We wish to approximate an integral of the form

$$\mathcal{F}(\nu) = \int_0^\infty dt e^{i\nu t} f(t) \tag{1}$$

for a function $f(t)$ decays to zero over a timescale τ. Taking N samples $f_n = f(t_n)$ at equally spaced times $t_n = 0, T/N, 2T/N, \ldots (N-1)T/N$ where $T > \tau$,

$$\begin{aligned} \mathcal{F}(\nu) &\approx \int_0^T dt e^{i\nu t} f(t) && (2)\\ &\approx \sum_{n=0}^{N-1} e^{i\nu t_n} f_n \Delta t \qquad (\Delta t = T/N) && (3)\\ &= \Delta t \sum_{n=0}^{N-1} e^{i\nu n T/N} f_n && (4) \end{aligned}$$

This should be compared to the definition of the FFT, as implemented in `numpy`:

$$F_k := \sum_{n=0}^{N-1} f_n e^{-2\pi i n k/N}, \quad k = 0, \ldots, N-1 \tag{5}$$

We see that

$$\mathcal{F}\left(-2\pi k/T\right) = \Delta t F_k, \quad k = 0, \ldots, N-1 \tag{6}$$

i.e. evaluating ΔF_k (F_k the k^{th} Fourier component) gives the required function, but at frequencies

$$\nu = -\frac{2\pi}{T} k = -\frac{2\pi}{N\Delta t} k \tag{7}$$

for N consecutive integers k. By default, `np.fft.fft` takes N frequencies *centred at* 0, and in the order 'zero frequency, positive frequencies, negative frequencies' e.g. $k = 0$, $k = 1, 2, \ldots, (N-1)/2$, $k = -(N-1)/2, \ldots -1$ for N odd. Applying `np.fft.fftshift()` to the result of `np.fft.fft` moves the elements into the more sane order of ascending frequencies. The function `np.fft.fftfreq(N, d=dt)` returns frequencies[1] with spacing $1/(N\Delta t)$, so we need to multiply these frequencies by -2π (or explicitly construct N frequencies centred on 0 using (7)). Note the maximum frequency scales as $1/\Delta t$ i.e. higher resolution in real real space results in a larger range of frequencies in reciprocal space,[2] whilst the frequency resolution scales as $1/T$ i.e. is set by the sample time.

Using ifft To avoid the complication of having to negate the frequencies, it is simpler to use the inverse Fourier transform provided by numpy with the option `norm='forward'`, which gives directly

$$F_k = \sum_{n=0}^{N-1} f_n e^{2\pi i n k/N} \tag{8}$$

In summary, use the code

[1] N.B. one must apply `np.fft.fftshift()` to both the FFT result and these frequencies.

[2] Although this does not necessarily provide additional information; beyond a certain frequency (determined by the most rapidly changing part of f) the spectrum will be zero.

```
# times - array of equally spaced times at which function was sampled
dt = times[1] - times[0]
N = len(sample) # N.B. for higher frequency resolution, consider oversampling
sample_fft = np.fft.fftshift(np.fft.ifft(sample, norm='forward', n=N))
nus = 2 * np.pi * np.fft.fftshift(np.fft.fftfreq(N), d=dt)
```

Zero-padding For a function known to have decayed to 0 by the final sample time i.e. $f(t) = 0\ \forall t \geq T$, you may consider appending zeros to the array $\{f_n\}_n^N$ of samples in order to increase the resolution in frequency. As commented above, the `n` parameter of `np.fft.ifft` can be used for this purpose: setting $n = M$ for $M > N$ results in the sample being padded with $M - N$ zeros (for $M < N$ it is cropped). Coincidently, the FFT algorithm is most efficient when the number of samples is a power of 2, so you may want to consider setting

```
M=2**(int(np.ceil(np.log2( FAC * N ))))
```

where `FAC` is the desired oversample factor.

Endpoint correction Computing integrals in this way is susceptibility to error due to truncation error. This is discussed in [1, Sec. 13.9]. An endpoint correction scheme based on this text is implemented in `../fft_endpoint_correction/improved_fft.py` (also used in `self-energy.py`).

References

[1] W. Press, S. Teukolsky, W. Vetterling and B. Flannery, *Numerical Recipes: The Art of Scientific Computing*, 3e. Cambridge University Press (Cambridge, UK, 2007).