The speed of information in "fast light" pulse propagation

Michael D. Stenner
and
Daniel J. Gauthier

Duke University Department of Physics
and
the Fitzpatrick Center for Photonics and Communications Systems

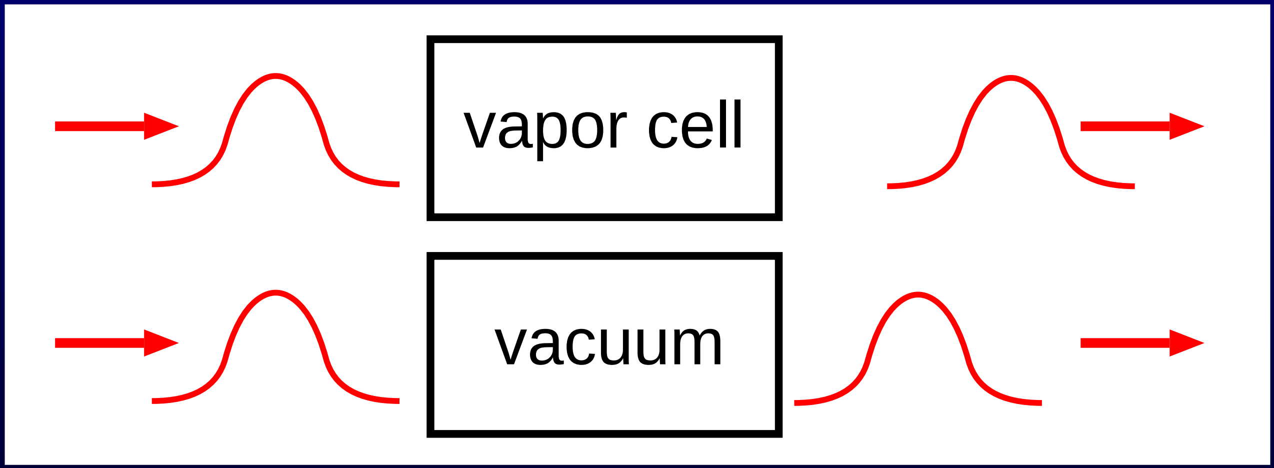
funded by the NSF

Introduction

what is “fast light”?

Fast light pulses have

$$v_g > c \qquad \text{or} \qquad v_g < 0$$



For $v_g < 0$, the peak can leave the medium before it enters!

early history of "fast light"

- before 1900: the group velocity (v_g) corresponds to the velocity of signals
- early 1900s: relativity states that information cannot travel faster than c
- $\approx$ 1910: Sommerfeld and Brillouin: pulses are distorted at $v_g > c$, with the "front" moving at c
- next 60 years: group velocity believed to be meaningless when faster than c

recent history of “fast light”

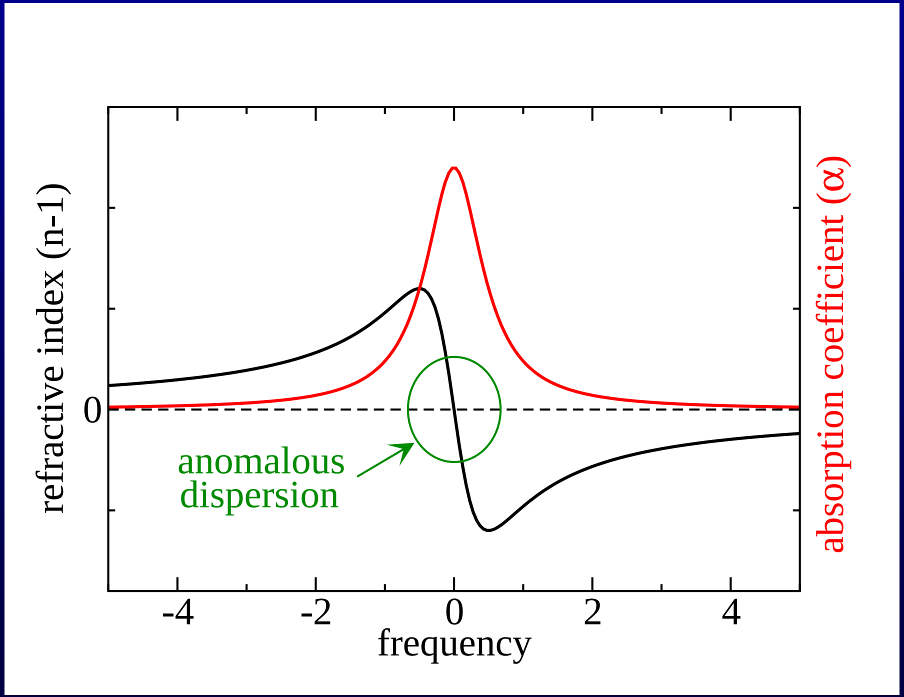
- 1970: Garrett and McCumber: theoretically, Guassian pulses can propagate at $v_g > c$ with little distortion in an absorber
- 1982: Chu and Wong experimentally verify the predictions of Garrett and McCumber
- 2000: Wang *et al.* demonstrated $v_g > c$ in a non-absorbing medium

“fast light” via rephasing

$$v_g \equiv \frac{c}{n_h + \omega \frac{dn}{d\omega}}$$

To have $v_g > c$, we need anomalous dispersion: $\frac{dn}{d\omega} < 0$

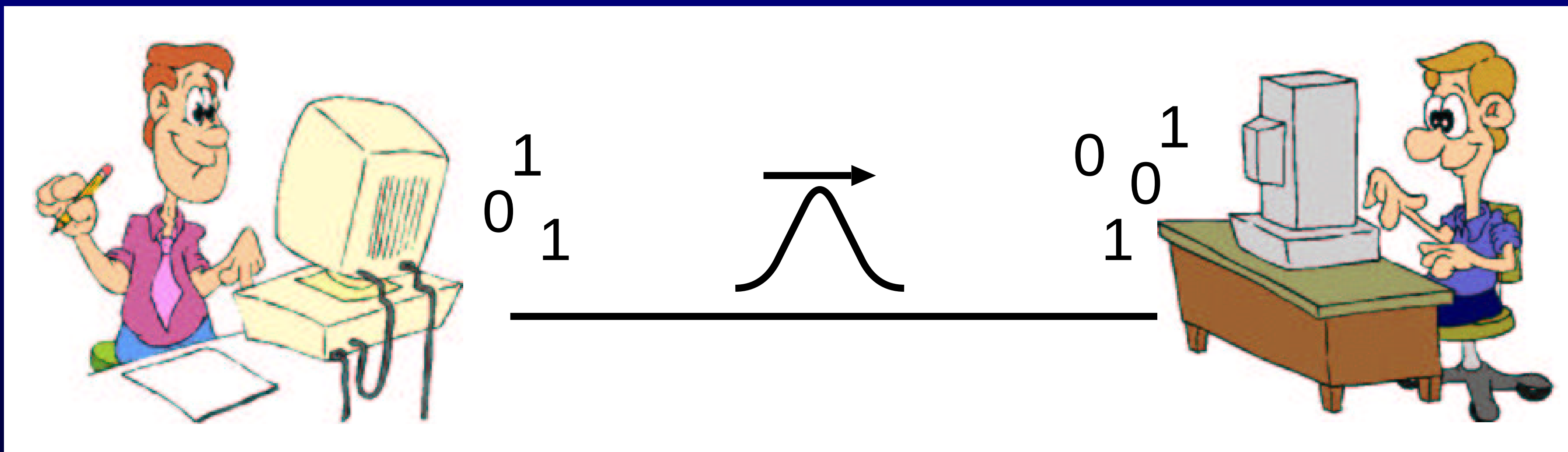
Different frequencies, moving with different phase velocities $c/n(\omega)$ interfere at some moving point. That point moves at v_g.



Steeper anomalous dispersion means faster pulses.

what is the information velocity?

Most velocities associated with pulse propagation can be faster than c: group velocity, energy velocity, "signal" velocity.

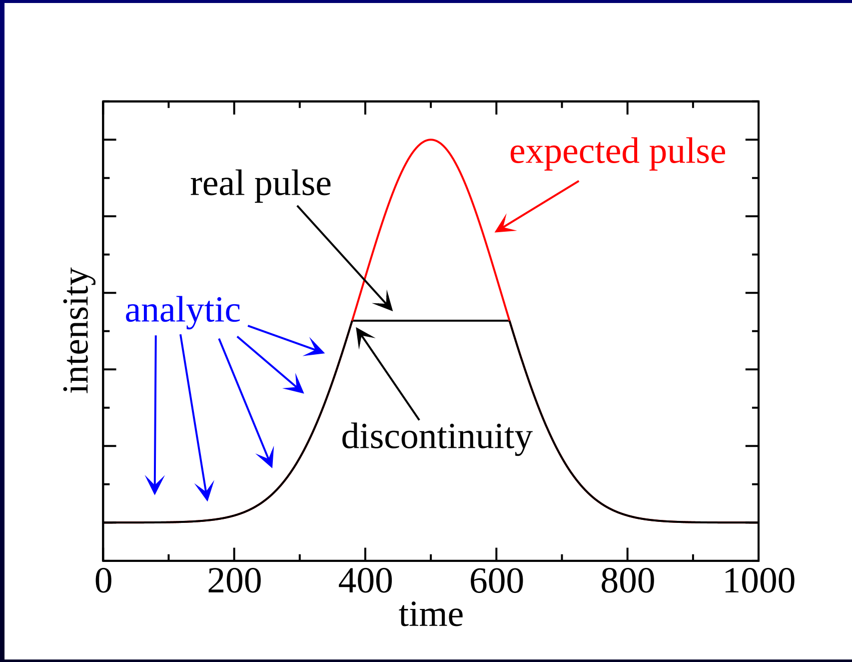


How do we describe the information velocity?

discontinuities?

Chiao and Steinberg propose that discontinuities in the pulse envelope represent new information.

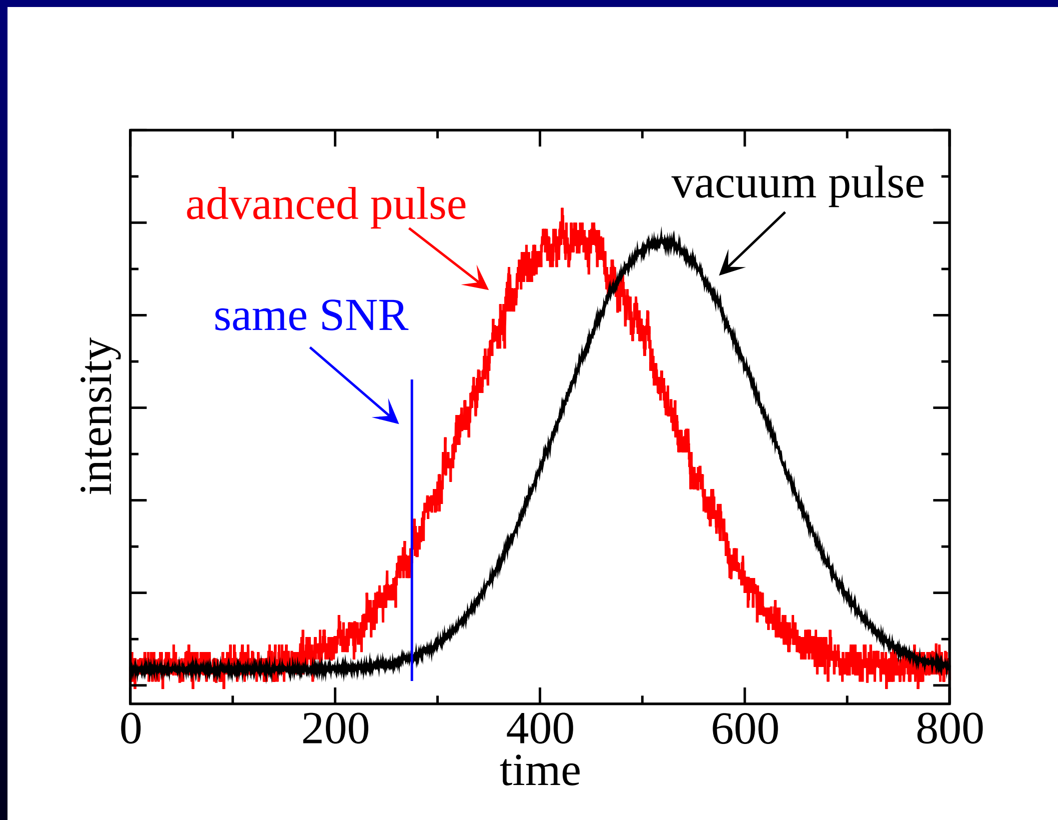
If an analytic function is fully known at one point, it is known at all points. Discontinuities allow for surprises!



Are true discontinuities physically possible?

quantum signal-to-noise ratio?

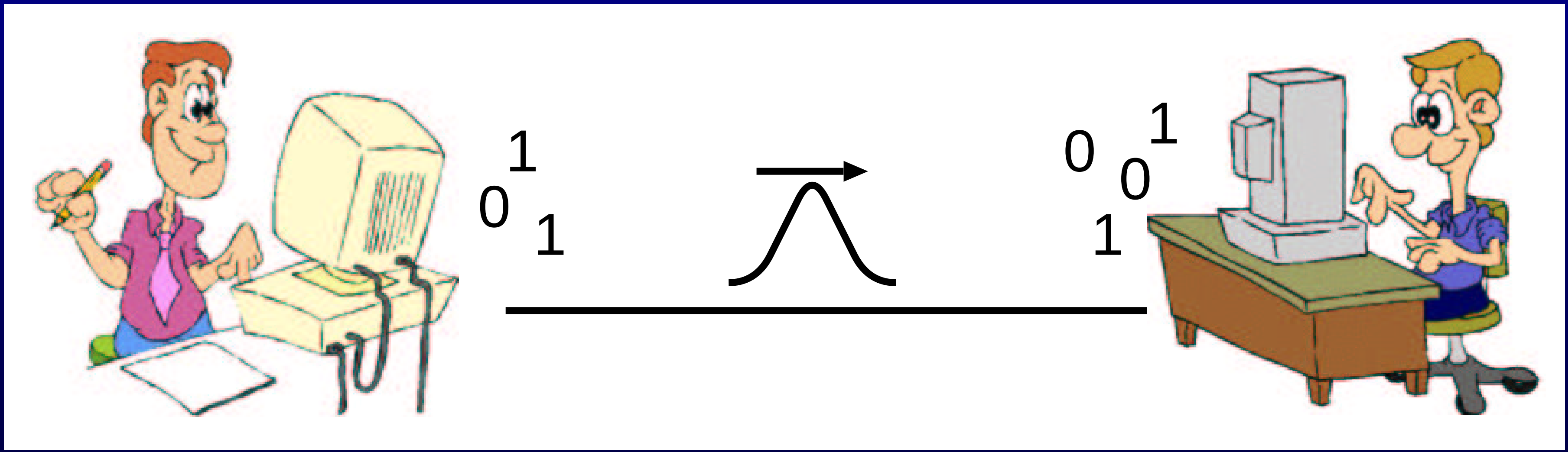
Wang *et al.* propose that points on the pulse with a constant SNR move at velocities $\leq c$.



These two explanations are completely unrelated!

information theory to the rescue?

What does the IT community have to say about this?



Surprisingly, not much!

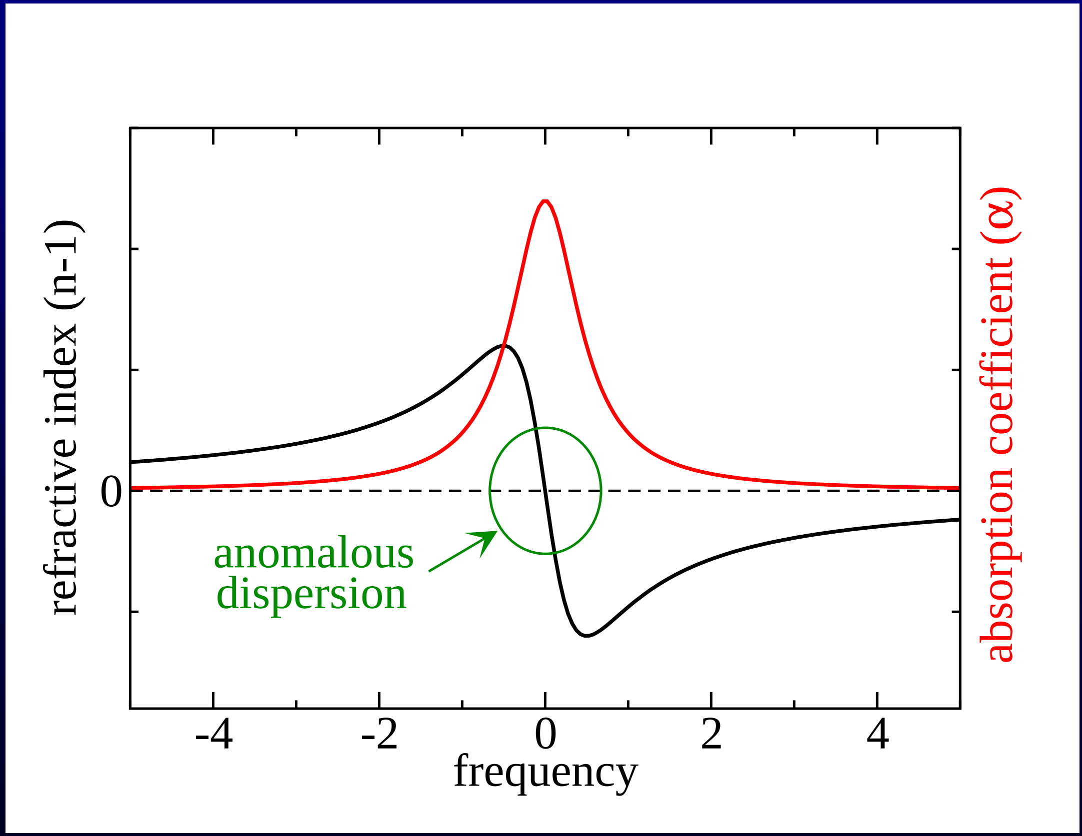
Information theory addresses information *rate*, but not information *velocity*!

Implementing “fast light”

absorption technique

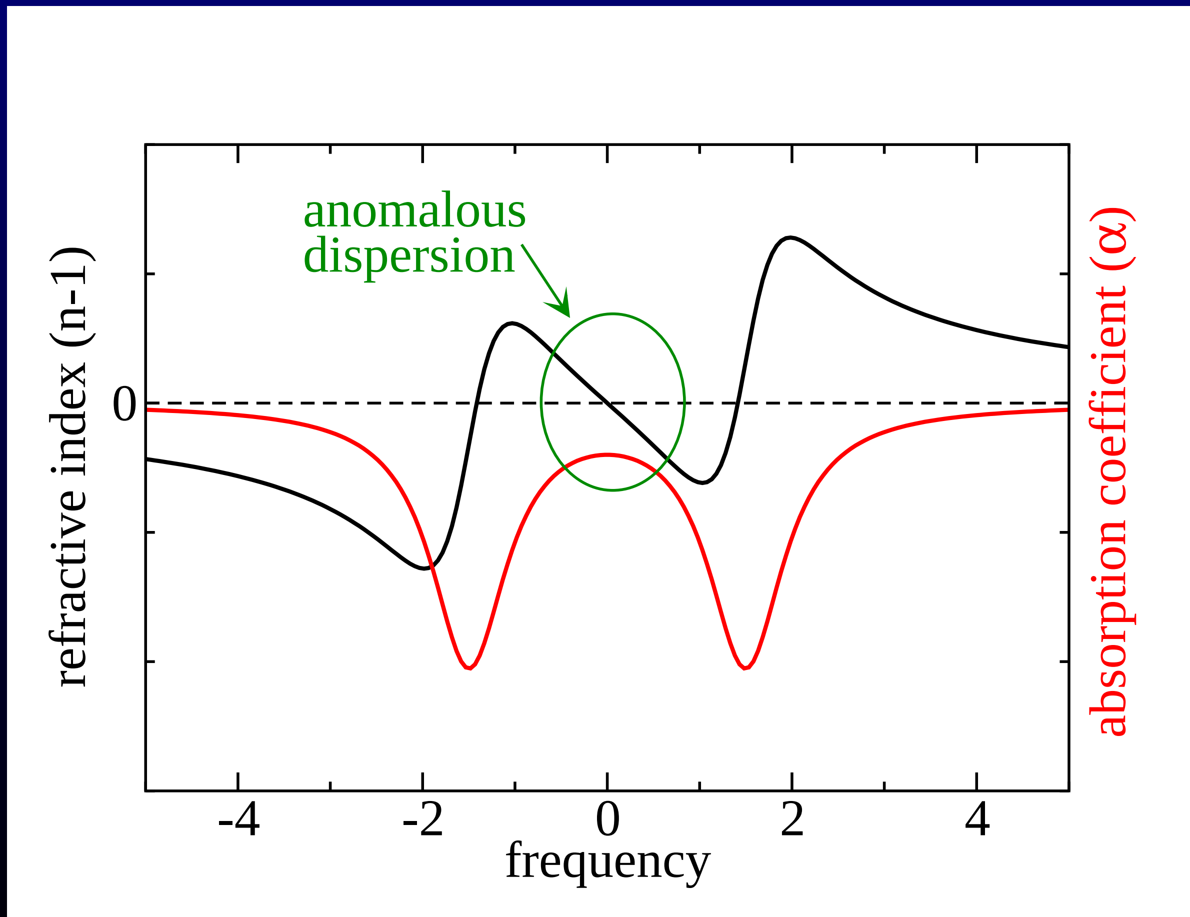
We can use an absorption line to generate anomalous dispersion

- Pulse is attenuated
- Hard to tune



dual-gain technique

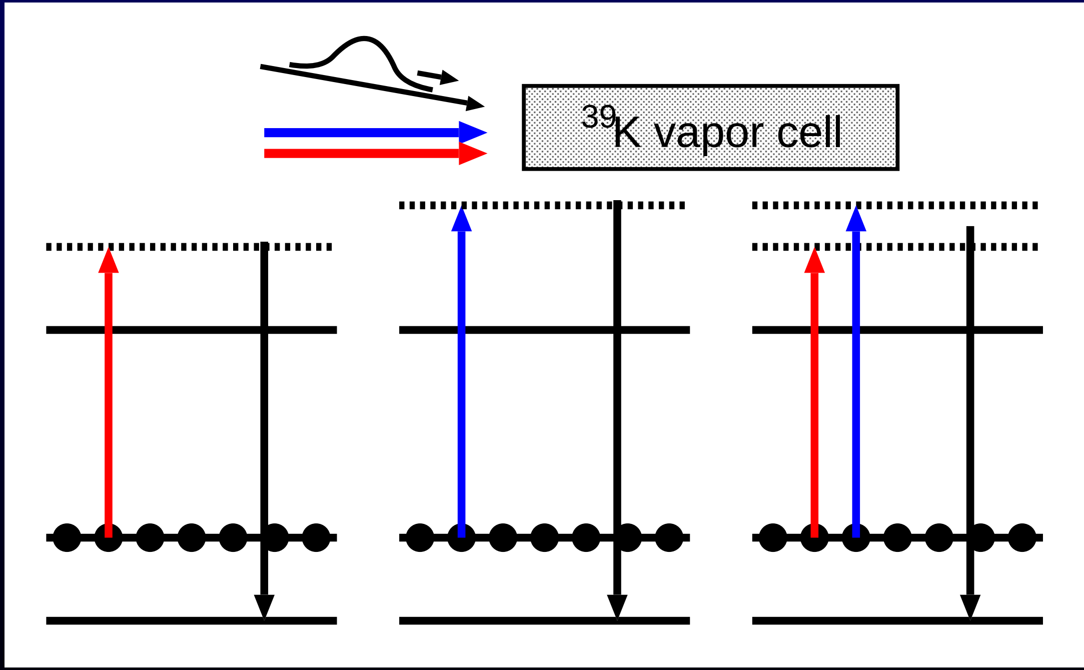
Alternatively, we can use two gain lines, which causes no attenuation (actually, a little gain).

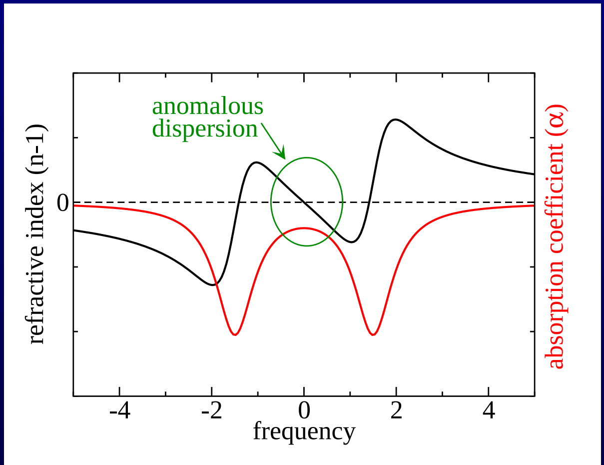


generating dual gain

Dual gain can be generated easily with bichromatic Raman gain

Two Raman pumps to generate two gain lines.

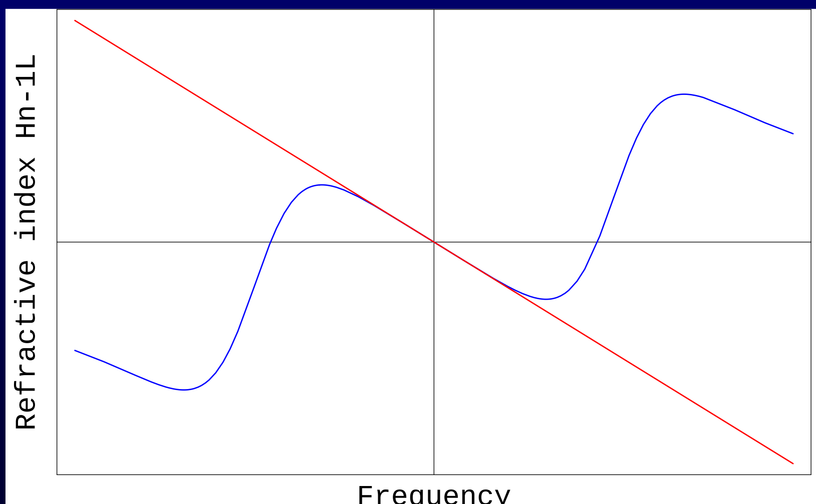


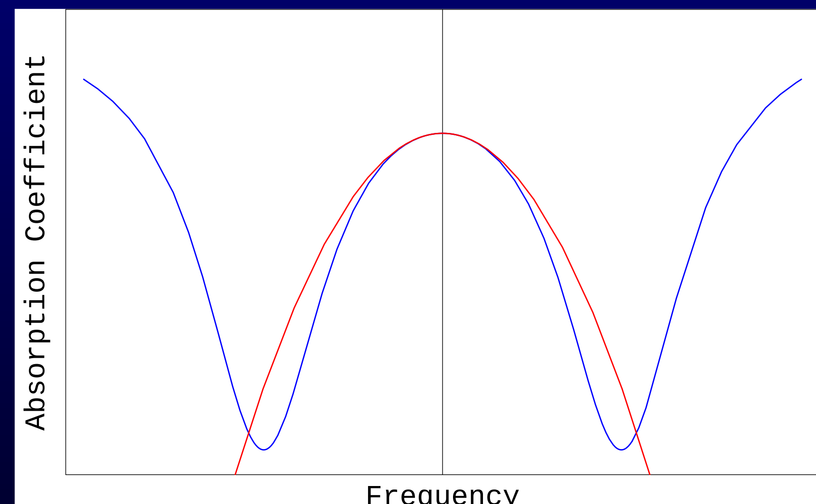


Tunable frequency and separation.

linear distortion

To avoid distortion, we must keep the pulse bandwidth small relative to the gain features!





large advancement

We need large advancement to clearly study the information velocity. We define relative advancement as:

$$\mathcal{A} = \frac{t_{adv}}{t_p}$$

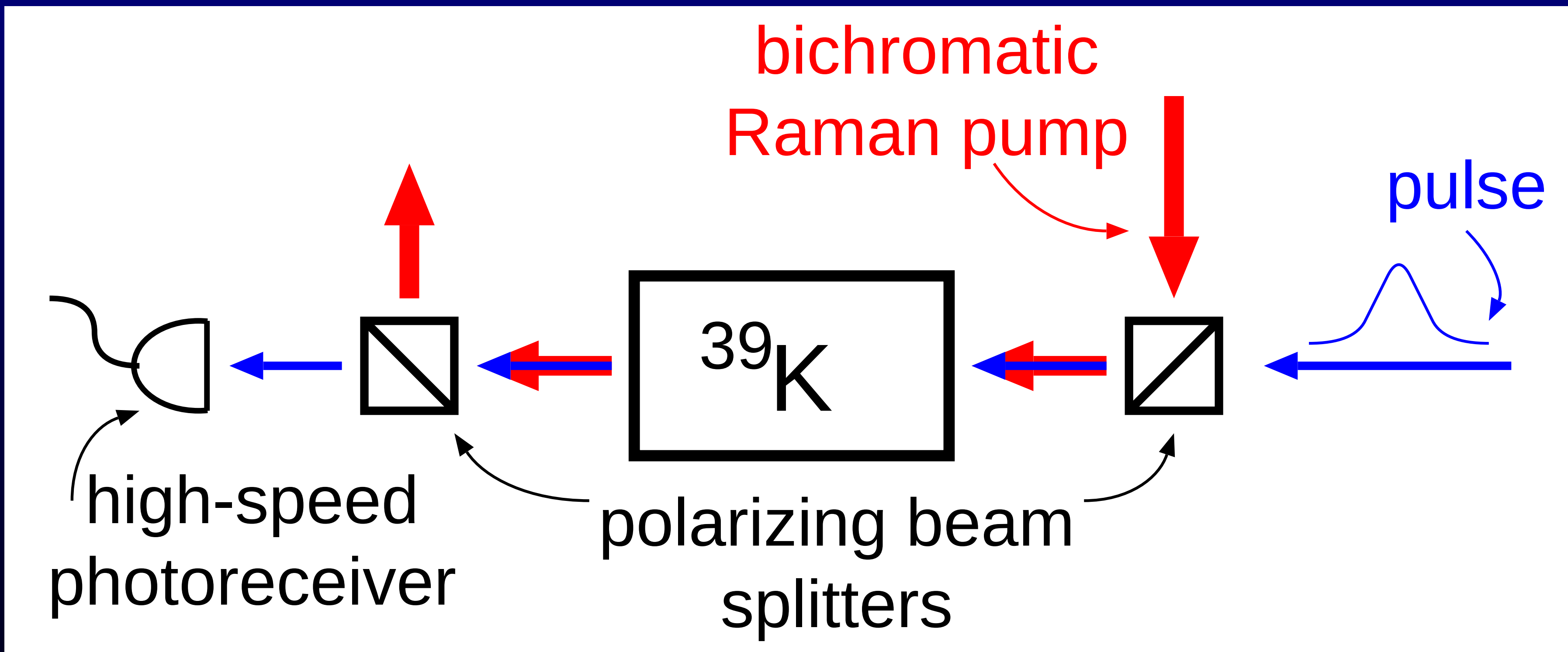
Choosing pulse width t_p (which sets the bandwidth) and gain feature frequencies to avoid linear distortion, we find

$$\mathcal{A} \approx 0.03\, g_0 L$$

We need large gain!

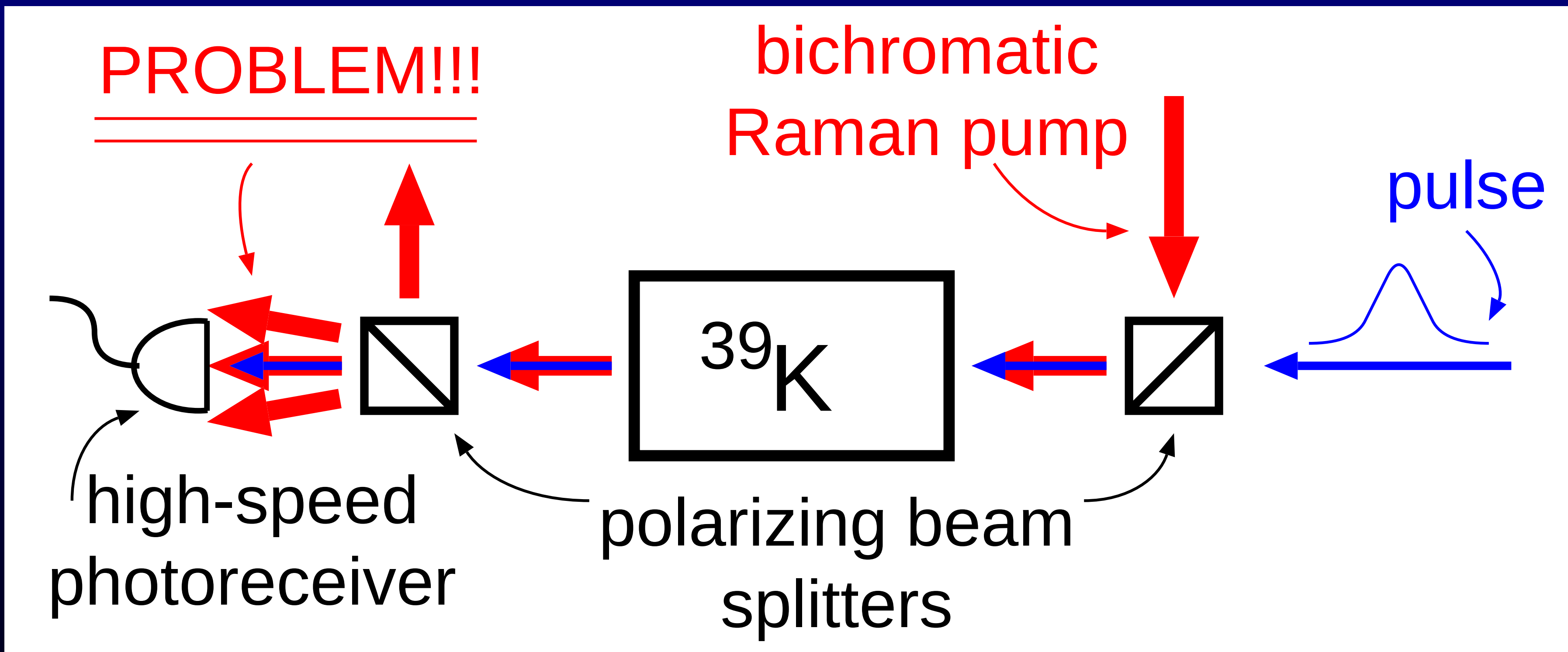
experiment

Use a pulse advancement system like that of Wang *et al.*, but with high gain.



experiment

Use a pulse advancement system like that of Wang *et al.*, but with high gain.



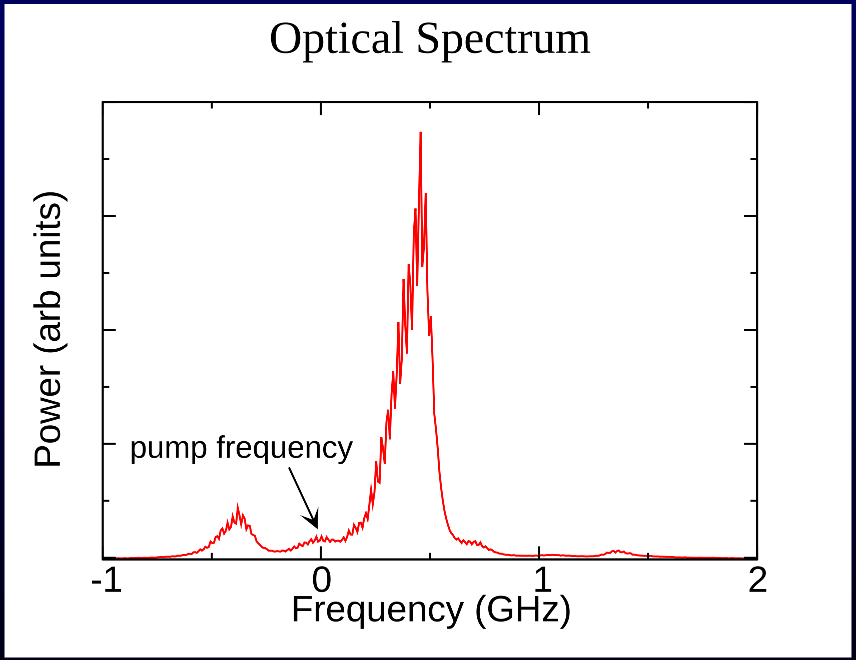
Light sprays out of the cell. This arises from a pump beam instability!

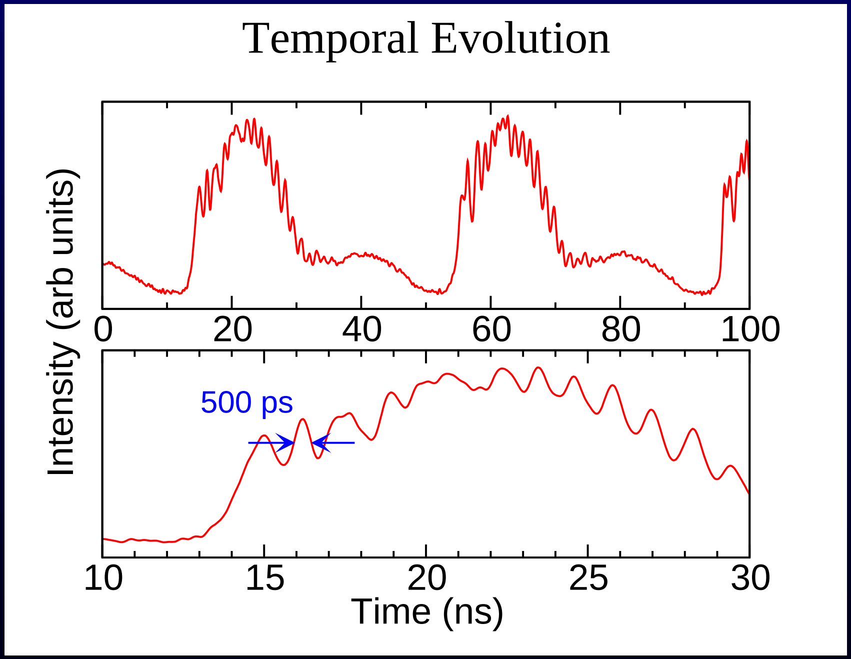
characterization of the instability

Light is generated by the induced modulation instability, with

NO PROBE PULSE!

The IMI is based on an interaction between the two pumping beams.

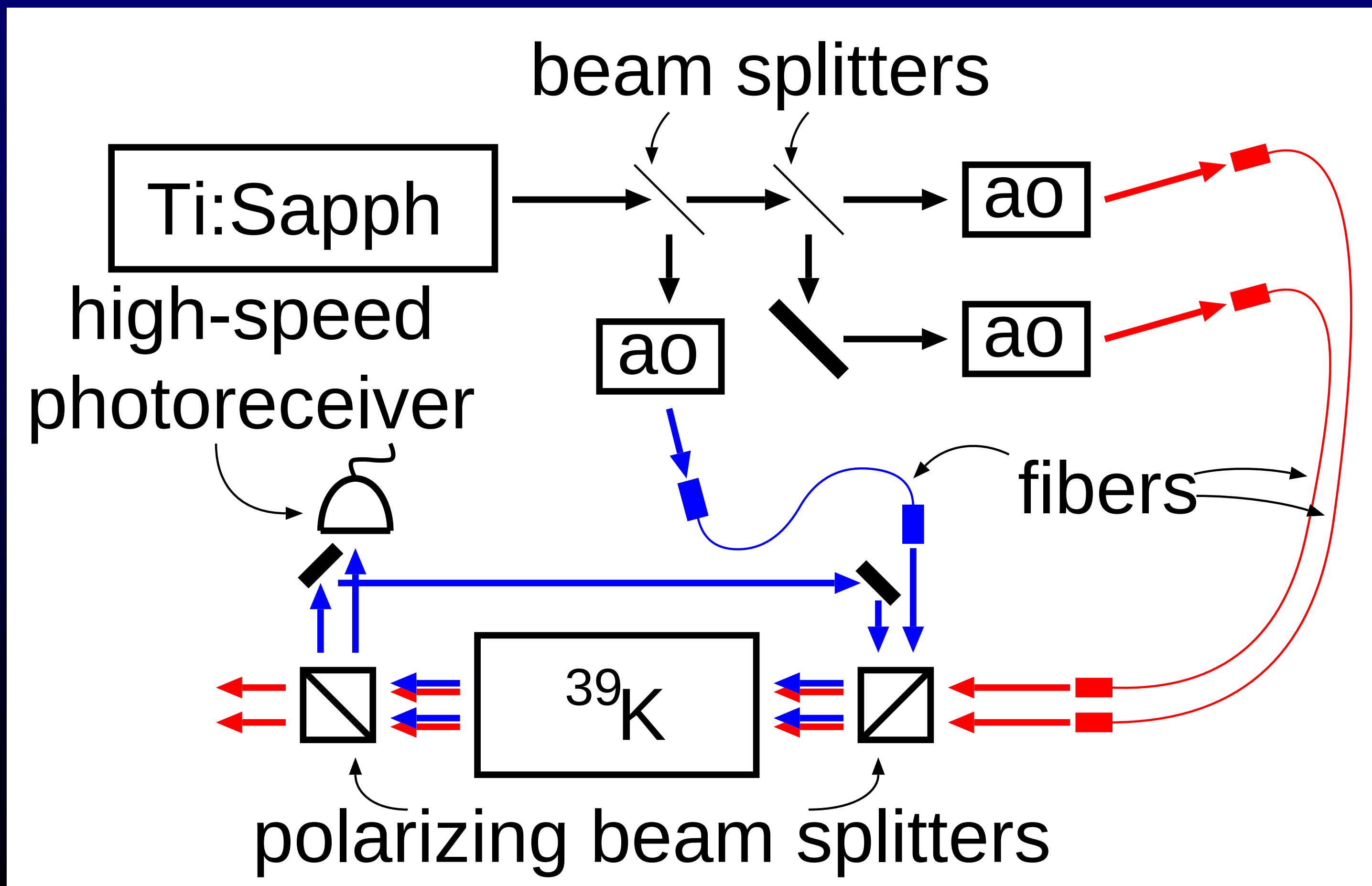




It is most problematic in the high-gain limit.

solution

We have developed an experimental system which prevents interaction of the two pumping beams by keeping them in two separate zones!

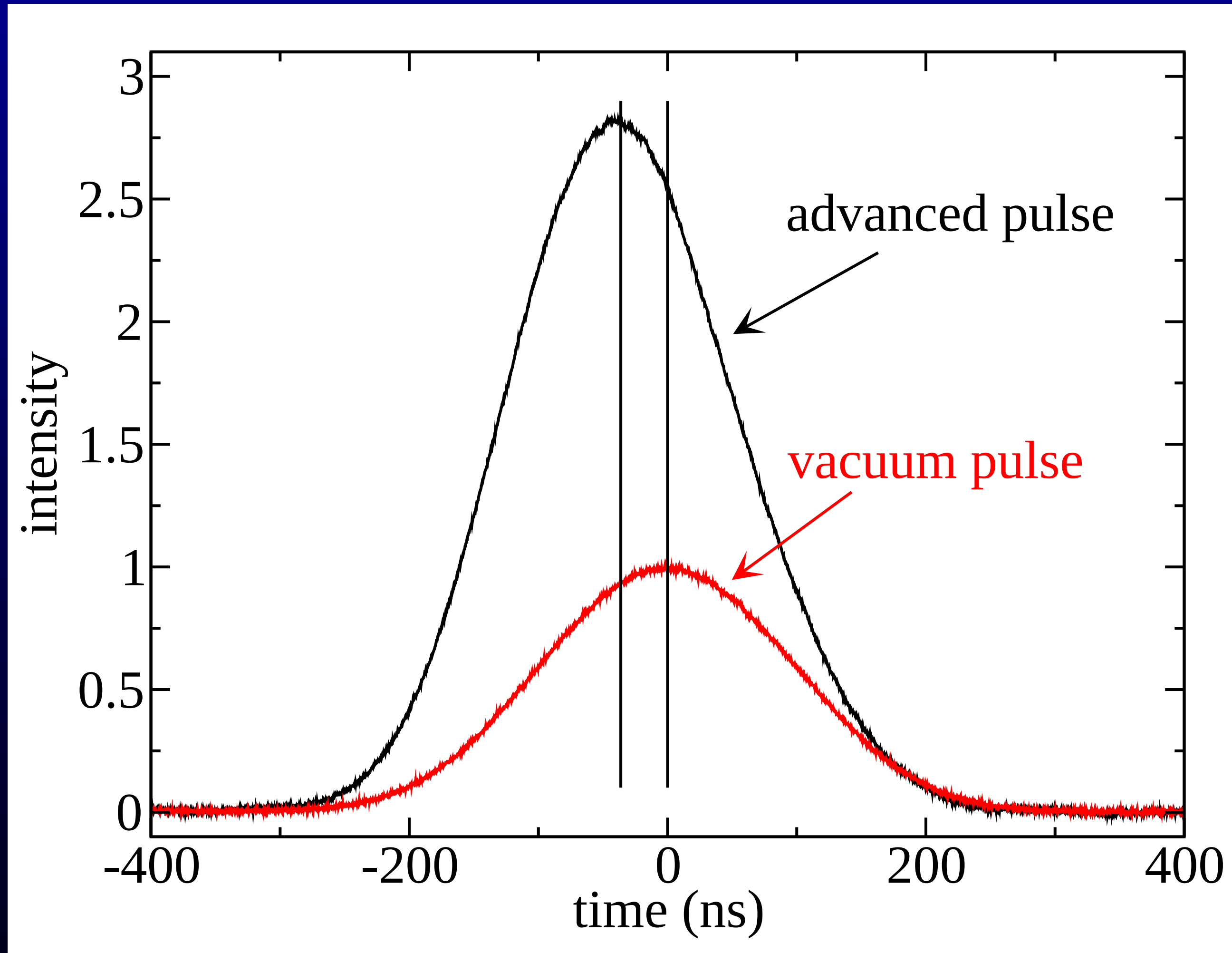


experimental results

$$t_p = 227\,\text{ns}$$

$$t_{adv} = 33.2\,\text{ns}$$

$$\frac{t_{adv}}{t_p} = 15\%$$



conclusions

We have...

- produced a high-gain pulse-advancement system
- overcome competing nonlinear effects
- produced highly advanced pulses with little distortion

What's next?

- explore limitations of low-distortion advancement
- research behavior of discontinuities on "fast light" pulses
- consider ramifications for relativity, quantum mechanics, and information theory