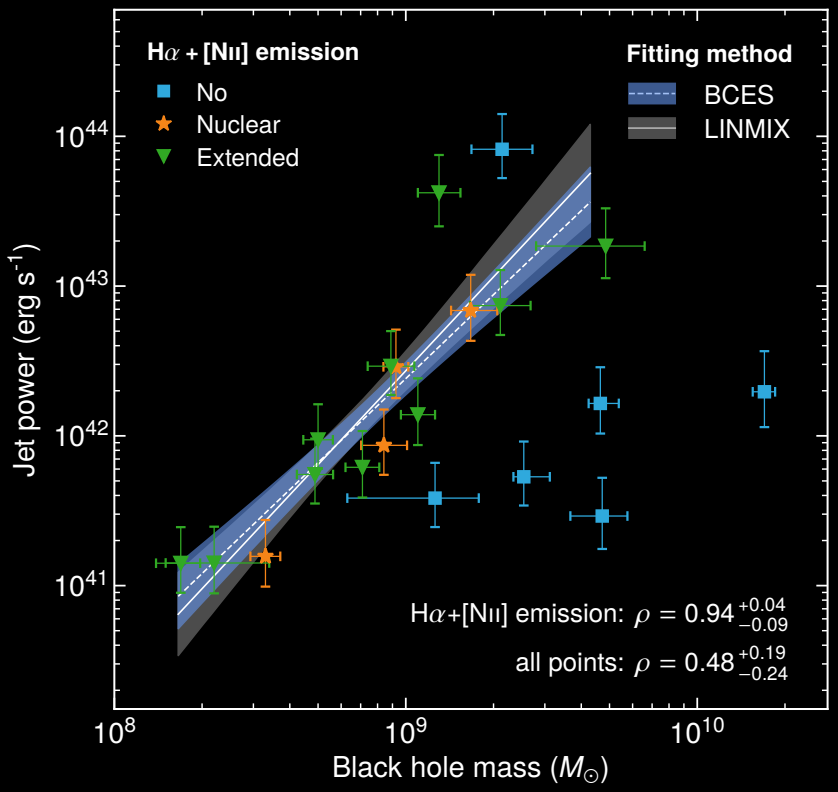




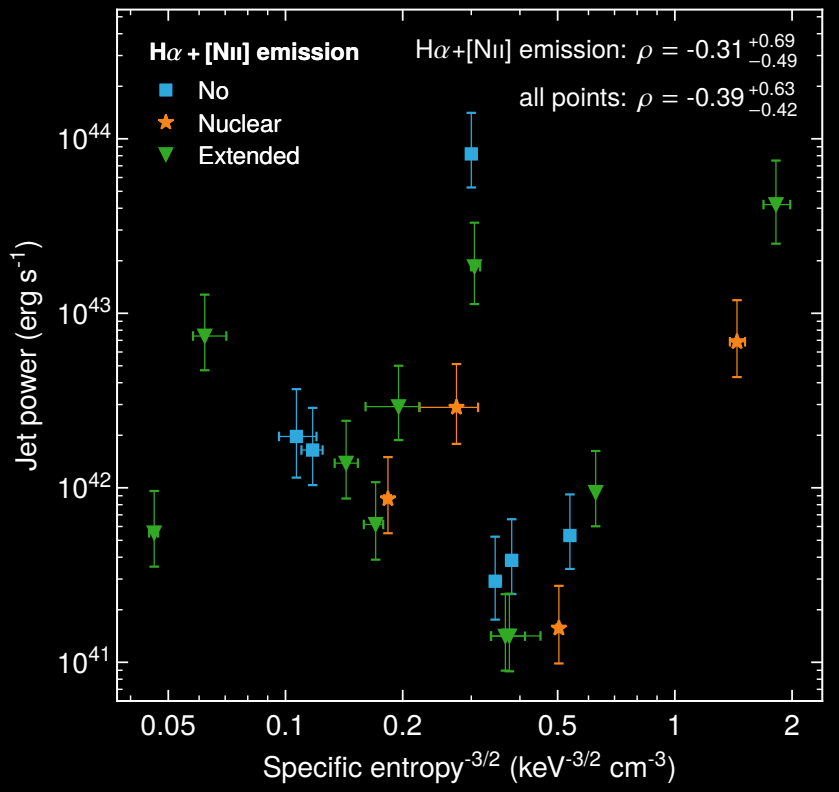
Apparent Bondi to jet power correlation

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

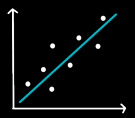
$$P_{\rm jet} \propto M_\bullet^{2.08\pm0.42}$$

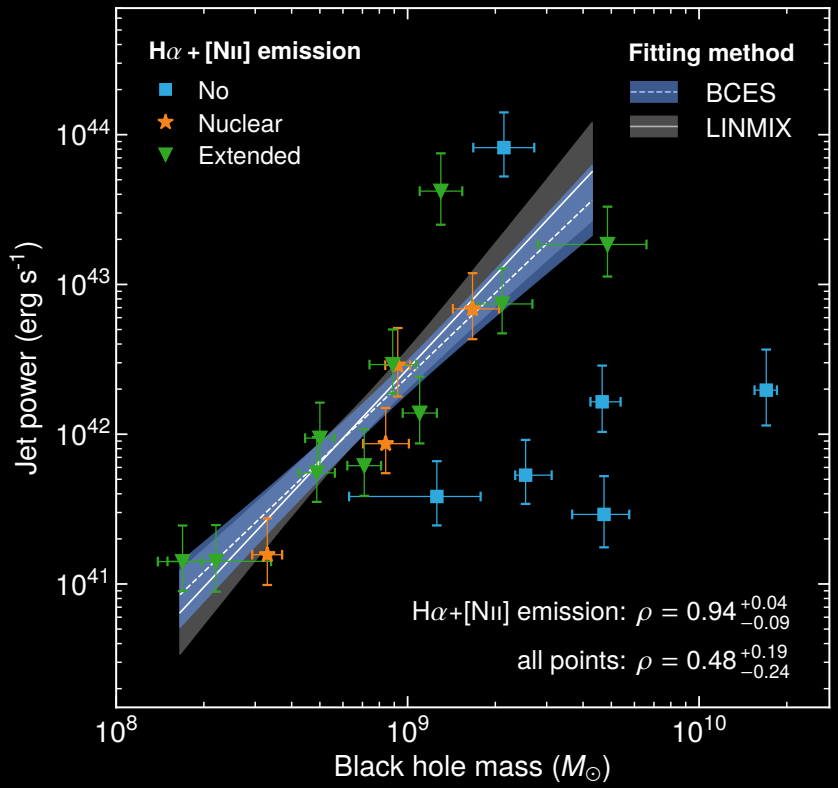


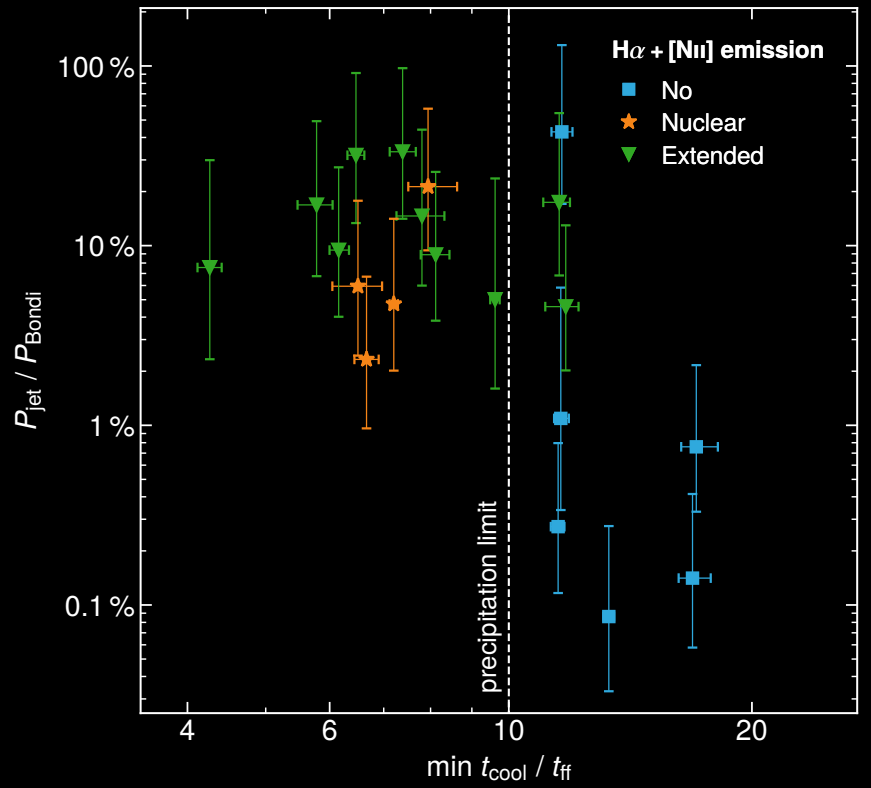
$$P_{\rm jet} \neq f(K^{-3/2})$$



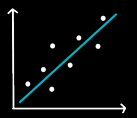
Feeding from thermally unstable atmospheres

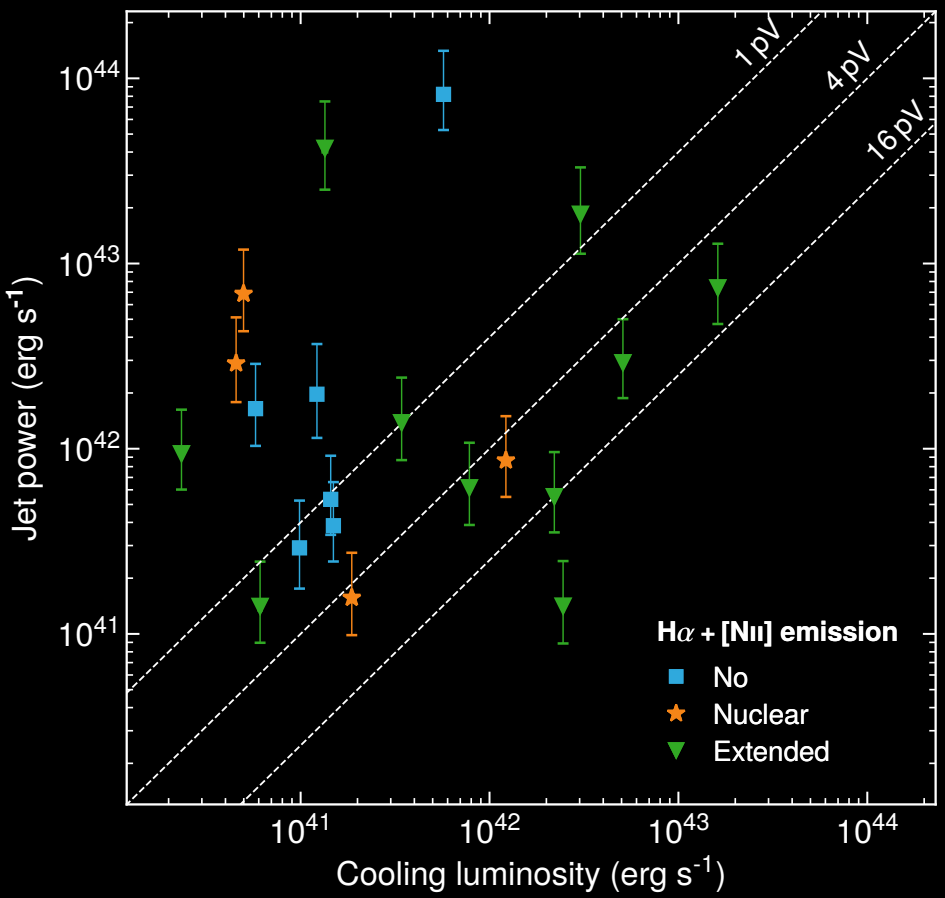




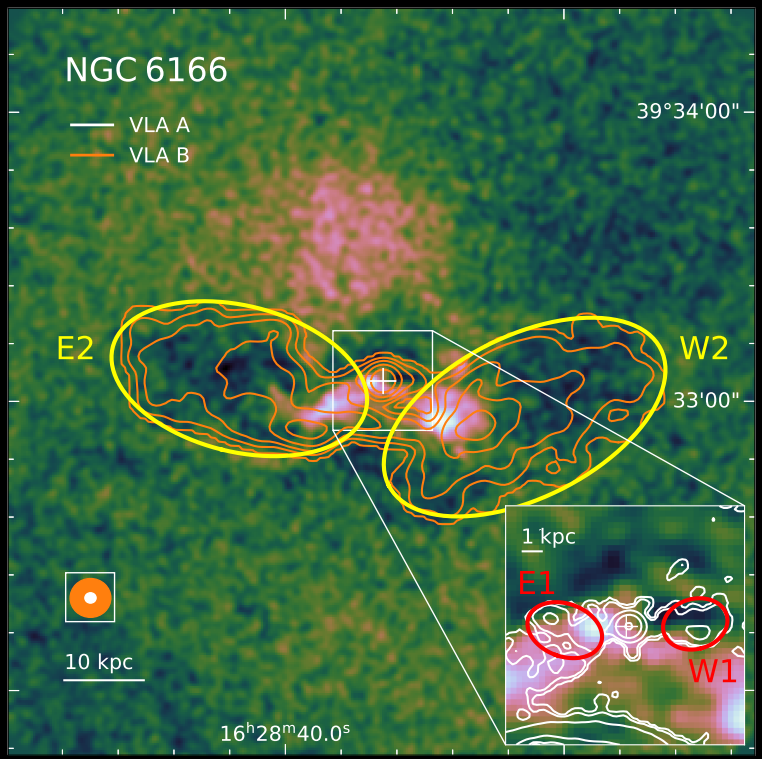


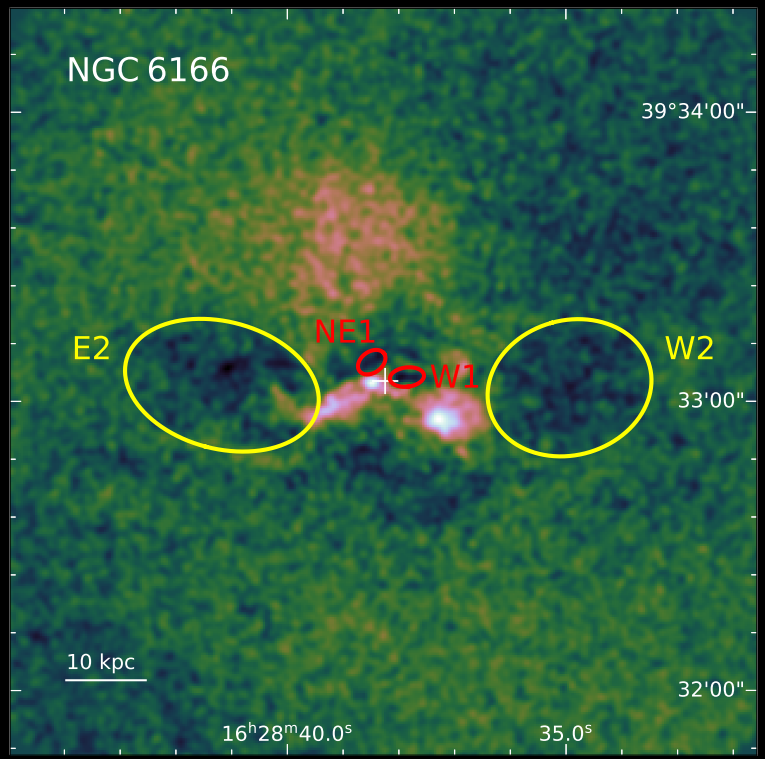
Lack of 'true AGN feedback'?



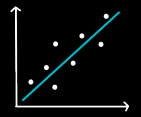


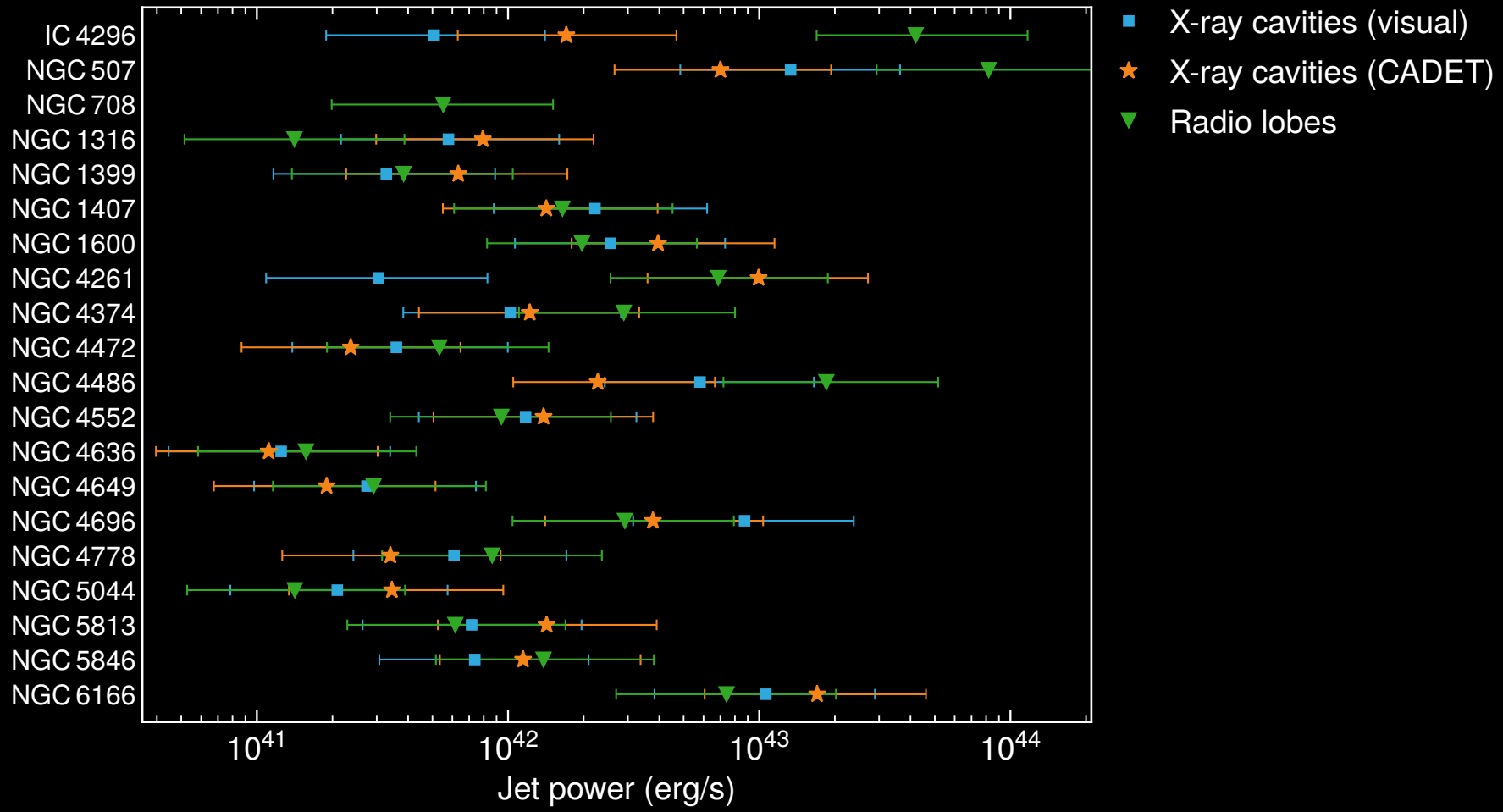
Discrepancy between radio lobes & cavities



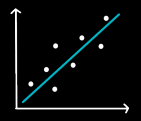


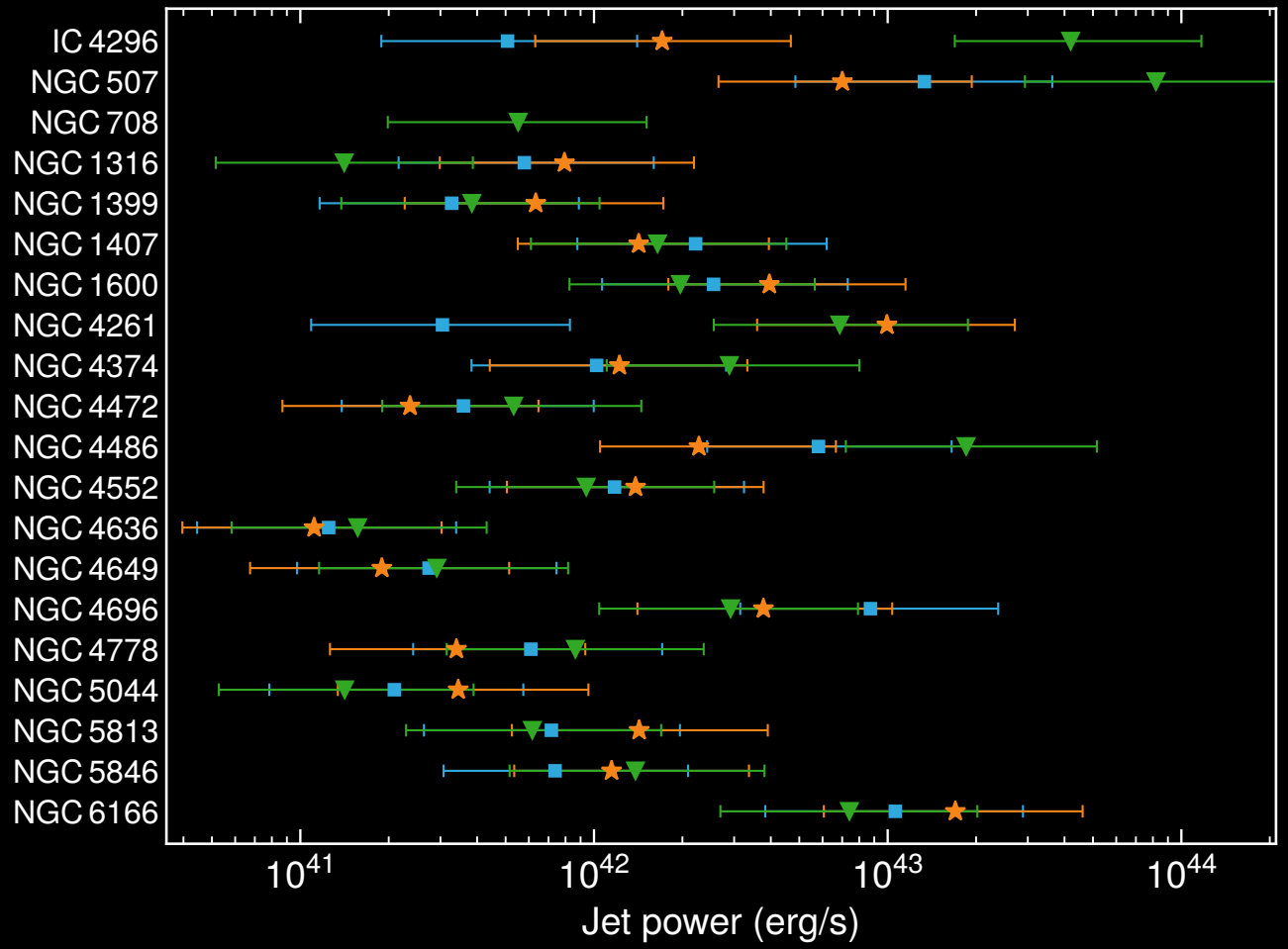
Discrepancy between radio lobes & cavities





Discrepancy between radio lobes & cavities





X-ray cavities (visual)

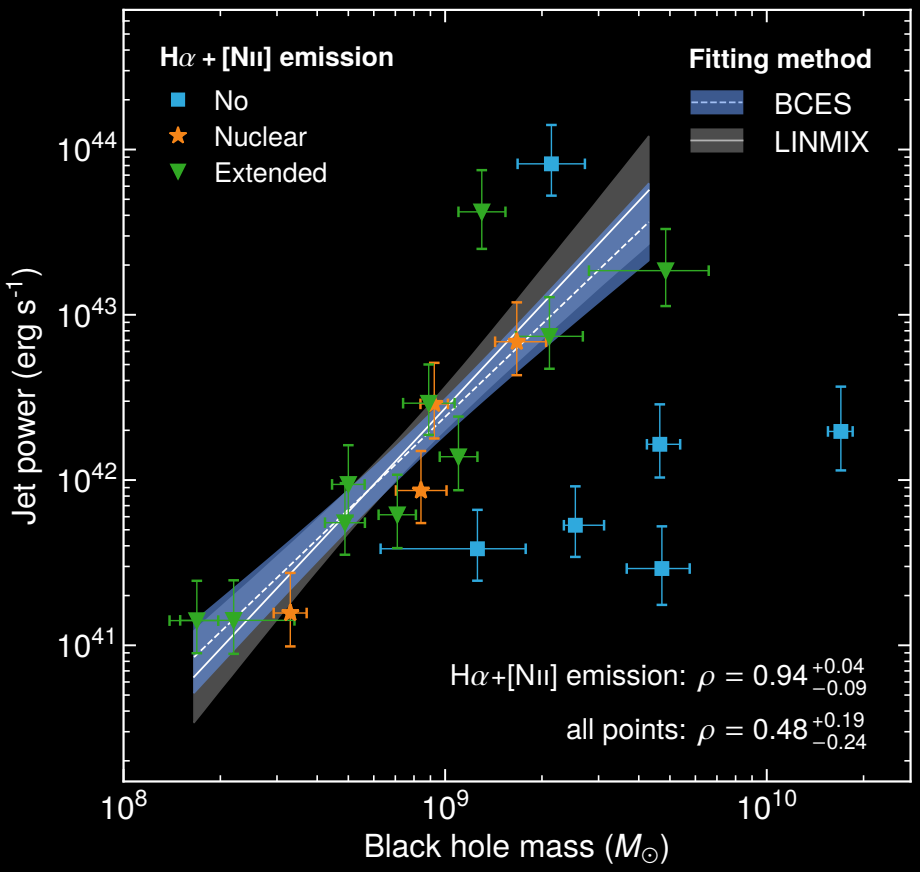
X-ray cavities (CADET)

Radio lobes

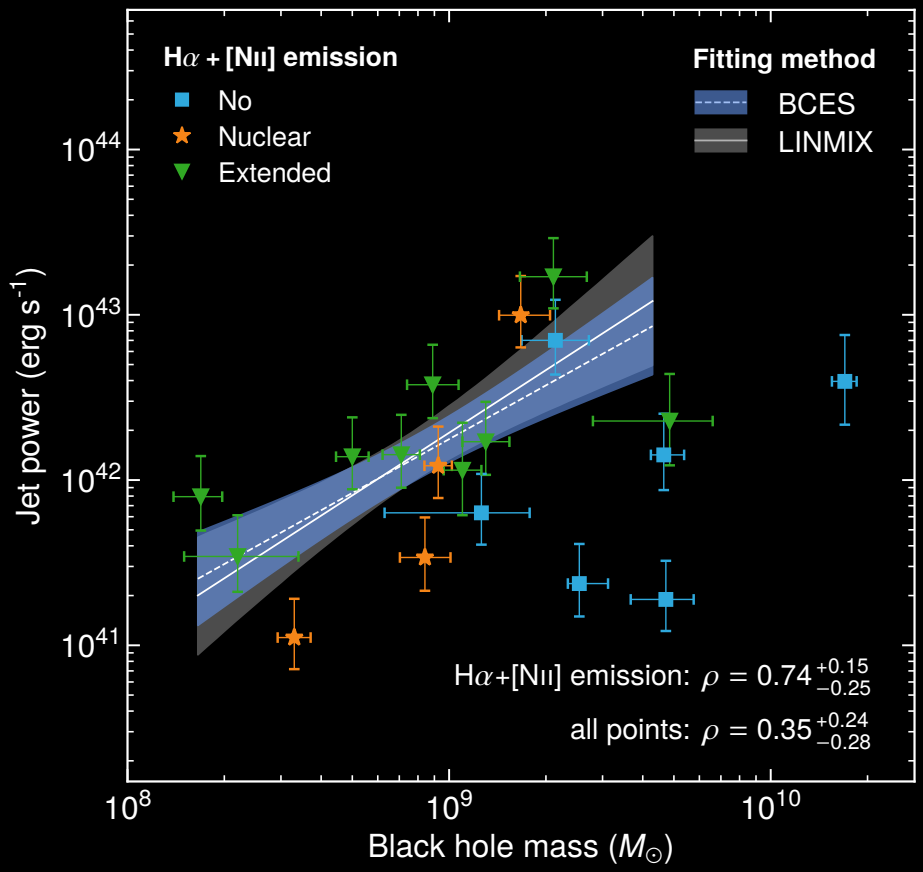
on average 1.5× higher P_{jet}

Discrepancy between radio lobes & cavities

Radio lobes

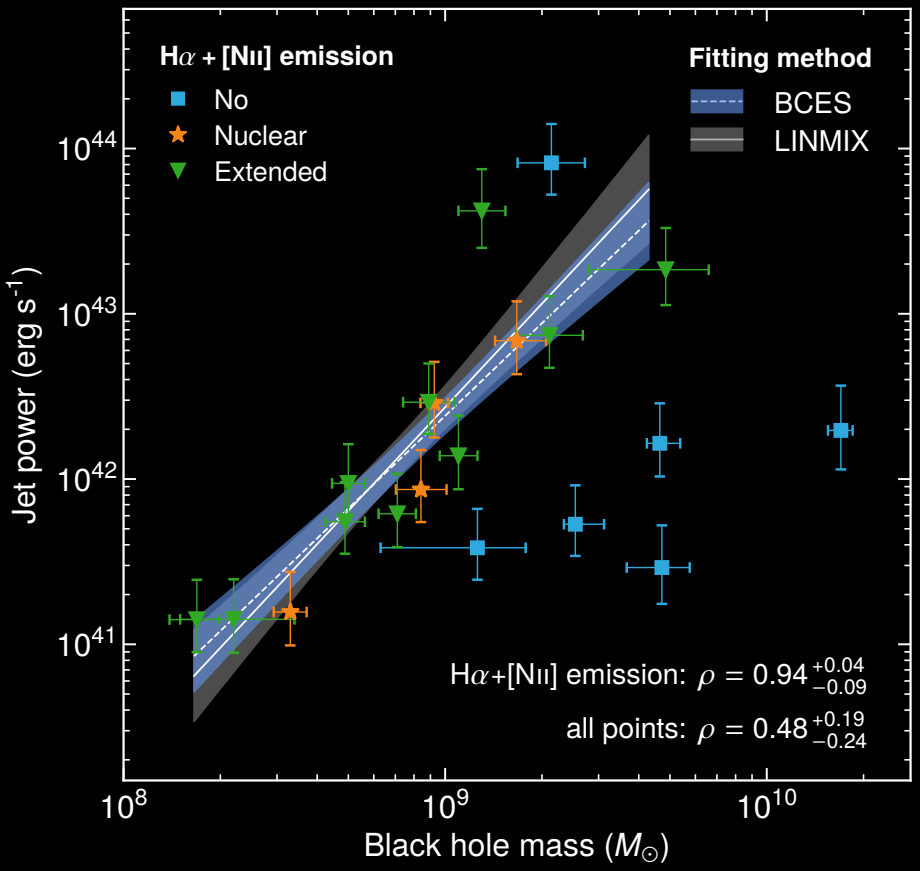


X-ray cavities (CADET)



Discrepancy between radio lobes & cavities

Radio lobes



X-ray cavities (visual)