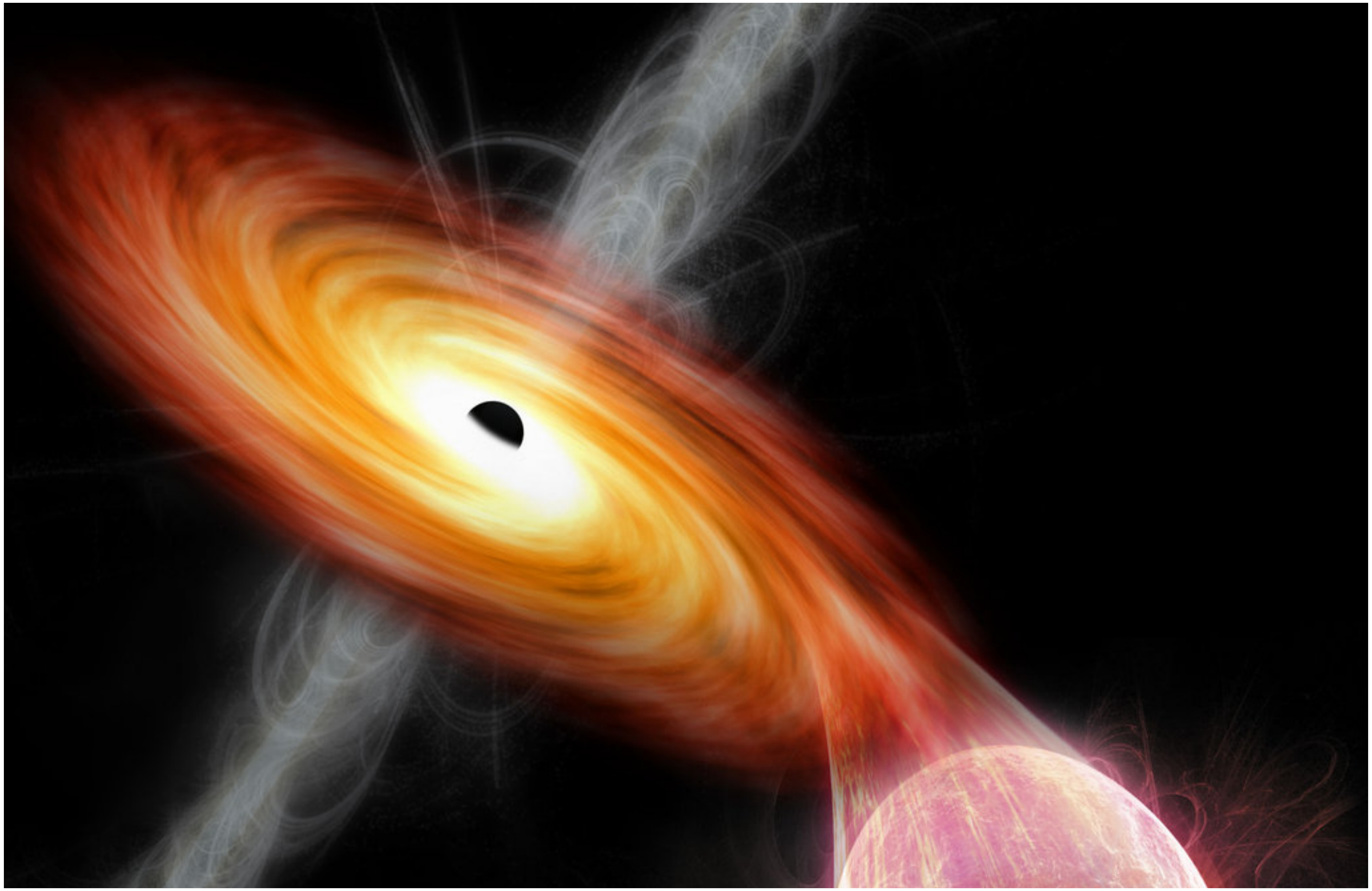
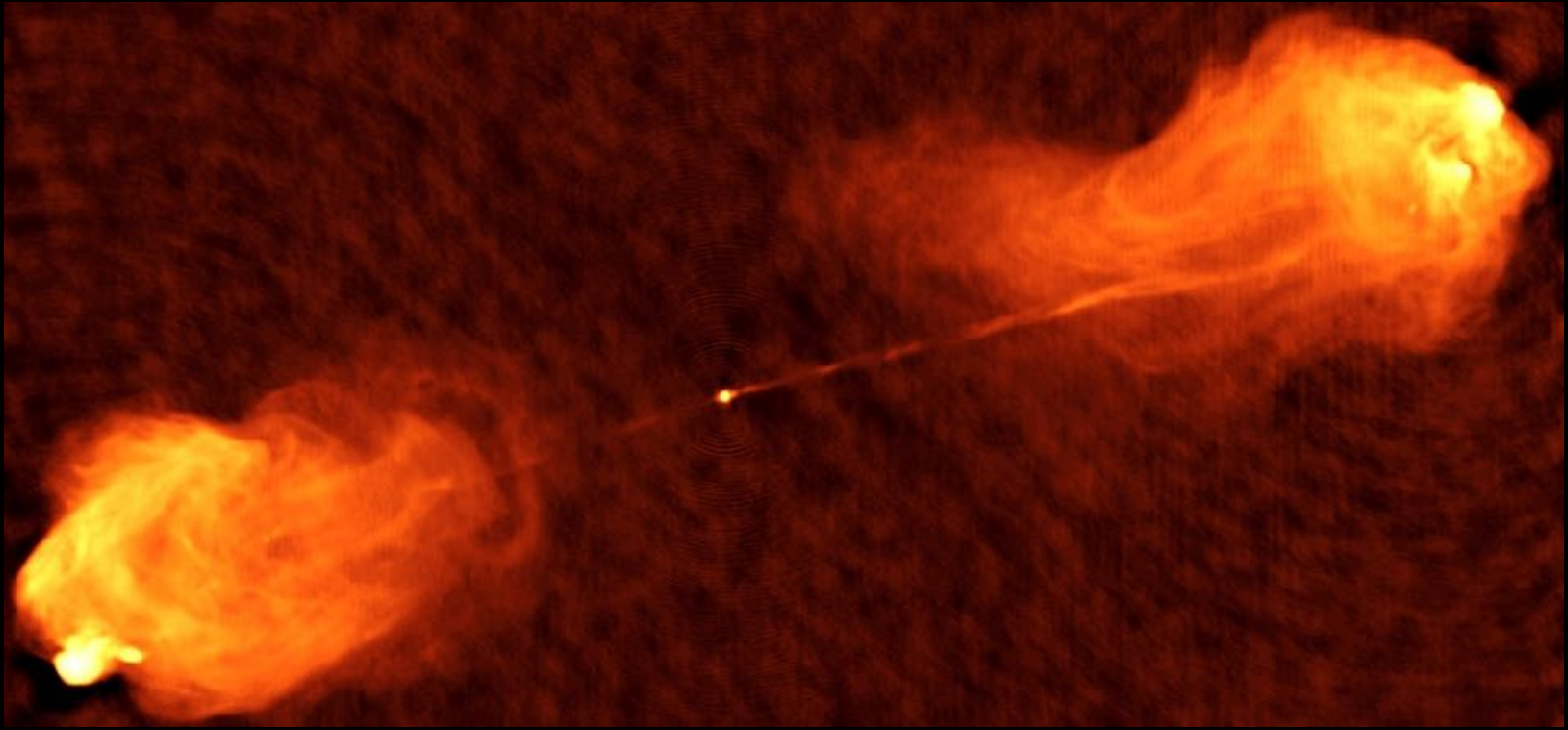
High Energy Astrophysics

Dr. Adam Ingram



Lecture 4

Synchrotron Radiation

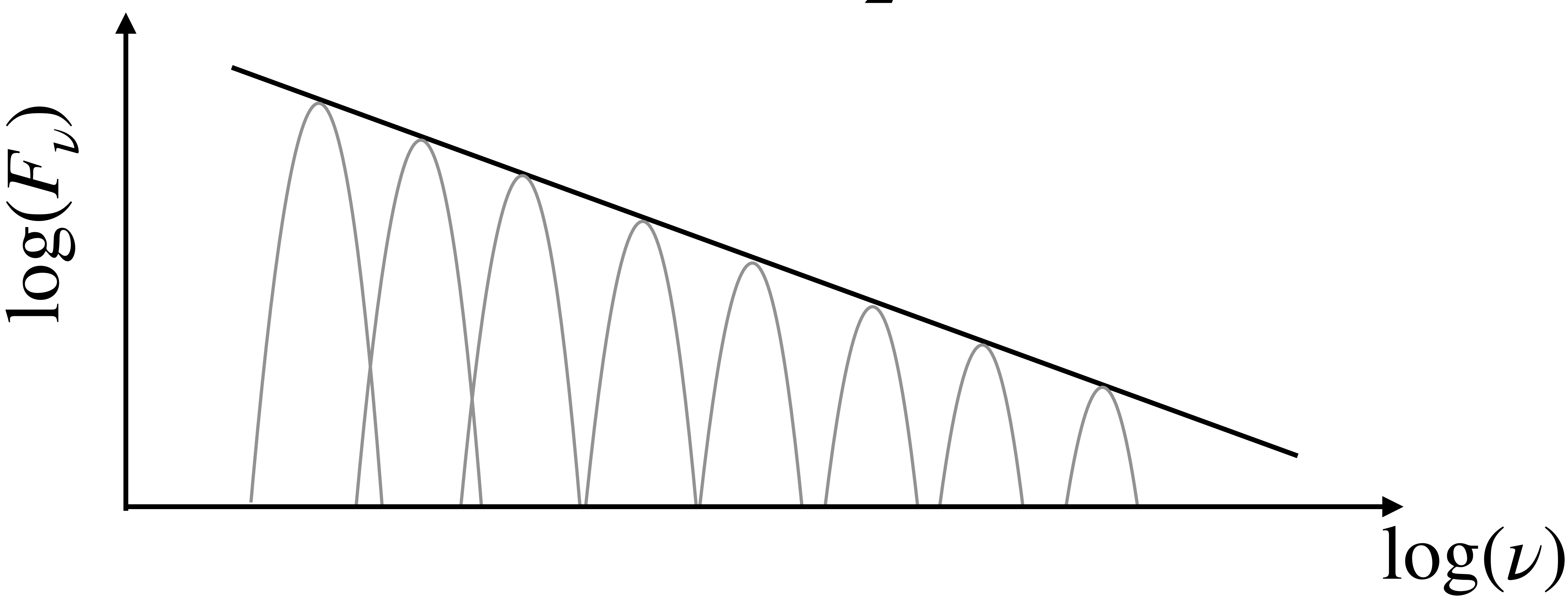


Last Time

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

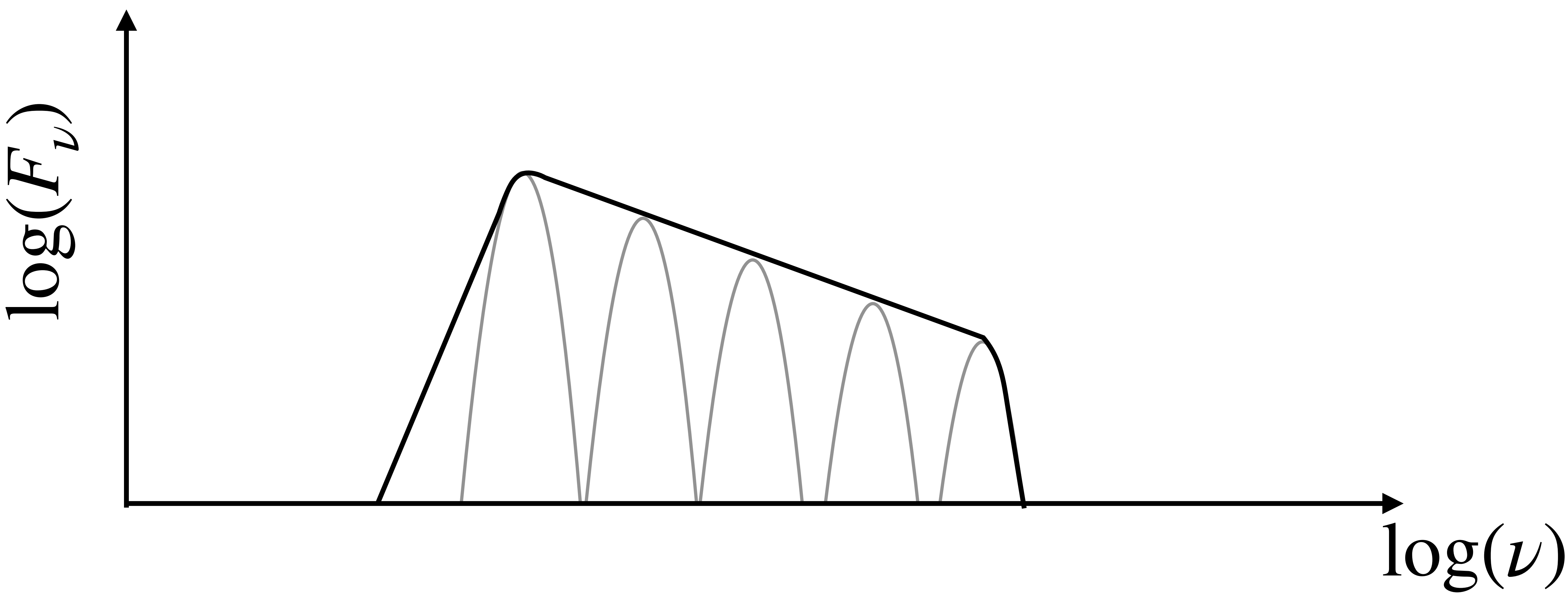
$$\frac{dN}{d\gamma} \propto \gamma^{-k} \qquad \nu_c \approx \gamma^2 \frac{eB}{m}$$

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



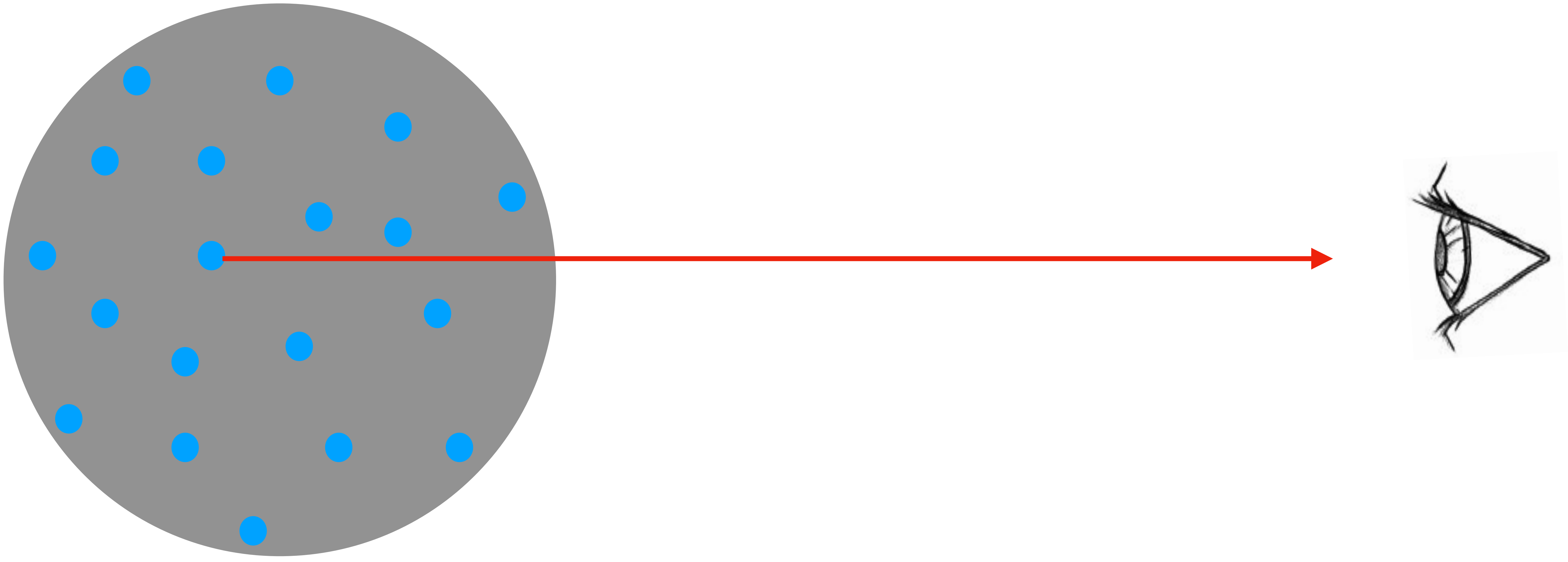
This Time

- Spectrum of synchrotron radiation: power-law because the electron energy distribution is a power-law.
- We will understand why synchrotron spectra really show low and high frequency breaks.



Self-absorption

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



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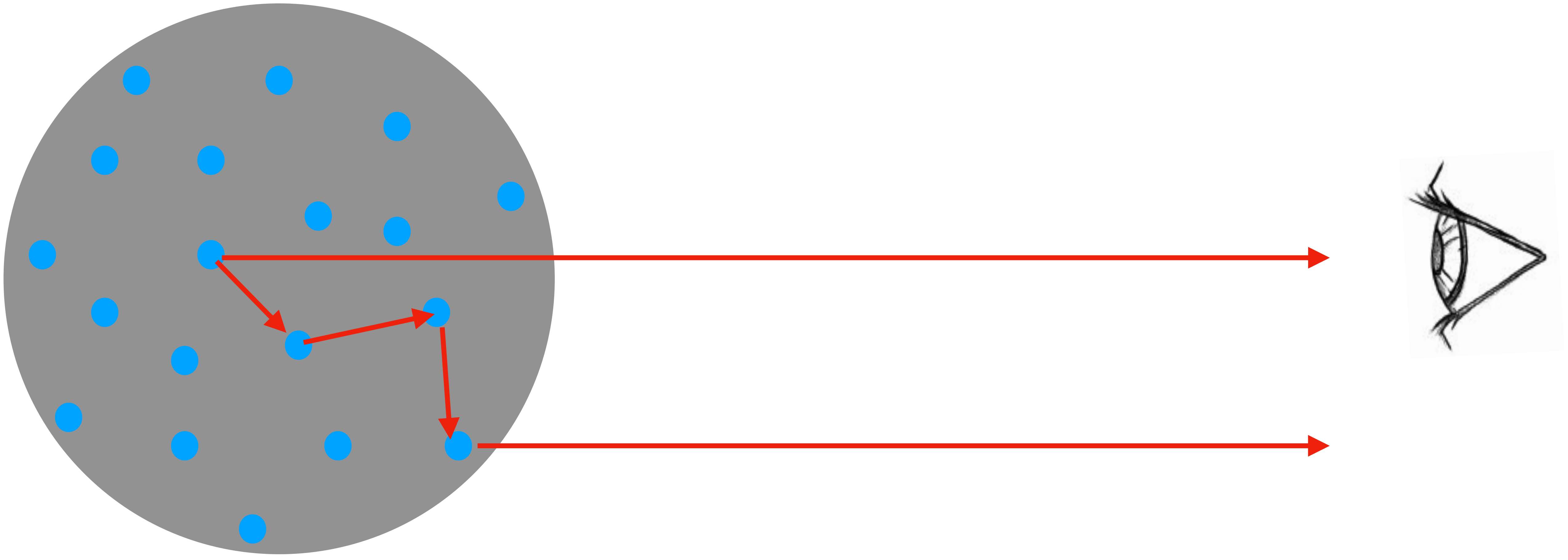

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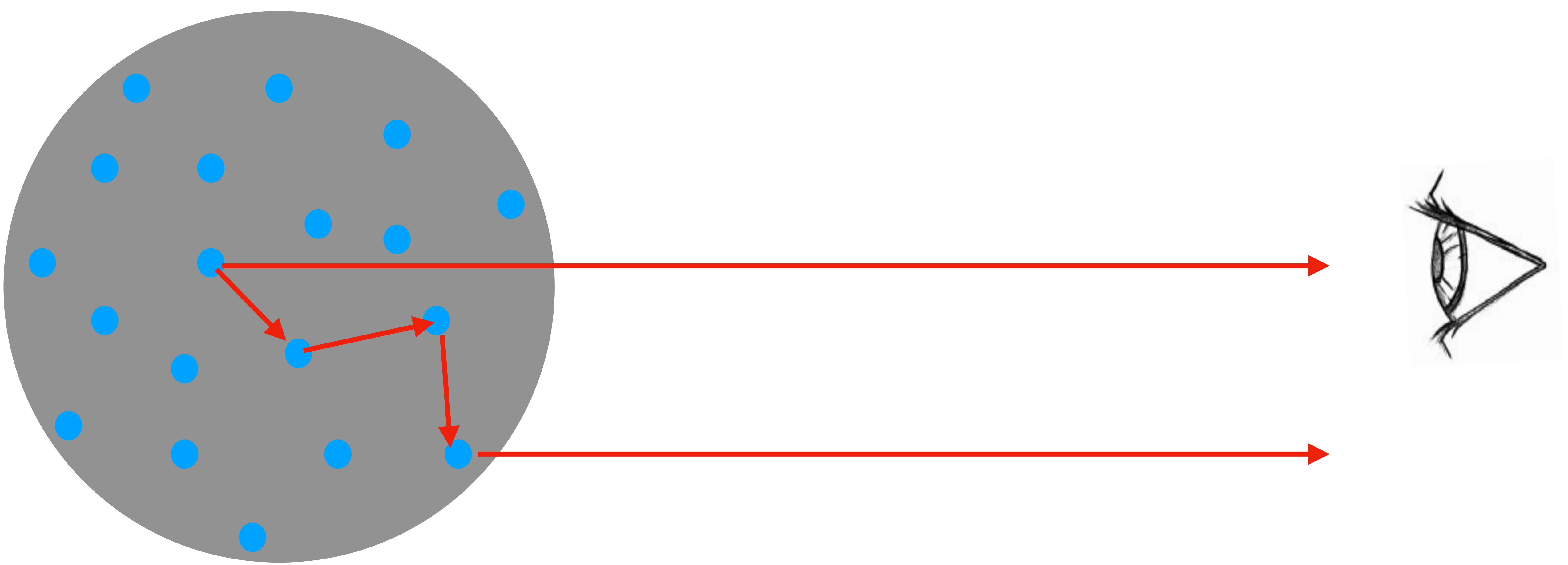

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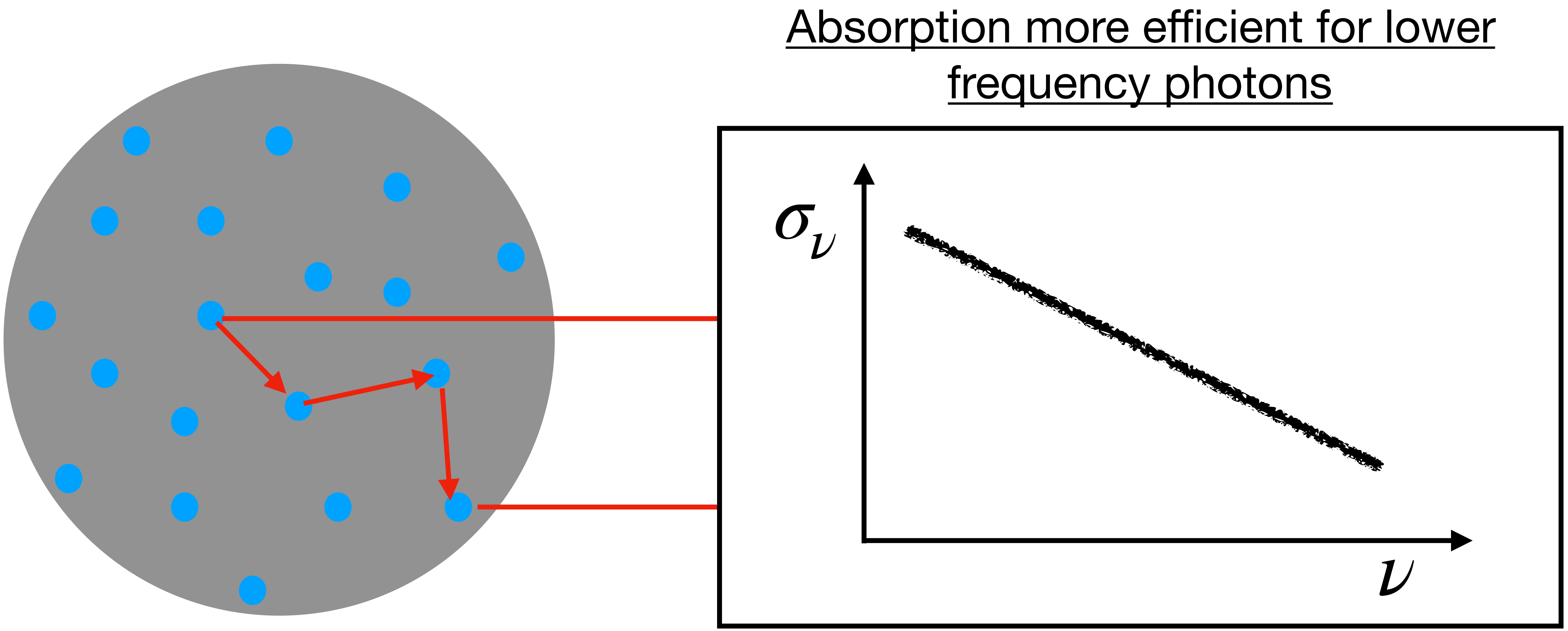
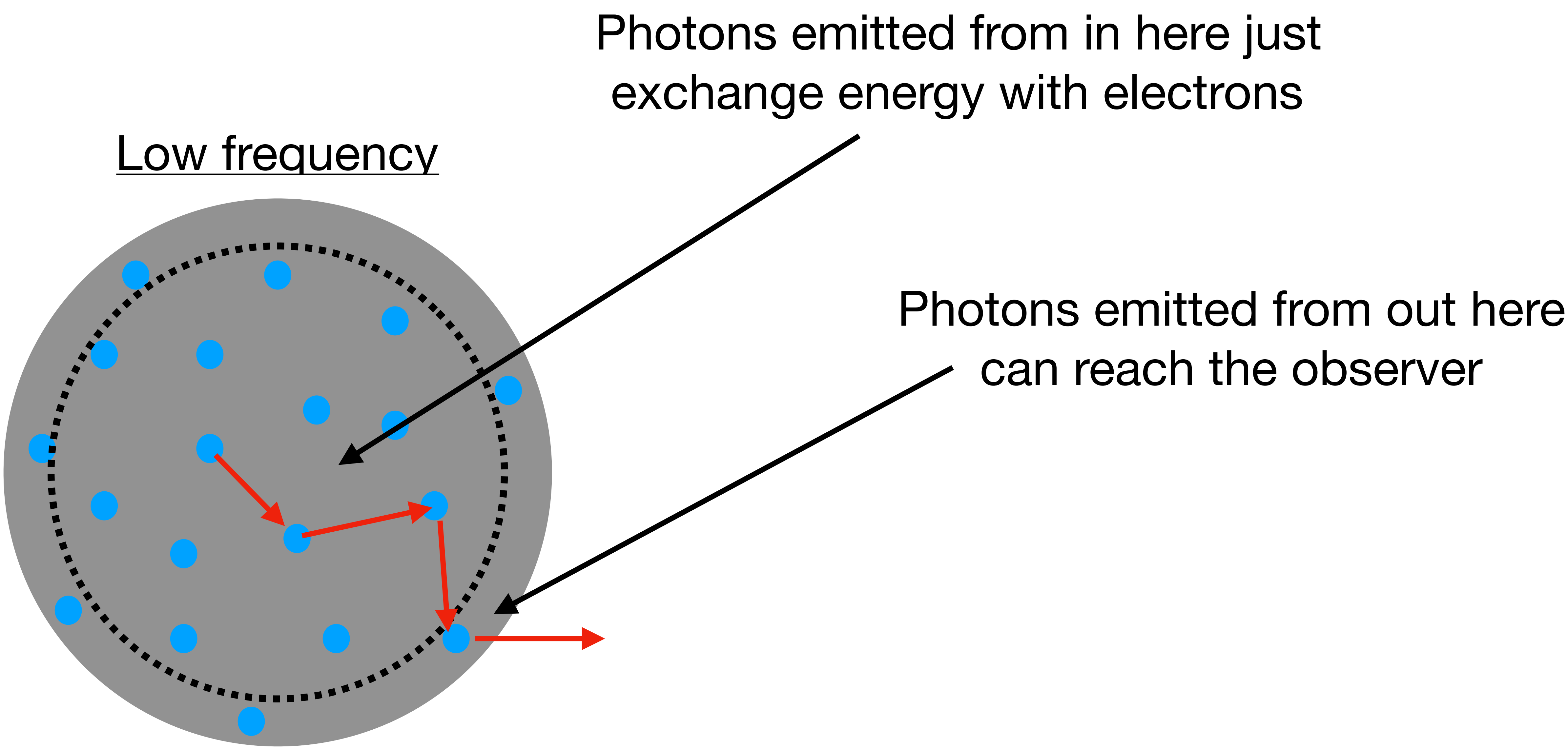


Self-absorption

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



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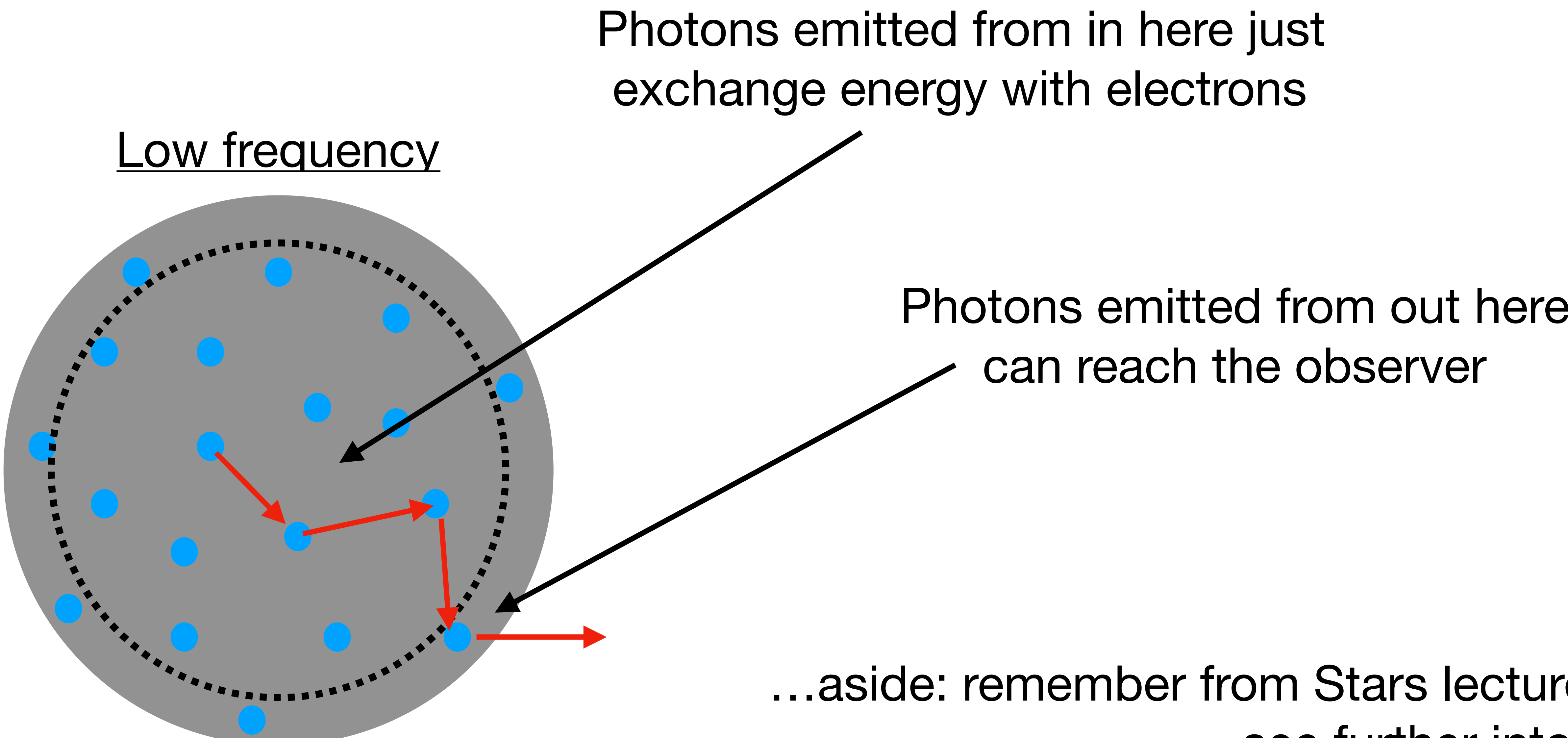

…aside: remember from Stars lecture that we see further into the core

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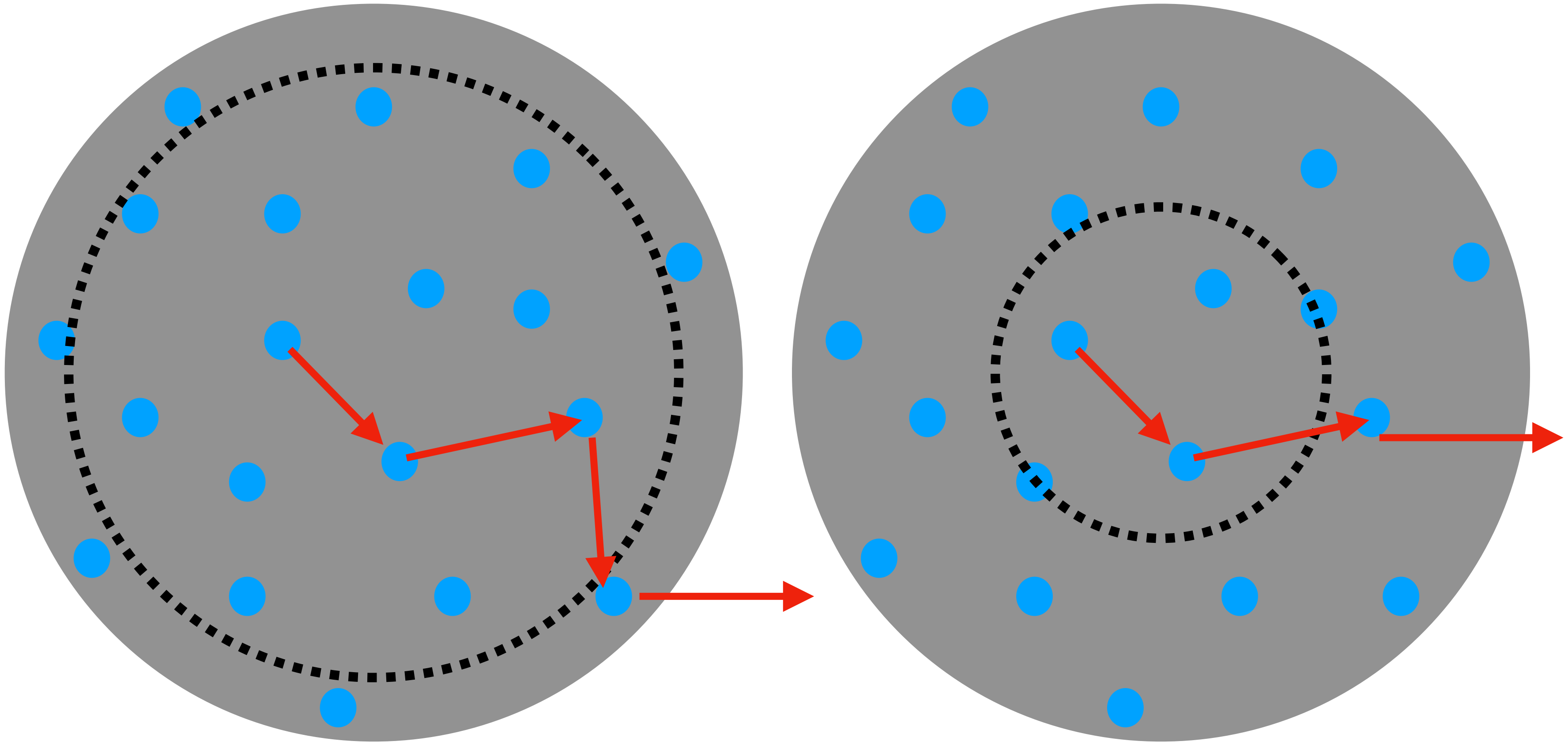
Low frequency Intermediate frequency



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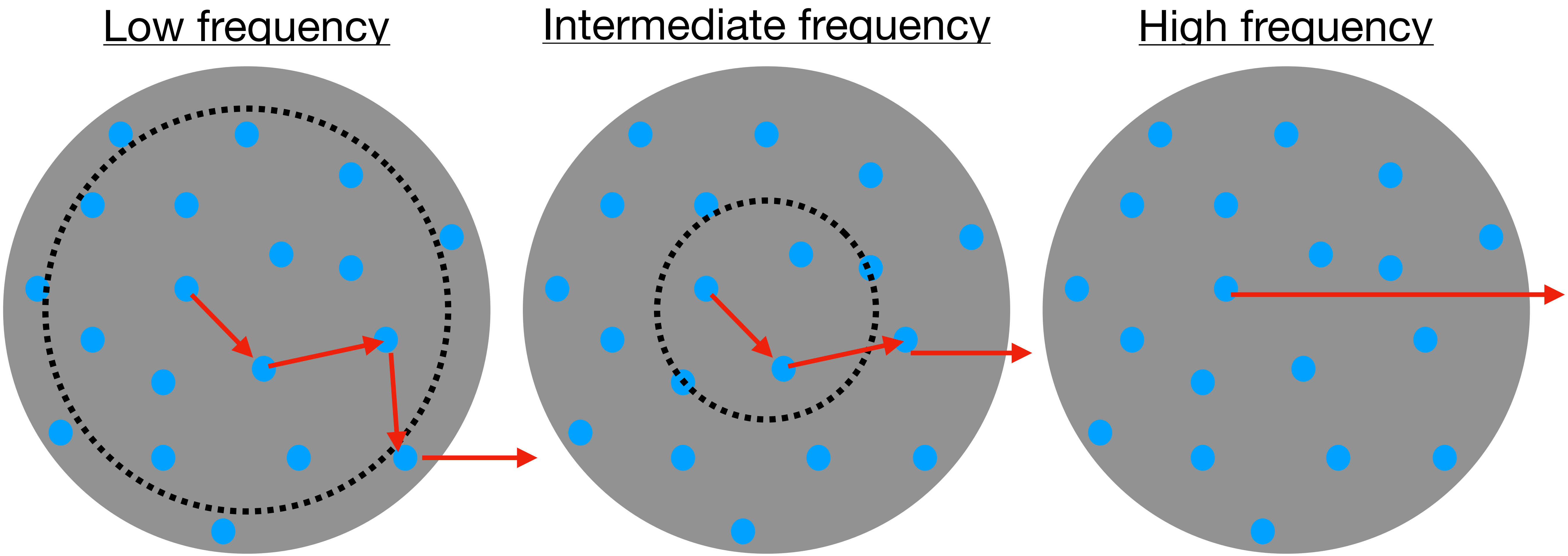
- The highest frequency photons can stream through the whole cloud: so we just see the synchrotron power-law for the highest frequencies.



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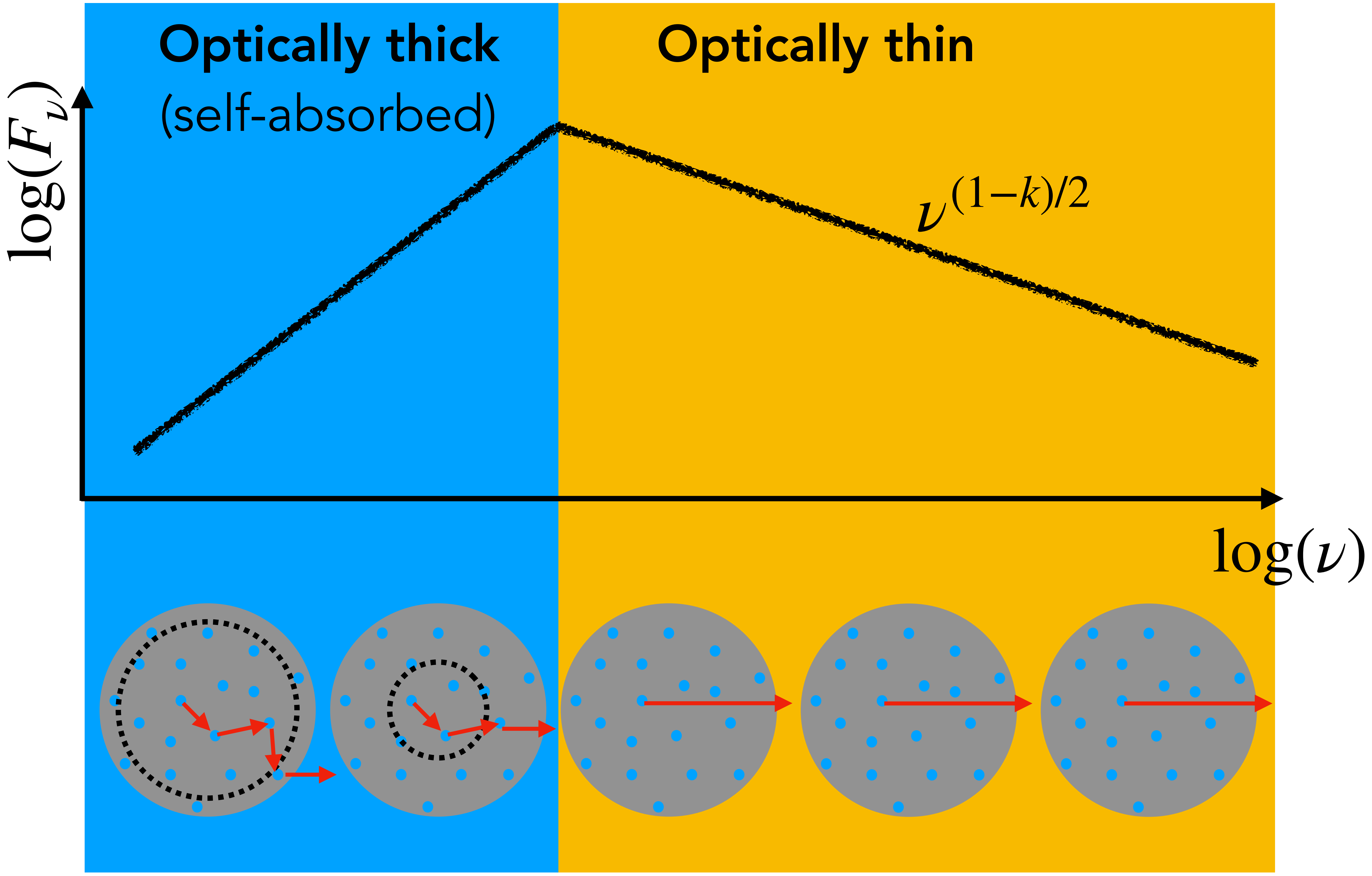

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$$kT_{\text{eff}} \propto \nu^{1/2} \qquad \implies \qquad \boxed{I_\nu \propto \nu^{5/2}}$$

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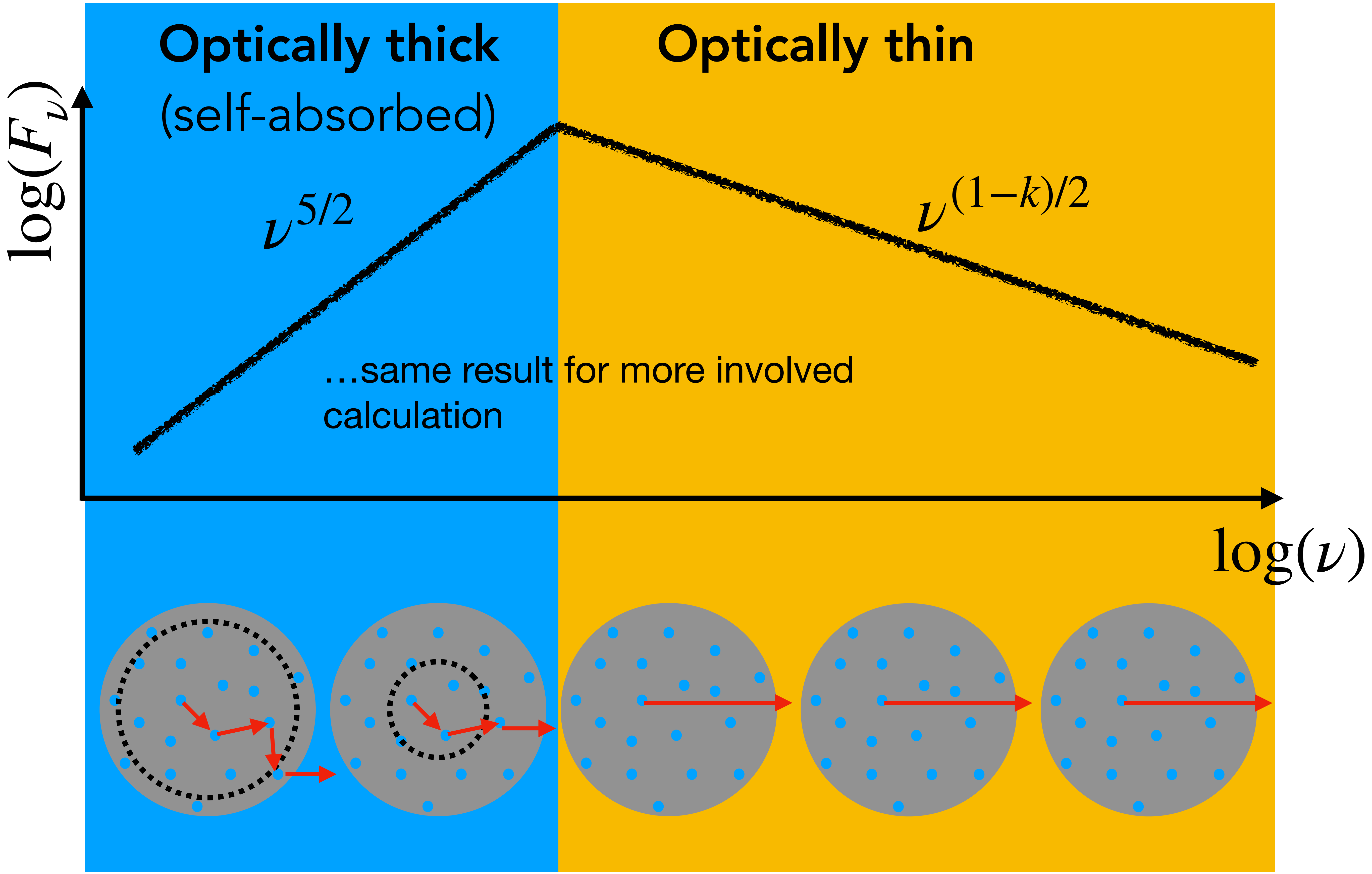


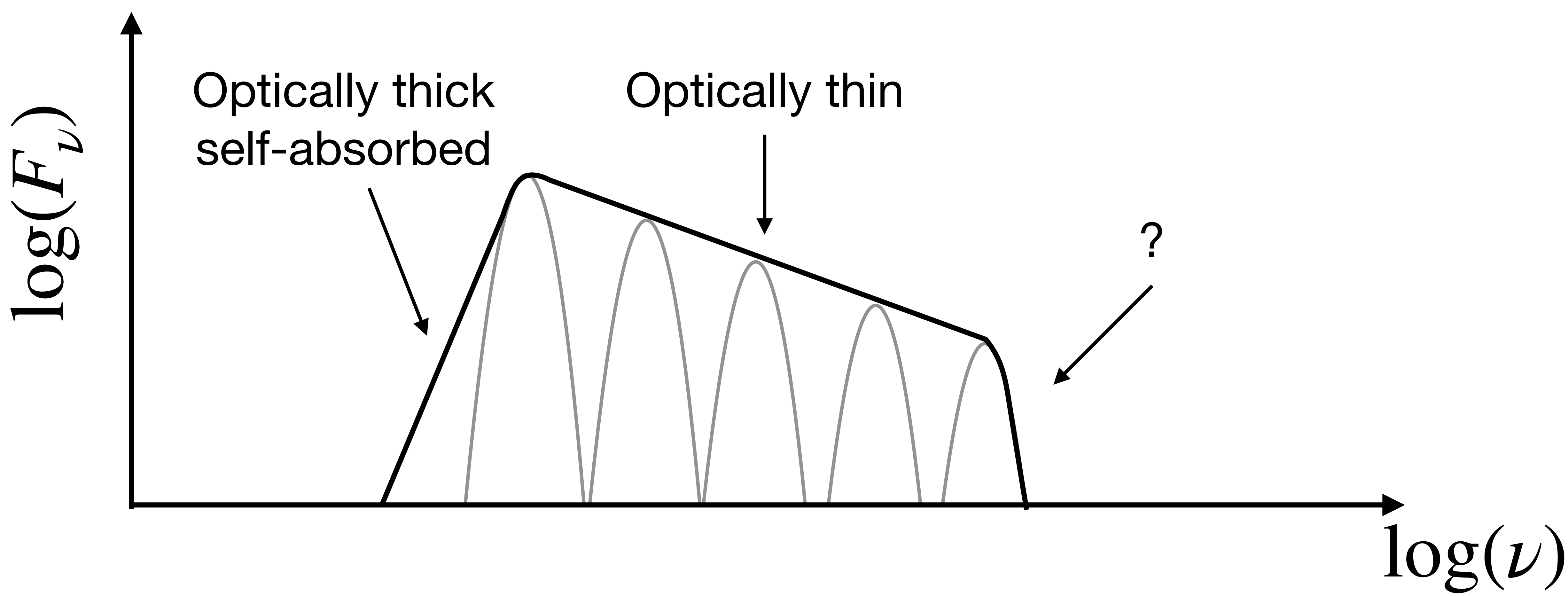
High frequency cut-off

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

$$r_g = \frac{\gamma m v}{eB}$$

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~10^{15} eV in supernova remnants and E~10^{20} eV in AGN (thus the highest energy cosmic rays thought to be from AGN)



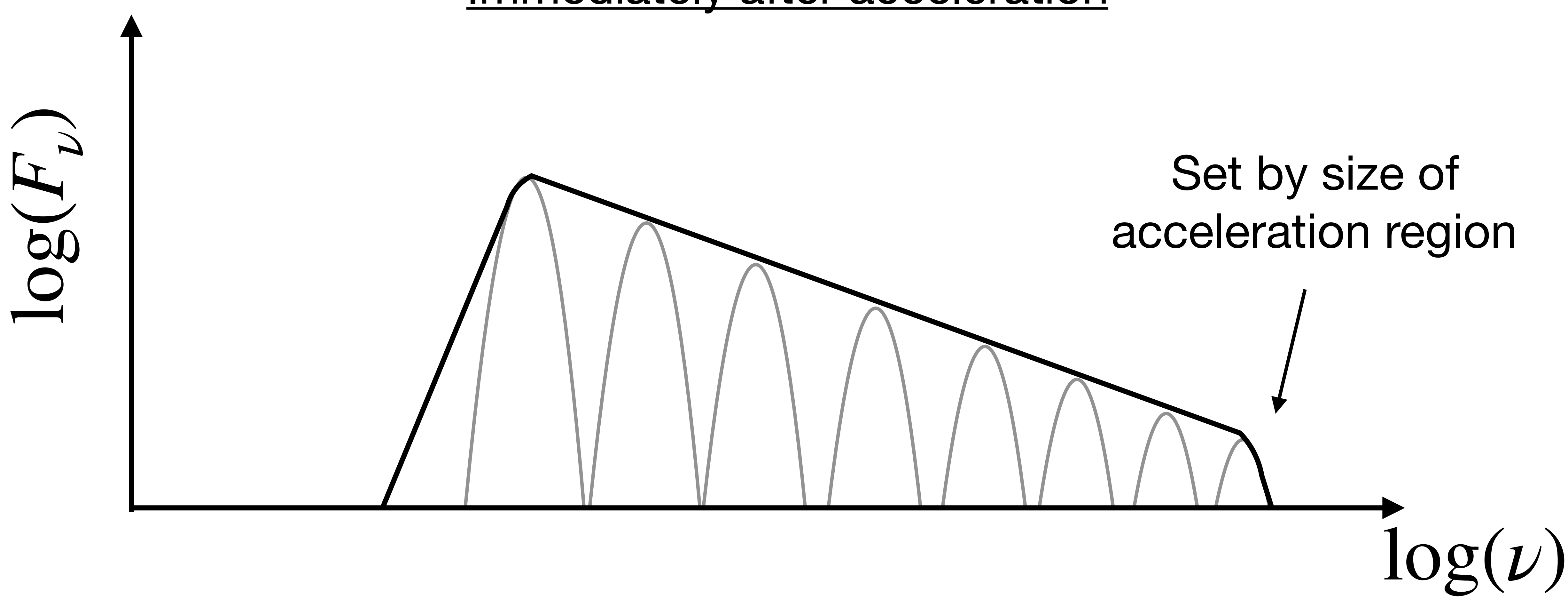
High frequency cut-off

- 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!

Immediately after acceleration



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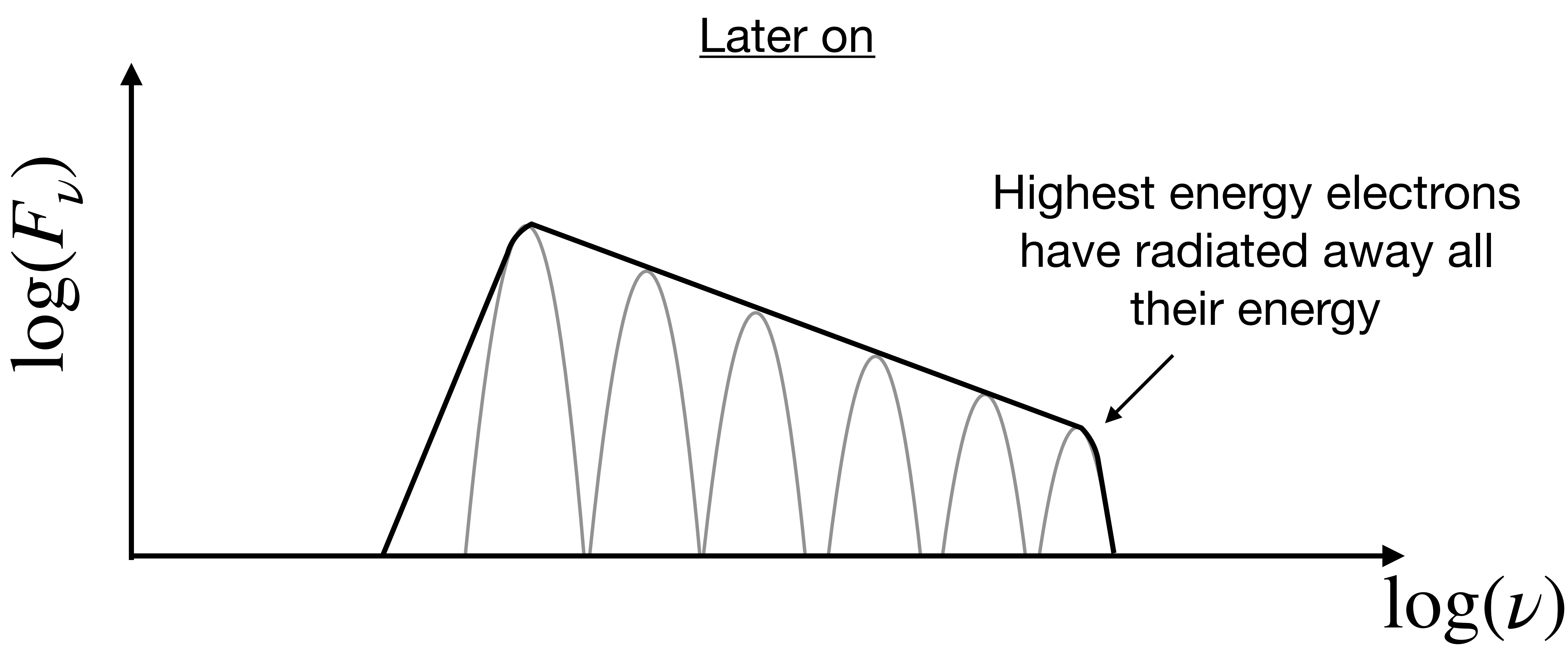

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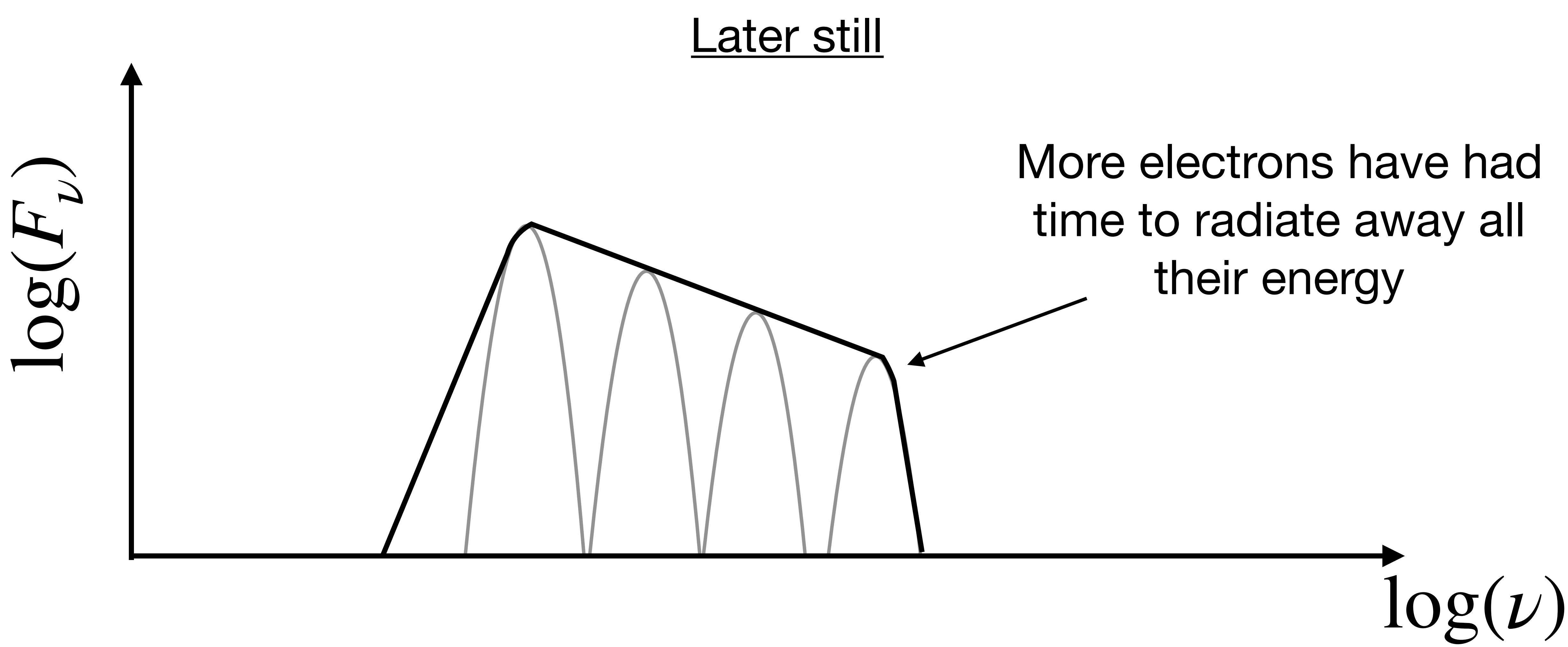
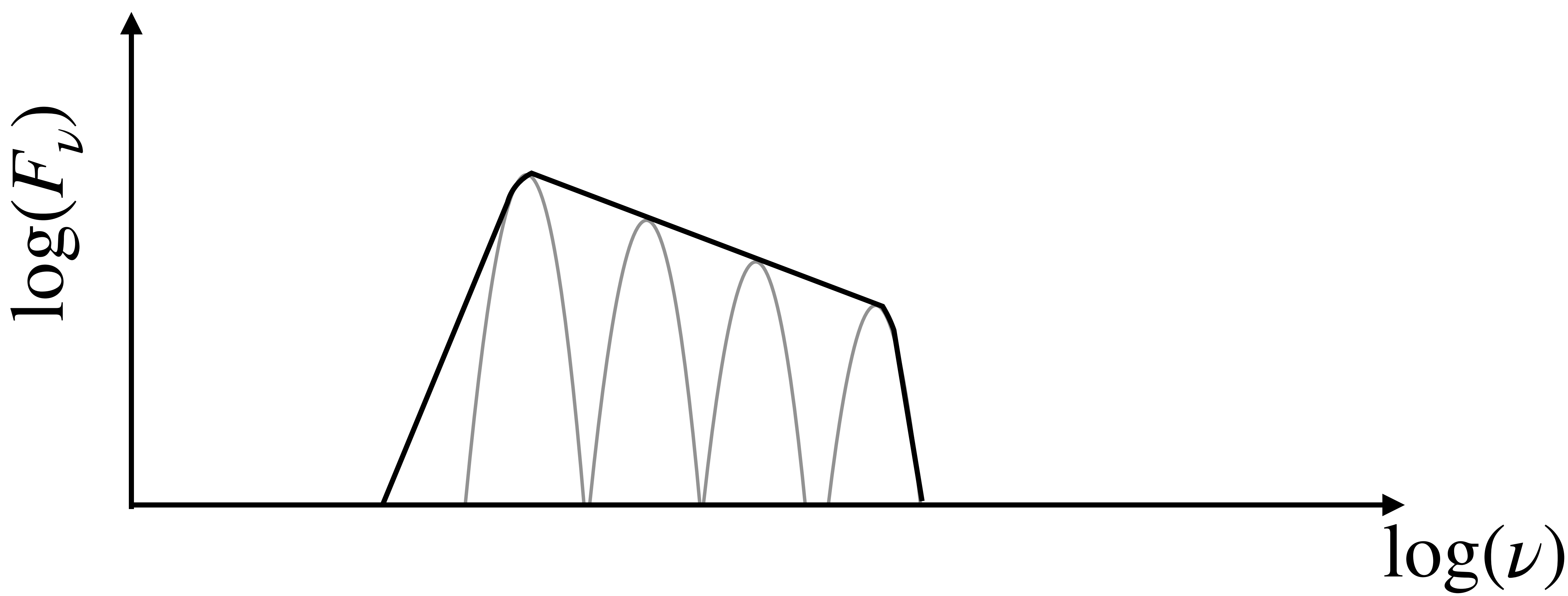


High frequency cut-off

- Timescale to radiate away all energy:

$$\tau = \frac{E}{dE/dt}$$



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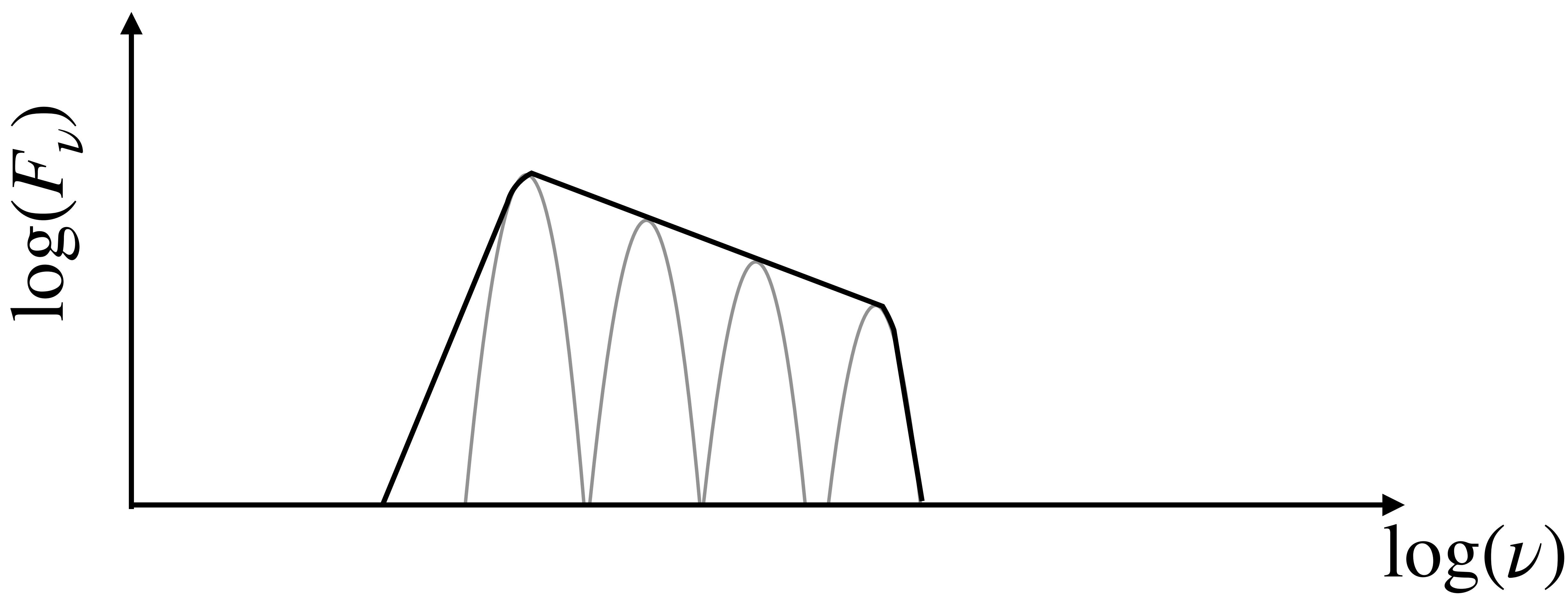

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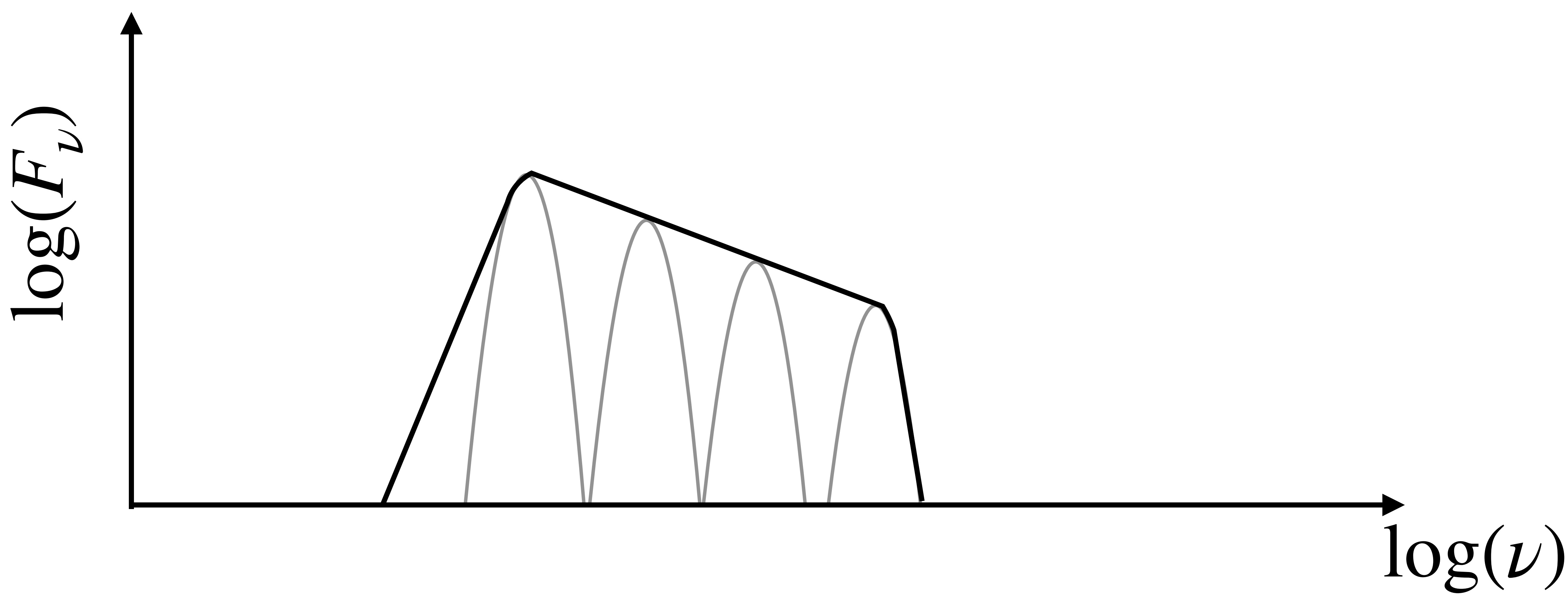

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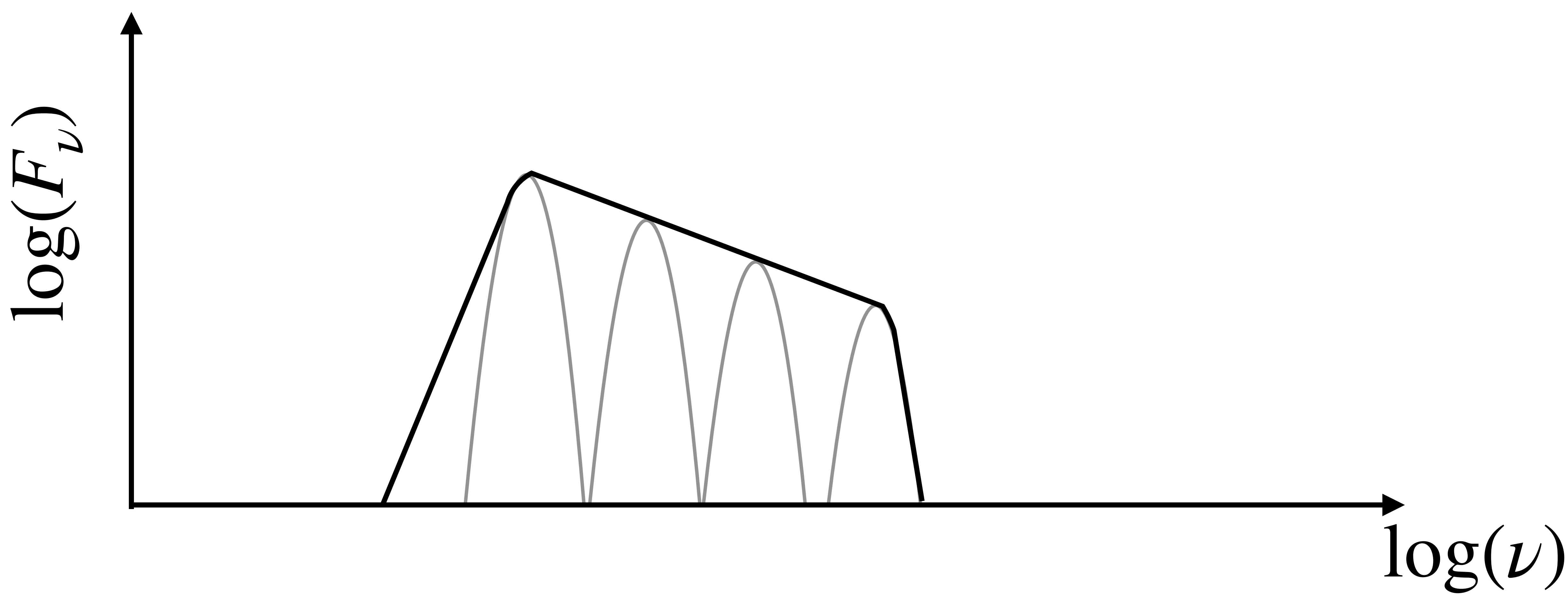

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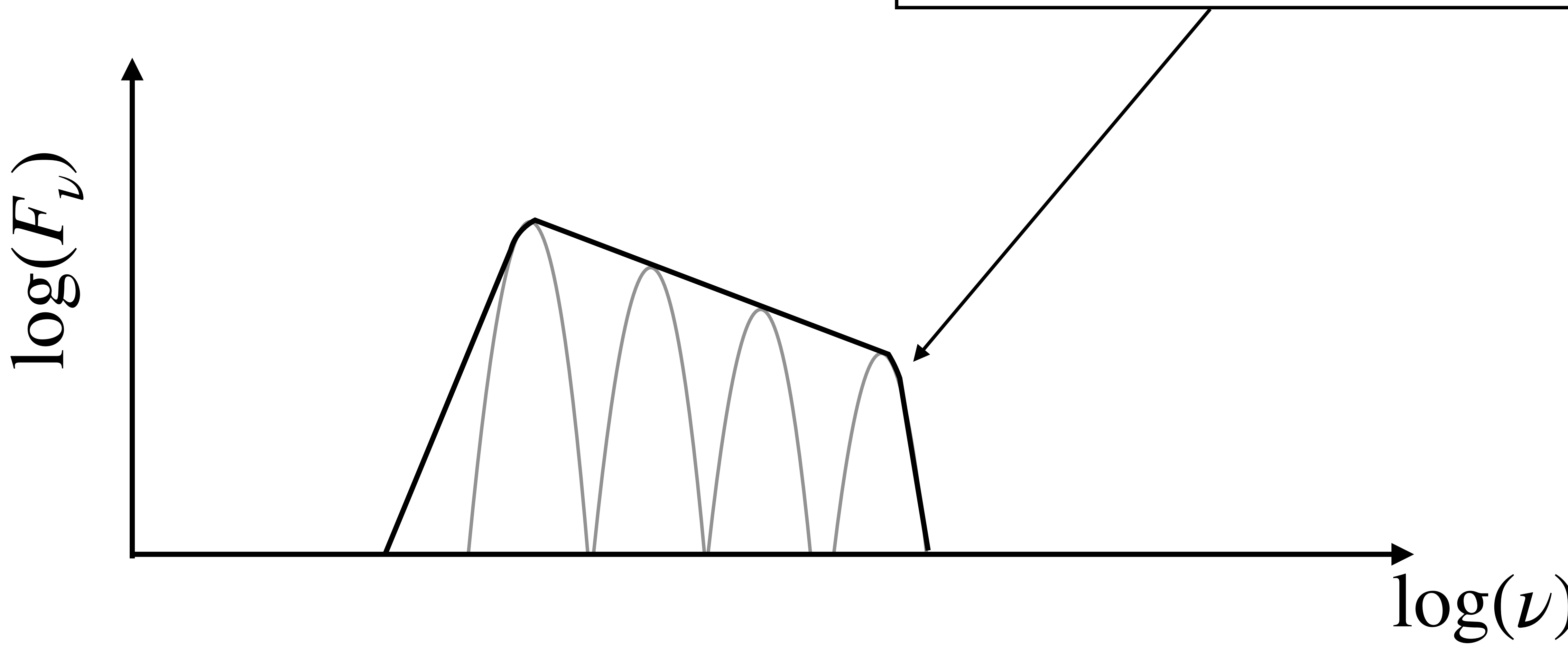
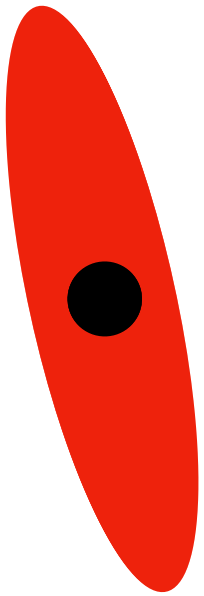


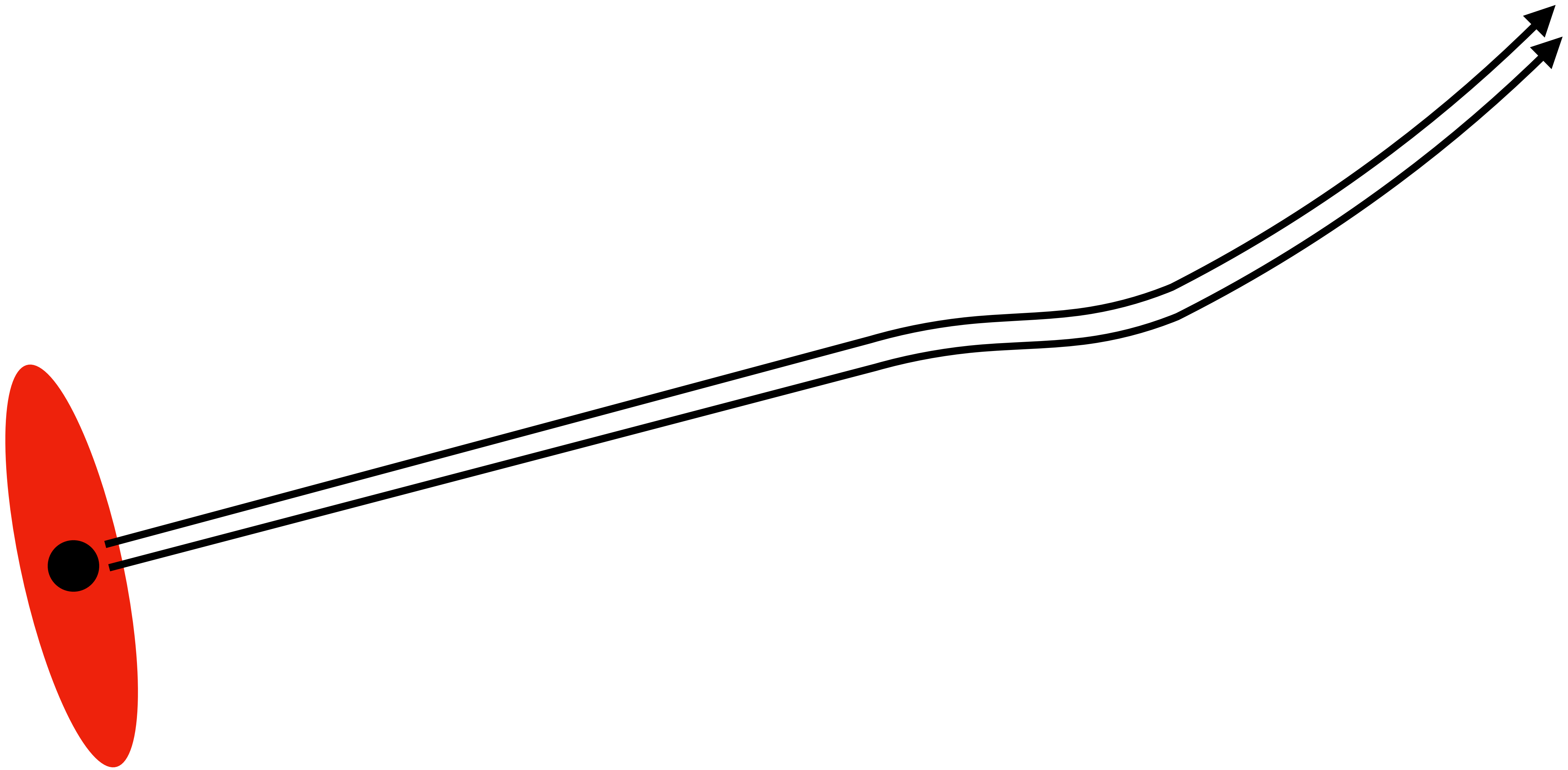
Spectral Ageing

Black hole accretes gas via accretion disc.



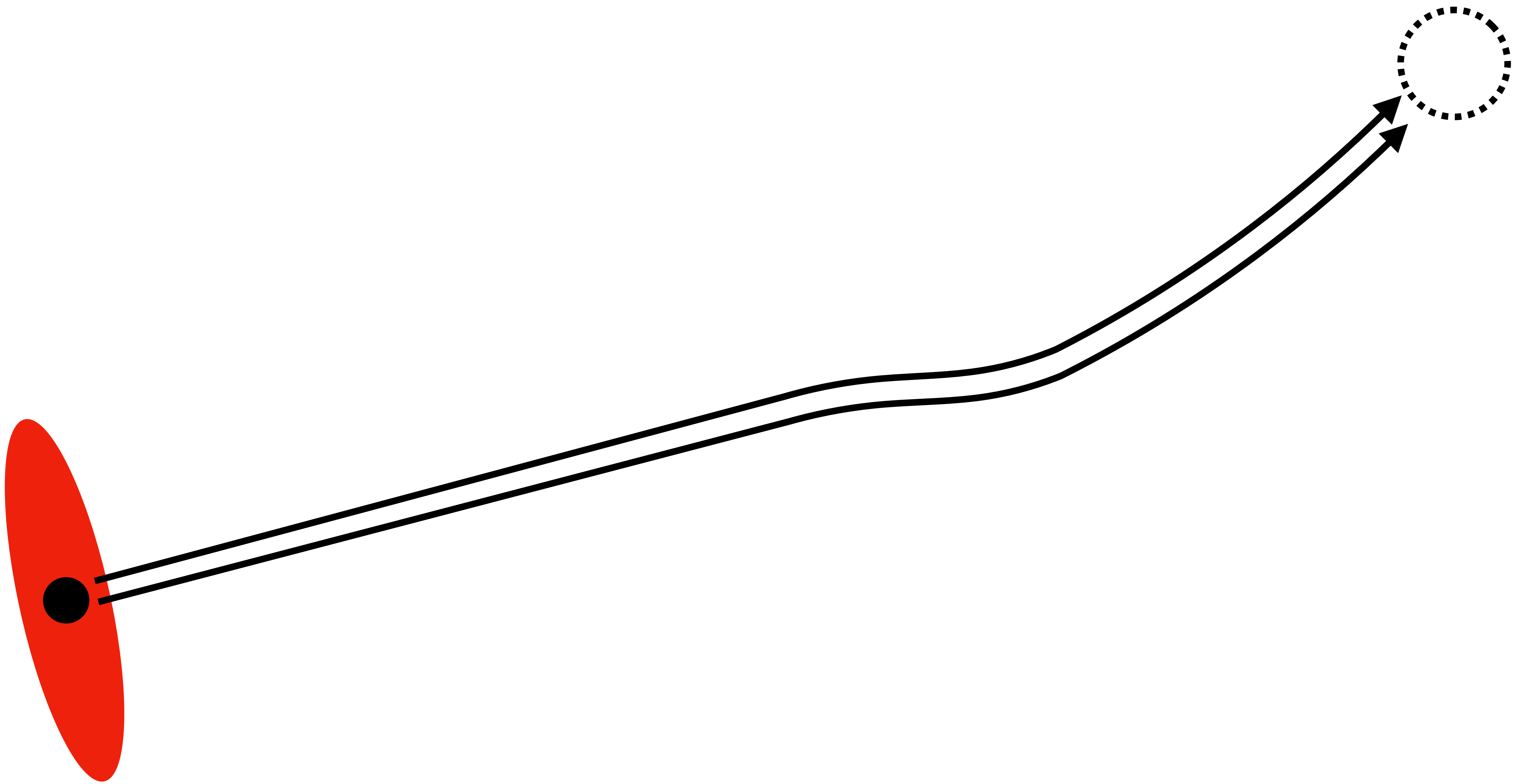
Spectral Ageing

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



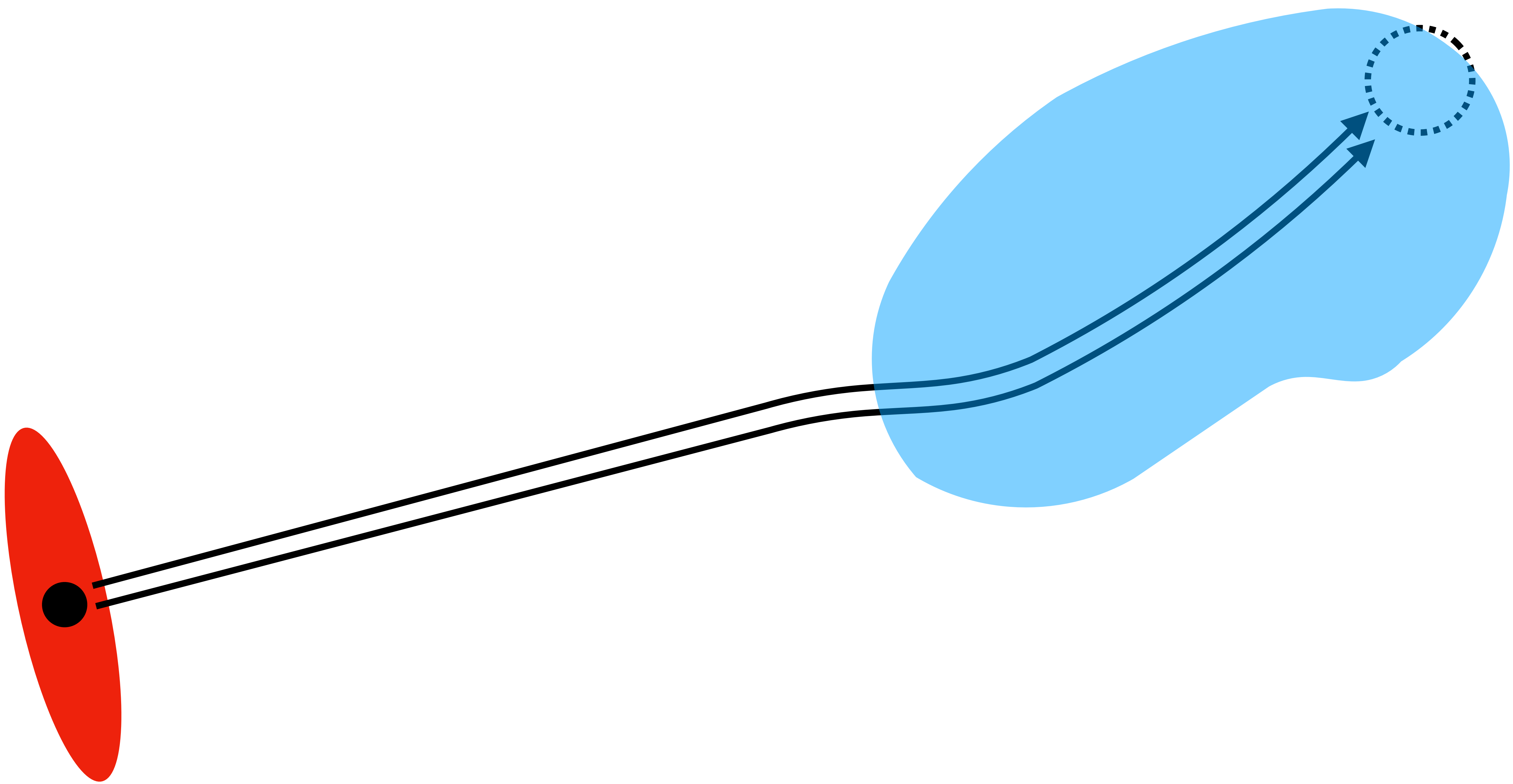
Spectral Ageing

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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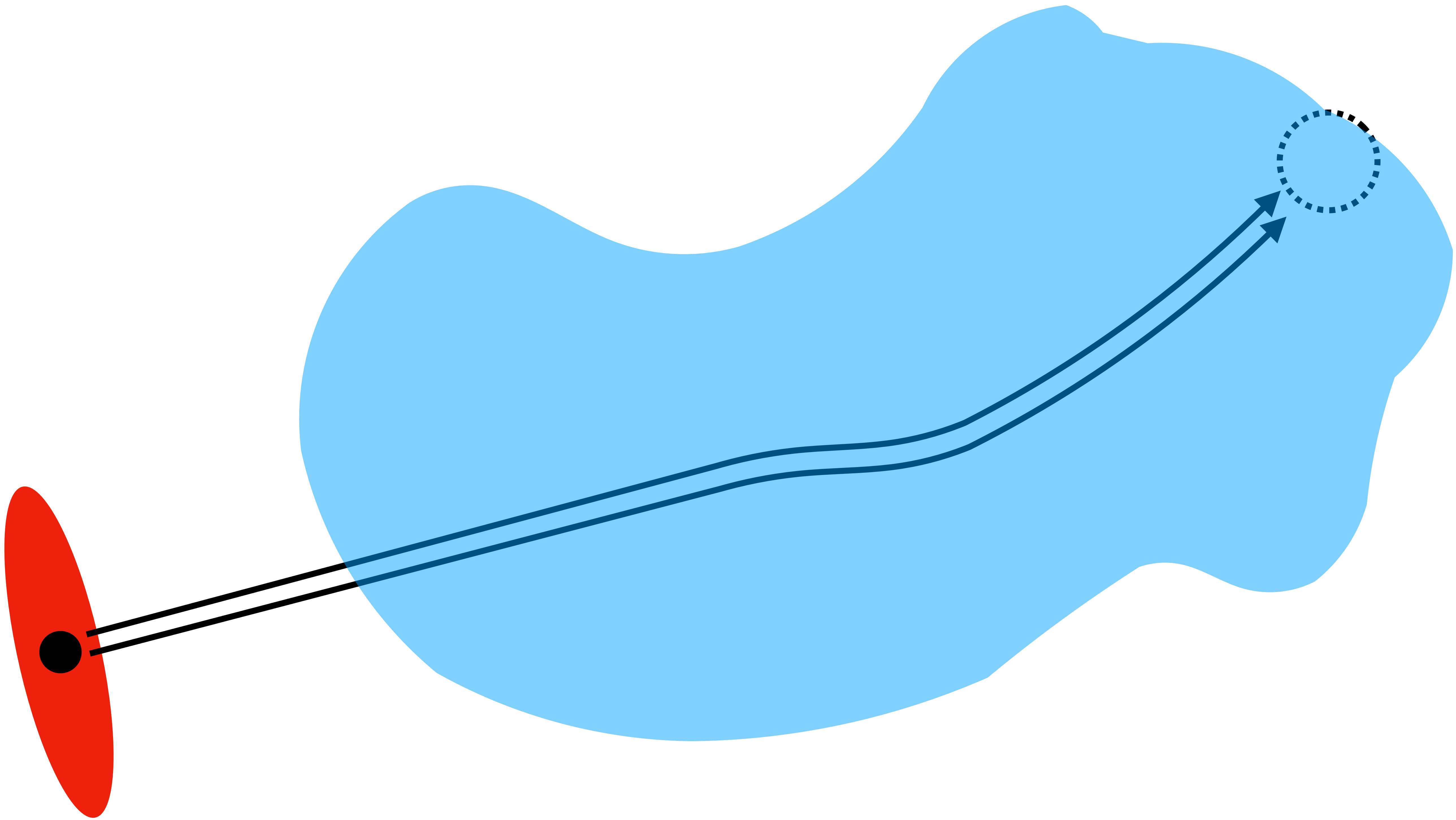

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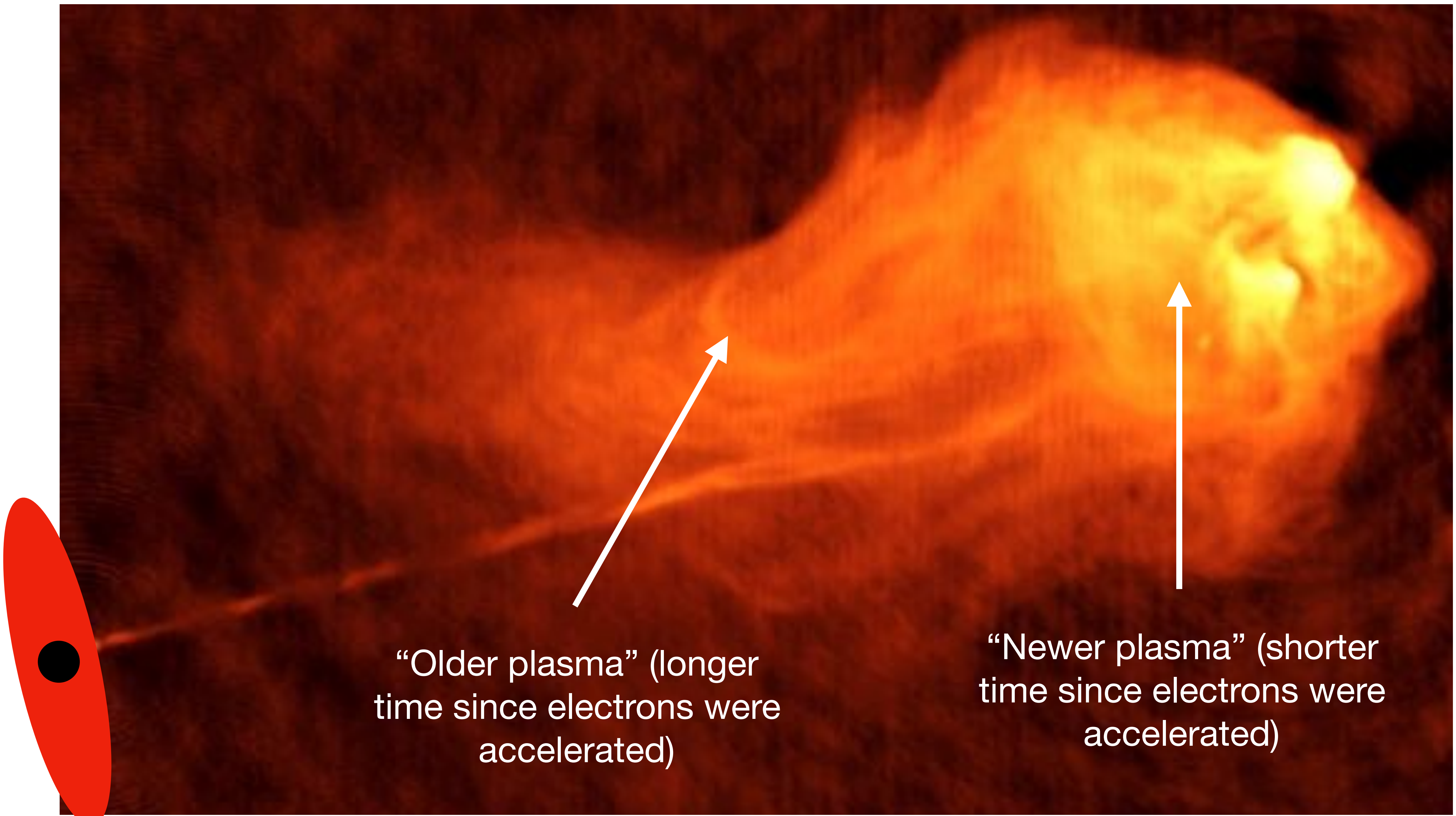

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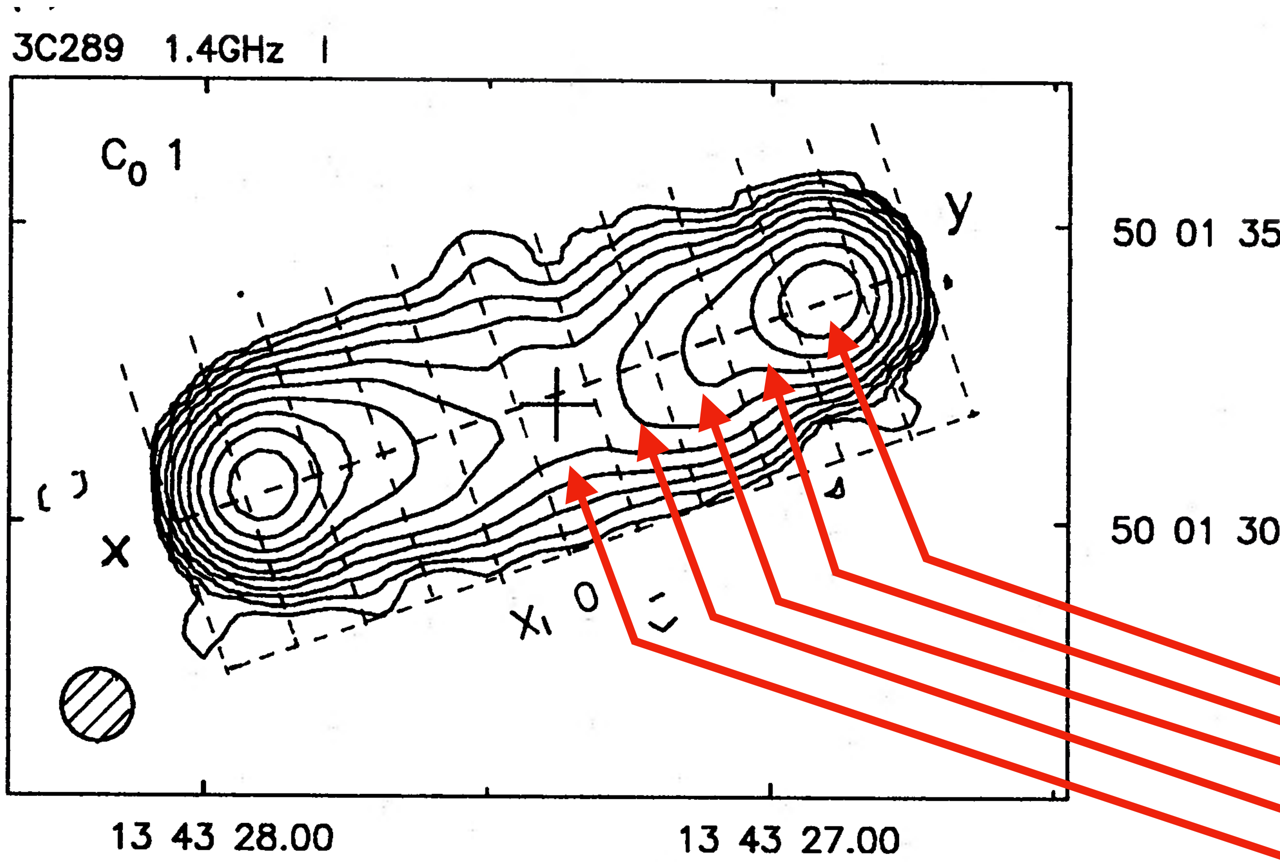

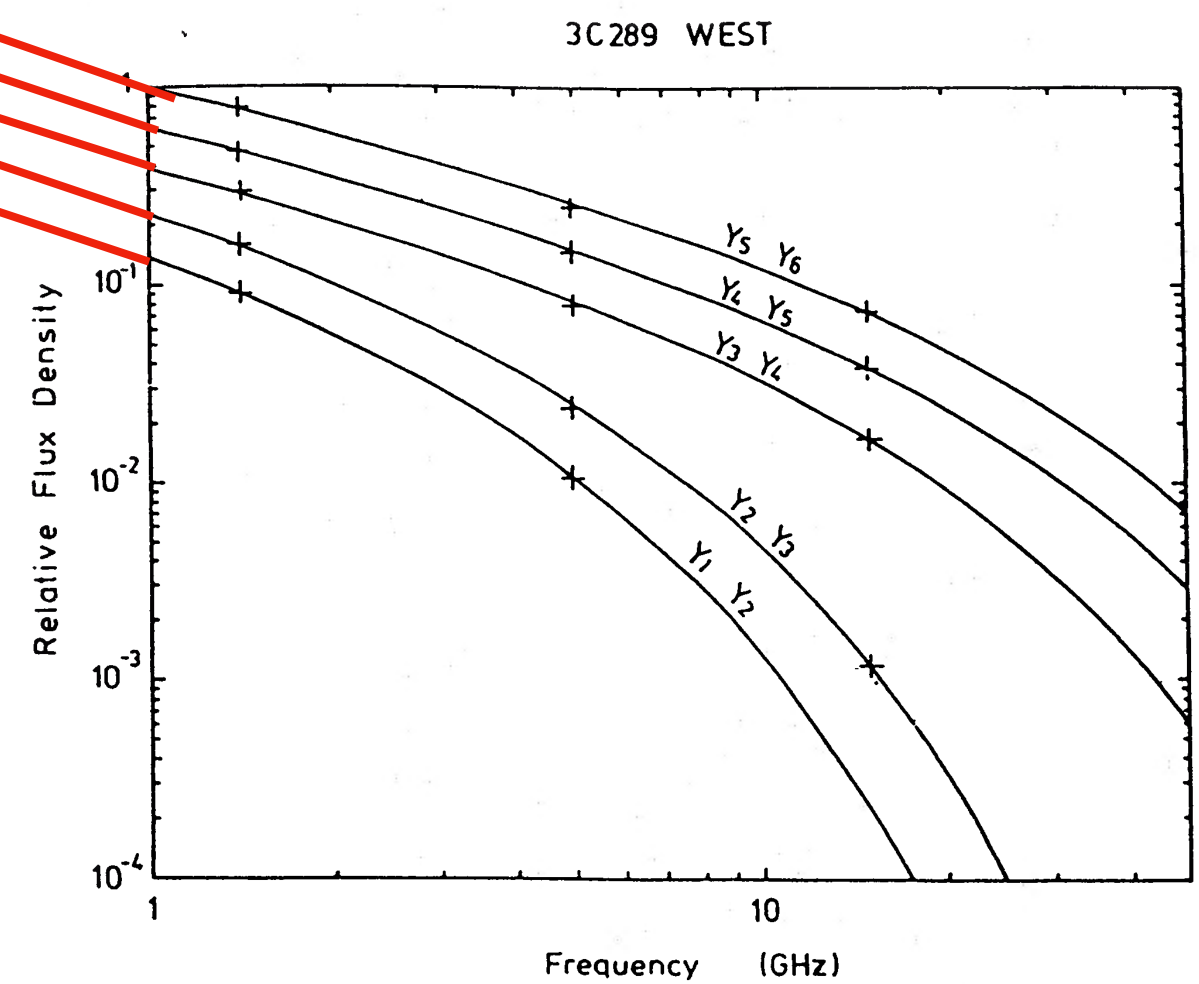

Break frequency really is lower in plasma further from hotspot: this plasma has cooled via synchrotron emission.

Liu & Pooley (1992)

Spectral Ageing

- Estimate magnetic field strength from minimum energy method: $\tau \propto B^{-3/2} \nu_{\rm max}^{-1/2}$

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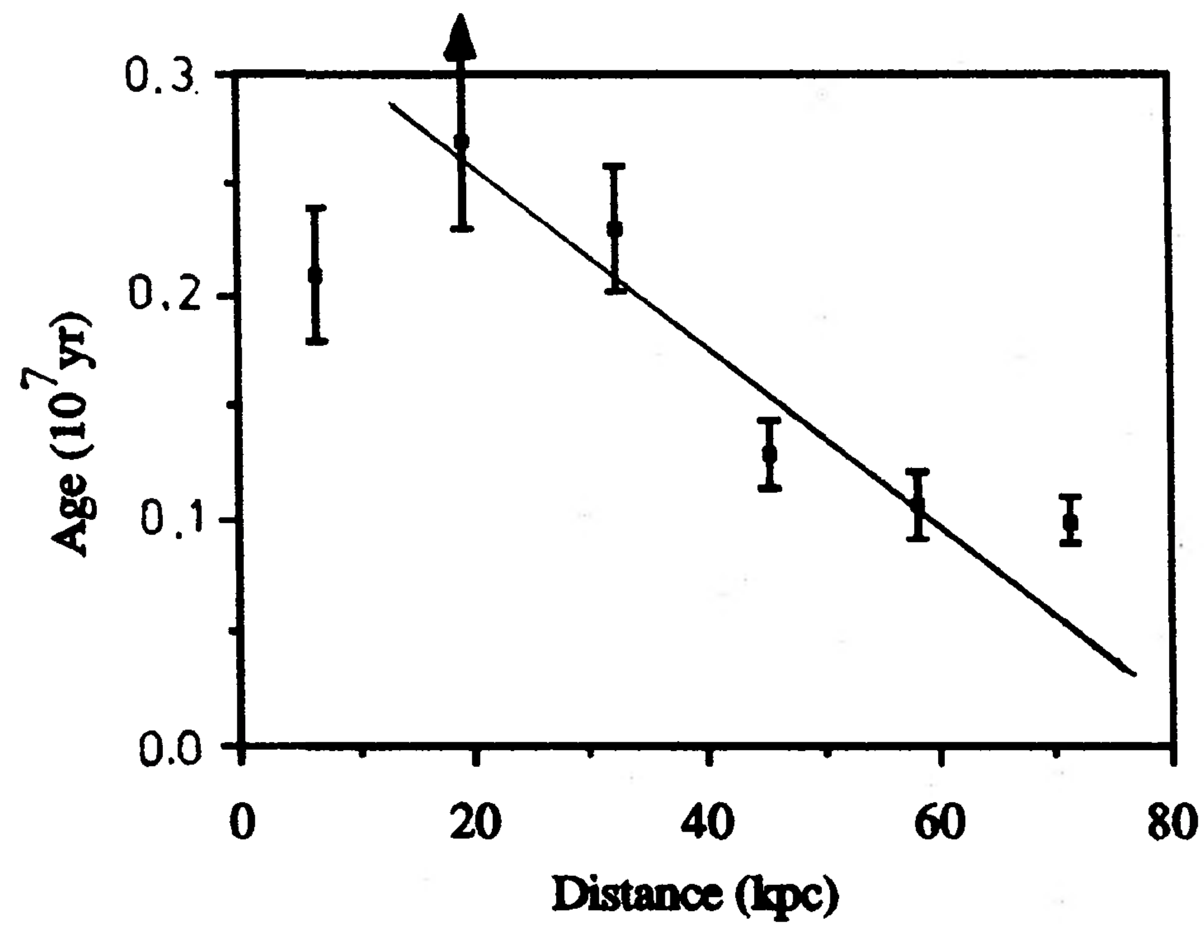
- Growth speed ~constant throughout lifetime of source.
- Oldest (i.e. largest) sources have ages of ~few 10^8 years.



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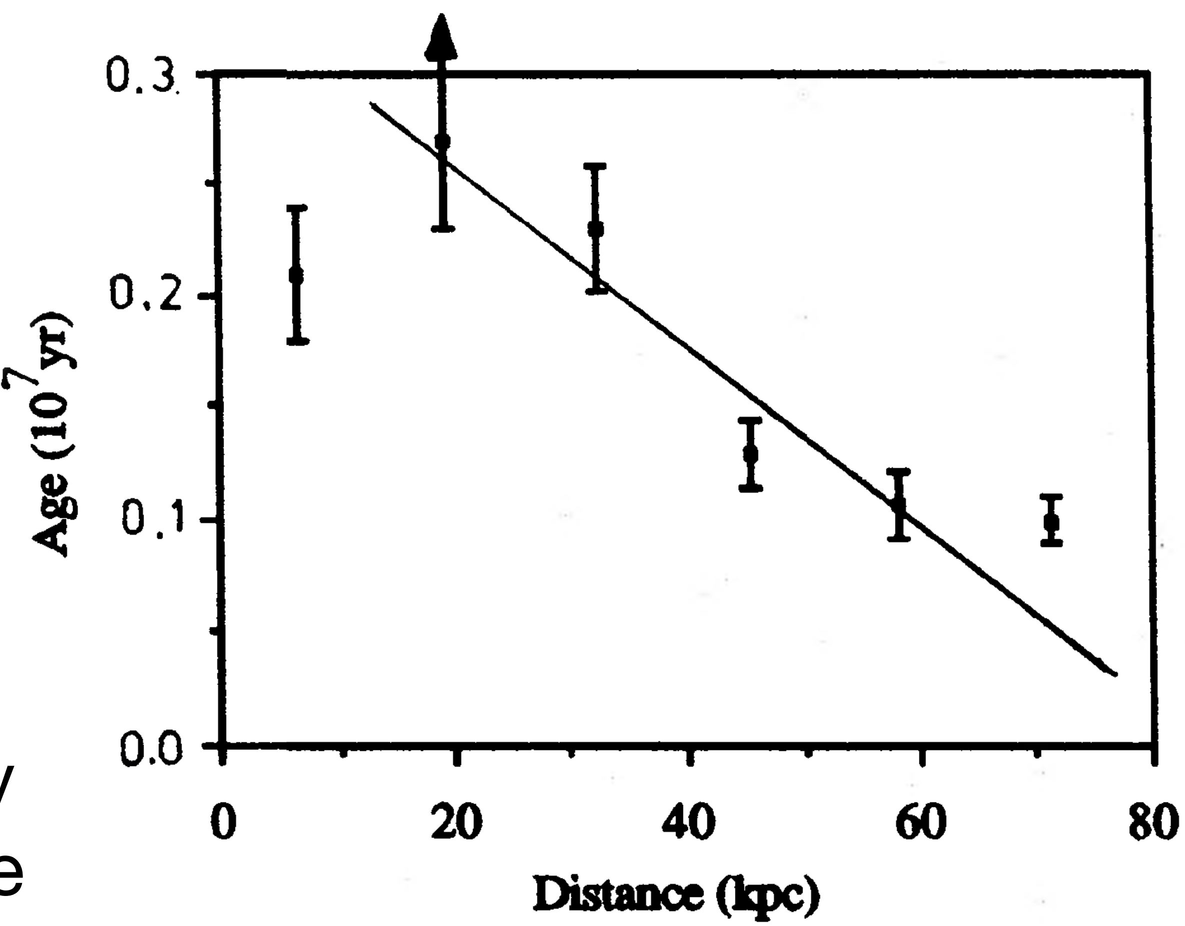
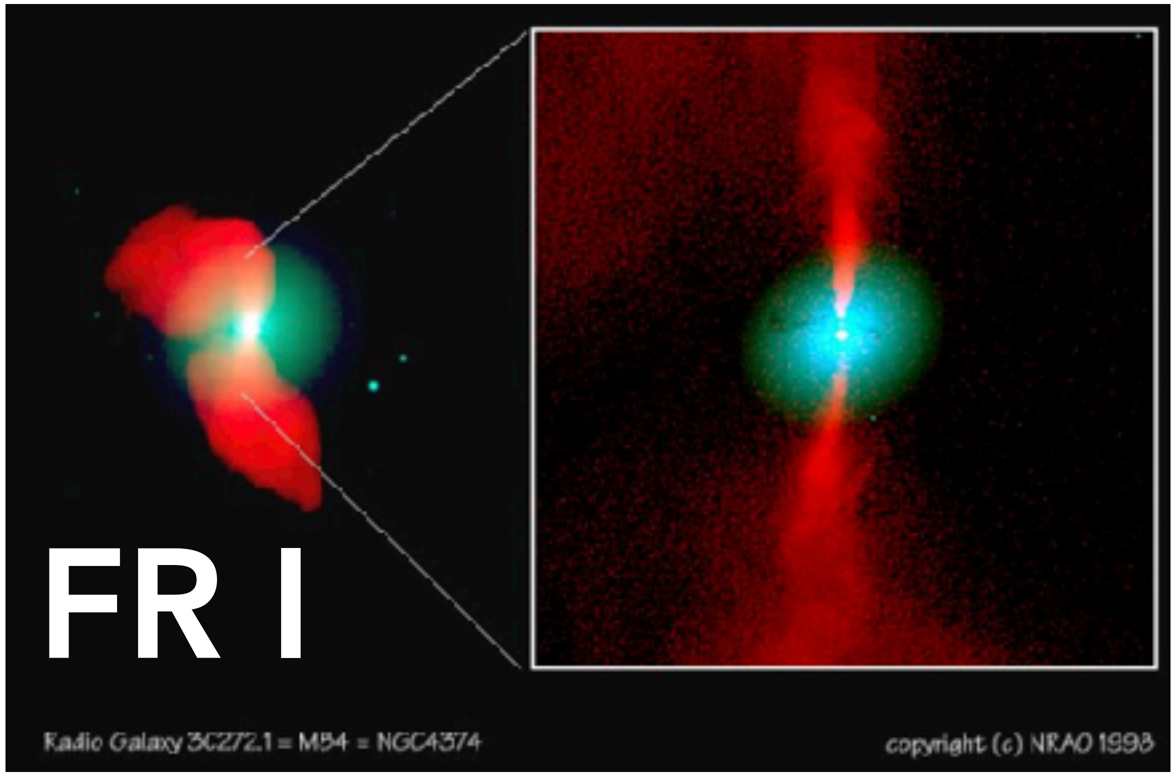
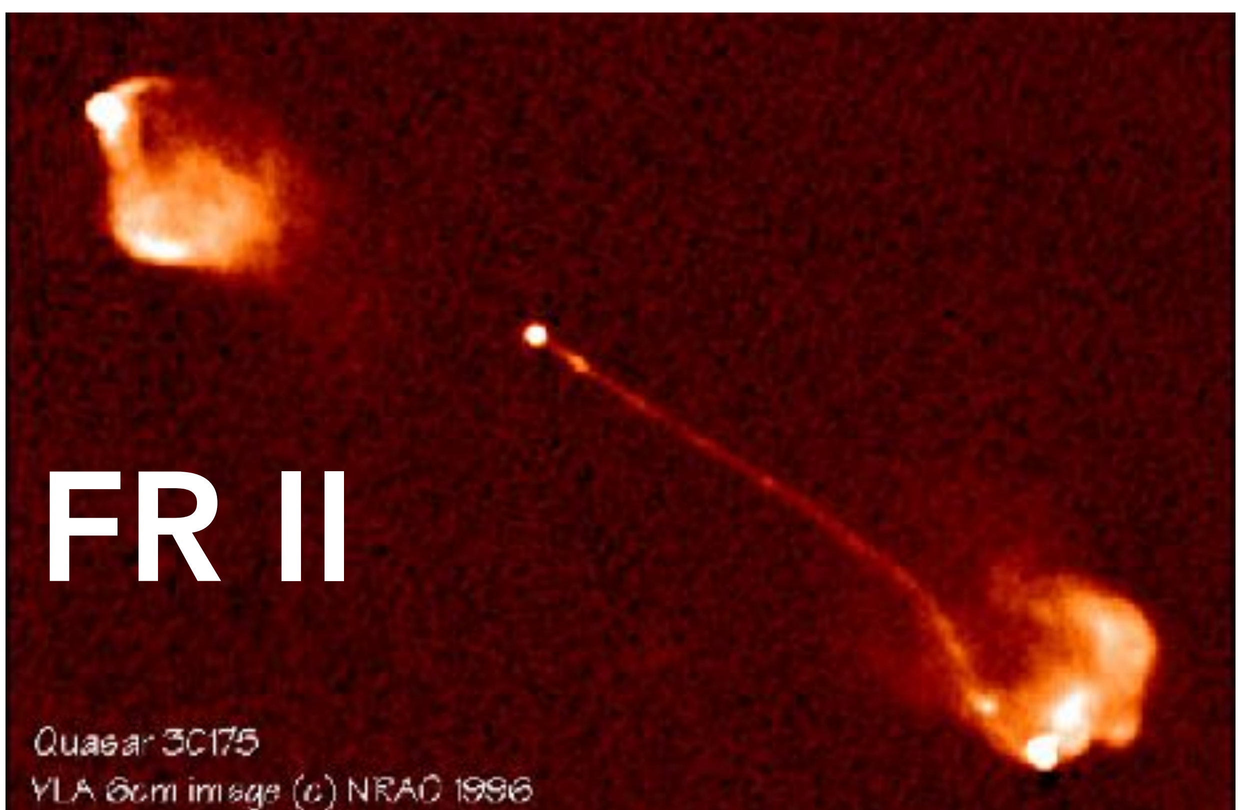


The most powerful radio sources are short-lived (tiny fraction of Hubble time), probably limited to accretion episodes. Given that we see lots of these sources out to high redshift, this is likely a phase that most massive galaxies go through at some point in their lifetime.

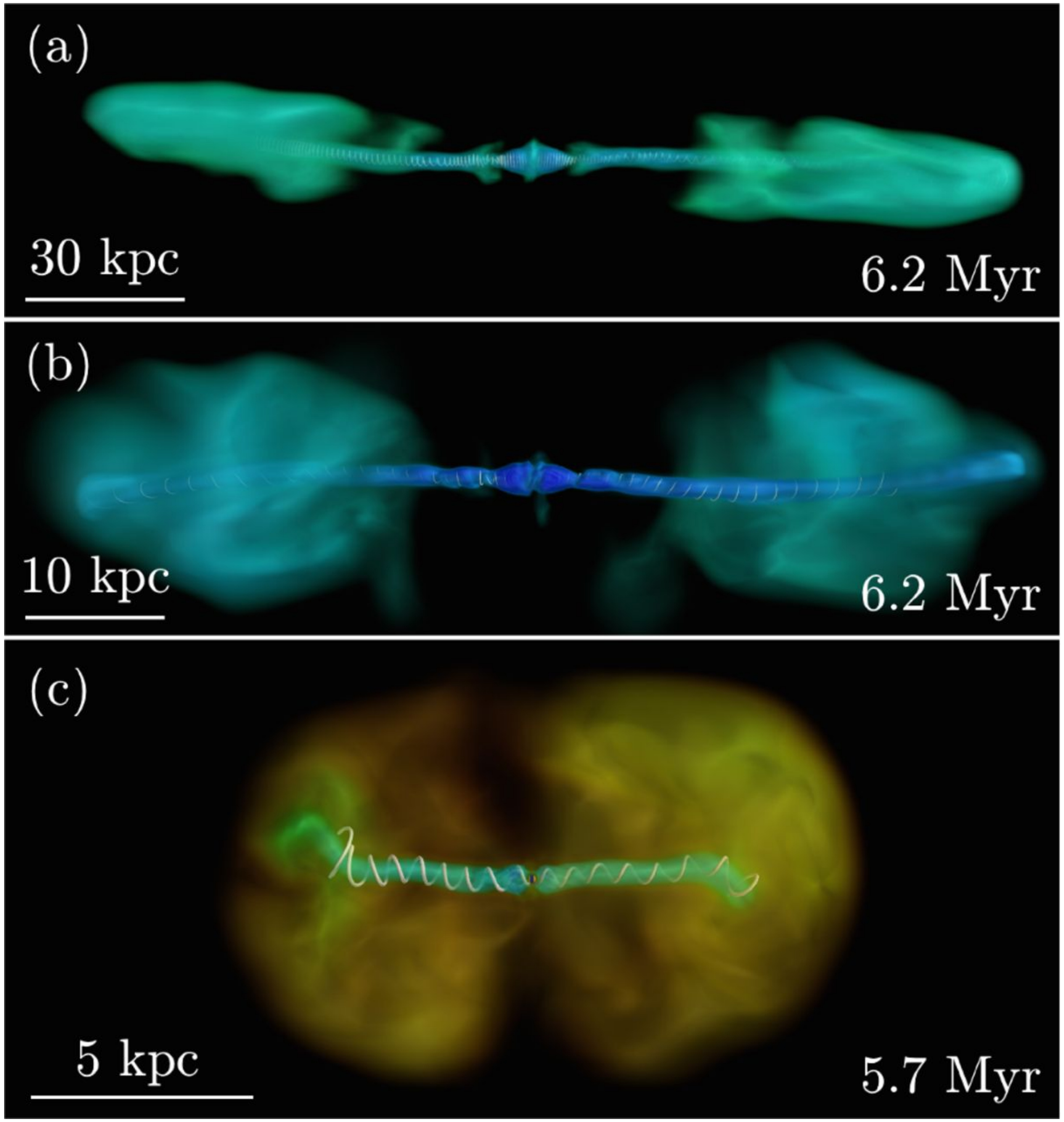
Weaker sources





- 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 - FRII 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 FRII sources whose jets have powered down?

Simulations of Tchekhovskoy & Bromberg (2016)

movie at: https://youtu.be/ErmoeAk8MvA