Afshar Explained

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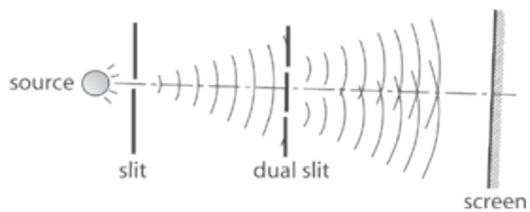
The Question

- Young interferometer (c.1800) with two coherent sources of light (slits) exhibits interference (a la **waves**) with dark and light bands appearing on an opaque screen positioned several feet from slits [1,2]



- Quantum version (c.1927). Light is comprised of **photons** (discrete particles), but interference pattern implies wave behavior.
- Bohr's *Complementarity Principle* states we cannot measure both:
  - Photon's exact path to the screen (knowledge K=1)
  - Wave character which produces interference fringes (visibility V=1)
- Other experiments (1999-2004) support $V^2 + K^2 \leq 1$
- Afshar (2004) replaces screen with a convergent lens (like a camera)
  - Two images spots are visible (K=1) in the presence of interference (V=1)
  - He concludes that $V^2 + K^2 = 2$ and therefore Bohr was wrong [3]
- Which position is correct?

Opposing Interferometers

- W.Uruh [4] has proposed a counter-argument to Afshar's claim
- Unruh's thought experiment employs a tandem Mach-Zehnder interferometer to show that path information is lost
- We first list the essential differences b/w these interferometers and then examine their operation in detail

YAW (Young-Afshar-Wheeler)

- *Real* experiment [3]
- Modified Young I/F
- Lens replaces screen
- Fine wire comb positioned in front of lens proves presence of fringes (V=1)
- Two distinct image spots à la J.A. Wheeler (K=1)
- Hence $V^2 + K^2 = 2$

UMZ (Unruh-Mach-Zehnder)

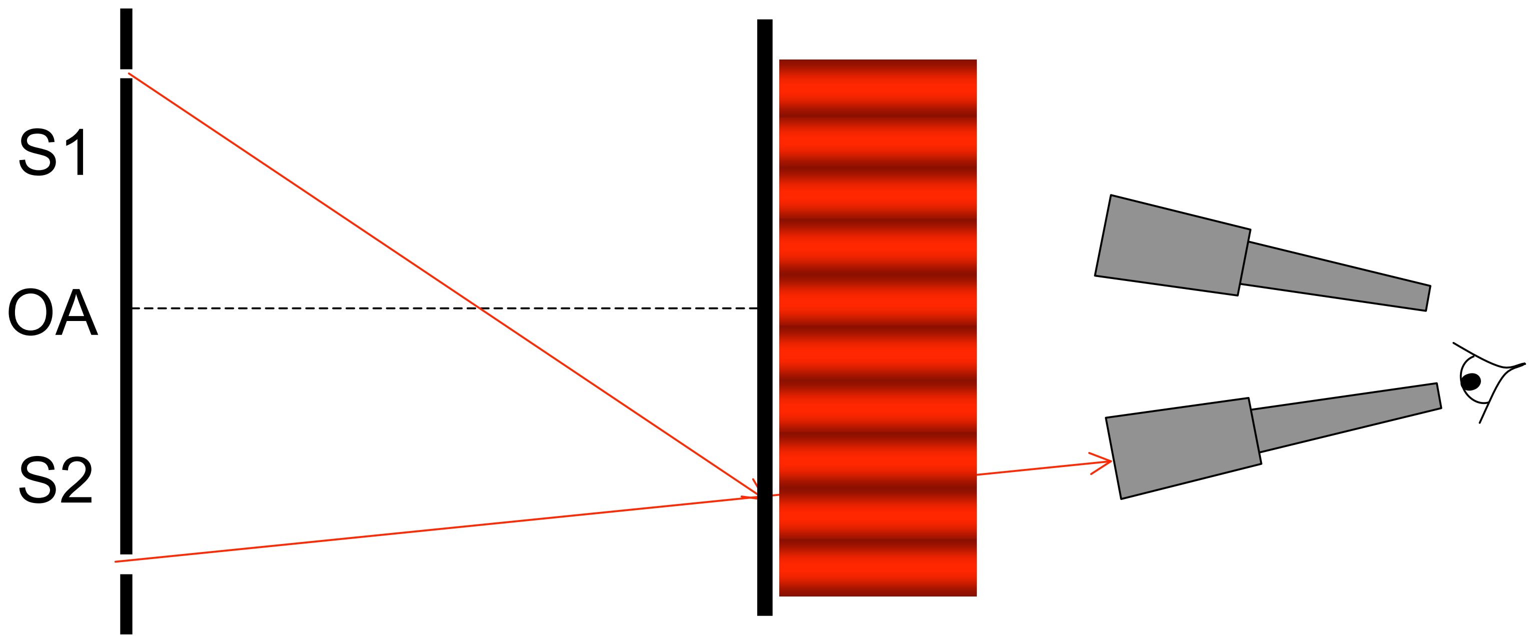
- Thought experiment [4]
- Tandem Mach-Zehnder I/F with absorbers
- No lenses, no screens
- Absorber proves interference (V=1)
- Either detector triggered 50% of the time (K=0)
- Hence $V^2 + K^2 \leq 1$

The YAW Interferometer

Imaging Photon Paths
in the Presence of Interference

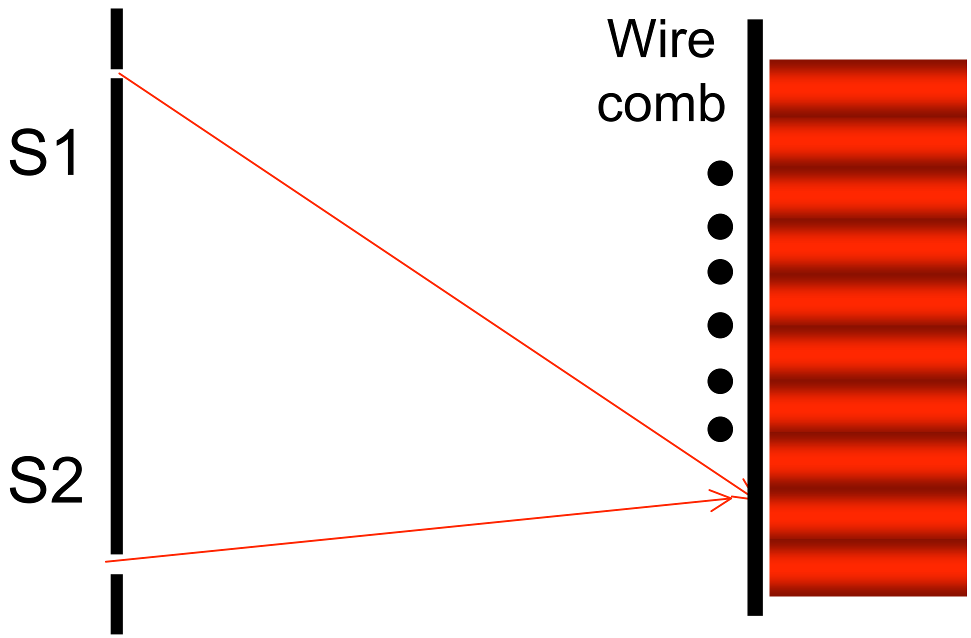
Wheeler Interferometer

J. A. Wheeler, "Delayed Choice," in Mathematical Foundations of Quantum Theory: Proceedings of the New Orleans Conference on the Mathematical Foundations of Quantum Theory, edited by A. R. Marlow (Academic, New York, 1978)



Decide *after* photon leaves pinholes either to look at a pinhole with telescopes (K=1) or insert screen (V=1).

Afshar Modification #1

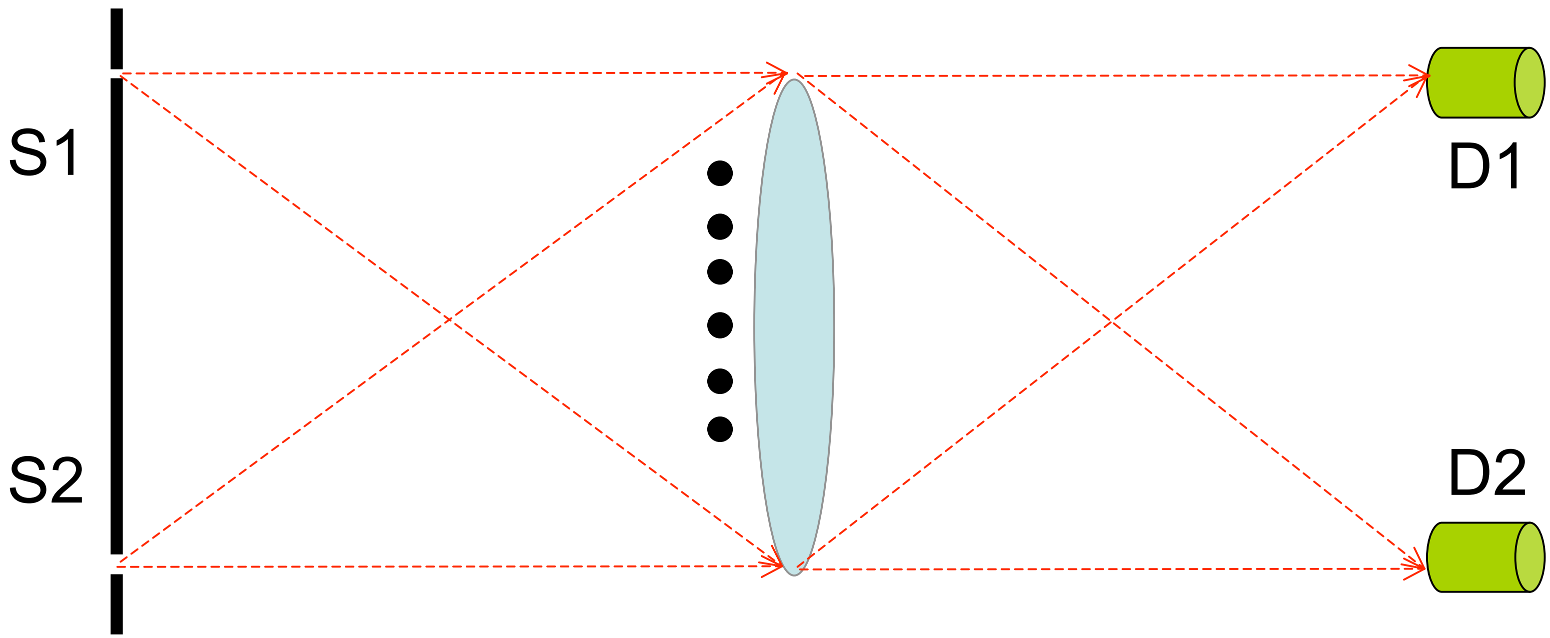


Essentials only. We don't discuss confounding effects such as:

- Losses in lens
- Diffraction
- Airy disks
- Apodization
- See [1,2,3]

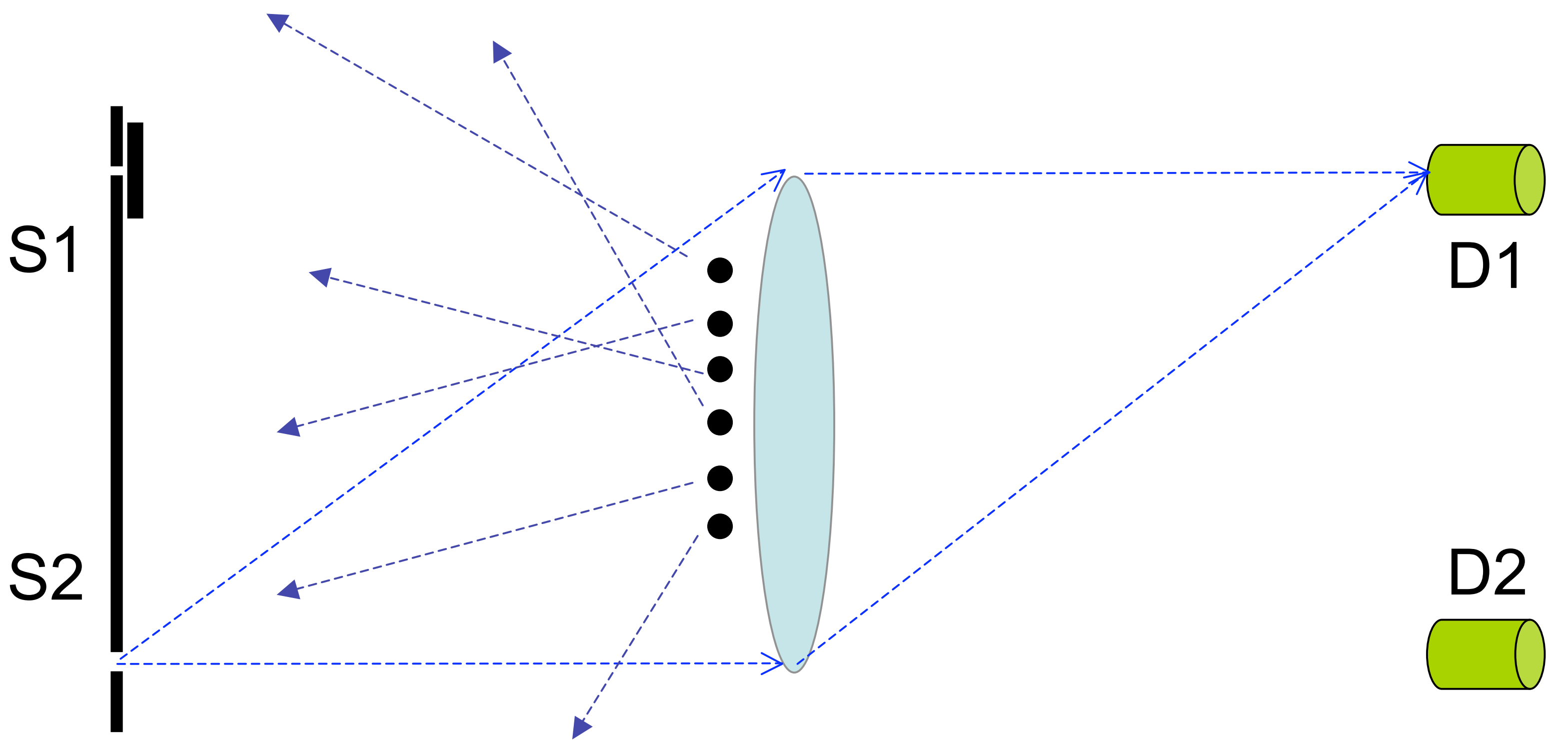
Insert screen to image the interference fringes.
Place 6 fine wires where dark fringes appear on screen.

Afshar Modification #2



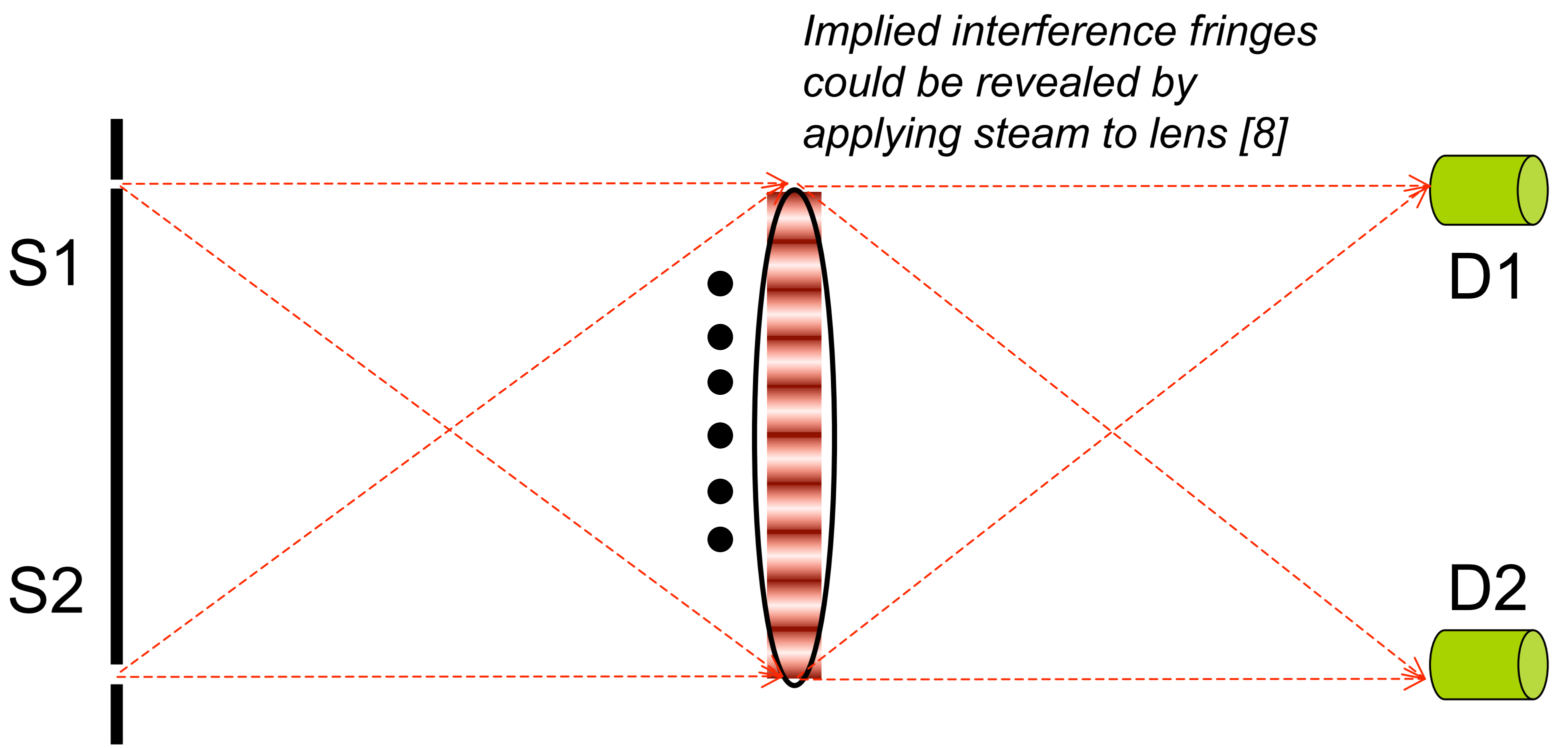
Replace screen behind wires with a convergent lens.
Replace Wheeler telescopes with photon detectors.

YAW Experiment: Step 1



Close one of the pinhole sources (e.g., S1).
Single incoherent source (S2) means there is no interference.
Wire comb scatters 6% of light flux if only S2 (or S1) is open.

YAW Experiment: Step 2



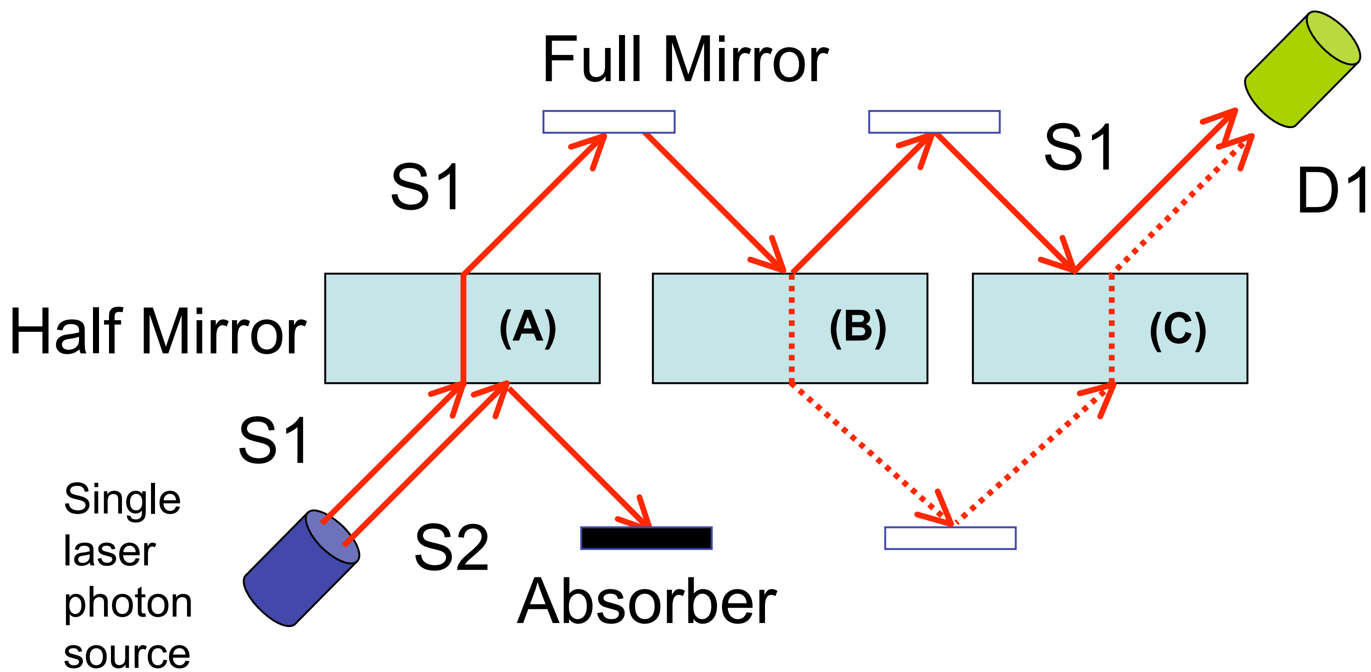
Now open both pinholes to produce *coherent* sources.
No scattering off wires when *interference* is present (V = 1).
But also record two distinct image spots at detectors (K = 1).

The UMZ Interferometer

How Path Information Becomes Lost
in the Presence of Interference

Block Path S2

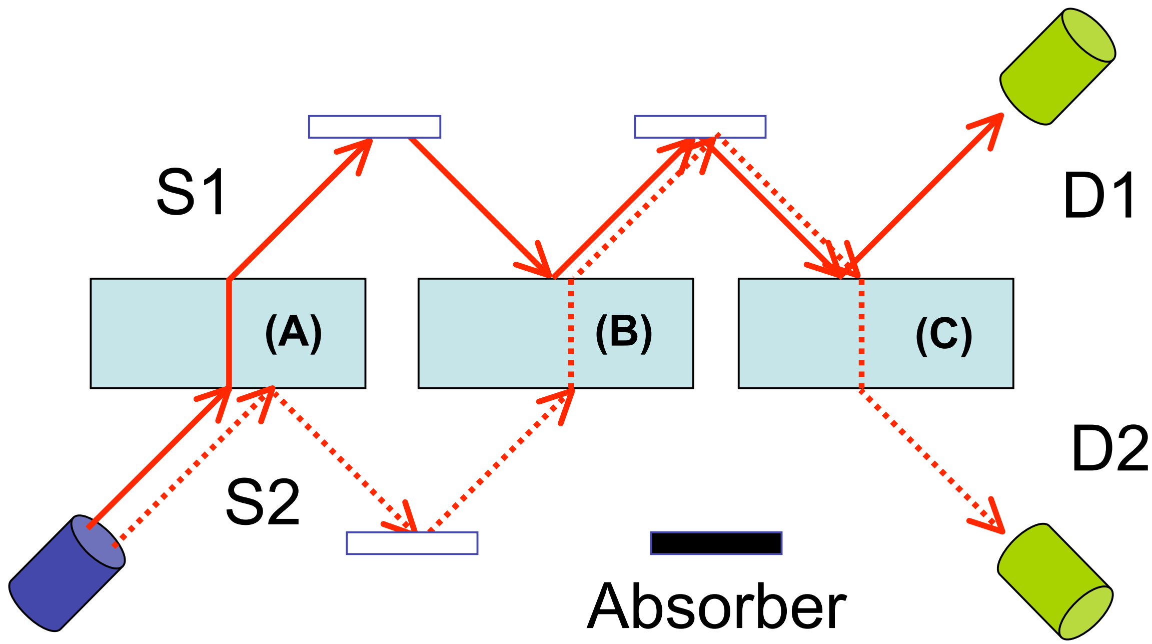
Next 3 slides summarize Unruh's counter-argument [4]



This arrangement is the logical equivalent of Afshar step 1.
HSM (A) simply creates twin coherent photon sources.
Only photons on path S1 can trigger D1.
Similarly for S2 and D2. Path can be known (K=1).

Interfering Paths: Case 1

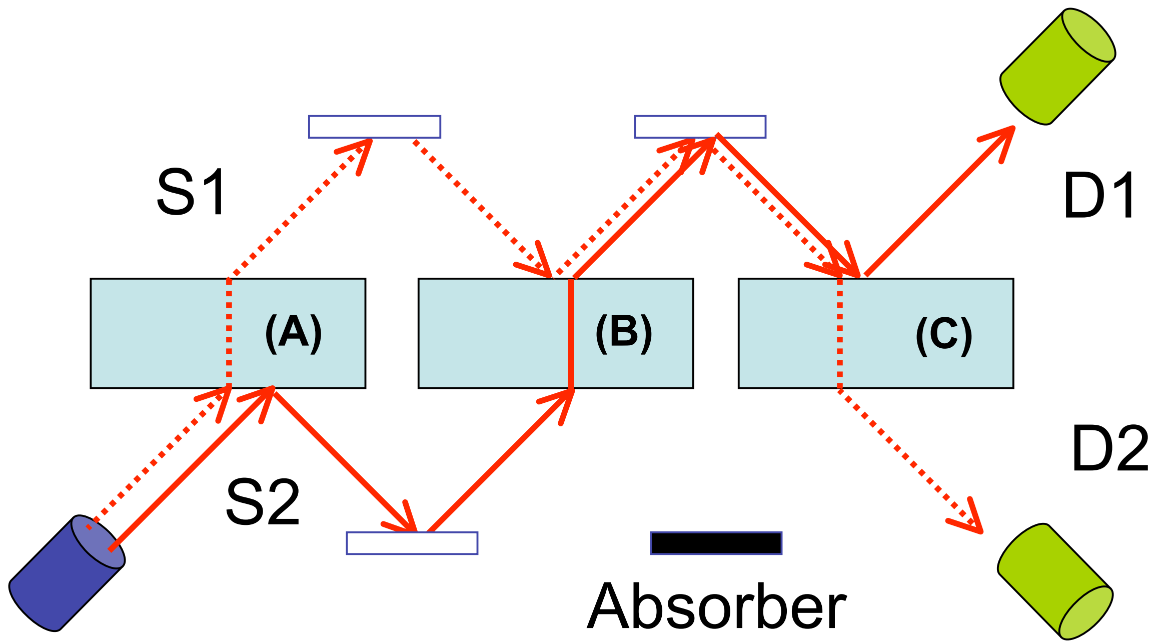
UMZ interferometer now adjusted to produce interference



This arrangement is the logical equivalent of Afshar step 2.
Mirror arrangement produces *destructive interference* in lower channel.
Full mirror near (B) now replaced with an absorber (cf. Afshar wires).

Interfering Paths: Case 2

With interference (V=1), **path information is lost** (K $\neq$ 1).
Therefore, QM is correct and Afshar's claim is invalidated.



Absorber provides a *null measurement* of complete interference.
D2 always sees a "dotted" photon coming from either S1 or S2.
This ambiguity means that complete path information is lost.

Slippery Road Ahead

YAW Interferometer

- State-of-yore
- Pinholes
- Diffraction effects
- Flux measurements
- Wire comb
- Optical path ~5m
- Less precise, more error
- Limited to measuring interference effects only

UMZ Interferometer

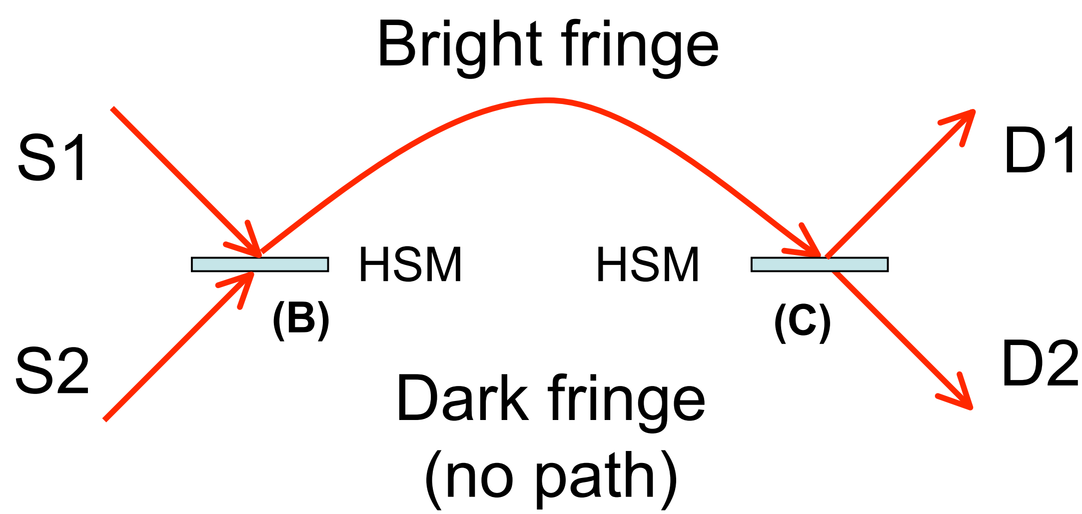
- State-of-the-art
- Beam splitters
- No diffraction
- Count photons
- Absorbers
- Optical path ~0.5m
- High precision measurements
- Beyond interference: entanglement, erasure

- Afshar dismisses Unruh's analysis on the grounds that UMZ is not a faithful representation of YAW [9]. Subsequently, we show that Afshar is indeed vindicated on that particular point; YAW physics *is* subtly different, although Unruh's argument is logically correct.
- Moreover, the UMZ analysis forces Afshar into the weaker logical position of claiming that we must use his special (more confounded) YAW interferometer in order to observe what is otherwise supposed to be a *universal* quantum effect.

Mapping Between YAW and UMZ

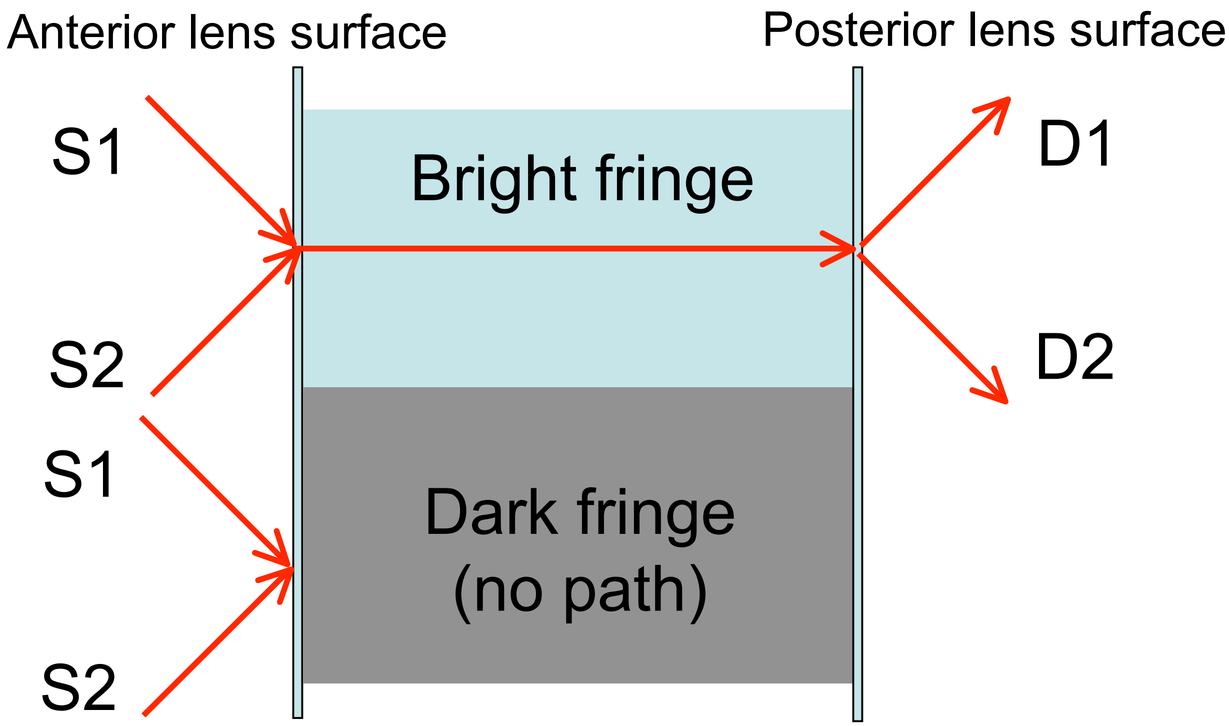
Why These Two Interferometers
Are Not Identical

Simplified UMZ Schematic



Only half-silvered mirrors (**HSM**) are shown.
HSM (A) responsible for creating 2 sources elided.
Full mirrors and absorber have also been elided.

Equivalent UMZ Model of Lens



But a real lens is not like UMZ. No HSMs or birefractive crystals. Single refractive index. Surfaces are not parallel.

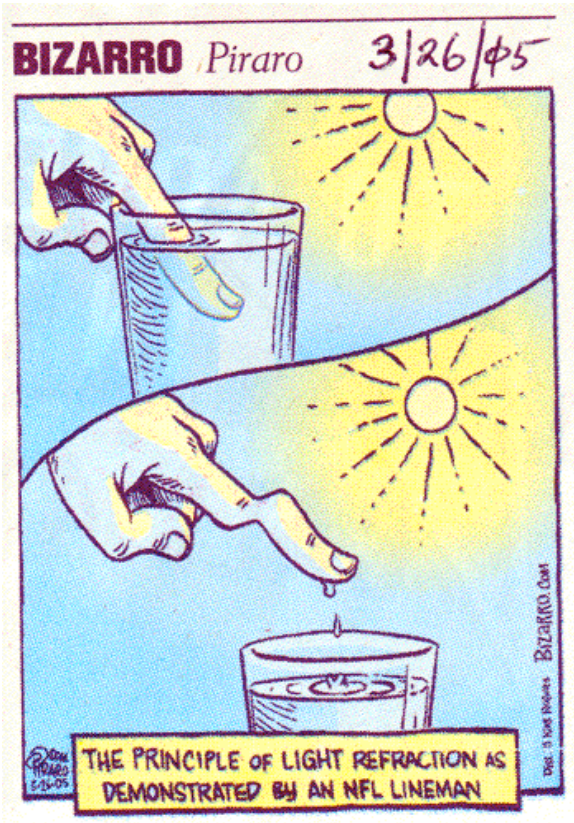
The Paradox

- Interference effects:
  - Coherent UMZ sources => interference
  - Interference => xmit photon (bright) or not (dark)
  - Interference => *must* lose path information
- Refractive effects:
  - UMZ experiment uses **bi**-refractive HSMs
    - Photon paths split 50/50, so path info is lost
  - YAW lens has a **single** refractive index
    - So, Afshar claims path information is *not* lost

How Lenses Work

Bending Light Without Refraction

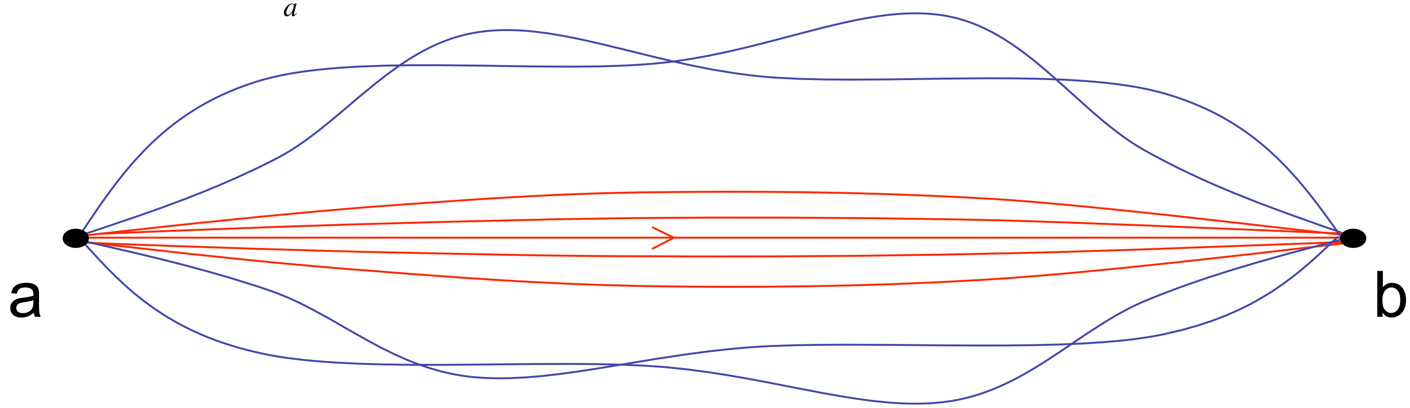
Index of Refraction



- Usual explanation of why objects appear to bend as light goes from air to water relies on the difference in *refractive index*.
- Snell's law: $n_a \sin\theta_a = n_w \sin\theta_w$
- But this is merely an approximation to the actual quantum behavior of light

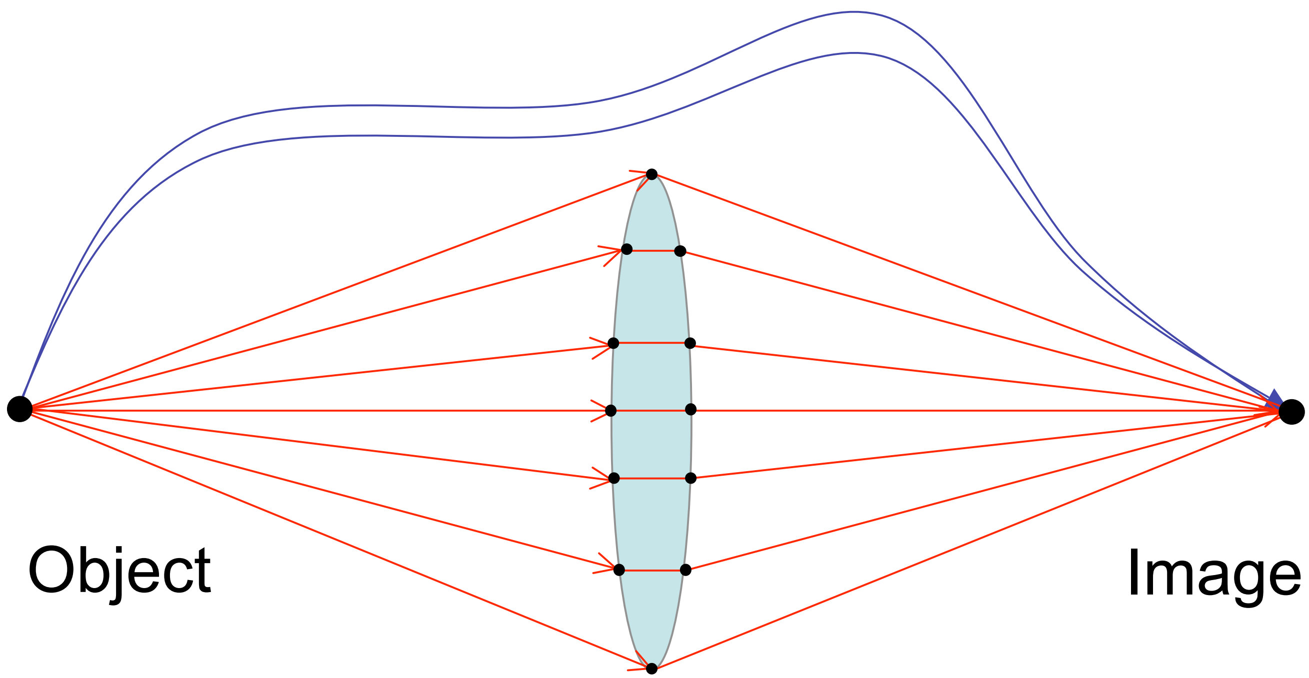
QPI Paths Through Free Space

$$G(x_b, t_b \mid x_a, t_a) = \int_a^b Dx(t) \exp(iS(t_b, t_a)/\hbar)$$



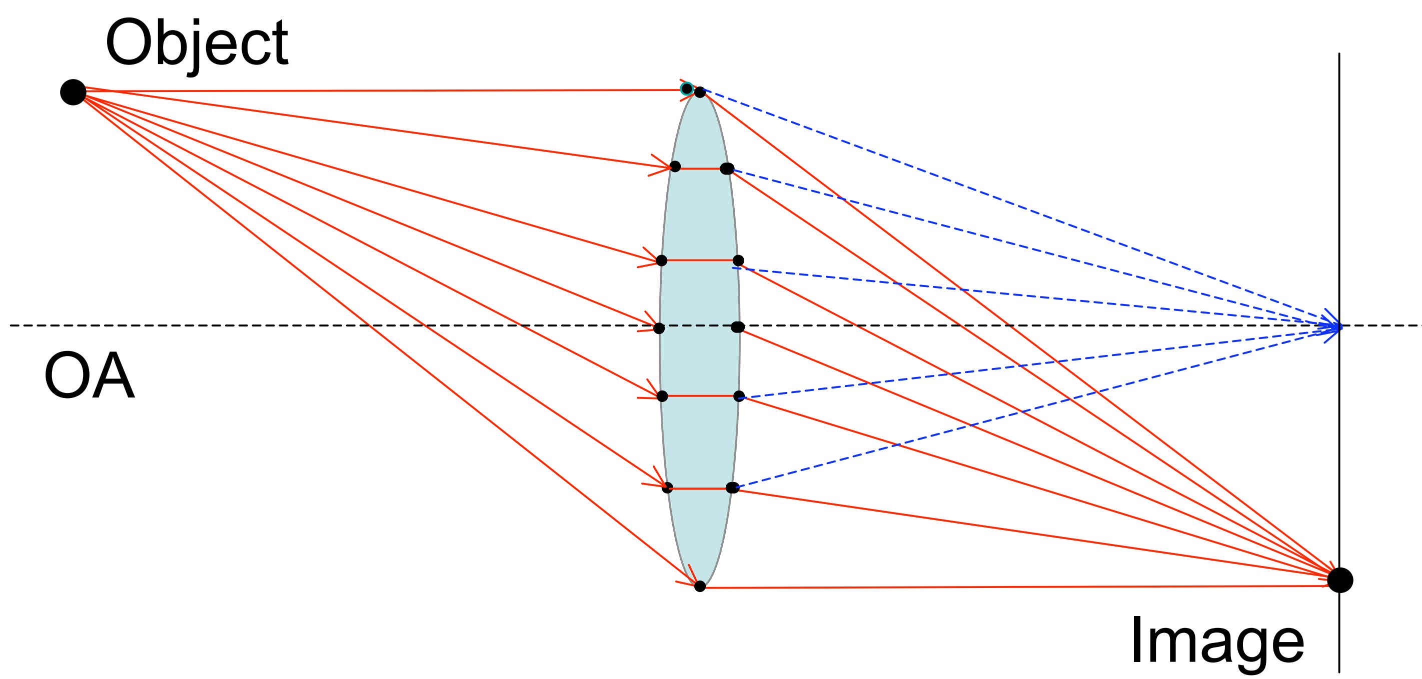
- Quantum path integral (QPI) formulation [5].
- Sum over all paths from A to B given formally by propagator G(b|a).
- Light travels from point A to point B via a "tube" of *virtual photon* paths. See [6] for a more detailed qualitative discussion.
- Neighboring paths are phase-reinforced (**red**). All others (e.g., **blue**) tend to arrive at B with opposing phases and cancel.
- Red paths are *least-time* (Fermat) paths analogous to principle of *least action* in mechanics [7]. More generally *stationary* paths.

QPI Paths Through a Lens



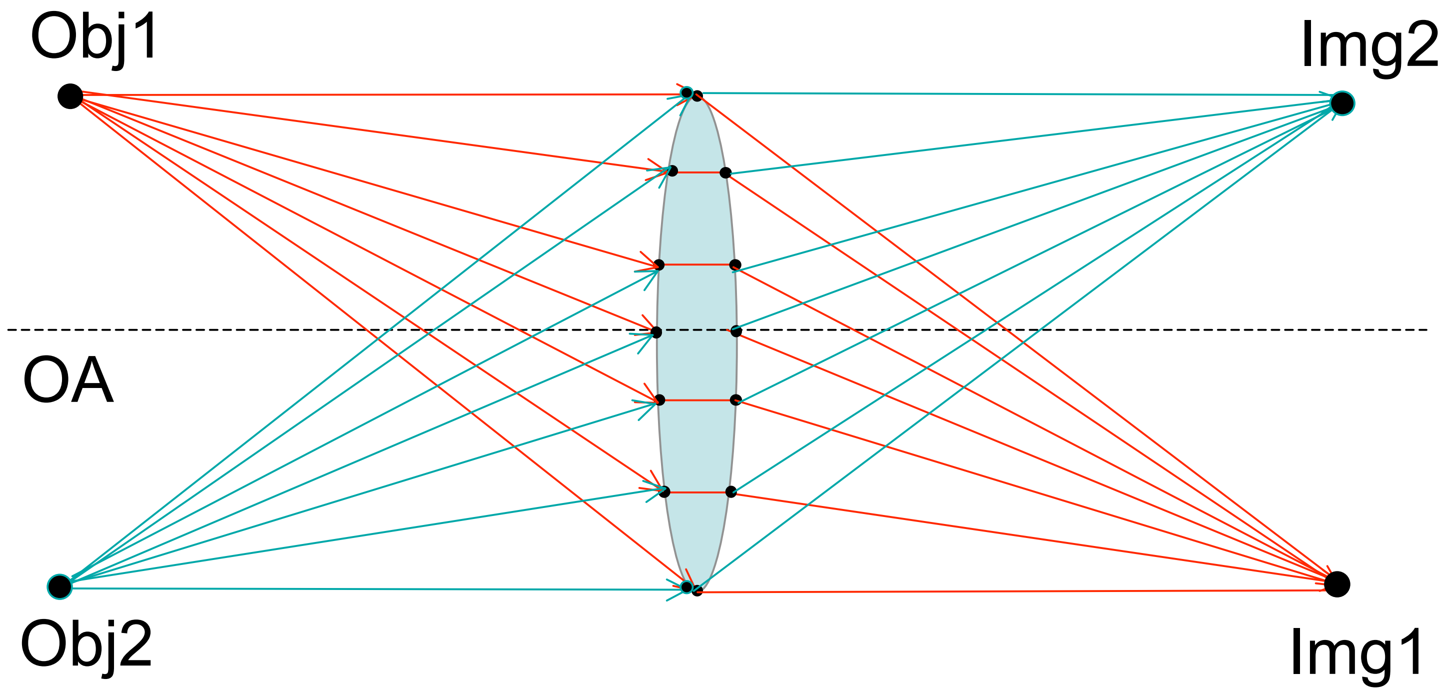
Quantum path integral (QPI) explanation of *refraction* in lens [5,6].
Time through lens is longer at thicker center than at thinner edges.
Lens makes QPI paths *isochronous* and thus reinforce at image.
Blue (non-iso) paths exist but they ultimately cancel at the image.

Off-Axis QPI Iso-Paths



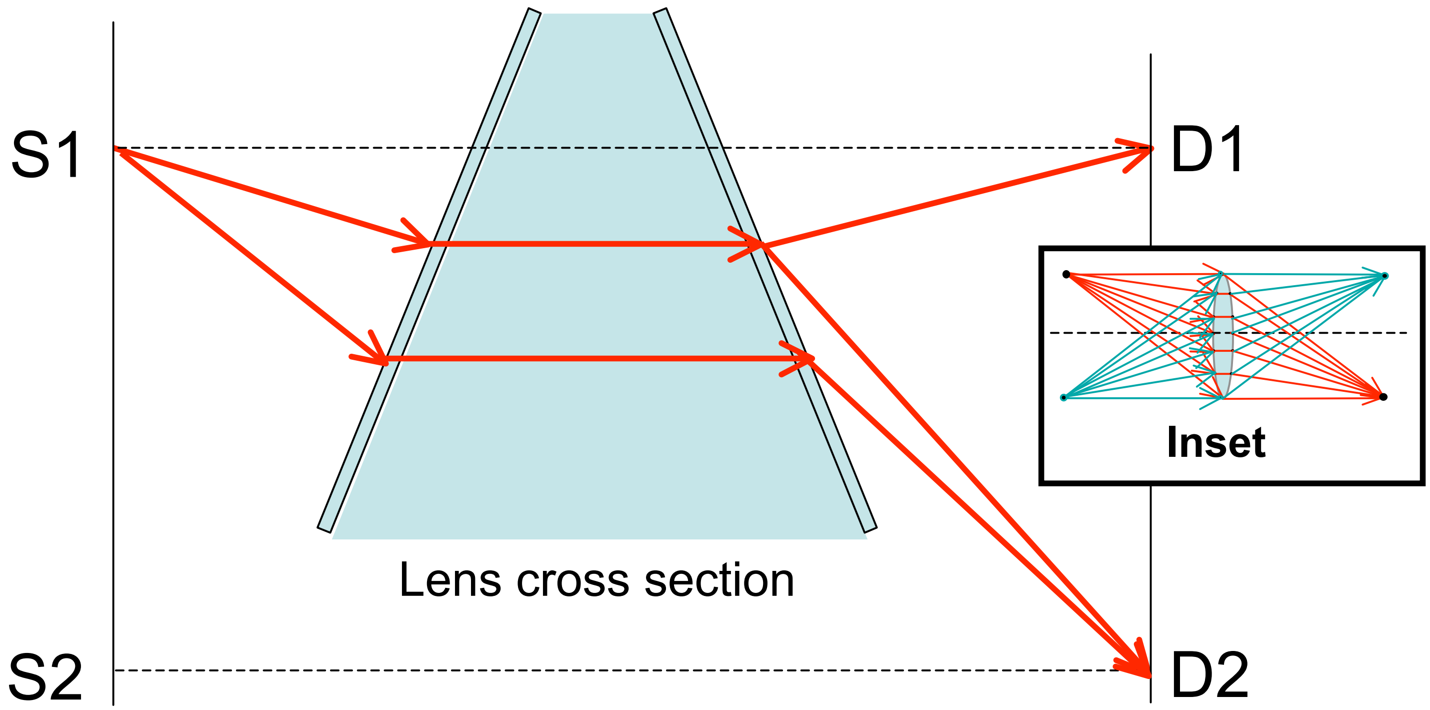
Inverted image in convergent lens (red iso-paths).
Non-iso blue paths *exist, but cancel at image plane.*

Imaging Two Objects



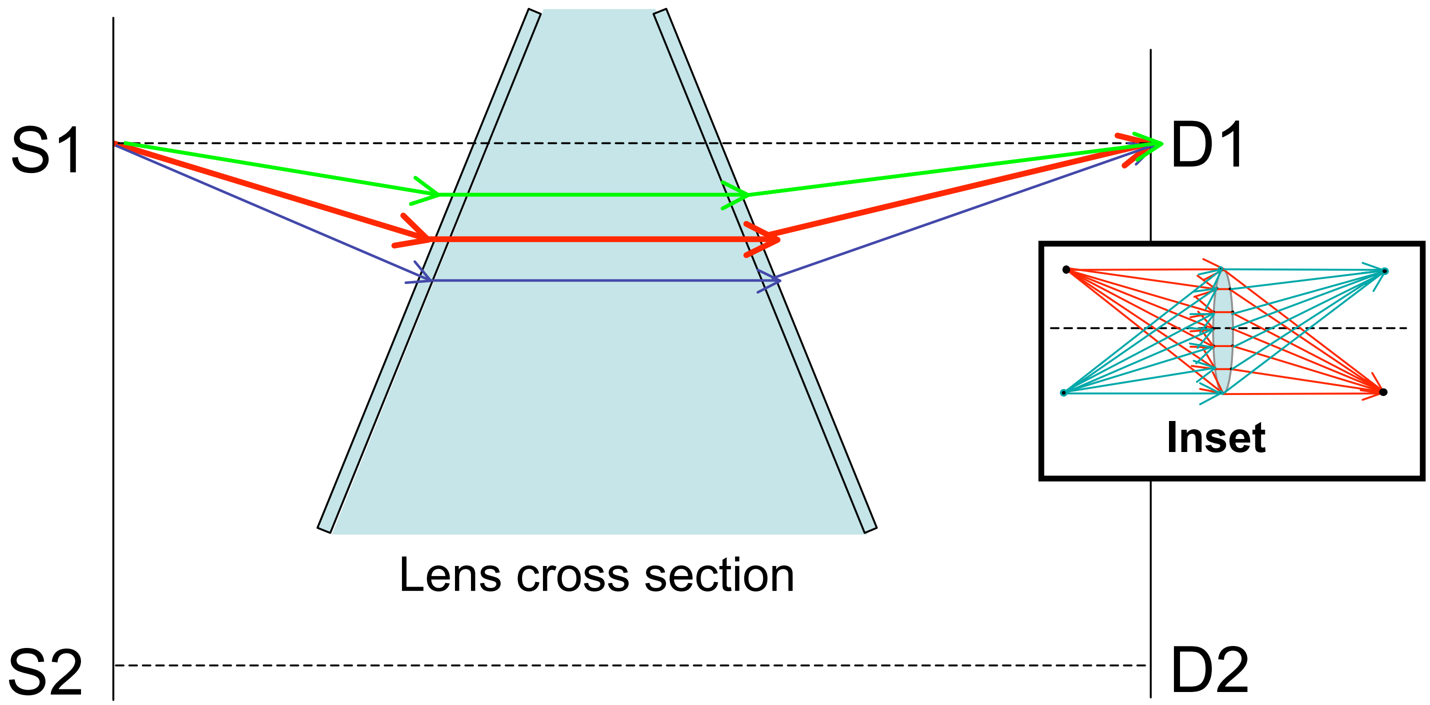
Light is either scattered or emitted by each object.
Sum over all virtual photon QPI paths.
Surviving iso-paths produce two *inverted* images.

Lens Refraction in Detail



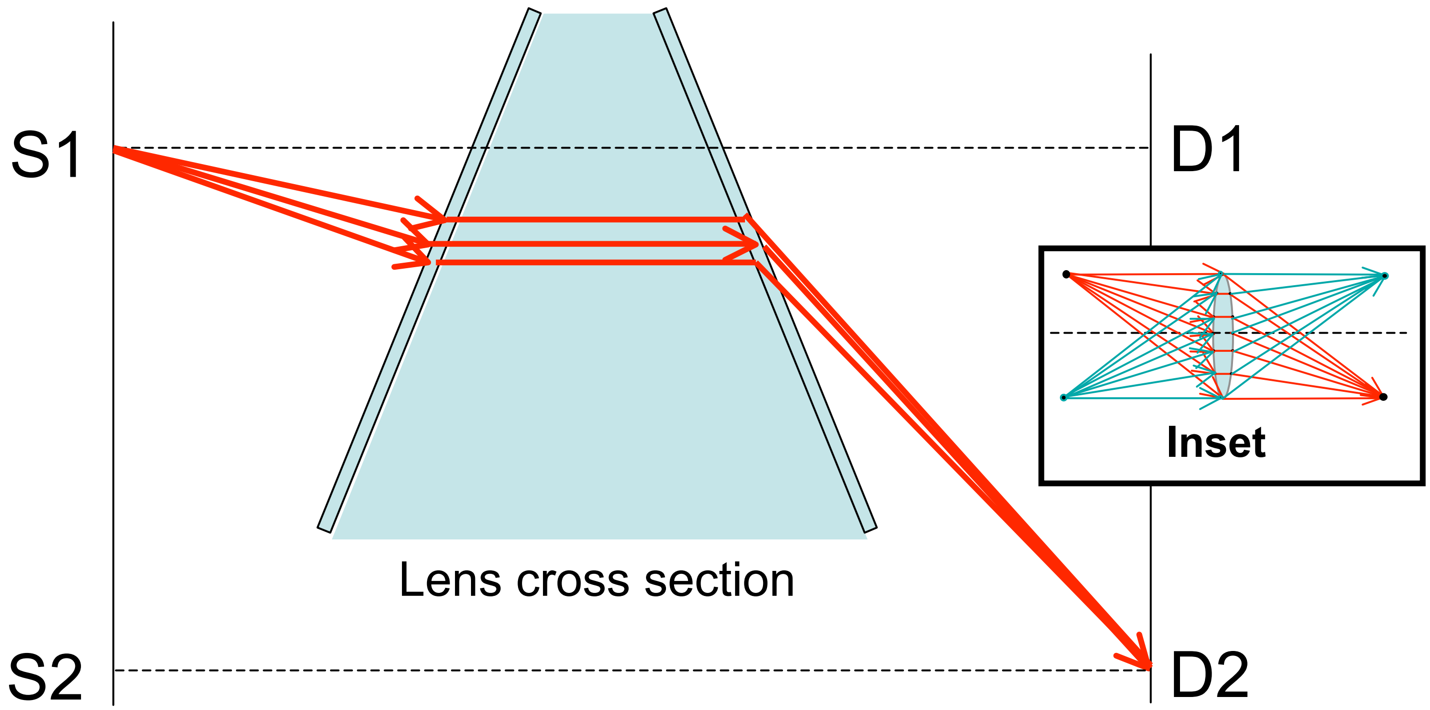
A path S1 ➔ D1 takes less time than S1 ➔ D2.
Any path S1 ➔ D2 takes the *same* time due to varying thickness of lens (*isochronous* paths).

Paths S1–>D1 Cancel at D1



Neighboring **BLUE** path is slightly *longer* than red path.
GREEN path is slightly *shorter*, so S1 ➔ D1 paths cancel.
Similar cancellations occur for paths from S2 ➔ D2.

Refraction from Reinforcement



All S1 ➔ D2 paths take *same* time to reach D2.
Phases of QPI paths reinforce each other at D2.

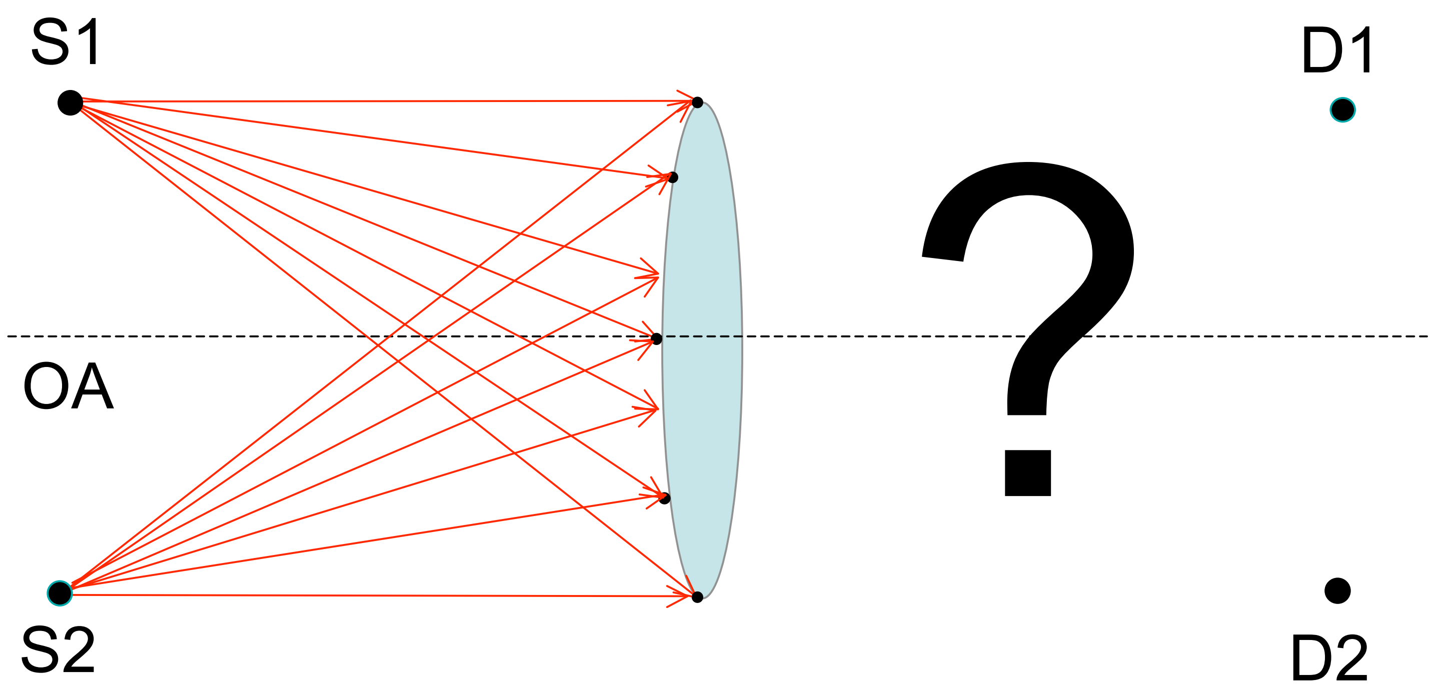
YAW Paradox Explained

How non-classical paths

S1 ➔ D1 and S2 ➔ D2

arise in a lens

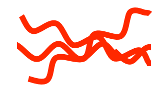
Imaging **Coherent** Sources



Coherent sources => *Interference* is present like UMZ.
But what happens beyond the lens at detectors D1, D2?

Phase Coherency

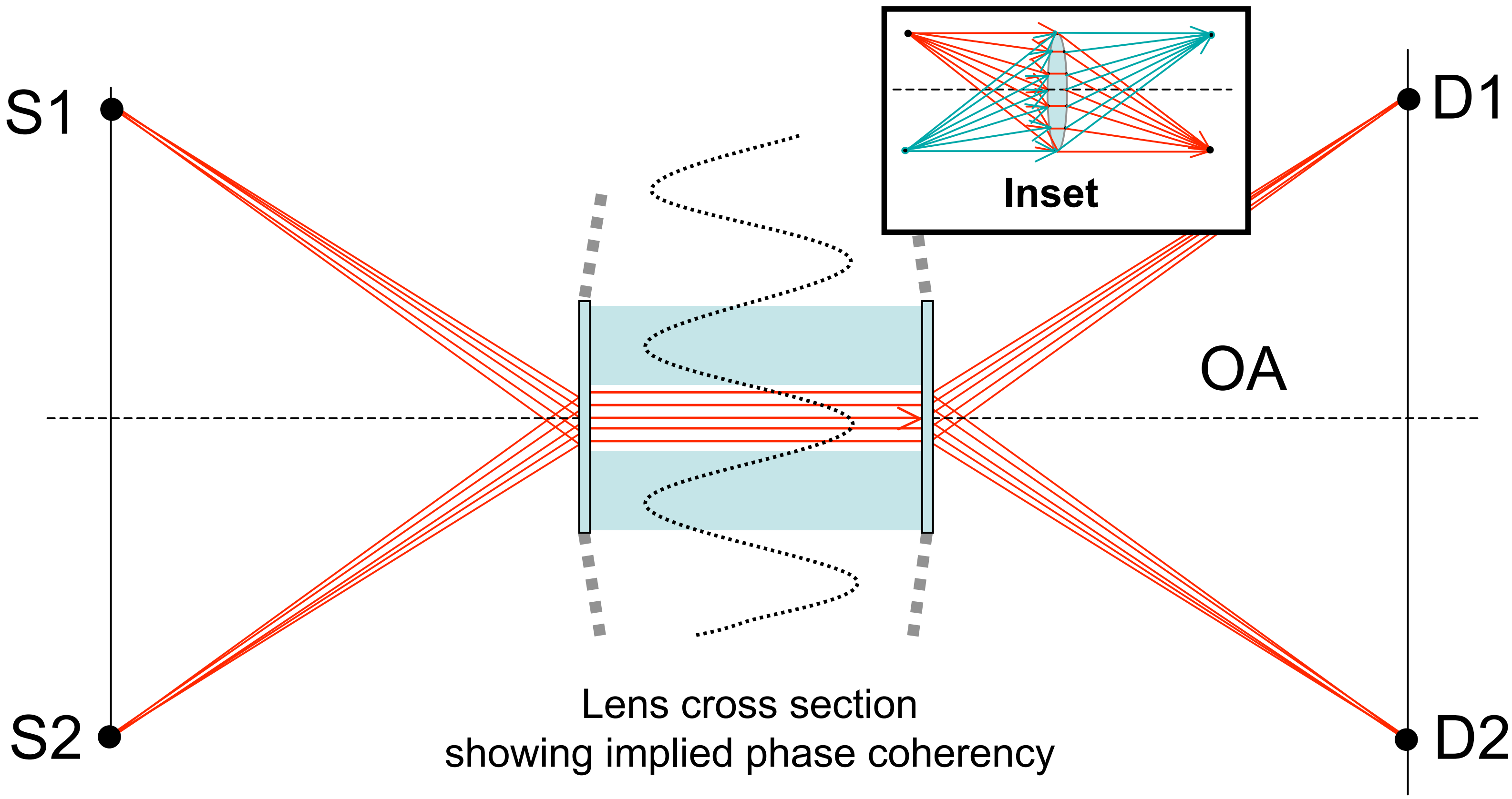
- Preceding discussion about refraction in lenses resulting from isochronous QPI paths is only true for *incoherent* light



- But **YAW** uses *coherent* light ➔ interference

- Interference is present independent of “seeing” fringes
  - Interference is the **superposition** of coherent QPI paths
  - Fringes correspond to a **measurement** viz, |sum QPI paths| ^{2}
  - YAW wires or UMZ absorber constitute a null measurement
- Constructive interference produces BIFURCATION of photon paths
  - Maximally phase reinforced
  - Partially phase reinforced
- Maximally phase reinforced paths reach the image plane by simple transmission (no refraction)
- Partially phase reinforced paths act like incoherent light and refract as described previously

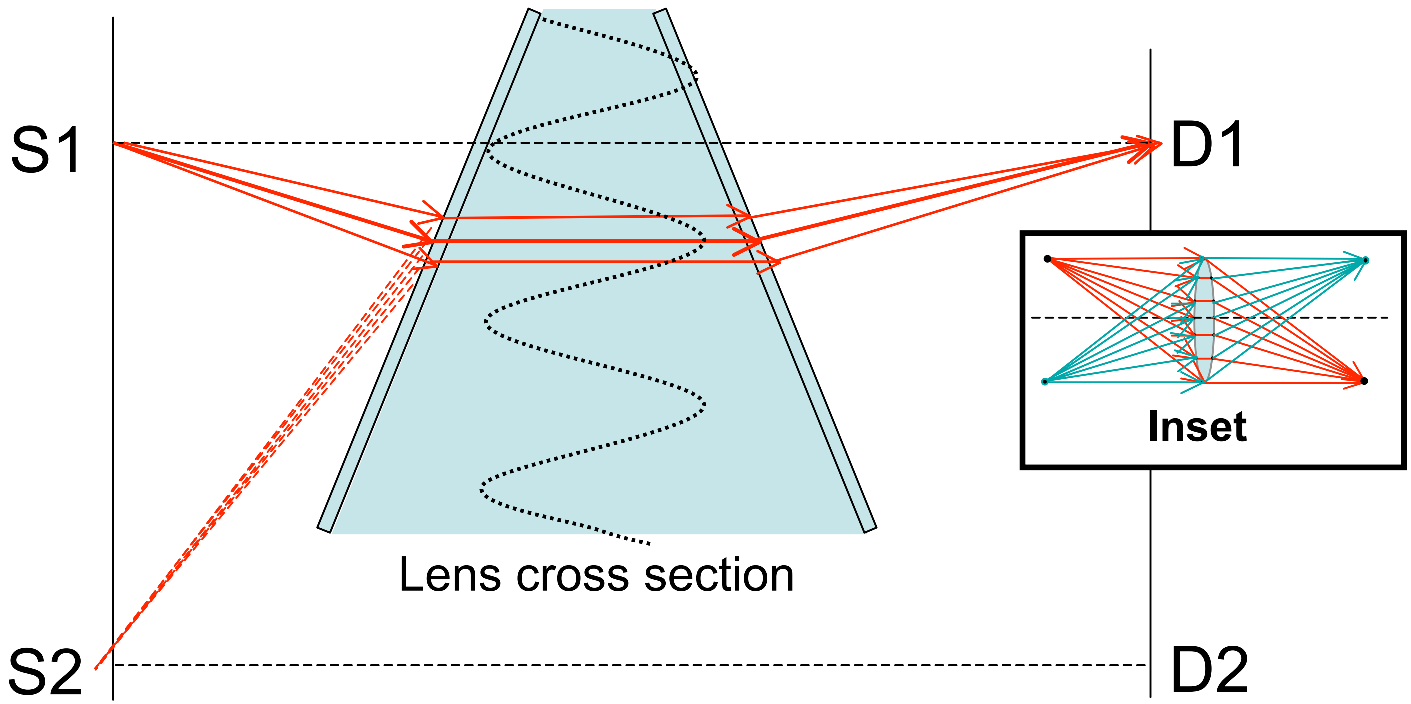
Bifurcation at Lens Center



Lens cross section
showing implied phase coherency

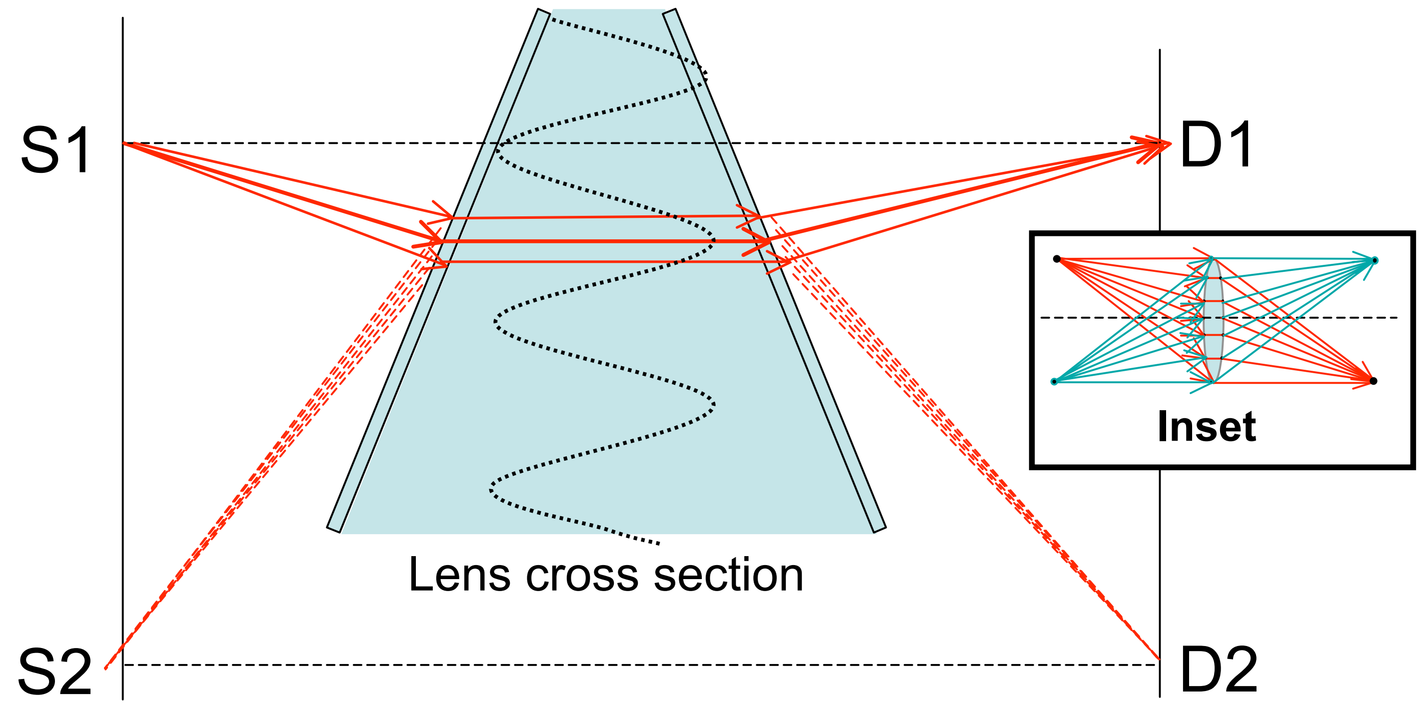
Near OA, coherent QPI tubes are identical to isochronous paths.
Surviving paths go from S1 ➔ D1, as well as from S1 ➔ D2.
Same as 50/50 split in UMZ, but this only represents a *partial* contribution in the case of a lens.

Maximal Coherence Away From OA



Phase-coherent QPI paths (**red**) reinforce pathway S1 ➔ D1.
No transmission of light at the phase minima.
This is a completely non-classical effect due to interference.

Bifurcation Away From OA



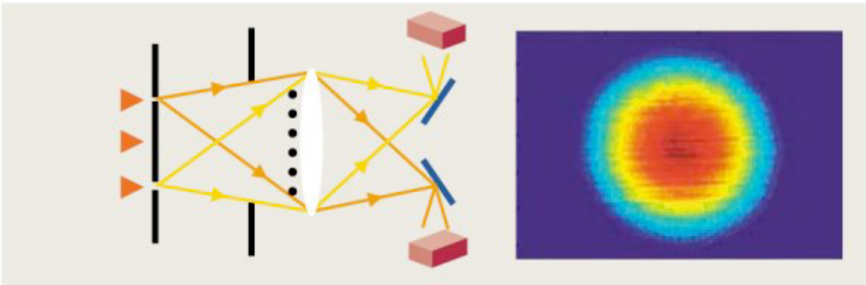
Maximally phase-coherent tube of paths from S1 ➔ D1.

Partially phase-coherent tube of paths from S1 ➔ D2.

All phase maxima result in similar bifurcations.

Bifurcation of QPI Paths

- Non-classical QPI paths explain YAW paradox
  - Afshar's incorrect conclusion rests on a *classical* analysis of the optics using **geometric ray** approximation
- Twin incoherent light sources (e.g., light bulb, stars)
  - Paths S1->D1 cancel due to phase cancellations at detector D1
  - Only isochronous paths reinforce: S1 ➔ D2, and S2 ➔ D1
- Twin coherent light sources in YAW
  - Non-classical optical effects
  - Phase-coherent paths can *bifurcate* inside mono-refractive lens
    - Bifurcation is a property of the light, not the lens
    - Physics of YAW is different from bi-refractive HSM in UMZ
  - See two image spots due to symmetric *transform* from lens
  - The lens images the interference region (not the pinholes), therefore image spots will also have a banded structure [8]



Some References

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