AMPLIFICATION OF SUPERLUMINALITY (?)

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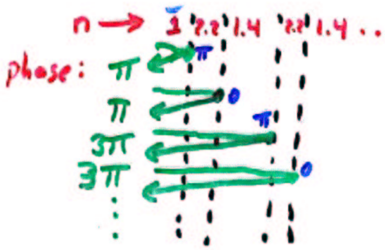
OUTLINE

- A few things I decided not to talk about (but will)
  - old MLD tunneling results
    a reshaping picture to bear in mind
  - our recent 2-photon exp'ts
    (nonlinear phase shifts...
    slow/fast photons?
    self-focussing, etc?
    quantum computing? ...but phase)
  - Parallel with EIT, slow light,...
  - The Tournois effect
- Weak measurements: a way to look at tunneling
  - Can a particle be 2 places at 1 time?
- Amplification of superluminality
  - MLDs with gain

Multilayer Dielectric Mirror is precisely such a structure.

$n_1 L_1 = n_2 L_2 = \lambda/4.$

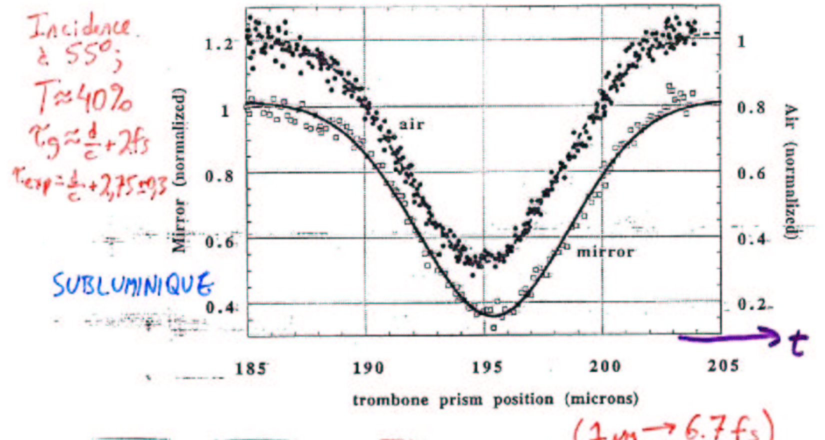


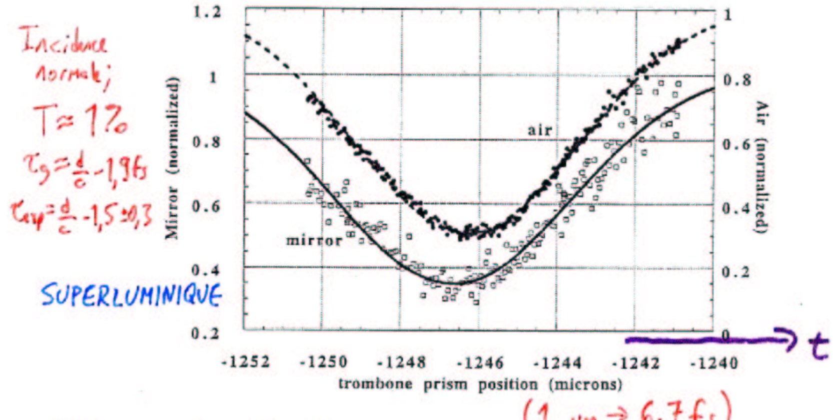
(Bragg reflection)

Successive reflections interfere constructively. By adding layers, even though at each interface R≈5%, total reflectivity can be arbitrarily close to 1.

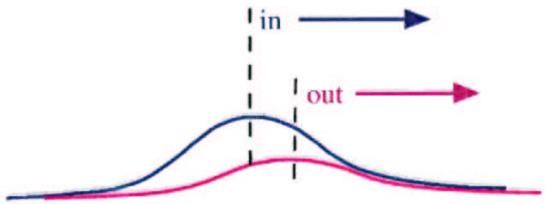
E.g., for 11 layers, T=1.2%, though $(95\%)^{11} = 57\%$.

(Tunnelling probability drops exponentially with d.)





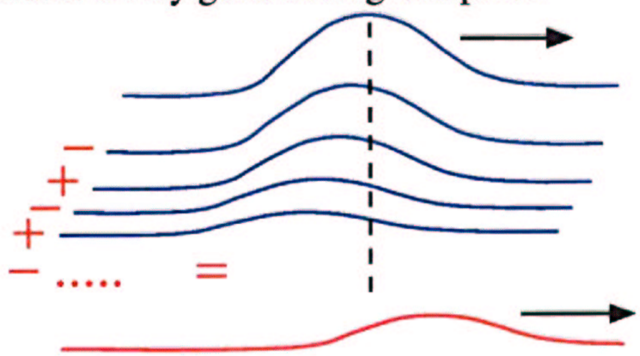
[Steinberg, Kwiat, + Chiao PRL 71, 708 (1993); Steinberg + Chiao PRA 51, 3525 (1995).]



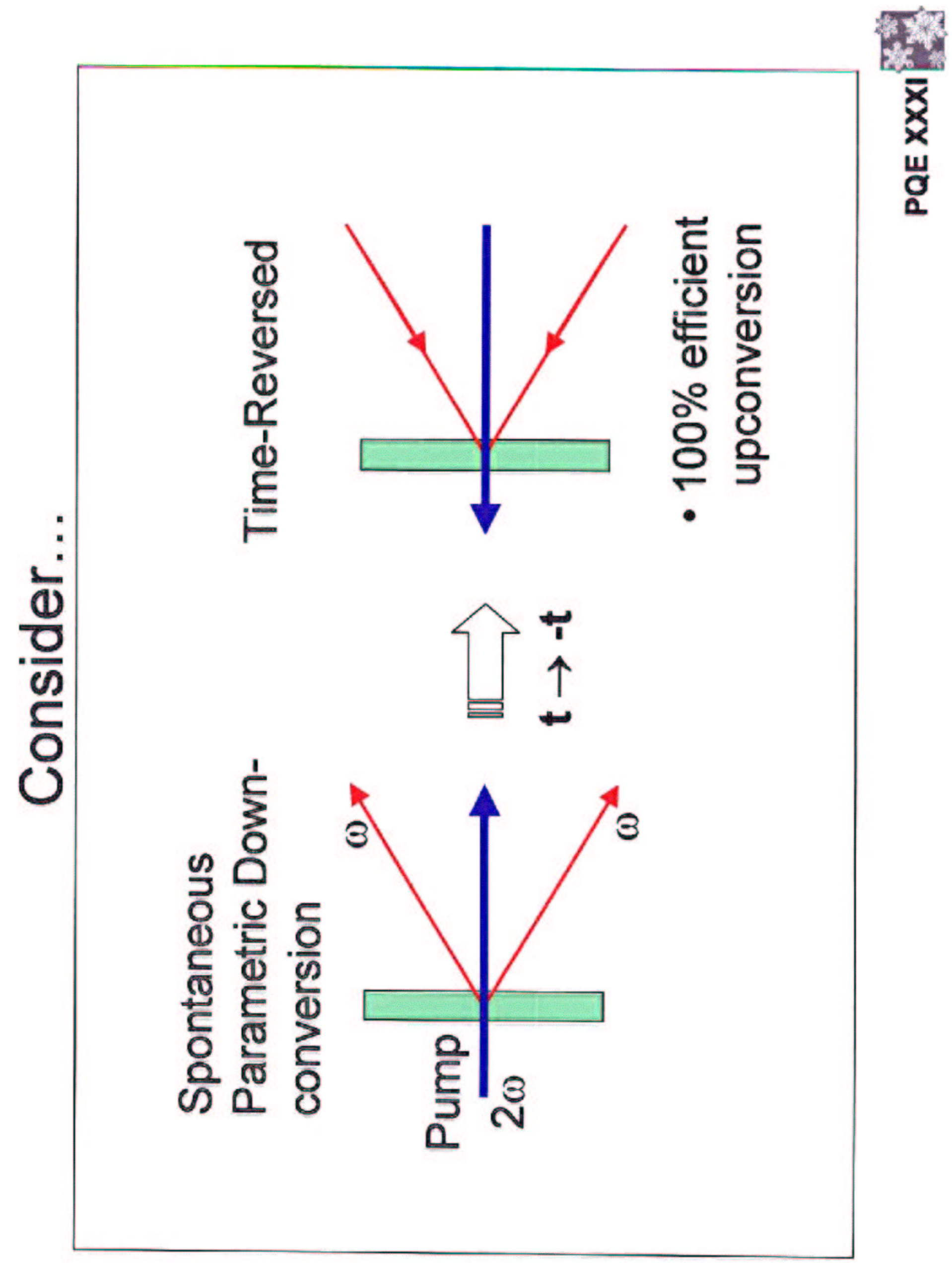
No energy need travel faster than *c*.

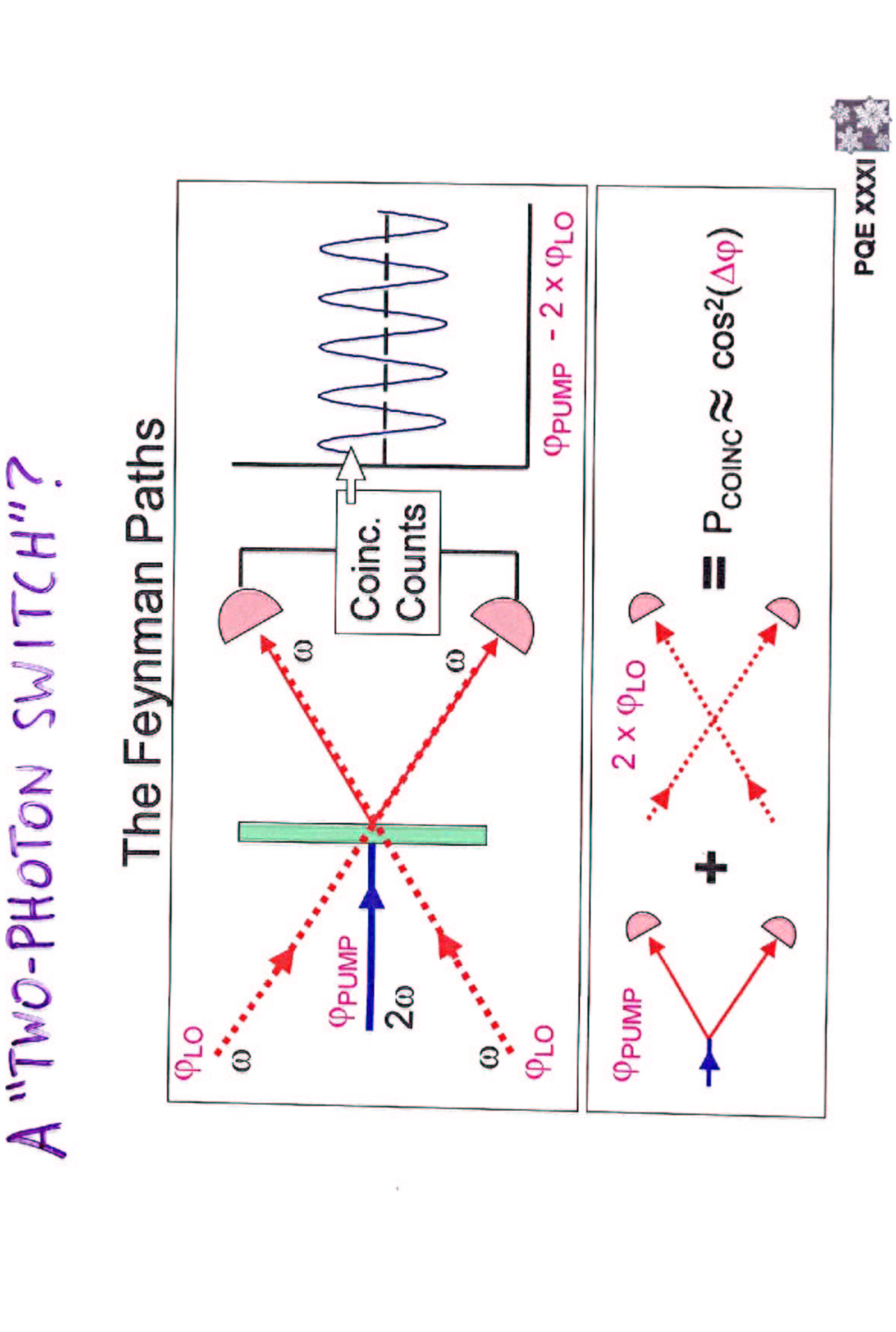
What about information, however?

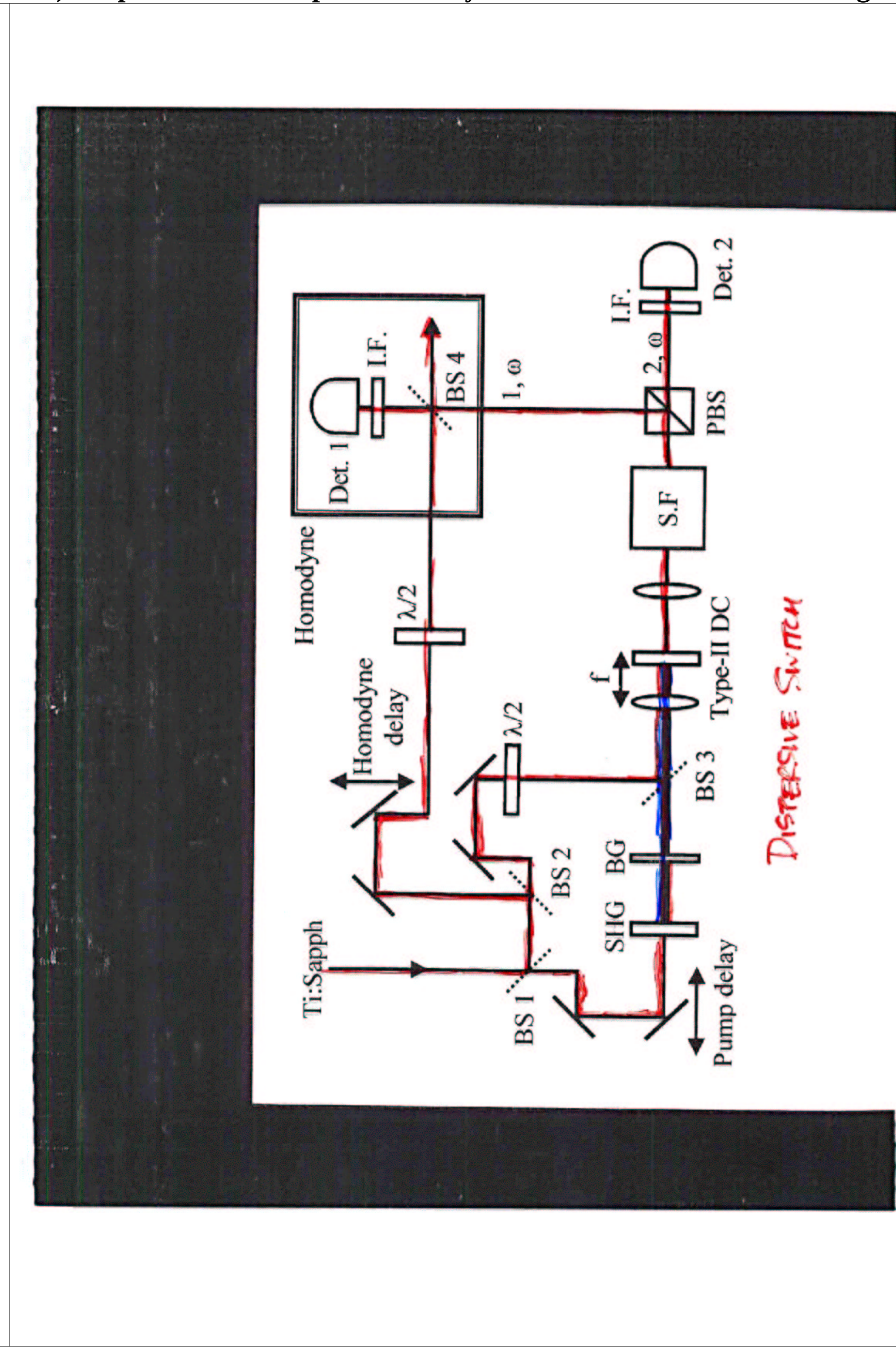
The transmitted pulse is constructed causally out of the initial pulse. Although it *looks* as though it travelled >c, this is merely a result of a Taylor expansion.
A barrier is a very good analog computer.

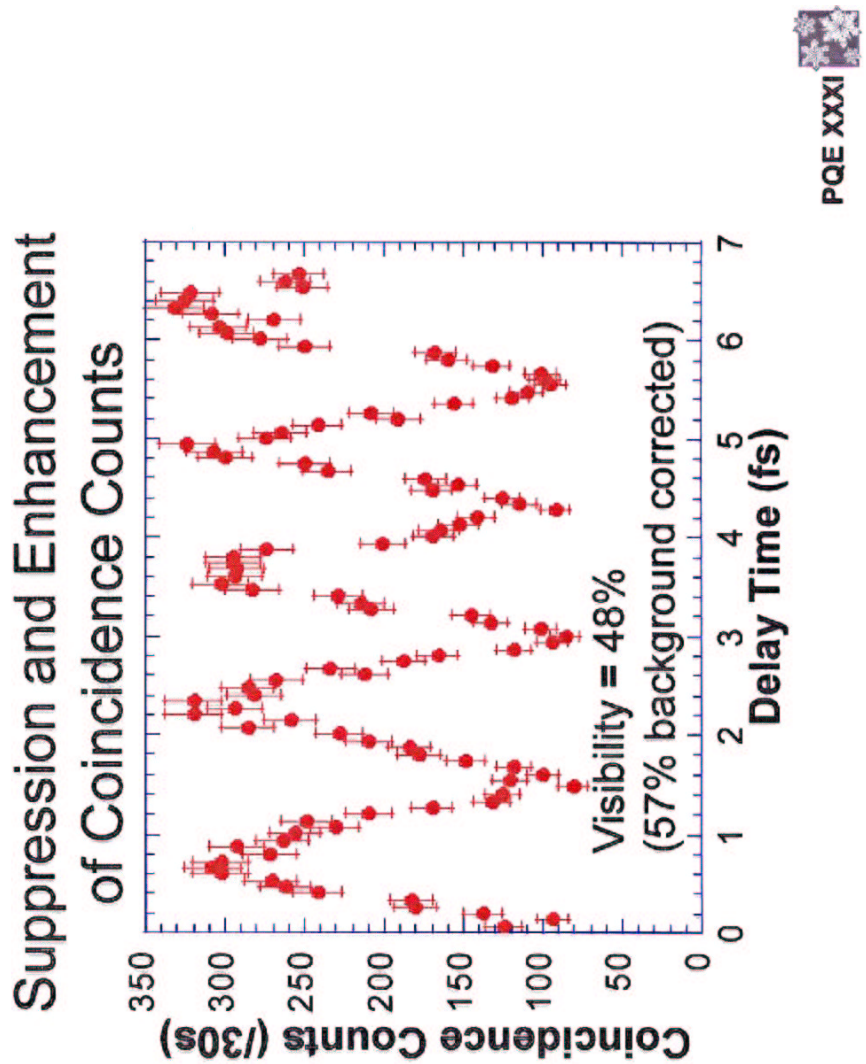


BUT:* no new *information propagates faster than c.

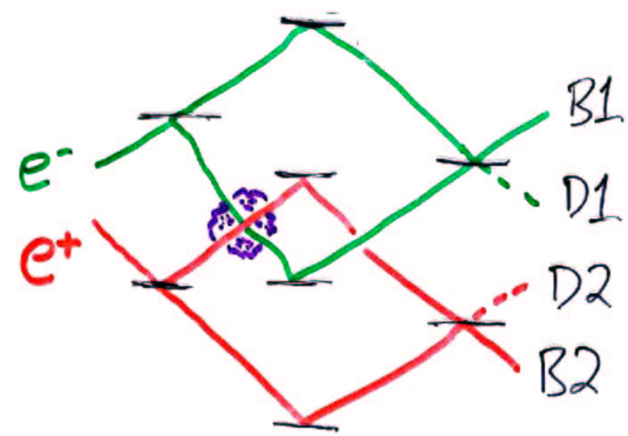



A "TWO-PHOTON SWITCH"?
The Feynman Paths
Coinc. Counts
φLO
ω
φPUMP
2ω
ω
φLO
ω
ω
φPUMP - 2 x φLO
φPUMP
+
2 x φLO
= PCOINC ≈ cos²(Δφ)
PQE XXXI


Ti:Sapph
BS 1
BS 2
SHG
BG
Pump delay
BS 3
λ/2
Homodyne delay
λ/2
Homodyne
Det. 1
I.F.
BS 4
1, ω
2, ω
PBS
S.F
Type-II DC
f
I.F.
Det. 2
DISPERSIVE SWITCH



HARDY'S PARADOX



D1 → e^+ was in the way
D2 → e^- was in the way
D1 & D2 → both were in the way
↳ they annihilate
↳ should never see them

BUT: QM says sometimes you do.

CONVENTIONAL CONCLUSION:
We can't reason about the past;
can't discuss what we don't measure.

OUTLANDISH CONCLUSION?

Reëxamine logic, probability,...

What would <u>weak</u> measurements say?

D1 & D2 fire ⇒ e^- & e^+ were "IN"

$P(e^- \text{ in}) = 1$

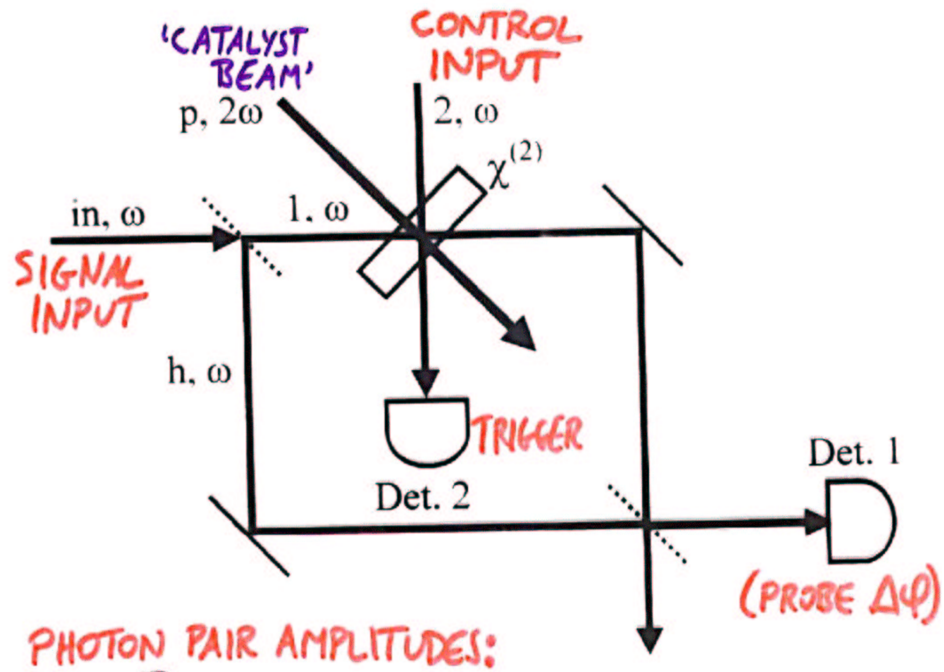
$P(e^+ \text{ in}) = 1$

They didn't annihilate ⇒ e^- & e^+ weren't <u>both</u> "IN"

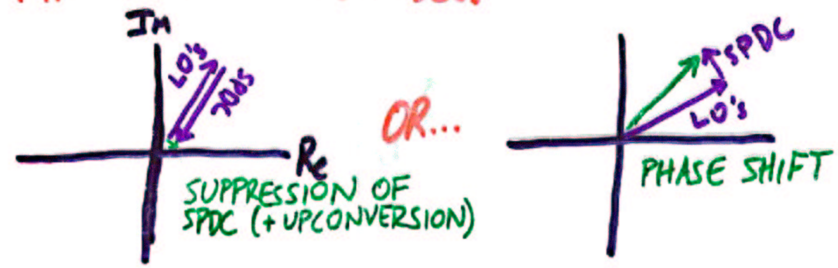
$P(e^- \text{ in} \ \& \ e^+ \text{ in}) = 0$

	e^- IN	e^- OUT	
e^+ IN	0	1	⇒ 1
e^+ OUT	1	−1	⇒ 0
	⇓ 1	⇓ 0	

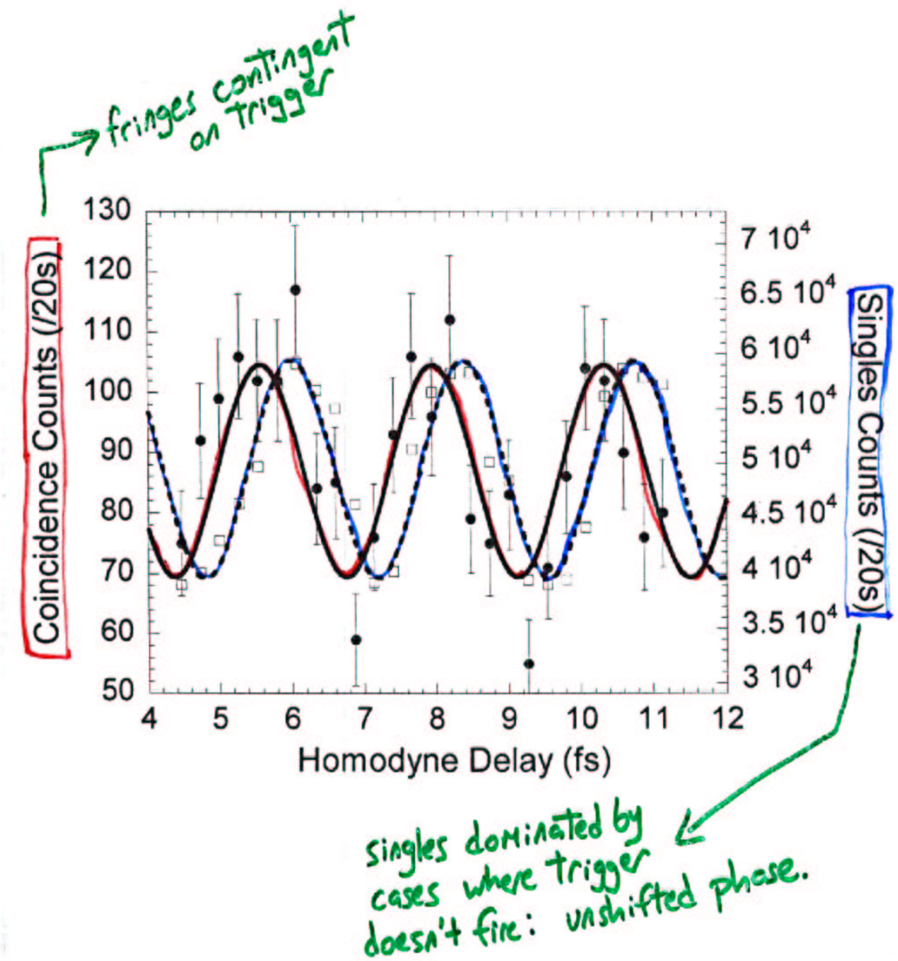
CROSS-PHASE MODULATION AT THE TWO-PHOTON LEVEL?



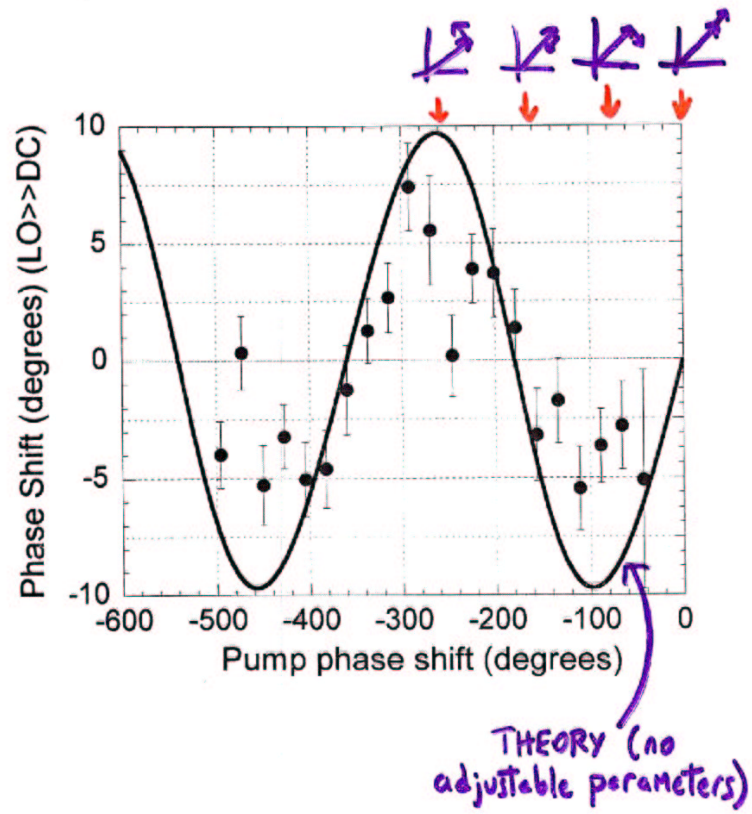
PHOTON PAIR AMPLITUDES:



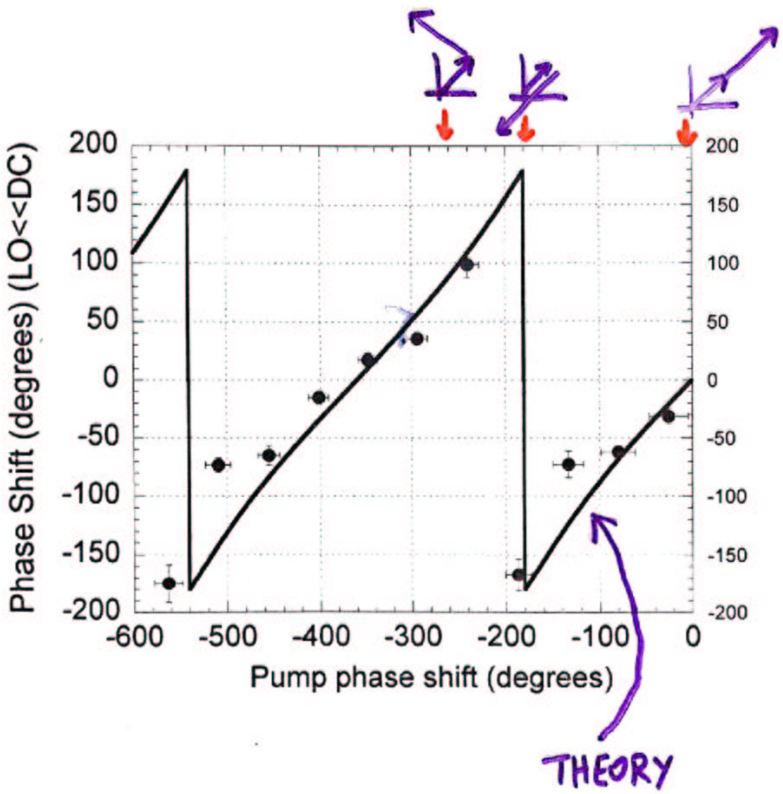
OBSERVED PHASE SHIFT



LOW PHASE-SHIFT REGIME (LO's >> SPDC)

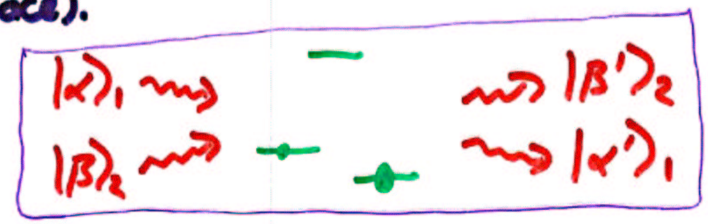


HIGH PHASE-SHIFT REGIME
(SPDC » LO's)

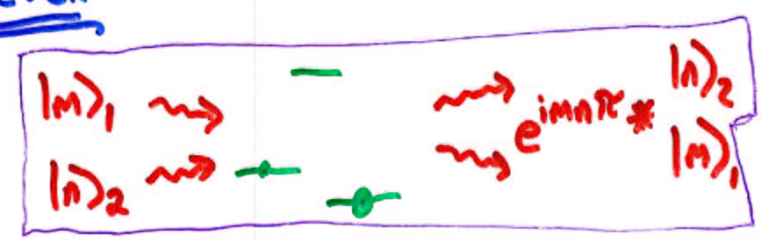


A^{V} THEOREM
(INTERESTING? RELEVANT? SURPRISING?)

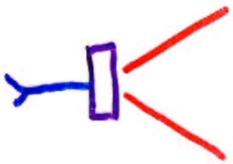
FOR A 3-LEVEL EIT SYSTEM (which one might use in a quantum logic gate) TO WORK FOR UNENTANGLED INPUTS, AND LEAVE THEM IN A PURE STATE (i.e., not entangled with the atoms), BOTH INPUTS MUST BE IN COHERENT STATES (e.g., not $|0\rangle$ and $|1\rangle$ qubit states in Fock space).



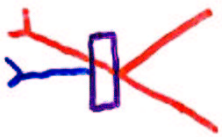
NEVER



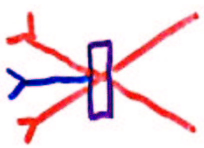
THE MENAGERIE



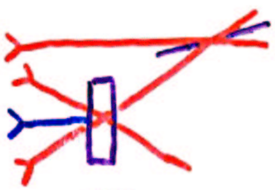
DOWN-CONERSION
(nondet. single-photon prep)



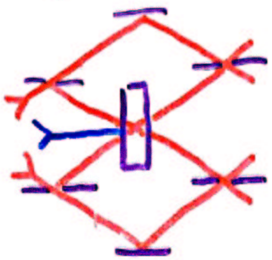
QUANTUM STATE PREP



2-PHOTON SWITCH



2-PHOTON
CROSS-PHASE MODULATION



HARDY'S PARADOX

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 33, NO. 4, APRIL 1997

Negative Group Delay Times in Frustrated Gires–Tournois and Fabry–Perot Interferometers

Pierre Tournois

Abstract— It is demonstrated in this paper that a Gires–Tournois interferometer illuminated with an angle of incidence greater than the critical angle for total internal reflection introduces a negative group delay time, whatever the orientation of the electric field vector of the wave with respect to the plane of incidence, when the evanescent wave in the dielectric layer is reflected by a dielectric substrate whose refractive index is between those of the incident medium and of the dielectric layer. When the evanescent wave in the dielectric layer is reflected by a nonabsorbing metal, the group delay time is negative when the electric field vector is in the plane of incidence and positive when the electric field vector is perpendicular to the plane of incidence. Similarly, a frustrated Fabry–Perot interferometer shows negative group delay times for angles of incidence greater than specific *p*-wave and *s*-wave critical angles.

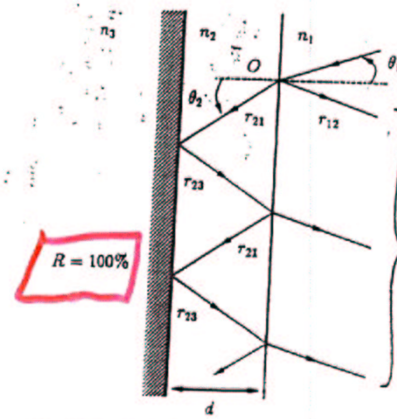


Fig. 1. The Gires–Tournois interferometer.

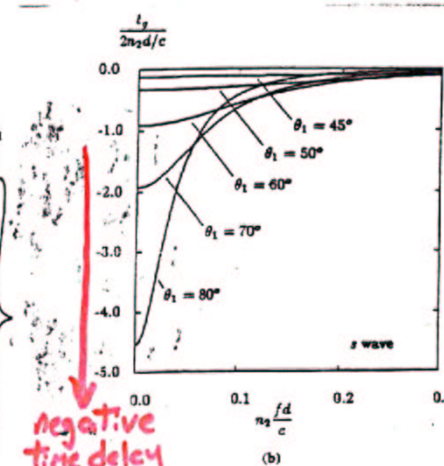
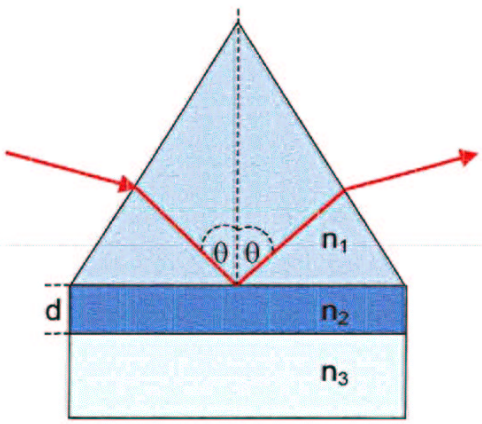


Fig. 2. Phase difference and group delay time in a frustrated Gires–Tournois interferometer, for an incident s wave and $n_1/n_2 = 1.5$, in the idealized case where $r_{23} = 1$.

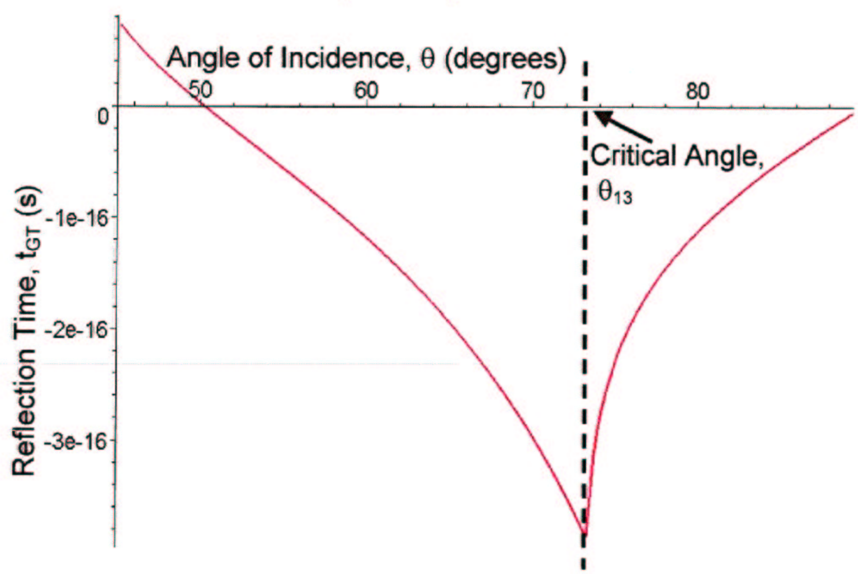
Frustrated Gires-Tournois Interferometer

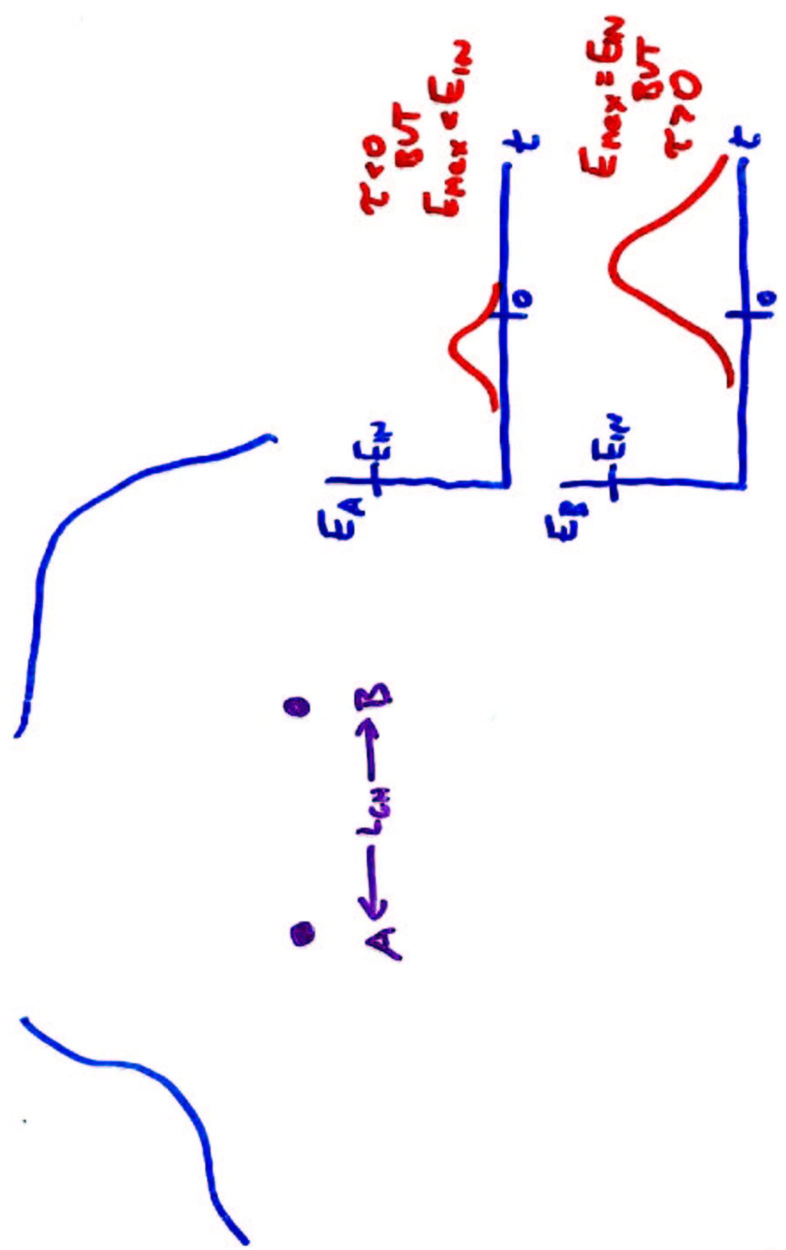


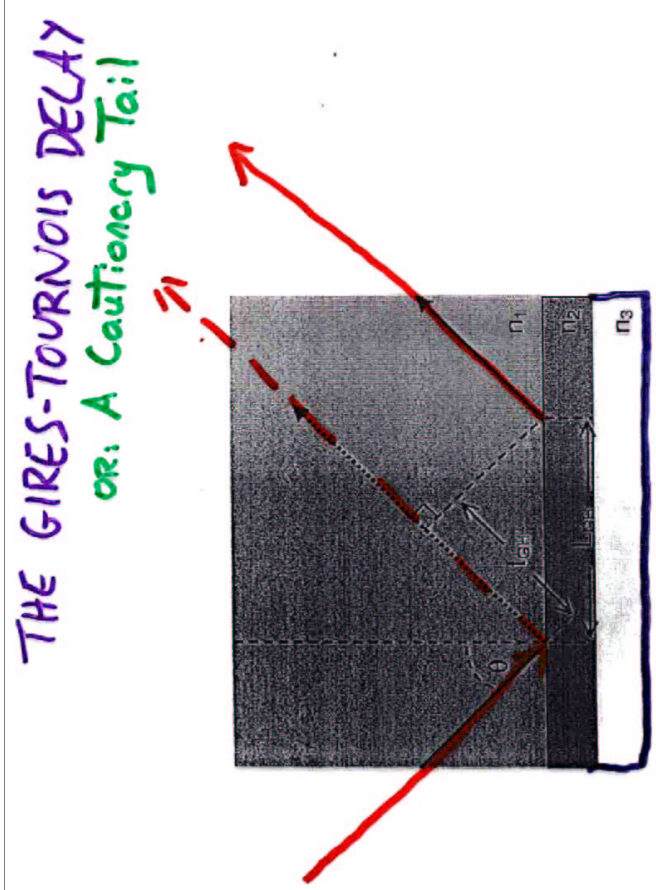
- When
  $n_1 > n_3 > n_2$ and
  $\theta > \theta_{13} = \sin^{-1}(n_3/n_1)$,
  where θ_{13} is the critical angle, the reflection time is negative.
- The light undergoes total internal reflection since $\theta > \theta_{13} > \theta_{12}$ and the reflection probability is 100%.
- The minimum negative reflection time is one optical period.
  $t_{GTmin} = -1/\omega$

Expected Reflection Time vs. Angle of Incidence

For Stated System Specifications




τ<0
BUT
E_max < E_IN
E_max = E_IN
BUT
τ>0
E_A
E_B
E_IN
t
0
A
B
L_CM


THE GIRES-TOURNOIS DELAY
OR: A Cautionary Tail
n1
n2
n3

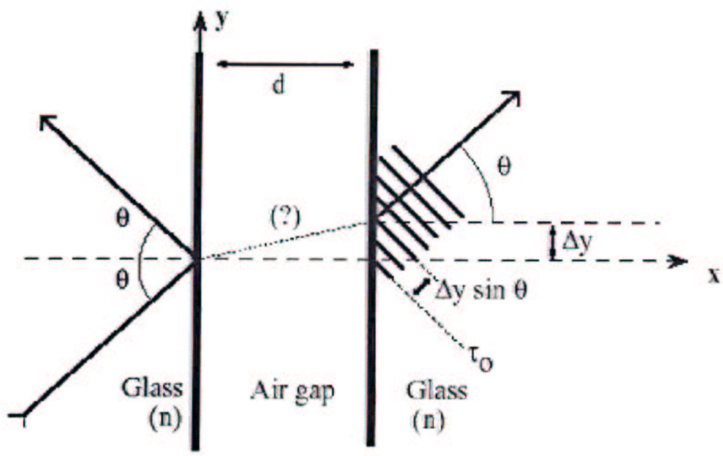
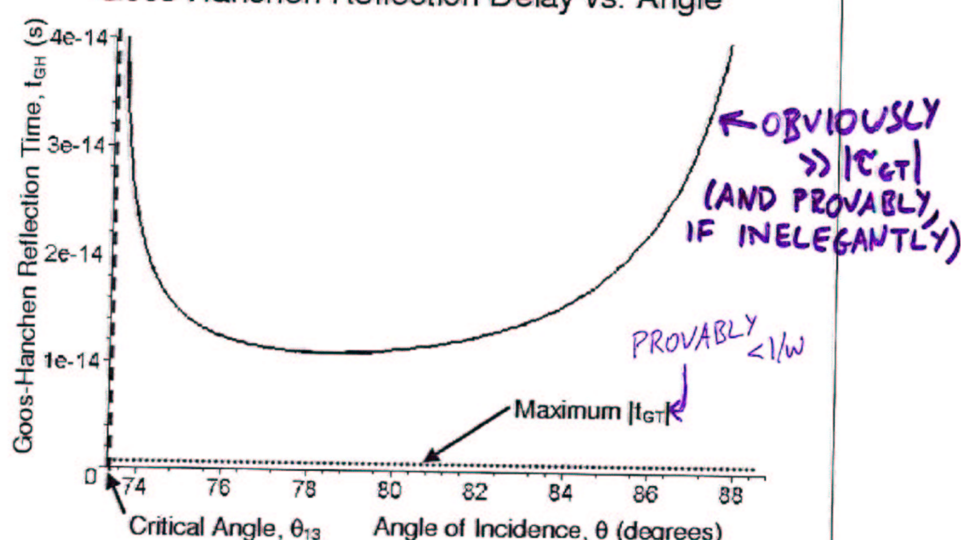
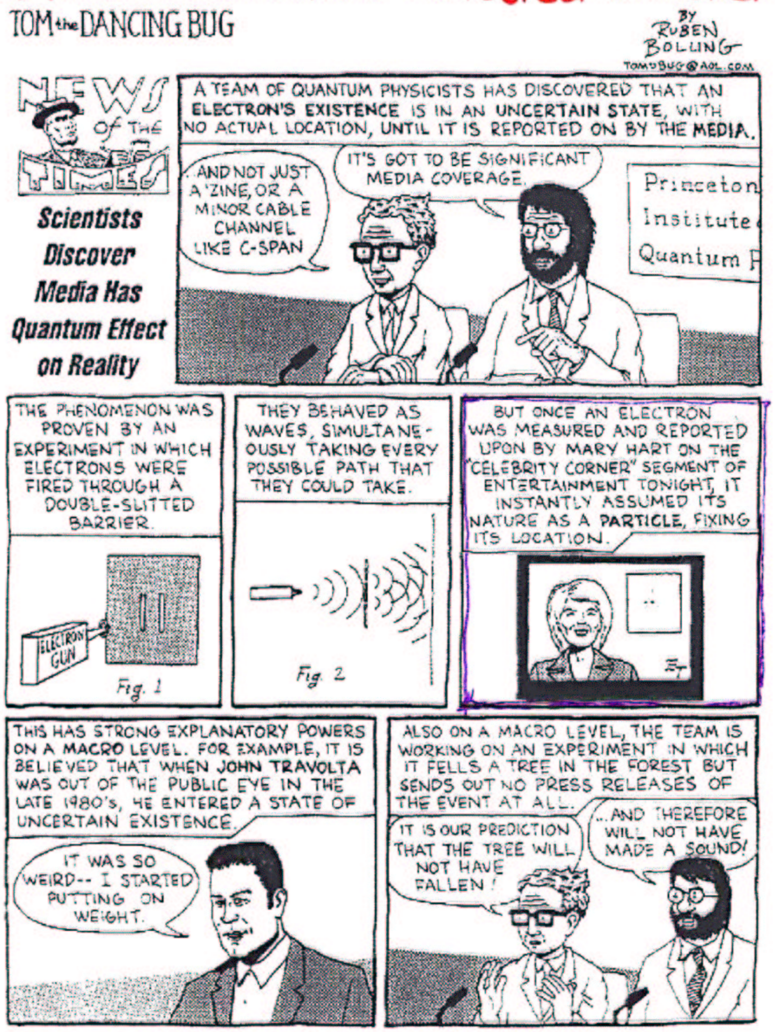


Figure 5.5: Regardless of incident angle θ, the transmitted beam reaches $y = 0$ sooner than it reaches $y = \Delta y$, by a delay of $(n/c)\Delta y \sin\theta$.

$$\tau_T = \tau_{GT} + \tau_{GH} > 0$$



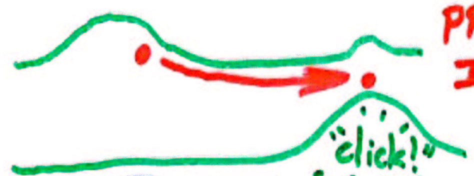
AND NOW FOR SOMETHING COMPLETELY DIFFERENT...



So for an ensemble (or a classical wave), no surprises.
Center-of-mass moves slower than light

(in fact, com is reflected)

How does a Copenhagenist understand that the subensemble which is transmitted appears early?



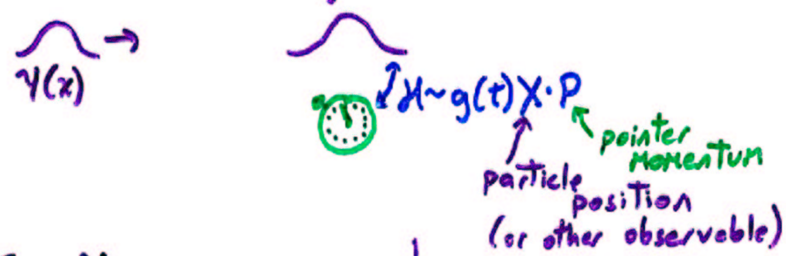
REMAINING QUESTION:
If you are not comfortable with collapse, how should you think about "that subset of the particles which is ultimately transmitted"?

'WEAK' (CONDITIONAL) MSMTS

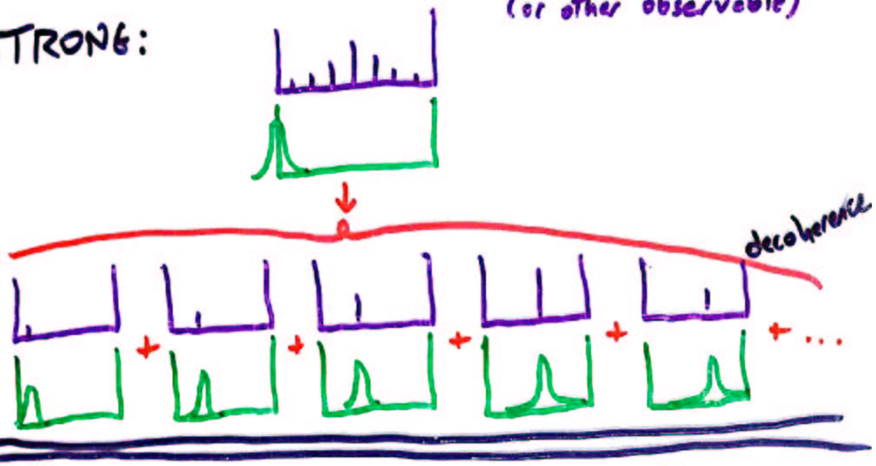
The Schröd. eq. is t-reversible:
why should a msmt at t_2 depend on preparation at t_1, but not on selection at t_3?

Irreversible measurement

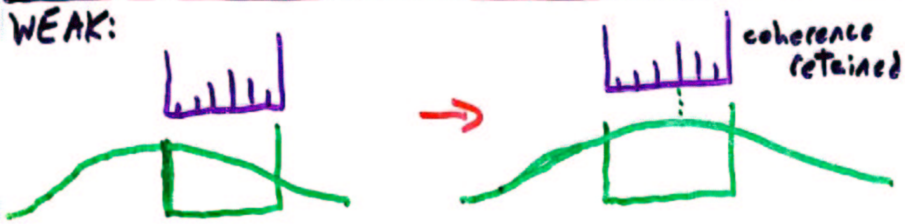
von Neumann msmt theory:



STRONG:



WEAK:



Prepare particle in $|i\rangle$
Measure observable A weakly
Postselect particles in $|f\rangle$

Outcome of each weak msmt very uncertain

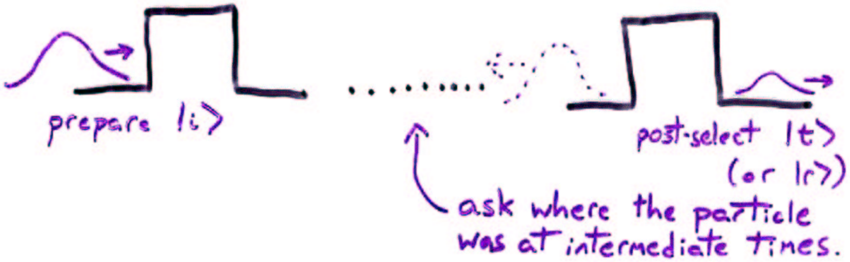
But on average, find $\frac{\langle f|A|i\rangle}{\langle f|i\rangle} \equiv \langle A\rangle_{fi}$

N.B. For $|f\rangle = |i\rangle$, $\langle A\rangle_{fi} = \langle A\rangle$

- For $\langle f|i\rangle \ll 1$, $\langle A\rangle_{fi}$ may be outside spectrum of A
- $\langle A\rangle_{fi}$ may be complex
- $A|i\rangle = a|i\rangle$ OR $A|f\rangle = a|f\rangle$ $\Rightarrow \langle A\rangle_{fi} = a$
- $\langle A+B\rangle_{fi} = \langle A\rangle_{fi} + \langle B\rangle_{fi}$ Even if $[A,B] \neq 0$!
- $P(A \& B|f) = P(B|f)\,P(A|B)$
- $\sum_j P(f_j)\langle A\rangle_{f_j i} = \langle A\rangle \Rightarrow |T|^2\tau_T + |R|^2\tau_R = \tau_d$

$$\sum \langle i|f_j\rangle\langle f_j|i\rangle \frac{\langle f_j|A|i\rangle}{\langle f_j|i\rangle} = \sum \langle i|f_j\rangle\langle f_j|A|i\rangle = \langle i|A|i\rangle$$

How does this apply to tunneling?



$$P(x) = |\psi(x)|^2 = \langle\psi|\underbrace{x\rangle\langle x}_{\text{Proj}(x)}|\psi\rangle$$

The prob. of being at x is just the expectation value of the projector onto x.

Bayes's thm. $\Rightarrow P(x|\text{trans}) = \dfrac{P(x \,\&\, \text{trans})}{P(\text{trans})}$

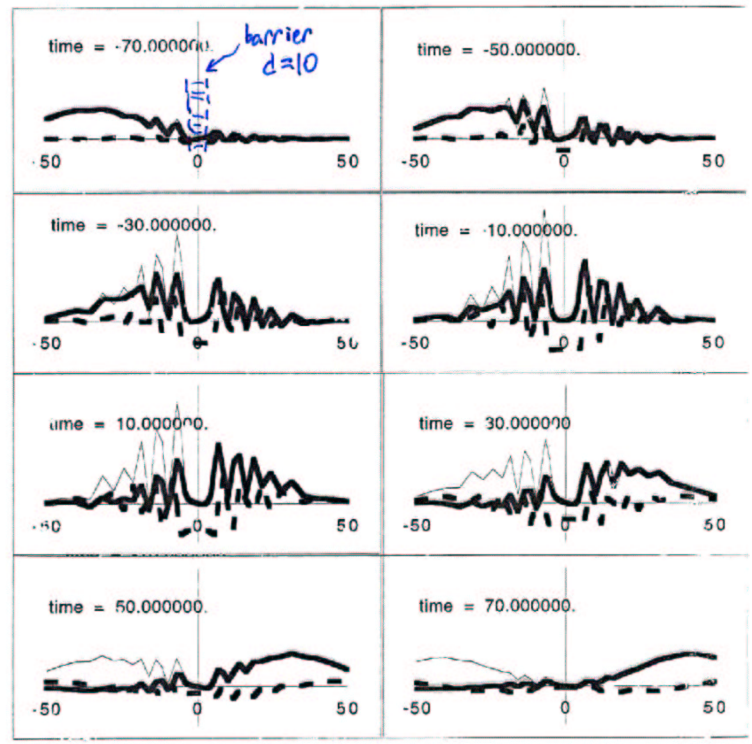
$$= \frac{\langle\ |t\rangle\langle t|\ \ |x\rangle\langle x|\ \rangle}{\langle\ |t\rangle\langle t|\ \rangle}$$

$$= \frac{\langle i|t\rangle\ \langle t|x\rangle\langle x|i\rangle}{\langle i|t\rangle\ \langle t|i\rangle} = \frac{\langle t|\ |x\rangle\langle x|\ |i\rangle}{\langle t|i\rangle}$$

Precisely A&V's result. $P(x|\text{trans}) = \frac{1}{T}\psi_T^*(x)\psi_I(x)$.

- We can write the prob. distrib. of either trans. or refl. particles, as a function of time.
- We can integrate over time + over the barrier to obtain a total "conditional dwell time."
- BUT: these results are complex.

35 52m
52.15



- ▬ – Prob. distrib. of tunneling particle
- — – " " " reflected "
- ▪▪▪▪ – "Back-action" on quantum measurement device

N.B. ① very little 'real time' spent at x=0
② no preferential transmission of leading edge

THE MEANING OF 'WEAK MEASUREMENTS' WITH COMPLEX VALUES

$$\tau_T \rightarrow \tau_d - i\,\tau_{BL}$$

"Has anyone ever seen a stopwatch with complex numbers on the dial?"

But consider a quantum-mechanical stopwatch.

$$\psi(x) \sim e^{-(x-t)^2/4\sigma^2}$$

↖ some inevitable uncertainty

t complex $\Rightarrow$ $\psi \sim e^{-(x-\mathrm{Re}\,t)^2/4\sigma^2}\, e^{ix\,\mathrm{Im}\,t/2\sigma^2} \ldots e$

- hand shifts by $\mathrm{Re}\,t$
- picks up momentum of $\hbar\,\mathrm{Im}\,t/2\sigma^2$
- normalization

This is precisely the meaning of weak (or conditional) measurements.

$\mathrm{Re}\,\tau_T$ describes clock hand's position shift (e.g., Larmor precession).

$\mathrm{Im}\,\tau_T$ describes back-action (e.g., spin aligning with $\mathbf{B}$.)

For large σ, back-action vanishes, but position shift of hand remains constant.

À la recherche du temps perdu

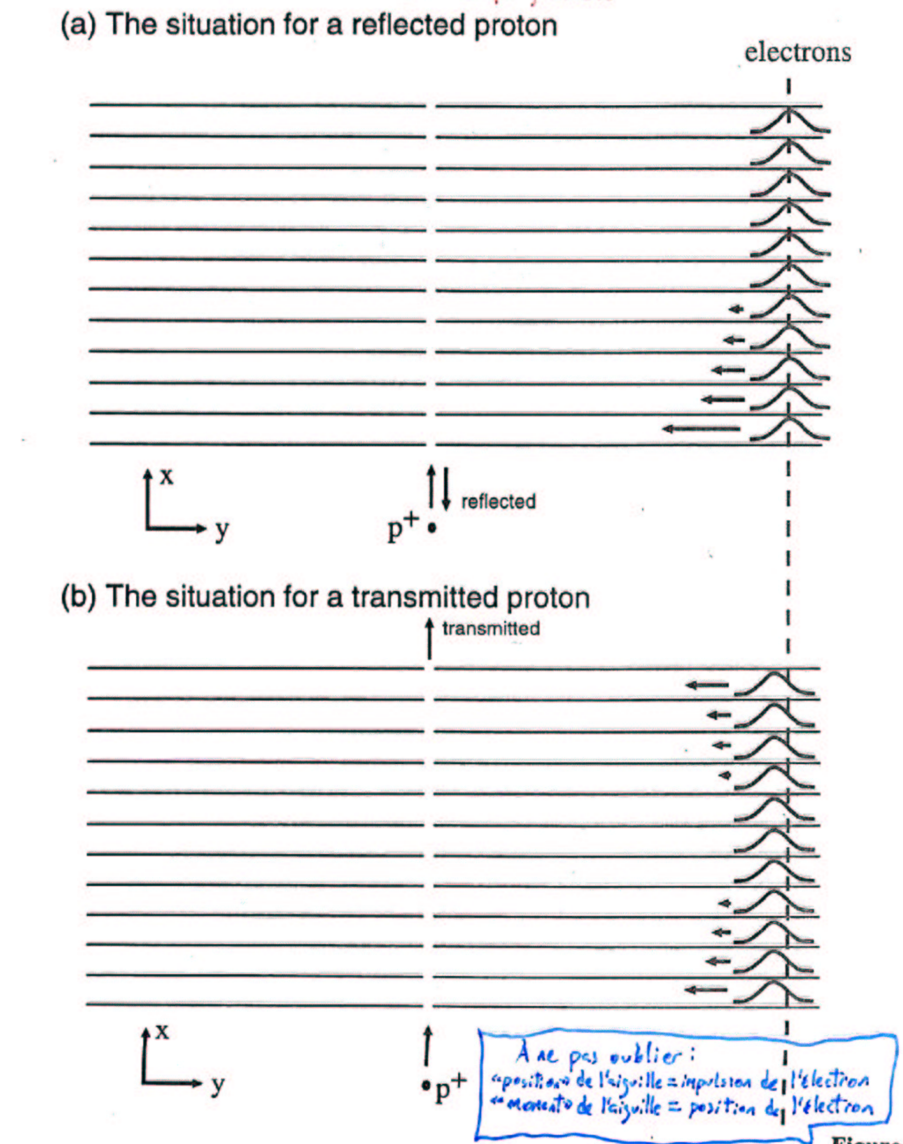
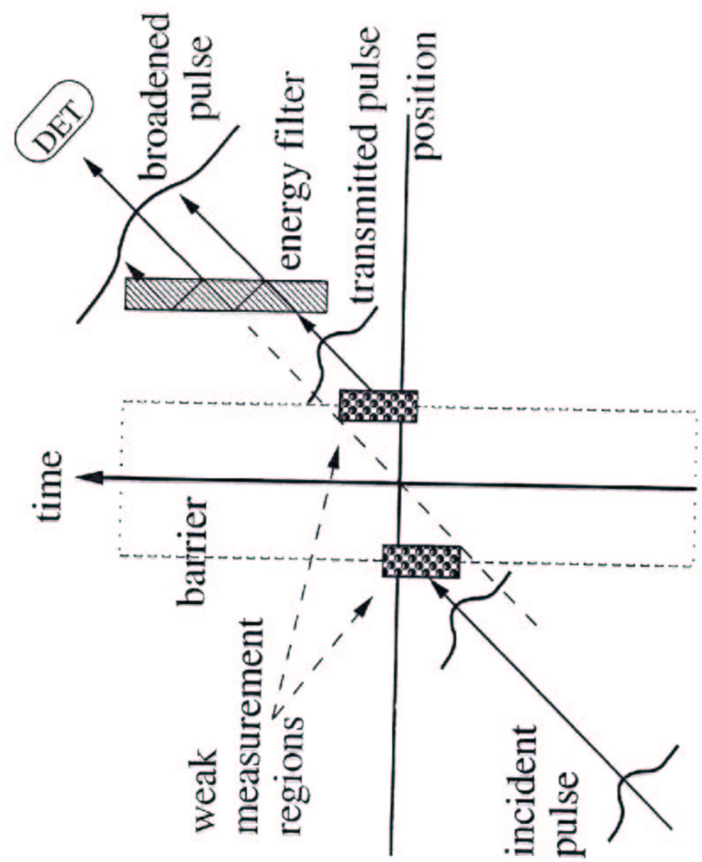
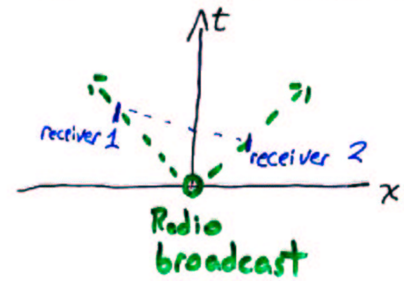


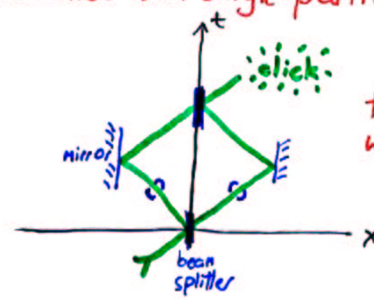
Figure 1



A cause may have two spacelike-separated effects.



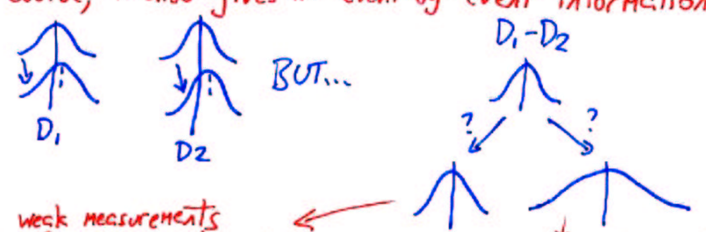
But if the cause is a single particle?



the wave went both ways.
will detectors both see the particle?

NO — a good detector collapses the state, s.t. only one detector fires.

BUT: a "weak" detector does no such thing.
Of course, it also gives no event-by-event information.



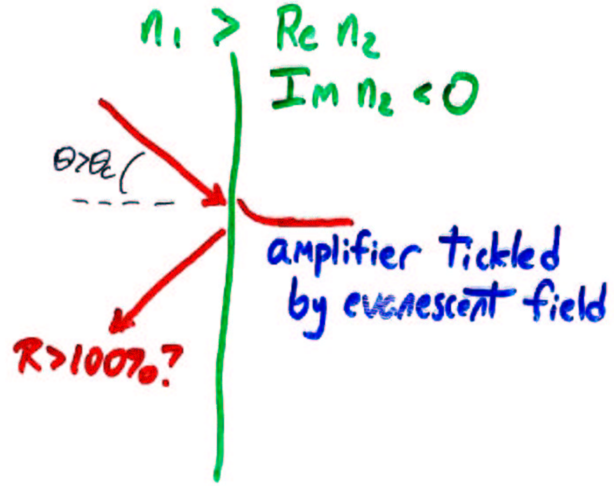
weak measurements May (CONJECTURE) predict no broadening. If experiment confirms this, and a quantitative inequality derived, we can show that some particles are in 2 places at once.

a naive corpuscular model would say $D_1 - D_2$ undergoes a random walk.

SIEGMAN'S QUESTION

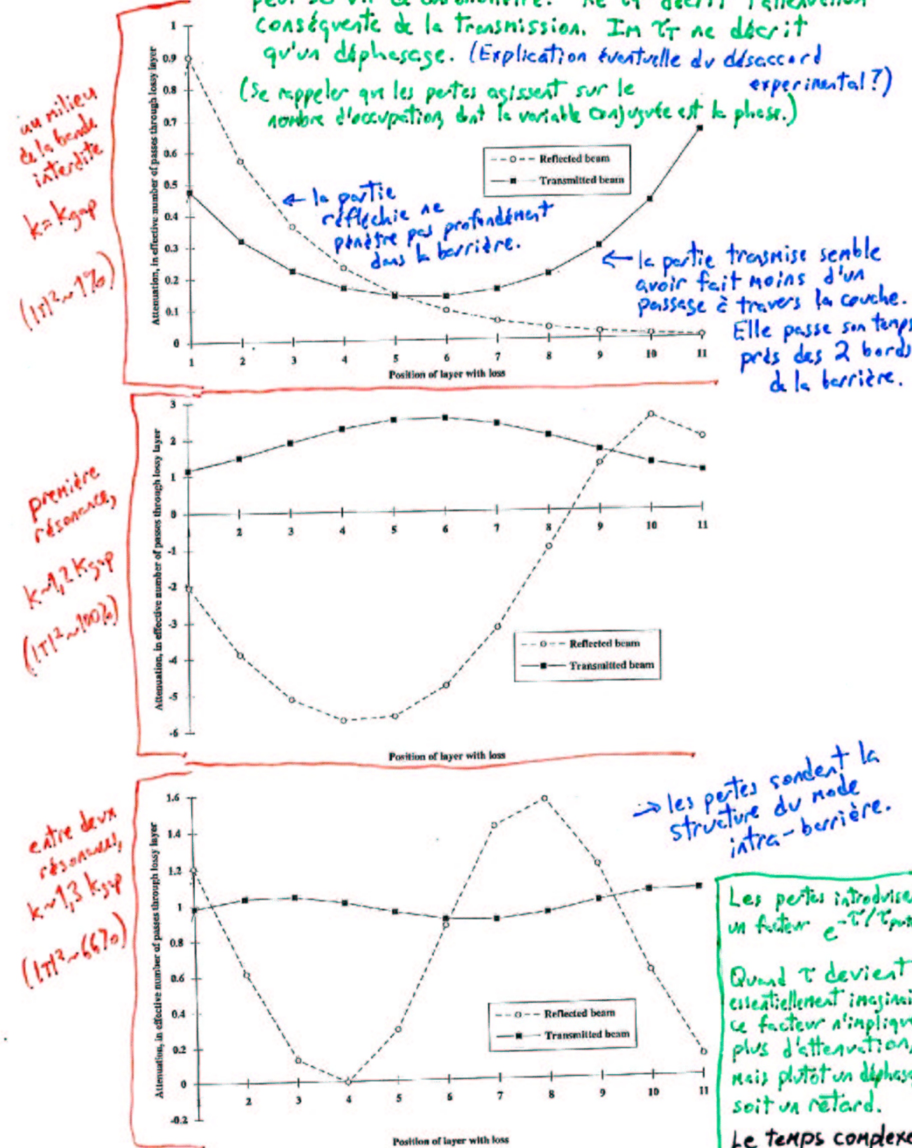
What is the effect of an amplifier in a forbidden region?

For example...



Ajouter de faibles pertes dans une des couches diélectriques du miroir, ça peut servir de chronomètre. Re τ_T décrit l'atténuation conséquente de la transmission. Im τ_T ne décrit qu'un déphasage. (Explication éventuelle du désaccord expérimental?)

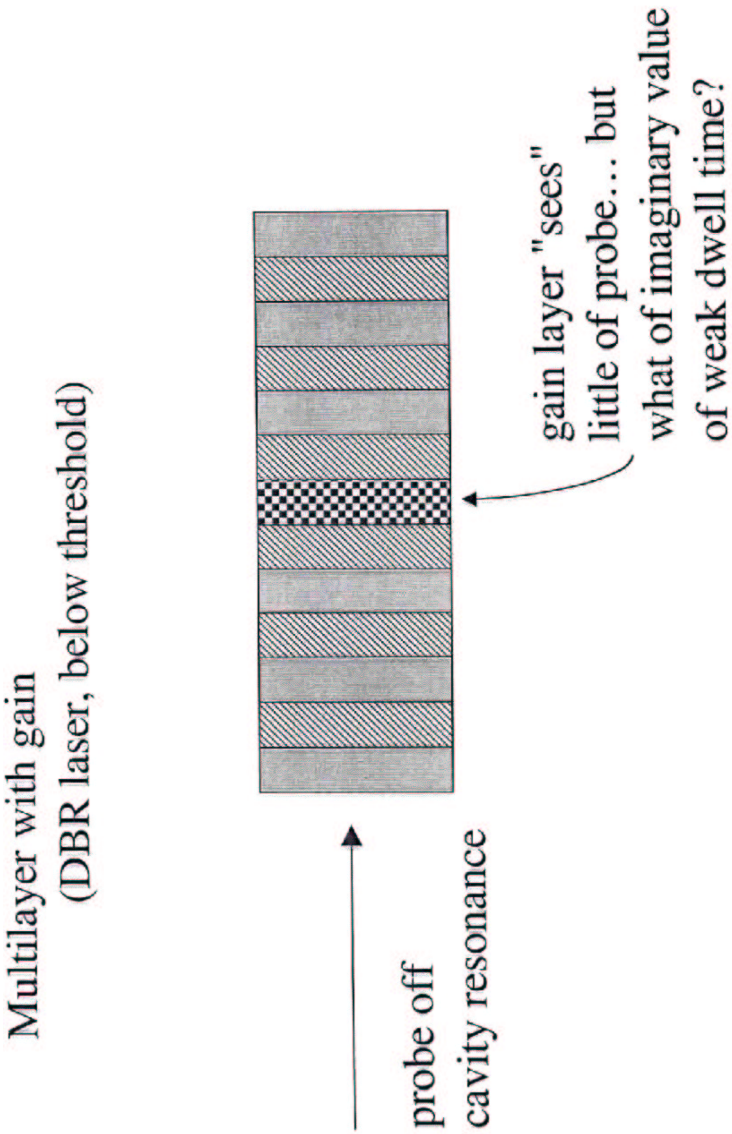
(Se rappeler que les pertes agissent sur le nombre d'occupation dont la variable conjuguée est la phase.)



Les pertes introduisent un facteur $e^{-\tau/\tau_{pertes}}$.

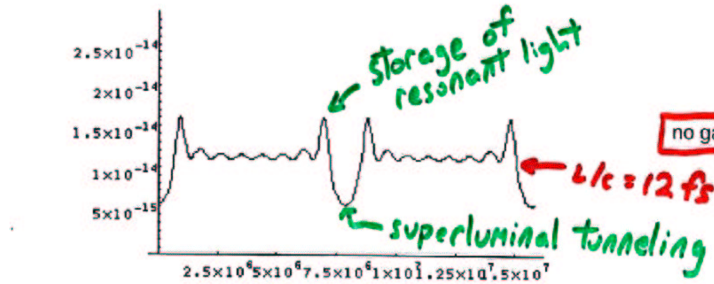
Quand τ devient essentiellement imaginaire, ce facteur n'implique plus d'atténuation, mais plutôt un déphasage, soit un retard.

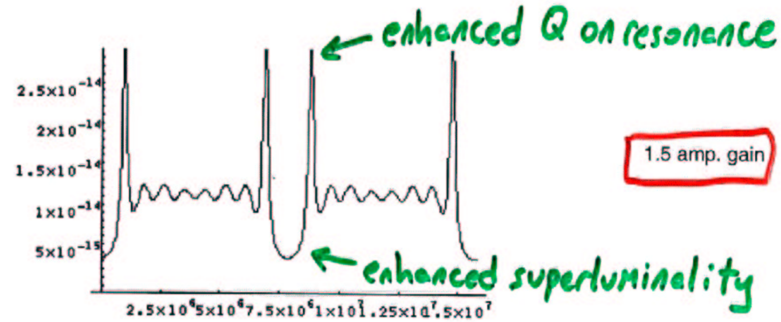
Le temps complexe est réel!



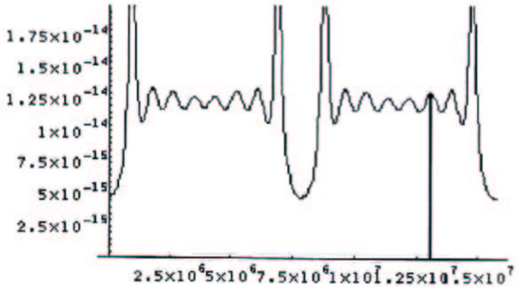
DELAY TIMES FOR A 9-LAYER STRUCTURE

(4% reflectivity per layer makes 45% per end)



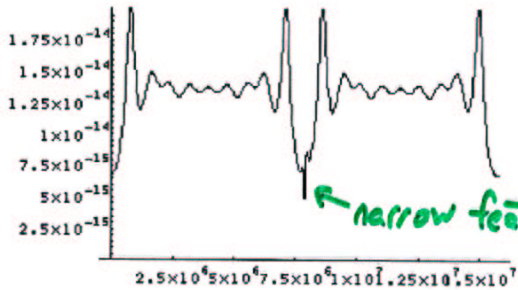


JUST DUE TO NEGLECTING GAIN DISPERSION?



FLAT GAIN MODEL

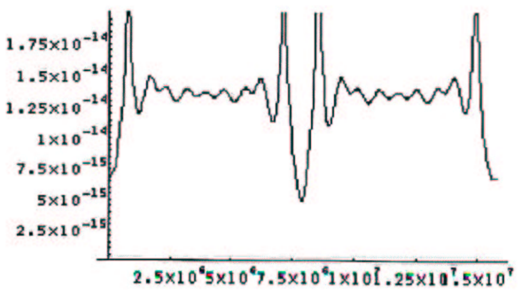
amplitude gain of 1.37 (88% in intensity, single-pass)



LORENTZ: $\gamma = \omega_0/40$

← narrow feature due to atoms

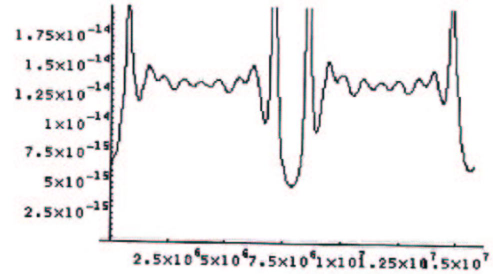
gamma = ko/40



$\gamma = \omega_0/10$

gamma = ko/10

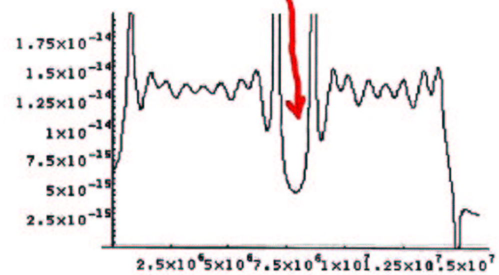
FOR BIG γ, APPROACHES NAÏVE MODEL



$\gamma = \omega_0/2$

gamma = ko/2

RETRIEVE BROAD FLAT MINIMUM

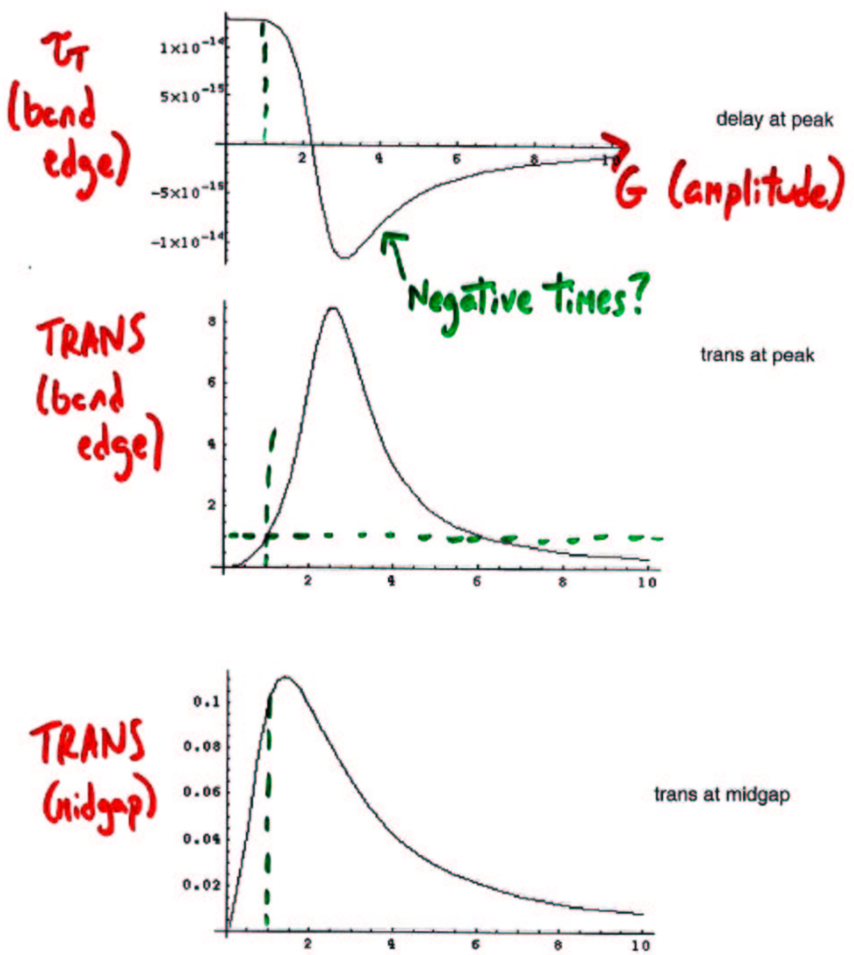


$\gamma = 10\omega_0$

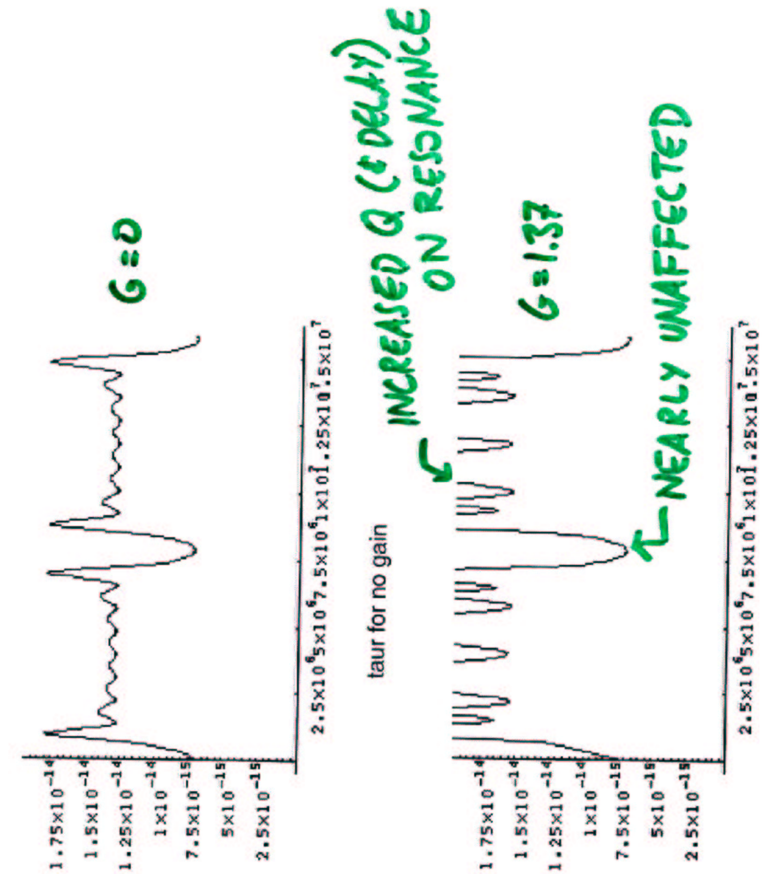
gamma = 10 ko

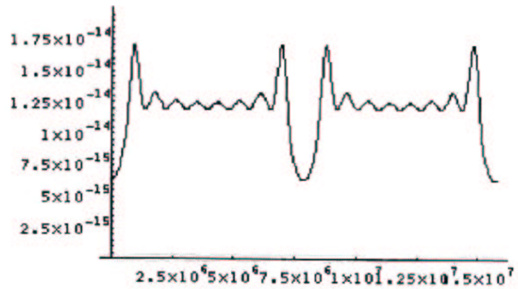
MIDGAP SPEED UP FROM 1.9c TO 2.5c, AS TRANSMISSION CHANGES FROM 10% TO 11%.

(FOR 1-PASS INTENSITY GAIN OF 88%)

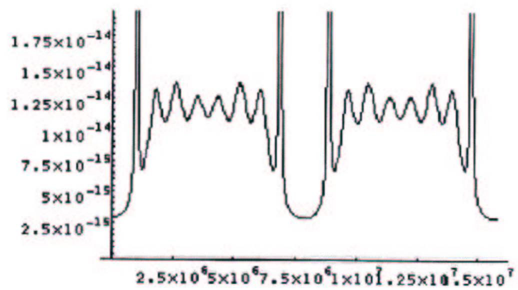


REFLECTION TIMES ARE INSENSITIVE TO GAIN FOR ω IN GAP.

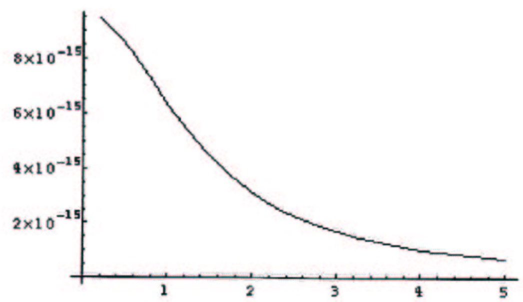




(9L/c = 1.2 E -14 sec)



88% peak gain; 4% reflection per layer; 4 layers + gain + 4 layers



midgap delay versus gain

SUMMARY

1. NLO can be done at 1-photon level with help of spectator fields... new effects should be explored
2. Using coherence effects for QI may be subtle since $\Delta n \Delta \phi \geq 1/2$
3. 2D effects introduce subtleties for defining delay times.
   Passive media do not transmit/reflect light with negative delays and 100% efficiency.
4. Weak measurements often describe what we really do in the lab, and may be useful for guiding the intuition.
5. Adding gain to MLD structures may enhance superluminality without hurting transmission much (cf. longer or higher-Q structures)... perhaps less prone to instability than other gain-assisted superluminality? WHY?