Emission Mechanisms

Spectral Lines (ERA Chap. 7)

Free-Free (ERA Chap. 4)

Synchrotron (ERA Chap. 5)

Pulsars (ERA Chap. 6)

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Spectra (5.3)

(5.3.2) ***Synchrotron Spectra of Optically Thin Radio Sources***

Most astrophysical sources of synchrotron radiation behave as power laws and have spectral indices near α ~ 0.75 (**$\delta \sim 2.5$**) that reflects electron energy distributions

The rate at which an electron loses energy to synchrotron radiation is proportional to E^2 and therefore higher energy electrons are depleted more rapidly AND as we just saw, the critical frequency is also proportional to E^2 so the **source spectra steepens at high frequencies!**

As we did for free-free, now we can write the **emission coefficient j_ν** for an ensemble of electrons where 'δ' is now used for our power law that describes the **number of electrons per unit volume**,

$$n(E)\,dE \propto E^{-\delta}dE, \qquad (5.70)$$

$$j_\nu d\nu = -\frac{dE}{dt}n(E)\,dE, \qquad (5.73)$$

Lots of substituting later (see text) we have,

$$\boxed{j_\nu \propto B^{(\delta+1)/2}\nu^{(1-\delta)/2}.} \qquad (5.78)$$

The spectral index α=−dlnS/dlnν depends only on δ:

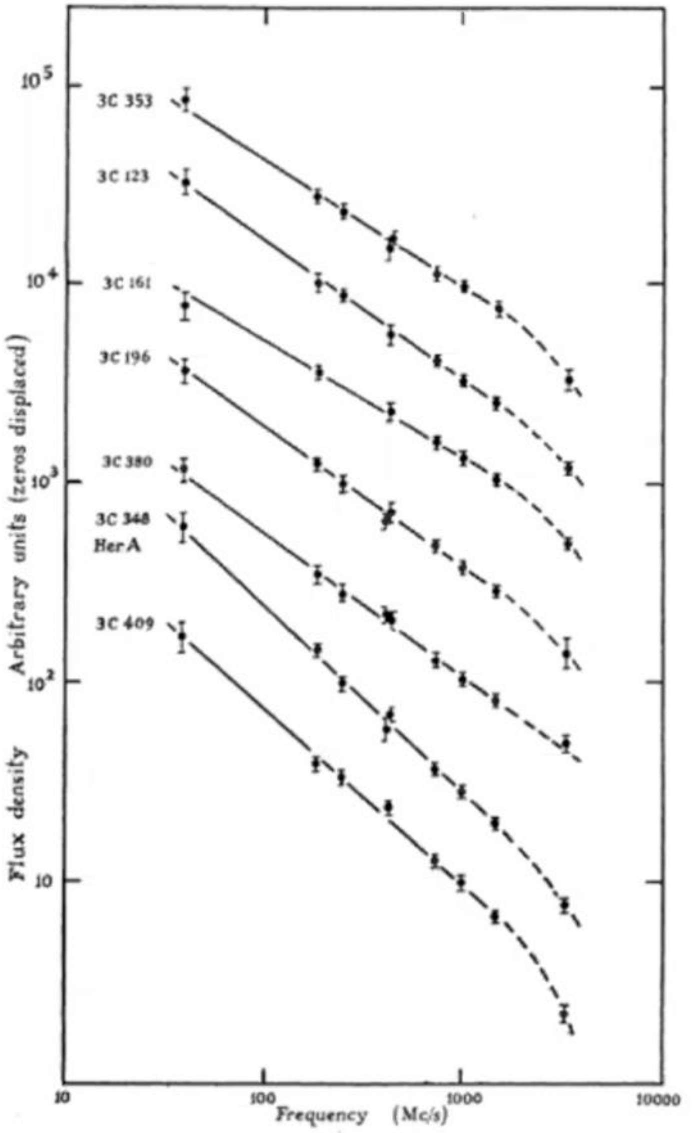
$$\boxed{\alpha = \frac{\delta - 1}{2}.} \qquad (5.79)$$

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Spectra (5.3)

Spectrum of radio galaxies that are→ strong synchrotron emitters

Power-law evident here, with some mild differences which is determined by relativistic electron distribution



Slide Credit: Jim Braatz

Synchrotron Radiation (ERA Chapter 5)

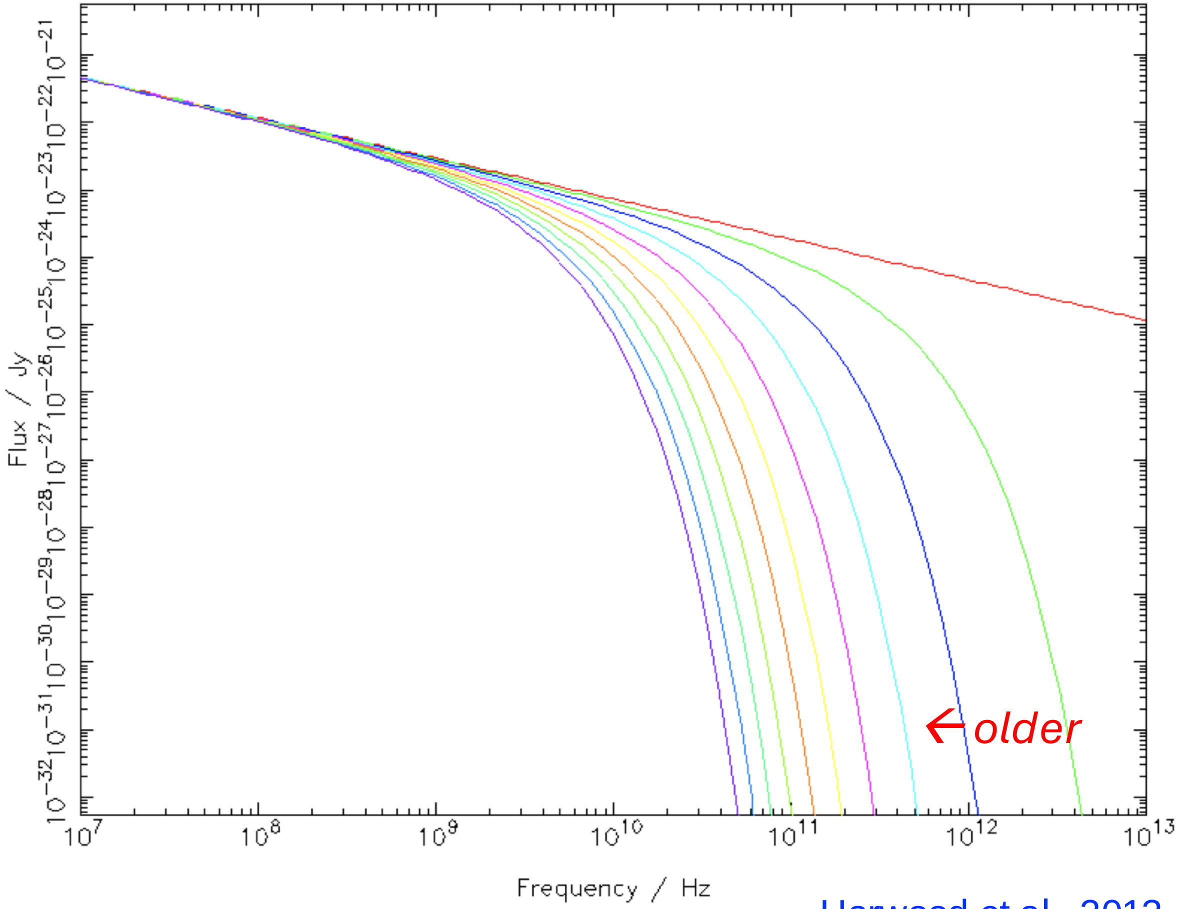
Synchrotron Spectra (5.3)

The rapid depletion of high-energy electrons steepens the radio spectrum

Higher energy particles lose energy faster than the lower energy particles! Therefore, you can use the synchrotron spectrum to 'age' your emission

Broadband Radio Astronomy ToolS (BRATS) software package →

model ages between 0 (red) and 10 (purple) Myrs



Harwood et al., 2013

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Spectra (5.3)

(5.3.3) ***Synchrotron Self-Absorption***

Here **we discuss line brightness and fluxes**…

Even if the ensemble of electrons has a nonthermal energy distribution, we still define an **'effective temperature'** of relativistic electrons:

$$T_e \equiv \frac{E}{3k} = \frac{\gamma m_e c^2}{3k}, \qquad (5.83)$$

Removing γ and solving numerically we have,

$$\boxed{\left(\frac{T_e}{\mathrm{K}}\right) \approx 1.18 \times 10^6 \left(\frac{\nu}{\mathrm{Hz}}\right)^{1/2} \left(\frac{B}{\mathrm{gauss}}\right)^{-1/2}.} \qquad (5.85)$$

→ Relativistic electrons emitting synchrotron radiation at ν = 0.1 GHz =10^8 Hz in a B=100μgauss = 10^{-4} gauss magnetic field is T_e ~ 10^{12} K

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Spectra (5.3)

*(5.3.3) **Synchrotron Self-Absorption***

At **low frequencies**, the **brightness temperature approaches the effective temperature**, the source become optically thick to synchrotron self-absorption.
We are in the Rayleigh Jeans limit so,

$$I_\nu \approx \frac{2kT_e\nu^2}{c^2} \propto \nu^{1/2}\nu^2 B^{-1/2} = \nu^{5/2}B^{-1/2}. \qquad (5.88)$$

Where,

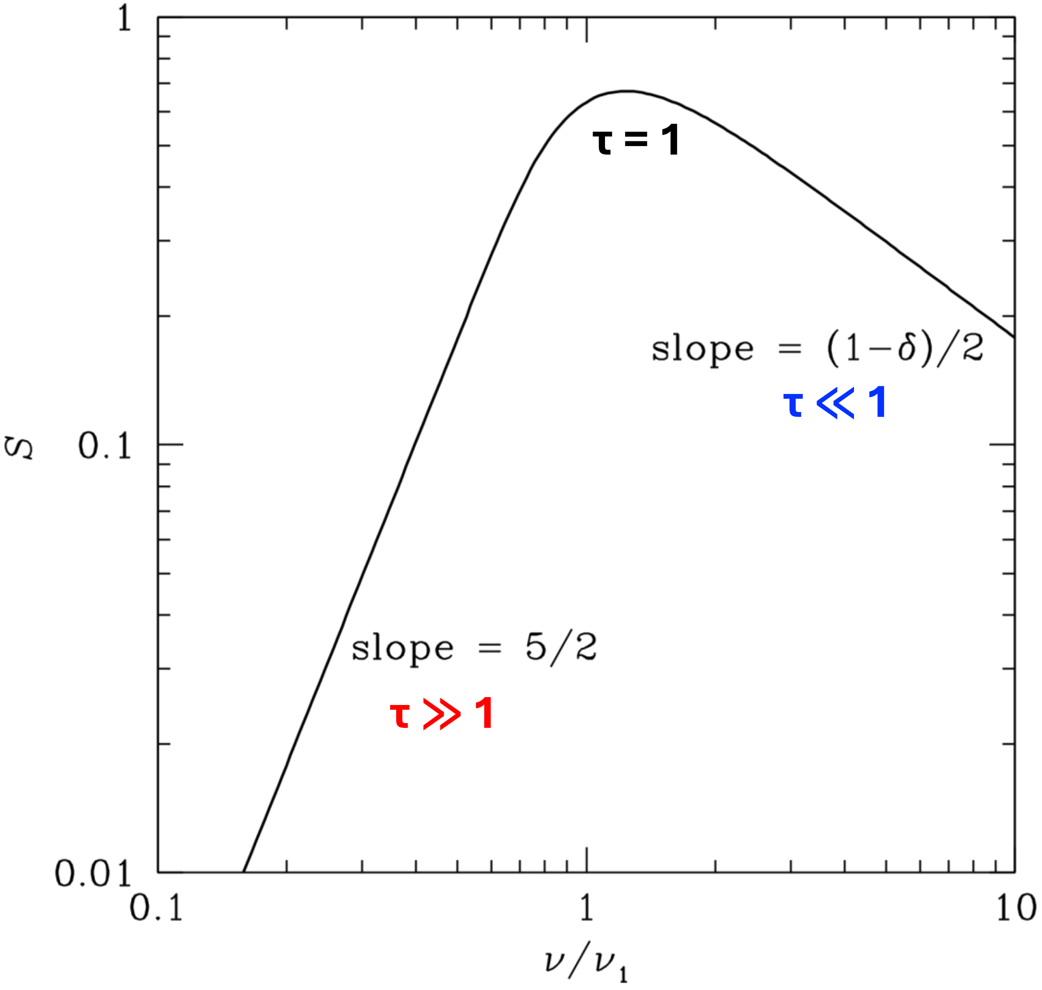
$$\boxed{S(\nu) \propto \nu^{5/2},} \qquad (5.89)$$

The full spectrum of a homogeneous cylindrical synchrotron source →

$$S \propto \left(\frac{\nu}{\nu_1}\right)^{5/2}\left\{1 - \exp\left[-\left(\frac{\nu}{\nu_1}\right)^{-(\delta+4)/2}\right]\right\}, \qquad (5.90)$$

Fig. 5.7 (ERA)

Idealized case:



Synchrotron Radiation (ERA Chapter 5)

Synchrotron Spectra (5.3)

(5.3.3) ***Synchrotron Self-Absorption***

At **low frequencies**, the **brightness temperature approaches the effective temperature**, the source become optically thick to synchrotron self-absorption.

$$\boxed{\left(\frac{T_e}{\mathrm{K}}\right) \approx 1.18 \times 10^6 \left(\frac{\nu}{\mathrm{Hz}}\right)^{1/2} \left(\frac{B}{\mathrm{gauss}}\right)^{-1/2}.} \quad (5.85)$$

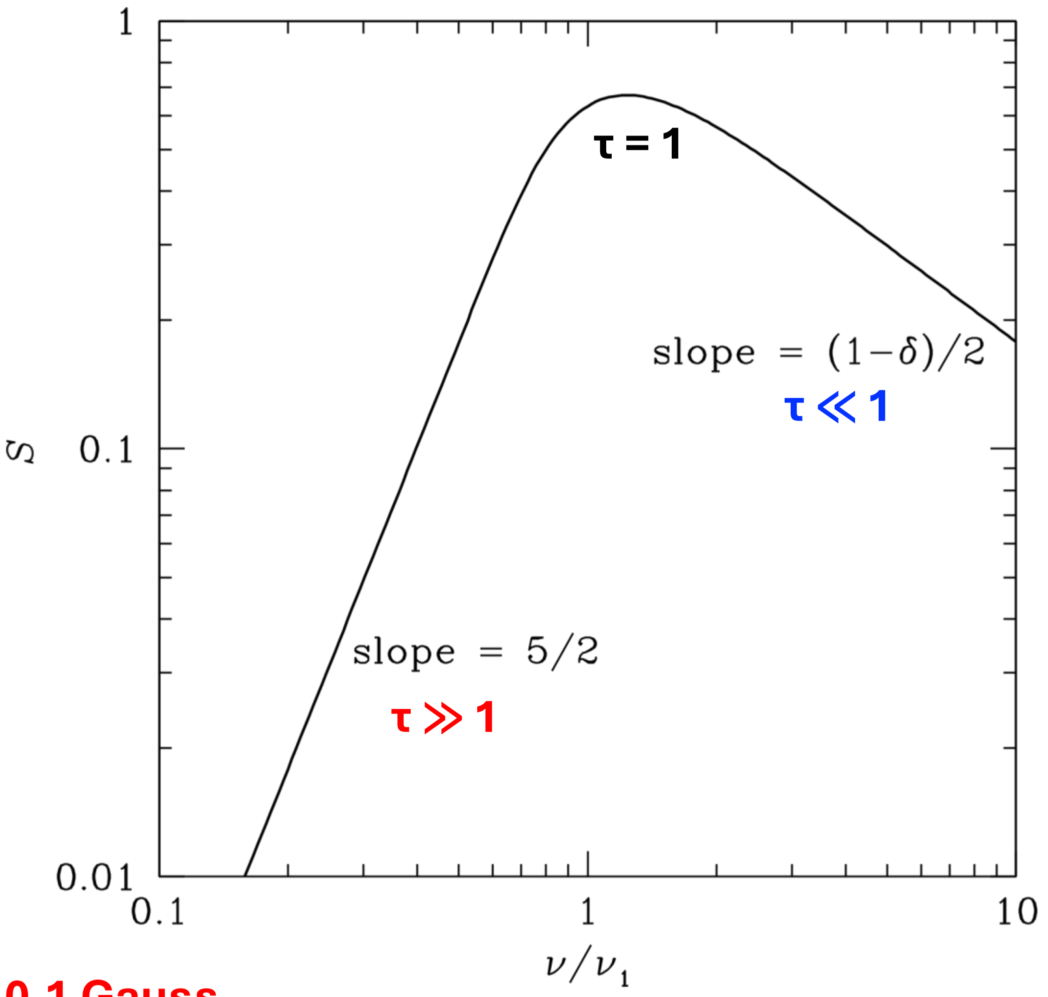
Can now estimate of the **magnetic field strength**

$$\boxed{\left(\frac{B}{\mathrm{gauss}}\right) \approx 1.4 \times 10^{12} \left(\frac{\nu}{\mathrm{Hz}}\right) \left(\frac{T_b}{\mathrm{K}}\right)^{-2}.} \quad (5.91)$$

→ $T_e = T_b \approx 10^{11}$ K at v=1 GHz has a magnetic field strength of 0.1 Gauss

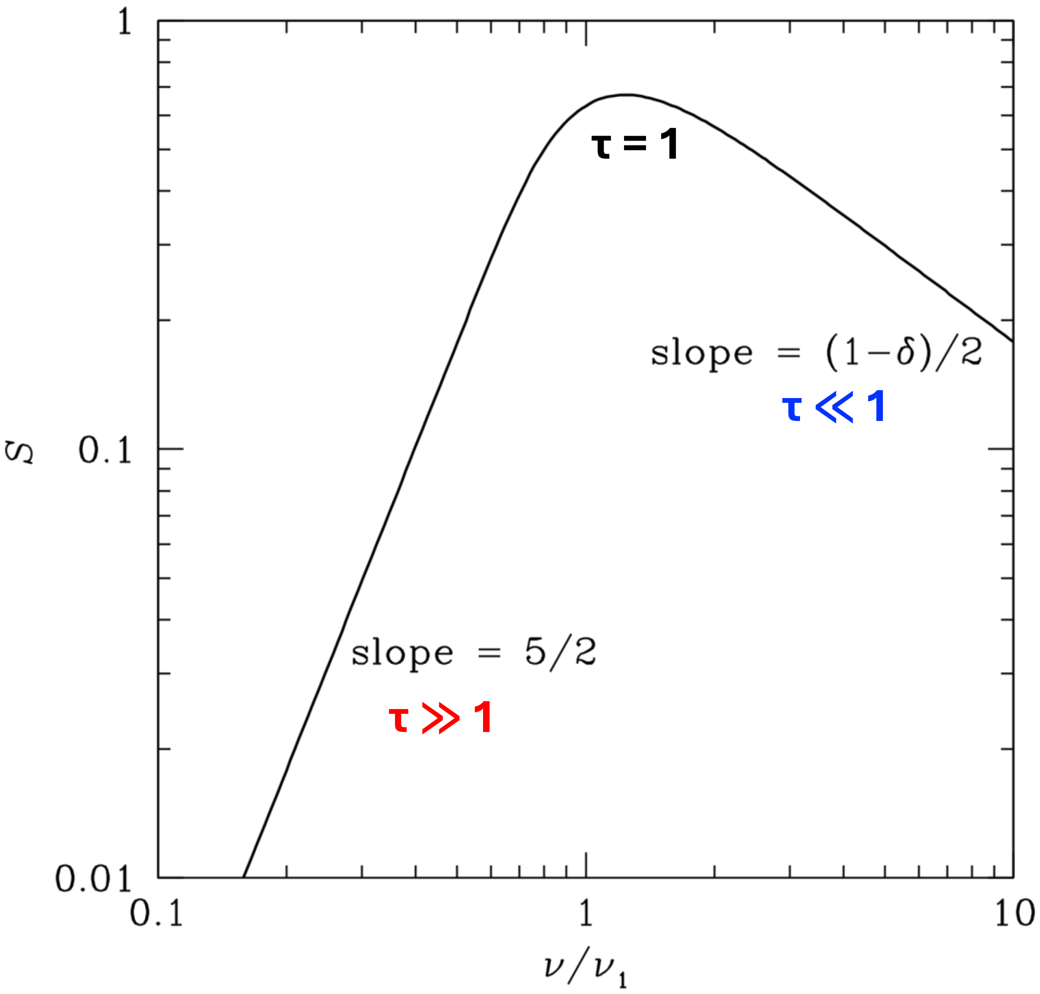
Fig. 5.7 (ERA)

Idealized case:



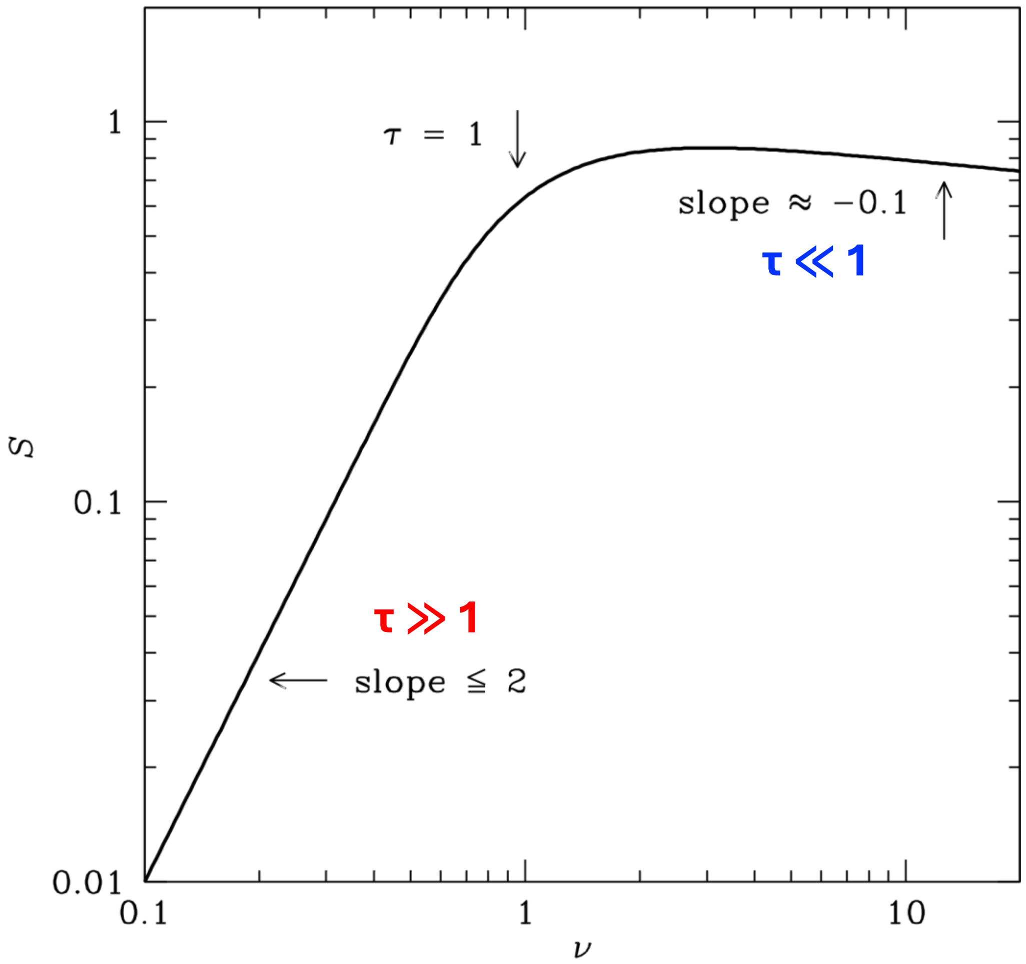
Synchrotron Radiation

Fig. 5.7 (ERA) Idealized case:



Free-Free Radiation

Fig. 4.8 (ERA) Idealized case:



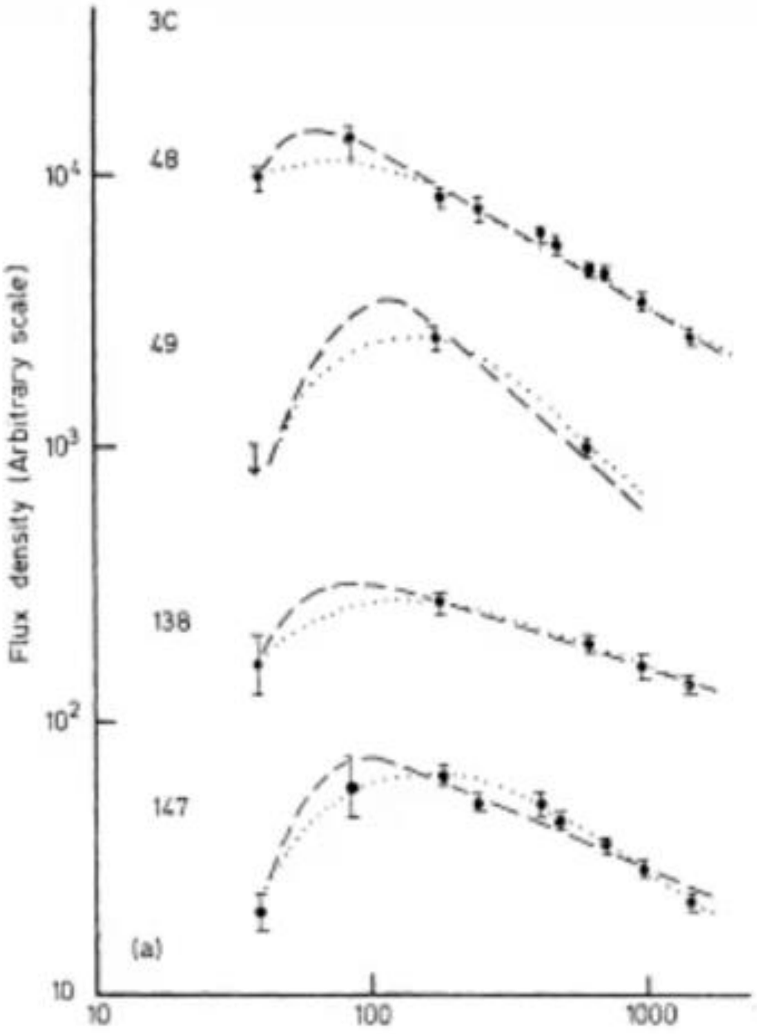
Synchrotron Radiation (ERA Chapter 5)

Synchrotron Spectra (5.3)

(5.3.3) ***Synchrotron Self-Absorption***

Spectrum of radio galaxies that are→
strong synchrotron emitters

Turn over or 'drop-off' at low
frequency that shows the
Synchrotron Self-Absorption



Slide Credit: Jim Braatz

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Spectra (5.3)

(5.3.3) ***Synchrotron Self-Absorption***

Representative spectra of radio galaxies → and quasars show diversity in nonuniform magnetic fields and electron energy distributions in geometrically complex structures

Fig. 5.8 (ERA)

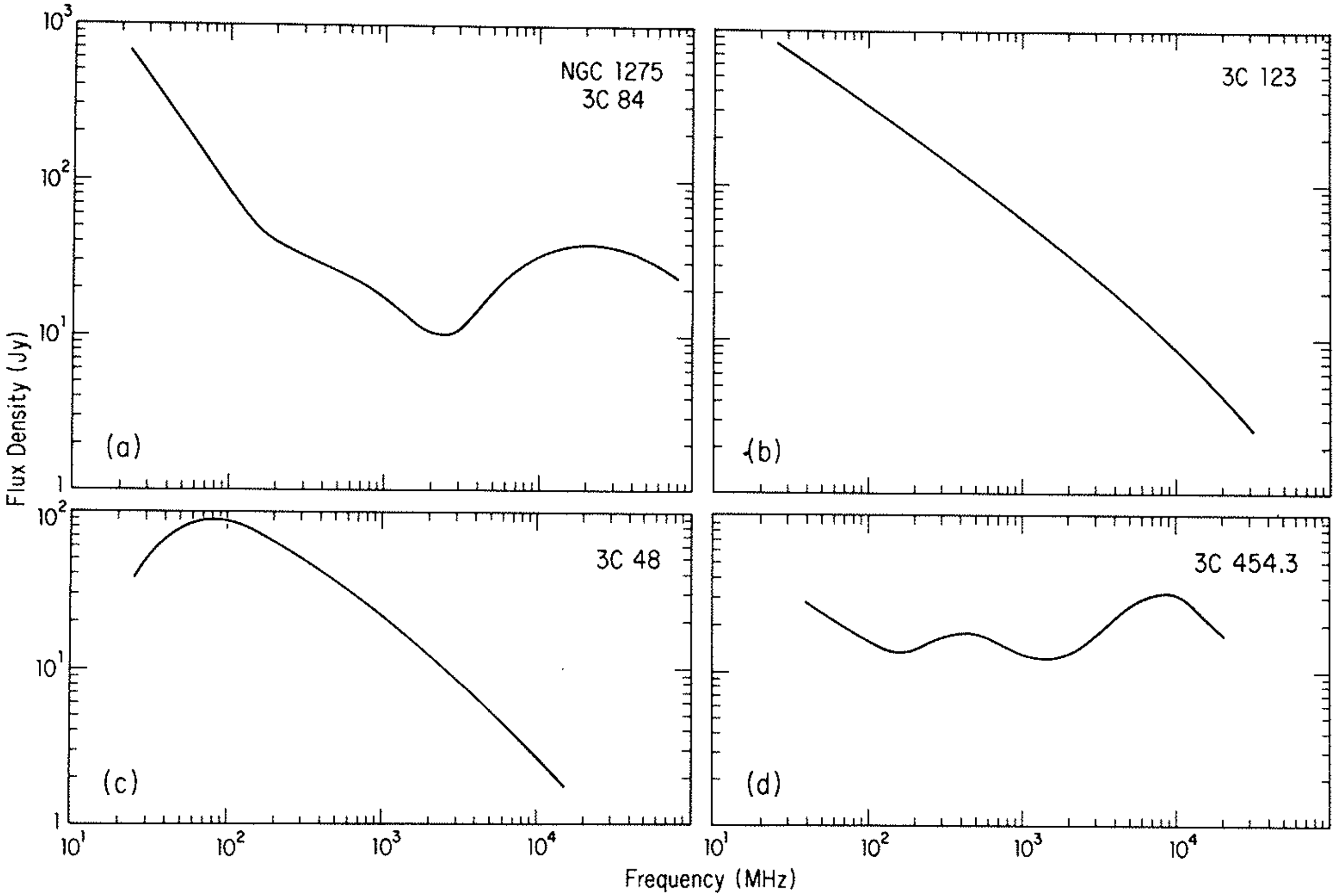


Fig. 2.24 (ERA)

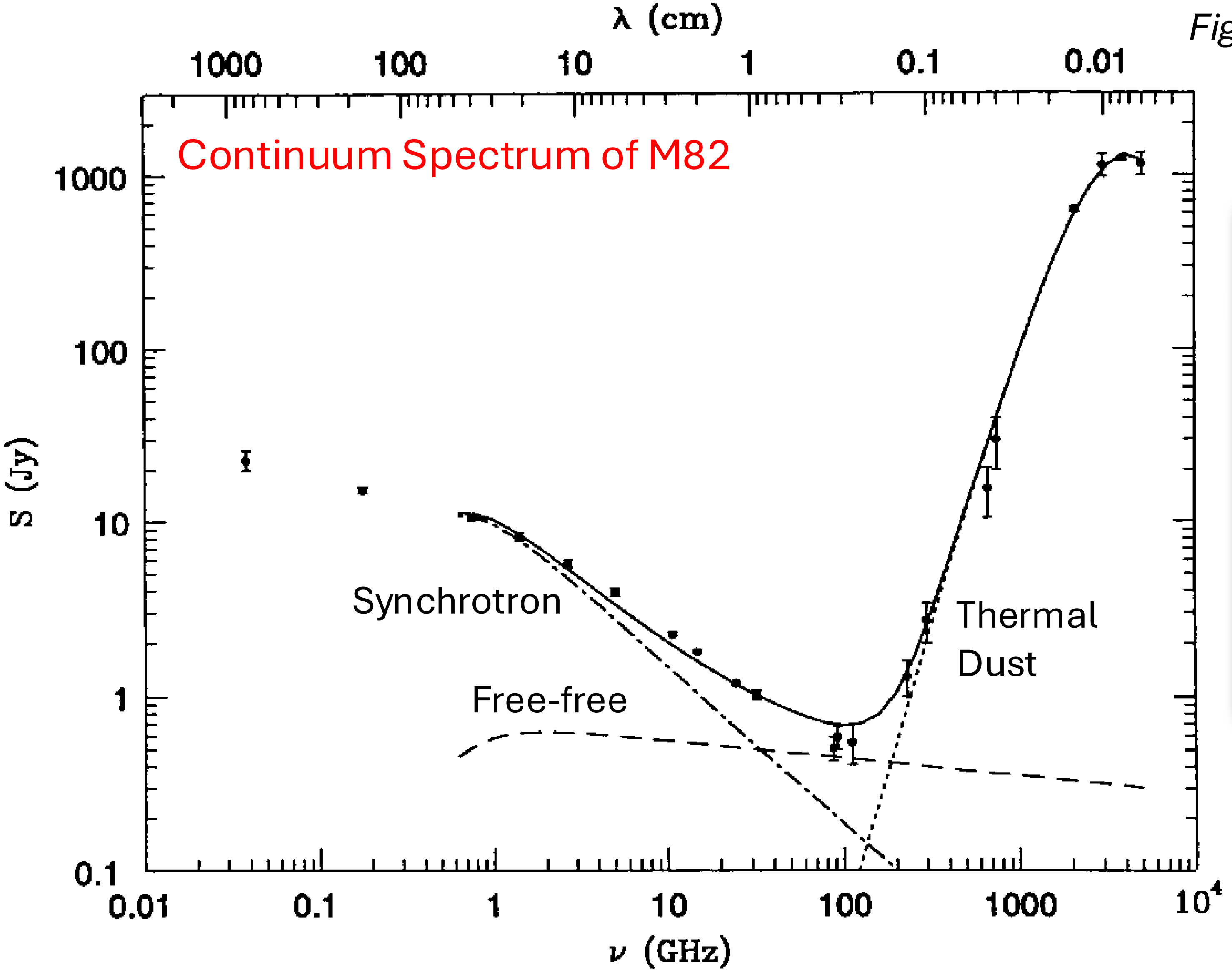


Fig. 8.13 (ERA) Radio continuum emission from M82. Image credit: Josh Marvil (NM Tech/NRAO), Bill Saxton (NRAO/AUI/NSF), Hubble (NASA/ESA/STScI).

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

(5.4.1) ***Minimum Energy and Equipartition***

Idea here to find the minimum total energy in relativistic particles and magnetic fields required to produced a synchrotron source of a certain radio luminosity

The text goes over derivations to solve for **electron energy density** by integrating over the number density of electrons *n(E)dE* in the energy range *E* to *E* + *dE* times electrons with energy, *E*.

We get:

$$\boxed{U_{\mathrm{e}} \propto B^{-3/2},} \quad (5.98)$$

and a total energy density (all cosmic rays) of $U_{\mathrm{E}} = (1 + \eta)\, U_{\mathrm{e}}$

Where we consider the "invisible" cosmic ray protons and heavier ions because they still contribute to the total cosmic-ray particle energy, where *η* is the ion/electron energy ratio

Combining the magnetic energy density, $U_B \propto B^2.$ (5.99)

The total energy is: $\boxed{U = (1 + \eta)\, U_{\mathrm{e}} + U_B.}$ (5.100)

Synchrotron Radiation (ERA Chapter 5)

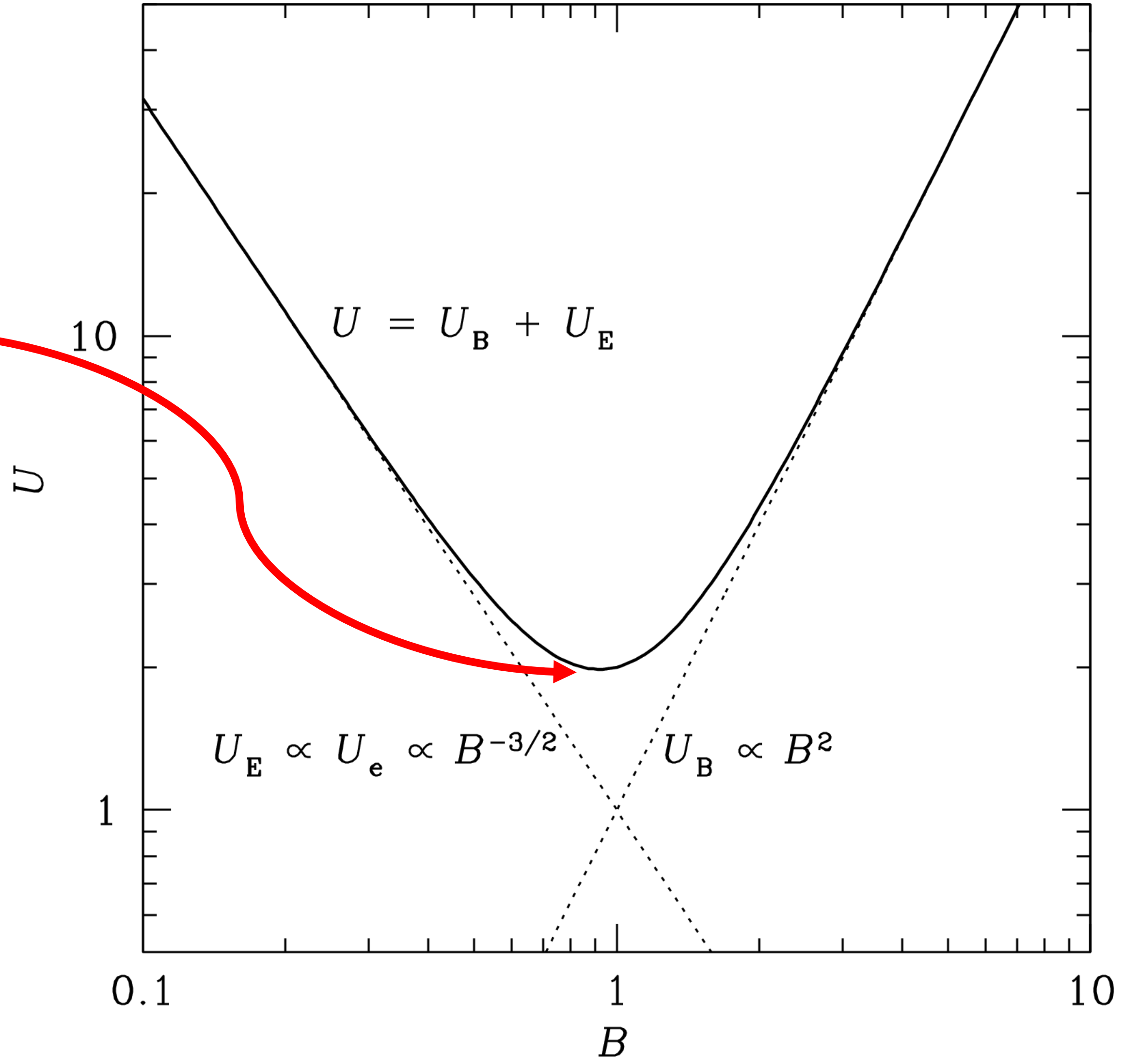
Synchrotron Sources (5.4)

(5.4.1) ***Minimum Energy and Equipartition***

Main Takeaway:

There are greatly differing dependences of U_e and U_b on 'B' so the total energy density E has a fairly sharp minimum near equipartition, i.e., the point at which $(1+\eta)U_e \approx U_B$

Fig. 5.9 (ERA)



Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

(5.4.1) ***Minimum Energy and Equipartition***

Main Takeaway:

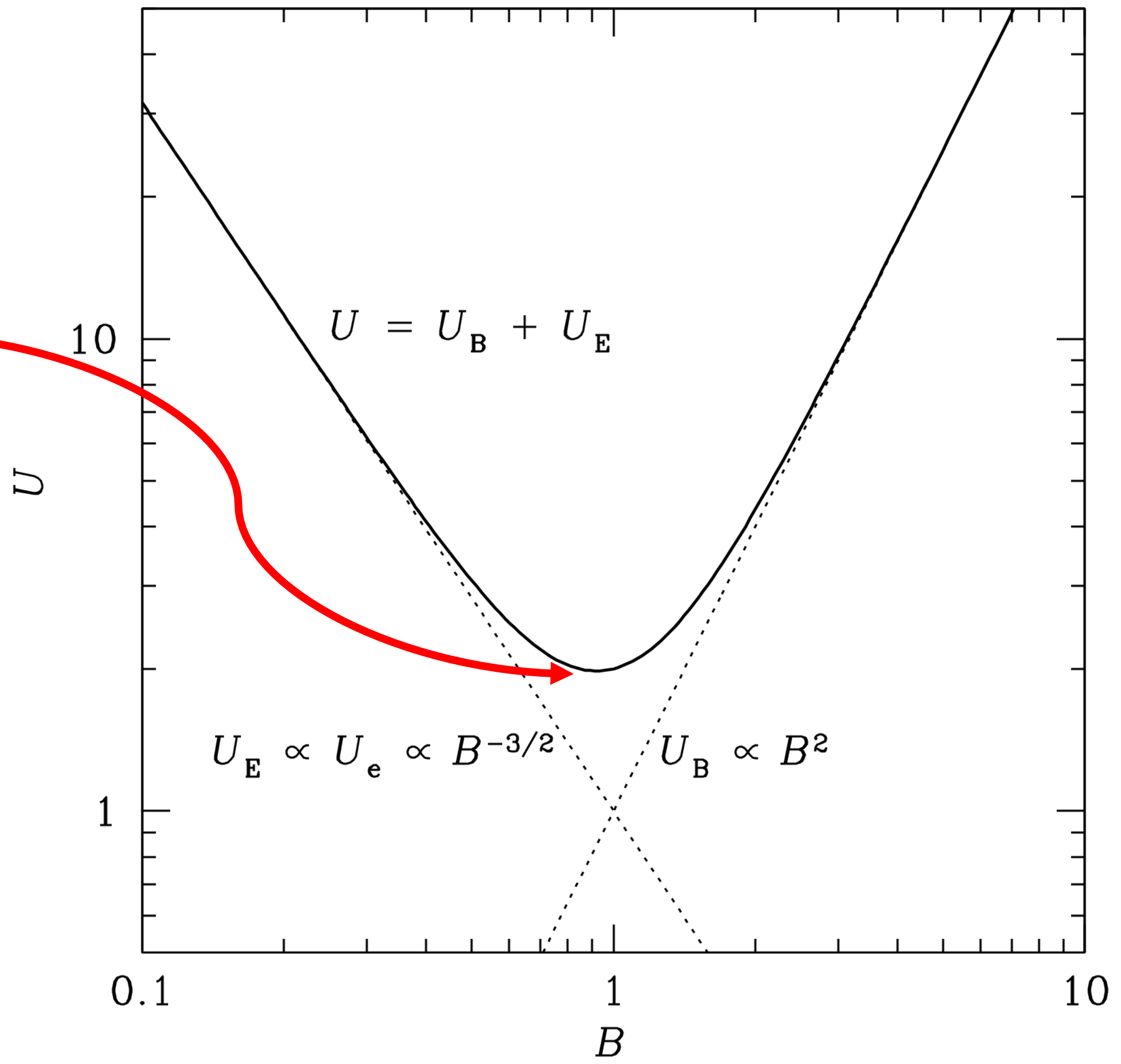
There are greatly differing dependences of U_e and U_b on 'B' so the total energy density E has a fairly sharp minimum near equipartition, i.e., the point at which $(1+\eta)U_e \approx U_B$

The ratio of cosmic-ray particle energy density to magnetic field energy that minimizes the total energy is,

$$\boxed{\frac{\text{particle energy density}}{\text{magnetic field energy density}} = \frac{(1+\eta)\,U_e}{U_B} = \frac{4}{3}.} \qquad (5.107)$$

Nearly unity!

Fig. 5.9 (ERA)



Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

(5.4.1) ***Minimum Energy and Equipartition***

Main goal then is to extract out the minimum-energy magnetic field strength for a source of radio luminosity *L* and radius *R*,

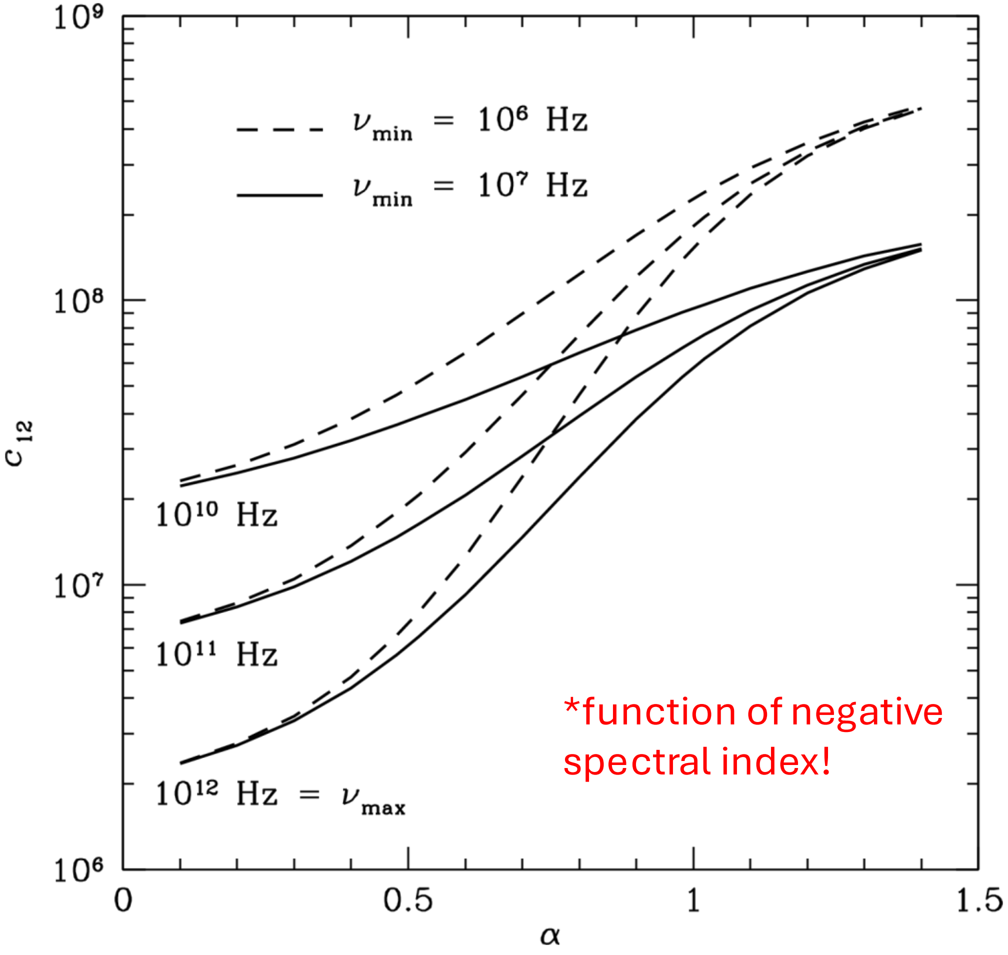
$$\boxed{B_{\min} = [4.5\,(1+\eta)\,c_{12}L]^{2/7}R^{-6/7}\quad \text{gauss}} \qquad (5.109)$$

And the corresponding total energy,

$$\boxed{E_{\min}\,(\text{total}) = c_{13}[(1+\eta)\,L]^{4/7}R^{9/7}\quad \text{ergs.}} \qquad (5.110)$$

Which have been simplified numerically (see text and references Wilson et al., and Pacholczyk).

Fig. 5.10 (ERA)



*function of negative spectral index!

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

(5.4.1) ***Minimum Energy and Equipartition***

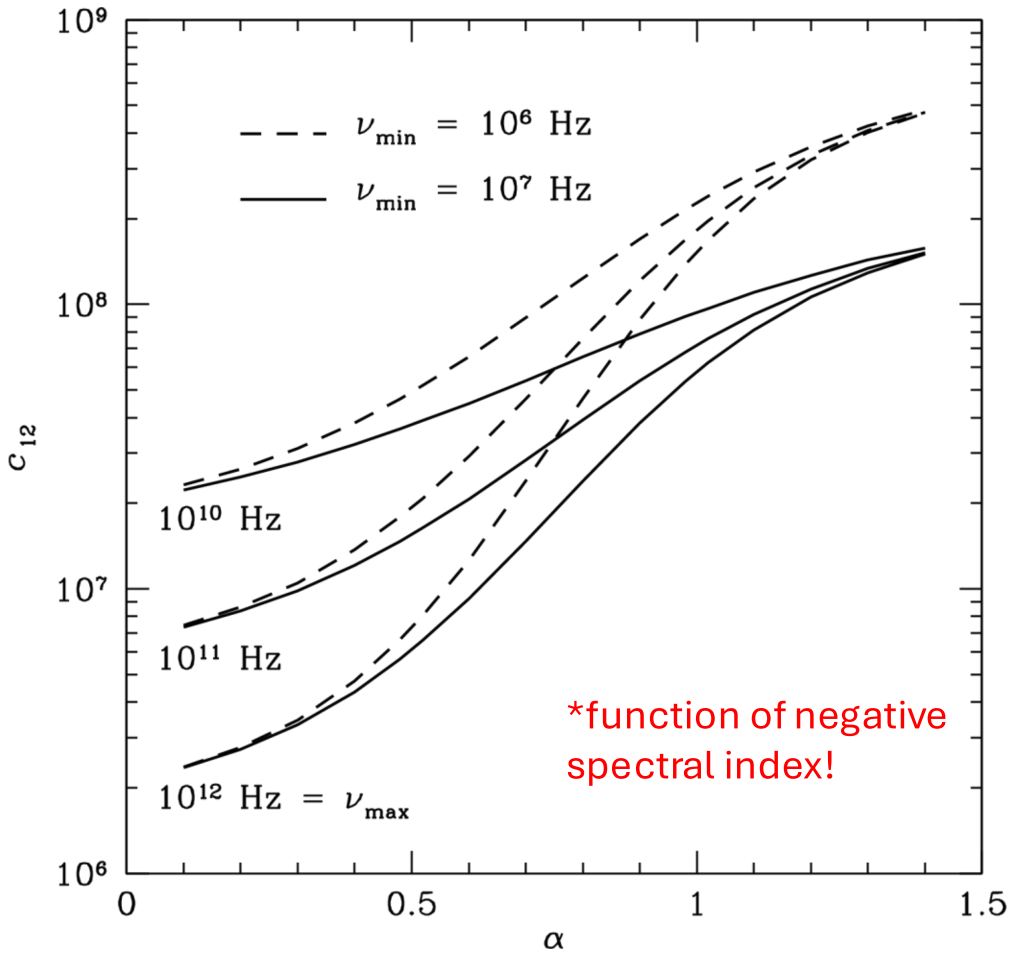
Another key term to know is the **synchrotron lifetime,** defined as the ratio of the total electron energy E_e to the energy loss rate in terms of luminosity *L:*

$$\tau_\mathrm{s} \equiv \frac{E_\mathrm{e}}{L}. \qquad (5.111)$$

If other loss mechanisms (e.g., inverse-Compton scattering) are significant, the **actual source lifetime will be shortened** And can be written in terms of c_{12} and B-field:

$$\boxed{\tau_\mathrm{s} \approx c_{12} B_\perp^{-3/2}.} \qquad (5.112)$$

Fig. 5.10 (ERA)



*function of negative spectral index!

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

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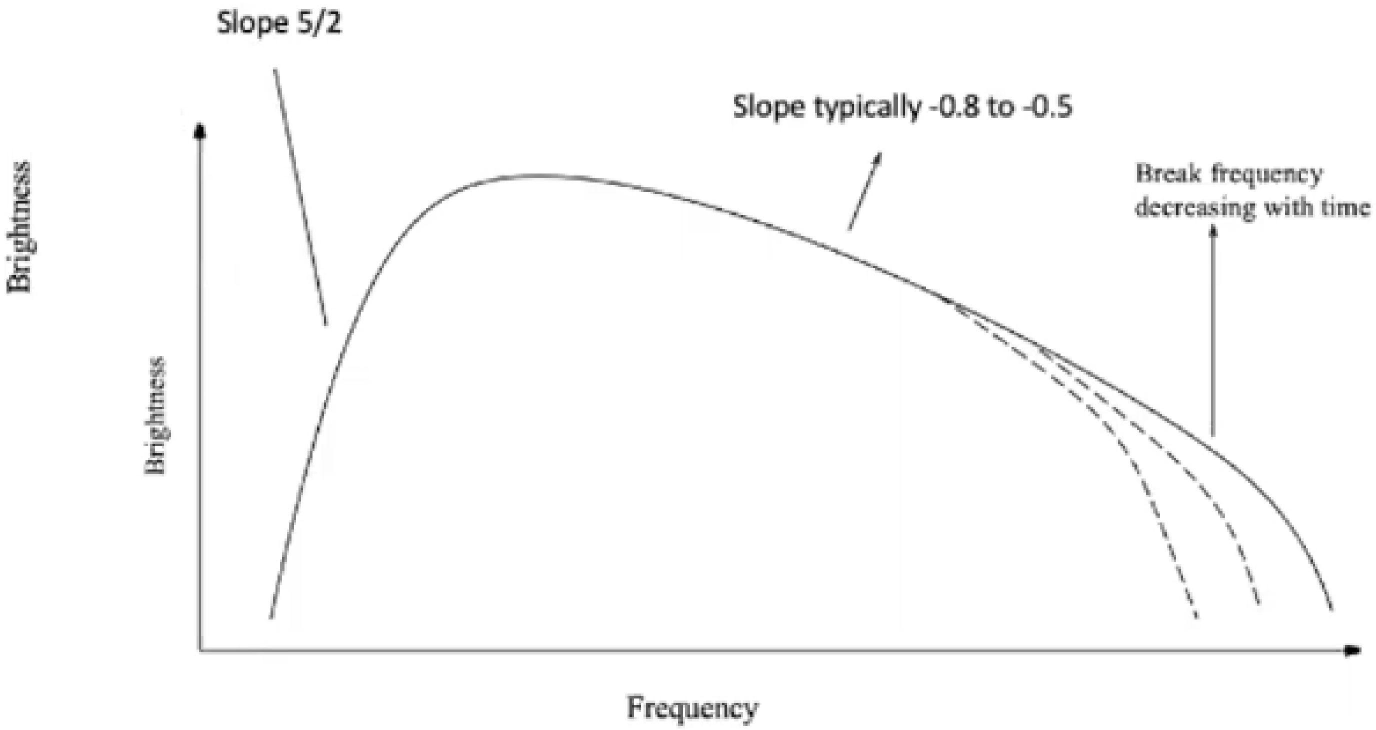


Slide Credit: Jim Braatz

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

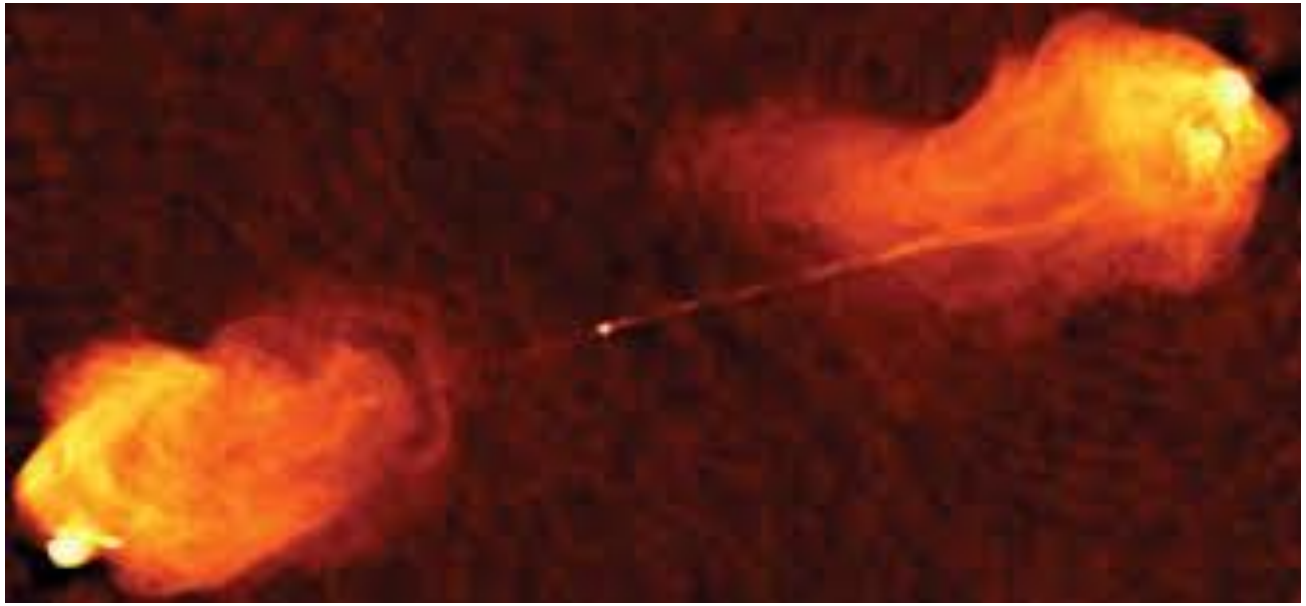
(5.4.3) ***Application to Cyg A***

Main part of this chapter section applies what we've learned to famous radio galaxy, Cyg A →

1) The radio power exceeds the power produced by all the stars in our galaxy!

$$\frac{L}{L_\odot} \approx \frac{1.33 \times 10^{45} \text{ erg s}^{-1}}{3.83 \times 10^{33} \text{ erg s}^{-1}} \approx 3.5 \times 10^{11}.$$

Fig. 5.12 (ERA)



Synchrotron Radiation (ERA Chapter 5)

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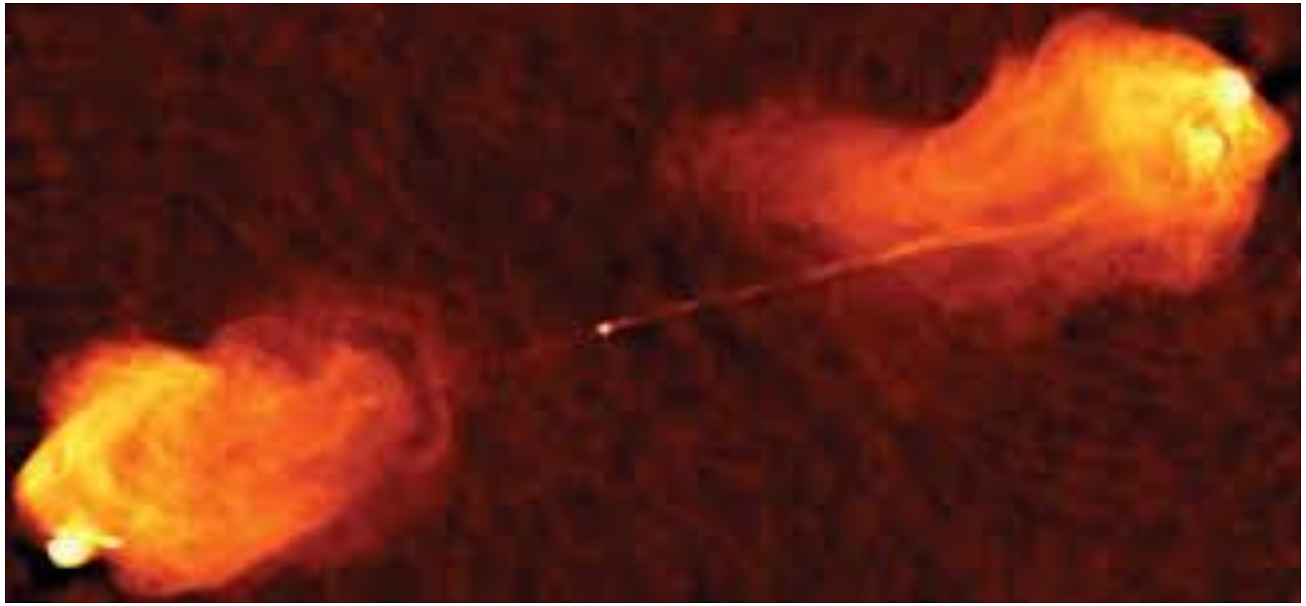

1) The radio power exceeds the power produced by all the stars in our galaxy!

2) Large energies $E_{\min} \sim 10^{60}$ ergs!

$$E_{\min} \approx 2\,(\text{lobes}) \cdot c_{13}[(1+\eta)\,L]^{4/7} R^{9/7}$$

$$\approx 2 \cdot 2.0 \times 10^{4} \left(\frac{1.33 \times 10^{45}\ \text{erg s}^{-1}}{2} \right)^{4/7} (9 \times 10^{22}\ \text{cm})^{9/7} (1+\eta)^{4/7},$$

$$E_{\min} \approx 4 \times 10^{4} \cdot 4.1 \times 10^{25} \cdot 3.26 \times 10^{29} \cdot (1 \text{ to } 80) \quad \text{ergs} \qquad (5.120)$$

$$\approx 5.4 \times 10^{59} \cdot (1 \text{ to } 80) \quad \text{ergs} \sim 5 \times 10^{60} \quad \text{ergs}. \qquad (5.121)$$

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

(5.4.3) ***Application to Cyg A***

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$$E_{\min} \approx 2\,(\text{lobes}) \cdot c_{13}[(1+\eta)\,L]^{4/7} R^{9/7}$$
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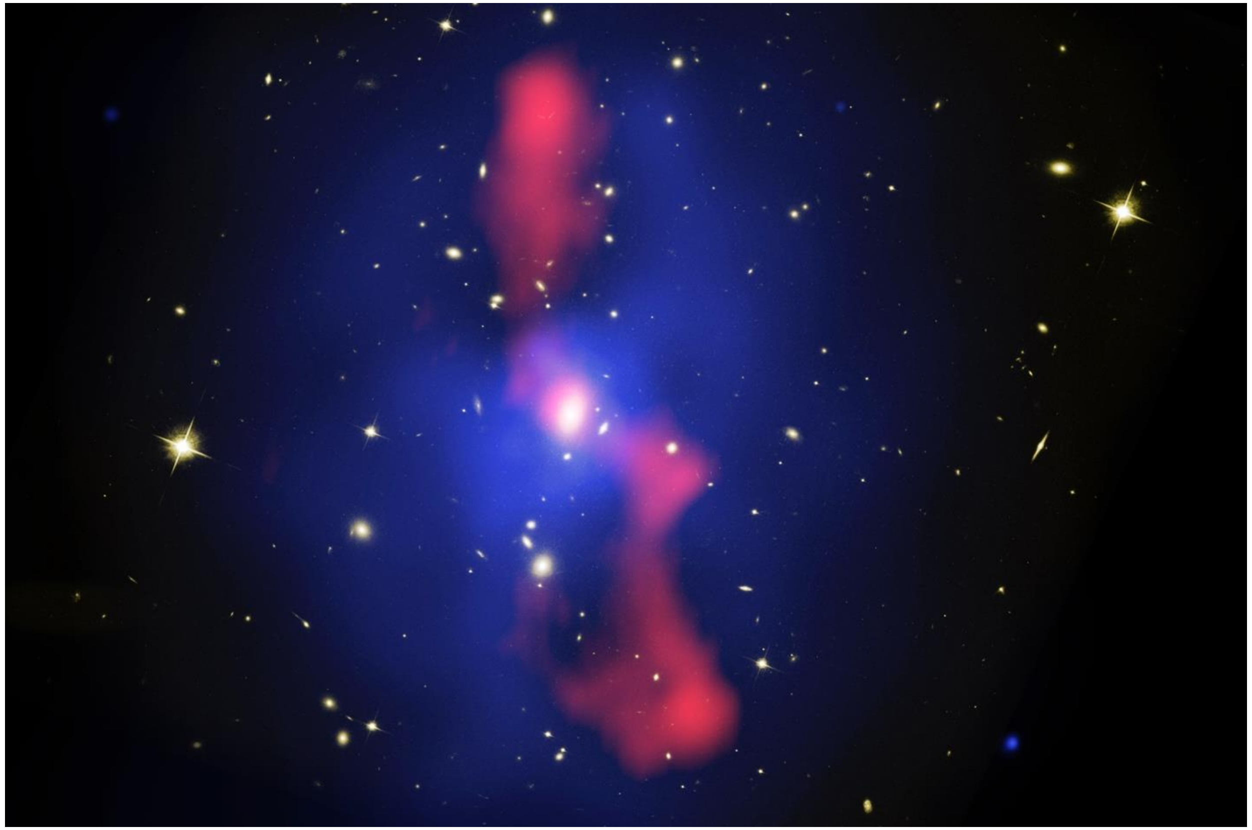
$$\approx 5.4 \times 10^{59} \cdot (1 \text{ to } 80) \text{ ergs} \sim 5 \times 10^{60} \text{ ergs.} \quad (5.121)$$

Fig. 8.15 (ERA)



The radio source (red) in the galaxy cluster MS0735.6+7421 has displaced the X-ray emitting gas (blue)

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

*(5.4.3) **Application to Cyg A***

Main part of this chapter section applies what we've learned to famous radio galaxy, Cyg A →

1) The radio power exceeds the power produced by all the stars in our galaxy!

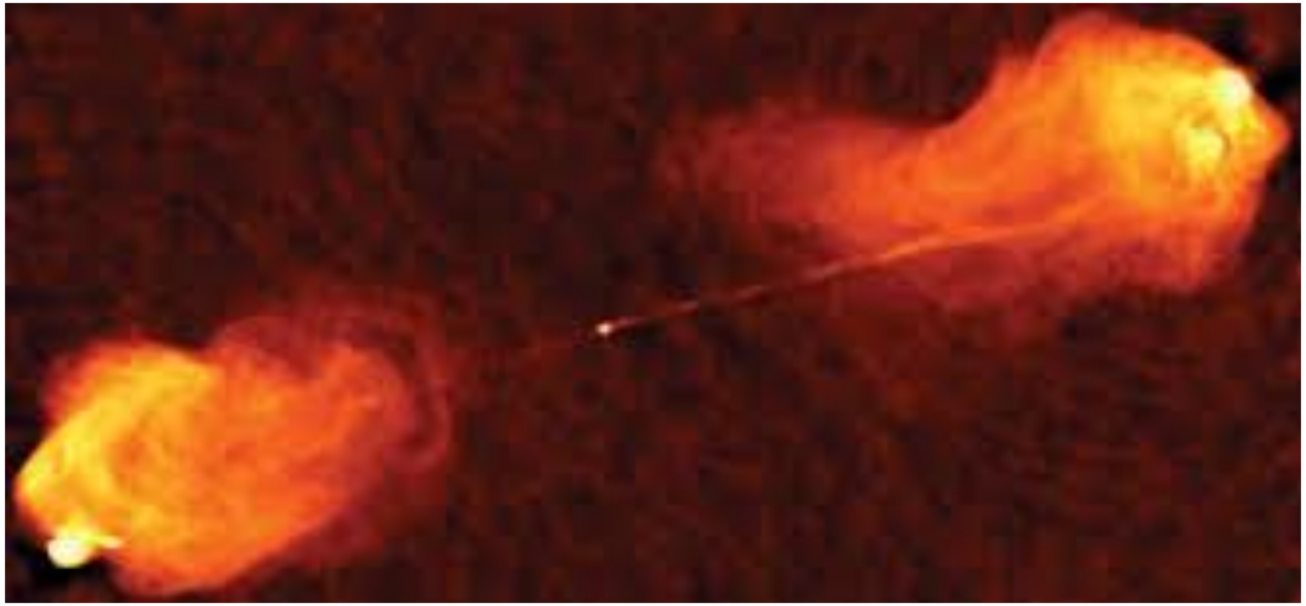
2) Large energies $E_{min} \sim 10^{60}$ ergs!

3) The energy source is a supermassive black hole with $M >> 3 \times 10^6 M_{sun}$

$$M \geq \frac{E_{\rm min}}{c^2} \approx \frac{5 \times 10^{60}\ \ {\rm ergs}}{(3 \times 10^{10}\ \ {\rm cm\ \ s^{-1}})^2} \approx 6 \times 10^{39}\ \ {\rm g},$$

$$M \geq 6 \times 10^{39}\ \ {\rm g} \left(\frac{M_\odot}{1.99 \times 10^{33}\ \ {\rm g}} \right) \approx 3 \times 10^6 M_\odot.$$

Fig. 5.12 (ERA)



Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

(5.4.3) ***Application to Cyg A***

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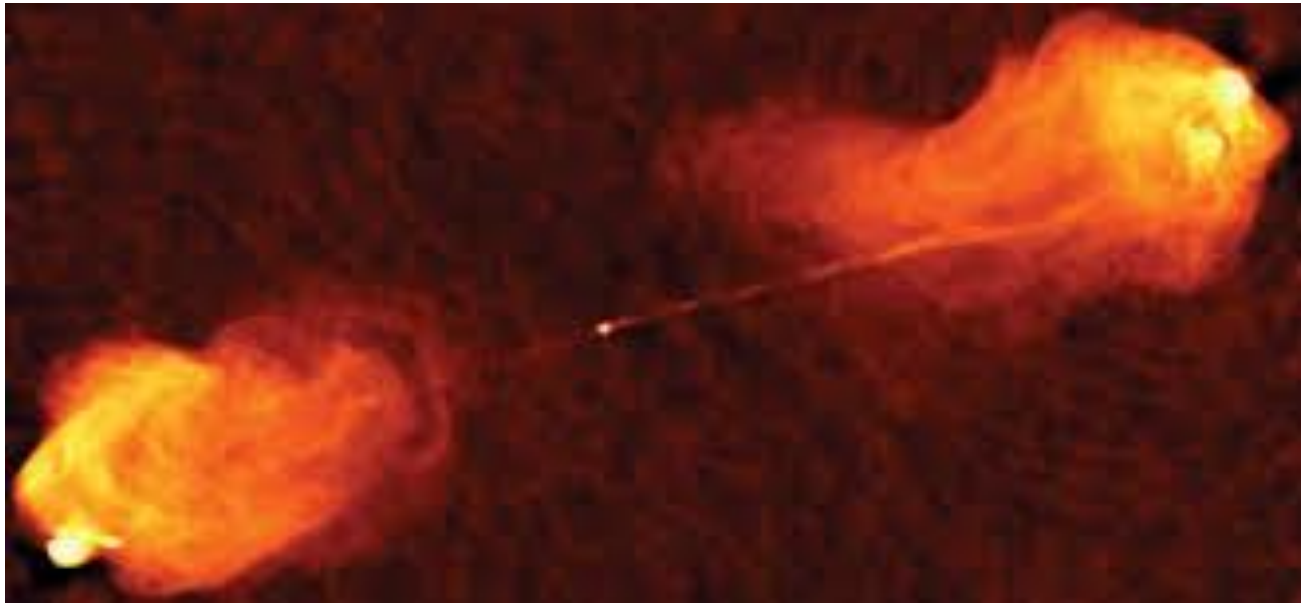


1) The radio power exceeds the power produced by all the stars in our galaxy!

2) Large energies $E_{min} \sim 10^{60}$ ergs!

3) The energy source is a supermassive black hole with $M >> 3 \times 10^6 M_{sun}$

4) The age of the radio source can be estimated,

$$\tau \geq \tau_s \equiv \frac{E_e}{L} \geq \frac{E_{min}/(1+\eta)}{L},$$

$$\tau \geq \frac{5.4 \times 10^{59} \text{ erg } (1+\eta)^{4/7}}{1.33 \times 10^{45} \text{ erg s}^{-1} (1+\eta)} \approx 4 \times 10^{14} \text{ s} \cdot \eta^{-3/7} \sim 10^{14} \text{ s} \sim 3 \times 10^6 \text{ yr}.$$

Synchrotron Radiation (ERA Chapter 5)

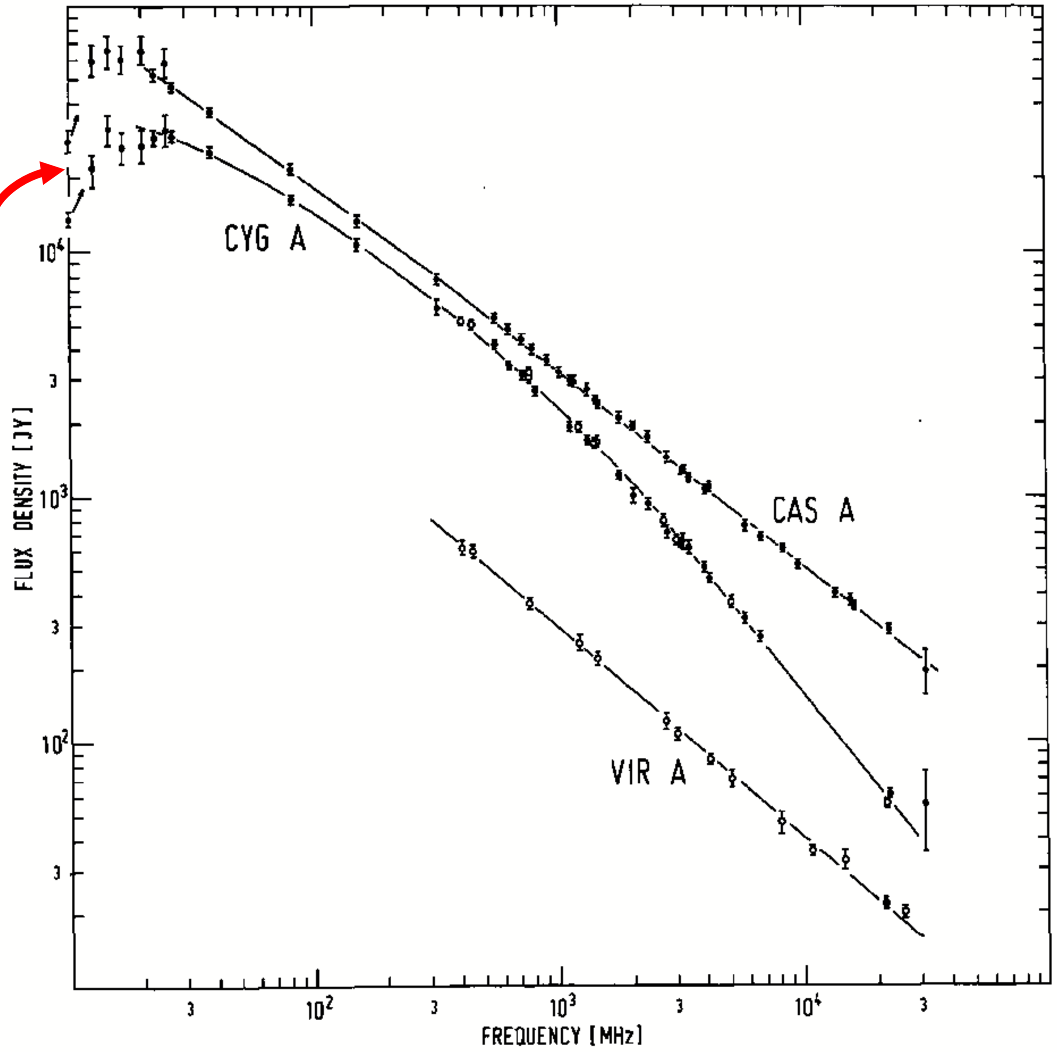
Synchrotron Sources (5.4)

(5.4.3) ***Application to Cyg A***

Let's put it all together!

Turn over at low frequency due to increased optical depth with $\alpha = 5/2$

Fig. 5.13 (ERA)



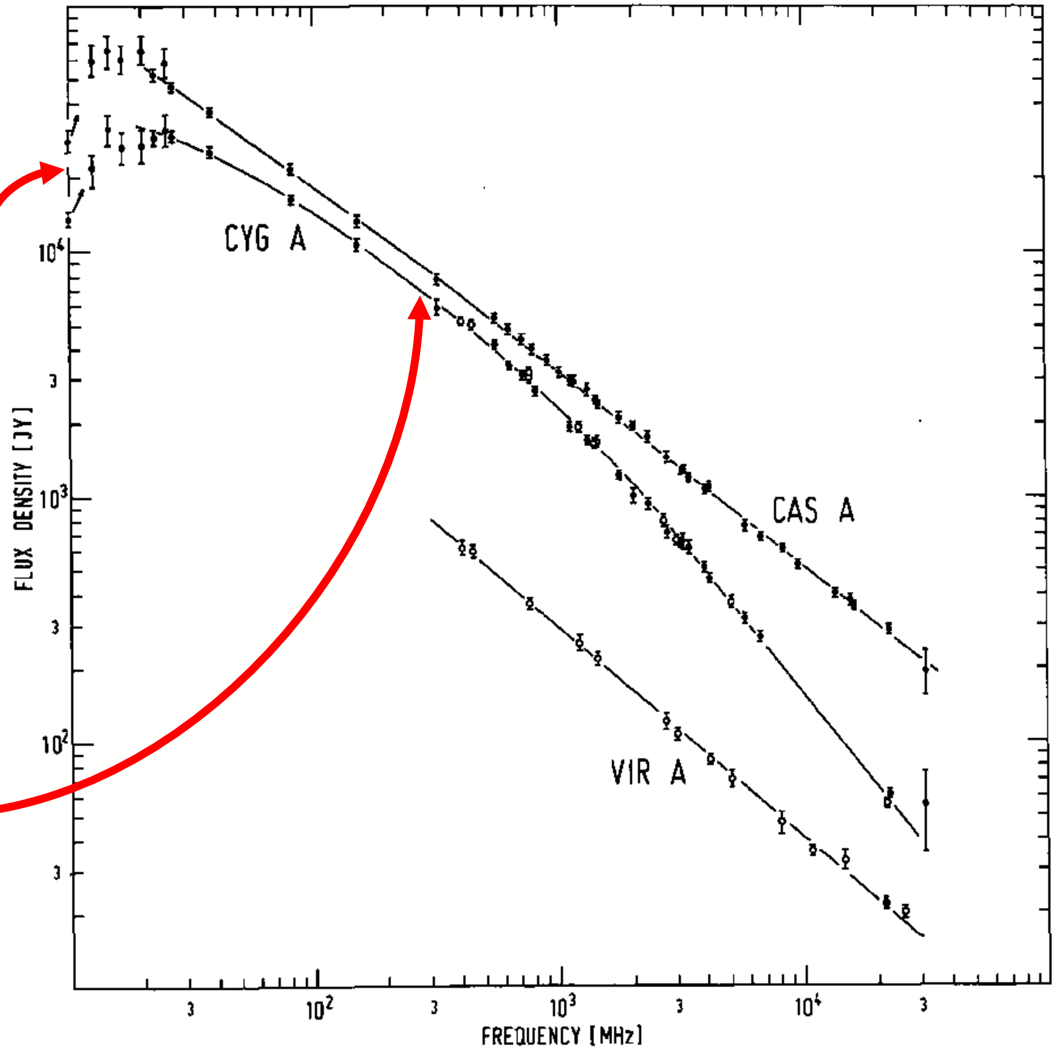
Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

(5.4.3) ***Application to Cyg A***

Let's put it all together!

Fig. 5.13 (ERA)



Turn over at low frequency due to increased optical depth with $\alpha = 5/2$

Relativistic electrons injected with power-law distribution $E^{-\delta}$ so the spectral index in 'typical' frequency range is $\alpha = (\delta - 1)/2$ (usually ~ -0.7)

Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

(5.4.3) ***Application to Cyg A***

Let's put it all together! 

Turn over at low frequency due to increased optical depth with $\alpha = 5/2$

Relativistic electrons injected with power-law distribution $E^{-\delta}$ so the spectral index in 'typical' frequency range is $\alpha = (\delta - 1)/2$ (usually ~ -0.7)

At higher frequencies, the spectrum steepens by $\Delta\alpha = 1/2$ due to rapid depletion of high energy electrons

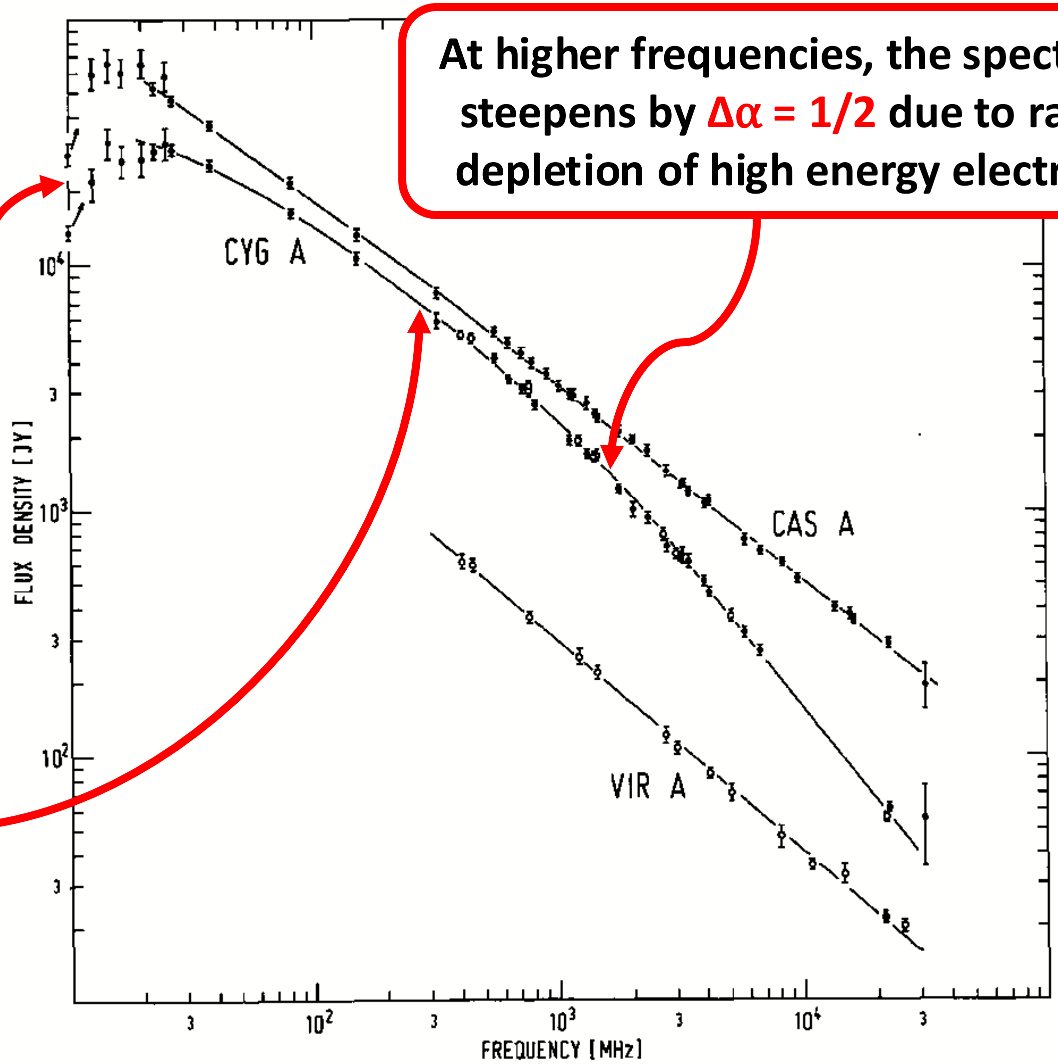


Fig. 5.13 (ERA)

Synchrotron Radiation (ERA Chapter 5)

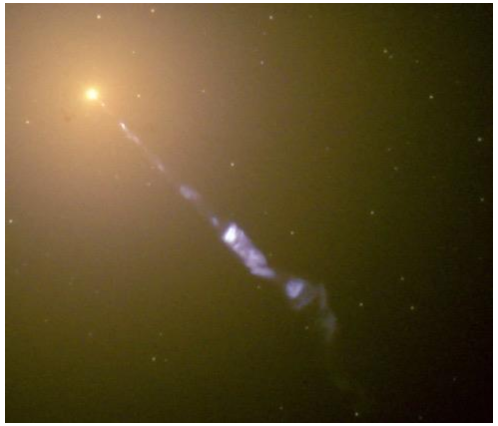
Fig. 5.13 (ERA)

Synchrotron Sources (5.4)

(5.4.3) ***Application to Cyg A***

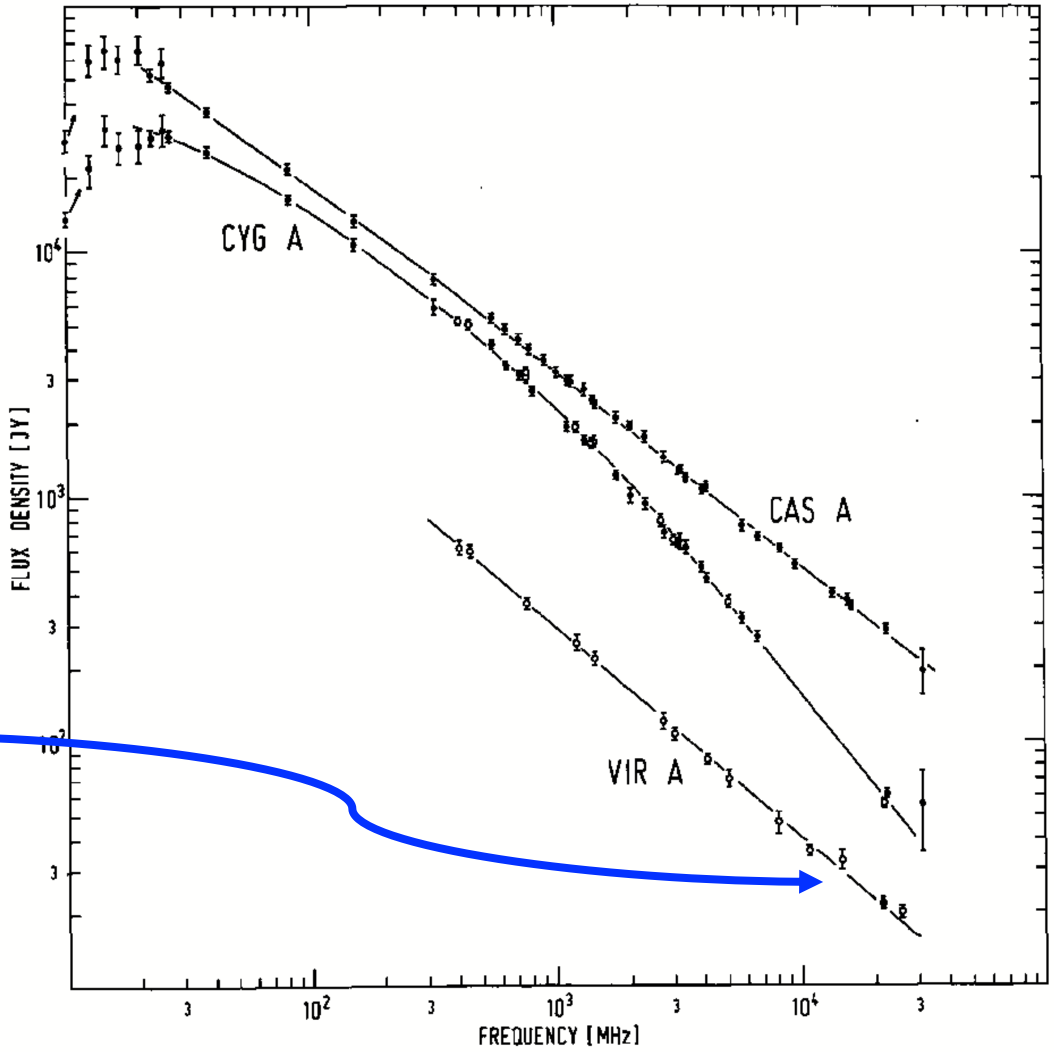
Let’s put it all together!

As we’ve seen, in M87 the jet→ extends to optical frequencies!



In the case of Vir A, the source in M87, the slope is straight even out to higher frequencies indicates very short timescales!

Something outside the radio core (e.g., shocks in the jet) must replenish the supply of relativistic electrons



Synchrotron Radiation (ERA Chapter 5)

Synchrotron Sources (5.4)

(5.4.1) ***Minimum Energy and Equipartition***

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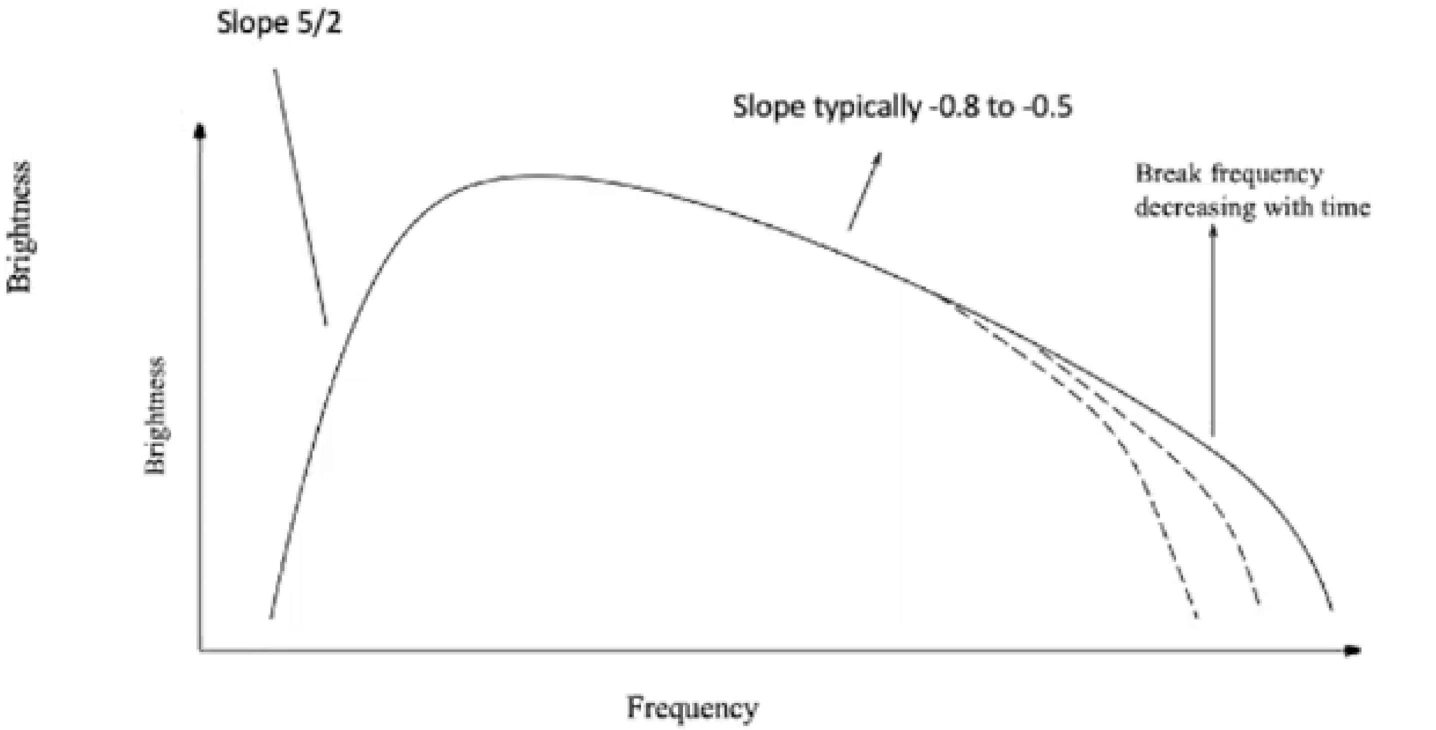


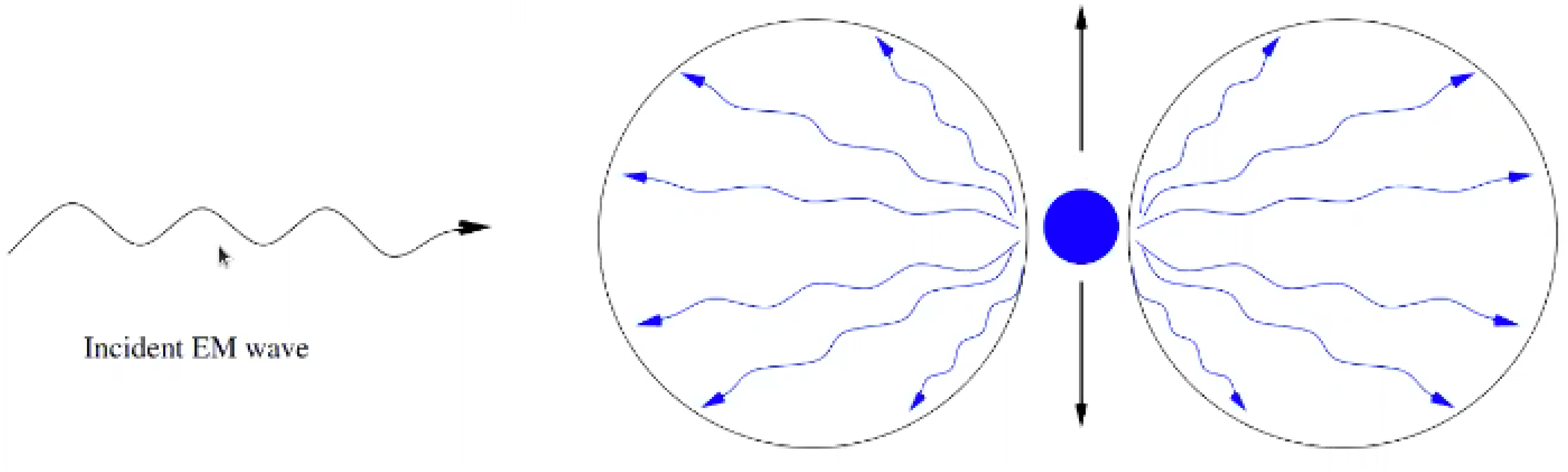
Slide Credit: Jim Braatz

Synchrotron Radiation (ERA Chapter 5)

3 types of scattering that are all related:

1) **Thomson scattering**
2) **Compton scattering**
3) **Inverse Compton scattering**

Thomson scattering



Electron oscillates sinusoidally: dipole emission uniformly in all azimuthal angles

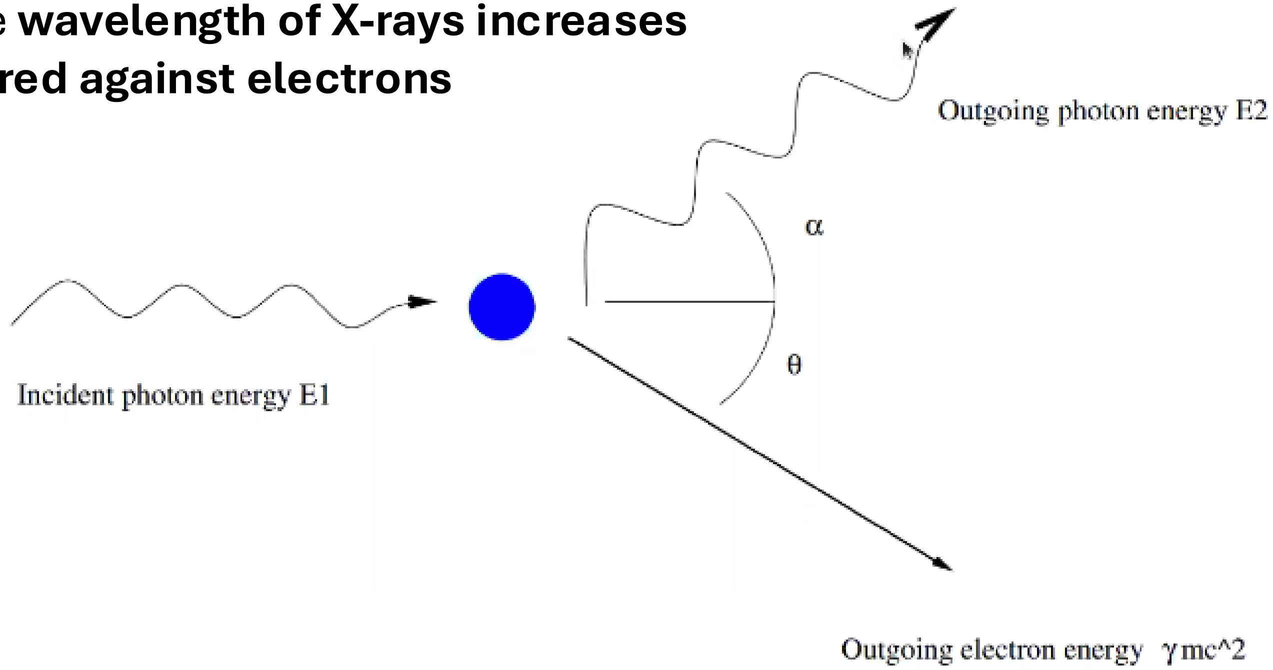
Synchrotron Radiation (ERA Chapter 5)

3 types of scattering that are all related:

1) **Thomson scattering**
2) **Compton scattering**
3) **Inverse Compton scattering**

Much higher energy… either the electrons are moving relativistic or E&M photons moving at high energy

Compton scattering: When the momentum of the incident photons becomes significant, we have to treat the scattering process as a relativistic particle-particle collision. This was originally experimentally demonstrated by Compton's measurement that the **wavelength of X-rays increases when they are scattered against electrons**



Synchrotron Radiation (ERA Chapter 5)

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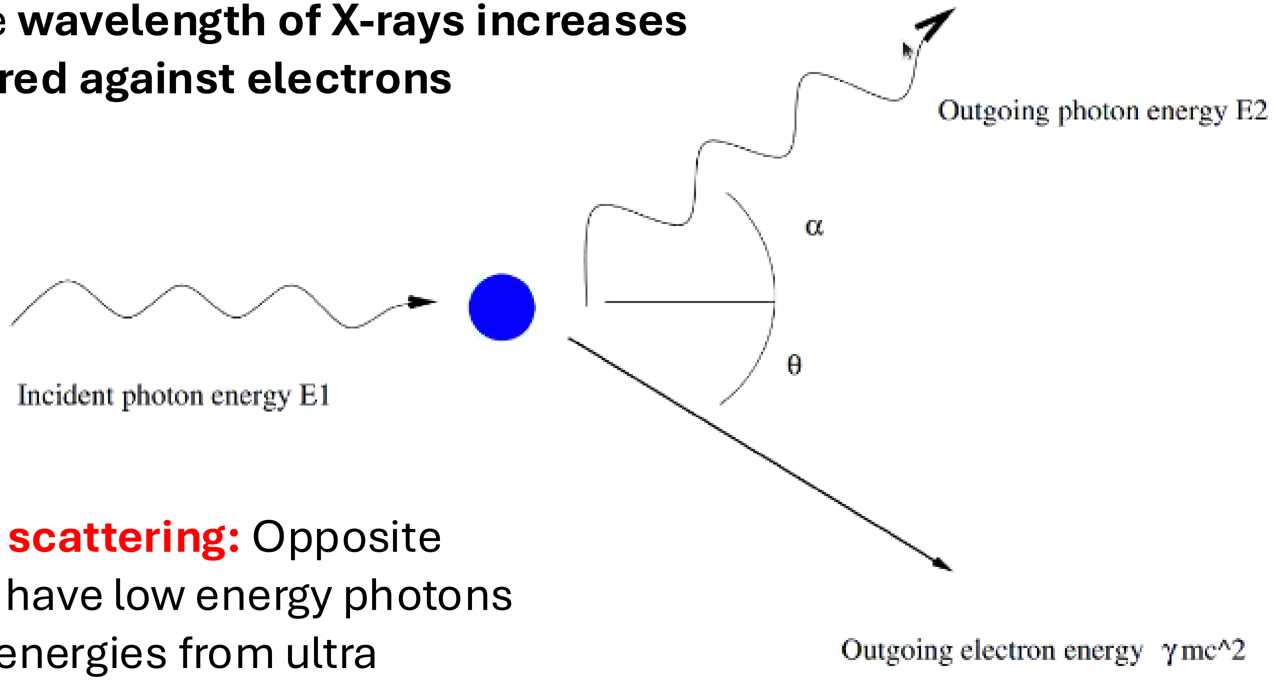
Compton scattering: When the momentum of the incident photons becomes significant, we have to treat the scattering process as a relativistic particle-particle collision. This was originally experimentally demonstrated by Compton's measurement that the **wavelength of X-rays increases when they are scattered against electrons**



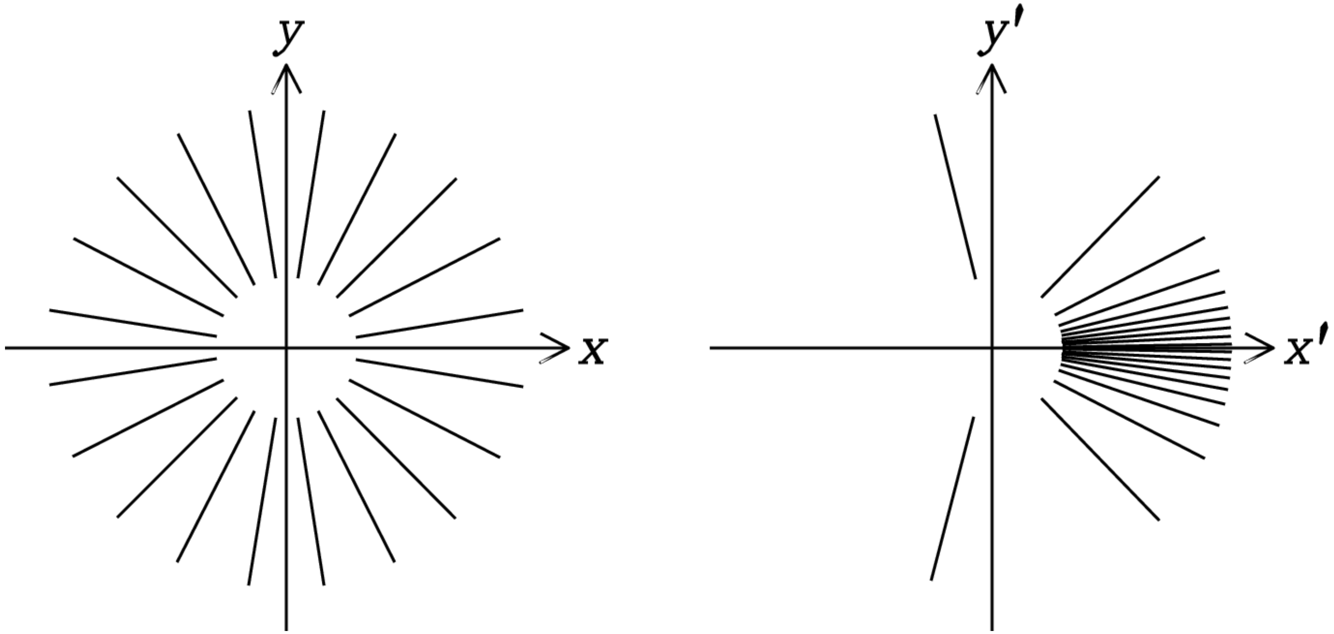
Inverse Compton scattering: Opposite process when you have low energy photons boosted to higher energies from ultra relativistic electrons

Synchrotron Radiation (ERA Chapter 5)

Inverse-Compton Scattering (5.5)

Thomson scattering of this highly anisotropic radiation systematically reduces the electron kinetic energy and converts it into **Inverse-Compton** (IC) radiation by upscattering radio photons to become optical or X-ray photons

Fig. 5.14 (ERA)



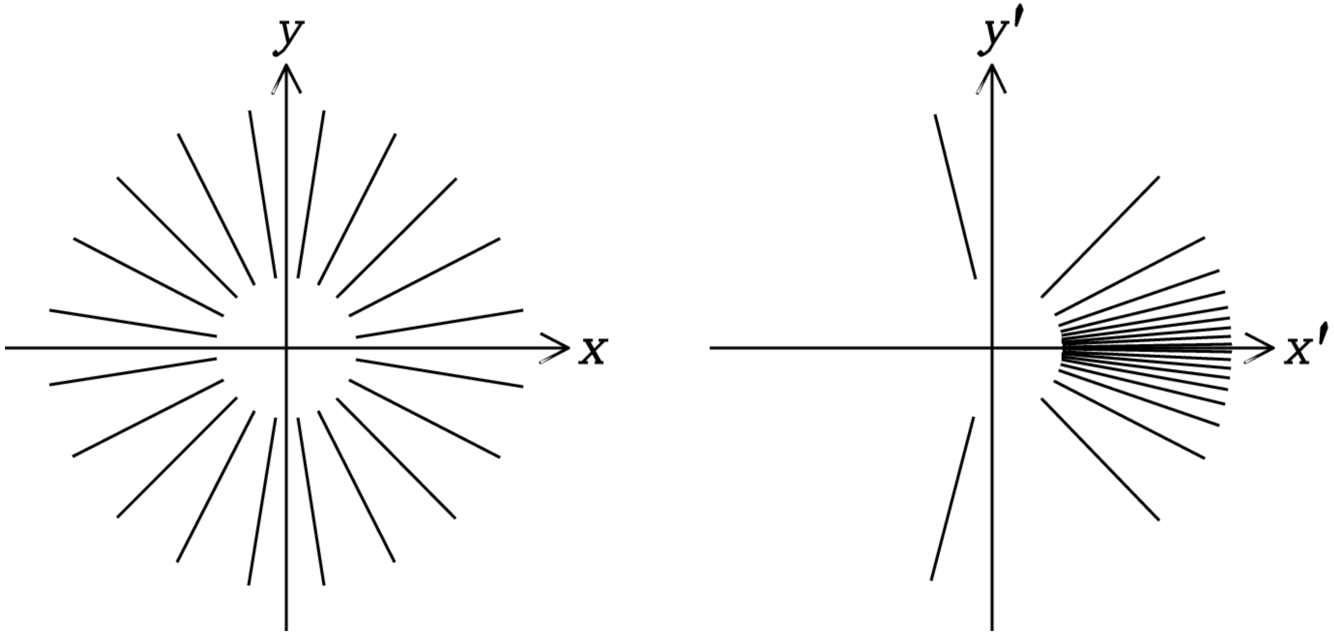
For a relativistic electron at rest in the "primed" frame moving with velocity *v* along the x-axis, the angle of incidence θ' of incoming photons will be much less than the corresponding **angle θ in the rest frame of the observer**

Beam width → $\Delta\theta = 2/\gamma$

Synchrotron Radiation (ERA Chapter 5)

Inverse-Compton Scattering (5.5)

Fig. 5.14 (ERA)



Thomson scattering of this highly anisotropic radiation systematically reduces the electron kinetic energy and converts it into **inverse-Compton** (IC) radiation by upscattering radio photons to become optical or X-ray photons

The scattered power can be rewritten as,

$$\boxed{P = \sigma_{\mathrm{T}} c U_{\mathrm{rad}},} \qquad (5.132)$$

Where $U_{\mathrm{rad}} = |\vec{S}|/c$ is the **energy density of the incident radiation**

We still need to apply Lorentz transforms to understand what the observers sees now that we are in the relativistic limit

For a relativistic electron at rest in the “primed” frame moving with velocity *v* along the x-axis, the angle of incidence θ' of incoming photons will be much less than the corresponding **angle θ in the rest frame of the observer**

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Synchrotron Radiation (ERA Chapter 5)

Inverse-Compton Scattering (5.5)

The time between being hit by the two photons in the electron's frame is $\Delta t' = t'_2 - t'_1$ so,

$$\Delta t = \Delta t' \left[\gamma\left(1 + \beta\cos\theta\right)\right]. \qquad (5.140)$$

And in the electron's frame the frequency is,

$$\boxed{\nu' = \nu\left[\gamma\left(1 + \beta\cos\theta\right)\right].} \qquad (5.142)$$

And the energy density is boosted by this $[\gamma(1+\beta\cos\theta)]$ factor twice:

$$U'_{\text{rad}} = n'_\gamma h\nu'$$

$$= n'_\gamma h\nu' = n_\gamma\left[\gamma\left(1 + \beta\cos\theta\right)\right] h\nu\left[\gamma\left(1 + \beta\cos\theta\right)\right]$$

$$= U_{\text{rad}}\left[\gamma\left(1 + \beta\cos\theta\right)\right]^2. \qquad (5.144)$$

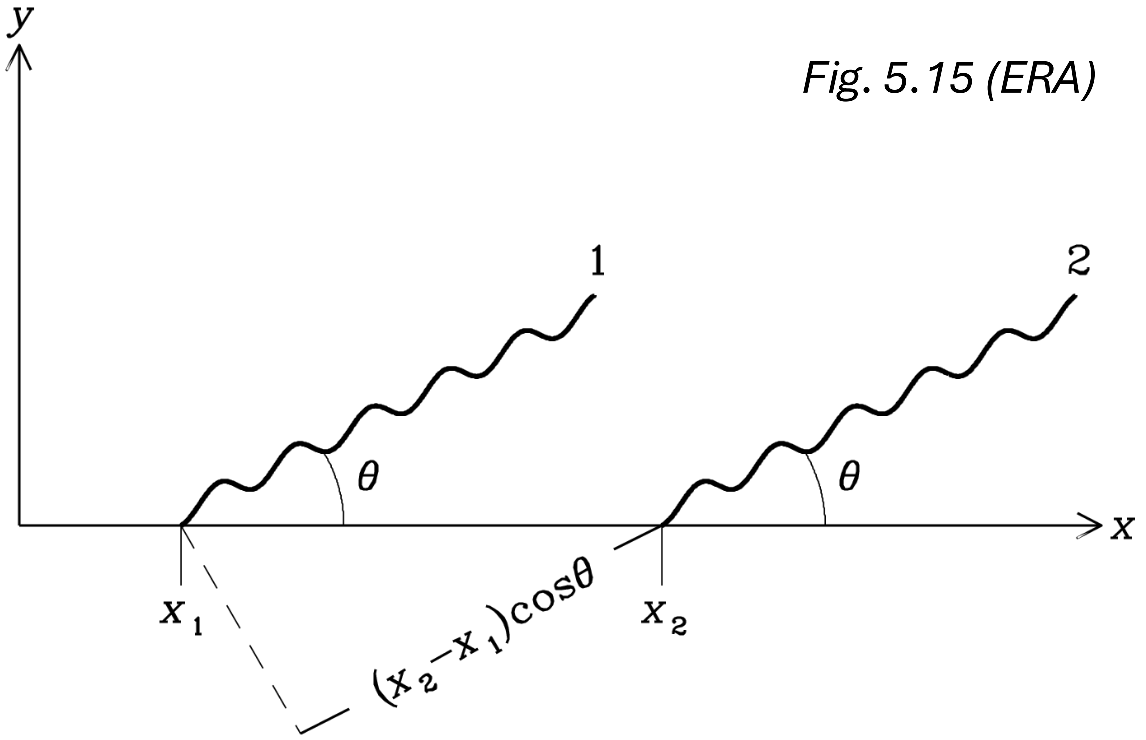

Fig. 5.15 (ERA)

Two successive photons striking an electron moving to the right. The photons approach at angle *θ* from the x-axis, as seen in the unprimed observer's frame.

Synchrotron Radiation (ERA Chapter 5)

Inverse-Compton Scattering (5.5)

Then, the transformation between U_{rad} and U'_{rad} depends on the angle θ between the direction of the photons and the direction of the electron motion…

Lots of math and algebra later gives us 'P_{IC}' which is the **net Inverse–Compton power gained by the radiation field and lost by the electron**:

$$\boxed{P_{\mathrm{IC}} = \frac{4}{3}\sigma_{\mathrm{T}} c \beta^2 \gamma^2 U_{\mathrm{rad}}} \qquad (5.152)$$

Synchrotron Radiation (ERA Chapter 5)

Inverse-Compton Scattering (5.5)

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Remember synchrotron – constants the same!

$$\boxed{\langle P \rangle = \frac{4}{3}\sigma_{\mathrm{T}} \beta^2 \gamma^2 c U_B.} \qquad (5.42)$$

So, the **ratio of IC to synchrotron radiation losses** is:

$$\boxed{\frac{P_{\mathrm{IC}}}{P_{\mathrm{syn}}} = \frac{U_{\mathrm{rad}}}{U_B}.} \qquad (5.154)$$

And the IC loss is proportional to the radiation energy density and the synchrotron loss is proportional to the magnetic energy density

Synchrotron Radiation (ERA Chapter 5)

Inverse-Compton Scattering (5.5)

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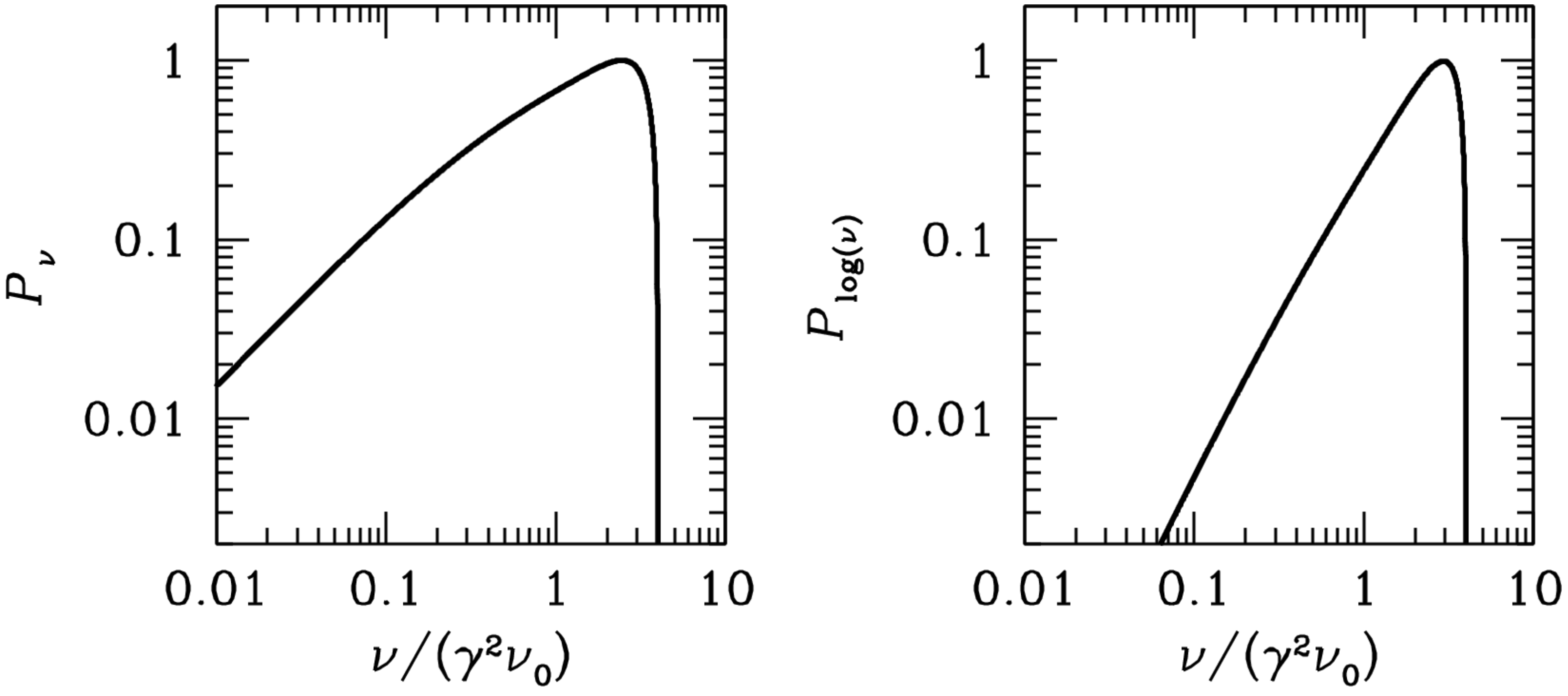
And the IC loss is proportional to the radiation energy density and the synchrotron loss is proportional to the magnetic energy density

Their effects on the radio spectra are indistinguishable!

Synchrotron Radiation (ERA Chapter 5)

Inverse-Compton Scattering (5.5)

Fig. 5.16 (ERA)



The inverse-Compton spectrum of electrons with energy γ irradiated by photons of frequency ν_0.

The **maximum frequency** of the upscattered radiation in the observer's frame,

$$\boxed{\frac{\nu}{\nu_0} \approx 4\gamma^2.} \quad (5.157)$$

and the **average frequency** ⟨ν⟩ of upscattered photons is,

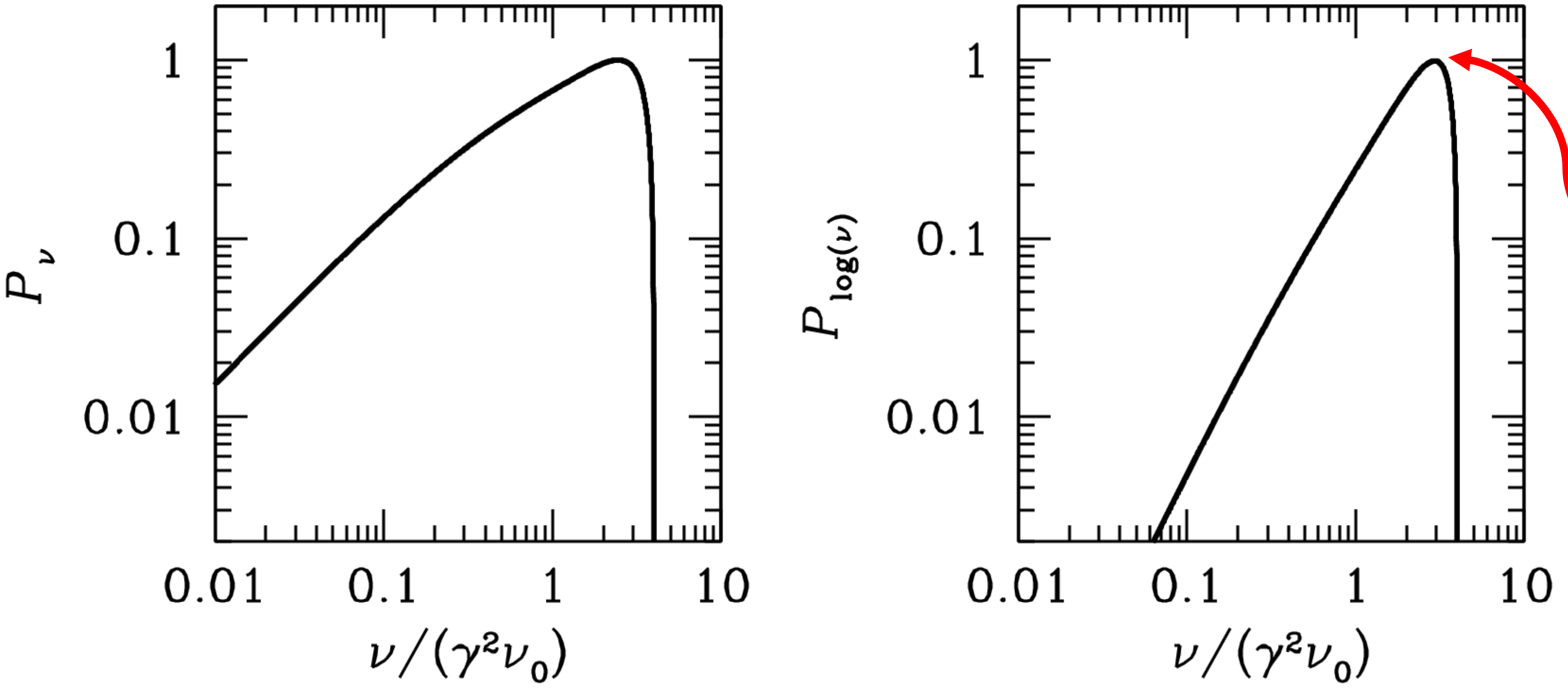
$$\boxed{\frac{\langle \nu \rangle}{\nu_0} = \frac{4}{3}\gamma^2.} \quad (5.160)$$

→ e.g., for isotropic radio photons at ν_0=1 GHz, IC scattered by electrons having $\gamma=10^4$, will be upscattered to an average frequency of 1.3 x 10^{17} Hz **(X-ray frequencies!!)**

Synchrotron Radiation (ERA Chapter 5)

Inverse-Compton Scattering (5.5)

Fig. 5.16 (ERA)



This spectrum is even more peaked than the synchrotron spectrum of monoenergetic electrons.

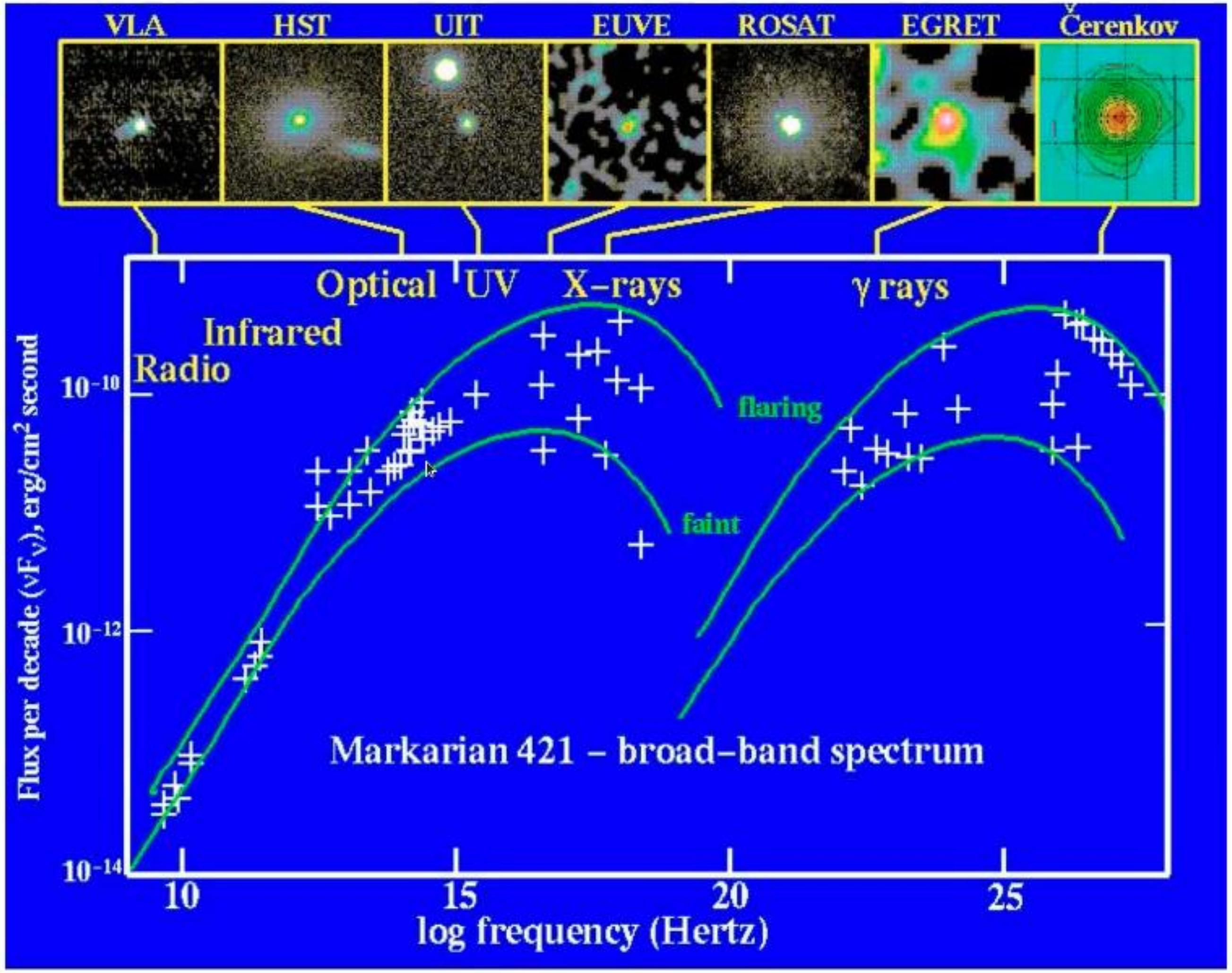
the inverse-Compton spectrum will also be a power law with spectral index **$\alpha = (\delta - 1)/2$**

The inverse-Compton spectrum of electrons with energy γ irradiated by photons of frequency ν_0.

Synchrotron Radiation (ERA Chapter 5)

Inverse-Compton Scattering (5.5)

Example spectrum of galaxy Mk 421 →



Synchrotron Radiation (ERA Chapter 5)

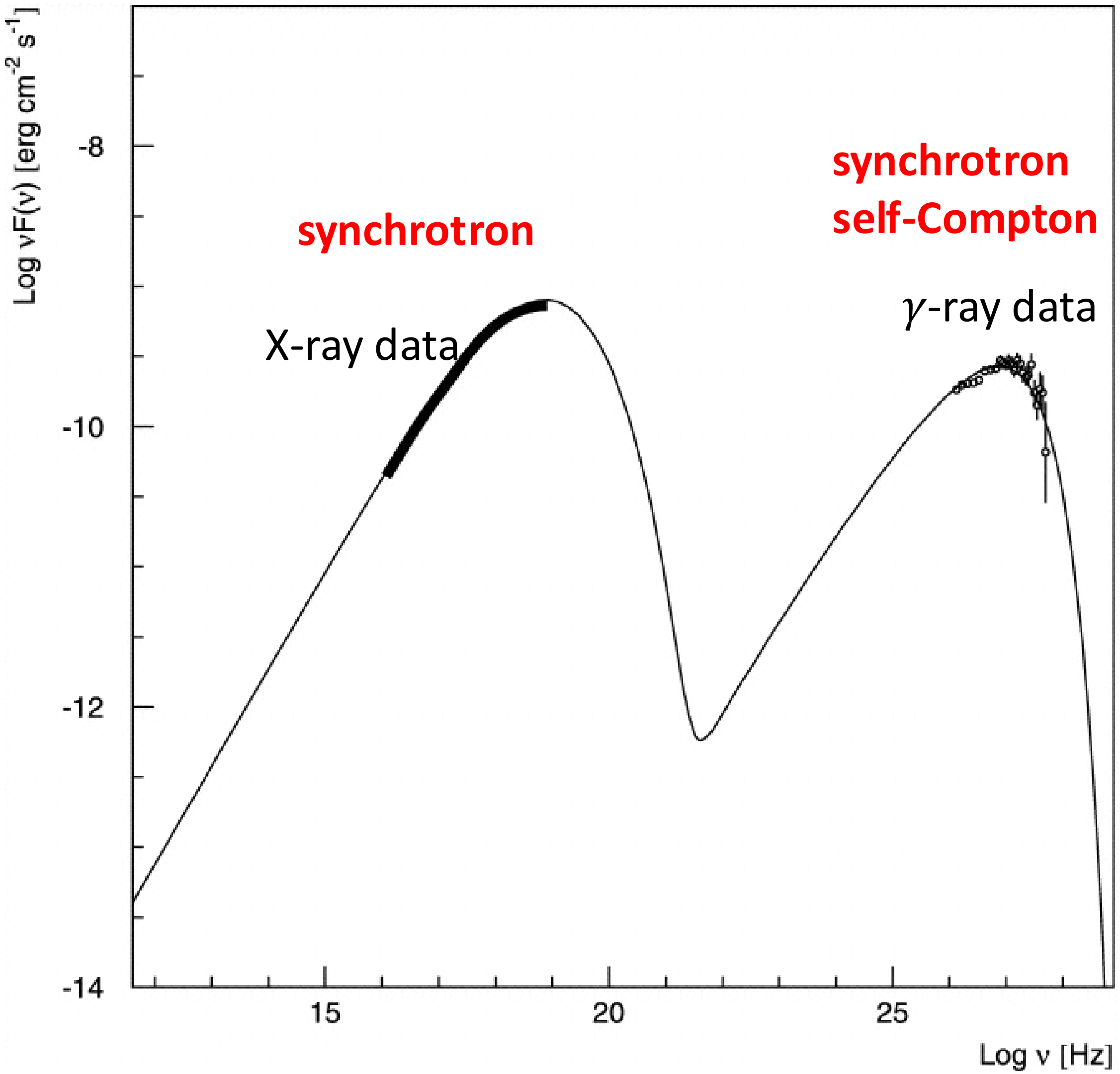
Inverse-Compton Scattering (5.5)

NOTE: Inverse-Compton losses very strongly cool the relativistic electrons if the source brightness temperature exceeds $T_b \sim 10^{12}$ K in the rest frame of the source

Aka there is a feedback loop and runaway feedback process that prevents brightness temperatures from reaching larger values than 10^{12} K

Example spectrum of galaxy Mk 501 →

Fig. 5.17 (ERA)



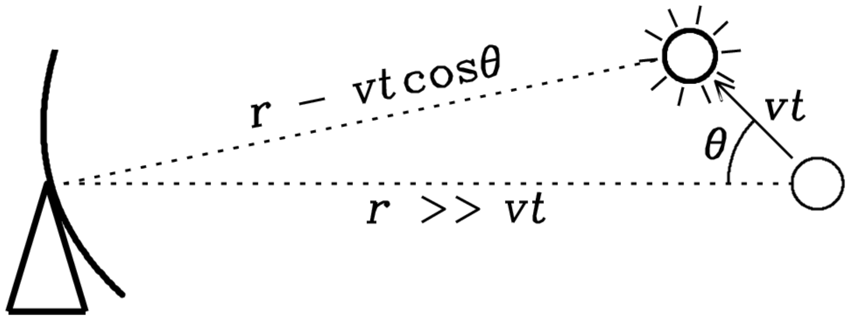
Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

Bright radio-source **components** (discrete regions of enhanced brightness) are often **seen to move with apparent transverse velocities exceeding the speed of light**.

This illusion of **superluminal velocities** can occur if the components are moving obliquely toward the observer with relativistic speeds →

Fig. 5.18 (ERA)



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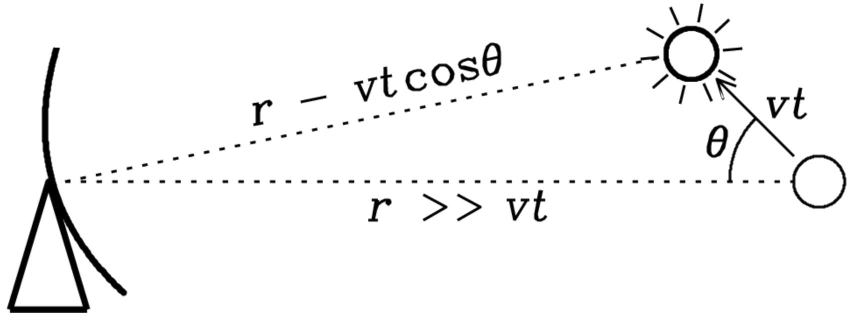
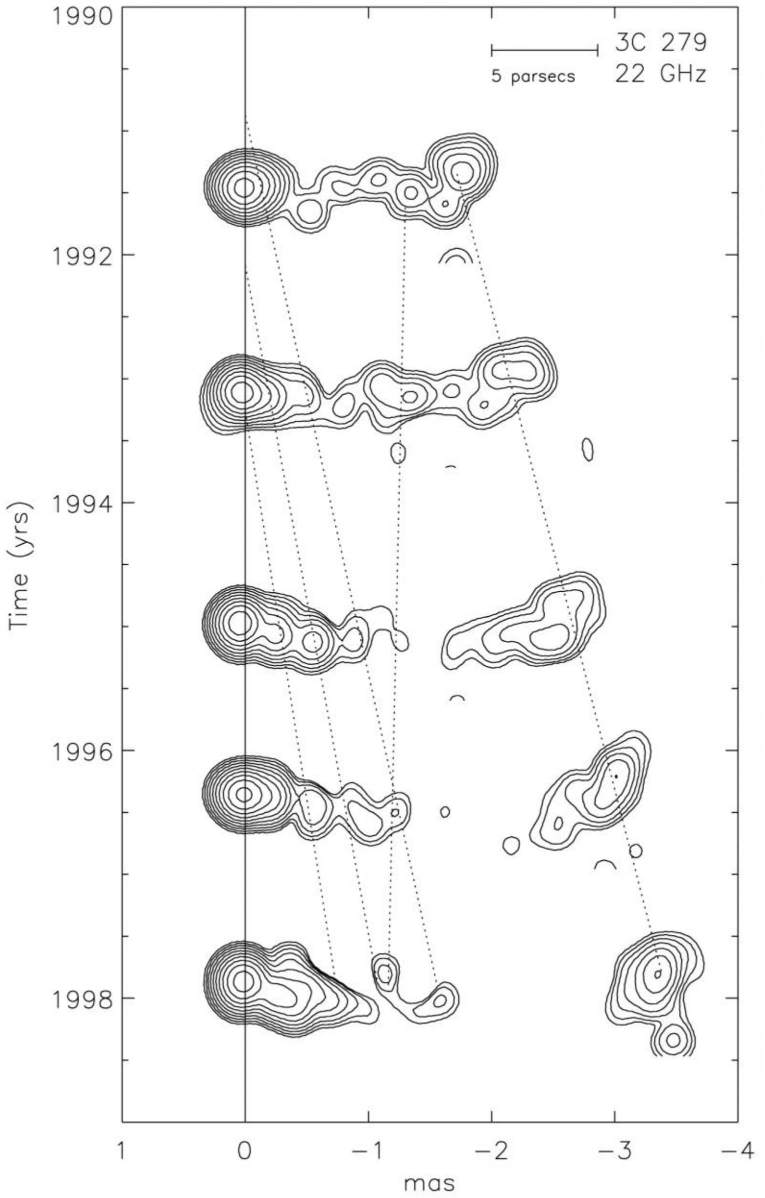


Fig. 5.19 (ERA)



Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

“Radio quasars aren’t’ isotropic candles spread throughout the universe, they are beamed flashlights”

AKA the brightest aren’t always the most luminous, they are just pointing in our direction!

Angle that maximizes β is, $\boxed{\cos\theta_{\mathrm{m}} = \beta}$ (5.170)

And the maximum apparent β is across the plane of the sky:

$$\boxed{\max\left[\beta_\perp\,(\text{apparent})\right] = \frac{\beta(1-\beta^2)^{1/2}}{1-\beta^2} = \beta\gamma.} \quad (5.172)$$

The beam also has a **Transverse Doppler Shift** affect (due to time dilation) and **Doppler Boosting** causing increase in flux of beam coming towards us and decrease for one away from us!

→ e.g., quasar 3C 279 (from previous slide) the β is greater or equal to 0.96 and thus θ_m is max at 16 degrees

See animation: http://www.cv.nrao.edu/~abridle/3c31free/3c31anim_const_sen_flame.htm

Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

Fig. 20 (ERA)

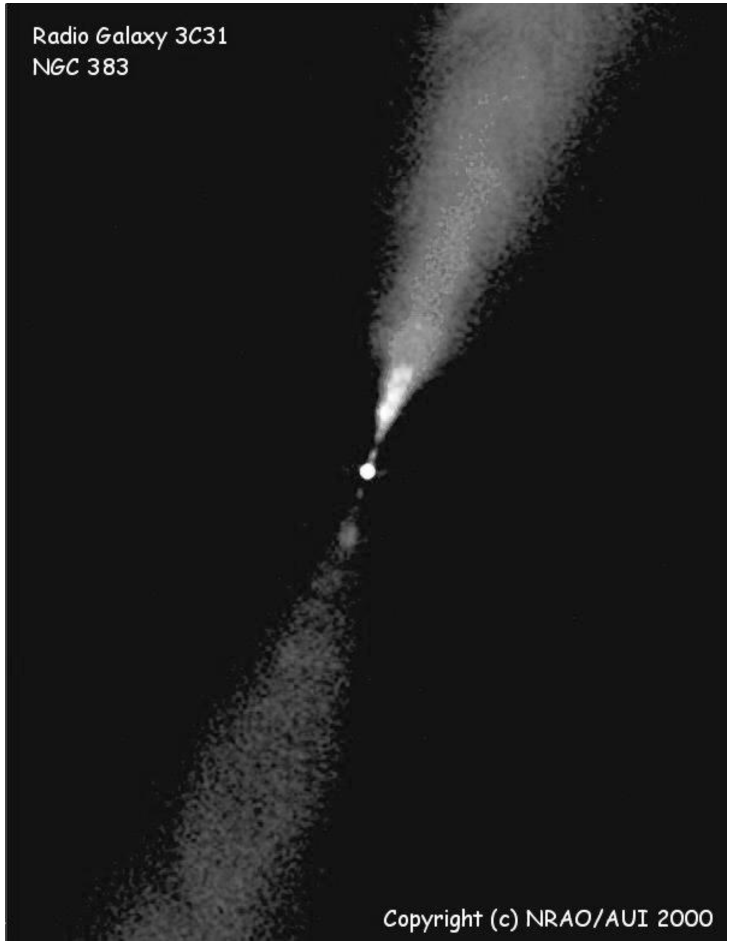
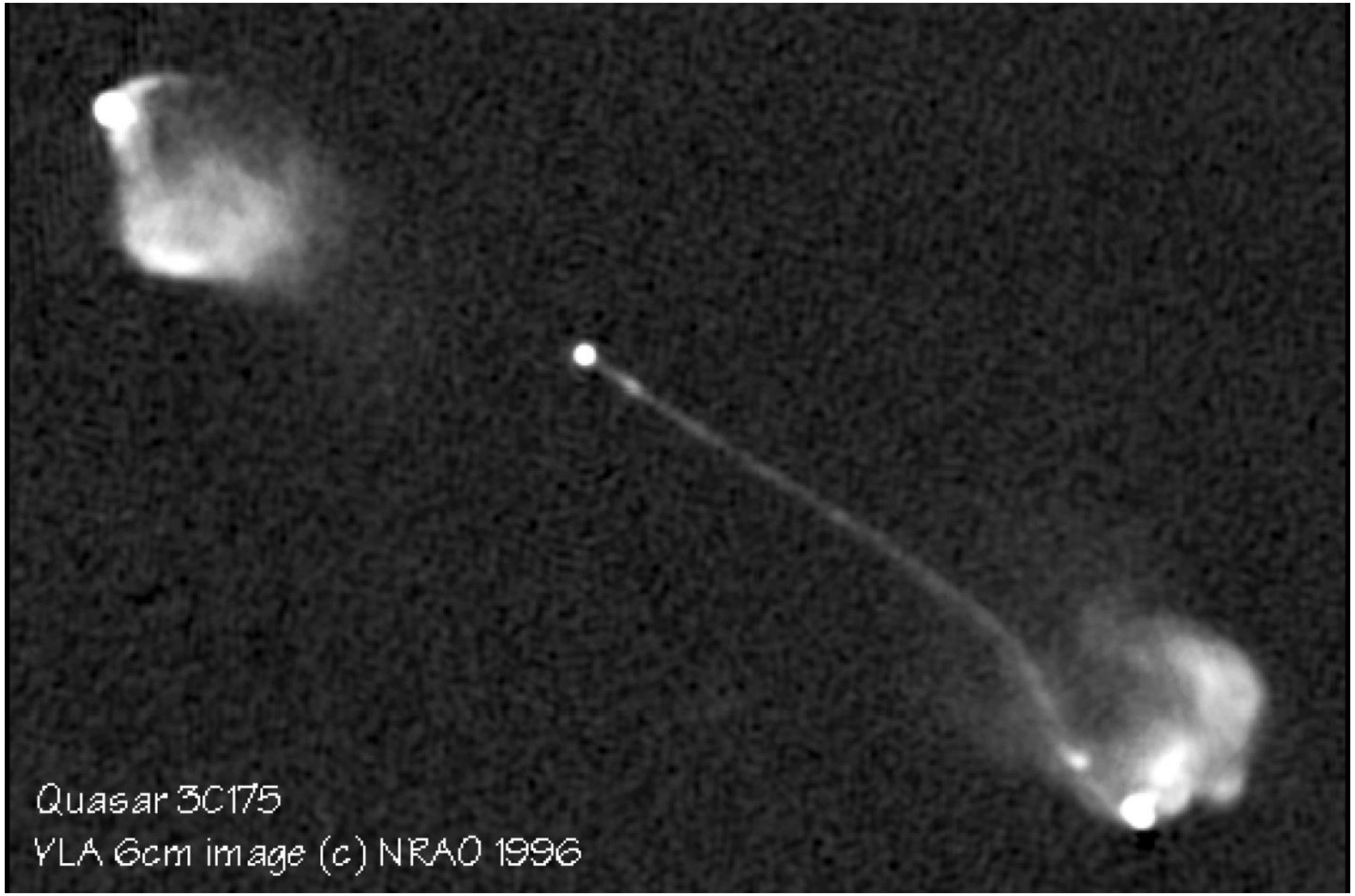


Fig. 21 (ERA)

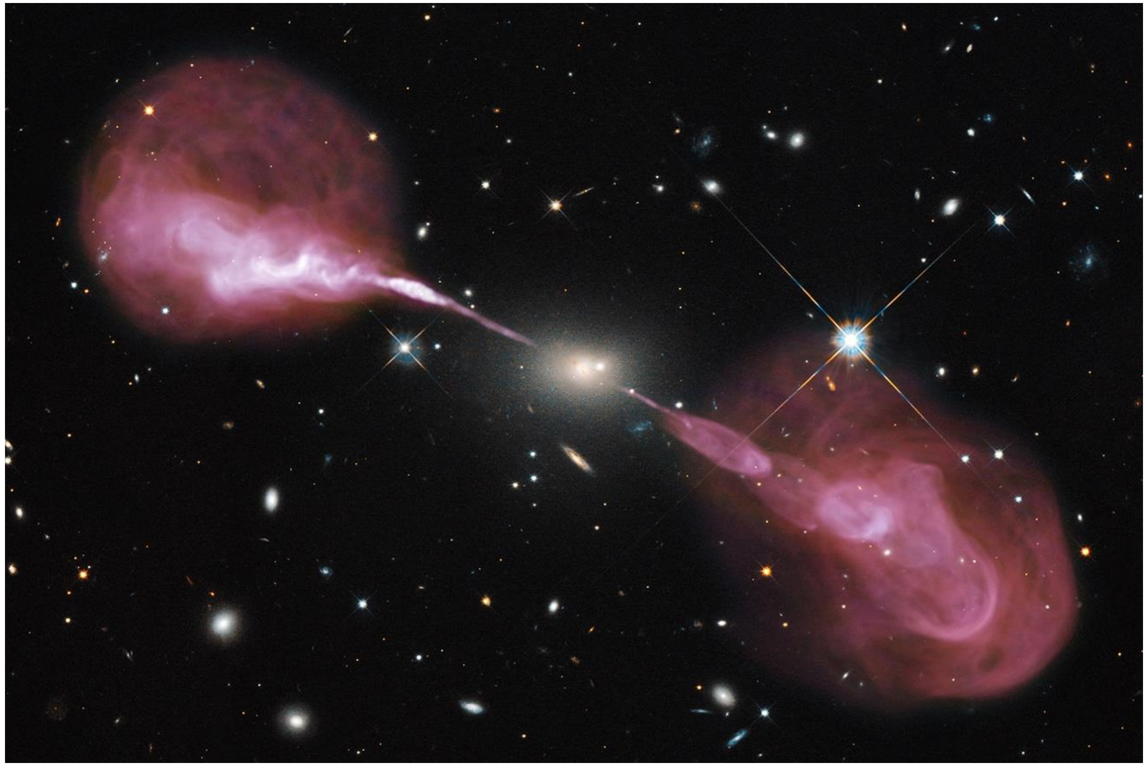


Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

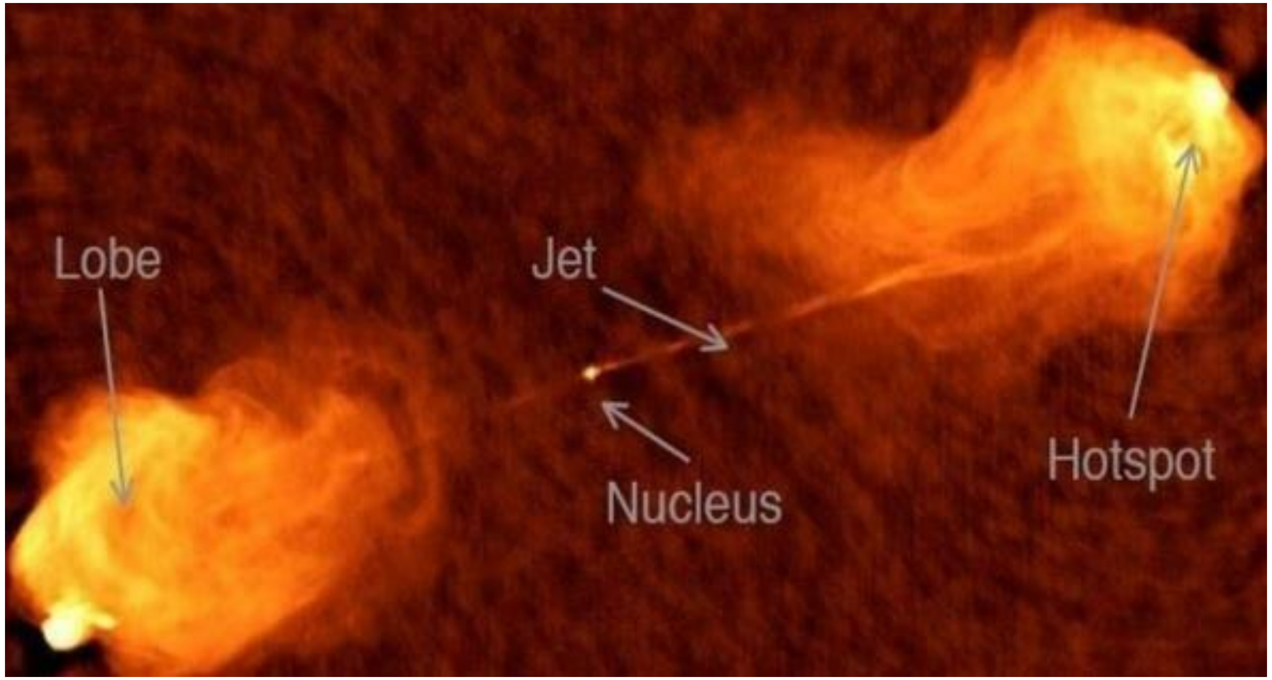
3C 348

Fig. 8.14 (ERA)



Cyg A

Fig. 5.12 (ERA)



Synchrotron Radiation (ERA Chapter 5)

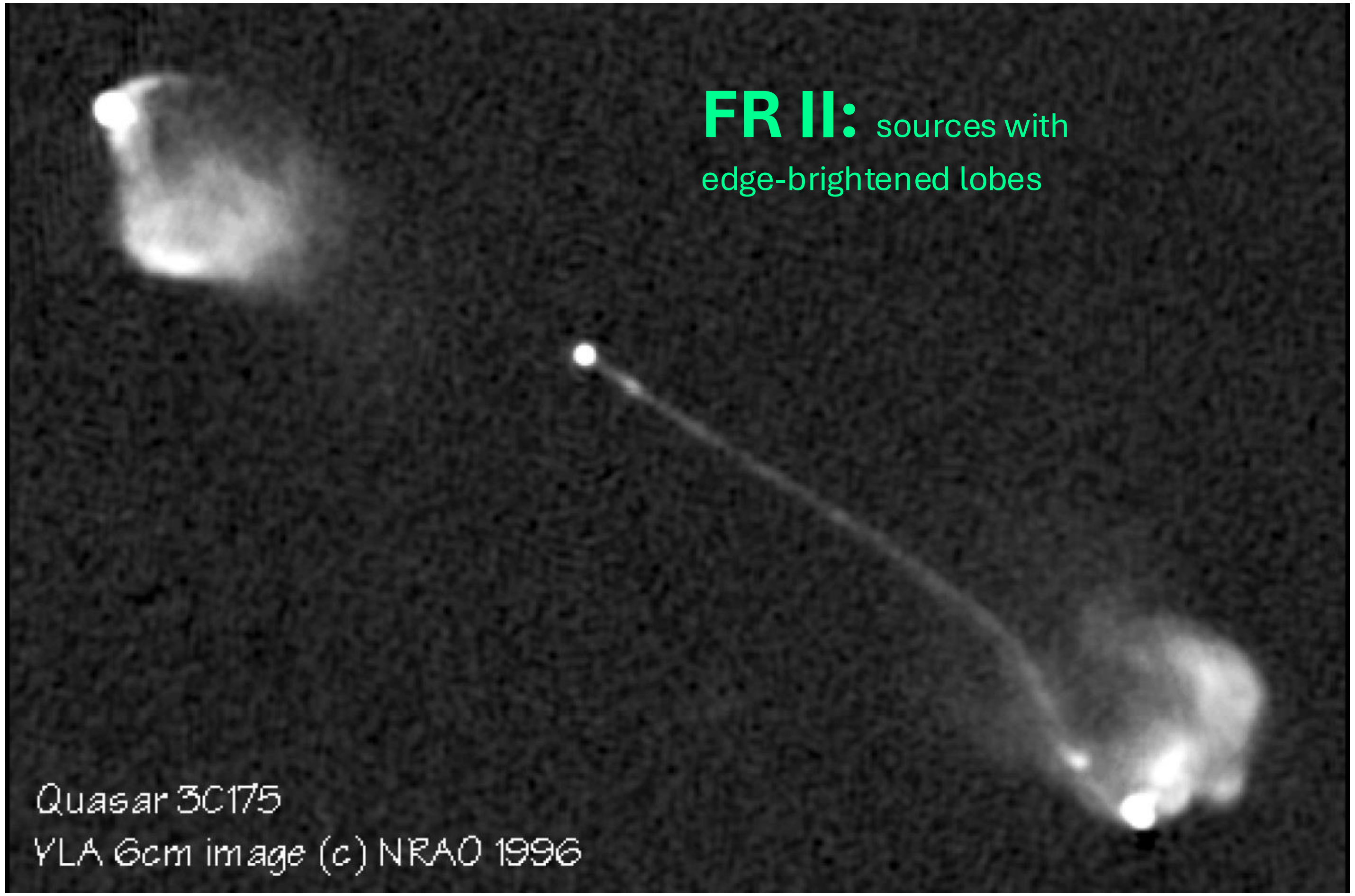
Relativistic Bulk Motion (5.6)

Fig. 20 (ERA)

FR I:

Jets/lobes that appear to fade away at large distances from the center

Fig. 21 (ERA)



FR II: sources with edge-brightened lobes

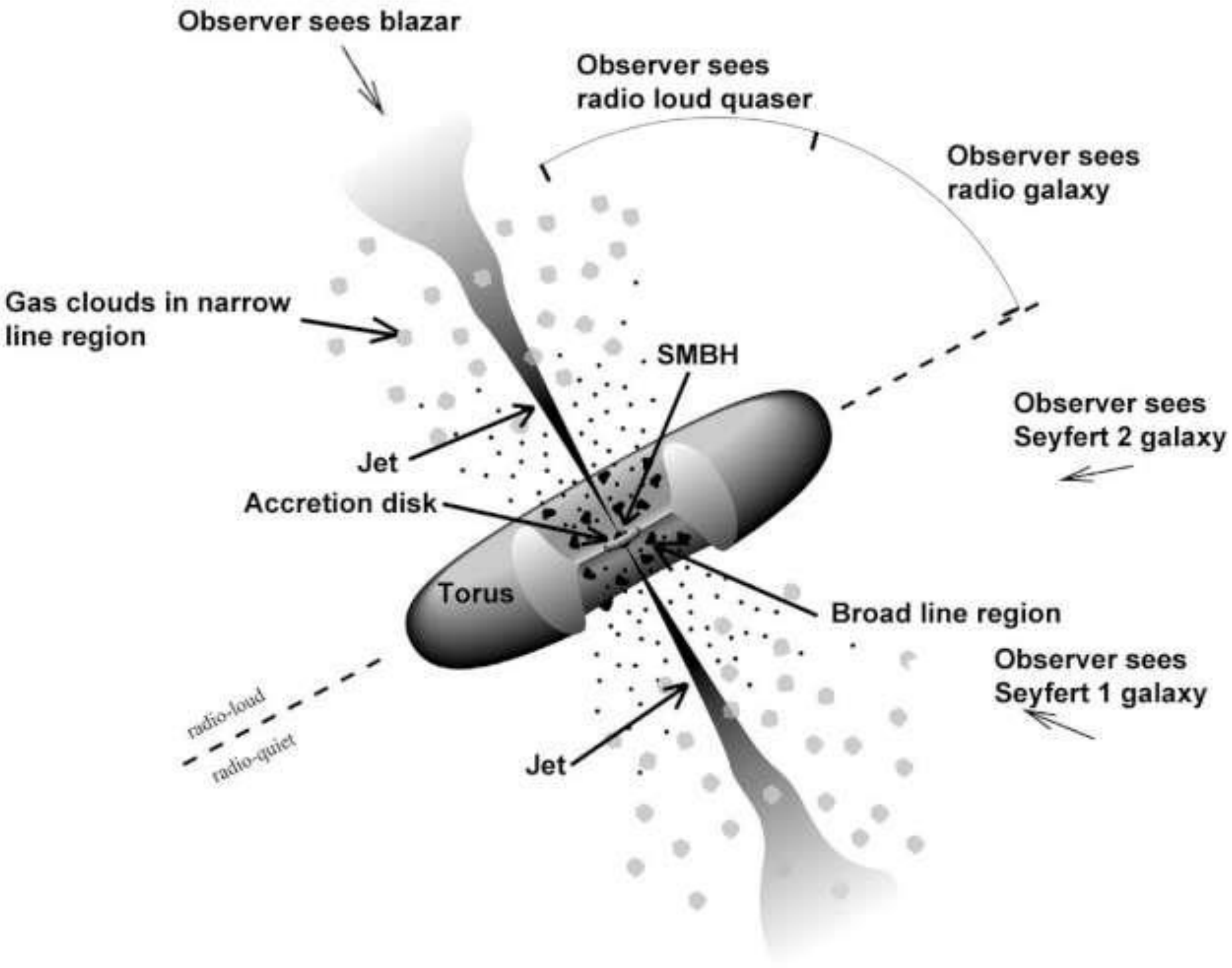
Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

(5.4.3) ***Unified Models***

Models for **active galactic nuclei (AGN)** attribute some or all of the **differences between observationally different objects to the inclinations of their jets relative to the line of sight**

Fig. 5.22 (ERA)



Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

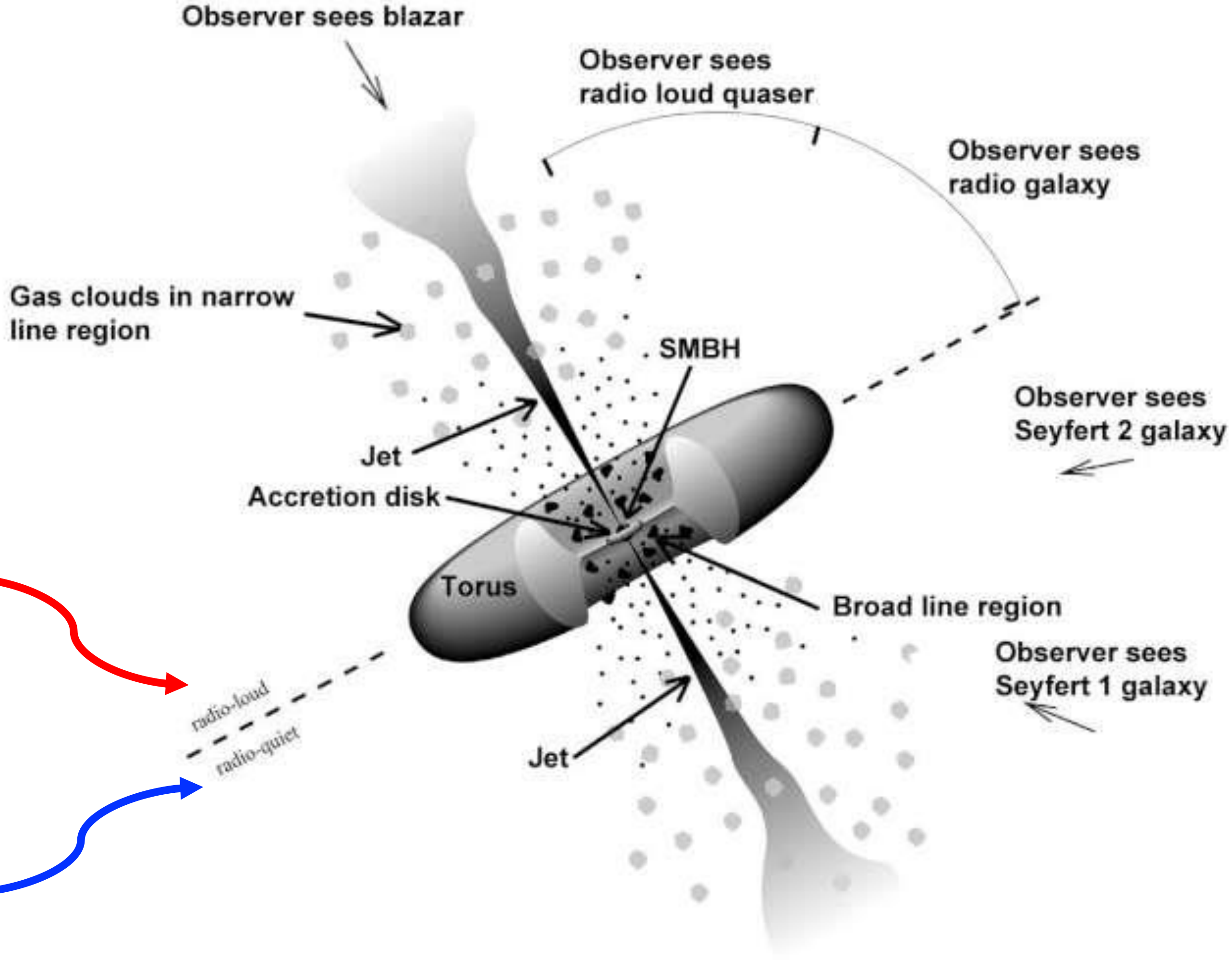
(5.4.3) ***Unified Models***

Models for **active galactic nuclei (AGN)** attribute some or all of the **differences between observationally different objects to the inclinations of their jets relative to the line of sight**

“Radio-loud” typically elliptical galaxies

“Radio-quiet” typically spiral galaxies

Fig. 5.22 (ERA)



Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

(5.4.3) ***Unified Models***

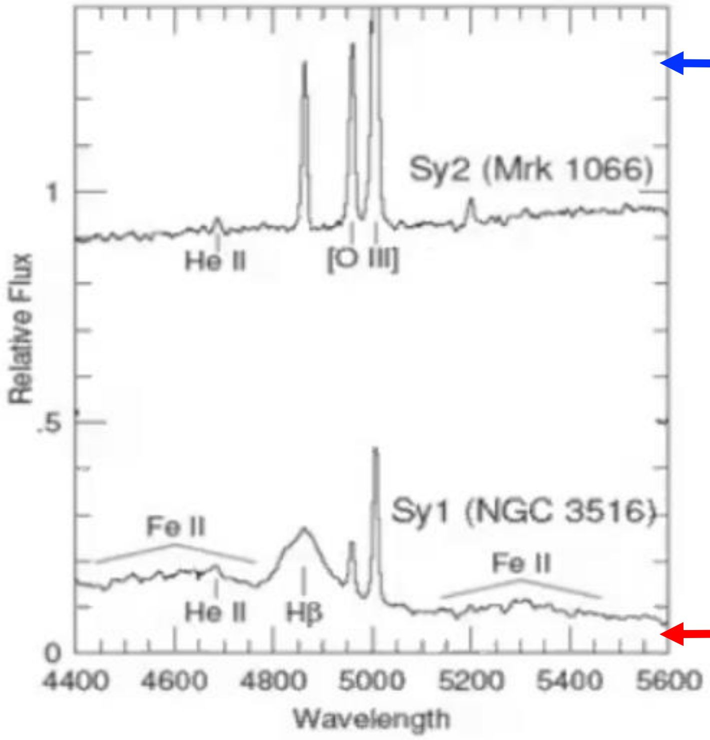


Fig.1 Typical optical spectrum of a Sy1 and a Sy2 (adapted from Pogge, 2000)

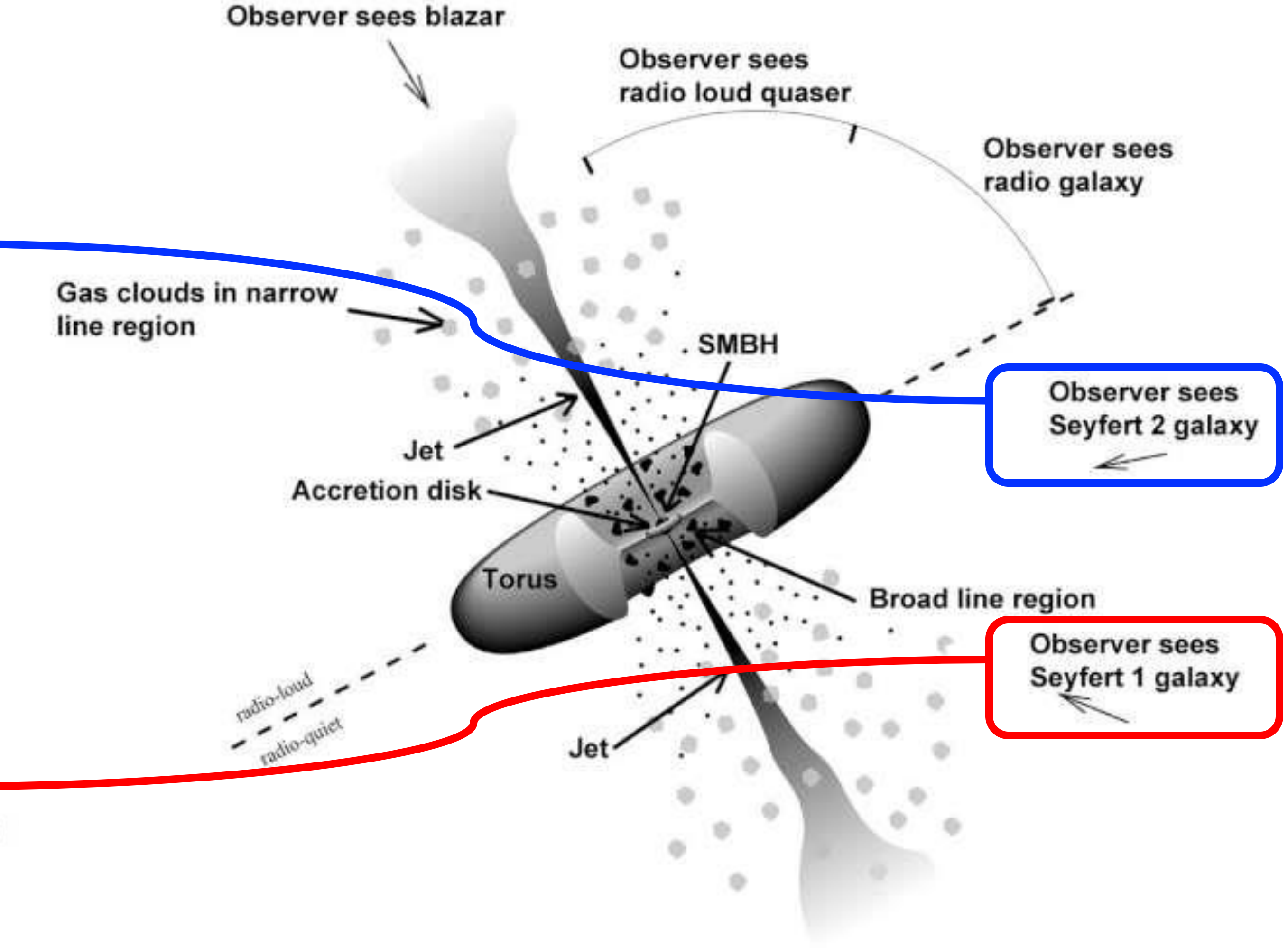


Fig. 5.22 (ERA)

Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

(5.4.3) ***Radio Emission from Normal Galaxies***

The radio emission from a "**normal galaxy**" is not powered by an AGN. The continuum radio emission from normal galaxies is dominated by a combination of:

1. **free–free emission** from HII regions ionized by massive ($M > 15 M_\odot$) main-sequence stars

2. **synchrotron radiation** from cosmic-ray electrons, most of which were accelerated in the supernova remnants (SNRs) of massive ($M > 8 M_\odot$) stars.

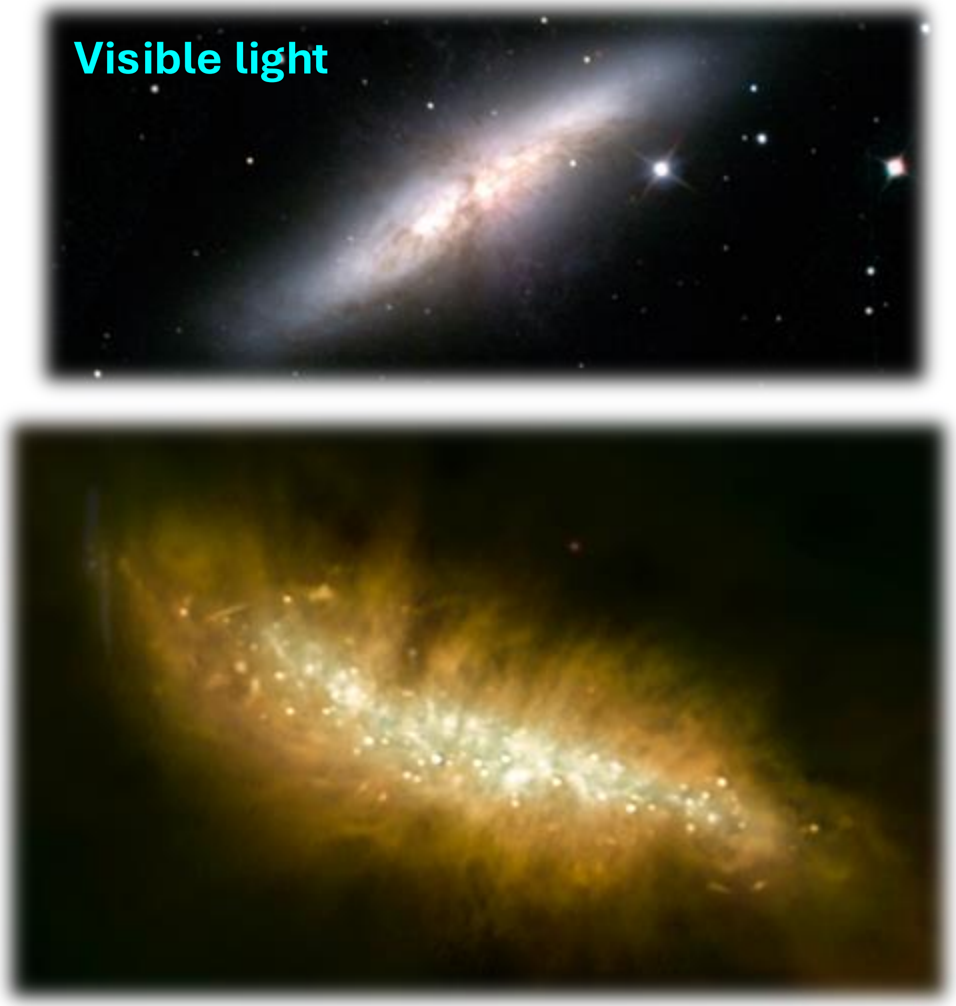


Fig. 8.13 (ERA) Radio continuum emission from M82. Image credit: Josh Marvil (NM Tech/NRAO), Bill Saxton (NRAO/AUI/NSF), Hubble (NASA/ESA/STScI).

Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

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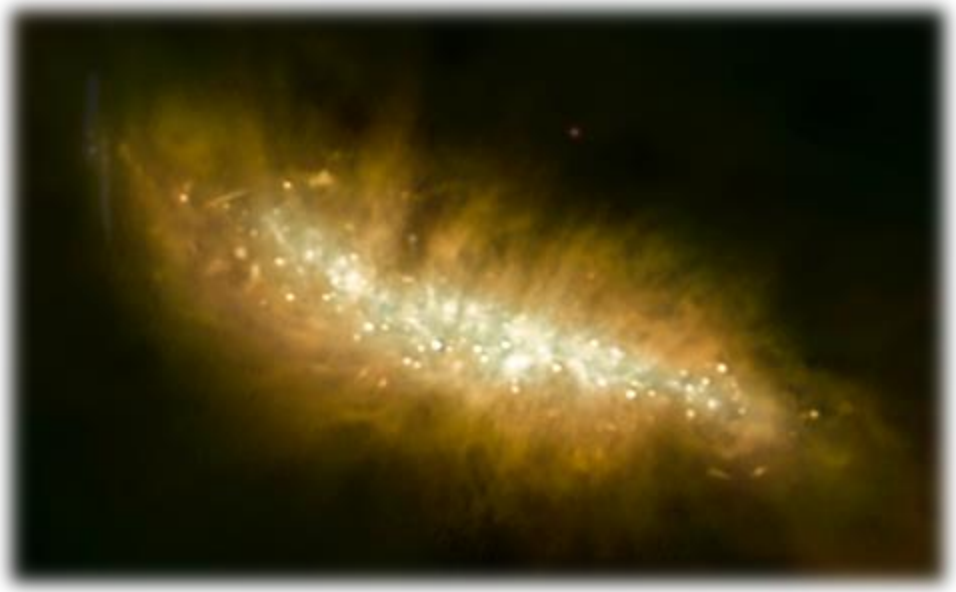
The current radio continuum emission from normal galaxies is an extinction-free **tracer of recent star formation**, unconfused by emission from older stars



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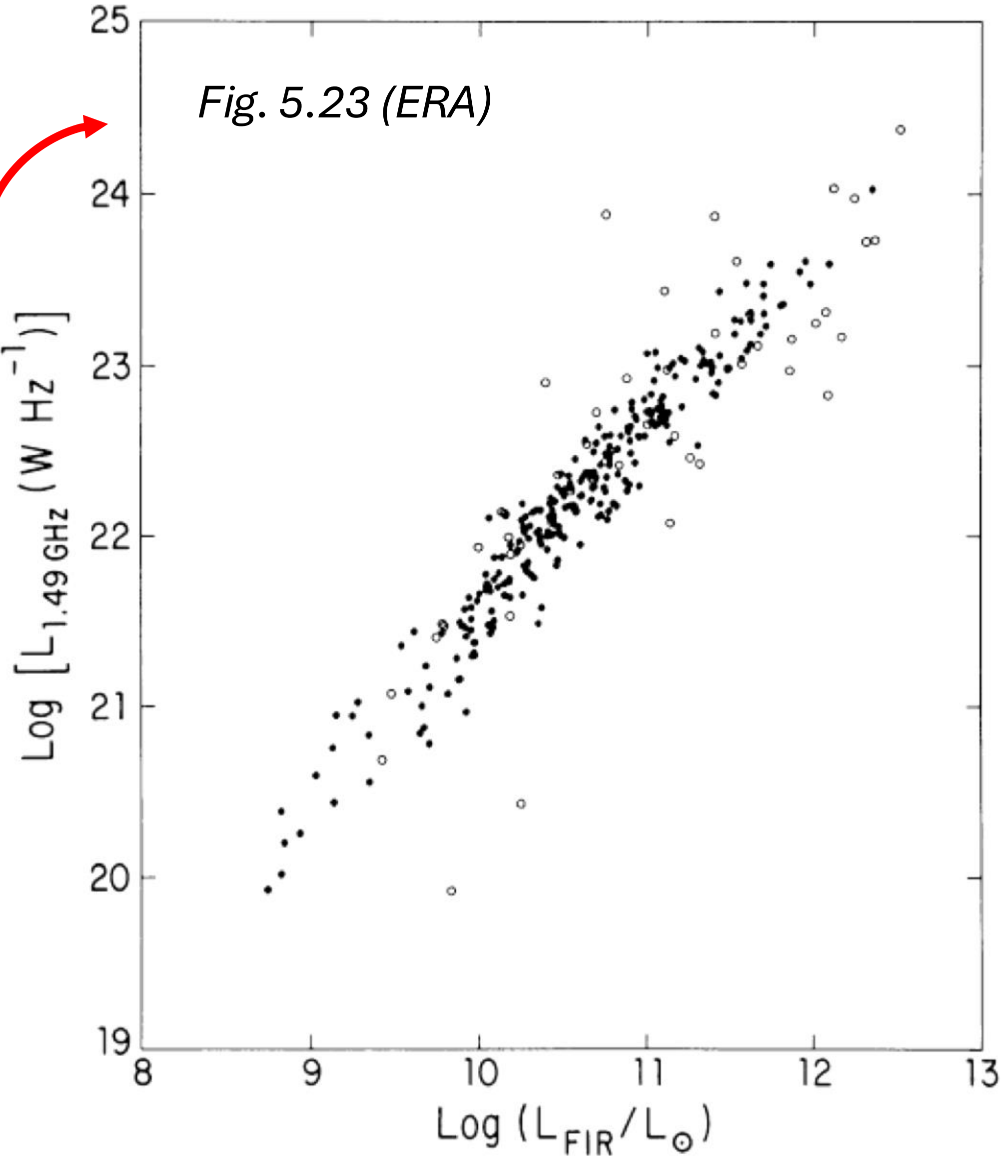
Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

(5.4.3) ***Radio Emission from Normal Galaxies***

The radio luminosities of normal galaxies are very tightly correlated with their FIR luminosities!

Physical origin of this FIR/radio correlation is still poorly understood…



Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

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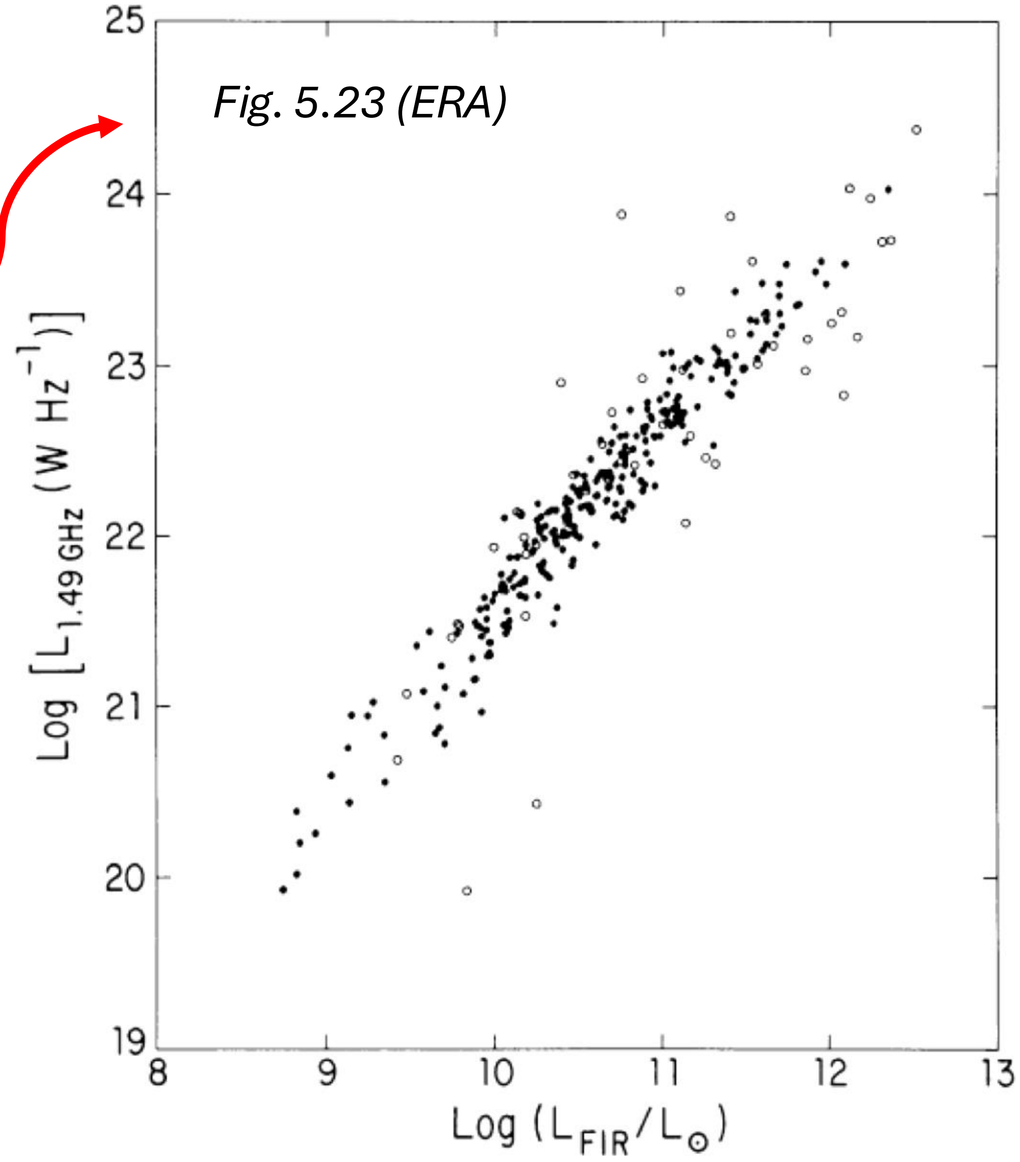


Fig. 5.23 (ERA)

The rate (in units of solar masses per year) at which stars M > 5$M_\odot$ are formed in a galaxy can be estimated from **free–free** and **synchrotron** spectral luminosities by:

$$\boxed{\left(\frac{L_T}{\mathrm{W\ \ Hz^{-1}}}\right) \approx 5.5\times 10^{20}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-0.1}\left[\frac{\mathrm{SFR}\,(M>5M_\odot)}{M_\odot\ \ \mathrm{yr^{-1}}}\right],} \quad (5.184)$$

$$\boxed{\left(\frac{L_{NT}}{\mathrm{W\ \ Hz^{-1}}}\right) \approx 5.3\times 10^{21}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-0.8}\left[\frac{\mathrm{SFR}\,(M>5M_\odot)}{M_\odot\ \ \mathrm{yr^{-1}}}\right].} \quad (5.185)$$

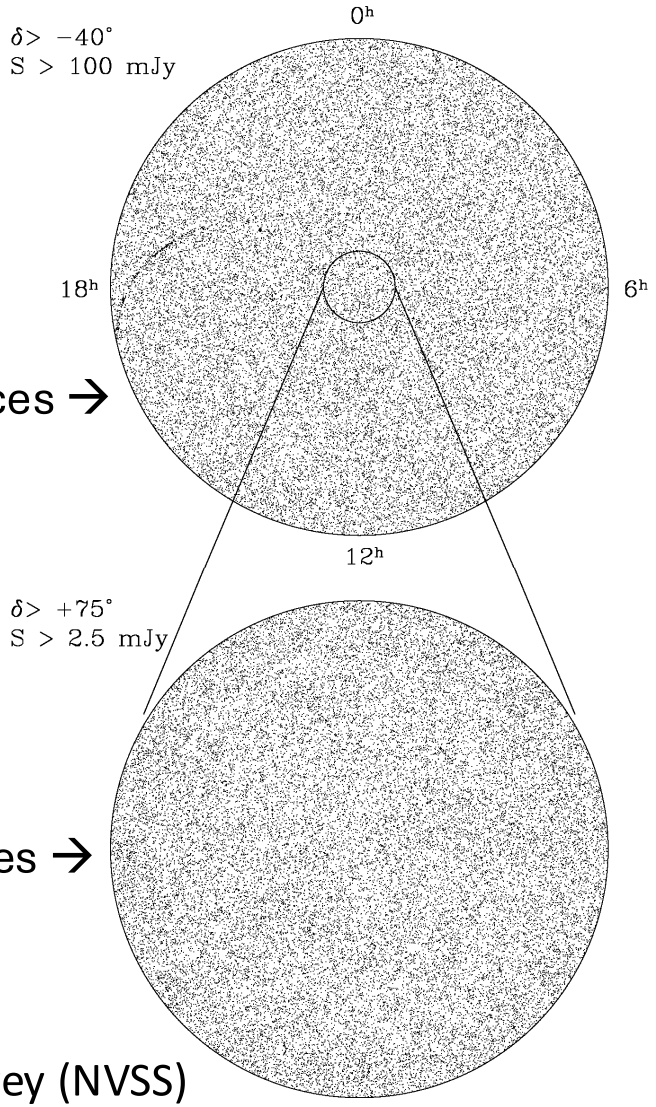
Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

(5.4.3) ***Extragalactic Radio-Source Populations and Cosmological Evolution…***

Sources detected by **blind surveys** covering representative areas of sky give us an unbiased statistical sample of the radio-source population.

Fig. 5.24 (ERA)



Bright sources →

Fainter sources →

NRAO VLA Sky Survey (NVSS)

Synchrotron Radiation (ERA Chapter 5)

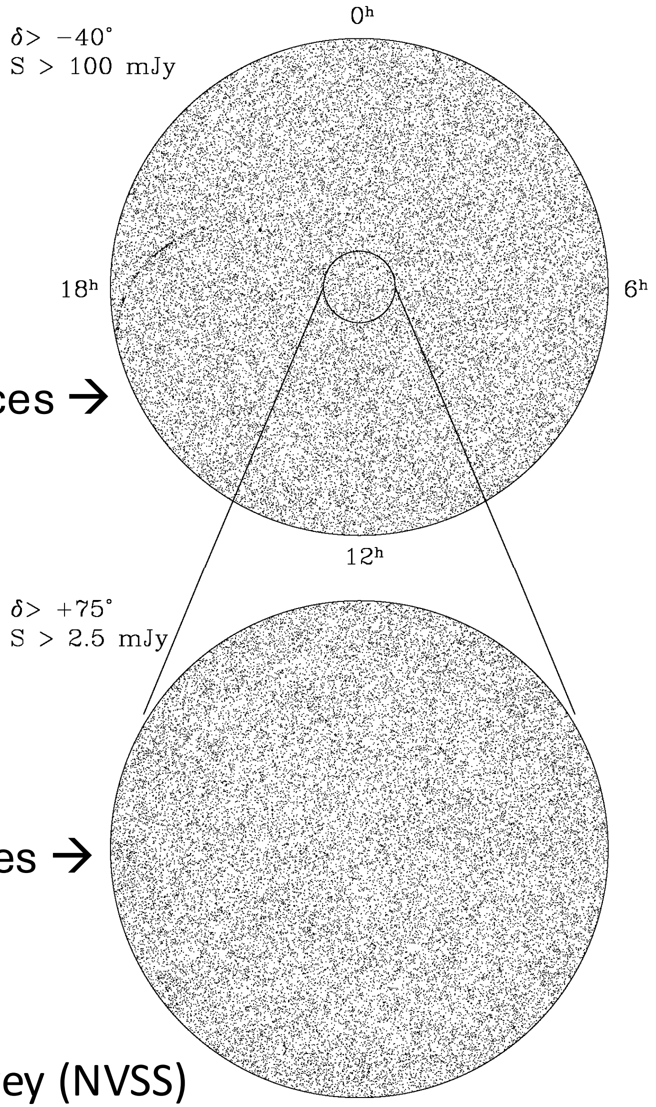
Relativistic Bulk Motion (5.6)

*(5.4.3) **Extragalactic Radio-Source Populations and Cosmological Evolution…***

Sources detected by **blind surveys** covering representative areas of sky give us an unbiased statistical sample of the radio-source population.

Sources need to be separated at large distances in order to be isotropic… thus, many of these radio sources are at much larger distances (z ~ 1)

Fig. 5.24 (ERA)



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Synchrotron Radiation (ERA Chapter 5)

Relativistic Bulk Motion (5.6)

(5.4.3) ***Extragalactic Radio-Source Populations and Cosmological Evolution…***

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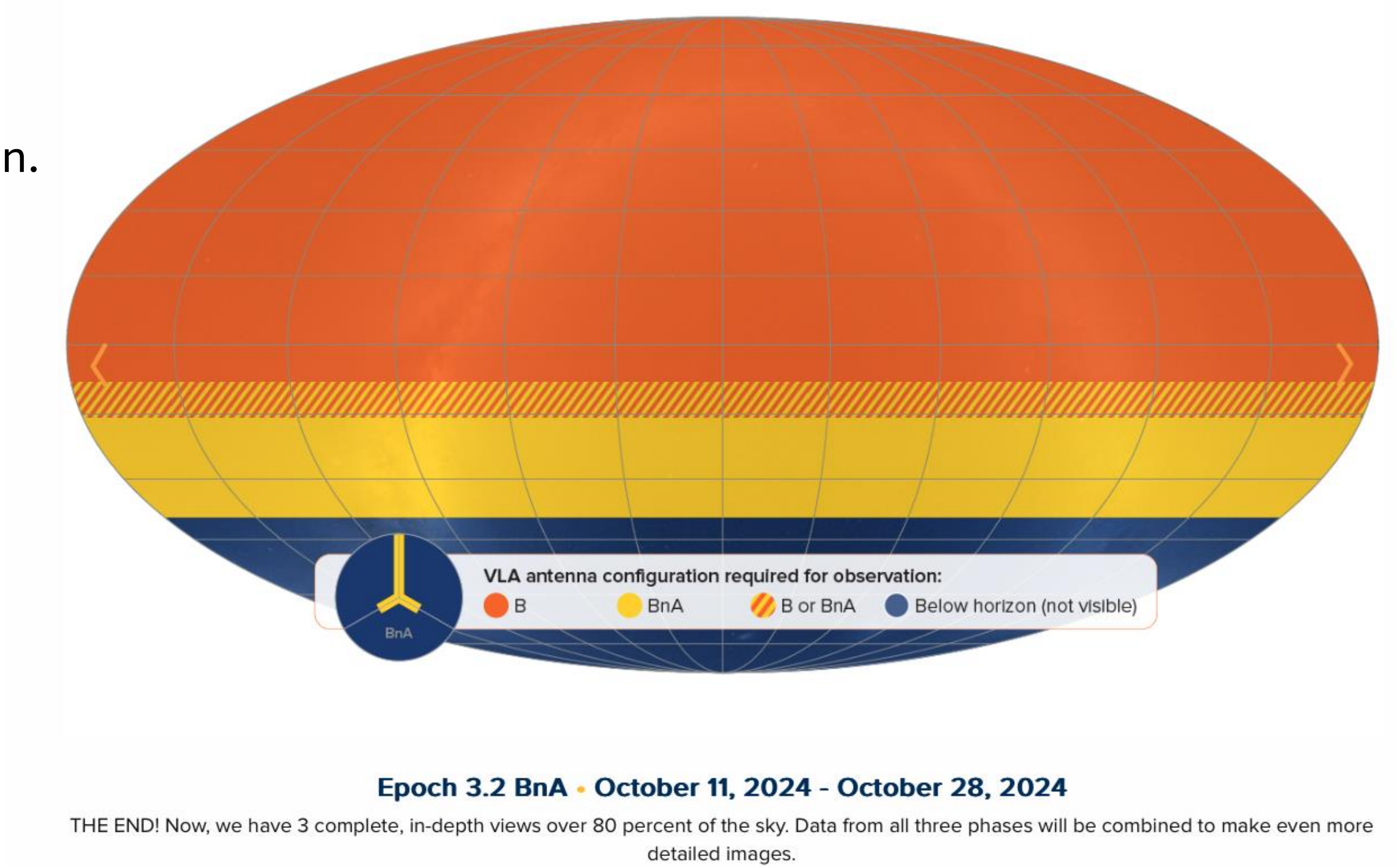
The Very Large Array Sky Survey –
VLASS Survey!

- Sky visible to the VLA: decl. > -40 degrees
- Frequency: 3 Ghz (2-4 GHz) “S-band”
- High angular resolution ~2.5’’ (VLA B/BnA-configuration)



Epoch 3.2 BnA • October 11, 2024 - October 28, 2024

THE END! Now, we have 3 complete, in-depth views over 80 percent of the sky. Data from all three phases will be combined to make even more detailed images.

https://public.nrao.edu/vlass/vlass-progress/

VLASS Radio-Jet Menagerie!

Credit: NRAO/AUI/NSF