HOMER'S PHYSICS:

The naked truth about THz radiation

Dave Cooke

Outline

- Terahertz light: What is it? Why should I care?
- THz imaging: What lies beneath…
- THz spectroscopy: What’s shakin’?

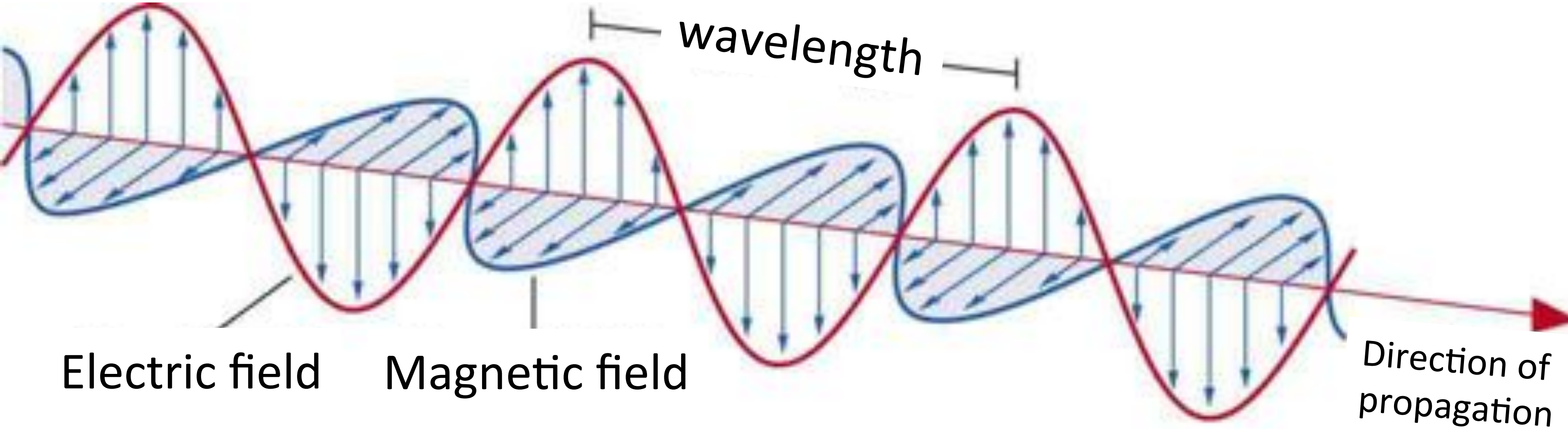
(Ans: charge, not bacon. mmmm…bacon….)

DISCLAIMER

Warning:

The following presentation contains some images of blurry naked people with stuff taped to their body. Viewer discretion is advised.

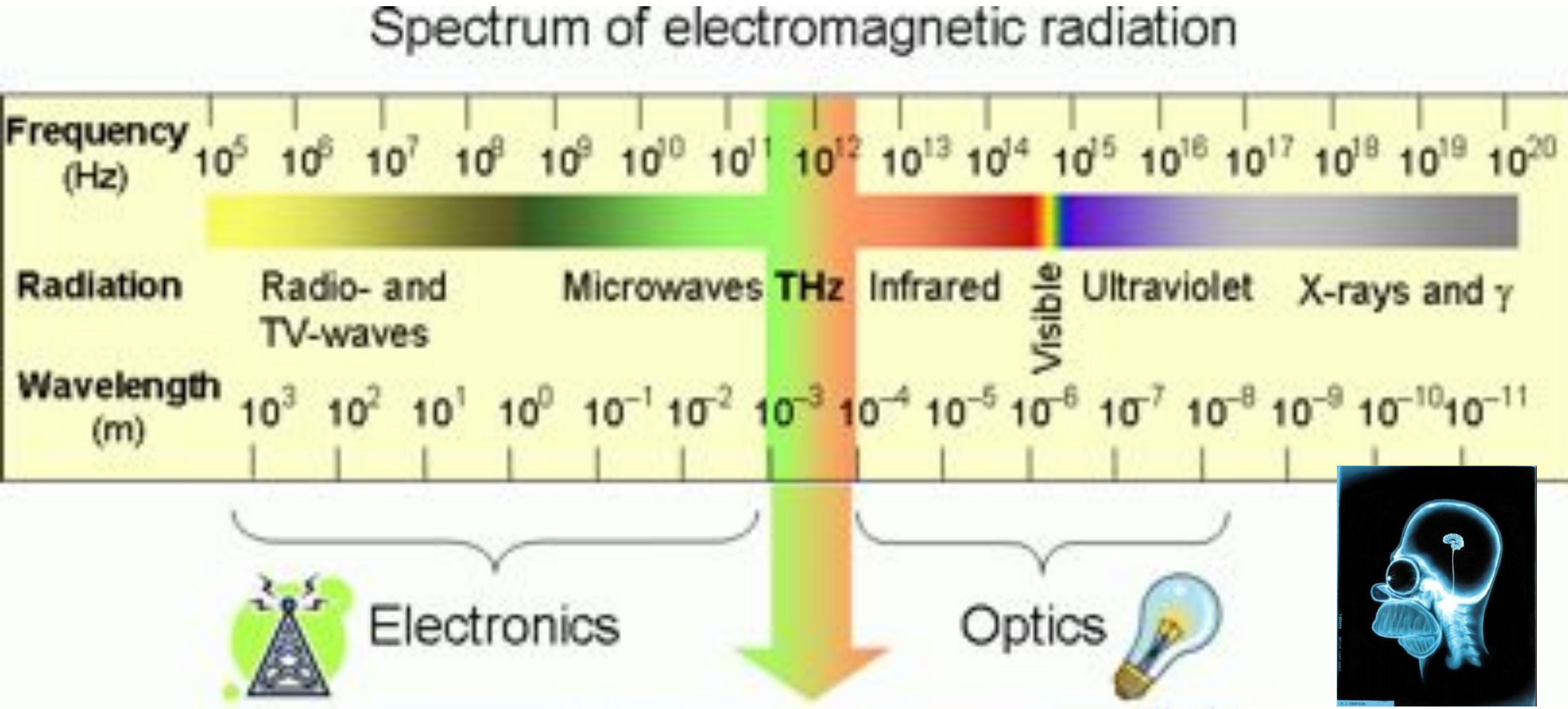
Light is a electromagnetic wave



Periodicity of wave defined by unit of length: wavelength of light

Electric and magnetic field oscillates with frequency ν

Product of frequency and wavelength gives speed of light $c = 2.998 \times 10^8$ m/s

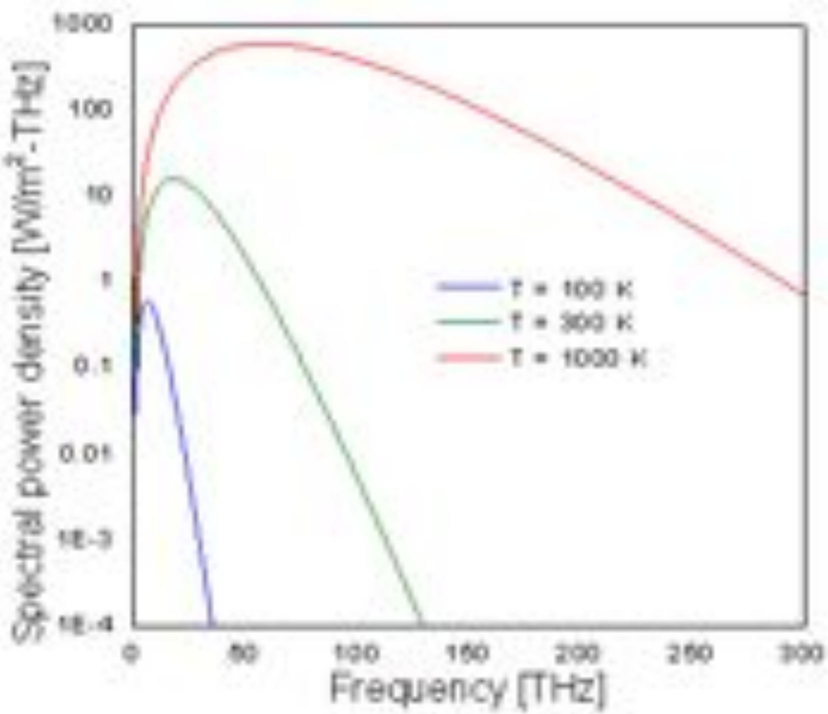


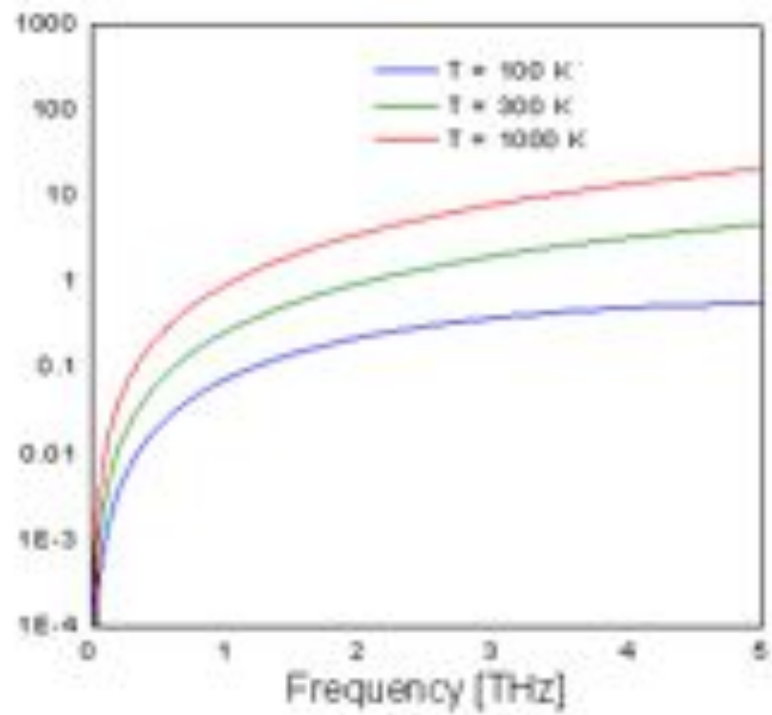
Leftover bit

You can do a lot with this leftover bit!!

Sources of THz radiation

- **Everything in this room!**
- Hot bodies emit radiation according to a blackbody spectrum.
- Blackbody sources at elevated temperatures (actually also at low temperatures) emit radiation in the THz range
- Very weak source of THz radiation…





Other sources: the Universe!

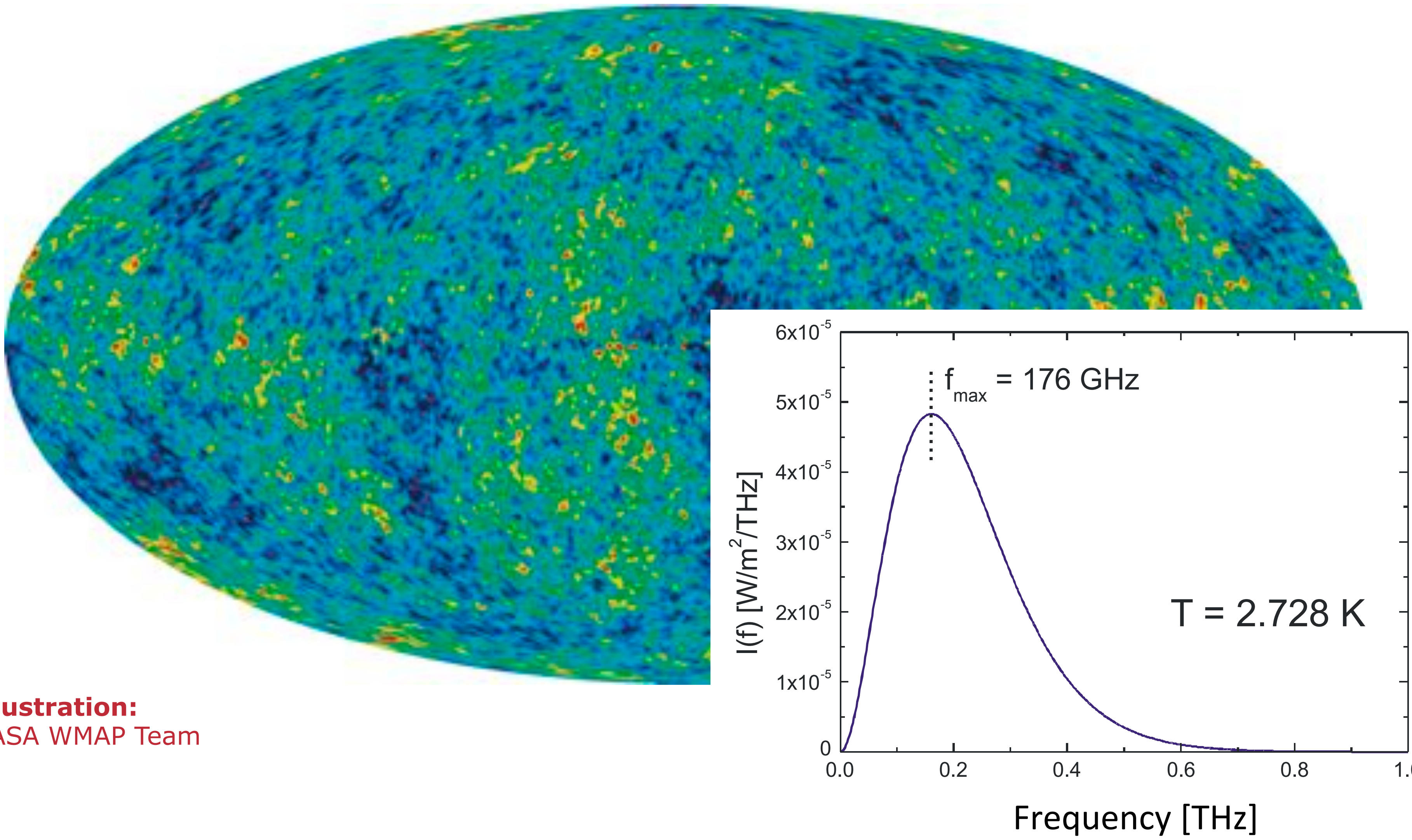
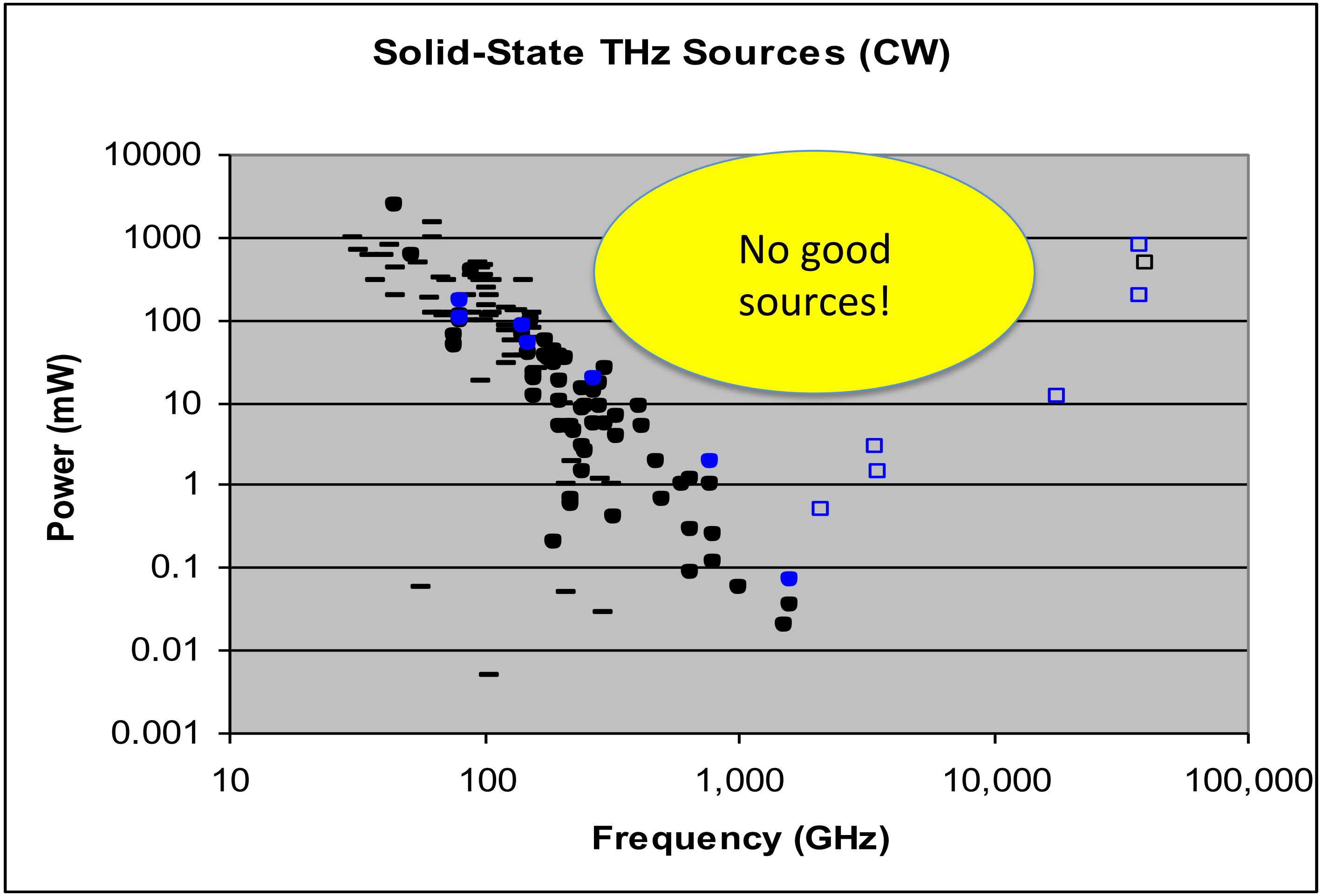


Illustration:
NASA WMAP Team

Before 1990: THz science “not so bright”



Early pioneers in THz radiation

Y. R. Shen
University of California, Berkeley

Optical rectification of intense laser pulses

David Auston
Columbia University, New York

Picosecond pulses from photo-conductive switches
(the Auston switch)

Gerard Mourou
University of Rochester

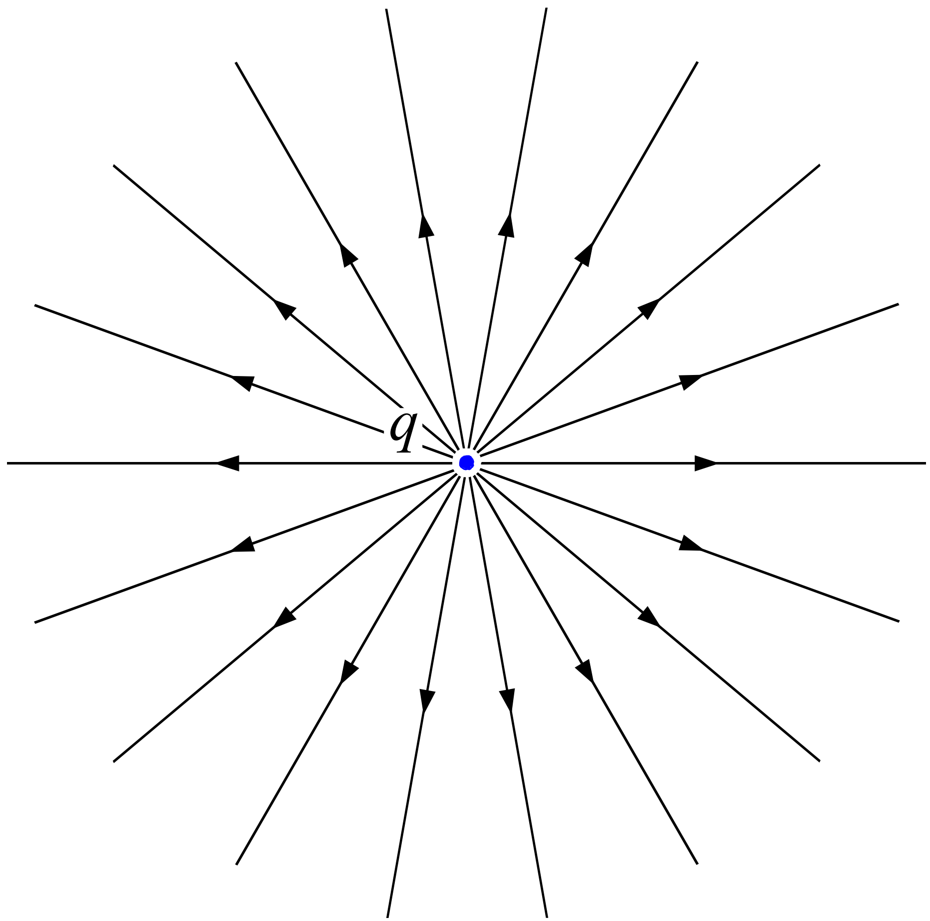
Generation of picosecond electrical transients
Time-resolved measurements with far-IR radiation

Daniel Grischkowsky
Oklahoma State University

Free-space THz transients
Optical THz technology
THz time-domain spectroscopy

Source of light…accelerating charge

Radial electric field from point charge *q*:



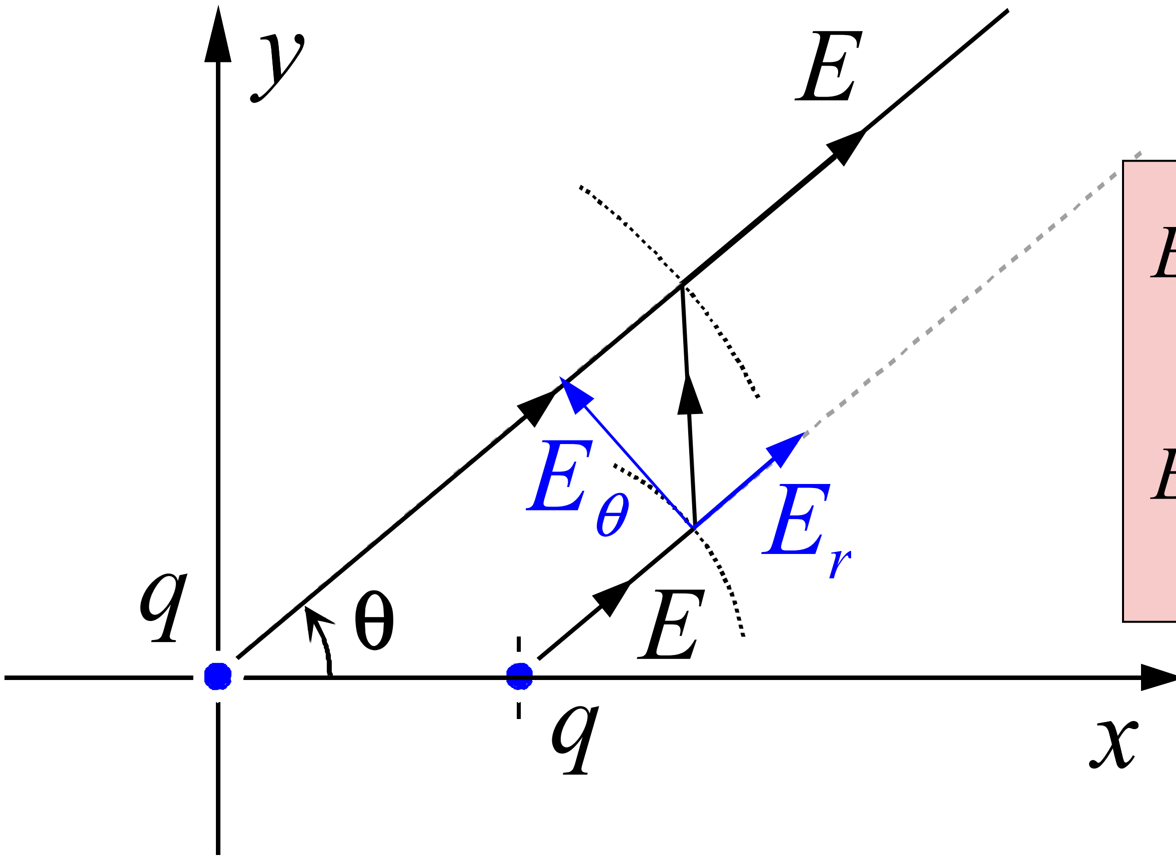
$$E_r = \frac{q}{4\pi r^2}$$

Now we look closer at a single field line:

The charge q is accelerated for a short time Δt, we look again a bit later:

The information about the moving charge propagates at the speed of light.

This leads to a kink in the field that propagates away from charge at the speed of light. (LIGHT!)

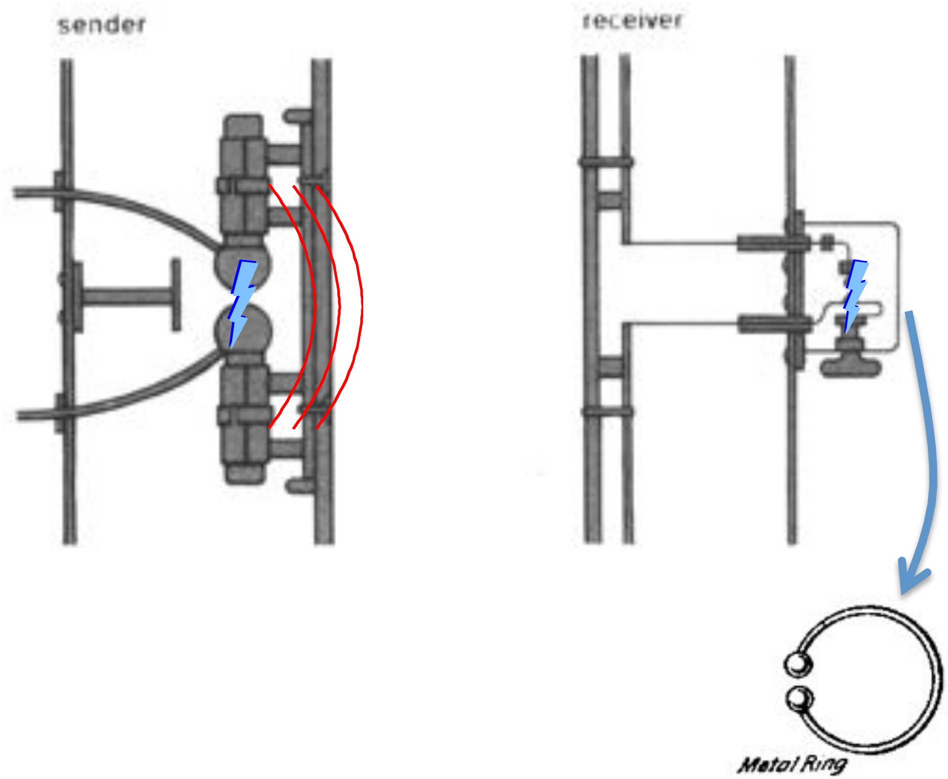


$$E_\theta = \frac{aq}{4\pi\varepsilon_0 r}\sin\theta$$

$$E_r = \frac{q}{4\pi\varepsilon_0 r^2}$$

Yet another famous bearded physicist

Karlsruhe, 1887:



1. Sudden current burst from spark gap. Faster the burst, the higher frequency the radiation.
2. Light emitted and travels in free space to detector.
3. Electric field of light causes current in copper wire antenna, sparks across the gap. First transmission and receiving of electromagnetic waves!

To generate/detect THz radiation, we need to **switch on the current much faster**.

Switch current within 1 picosecond (10^{-12} s) or a millionth of a millionth of a second

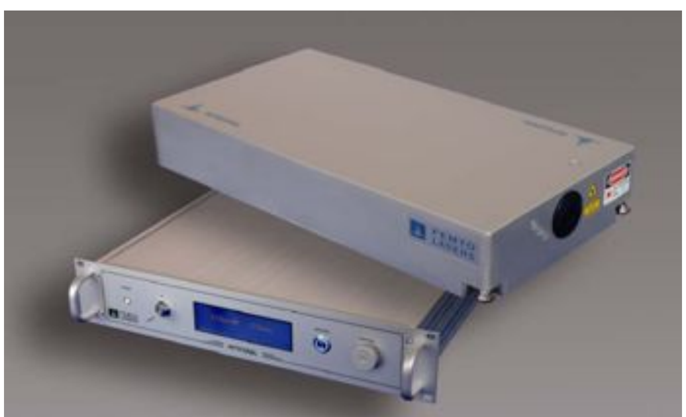
Short laser pulses

Short laser pulses: trigger/observe events on **femtosecond time scales**

1 fs = 10^{-15} s = 0.000000000000001 seconds

1 fs = 10 minutes / **age of the universe**

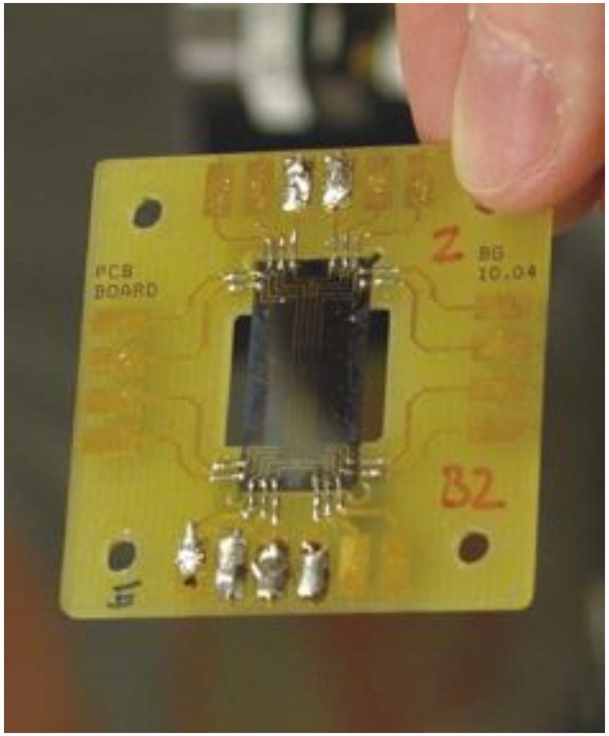
100 fs = Time it takes for light to travel the thickness of 1 human hair

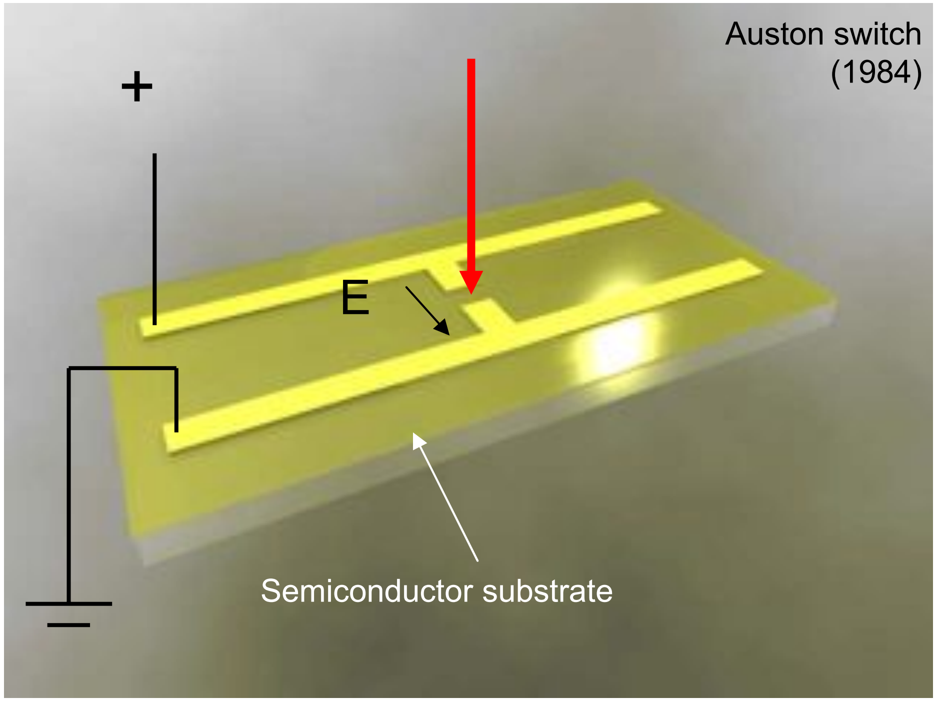


The latest tech:

FemtoLasers Integral FemtoSource
< 10 fs pulse duration
0.5 W average power
800 nm center wavelength (red)

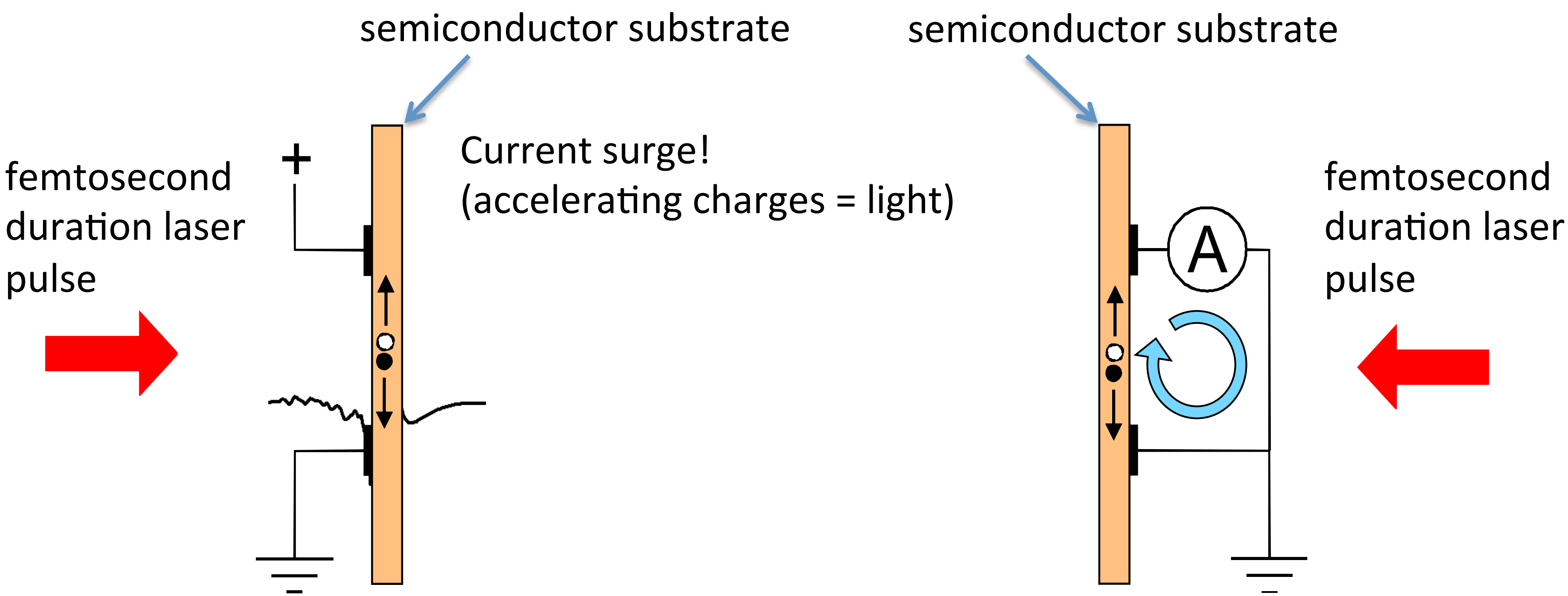
Small dipole antennas (Austin switches)





Typically 30 μm gapped antenna structure on a semiconducting substrate.

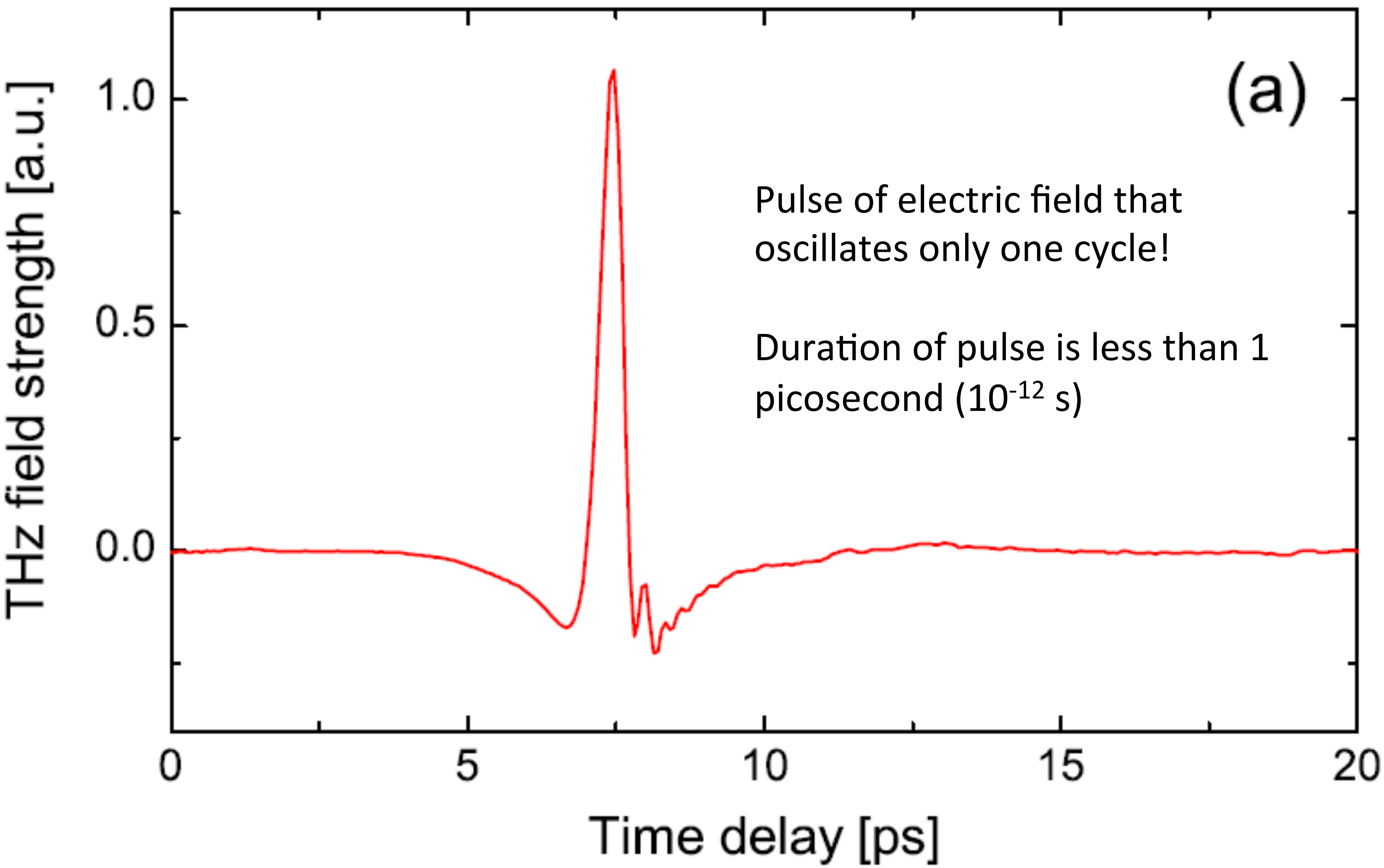
Hertz's experiment in the 1990's…



SO….what did we just do….

Electric field of pulse accelerates charges in material.
Detect current proportional to electric field.

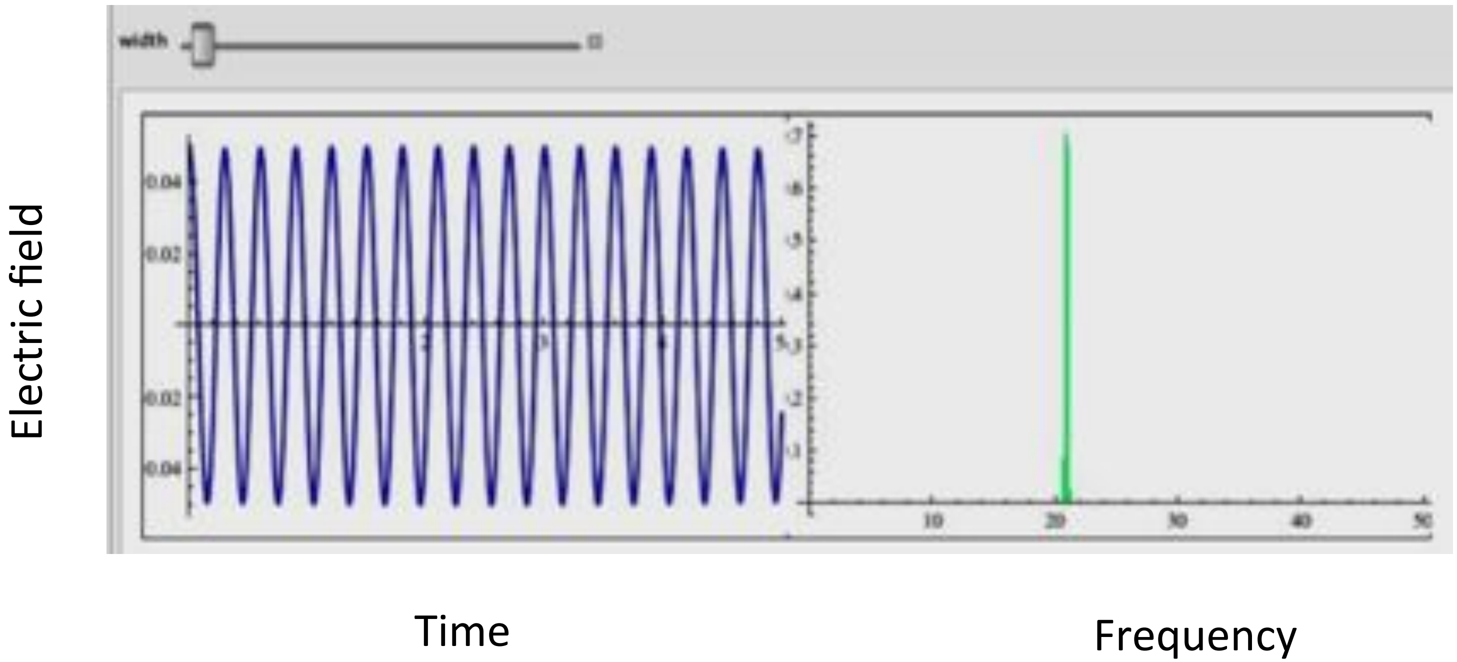
Generated and detected a THz pulse



Pulse of electric field that oscillates only one cycle!

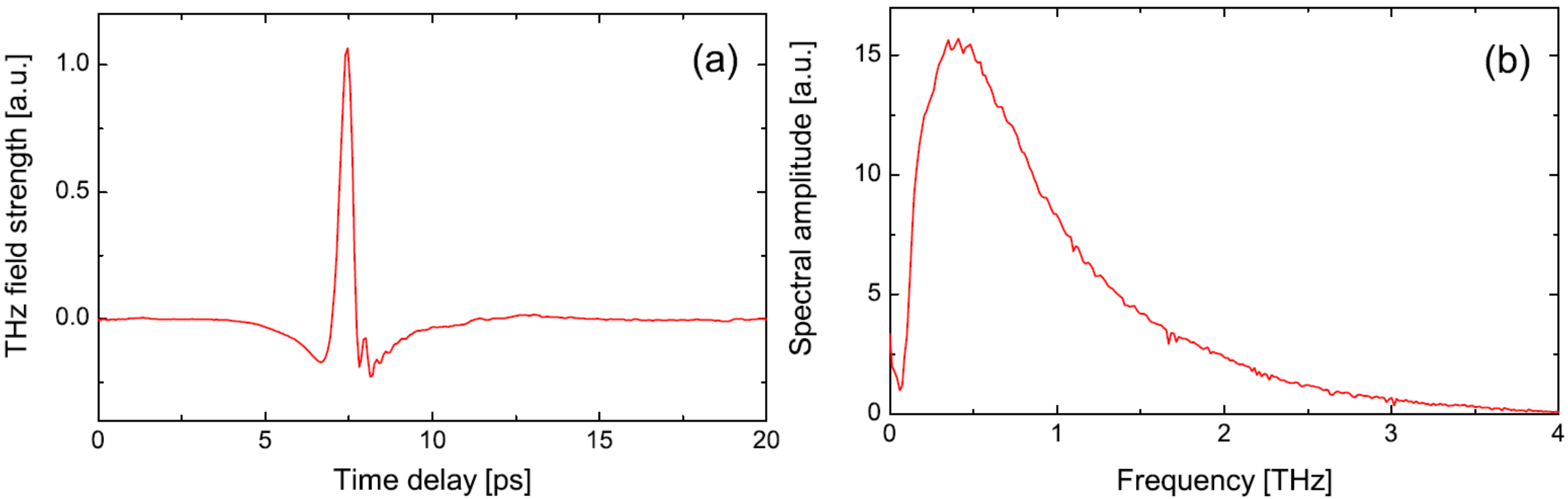
Duration of pulse is less than 1 picosecond (10^{-12} s)

The shorter the pulse in time the more colours (frequencies) it contains



Time bandwidth product: $\Delta t \Delta \omega \geq \frac{1}{2}$

Broadband THz Pulses

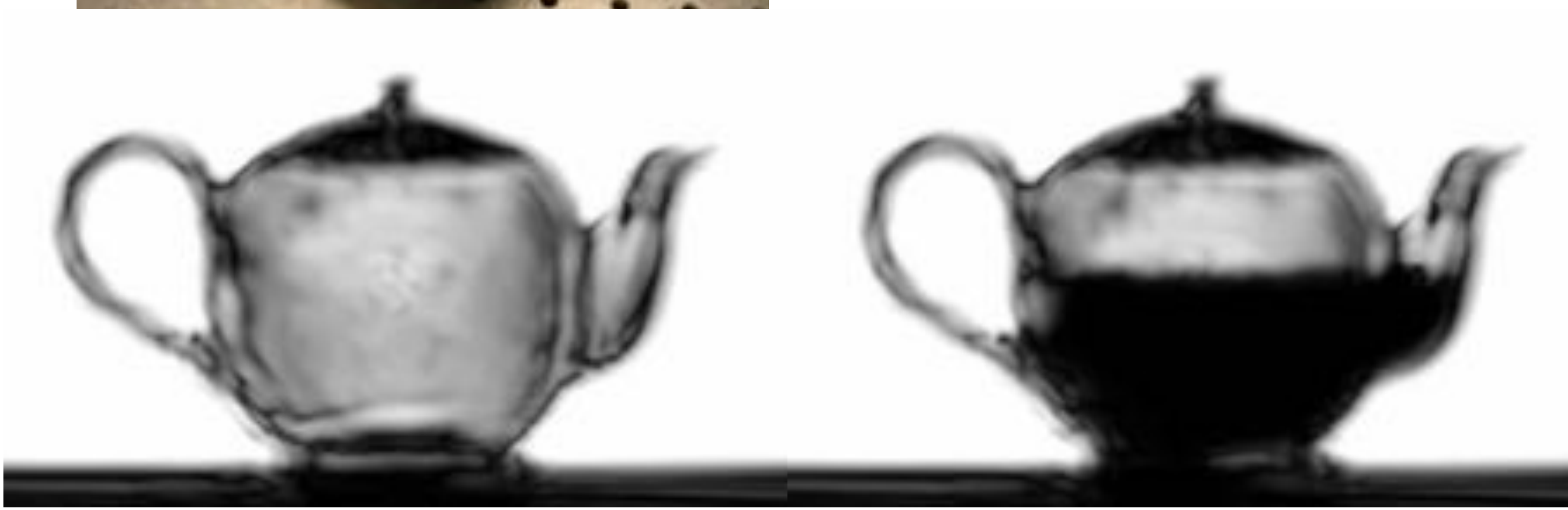


Bright source of THz radiation. ✓
Detection sensitivity 1,000,000 : 1 ✓
NOW, what do we do with these?

THz Imaging

http://www.rpi.edu/~zhangxc

How much water is in the tea pot?

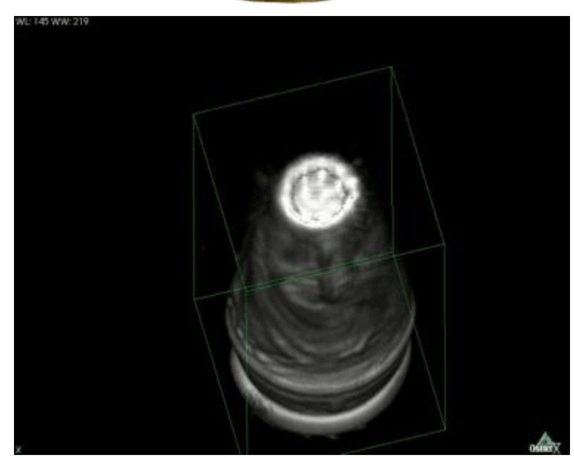


THz Imaging

How fresh is your air freshener?

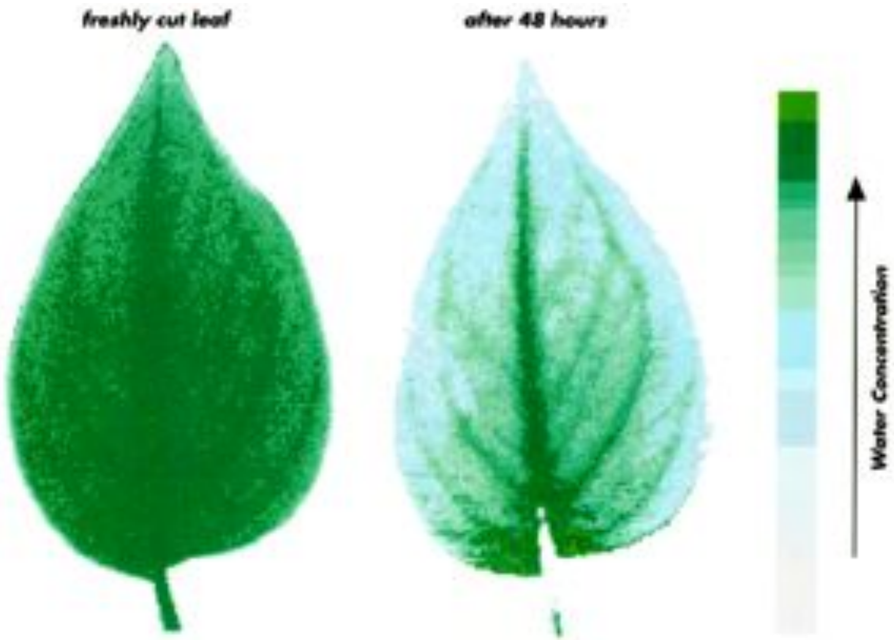
air freshener

THz image

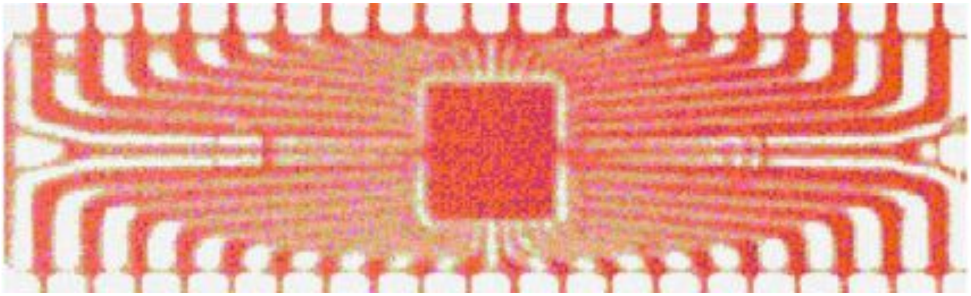


THz Imaging

THz image of a freshly cut and 48 hours old leaf



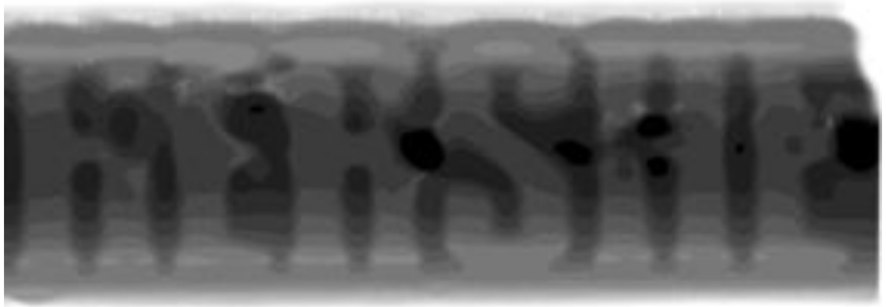
THz image of a packaged semiconductor integrated circuit



Hu and Nuss, Opt. Lett. 20, 1716 (1995)

THz transmission image of a Hershey bar

THz time delay image of a Hershey bar



Mittleman et al. Appl. Phys. B **68,** 1085 (1999)

THz Imaging

Visual inspection:
Nothing dangerous…

THz picture:
hidden knife is visible.

[Source: QinetiQ, http://www.qinetiq.com]

How can terahertz light go through clothing but reflects off the metal knife?

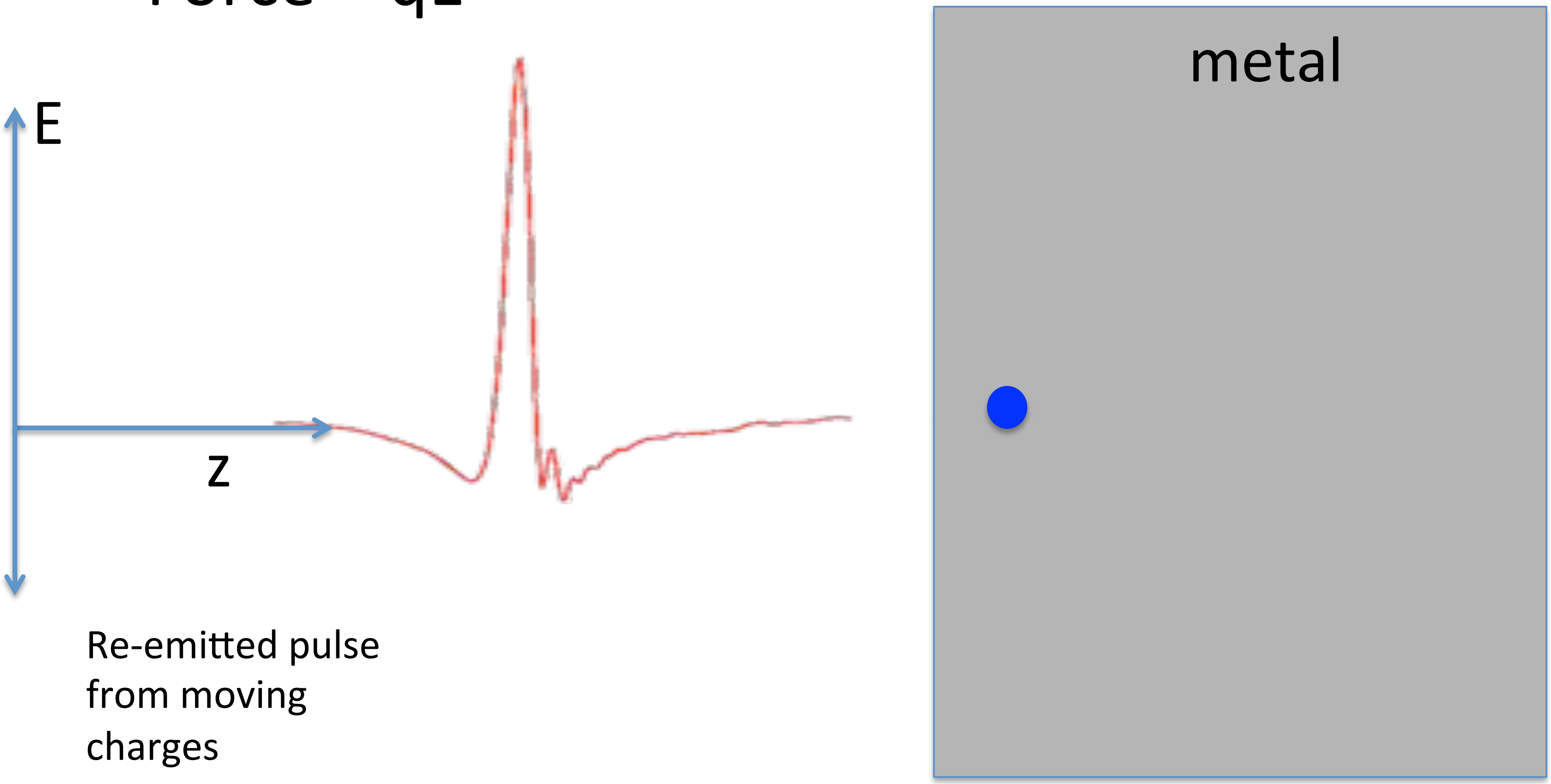
Metal = electrons that can move

Insulator = no free charges to move

- Plastics
- Glass
- Ceramics
- Clothing
- Paper

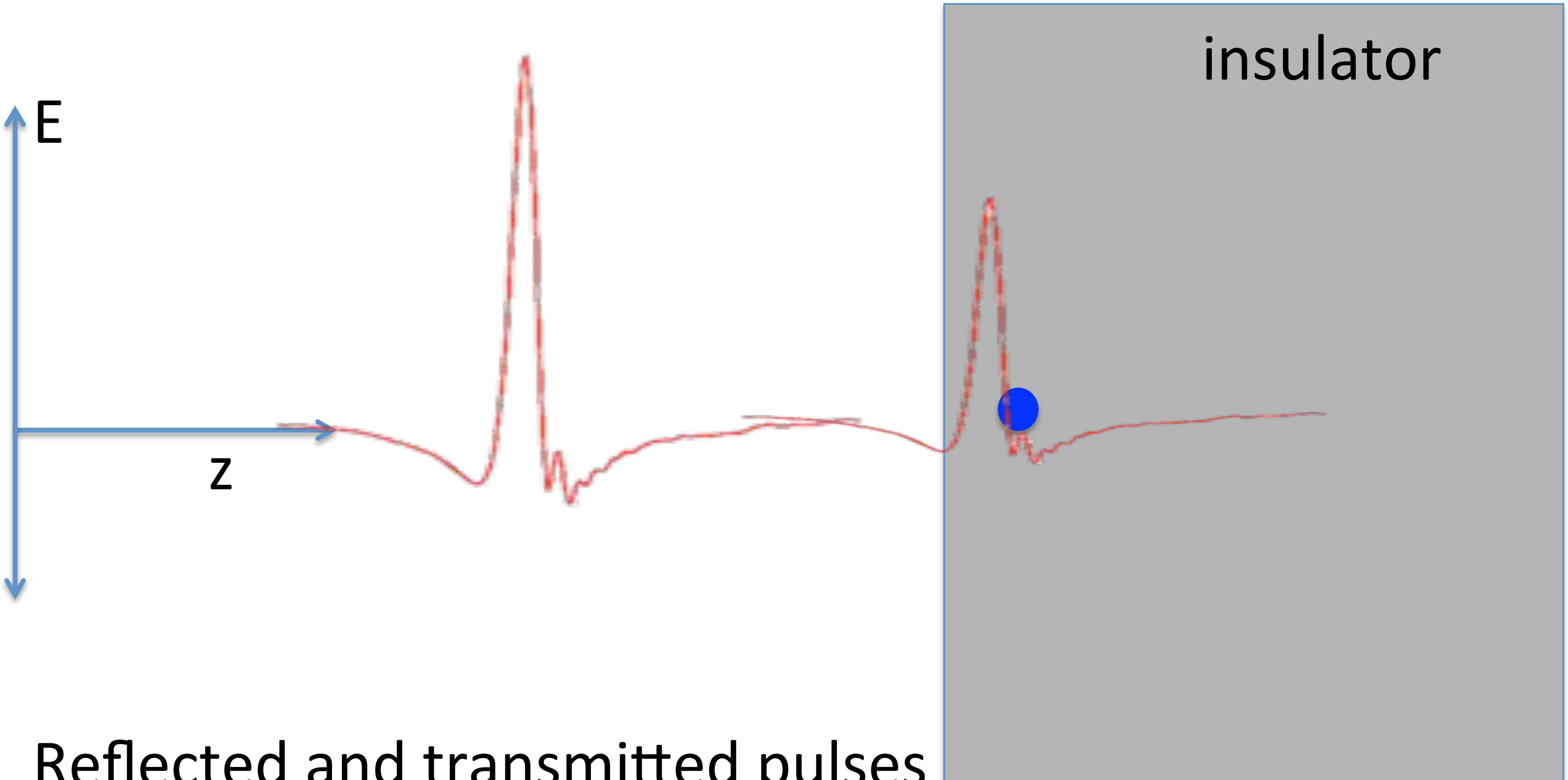
Metals

Force = qE



Insulators

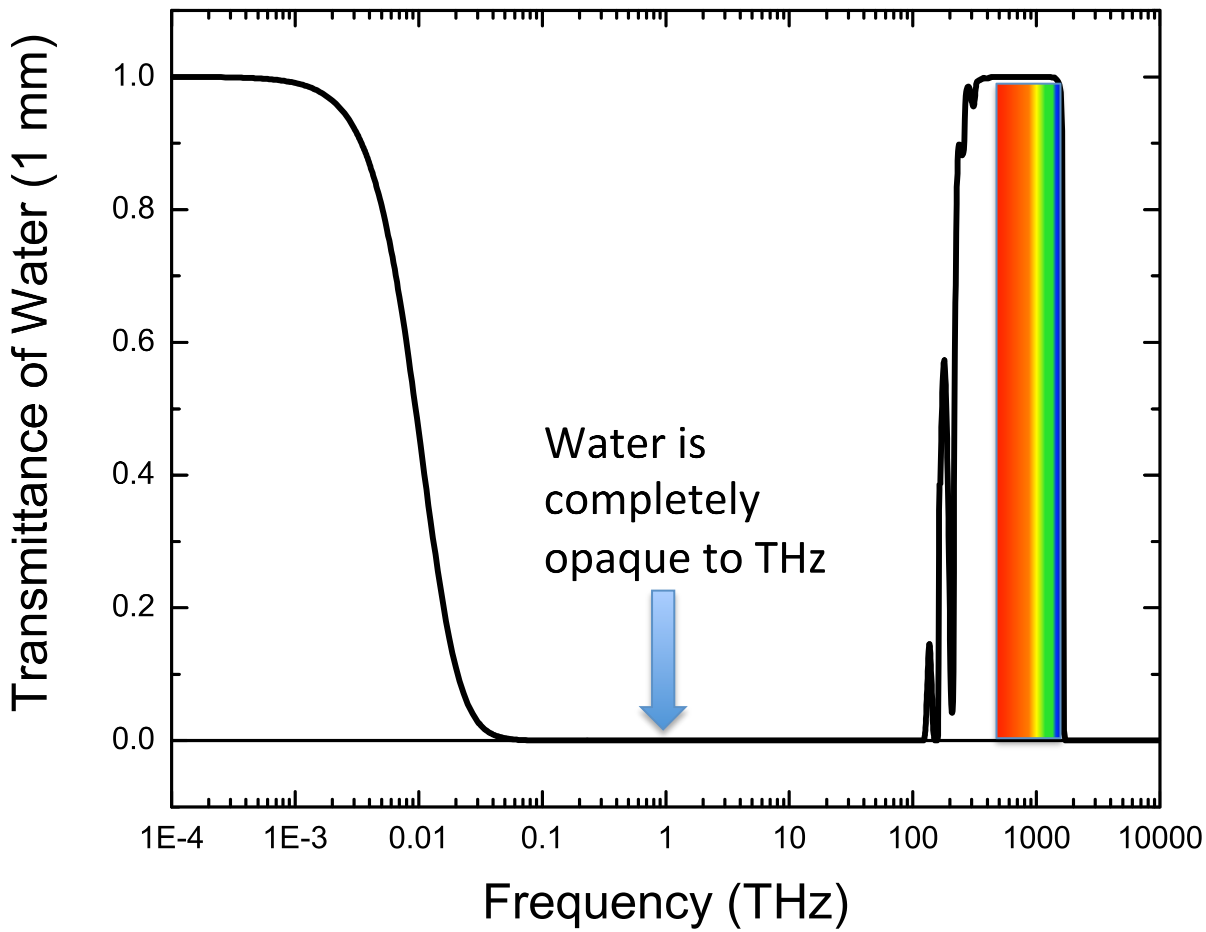
No “free” charges capable of moving in phase with the field



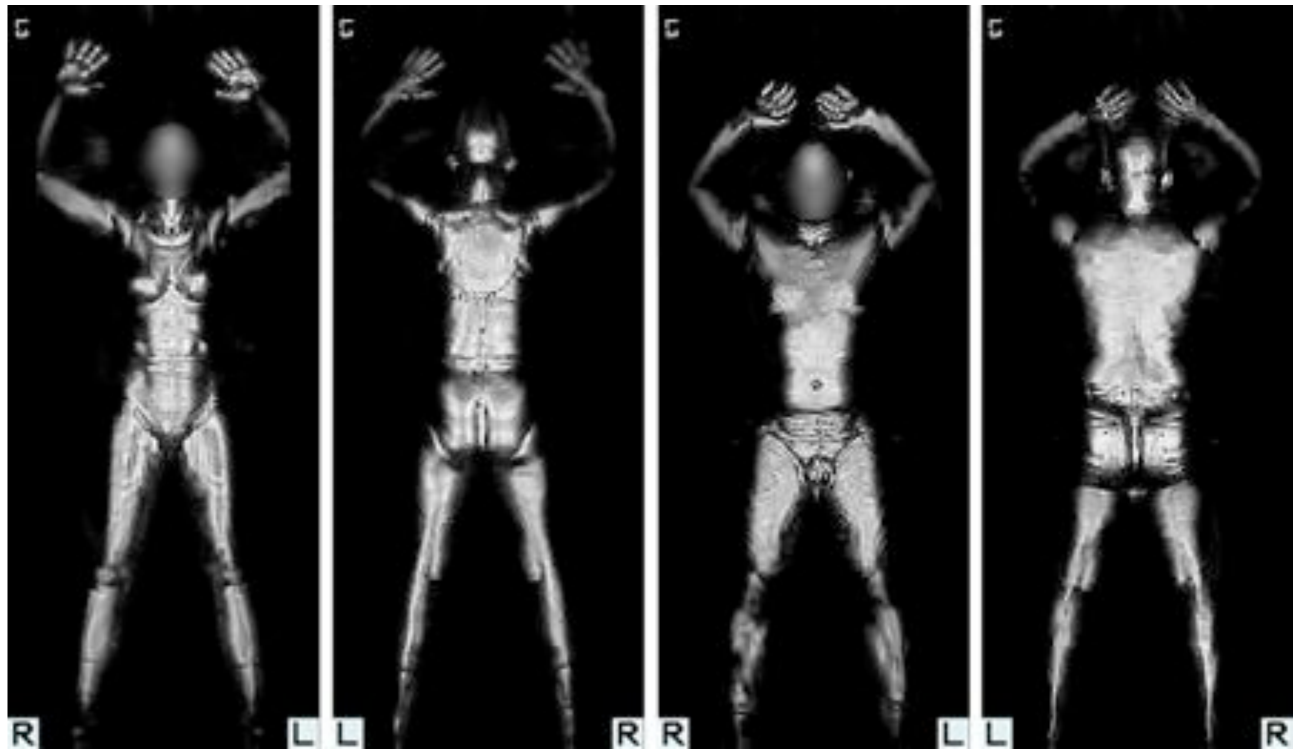
Reflected and transmitted pulses

Humans: “Ugly bags of mostly water”

- THz is strongly absorbed by liquid water.
- A good absorber is also a good reflector.



Airport naked scanners (millimeter-wave scanners)



Human skin is anywhere between 60 and 80% water, typically.

sub-THz radiation passes through clothing reflects off skin and image is returned.

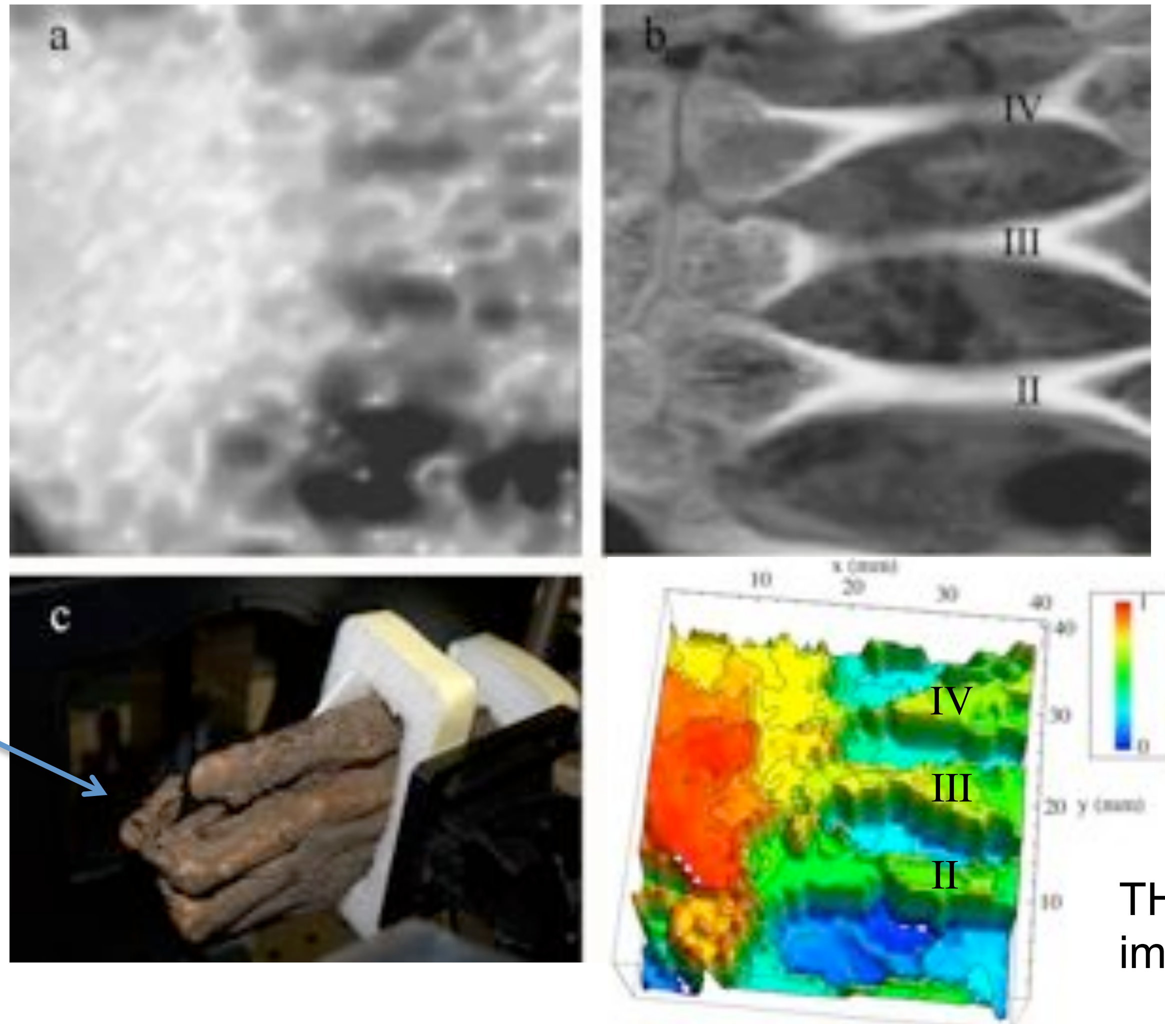
Scanners installed in Toronto, Montreal, Quebec City, Calgary, Halifax + 40 US cities

Of course, if you remove the water…

THz-Transission
at 0.16 THz

X-ray

Egyption
mummy
hand!



THz-pulse delay
image

Lena Öhrström,
P.D. Dr. Dr. Frank Rühli

Klinische Paläopathologie
Medizinhistorisches Institut, Universität Zürich

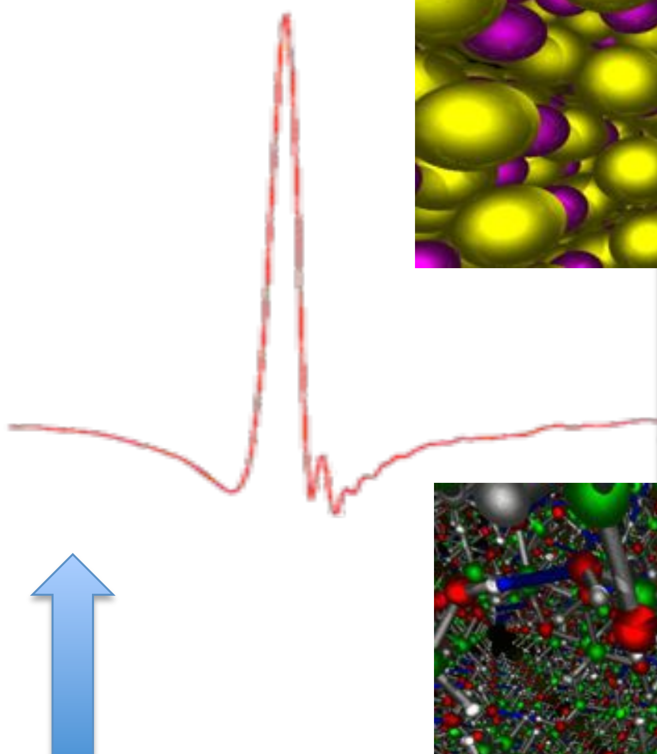
Courtesy of Dr. Markus Walther, Univ. Freiburg

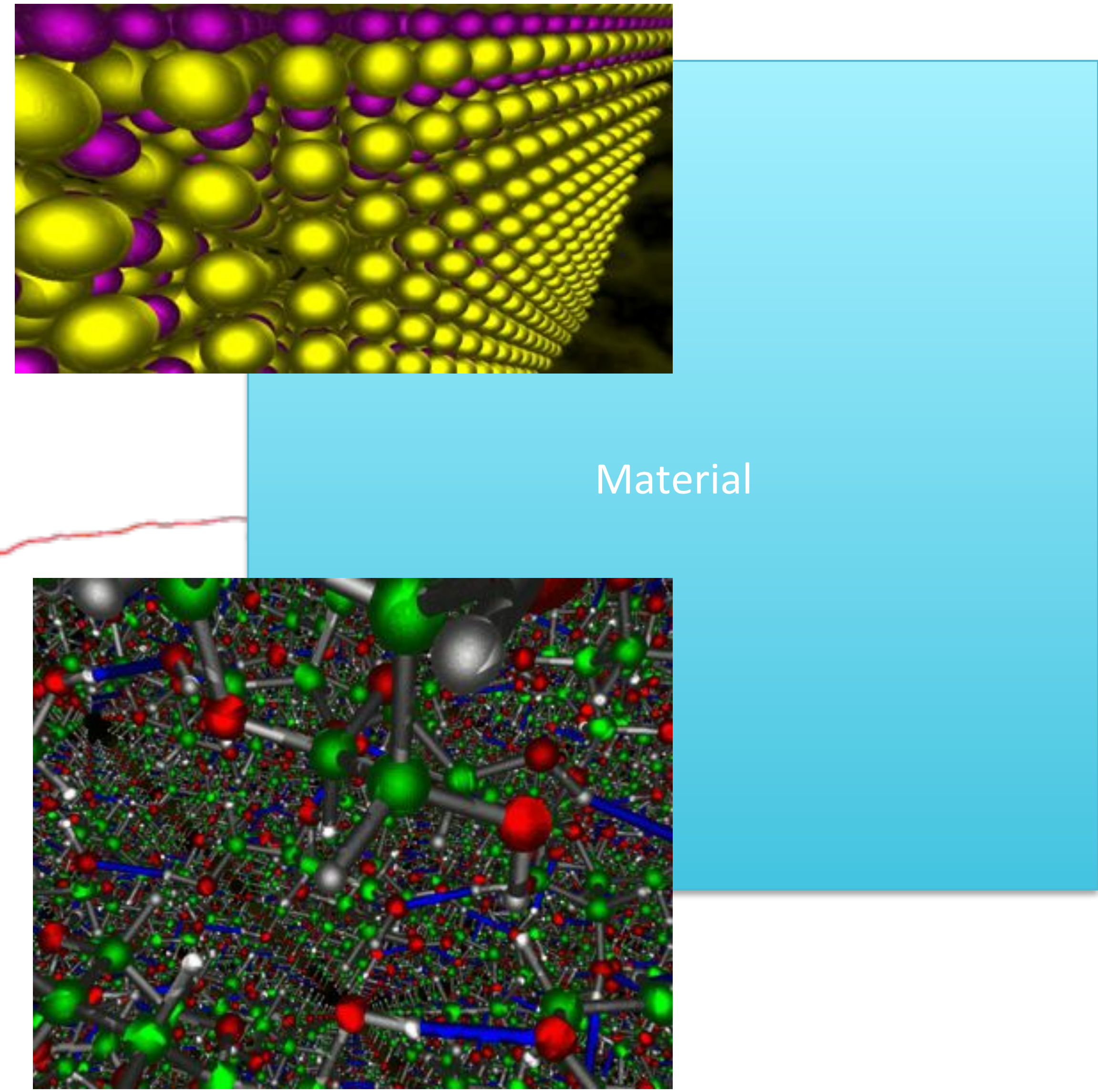
L. Öhrström et al., *submitted* (2009)

Alcohol concentration measurements (P. U. Jepsen)

Inspection of liquids in bottles (P. U. Jepsen)

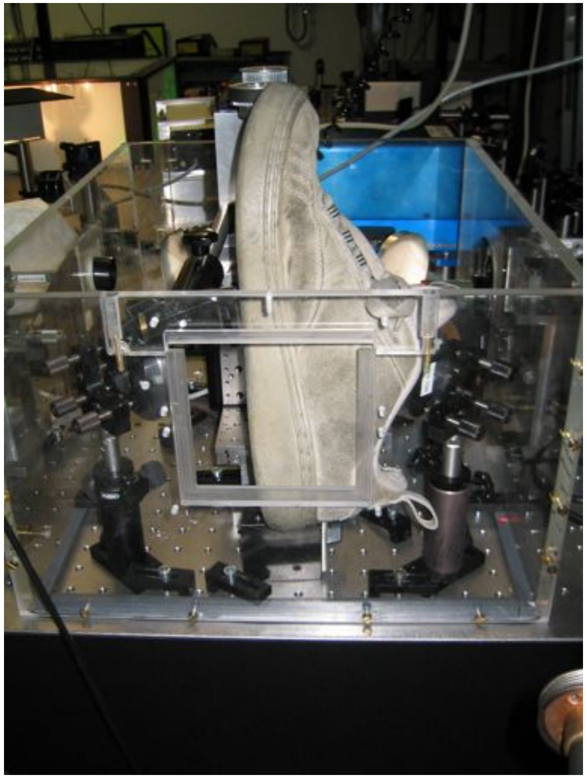
THz spectroscopy



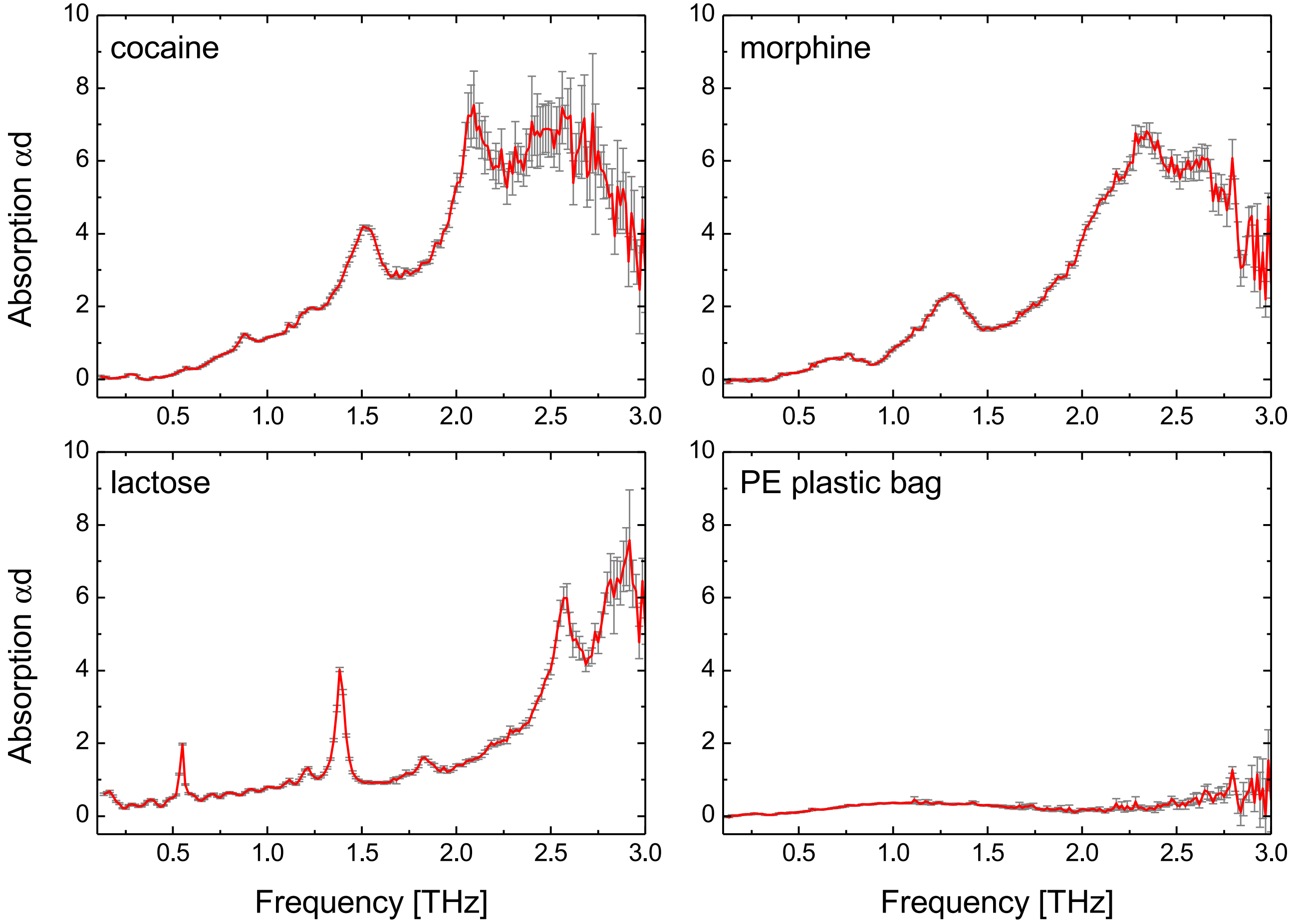


Oscillations at frequency of atomic/molecular vibrations!

Chemical identification

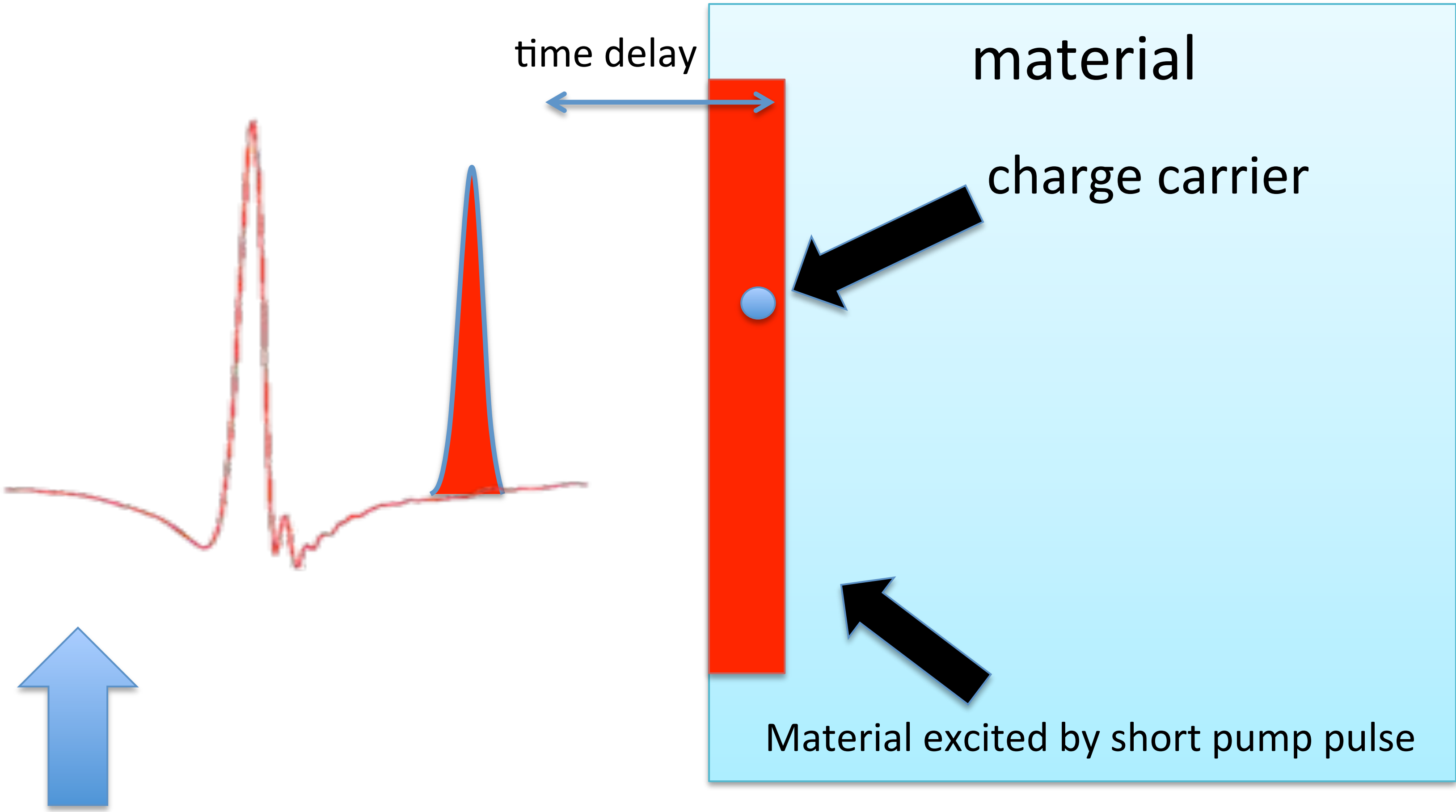


Markus Walter's experiment
(and sneaker)



Phonon signatures of molecular crystals can be used for identification purposes. Packing material is (often) transparent.

THz Spectroscopy of Ultrafast Events

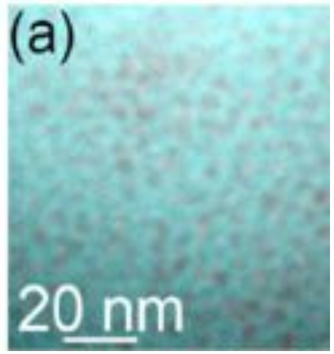


Amplitude and phase change of THz pulse gives a snapshot of carrier motion, just a few moments (~100 fs) after excitation!

Ultrafast carrier motion in novel materials

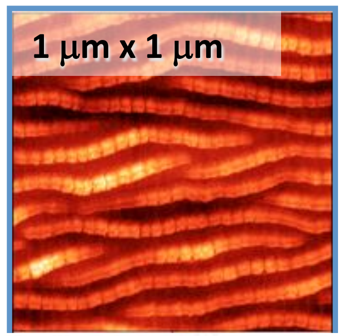
Carrier localization in silicon nanocrystals

D. G. Cooke et al., PRB **73**, 193311 (2006).



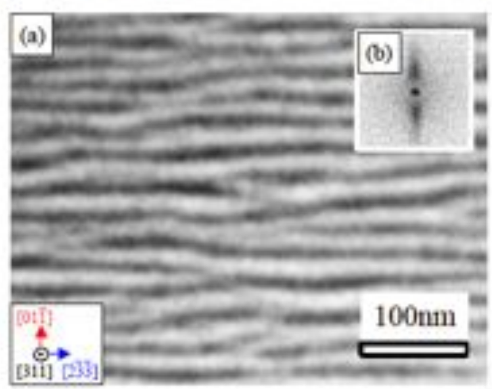
Anisotropic conductivity in aligned quantum dots

D. G. Cooke et al., Appl. Phys. Lett. 85 3839 (2004)

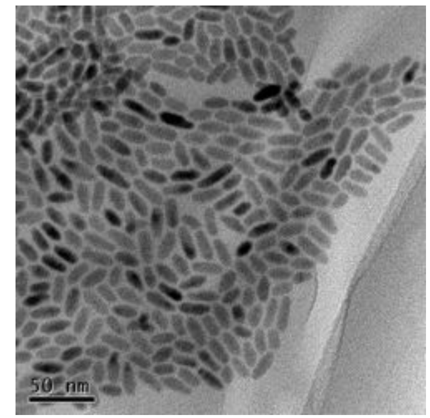


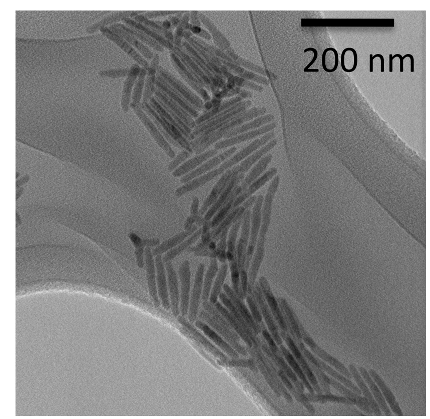
Direct observation of charge capture into InGaAs/GaAs quantum wires

D. G. Cooke et al., J. Appl. Phys. **103** 023710 (2008).



Microscopic mobility in CdSe nanorod/P3HT hybrid polymer solar cells





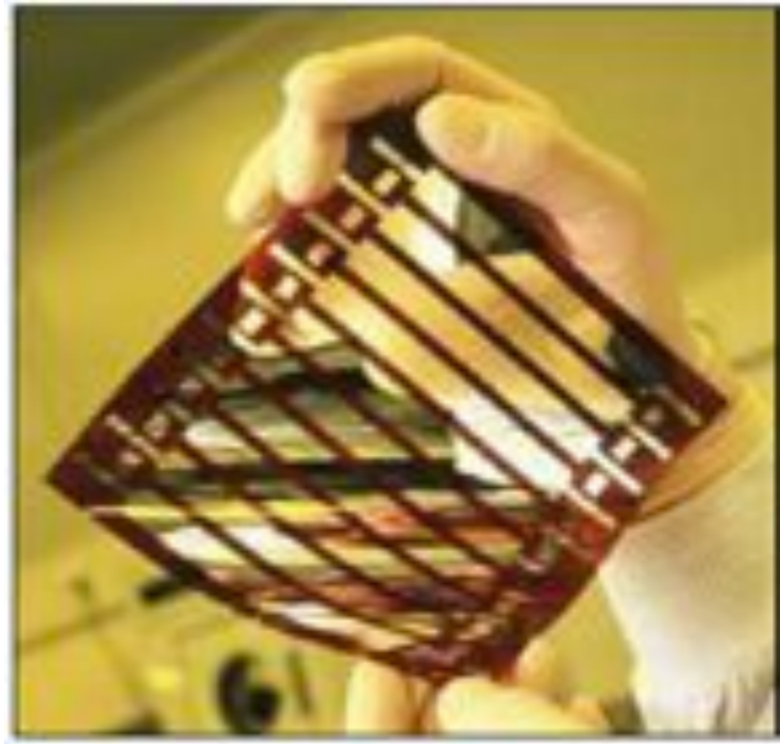
Carrier dynamics in plastic solar cells

Lightweight and can be mass-produced by inkjet printing and roll-to-roll processing.

Flexible plastic could one day coat buildings, clothing, etc.

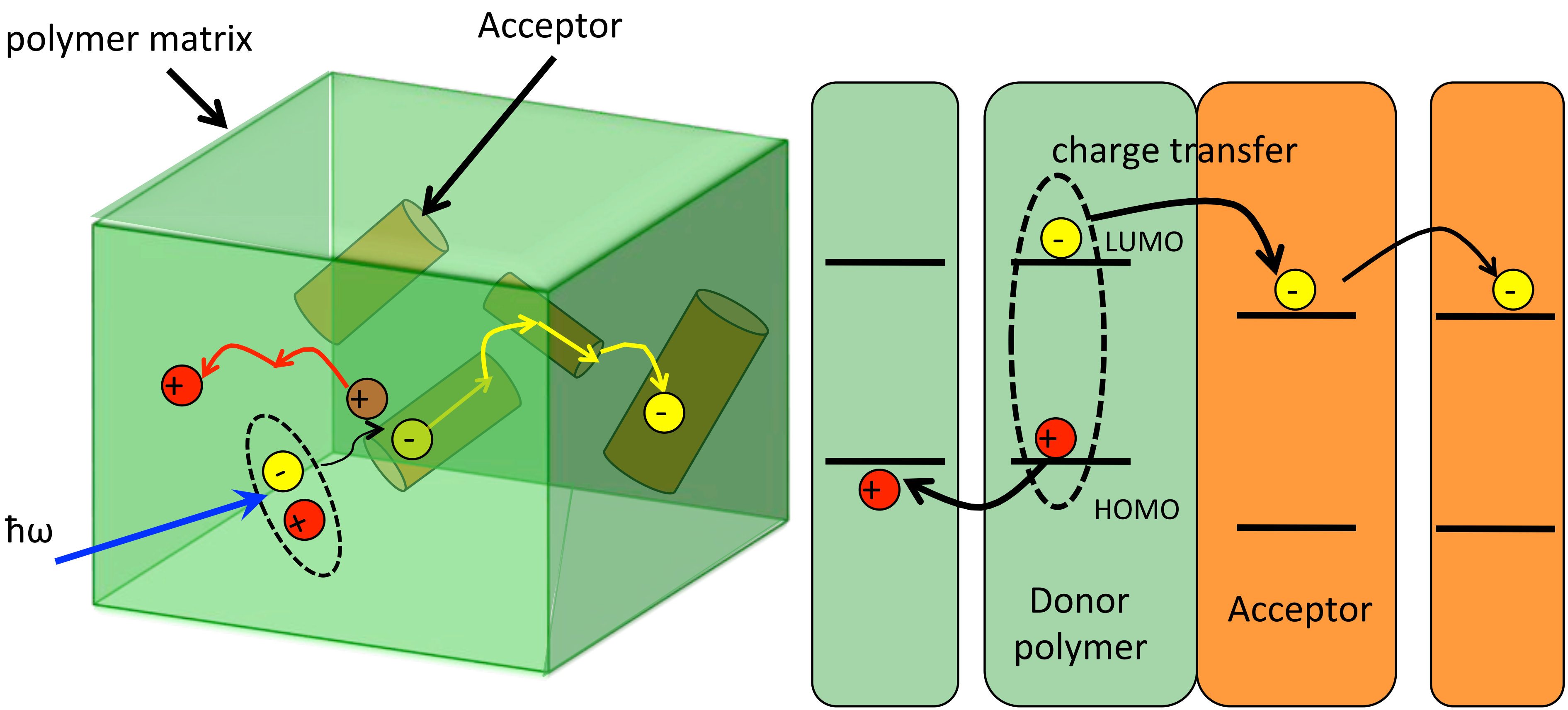
Composed of a type of semiconducting polymer that becomes conducting after illumination with light.

Current debate: how long does it take for the charges to become mobile (i.e. able to move in response to a field)?



Organic materials promise inexpensive flexible solar fabric for powering personal electronics or for integration into buildings. Source: BRN Solar Report, Konarka

Active material



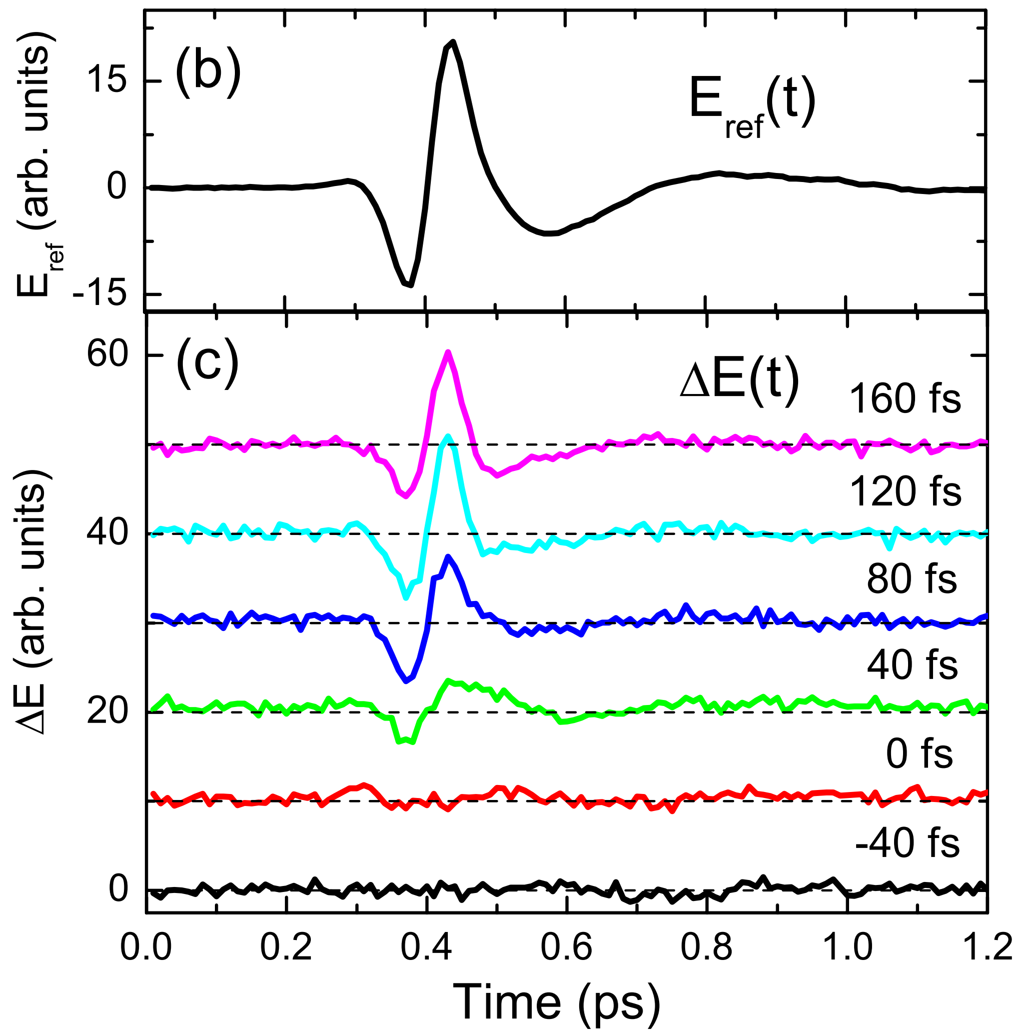
How long does it take to make a mobile charge carrier?

Some take only 120 fs, 30 times less than previously thought

Incident THz pulse:

Change in THz pulse at different pump-probe delay times, due to pump induced mobile charges.

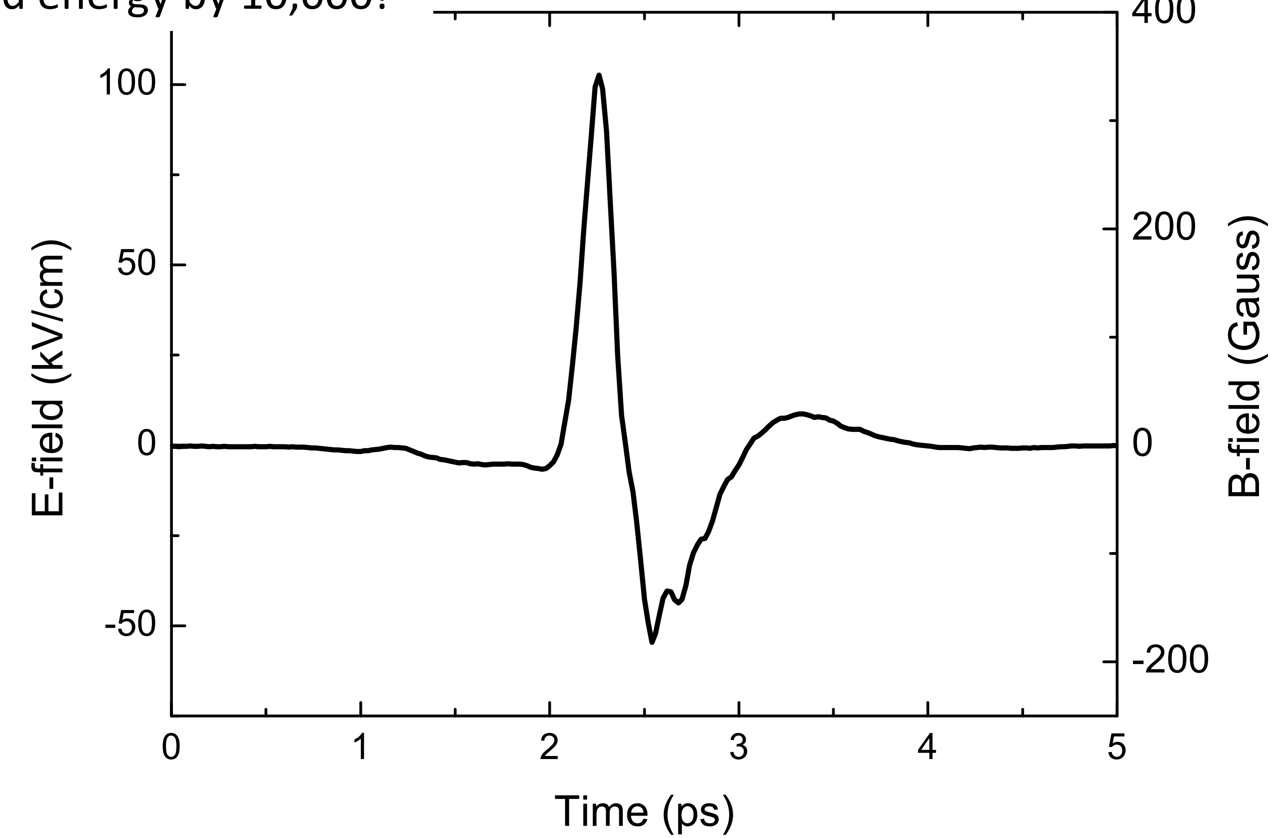
Fully developed after 120 fs.



A new direction: turning up the power…

Increase E-field by 100 times.
Increased energy by 10,000!

B-field 600 times that at Earth's surface (~0.5 Gauss)



Intense electric field permits not just probing, but CONTROL of charges in materials.

Magnetic field of pulse is also significant: CONTROL ultrafast magnetic phenomena

Final thoughts

- The THz part of the EM spectrum is starting to be tamed.
- Applications are many: chemical sensing, spectroscopy and voyeurism/security
- THz light lets us see how charge moves through a material, even on fs time scales.
- THz control of materials is on the horizon…

Which would you rather…

OR