Imaging and Sensing with Terahertz Radiation

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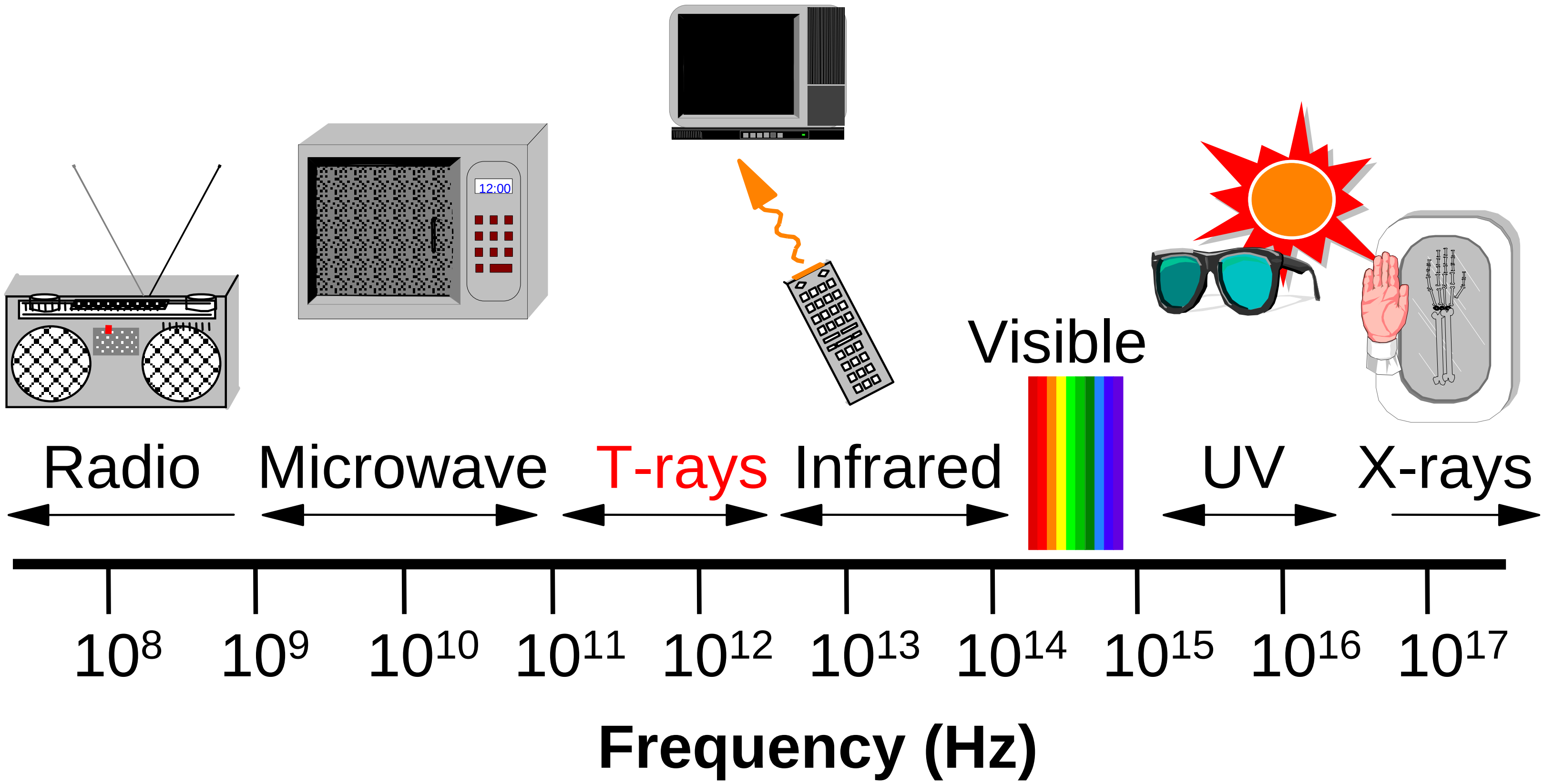
What is terahertz radiation?

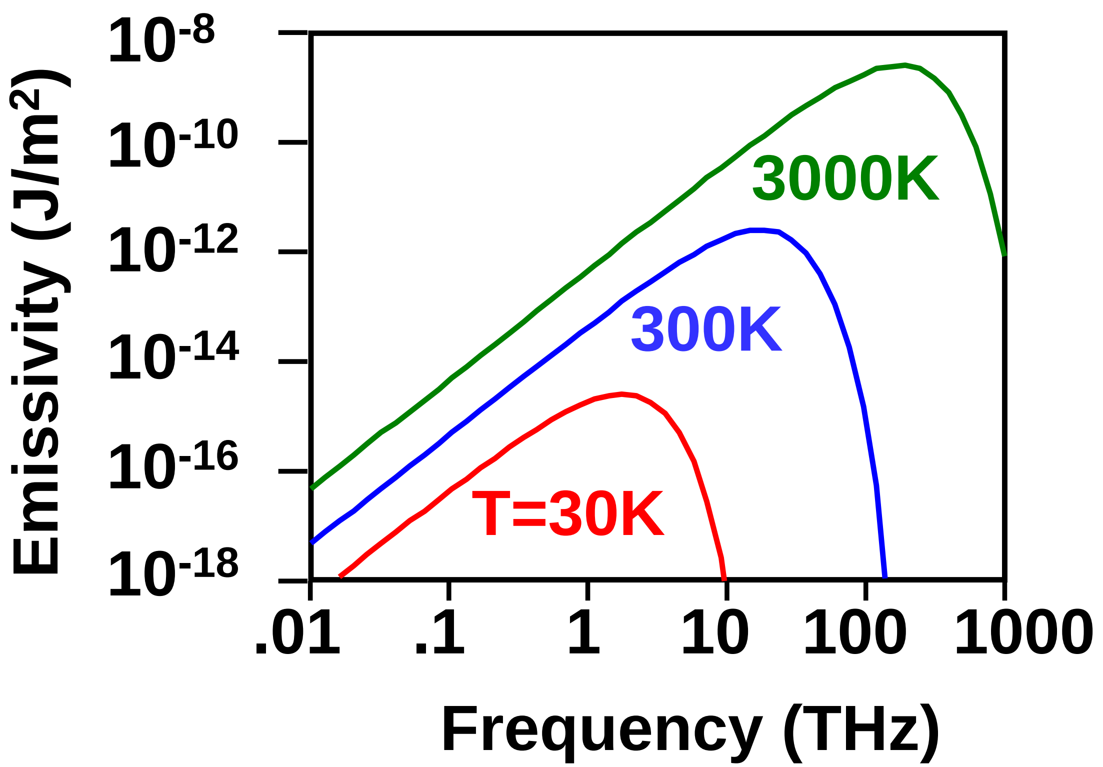


$\nu = 1$ THz → $\lambda = 300\ \mu m$

→ $h\nu = 33\ cm^{-1}$ or 4.1 meV

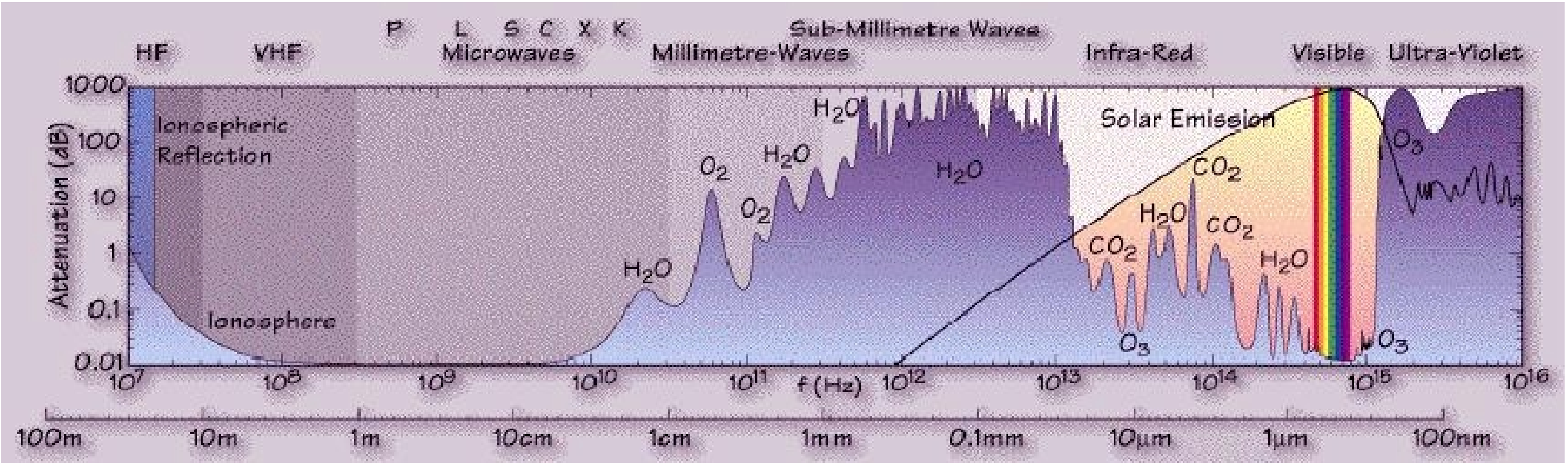
→ $T = 48$ K

The challenge (part 1)



Blackbody spectrum rolls off very rapidly in the THz spectral range

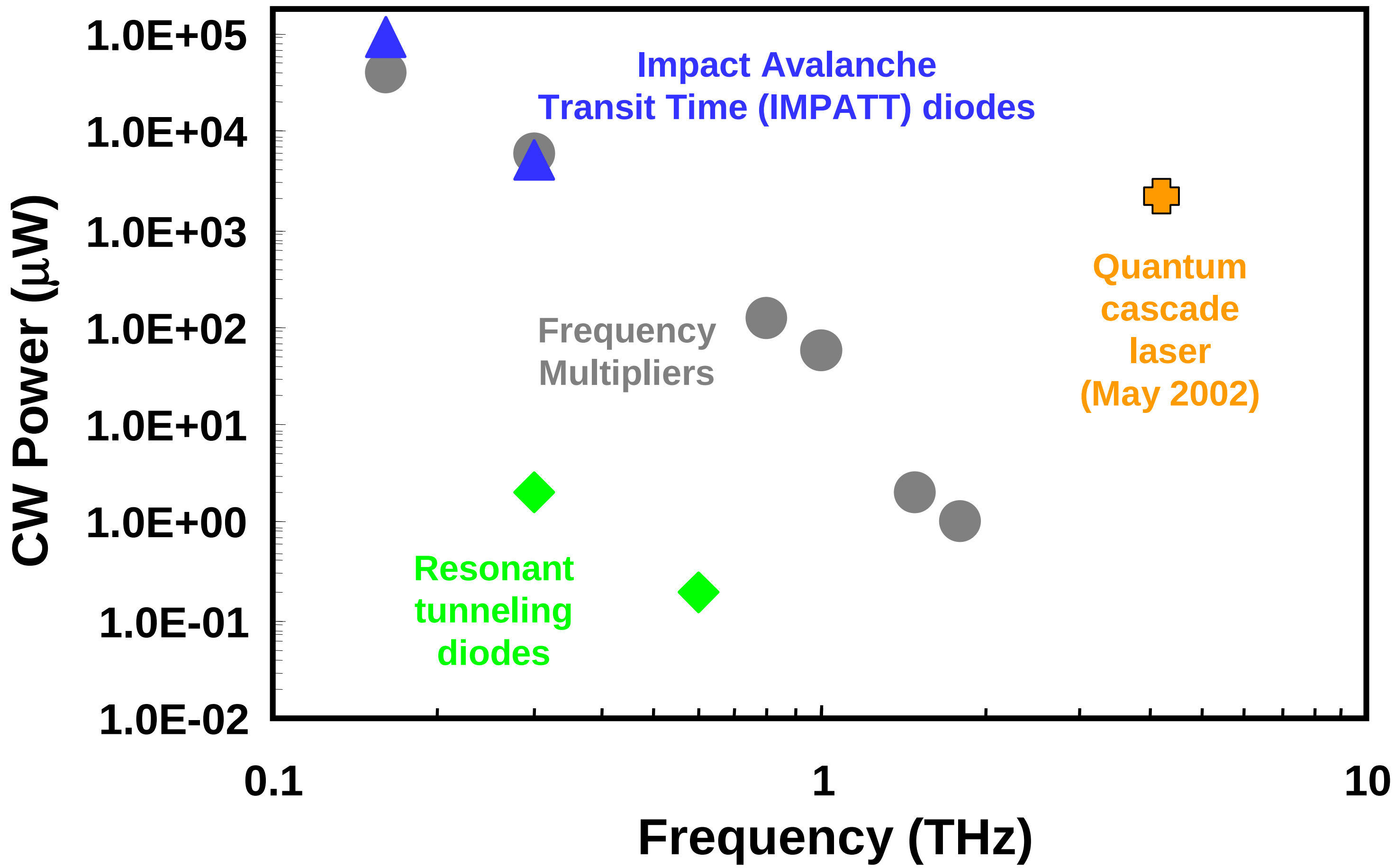
The challenge (part 2)



Long distance atmospheric transmission is very challenging

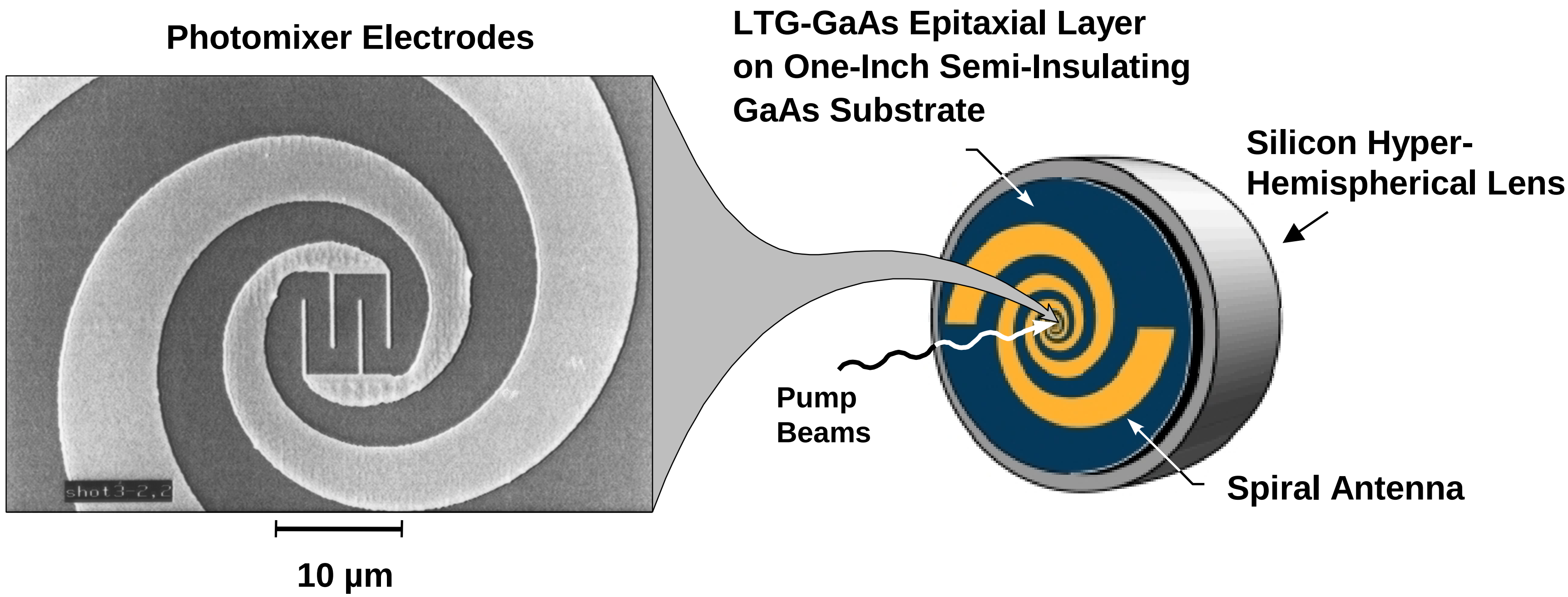
(but not too bad for D < 100 m…)

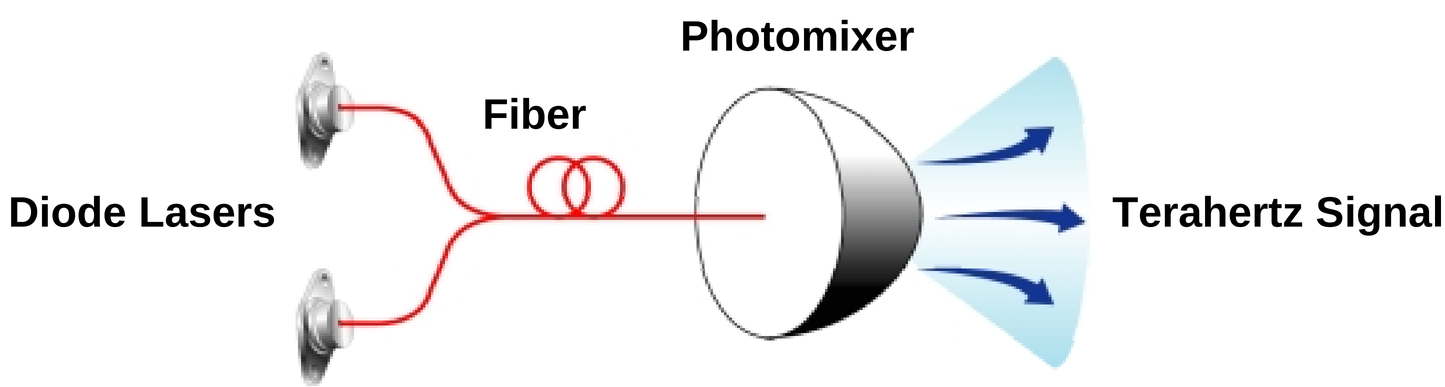
“Traditional” electronic sources



Peter Siegal, JPL

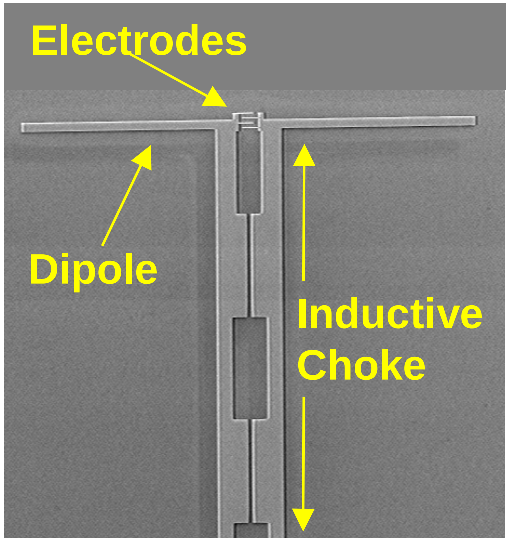
Mixing of optical sources

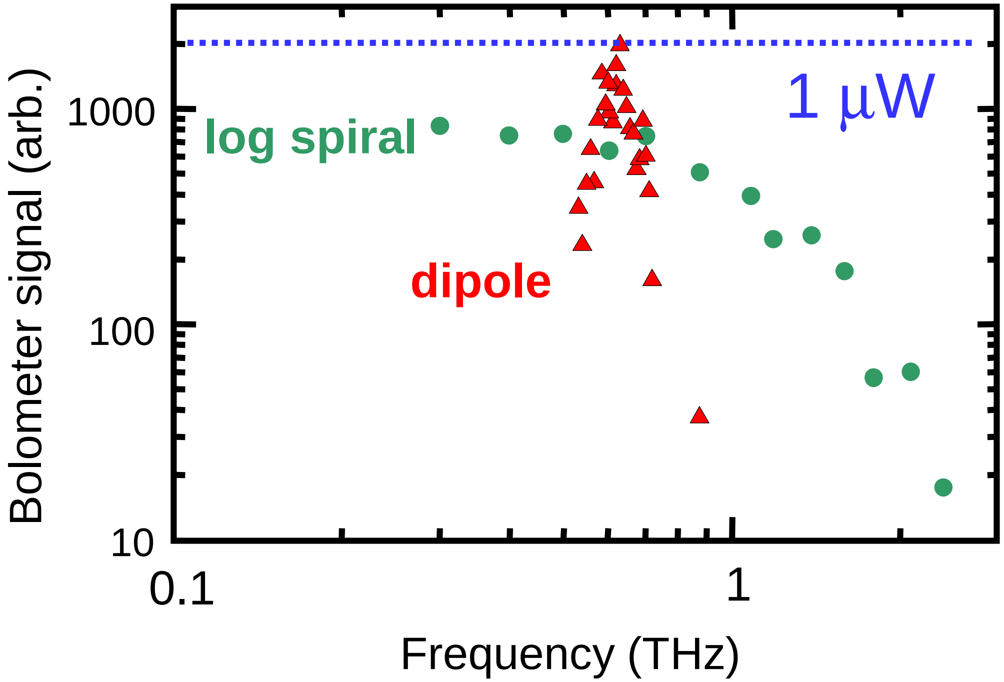




S. Duffy & K. McIntosh, MIT Lincoln Labs

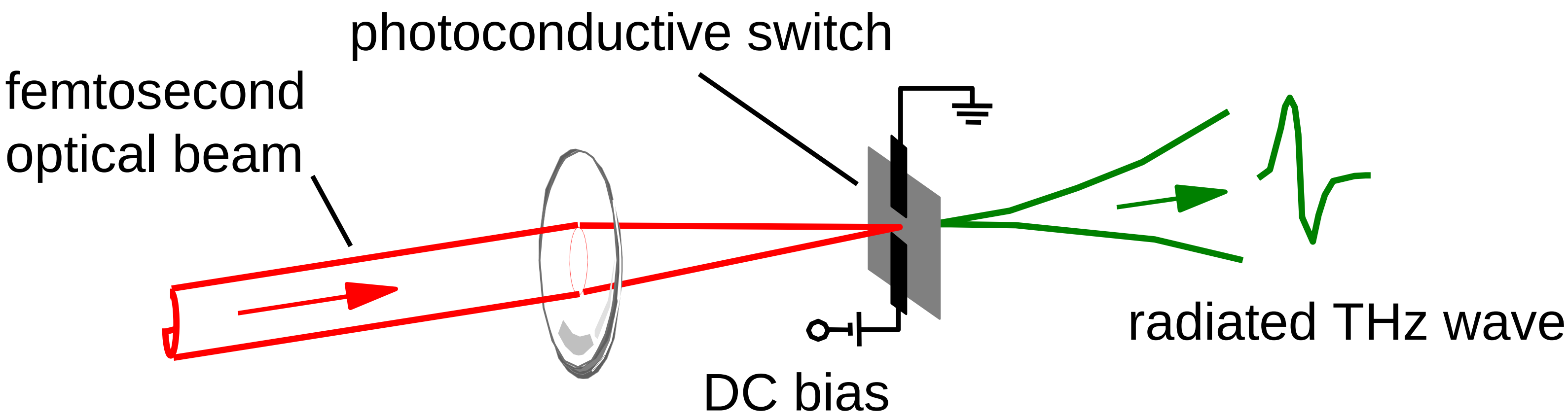
Tunability and power





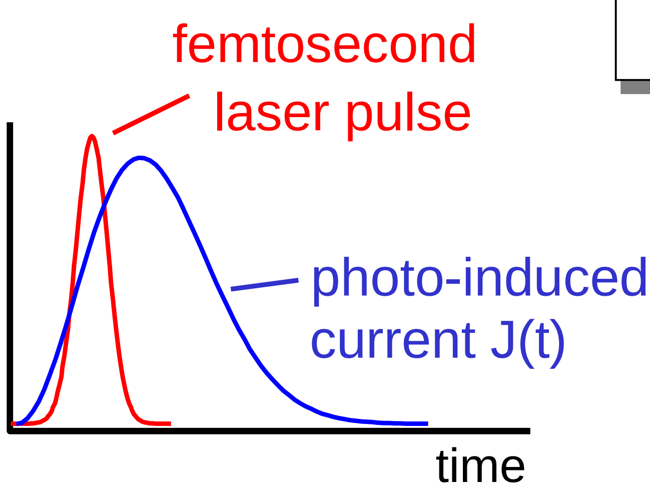
S. Duffy & K. McIntosh, MIT Lincoln Labs

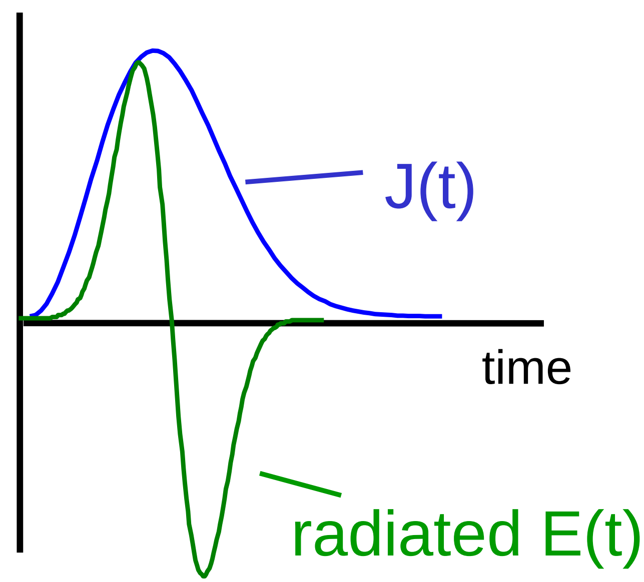
Generation of free-space THz pulses



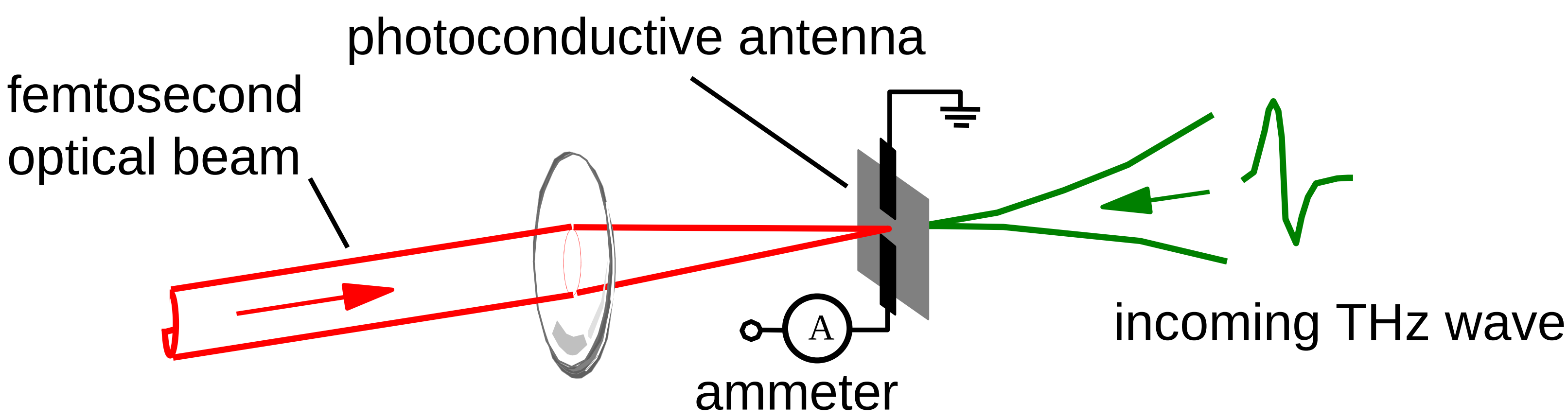
Radiated field:

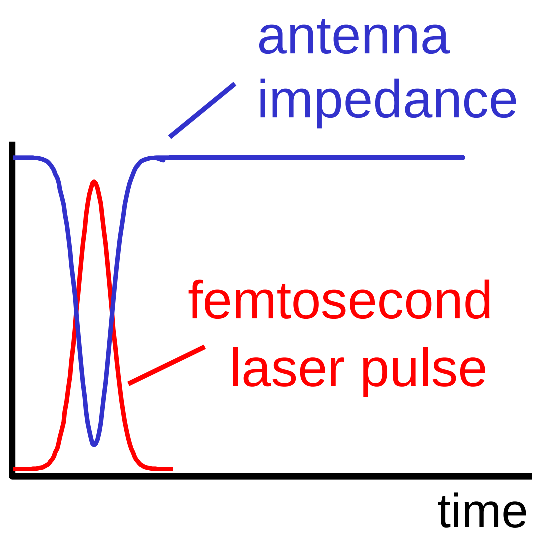
$$E(t) \propto \frac{\partial J}{\partial t}$$

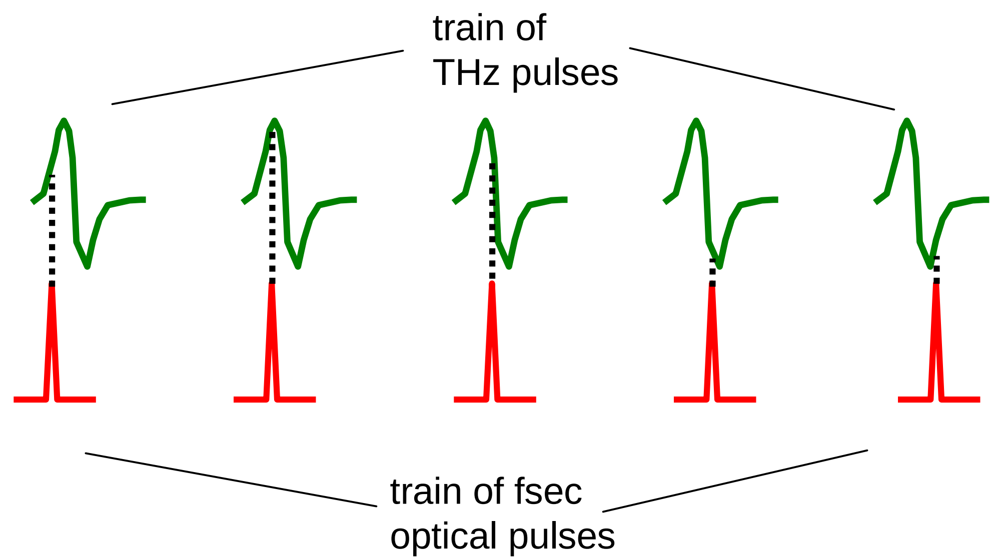




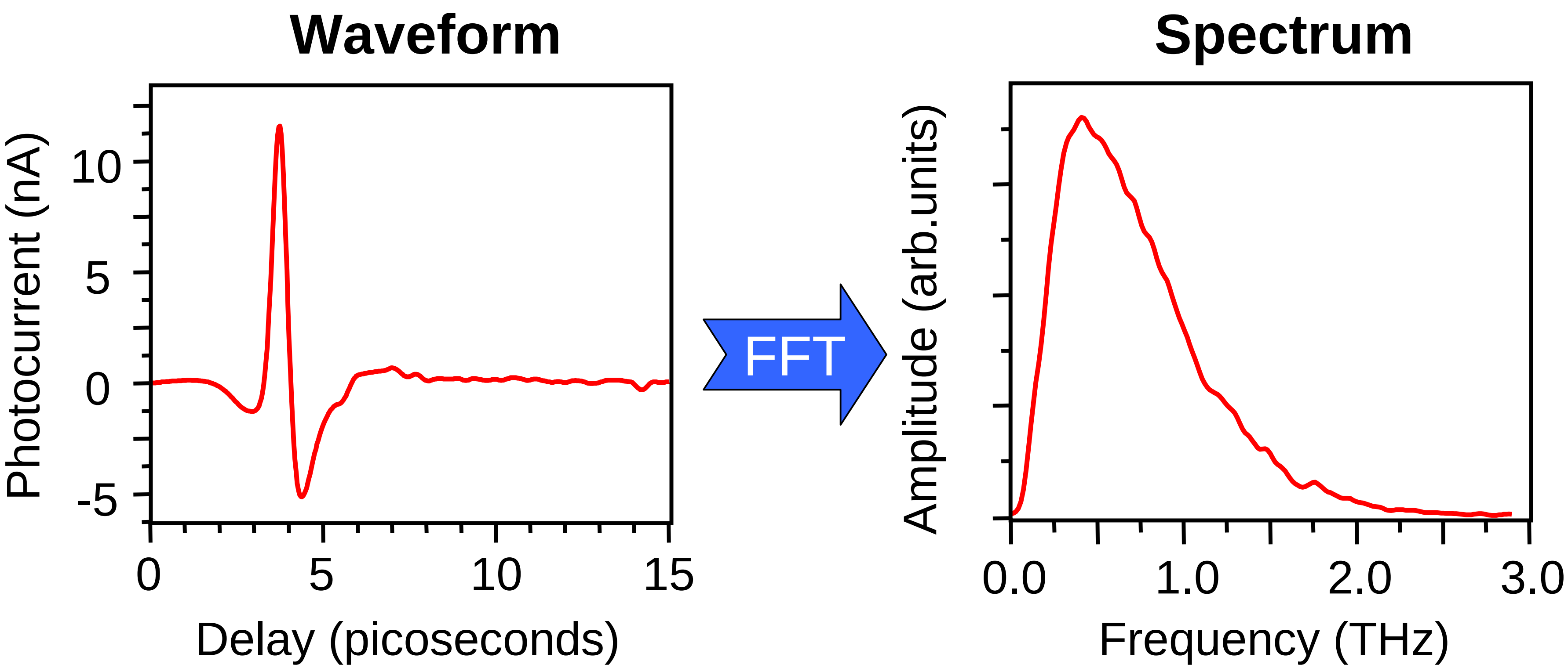
Detection via photoconductive sampling





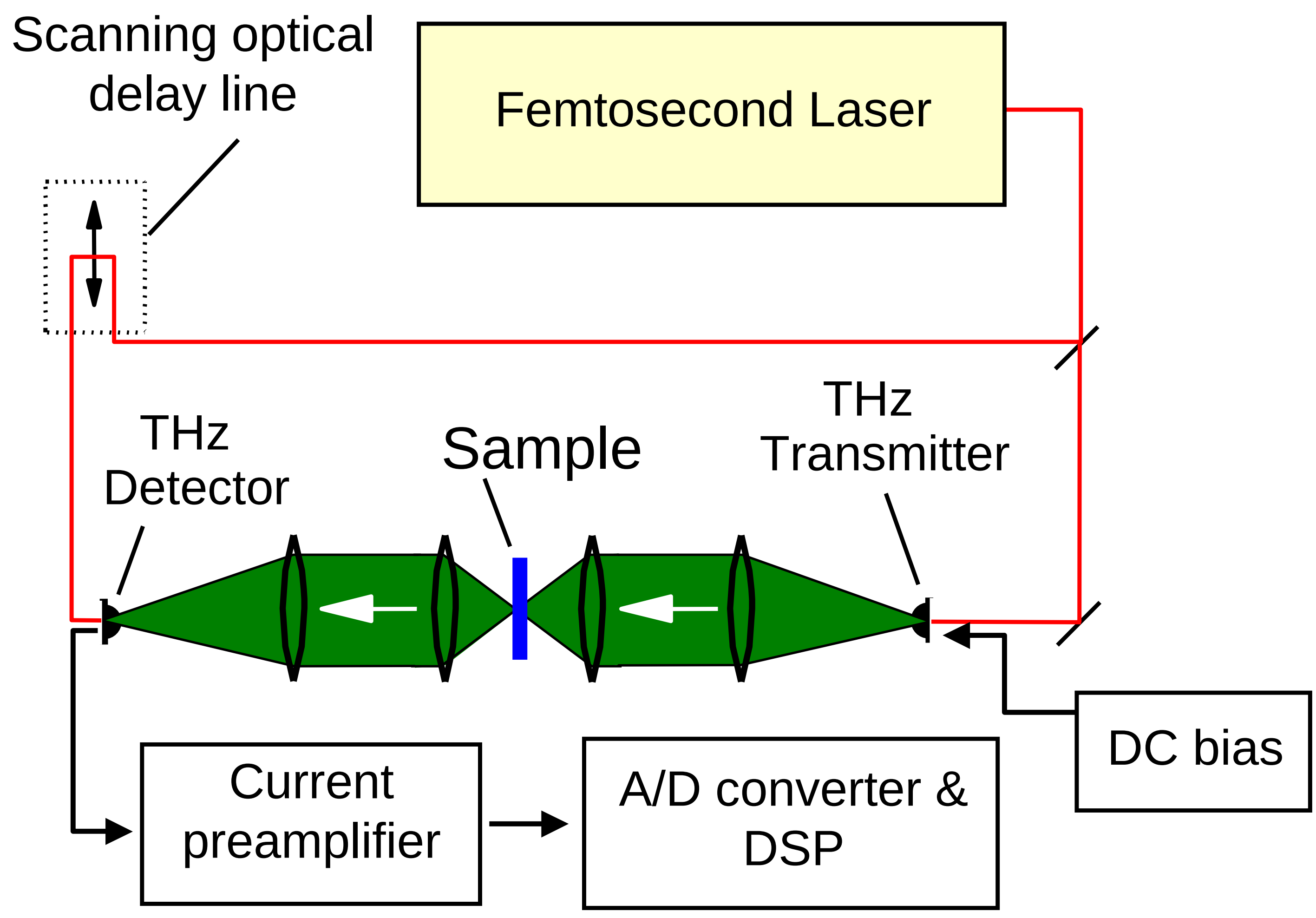


Typical THz wave forms

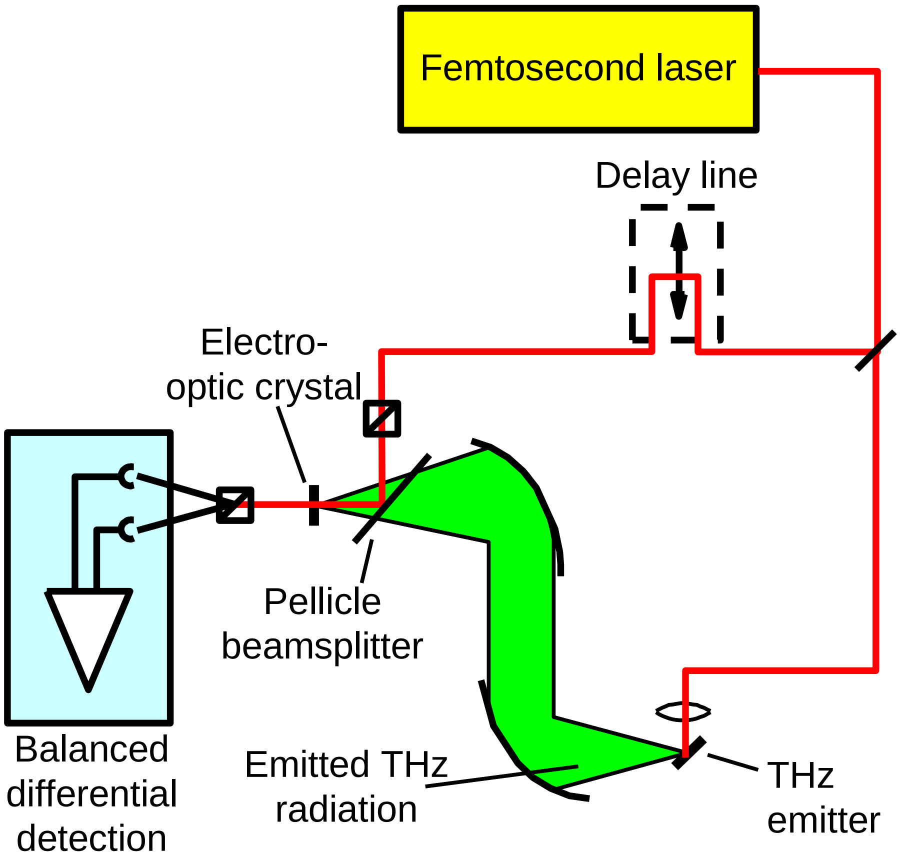


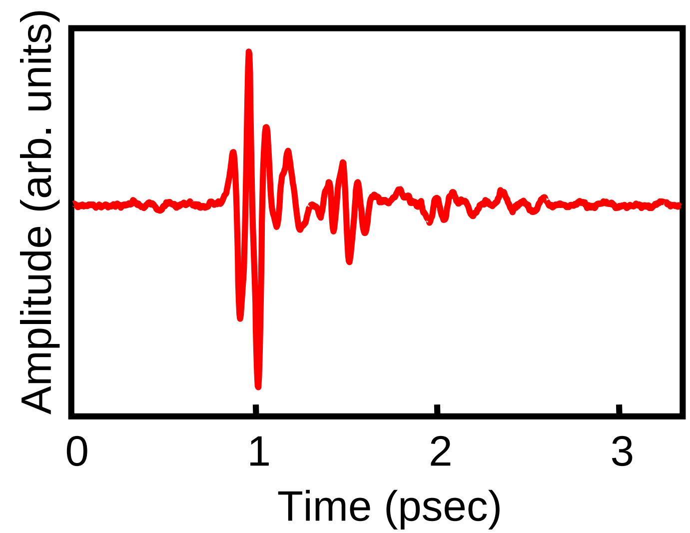
- **Single cycle of the electromagnetic field**
- **Bandwidth of 2.5 - 5 THz**
- **Coherent detection of electric field**

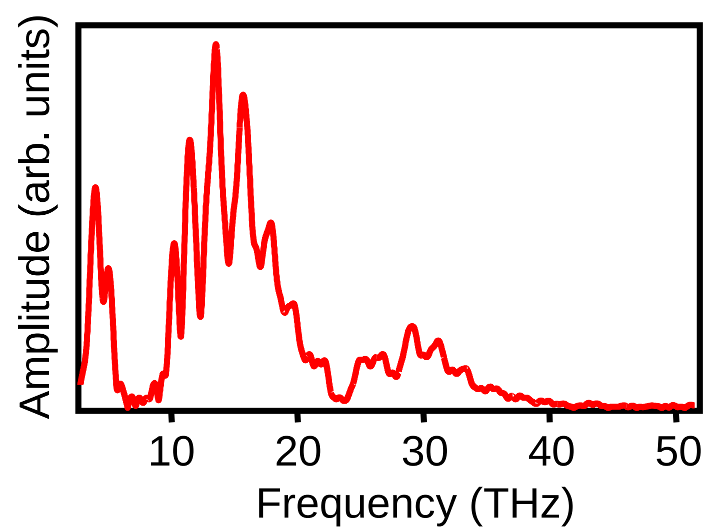
THz time-domain spectrometer



THz free-space electro-optic sensing





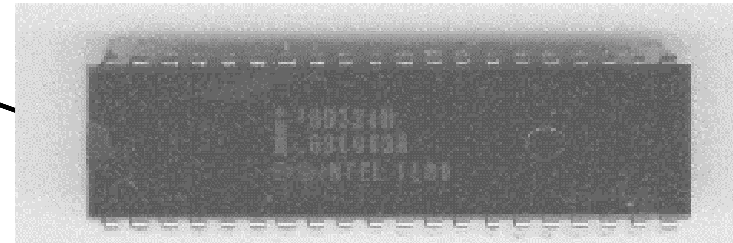


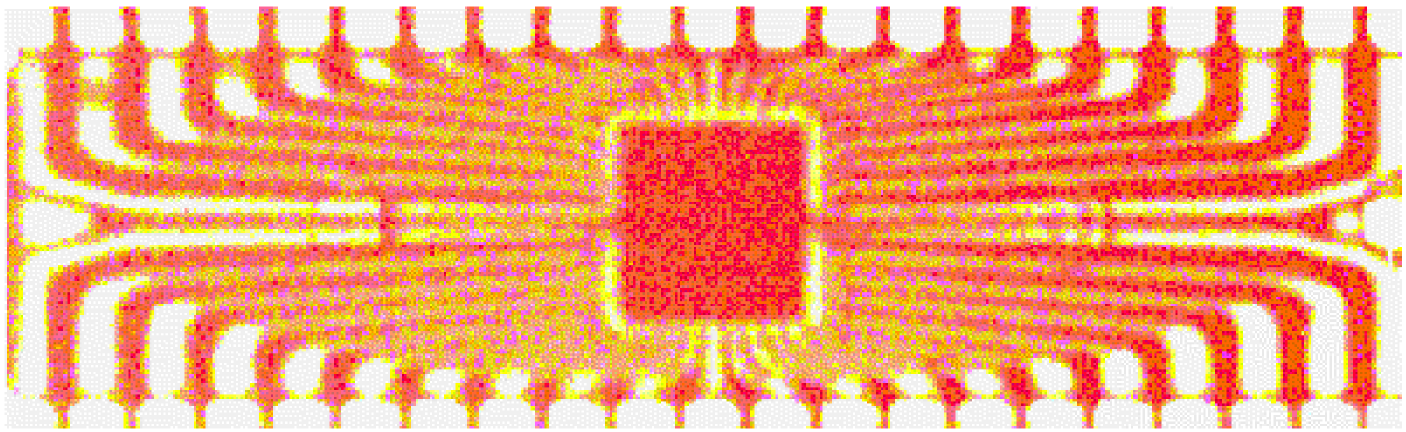
Up to 50-100 THz of bandwidth!

X.-C. Zhang, Rensselaer Polytechnic Institute

THz image of a semiconductor integrated circuit

Visible image

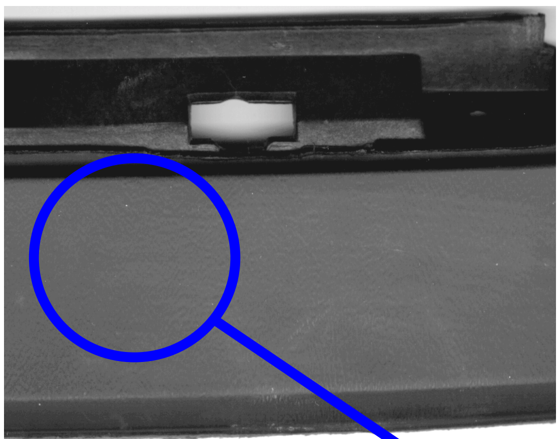




- Imaging metal leads through plastic packaging
- ~ 0.25 millimeter spatial resolution
- Useful for fault detection, delamination

THz image of an automobile dashboard

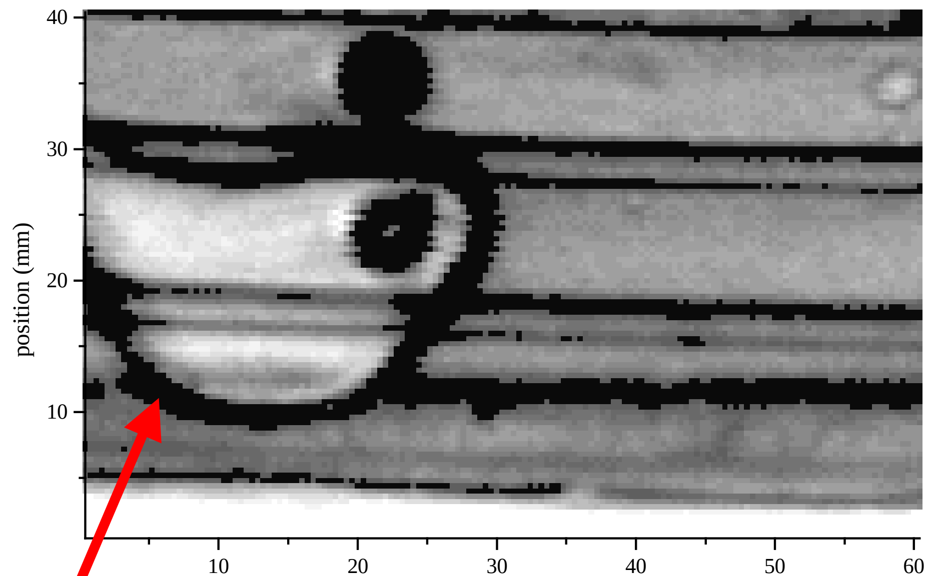
Visible Images



Front View

Rear View

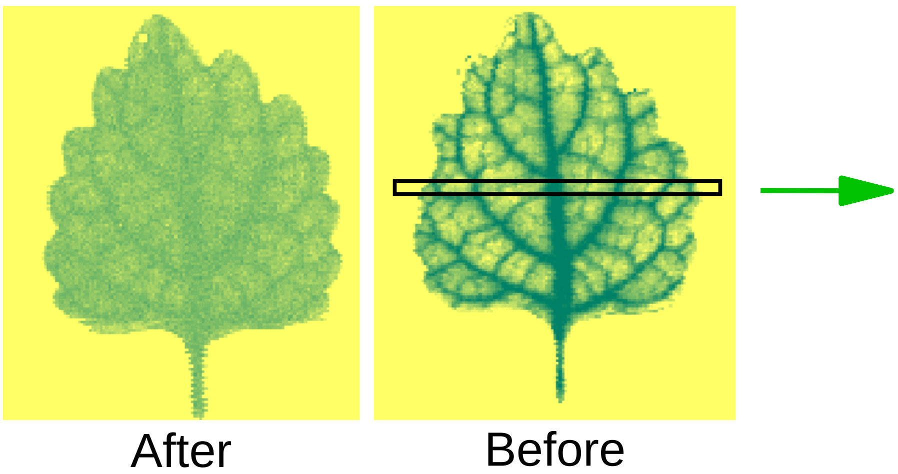
THz Image

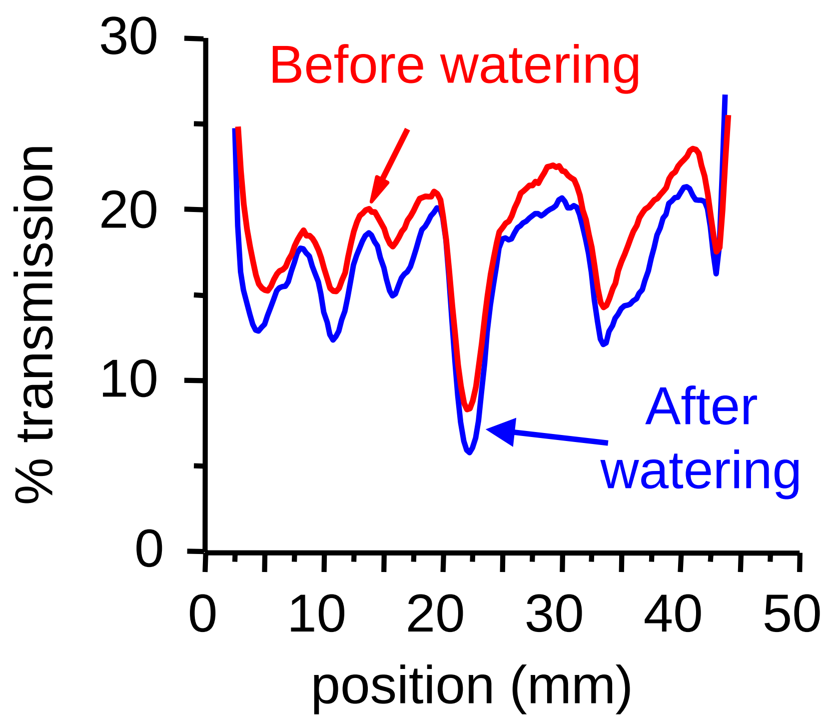


Gap in foam filling hidden beneath opaque plastic

Easily visible in THz image

Water content in a living leaf

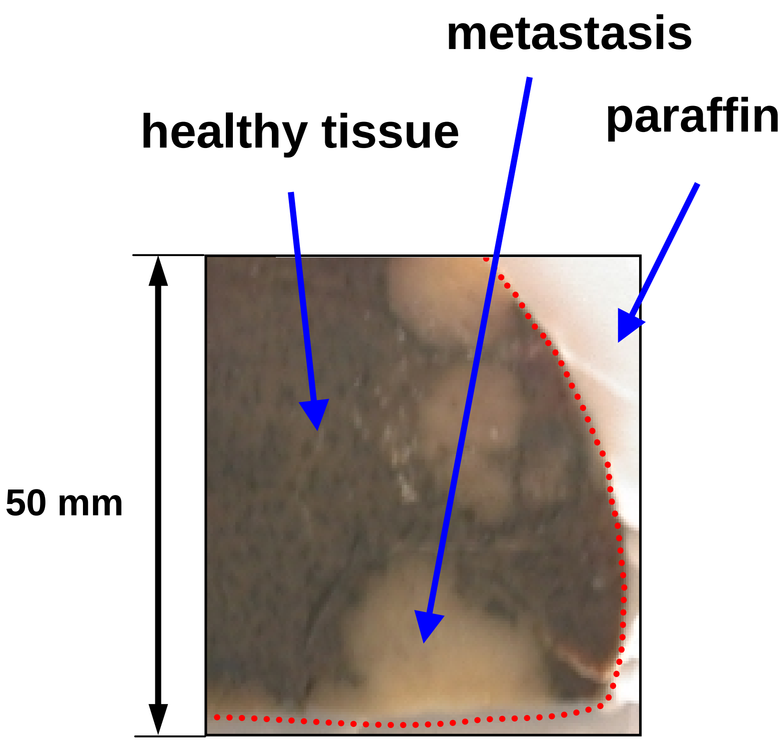




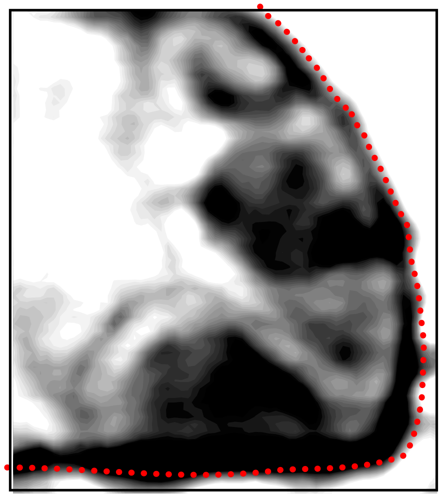
Proof of principle experiment:

- Plant is allowed to dry somewhat, and then watered
- As the leaf rehydrates, THz transmission decreases
- Changes smaller than 1% are detectable

THz imaging for tumor detection

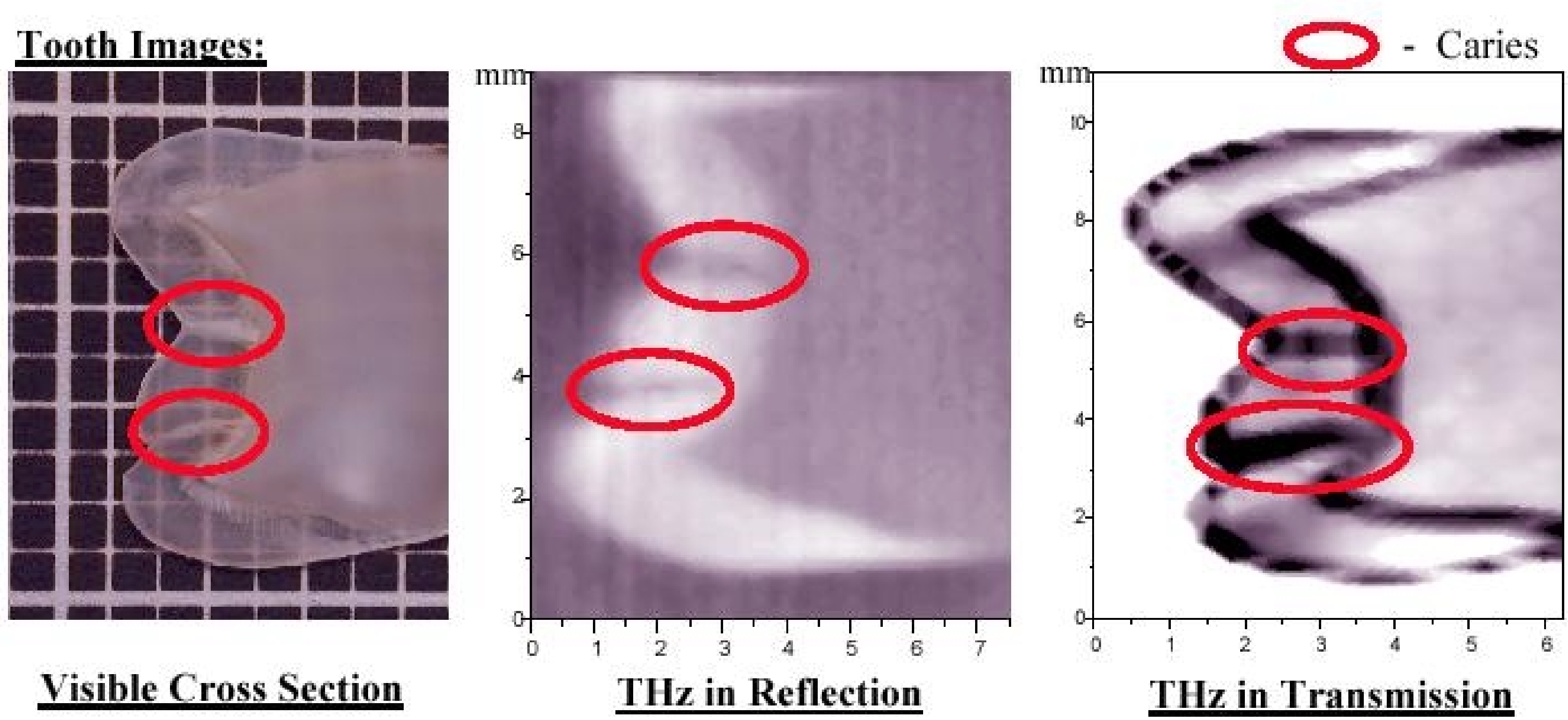


Optical image of a liver sample containing tumors



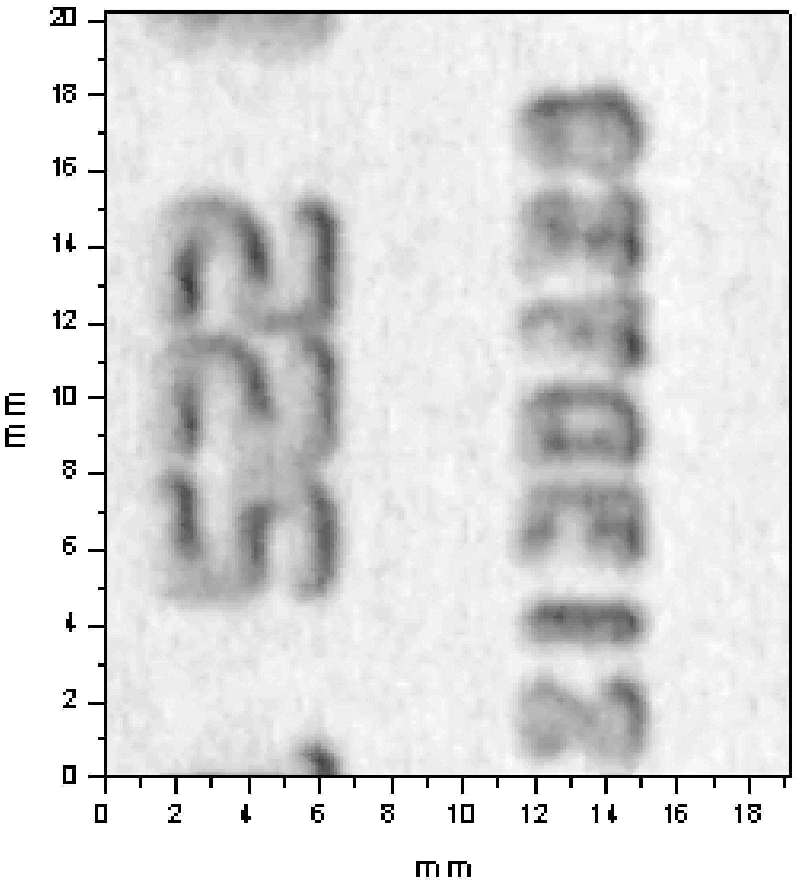
THz image: 0.2 - 0.5 THz

THz imaging of tooth decay



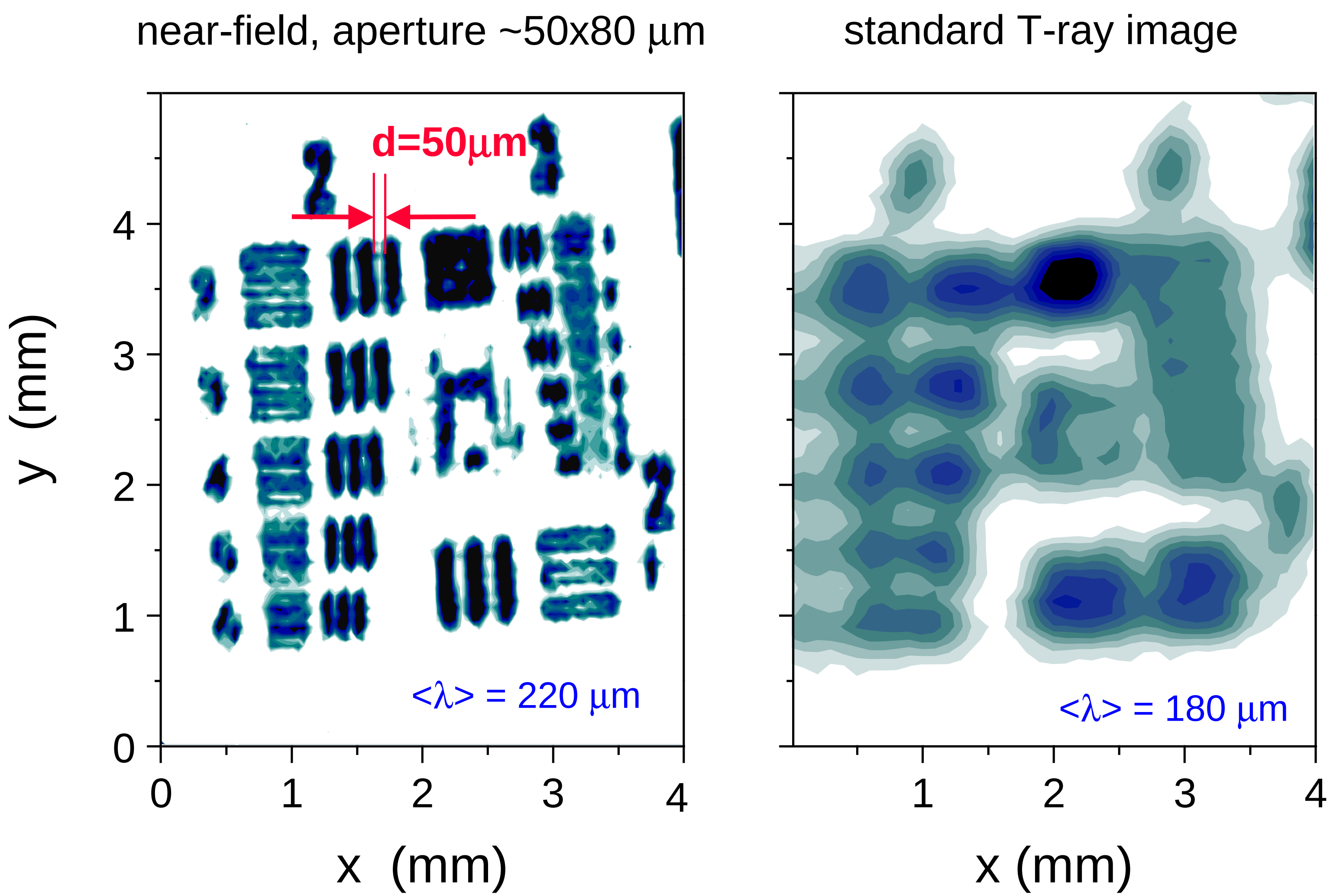
D. Arnone, Teraview Ltd.

Attainable resolution

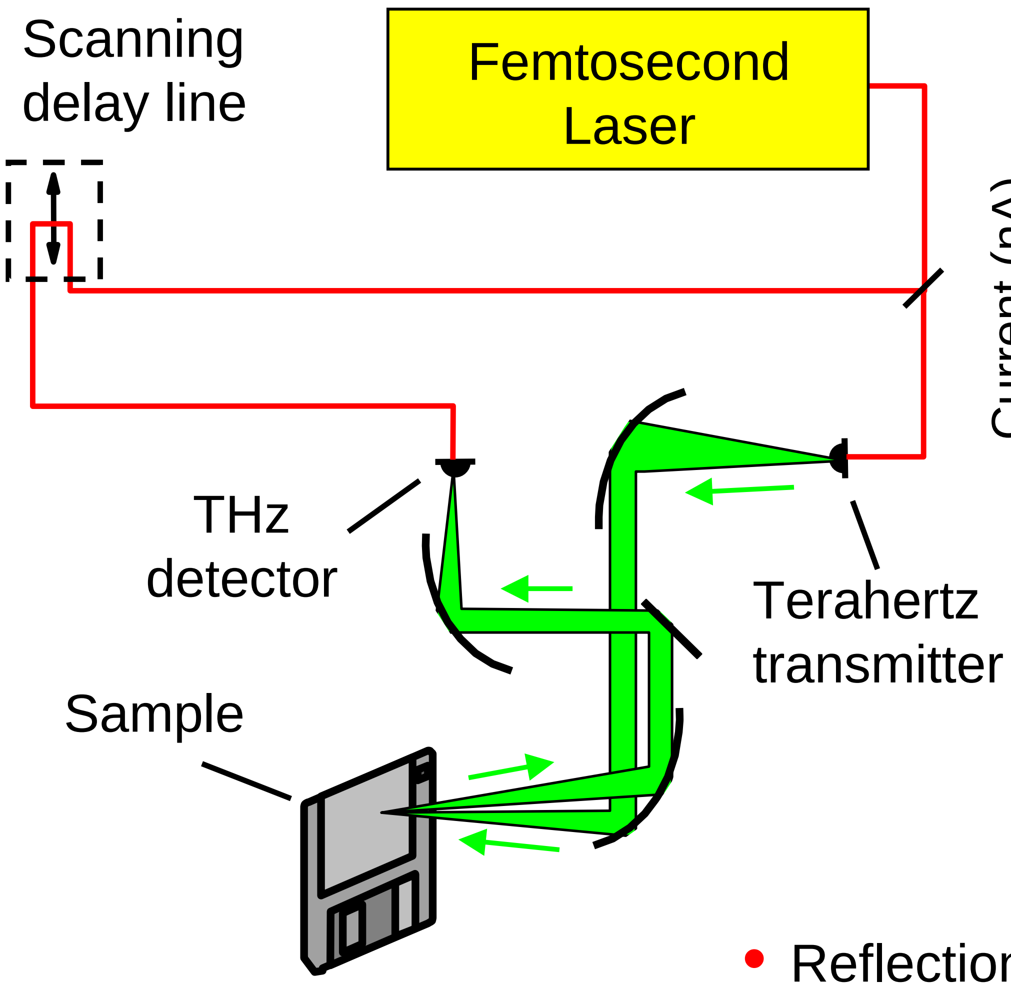


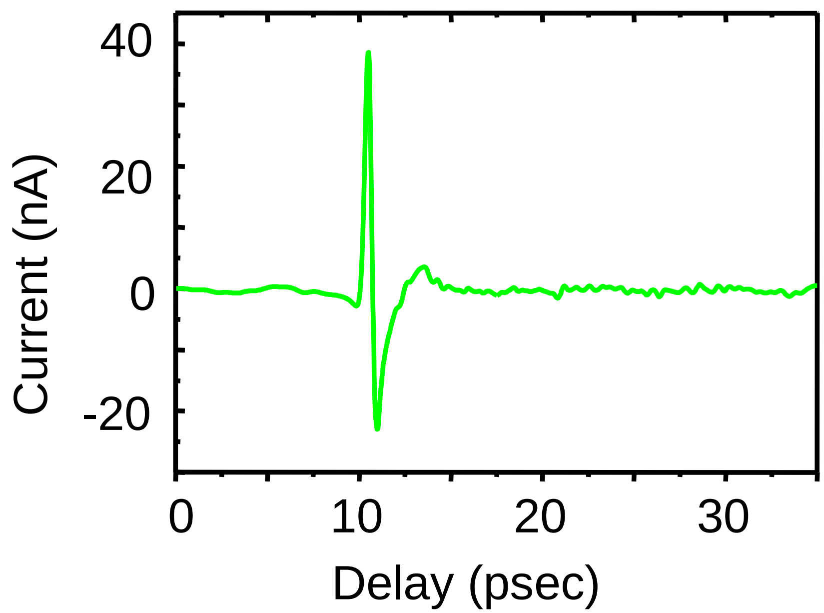
Dave Zimdars, Picometrix, Inc.

Near-field imaging



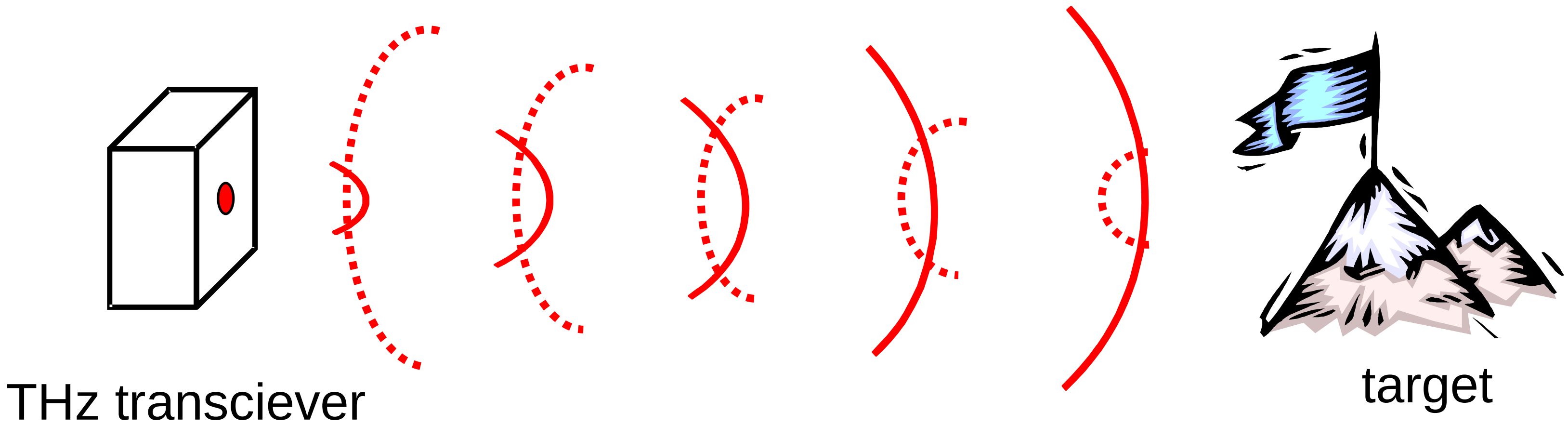
THz imaging in a reflection geometry

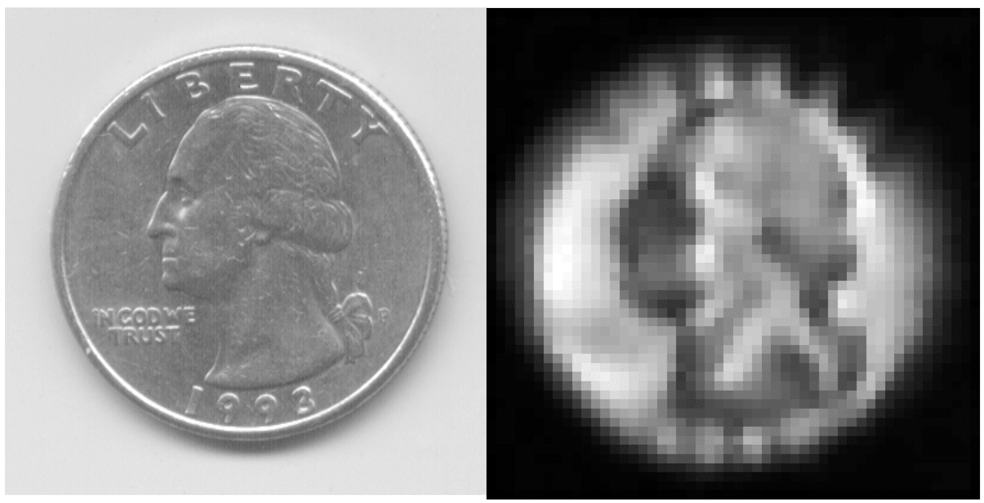




- Reflection at nearly normal incidence
- Time-of-flight imaging for 3D information

Stand-off imaging and sensing

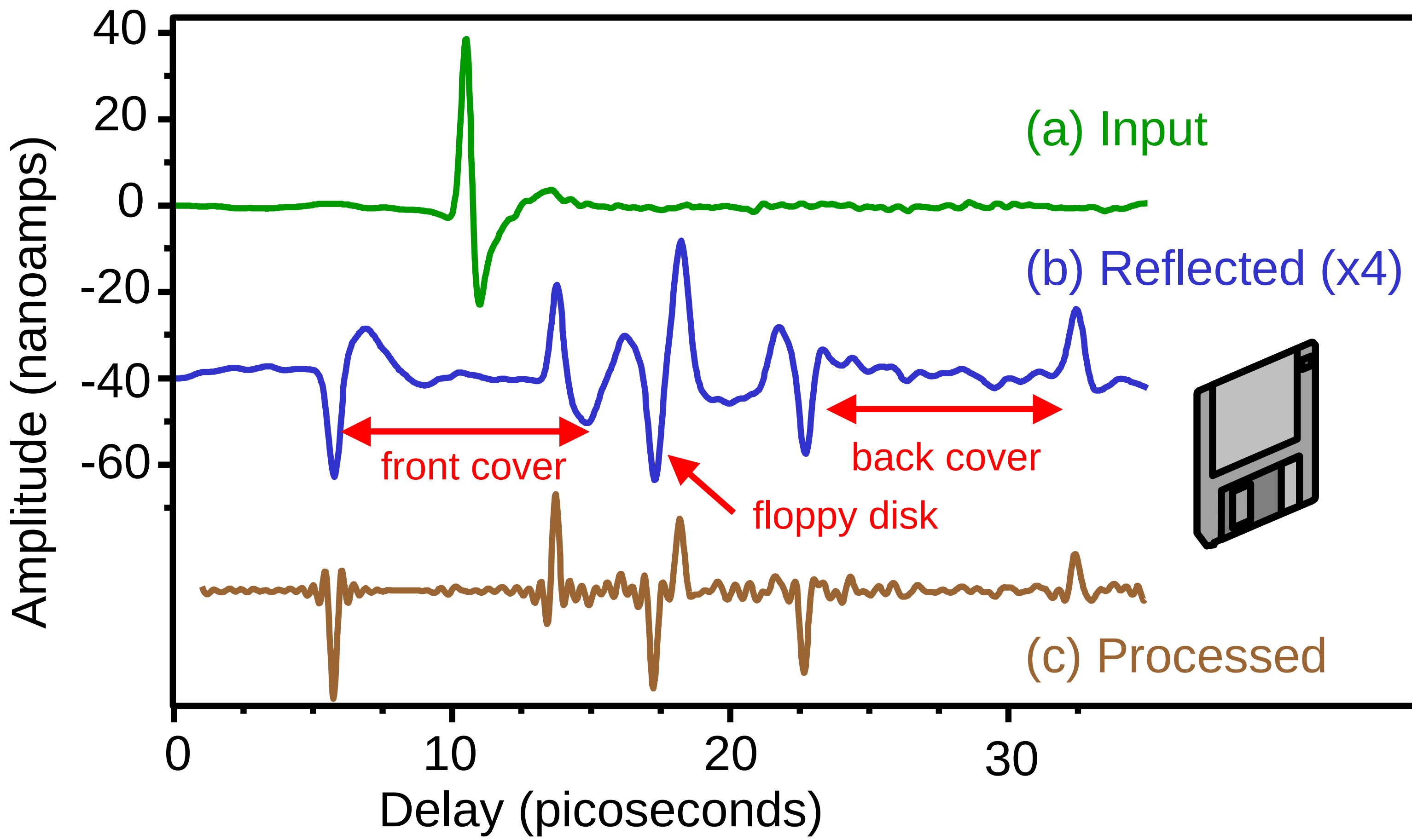




Distance: 15 meters

X.-C. Zhang, RPI

THz time-of-flight imaging

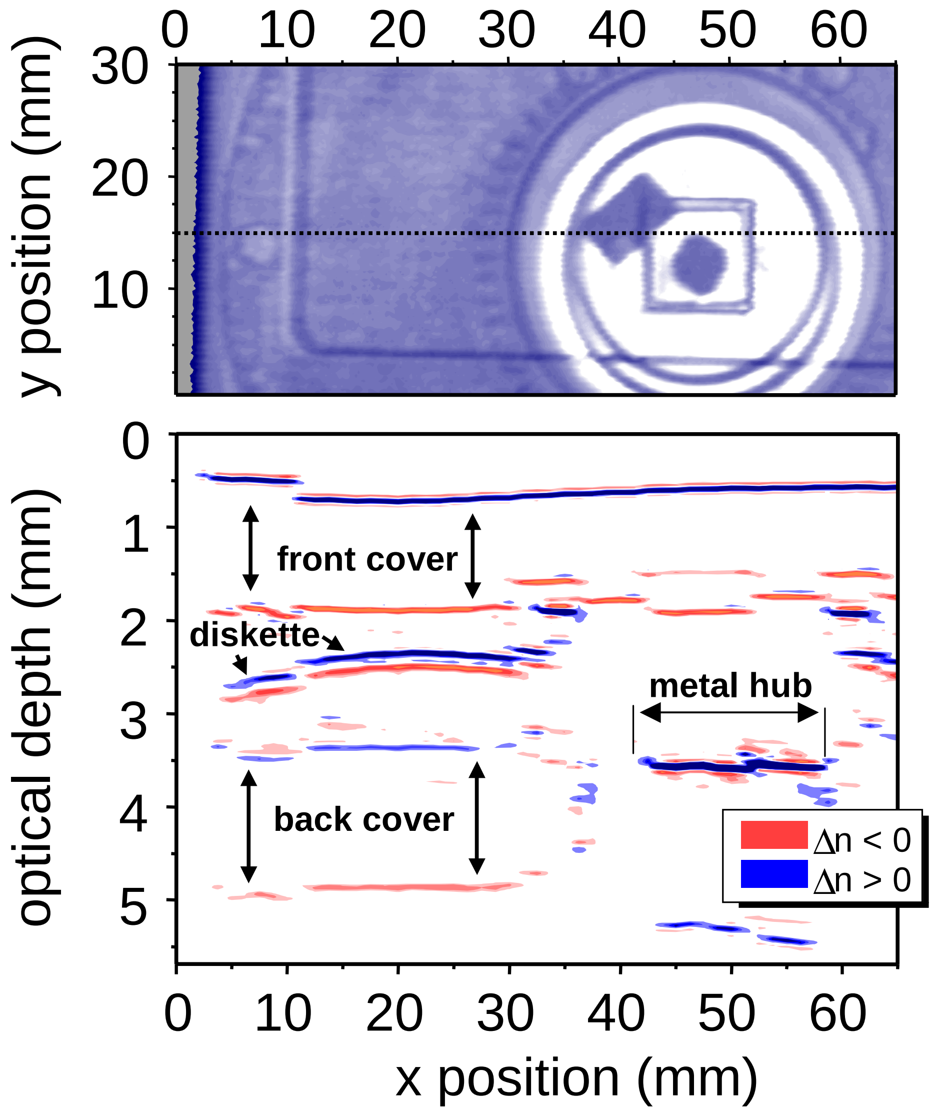


- Internal dielectric interfaces can be distinguished
- Depth resolution ~ $1/\Delta\omega$ (approx. 100 μm)

THz images of a 3.5" floppy disk

"Normal" THz image
(total reflected energy)

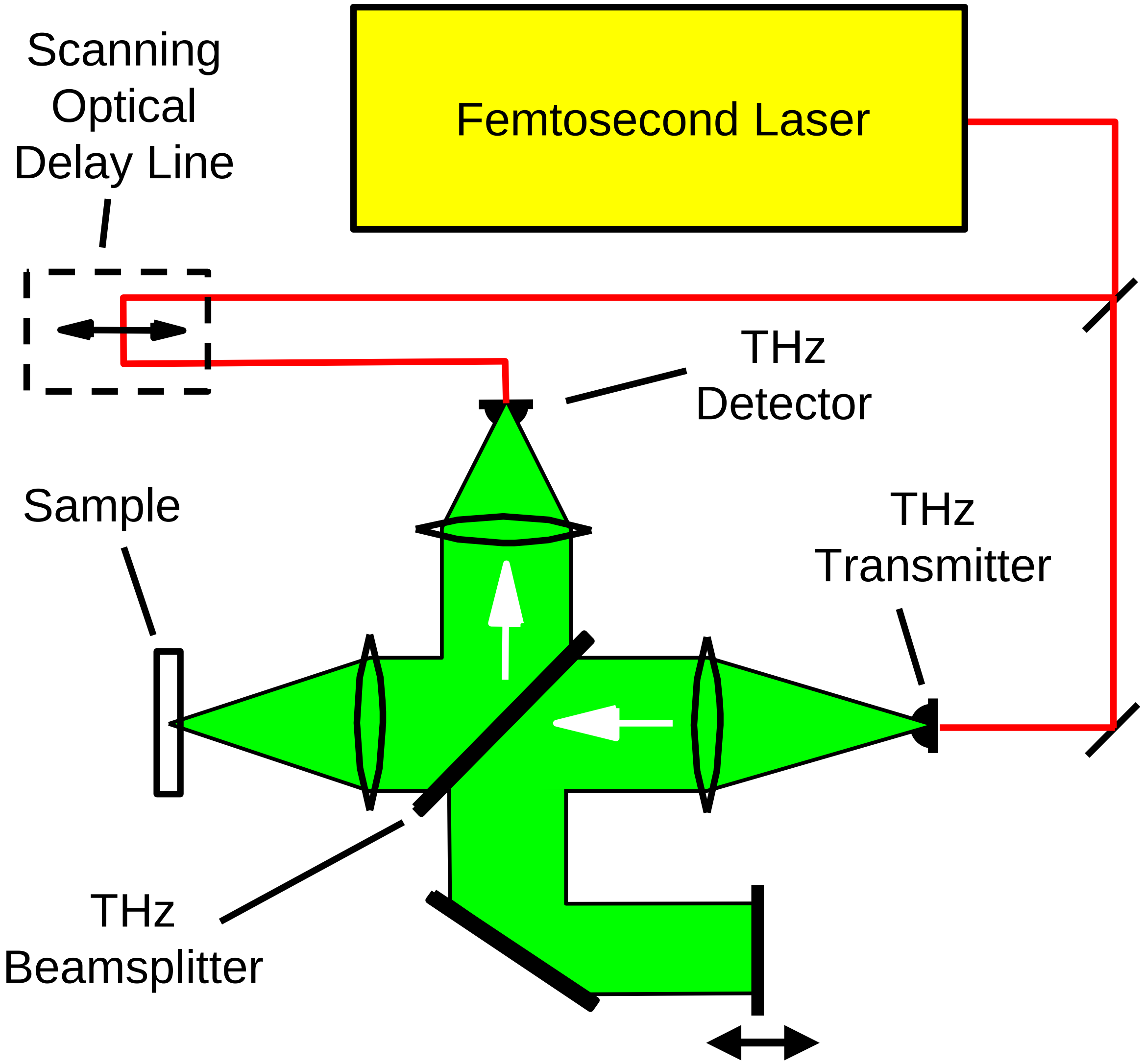
Time-of-flight
THz image



Imaging issues:
- Depth resolution
- Lateral resolution

D. Mittleman, *et al.*, *Opt. Lett.*, **22**, 904 (1997).

Improving the depth resolution



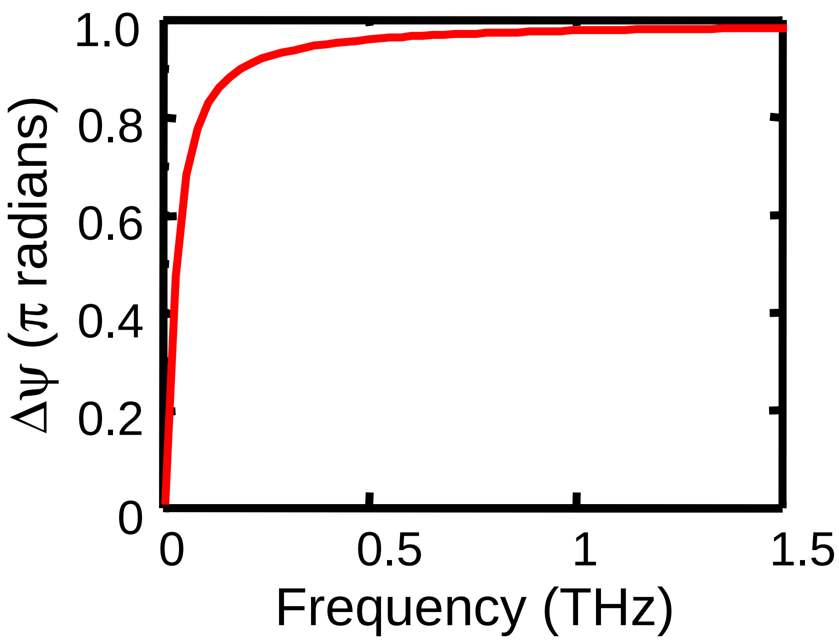
Gouy phase shift

- Phase shift acquired by a focusing optical beam
- Approximately equal to π

$$\Delta\psi = \pi - 2 \bullet \tan^{-1}\left[\frac{2 \bullet f \bullet c}{\pi \bullet w_0^{2}}\right]$$

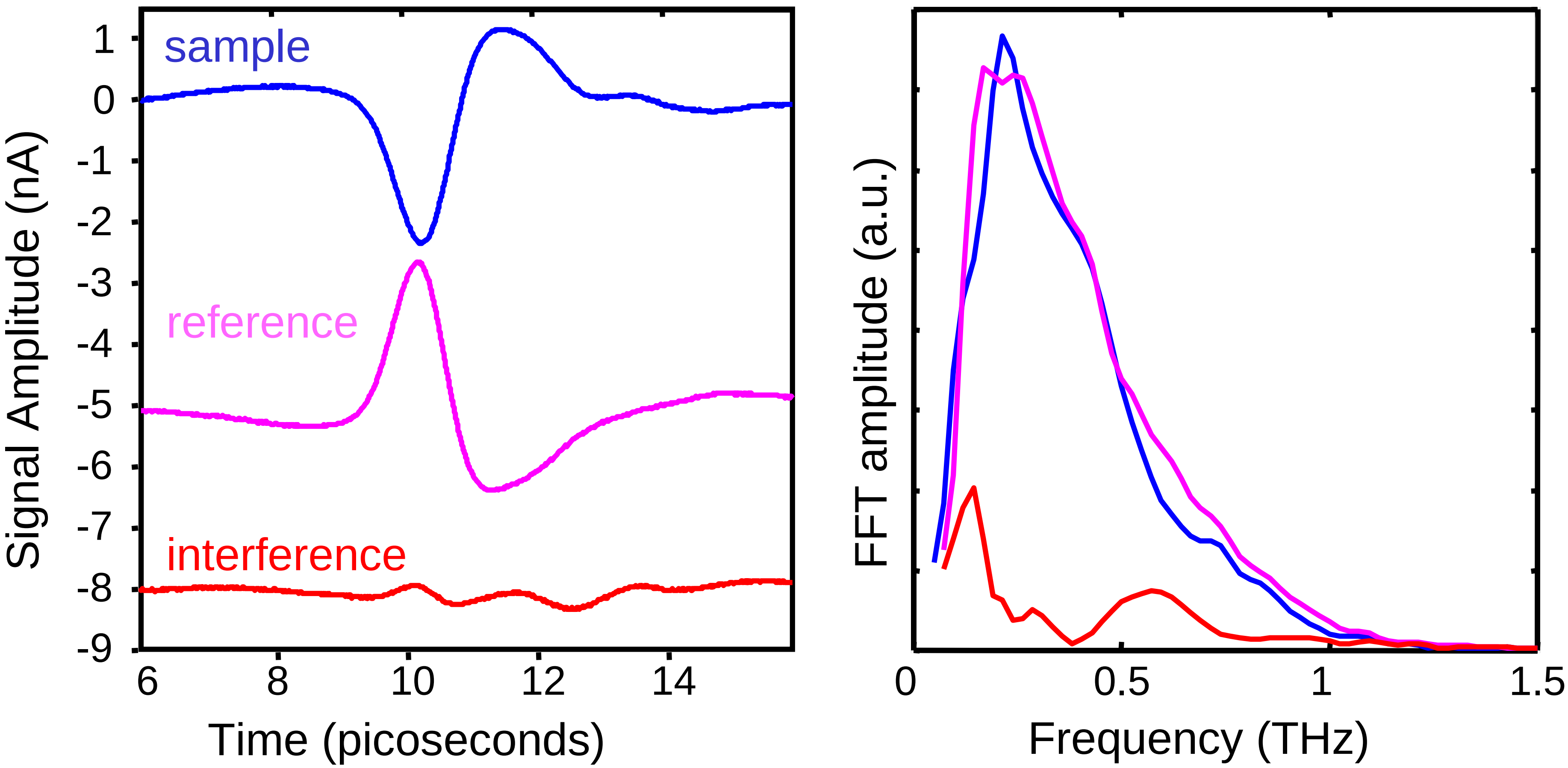
f = focal length ~ 13 cm

w_0 = beam waist ~ 3 cm



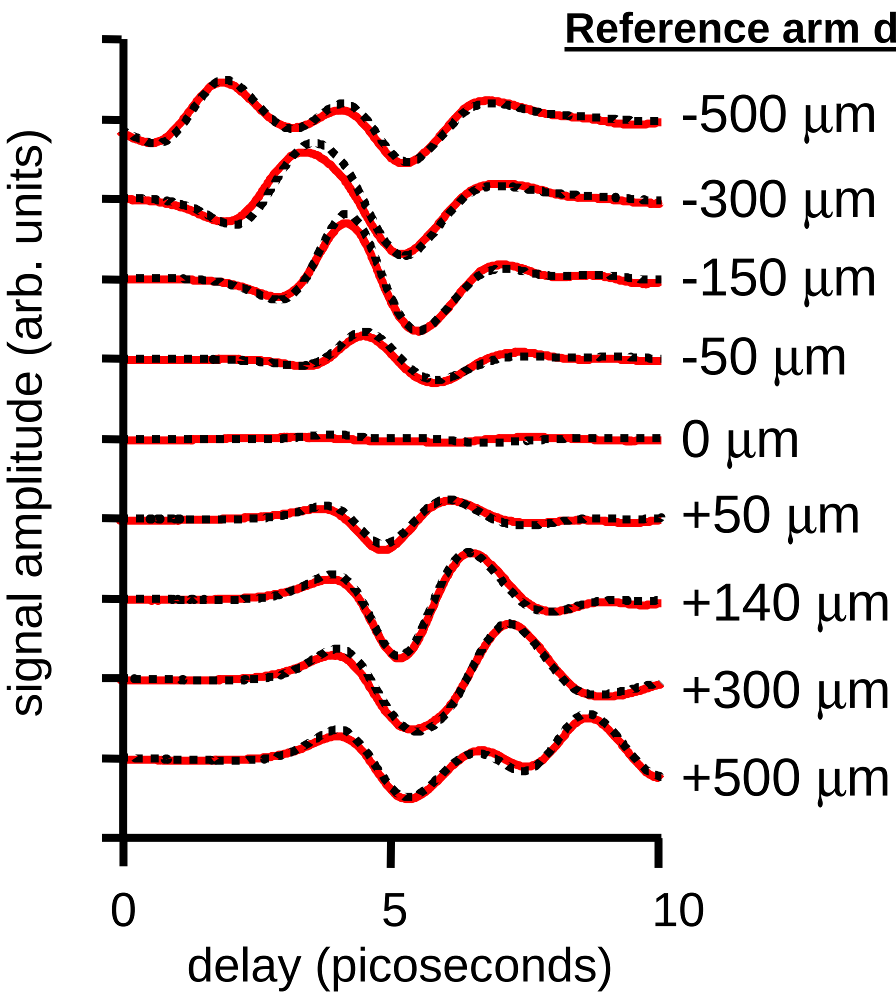
A.B. Ruffin, *et. al.*, Phys. Rev. Lett., **83**(17), p3410-3413.

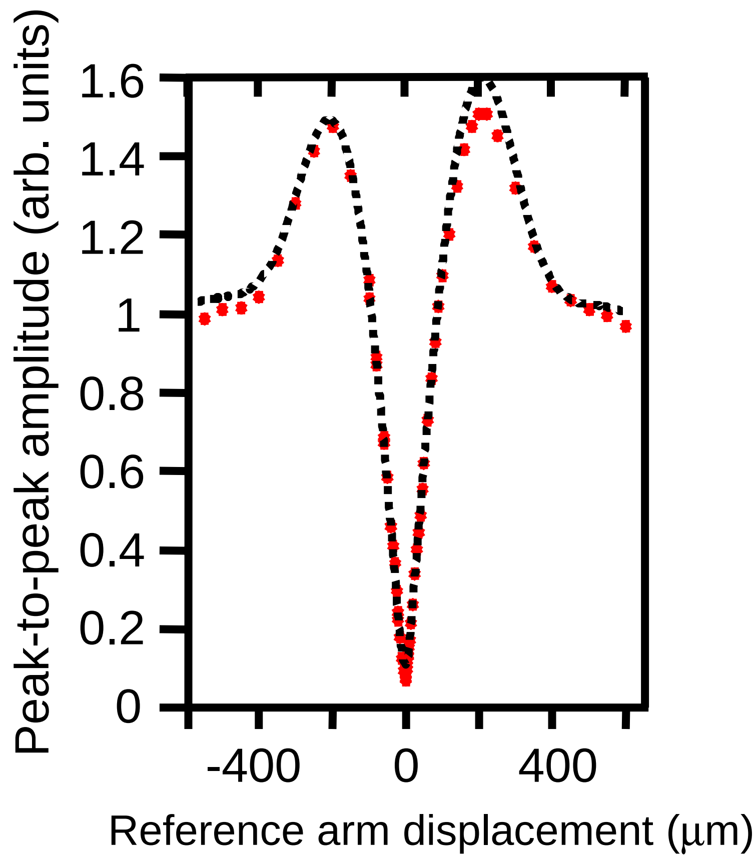
Destructive interference



→ Gouy phase shift leads to destructive interference between sample and reference

Sensitivity to position of the reference arm

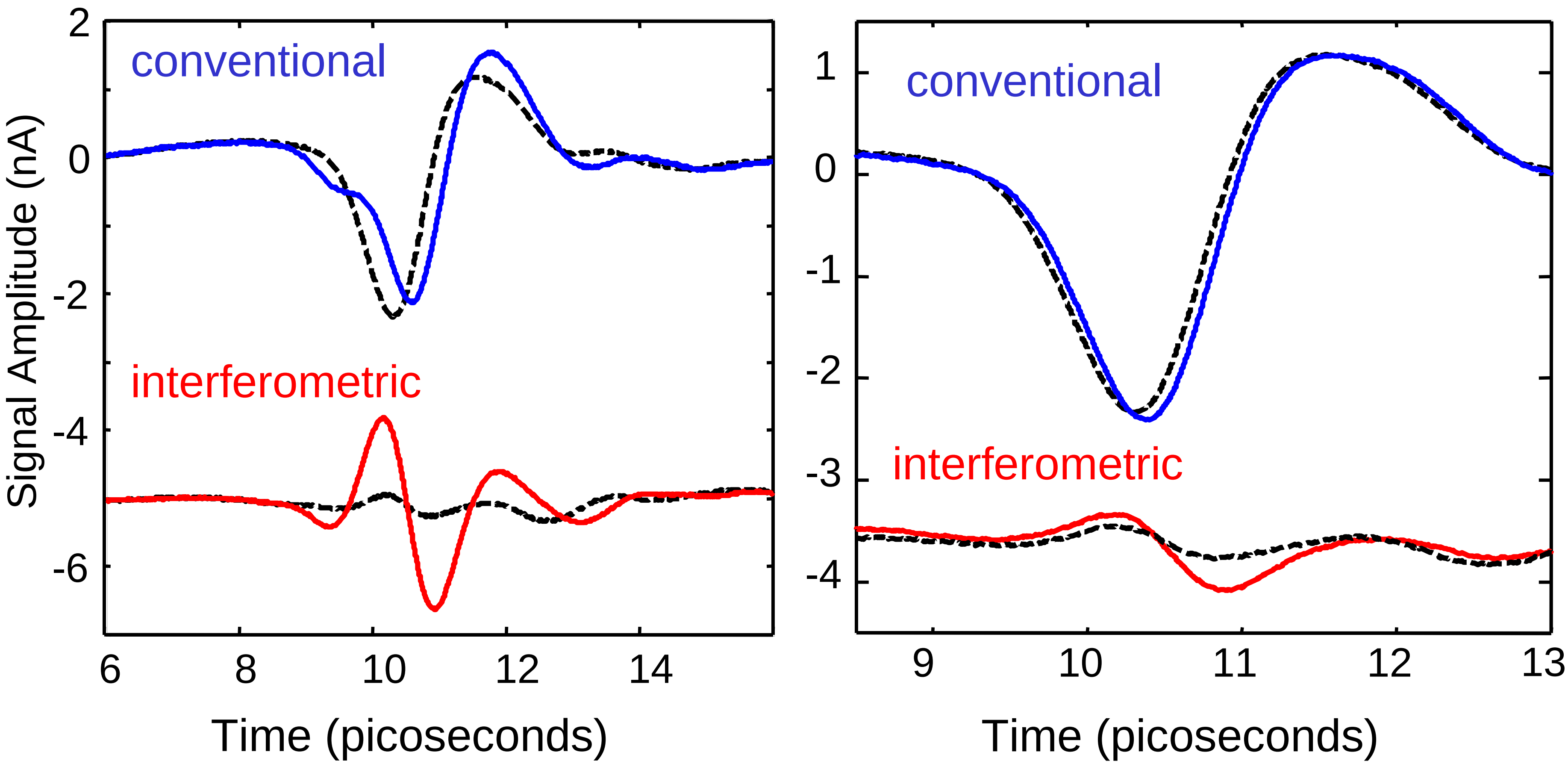




Johnson, *et al.*, *IEEE J. Sel. Top. Quant. Elec.*, **7**, 592 (2001)

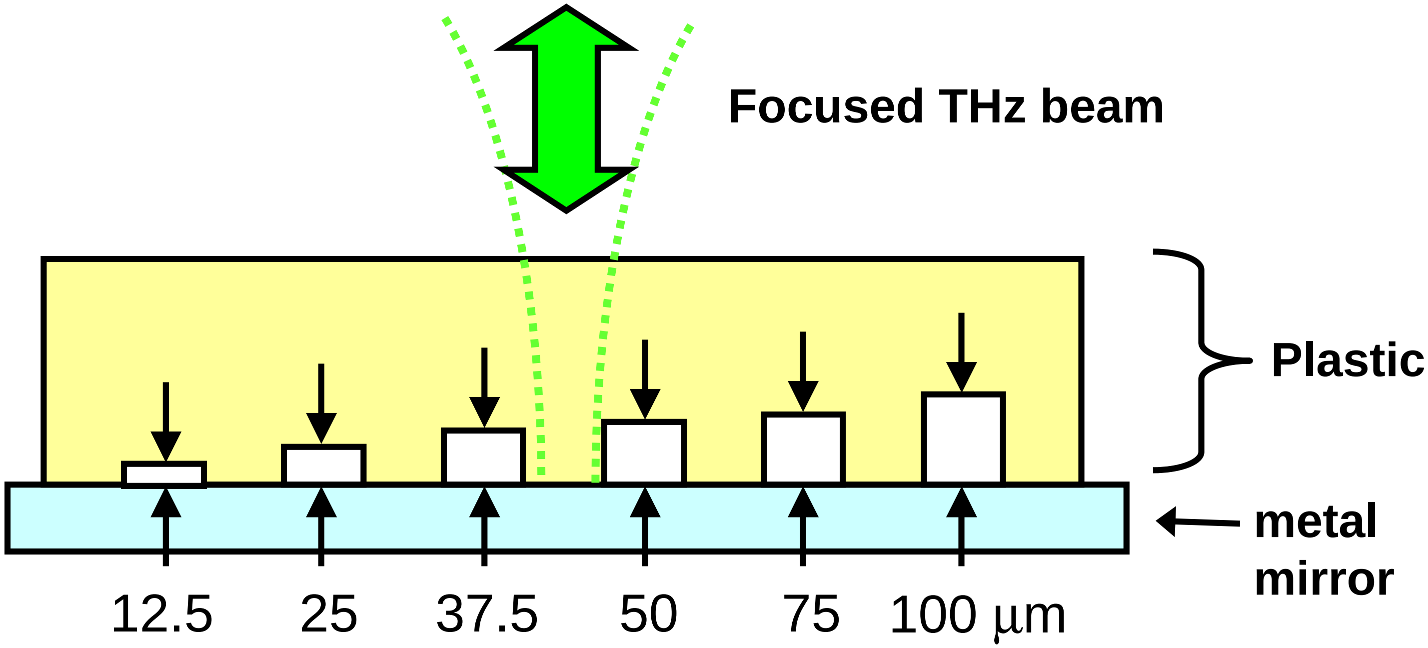
Interferometric effects

- **packing tape: ~75 μm thick**
- **saran wrap: ~25 μm thick**



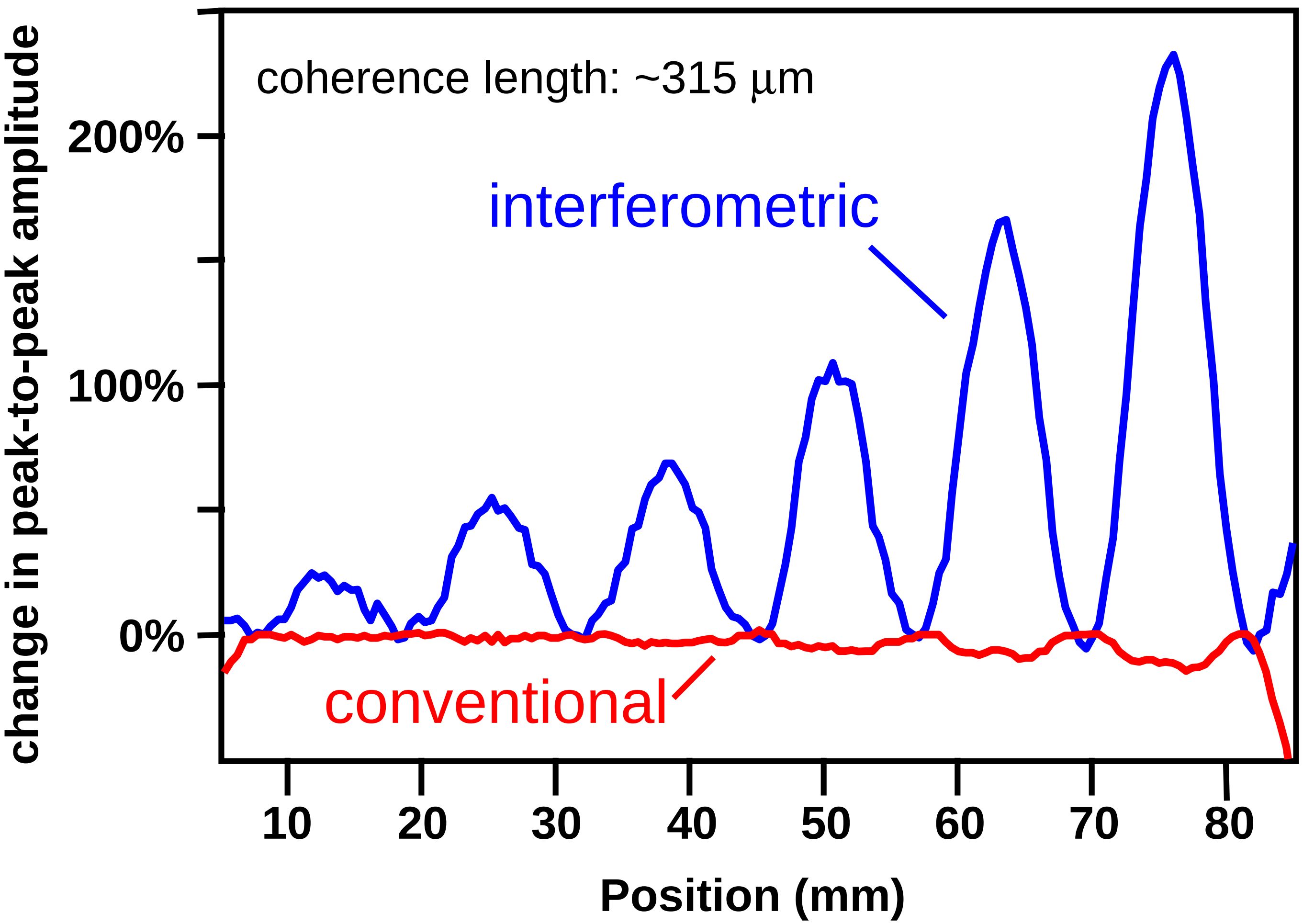
→ Subtle features more readily observable!

A test sample



- Air gaps of calibrated depths
- Line scan across the sample

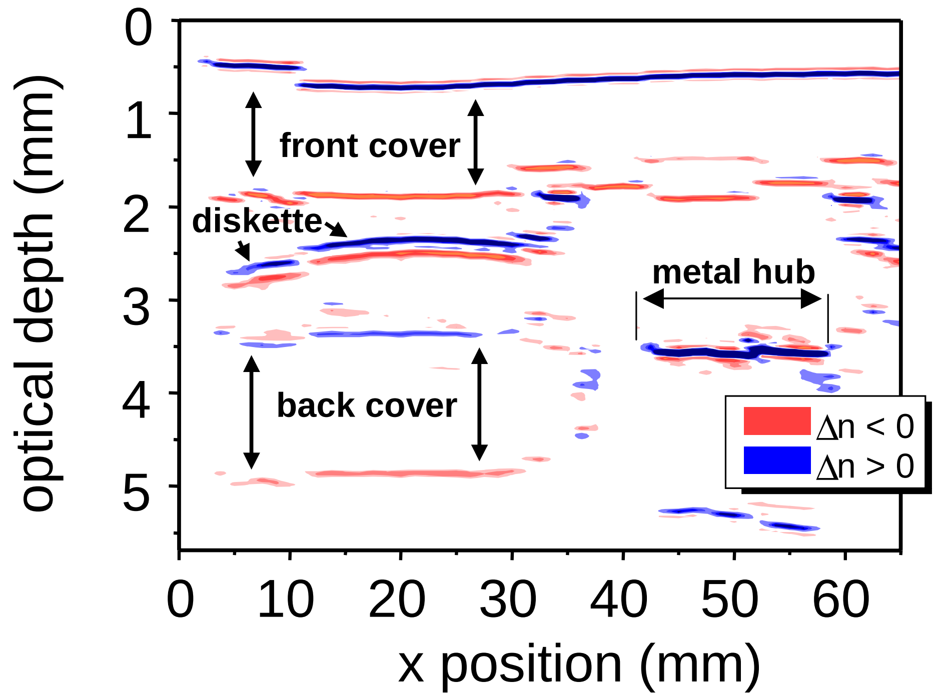
Enhanced sensitivity to small features



Johnson, *et al.*, *Appl. Phys. Lett.*, **78**, 835 (2001)

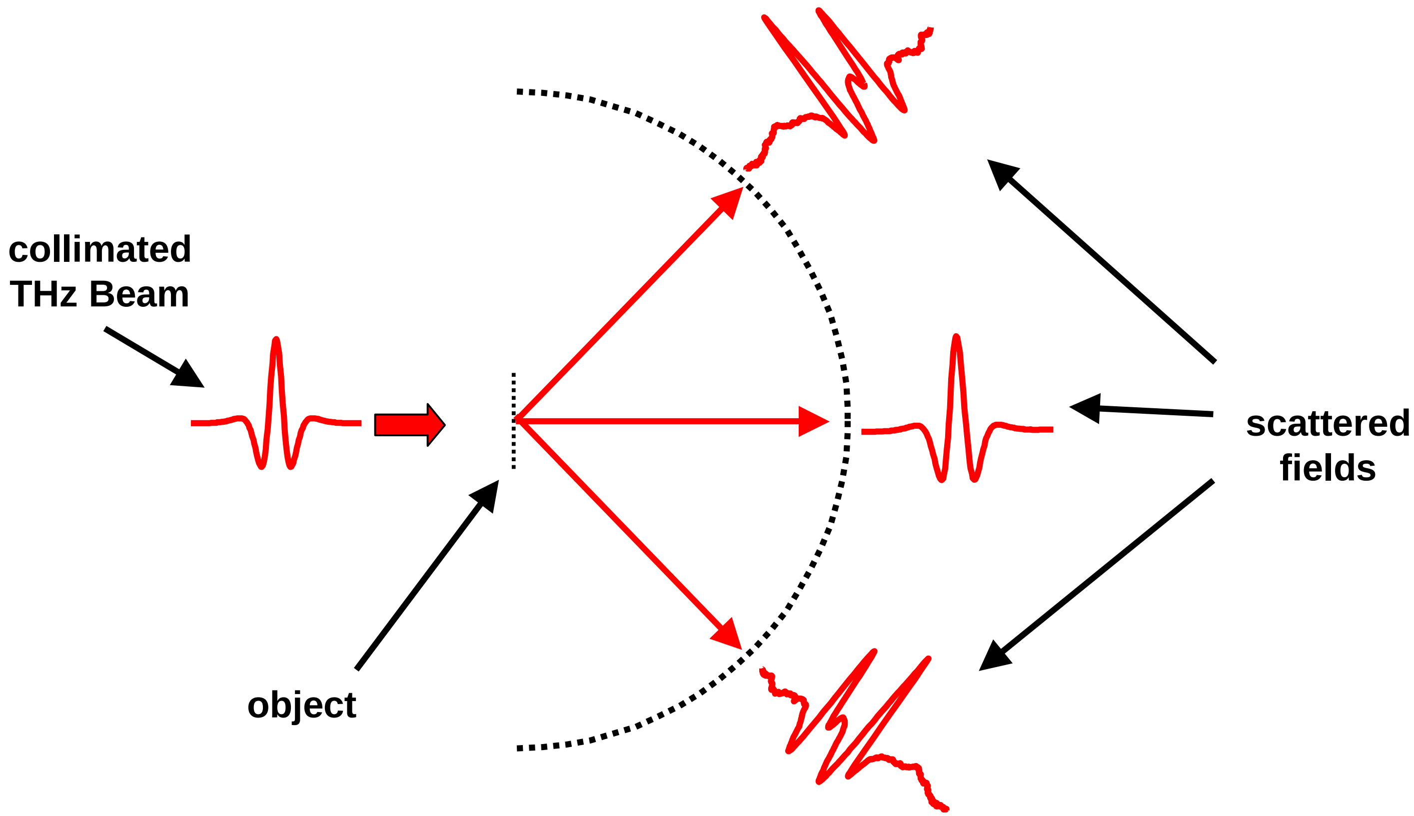
Towards tomography

Imaging issues:
✓Depth resolution
Lateral resolution



Tomographic imaging: multiple views of the target

THz holography



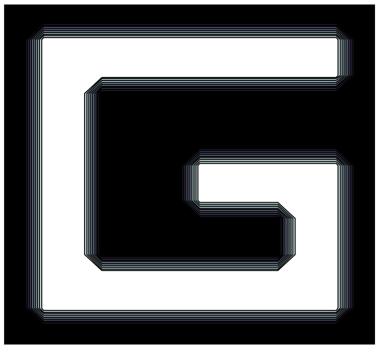
Backwards propagation (Huygens-Fresnel diffraction):

$$u(P_1,t) = -\frac{1}{4\pi c}\iint_{\Sigma}\frac{\left(1+\cos\left(\hat{n},\vec{r}_{01}\right)\right)}{r_{01}}\frac{\partial}{\partial t}u\left(P_0, t-\frac{r_{01}}{c}\right)ds$$

T. B. Norris, Univ. of Michigan

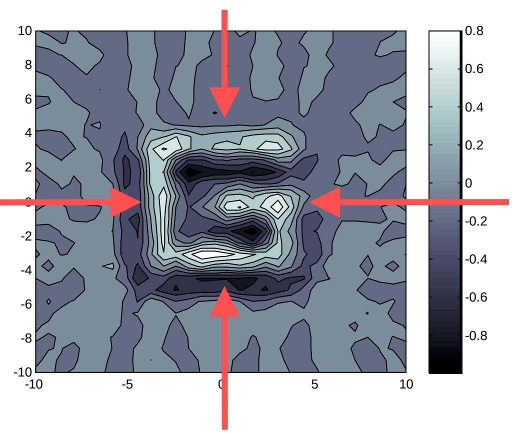
Two-dimensional planar target - reconstruction

simulation

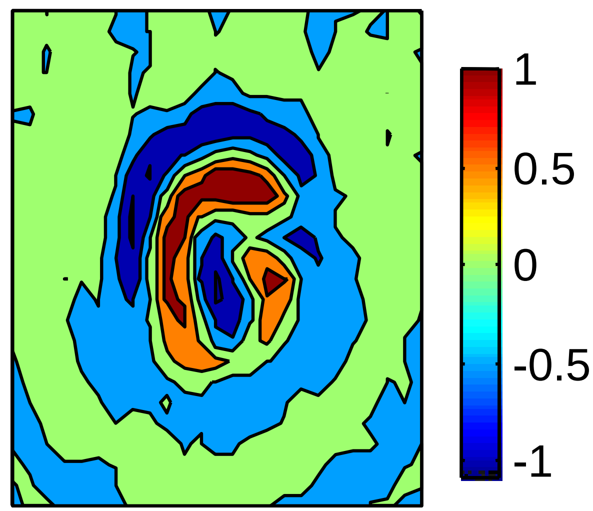


10 x 10 mm

10 x 10 mm

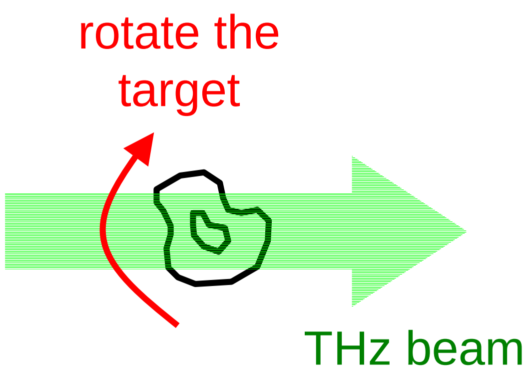


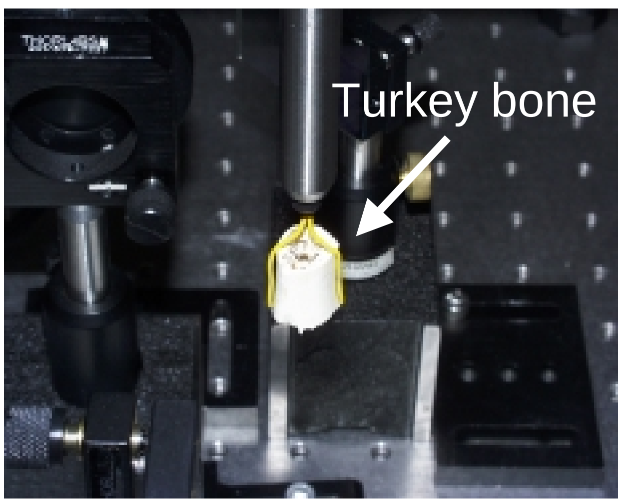
experimental results

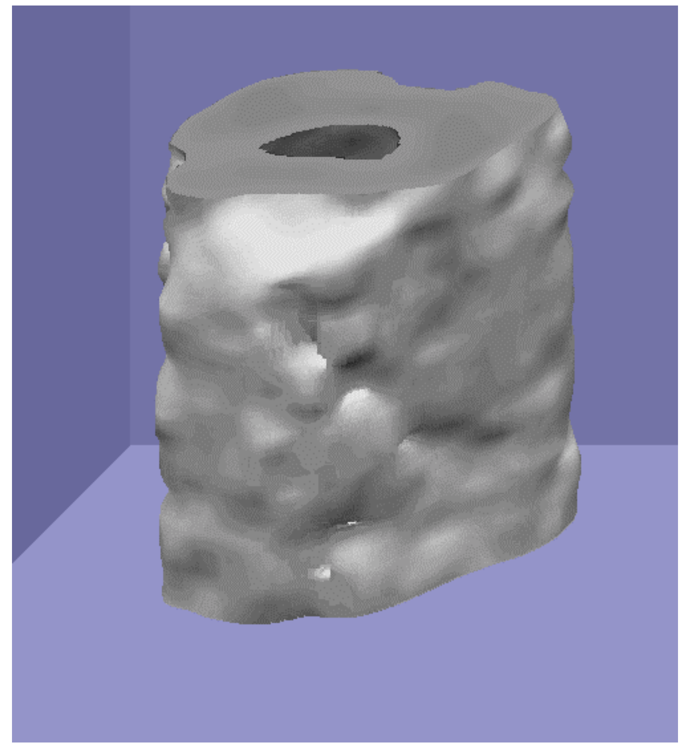


T. B. Norris, Univ. of Michigan

THz computed tomography (CT)

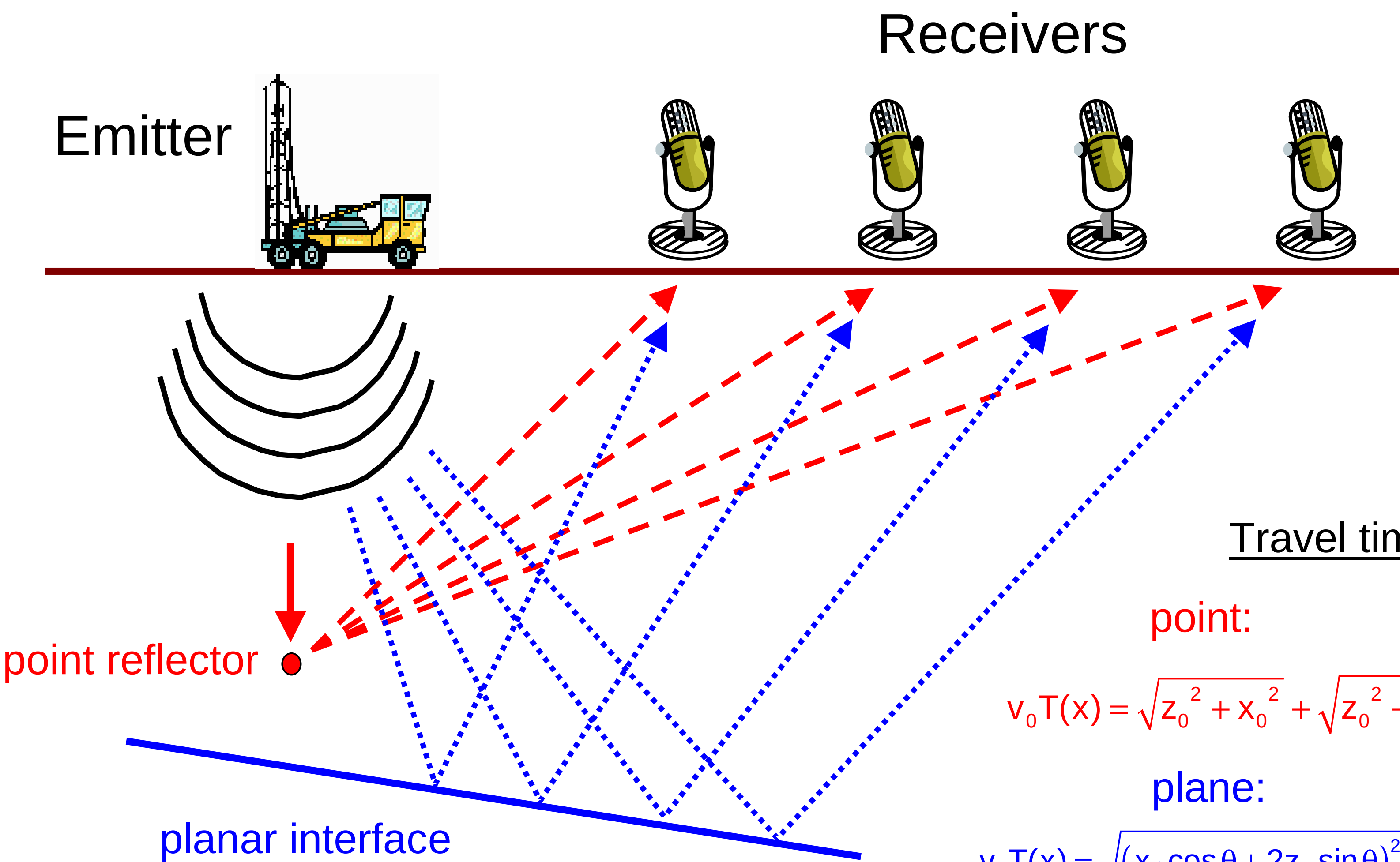






X.-C. Zhang, RPI

THz reflection (seismic) tomography



Travel times

point:

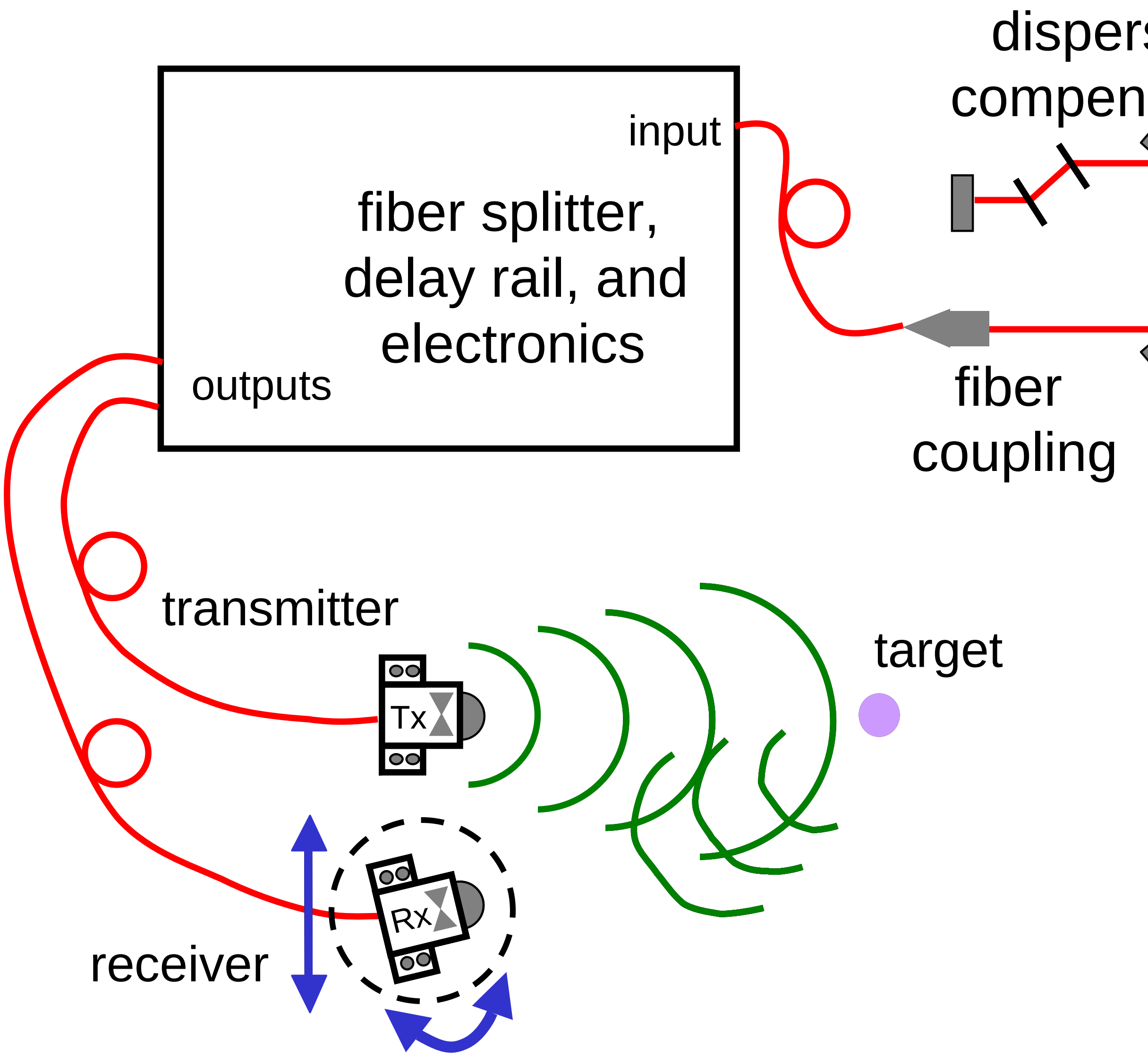
$$v_0T(x) = \sqrt{z_0^2 + x_0^2} + \sqrt{z_0^2 + (x - x_0)^2}$$

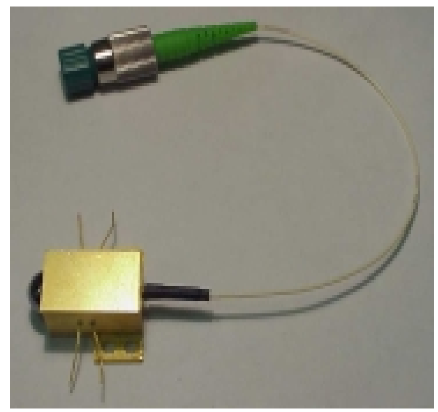
plane:

$$v_0T(x) = \sqrt{(x \cdot \cos\theta + 2z_0 \sin\theta)^2 + (x \cdot \sin\theta)^2}$$

Reflectors generate hyperbolae

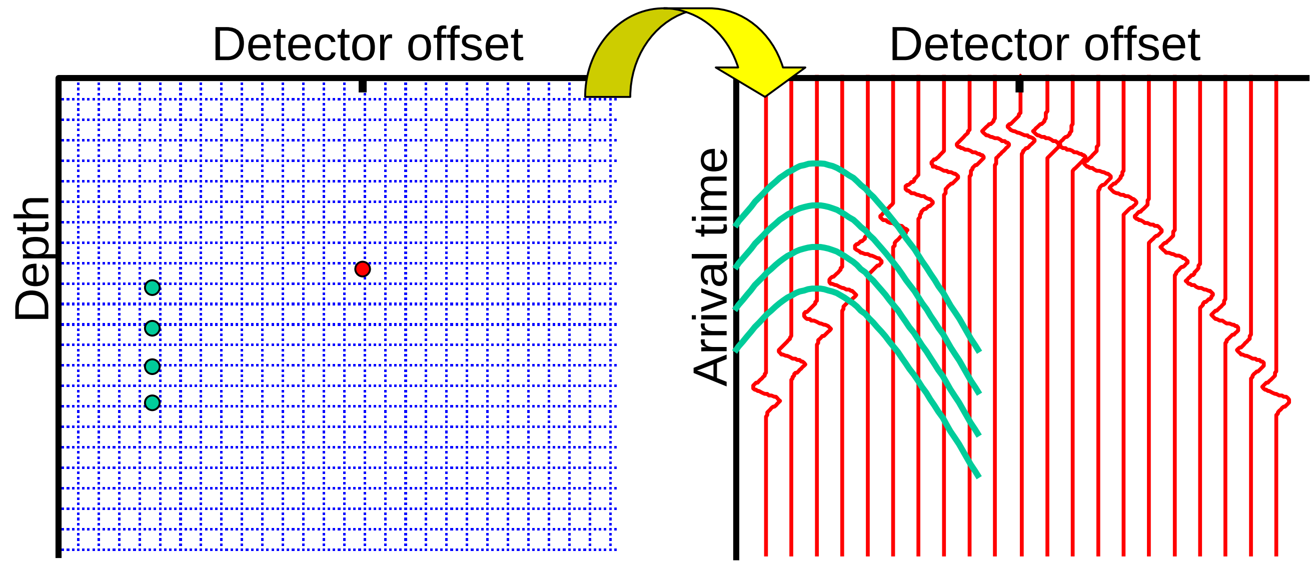
THz testbed for seismic tomography

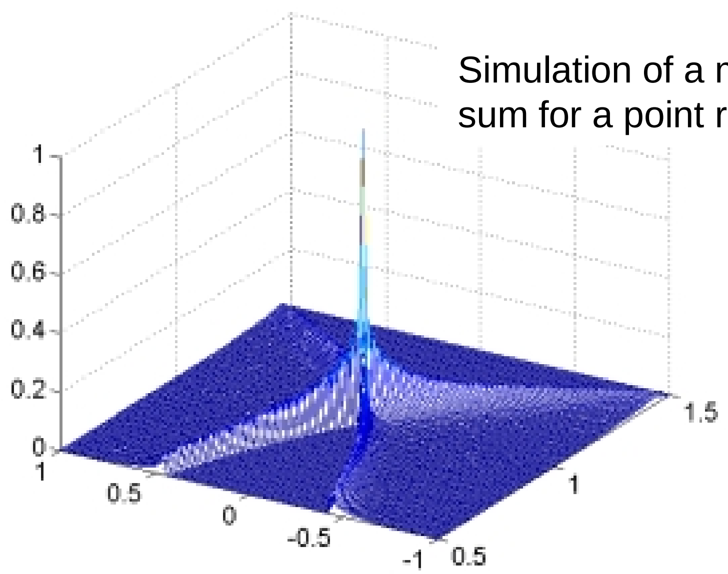




THz module

Inversion by Kirchhoff migration



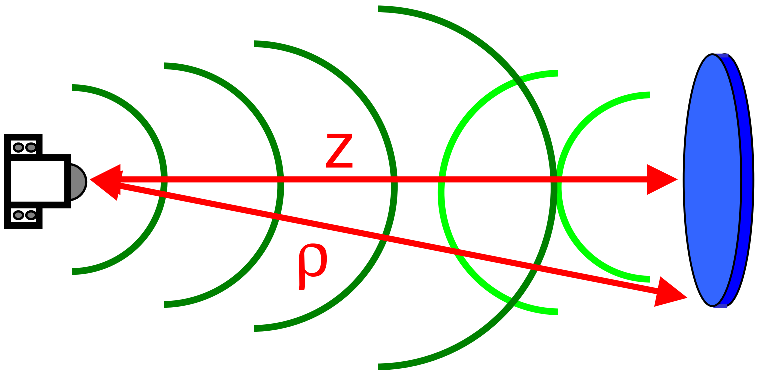


Simulation of a migration sum for a point reflector

- Emphasis on time of flight
- Extremely simple algorithm
- Image artifacts are inevitable

What is the lateral resolution in a tomographic image?

Resolution: the Fresnel zone



Detection limit:
returned signal > noise

Resolution limit:
returned signal exhibits destructive interference between center and edge of target

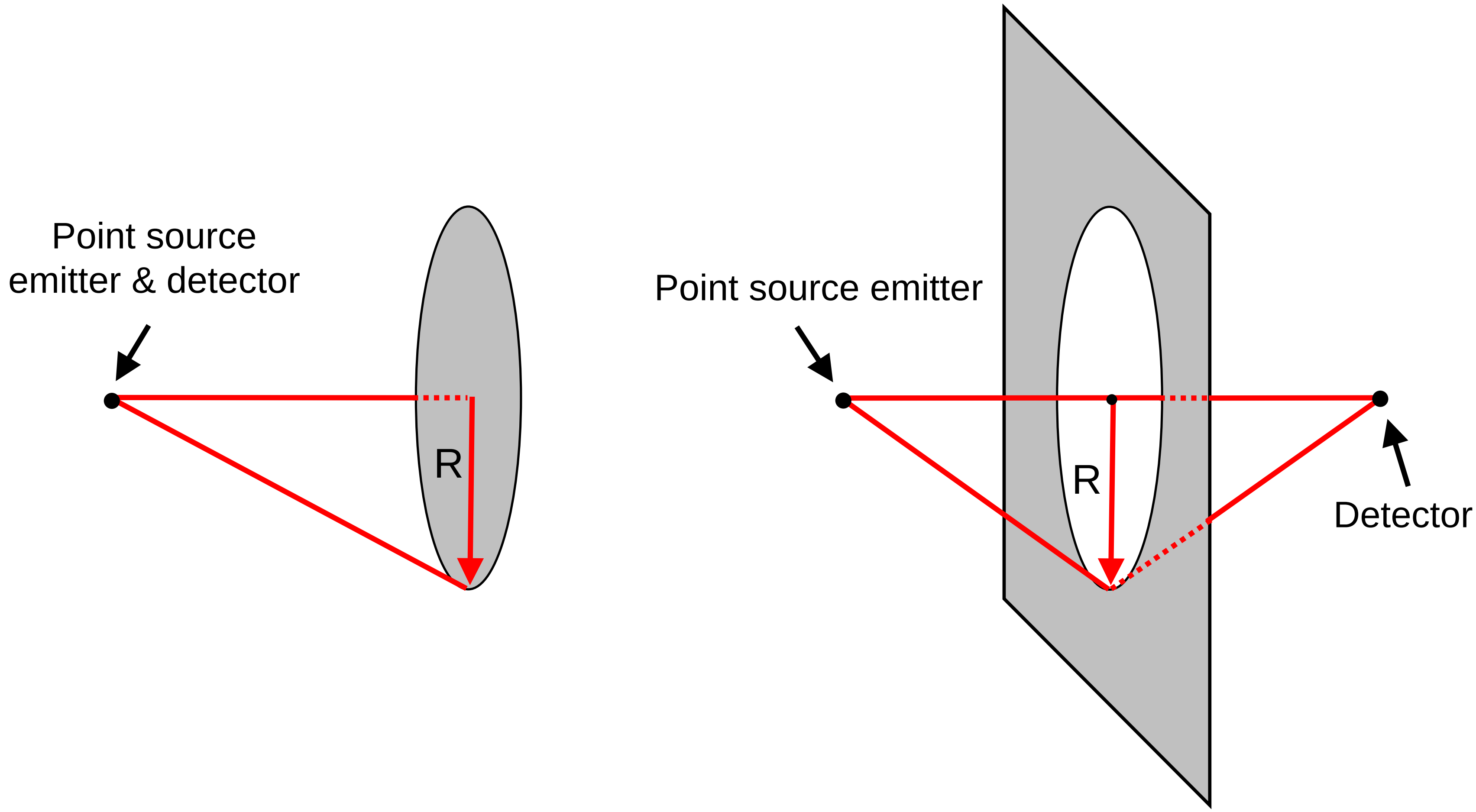
Resolution limit: $2(z-\rho) \geq \frac{\lambda}{2}$

Minimum target radius = size of first Fresnel zone

$$R_F \approx \sqrt{\frac{z\lambda}{2}}$$

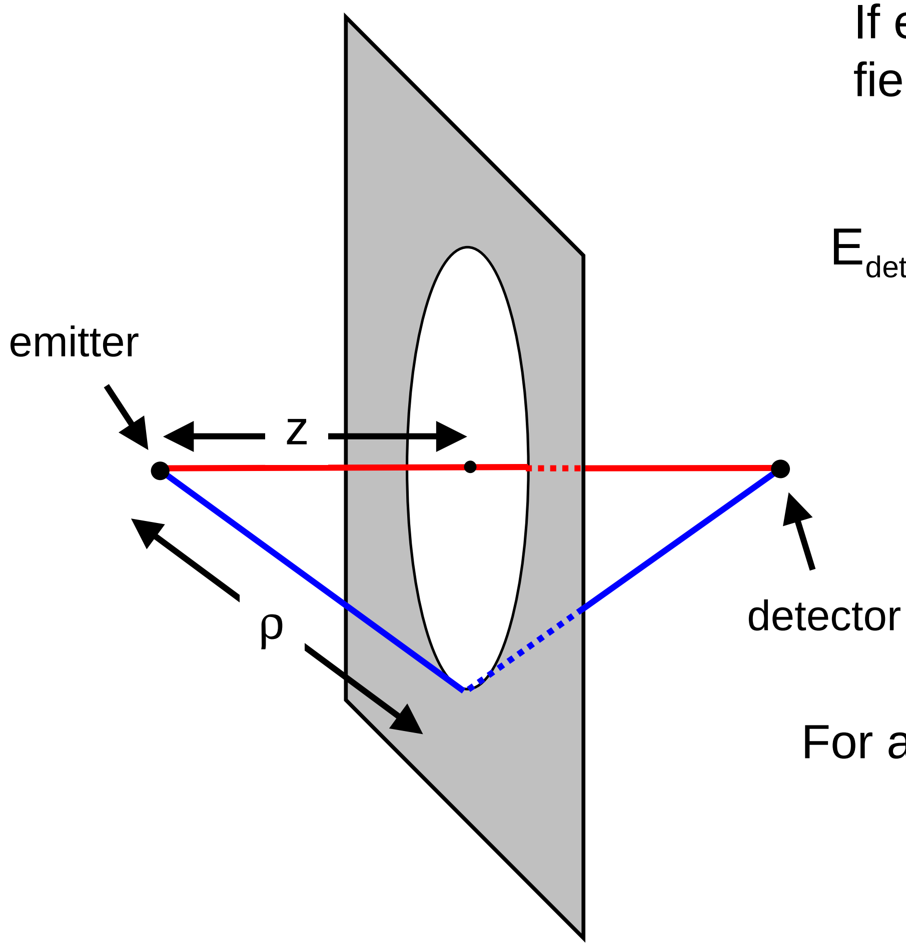
But what if the radiation is broadband?

Transmission vs. reflection



These two situations are equivalent by Babinet's Principle

Detected field



If emitted field is E(t), then the field at the detector is:

$$E_{det}(t) \propto \frac{E(t-2z/c)}{2z} - \left(\frac{z}{\rho}\right)\cdot\frac{E(t-2\rho/c)}{2\rho}$$

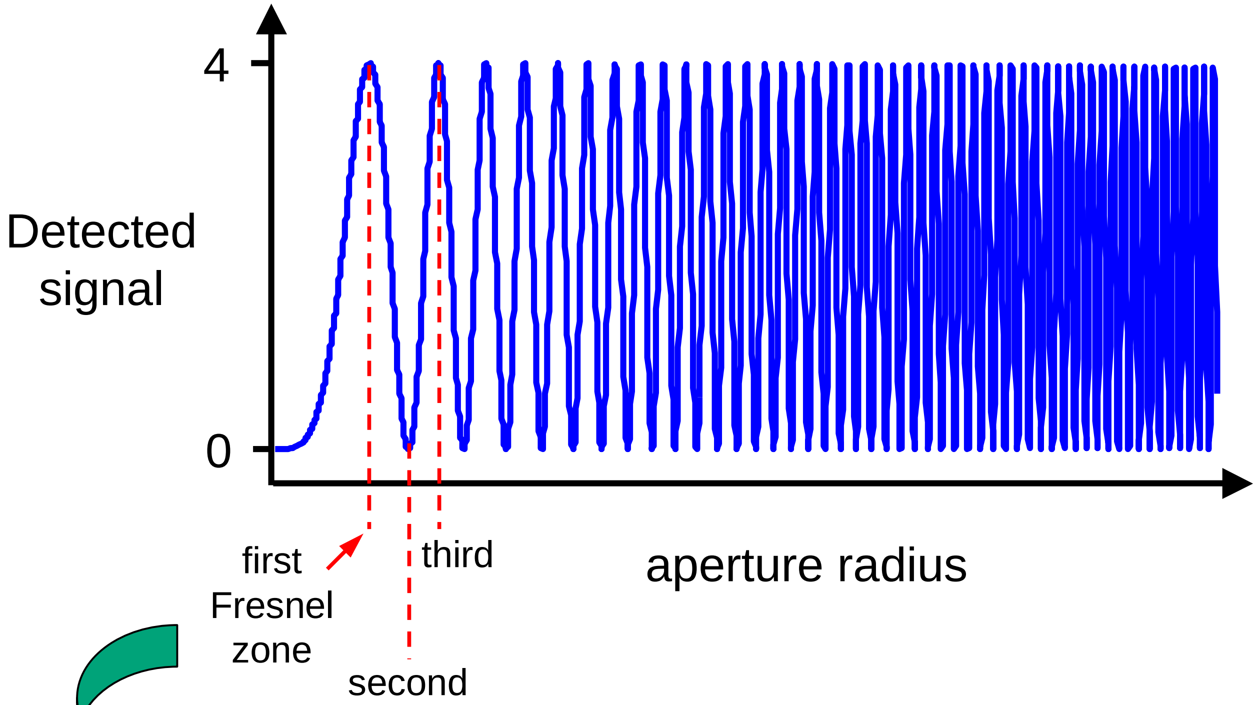
unperturbed wave front

diffraction from aperture edge

For a cw source, $E(t) \sim e^{ikr}/r$, signal is:

$$S_{det} \propto 1+\frac{z^4}{\rho^4}-\frac{2z^2}{\rho^2}\cos\left[2k(\rho-z)\right]$$

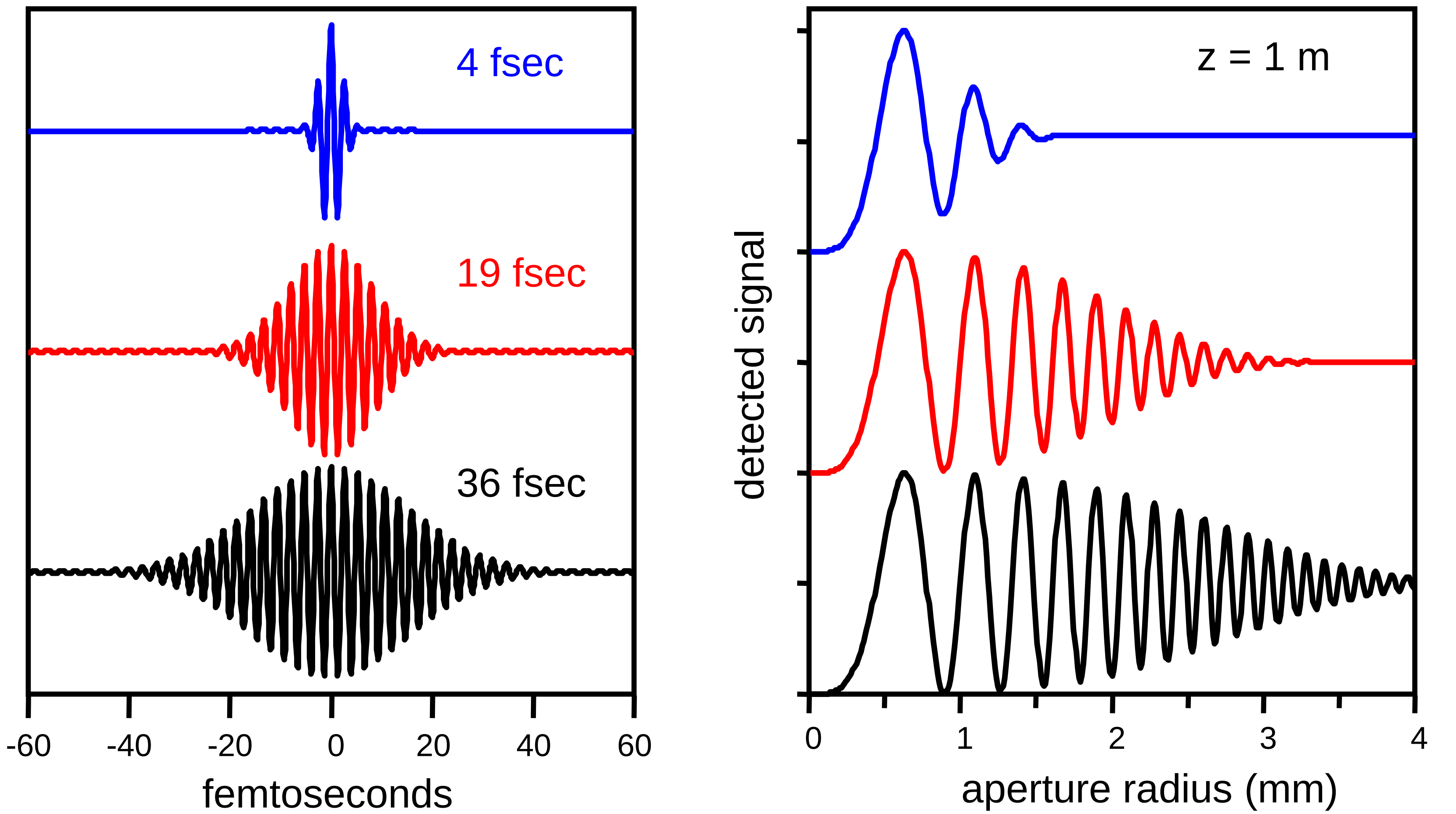
Result for cw illumination



first radius at which detected energy is maximum

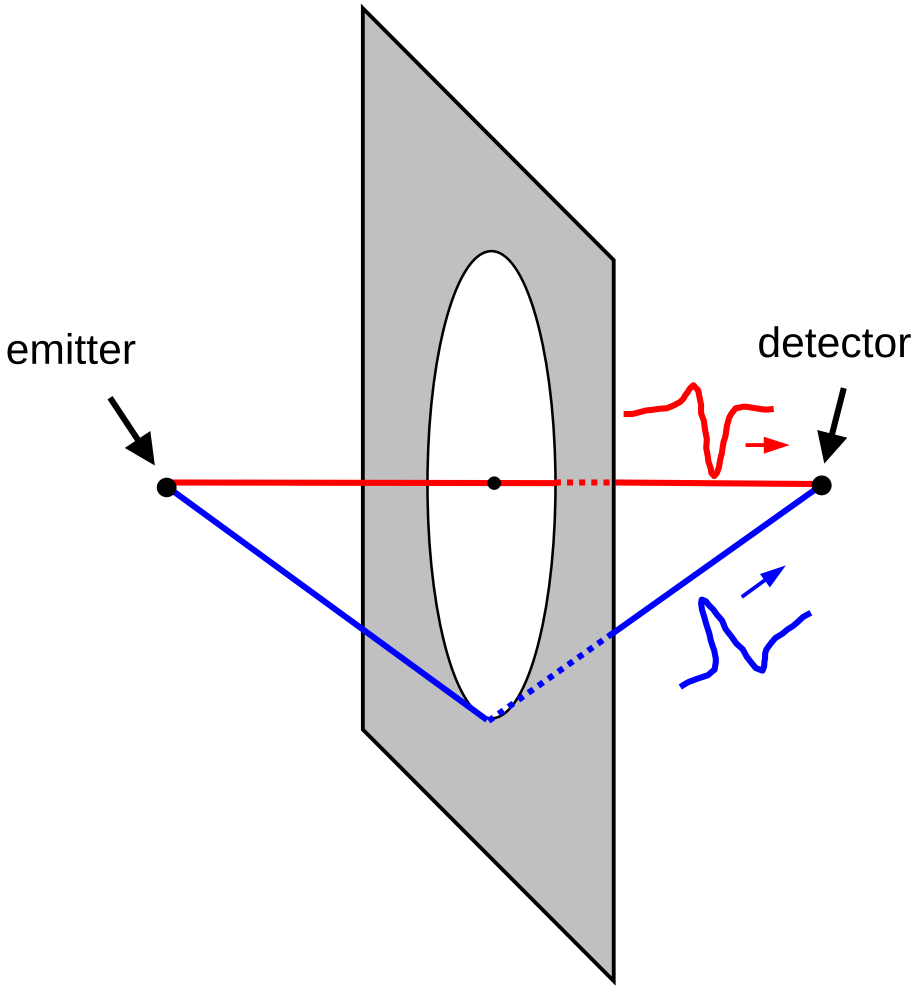
$$R_F = \frac{\lambda}{4}\sqrt{1+\frac{8z}{\lambda}} \approx \sqrt{\frac{z\lambda}{2}} \quad \text{for} \quad z >> \lambda$$

Result for pulsed illumination

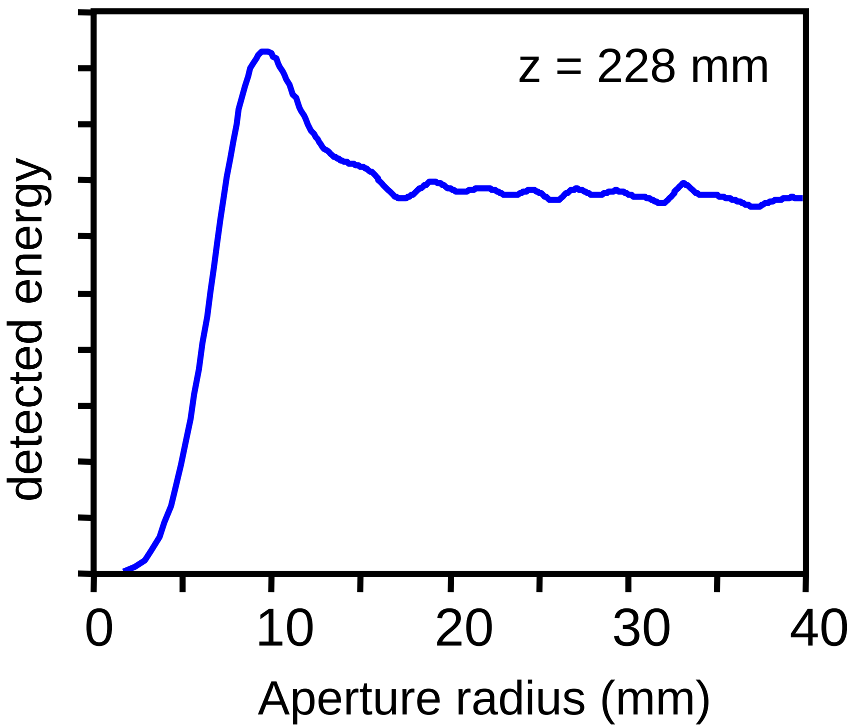


# of Fresnel zones depends on the coherence length!

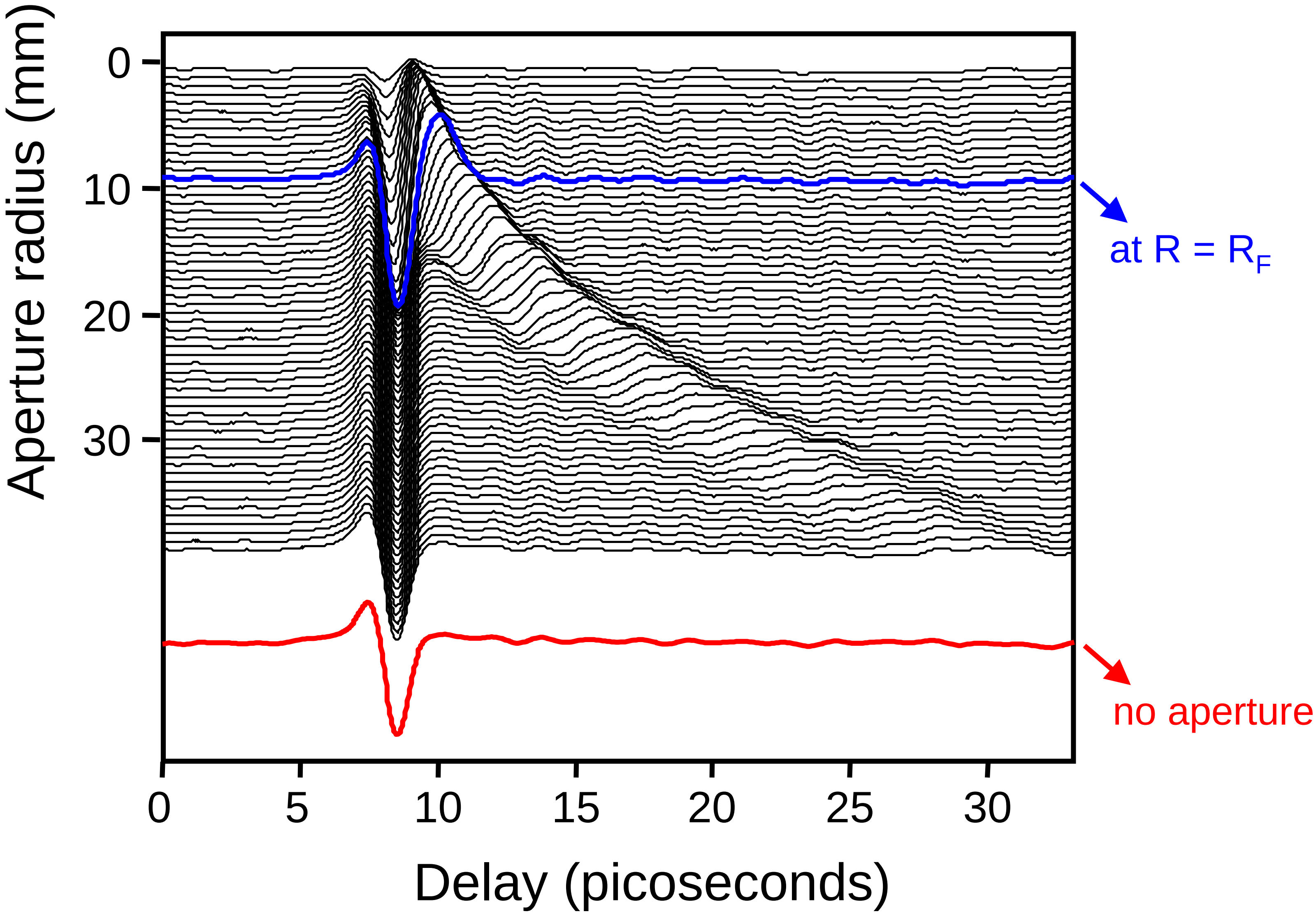
Fresnel zone for a THz pulse



A single-cycle pulse has only one Fresnel zone!

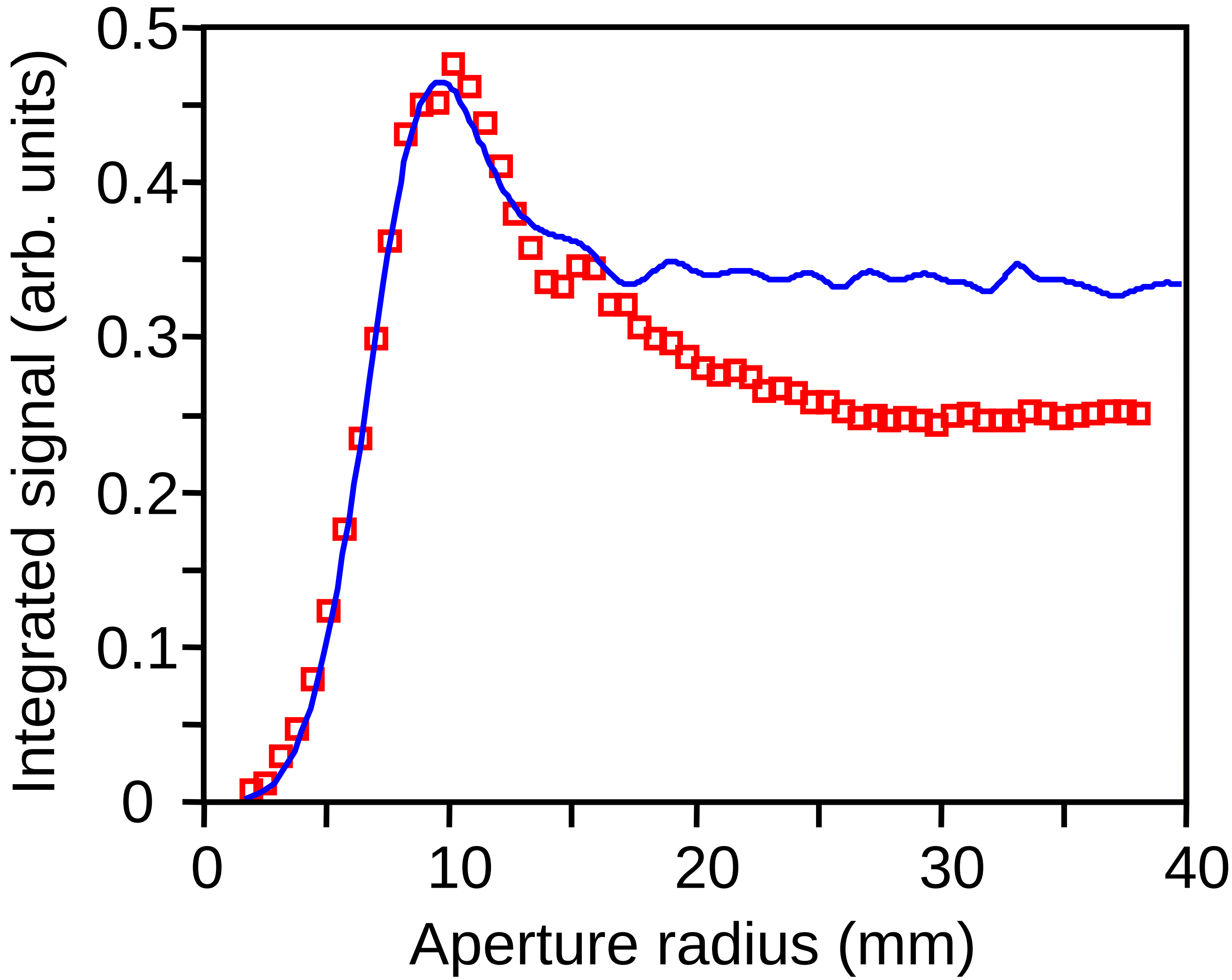


Waveforms



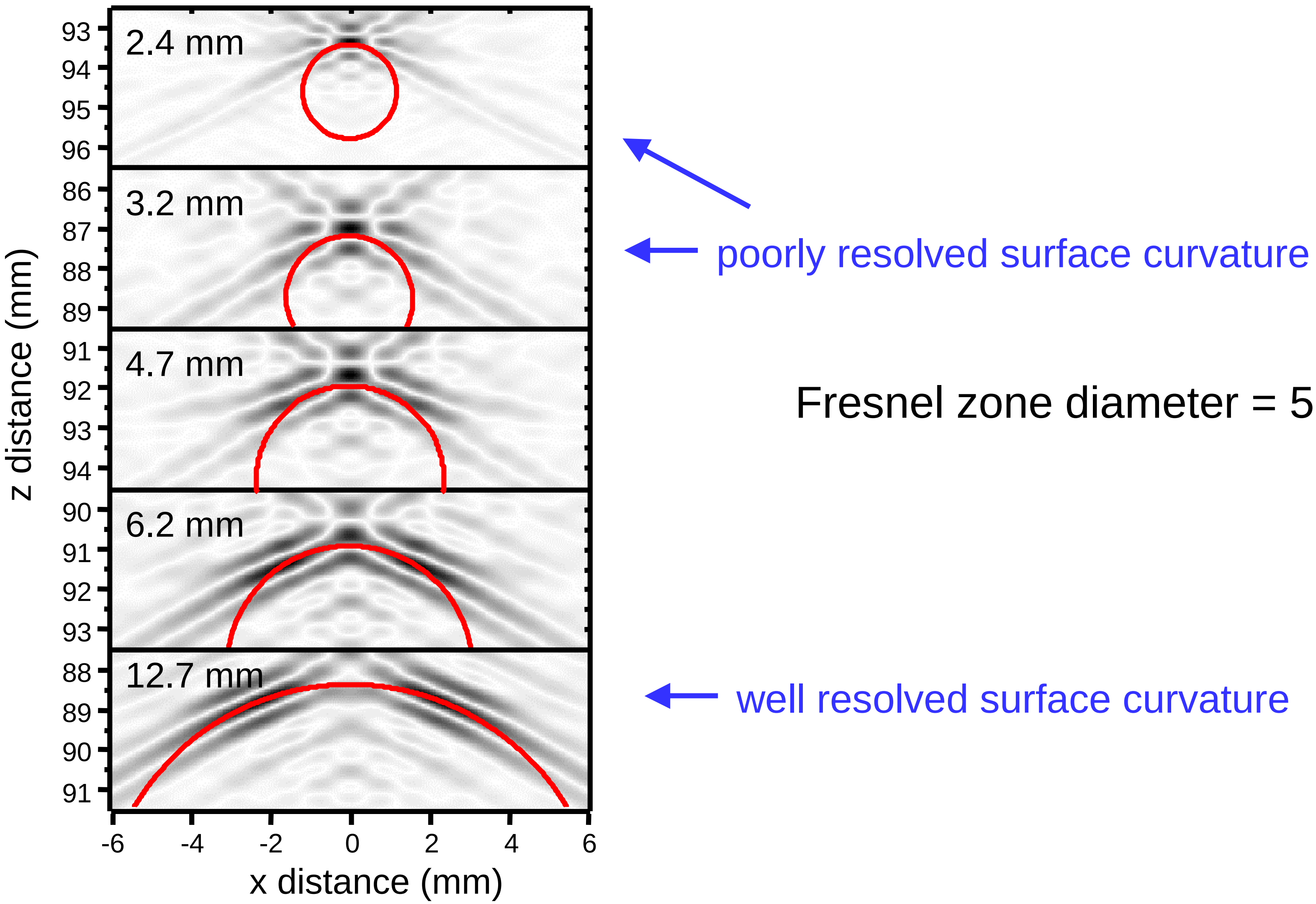
Pearce, *et al.*, *Phys. Rev. E*, **66**, 056602 (2002).

THz energy reaching the detector



Pearce, *et al.*, *Phys. Rev. E*, **66**, 056602 (2002).

Cylindrical targets



Fresnel zone diameter = 5.8 mm

Dorney, *et al.*, *J. Opt. Soc. Am. A*, **19**, 1432 (2002).

Conclusions

- THz imaging and sensing – many applications!
- Unique possibilities with single-cycle optical pulses

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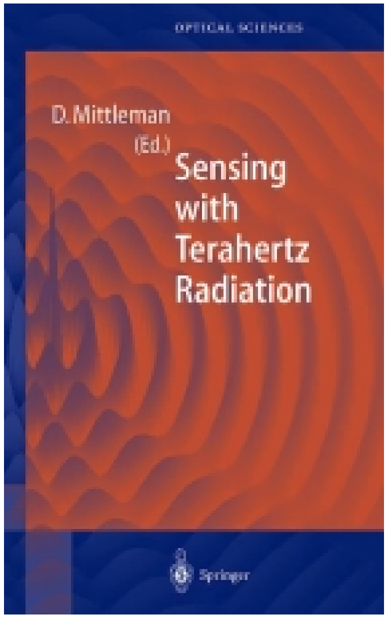

Available soon!

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