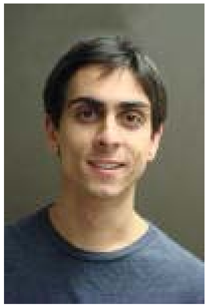
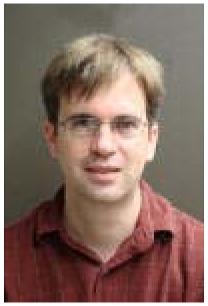
UNIVERSITY OF MARYLAND AT COLLEGE PARK
Dept. of Physics
Dept. of Electrical and Computer Engineering
Institute for Research in Electronics and Applied Physics

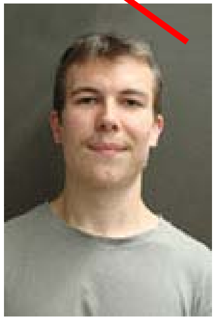
Is there order in the catastrophic collapse of optical beams?

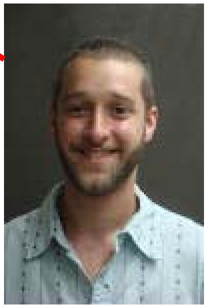
N. Jhajj, I. Larkin, E.W. Rosenthal, J.K. Wahlstrand, S. Zahedpour, and H.M. Milchberg


Nihal


Jared


Sina


Ilia

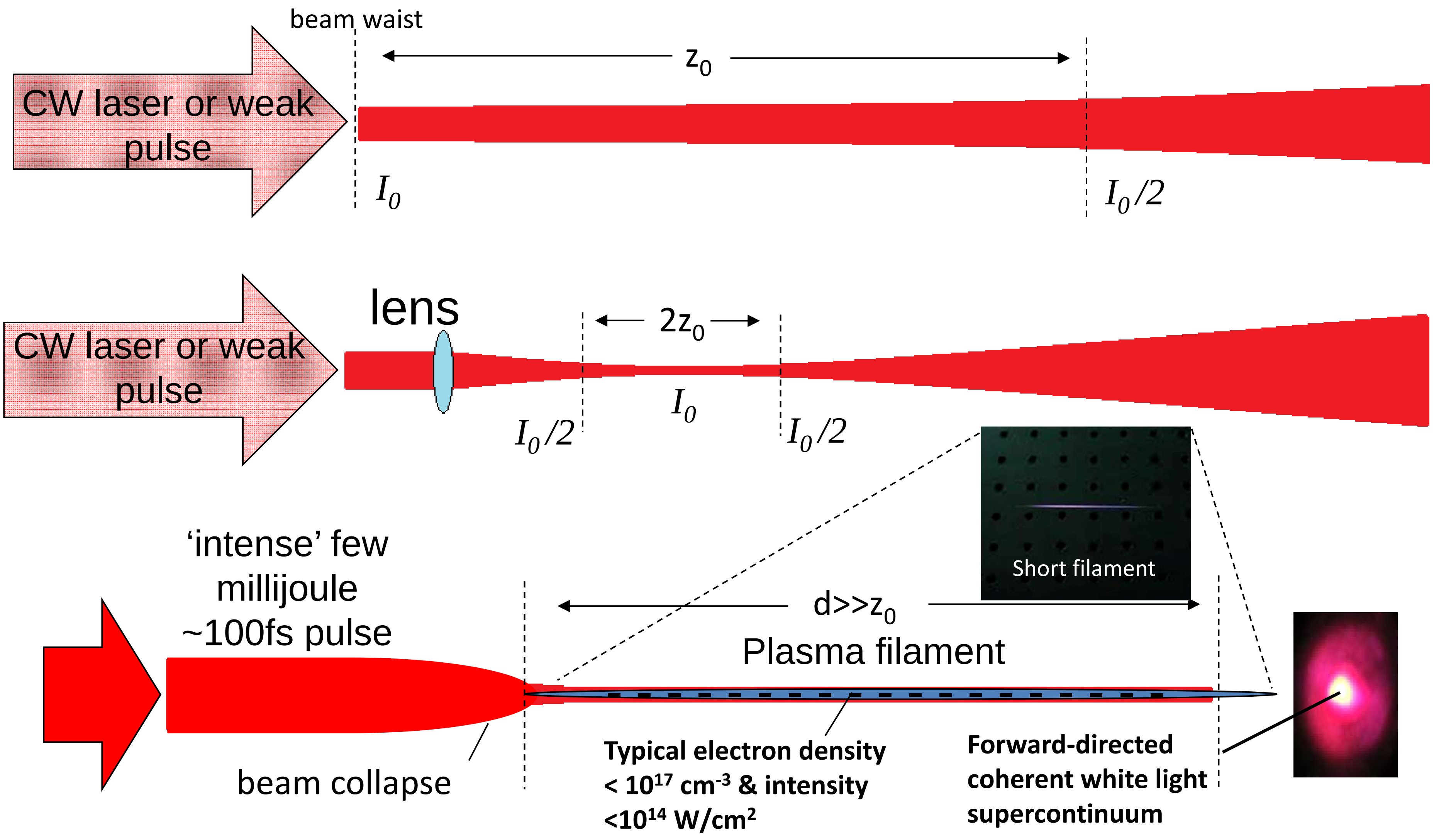

Eric

Thanks to John Palastro, NRL, for help with simulation code

Fischfest !
March 28-30, 2016

Support: AFOSR, NSF, ARO, DARPA, DoE, DTRA

Ultra short pulse propagation in gases



beam waist

CW laser or weak pulse

z_0

I_0

$I_0/2$

lens

CW laser or weak pulse

$2z_0$

$I_0/2$

I_0

$I_0/2$

Short filament

'intense' few millijoule ~100fs pulse

$d \gg z_0$

Plasma filament

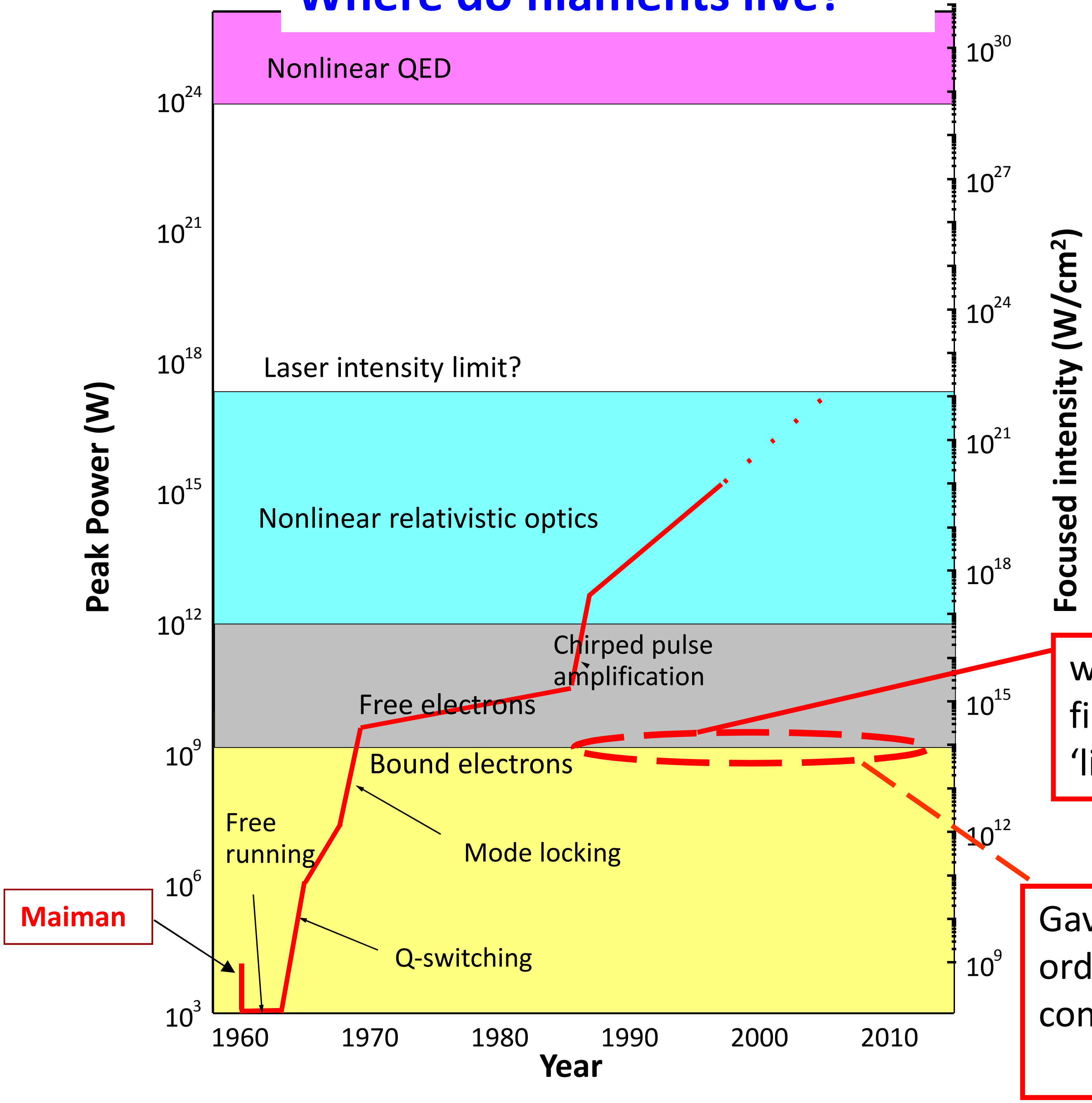
beam collapse

Typical electron density $< 10^{17}$ cm^{-3} & intensity $<10^{14}$ W/cm^2

Forward-directed coherent white light supercontinuum

Braun, Korn, Mourou Optics Letters 1995

Where do filaments live?



where filaments 'live'

Gave rise to 'high order Kerr effect' controversy

Some applications of filaments

- directed energy (?), directed intensity (√)
- triggering and guiding of electrical discharges (?)

  B. Forestier *et al.*, AIP ADVANCES **2**, 012151 (2012)
- triggering of rain (?) P. Rohwetter et al., Nature Photonics **4**, 451(2010)
- remote lasing of air molecules (?√) P. Sprangle *et al.*, Appl. Phys. Lett. **98**, 211102 (2011)
- remote detection: LIBS, LIDAR (?√) J. Kasparian *et al.*, Science **301**, 61 (2003)
- directed, remote THz generation (√) J. Dai *et al*, PRL **97**, 103903 (2006), K. Y. Kim *et al.*, Nature Photonics **2**, 605 (2008)
- high harmonic generation (√) D. S. Steingrube et al., NJP **13**, 043022 (2011)
- broadband light generation for few-cycle pulse generation (√) N. Zhavoronkov, Opt. Lett. **36**, 529 (2011)
- directed energy/directed average power (√)
- remote detection (√)

N. Jhajj *et al.*, Phys. Rev. X 4, 011027 (2014), Phys. Today 2014

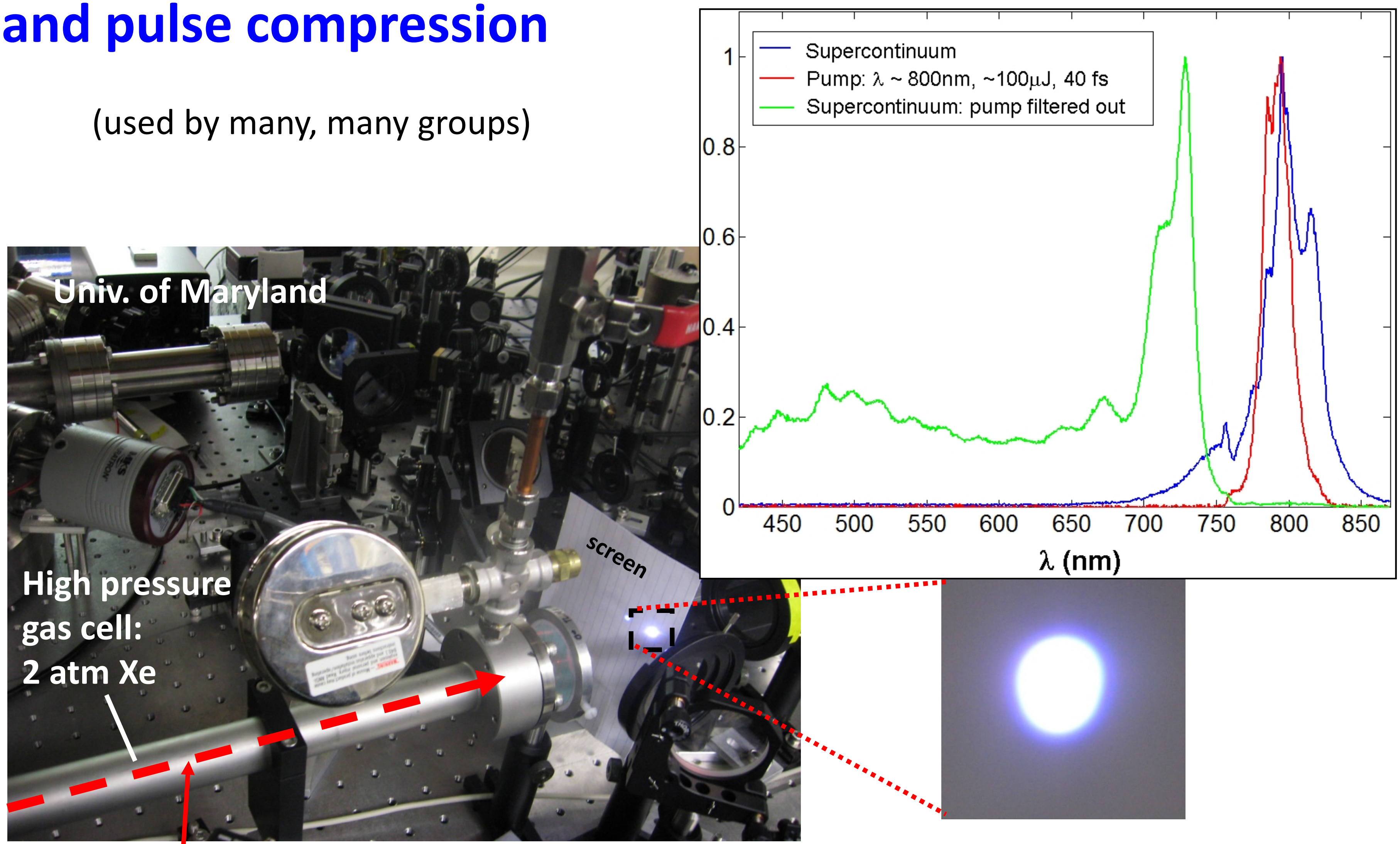
E. Rosenthal et al., Optica 1, 5 (2014)

Good introduction and early review of filaments:

A. Couairon and A. Mysyrowicz, Phys. Rep. ***441****, 47-189 (2007).*

Supercontinuum generation and pulse compression

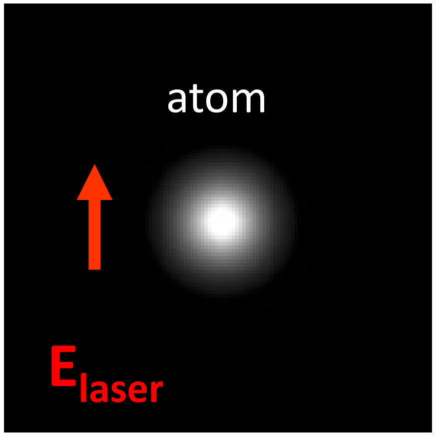
(used by many, many groups)



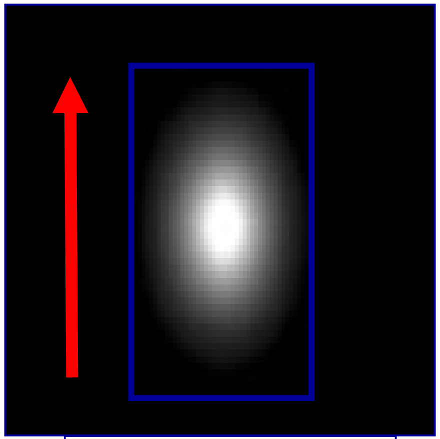
Filamenting λ~800 nm, 40 fs femtosecond pulse

Coherent white light beam

Nonlinear response of electrons in simple atom

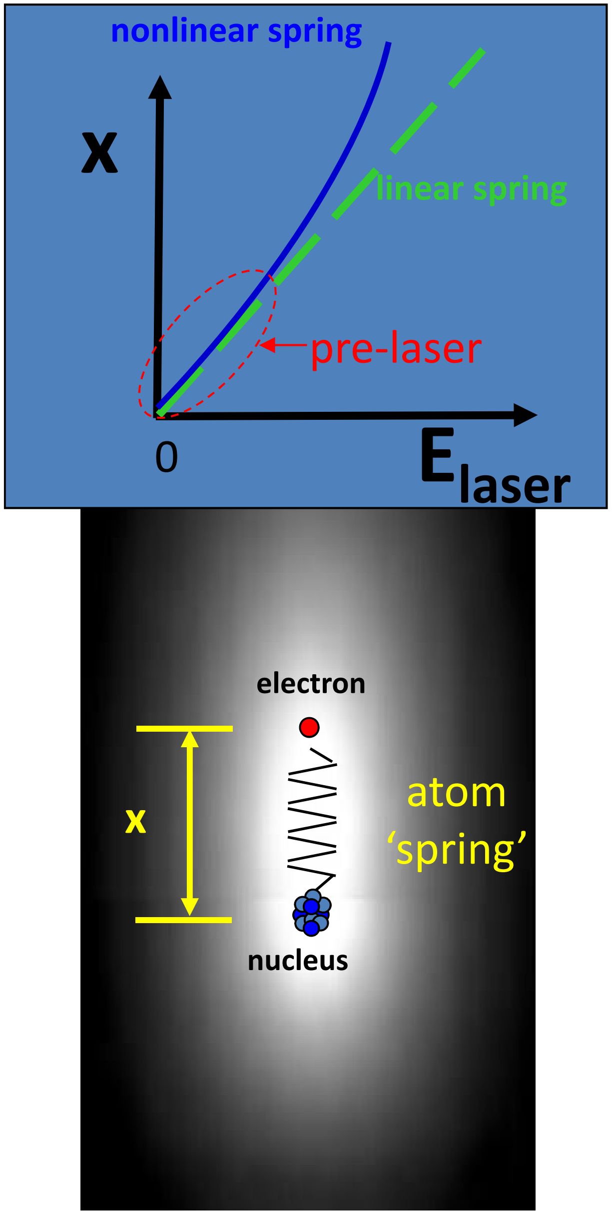


small E-field



large E-field
of laser beam

Nonresonant response is instantaneous



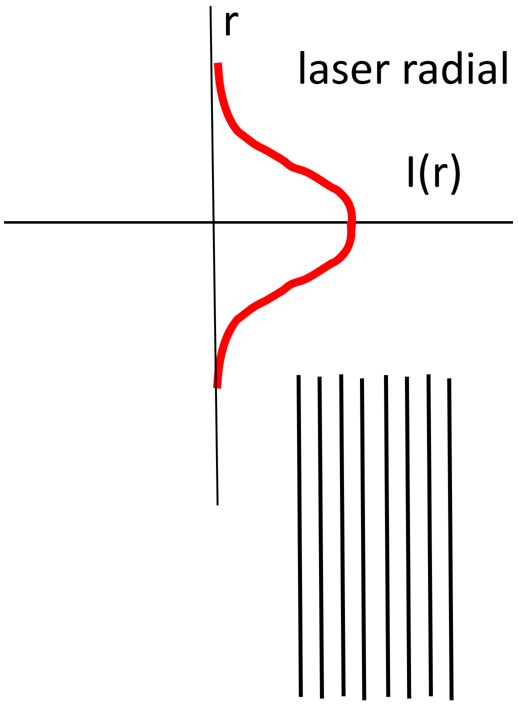
Bound electron response

Perturbation regime: nonlinear self-focusing

In perturbation theory

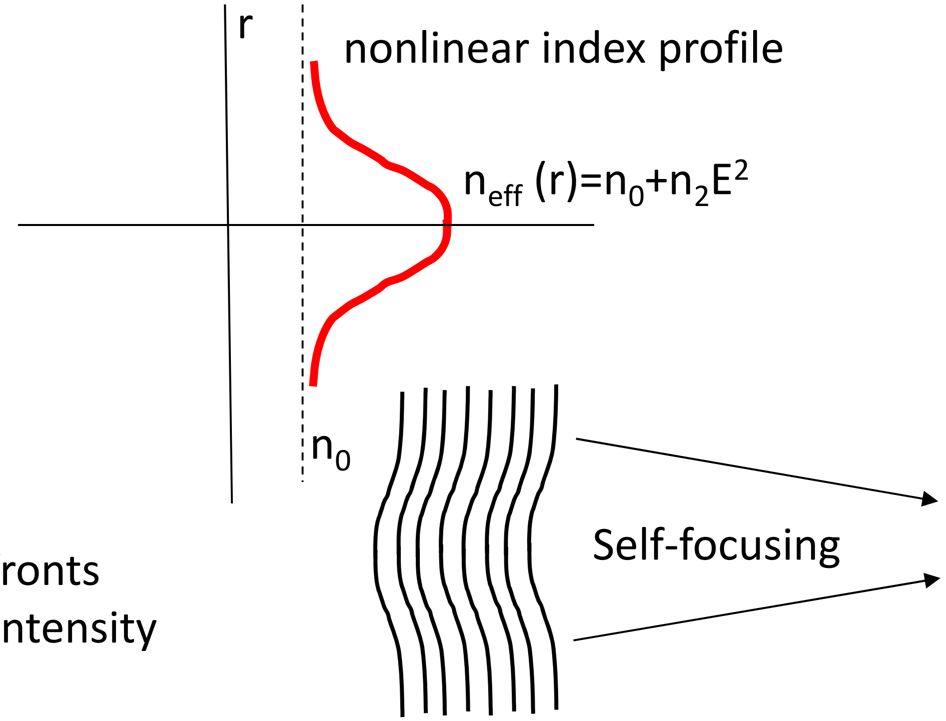
$$P=\chi^{(1)}E + \cancelto{0}{\chi^{(2)}}E^2 + \chi^{(3)}E^3 + \dots \quad \rightarrow \quad P=(\overbrace{\chi^{(1)} + \chi^{(3)}E^2}^{\chi_{eff}})E + \dots$$

$$n_{eff}^2 = 1+4\pi\chi_{eff} \rightarrow n_{eff} = n_0+n_2E^2$$



laser radial profile

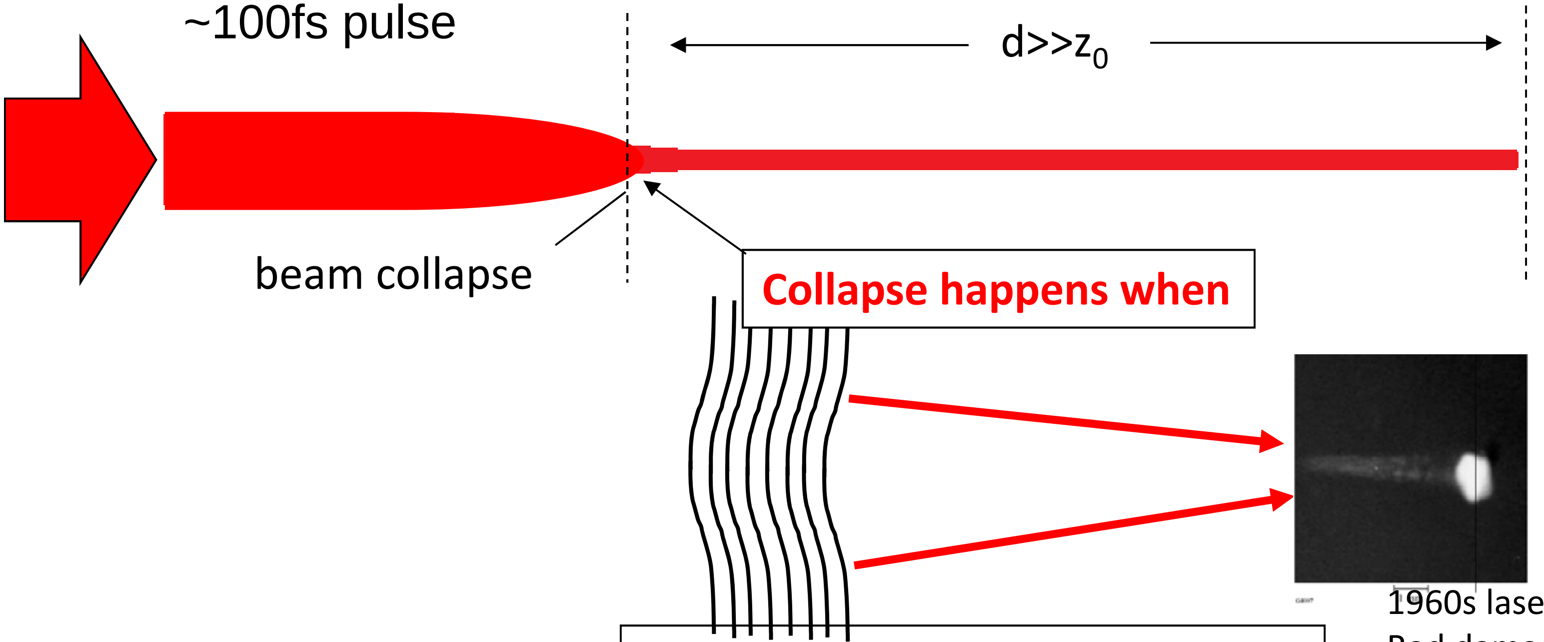
Phase fronts
at low intensity



nonlinear index profile

Self-focusing

Self-focusing beam collapse



few millijoule
~100fs pulse

$d >> z_0$

beam collapse

Collapse happens when

Self-focusing beats diffraction

1960s laser
Rod damage
@ 10 MW

for critical power $P_{cr} \sim \lambda^2 / 8 n_0 n_2$

P_{cr}~ 2-10 GW for air

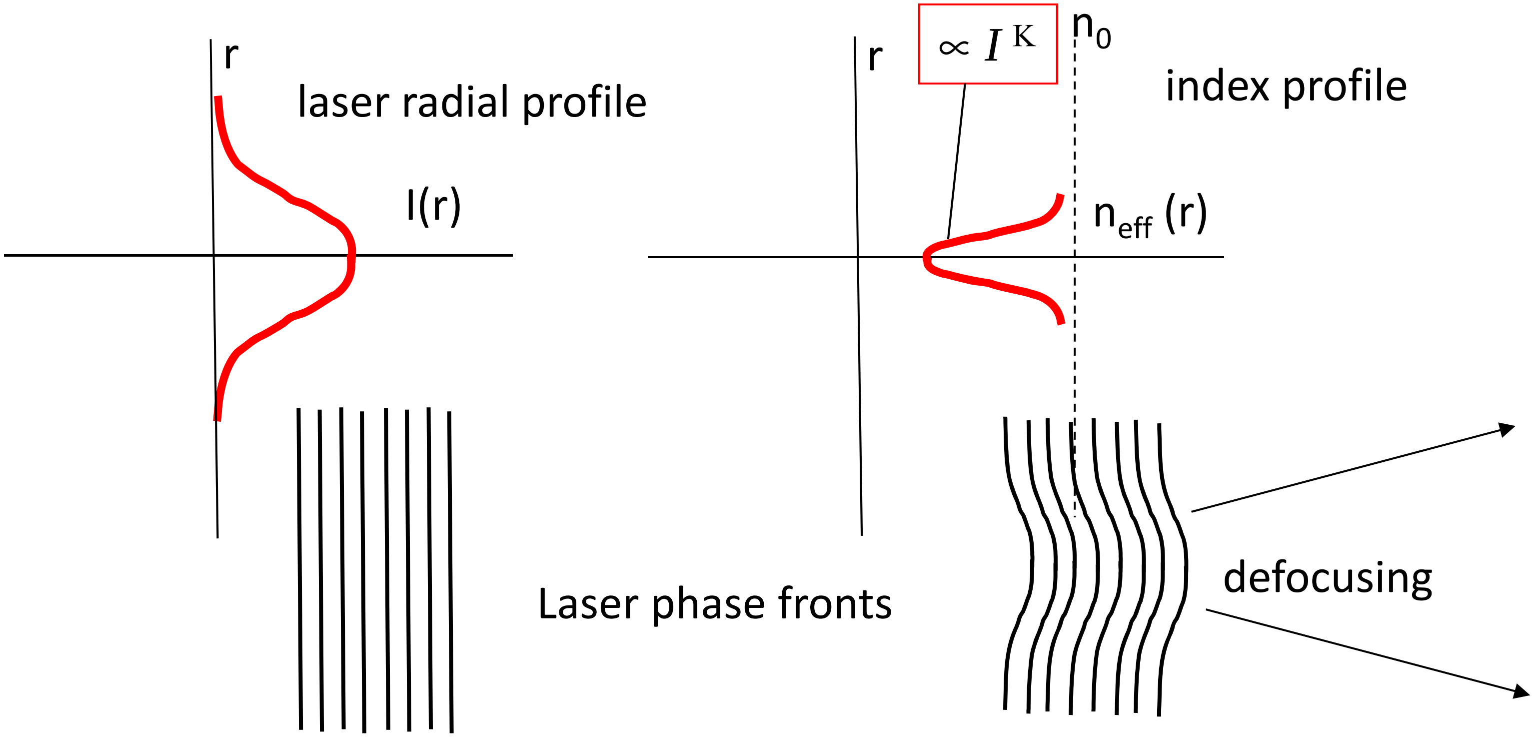
(P_{cr} >10 MW in solids)

Ionization and plasma defocusing

Ionization important at peak intensity > ~10^{13} W/cm^2

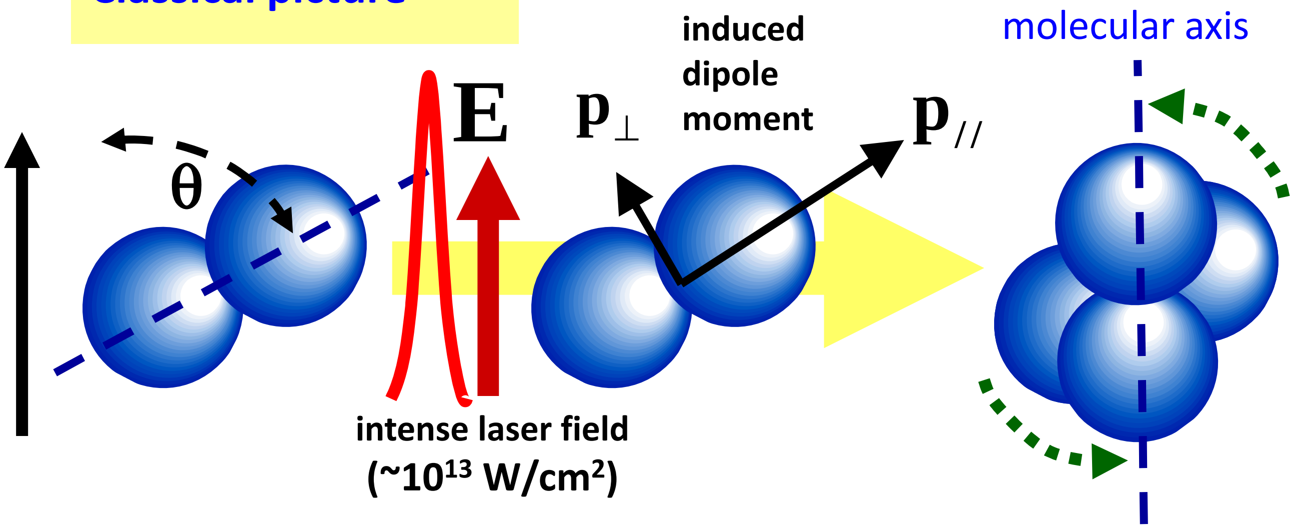
$dN_e/dt = N_0\sigma I^K$ multiphoton ionization with K photons

$$n^2 = 1+4\pi\chi_{free\ elec} = 1-\omega_p^2/\omega^2 = 1-N_e/N_{cr} \quad , \quad n\sim 1-N_e/2N_{cr}$$



Air: Laser field alignment of linear gas molecules

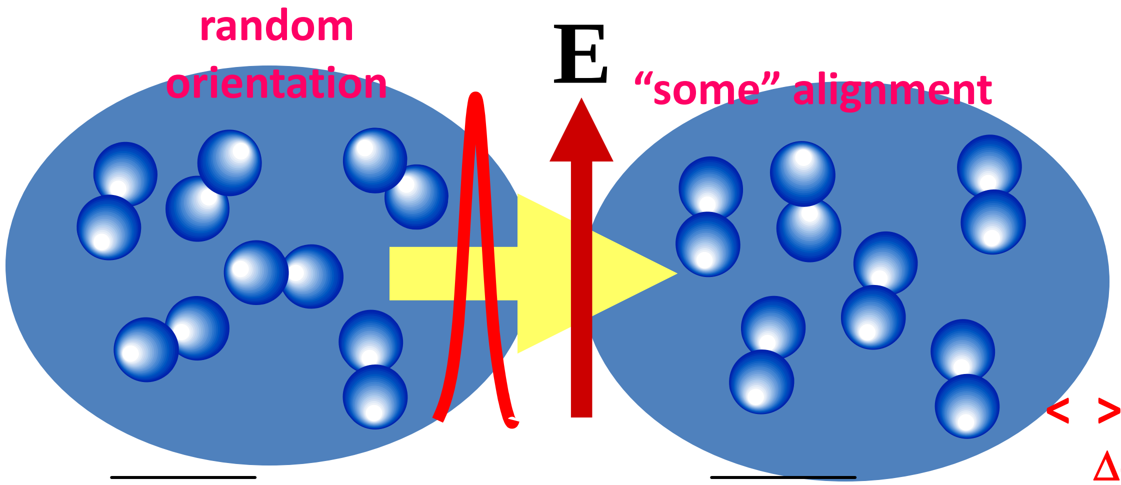
Classical picture



-laser field applies a net torque to the molecule

-molecular axis aligns along the E field

-delayed response (ps) due to inertia



$$\overline{\cos^2\theta} = 1/3$$

$$\overline{\cos^2\theta} \neq 1/3$$

time-dependent refractive index shift

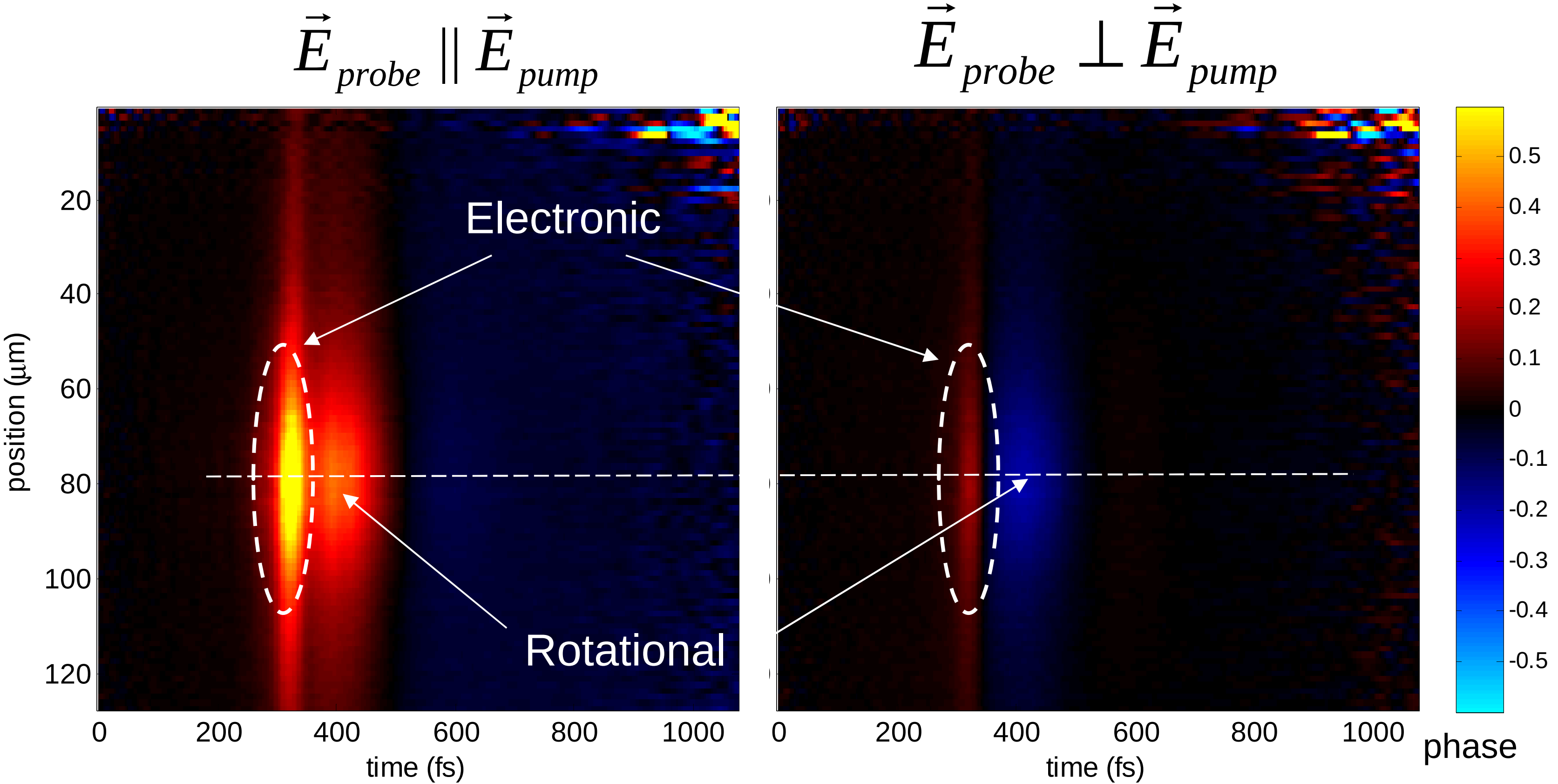
$$\Delta n(t) = \frac{2\pi N}{n_0}\Delta\alpha\underbrace{\left(<\cos^2\theta>_t - \frac{1}{3}\right)}_{\text{degree of alignment}}$$

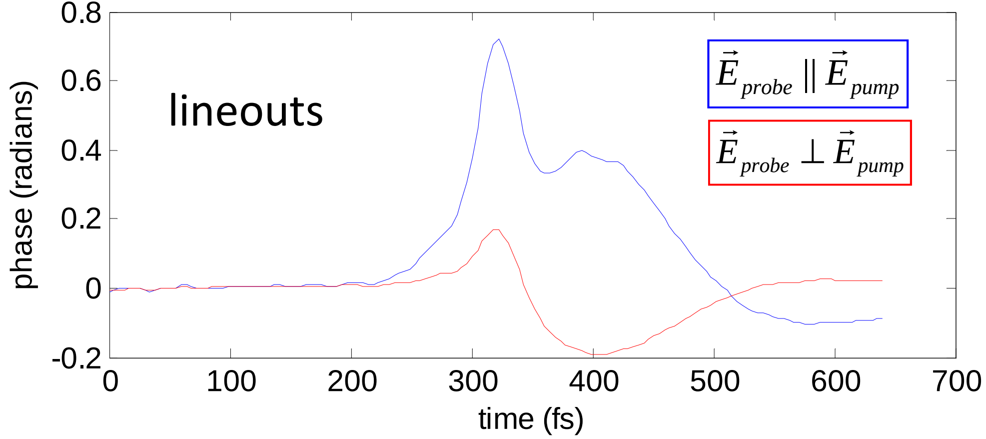
$< \; >_t$: time-dependent ensemble average

$\Delta\alpha = \alpha_\parallel - \alpha_\perp$ polarizability asymmetry

$n_0 = n$(random orientation)

Nitrogen: electronic + rotational nonlinearity





Molecules: delayed response due to rotational alignment

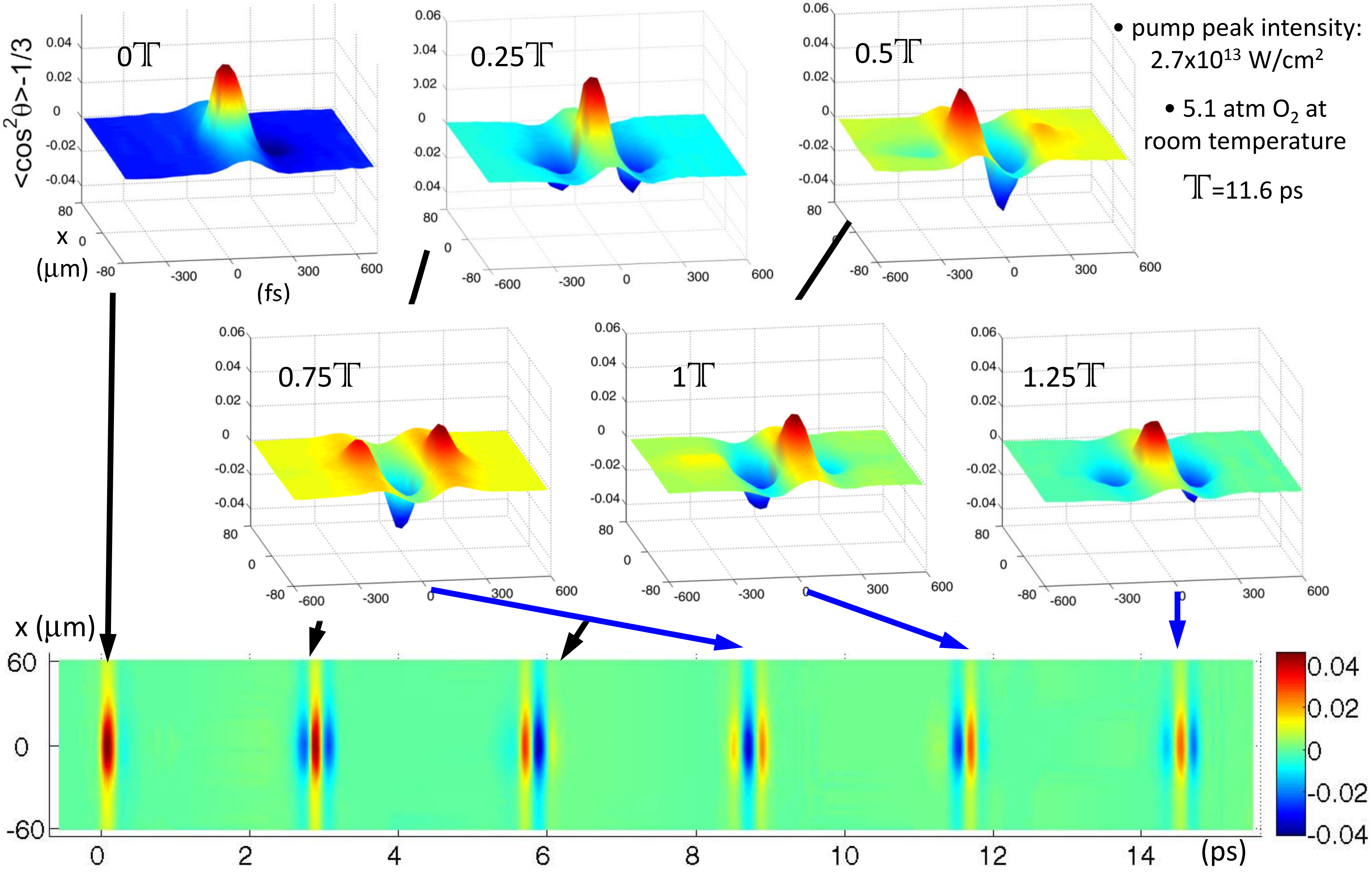
Pump 40 fs, 75 TW/cm^2

Wahlstrand et al., PRL **107**, 103901 (2011)

Spatially resolved temporal evolution of O_2 alignment

Y.-H. Chen *et al.*, Opt. Express **15**, 11341 (2007)

$\mathbb{T}$= fundamental rotation period



- pump peak intensity: 2.7×10^{13} W/cm^2
- 5.1 atm O_2 at room temperature

$\mathbb{T}$=11.6 ps

Field alignment and quantum echoes of rotational wavepacket

See Y.-H. Chen *et al.*, Opt. Express **15**, 11341 (2007)
for theoretical/ experimental description

Quantum description of rigid rotor

$$|j,m\rangle \exp(-i\omega_j t)$$ eigenstate

where $\omega_j = E_j/\hbar = 2\pi c B\overbrace{j(j+1)}^{\text{even}}$ (j: ≥0 integer)

$B = h(8\pi^2 c I)^{-1}$ (“rotational constant”)

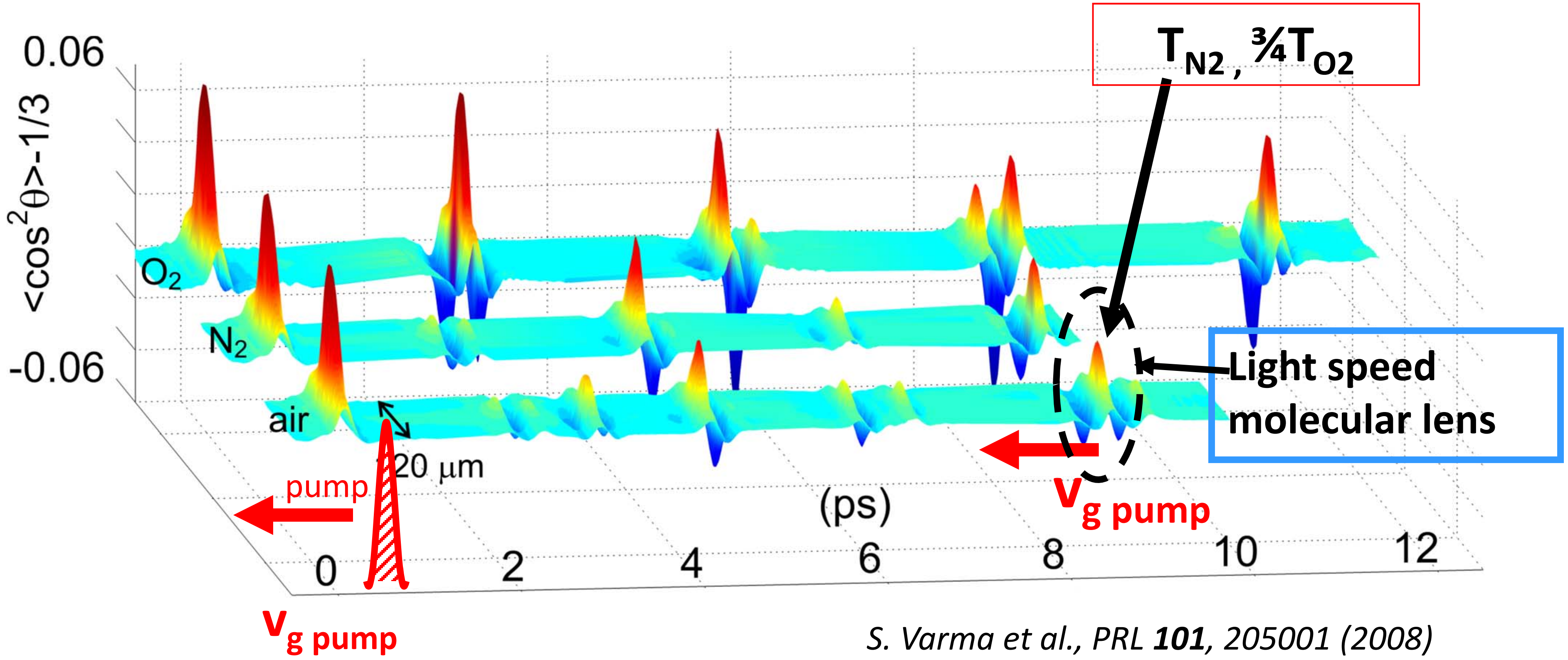
I : moment of inertia

Rotational wavepacket

$$|\psi\rangle = \sum_{j,m} a_{j,m} |j,m\rangle \exp(-i\omega_j t)$$

An intense fs laser pulse “locks” the relative phases of the rotational states in the wavepacket– (non-resonant Raman pumping of many *j* states)

Rotational quantum wakes in air



T_{N2}, $\frac{3}{4}T_{O2}$

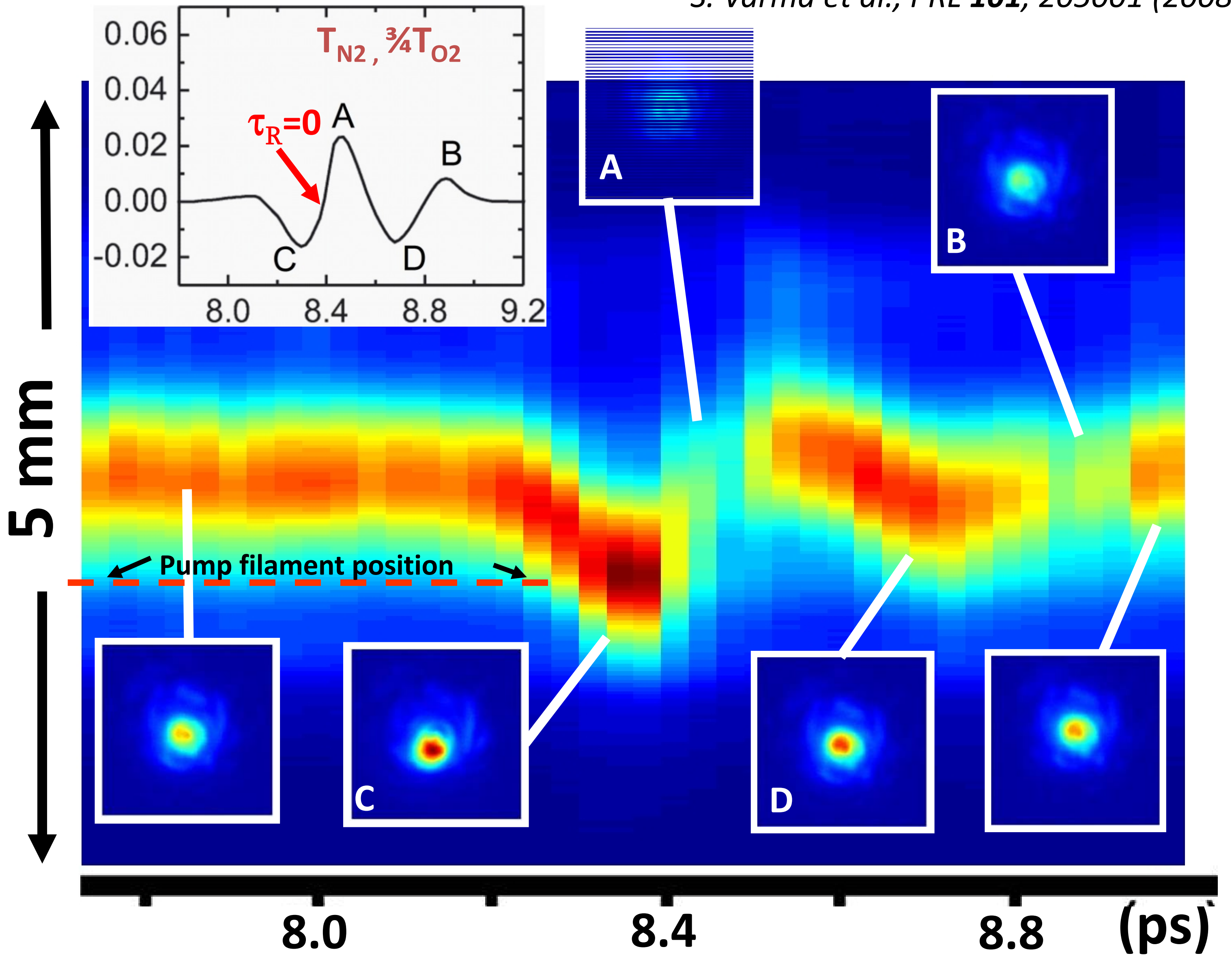
Light speed molecular lens

S. Varma et al., PRL ***101****, 205001 (2008)*

Measurement showing alignment and anti-alignment “wake” traveling at the group velocity of the pump pulse.

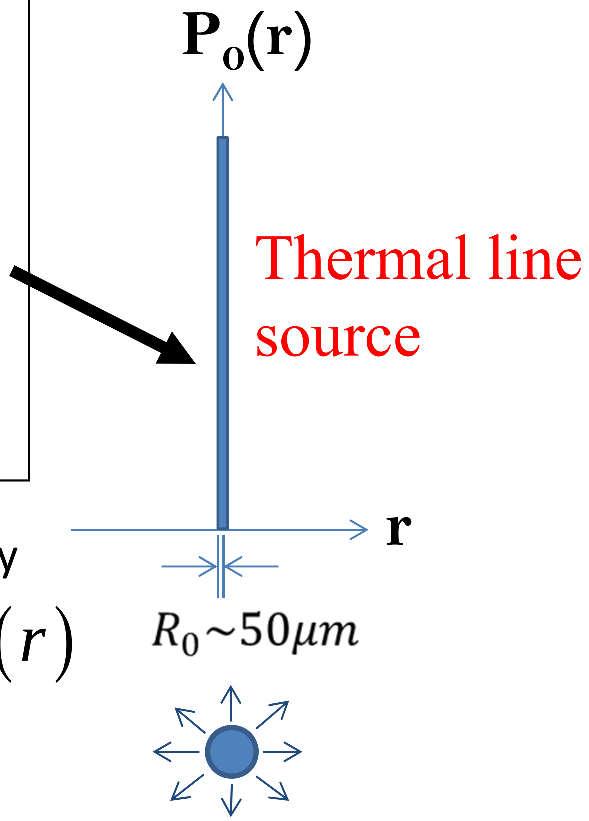
Probe filaments are steered/trapped or destroyed

S. Varma et al., PRL ***101****, 205001 (2008)*



What happens after the filament passes through the gas?

- filament: plasma generated and molecules heated
- plasma recombination and molecular thermalization (~10 ns)
- energy repartitioned to neutral gas
- Small gas thermal conductivity maintains tight radial confinement of thermal energy



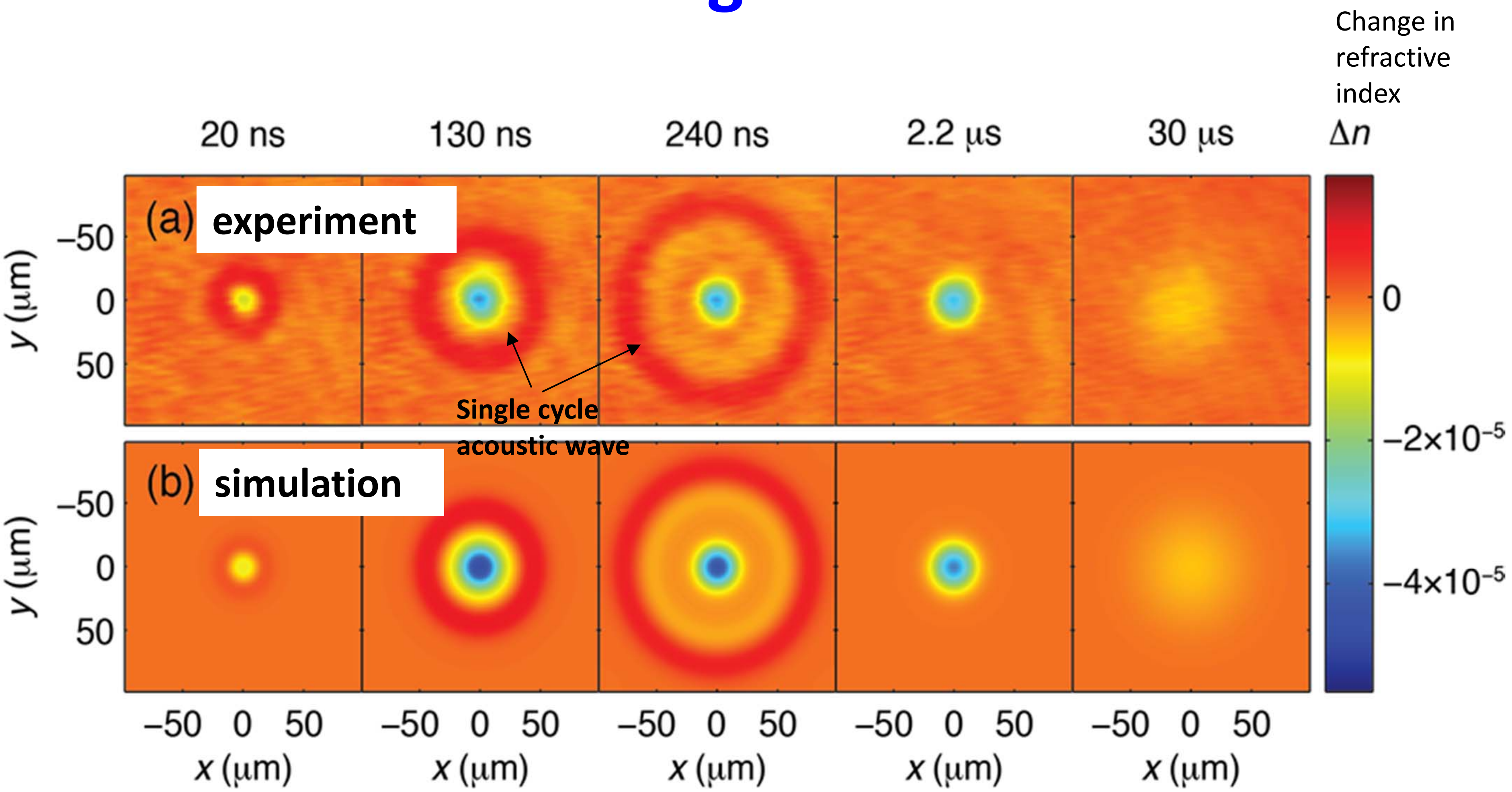
plasma energy

$$P_0(r) = N(r)k_B T(r) \approx \left(f_e / f_g\right) N_e(r) k_B T_e(r)$$

$$+ 2\Delta\varepsilon_{rot} / f_g$$

rotational energy

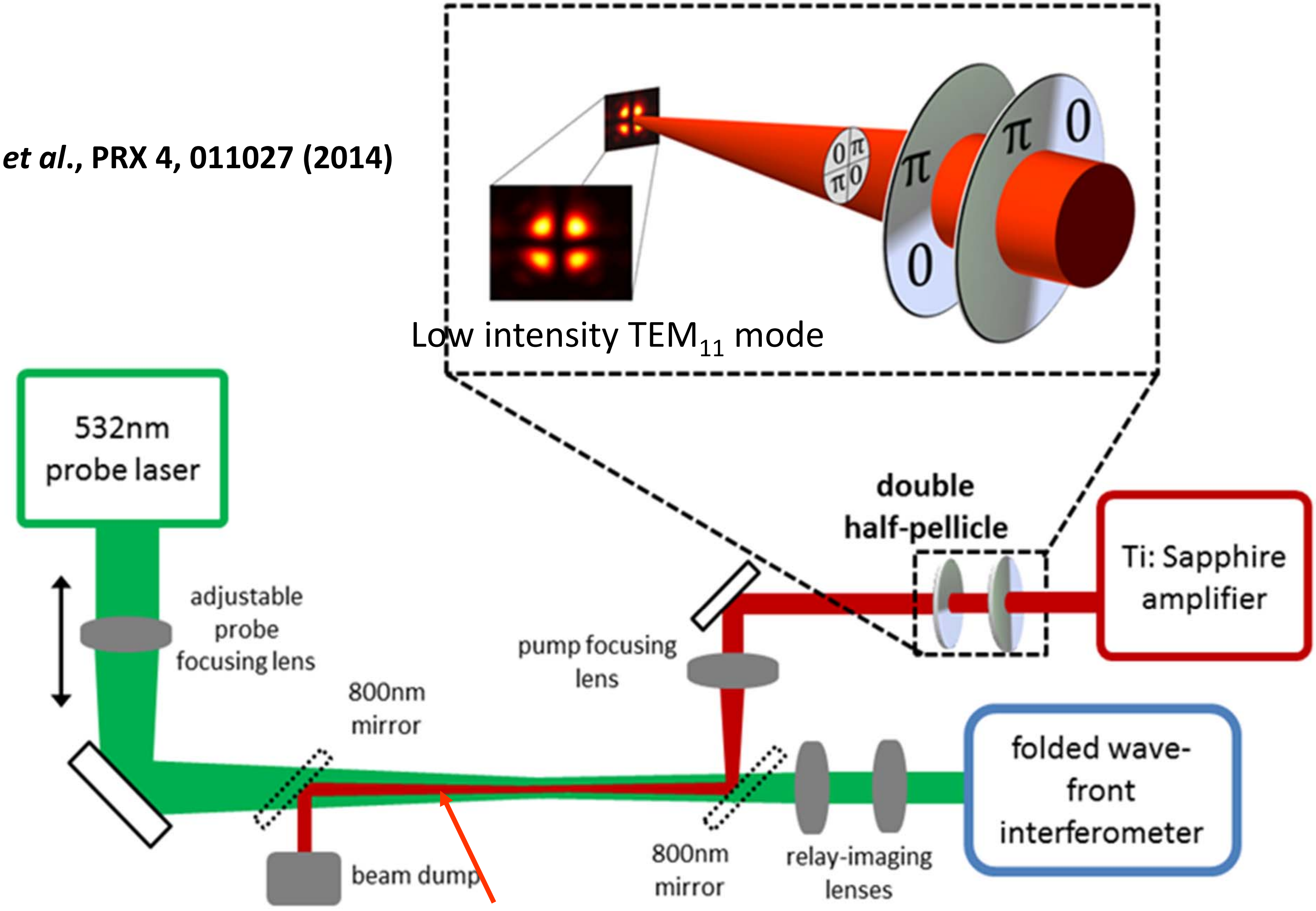
Post-filament gas evolution



N. Jhajj *et al.*, PRX **4**, 011027 (2014)
J.K. Wahlstrand *et al.*, Opt. Lett. **39**, 1290 (2014)

Generating a quad density hole

N. Jhajj *et al.*, PRX 4, 011027 (2014)

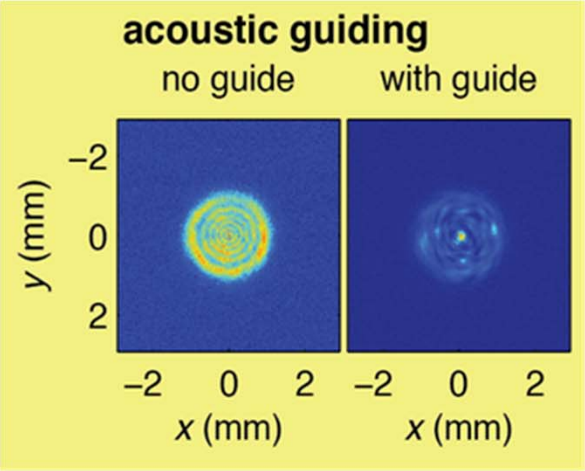


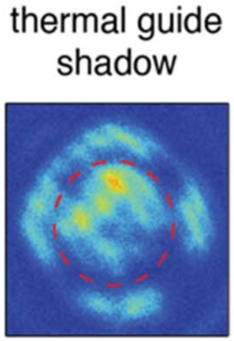
Low intensity TEM_{11} mode

70 cm quad filament

Guiding experiment

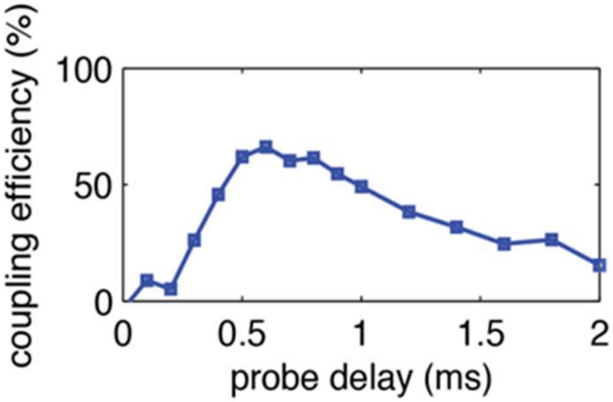
Jhajj et al., PRX **4**, 011027 (2014)

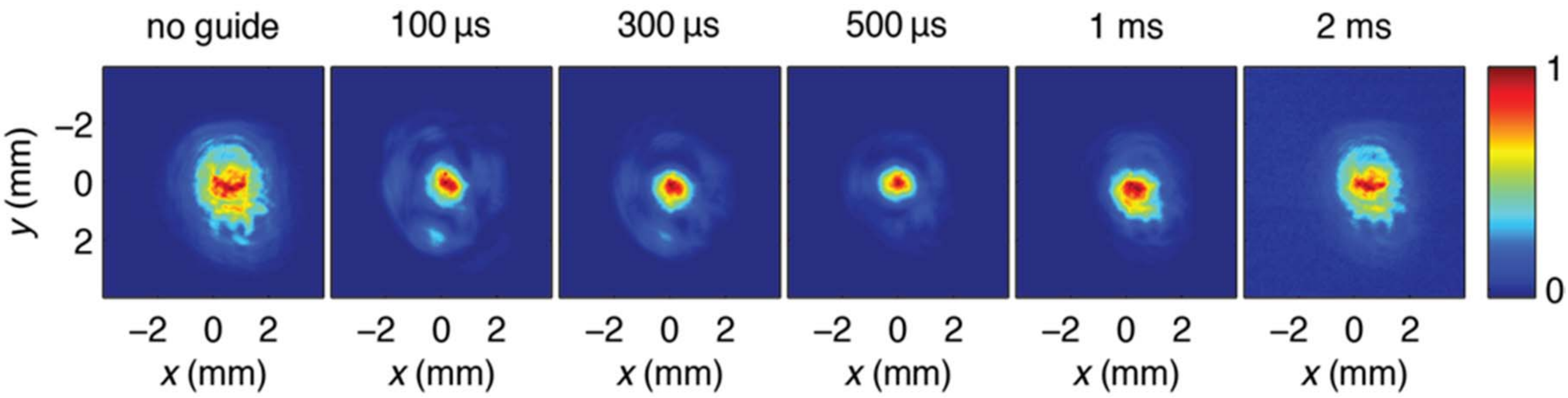




Guided: 110 mJ, 7ns, 532 nm

thermal guiding





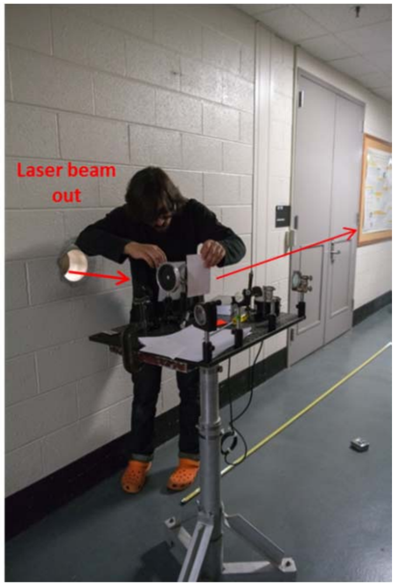
$$P_g \Delta t / A = 1.5\eta\alpha^{-1} p$$

Air/aerosol absorption coefficient

P. Sprangle *et al.*, Journal of Directed Energy **2**, 71 (2006)

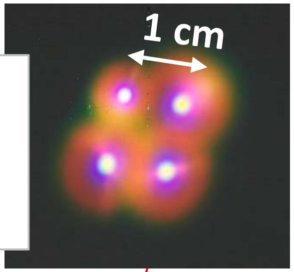
Refractive index depth η = 2%
→Thermal blooming average power guiding limit ~ 1 MW

Lensing of λ=532 nm pulses by ~10m quad thermal guide



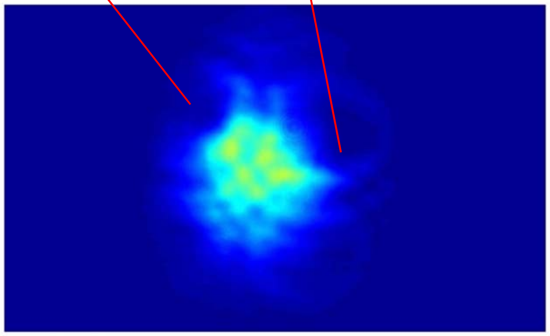
The IREAP hallway!

Supercontinuum from femtosecond quad-filament at ~ 5m mid-guide location

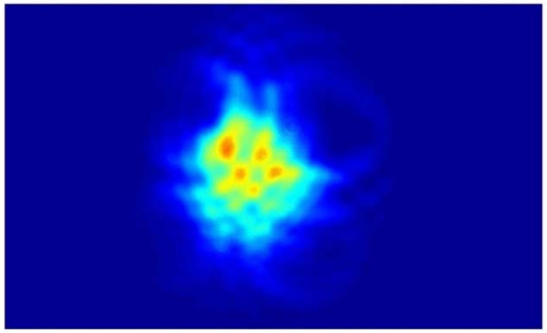


Filament-induced thermal imprint

0.5 ms

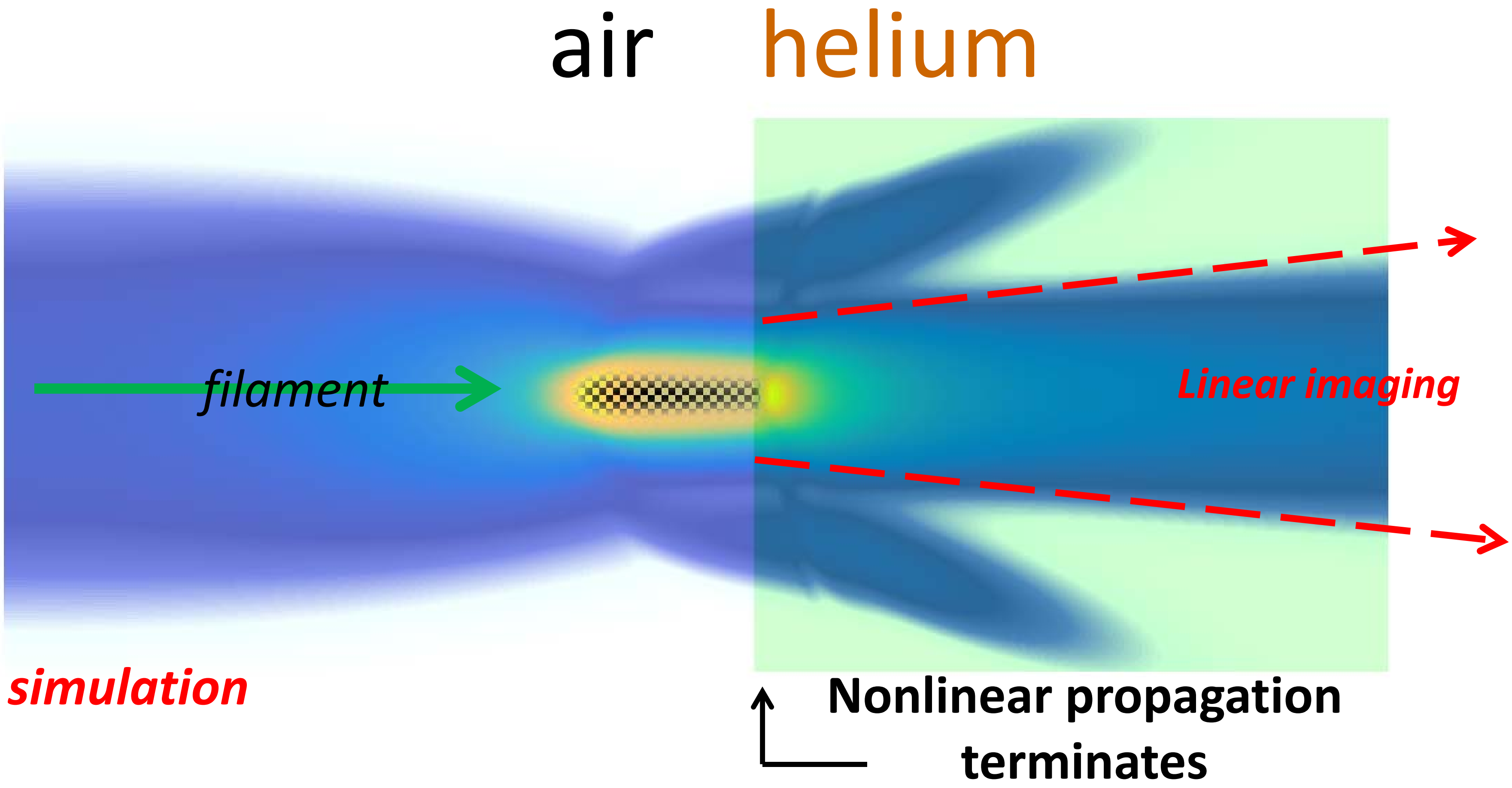


1 ms



Even after collapse, filament cores appear phase linked—why??

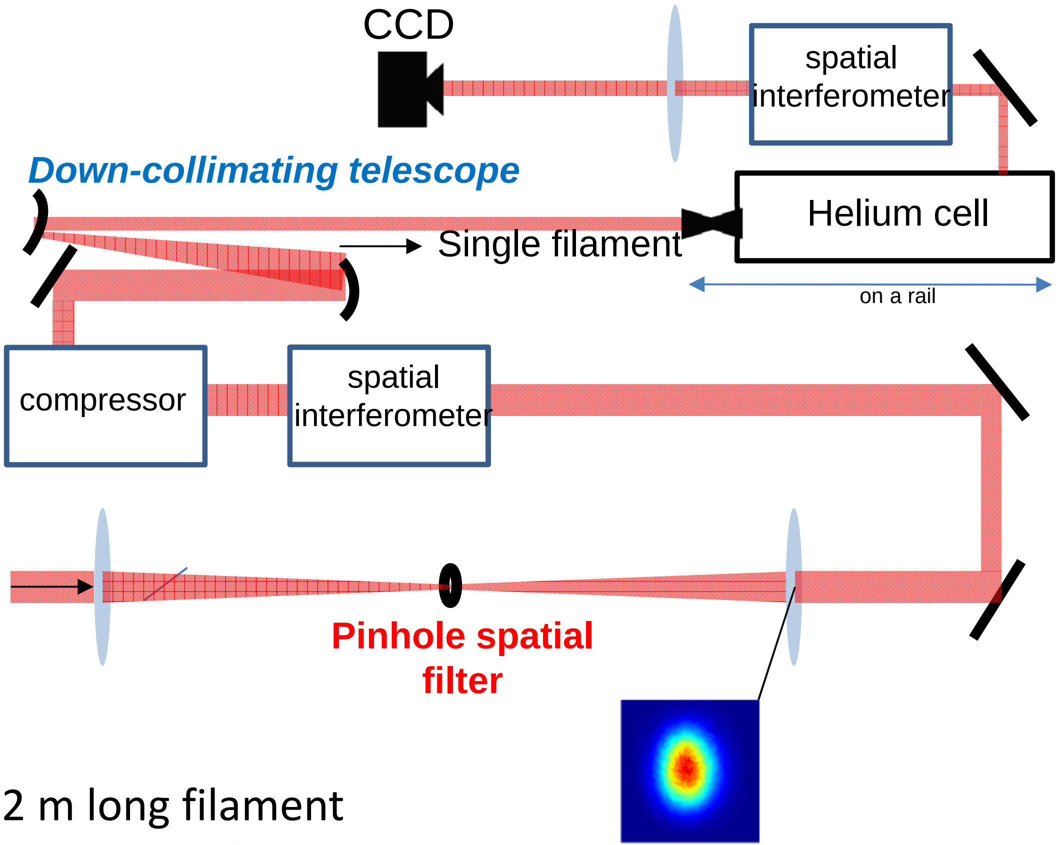
We want to measure the beam phase **INSIDE** a filament (at peak intensity 10^{14} W/cm^2) —*How to do this?*

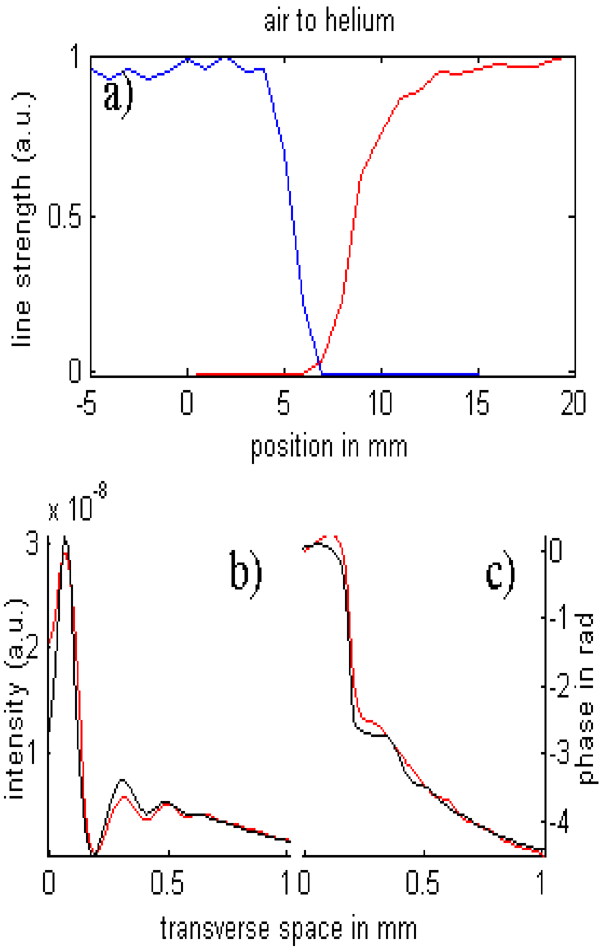


arXiv:1604.01751

Imaging the amplitude and phase inside a filament

arXiv:1604.01751



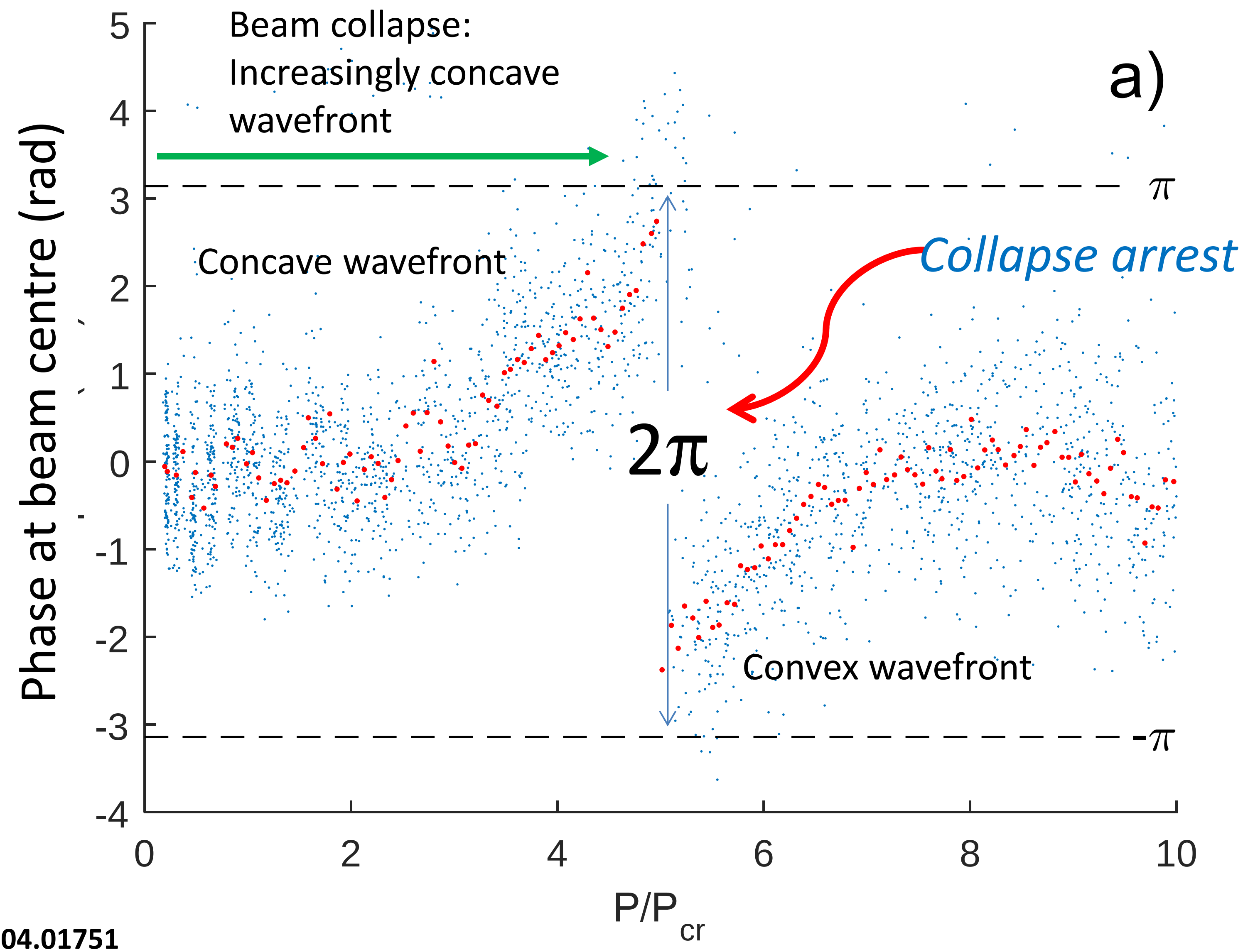


- <2 m long filament
- Image every few cm
- 0-5 mJ at each position
- 100 shots at each energy
- Huge (z, P/P_{cr}) space

Helium cell for intensity profiles: Tony Ting, NRL

Phase at beam centre vs. laser power scan

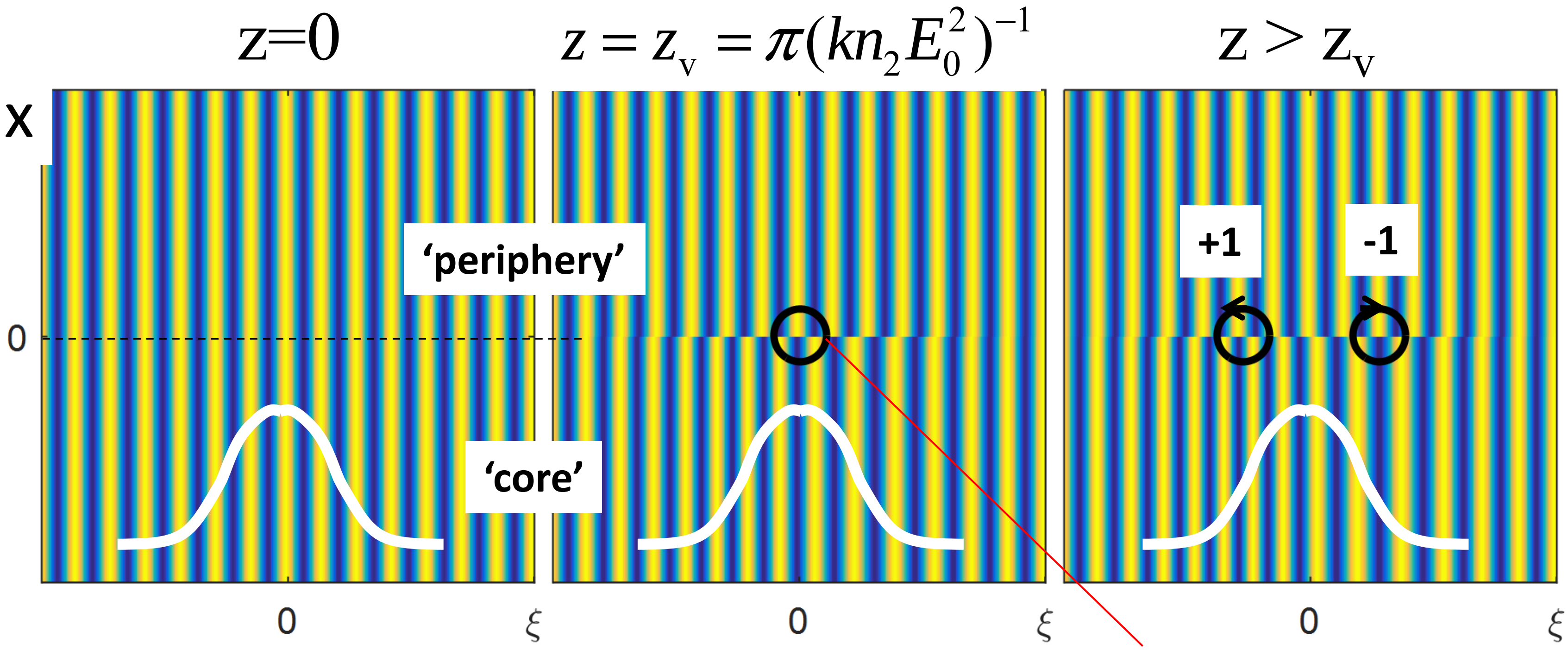
(*helium cell at fixed position z_h=150cm, for example*)



arXiv:1604.01751

Toy model: Half plane wave

Nonlinear Kerr phase $\phi_{NL}(x,z,\xi) = kn_2 \left|E(x,z,\xi)\right|^2 z$

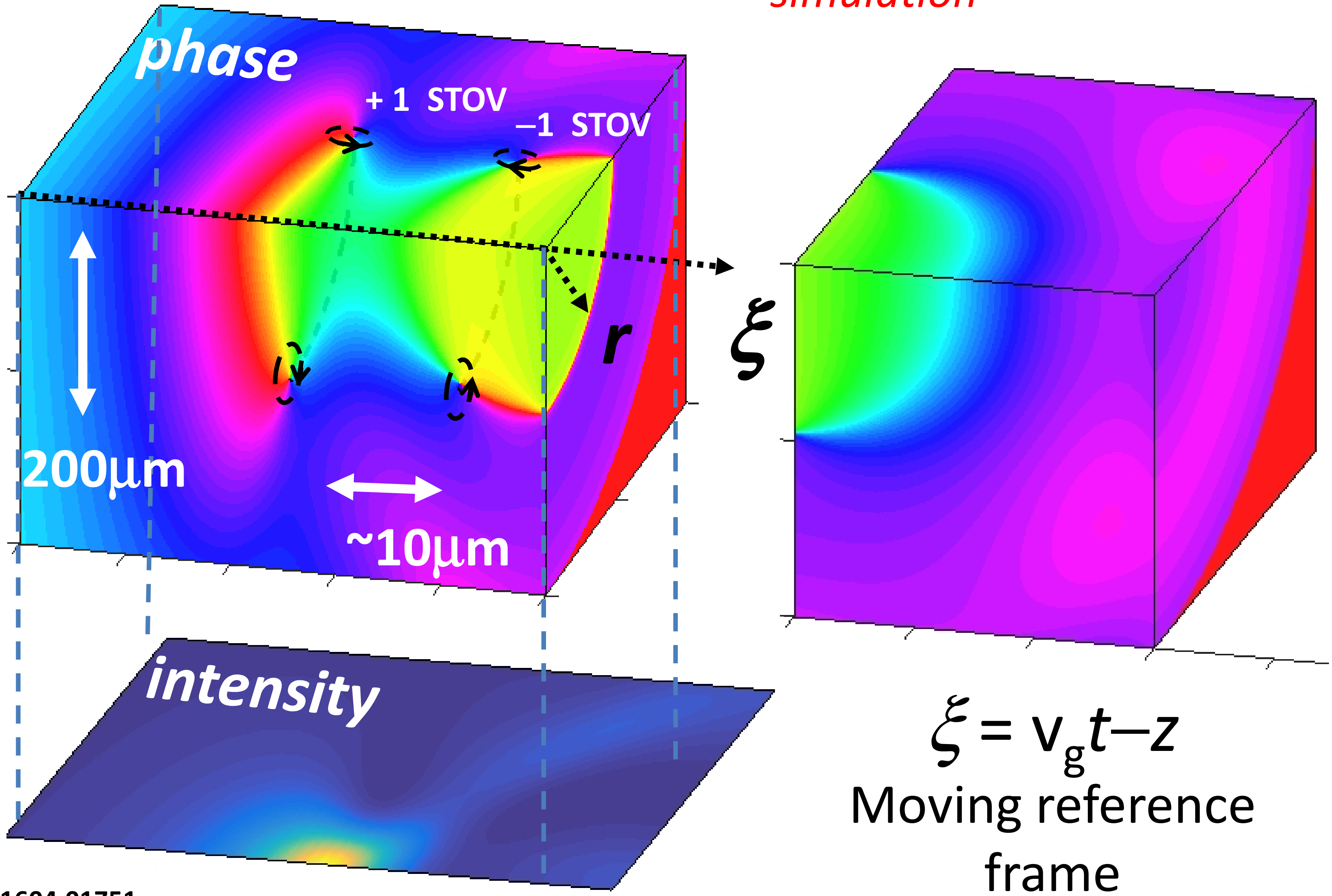


"Edge dislocation" (Berry)
Field amplitude null

arXiv:1604.01751

Spatio-temporal optical vortices (STOV)

simulation



$\xi = v_g t - z$

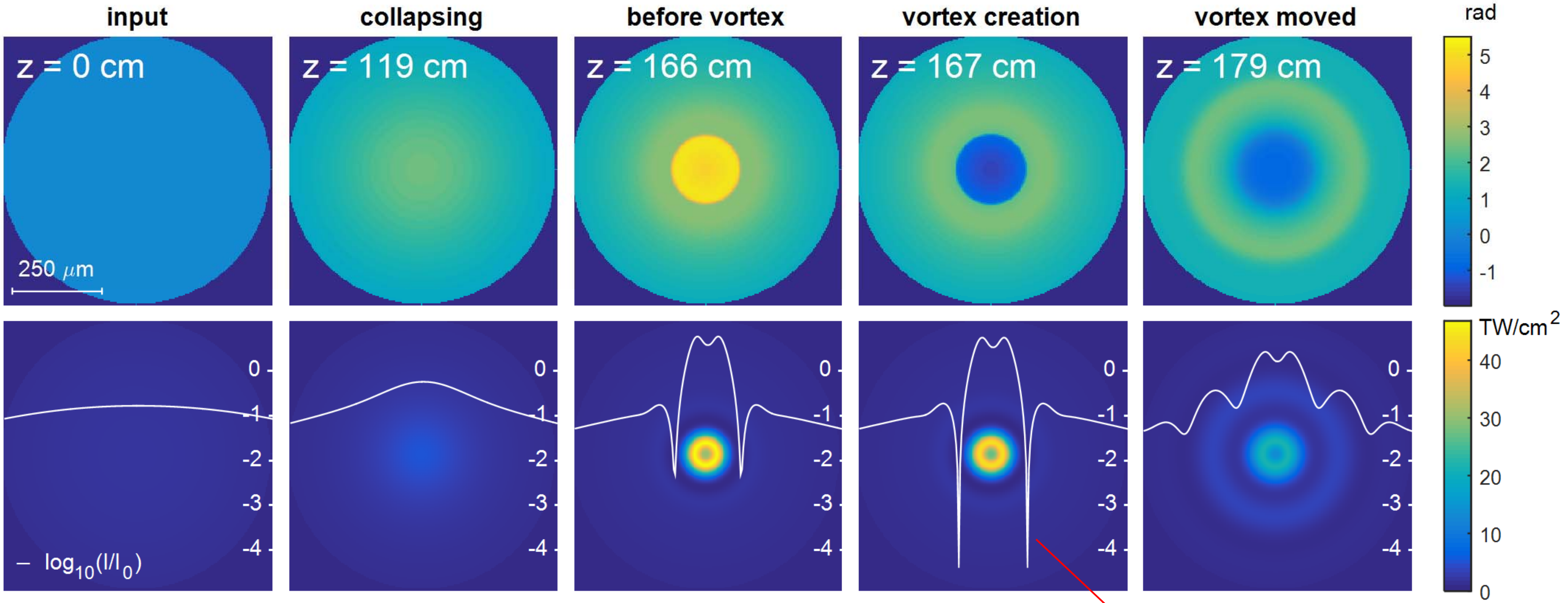
Moving reference frame

arXiv:1604.01751

Air propagation simulation: Appearance of STOV

Following a fixed plane ξ_v where vortex later appears:

phase

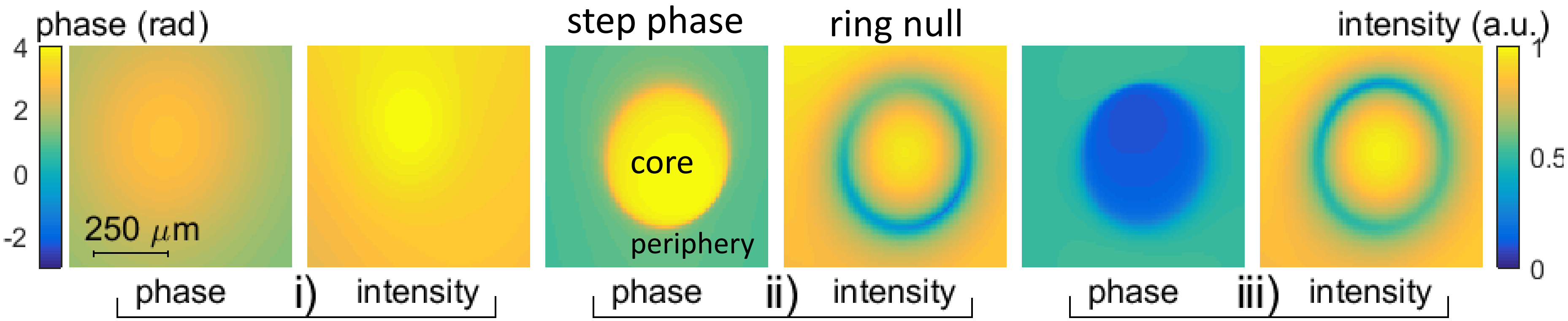


intensity

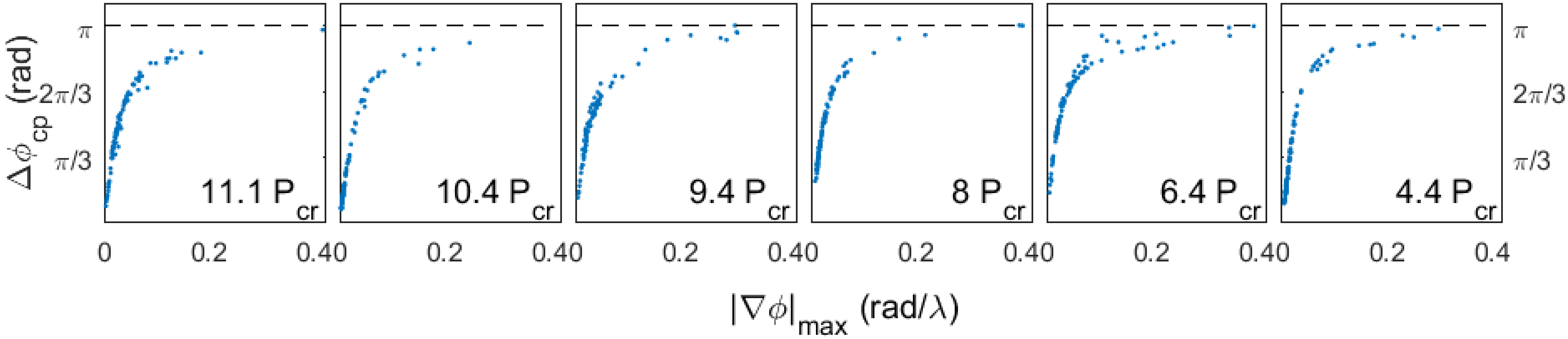
Field null

arXiv:1604.01751

Intensity and phase images at P/P_{cr} =4.4 collapse:



Core-periphery phase shift vs phase gradient:



arXiv:1604.01751

Conclusions

- Spatio-temporal optical vortices (STOVs) appear universally in the arrest of beam collapse. (For example, they should appear in relativistic self-focusing, where arrest is from electron cavitation)
- STOVs are embedded in the pulse and carry topological charge (a conserved quantity) which prevents them from decaying away – they can only be created and annihilated in topologically permissible ways
- Morphological and topological changes to pulses are linked to STOV movement, generation, and annihilation
- *University of Maryland graduate students are awesome!*

HAPPY BIRTHDAY, NAT & take the day off!