Interferometry without delay lines –
the promise of Quantum Methods

CHARA Consortium Meeting

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The program today

- The Quantum Memory perspective
- The benefits of high spectral resolution
- Putting it together – microarcsecond arrays

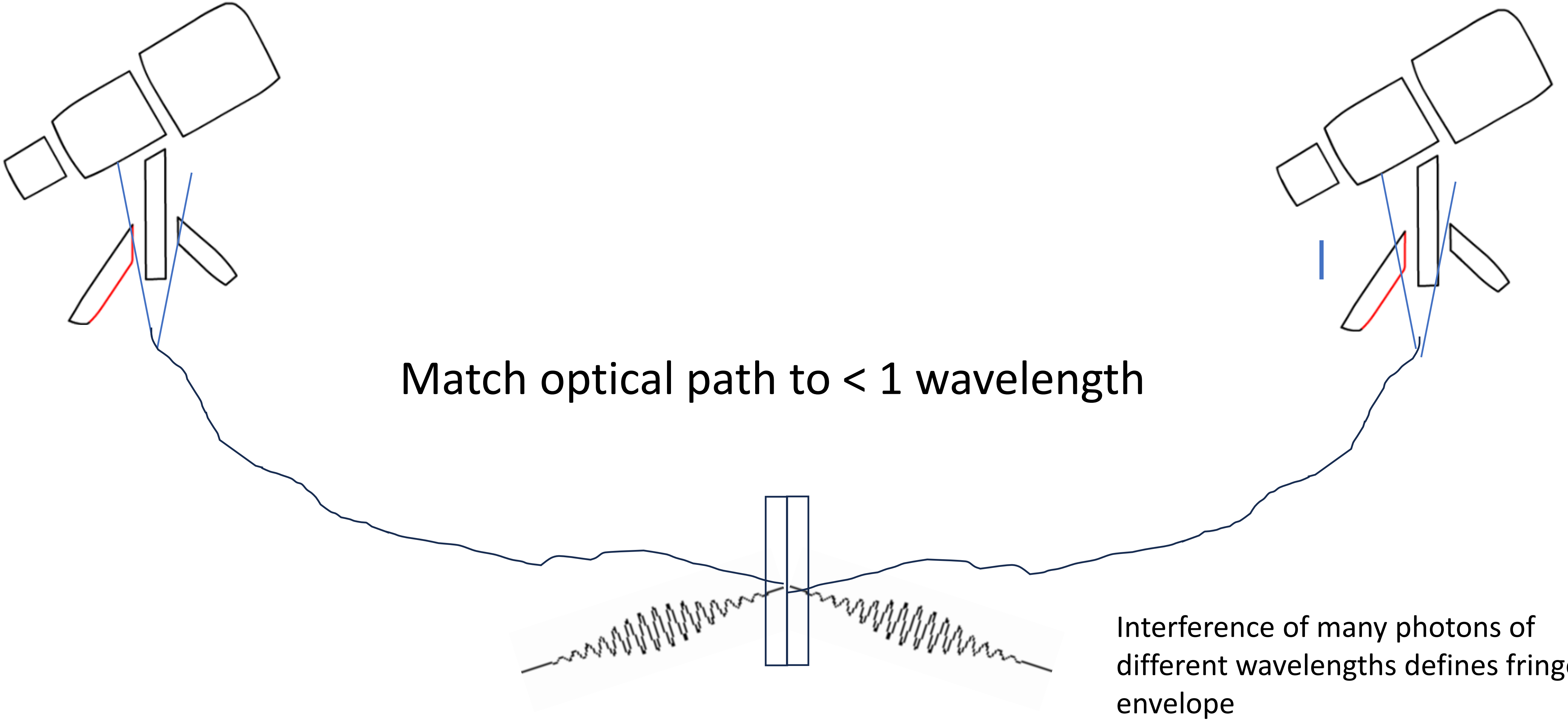
Different types of quantum memory

- **Quantum Memory for Photonic Delay and Restoration** ("Delay Line")

!

- **Quantum Memory That Converts Photons into Qubits**
  - Captures phase and coherence properties of a photon wavefront
  - Photon no longer exists as propagating wave packet, but also not “measured”
  - Quantum memory captures “probability” of a photon
  - Qubit now “quantum computing ready” – including for entanglement with another qubit

Photon capture – classical fringes view

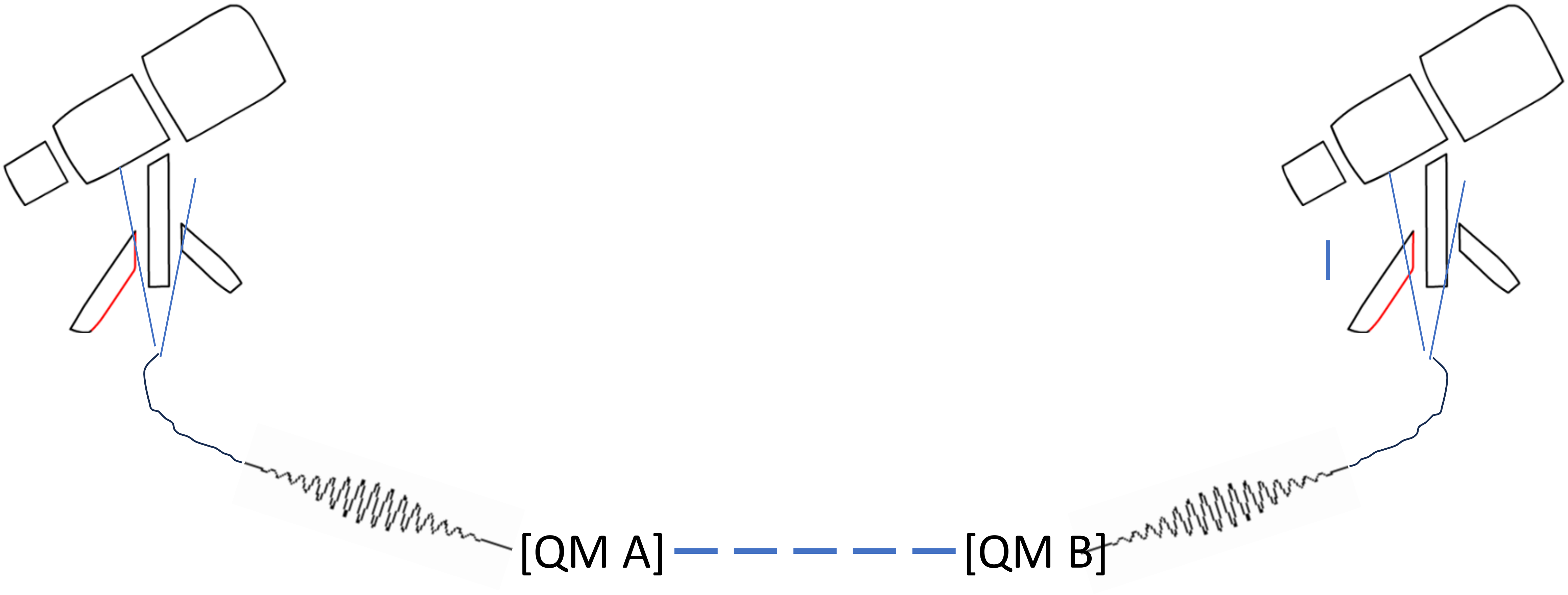


Interference of many photons of different wavelengths defines fringe envelope

Wavefront capture – wave packet view

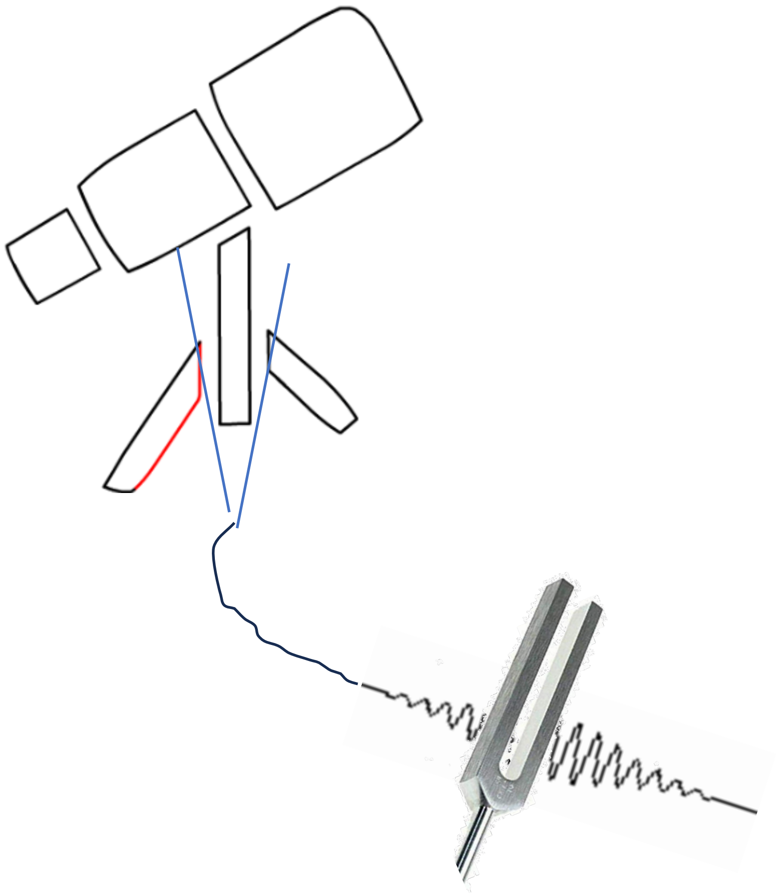
Interference of many “possible” wavelengths for a single photon defines coherence envelope

Wavefront capture – by quantum memory

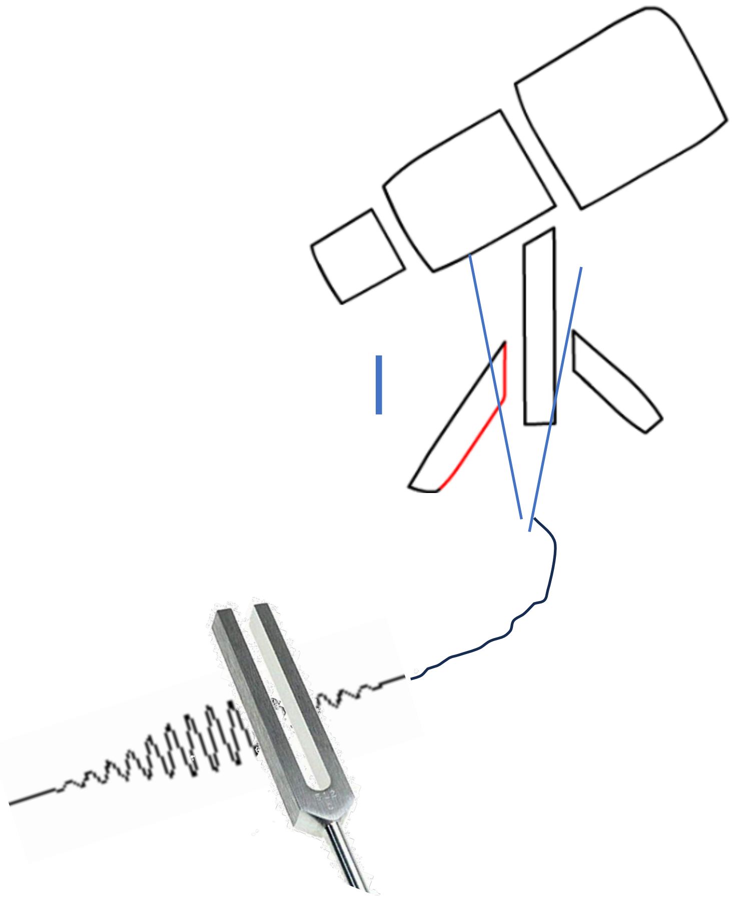


Extract Phase and spatial coherence amplitude – via entangled comm link……..one photon at a time!

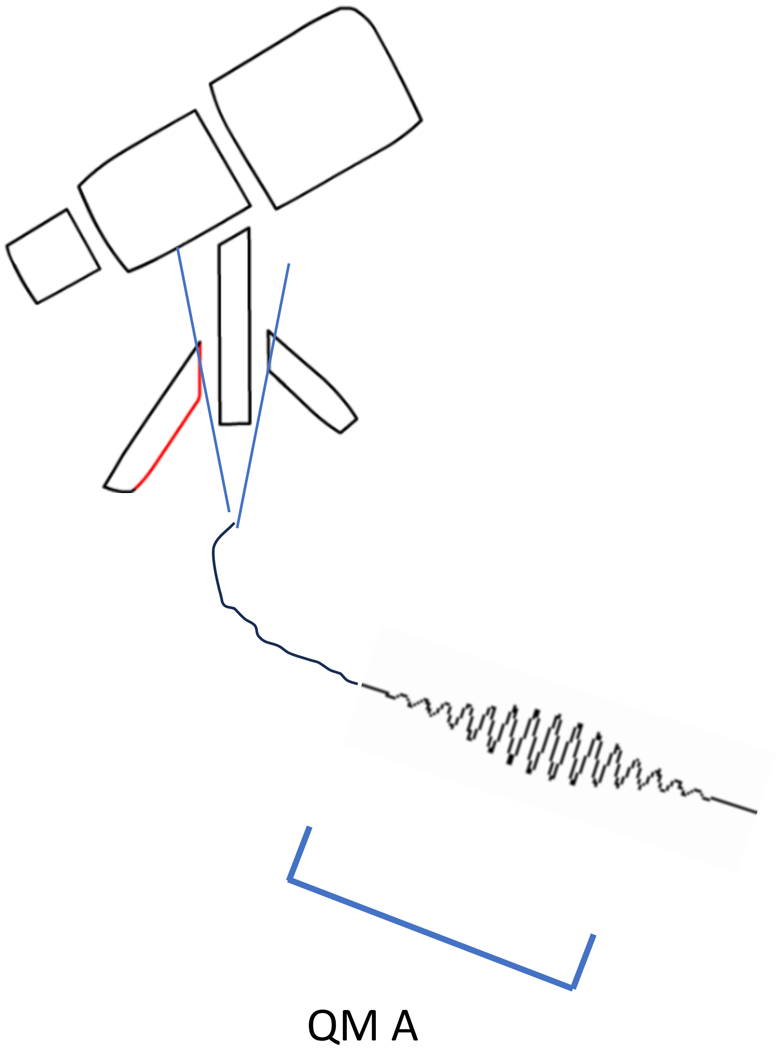
Quantum memory – tuning fork analog



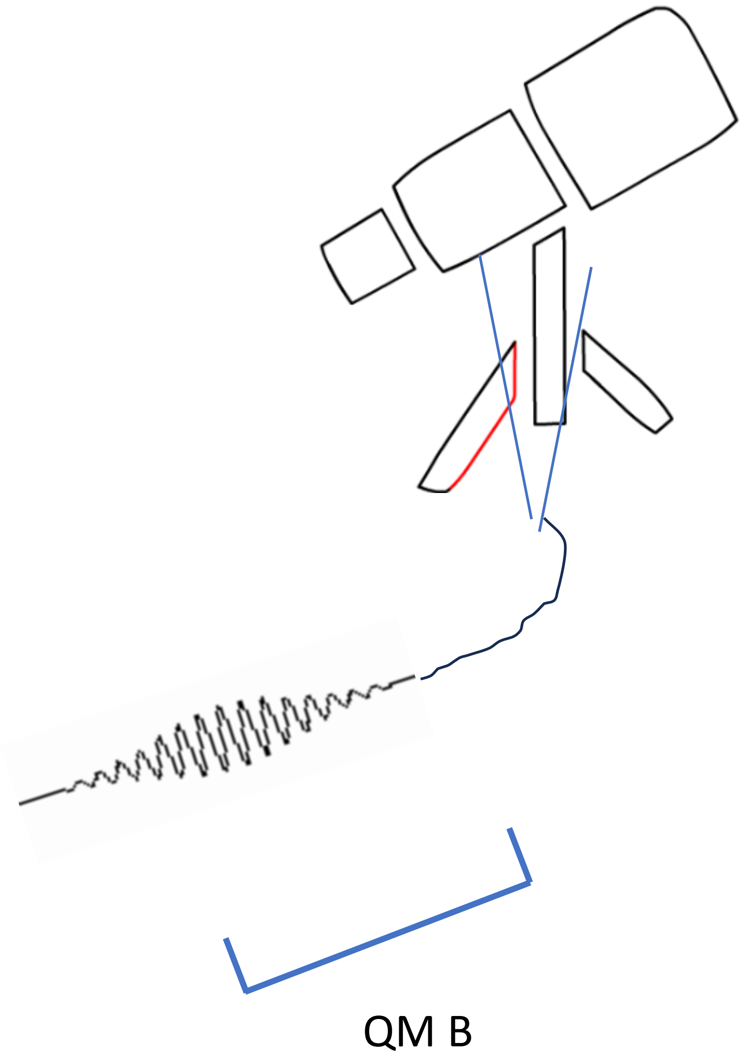
The tuning fork analogy – phase between packets independent of where sampled within packet



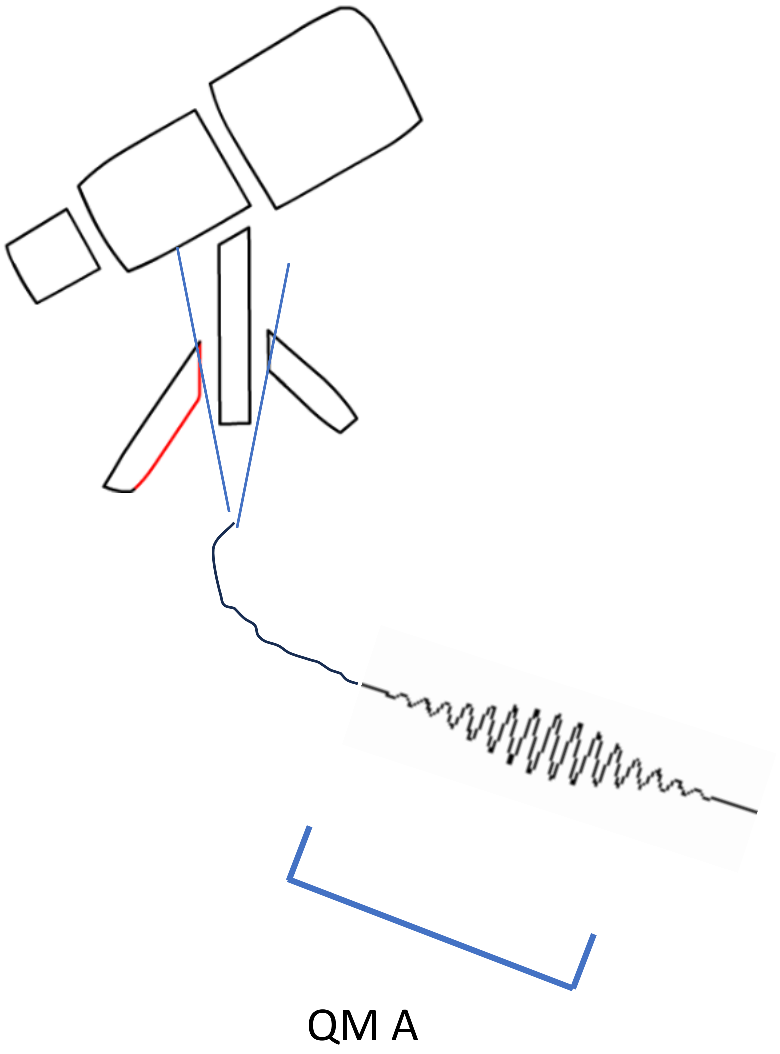
Wavefront capture –
wavefront -> quantum memory



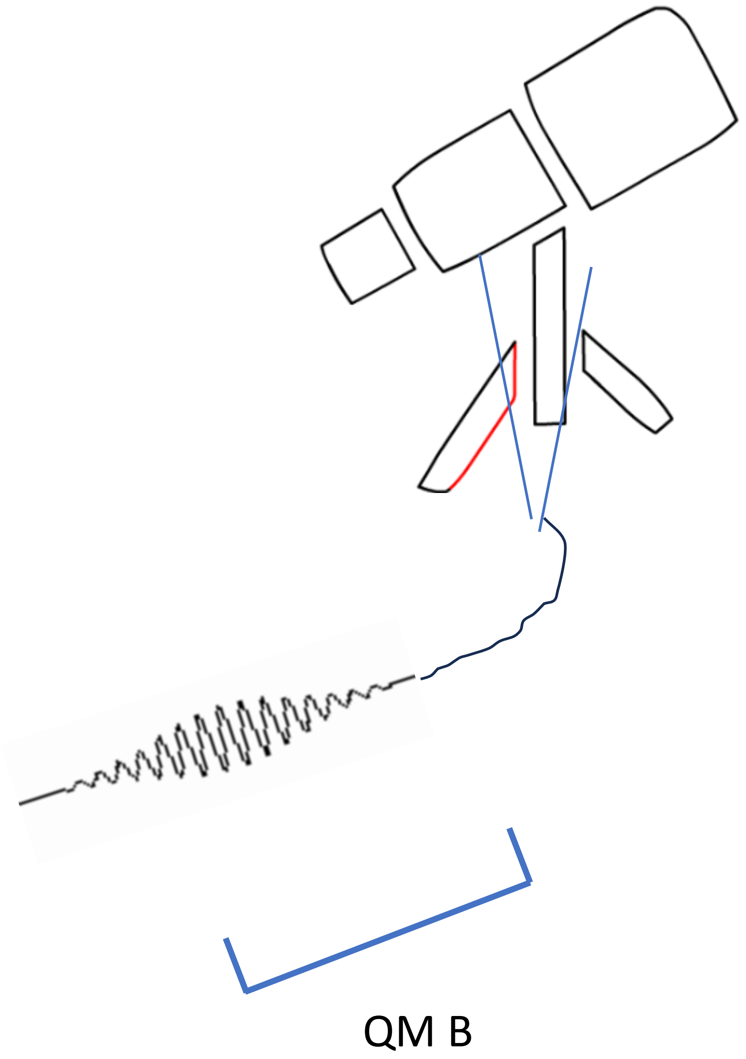
Each QM acquisition has an associated temporal window



Wavefront capture – wavefront -> quantum memory



Match optical path to
~coherence length
~ R = λ/Δλ wavelengths

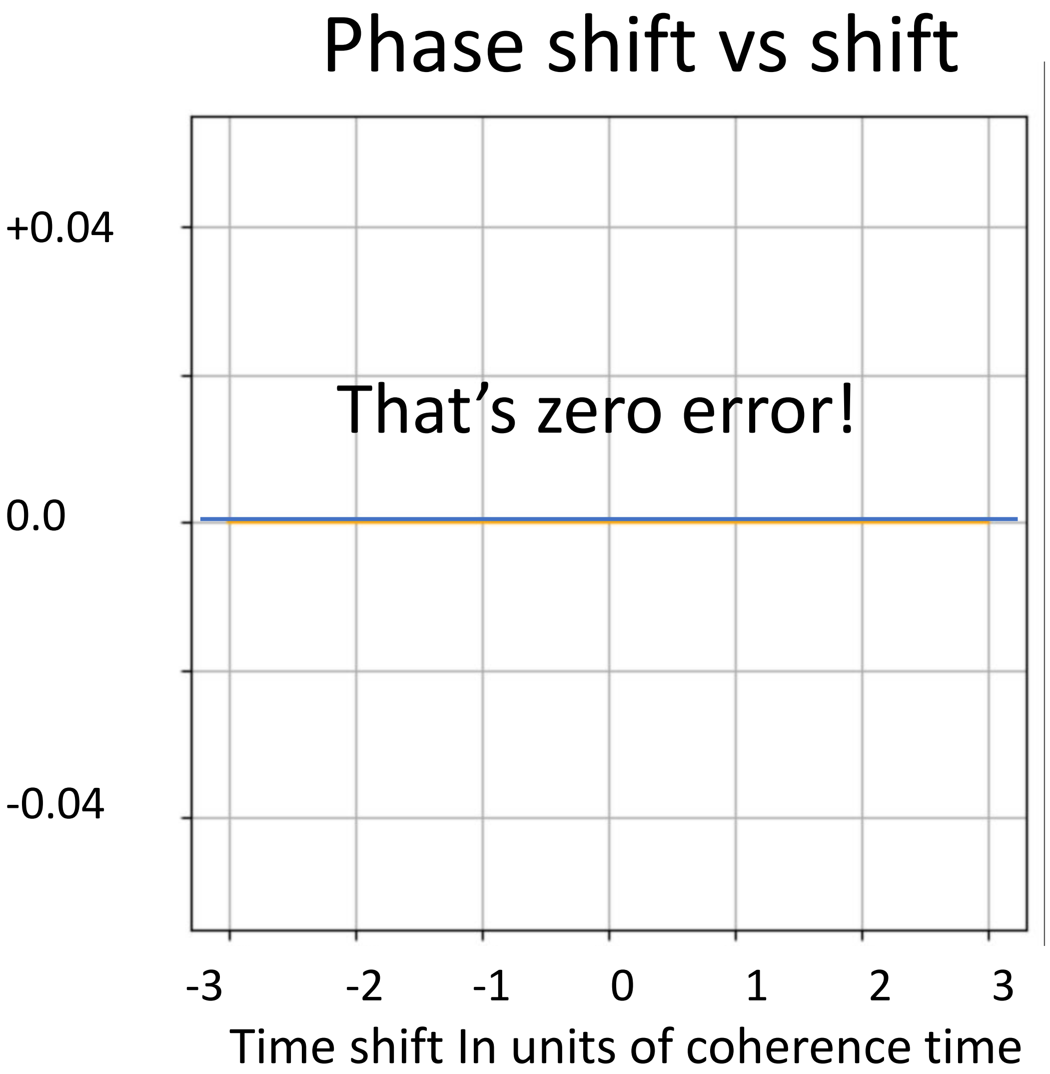


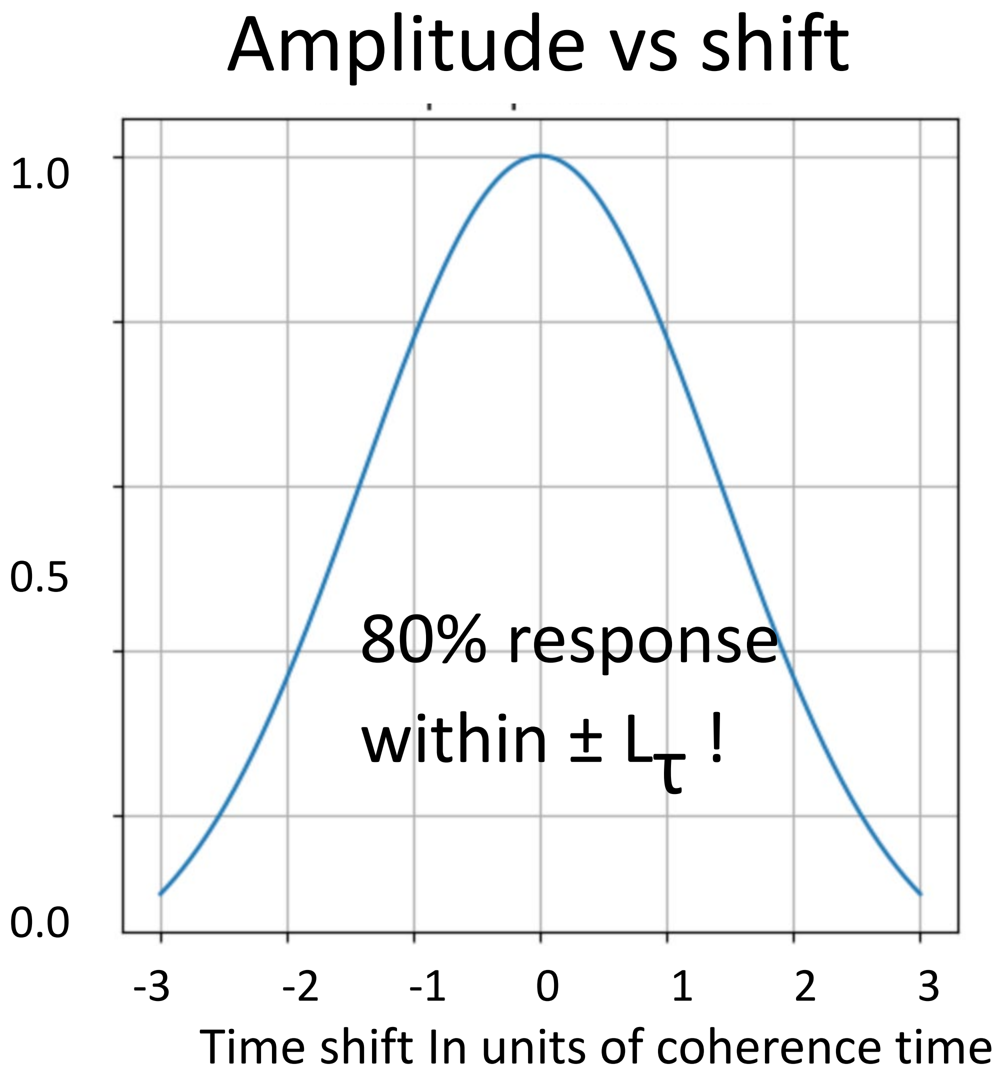
First order Glauber coherence function –
describes **interference visibility** and **phase preservation**

$$g^{(1)}(\tau) = \frac{\langle E^*(\tau)E(\tau_c + \tau)\rangle}{\langle |E(\tau)|^2\rangle}$$

Normalized correlation function of the electric field at two space-time points.

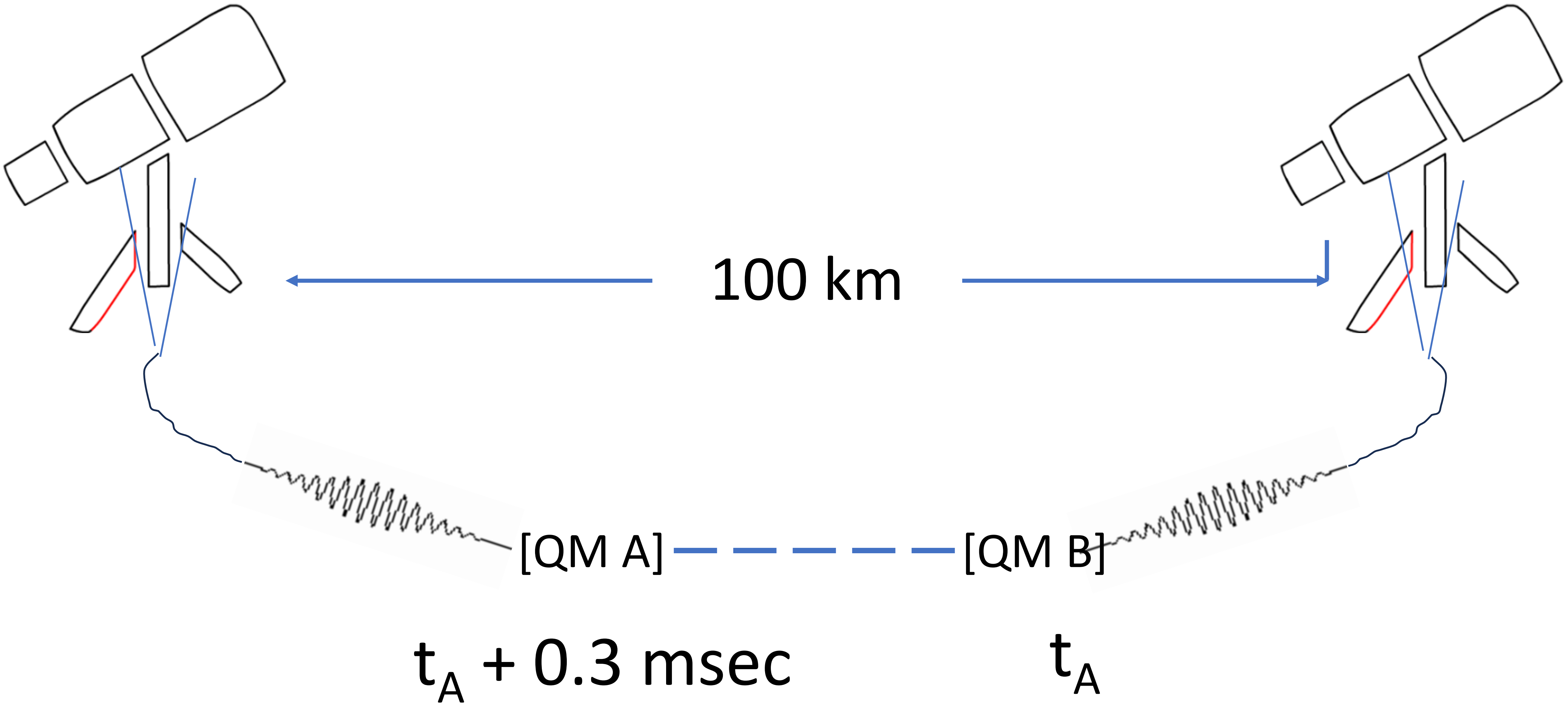
How well can we know phase and amplitude?





*Gaussian bandpass, quant. memory capture window large enough to not truncate wave packet

Replace optical delay Δx with time delay Δt= Δx /c



Did I mention….

- Quantum memory and quantum communication protocols require narrow spectral bandwidth
- Some of the attractive features described here arise from that

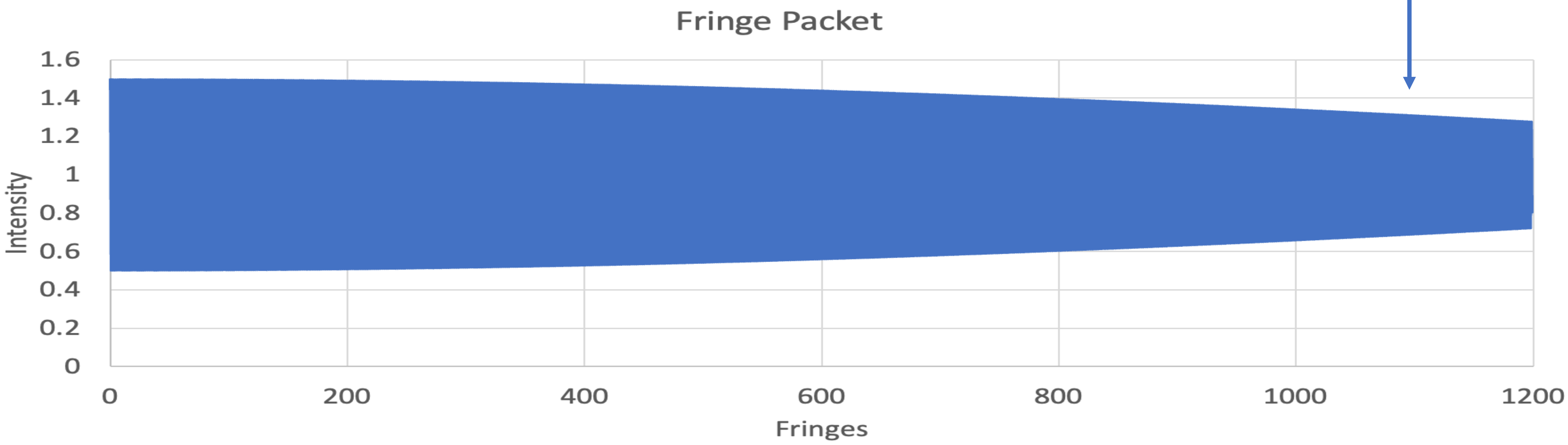
Suggest spectral parameters for discussion

- Wavelength
  - Adaptive optics performance for visible light is currently poor
  - Thermal emission > 2 μm will not play gracefully with quantum memory
  - Select 1.6 μm as nominal spectral band
- Bandwidth
  - Quantum favors narrow bandwidth
  - Select bandwidth $R = \lambda/\Delta\lambda = 20000$
  - May be workable R for quantum devices
  - Spectral multiplexing at this resolution already used in astronomy*

* E.g. Keck HiRes, cross-dispersed echelle with each waveband falling on a different detector pixel. We need – a 2-d array of quantum memories

Visualization R=20000

Suppression of visibility
40% due to R=20000



OPD = 6 mm

Can we “point blind” to coherence envelope?

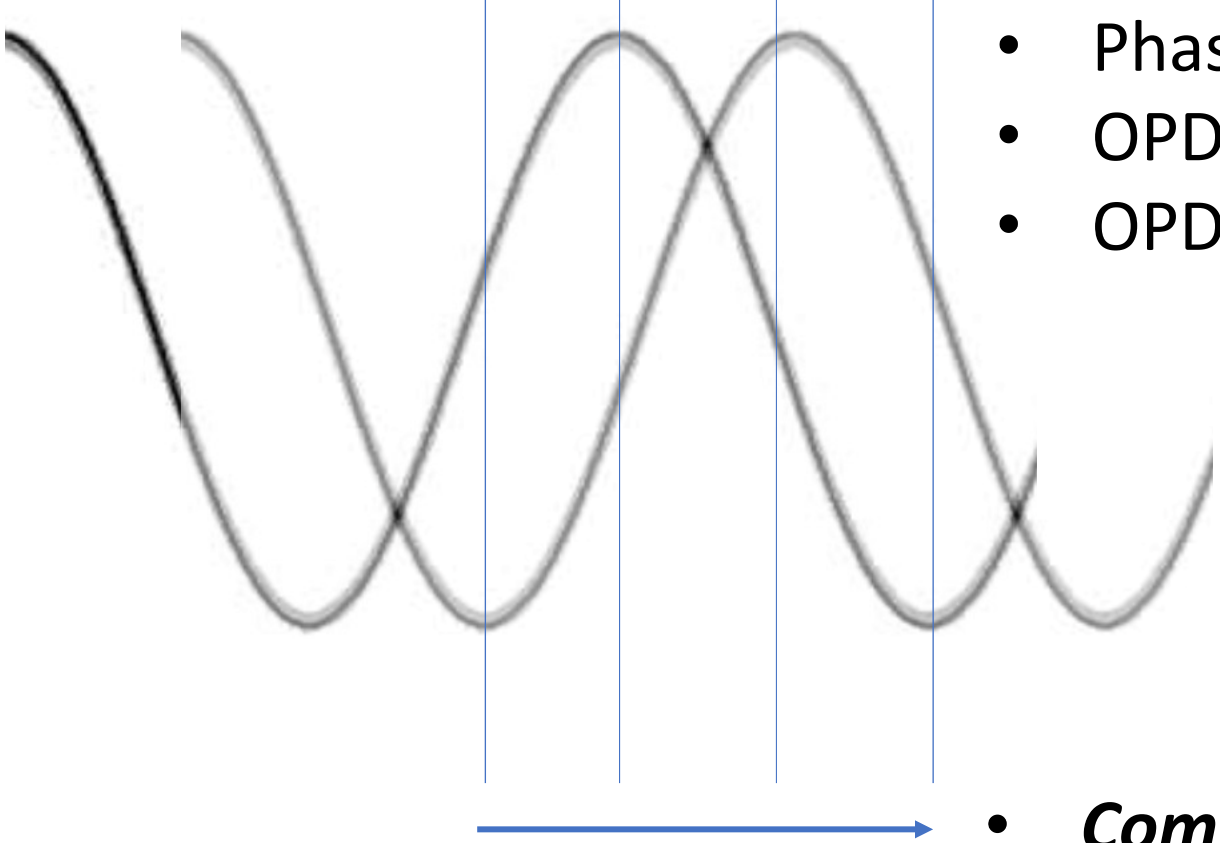
- Wavefront FWHM (Gaussian) = 2.6 cm
- Purely GPS accuracy 1-2 mm (Earth-based inertial coord system)
- What Earth modeling adds: precession, nutation, sidereal to rotation
  - Offers ~ 1mm differential relative to stars
- VLBI
  - Offers less than 1mm
- Yes, can predict fringe packet zero path to a fraction of its width

Can we match time bins at different telescopes?

- A FWHM 2.6 cm fringe packet has a temporal duration of 48 ps
- A rubidium clock synchronized to GPS – GPS-disciplined oscillator (GPSDO)
  - Accurate to 0.1 ps
- Yes, we can select corresponding time bins from different telescopes with confidence

Determine phase and visibility at 2+ wavelengths

Observe 2 wavelengths differing by 1/20000



- Phase variation with wavelength => OPD
- OPD allows correction of visibility to ZPD value
- OPD measure supports OPD control

OPD dither by quantum ops over fractional wavelength

- ***Complete interferometric measurement with OPD up to ~ cm from ZPD***

Conclusions on Feasibility of Eliminating Delay Lines

- Purely by metrology and timing, we can “point” an array and sample wavefronts within a fraction of the wavefront coherence length
- This can support quantitative interferometry – without optical path servo

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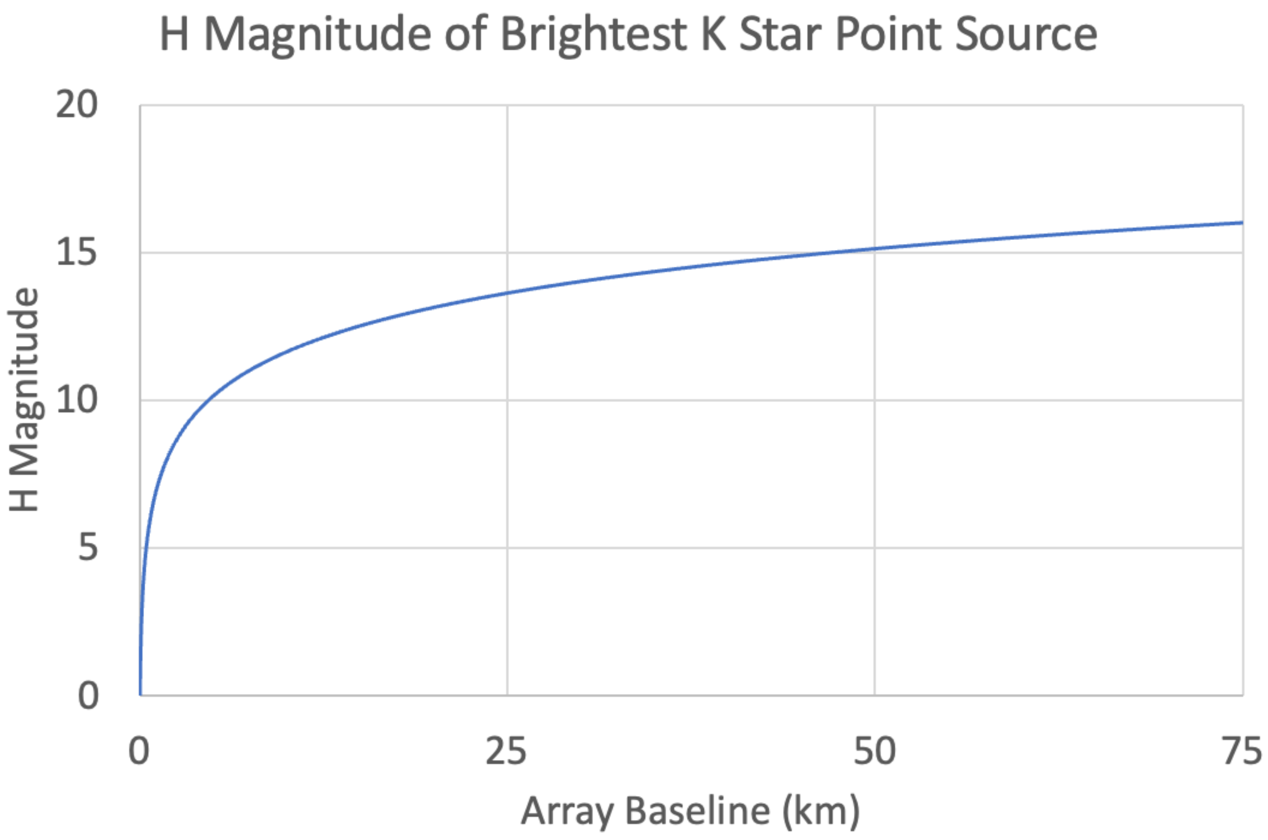
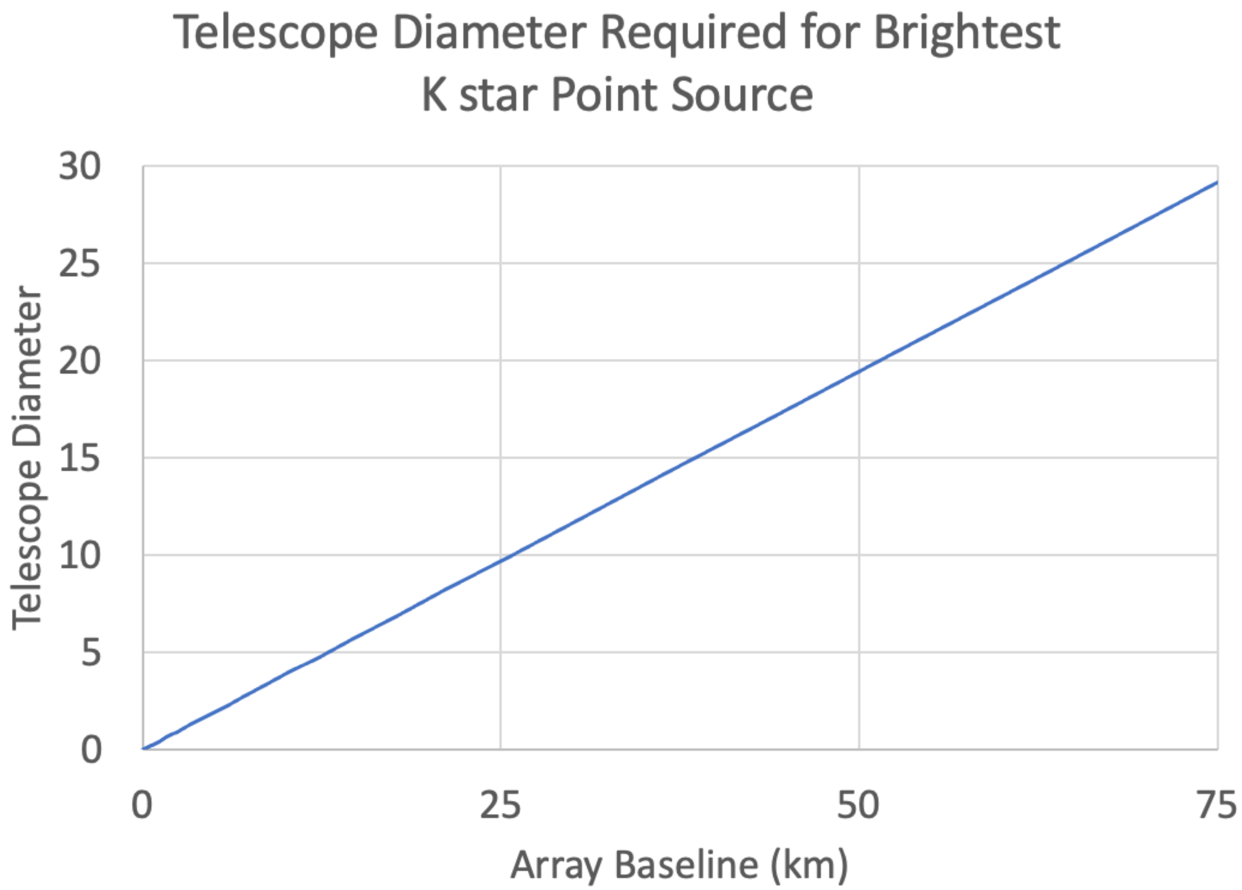
- Without servo, we would prefer to have enough signal to calibrate the spatial coherence amplitude. This requires a minimum signal (over two or more spectral bands)
- In a lower signal regime, it may still be possible to acquire fringe closure measurements one photon at a time.

Designing a Microarcsecond Array



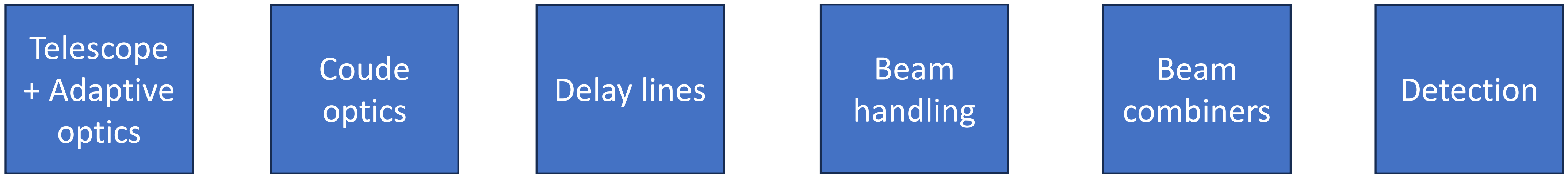


With current interferometer efficiencies, need bootstrapping beyond ~10-20 km baseline

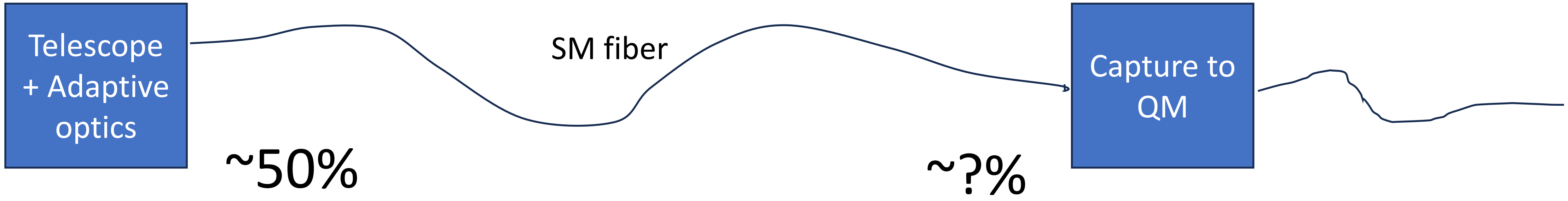
Assumptions in previous slide

- Fringe reference star is a K star observed in the H band
- Fringe tracking requirement defined by VLTI performance
  - AT Diameter = 1.8m
  - Limit fringe tracking magnitude = 9.5
  - Photon rate = 7.07E5 per second

Efficiency improvements?



Classical – 1% throughput



Next steps toward quantum interferometery

- Parameters to develop next:
    - Quantum memory characteristics
    - Quantum communications/computing support
- Efficiency budget for photon losses
- Calibration budget for derived visibilities and phases
- Astronomers observing calculator
    - Predicted S/N for standard measurements of simple targets
        - Point sources
        - Uniform disks
        - Equal amplitude binaries
        - Faint companions