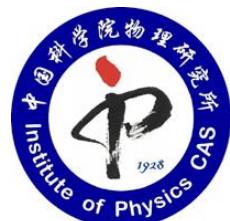


TW-level Terahertz radiation driven by high-intensity laser pulses

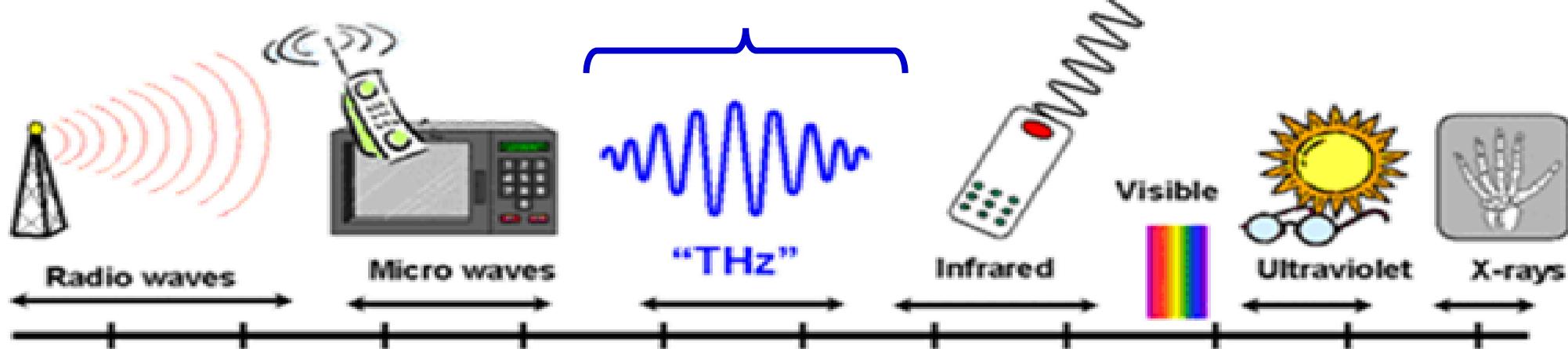
Guoqian Liao

Institute of Physics, Chinese Academy of Sciences, China

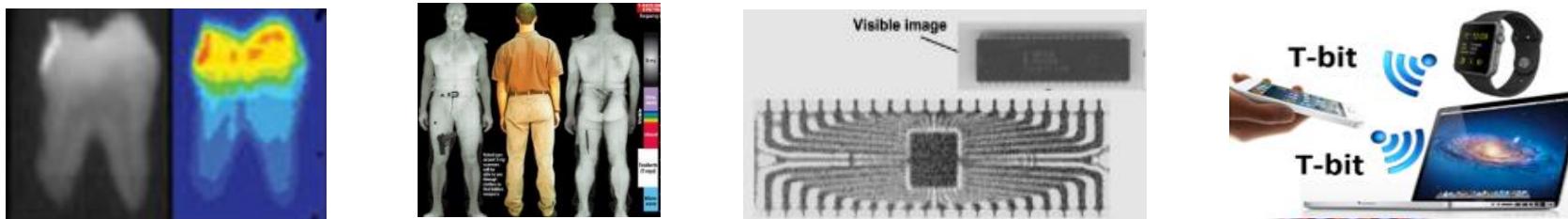
E-mail: gqliao@iphy.ac.cn



Terahertz (THz) radiation (0.1-10THz / 3mm-30μm)



- $1\text{THz} \sim 1\text{ps} \sim 300\mu\text{m} \sim 4\text{meV} \sim 47.6\text{K}$
- Low photon energy
 - Selective transmission
 - Fingerprint-like spectrum
 - Broad bandwidth



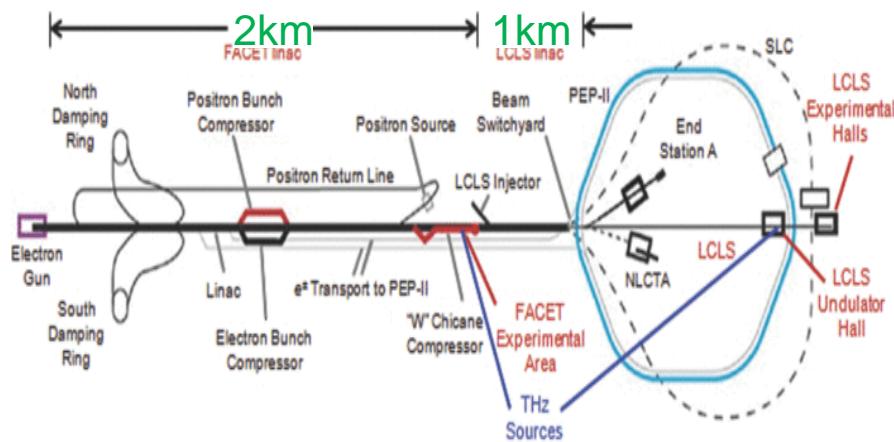
High-power THz sources are essential for applications !

High average power (FEL, QCL...) vs High peak power

Approaches to producing intense THz pulses

Electronics

Accelerating energetic electrons in conventional accelerators

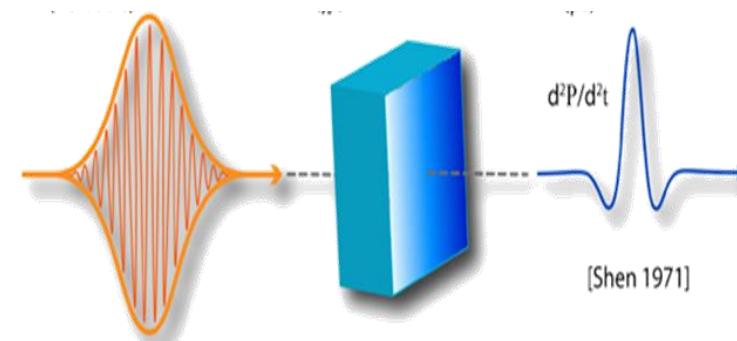


~0.6mJ @ SLAC

High-charge ultrashort electron bunches are required.

Optical

Optical rectification of femtosecond laser pulses in nonlinear crystals



Laser Photon. Rev. 15, 2000295 (2021)

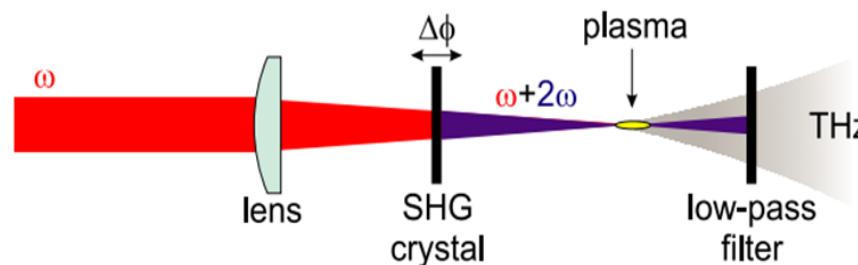
1.4mJ from 8cm*7cm LN @ 91K

Optical damage

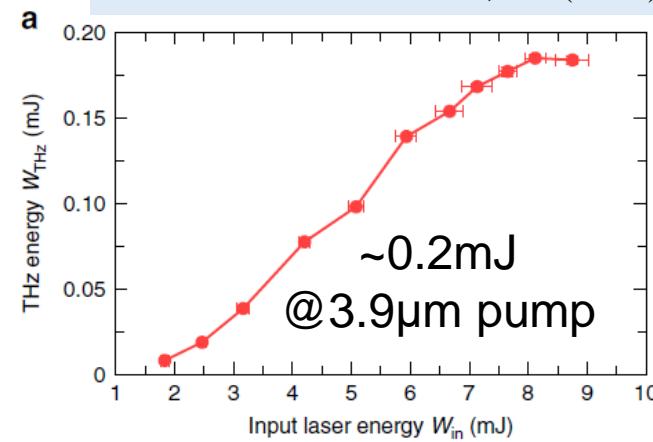
Laser-plasma based THz generation

Plasma: free of optical damage

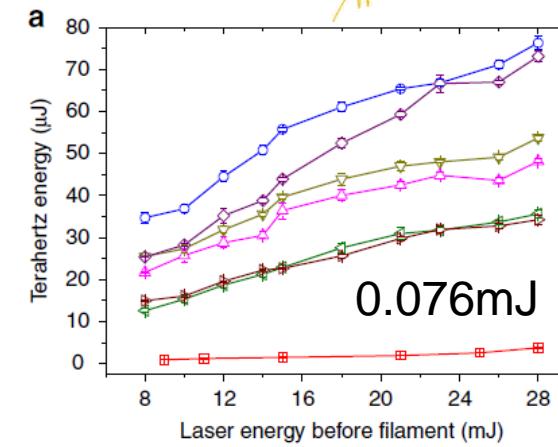
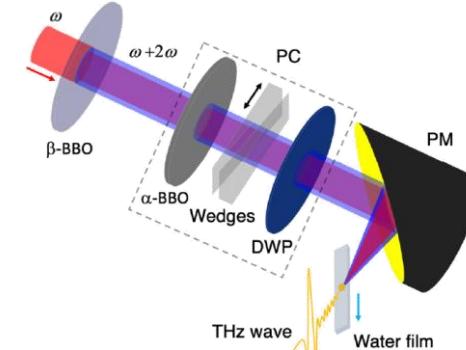
Filamentation in gas (air)



Nat. Communications 11, 292(2020)



Laser-produced plasma in liquids



Low laser intensity ($< 10^{15-16} \text{ W/cm}^2$)/ **THz saturation**

How to produce higher-peak-power (higher-energy) THz pulses?

THz generation from ultraintense laser-plasma interactions

VOLUME 71, NUMBER 17

PHYSICAL REVIEW LETTERS

25 OCTOBER 1993

Subpicosecond, Electromagnetic Pulses from Intense Laser-Plasma Interaction

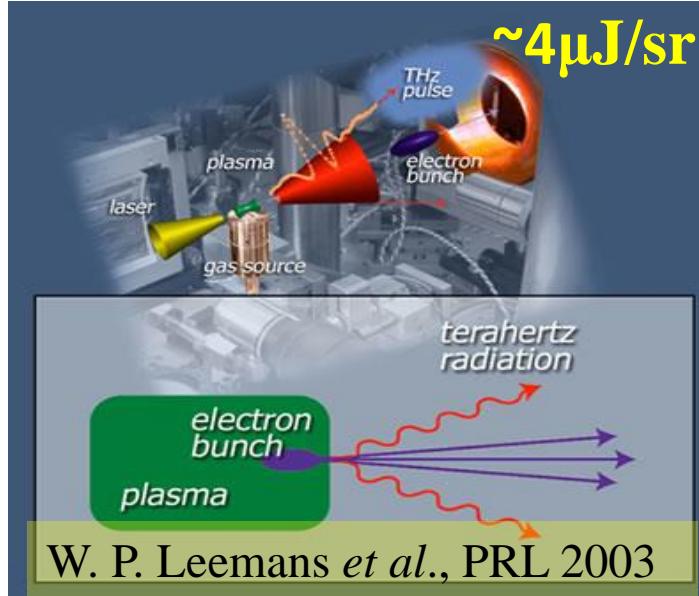
H. Hamster, A. Sullivan, S. Gordon, W. White,* and R. W. Falcone

*Department of Physics, University of California at Berkeley, Berkeley, California 94720
(Received 16 April 1993)*

Laser pulses with a power of 10^{12} W and a duration of 10^{-13} s were focused onto both gas and solid targets. Strong emission of pulsed radiation at terahertz frequencies was observed from the resulting plasmas. The most intense radiation was detected from solid density targets and was correlated with the emission of MeV x rays and electrons. Results indicate that radiative processes in such plasmas are driven by ponderomotively induced space charge fields in excess of 10^8 V/cm. This work constitutes the first direct observation of a laser-induced wake field.

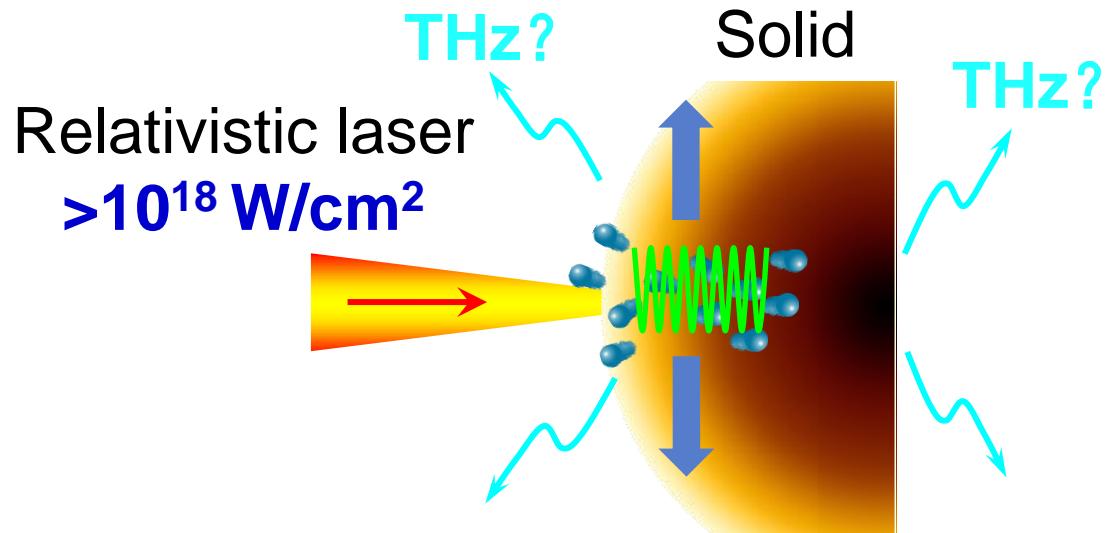
- Laser: 0.5J, 120fs
- Target: Al-coated glass slide
- **THz @ front: ~0.3 μ J/sr**

• THz transition radiation by laser-wakefield accelerated electrons



	Gas target
Charge Q	~10s pC (<nC) ☹
E_{ke}	100MeV-GeV ☺
Boundary size ρ	~100 μ m ☹
Boundary gradient	Not sharp ☹
THz radiation	~4 μ J/sr

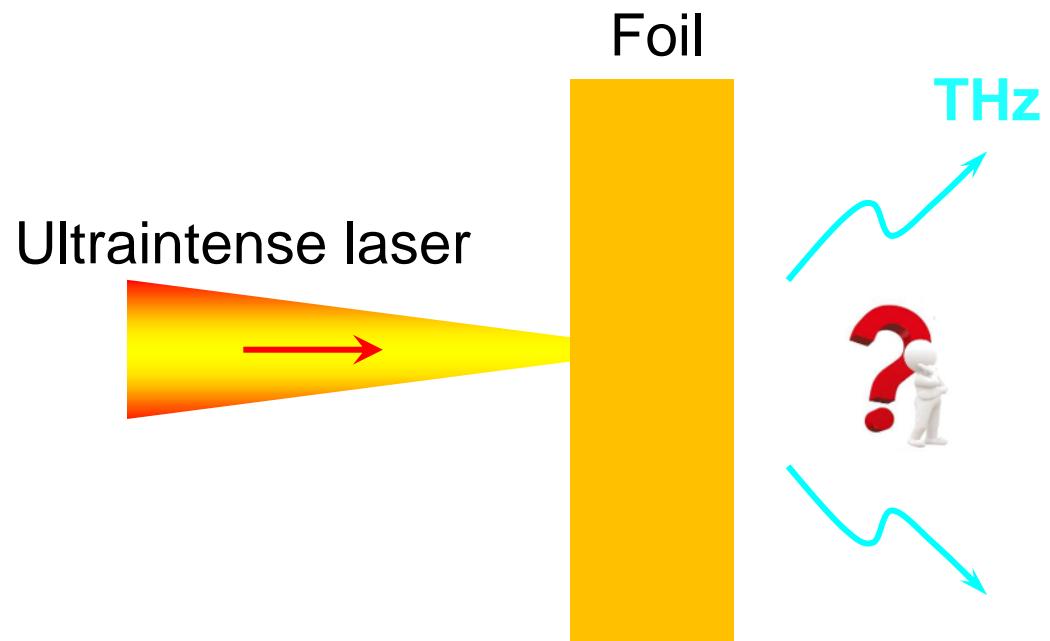
THz generation from ultraintense laser-solid interactions



- Physical mechanisms
- THz performance

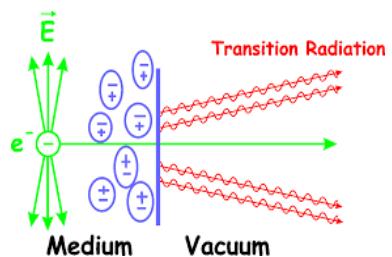
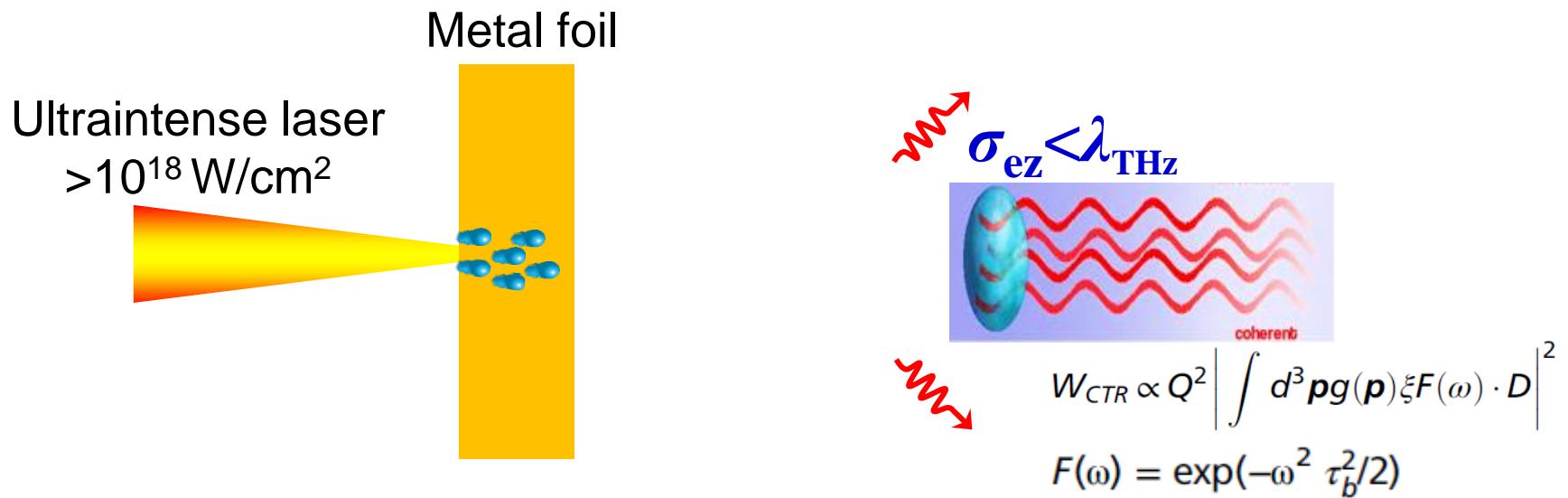
- H. Hamster *et al.*, PRL 71, 2725(1993).
- H. Hamster *et al.*, PRE 49,671(1994).
- W. P. Leemans *et al.*, PRL 91, 074802(2003).
- A. Sagisaka *et al.*, APB 90, 373 (2008).
- Y. Gao *et al.*, OL 33, 2776 (2008).
- C. Li *et al.*, PRE 84, 036405 (2011).
- Y.-T. Li *et al.*, APL 100, 254101 (2012).
- A. Gopal *et al.*, NJP 14, 083012 (2012).
- A. Gopal *et al.*, PRL 111,074802 (2013).
- A. Gopal *et al.*, OL 38, 4705 (2013).
- G.-Q. Liao *et al.*, PRL 114, 255001 (2015).
- G.-Q. Liao *et al.*, PRL 116,205003 (2016).
- Z. Jin *et al.*, PRE 94, 033206 (2016).
- C. Li *et al.*, OE 24, 4010 (2016).
- G.-Q. Liao *et al.*, PPCF 59, 014039 (2017).
- S. Herzer *et al.*, NJP 20, 063019 (2018).
- A. H. Woldegeorgis *et al.*, PRE 98, 061201 (2018).
- A. Woldegeorgis *et al.*, Optica 5, 1474 (2018).
- G.-Q. Liao *et al.*, PNAS 116, 3994 (2019).
- G.-Q. Liao *et al.*, IEEE TPS 47, 3002 (2019).
- A. Gopal *et al.*, PRE 100, 053203 (2019).
- Woldegeorgis *et al.*, PRE 100, 053204 (2019).
- Y. Zeng *et al.*, OE 28, 15258 (2020).
- G.-Q. Liao *et al.*, PRX 10, 031062 (2020).

Forward THz generation from laser-foil interactions



- Theoretical modeling
- Experimental demonstration
- Performance improvement (energy, tunability)
- Preliminary applications

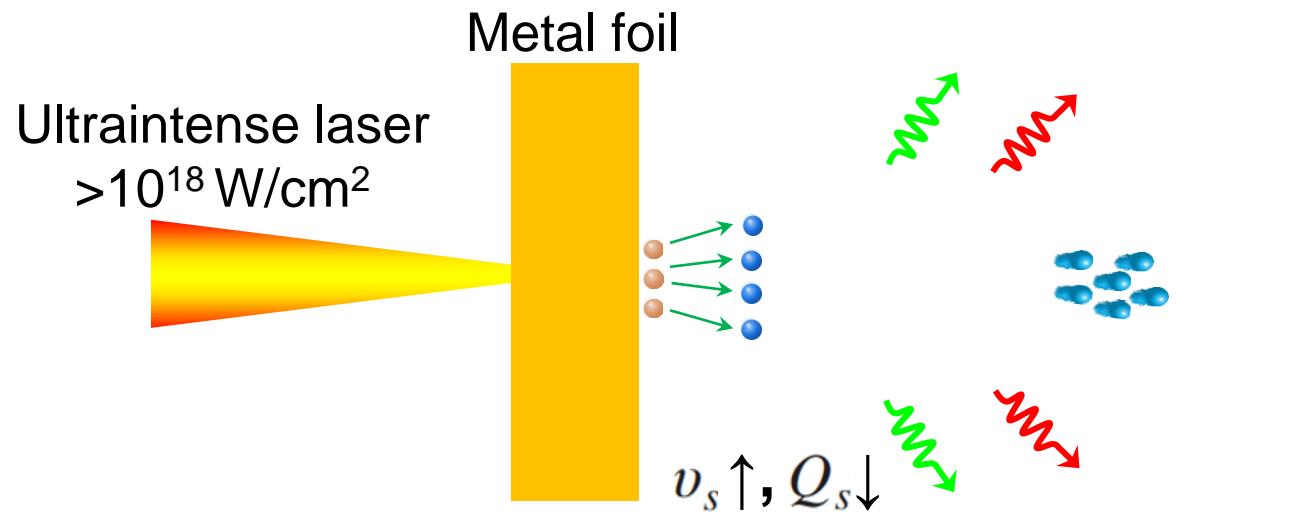
THz generation process I: Transition radiation (TR)



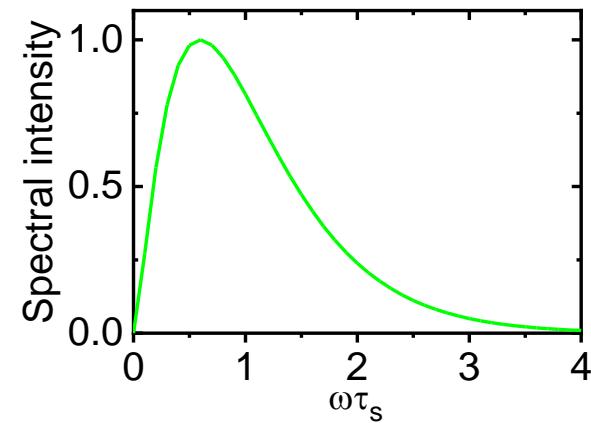
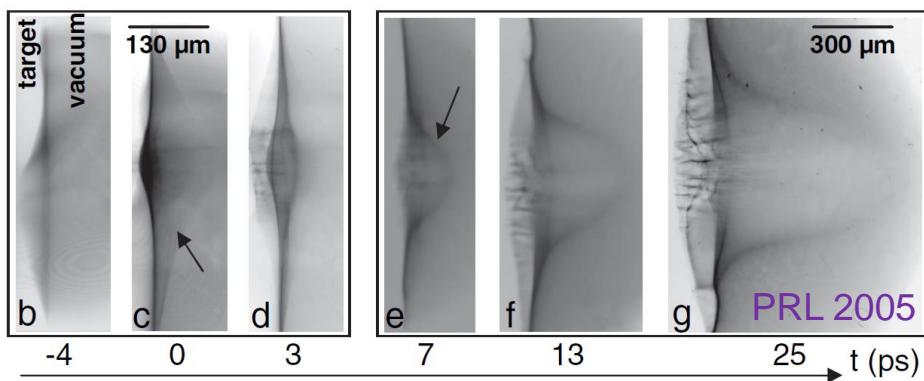
- **Bunch duration $\tau_b \sim \tau_{\text{laser}} \sim 10\text{fs-ps}$**
- **Bunch charge $n\text{C} \sim \mu\text{C}$**

THz radiation ?!
High-energy ?!

THz generation process II: Sheath radiation (SR)

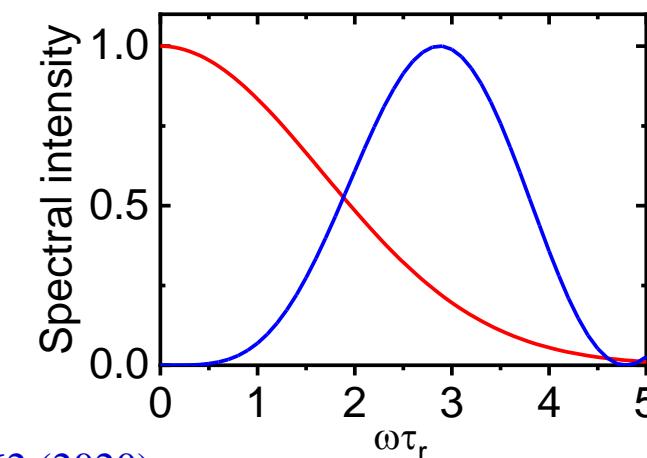
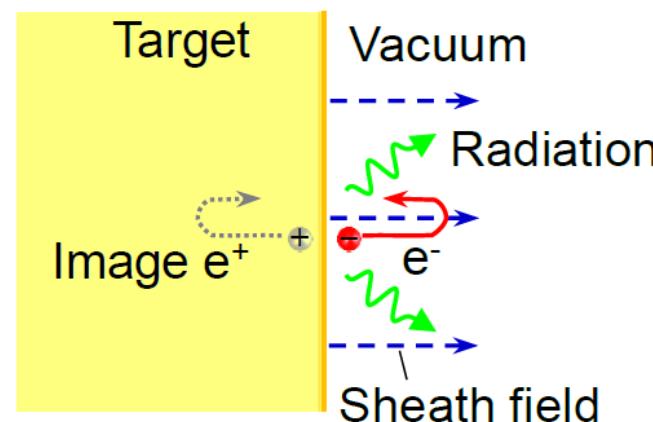
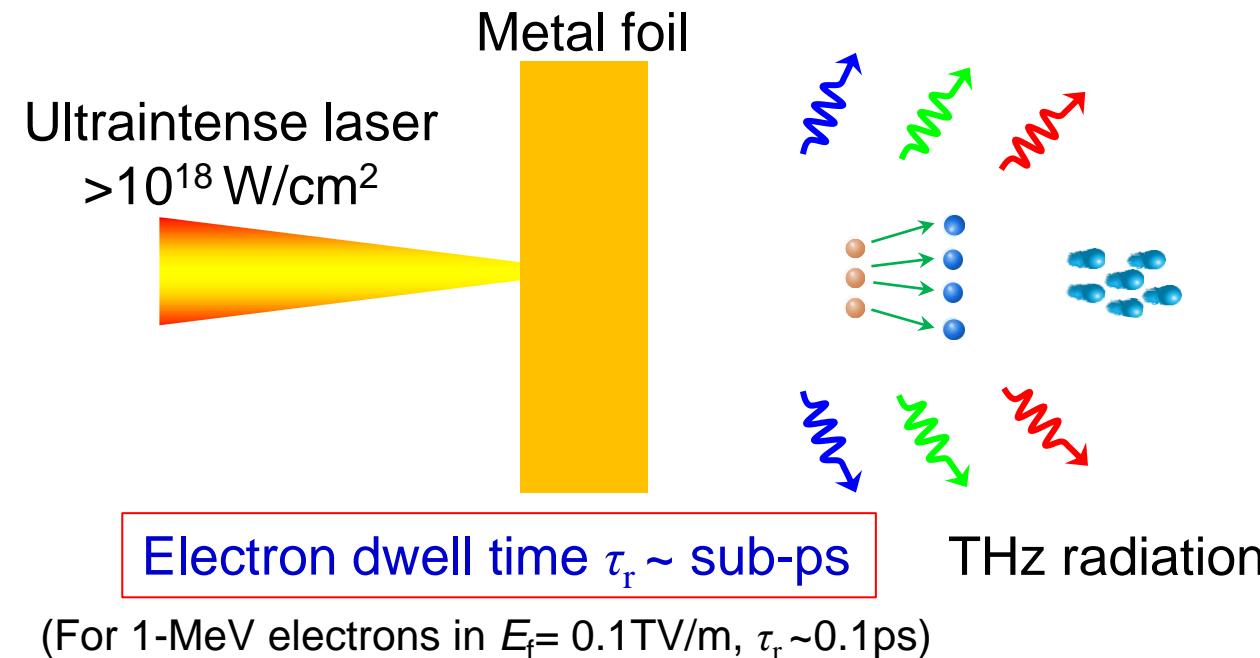


$$\mathbf{J}(x, t) = Q_s v_s \delta(x - x_s) \mathbf{e}_x$$

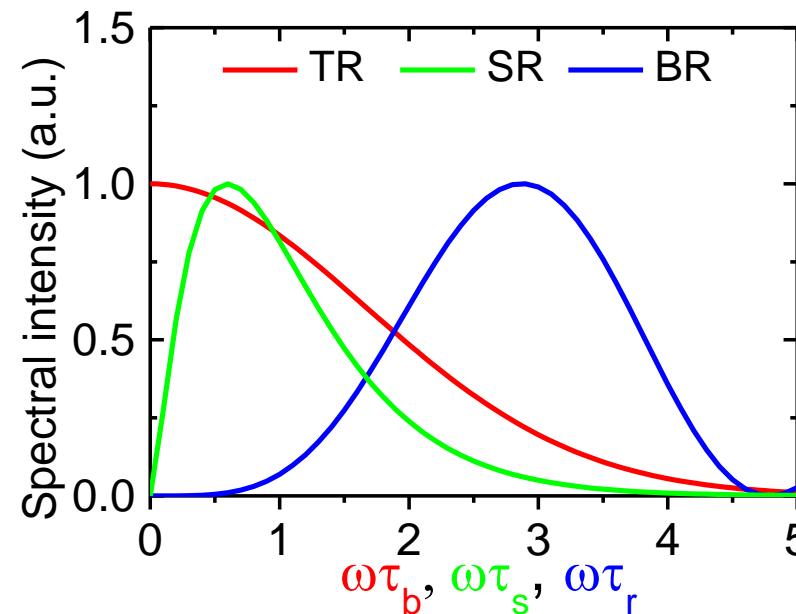


A. Gopal *et al.*, PRL 111.074802(2013); S. Herzer *et al.*, NJP 20, 063019 (2018); G.-Q. Liao *et al.*, PRX 10, 031062 (2020).

THz generation process III: Bremsstrahlung-like radiation (BR)



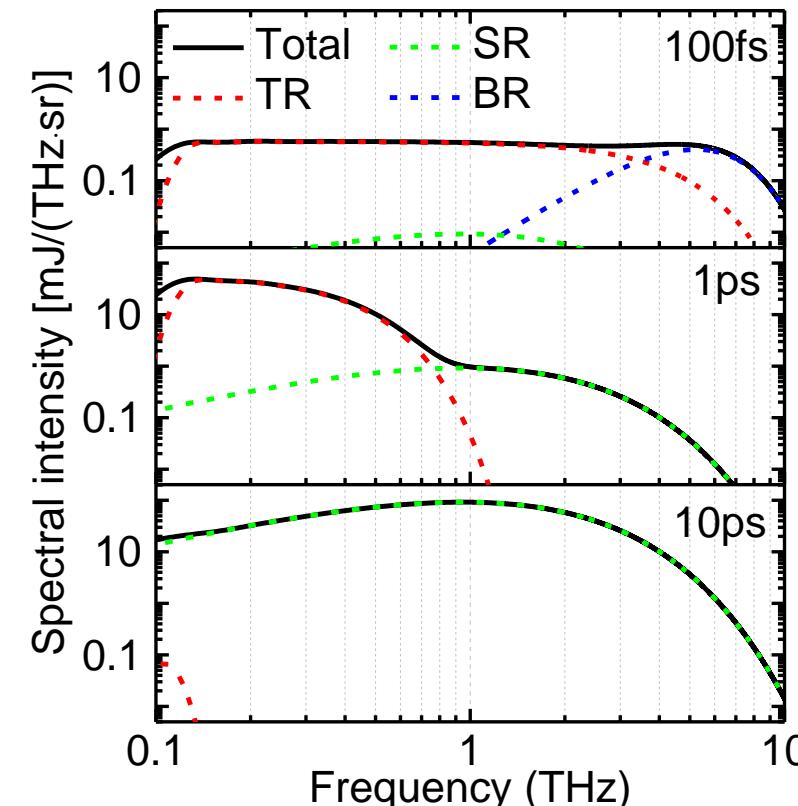
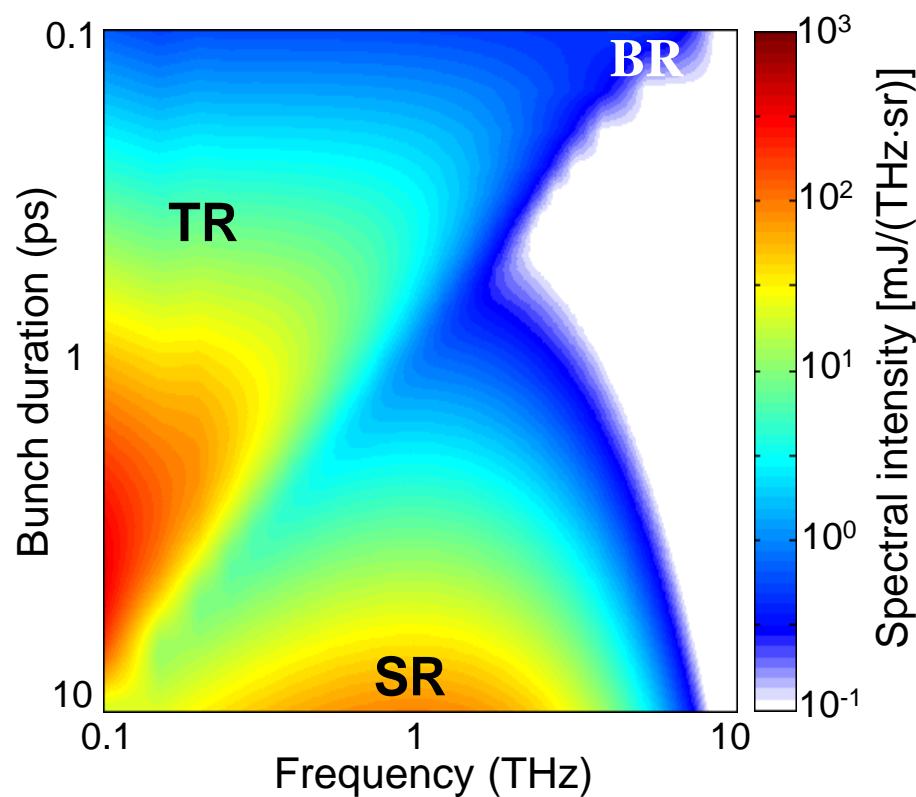
Spectrum comparison



Distinct spectra as a function of different parameters

- ① Variable dominated THz generation process;
- ② Tunable spectra.

Numerical calculation & Theoretical projection

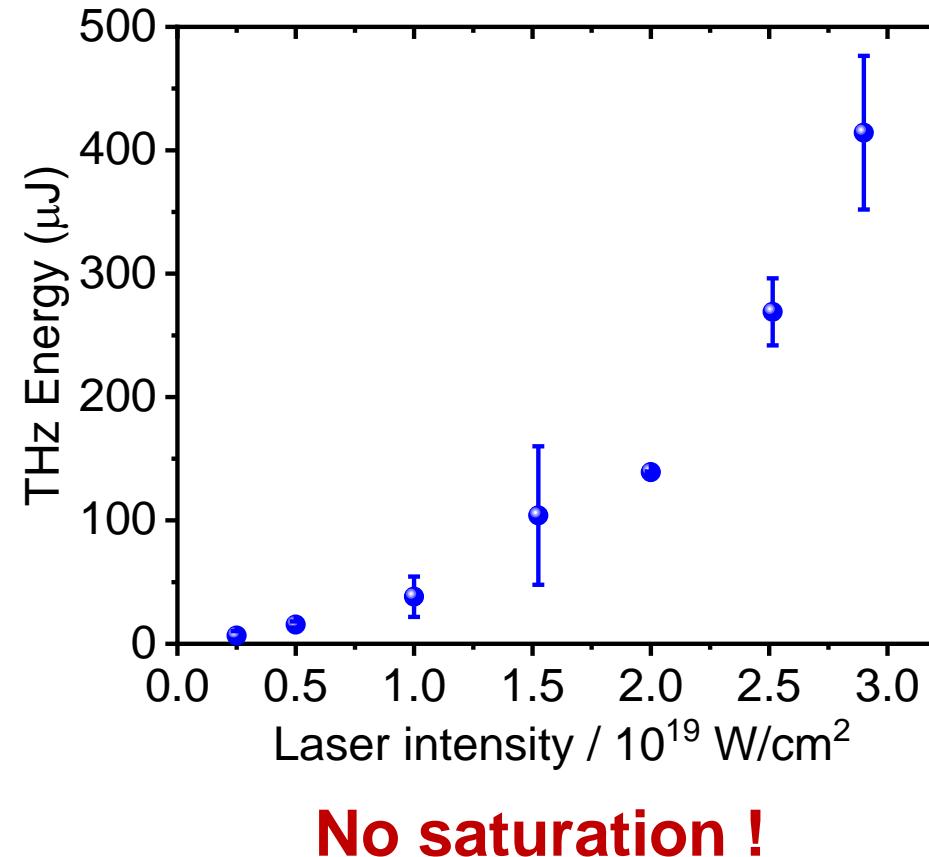
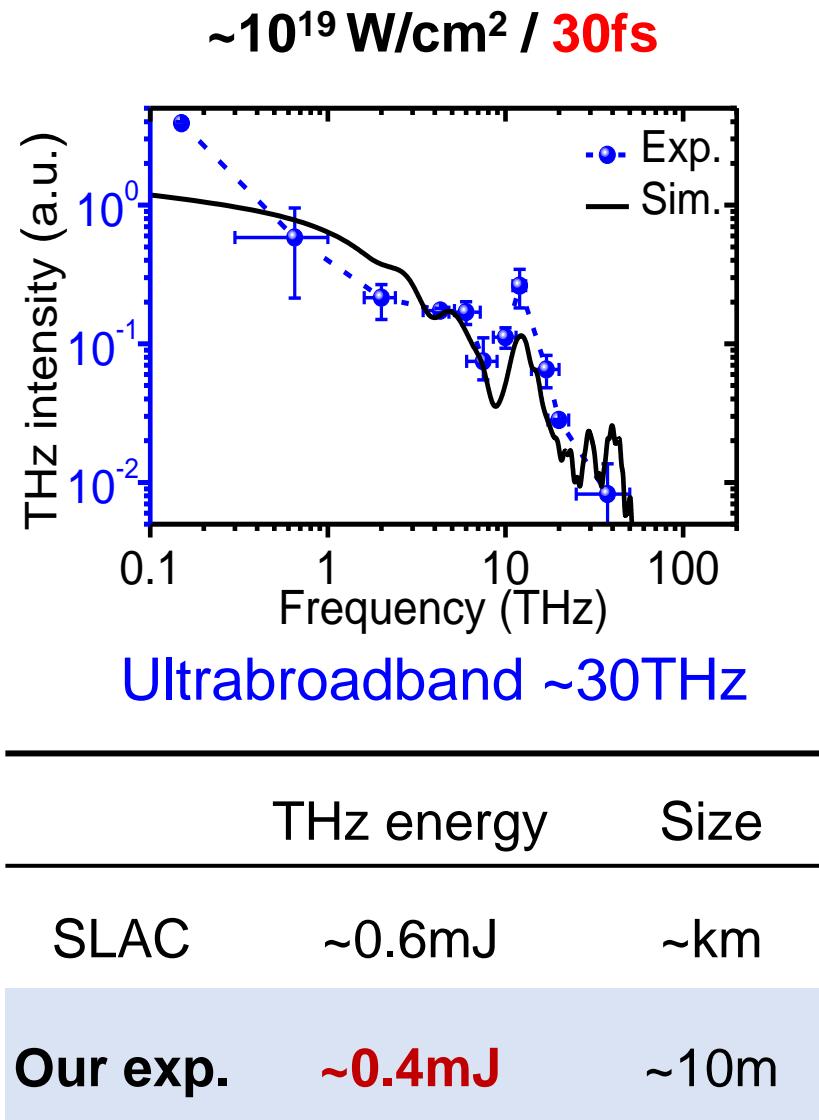


High-energy, spectrally-tunable THz radiation !

Dominated mechanism

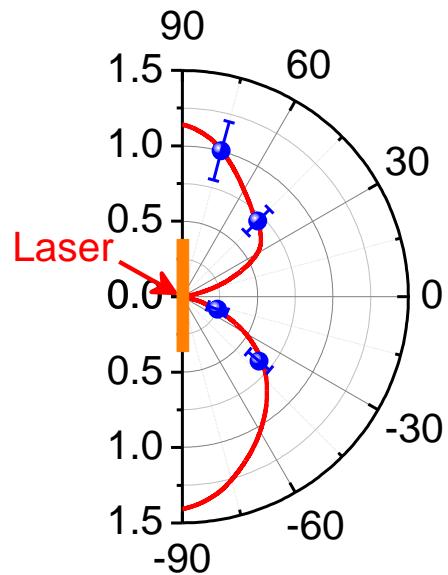
- Short duration (< few ps): TR
- Long duration(> few ps): SR

Proof-of-principle experimental demonstration @ fs exp.

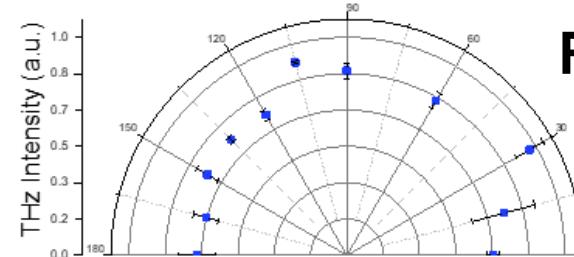
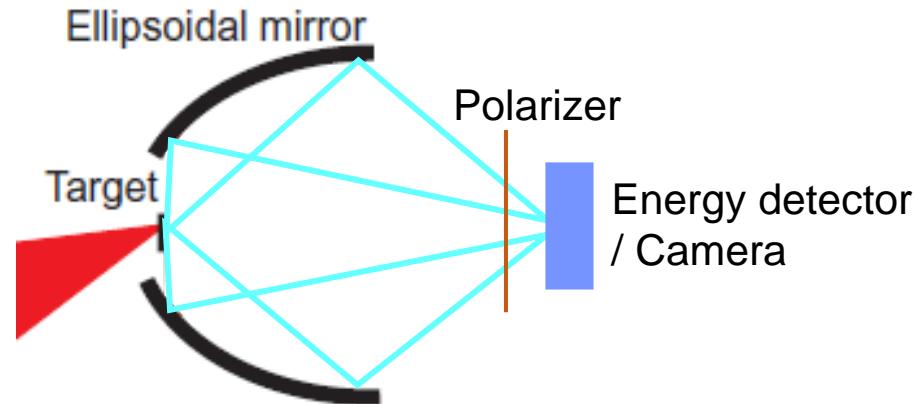
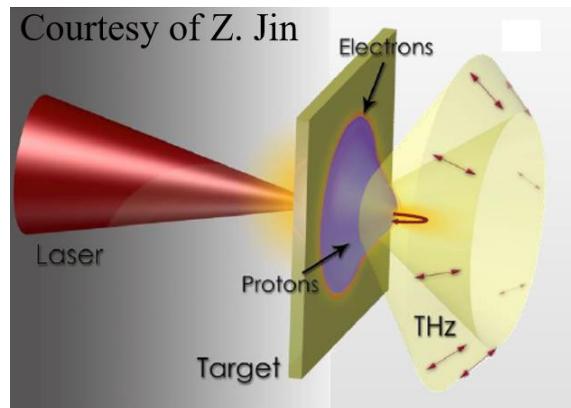


G.-Q. Liao *et al.*, PRL 116,205003 (2016).

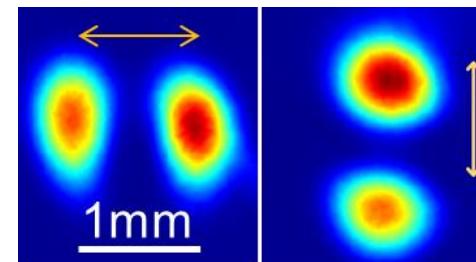
THz angular distribution & polarization



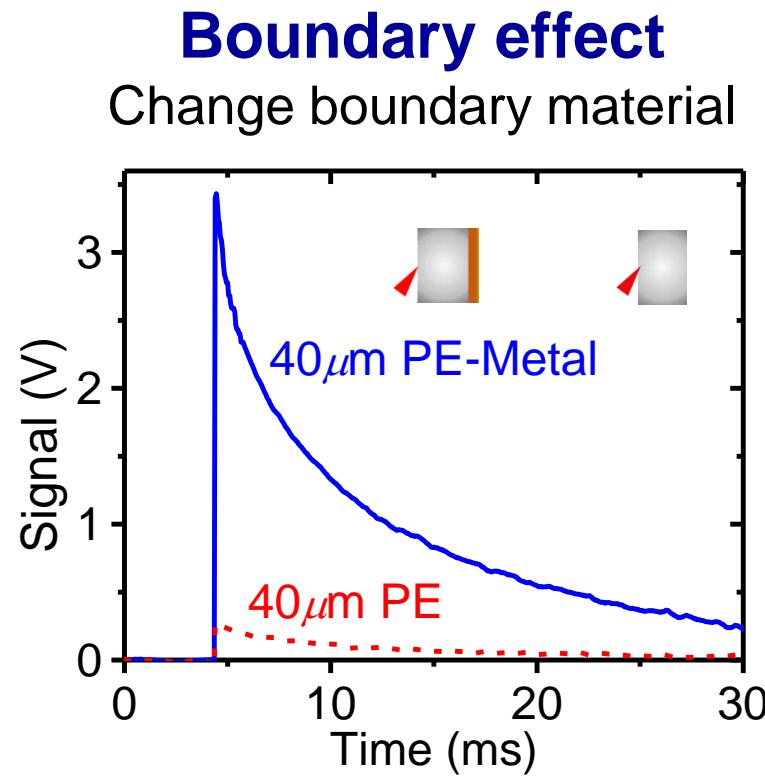
Cone-like angular distribution



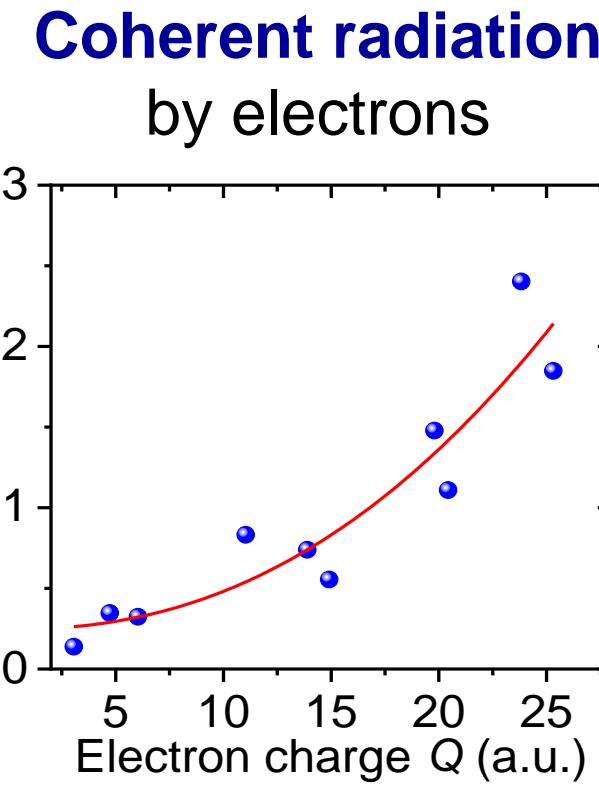
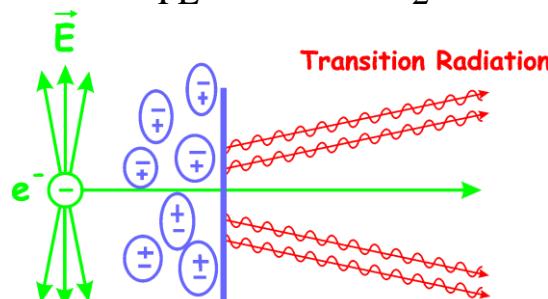
Radially polarized



Experimental verification of coherent transition radiation (CTR)



$$|\epsilon_M| \gg 1, \epsilon_{PE} \sim 2.3 \quad \epsilon_2 = 1$$



THz energy $\sim \propto Q^2$

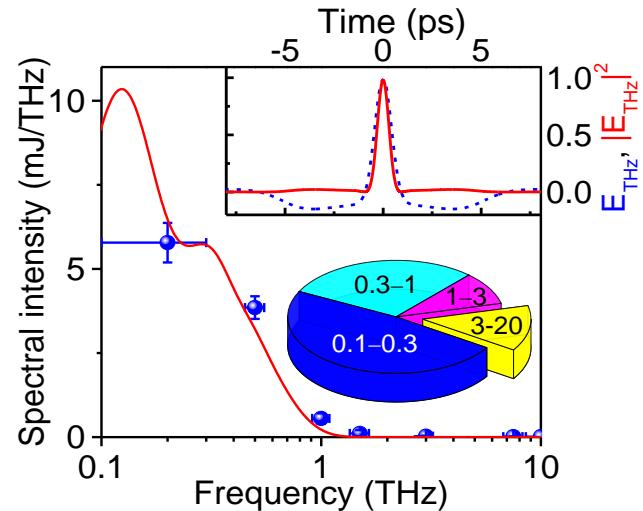
Boosting THz energy

$$W_{CTR} \propto W_e \cdot Q_{esc}^2$$

Escaping charge

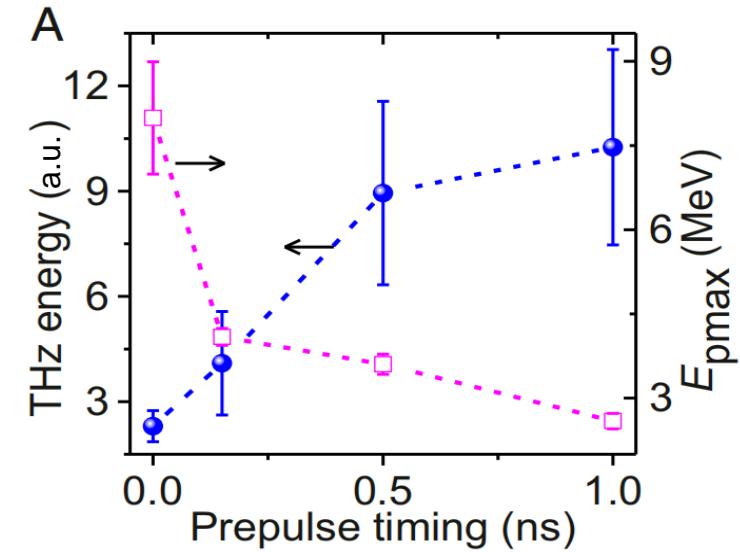
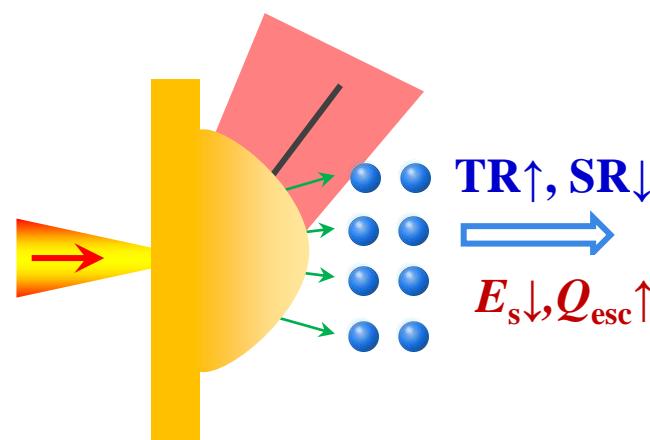
Electron yield Q
 Escaping portion η_{esc}

Exp. @ RAL Vulcan (60J / 1.5ps)



	SLAC	fs exp.	ps exp.
W_{THz} (mJ)	0.6	0.4	55
Q (nC)	0.35	~5.5	~300
E_k	14GeV	~1MeV	~1MeV

Target-rear laser pre-ablation



~3-fold increase !

Total THz energy ~ 200 mJ !

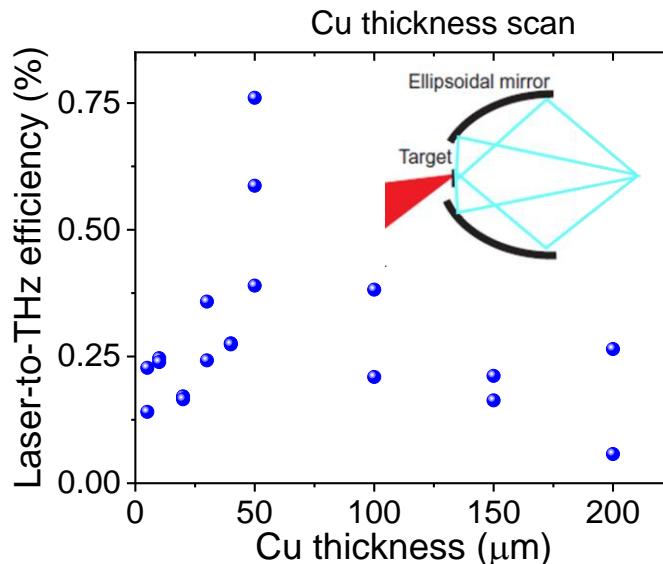
Improving laser-to-THz energy conversion efficiency

$$\eta_{\text{Laser-THz}} = \eta_{\text{Laser-e}} \cdot \eta_{\text{e-THz}}$$

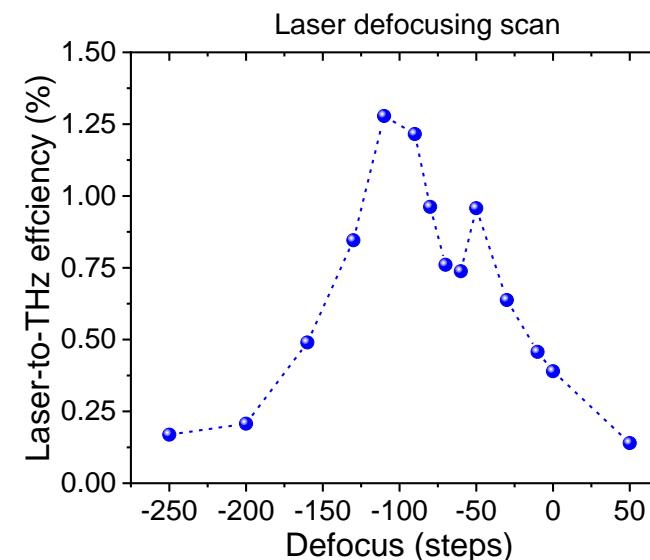
0.3% @ ps exp.

$\eta_{\text{Laser-THz}} \sim 1\%$

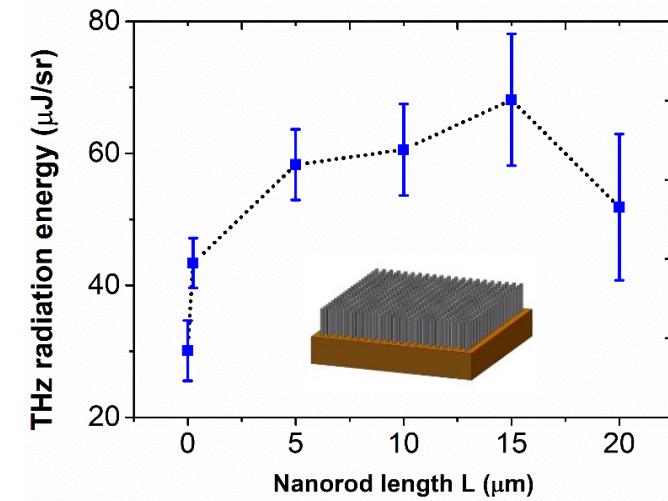
Target thickness scan



Laser focal spot size scan

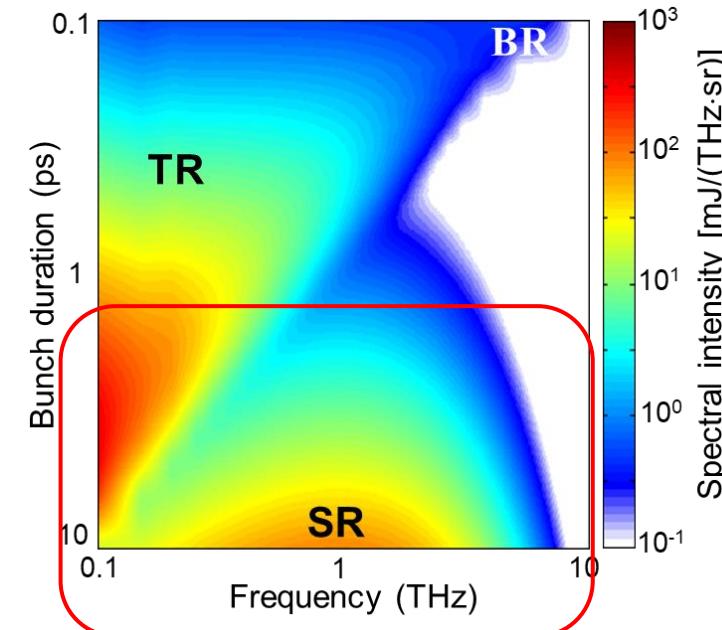
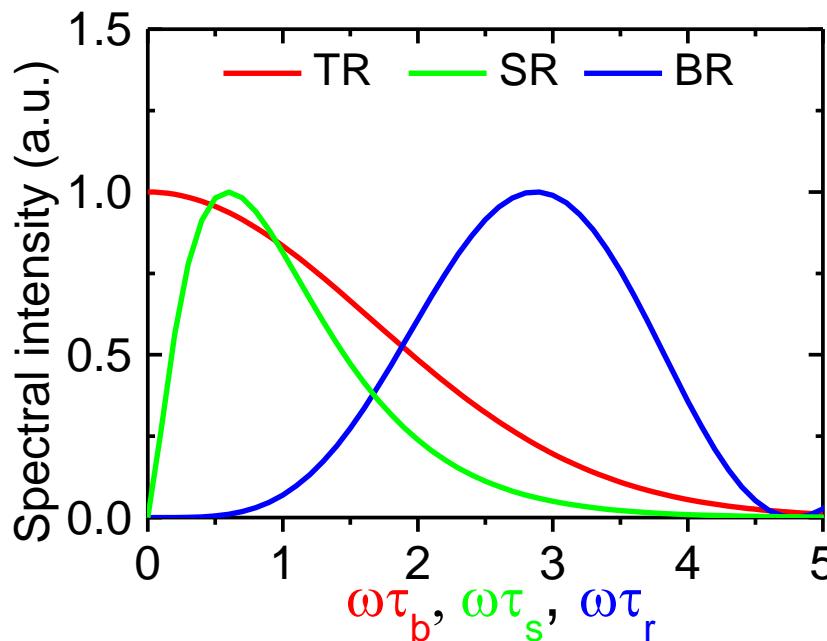


Nanostructured target



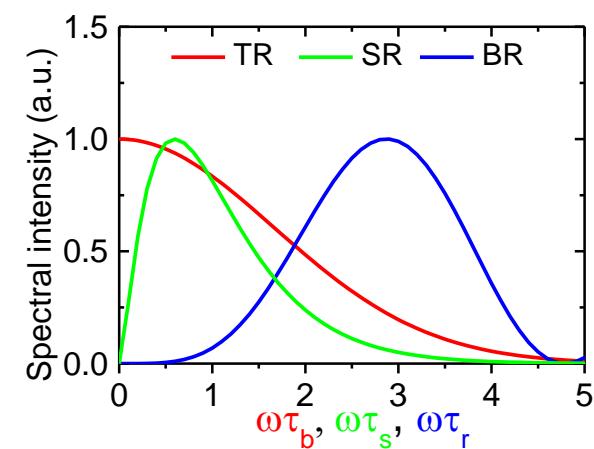
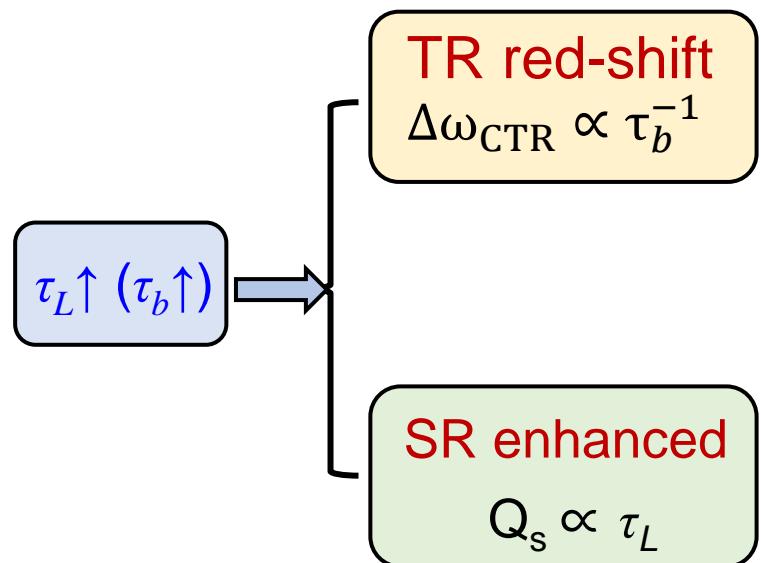
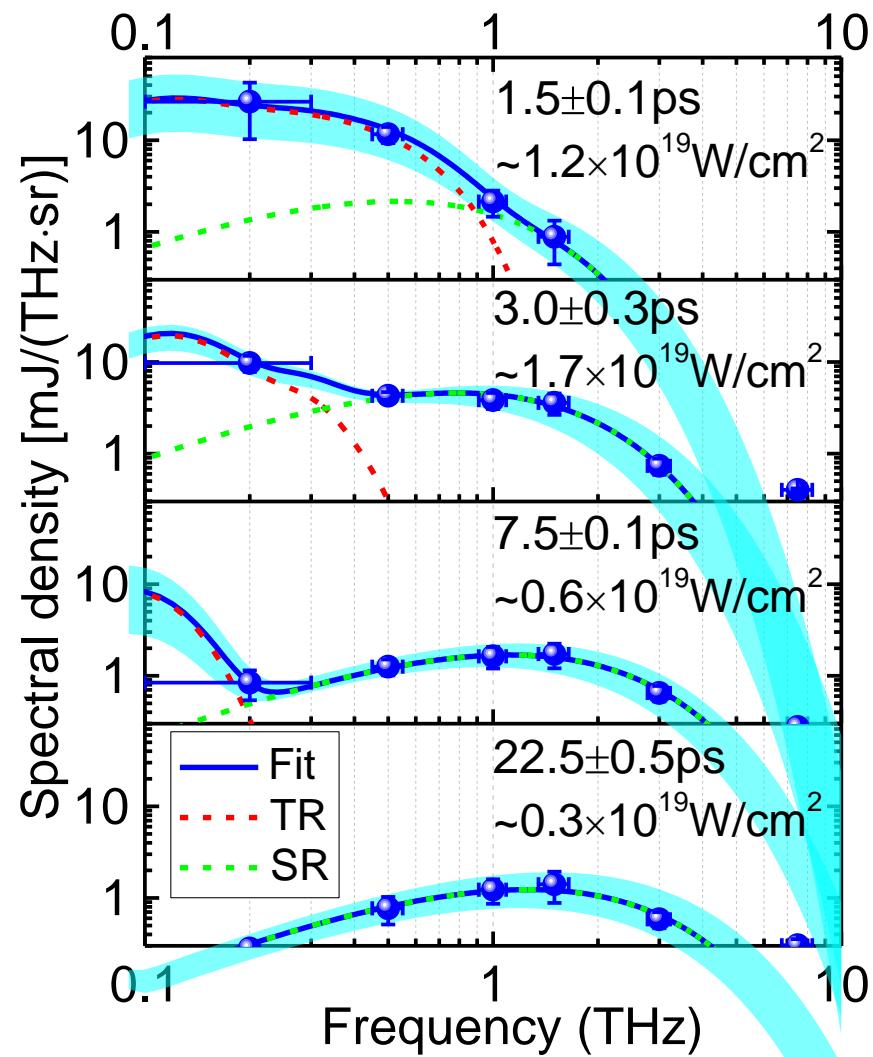
Courtesy of H. Liu

Tuning THz spectra

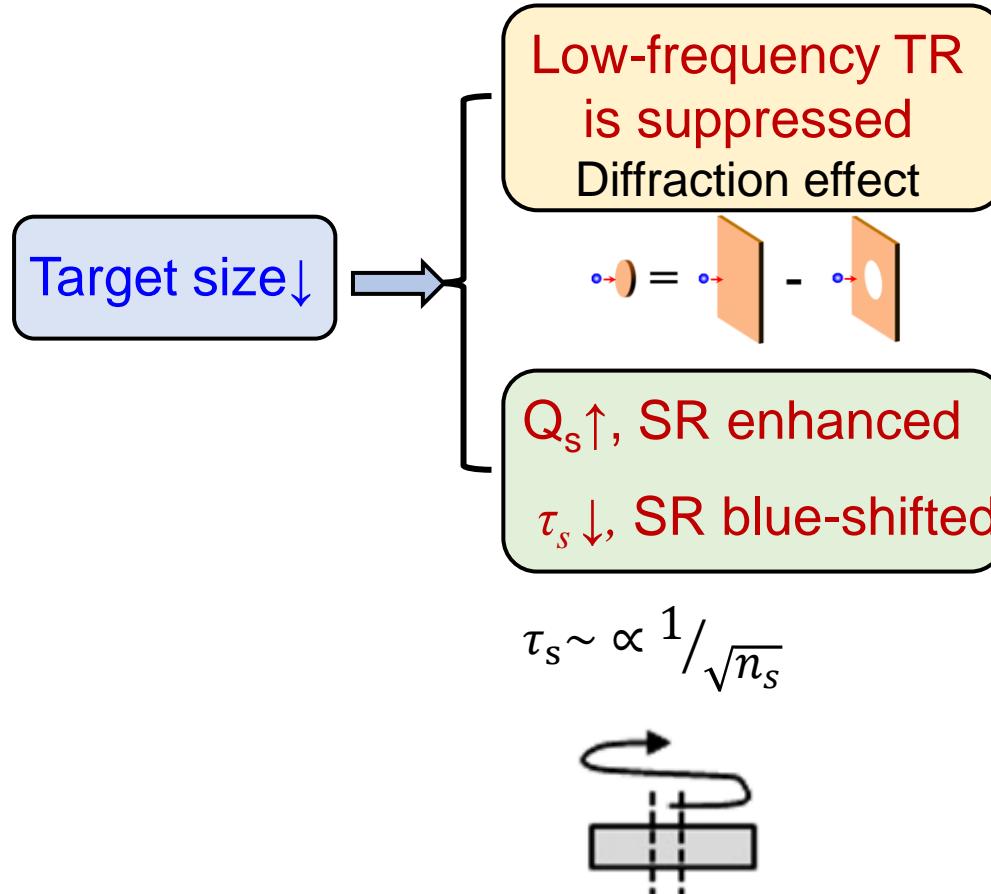
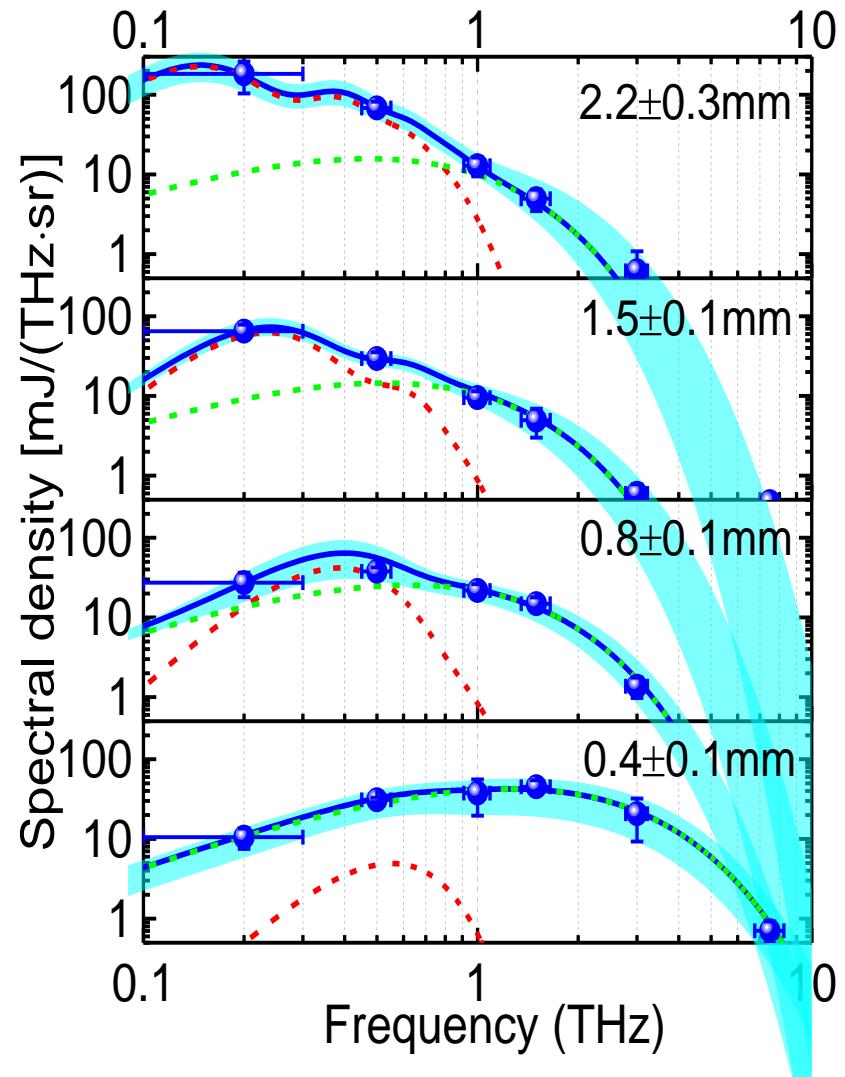


- ① Tuning TR spectra (e.g. 30-fs vs 1.5-ps exp.)
- ② Tuning the relative contribution from TR and SR

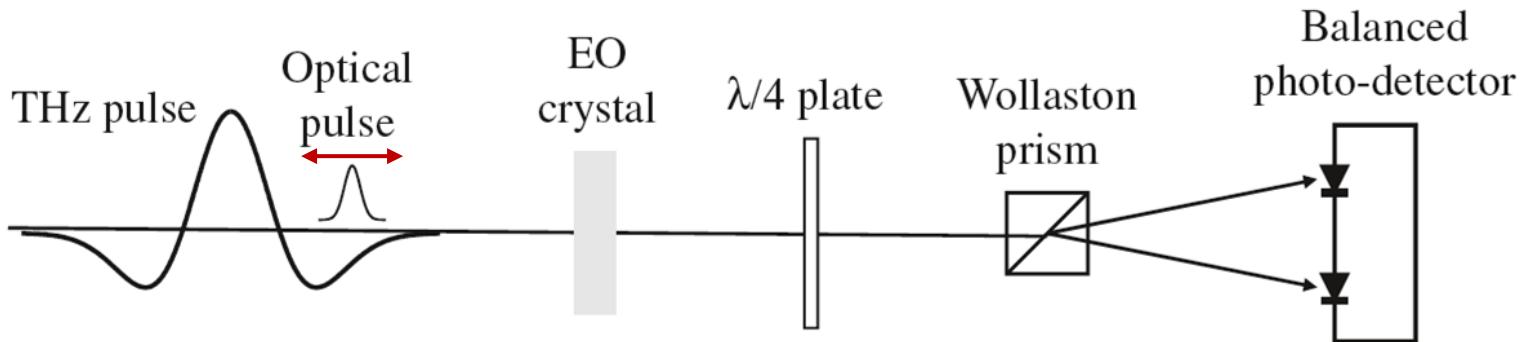
Spectral manipulation scheme I: Varying laser pulse duration



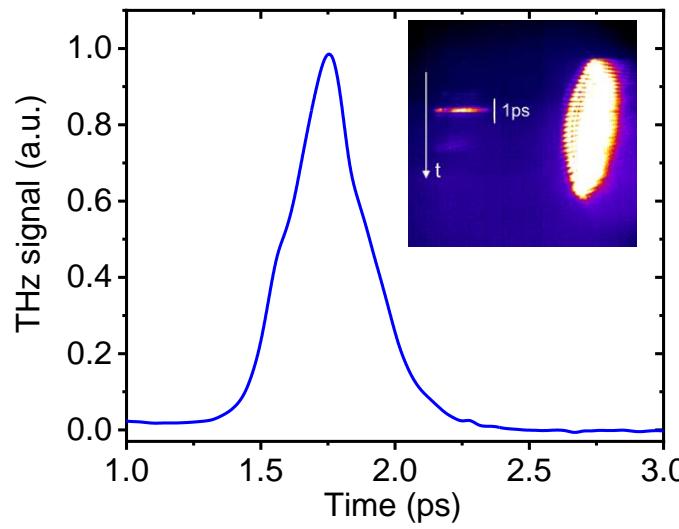
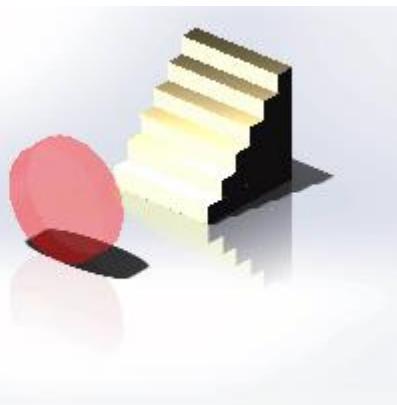
Spectral manipulation scheme II: Tuning target size



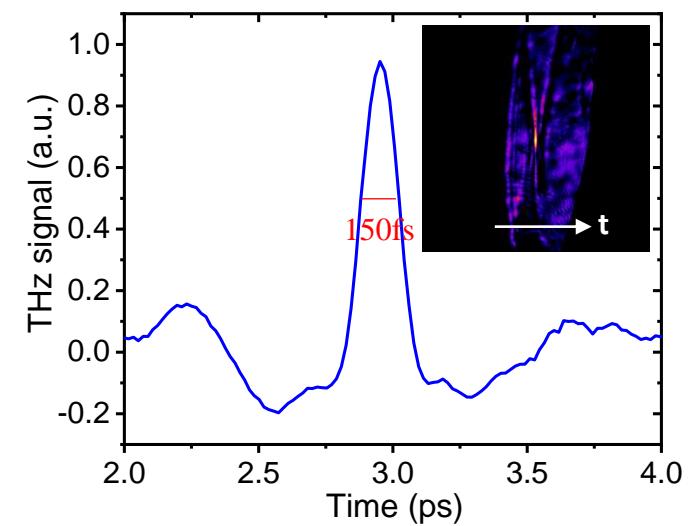
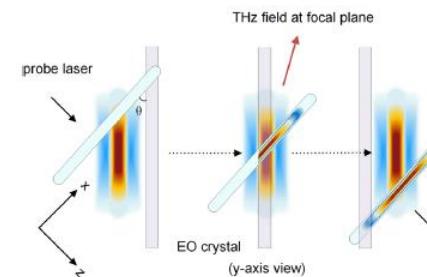
Single-shot THz time-domain waveform characterization



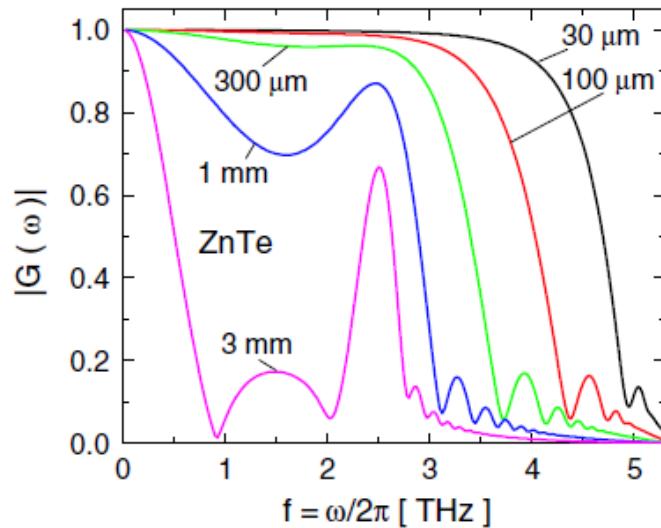
Echelon-based spatially encoding



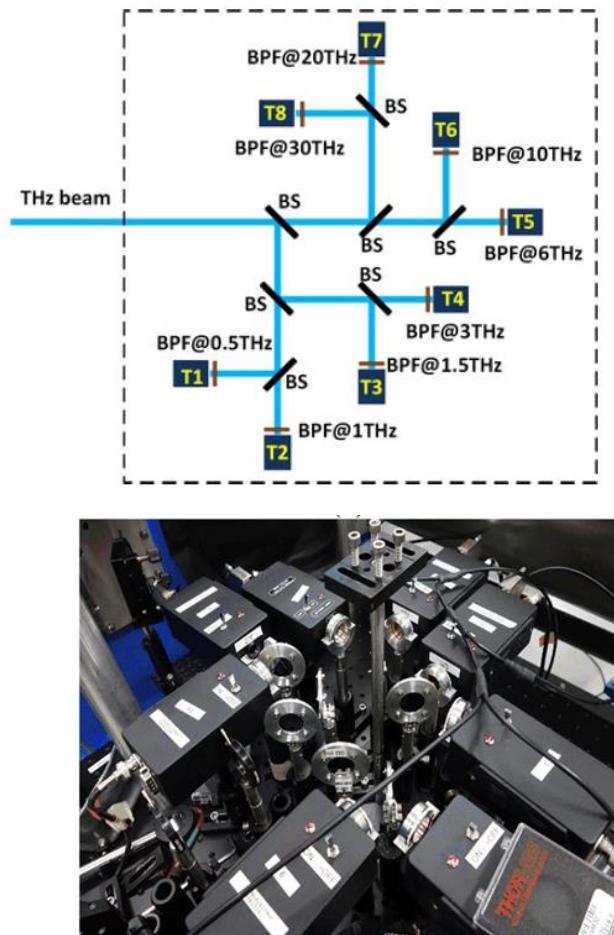
Non-collinear geometry



A multi-channel calorimeter system is developed to evaluate the broadband THz spectrum in single shot

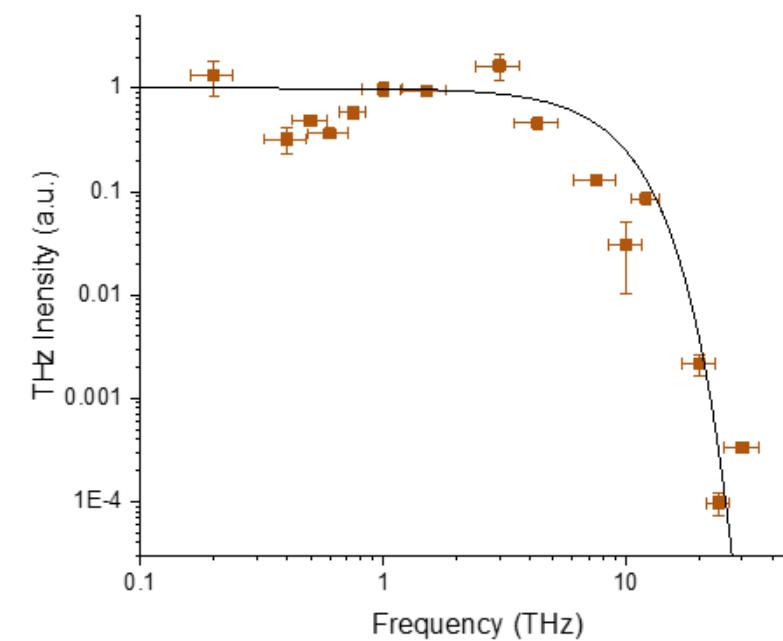


Electro-Optical Sampling (EOS)
“High-frequency cutoff”

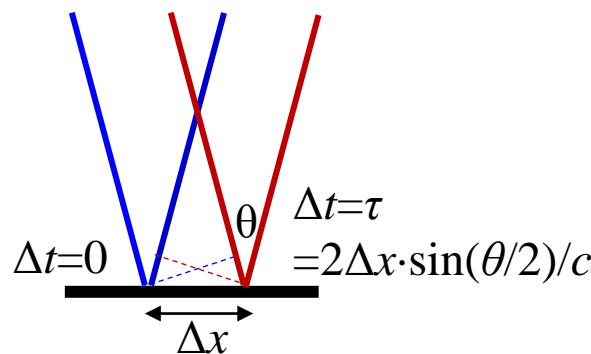
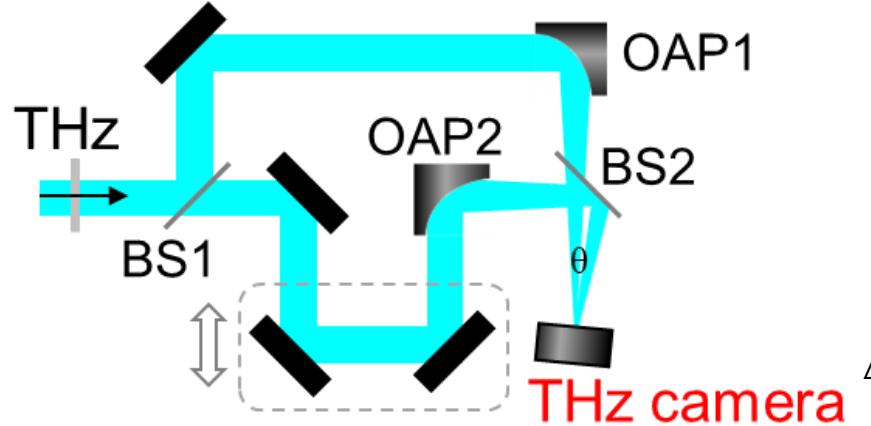


$$S_{\text{det}}(\omega_i) = S_0(\omega_i) \cdot T_{\text{col}}(\omega_i) \cdot T_{\text{bs}}(\omega_i) \cdot T_{\text{filter}}(\omega_i) \cdot R_{\text{det}}(\omega_i)$$

$$I(\omega_i) = S_0(\omega_i) / (\Delta\omega_i \cdot \Delta\Omega)$$



Non-collinear THz autocorrelator



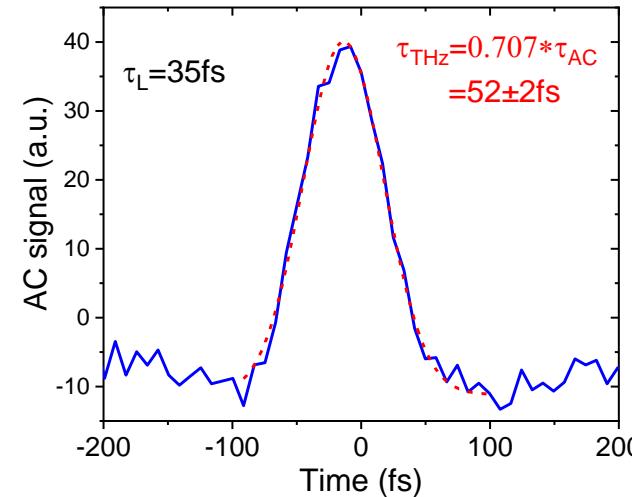
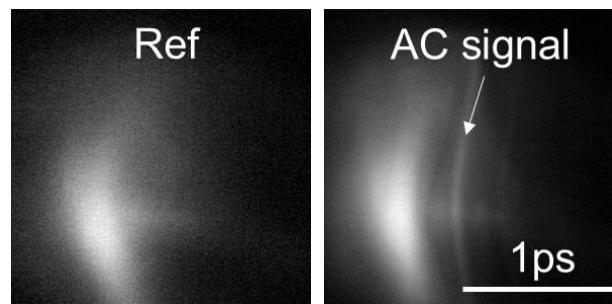
$$I(\tau) \propto \int_{-\infty}^{+\infty} |E(t) + E(t - \tau)|^2 dt$$

$$= 2I_0 + 2 \int_{-\infty}^{+\infty} E(t) \cdot E^*(t - \tau) dt$$

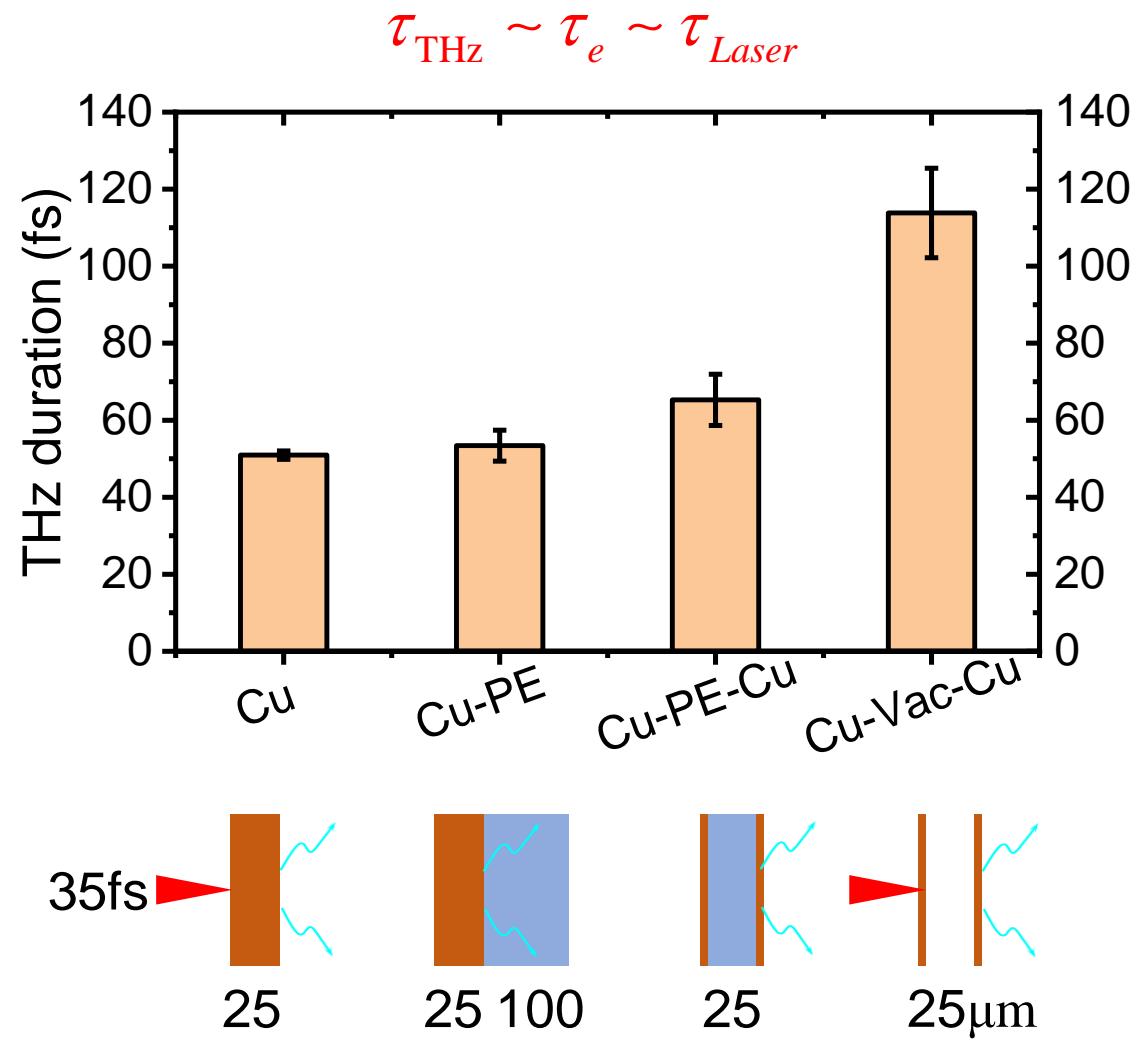
Auto-correlation $\Gamma(\tau)$

$$|\tilde{E}(\omega)|^2 = \mathcal{F} \left\{ \int_{-\infty}^{\infty} E(t) E^*(t - \tau) dt \right\}$$

For a Gaussian pulse, $\tau_p = 0.7071 * \tau_{AC}$



Ultrafast THz pulse versus target configuration



The most intense (200-mJ / 1-TW) THz pulse reported in lab

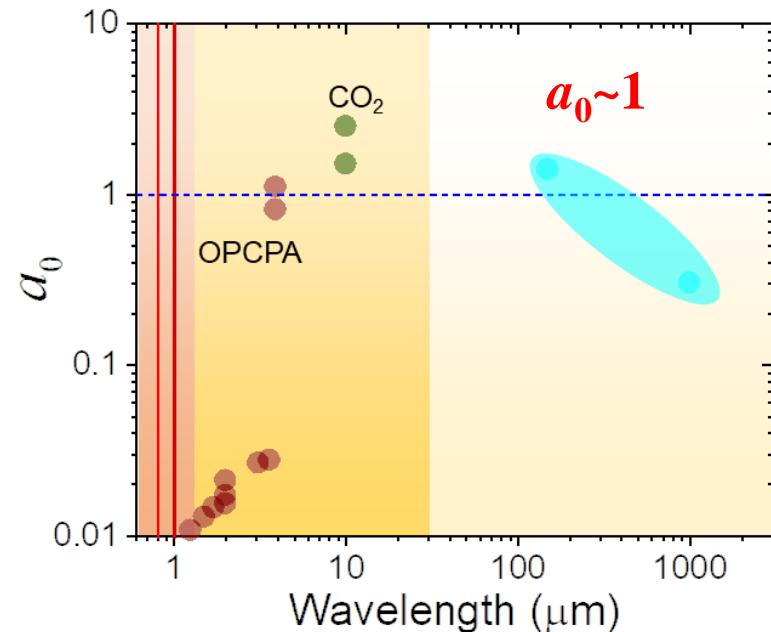
THz sources	Pulse energy (mJ)	Peak power (GW)	$\eta_{\text{laser-THz}}$
FEL	0.1	~0.001	—
Accelerator (TR)	0.6	~(2–4)	—
Organic crystal (OR)	0.9	~4	~3%
LiNbO_3 (OR)	~1.4	~1	~0.77%
Air plasmas	0.2	~0.1	2.36%
Liquid plasmas	0.04	~0.04	~0.1%
Solid plasmas	~200	$\sim 1.2 \times 10^3$	~1.25%

Ultraintense laser driven TW-level THz radiation !

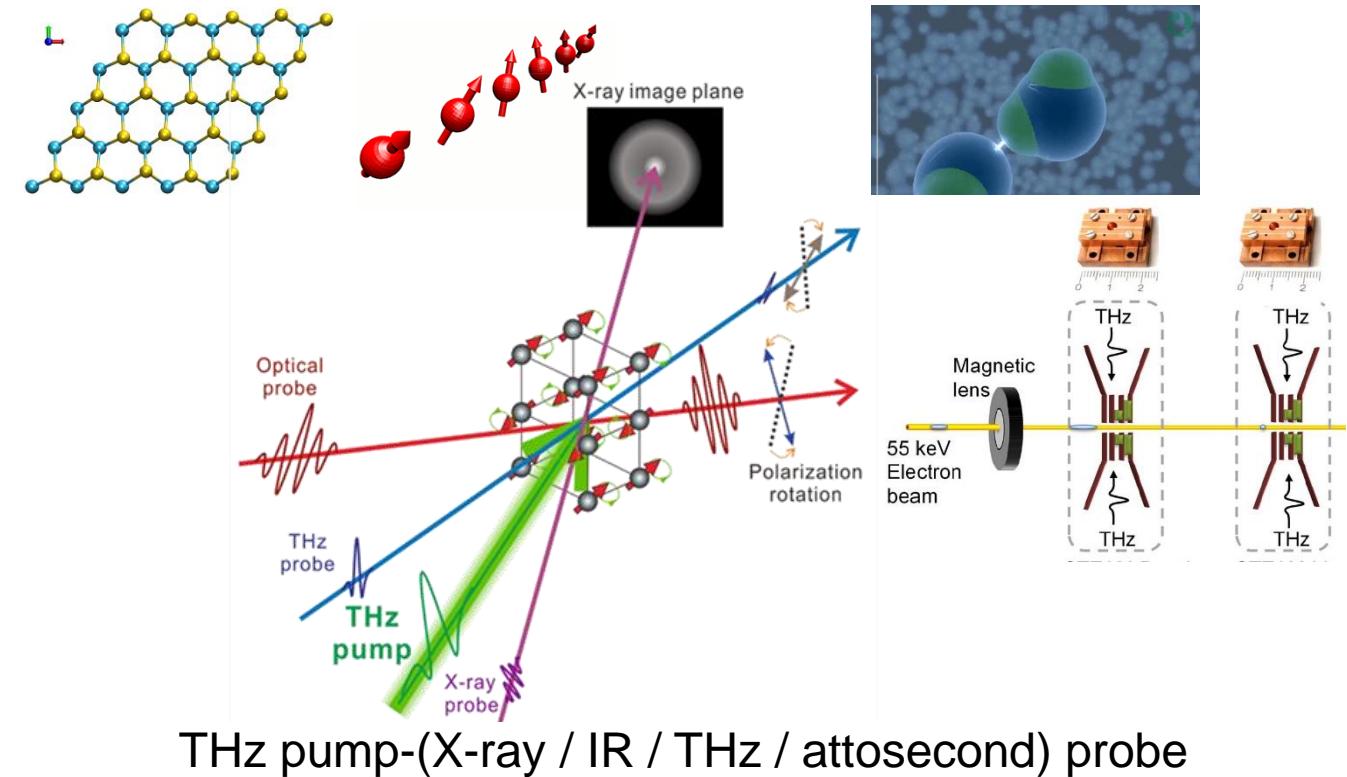
Prospects for extreme THz applications

□ THz strong-field physics / THz relativistic optics

$$E_{\text{THz}} > 10 \text{ GV/m}, B_{\text{THz}} > 30 \text{ T}$$

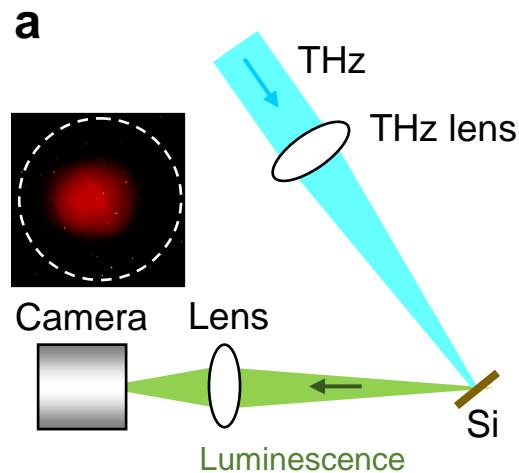


□ Ultrafast control of matter

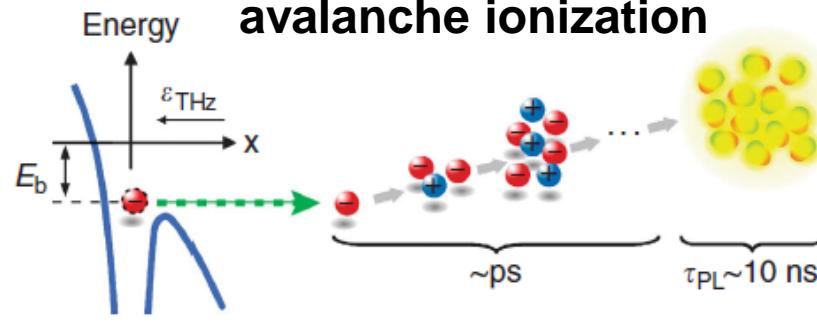


Preliminary THz application demonstration

Impact ionization

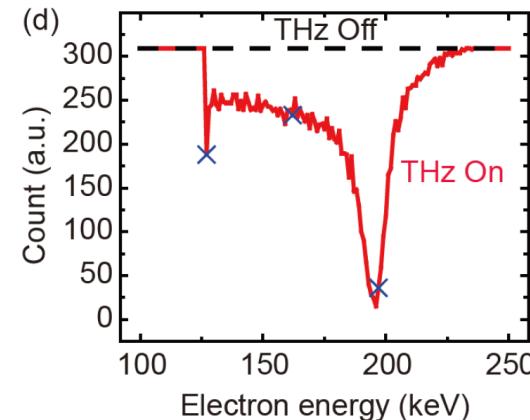
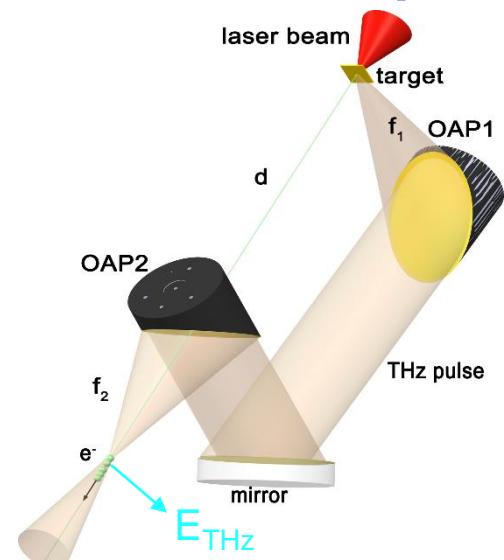


avalanche ionization



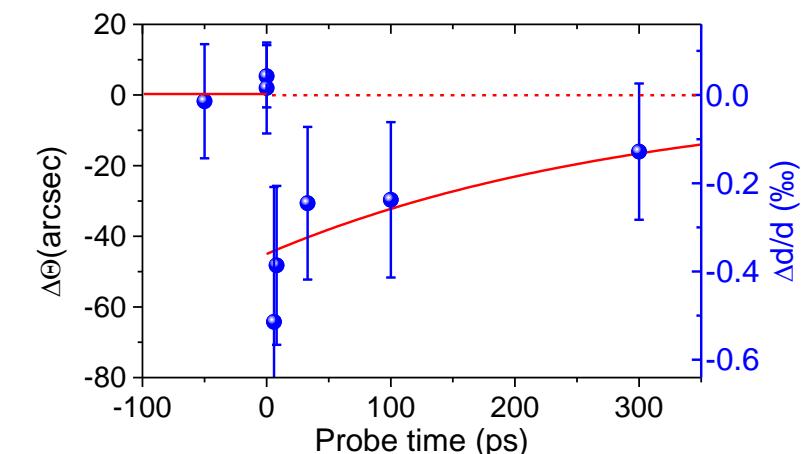
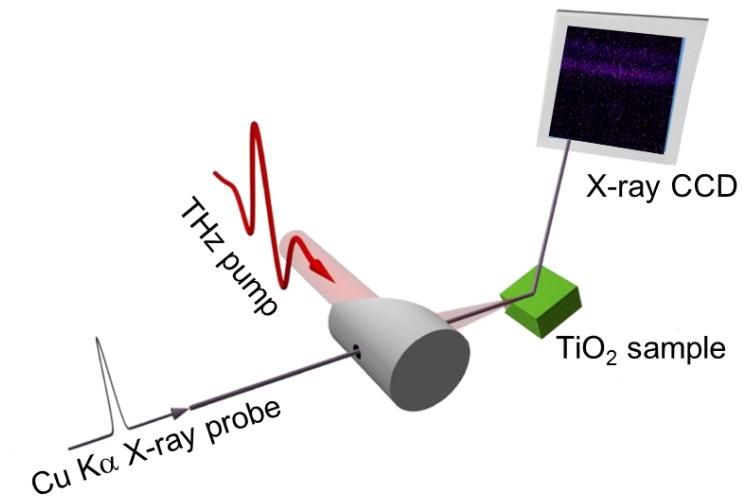
$$U_p = \frac{e^2 E_{\text{Thz}}^2}{4m_e \omega_0^2} \sim 220 \text{ eV}$$

Electron manipulation

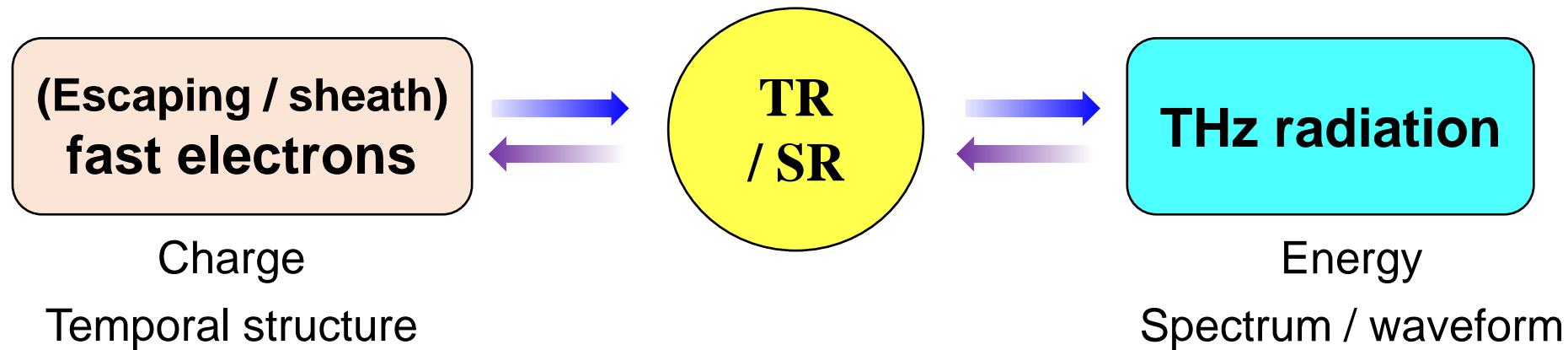


$$v = \frac{d + f_2}{2f_1 + d + f_2} c$$

THz pump –XRD probe



THz application as an *in-situ* fast-electron diagnostic

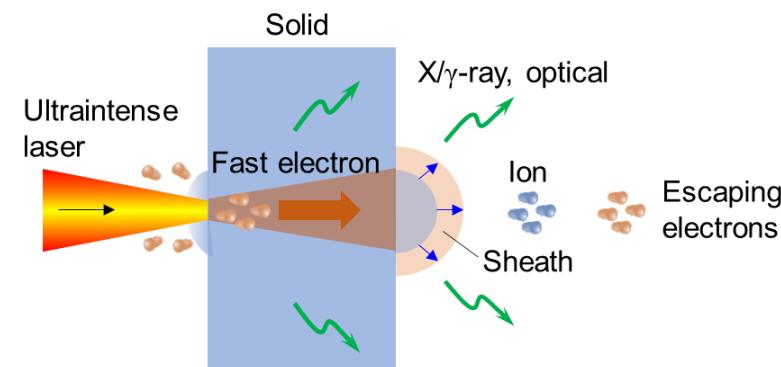
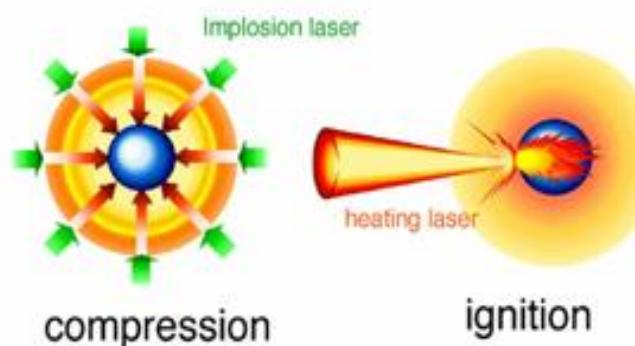


$$I_{CTR} \simeq \left\langle \frac{d^2 u}{d\omega d\Omega} \right\rangle N_e^2 F(\omega)$$

$$F(\omega) = \exp(-\omega^2 \tau_b^2 / 2)$$

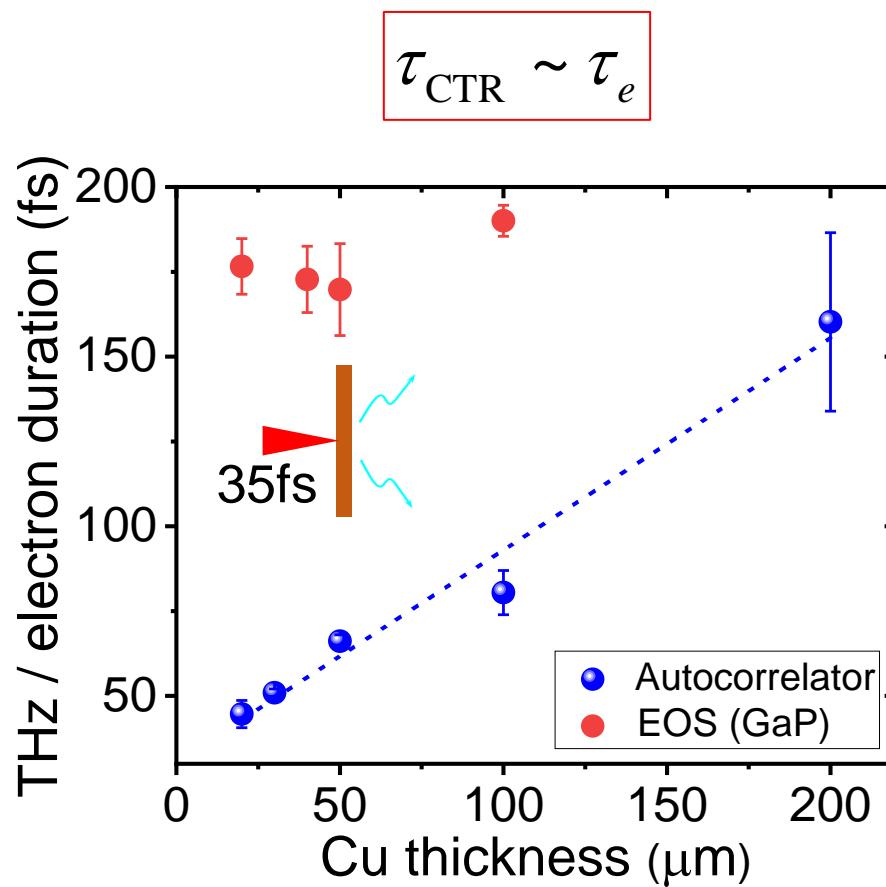
$$I_{SR} = \frac{Q_{s0}^2 \beta_s^2 \sin^2 \theta}{16\pi^3 \epsilon_0 c} |G_{SR}(\omega \tau_s)|^2$$

$$G_{SR}(\omega) = \omega \int 1/\sqrt{1+t^2} e^{i\omega t} dt$$

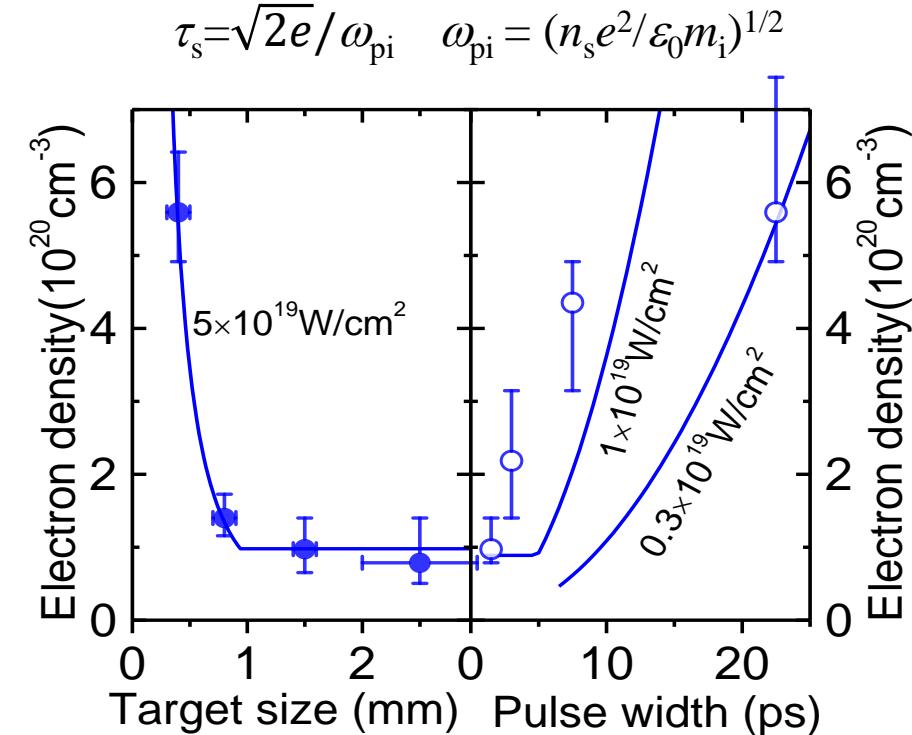


THz diagnosis of fast electrons

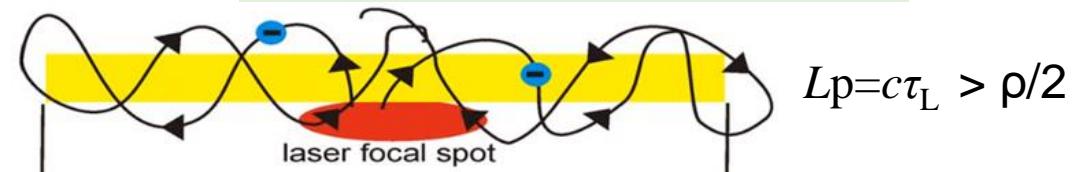
Electron bunch duration



Sheath electron density



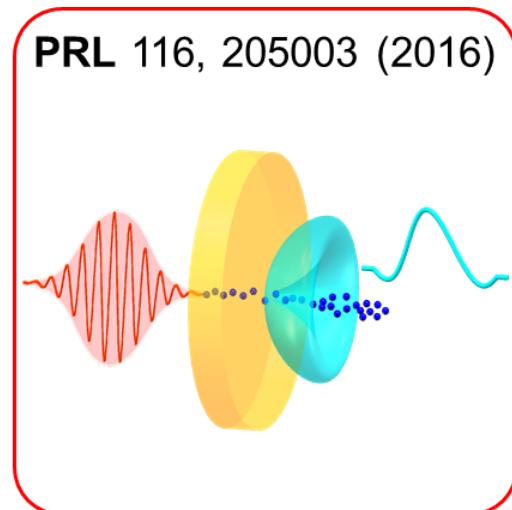
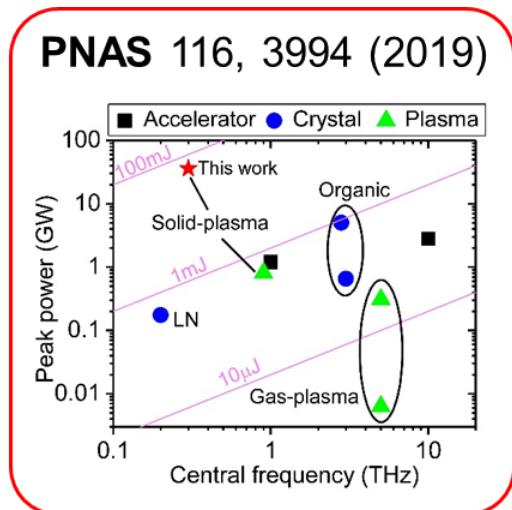
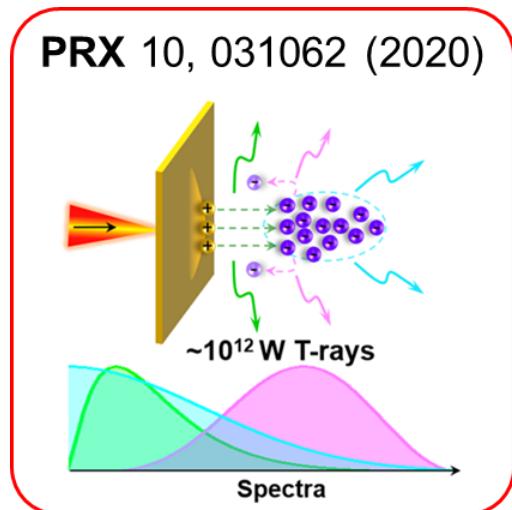
Transverse refluxing effect



Concluding Remarks

Ultraintense laser driven extreme terahertz radiation

- ✓ Physical mechanisms: TR, SR, BR
- ✓ High pulse energy (~200 mJ), high peak power (~1 TW), high efficiency (~1%), ultrabroadband spectrum (0.1-30THz), ultrashort duration (30fs-10ps)
- ✓ Extreme THz wave – matter interactions
- ✓ THz radiation as an *in-situ* fast-electron diagnostic



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Thank you for your attention !

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