Strong THz generation from air plasma using a long wavelength laser

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Project goals

❑ Study of THz/microwave emission from 10 μm filamentation

- Investigate THz/microwave generation mechanisms
  (single-color, two-color, 10.3 μm + 10.6 μm mixing schemes)
- High-power THz/microwave generation

❑ Development of THz/microwave detection schemes

- THz/microwave characterization (energy, spectrum, polarization,…)
- Single-shot THz/microwave spectroscopy

❑ Characterization of CO_2 laser produced air filaments

- THz/microwave radiation spectral analysis
- Plasma density measurement with a B-dot probe
- Time-resolved THz spectroscopy with a femtosecond laser

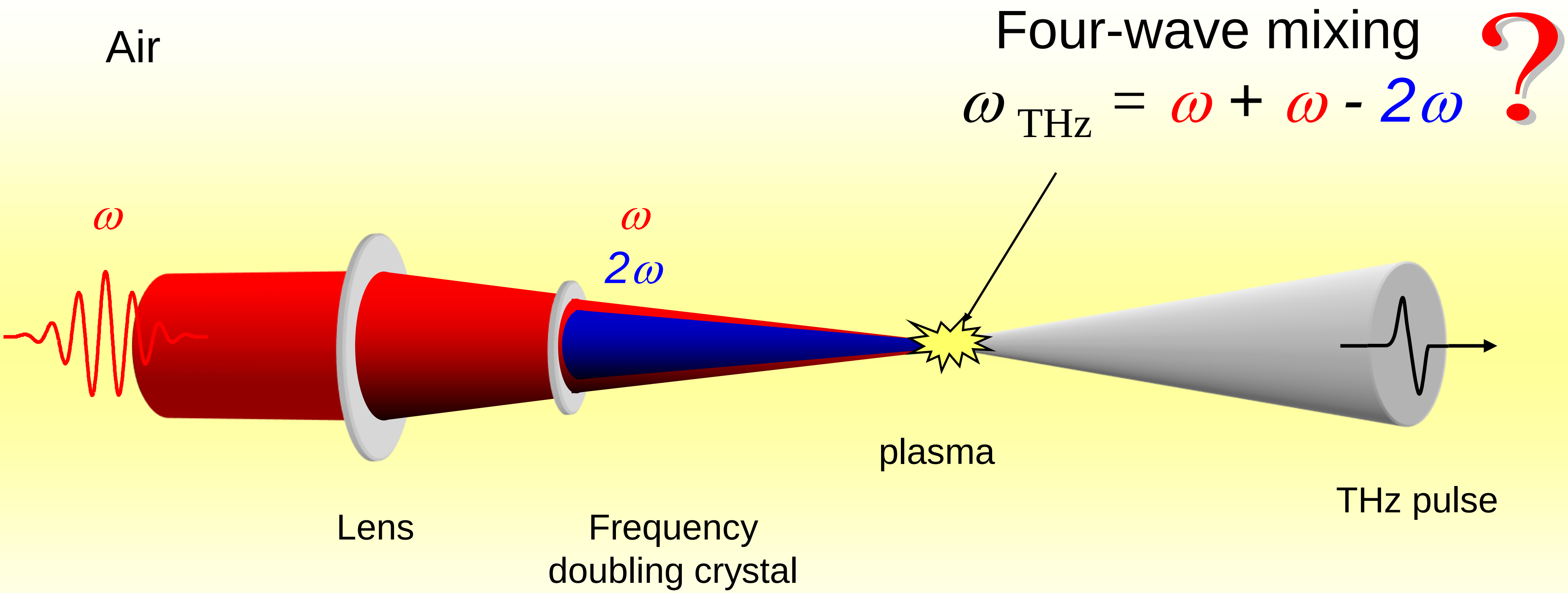
Outline

- Strong THz field generation
  - Two-color laser mixing
- THz/harmonics generation at long wavelengths
  - 1% laser-to-THz conversion efficiency
  - Coherent control of ionization, THz, and harmonics
- Future experiments & simulation
  - mJ-level THz generation
  - Accurate phase-dependent measurements
  - UPPE simulation
- Summary

Strong THz field generation:

Two-color laser mixing

THz generation via two-color laser mixing:

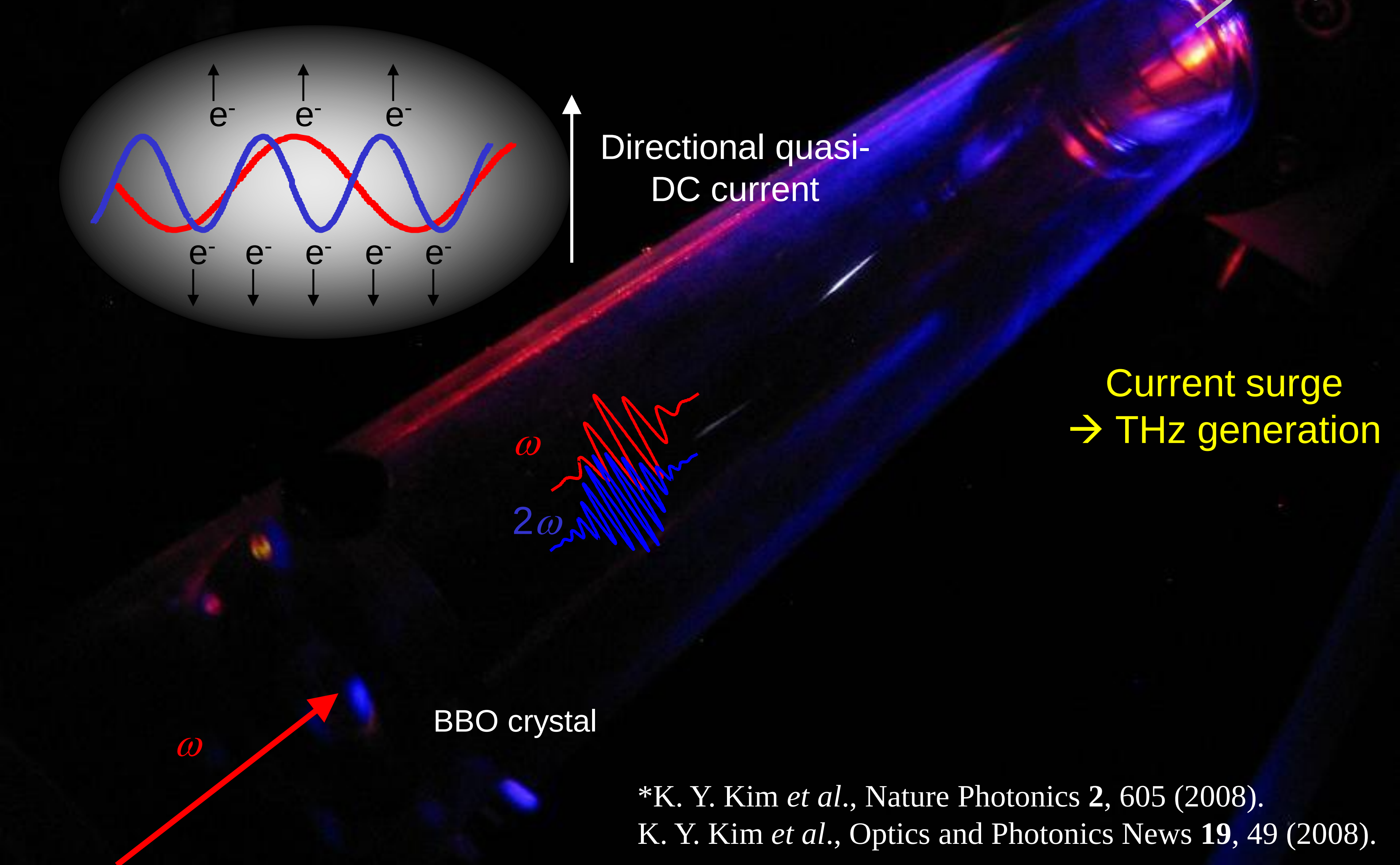


$$\mathbf{P}(t) = \varepsilon_0 \left(\chi^{(1)} \mathbf{E}(t) + \chi^{(2)} \mathbf{E}^2(t) + \chi^{(3)} \mathbf{E}^3(t) + \dots \right)$$

D. J. Cook and R. M. Hochstrasser, Opt. Lett. **25**, 1210 (2000).

THz generation mechanism:

Plasma current model*



*K. Y. Kim *et al*., Nature Photonics **2**, 605 (2008).
K. Y. Kim *et al*., Optics and Photonics News **19**, 49 (2008).

Plasma current model (semiclassical model):

Laser field

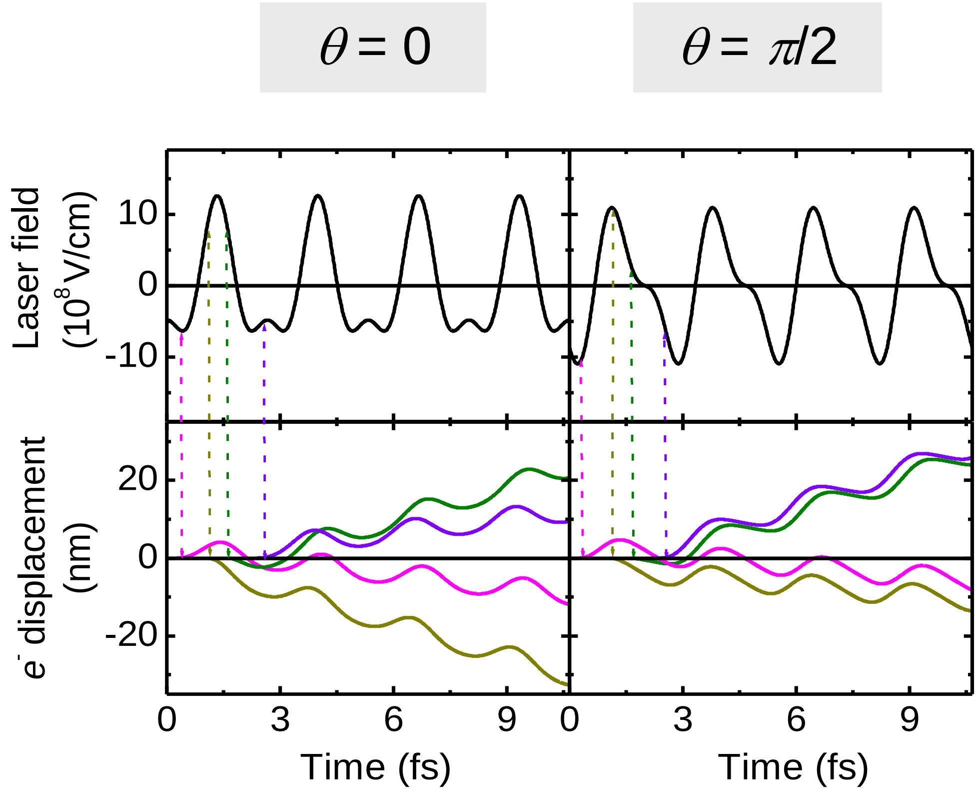
$$E_L(t) = \underbrace{E_1 \cos(\omega t)}_{\omega \text{ field}} + \underbrace{E_2 \cos[2\omega t + \theta]}_{2\omega \text{ field}}$$

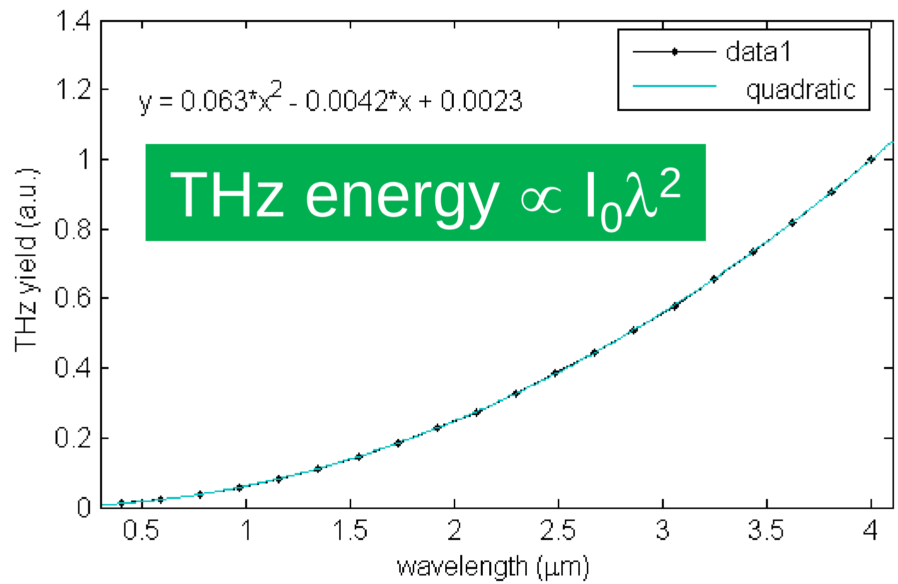
θ : relative phase

Electron drift velocity

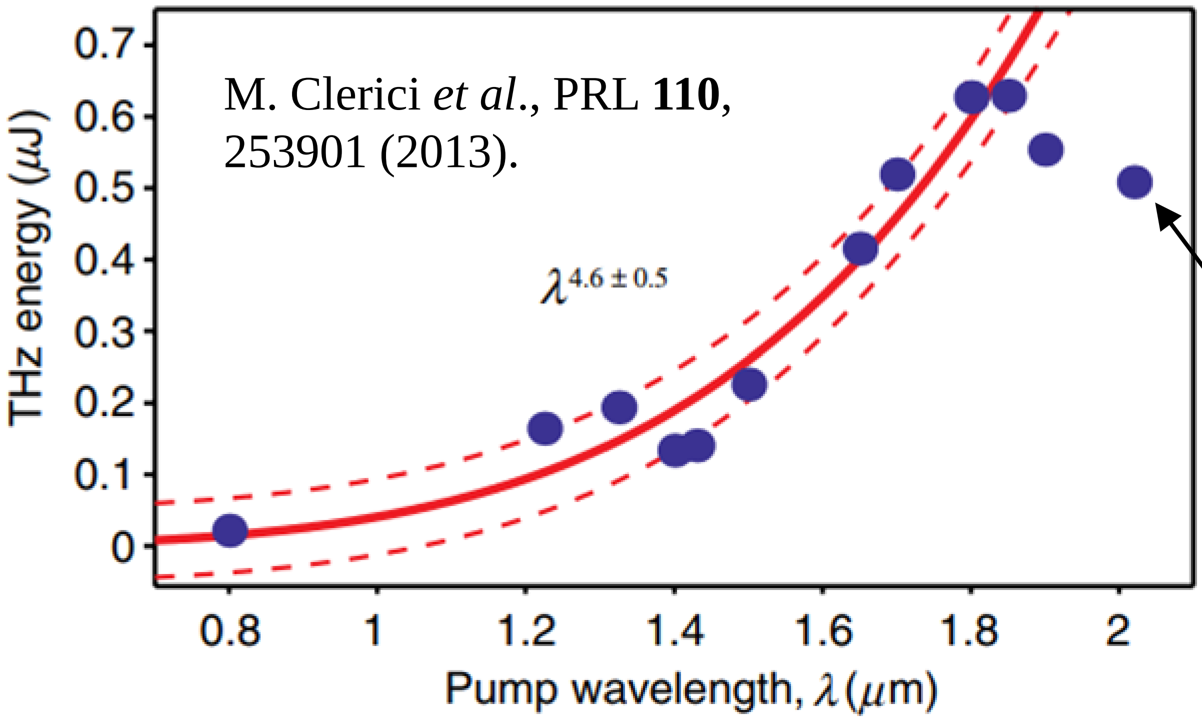
$$\upsilon_d = \frac{eE_1}{m_e \omega} \sin\phi + \frac{eE_2}{2m_e \omega} \sin(2\phi + \theta)$$

electron freed at ϕ





Wavelength scaling with two-color mixing



Due to laser peak intensity drop

THz energy scaling:

Plasma current $(\sim\lambda^2)$
Plasma length & radius $(\sim\lambda)$
Peak intensity $(\sim\lambda^{-2})$
Longitudinal current $J_z^{(2)}$ $(\sim\lambda^4)$
Transverse current $J_x^{(3)}$ $(\sim\lambda^6)$

Need more studies!

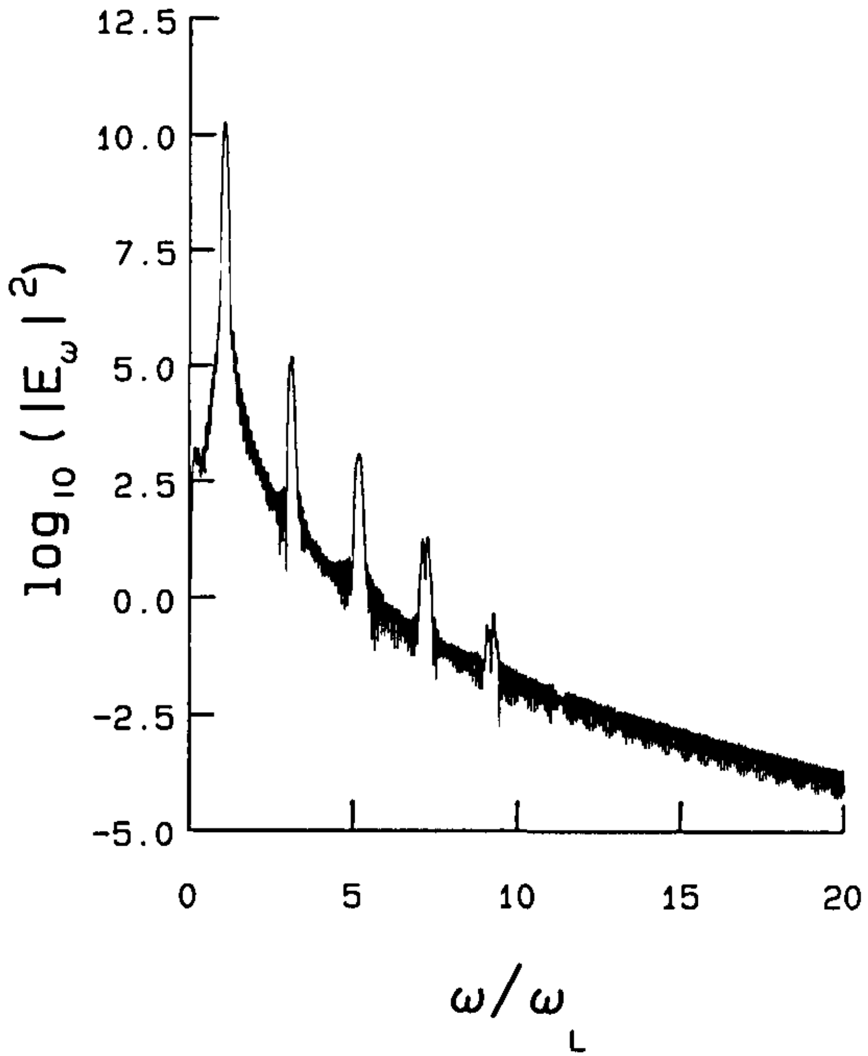
Brunel radiation*

- Brunel proposed harmonic generation due to plasma effects in a gas undergoing ionization
- Bound-free transition (plasma current) produces harmonics
- THz = 0th order Brunel radiation
- Explains lower-order harmonics

(N. H. Burnett *et al.*, PRA **51**, R3418 (1995))

- Higher-order harmonics due to recollisions

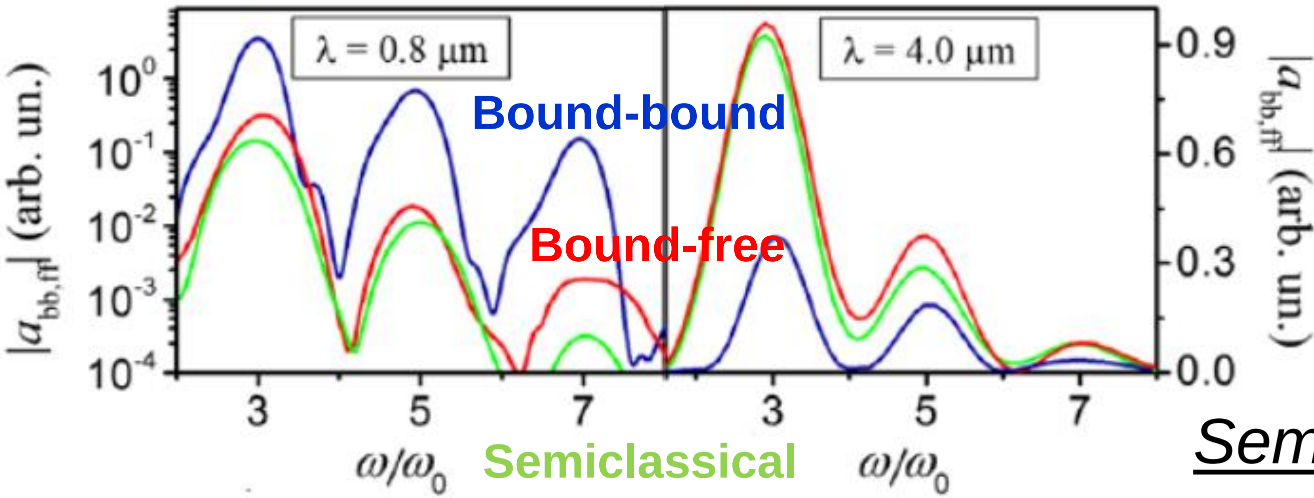
(P. B. Corkum, PRL **71**, 1994 (1993))



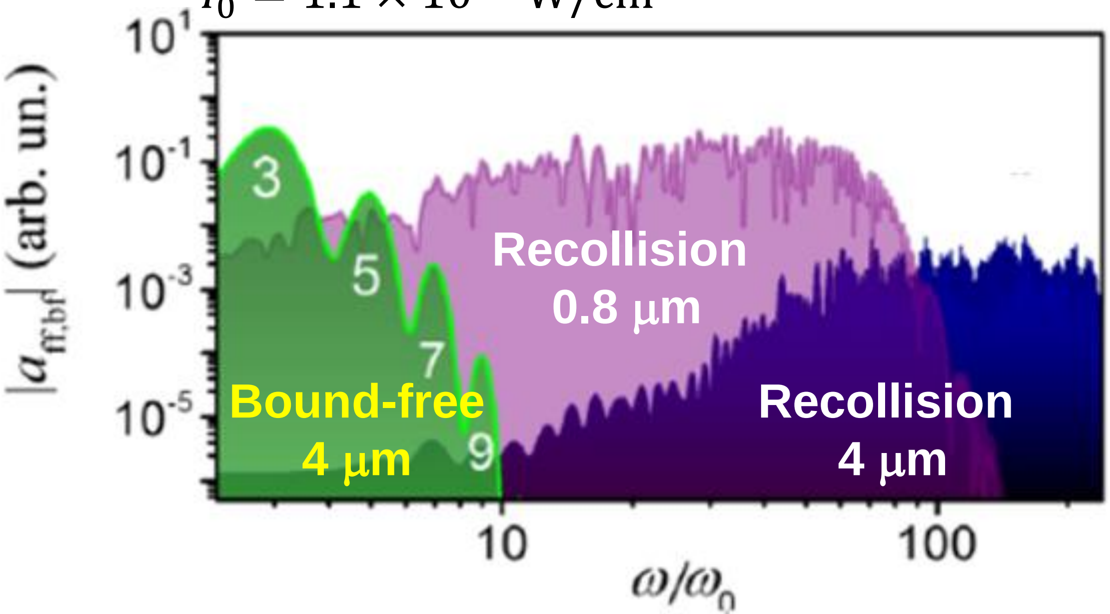
*F. Brunel J. Opt. Soc. Am. B **7**, 521 (1990)

Contributions from bound vs free electrons

Time-dependent Schrödinger equation (TDSE)



$I_0 = 1.1 \times 10^{14}\ \mathrm{W/cm^2}$



At long wavelengths

Bound-free
>>
Bound-bound

Semiclassical plasma current (Brunel radiation) dominant

Bound-free
>>
Free-bound (Recollision)

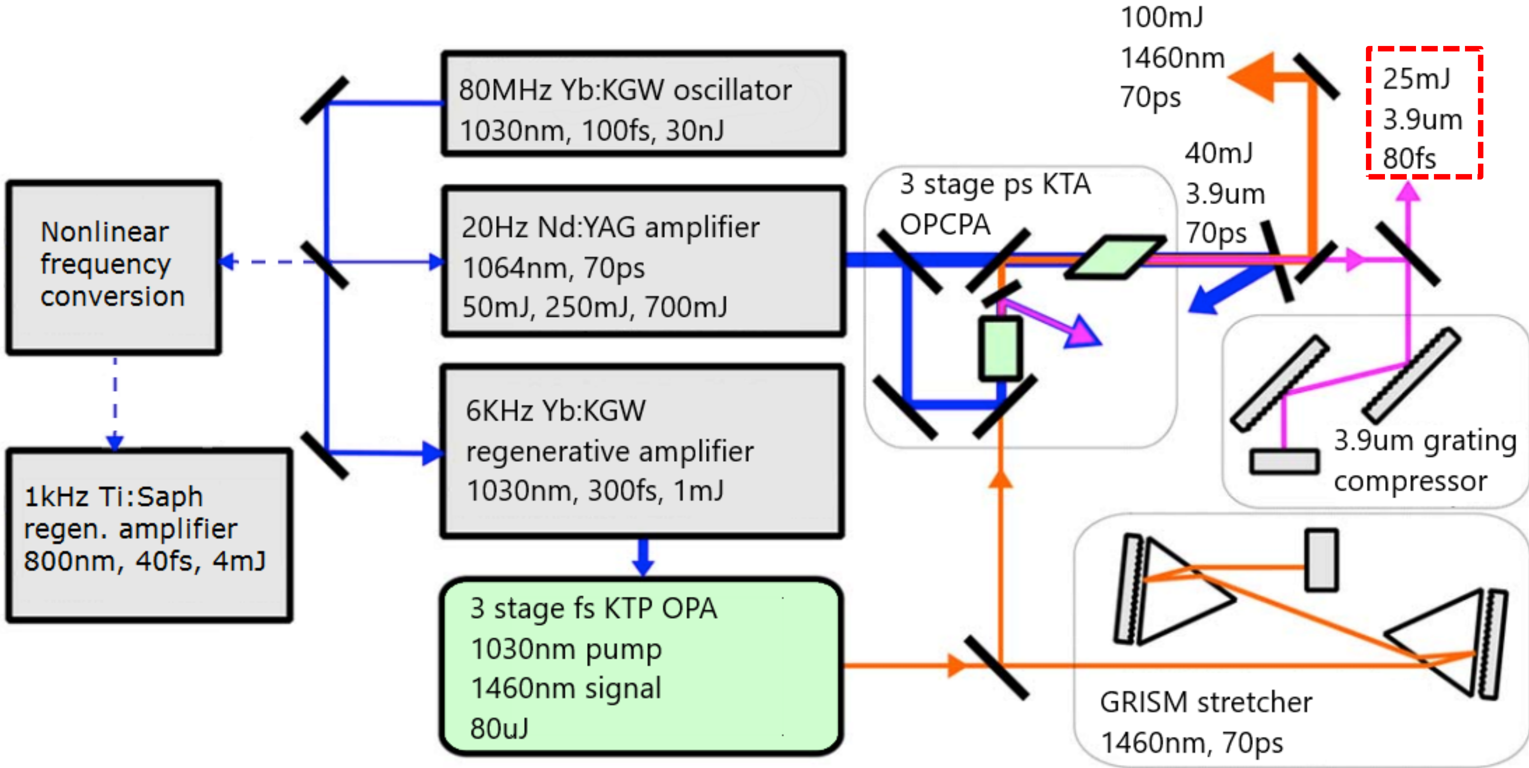
E. E. Serebryannikov and A. M. Zheltikov, PRL **113**, 043901 (2014)

THz & harmonics generation:

Experiment

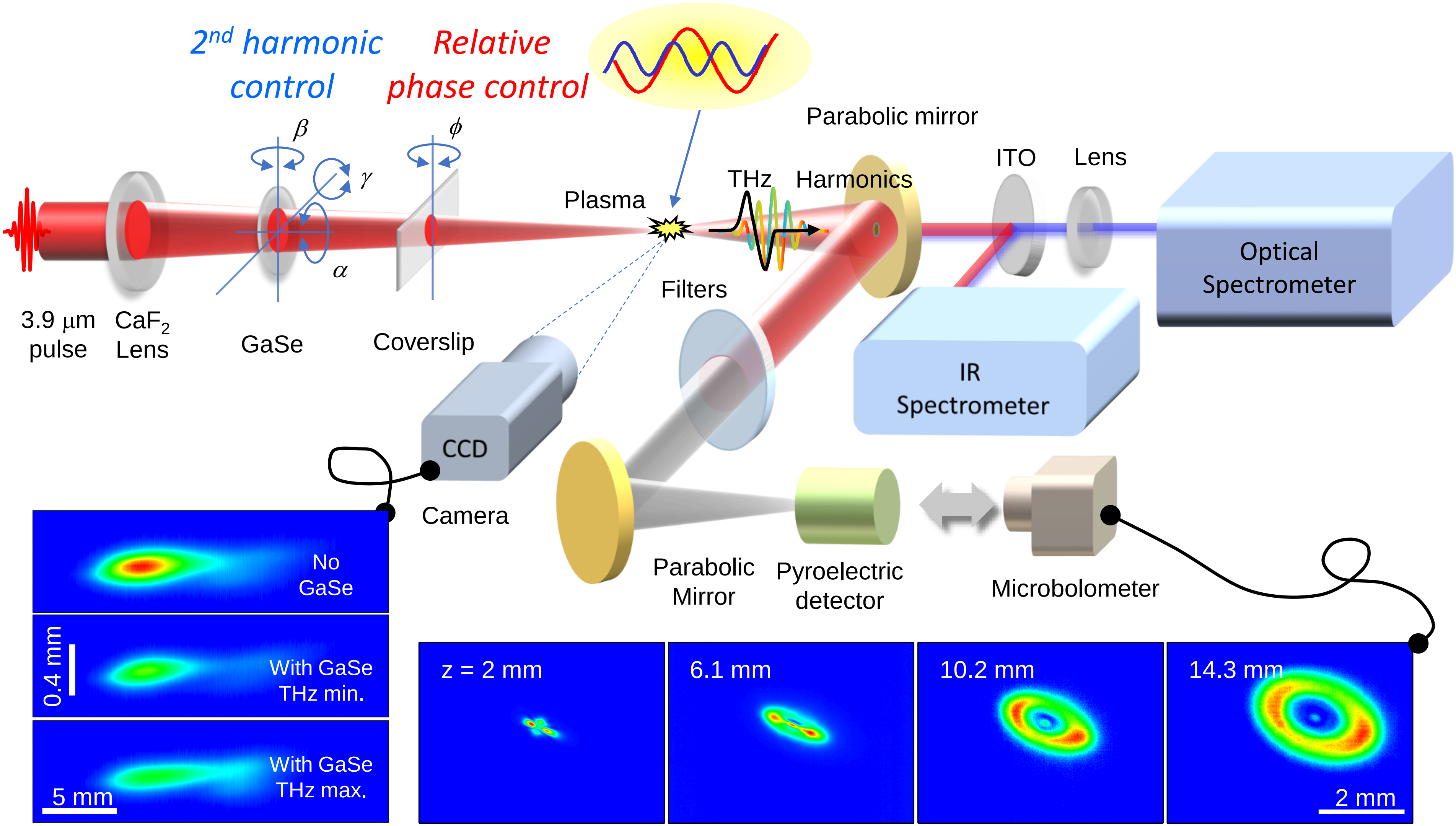
OPCPA laser at UMD (λ = 3.9 μm)

Optical Parametric Chirped-pulse Amplification (OPCPA)



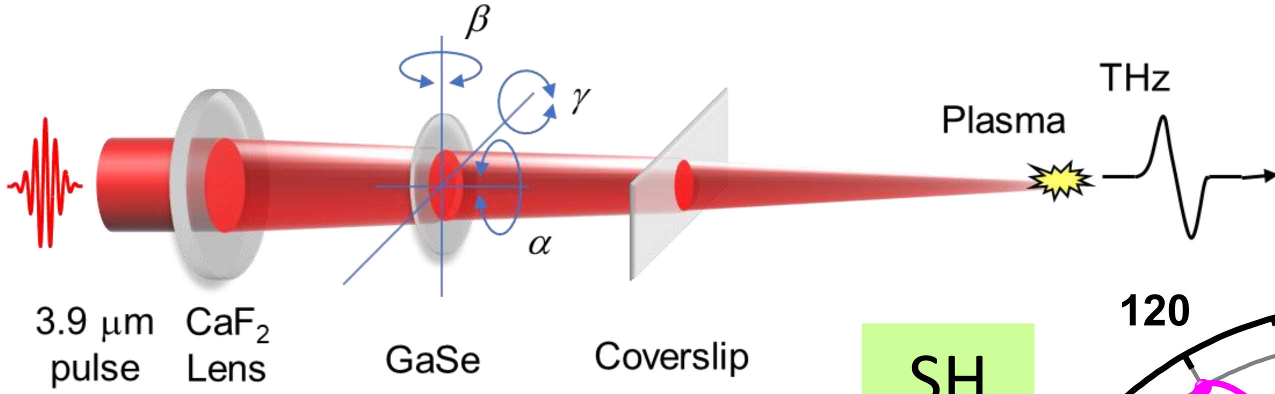
- High harmonic generation: T. Popmintchev et al., Science **336**, 1287 (2012).
- Mid-IR filamentation in air: A. V. Mitrofanov et al., Sci. Rep. **5**, 8368 (2015).
- Plasma wakefield acceleration: D. Woodbury *et al*., Opt. Lett. **43**, 1131 (2018).

Experimental setup

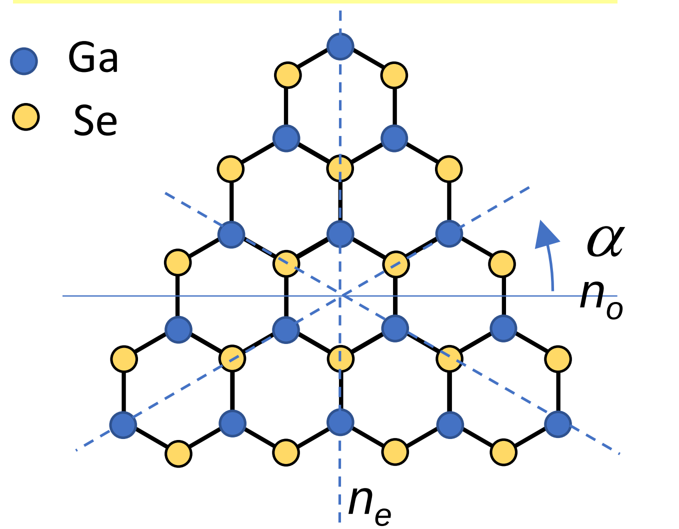


- Measured phase dependent THz, harmonics, and plasma fluorescence

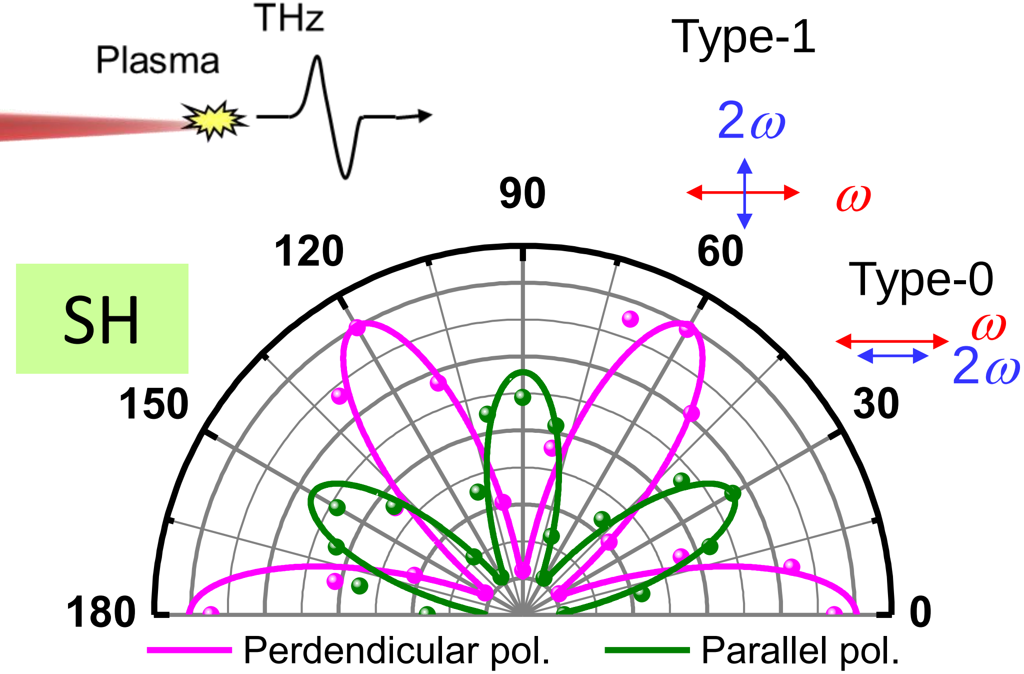
Second harmonic generation in GaSe

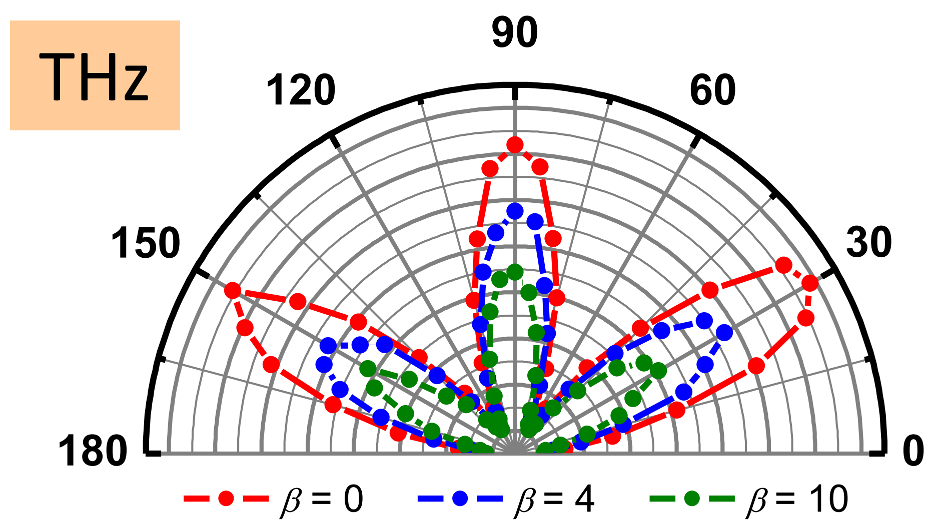


GaSe (layered material)



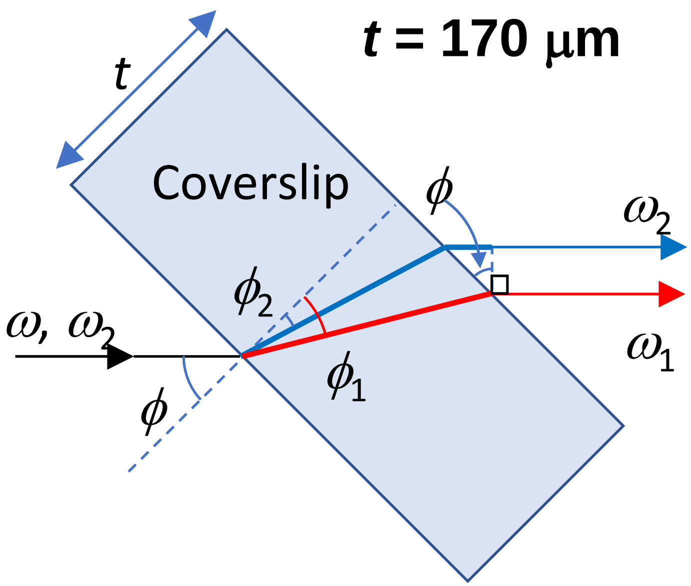
Six-fold rotational symmetry





Max. THz generation from colinear and ω and 2ω

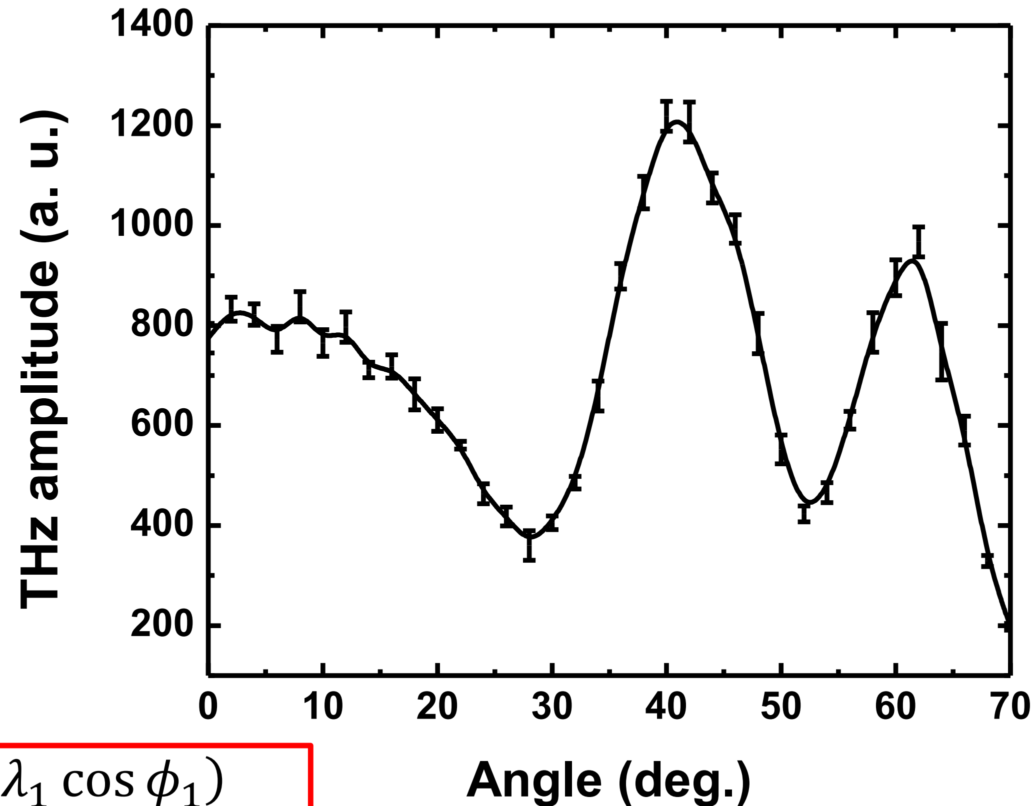
Relative phase θ control



$$\phi_1 = \sin^{-1}(\sin\phi / n_1)$$

$$\phi_2 = \sin^{-1}(\sin\phi / n_2)$$

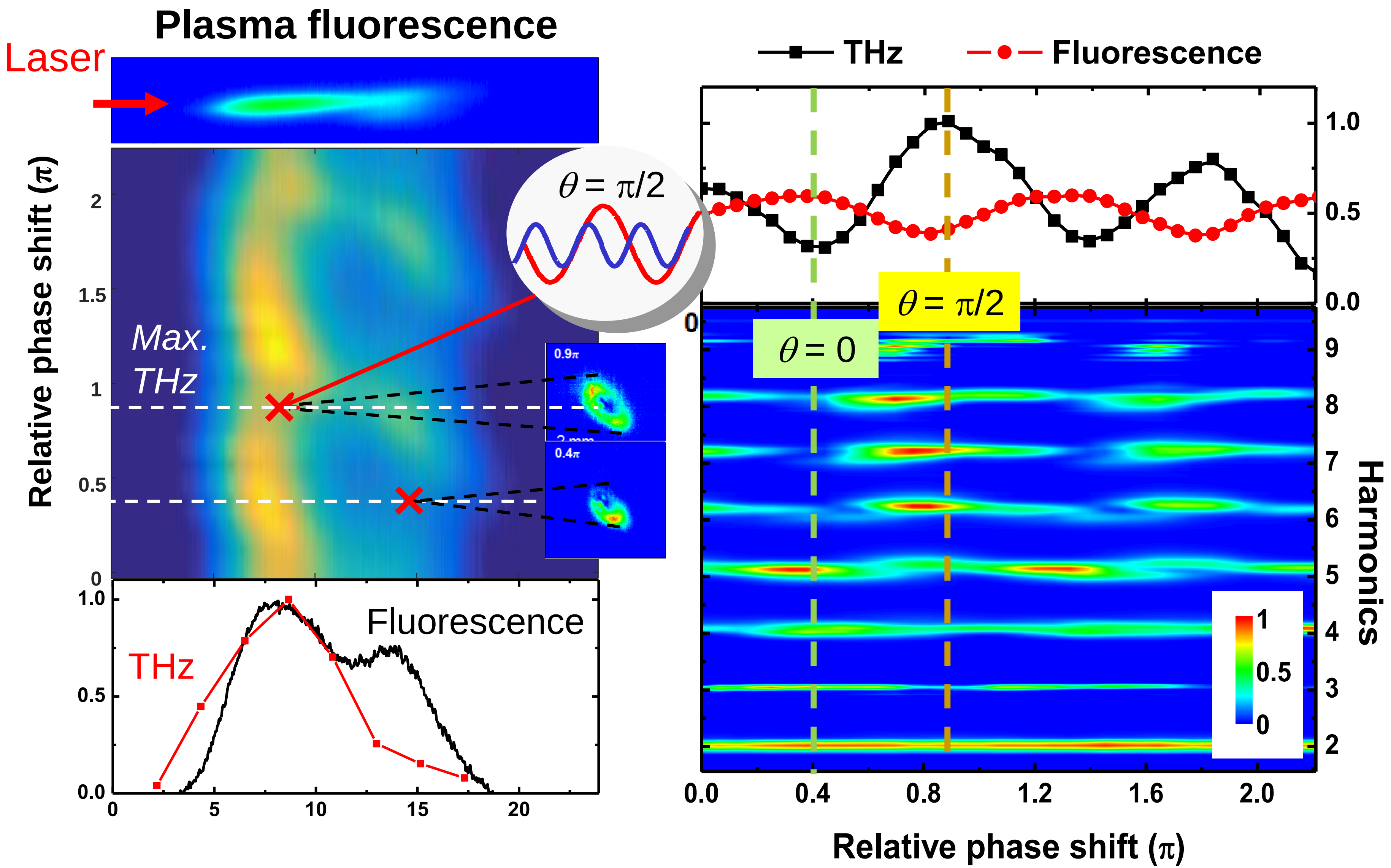
THz yield vs coverslip angle ϕ



$$\theta = 2\pi t\{n_2/(\lambda_2 \cos\phi_2) - 2n_1/(\lambda_1 \cos\phi_1) + \sin\phi\,(\tan\phi_1 - \tan\phi_2)/\lambda_2\}$$

- Laser energy loss ≈ 10 % at ϕ = 0°
- Group velocity walk-off ≈ 20 fs at ϕ = 42°
- Transverse beam separation ≈ 1 μm *at* ϕ = 42°

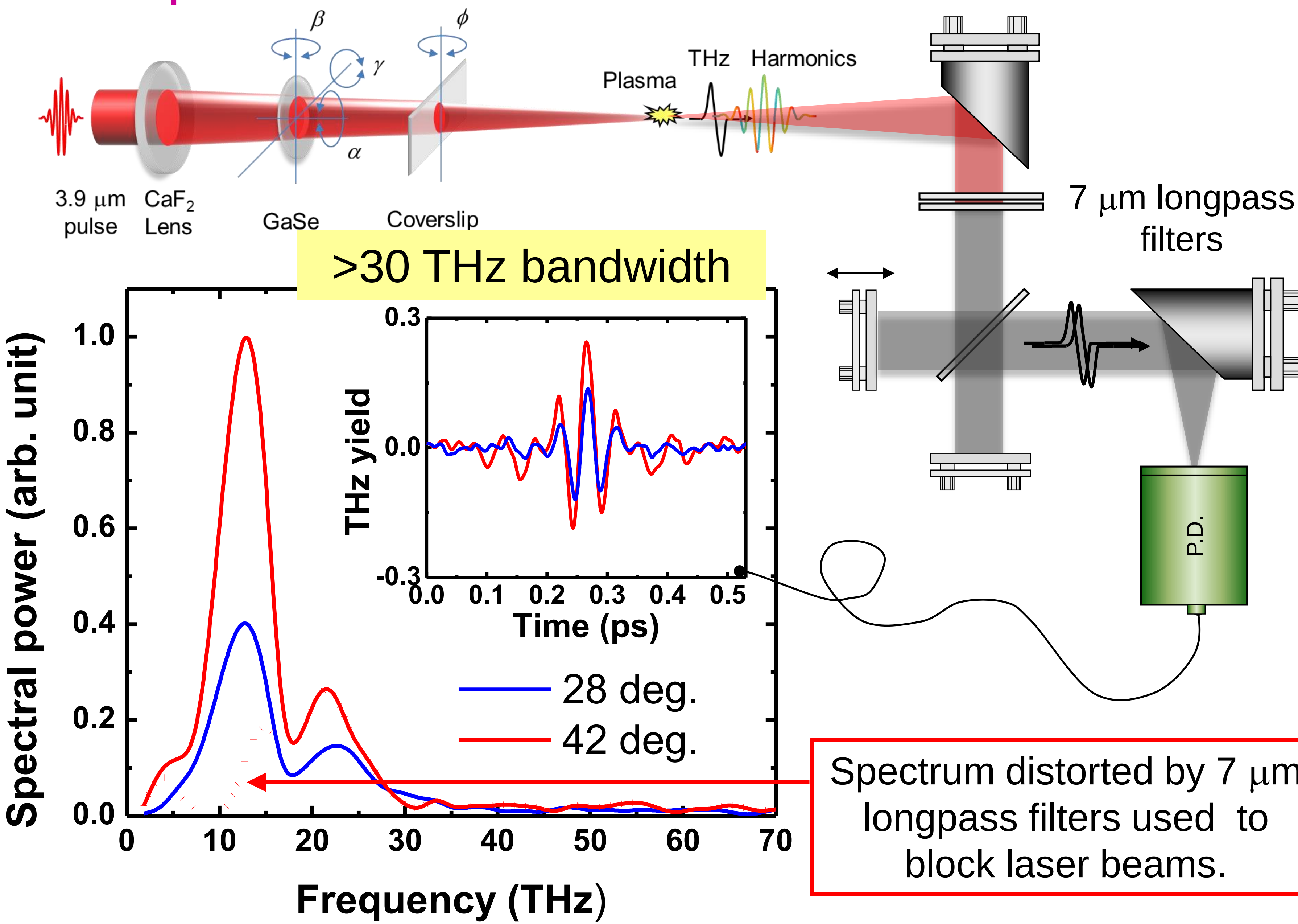
Phase dependent ionization, THz, & harmonics



At θ = π/2, less ionization but more THz expected from plasma current model

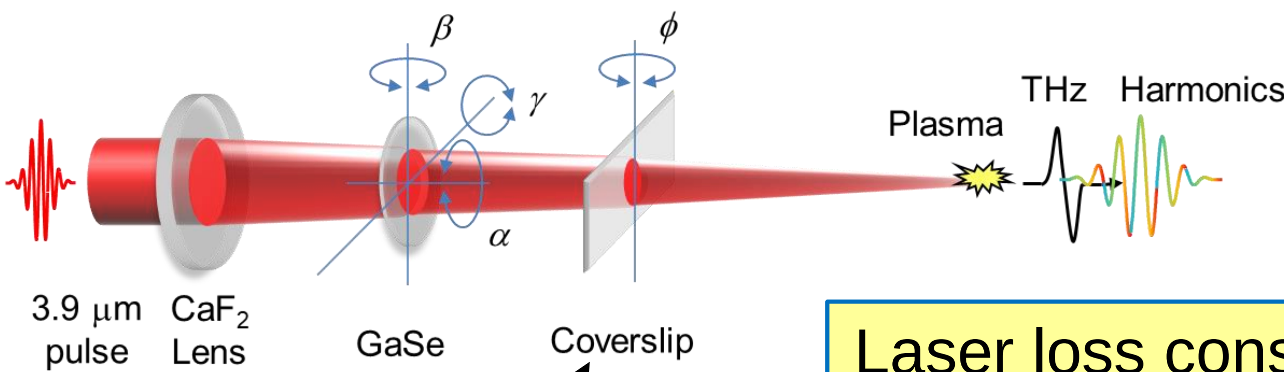
THz spectrum

Fourier-transform infrared (FTIR) spectrometer



Spectrum distorted by 7 μm longpass filters used to block laser beams.

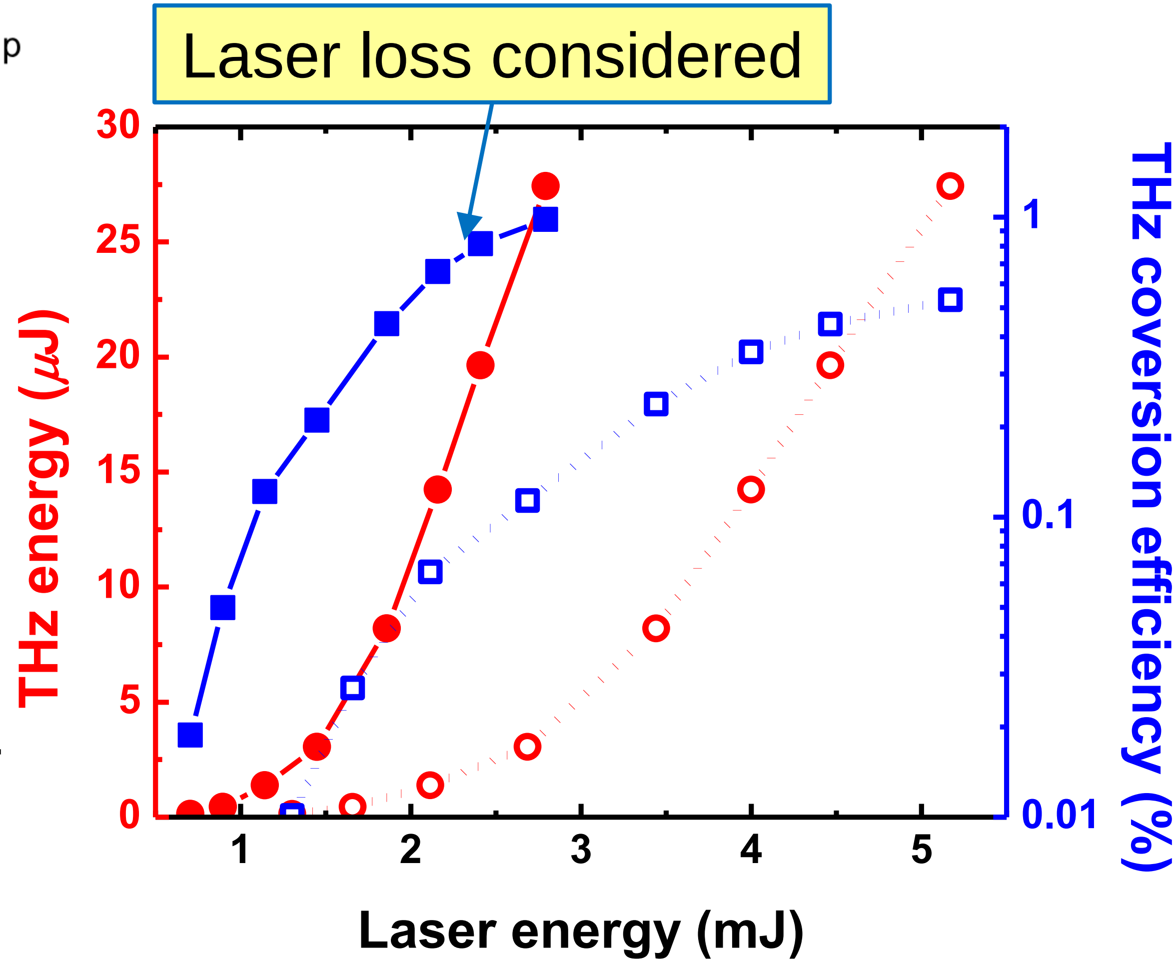
Laser-to-THz conversion efficiency



30% Fresnel loss

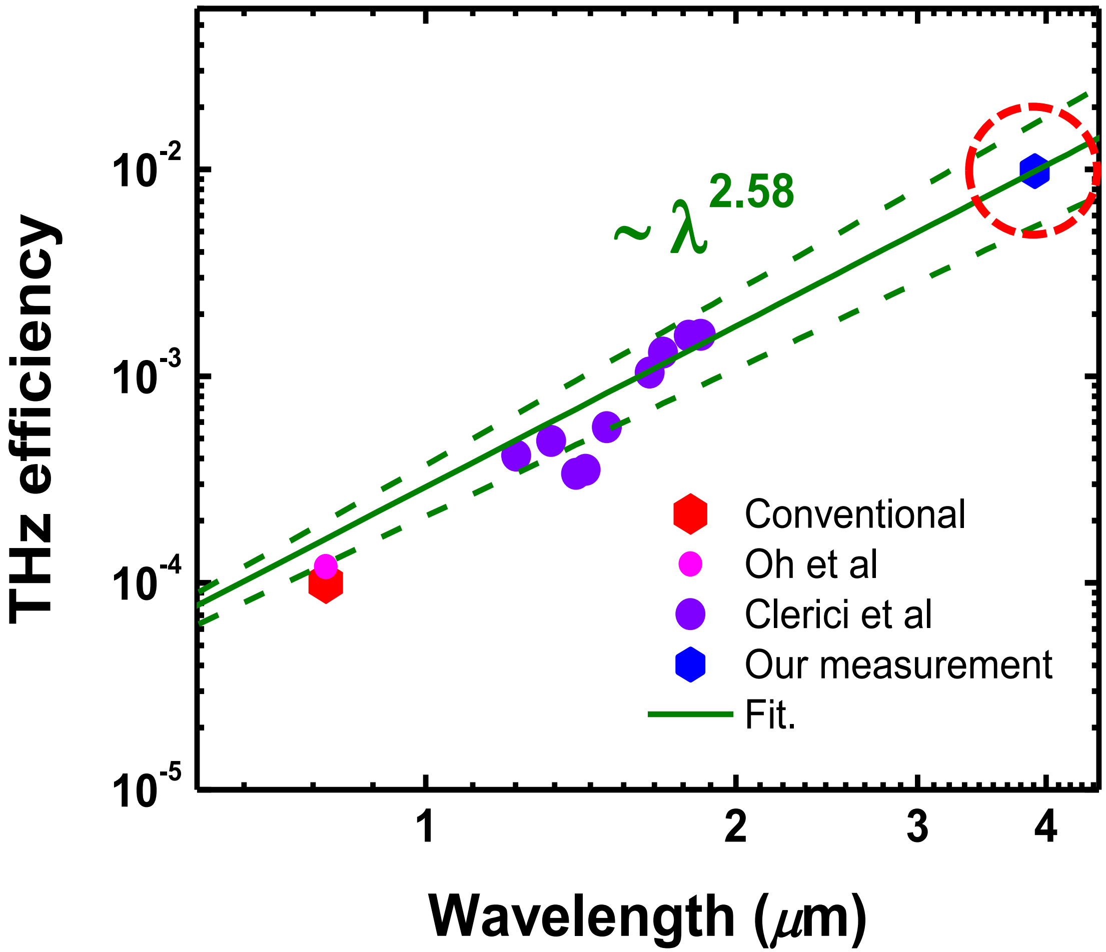
10% loss

- Max. 1% efficiency with $I_{2\omega}/I_{\omega} = 0.02$
- Higher efficiency expected with greater $I_{2\omega}/I_{\omega}$



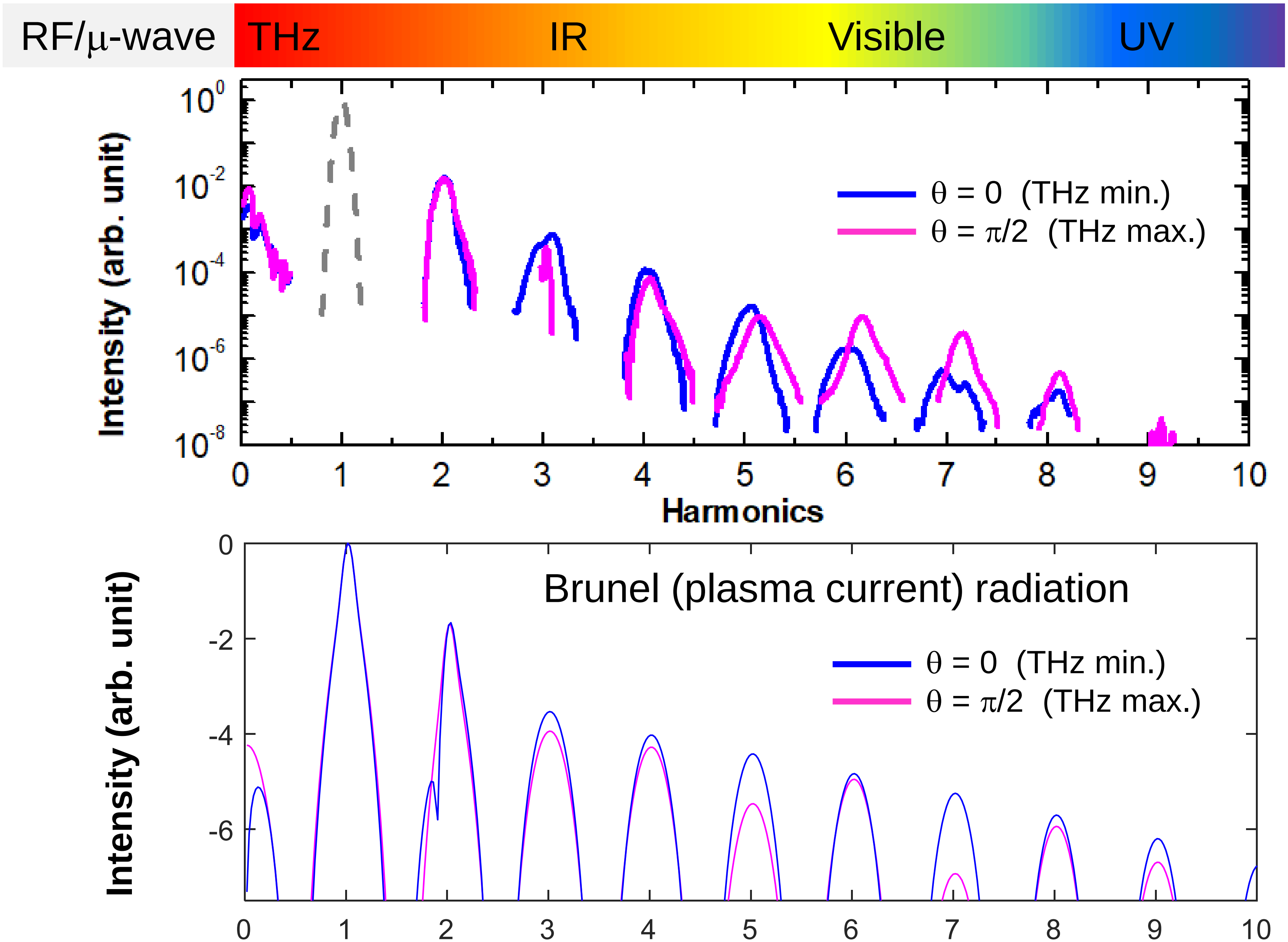
Wavelength scaling

THz generation via two-color mixing



- Better than λ^2
- Surprisingly high THz energy expected at 10 μm

Coherent control of broad EM waves



Future Experiments & Simulation:

UPPE simulation

Unidirectional pulse propagation equation (UPPE)*

$$\frac{\partial \tilde{E}(z,\omega,k)}{\partial z} = ik_z\tilde{E}(z,\omega,k) + \frac{i\omega^2}{2\varepsilon_0 c^2 k_z}\tilde{P}_{NL}(z,\omega,k) - \frac{\omega}{2\varepsilon_0 c^2 k_z}\tilde{J}(z,\omega,k)$$

Dispersion **Nonlinear polarization** **Plasma current**

$$k_z = k_z\,(\omega,k) = \sqrt{\omega^2\varepsilon(\omega)/c^2 - k^2}$$

$$\tilde{P}_{NL} = \varepsilon_0\left(\chi^{(3)}E^3 + \chi^{(5)}E^5 + \cdots\right)$$

$$\tilde{J} = \frac{e^2(\nu_e + i\omega)}{m_e(\nu_e^2 + \omega^2)}\widetilde{\rho E}$$

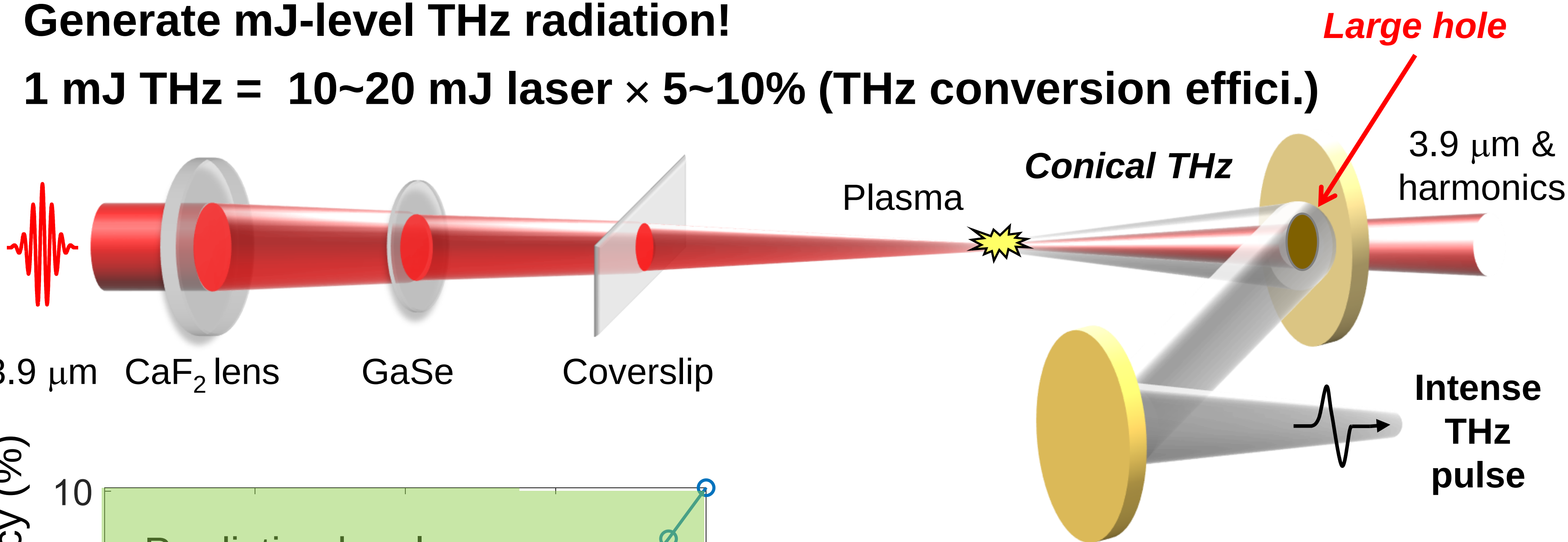
- Carrier based, no envelope approximations used
- Capture phase-dependent plasma, THz, harmonics generation with propagation

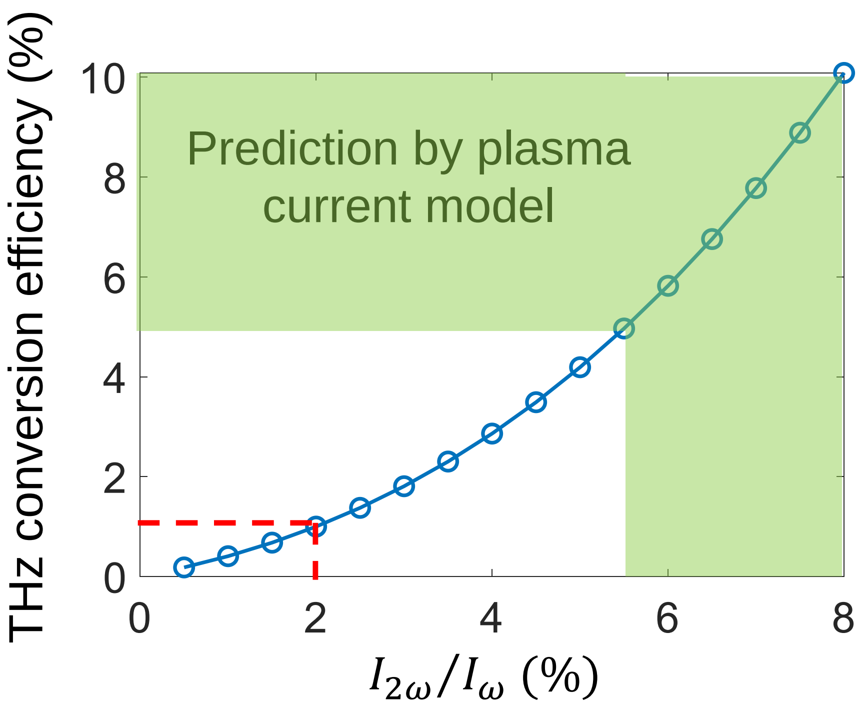
*M. Kolesik and J. V. Moloney, PRE **70**, 036604 (2004)

Next experiment with 3.9 μm laser (1)

Generate mJ-level THz radiation!

1 mJ THz = 10~20 mJ laser × 5~10% (THz conversion effici.)

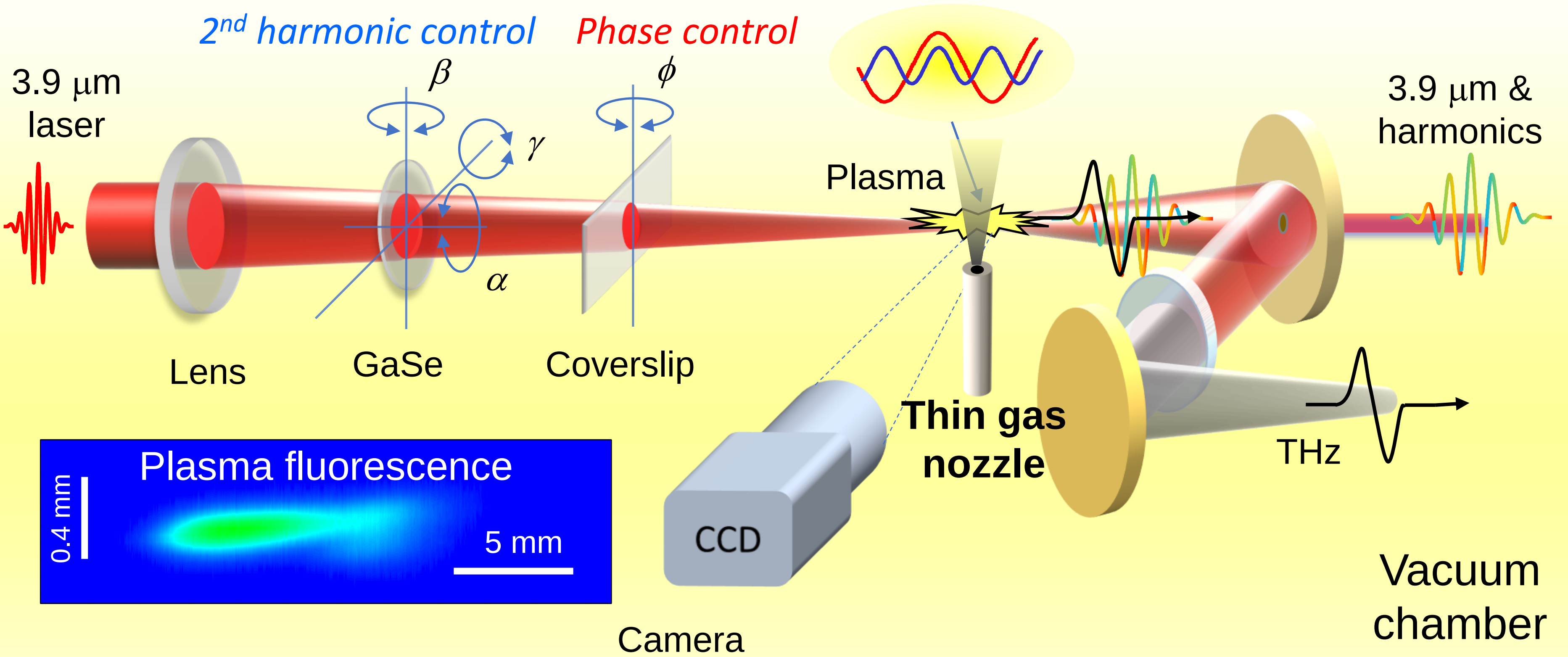




- **More 2nd harmonic energy**—use a more efficient SHG crystal
- **THz/laser separation**—use a parabolic mirror with a large hole (no filter necessary).

Next experiment with 3.9 μm laser (2)

Short plasma generation for accurate phase measurements



- Phase integrated effects occur by a long plasma created in air (due to plasma dispersion and Gouy phase shift)
- A short plasma will allow accurate measurements of phase θ dependent plasma, THz, and harmonic generation

Summary:

- **THZ generation at long wavelengths:**
  - Observed 1% THz conversion efficiency with two-color laser mixing in air
  - Generated broadband EM waves from microwave to UV
  - Studied coherent control of ionization, THz, and harmonic generation
- **Near future experiments & simulation:**
  - Generate mJ level THz radiation with 5~10% efficiency
  - Use a thin nozzle to localize phase-dependent effects in plasma, THz, and harmonic generation
  - UPPE simulation for propagation effects
- **Anticipate more exciting results over the next 4 years!**