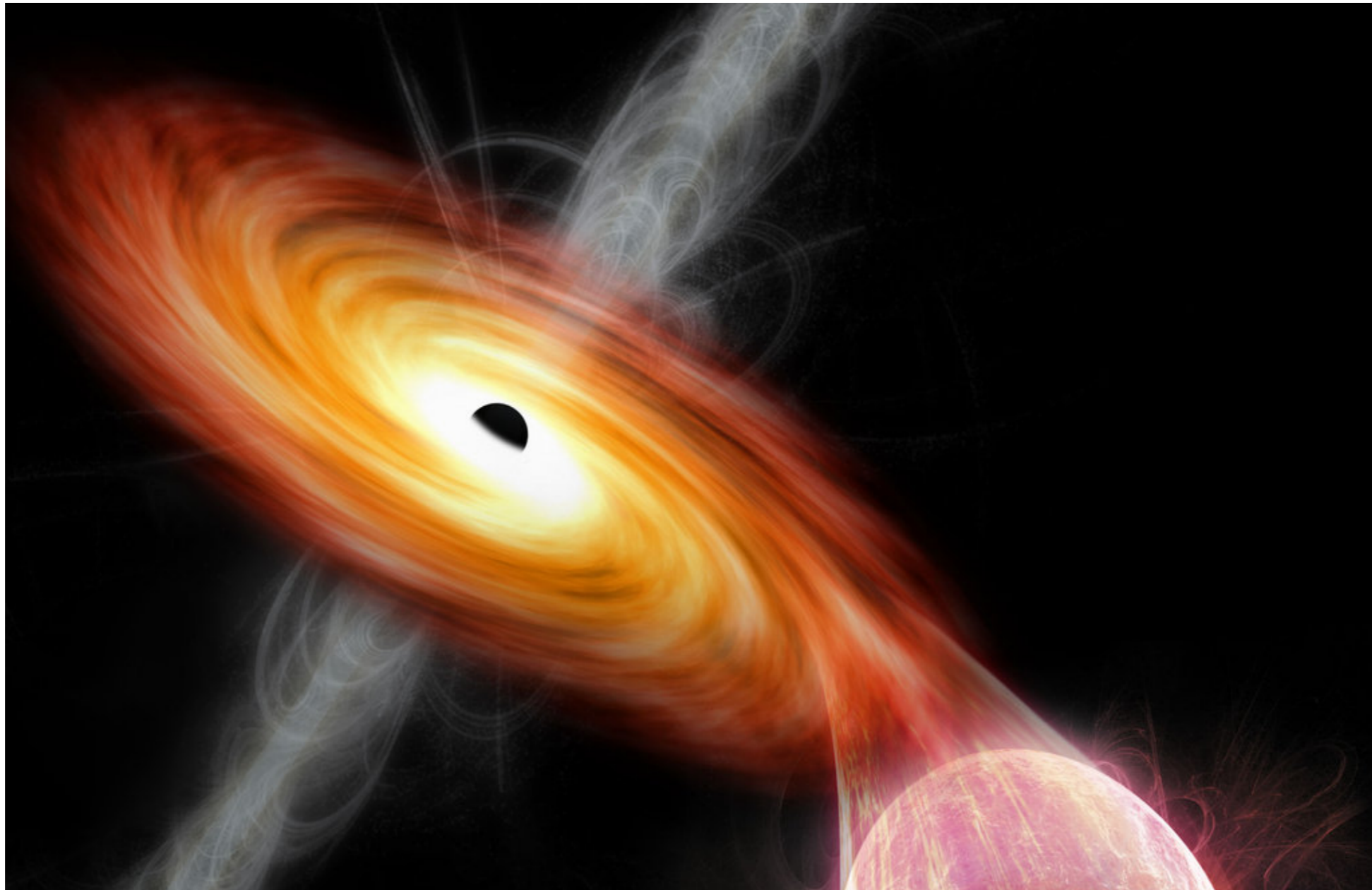


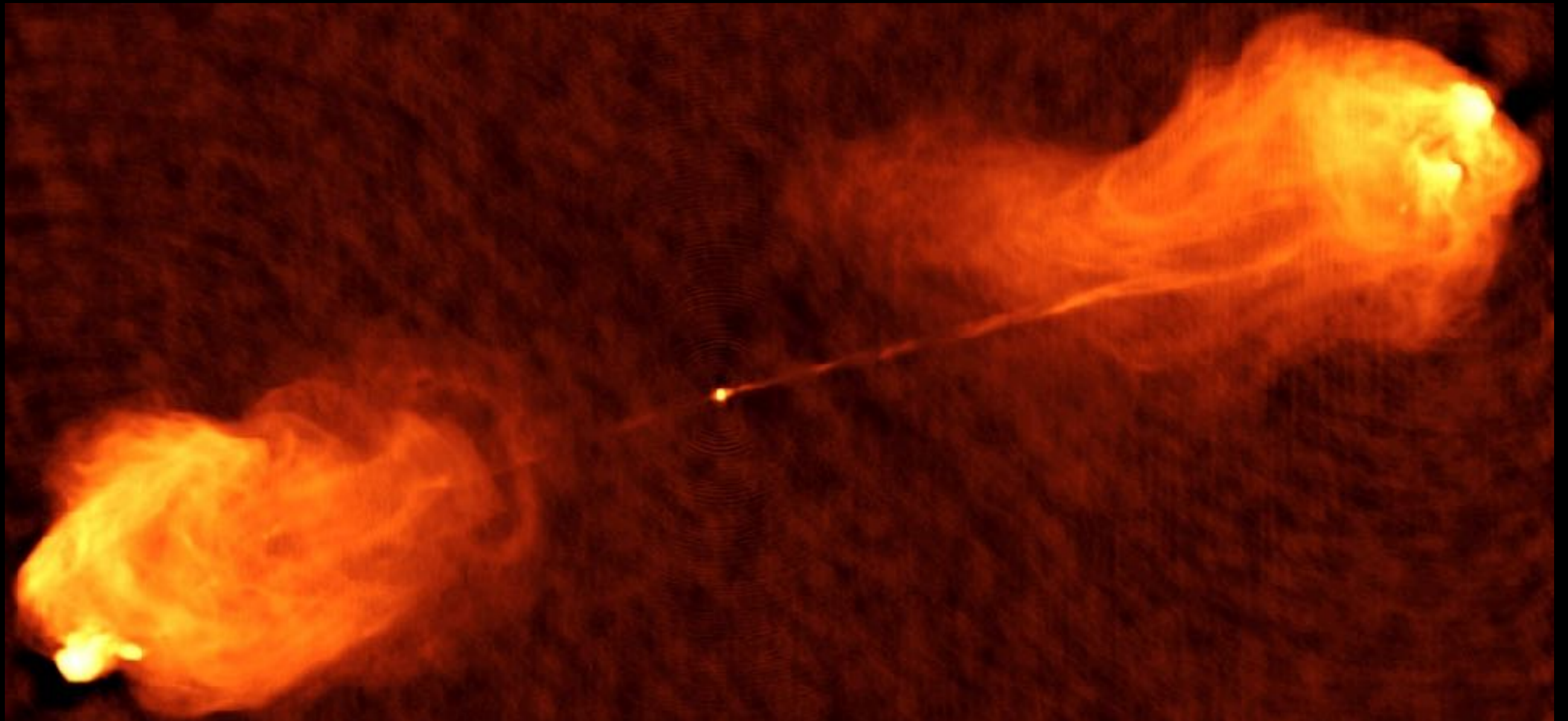
# High Energy Astrophysics

Dr. Adam Ingram



# Lecture 4

## Synchrotron Radiation

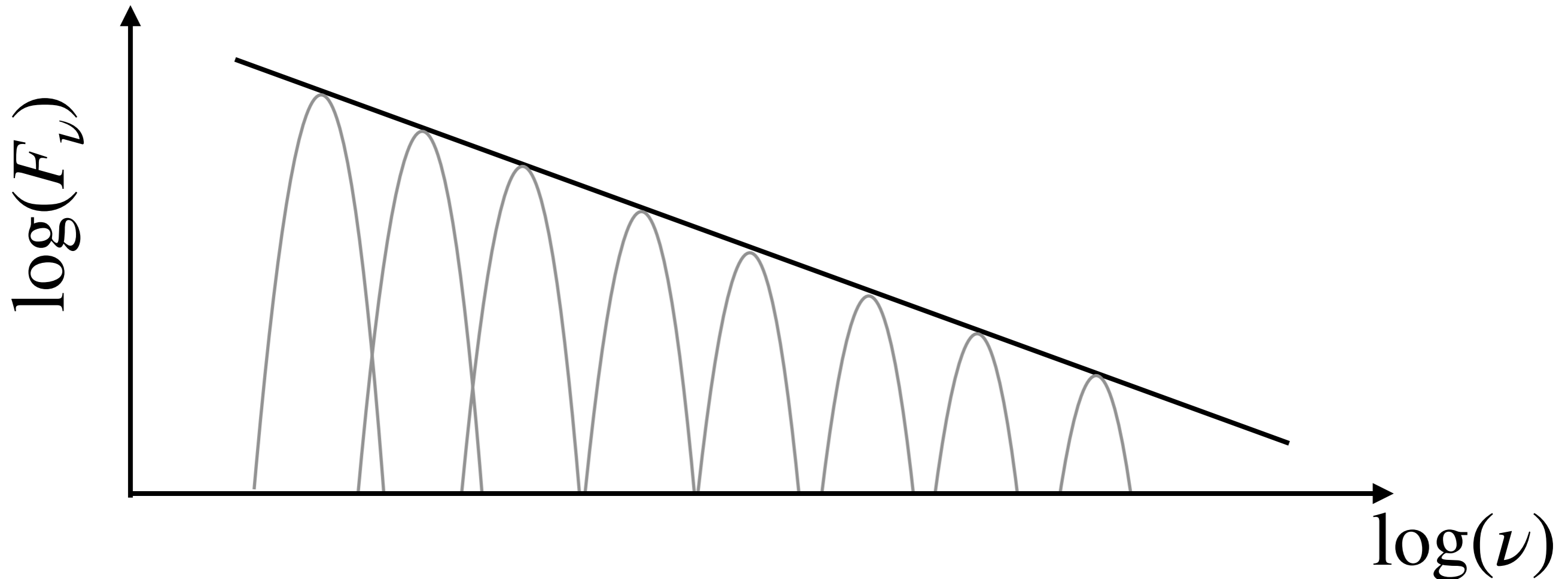


# Last Time

- Spectrum of synchrotron radiation: power-law because the electron energy distribution is a power-law.

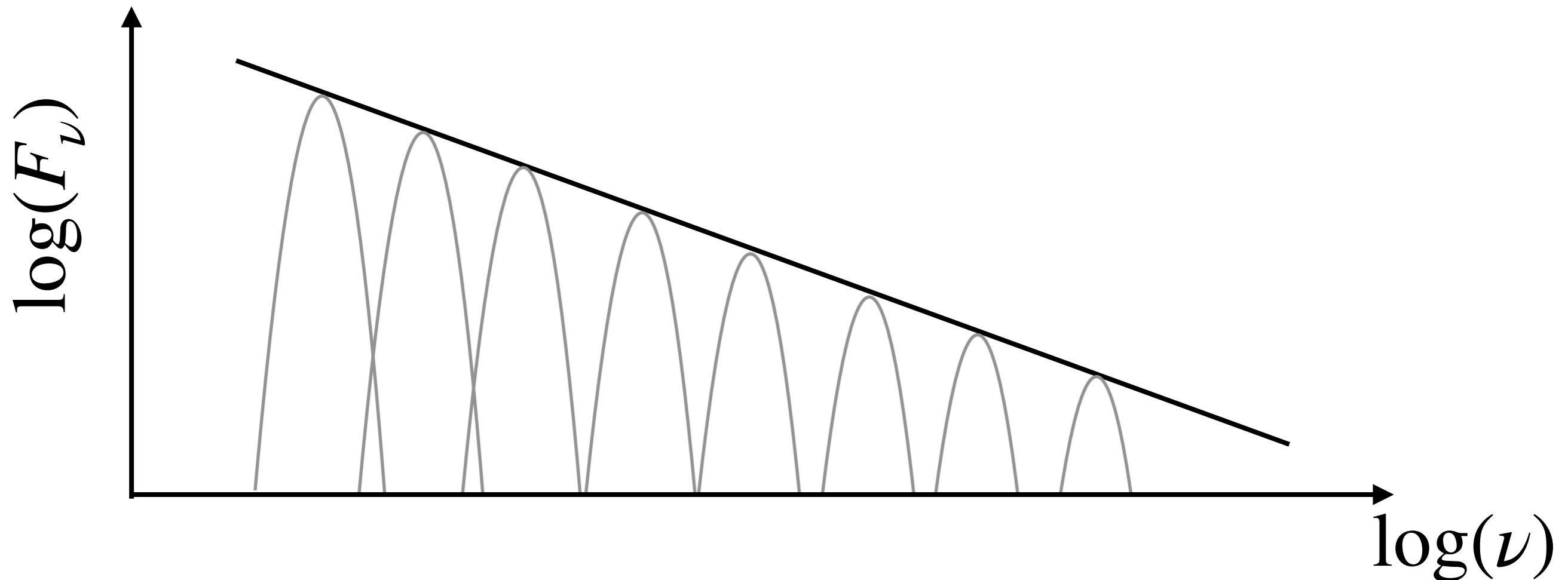
$$\frac{dN}{d\gamma} \propto \gamma^{-k} \quad \nu_c \approx \gamma^2 \frac{eB}{m}$$

$$\implies F_\nu \propto \nu^{-\alpha} \text{ where } \alpha = \frac{k-1}{2}$$



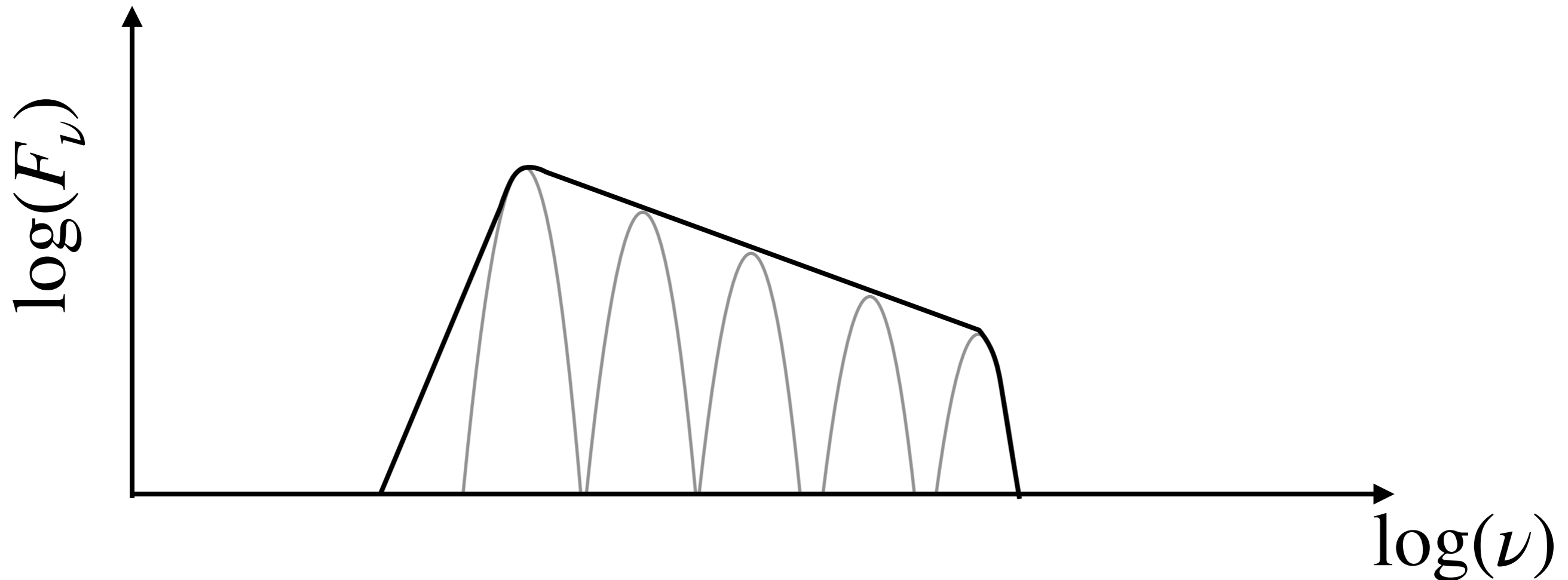
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- We will discuss how to measure the magnetic field strength from the observed synchrotron power.



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- Spectrum of synchrotron radiation: power-law because the electron energy distribution is a power-law.
- We will discuss how to measure the magnetic field strength from the observed synchrotron power.
- We will understand why synchrotron spectra really show low and high frequency breaks.



# Minimum energy

- By integrating the spectrum of a synchrotron emitting object, we can measure the total energy density emitted by the plasma (need an estimate for distance and size).

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- To break this degeneracy, and therefore measure B-field, we can use the minimum energy method (Burbidge 1956)

$$U_{\text{mag}} = \frac{B^2}{2\mu_0}$$

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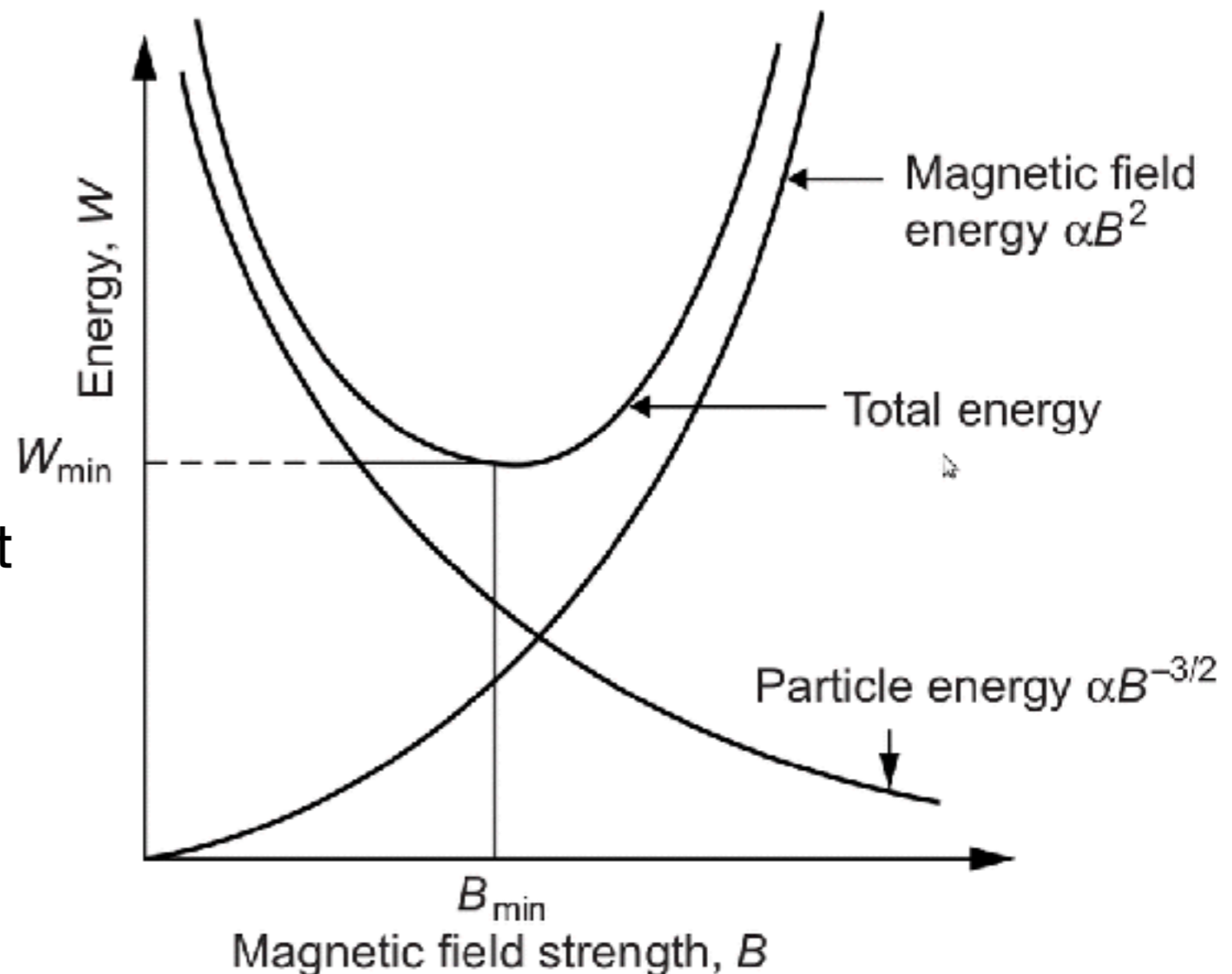
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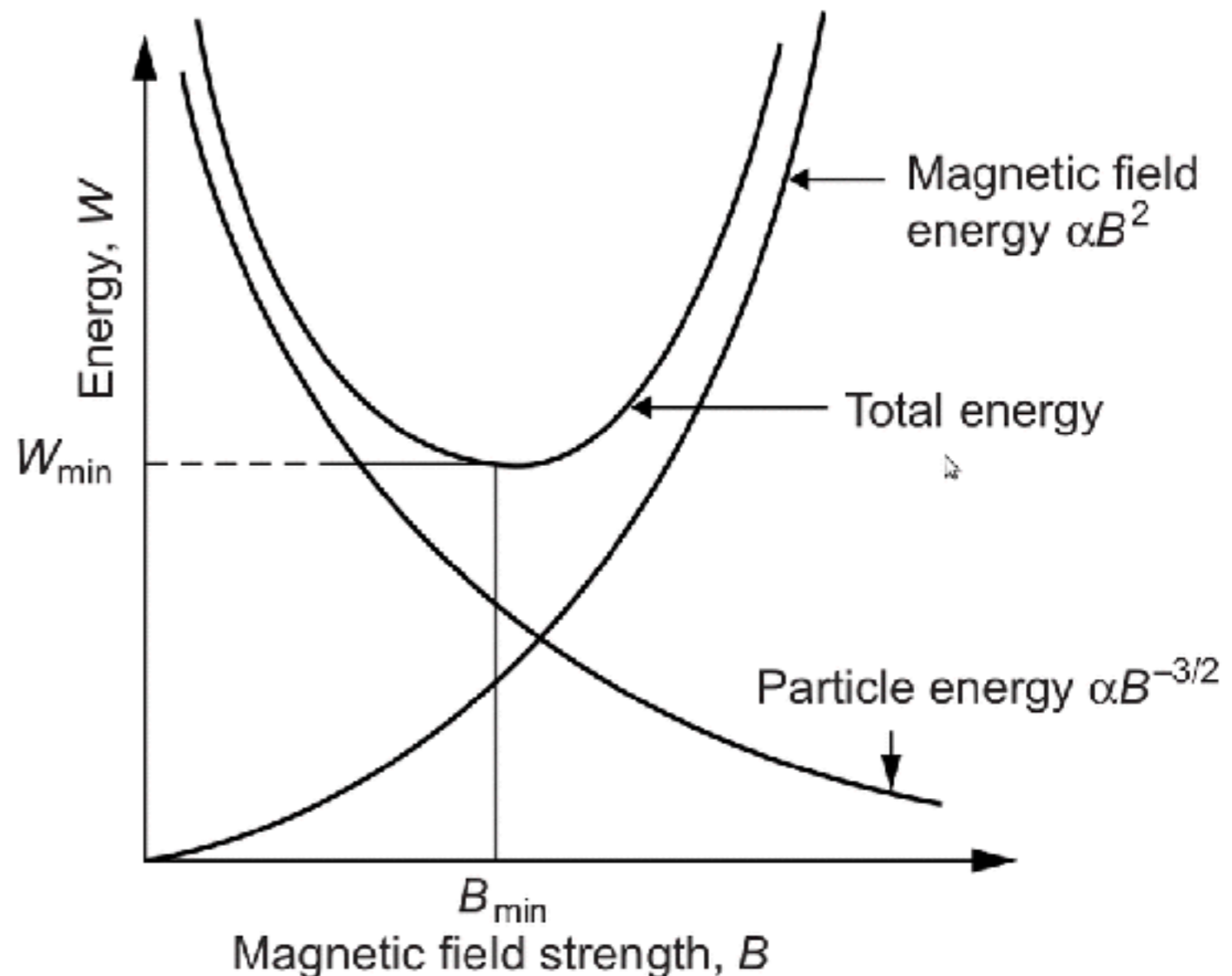
$$U_e = \int E(\gamma) \frac{dN}{d\gamma} d\gamma \propto B^{-3/2}$$

- Plasma presumably finds ~lowest energy state in equilibrium.

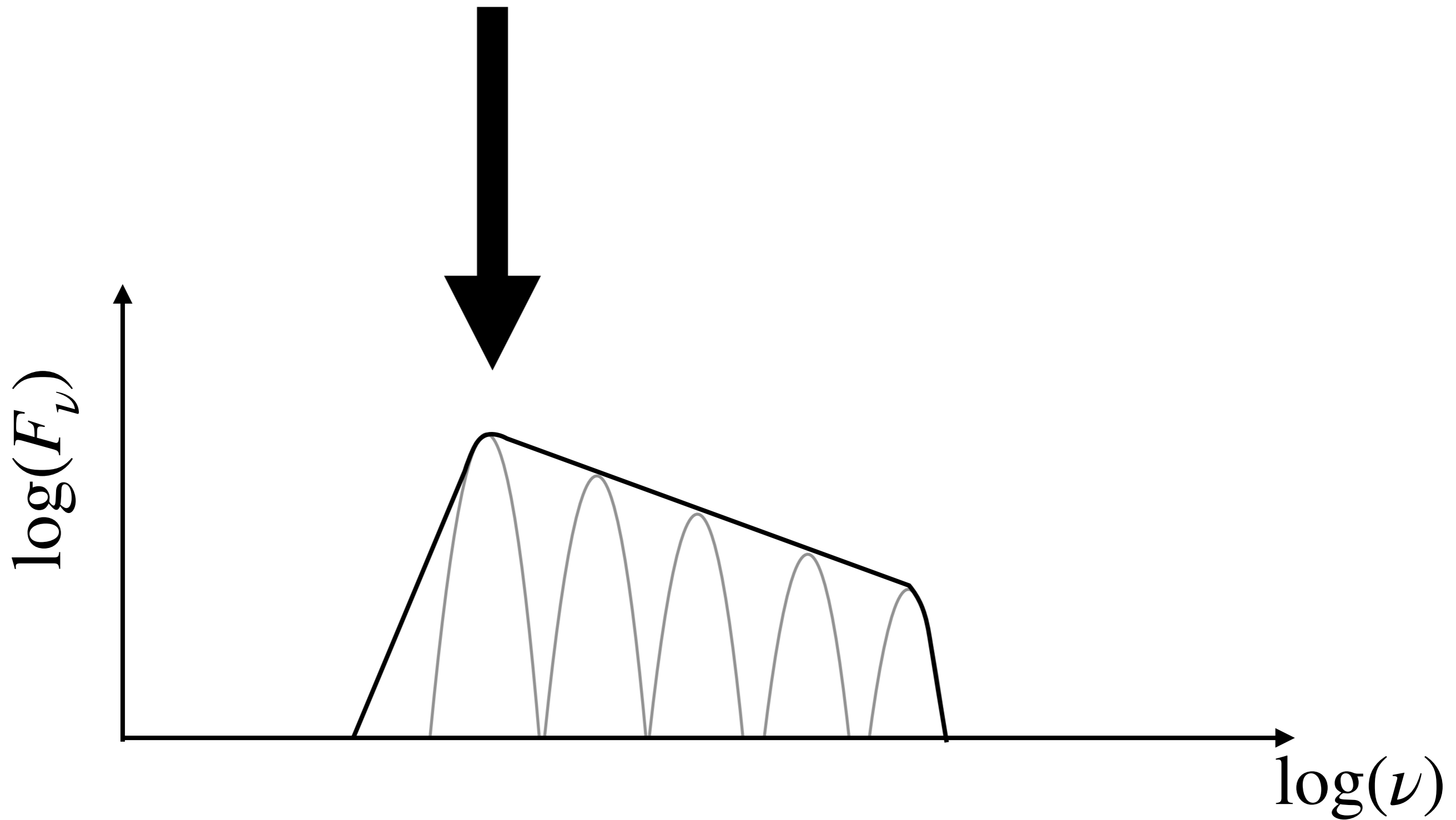


# Minimum energy

- Minimum energy requirement:  $U_e \sim U_{\text{mag}}$  (equipartition).
- Will calculate true minimum energy relation for homework problem.
- Roughly equipartition values expected from particles jiggling around and sharing energy in the plasma.
- See <https://github.com/robfinder/ThunderBooks/blob/master/Equipartition%20analysis.ipynb>

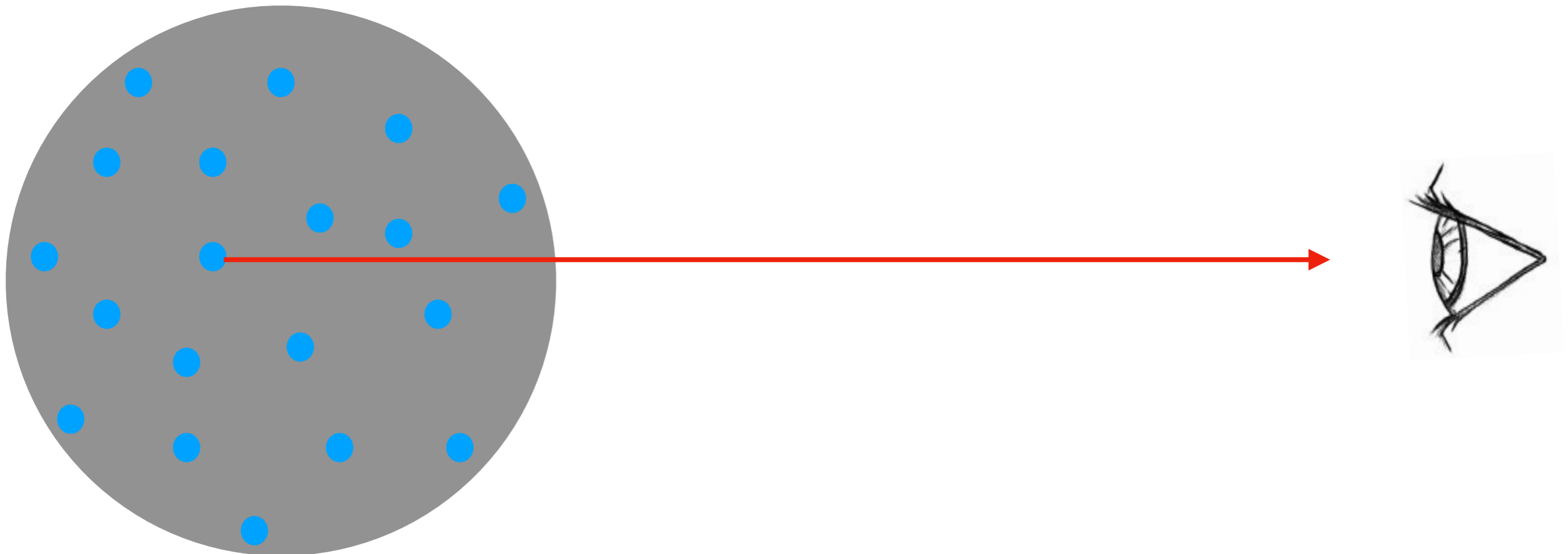


# Low frequency break



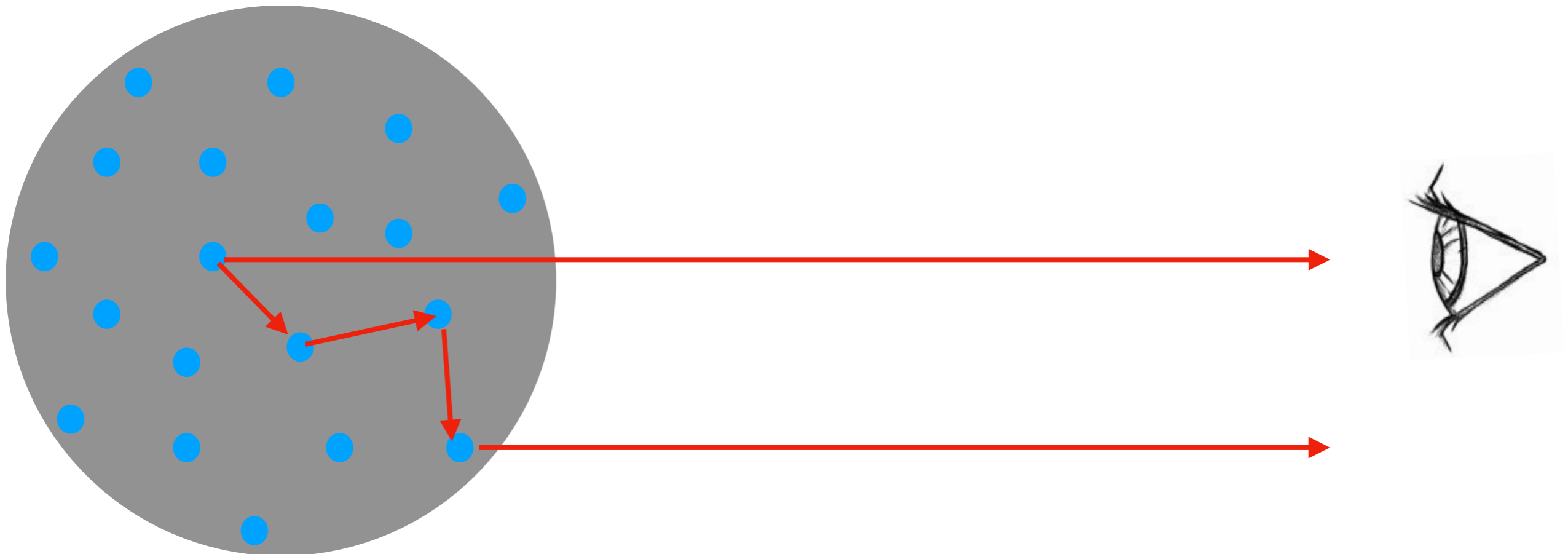
# Self-absorption

- So far, we have implicitly assumed that all synchrotron radiation emitted by each electron reaches the observer.



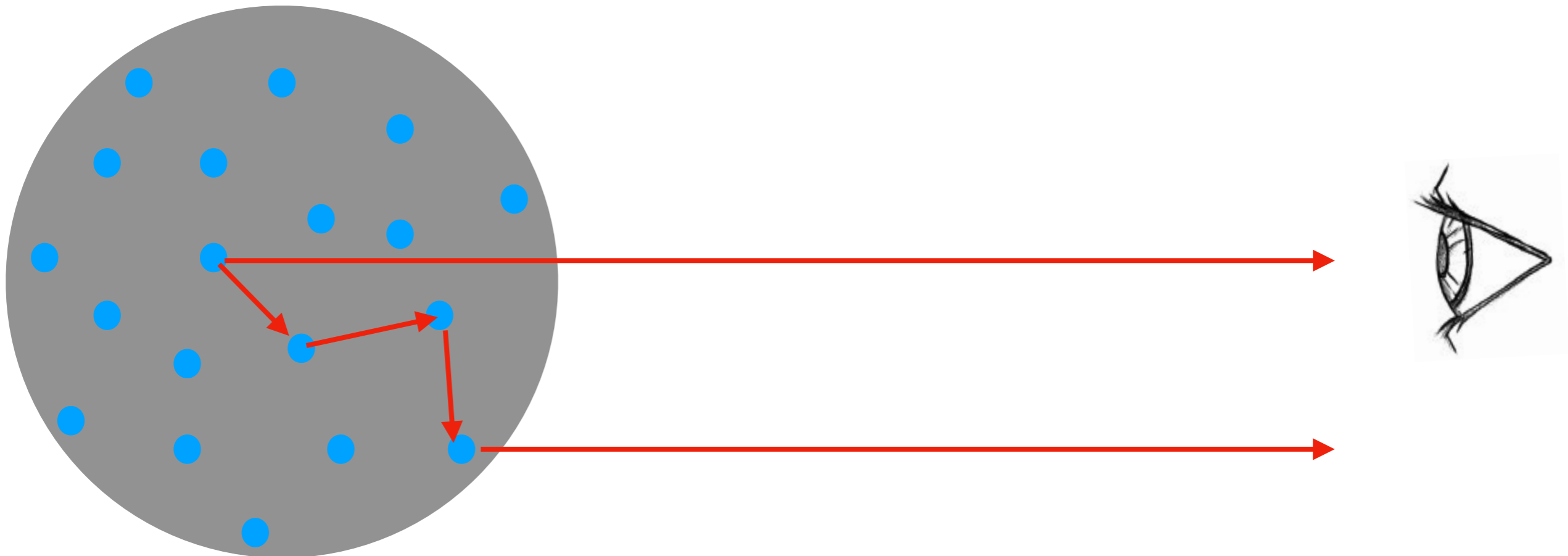
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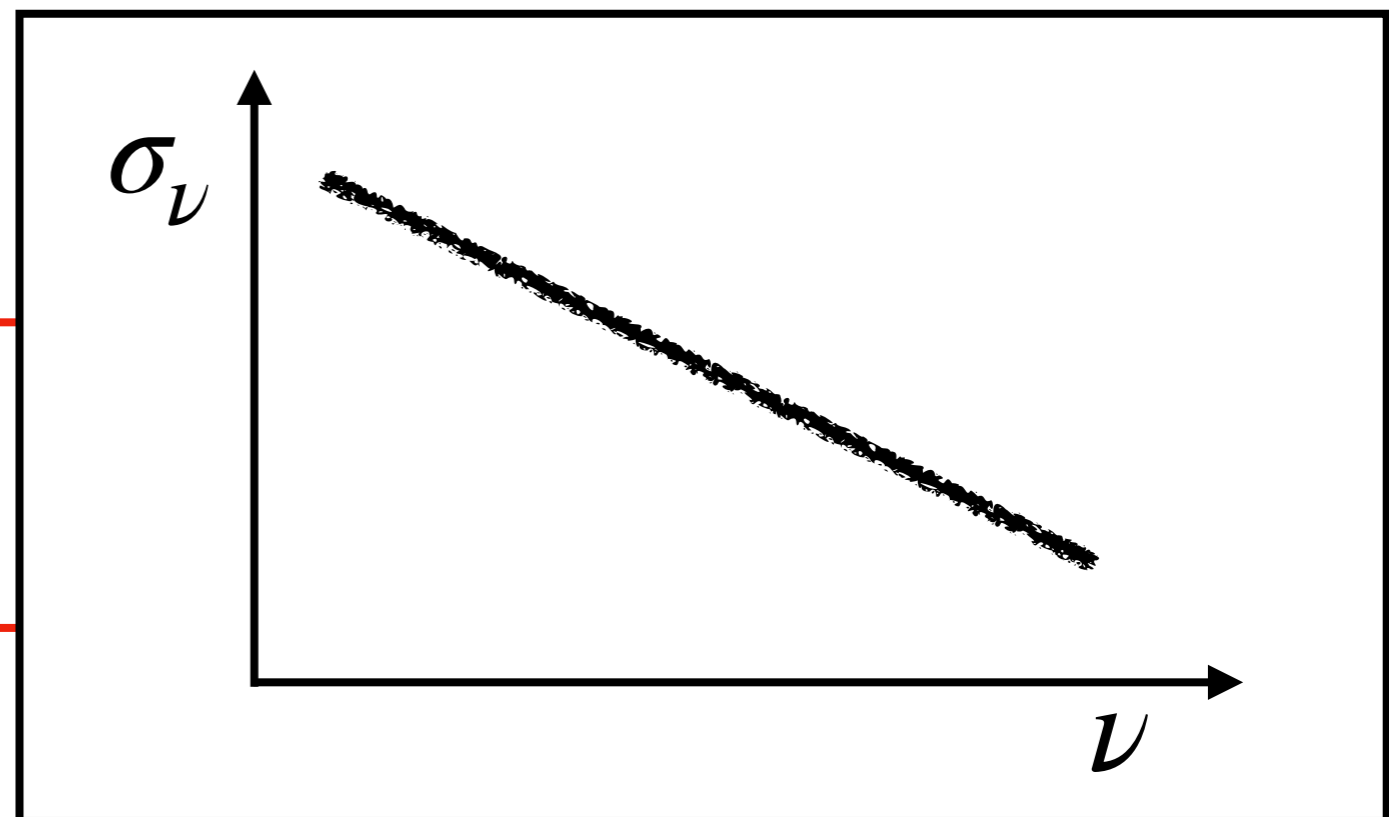
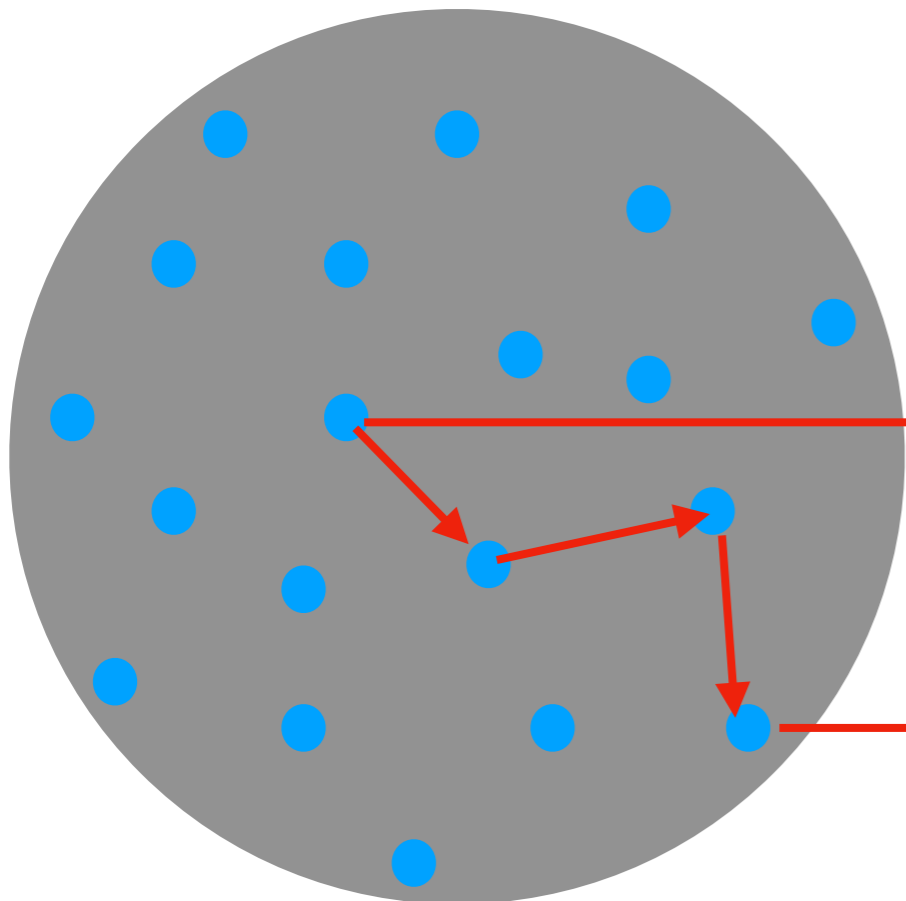
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Absorption more efficient for lower frequency photons



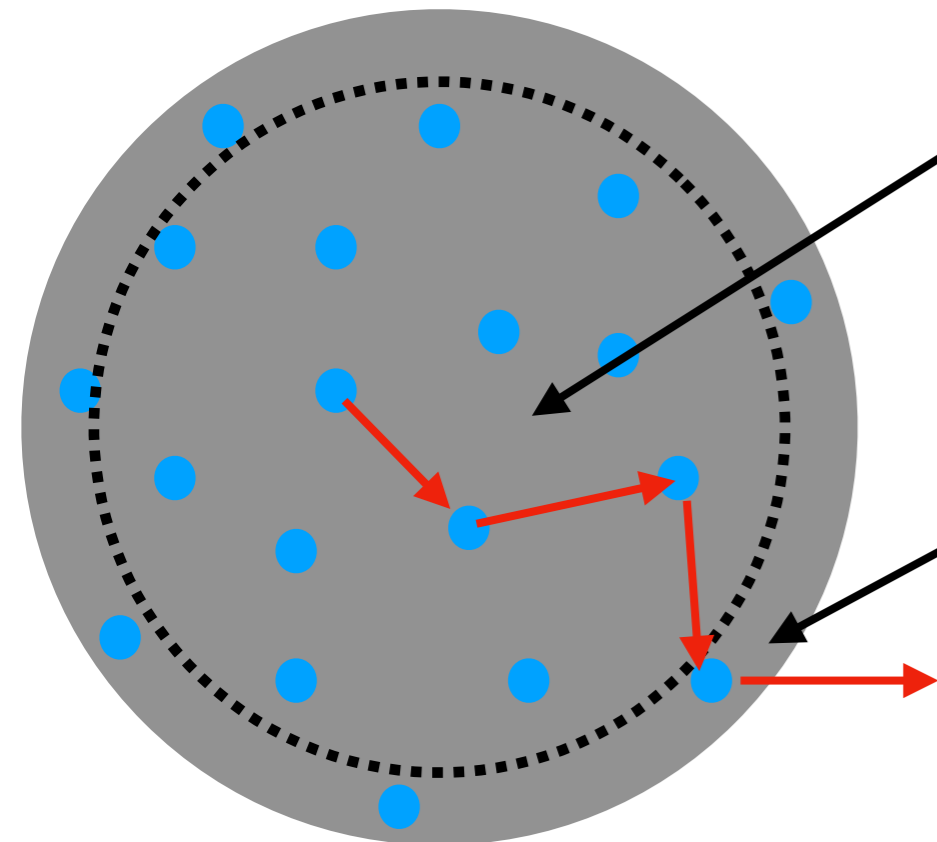
# Self-absorption

- Only “see” photons from outskirts of the plasma cloud.
- Just like stars, we see photons from outer  $\tau \sim 1$ .

Low frequency

Photons emitted from in here just exchange energy with electrons

Photons emitted from out here can reach the observer





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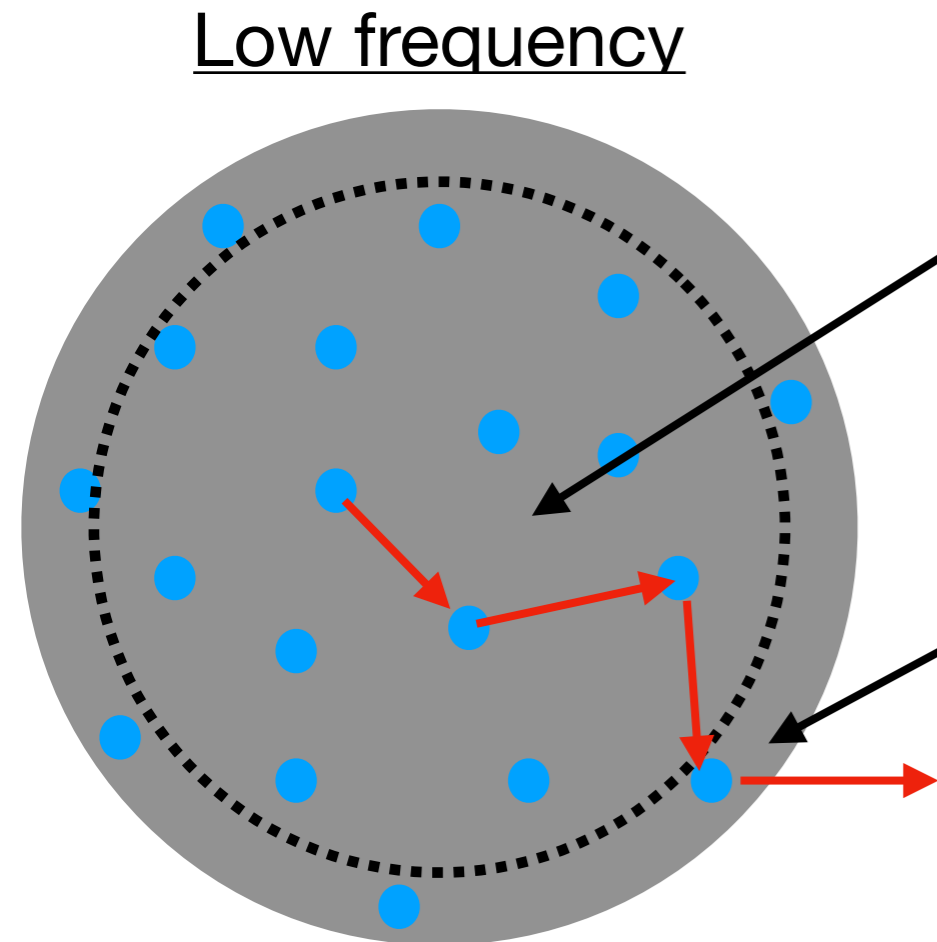
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...aside: remember from Stars lecture that we see further into the core

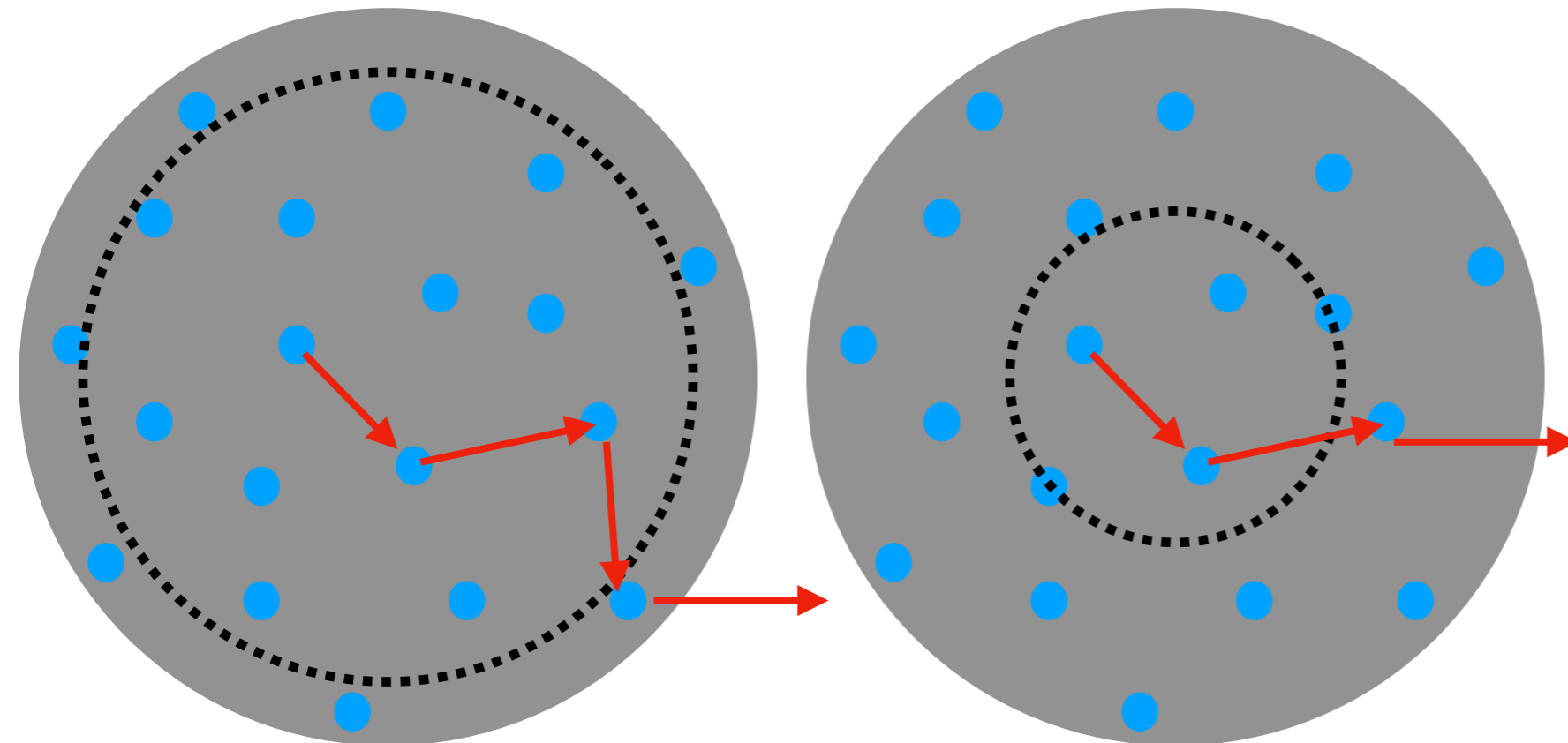


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Low frequency

Intermediate frequency



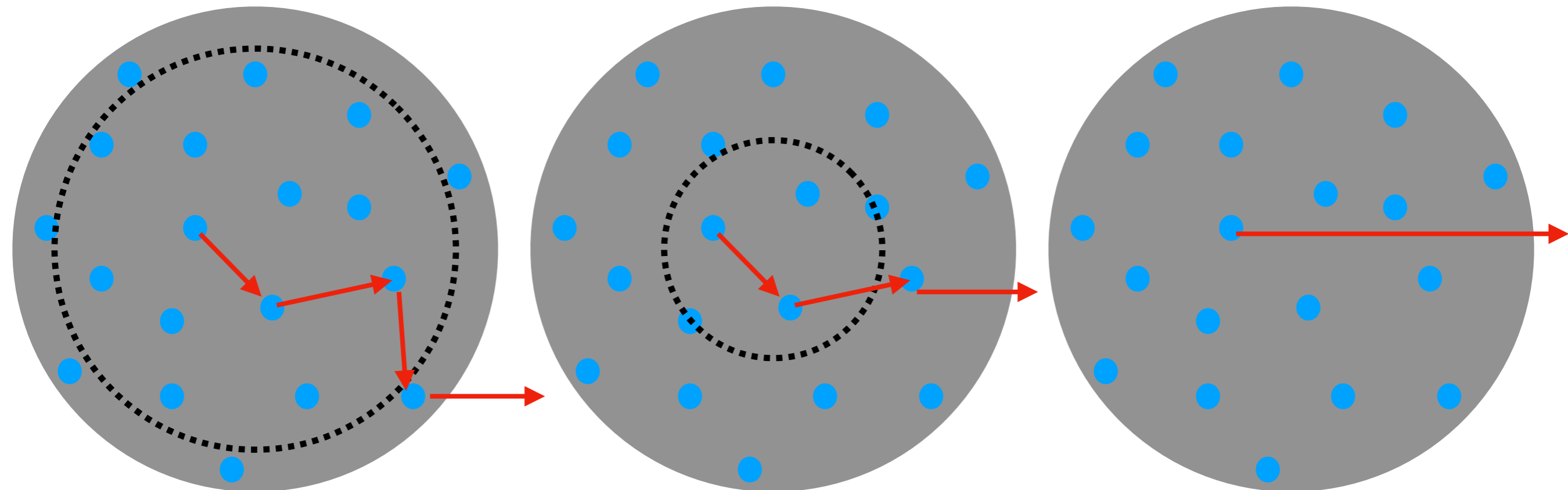
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- The highest frequency photons can stream through the whole cloud: so we just see the synchrotron power-law for the highest frequencies.

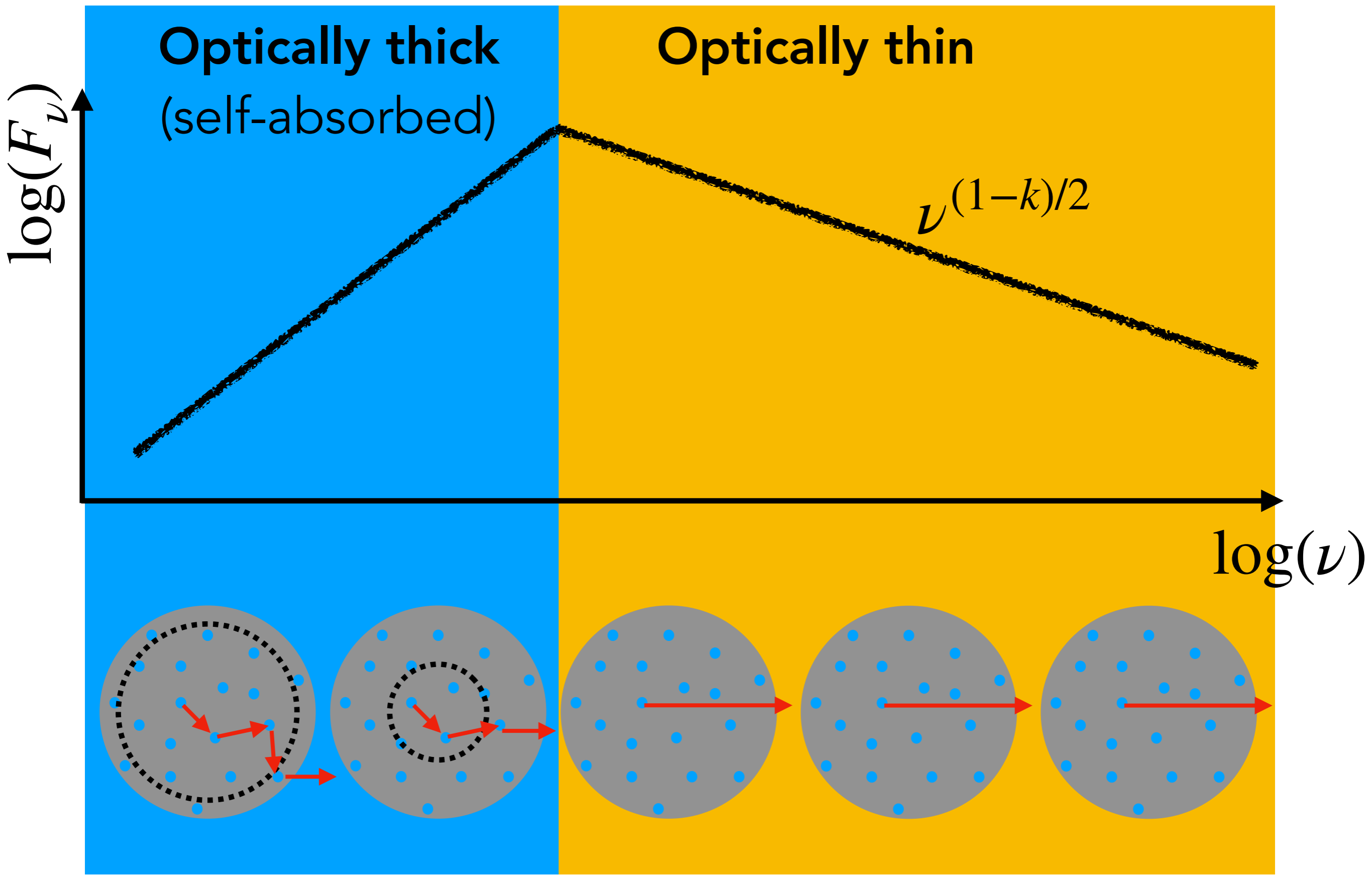
Low frequency

Intermediate frequency

High frequency



# Self-absorption



# Self-absorption calculation

- Electron distribution *not* thermal, but can get correct form for self-absorbed spectrum by assigning electrons an effective temperature:  $kT_{\text{eff}} = E \propto \gamma$

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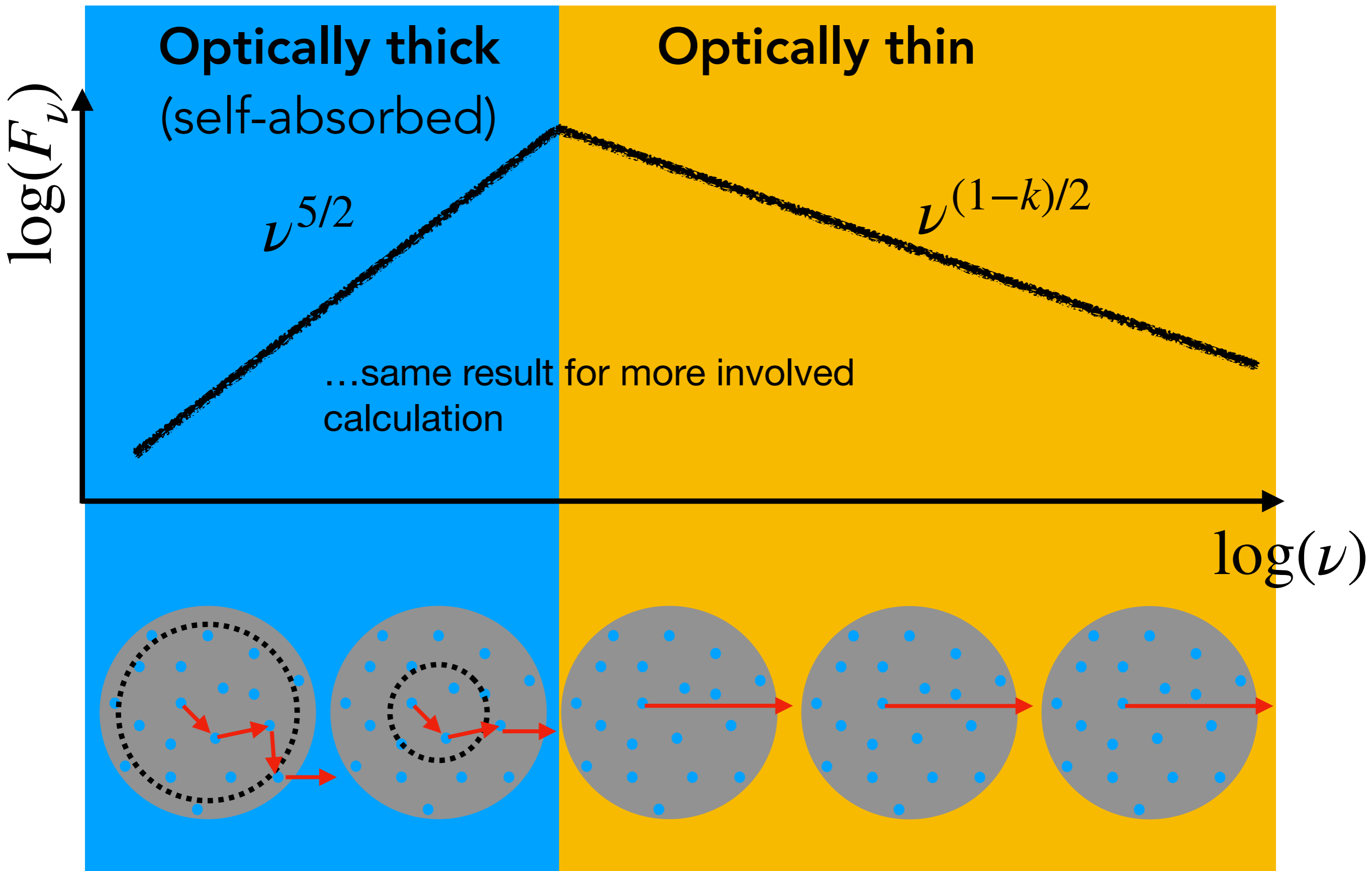
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$$kT_{\text{eff}} \propto \nu^{1/2}$$

$$\implies$$

$$I_\nu \propto \nu^{5/2}$$

# Self-absorption calculation



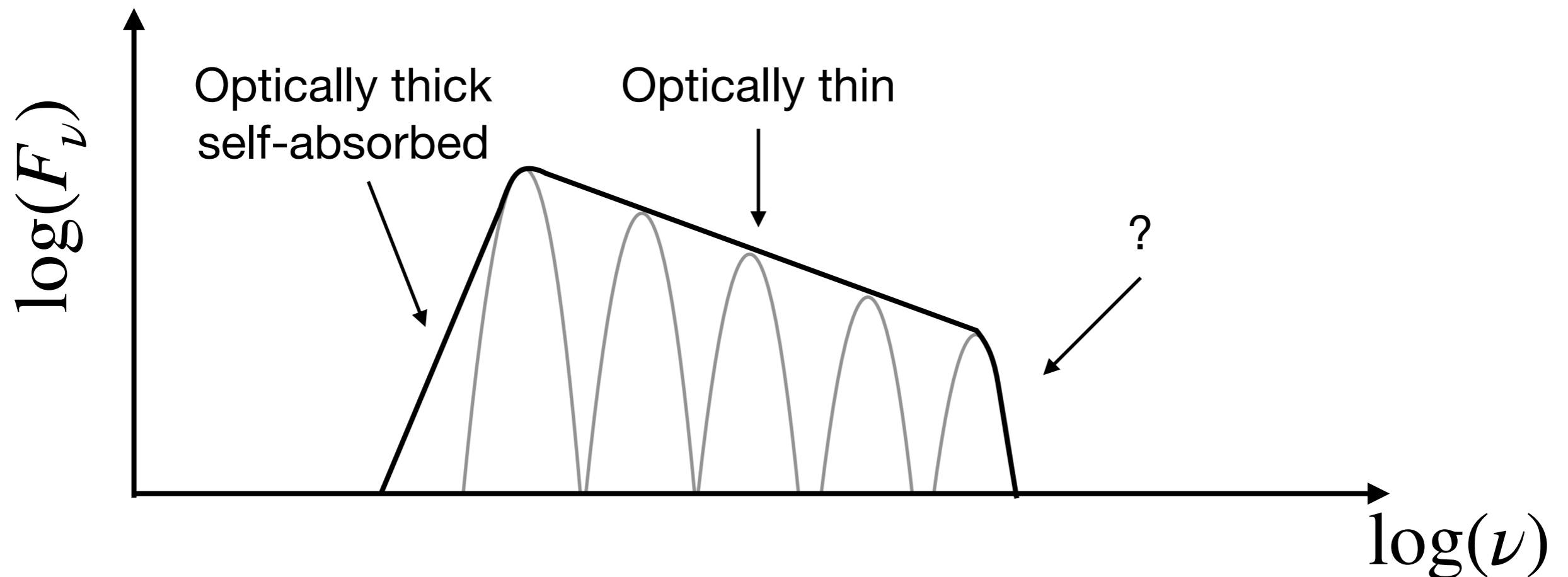
# High frequency cut-off

- Upper limit for energy that diffusive shock acceleration can give to electrons: when the gyroradius:

$$r_g = \frac{\gamma m v}{e B}$$

is larger than the accelerating region, the electron can't cross the shock front any more times to gain more energy.

- Leads to maximum energy of  $E \sim 10^{15}$  eV in supernova remnants and  $E \sim 10^{20}$  eV in AGN (thus the highest energy cosmic rays thought to be from AGN)

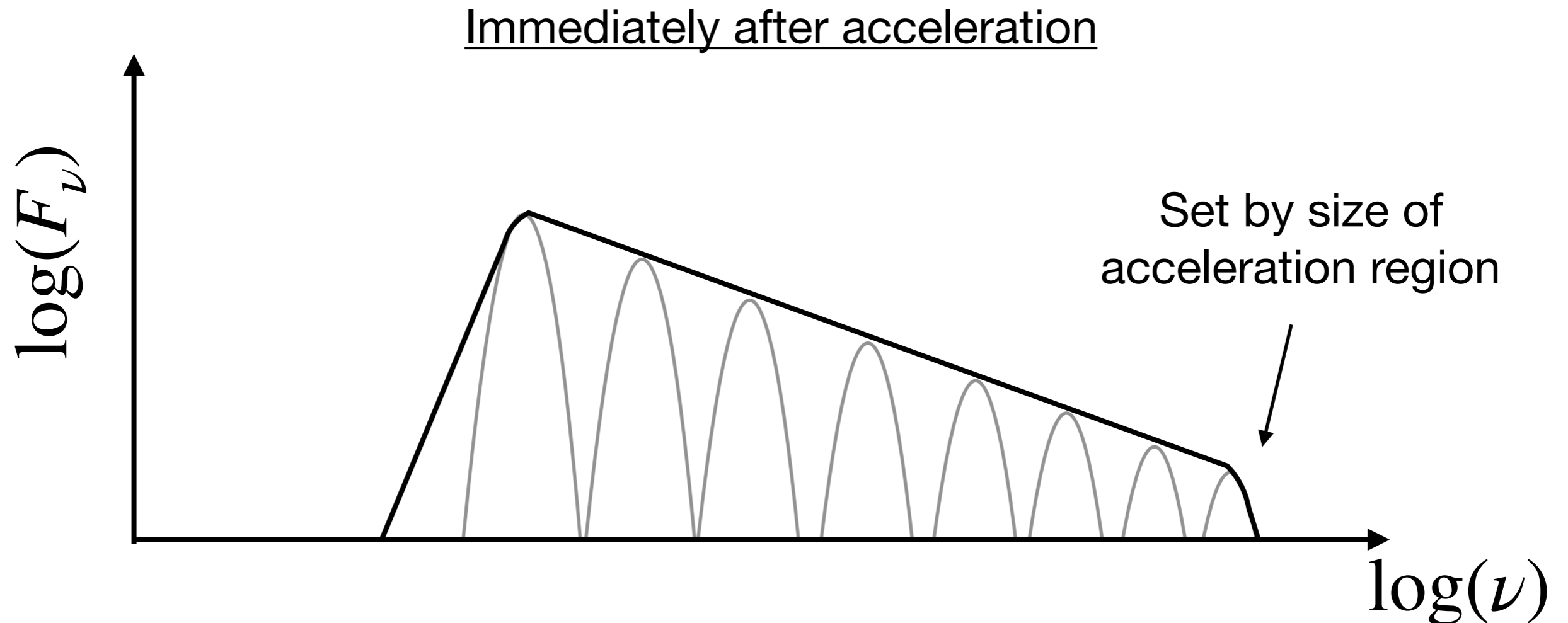


# High frequency cut-off

- But synchrotron radiation *drains* energy of electrons.
- Electrons lose energy at a rate:

$$P = \frac{4}{3} \sigma_T c \frac{B^2}{2\mu_0} \left( \frac{v}{c} \right)^2 \gamma^2$$

- Therefore, highest energy electrons in the population radiate all of their energy away first!



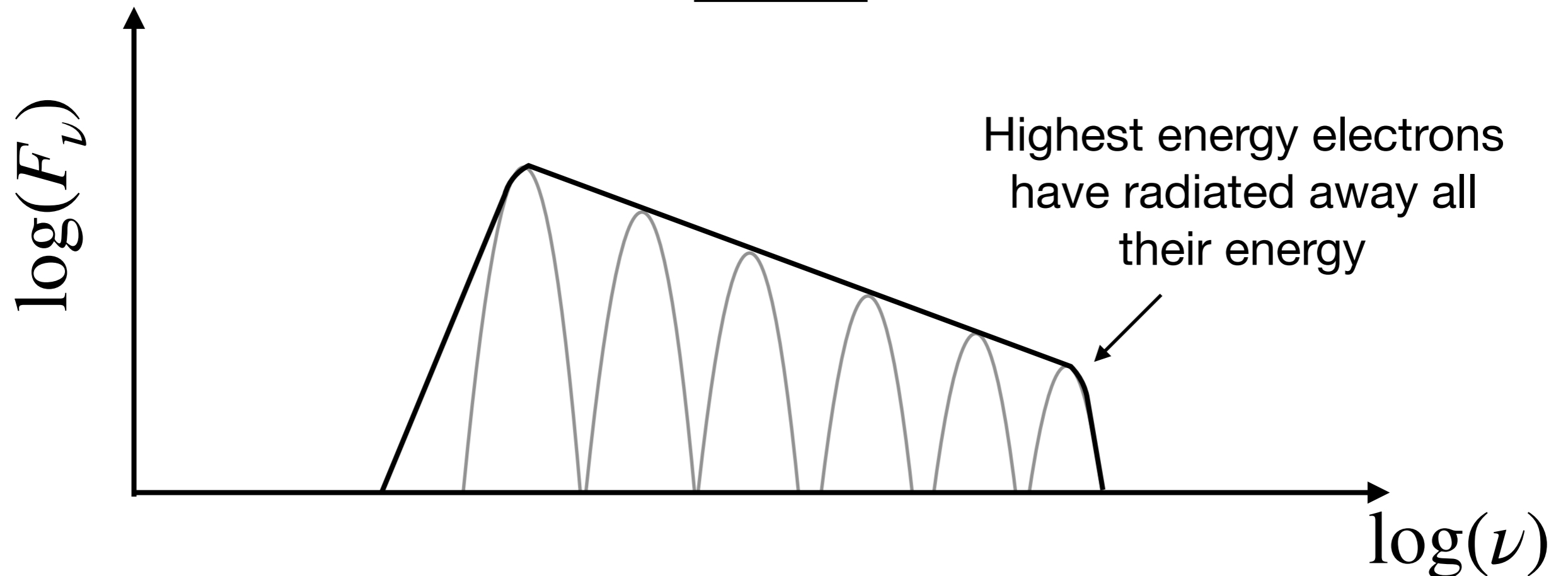
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Later on



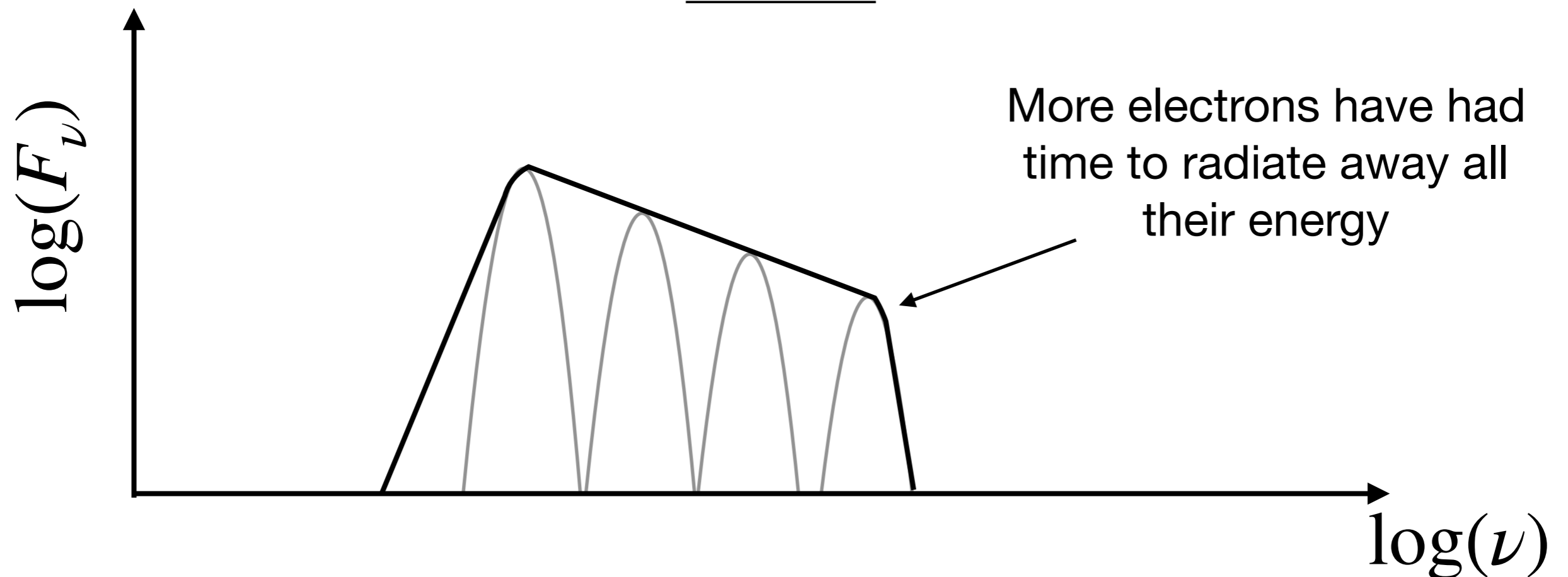
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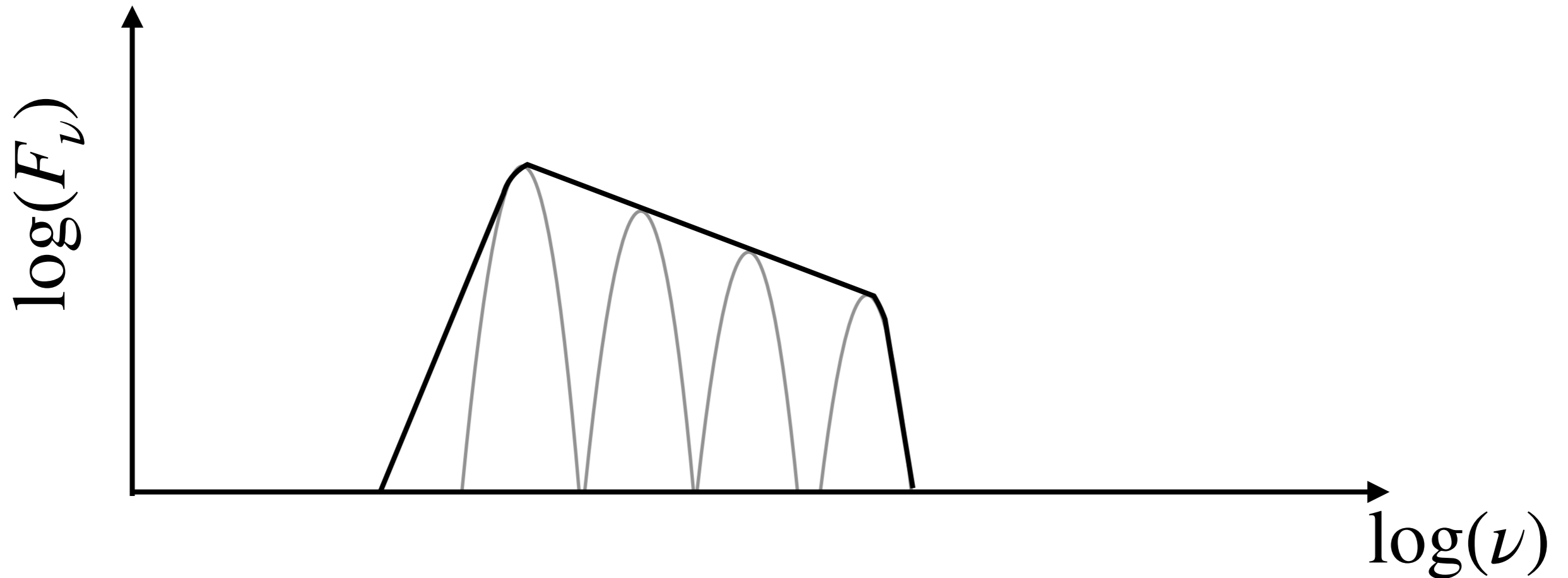
Later still



# High frequency cut-off

- Timescale to radiate away all energy:

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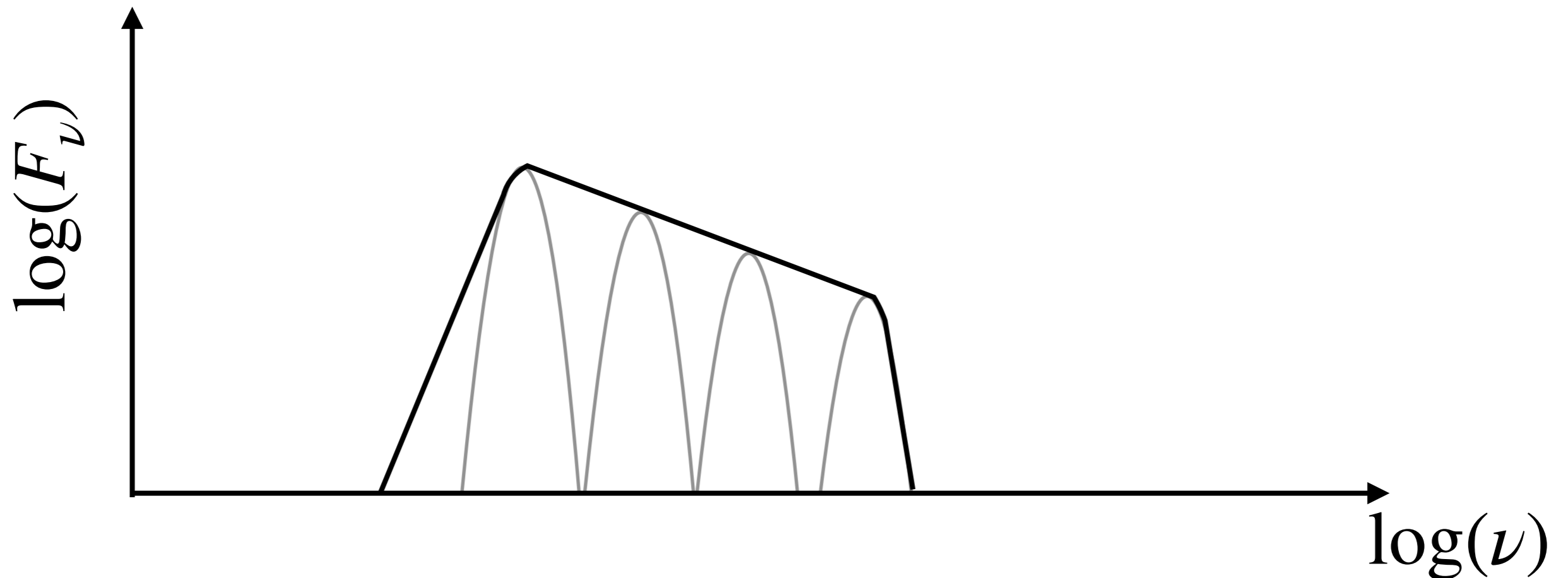




# High frequency cut-off

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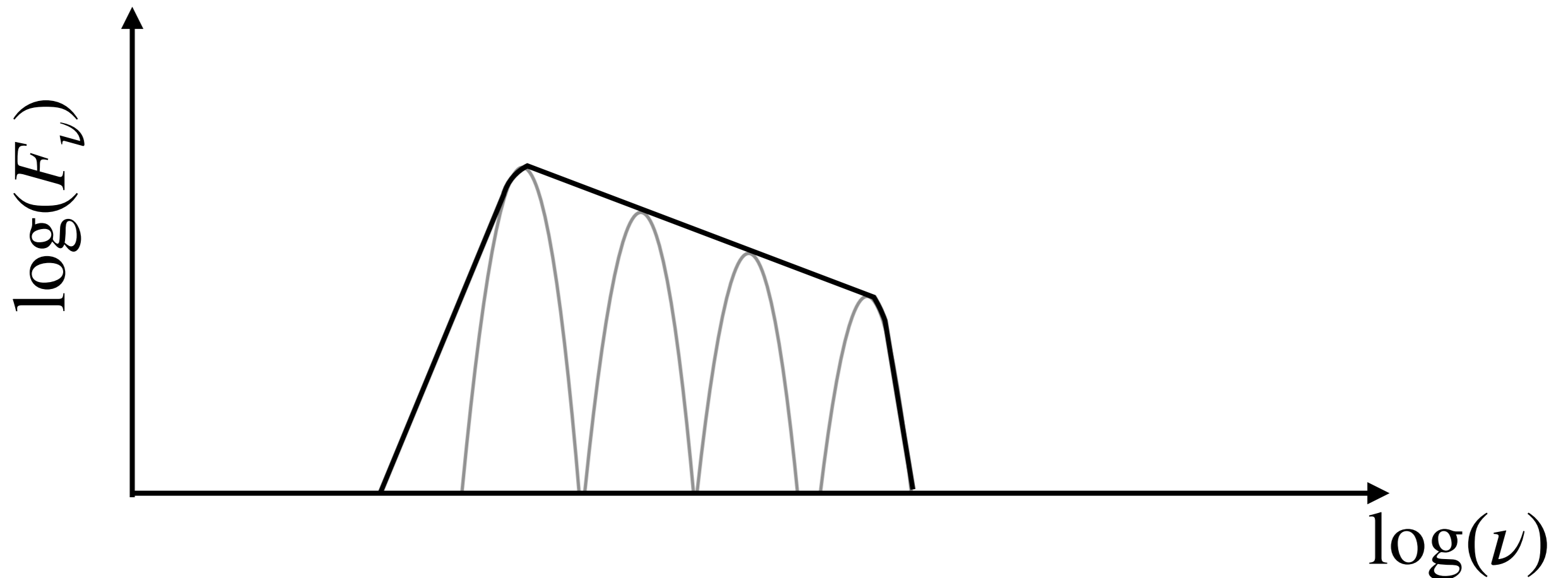


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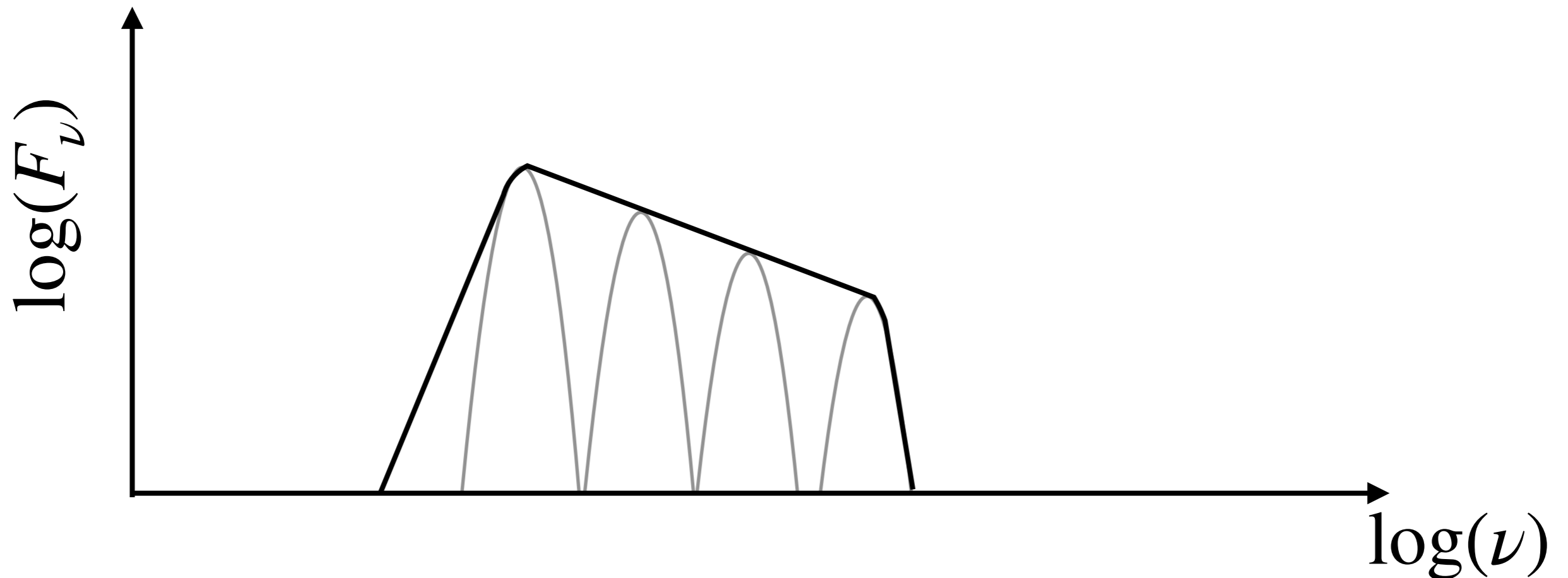


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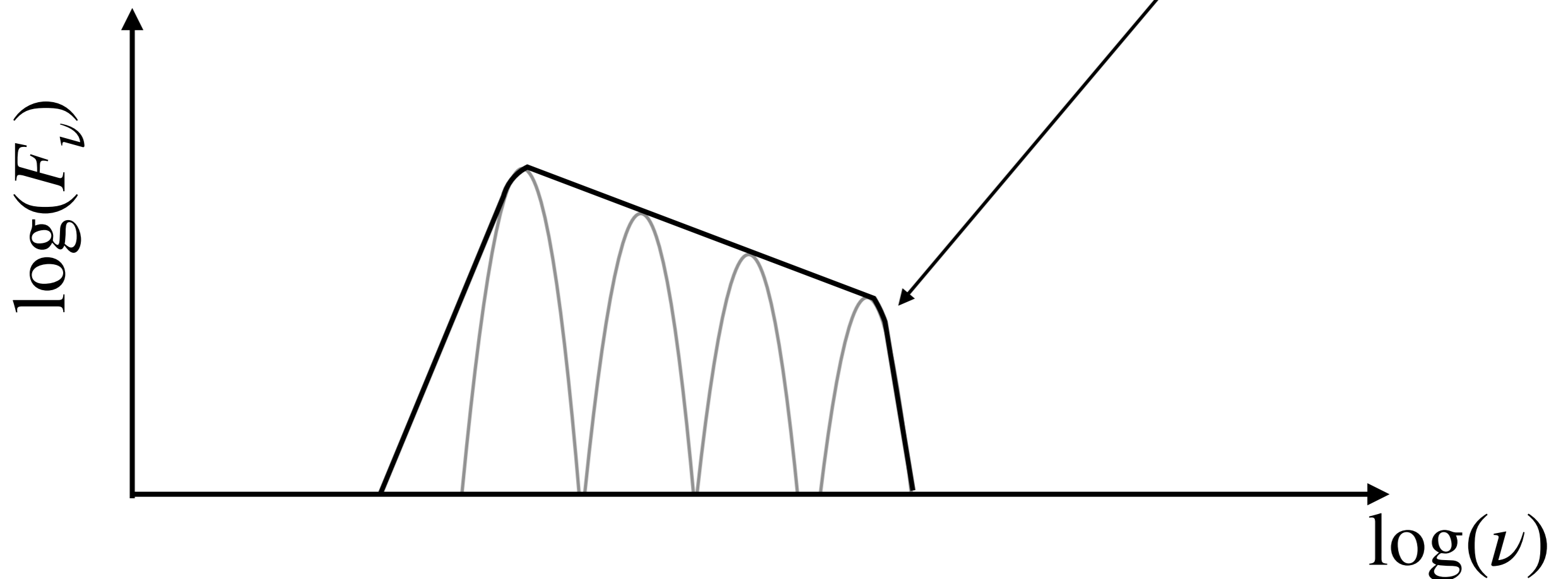
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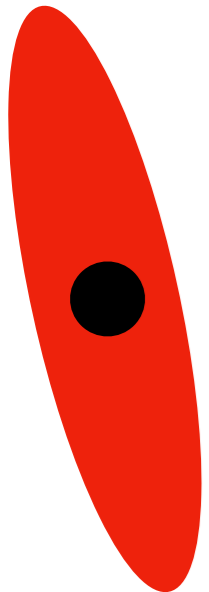
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- Therefore:  $\gamma_{\max} \propto 1/(B^2 \tau) \implies \nu_{\max} \propto \gamma_{\max}^2 B \propto 1/(B^3 \tau^2)$



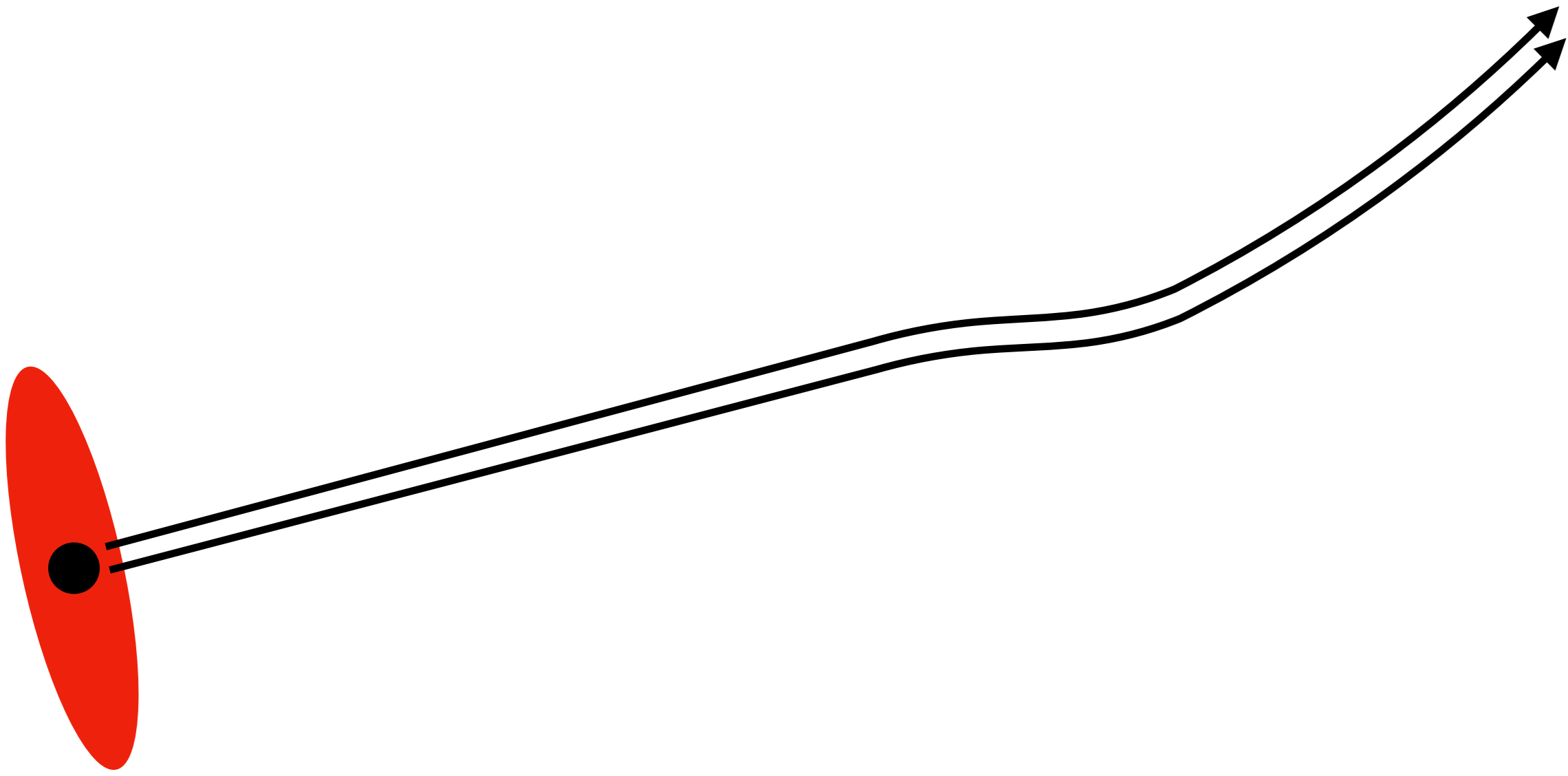
# Spectral Ageing

Black hole accretes gas via accretion disc.



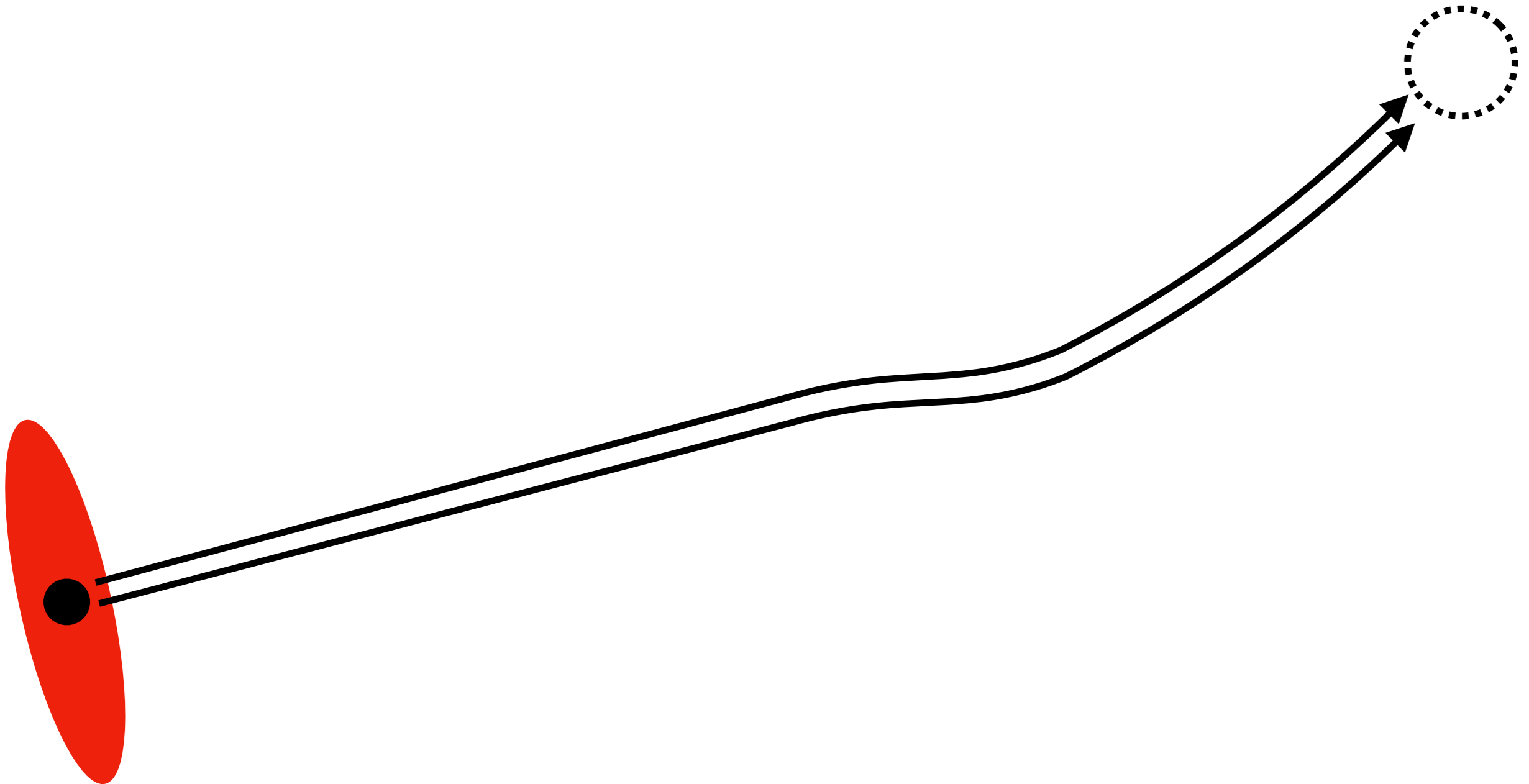
# Spectral Ageing

Launches jet that plows into the IGM (over-densities can bend the jet).



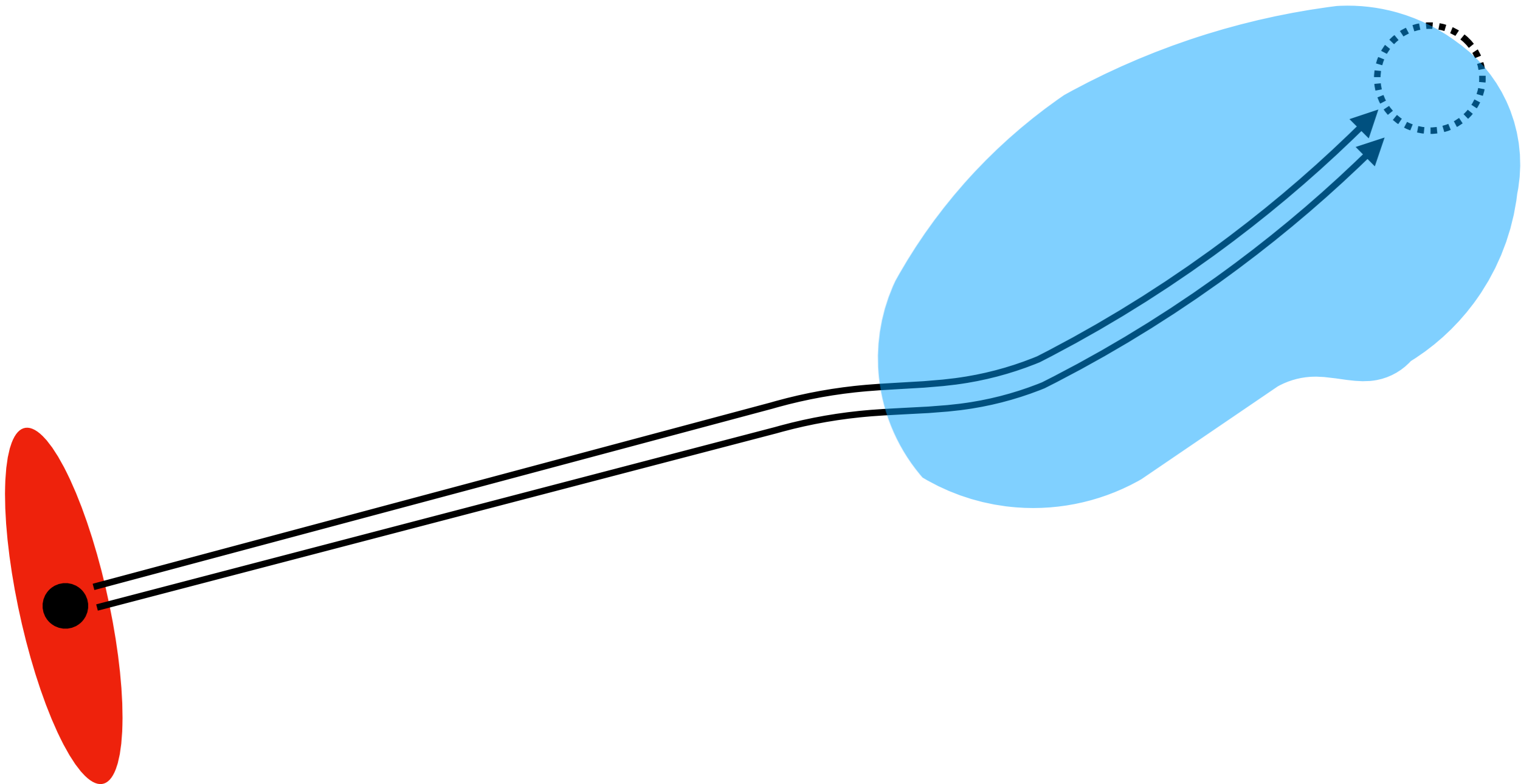
# Spectral Ageing

Jet terminates eventually, strong shock forms at a hotspot.  
Fermi acceleration of electrons at shock.



# Spectral Ageing

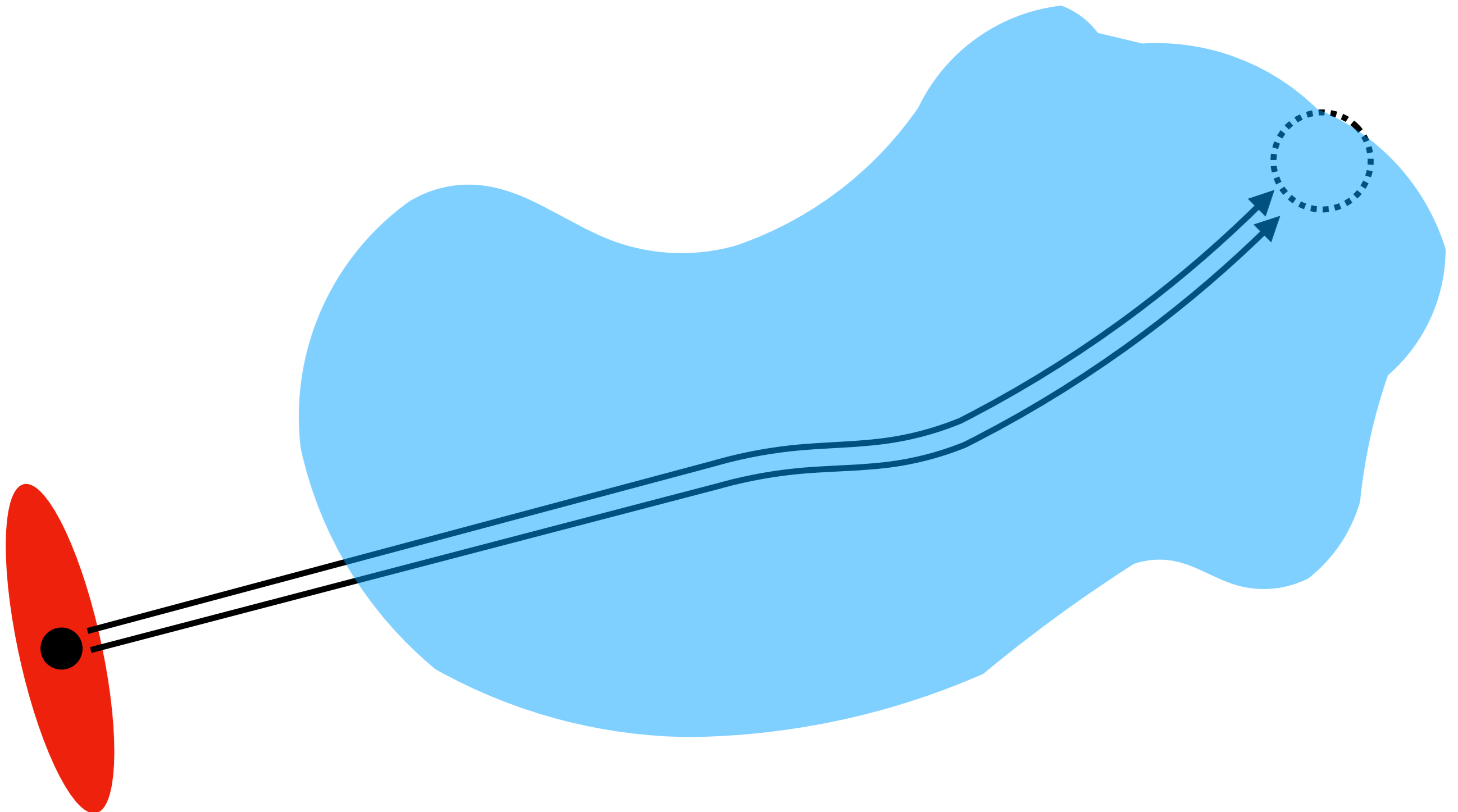
Plasma expands back towards the galaxy.



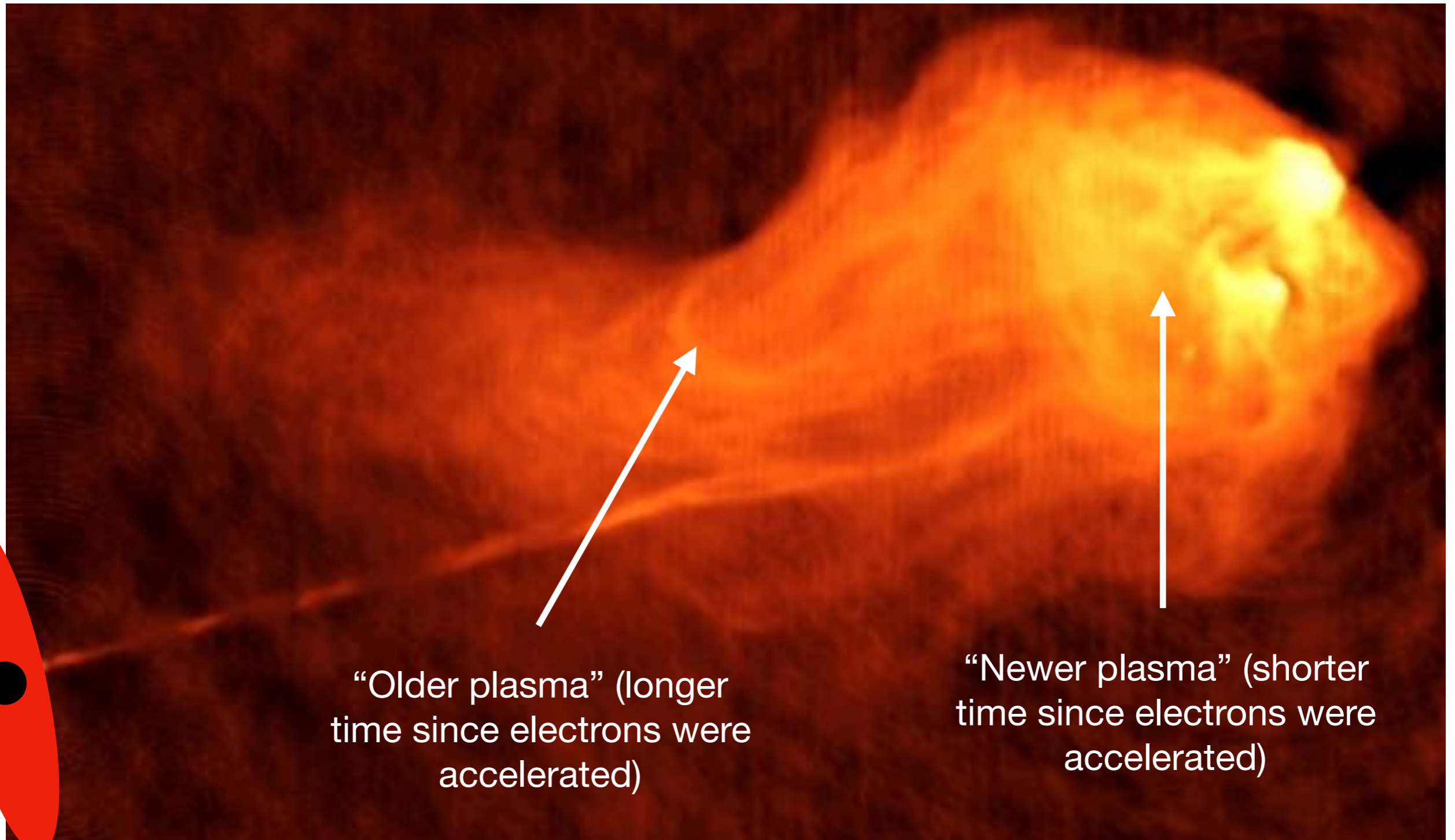


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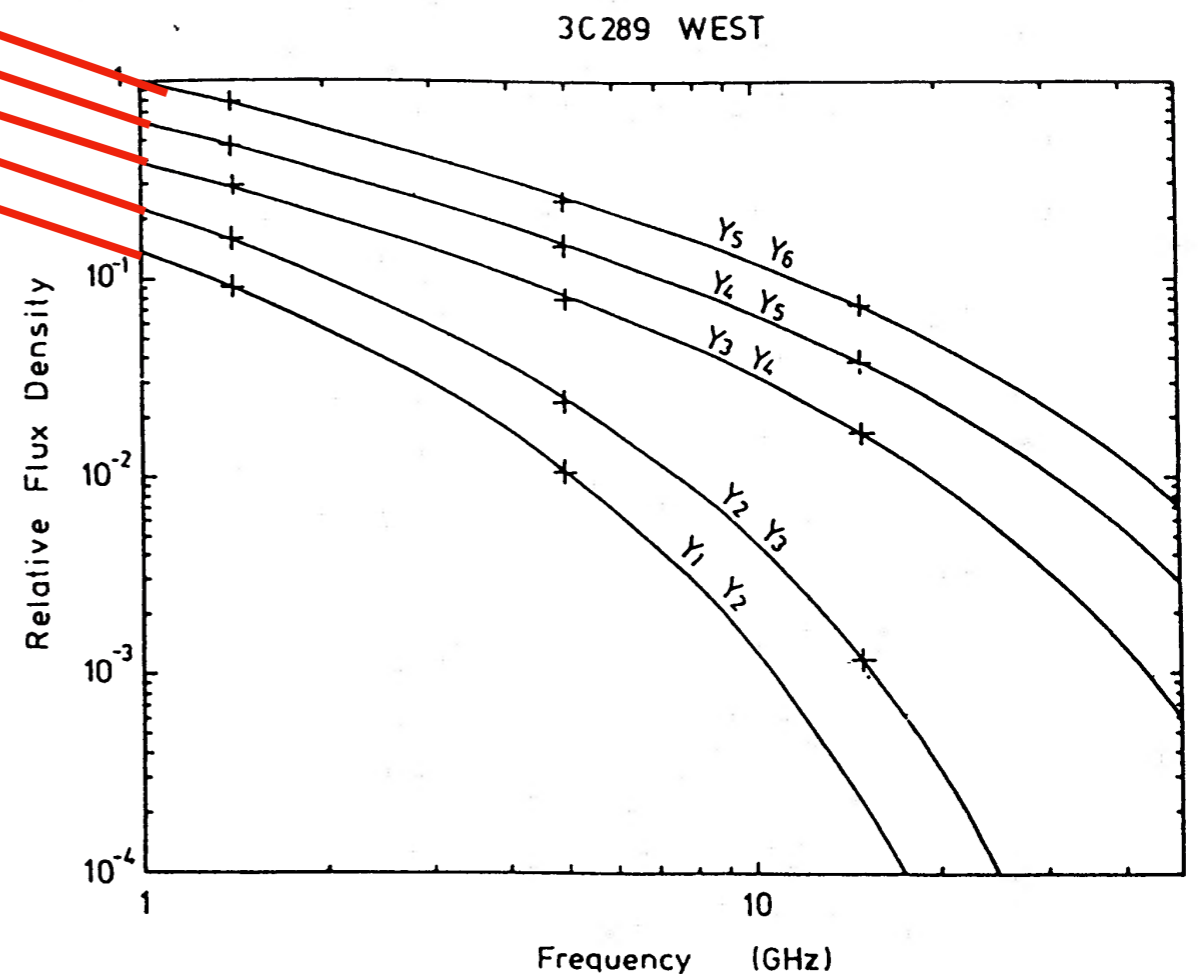
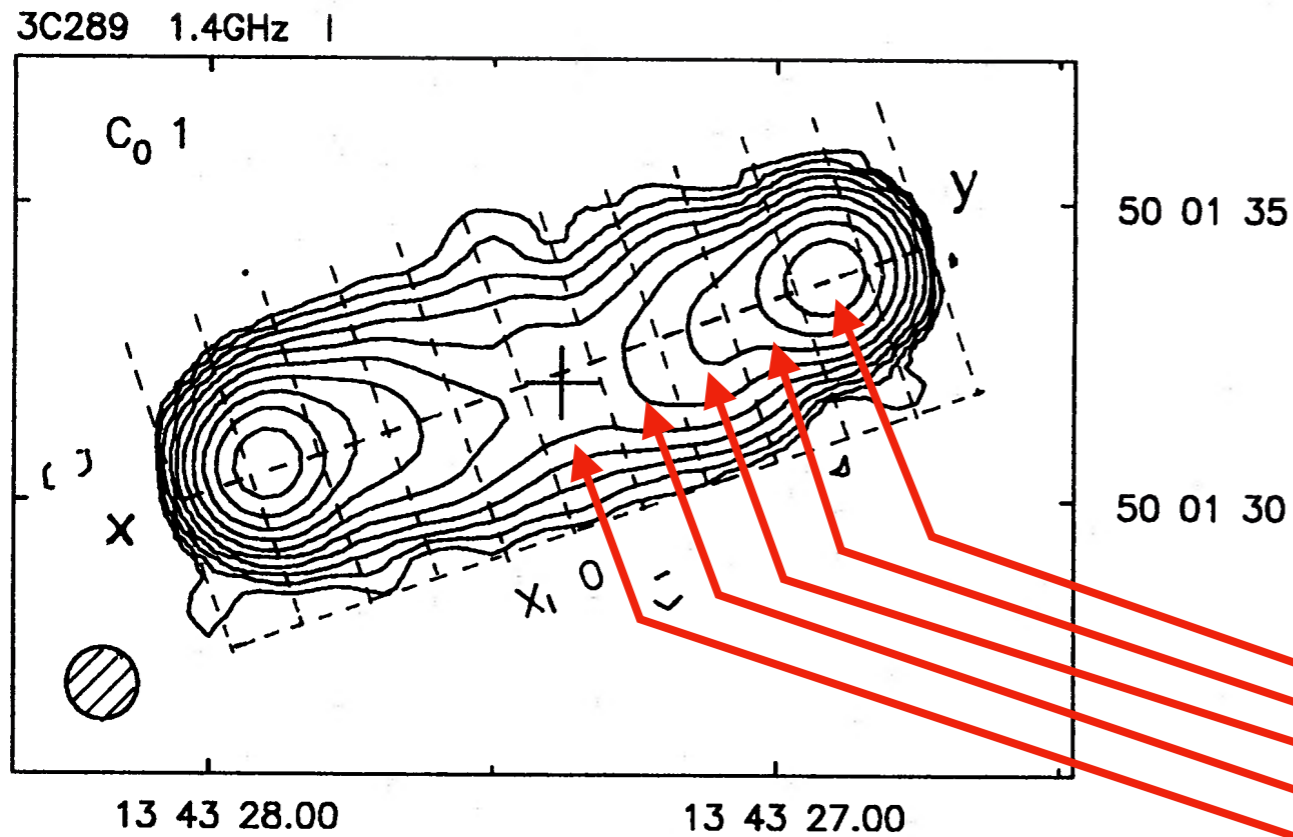
Plasma expands back towards the galaxy.



# Spectral Ageing



# Spectral Ageing



Break frequency really is lower in plasma further from hotspot: this plasma has cooled via synchrotron emission.

# Spectral Ageing

- Estimate magnetic field strength from minimum energy method:

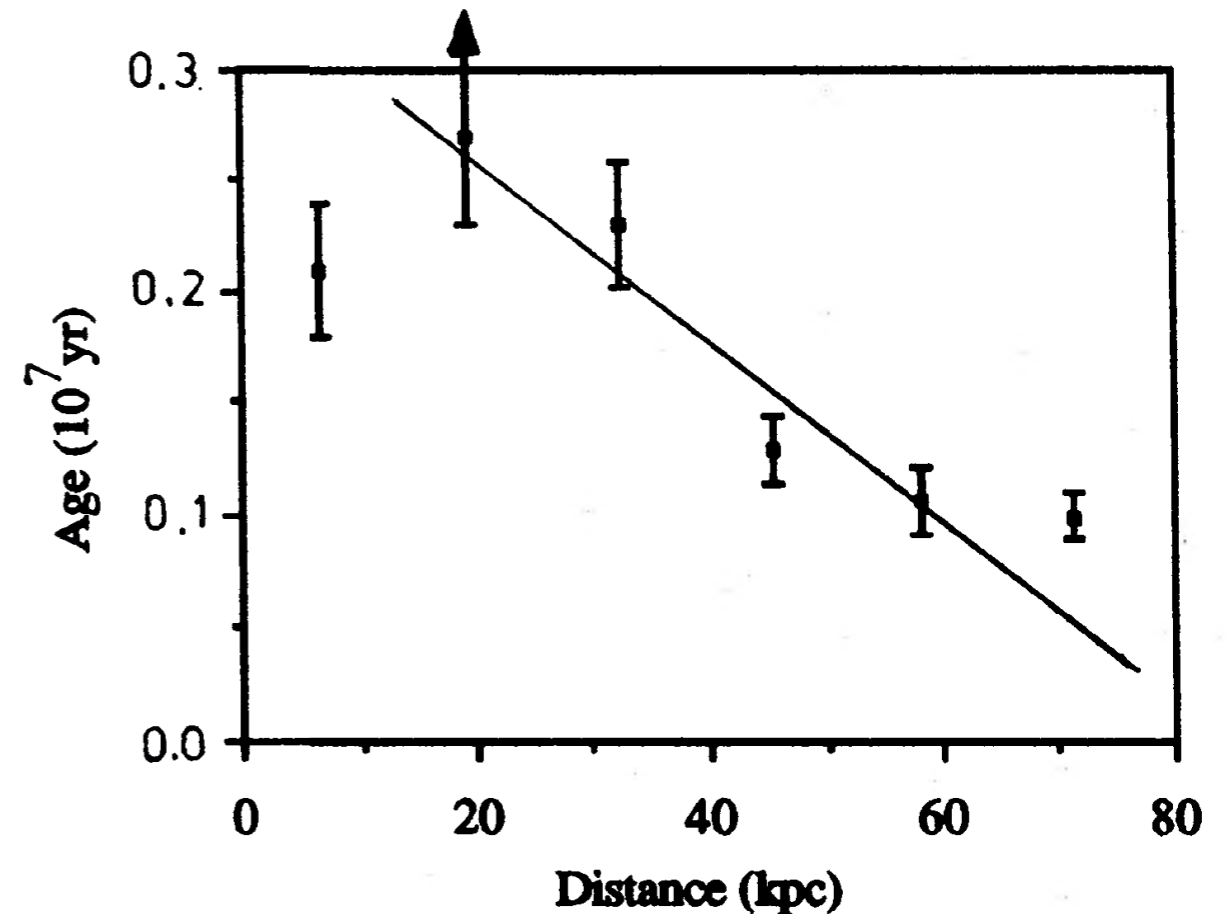
$$\tau \propto B^{-3/2} \nu_{\max}^{-1/2}$$

# Spectral Ageing

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- Plasma typically expands at  $\sim 0.01c$ ; most extreme examples  $\sim 0.1c$ .
- Growth speed  $\sim$ constant throughout lifetime of source.
- Oldest (i.e. largest) sources have ages of  $\sim$ few  $10^8$  years.



# Spectral Ageing

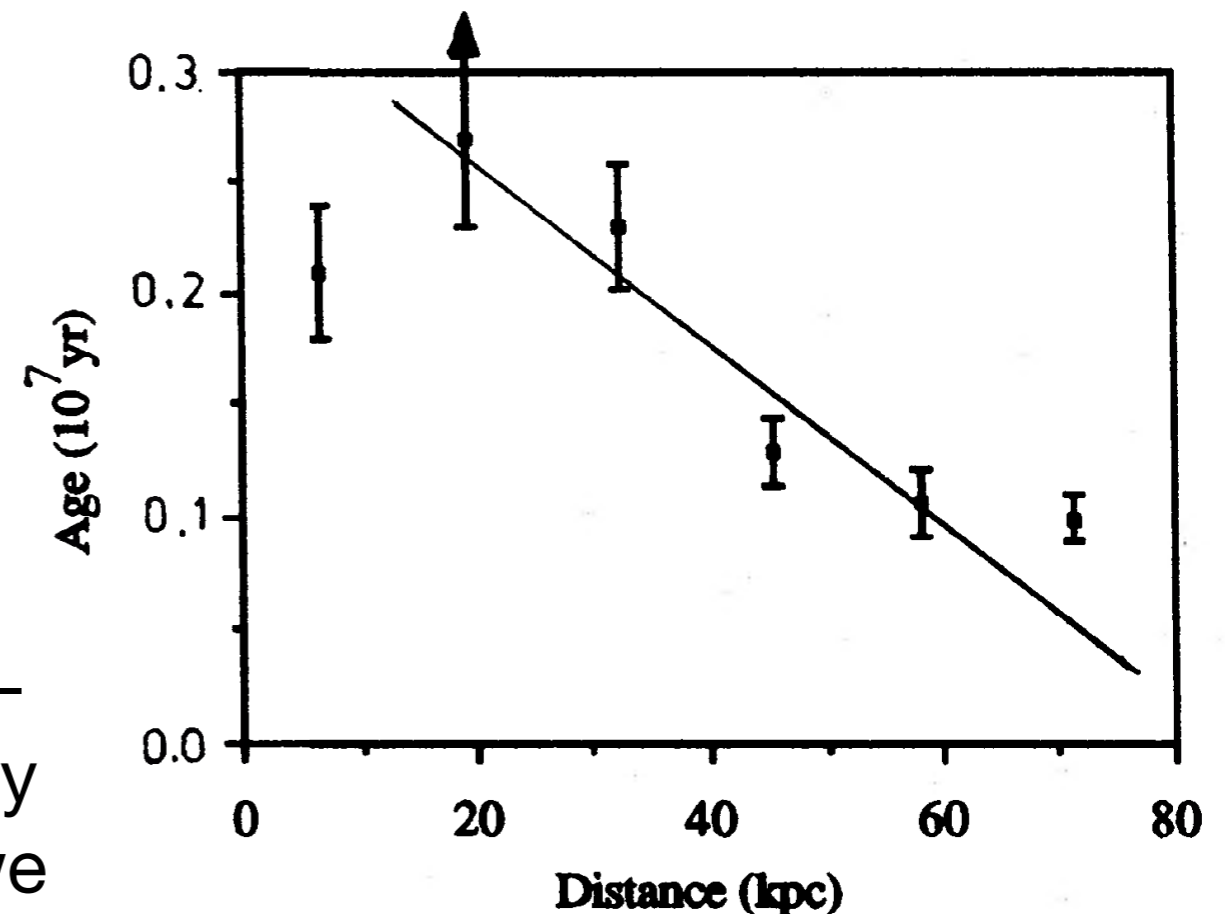
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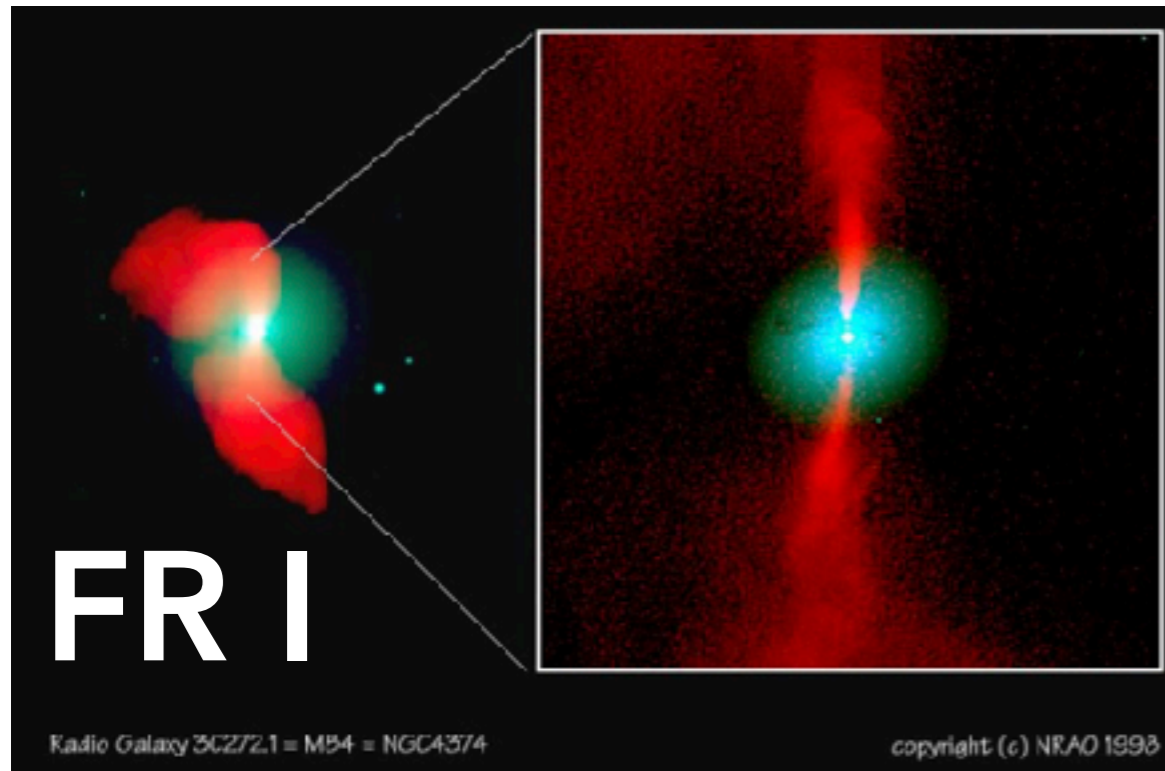
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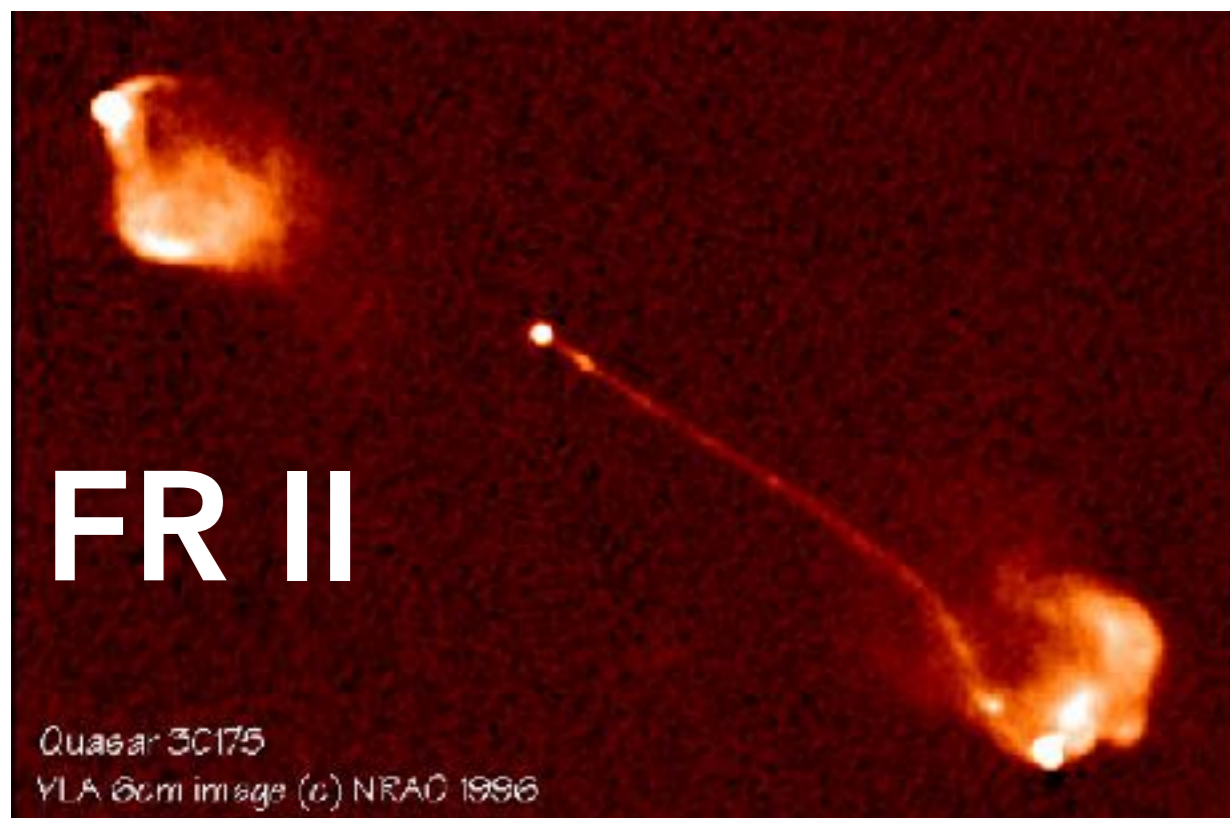
The most powerful radio sources are short-lived (tiny fraction of Hubble time), probably limited to accretion episodes. Given that we see lots of these sources out to high redshift, this is likely a phase that most massive galaxies go through at some point in their lifetime.



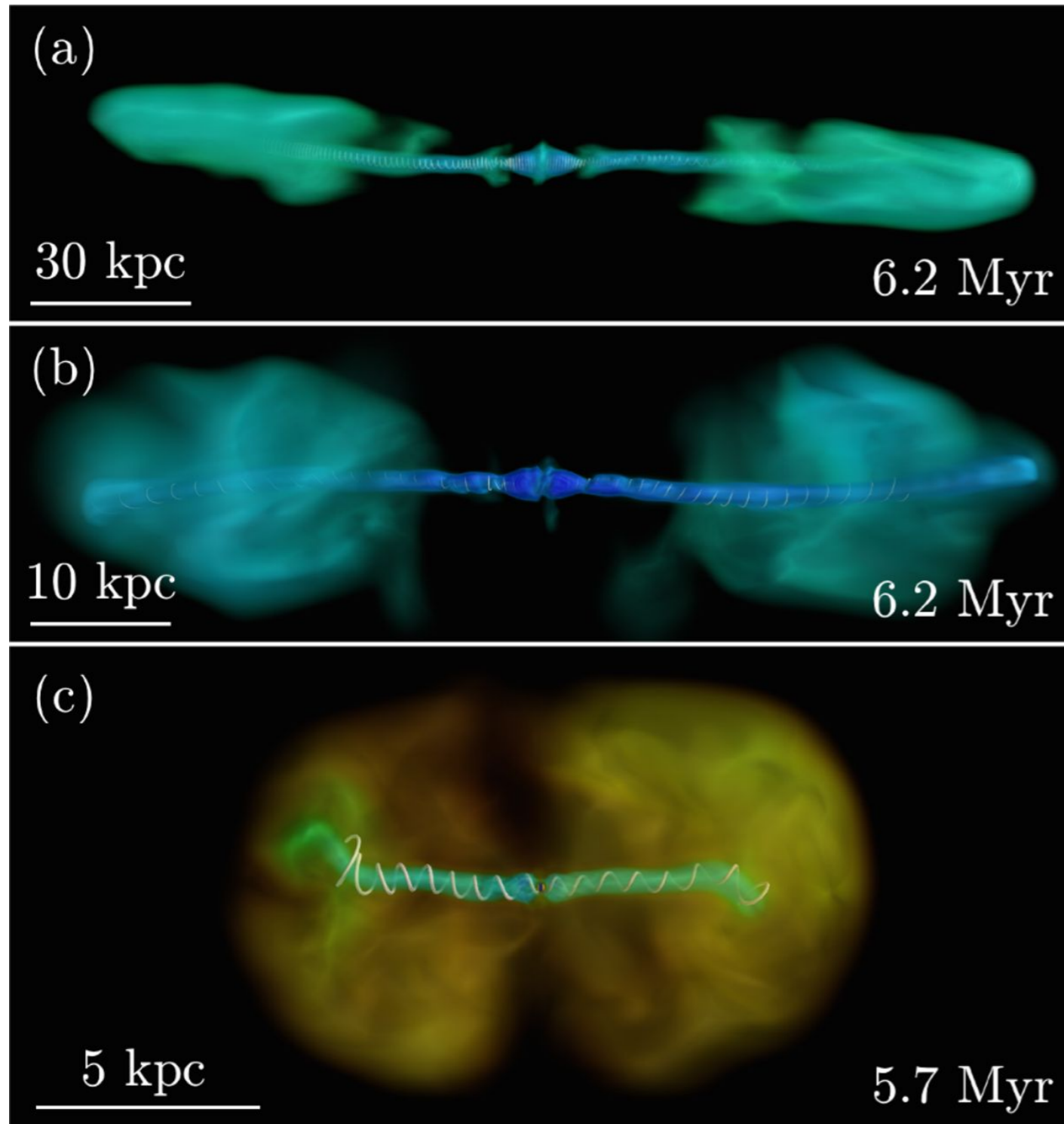
# Weaker sources



- Only the most powerful sources have bright lobes ~tens of kpc away from galaxy (bottom).
- Farenhoff & Riley (1974) noted that weaker sources have more centrally peaked morphology (top).
- They introduced the FRI, FRII classification.
- Spectral ageing can't be used on FRI sources — plasma is gently “blowing away” from the host.
- We therefore have no idea of the age of FRI sources.



# FRI - FR II Dichotomy



- Makes sense that weaker jets cannot punch as far into the IGM.
- Difference in jet power due to magnetic field strength? Black hole spin?
- Different environment?
- Or are FRI sources remnants of FR II sources whose jets have powered down?

Simulations of Tchekhovskoy & Bromberg (2016)

movie at: <https://youtu.be/ErmoekAk8MvA>