"Normal" galaxy:

star-dominate emission.

↓ (atmosphere)

hydrodynamical, thermal equilibrium => Σ Planck spectrum

T: 3e3K ~ 4e4 K => λ: 4e3 Å ~ 2e4 Å

if actively forming stars / dusts

young hot star => smaller λ ; larger λ => far-infrared

"Active" galaxy

full wavelength emission: radio ~ X-ray

non-thermal emission.

strong, broad emission lines.

AGN

Table 14.1. Local number densities.

Type of object	Number density [Mpc^{-3}]
Field galaxies	10^{-1}
Luminous spirals	10^{-2}
Seyfert galaxies	10^{-4}
Radio galaxies	10^{-6}
QSOs	10^{-7}
Radio-loud quasars	10^{-9}

How to define an AGN by observation?

(i) a compact nuclear region much brighter than a region of the same size in a normal galaxy;
(ii) non-stellar (non-thermal) continuum emission;
(iii) strong emission lines;
(iv) variability in continuum emission and/or in emission lines on relatively short time scales.

Population: Too boring, please see textbook, if you want details.

(a) Seyfert Galaxies: I, II, LINERs => difference: emission line.

(b) Radio Galaxies: strong radio emission

↳ subgroup: emission line: => BLRGs / NLRGs

(broad/narrow line radio-galaxy)

radio morphology: FR I, FR II

distance between the two most indense spots on either side of necleus

V.S. half the overall source size.

radio spectral properties:

steep-spectrum, flat-spectrum

(c) Quasars and QSOs → Quasi-Stellar Object. ⇒ according to optical.

↓

Quasi-Stellar Radio Source

now it's common to use them without distinction.

QSOs: most luminous AGNs, luminosity ~ 1000 L^* galaxy.

(d) BL Lac Objects and OVVs ⇒ grouped together in "Blazars"

OVVs: 1. optically violently variables

↓

strong and rapid

2. relatively strong polarization of optical

BL Lac Objects: strong radio emission

highly variable in optical and X-ray

strongly polarized radio and optical emission

How to explain AGN?

SMBH Paradigm:

some physical quantities: (simple spherical model)

1. Eddington luminosity of M_{BH}

$$L_{Edd} = \frac{4\pi G c m_p}{\sigma_T} M_{BH} \approx 1.28 \times 10^{46} M_8 \ \mathrm{erg \cdot s^{-1}} \qquad M_8 = M_{BH}/10^8 M_\odot$$

2. for a given L, the minimum M_{BH}:

$$M_{BH} = 8 \times 10^7 L_{46} \ M_\odot \qquad L_{46} = L/10^{46} \ \mathrm{erg \cdot s^{-1}}$$

3. accretion luminosity:

$$L = \frac{G M_{BH}}{r} \dot{M}_{BH}$$

4. rest mass of accrete material ⇒ radiation ∝ efficiency

$$\epsilon_r = \frac{L}{\dot{M}_{BH} c^2}$$ typical value: 0.1

while $H \to He$: 0.007

Accretion disk:

a simplest model: axisymmetric, thin, optically thick, keplerian disk
↓
multi-temperature black-body spectrum.

mass and angular momentum conservation dominate evolution.

Undoubtedly, fact is more complicate.

Continuum Emission:

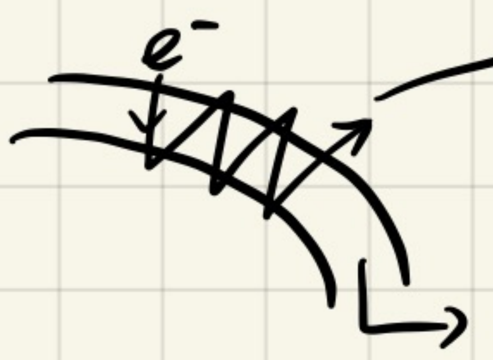
from radio to γ-ray

rough approximation: power law, $F_\nu \propto \nu^{-\alpha}$ $\quad 0 \lesssim \alpha \lesssim 1$

"brightness temperature" $T_b \sim 10^{11}$ K
↓
if thermal emission → gamma-ray → observation defy
so can't be thermal emission

Relativistic electron

generation: 1st-order Fermi acceleration.



⇒ power-law energy distribution for accelared particle.

Radiation Mechanism:

Synchrotron Emission. ⇒ radio emission ⇒ concentrated within a small beam

Inverse Compton process ⇒ energy > radio

S V.S. IC

$$\frac{\langle P_{IC} \rangle}{\langle P_S \rangle} \sim \left(\frac{T_b}{10^{12} K}\right)^5 \left(\frac{\nu_*}{1 GHz}\right)$$

if $T_b > 10^{12}$ K ⇒ $\langle P_{IC} \rangle$ larger than $\langle P_S \rangle$

cause: the cooling of the electrons by radiation is catastrophic

thus, T_b must $< 10^{12}$ K to keep electrons relativistic.

Emission line

permitted line

forbidden line [ ] e.g. [OIII]

semiforbidden line] CIII]

→ typically in low density gas.

if gas is dense, relevant ions can be removed quickly from the excited state by collisions with electrons.

line luminosity volume due to collisional excitation:

$$\mathcal{L}_c = n_2 A_{21} h_p \nu_{12} = \frac{n_e n_1 P_{12} h_p \nu_{12}}{1 + n_e P_{21}/A_{21}}$$

spontaneous emission

$$\approx \begin{cases} n_e n_1 P_{12} h_p \nu_{12} & (\text{if } A_{21} \gg n_e P_{21}) \\ n_1 (P_{12}/P_{21}) A_{21} h_p \nu_{12} & (\text{if } A_{21} \ll n_e P_{21}) \end{cases} \rightarrow n_e - \frac{A_{21}}{P_{21}}$$

collision-caused probability

low density: $n_e \ll \frac{A_{21}}{P_{21}} \Rightarrow \mathcal{L}_c$ independent of A_{21}

→ both p-line & f-line generate

high density: $n_e \gg \frac{A_{21}}{P_{21}}$ for f-line but not for p-line

f-line is reduced by a factor of $A_{21}/n_e P_{21}$

$\Rightarrow \frac{\text{f-line}}{\text{p-line}}$ as a tracer of emitting gas.

two important lines: [OIII] , CIII]

critical electron density: $\sim 10^6 \text{cm}^{-3}$ $\sim 10^{10} \text{cm}^{-3}$ → $\frac{A_{21}}{P_{21}}$

broad lines ⟺ $v \gtrsim 10^3 \text{km/s}$ ⇒ only p-line → high v, high ρ

narrow lines ⟺ $v \sim 10^2 \text{km/s}$ ⇒ p-line & f-line → low v, low ρ

How is the emitting gas ionized?

1. collisional process
2. photoionization

get properties of source by fitting.

BPT diagram.

Line ratio to seperate AGN, star-forming galaxies.

emission line due to H II regions generated by young massive star.

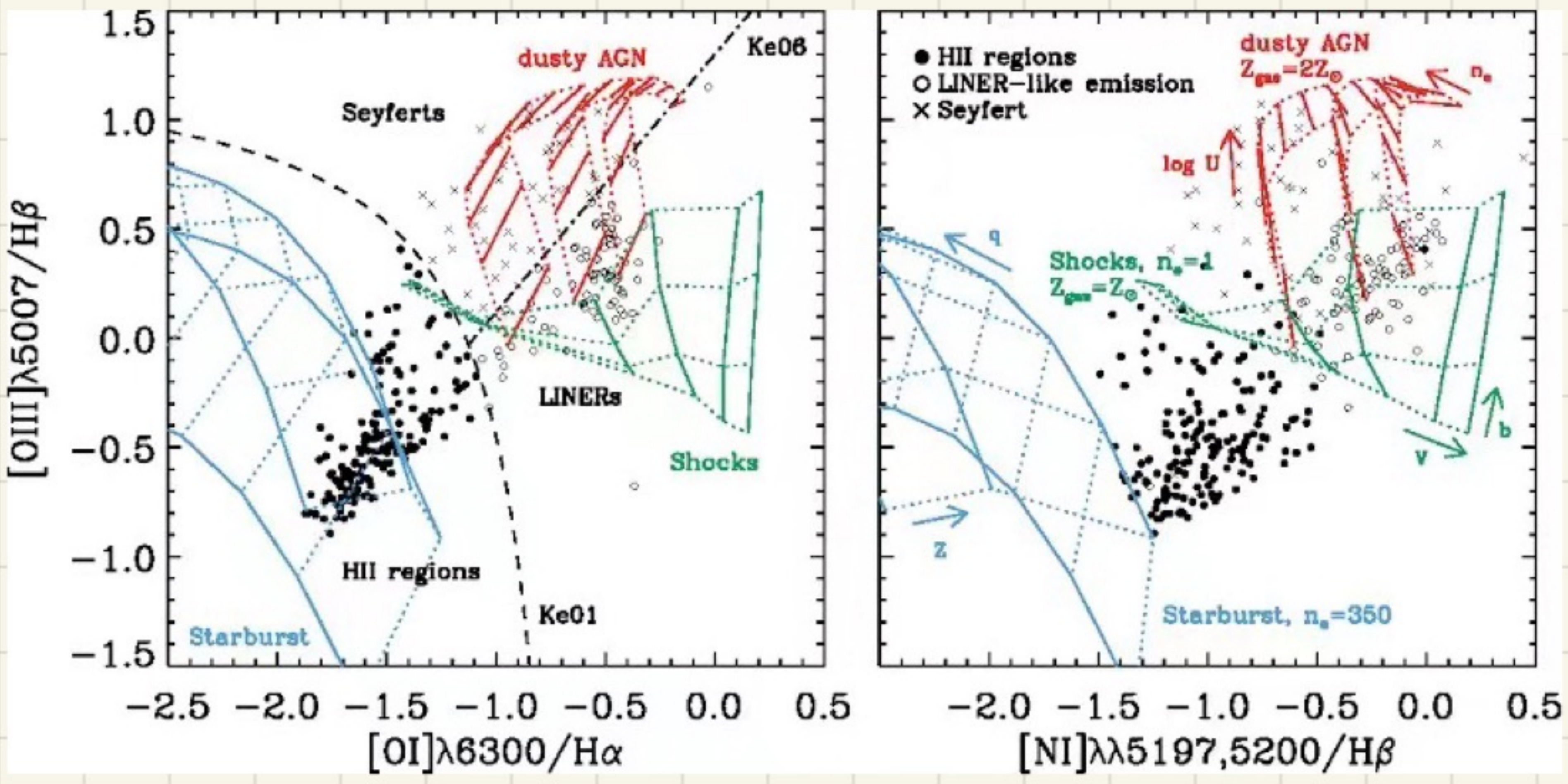
the level of ionization and temperature of emitting gas:

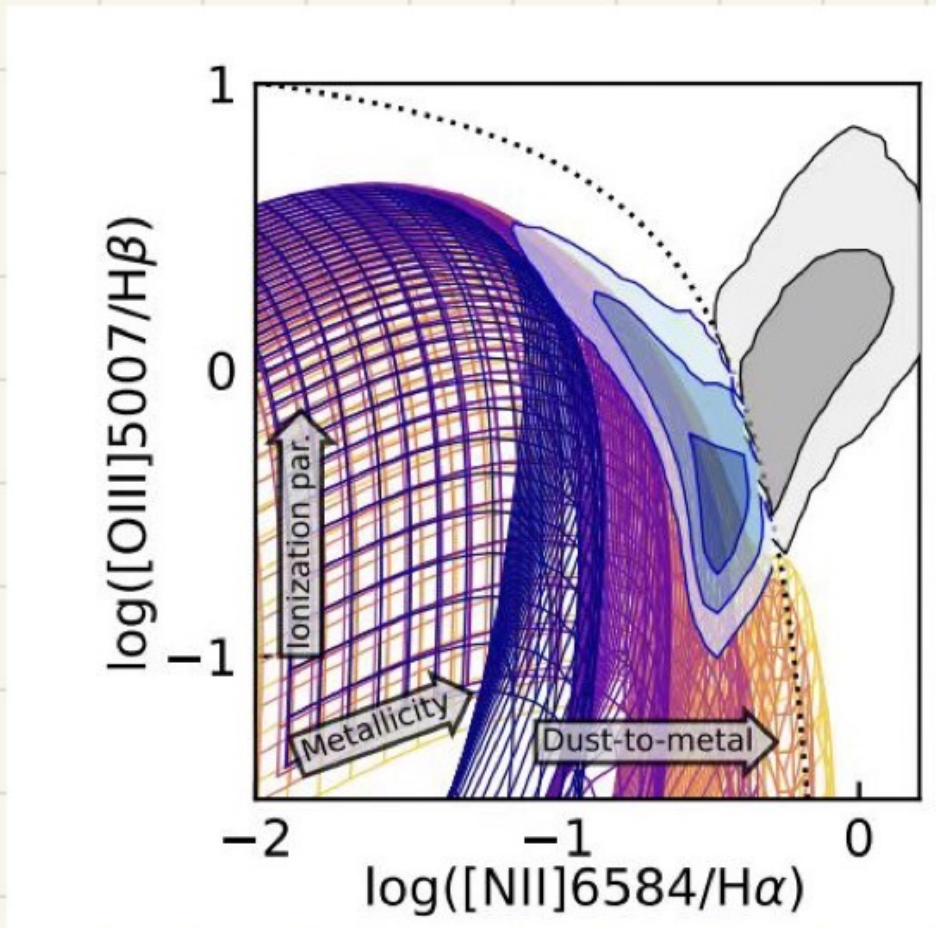
AGN > star-forming galaxy.

[OIII] $\lambda 5007/H\beta$: mean level of ionization and T (temp)

[OI] $\lambda 6300/H\alpha$, [SII] $\lambda\lambda$ 6717, 6731 $/H\alpha$, [NII] $\lambda 6583/H\alpha$

: the relative importance of a large partially ionized zone produced by high-energy photoionization.





↳ from Xiaojing Lin ↲

§ 14.2.5 Jets, Superluminal Motion and Beaming.

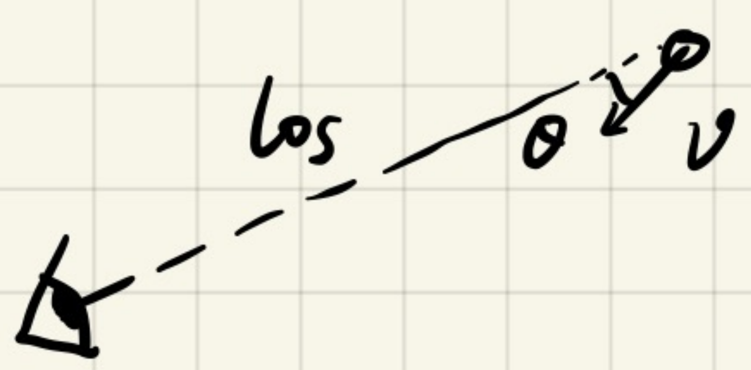
collimation due to supersonic motion

detailed derivation see Page 634.

due to relativistic effect, simple math

two identical jets propagating in opposite directions,

$$\frac{F_{\nu,in}}{F_{\nu,out}} = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^{2+\alpha}$$



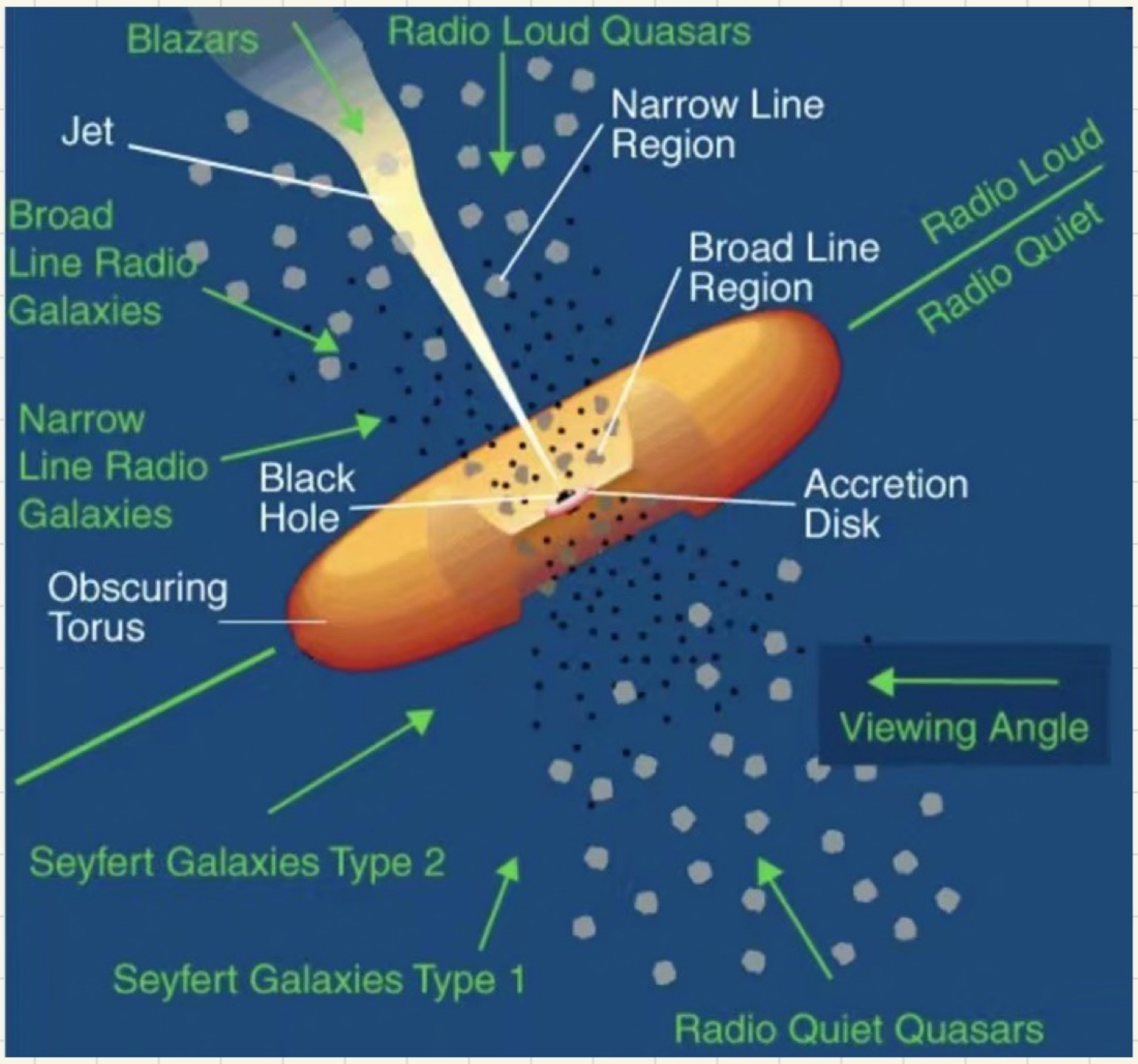
if $\beta \sim 1$, $\theta \ll 1$ $\quad \underset{\text{incoming}}{F_{in}} \gg \underset{\text{outgoing}}{F_{out}}$

BLR: typical size of ~ 0.3 pc $\rho_{gas} \sim 10^{10} cm^{-3}$ $T_{gas} \sim 10^4 K$

NLR: ~ 50pc from SMBH $\rho_{gas} \sim (10^4 - 10^6) cm^{-3}$ $T_{gas} \sim (1-2) \times 10^4 K$

Obscuring Torus: block BLR

AGN Unification model



Observational Test for SMBH

1. Milky way: radial velocities, proper motions, acceleration of <u>stars</u>
2. NGC 4258: water masers.
3. MCG-6-30-15: extreme broadness and asymmetry of fluorescent Fe K line. (~ 6 keV)
4: reverberation mapping
   $\downarrow$
   intrinsic flux varability of the UV/optical continuum generated in accretion disk.

& time delay τ in response of the broad emission lines to the change in the continuum flux.

$\Rightarrow$ BLR size: $r \sim c\tau$

§. 14.3

§. 14.3.1. Growth of SMBH and fueling of AGN

observational fact: oldest AGN $z = 7.6$ (2021) $\sim 0.5\,Gyr$

free-fall time scale of a virialized halo $\sim 0.05\,Gyr$ at $z=7$

If growth through radiative accretion.

mass accretion rate: $\dot{M}_{BH} = \frac{L}{\varepsilon_r c^2} = \left(\frac{L}{L_{Edd}}\right) \frac{M_{BH}}{\varepsilon_r t_{Edd}}$

if L/L_{Edd} and ε_r independent of time

$$M_{BH}(t) = M_{BH,0} \exp\left(\frac{t}{t_{BH}}\right)$$

$$t_{BH} = \left(\frac{L}{L_{Edd}}\right)^{-1} \varepsilon_r t_{Edd} \simeq 4.4\times10^7 \left(\frac{\varepsilon_r}{0.1}\right)\left(\frac{L}{L_{Edd}}\right)^{-1} yr.$$

3 possibilities for BH generated.

1. collapse of an isolated massive star
2. merger and accretion of neutron stars.
3. collapse of a gas cloud. $\Rightarrow$ uncertain

if $M_{BH,0} = 100\,M_\odot$ $M_{BH} = 10^8\,M_\odot$

$$t = 14\,t_{BH} \simeq 6\times10^8 \left(\frac{\varepsilon_r}{0.1}\right)\left(\frac{L}{L_{Edd}}\right)^{-1} yr.$$

if $\varepsilon_r \sim 1$, $L \lesssim L_{Edd}$ $t \simeq 6\times10^9\,yr = 6\,Gyr \gg 0.5\,Gyr$

so, to reduce t, $L\uparrow$ or $\varepsilon_r\downarrow$

$\swarrow$ super-Eddington rate $\qquad$ $\searrow$ quite low $\ll 0.1$

$\swarrow$ anisotropic accretion $\qquad$ $\downarrow$ will not last long time.

$\Downarrow$

a large amount of gas.

$\downarrow$

the formation of AGN is to identify the mechanism(s) that can effectively bring gas into the center of host galaxy.

key point: how to concentrate the gas in a very small region.

/

gas lose its angular momentum very effectively.

Gravitational interaction with other galaxies.

e.g. merger, perturbated by satellite galaxies.

there're indeed some observational evidences

too faint for high-redshift case.

$z = 2\text{-}3$ AGN peak.

total number density of SMBH are not expected to decrease with time.

$z < 2 \Rightarrow$ due to decline of systems where gas is sufficient.

$z > 3 \Rightarrow$ Because SMBH need time to grow.

- feedback $\Rightarrow$ self-regulated SMBH $\Rightarrow > 10^{9.5} M_\odot$ is rare.
- Most of SMBH at low-z are observed to be hosted by early-type galaxies, e.g. ellipticals, bulges of early-type spirals.
- Disk may be geometrically thick and optically thin.

in ADAF (advection dominated accretion flow)

& ADIOS (advection dominated inflow-outflow solution)

$\Rightarrow \varepsilon_r \ll 0.1$, much of accretion energy is expected to be in strong gas outflow

$\Updownarrow$

many massive ellipticals are radio sources that have low ε_r, but radio jets and lobes.

§. 14.3.2 AGN Demographics

Observed luminosity functions:

$$\phi(L, z) = \phi^*(z) \left\{ \left[\frac{L}{L^*(z)}\right]^{\beta_1} + \left[\frac{L}{L^*(z)}\right]^{\beta_2} \right\}^{-1} \frac{dL}{L^*(z)}$$

redshift functions:

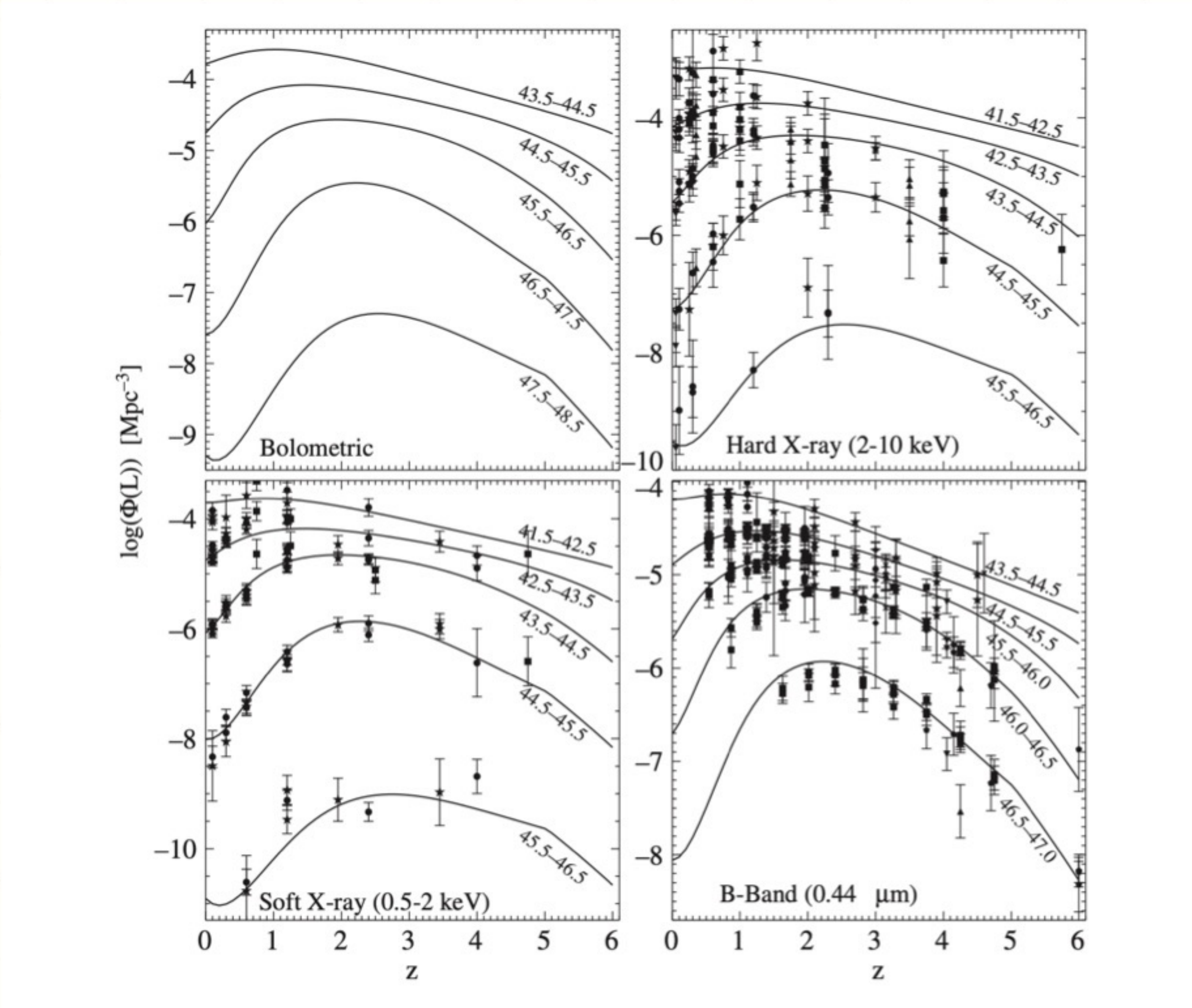


Fig. 14.9. The comoving space density as a function of redshift for QSOs of different luminosities. [Adapted from Hopkins et al. (2007) by permission of AAS]

Spatial clustering:

QSOs' spatial correlation function (CF)

2-point CF's amplitude increase with z

in ΛCDM, mass CF's amplitude decrease with z

$\Downarrow$

linear bias factor of QSOs: $\dfrac{\text{CF's amp of QSOs}}{\text{CF's amp of mass}}$ ↑ with z

if QSOs and DM halo one-to-one relation.

↓

bias parameter reflect which DM halo QSOs reside.

↓

result: host halo mass is roughly $10^{12.5}-10^{13}\,h^{-1}M_\odot$

duty cycle:

t_Q: average duty time of a halo.

$t(z)$: $z \leftrightarrow$ age of universe.

n_Q: number density of QSOs

n_{DM-Q}: nu.... den... of DM halos capable of hosting QSOs

$$\Rightarrow \frac{t_Q}{t(z)} = \frac{n_Q}{n_{DM-Q}} \Rightarrow t_Q \sim 10^7 \sim 10^8\,\text{yr}$$

for the case of decrease at $z<3$, possible reasons:

1. galaxies are less gas-rich at low-z
2. feedback is more effective at low-z $\Rightarrow \rho_{gas}$ is low
3. merger $\Rightarrow$ gas is too hot to be accreted by SMBH.

§.14.3.3 Outstanding Questions.

1. what is so special about halos of $10^{12.5} h^{-1} M_\odot$
   i.e. absent in lower mass halos.
   ? too faint to be detected
   ? don't host SMBH
   ? have no sufficient gas
2. What determines AGN to be radio-quiet (RQ) or radio-loud (RL).
   ? related to the environment where AG is located
   RL in local universe $\Leftrightarrow$ elliptical galaxies | central galaxies of groups and clusters
   $\updownarrow$
   triggering conditions different from optical AGN
   $\to$ a galaxy with a young stellar population.
   At low-z, most radio-galaxies $\to$ low-power FRI in elliptical
   $\to$ weak ongoing star formation, weak emission lines.
   Difference between FRI and FRII is gas accretion mode.
   ...... too many conclusions.

§.14.4 AGN and Galaxy formation (AGN feedback)

$$\underbrace{\frac{dE}{dt}}_{\text{energy output}} = \varepsilon \dot{M}_{BH} c^2 \qquad \varepsilon = \underbrace{\varepsilon_r}_{\text{radiative}} + \underbrace{\varepsilon_m}_{\text{mechanical}} \quad \text{feedback efficiency}$$

Three possible process.

1. Radiative process : radiation pressure and radiative heating

2. Mechanical process: jet, wind

3. Energetic particles (cosmic ray)
↓
in principle contribute to the overall pressure of gas

Radiative feedback

1. UV and X-ray photon
⇓
photoionization ⇒ ionize neutral atoms ⇒ IGM
heating

2. dust absorption

push away
wind

3. Compton heating (energy transfer from photon to e^-)

Mechanical feedback

radio jets, lobes.

X-ray cavities filled with relativistic gas
↳ observational evidence in some elliptical galaxies at the center of cluster.

jet-powered bubble ~ $\underbrace{\text{adiabatic}}$ stellar wind bubble.
↓
low P_{gas}, high T_{gas}
⇓
poor radiative cooling

supersonic expansion ⇒ shock sweep gas

subsonic expansion ⇒ PdV form. ⇒ buoyancy

May appear in all early-type galaxies
↳ heat gas, quench radiative cooling / star formation.
↓

reshape galaxy luminosity function

color-magnitude relation of galaxies