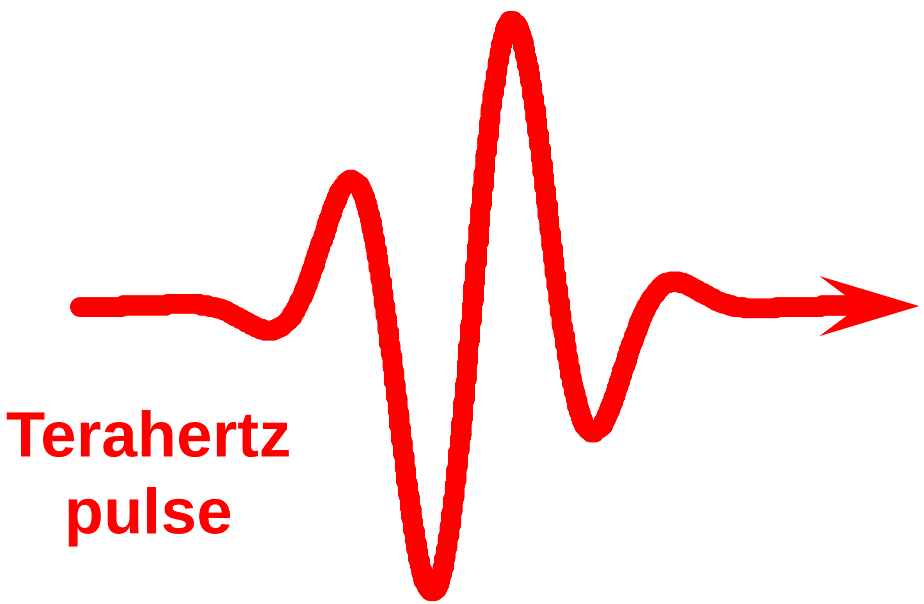
Practical: how to measure ultrafast spin and charge currents



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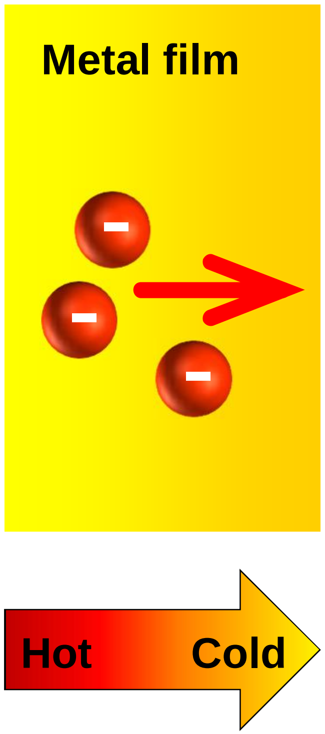
Heat-driven currents: the Seebeck effect



Temperature
gradient

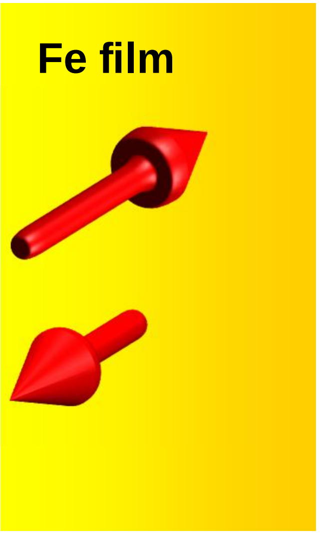
Thomas Seebeck (1821):

A temperature gradient drives an electron current

Ken-ichi Uchida (2008):

In ferromagnets, the Seebeck current
is spin-dependent

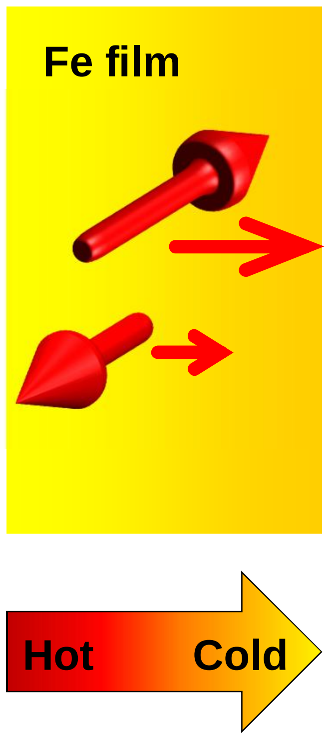
Spin-dependent Seebeck effect (SDSE)



↑ and ↓ electrons have very different transport properties

Uchida, Saitoh *et al.*, Nature (2008)
Bauer, Saitoh, Wees, Nature Mat (2013)

Spin-dependent Seebeck effect (SDSE)



Temperature gradient

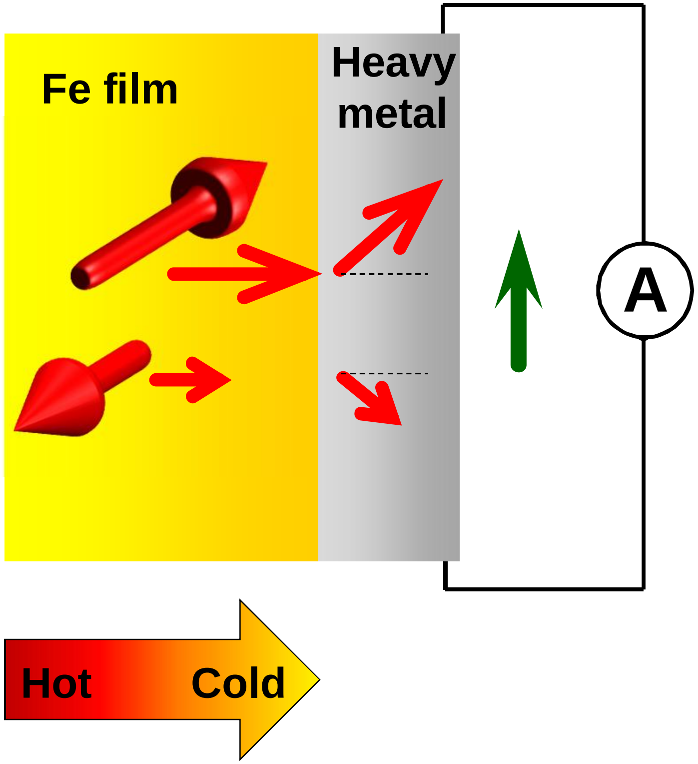
↑ and ↓ electrons have very different transport properties

Uchida, Saitoh *et al*., Nature (2008)
Bauer, Saitoh, Wees, Nature Mat (2013)

$\Rightarrow$ Spin-polarized current

Detection with the inverse spin Hall effect

Inverse spin Hall effect (ISHE)



Temperature gradient

Spin-orbit coupling deflects electrons

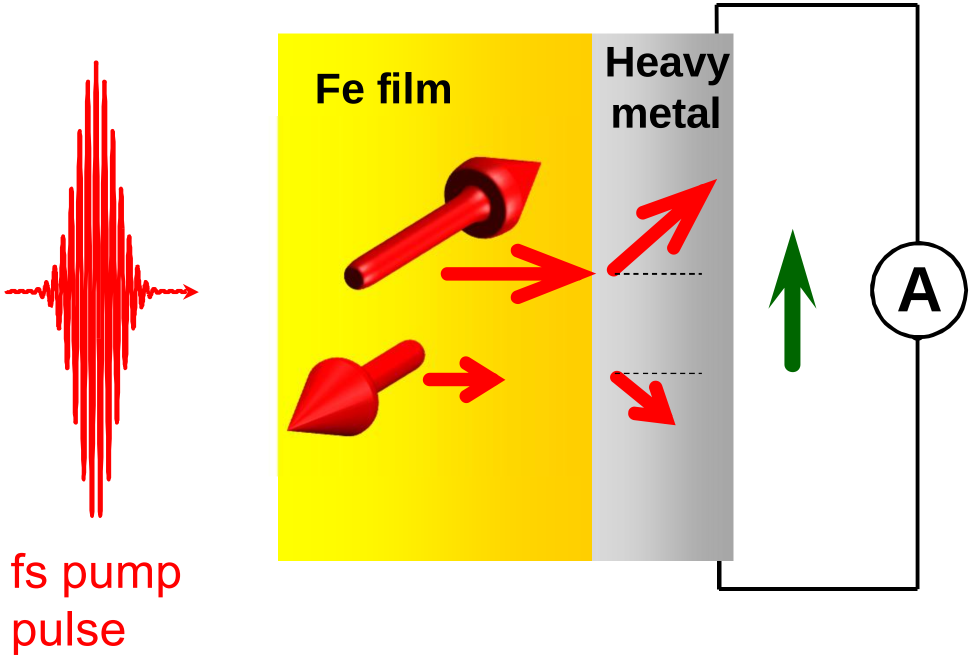
⇒ Transverse charge current

⇒ Spin-to-charge (S2C conversion

Saitoh *et al*., APL (2006)

How can we induce an imbalance as fast as possible?

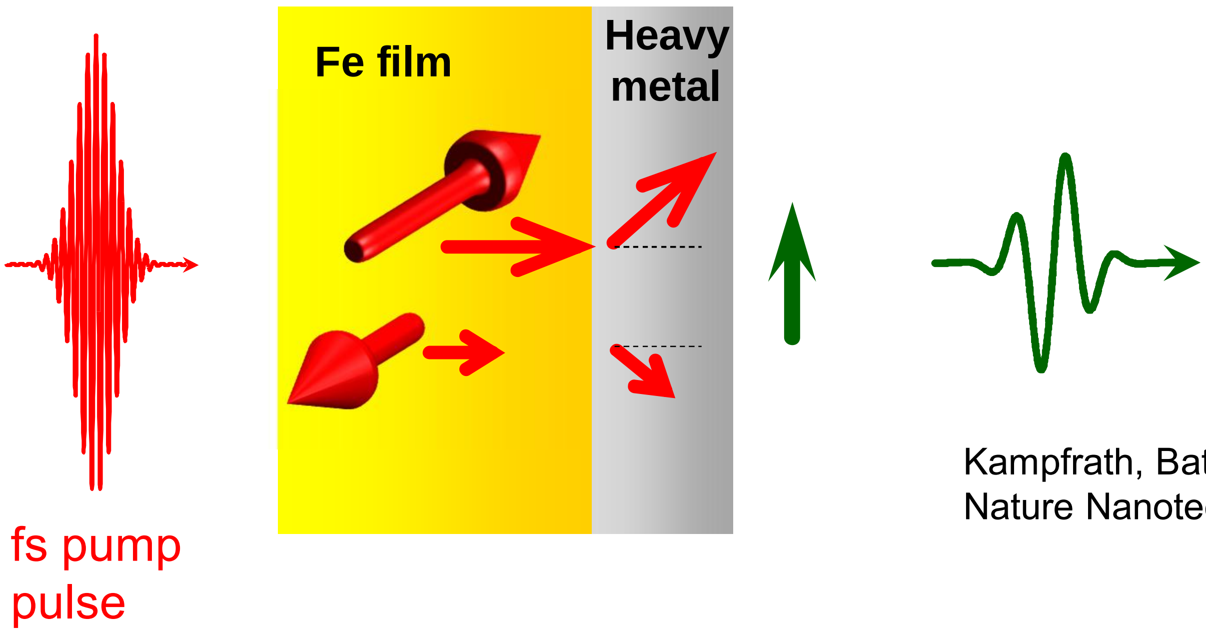
Inverse spin Hall effect (ISHE)



Technical challenge:

- Electric detection has cutoff at <50 GHz
- But expect bandwidth >10 THz

Inverse spin Hall effect (ISHE)



Kampfrath, Battiato, Münzenberg *et al.*, Nature Nanotech. (2013)

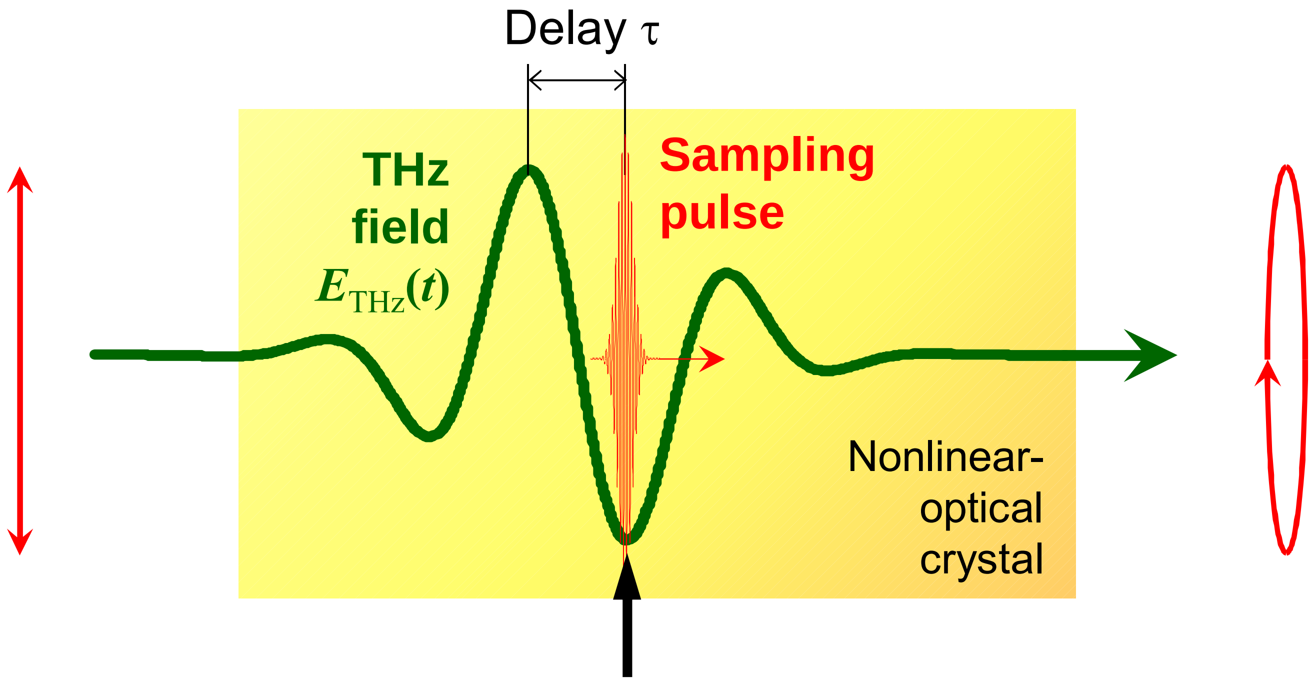
⇒ Measure THz emission from photoexcited FM|NM bilayers

Samples: polycrystalline films (labs of M. Kläui and M. Münzenberg)

Pump pulses: from Ti:sapphire oscillator (10 fs, 800 nm, 2.5 nJ)

How can we detect the THz pulse?

THz detection: electro-optic sampling



Wu, Zhang, APL (1995)

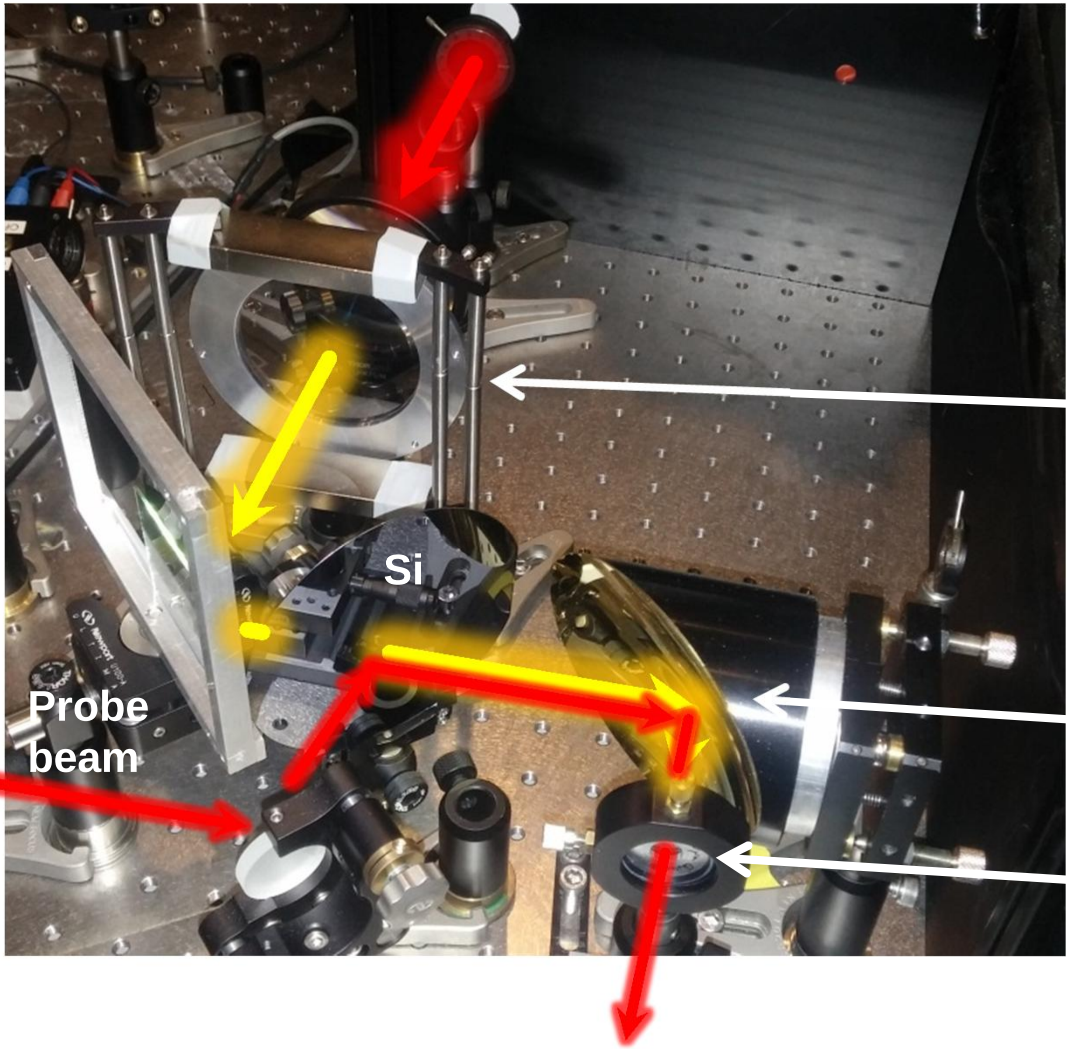
Electro-optic effect:

Change in refractive index $\propto E_{THz}(t) \Rightarrow$ Crystal becomes birefringent

Scan ellipticity of sampling pulse vs $\tau \Rightarrow$ Get THz electric field $E_{THz}(\tau)$

A look in the lab…

Simple THz emission setup in the lab



Optical pump beam

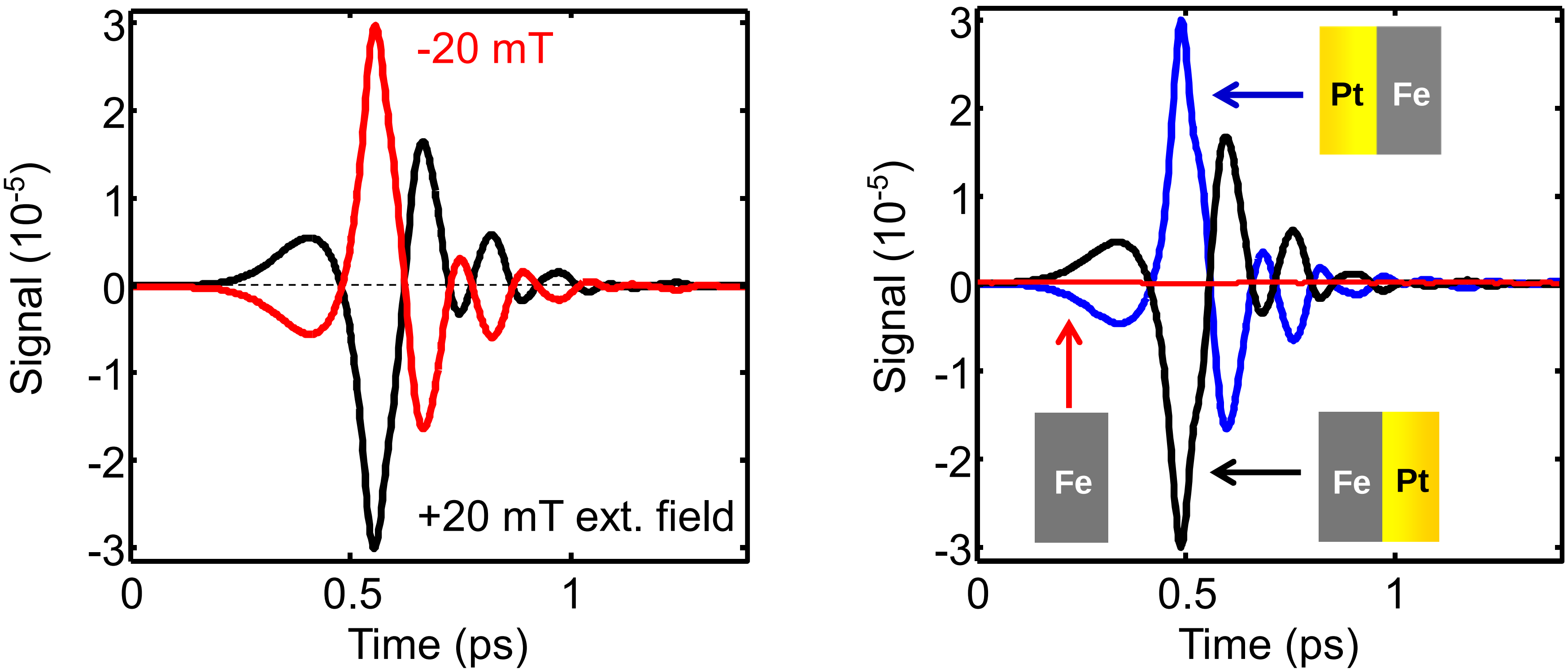
Spintronic sample

Parabolic mirror

Electrooptic crystal for sampling of the THz electric field

To detection of probe ellipticity

Typical THz waveforms from Fe|Pt bilayers



Further findings

- Signal ∝ pump power
- THz electric field ⊥ sample magnetization

Consistent with scenario spin transfer + ISHE

Need more evidence for the spin Hall scenario

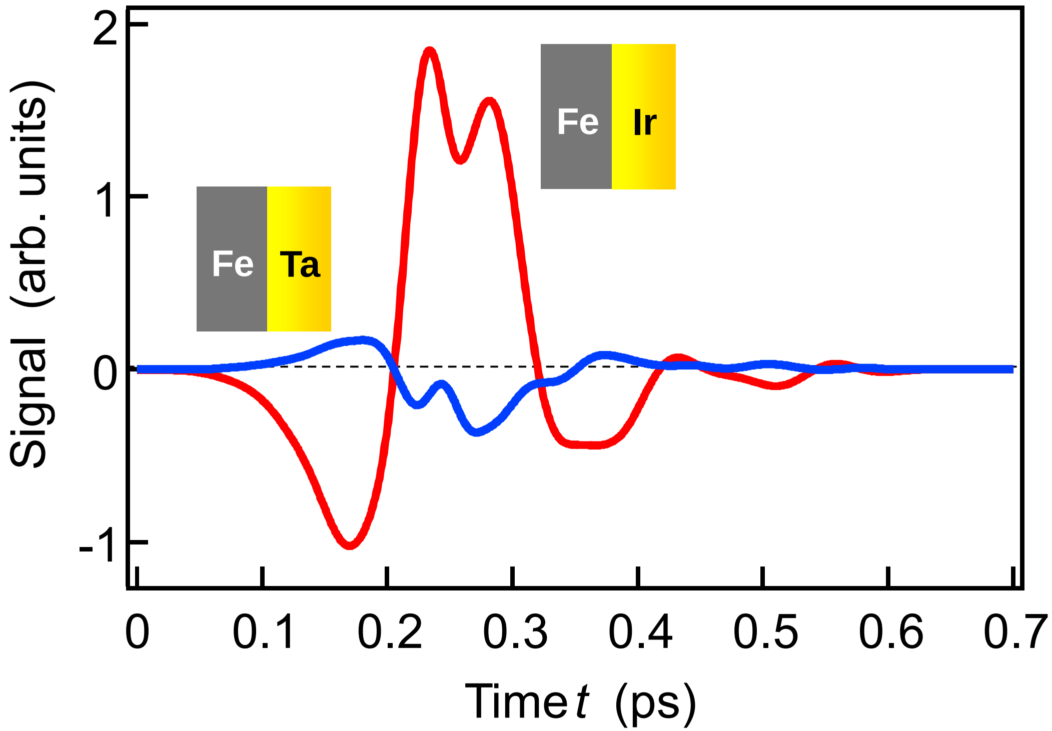
Ultrafast inverse spin Hall effect

Idea:

vary nonmagnetic cap layer

Ta vs Ir:

opposite spin Hall angles, Ir larger



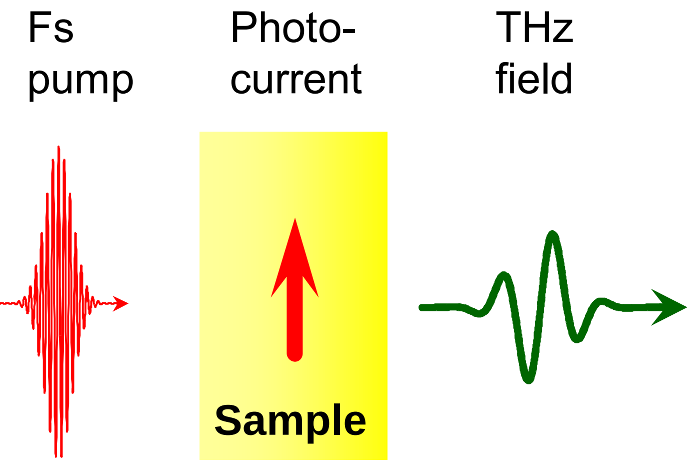
The inverse spin Hall effect is still operative at THz frequencies

Kampfrath, Battiato, Oppeneer, Freimuth, Mokrousov, Radu, Wolf, Münzenberg *et al.*, Nature Nanotech (2013)

This has interesting applications… tomorrow

Today: how can we determine the THz-emitting source current?

THz source current



$$I(t) \xrightarrow[Z]{} E(t)$$

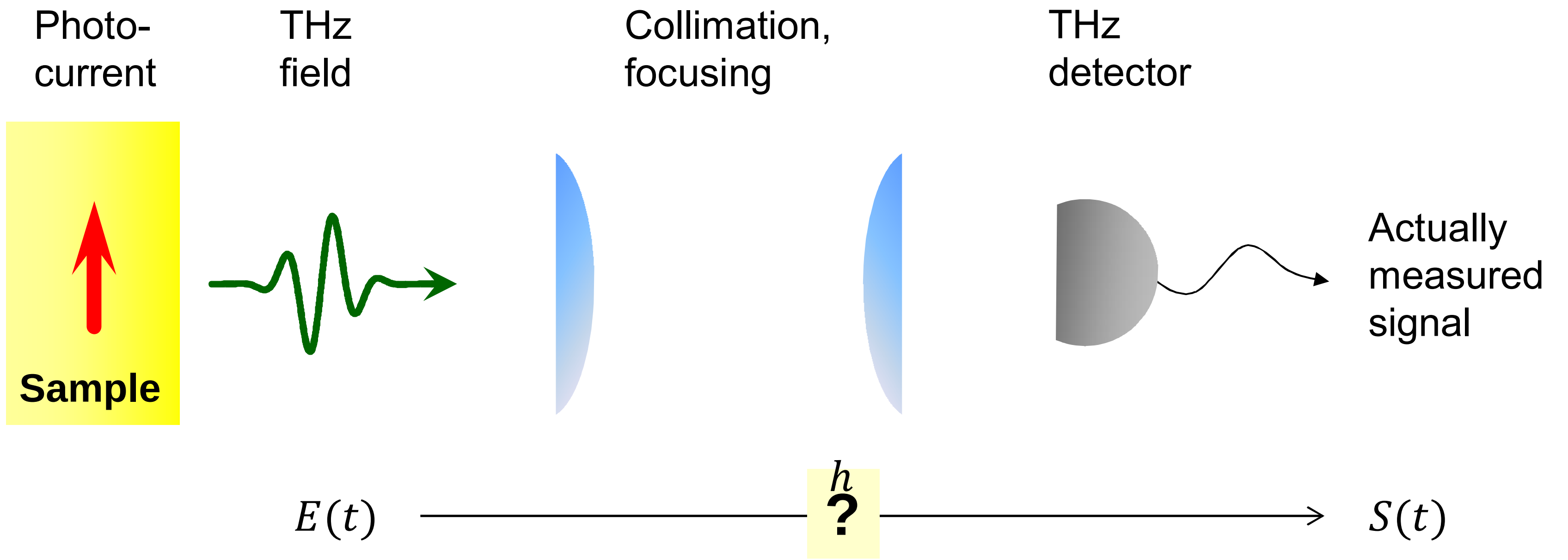
Sample impedance, usually known

Ohm's law: $E = Z * I$

$\Rightarrow$ Yields photocurrent $I(t)$

Issue: we do *not* measure $E(t)$

The transfer function of the THz setup



S depends linearly on E: $S(t) = (h * E)(t) \;= \int \mathrm{d}t'\, h(t - t')E(t')$

Convolution

Transfer function: response to δ-pulse

Simpler in frequency space: $\tilde{S}(\omega) = \tilde{h}(\omega) \cdot \tilde{E}(\omega)$

How can we get the transfer function h?

How to determine the transfer function?

$$S = h * E$$

Goal: determine h over large bandwidth (0.3 to 40 THz)

1) Calculate h: ~~requires approximations, e.g. idealized setup~~

2) Measure h: use a broadband THz reference emitter

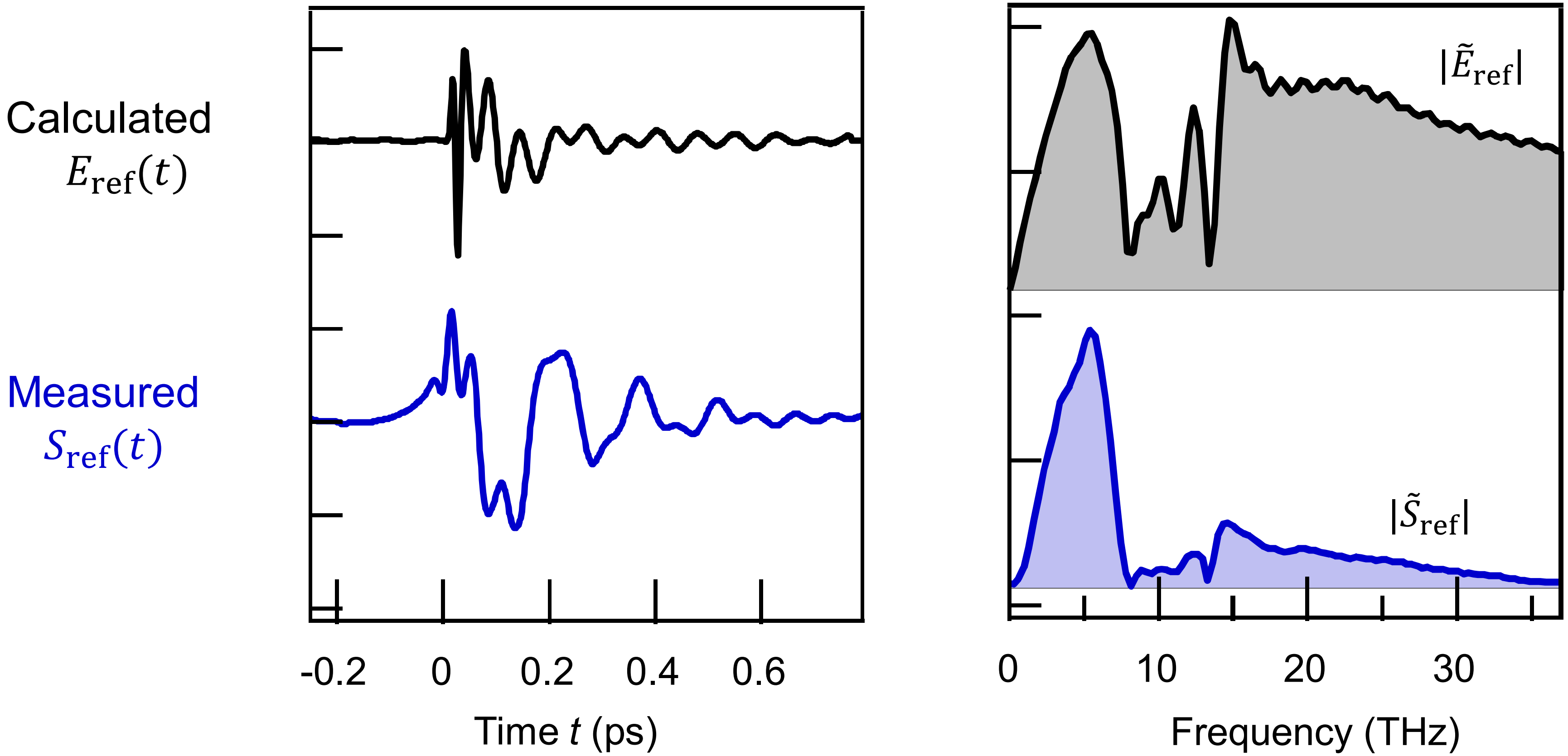
Measure → $S_{\mathrm{ref}} = h * E_{\mathrm{ref}}$ ← Calculate

Use optically transparent THz emitter:

- $\chi^{(1)}$ and $\chi^{(2)}$ are well known $\Rightarrow$ E_{ref} is quite well predictable
- We choose ZnTe and GaP

Calculate E_{ref} and measure S_{ref}

Reference emitter: GaP(110), 50 μm thick



$$E_{\mathrm{ref}} * h = S_{\mathrm{ref}}$$

Solve for h—directly in the time domain

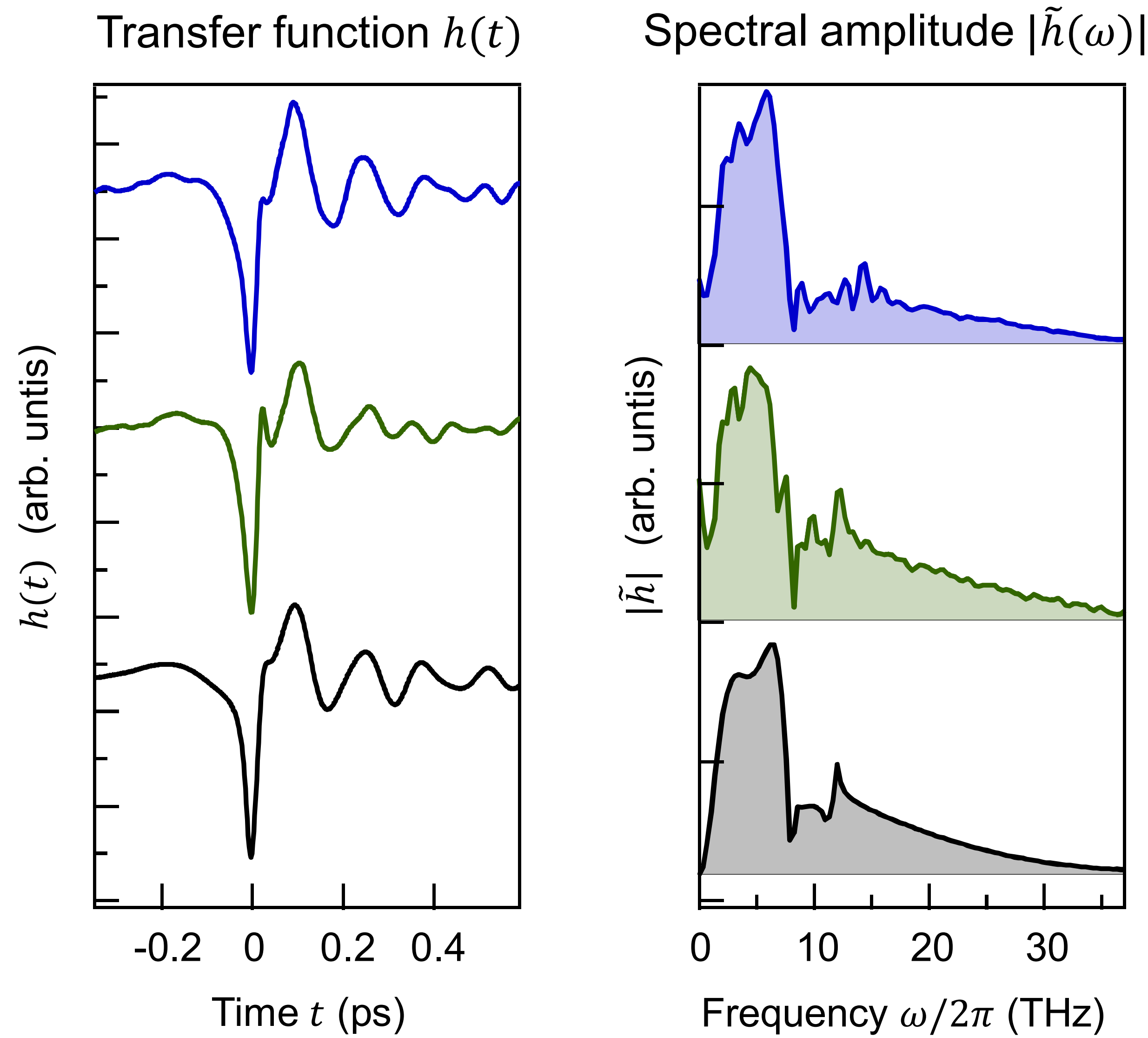
Experiment vs theory

Reference emitter:
GaP(110),
50 µm thick

Reference emitter:
ZnTe(110),
50 µm thick

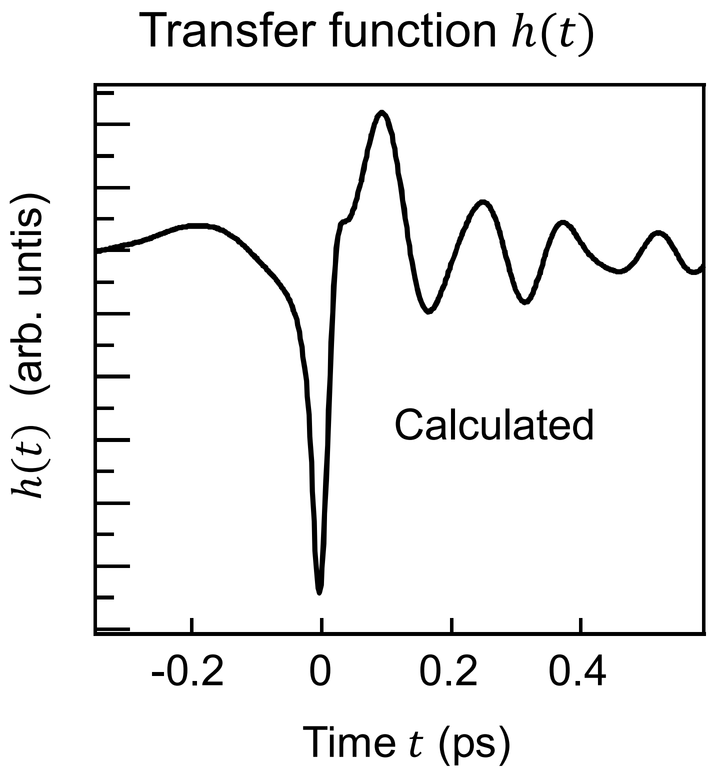
Calculated:

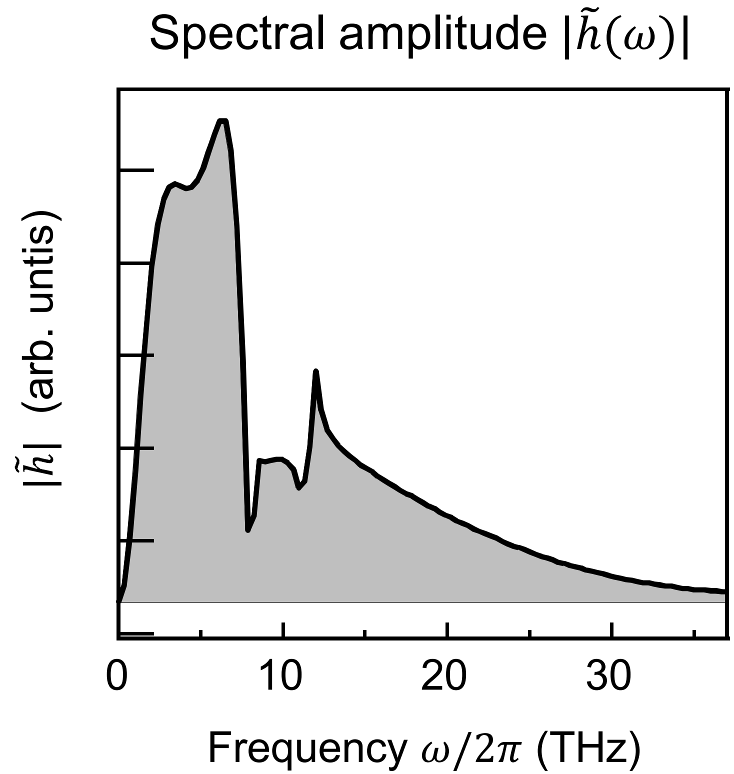
- Extended Gaussian beam propagation
- Detector response



Highly consistent results for h

Understanding the structure of h





- $t = 0$: remainder of input δ-peak
- $t < 0$: faster THz components
- $t > 0$: slower components, e.g. in Reststrahlen region

- High pass: DC cannot propagate
- Low pass: e.g. probe duration
- 8…12 THz: Restrahlen band of GaP

Ready to apply h

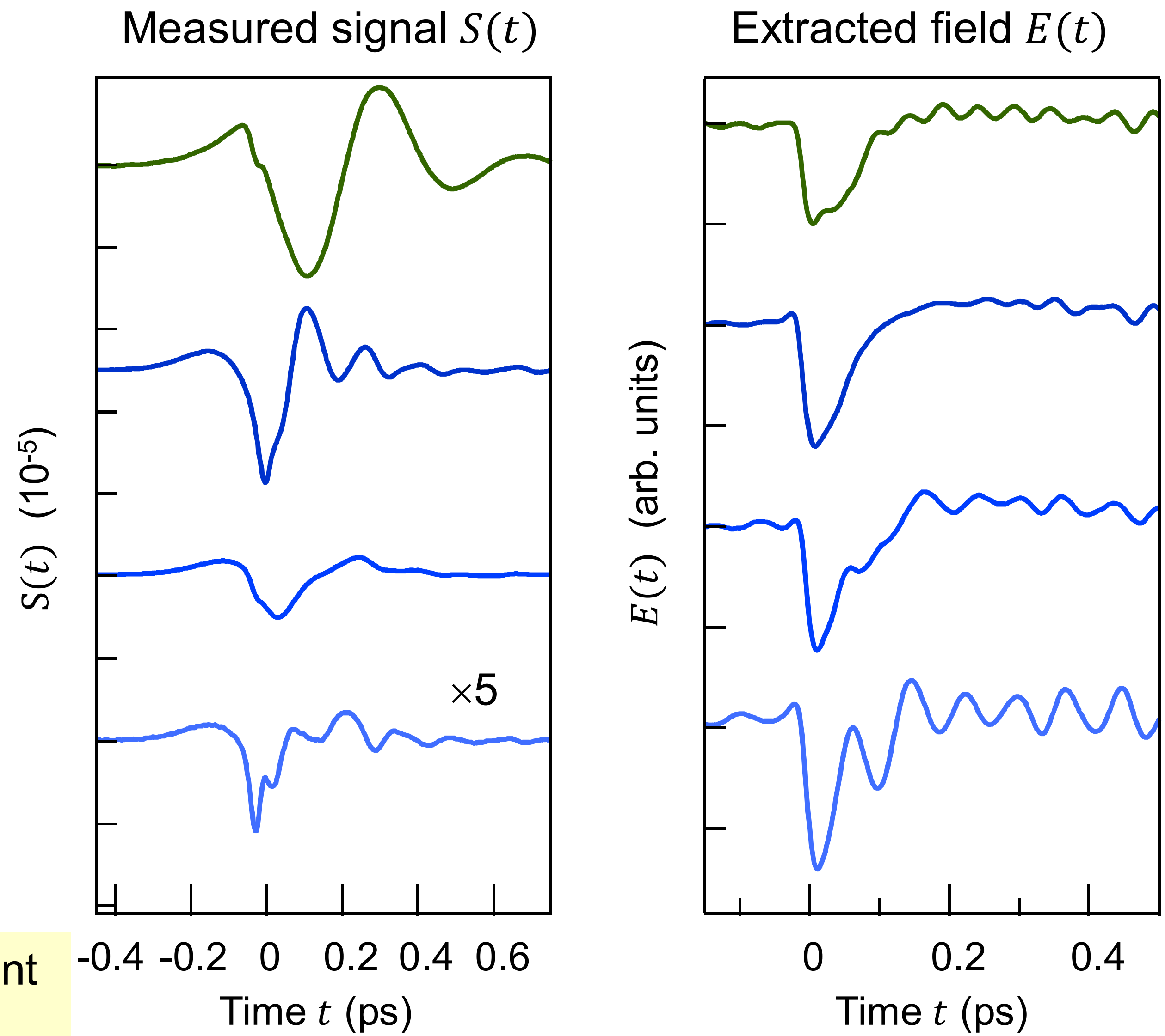
Spintronic THz emitter: from S to E

Electrooptic detector:
ZnTe(110)

GaP(110)

Detector
out of focus

Aperture (∅=2 cm)
in collimated
THz path



Demonstrates consistent extraction of THz field

Conclusion

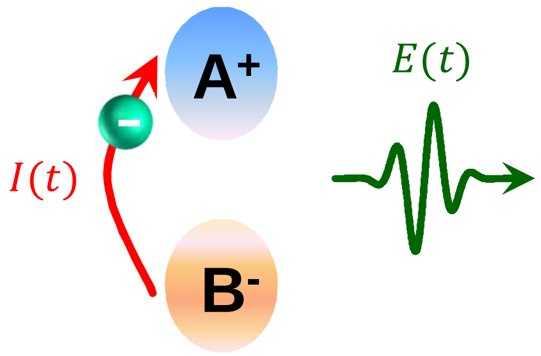
Developed reliable extraction method:

Measured electro-optic signal $S(t)$ $\xrightarrow{\quad h \quad}$ THz electric field $E(t)$ directly behind the sample

Application: quantitative measurement of ultrafast charge transfer in e.g.

- Spintronic multilayers
- Photovoltaic structures
- Molecules: photochemical processes

… so far very rarely implemented



Future extensions:

- Better reference emitters: thinner, stronger, flat spectral output