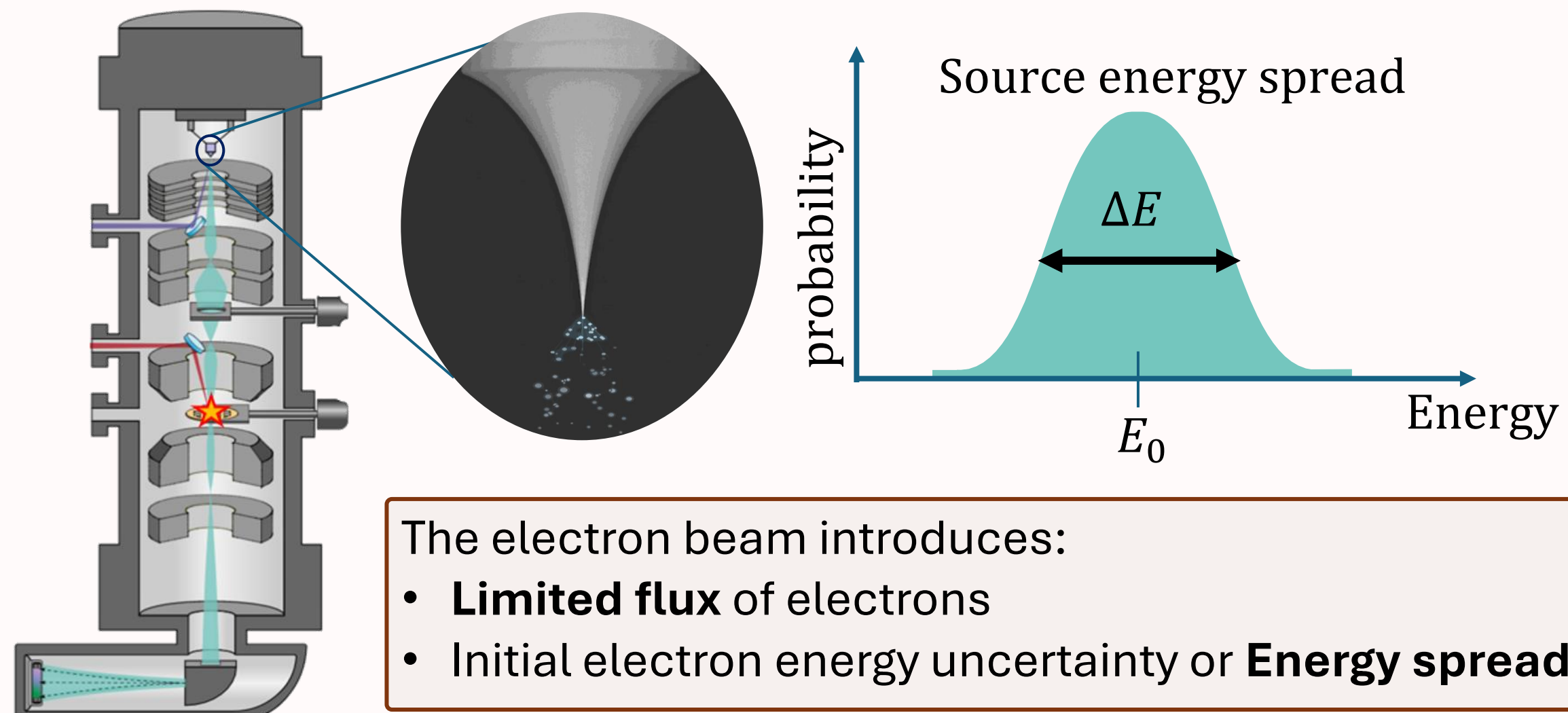
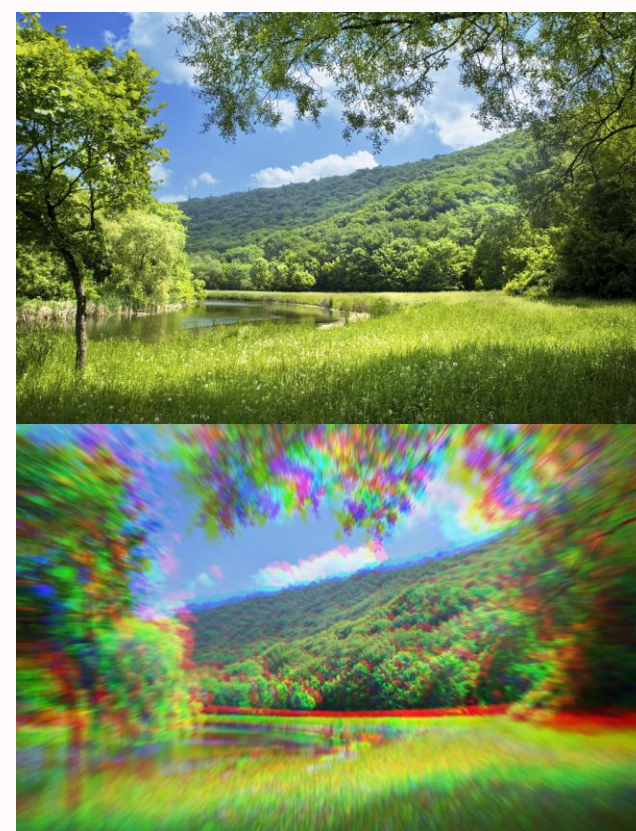


Passive Nanophotonic Doppler Cooling of Free Electrons

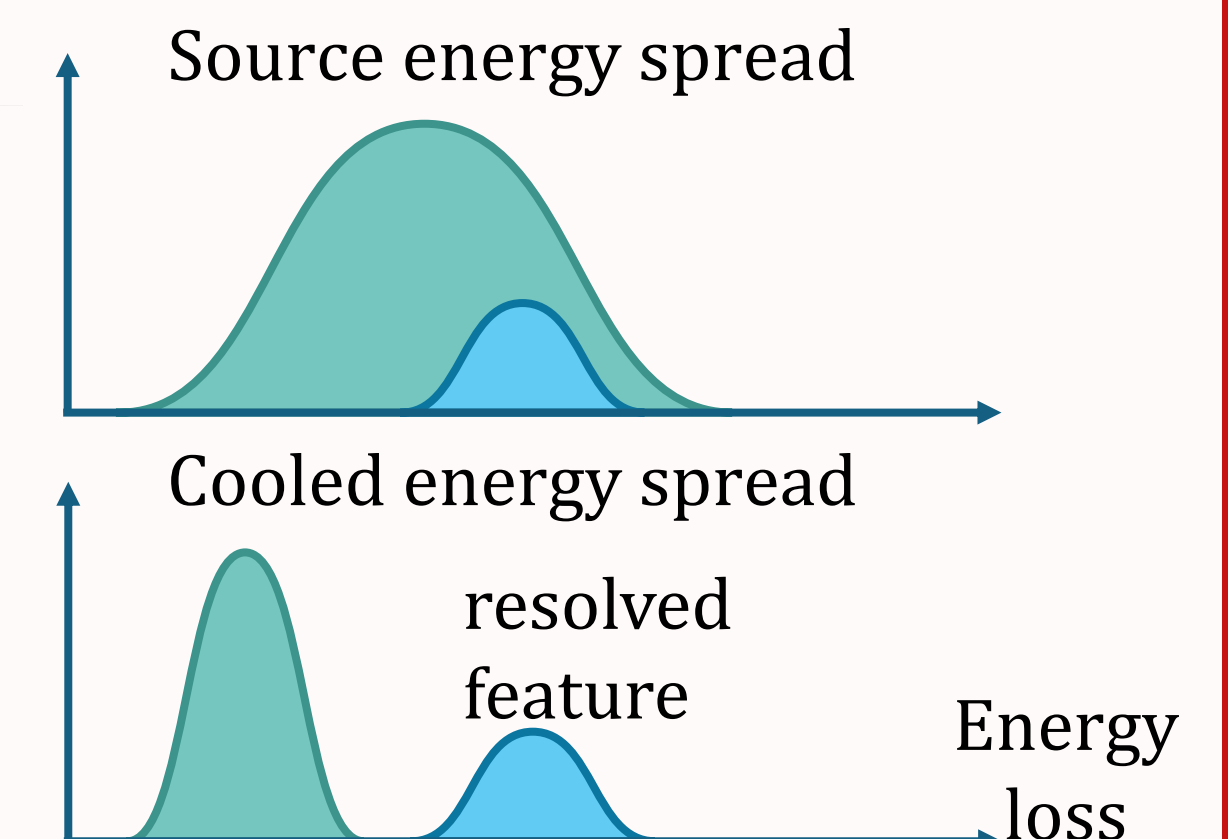
The problem: Electron beam energy spread



Microscopy (imaging)

Energy spread causes **chromatic aberrations**

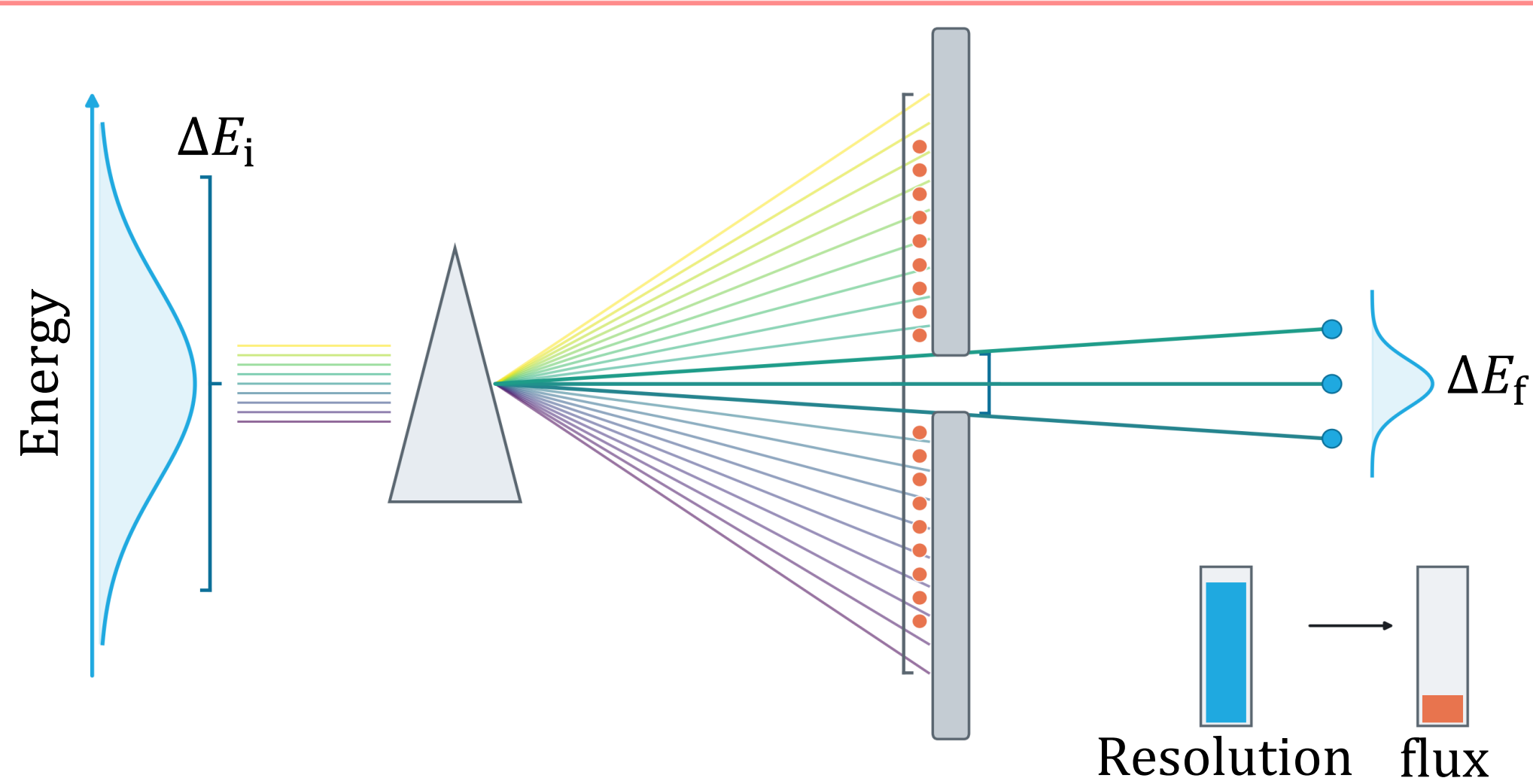
Spectroscopy (EELS)

Broad energy spread limit **spectral resolution** and hide weak features

Limitations of classical monochromators

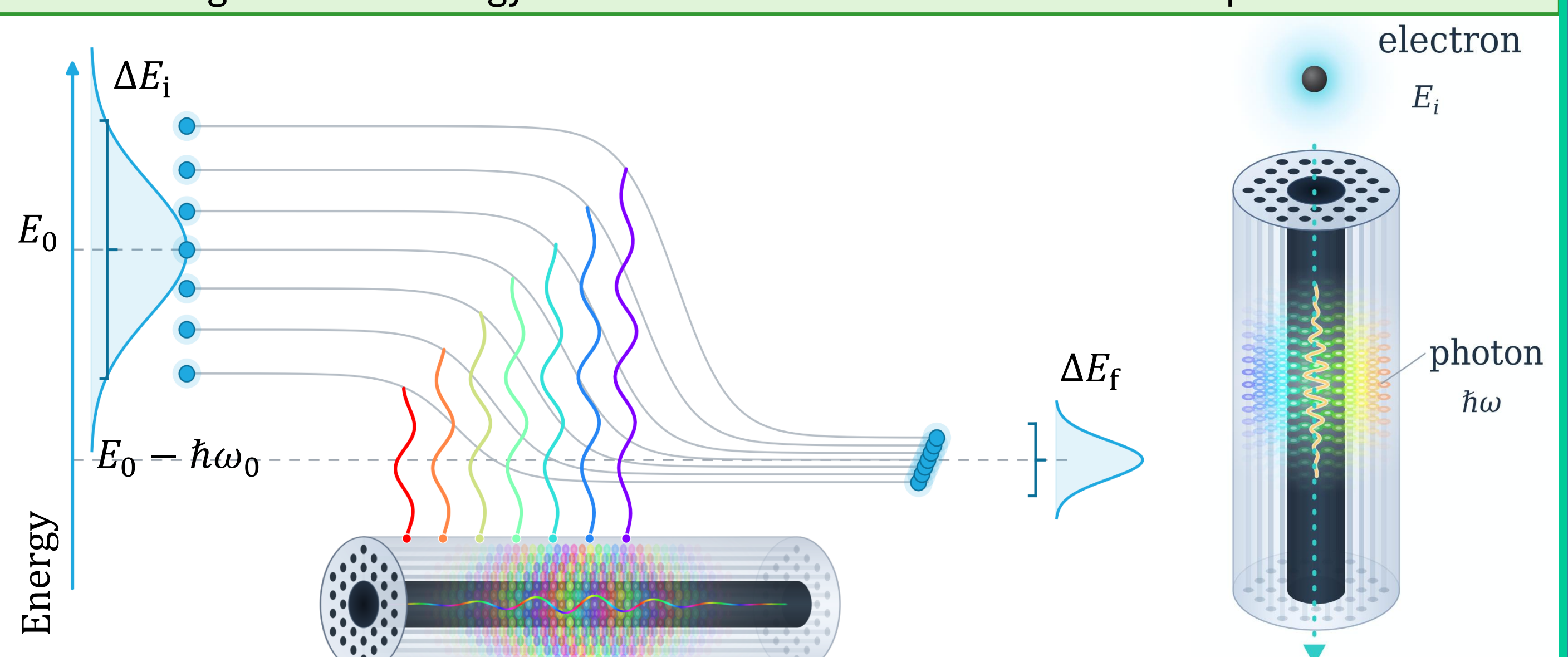
The resolution vs. flux trade-off

Monochromator filters electrons by energy



Our protocol: Optical monochromator mechanism

higher\lower energy electrons should emit blue\red shifted photons



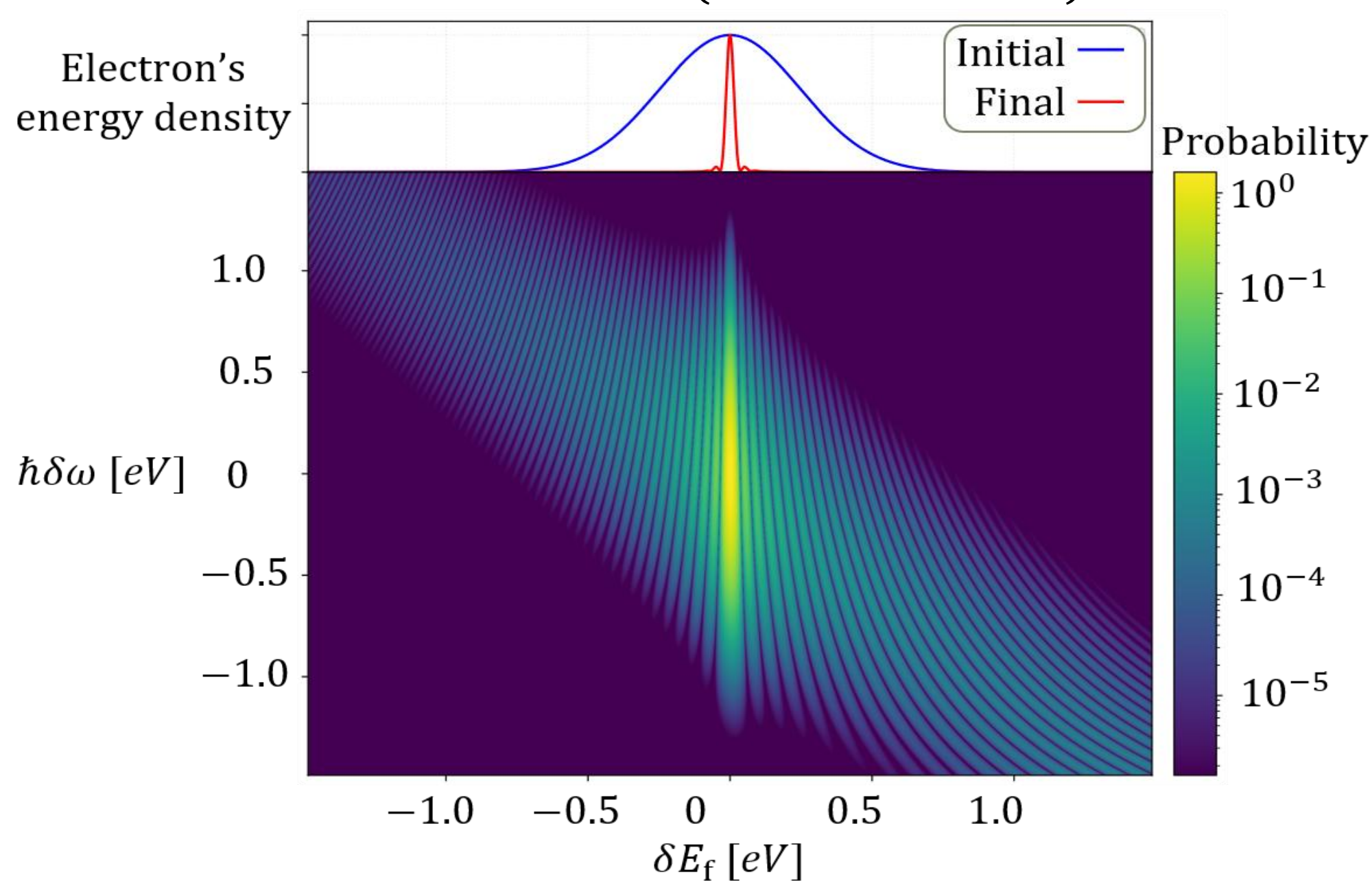
Solution by free electron quantum optics

Electron-photon interaction: $H_{\text{int}} = \frac{e}{m} \hat{A}(\hat{\mathbf{r}}) \cdot \hat{\mathbf{p}}$ Spontaneous emission 1st order perturbation (weak coupling) transition amplitude:

$$M_{E_f, \omega} = -\frac{i}{\hbar} \int_{-\infty}^{\infty} dt e^{-i\left(\frac{E_i - E_f - \hbar\omega}{\hbar}\right)t} \langle E_f, 1_\omega | H_{\text{int}} | E_i + \hbar\omega, 0_\omega \rangle$$

$$\propto L_{\text{int}} \text{sinc}\left(\Delta k \frac{L_{\text{int}}}{2}\right)$$

$$\Delta k = k(E_f + \hbar\omega) - k(E_i) - q(\omega)$$

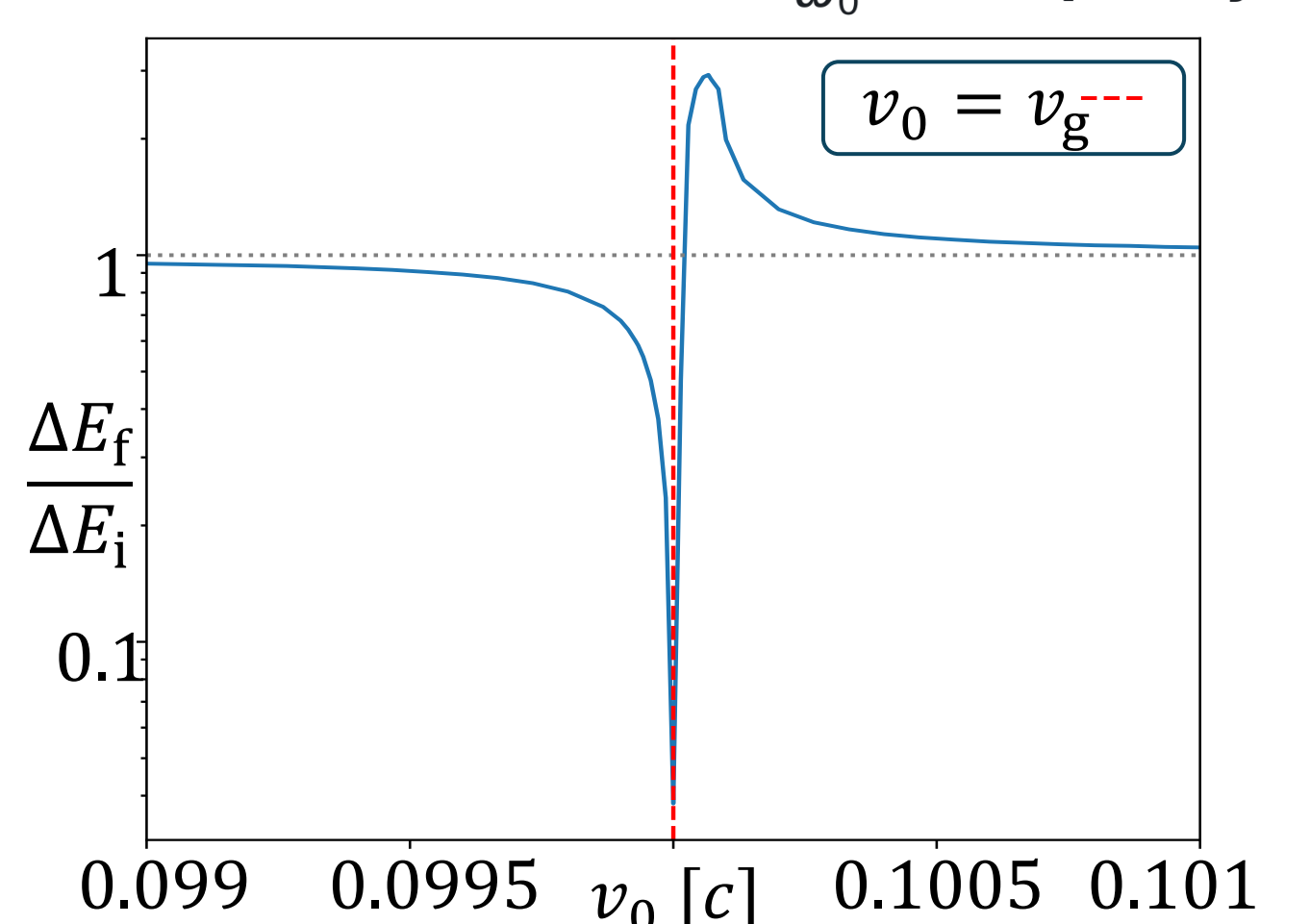
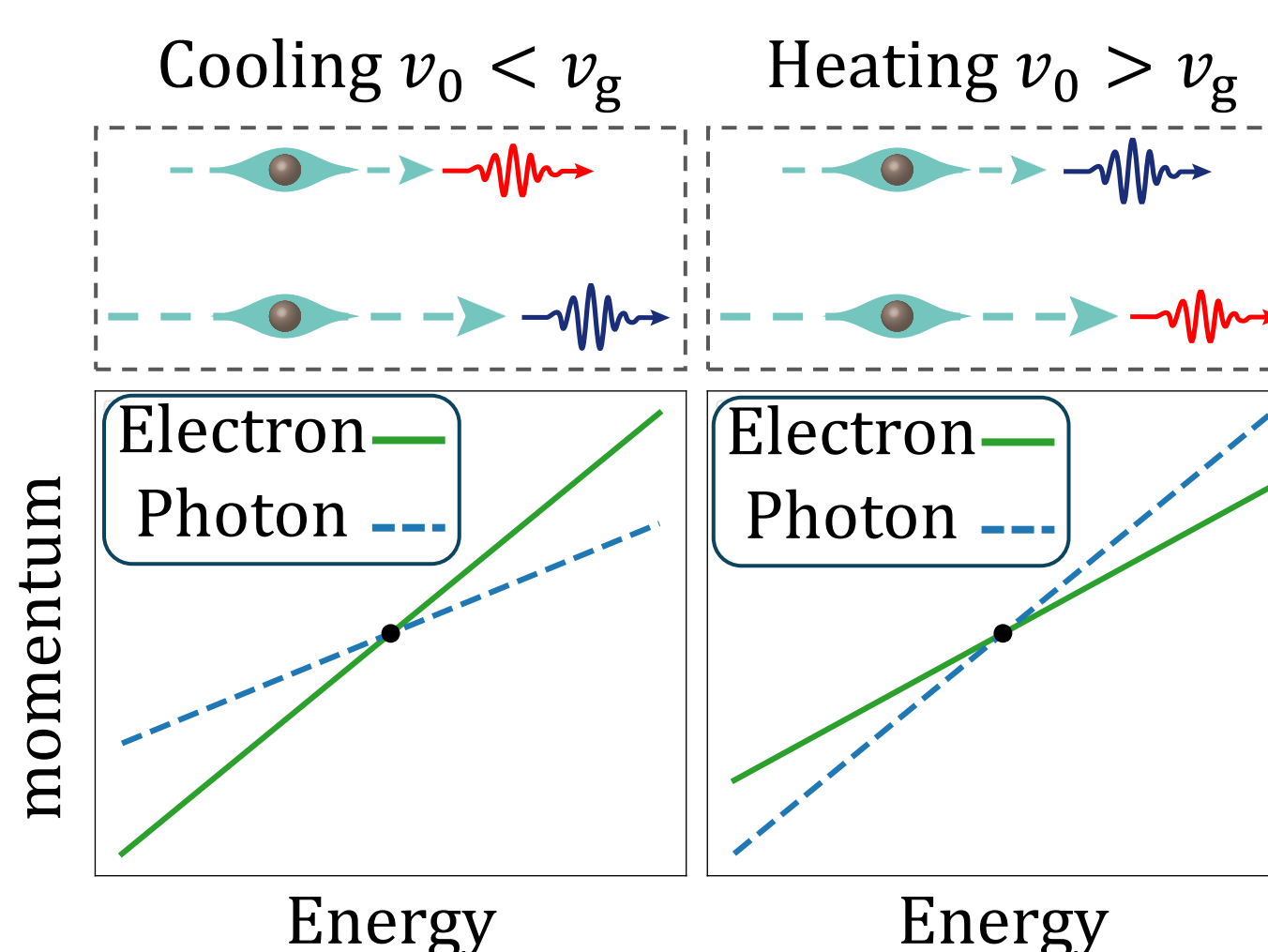
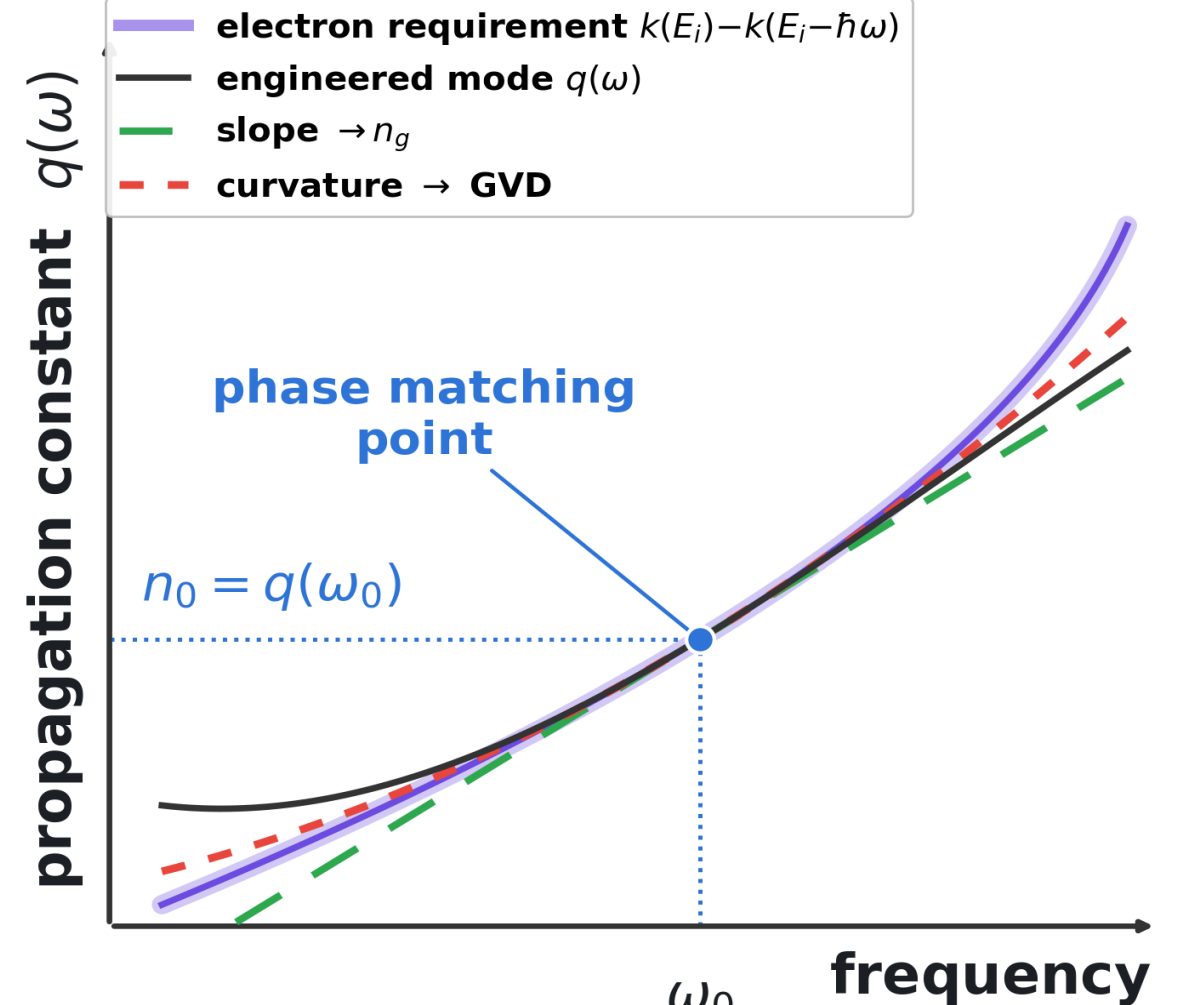
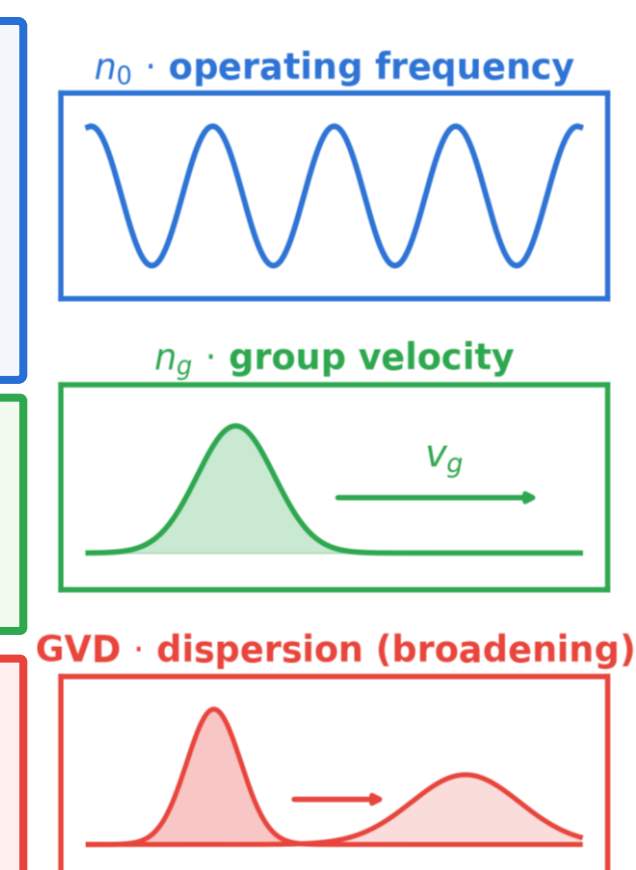
Our goal: $\Delta k \propto (E_f - (E_i - \hbar\omega_0))$ Resulting Cooling ratio: $\frac{\Delta E_f}{\Delta E_i} \propto \frac{L_0}{L_{\text{int}}}$, $L_0 \propto \frac{2v_0 E_0}{\omega_0 \Delta E_i}$

Dispersion engineering and design requirements

$$n_0 = \frac{c}{\omega_0} k(E_0) - \frac{c}{\omega_0} k(E_0 - \hbar\omega_0)$$

$$n_g = \frac{c}{\hbar k'(E_0)}$$

$$GVD = -\frac{\omega_0^2}{2\pi c} \hbar^2 k''(E_0)$$

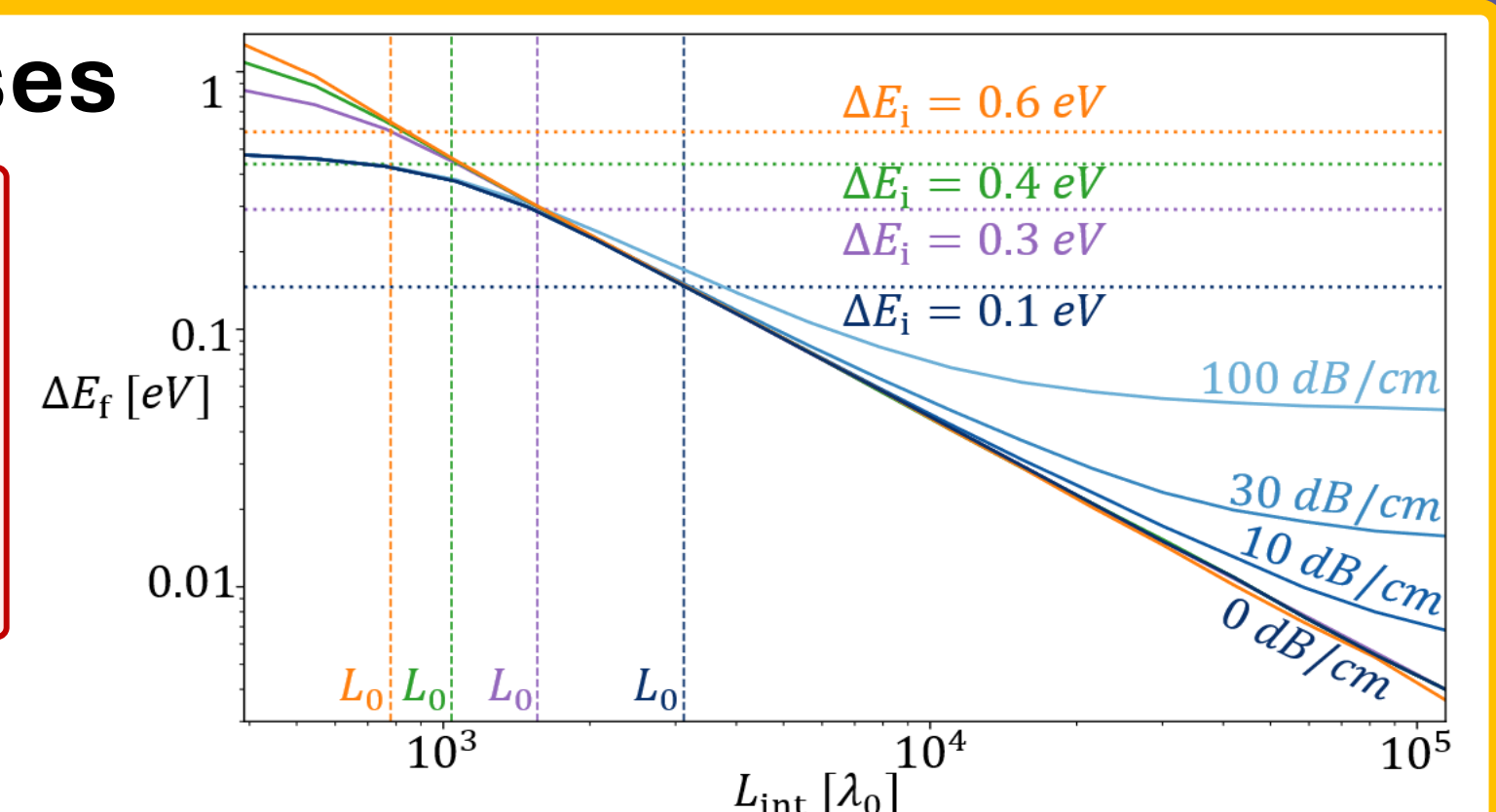


Limitation: photonic losses

Losses introduce saturation

- Losses limit the cooling ratio
- Saturation in the final width:

$$\Delta E_{\text{sat}} = \frac{2E_0 \alpha_\ell}{\omega_0}$$



Conclusions:

- Free electrons can be cooled by spontaneous emission, an all-optical **analogue of atomic Doppler cooling**.
- No inherent electron flux – resolution trade-off.
- Cooling is set by the interaction length of the dispersion engineered waveguide, and is limited by photonic losses.
- The photons inherit the electrons initial energy uncertainty.

References: [1] Hänsch and Schawlow, Opt. Commun. 13, 68 (1975). [4] Krivanek et al., Nature 514, 209 (2014). [2] Ruimy et al., Nat. Phys. 21, 193 (2025). [5] Barwick et al., Nature 462, 902 (2009). [3] Karnieli et al., ACS Photonics 11, 3401 (2024). [6] Konečná et al., Sci. Adv. 8, eabo7853 (2022). [7] Shiran Even-Haim[†], Dor Gelem[†], Aviv Karnieli[†], Renwen Yu, Ido Kaminer, Vladan Vuletić, and Shai Tseses, in preparation.