UNIVERSITY OF MARYLAND AT COLLEGE PARK
INSTITUTE FOR RESEARCH IN ELECTRONICS AND APPLIED PHYSICS

Applications of intense mid-infrared laser-plasma interactions

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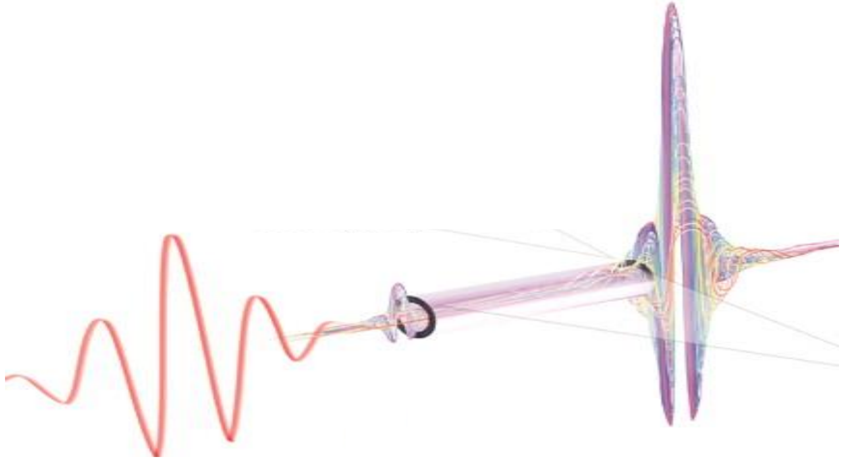
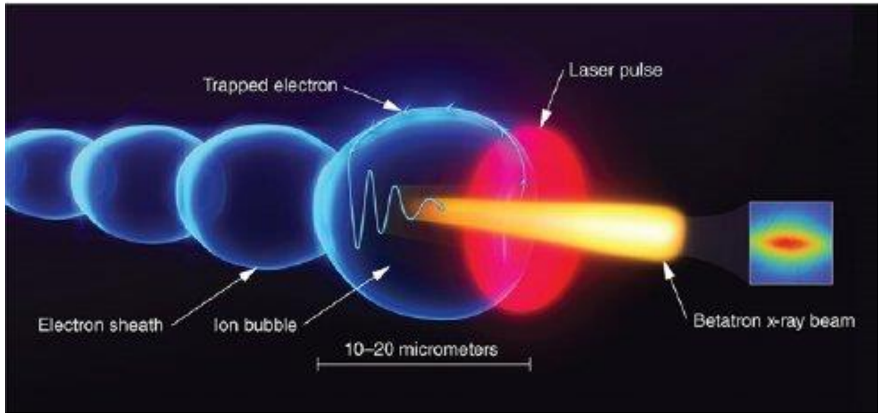
Selected laser-plasma applications

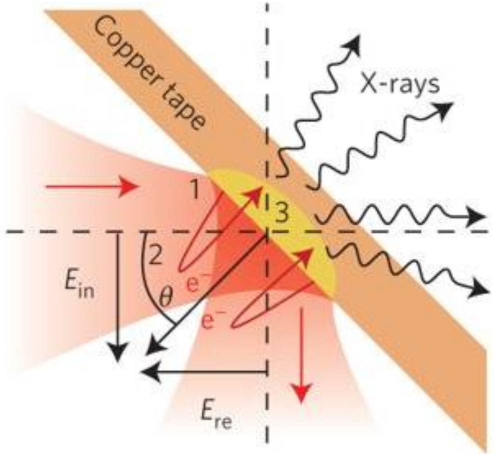
1. Coherent THz and harmonics



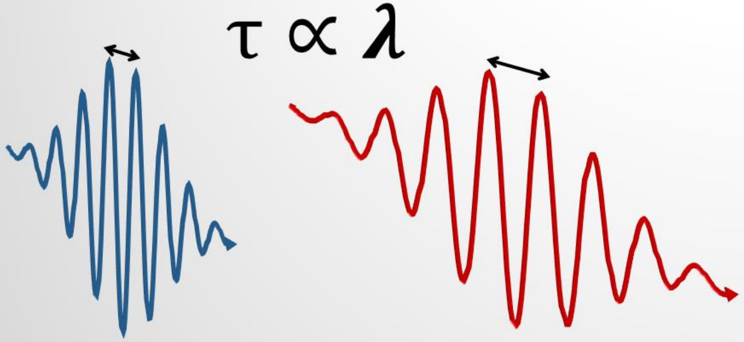
2. Nonlinear self-guiding

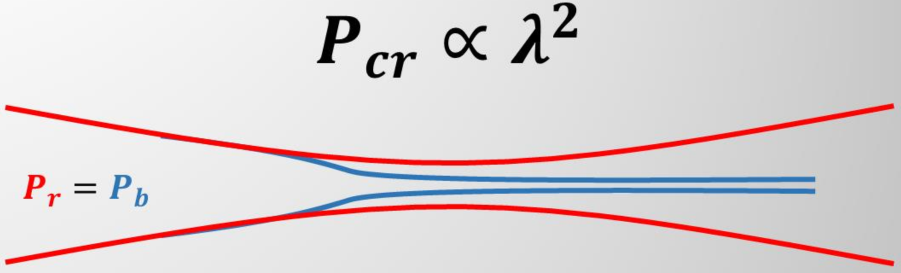
3. Laser-plasma acceleration and incoherent EUV/X-ray sources

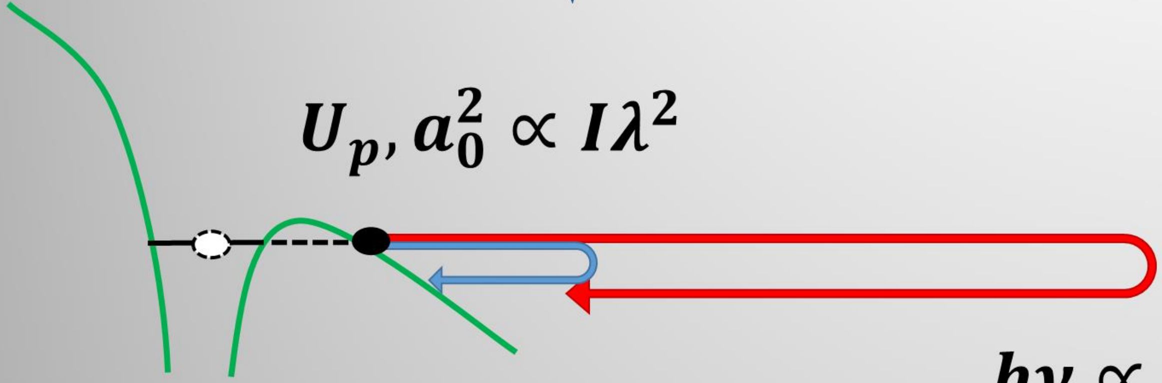


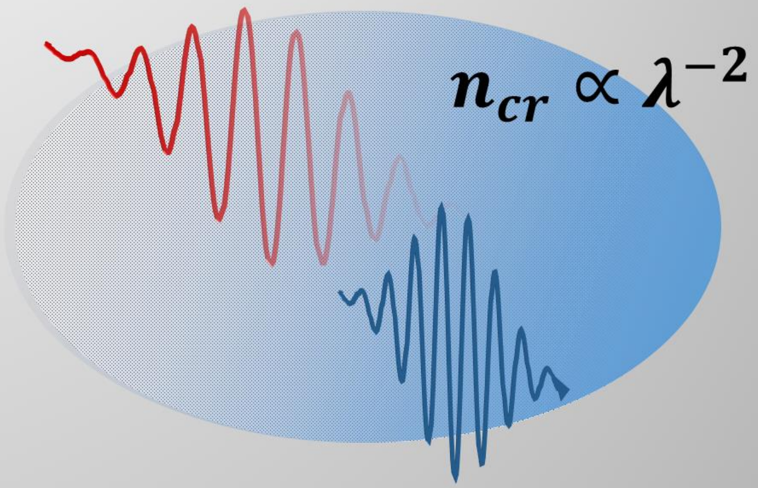


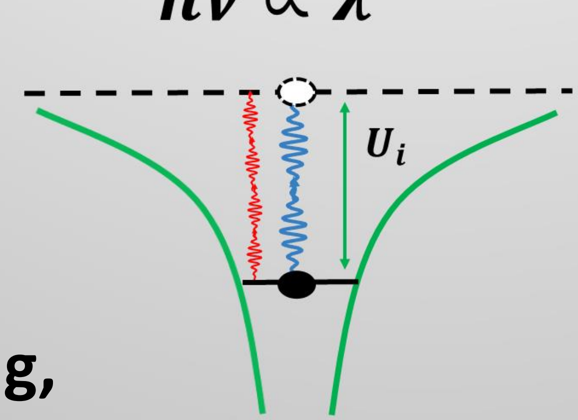
1. T. Popmintchev, *et* al. Science **336**, 1287-1291 (2012). 2. https://www.trumpf-scientific-lasers.com/products/dira-series/
3a. F. Albert *et al.*, Plasma Phys. Control. Fusion **56**, 084015 (2014). 3b. J. Weisshaupt, *et al.*, Nat. Photonics **8**, 927-930 (2014).





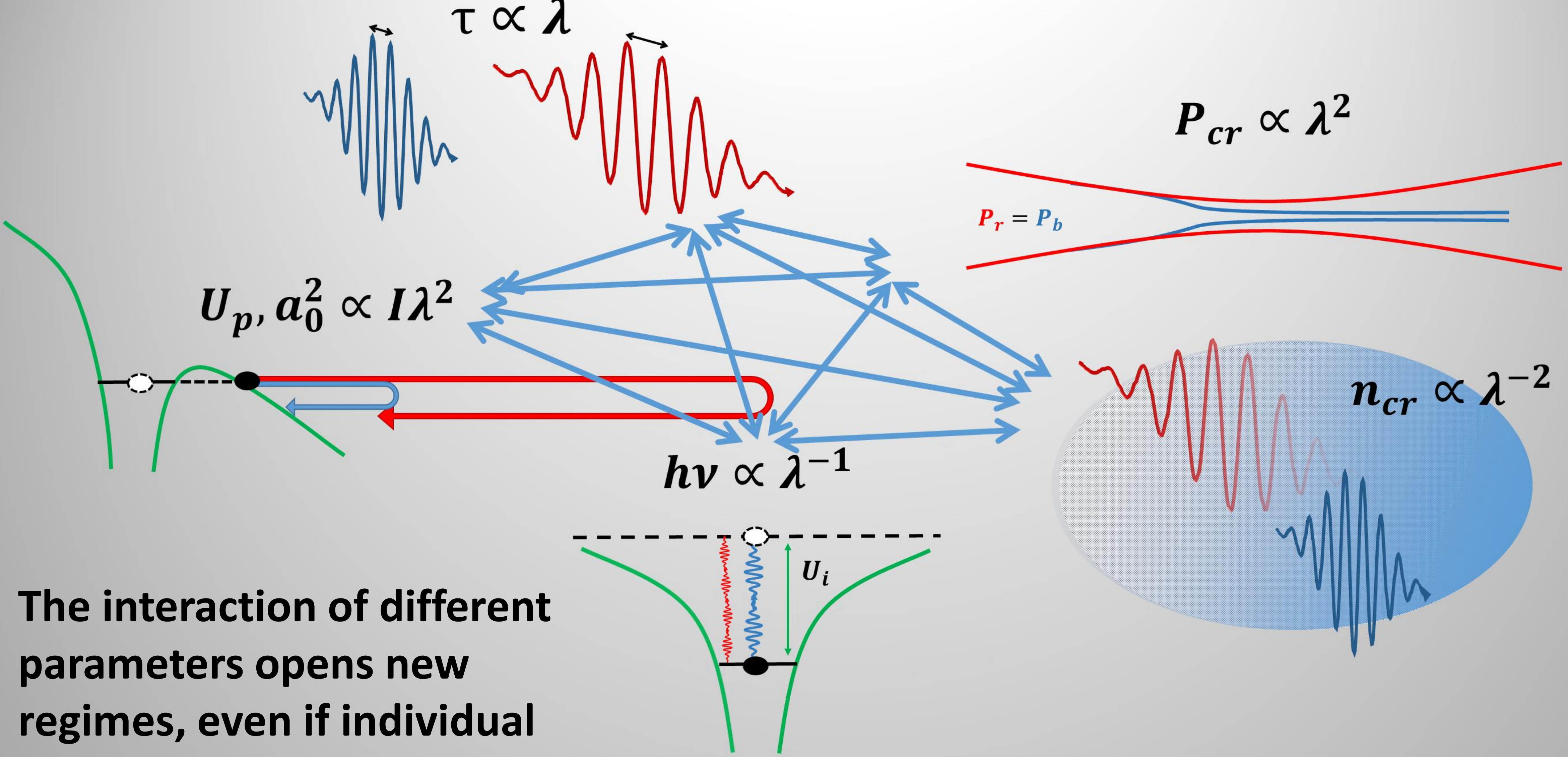






Why the mid-infrared?

Important parameter scaling,
which we will highlight throughout



$\tau \propto \lambda$

$P_{cr} \propto \lambda^2$

$P_r = P_b$

$U_p, a_0^2 \propto I\lambda^2$

$n_{cr} \propto \lambda^{-2}$

$h\nu \propto \lambda^{-1}$

U_i

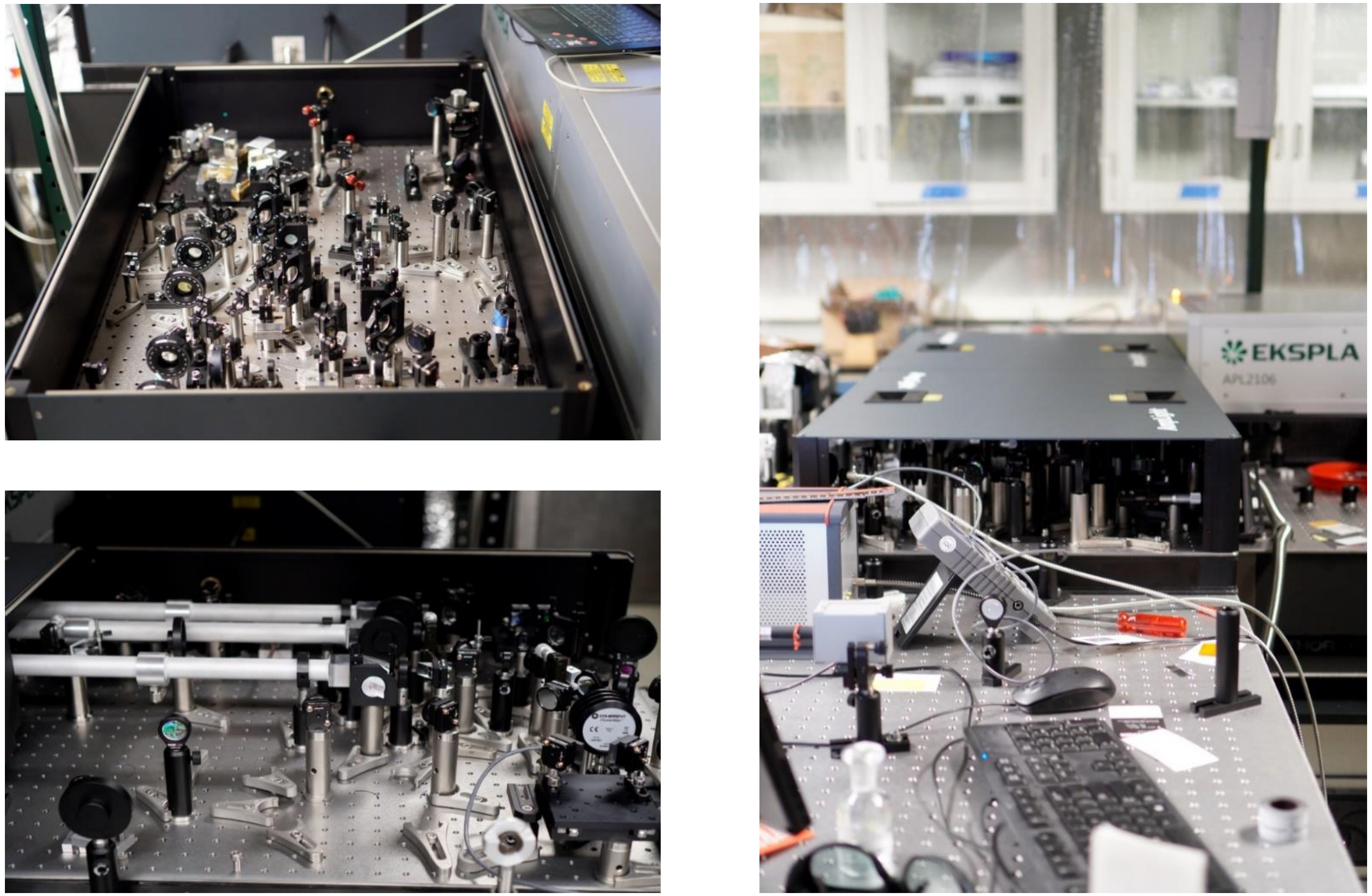
The interaction of different parameters opens new regimes, even if individual behaviors are understood

UMD mid-IR TW laser system

- 25 mJ, ~80 fs, λ=3.9 μm pulses, 0.3 TW (TW=10^{12} W)

- Bypassing compressor produces **chirped 70** ps pulses

- (G. Andriukaitis *et al*., *Optics Lett.* **36**, 2755 (2011))

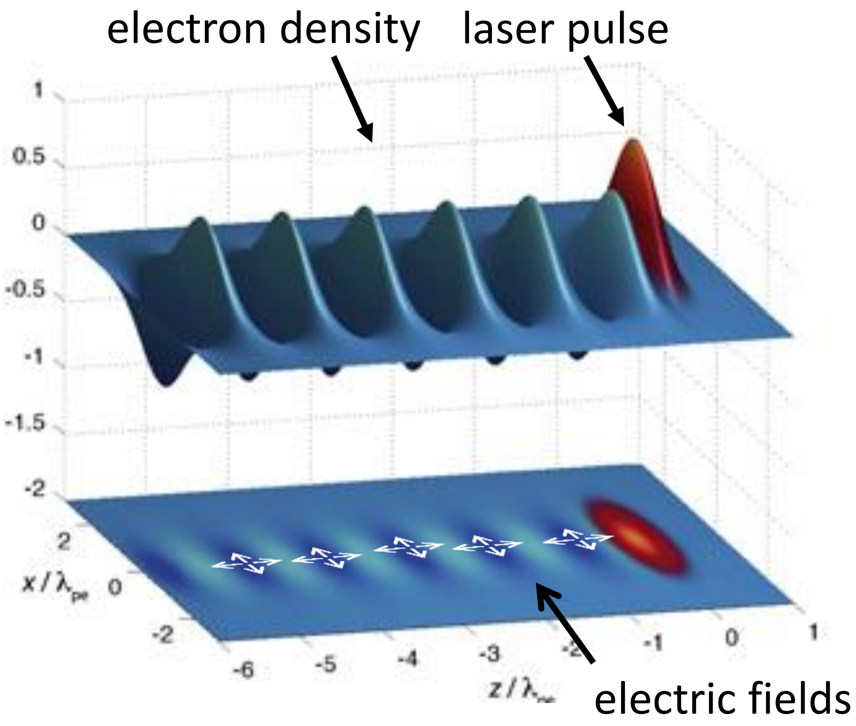


Outline

- Introduction
  - Mid-IR laser plasma interactions
  - Overview of UMD mid-IR laser system
- Laser wakefield acceleration with mid-IR laser pulses
  - Relativistic self-focusing in near-critical plasma
- Ultralow plasma density measurements with avalanche ionization
  - Overview of avalanche ionization
  - Remote radiation detection
- Mid-IR/LWIR self-guiding mediated by avalanche ionization
  - Ionization yield measurements over 14 decades
  - Effective refractive index; propagation simulations

Why are laser wakefield accelerators interesting?

- Laser pulse expels electrons through ponderomotive force $(a_0 \propto \sqrt{I\lambda^2})$.
- Resulting oscillations have high electric field gradients, reaching ~100 GV/m, compared to ~10 MV/m in conventional accelerators
- SLAC acceleration distance for a 50 GeV electron beam: 3.2 km; LWFA could shrink to ~30 cm
- However, requires large lasers (100 TW-PW)
- **How can you translate this to smaller, table-top (~1 TW) lasers?**



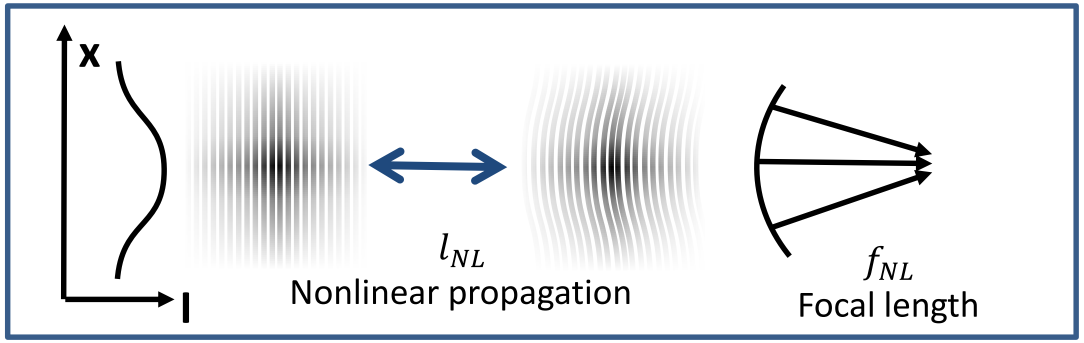
Adapted from S. M. Hooker *et al.*, J. Phys. B **47**, 234003 (2014).

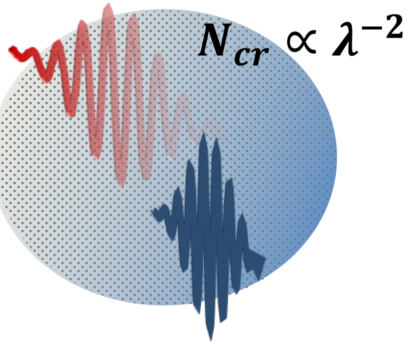
Nonlinear Plasma Optics: Self-focusing

- Nonlinear refractive index
    - Arises from relativistic shift of plasma frequency

$$\eta = \sqrt{1 - \frac{\omega_0^2}{\gamma \omega_p^2}} = \sqrt{1 - \frac{N_e}{\gamma N_{cr}}} \approx \eta_0 + \eta_2(\lambda) I$$

- Critical power for self-focusing, related to critical density

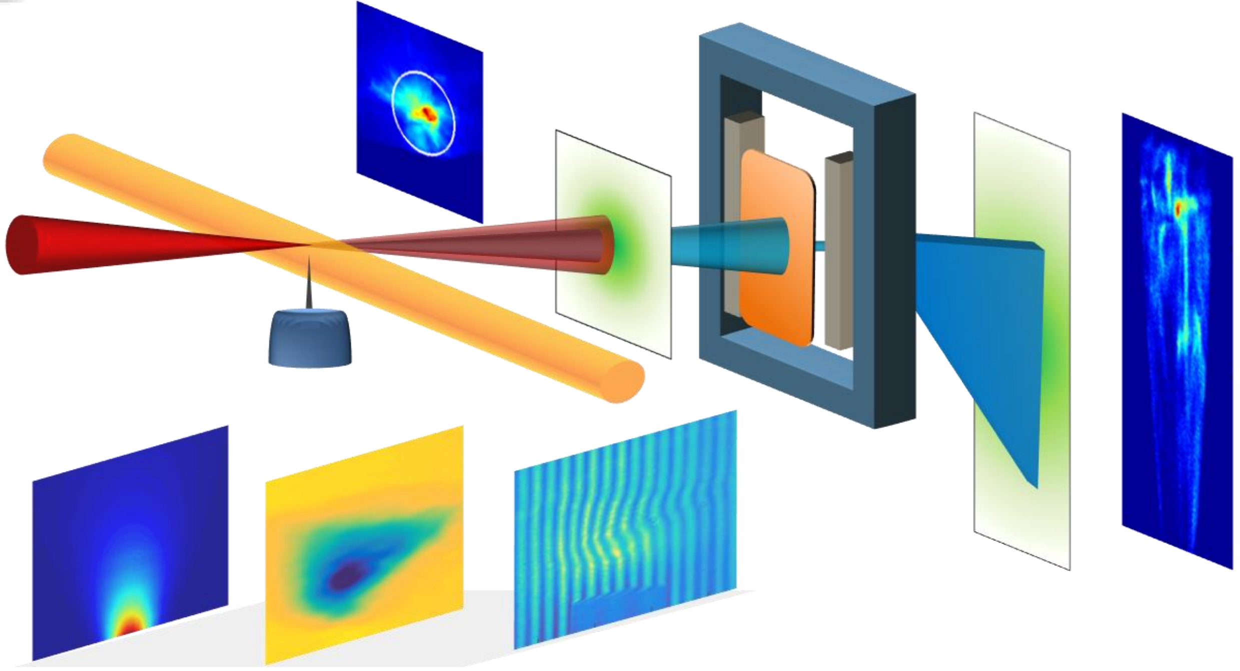


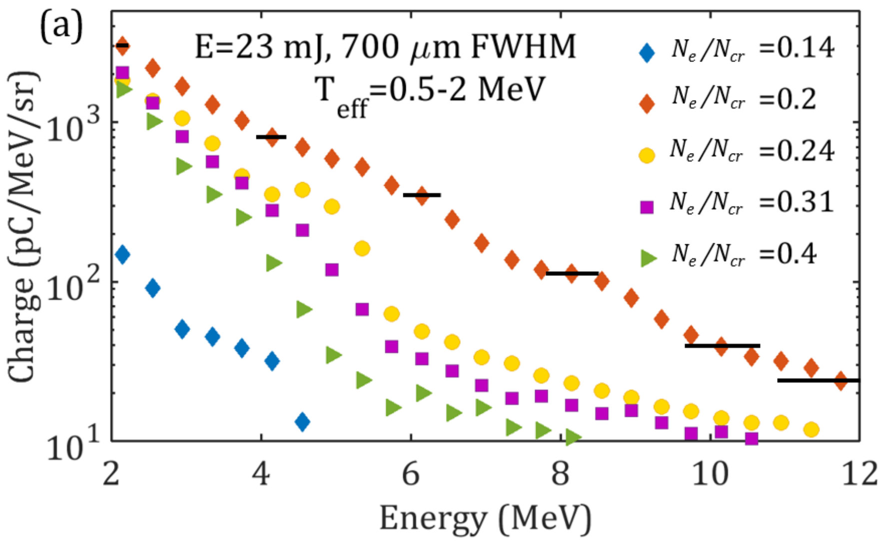


$$P_{cr}[GW] = 17.4\, {}^{N_{cr}}/_{N_e} \qquad N_{cr} = 1.1 \times 10^{21}\text{cm}^{-3}/(\lambda[\mu\text{m}])^2$$

- High ${}^{N_e}/_{N_{cr}}$ is easier to achieve at longer wavelengths, and allows self focusing to high intensities needed for LWFA

Mid-IR LWFA experimental setup





- Focal spot 30 μm FWHM, $I_0 \cong 2\,x\,10^{16}W/cm^2$, $a_0 \sim 0.5$
- Supercritical density in the mid-IR even for room temp gas jet
- Measured 2-10 MeV electron beam profiles and spectra
- Observed correlations of acceleration onset and quality with self-focusing length
- D. Woodbury, et al. Opt. Lett. **43**, 1131 (2018)

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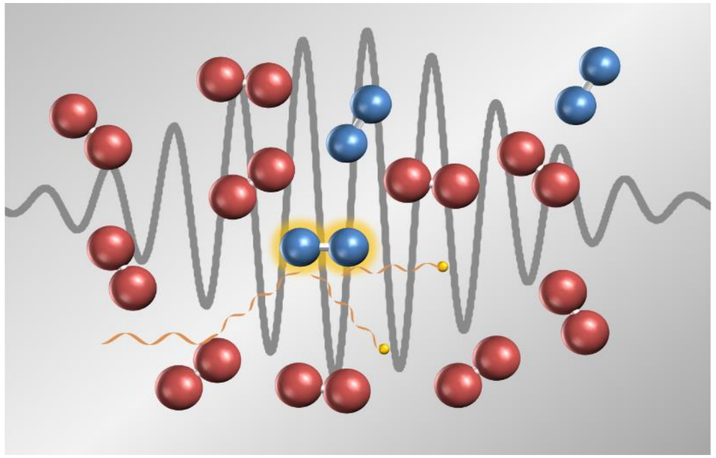
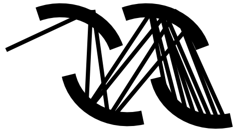
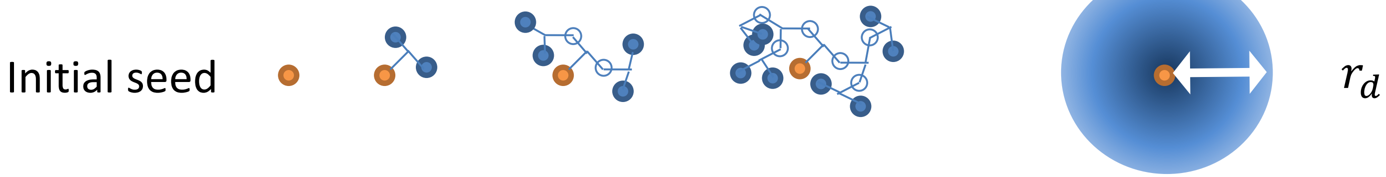
Avalanche Ionization: a single electron diagnostic

- Start with initial electron, heated by laser driven collisions
- Eventually gain enough energy to ionize another molecule



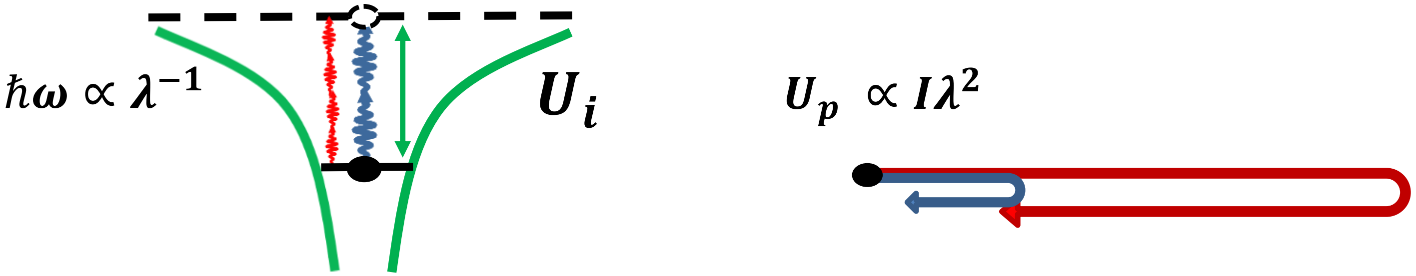


- Number of electrons double, and process repeats: single electron sensitivity
- For picosecond breakdown, electron motion is limited by diffusion, leading to discrete countable sites



Advantage of the mid-IR

- Experiments with shorter wavelengths suffered from unwanted laser driven multi-photon ionization creating extra electron seeds

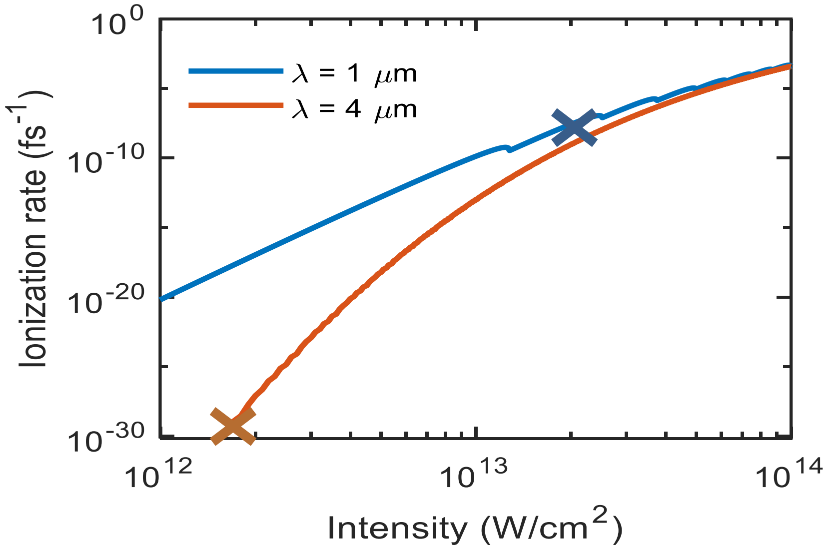


$\hbar\omega \propto \lambda^{-1}$

U_i

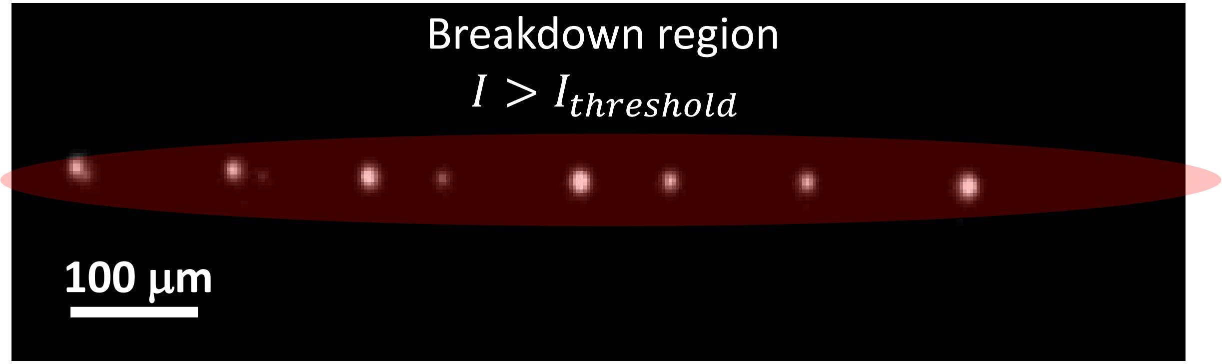
$U_p \propto I\lambda^2$

- Moving to longer wavelengths enhances collisional heating, while also suppressing multiphoton ionization

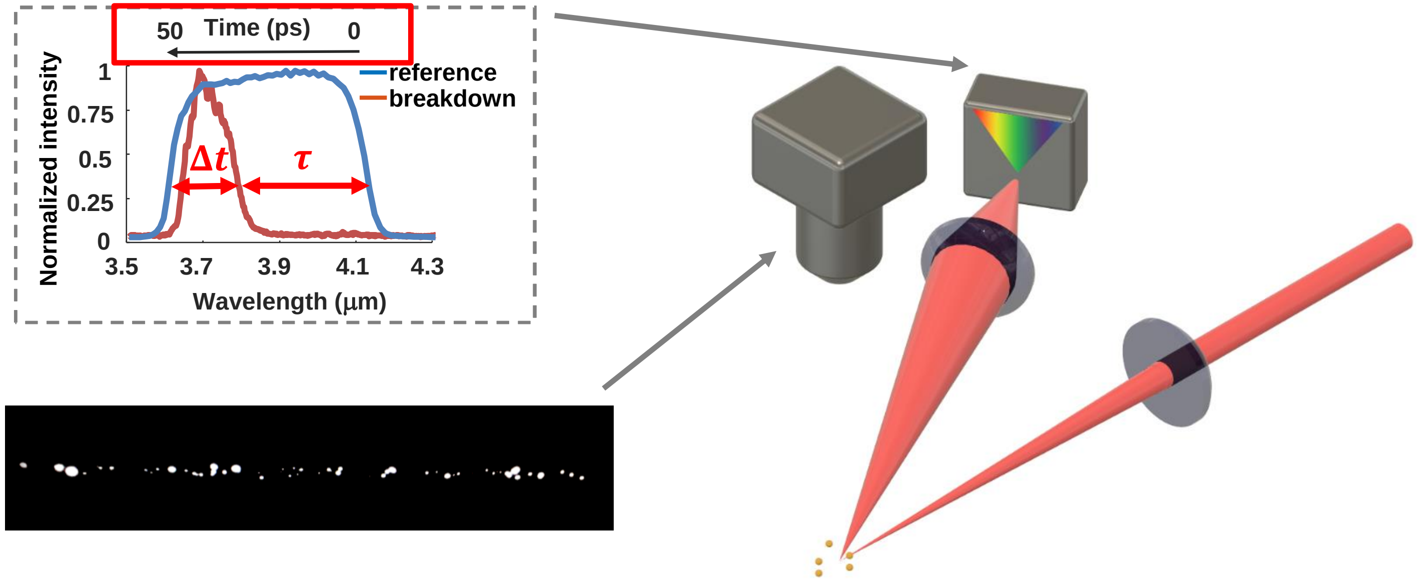


Avalanche as a practical diagnostic

- High resolution imaging of focal volume

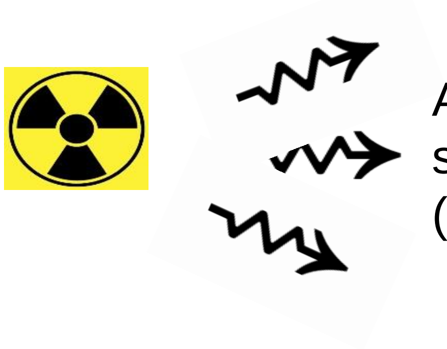


- Timing measured with spectrum of backscatter of the *chirped* avalanche pulse



Motivation: Measuring radioactivity remotely with avalanche

- Passive techniques: Conventional detectors and spectroscopy dramatically lose sensitivity with range

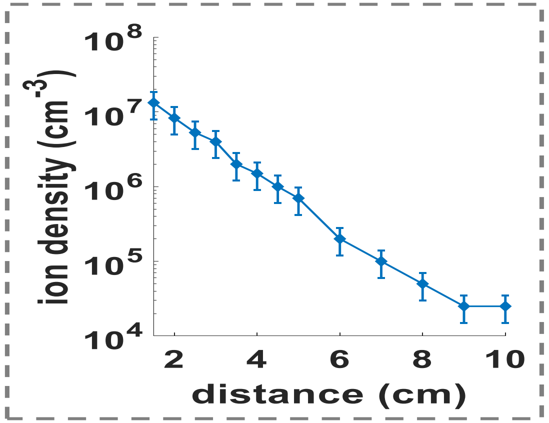


Alpha, beta have short range (scattering)

Gamma rays have linear absorption

$$I \propto \frac{1}{r^2} e^{-\alpha r}$$

- Detect radiation induced charges in air (~$10^4 - 10^7$ cm^{-3}) at range using avalanche breakdown

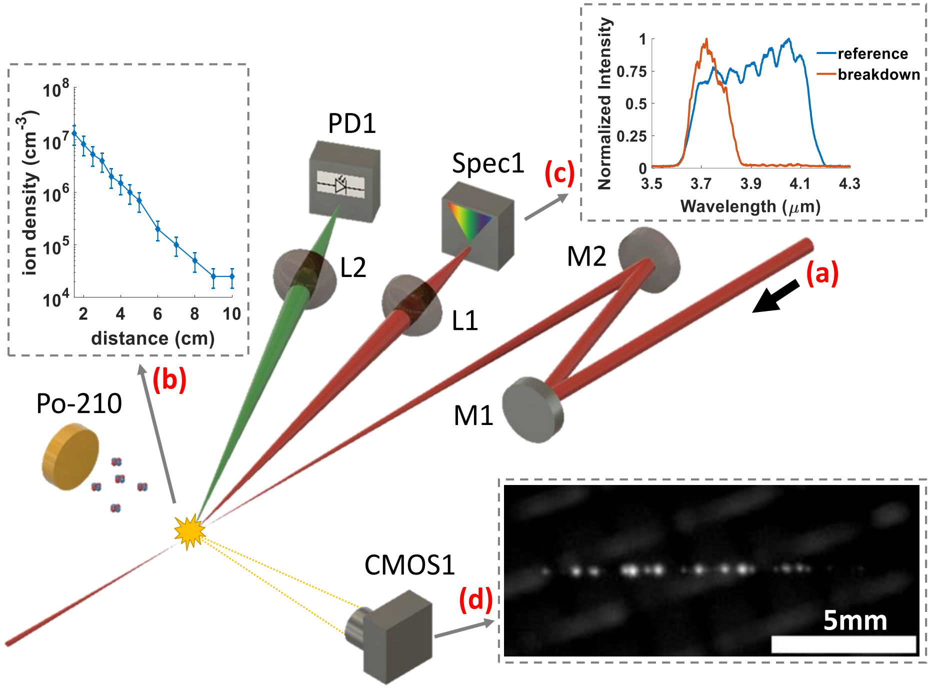


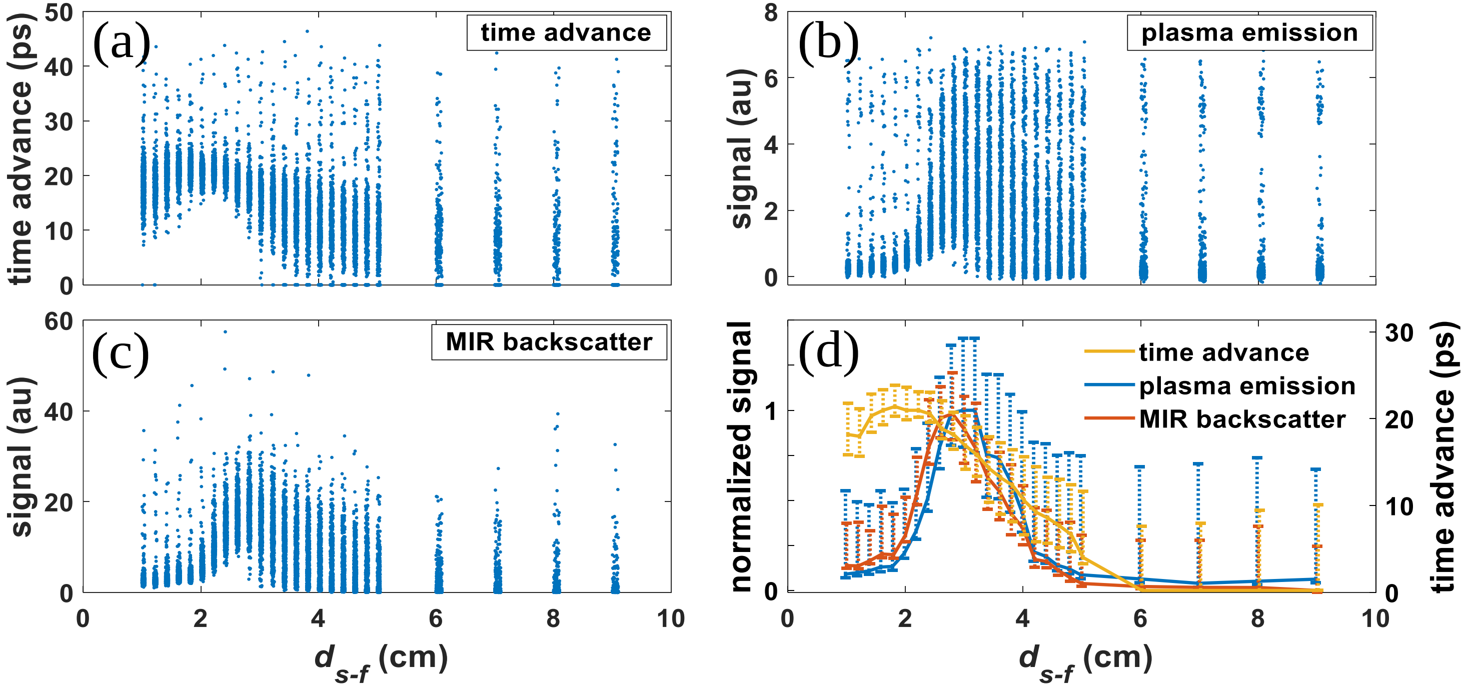
V. L. Granatstein and G. S. Nusinovich, J. Appl. Phys. **108**, 063304 (2010).
P. Sprangle, *et al.,* Phys. Plasmas **21**, 013103 (2014).

Experiment: Measuring radioactivity remotely with avalanche

- Avalanche seeded by electrons and weakly-bound negative ions near a Po-210 alpha source (inset)

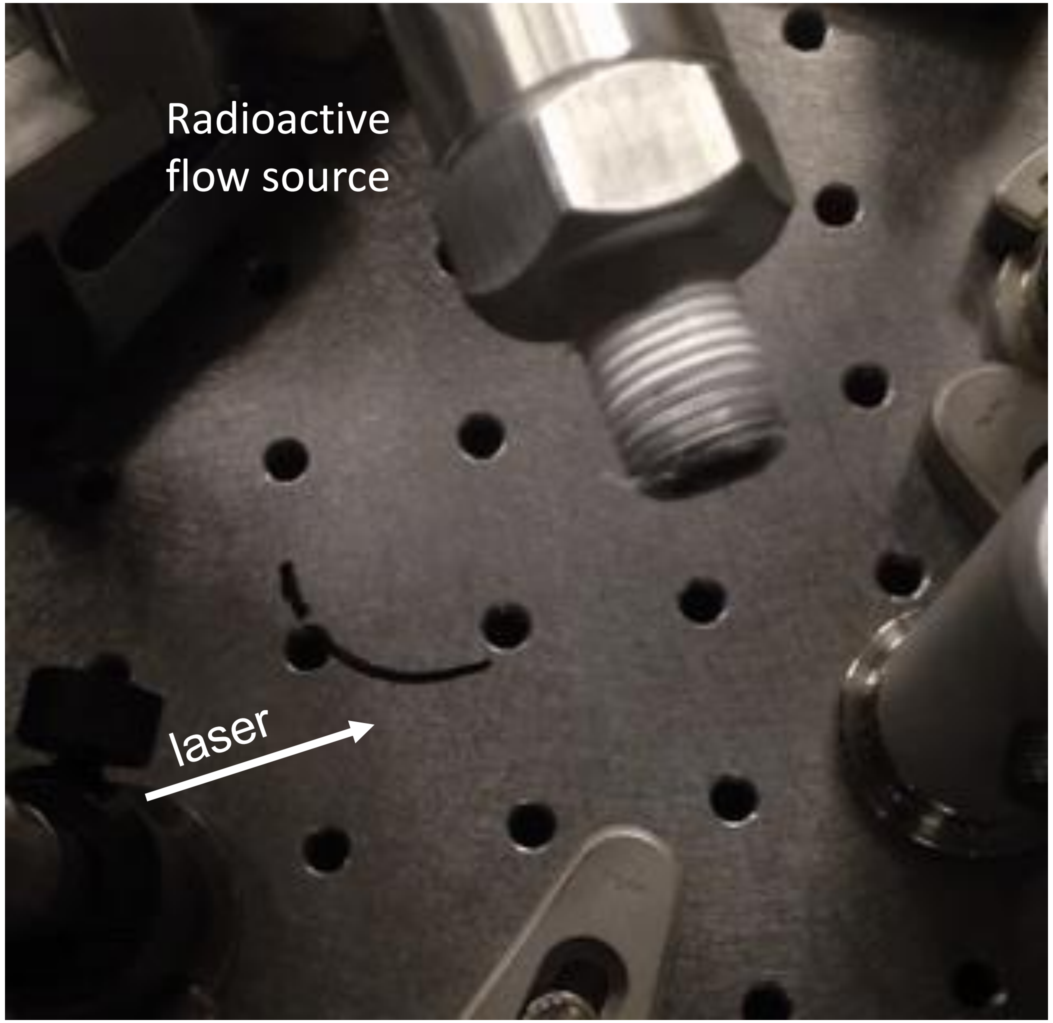
- Backscatter diagnostics to test viability of remote detection; received follow-up funding for a field demonstration





[R. Schwartz, et al. Sci Adv 5, eaav6804 (2019)], [D. Woodbury et al. Optica 6, 811 (2019)]

On-off sensitivity



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Self-focusing and filamentation

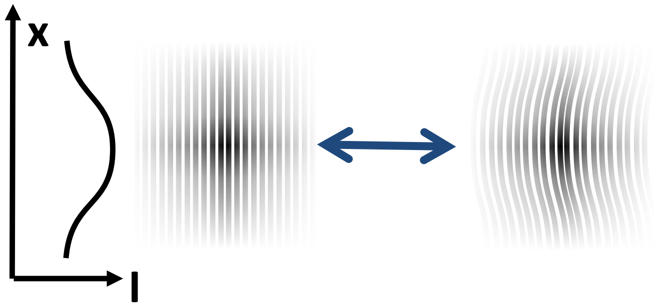
- Nonlinear refractive index $n = n_0 + n_2 I$ counteracts diffraction

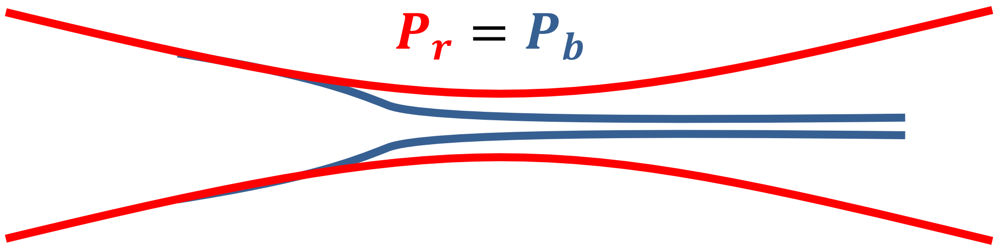
- Gives critical power:

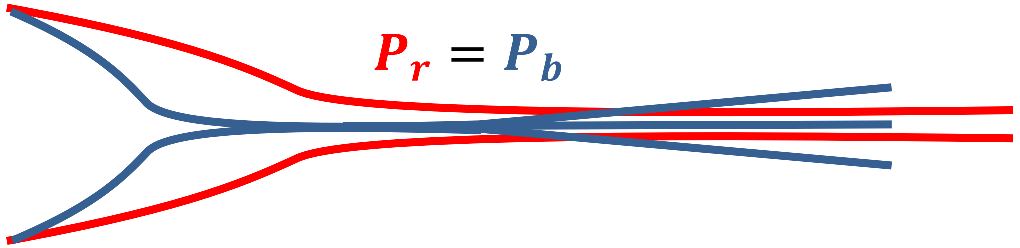
$$P_{cr} = \frac{\alpha\lambda^2}{n_0 n_2}$$

- Beams self-focus until stopped by a defocusing mechanism (ionization)

- For $P \gg P_{cr}$, beam is unstable to modulation and breakup → interest in LWIR

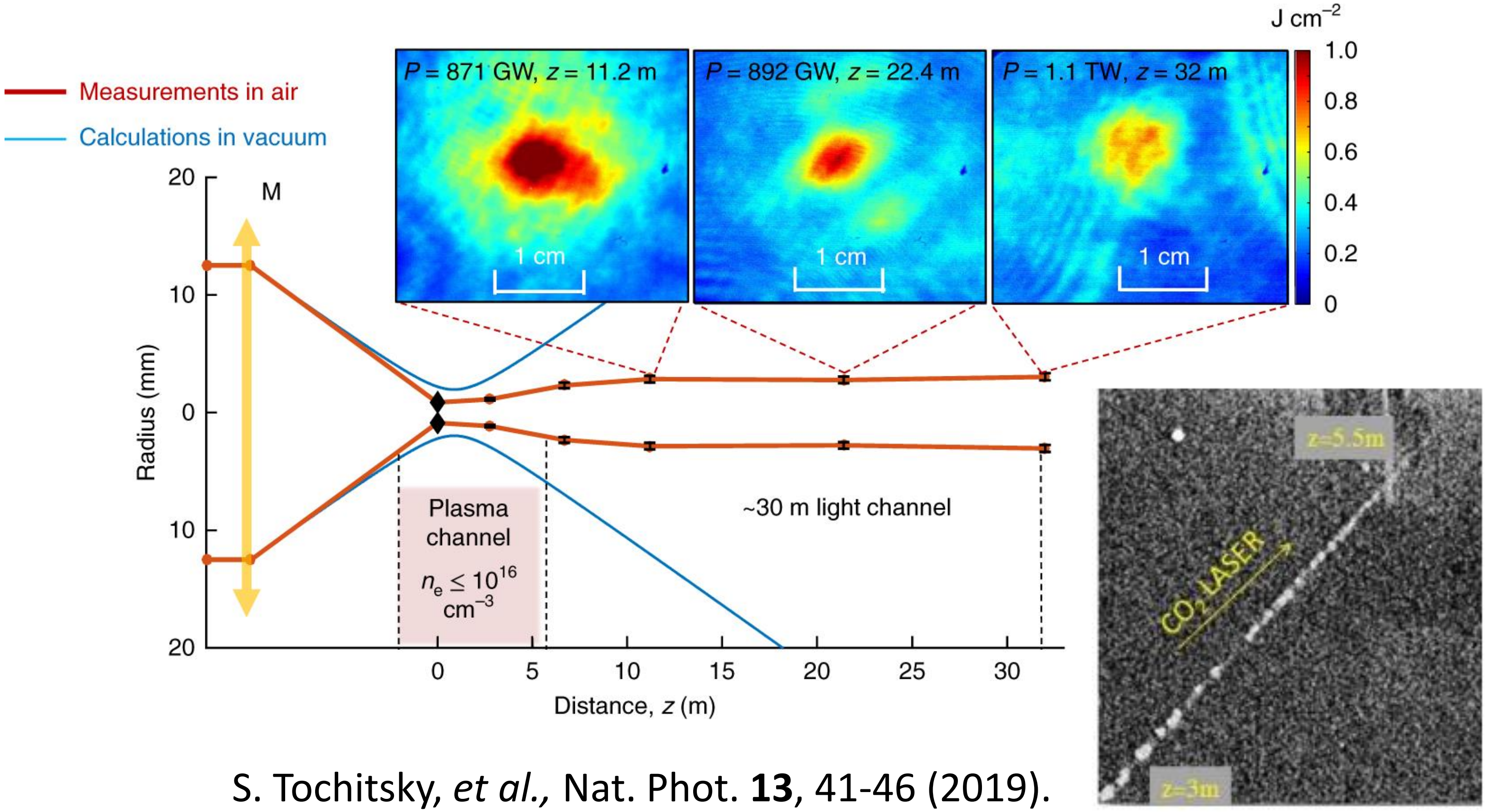






LWIR self-guiding

- Experiment with $P\sim 2P_{cr}, \lambda = 10.2\ \mu\text{m}$ pulses saw self-guiding in ~1 cm channel at ~1 TW/cm^2
- Negligible tunnel ionization at 1 TW/cm^2 : New collapse mechanism?

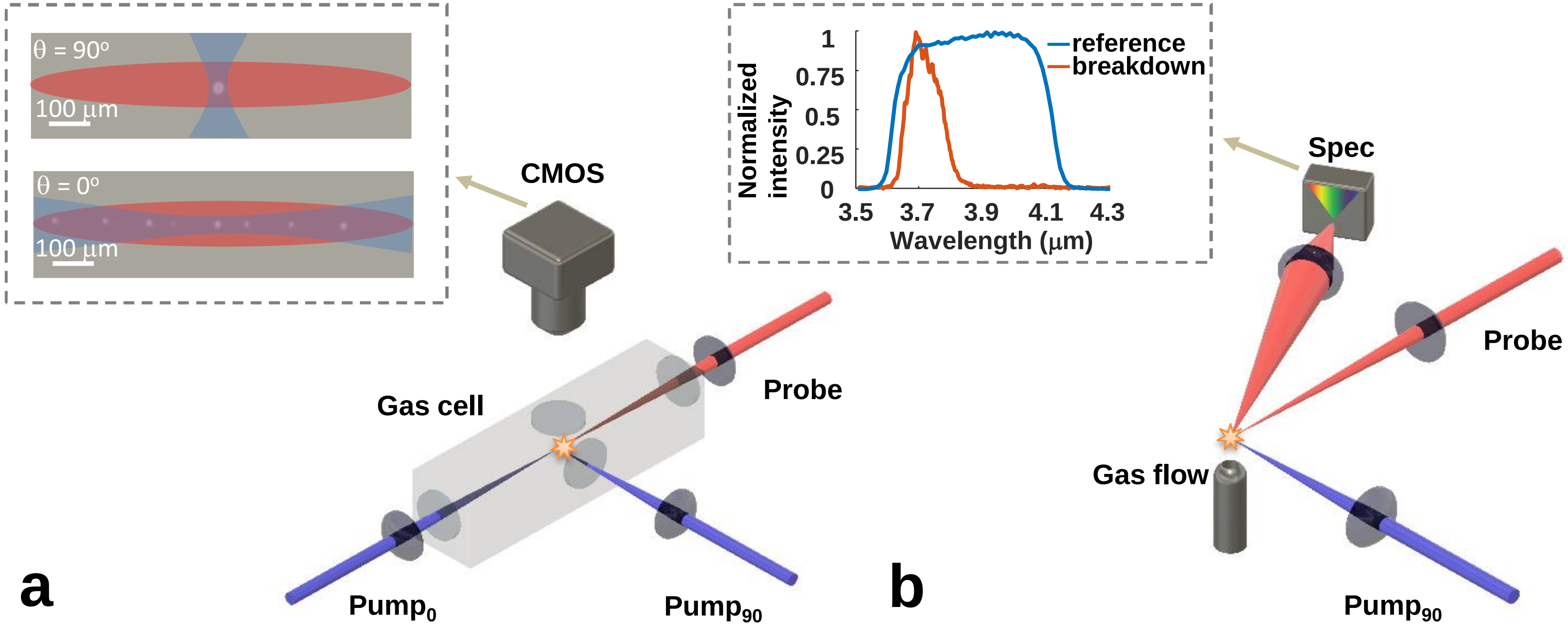


S. Tochitsky, *et al.*, Nat. Phot. **13**, 41-46 (2019).

Follow-up experiment: measuring low-level laser ionization

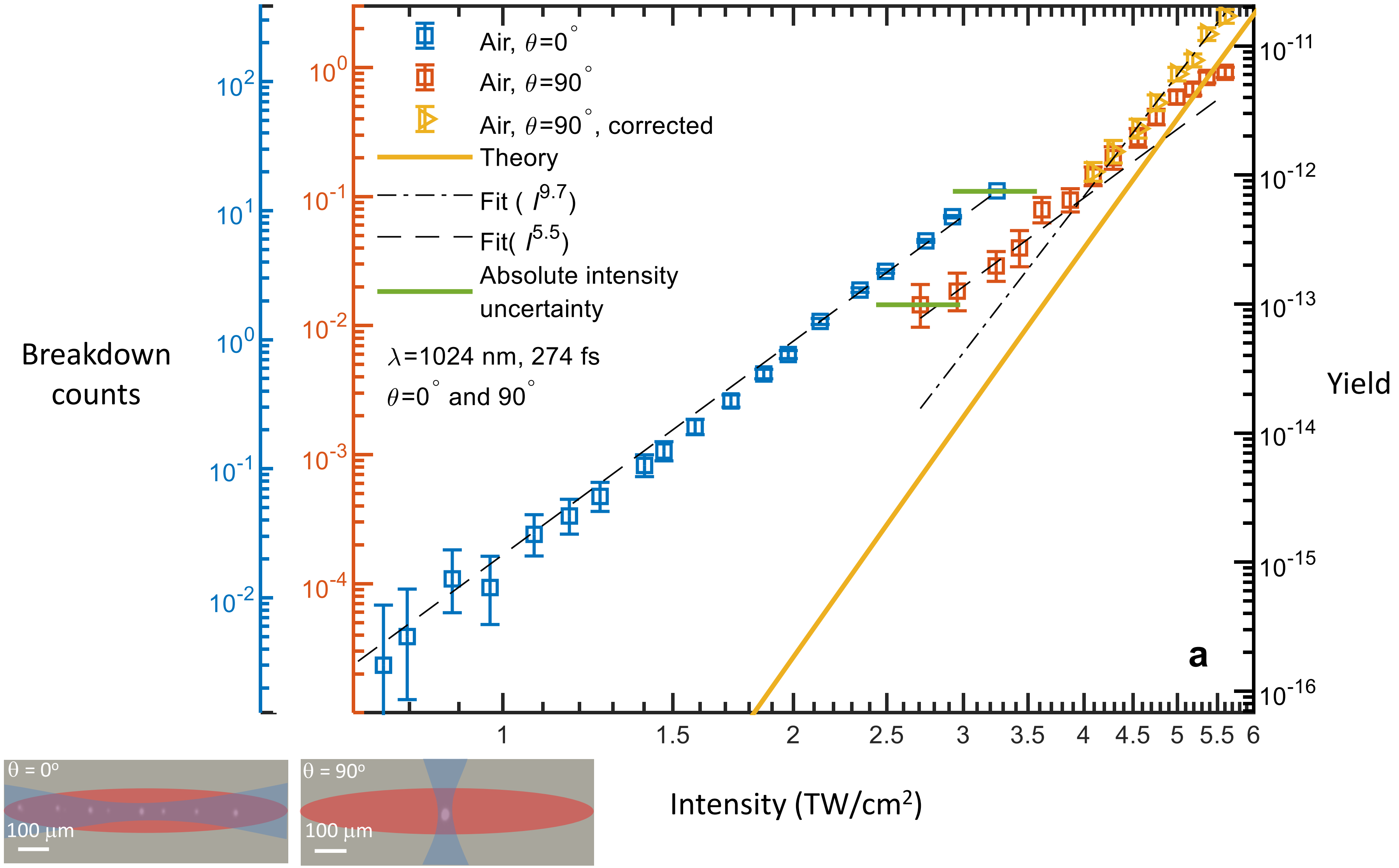
- Use methods to test laser produced (transient) plasma that can’t be measured any other way

- An ultrashort pump pulse (274 fs, 1 μm or 85 fs, 3.9 μm) ionizes target gas, and mid-IR probe amplifies it. Different geometries (a) and measurement techniques (a, b) capture wide range in yield



[D. Woodbury, et al. PRL 124, 013201 (2020)]

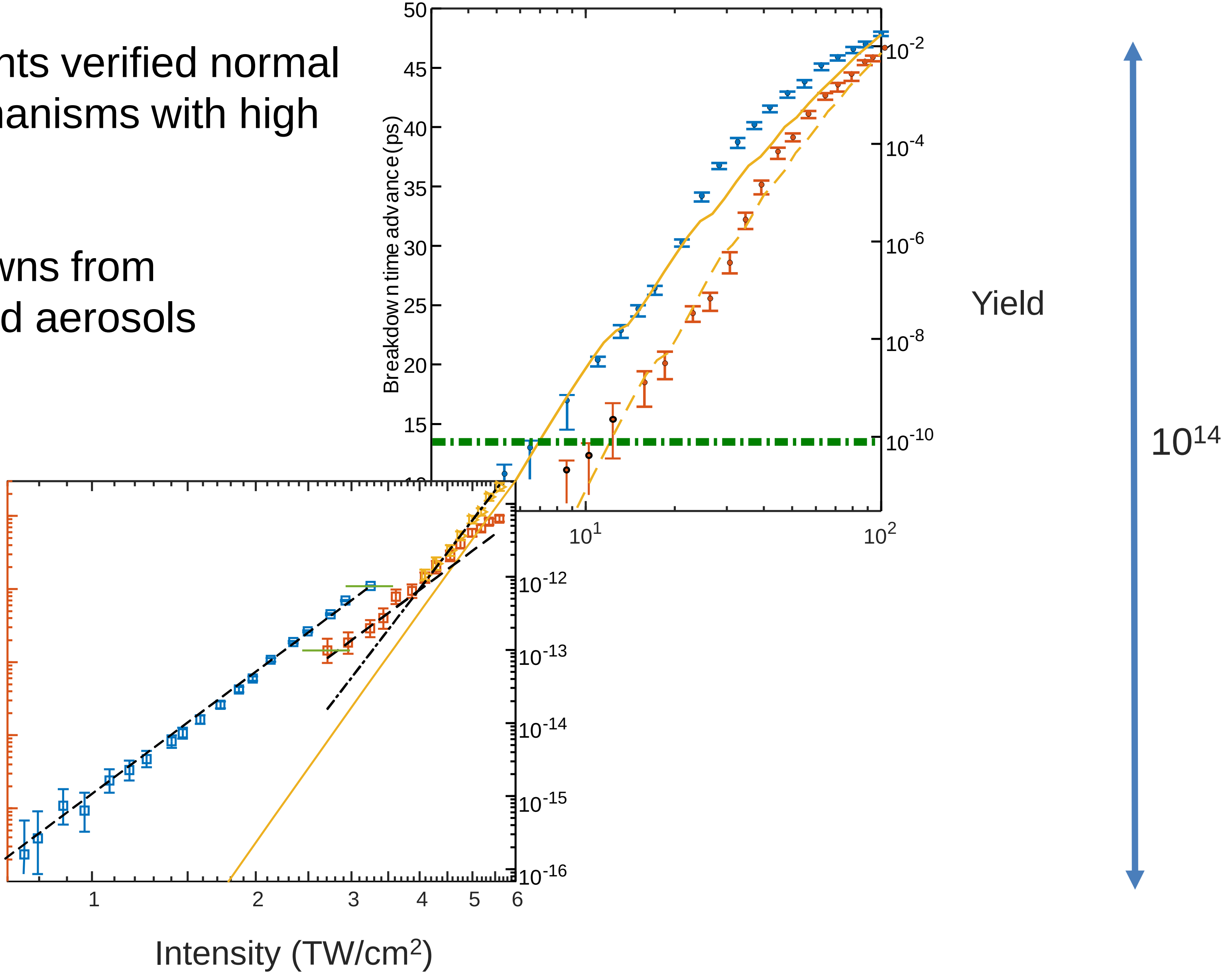
Measuring multiphoton ionization: 10^3-10^9 cm^{-3}



Extreme dynamic range and sensitivity

- Our experiments verified normal ionization mechanisms with high precision

- Saw breakdowns from contaminant and aerosols

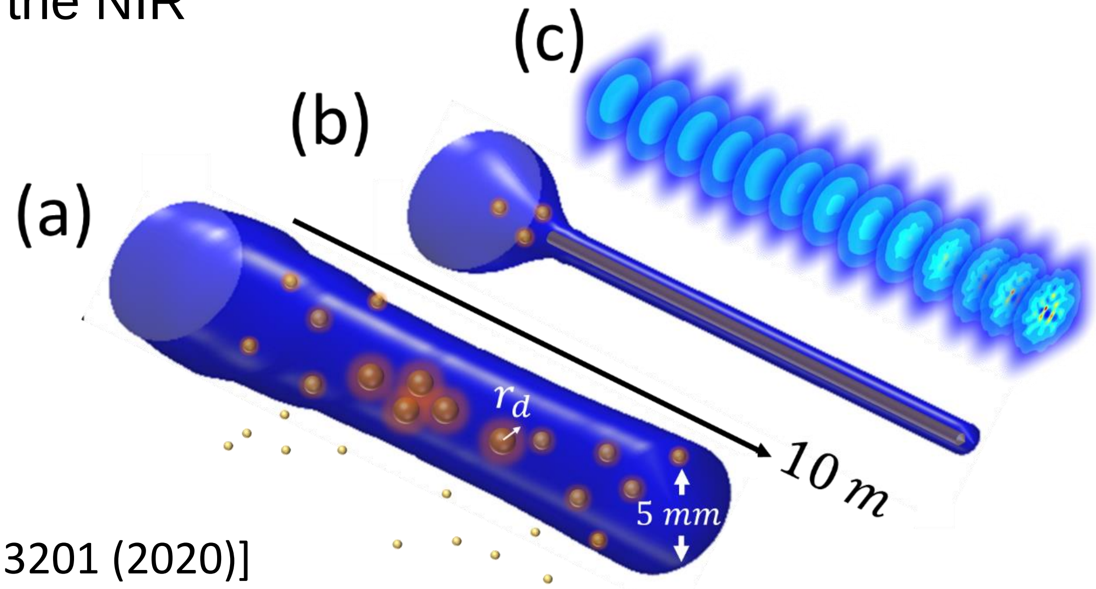


LWIR self-guiding: Aerosol initiated avalanche

- We developed a way to incorporate discrete avalanches into a nonlinear propagation code
    - Avalanche growth model
    - Effective plasma index
    - Incorporation of contaminants and aerosols

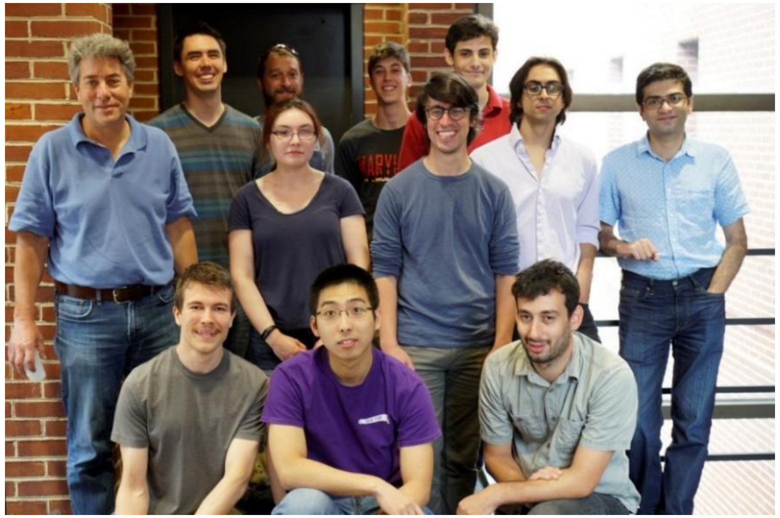
- Results summarized in figure for ~1 TW beams

(a) Aerosol initiated avalanche – leads to low intensity channeling
(b) Contaminant only – leads to high intensity channeling
(c) Comparison with same power in the NIR



[D. Woodbury, et al. PRL **125**, 133201 (2020)]

Many Thanks



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