

Quantum Entanglement and the Flow of Time Animations

By Mark Egdall 6/15/ 09
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Partially based on Brian Greene's *The Fabric of the Cosmos*

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Which Path? Part I

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6. Animation on Which Path/ Delayed Choice: **Part I**

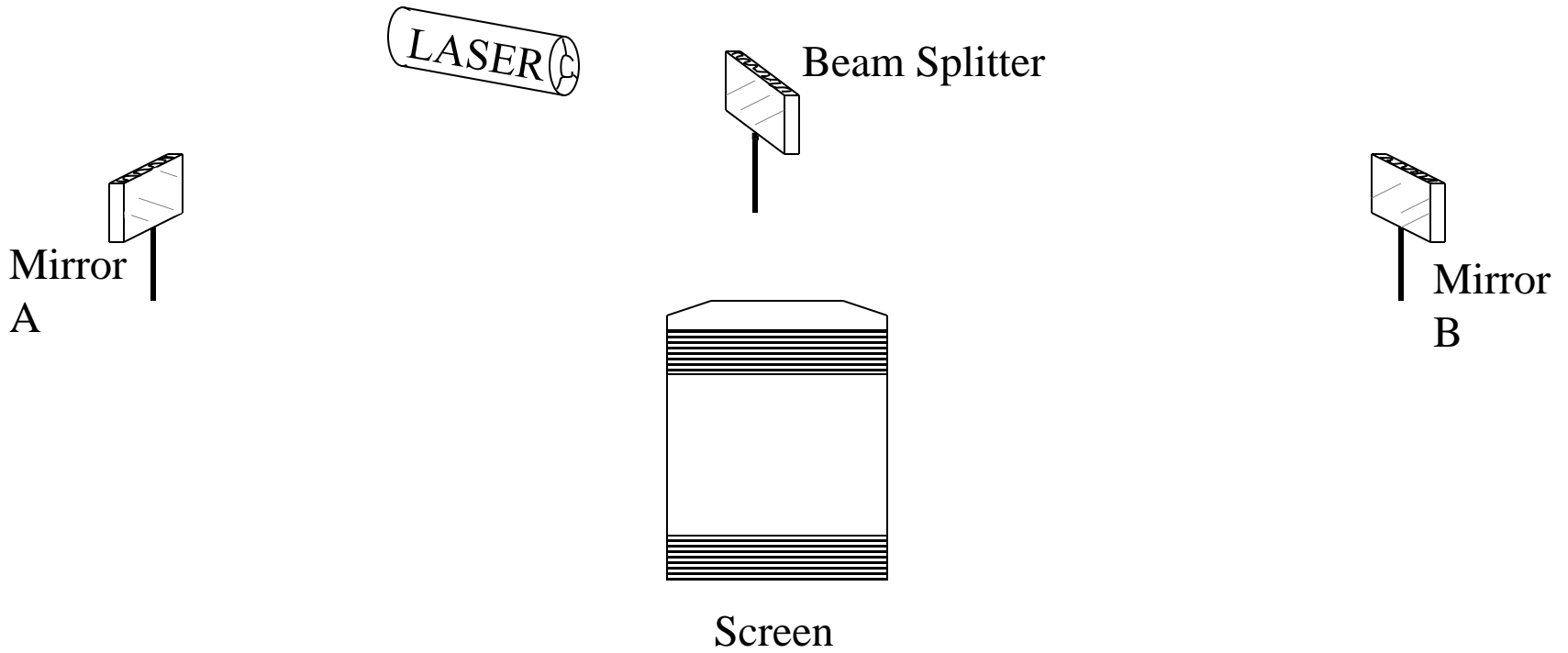
- A laser sends a light beam to a beam-splitter.
- It splits the beam into two paths.
- The two beams then reflect off mirrors, and meet at a screen.

6. Animation on Which Path/ Delayed Choice: **Part I**

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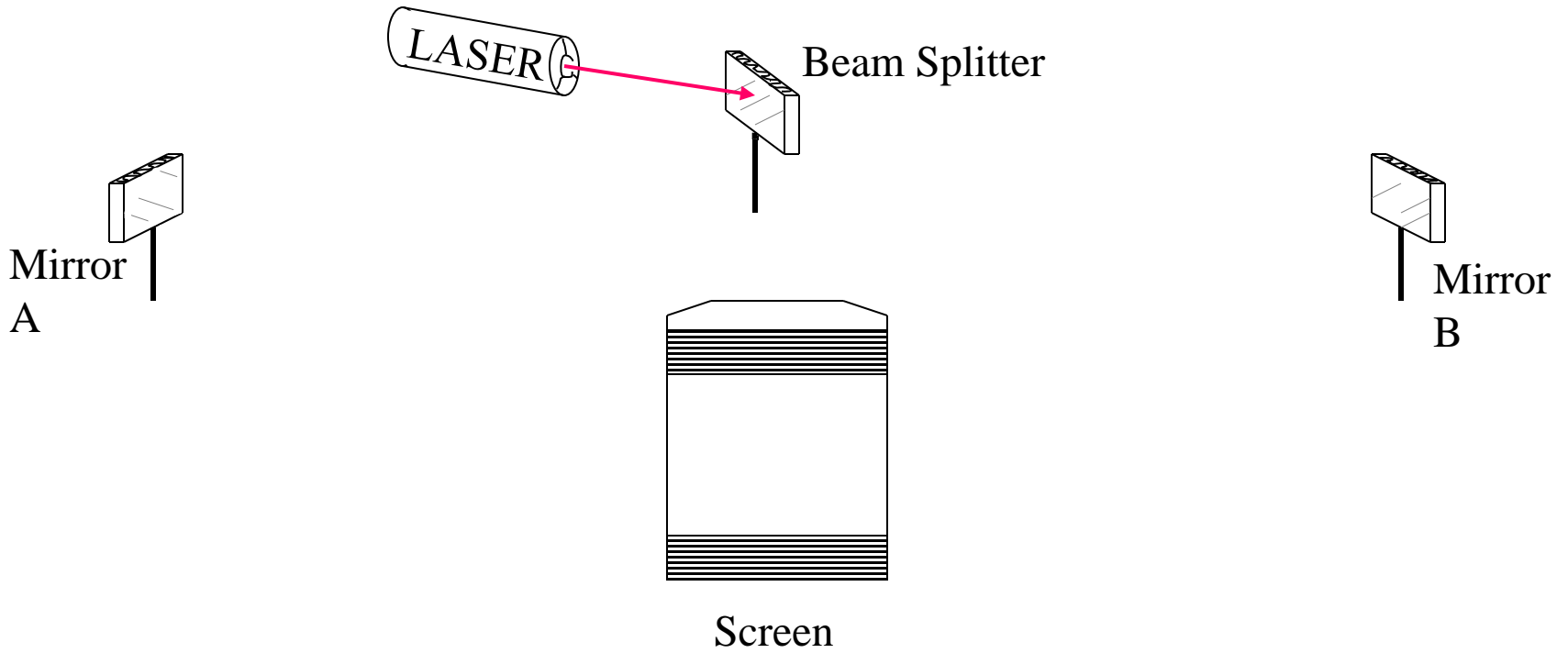
→ **We see a dark and light pattern on the screen called *interference*.**

Beam Splitter Set-up *



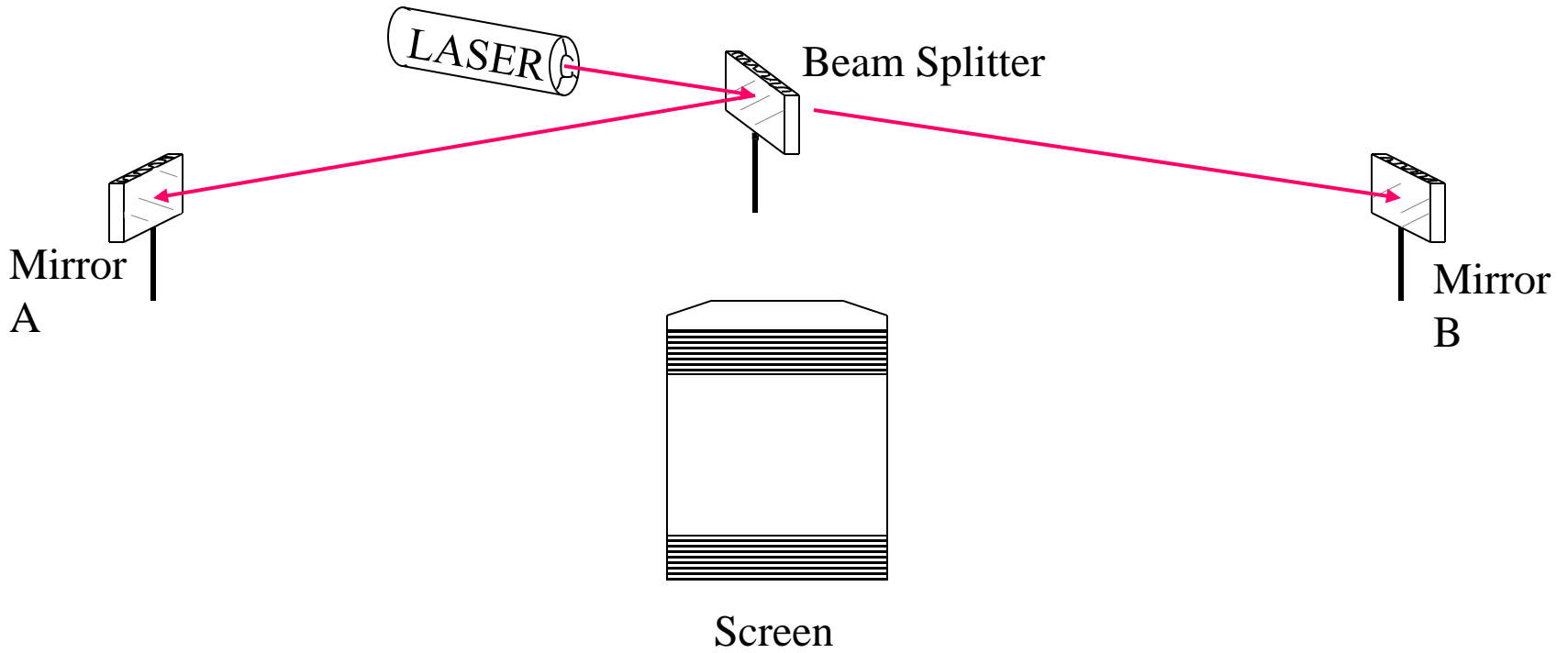
* p. 187, *The Fabric of the Cosmos*, B. Greene

Beam Splitter Set-up *



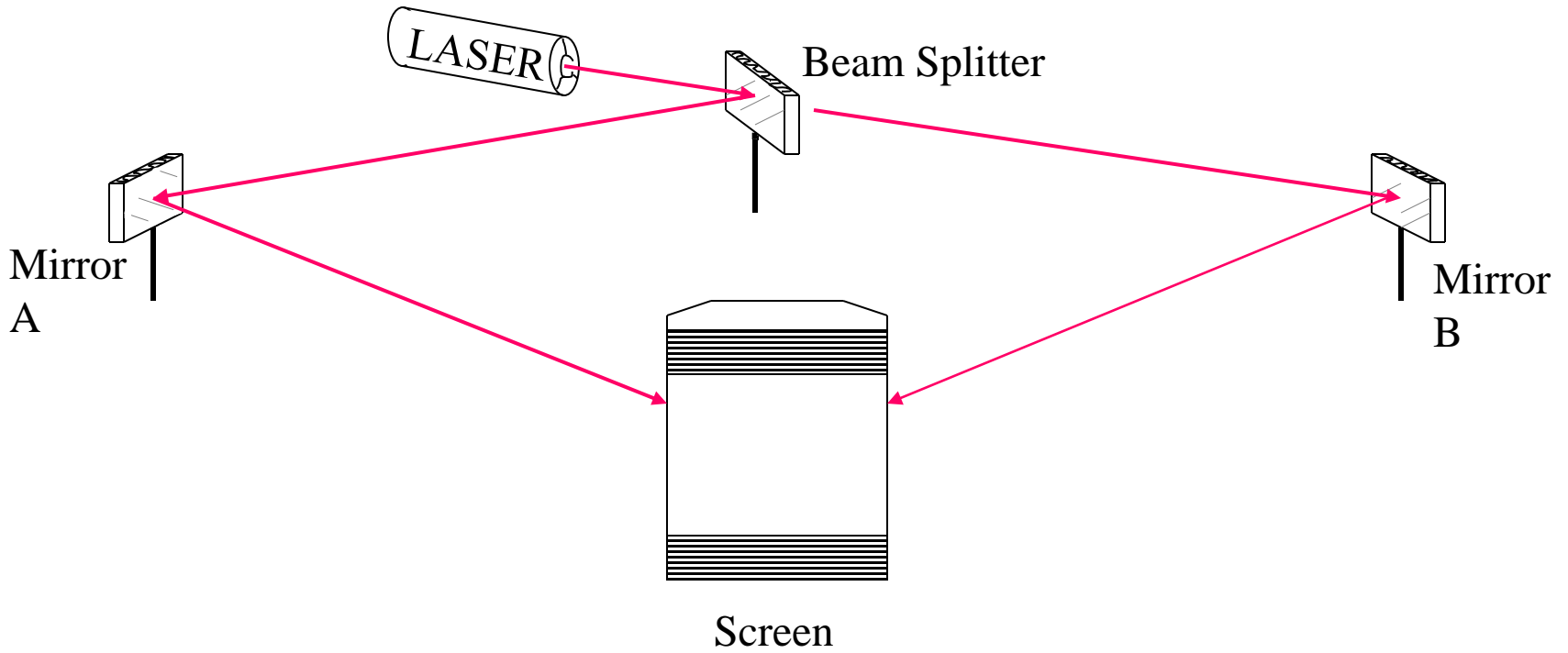
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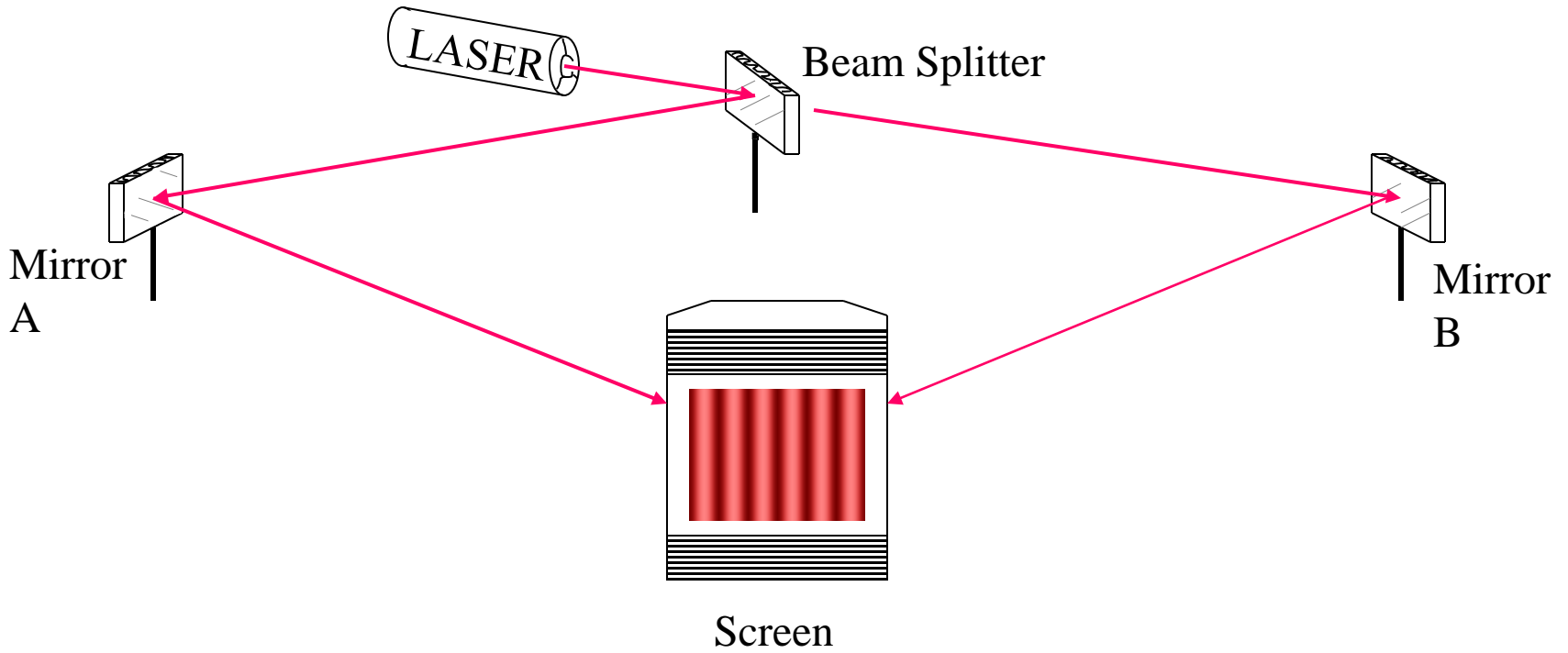
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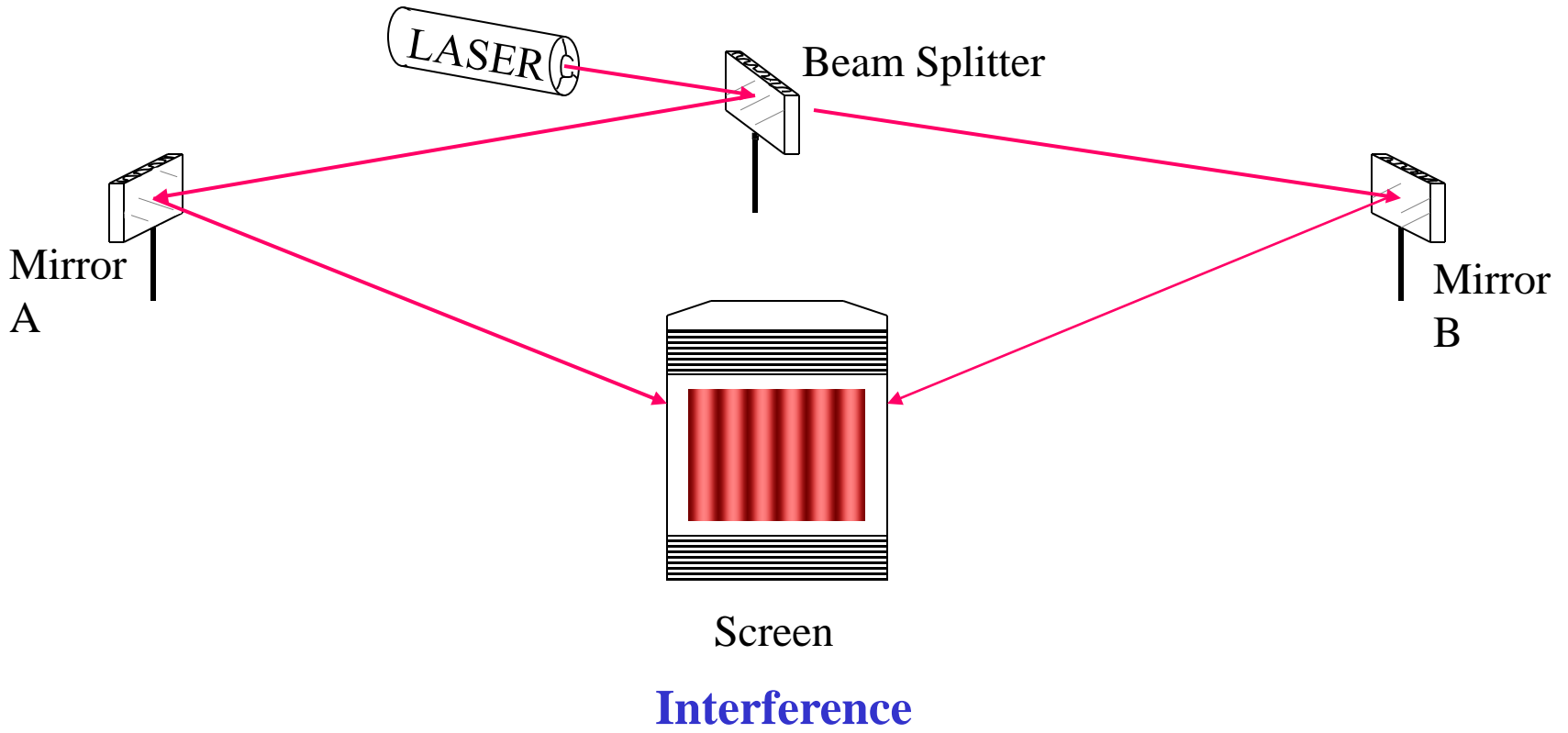
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Beam Splitter Set-up *



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Beam Splitter Set-up *

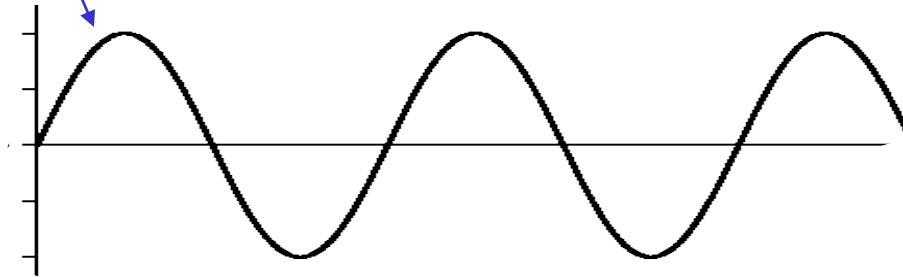


* p. 187, *The Fabric of the Cosmos*, B. Greene

Is light a wave or a particle?

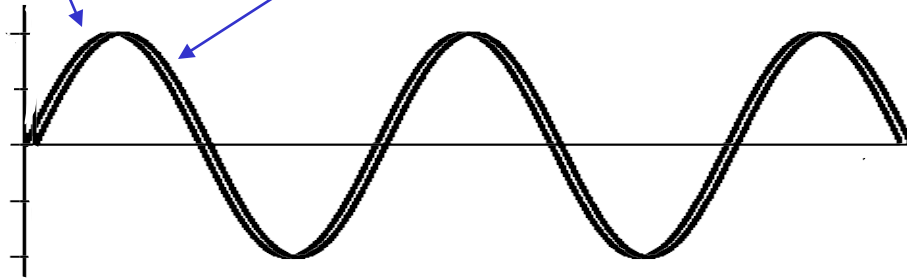
Light is a Wave

First Wave



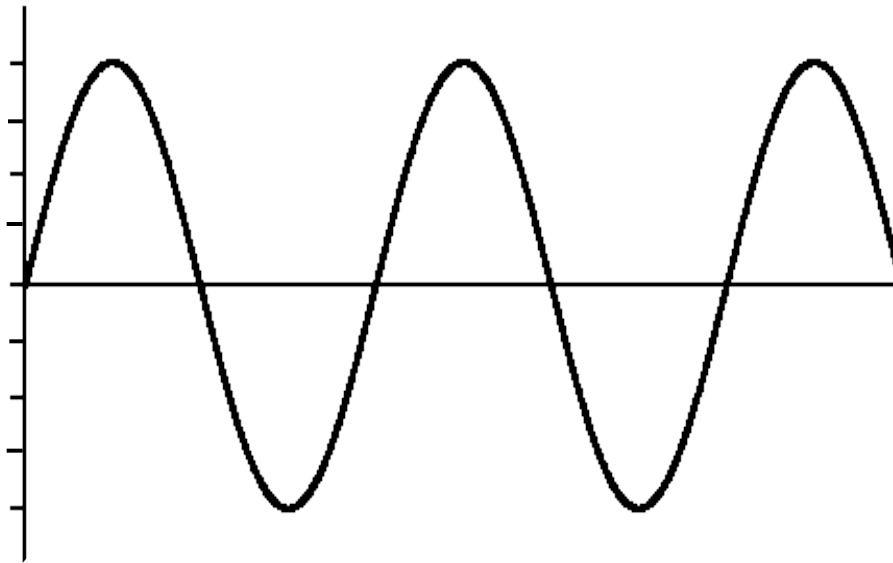
Light is a Wave

First Wave **Add Second Wave (In Phase)**



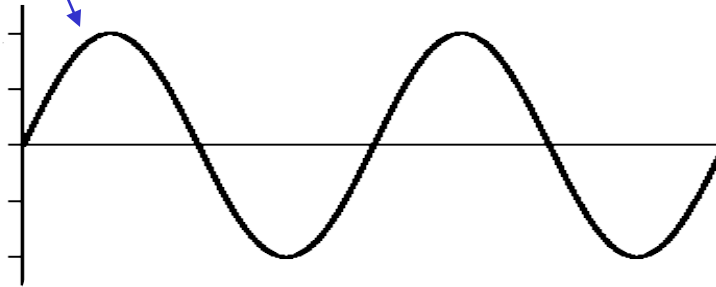
Light is a Wave

**The Two Waves Add
–Constructive Interference**

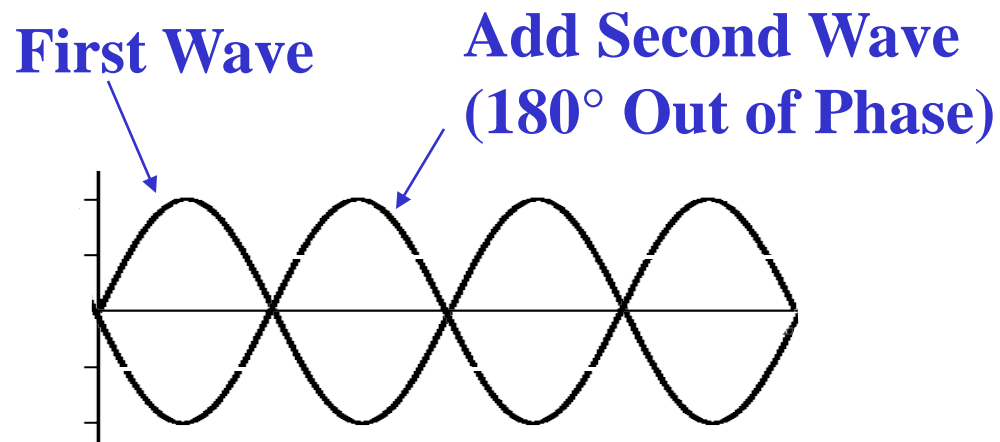


Light is a Wave

First Wave



Light is a Wave



Light is a Wave

**Waves Cancel Each Other -
Destructive Interference**



Light is a Wave

In some places on the screen, the two waves exactly overlap (they are in phase): So they add.

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In some places on the screen, the two waves exactly overlap (they are in phase): So they add.

In others, they are offset by half-cycle (180 degrees out-of-phase): So they cancel.

The combination causes a dark and light interference pattern:



Interference

Note: A tilt is added to one wave so the interference pattern presents itself as lines

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- But which path does a *single* photon take?

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(This way we know that one photon is not affecting another)

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What will the cumulative pattern be on the screen over time for lots of individual one-at-a-time photons?

One Photon at a Time

Slowly over time, we see:

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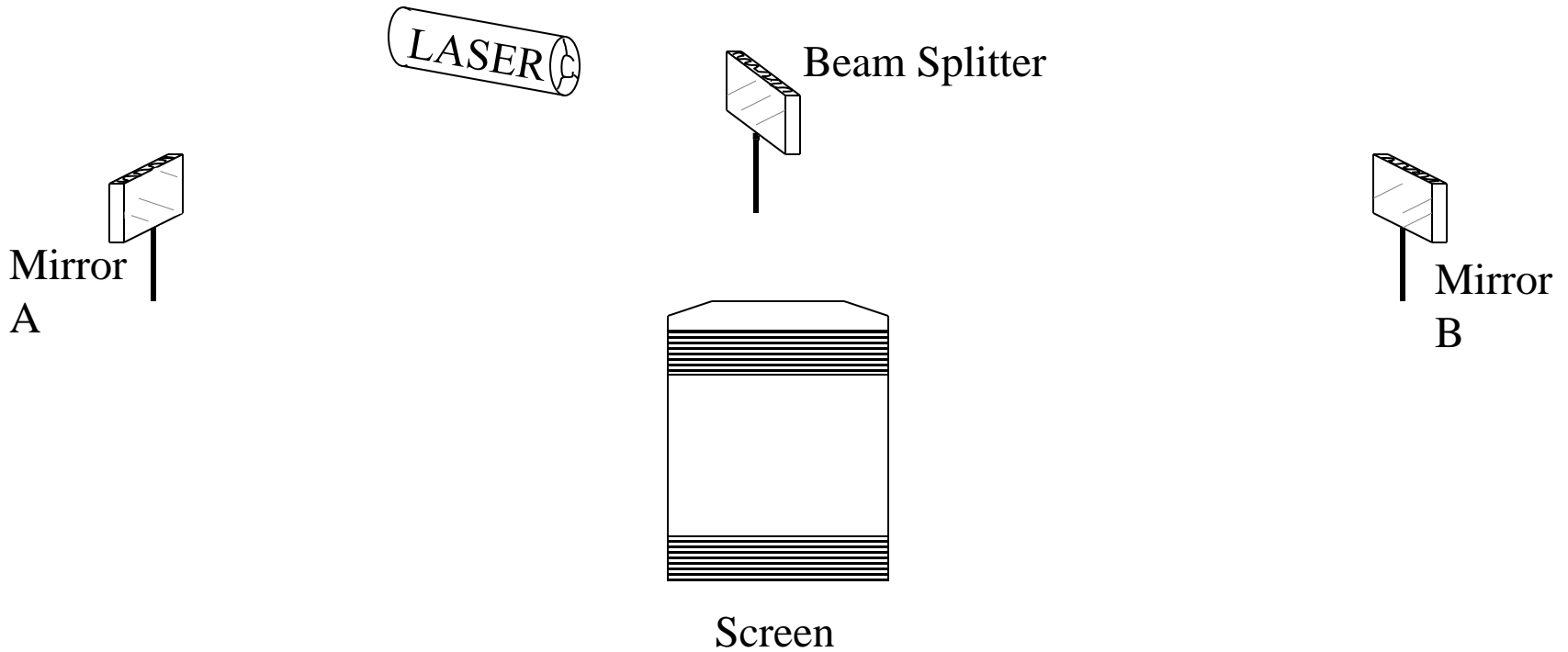
If we turn the detector off

- We see *interference* again.



Beam Splitter Set-up *

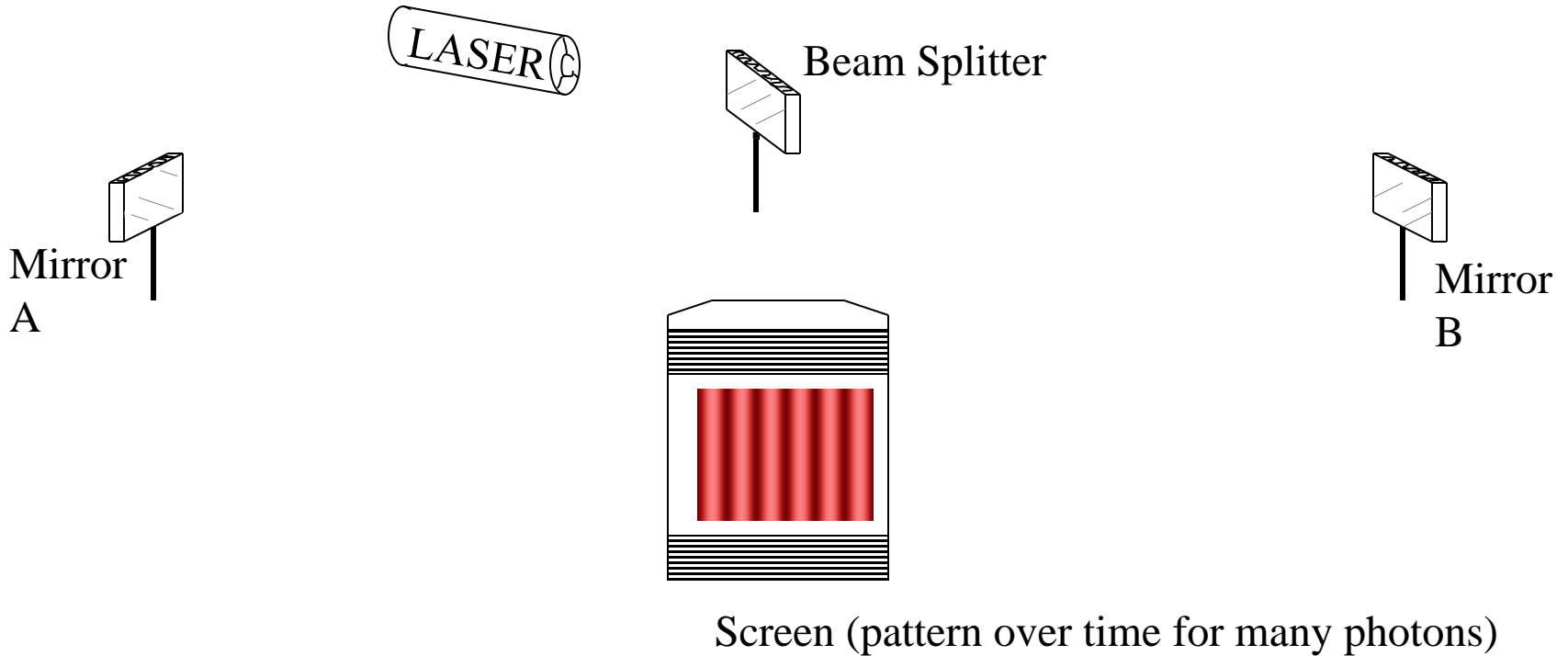
One photon at a time



* p. 187, *The Fabric of the Cosmos*, B. Greene

Beam Splitter Set-up *

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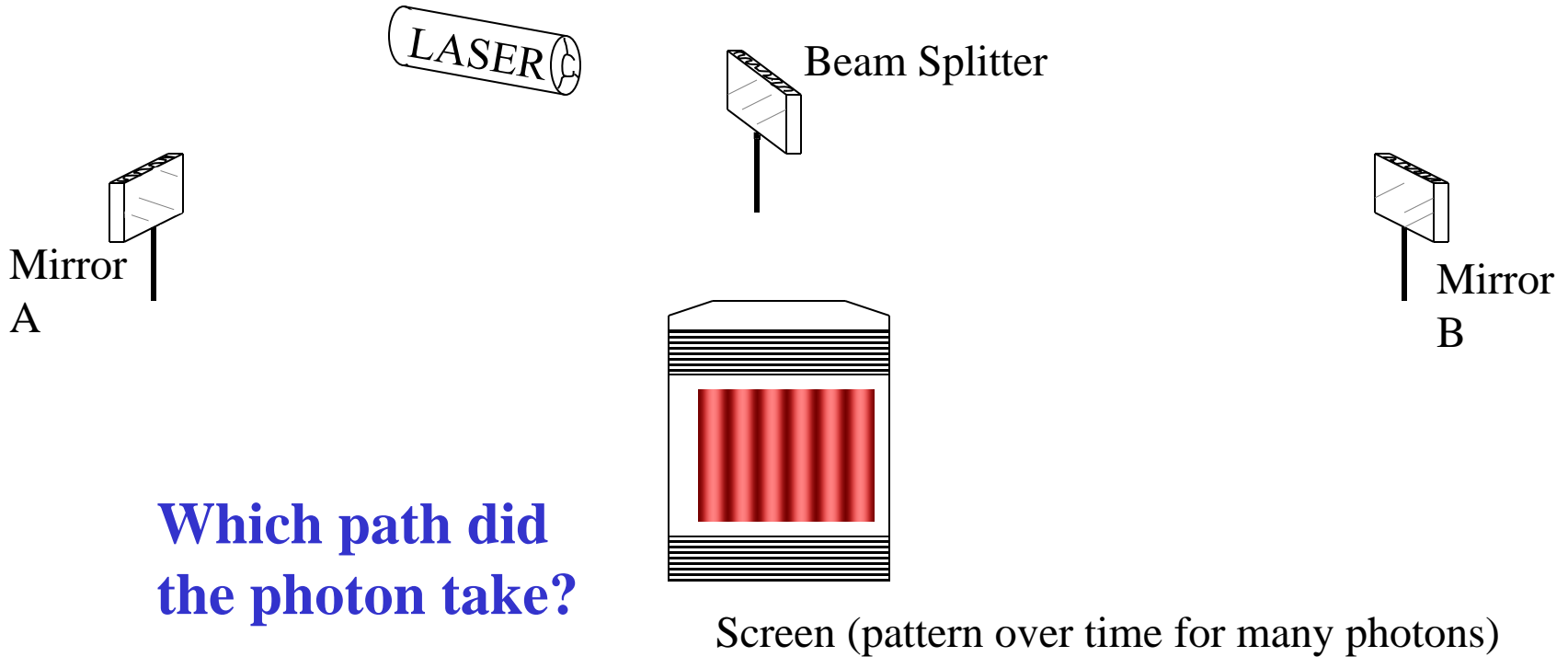


Interference

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Beam Splitter Set-up *

One photon at a time



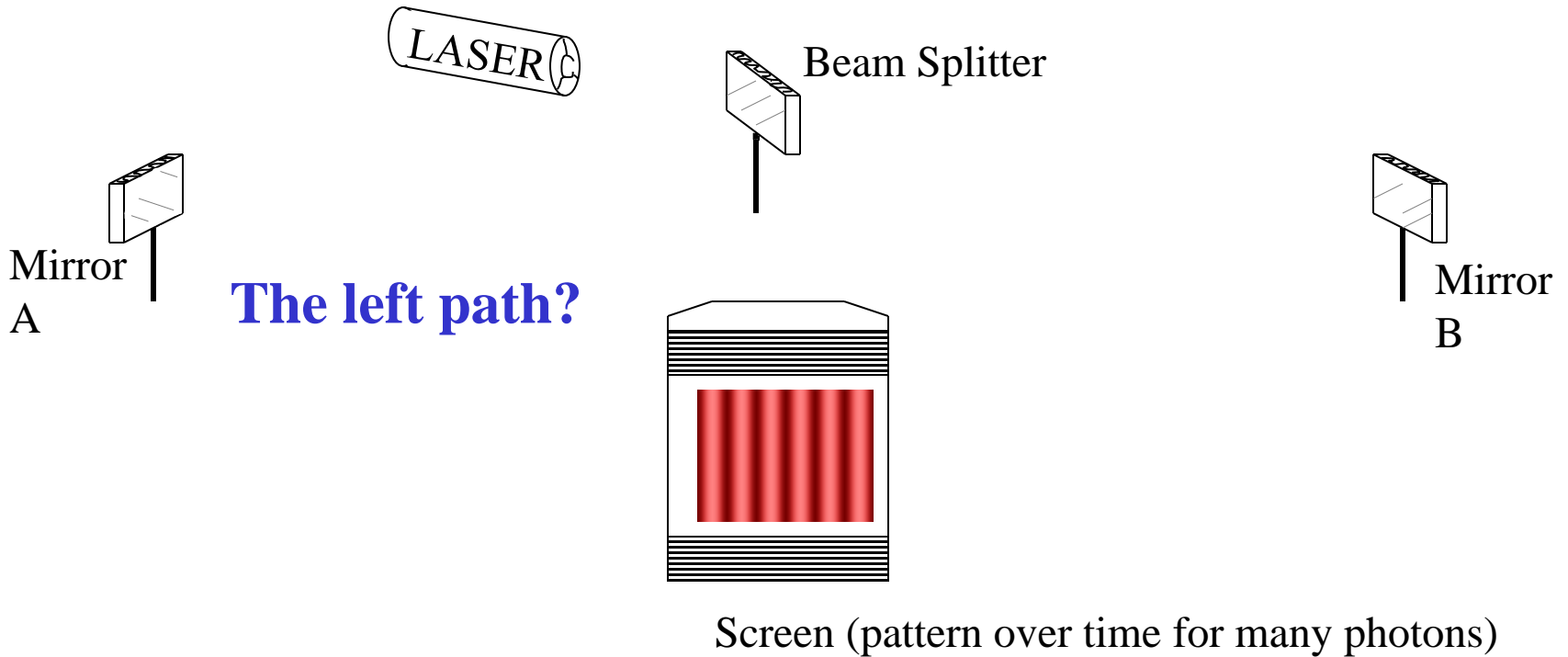
**Which path did
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Interference

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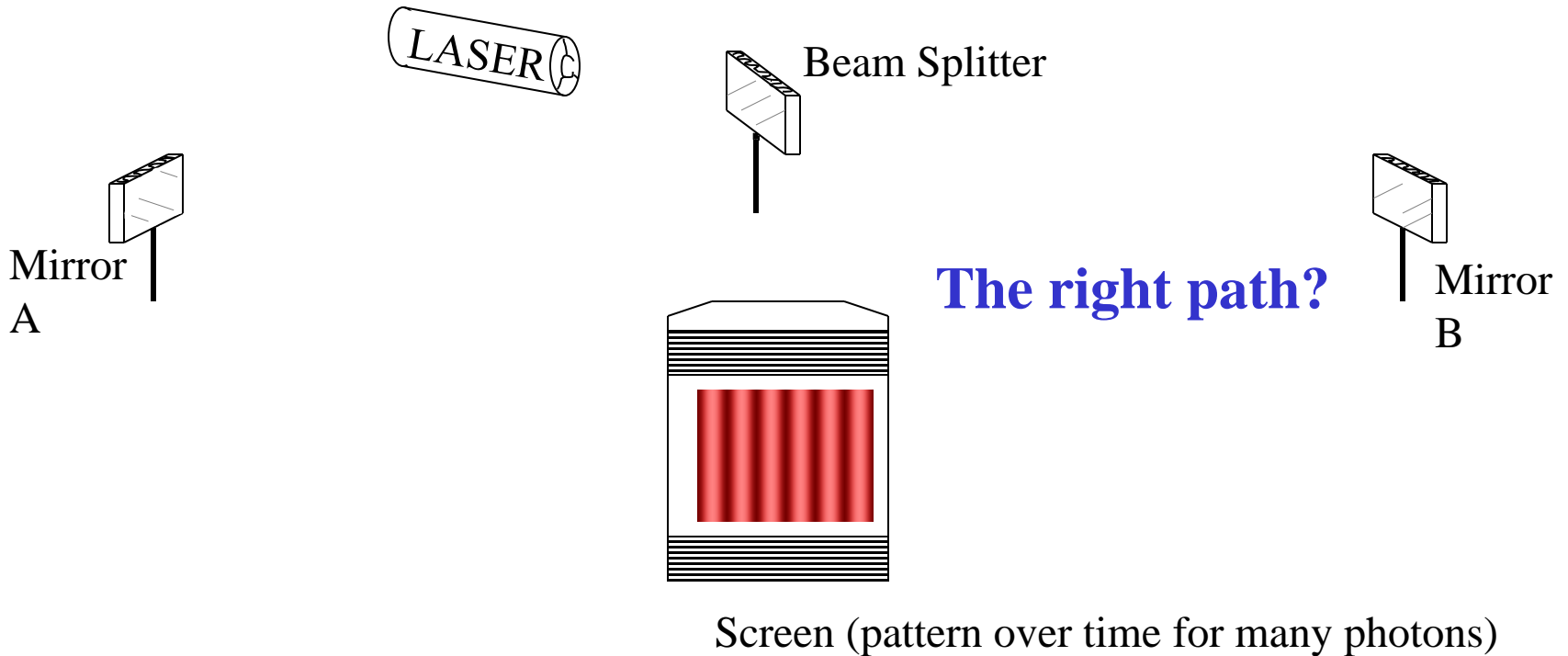


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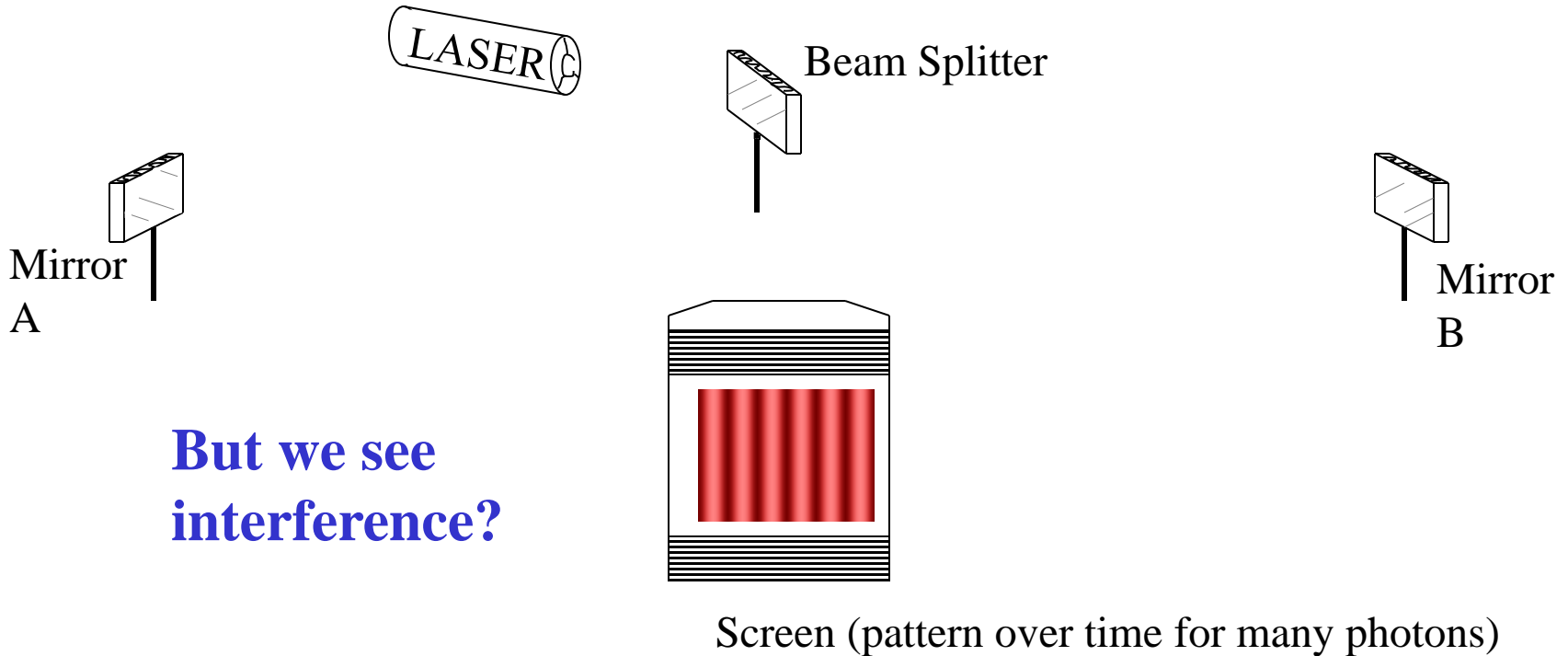


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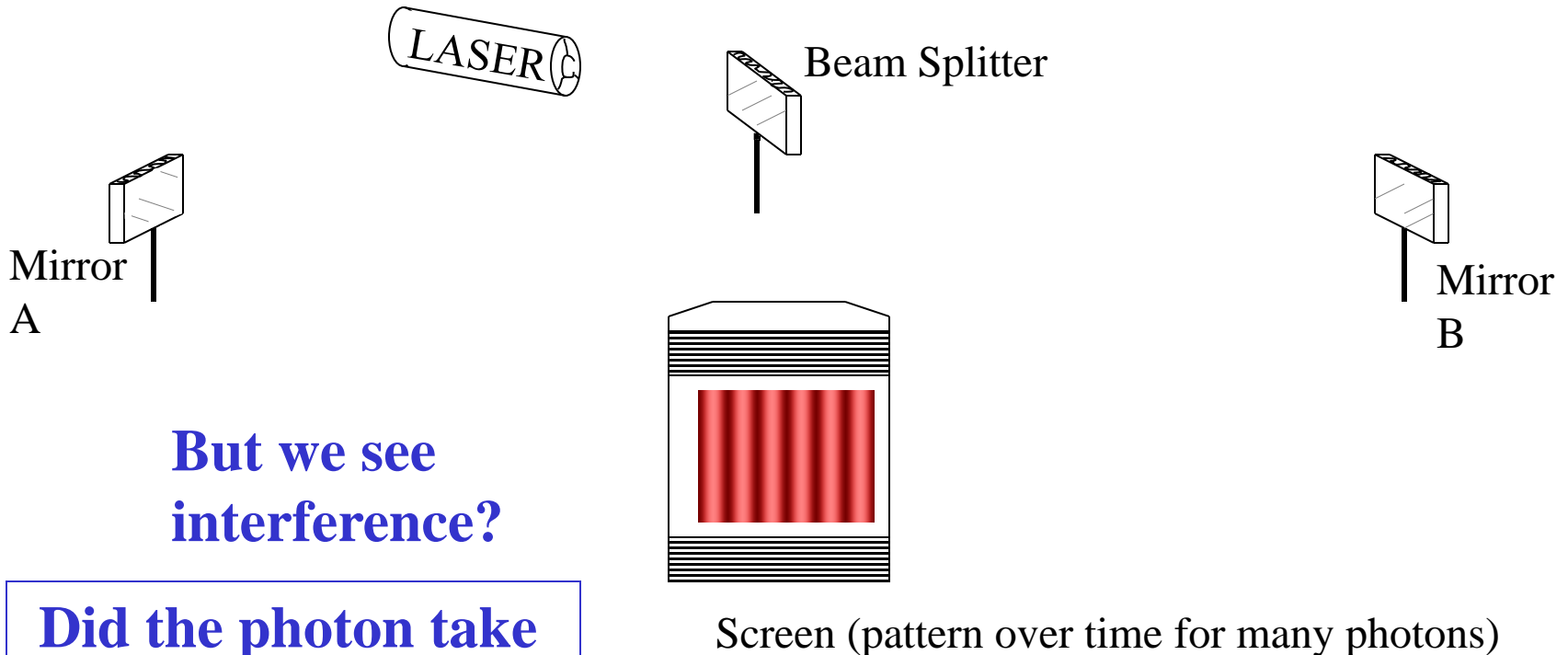
**But we see
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Interference

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Beam Splitter Set-up *

One photon at a time



**But we see
interference?**

**Did the photon take
both paths, and
interfere with itself?**

Interference

* p. 187, *The Fabric of the Cosmos*, B. Greene

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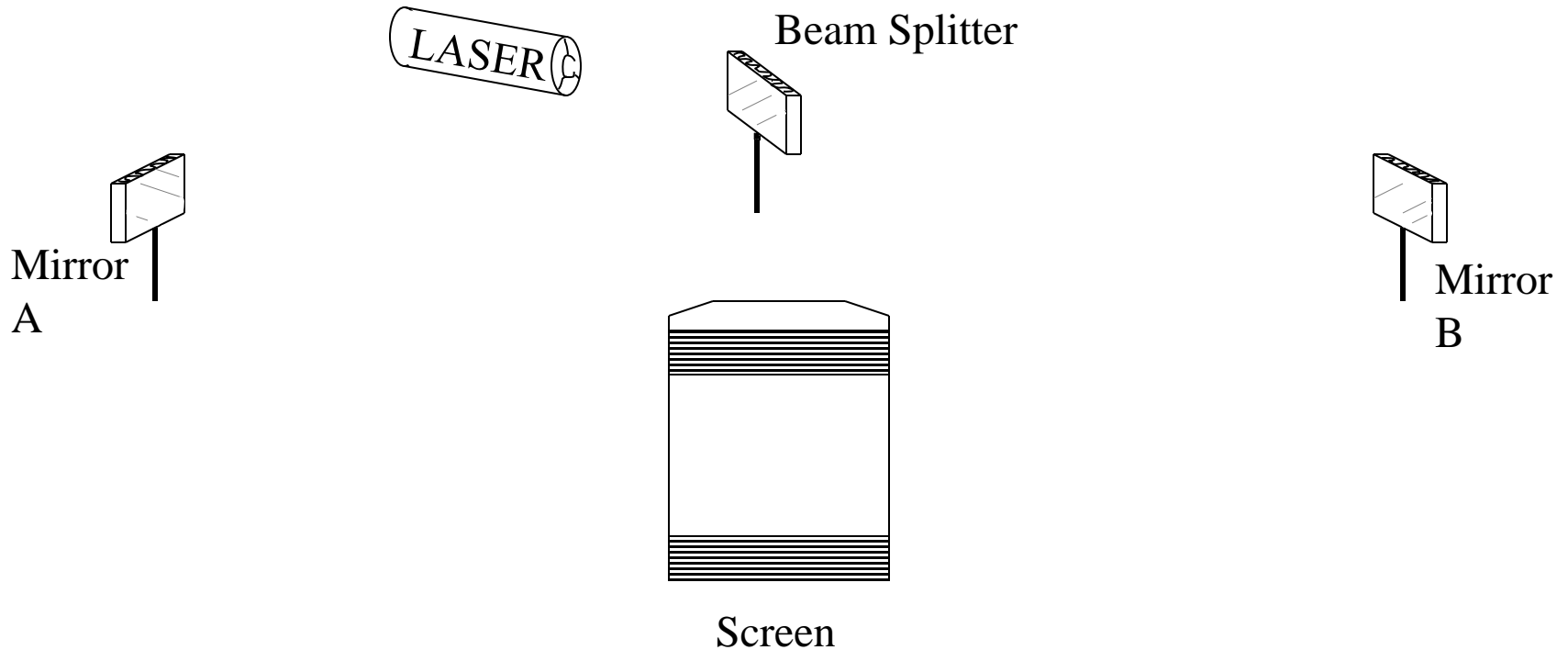
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So the detector will tell us *which path* the photon took. Or will it?

Add Detector to Determine *Which Path* Photon Takes *

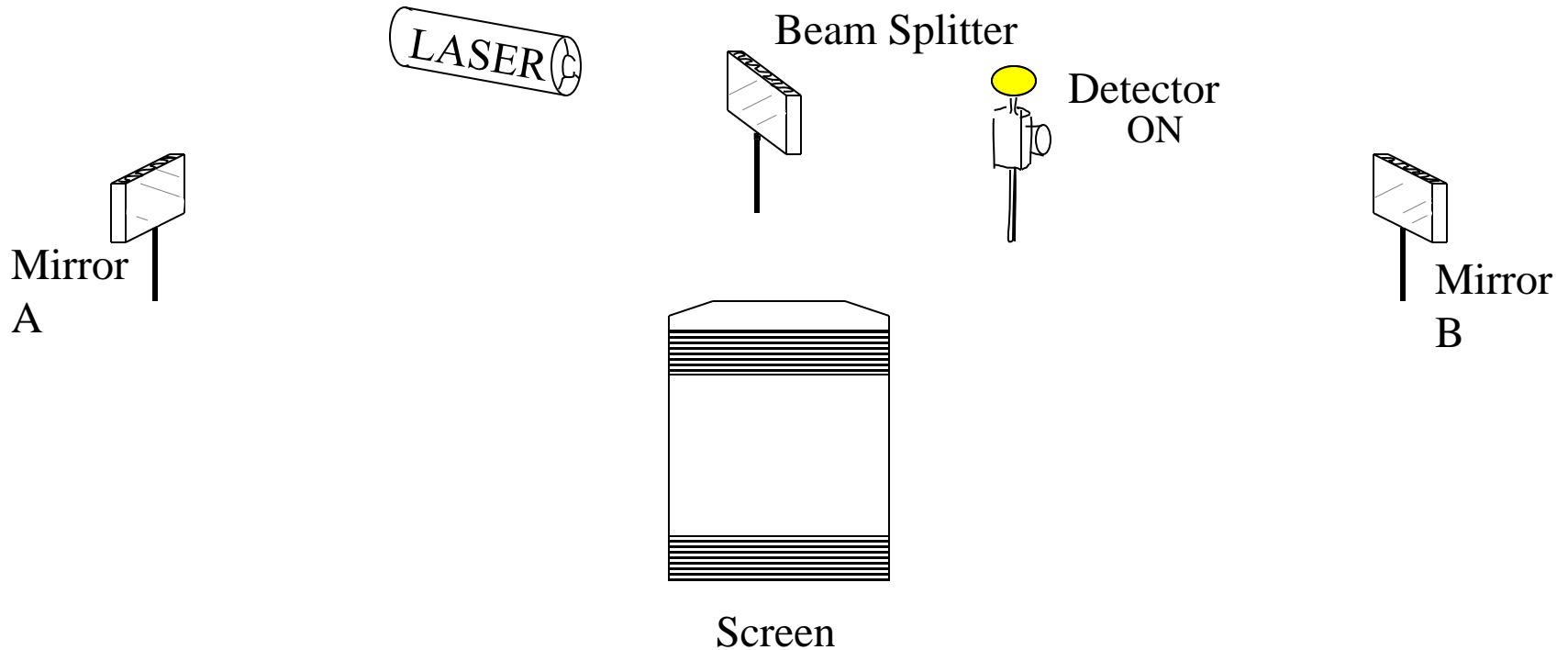
One photon at a time



* p. 187, *The Fabric of the Cosmos*, B. Greene

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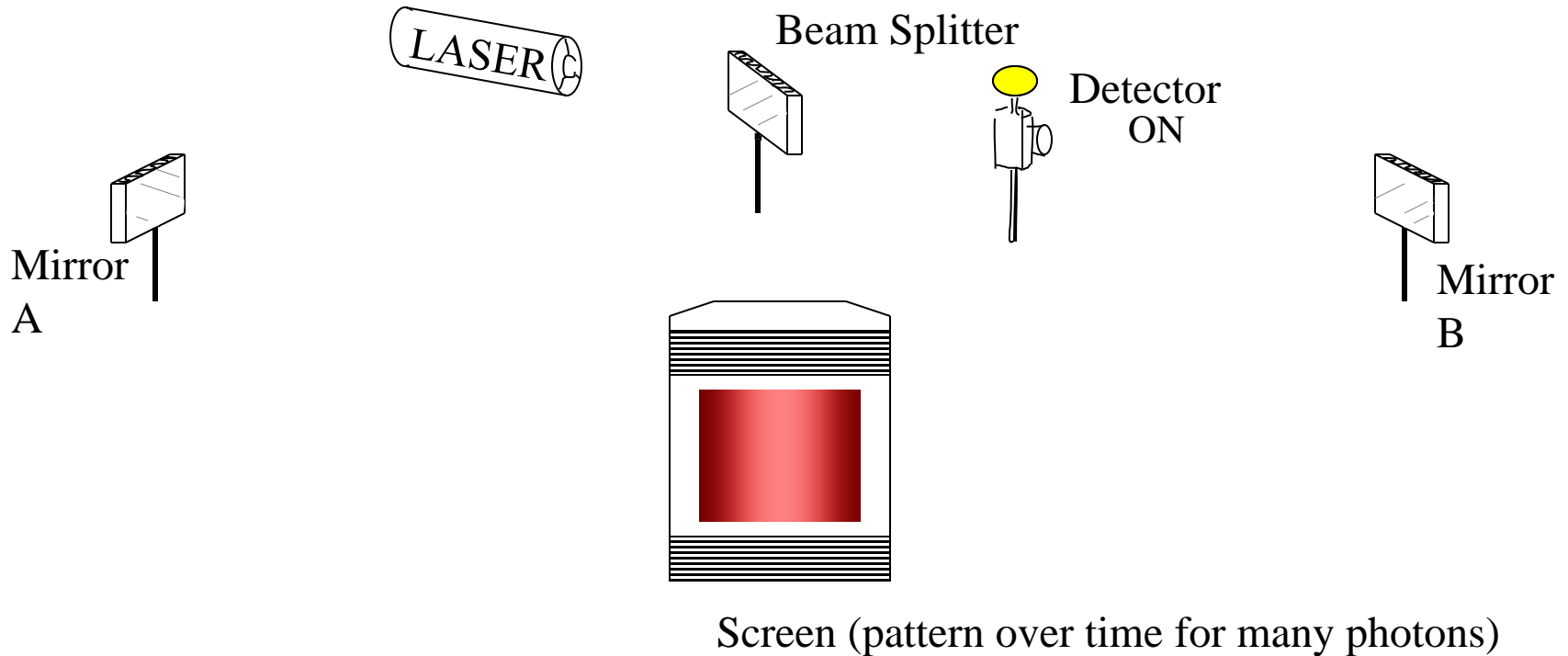
One photon at a time



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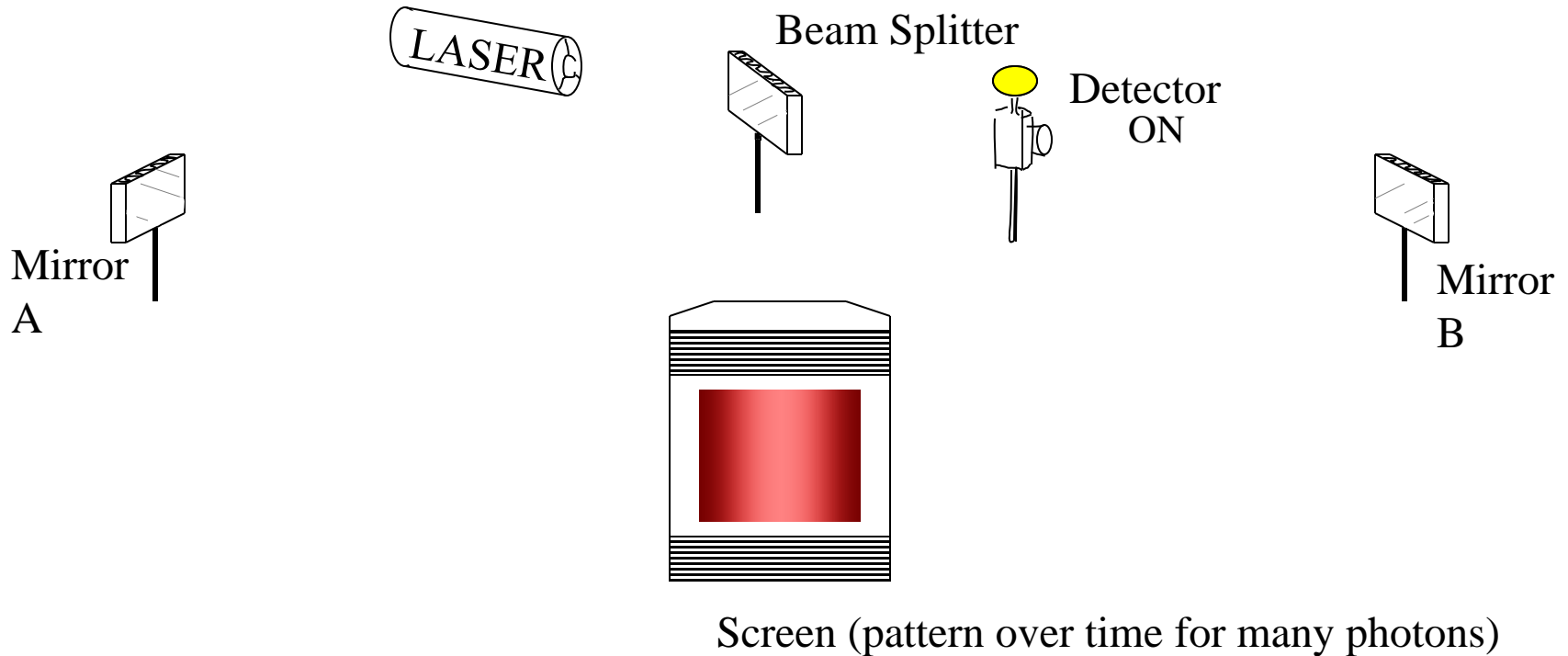
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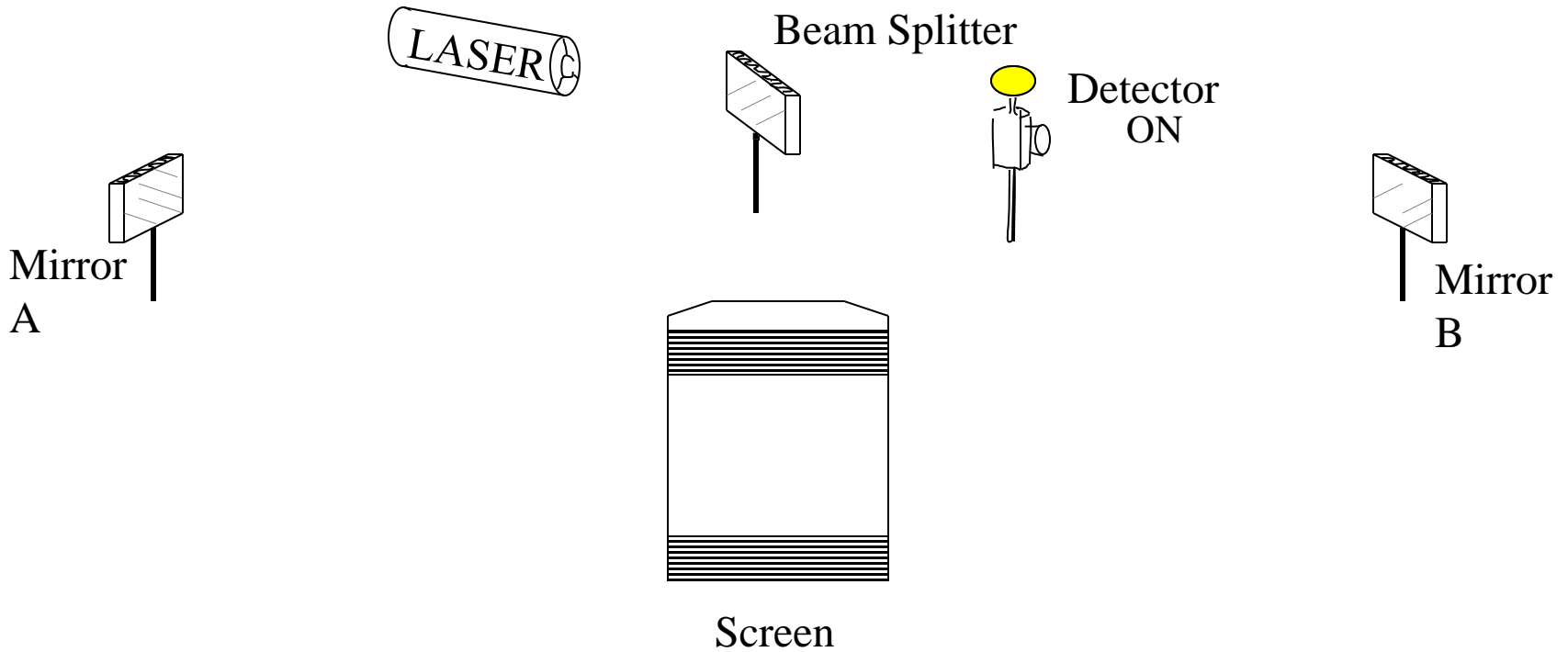


Which Path Detector : **ON** - **No Interference**

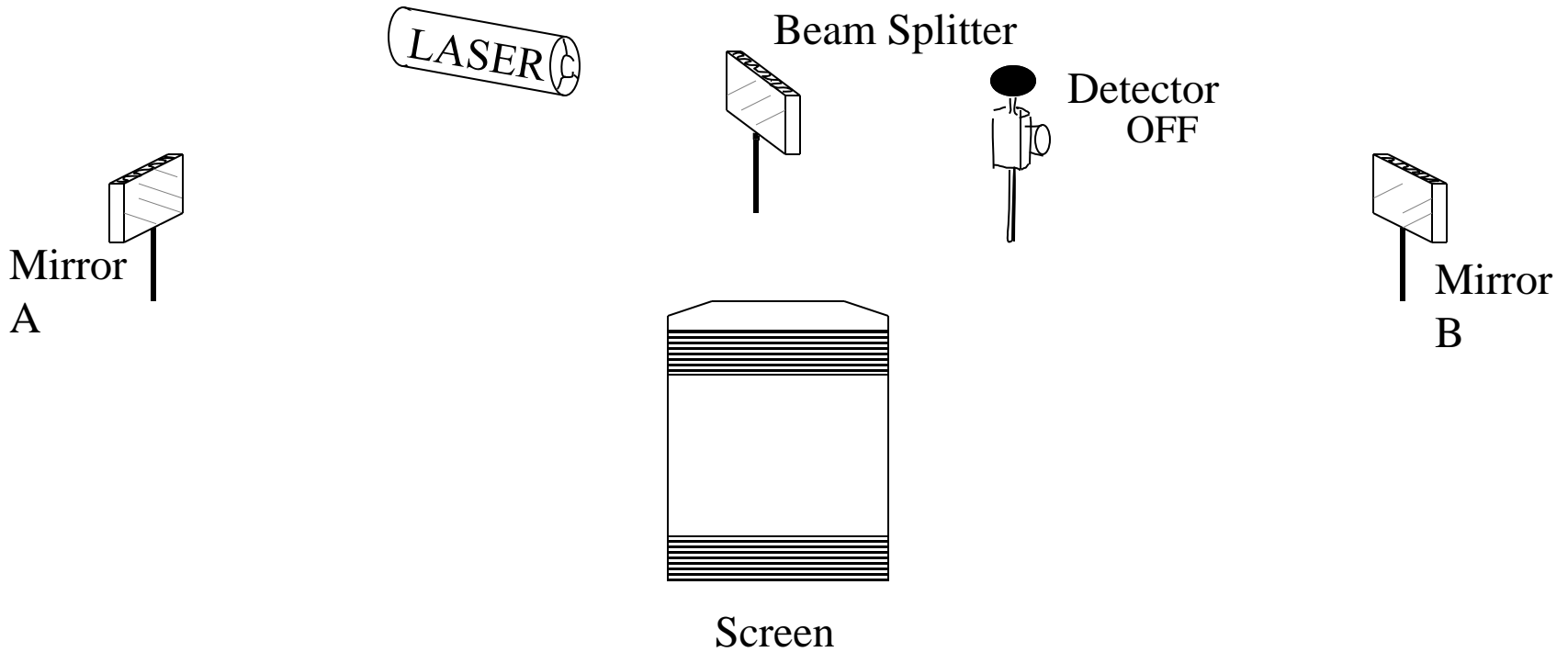
* p. 187, *The Fabric of the Cosmos*, B. Greene

Turn Detector --- *

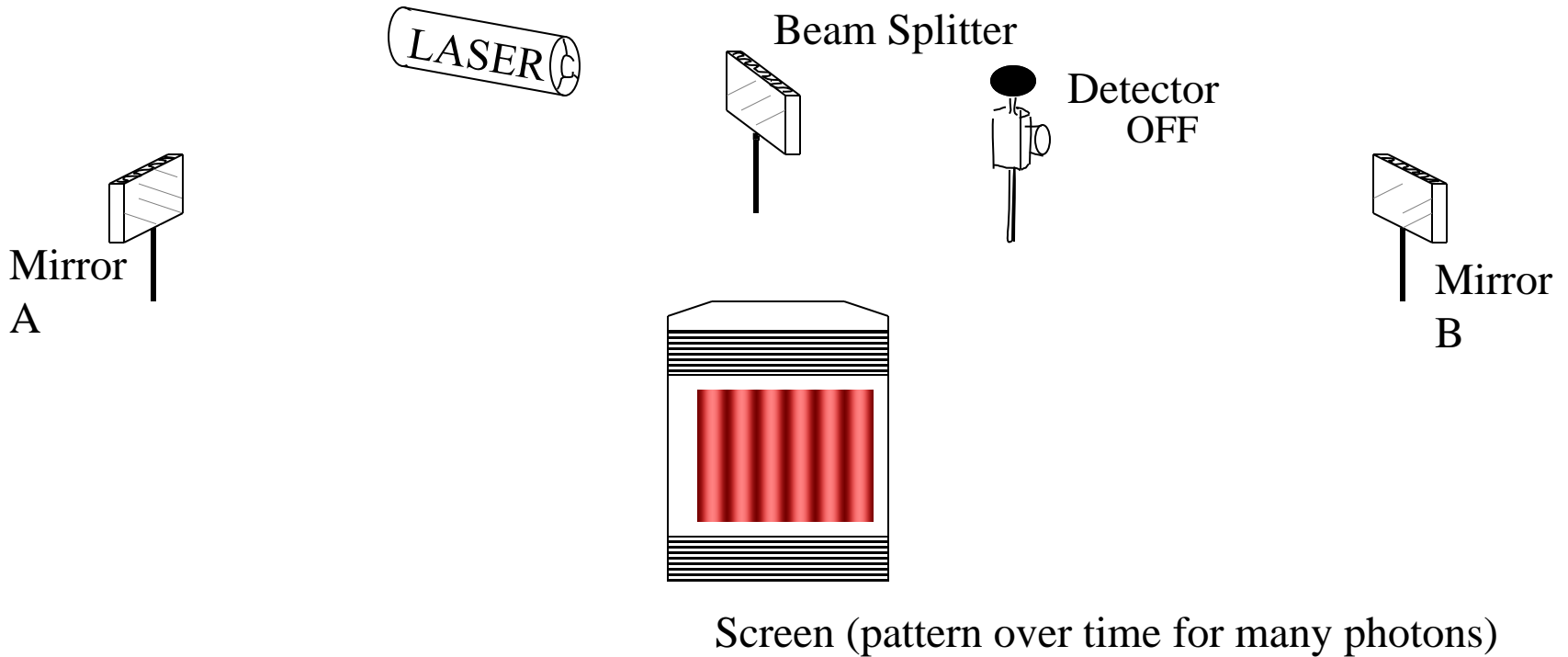
One photon at a time



Turn Detector **OFF** *
One photon at a time

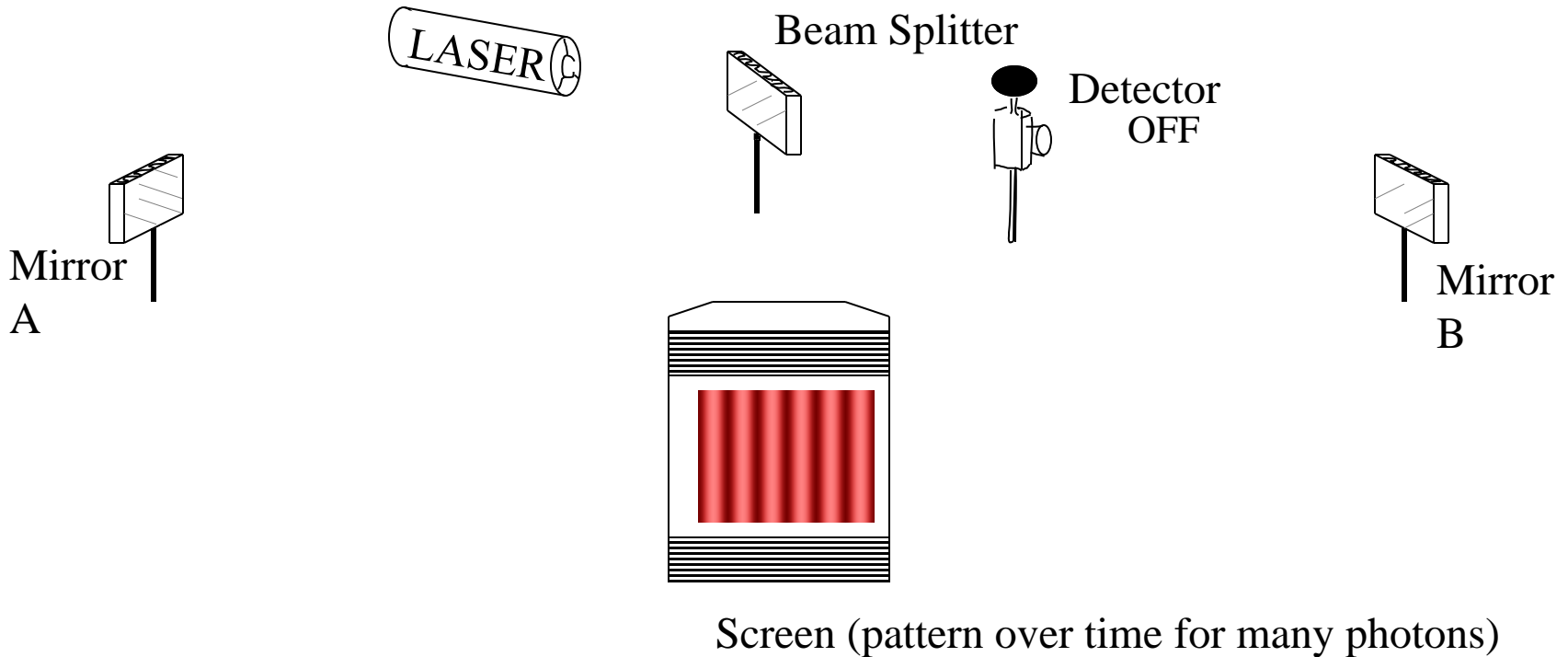


Turn Detector Off *
One photon at a time



* p. 187, *The Fabric of the Cosmos*, B. Greene

Turn Detector Off *
One photon at a time



Which Path Detector : **OFF - Interference**

With the detector ON

We get no interference!

The photon appears to have taken
only a single path

With the detector ON

We get no interference!

The photon appears to have taken
only a single path

With the detector OFF

We get interference again

Photon appears to have taken both paths at
the same time

With the detector ON

We get no interference!

The photon appears to have taken only a single path

With the detector OFF

We get interference again

Photon appears to have taken both paths at the same time

But we cannot tell **which path!**

Question *

Delayed Choice

What if beam splitter experiment arranged so that:

- detector is turned OFF *before* photon emitted by laser,
- but turned ON *after photon has passed beam splitter* ?

(Suggested by John Wheeler in 1980)

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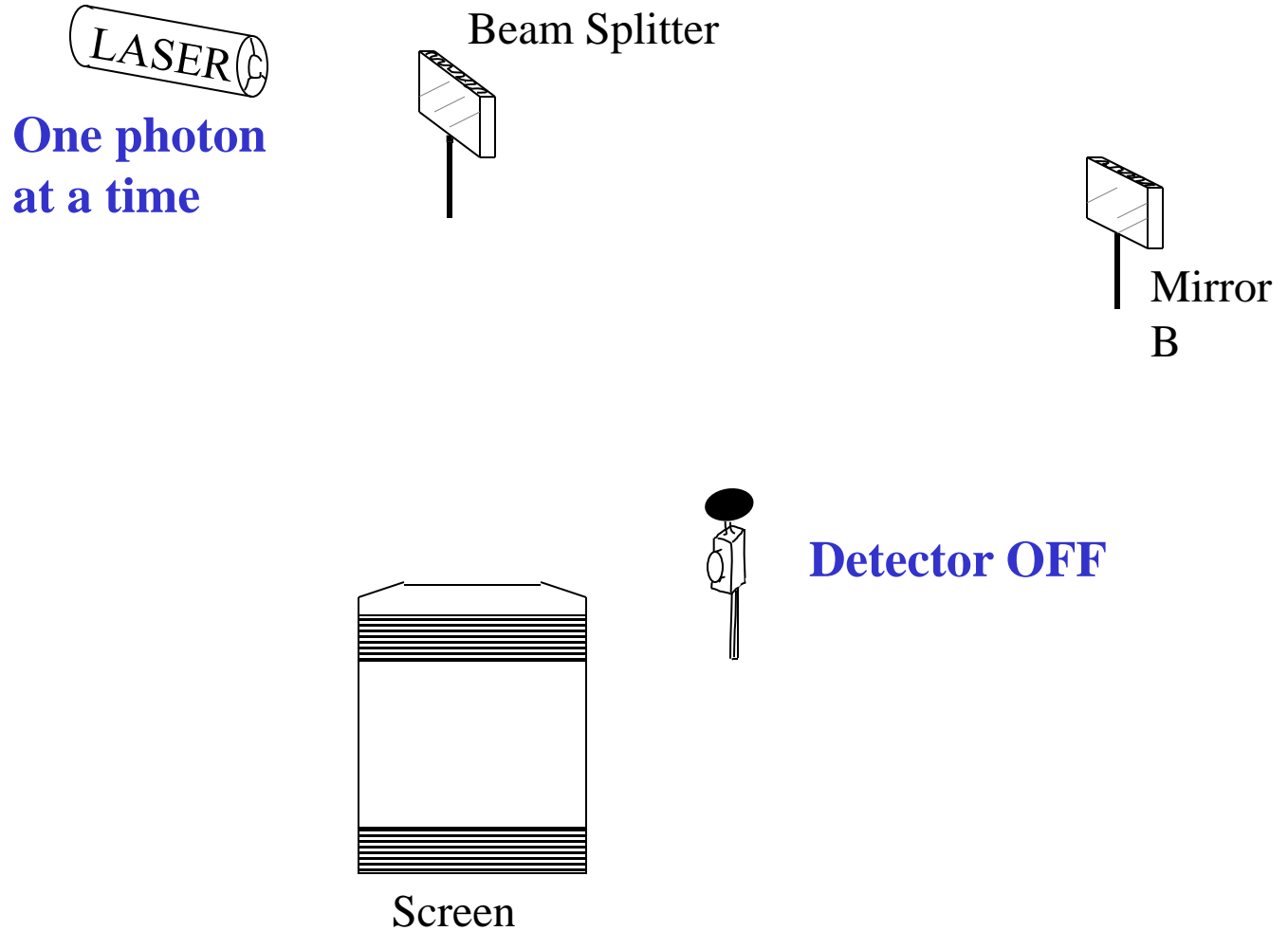
Will we get:

- A. Interference at screen
- B. No interference at screen, or
- C. A mix of the two ?

* Based on pp. 186, 187, *The Fabric of the Cosmos*, B. Greene

Delayed Choice *

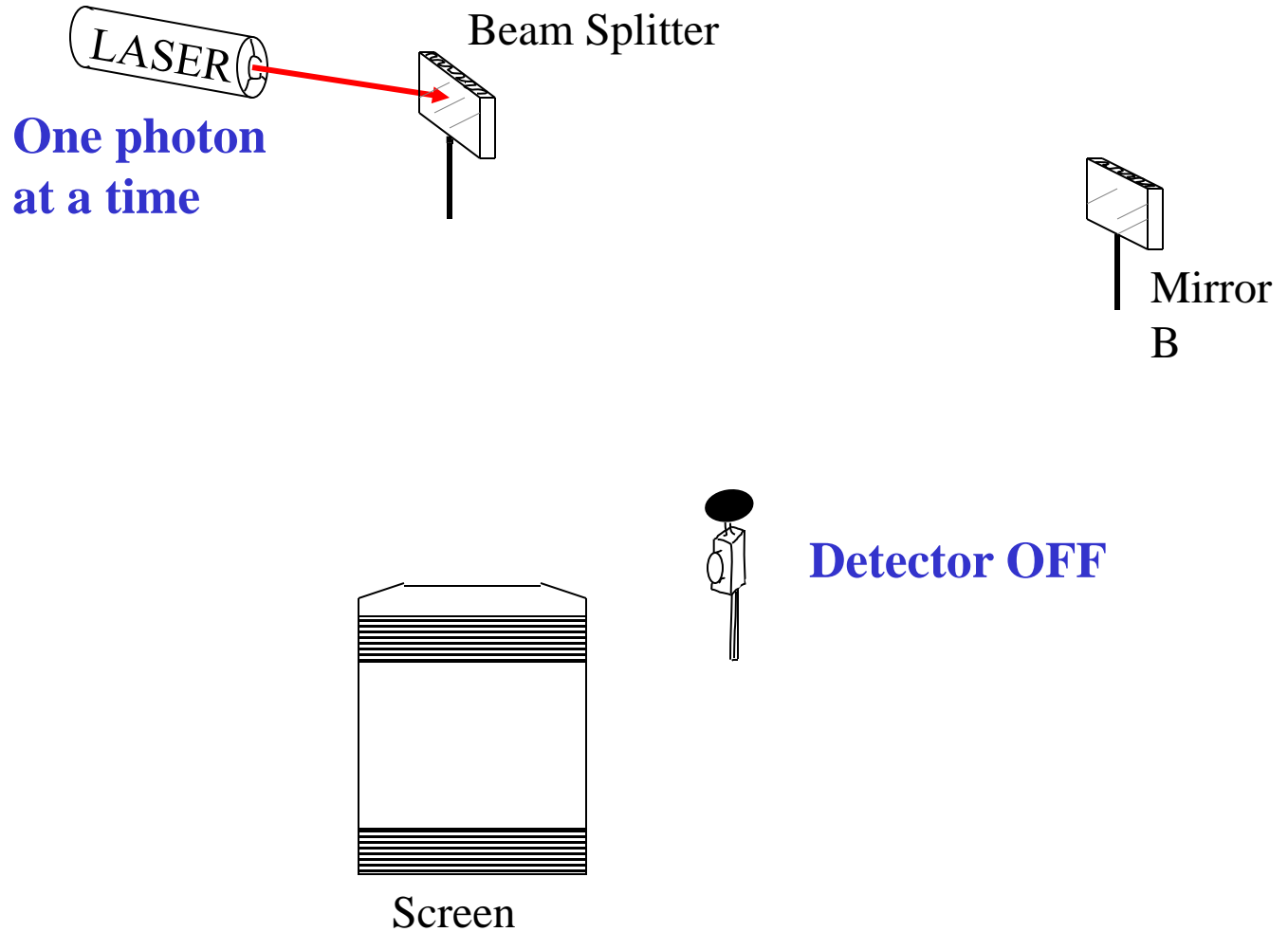
Detector OFF



* p. 187, *The Fabric of the Cosmos*, B. Greene

Delayed Choice *

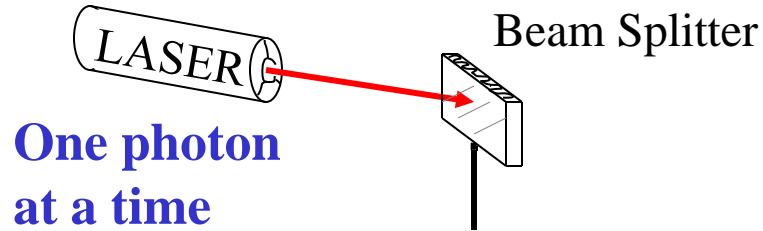
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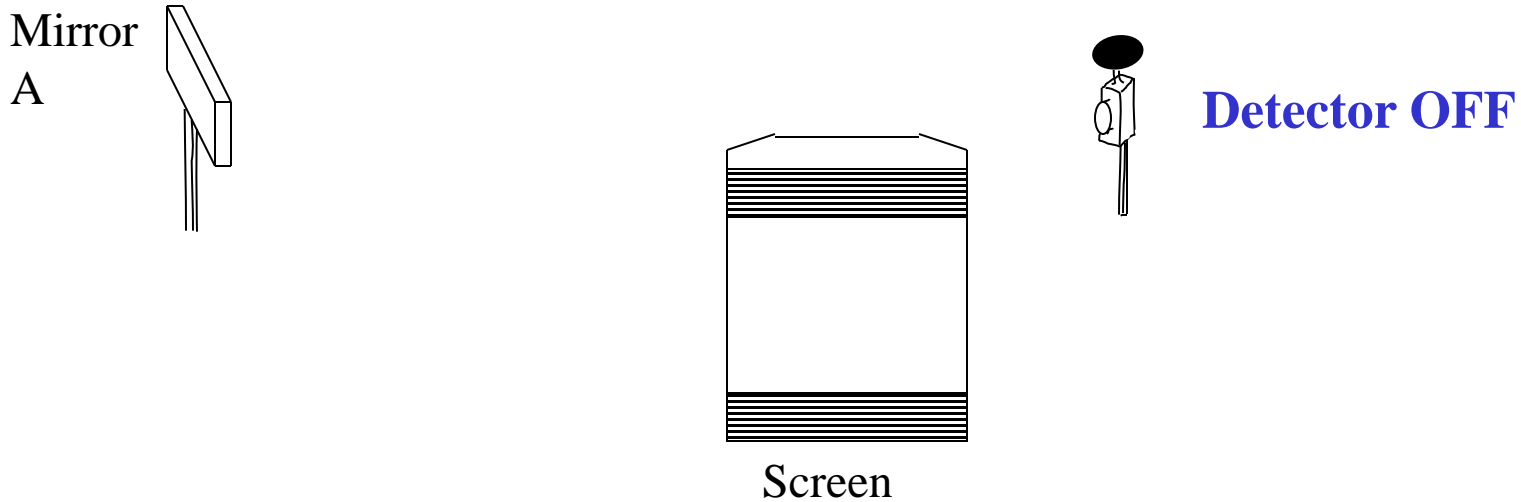
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Delayed Choice *

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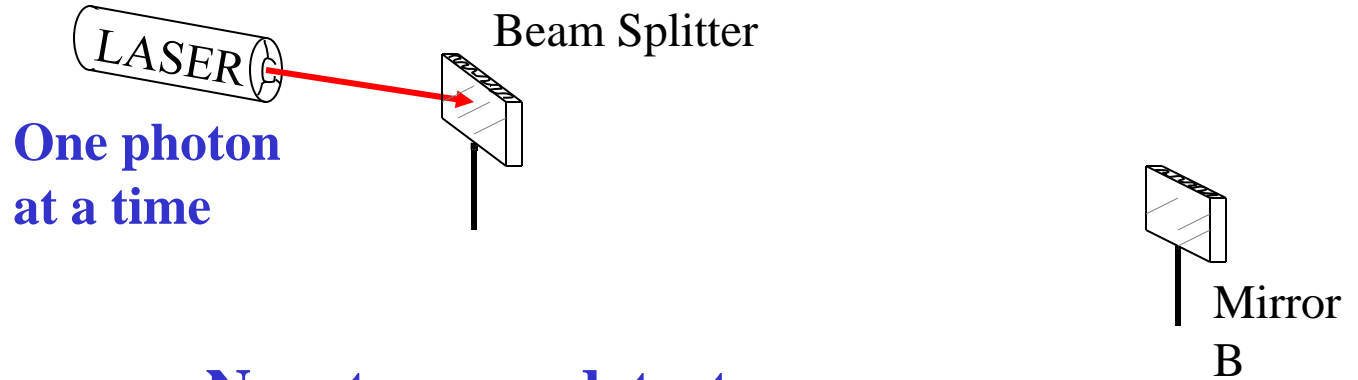
Now turn on detector



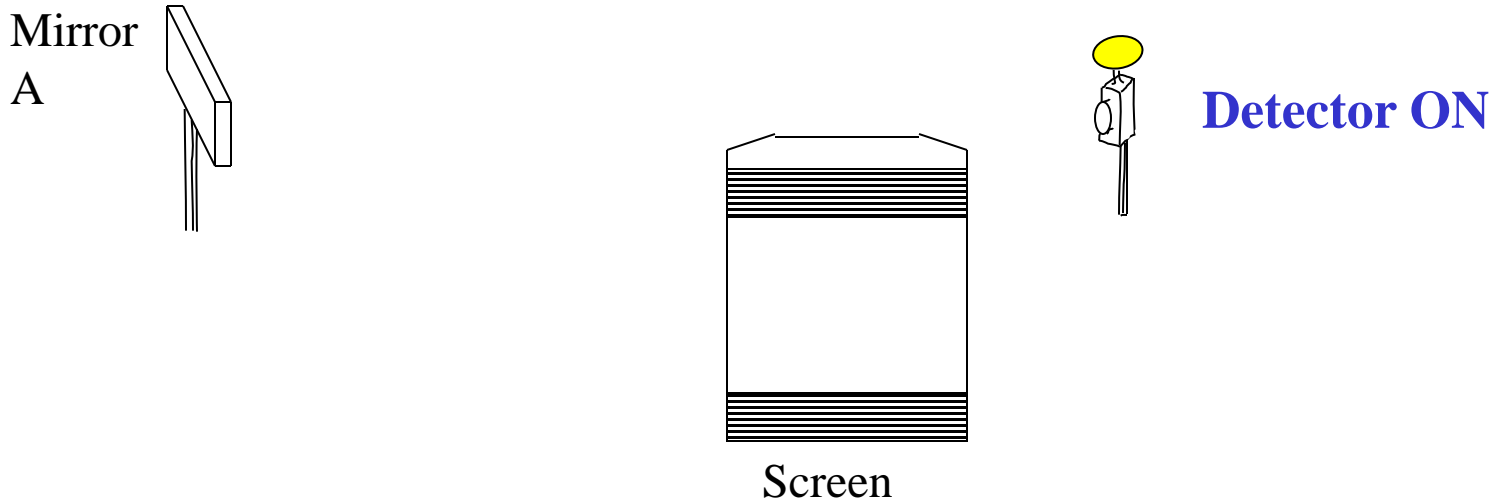
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Delayed Choice *

Now Turn on Detector

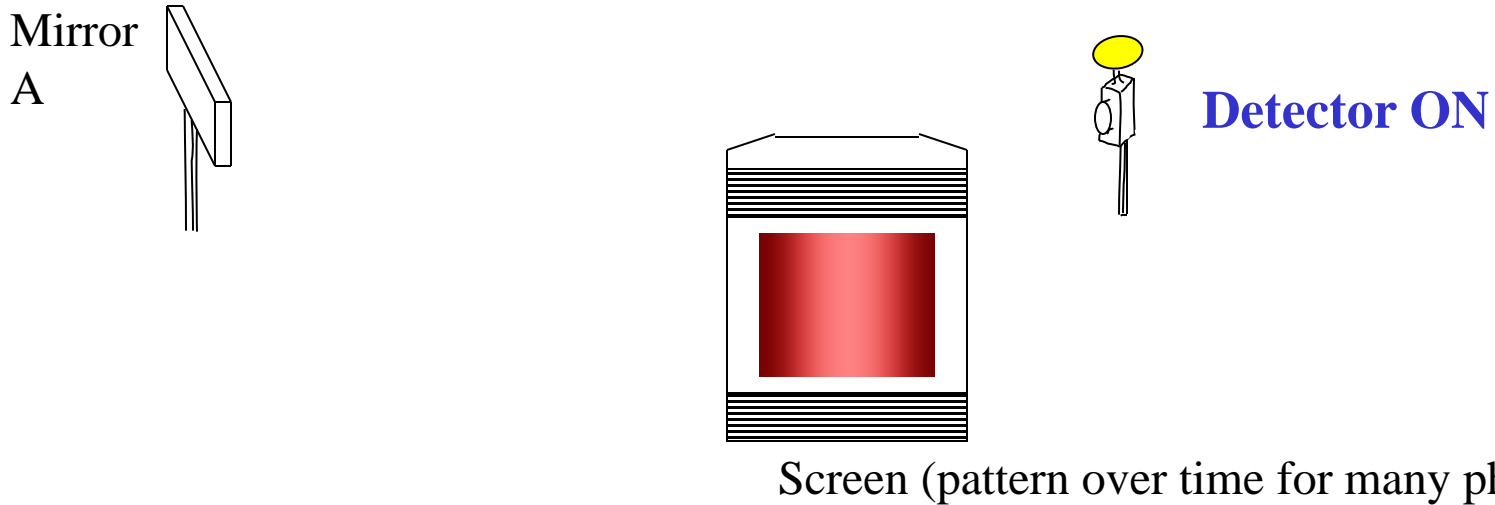
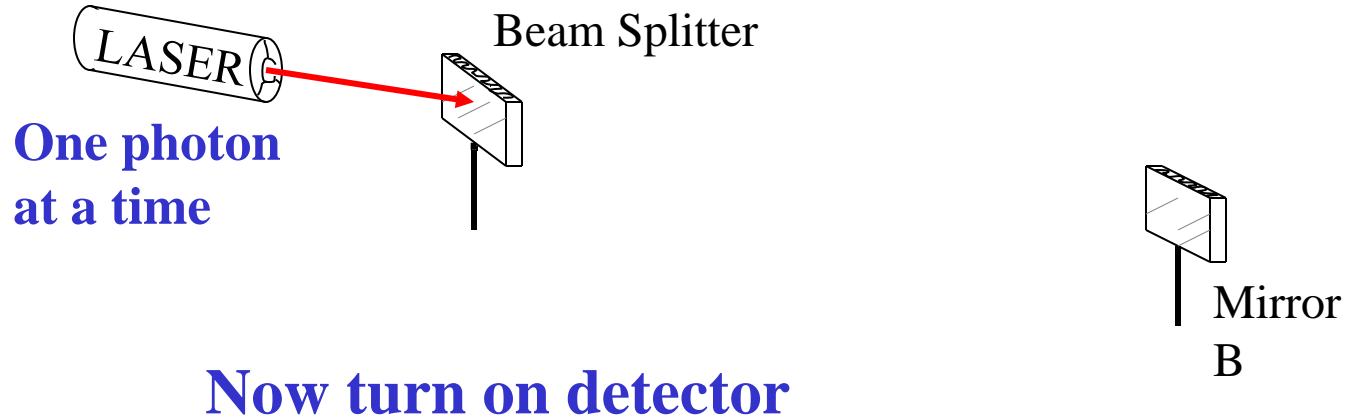


Now turn on detector



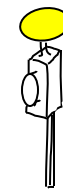
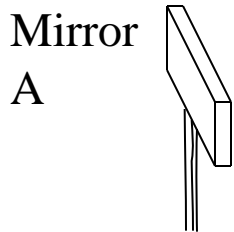
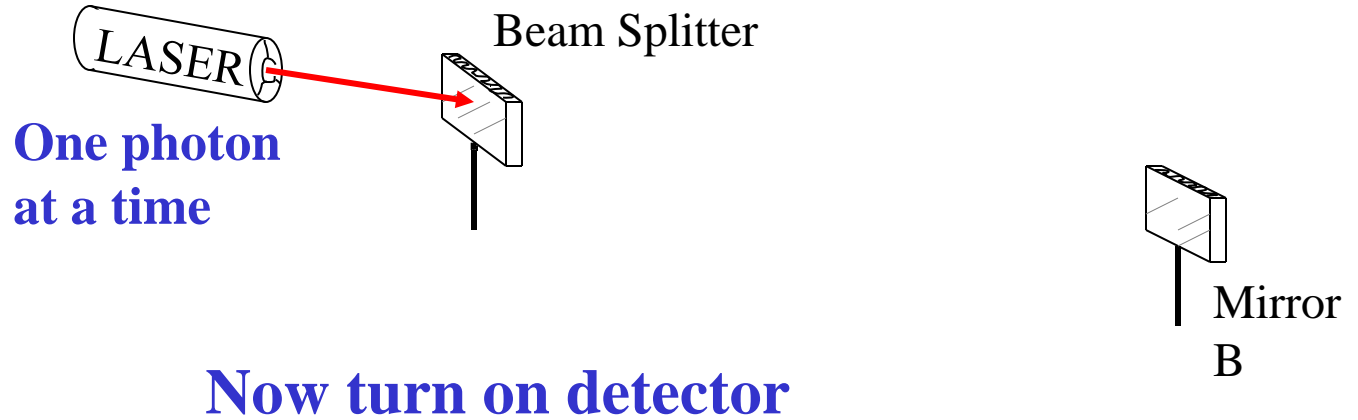
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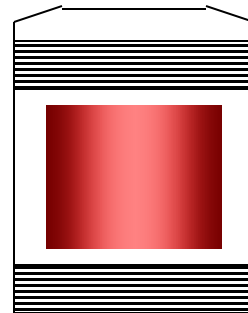


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Delayed Choice *



Detector ON

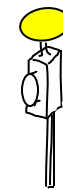
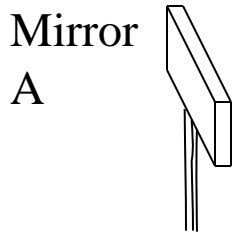
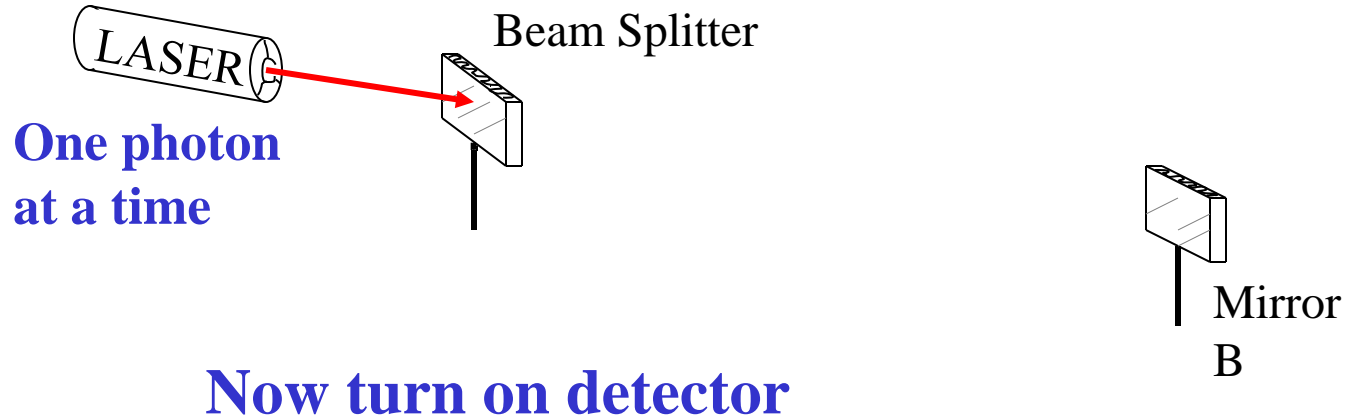


Which Path Detector : **ON**
- **No Interference**

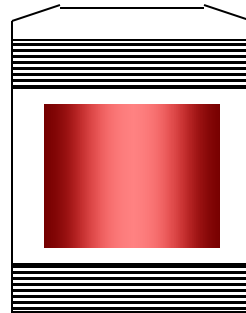
Screen (pattern over time for many photons)

* p. 187, *The Fabric of the Cosmos*, B. Greene

Delayed Choice *



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