New paradigm for multi-TW, multiple Joule 10 μm USP self-trapping over kilometer ranges

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Support: AFOSR FA9550-16-1-0088, FA9550-15-1-0272

Talk Outline

- ❑ Introduction
- ❑ Filament Modeling Hierarchy
- ❑ MWIR Light Bullet – shock regularization
- ❑ LWIR self-trapping at 10µm
  -many-body modification of NL response
- ❑ Summary & Conclusion

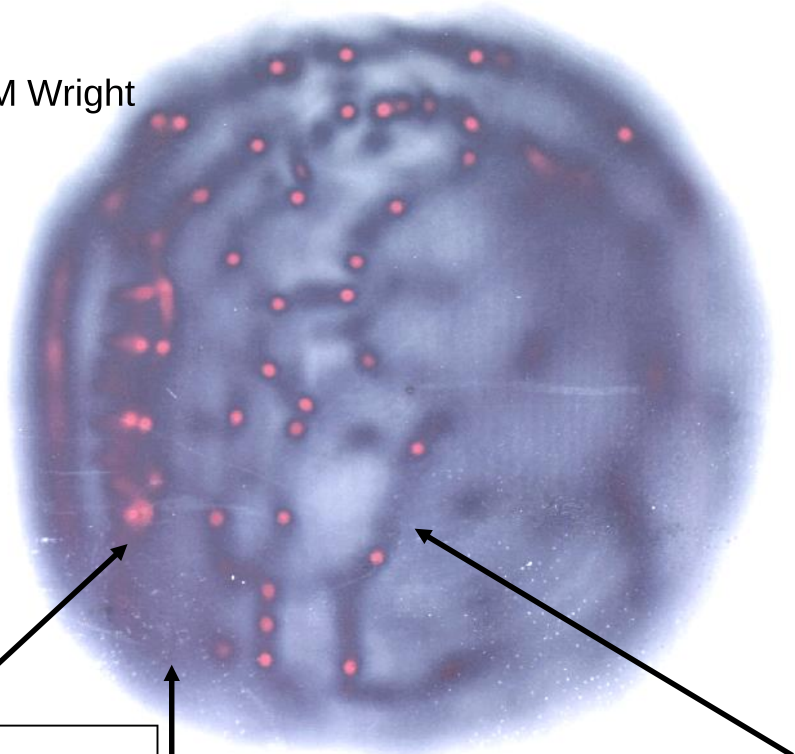
Chaotic Filamentation in 800nm TW Pulses

Relative disposition of filaments dictated by initial aberrations across the beam

D.E. Roskey, M. Kolesik, J.V Moloney and E.M Wright
Appl. Phys. B **86** 249 (2007)

NRL Laser Parameters

Pulse energy = 1.425 J
Pulse length = 400 fsec
Peak power = 3.56 TW
Propagation distance = 10 m



Intense self-focused filaments

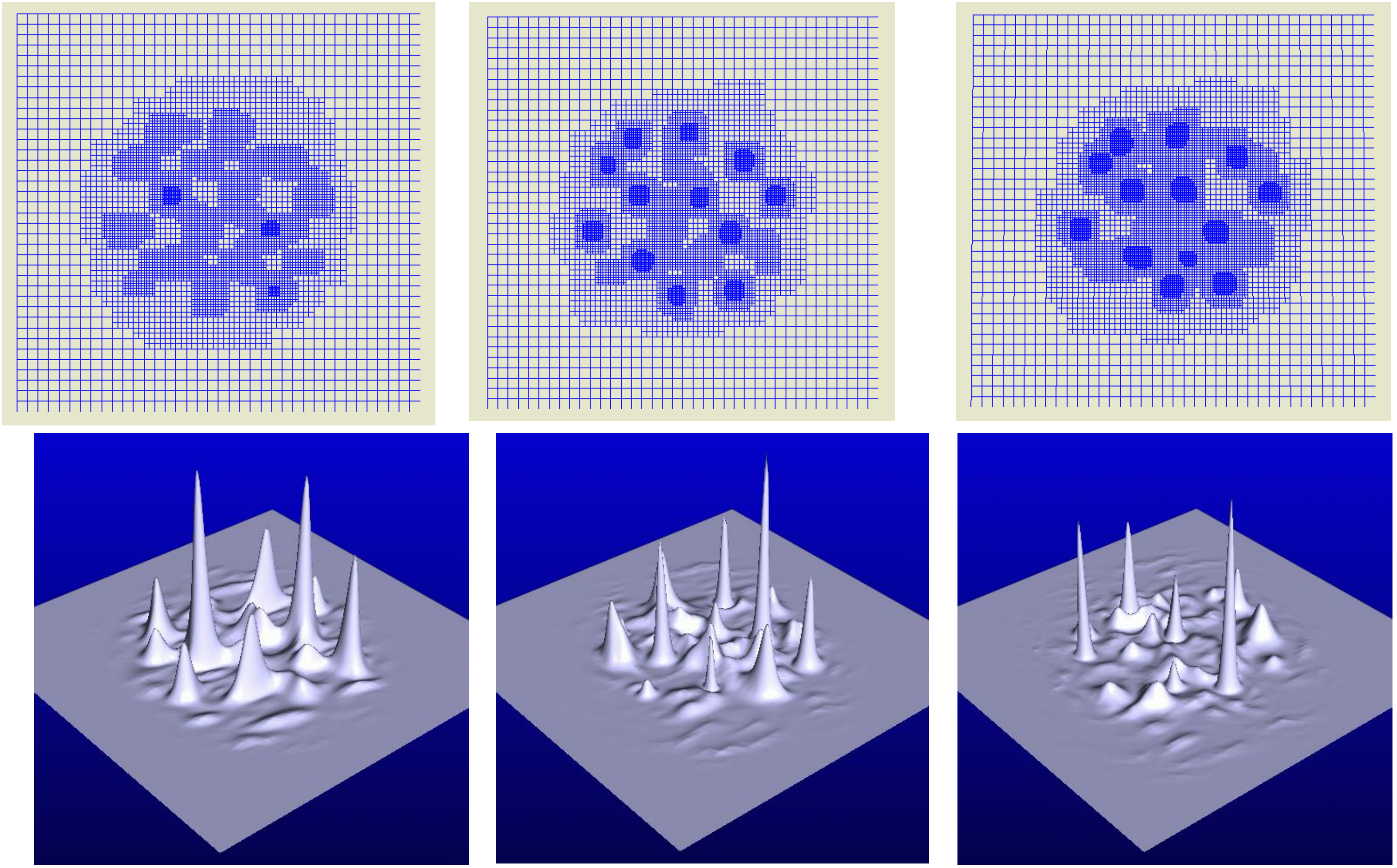
Veins are elevated ridges of intensity on which modulational instabilities grow

Broad background acts as an energy reservoir (photon bath) to sustain recurring filaments

M. Mlejnek, M. Kolesik, J.V. Moloney, E.M. Wright, *PRL,* **83**(15) pp. 2938-2941 (1999).

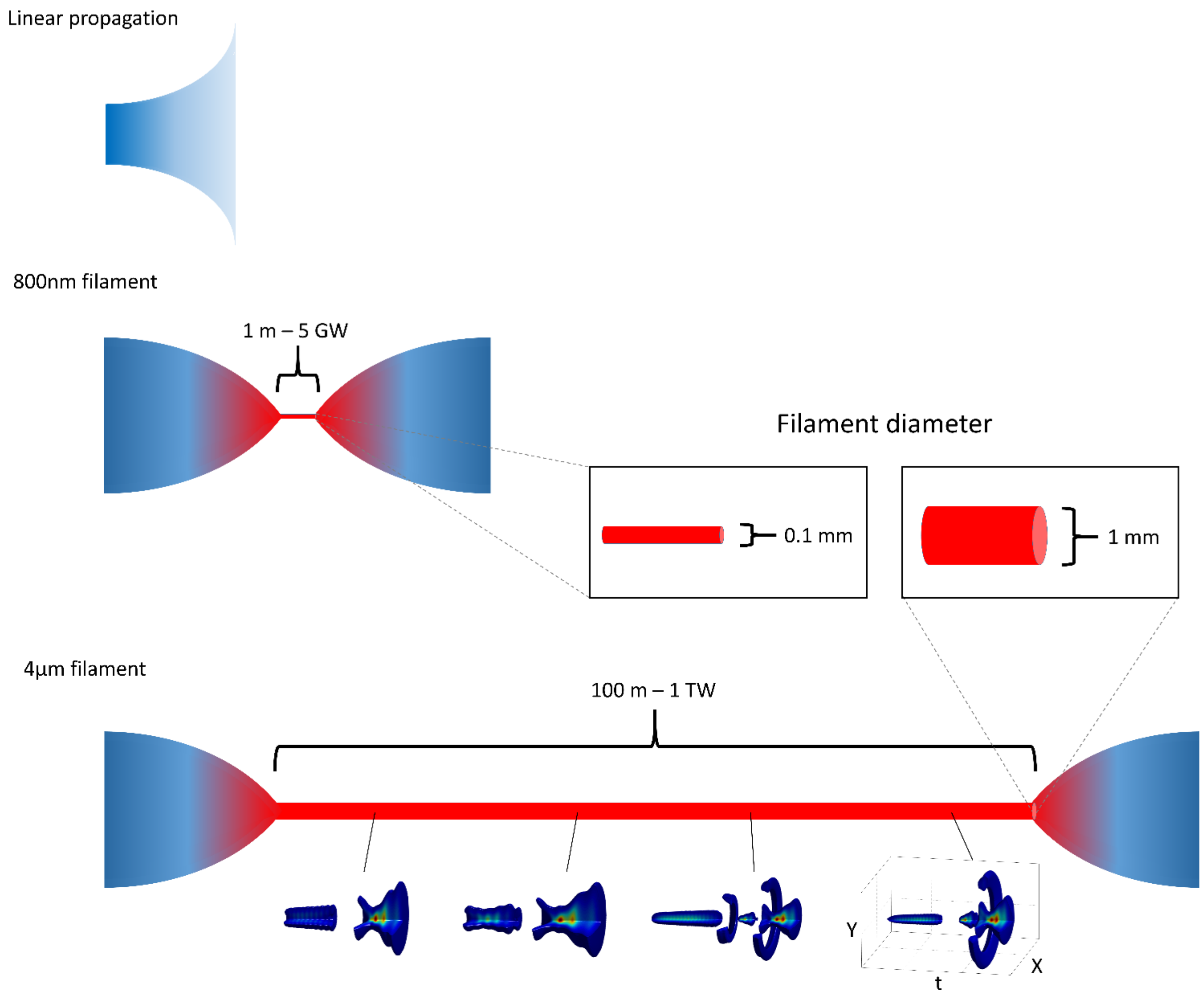
Adaptive Mesh GNLSE Parallel Solver

Dynamic regriding in space and time – Multiple light strings



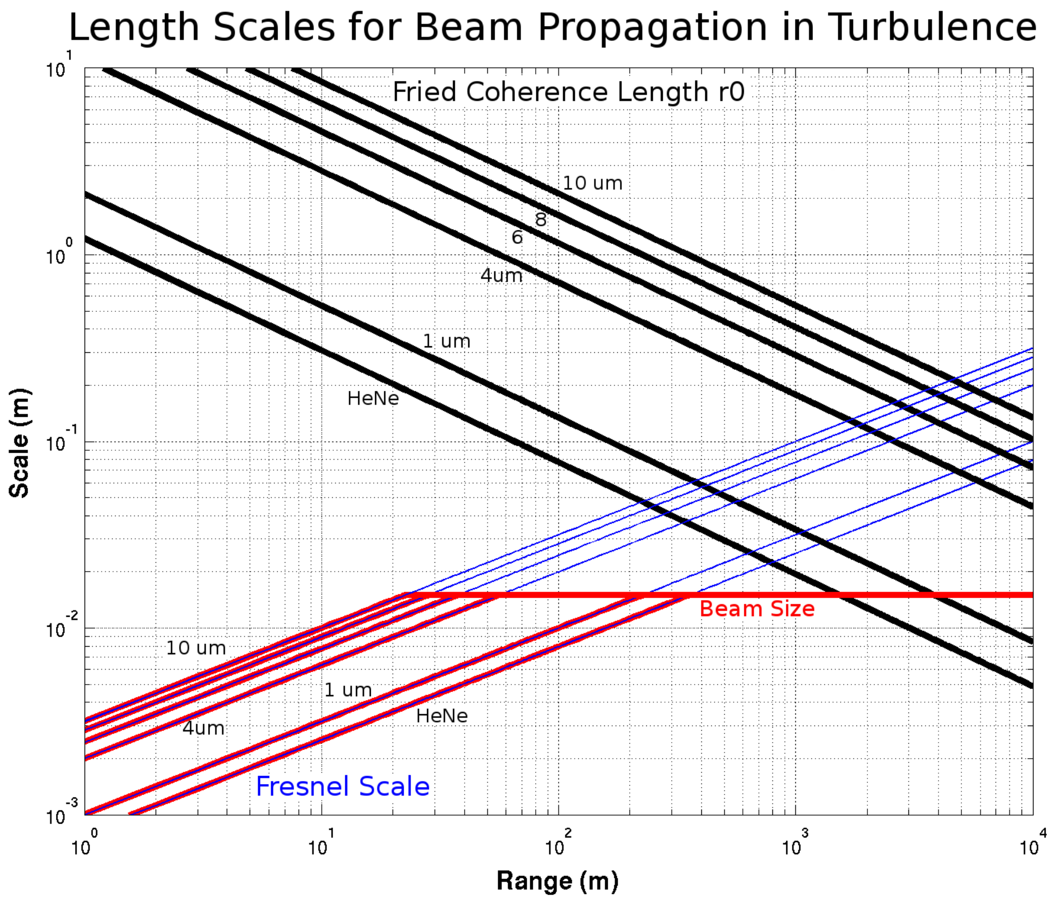
M. Mlejnek, M. Kolesik, J.V. Moloney, E.M. Wright, *PRL*, **83**(15) pp. 2938-2941 (1999).

IR vs Mid-IR Atmospheric Filament Scaling



Worst Case Scenario – Ground Level Turbulence

❑ Simple estimate for linear propagation of a 1.5 cm beam



- Confined filament or self-trapped beam can beat diffraction limitation

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Scalar UPPE Model (Unidirectional)

Unidirectional Pulse Propagating Equation (z-UPPE)

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

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

Accurate chromatic dispersion

Plasma-related current

Nonlinear polarization evaluated from real field

$$P(z,r,t) = \varepsilon_0 \Delta\chi_{sf}(z,r,t)E(z,r,t) = 2\varepsilon_0 \bar{n}_2 \left[\frac{1}{2}E^2(z,r,t) + \frac{1}{2}\int_0^\infty R(\tau)E^2(z,r,t-\tau)\mathrm{d}\tau\right]E(z,r,t)$$

Second Harmonic component = source of TH

Carrier based approach, no envelope approximations used

VOLUME 89, NUMBER 28 PHYSICAL REVIEW LETTERS 31 DECEMBER 2002

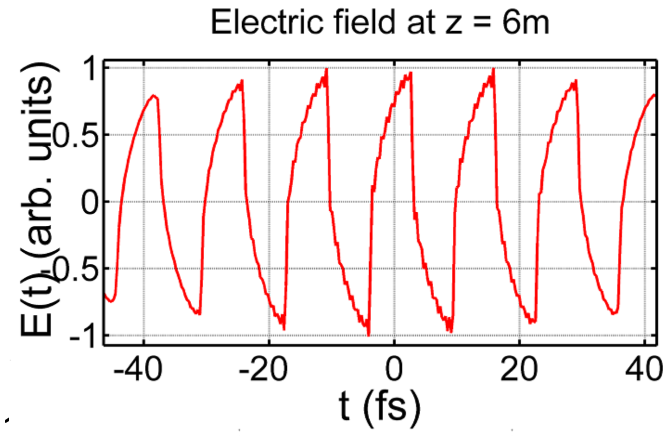
Unidirectional Optical Pulse Propagation Equation

M. Kolesik, J.V. Moloney, and M. Mlejnek*

Modified Kadomtsev-Petviashvili (MKP1)

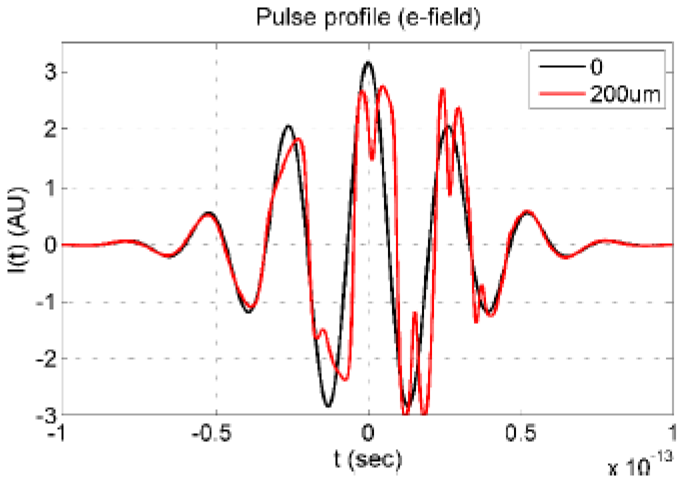
- Canonical Full Field Propagator for long wavelength USPs

$$\partial_\tau\left[\partial_z E(r,z,\tau)+\frac{4n_2}{c}E^2\partial_\tau E-a\partial_\tau^3 E\right]+bE=\frac{c}{2n(\omega_R)}\Delta_\perp E$$

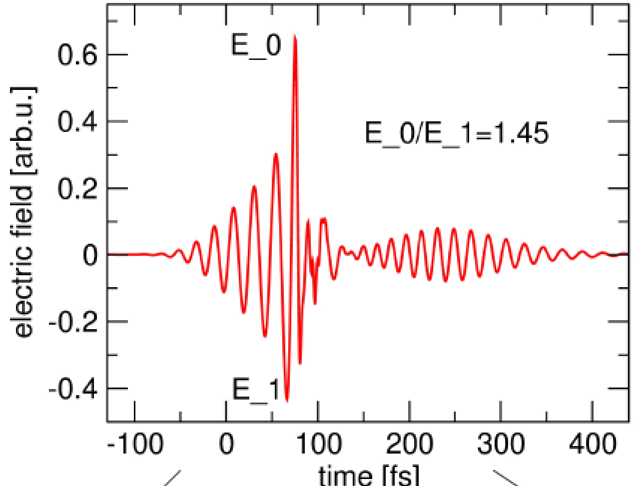


- Asymptotic limit of UPPE for strongly nonlinear weakly dispersive waves
  - K. Glasner et al, Int. J. Optics. http://dx.doi.org/10.1155/2012/868274 (201
- Exhibits carrier shock + blowup - Originally derived for ion-acoustic waves
- P. Whalen et al., Phys.Rev.A, **89**, 023850 (2014); P. Panagiotopoulos et al. JOSAB, **32**, 1718 (2015)
- Balakin, A.A., A.G. Litvak, V.A. Mironov, S.A. Skobelev. JETP, 2007, 104 363-378

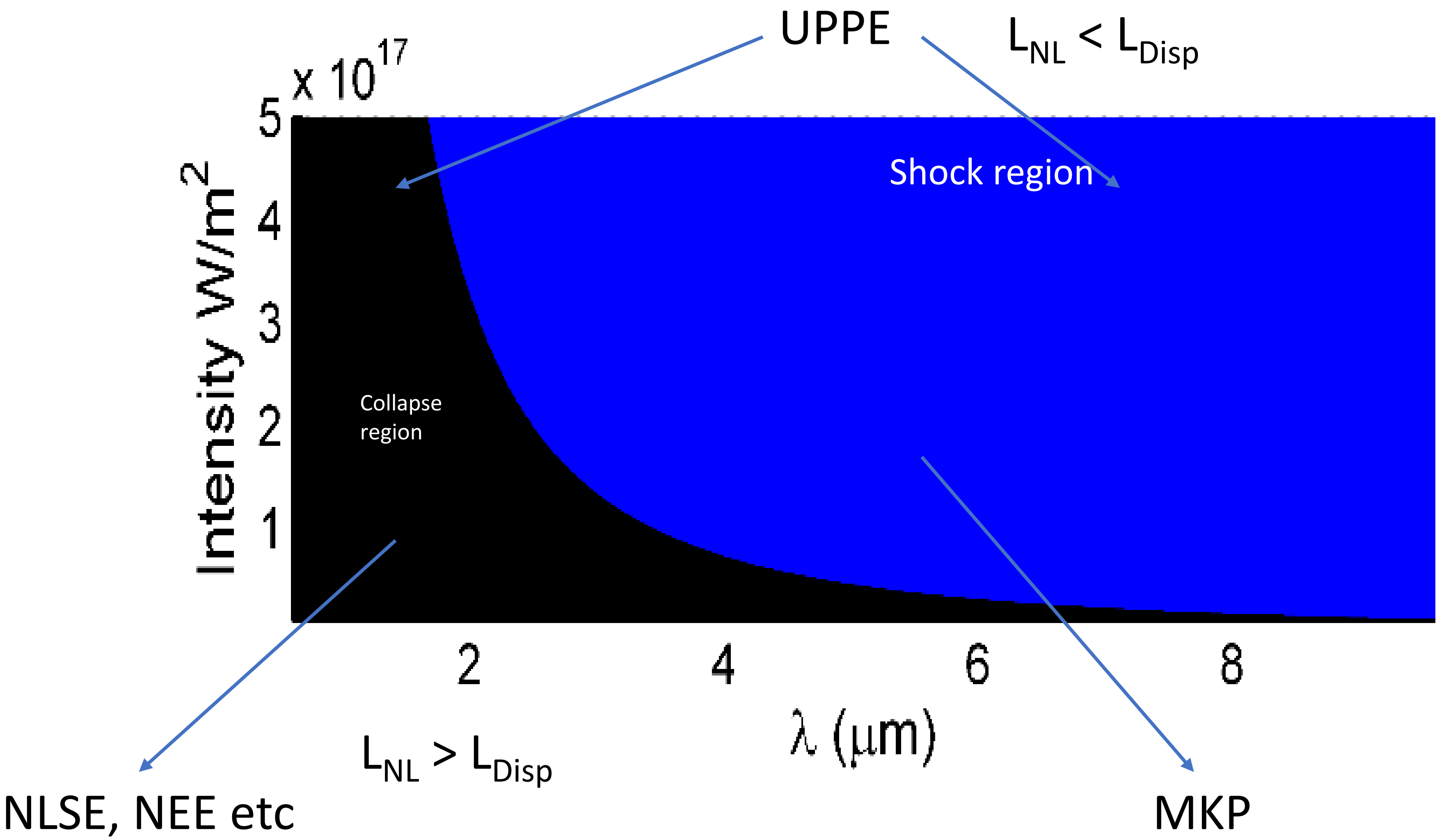
Carrier shock in Diamond at 8µm



“half-cycle” waveform from a 100fs pulse at 6 micron



Shock Regularization is Universal for Long Wavelengths



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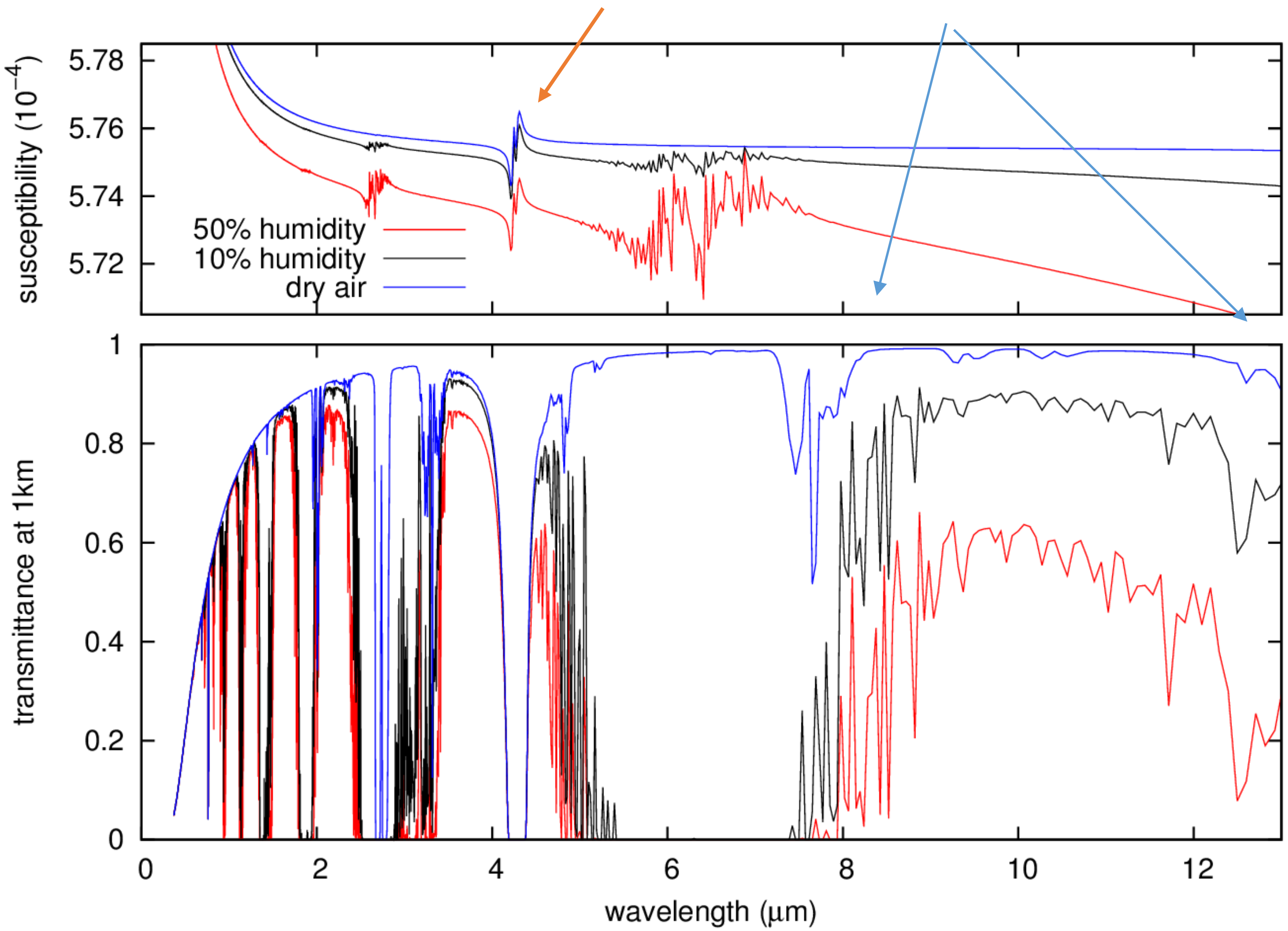
Atmospheric Transmission Windows (HITRAN)

MWIR

CO_2 Asymmetric stretch

LWIR

8 – 12 µm Transmission

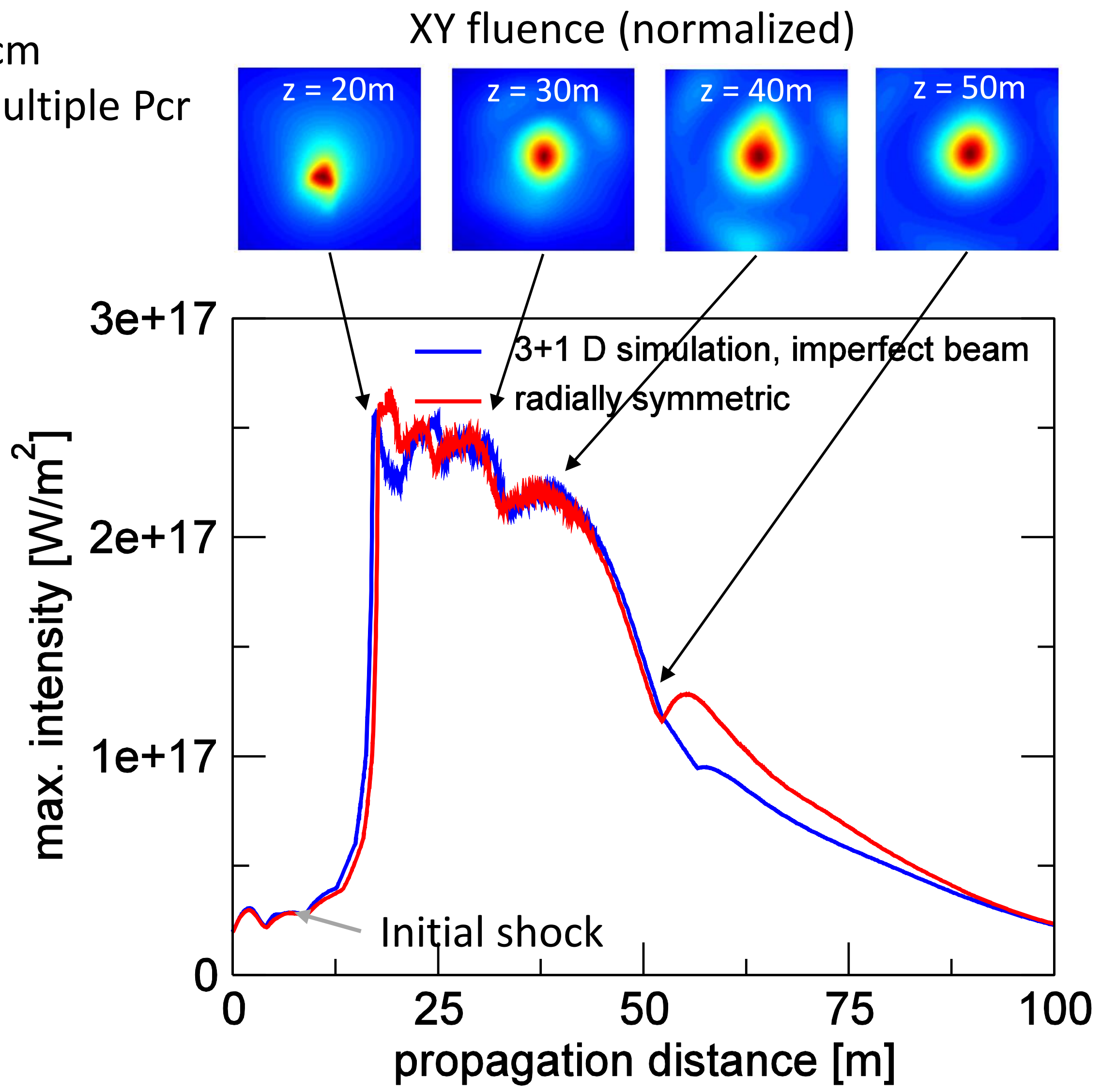


Multi-TW Mid-IR Light Bullet (4 μm)

P. Panagiotopoulos, P. Whalen, M. Kolesik, and J. V. Moloney, Nat Photon **9**, 543 (2015)

Waist = 1cm
Power = multiple Pcr
λ = 4μm
τ = 30fs

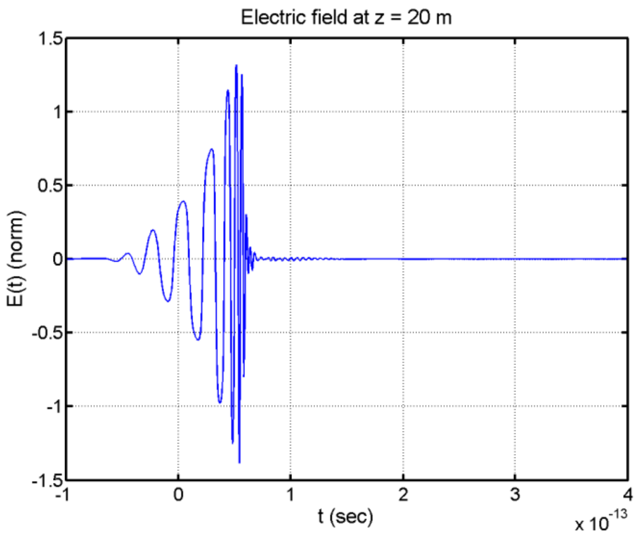
- ❑ Initial State
  - Onset of Collapse
  - NLSE like
- ❑ Intermediate State 1
  - high intensity shock
  - MKP like
- ❑ Intermediate State 2
  - slow shock walk-off
  - regularizes collapse
- ❑ Multiple Recurrence

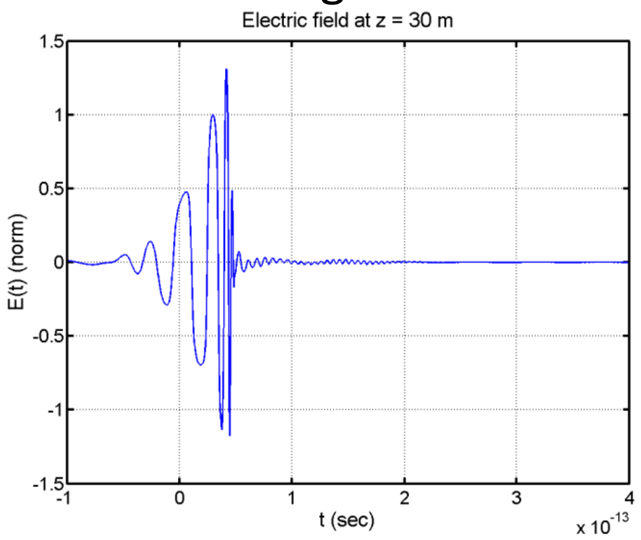


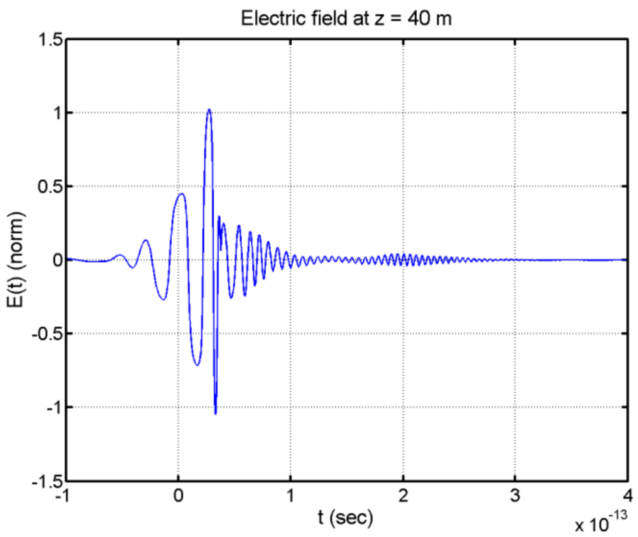
Light Bullet Dynamics

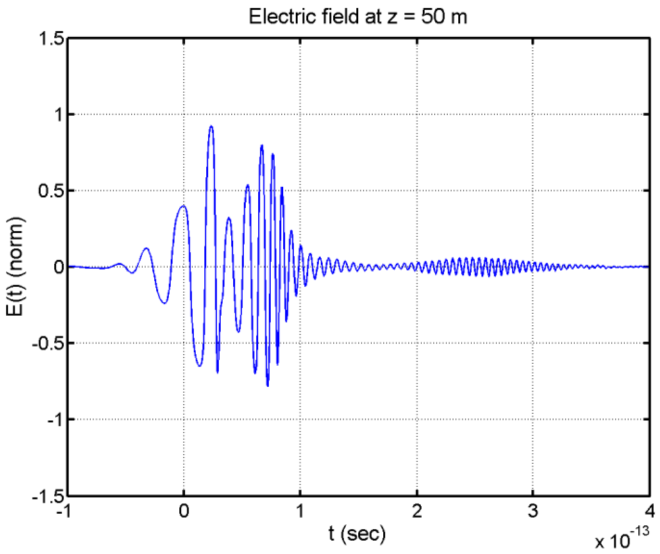
- Leading edge – quasi-invariant solitonic component
- Trailing edge – energy leakage into harmonics during walk-off

1D slice captured approximately by 1D mKdV with opposite sign for dispersion coefficient – nonintegrable case – P. Jakobsen

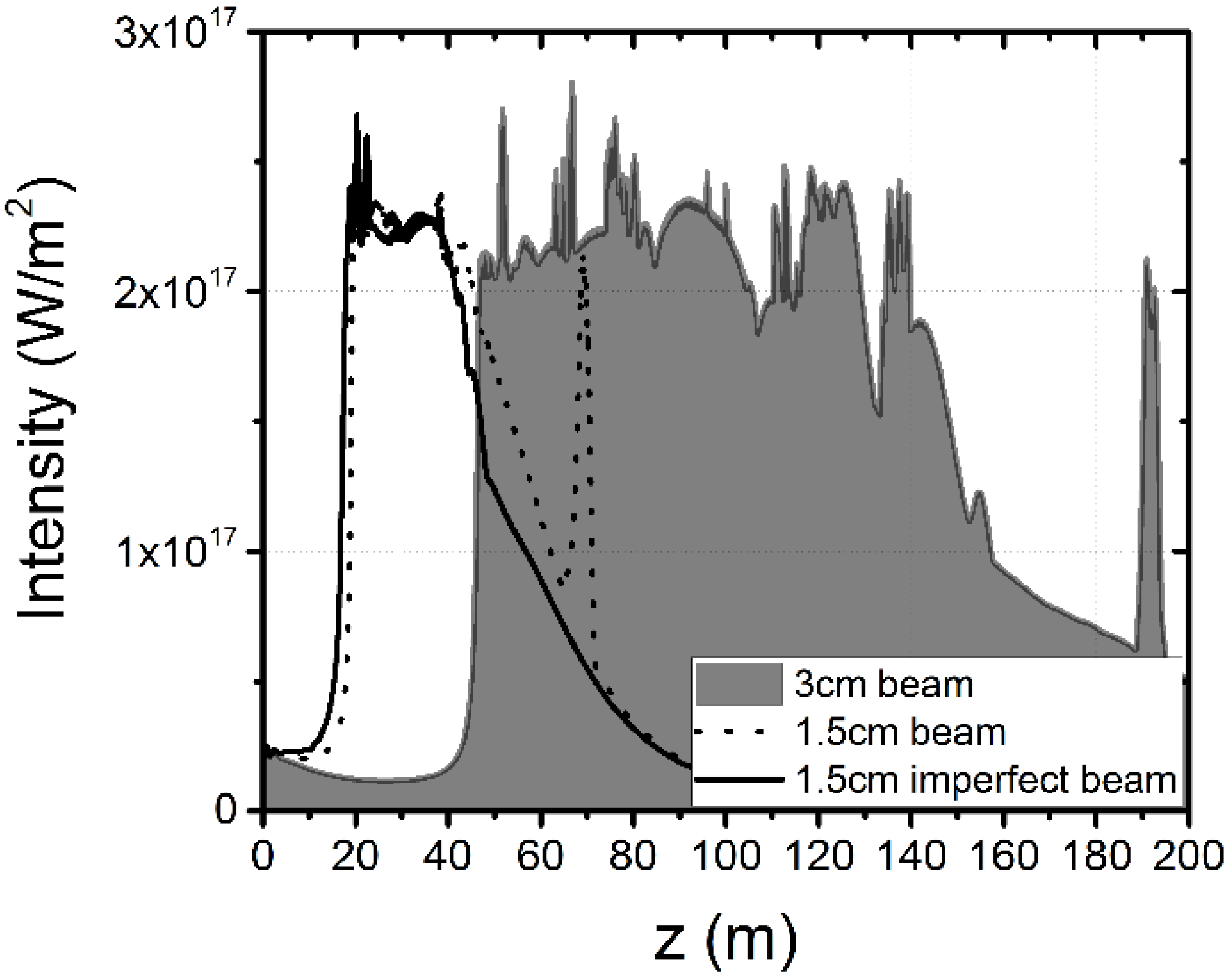






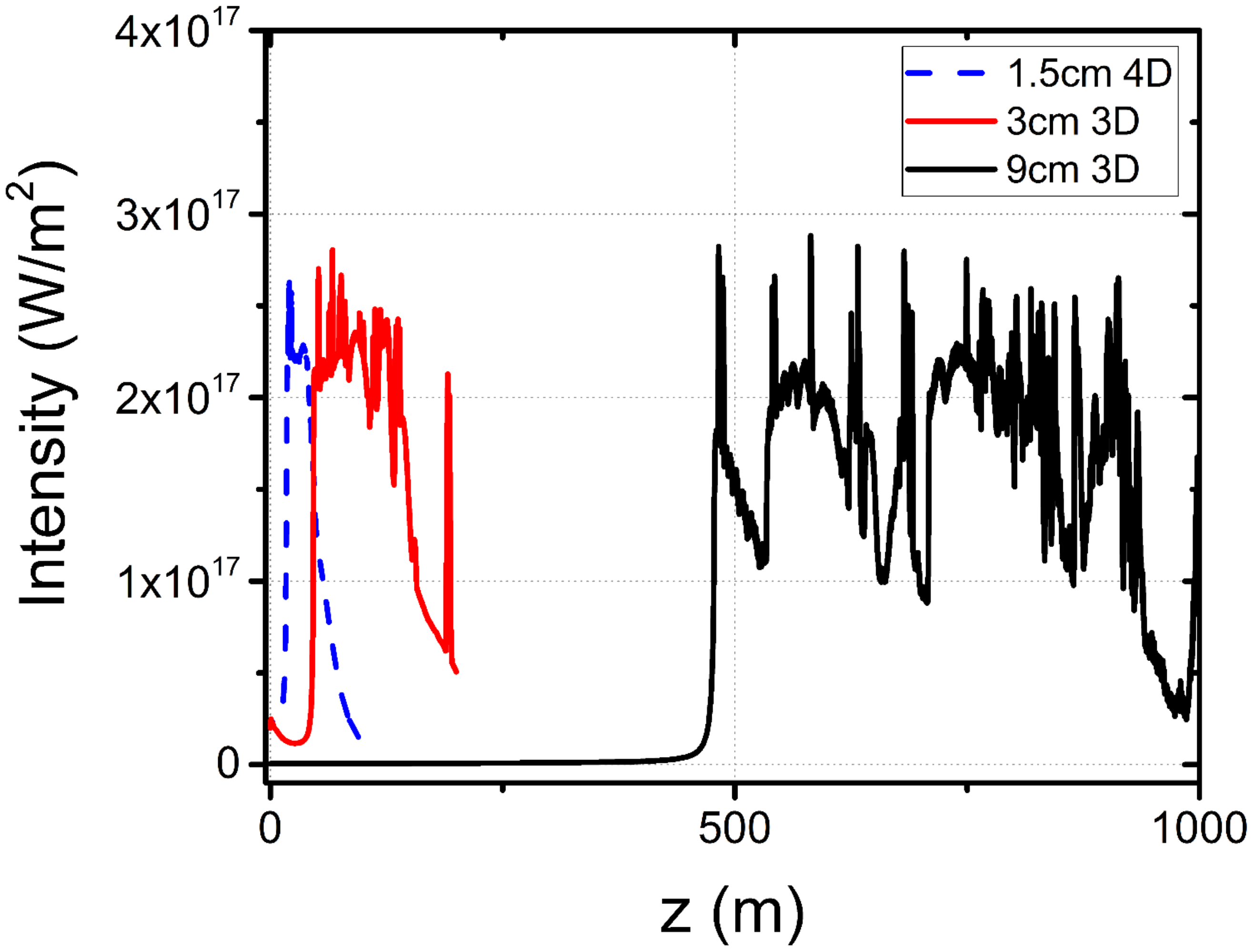


Scaling Propagation Distance (4 μm)



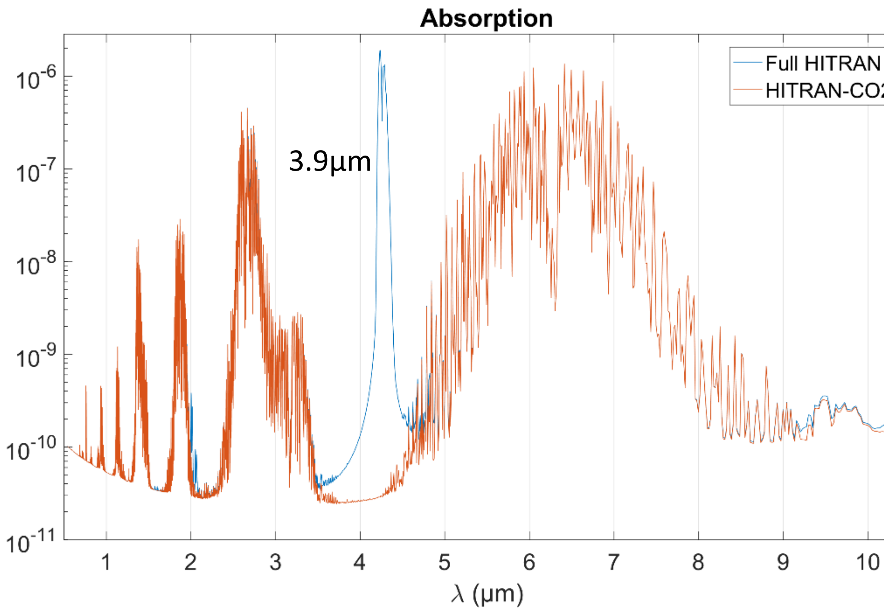
Filament Lengths vs pre-chirped 4µm – 9cm – 2.87 Joule

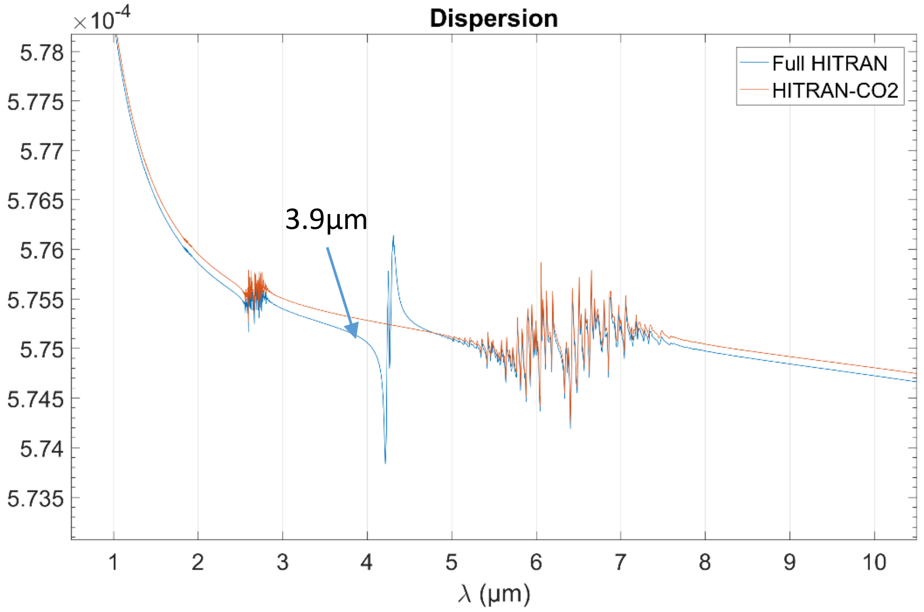
P. Paniagotopoulos et al. PRA **94,** 033852 (2016)



MWIR Transmission around 3.9µm

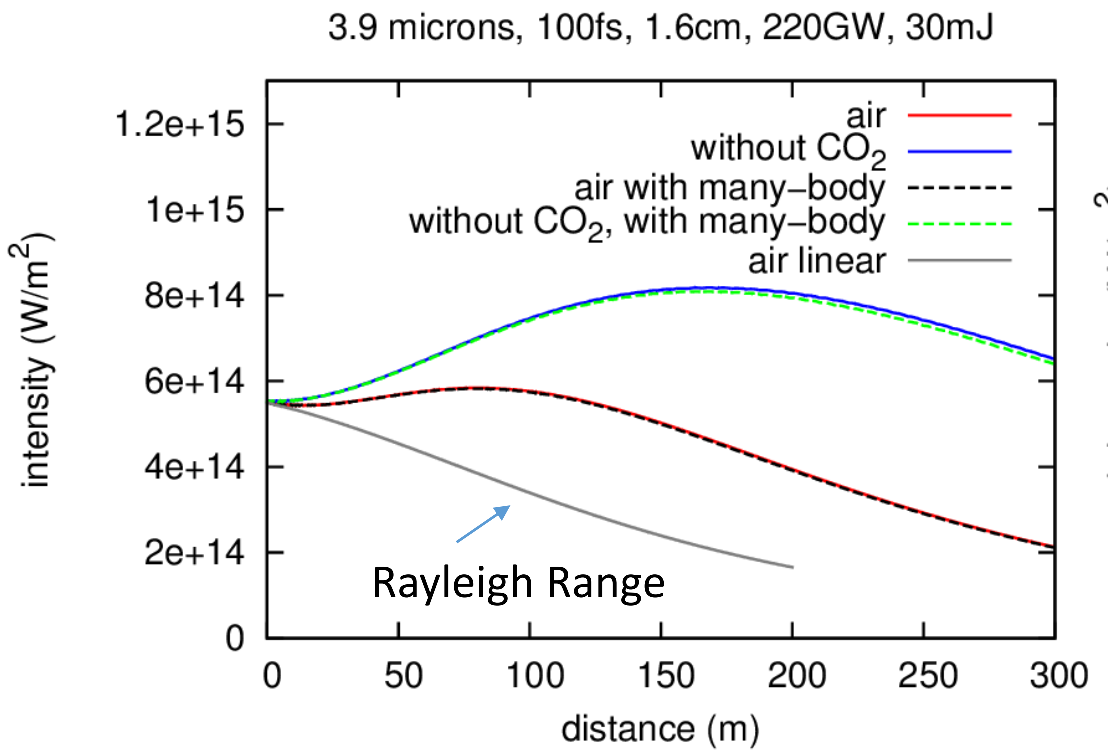
- Asymmetric CO_2 rovibrational stretch - anomalous dispersion and absorption at short wavelength – soliton regime?

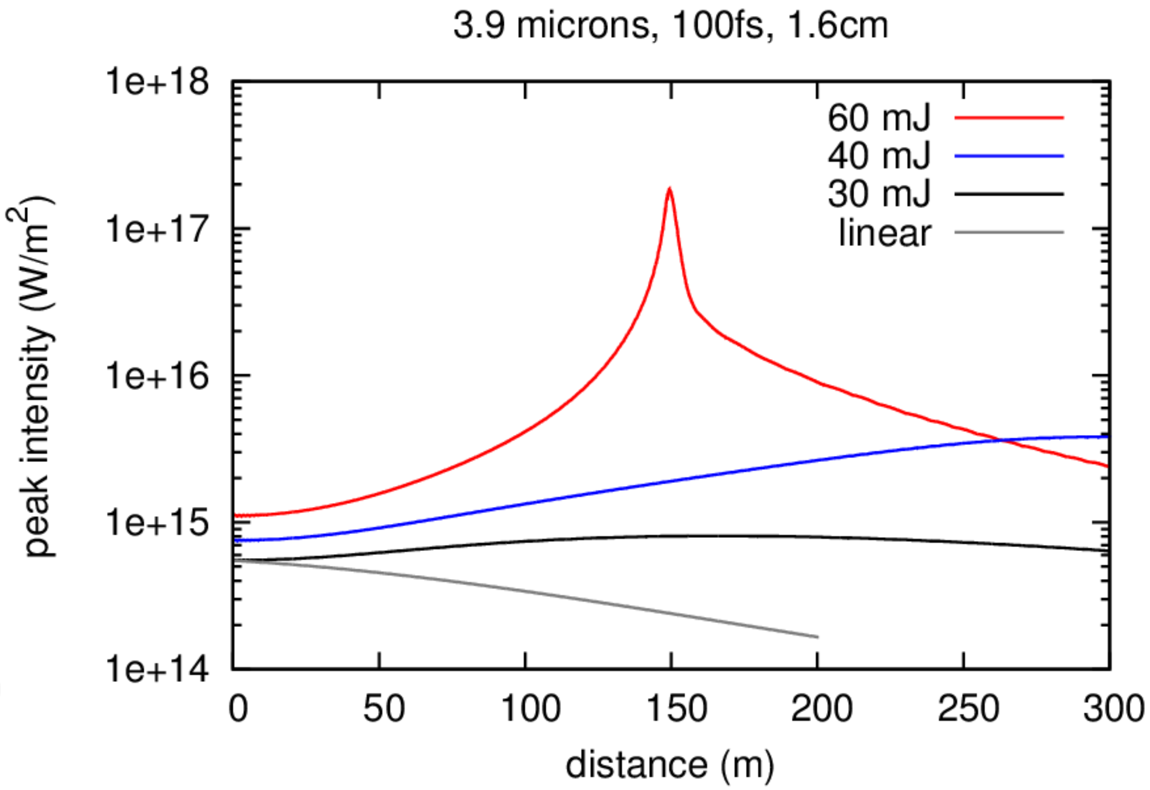




- Implications for long distance propagation?

Above Critical Long Range Propagation





- Well above critical leads to self-phase modulational spectral broadening.

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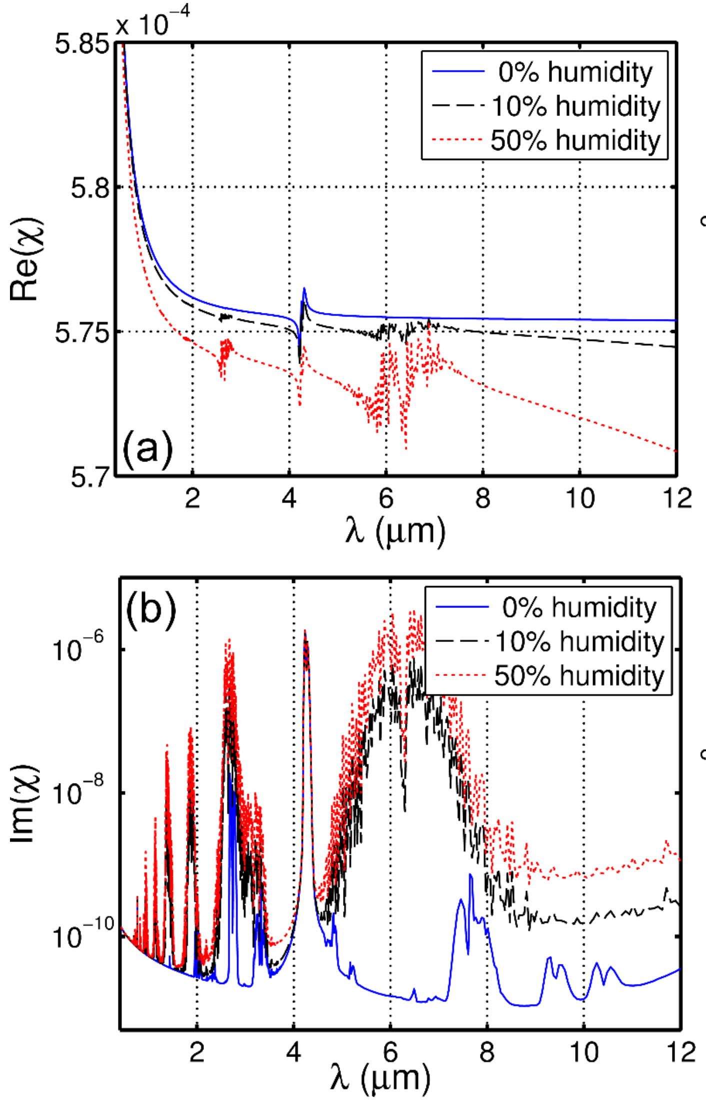
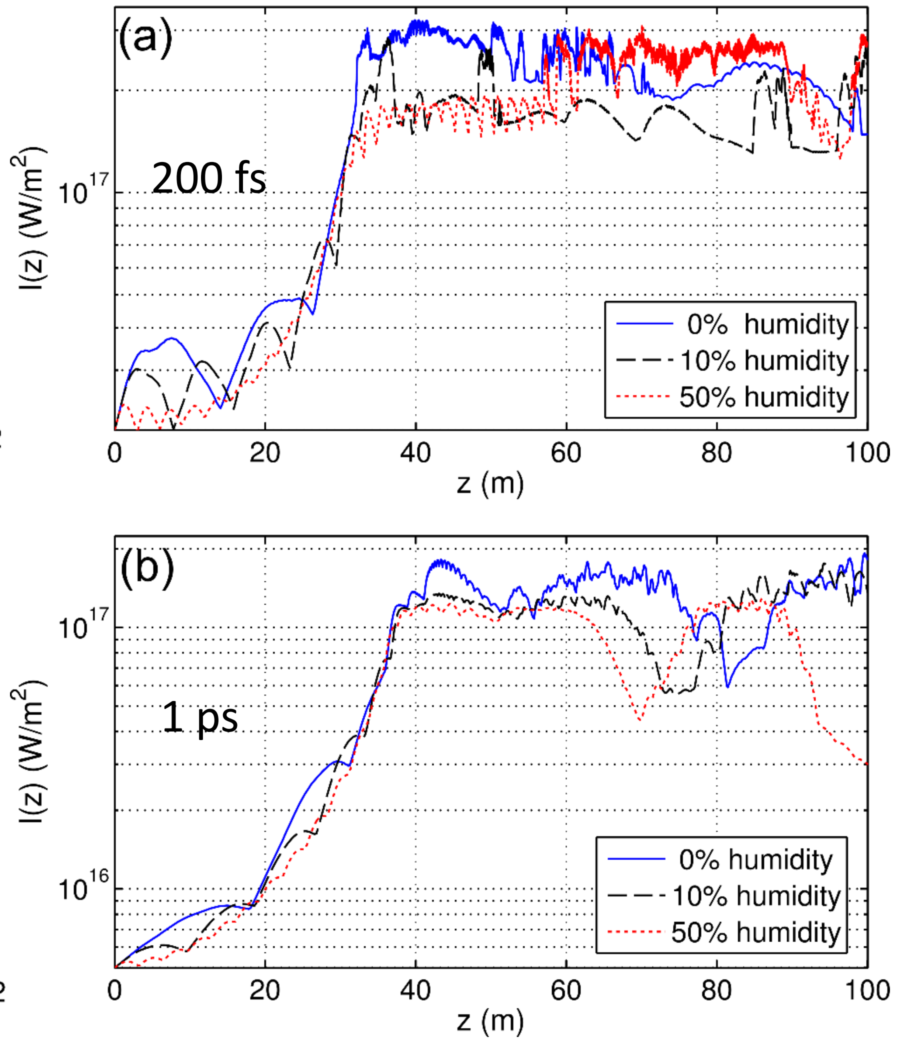
10 μm Pulse Propagation in a Realistic Atmosphere

P. Panagiotopoulos et al. JOSA B **33,** 2154(2016). Expt n_2 S. Tochitsky et al. Optics Letters **14,** 3924 (2016)

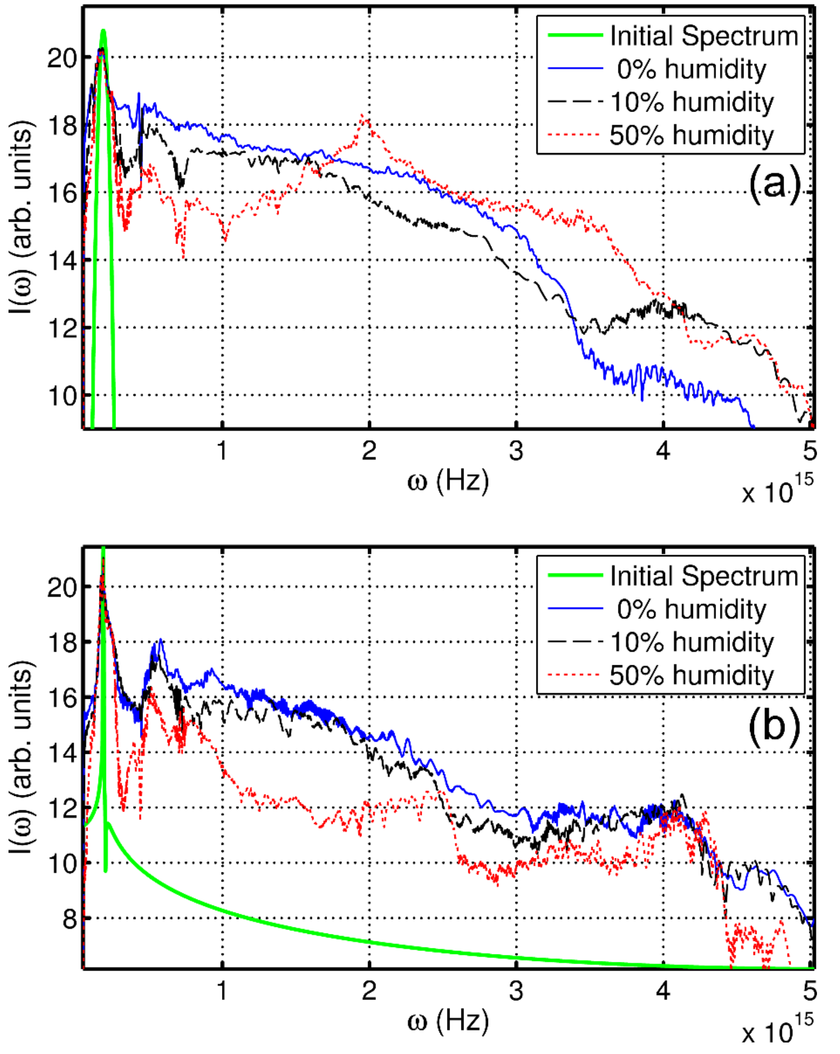
HITRAN Database



Peak Power over 100m

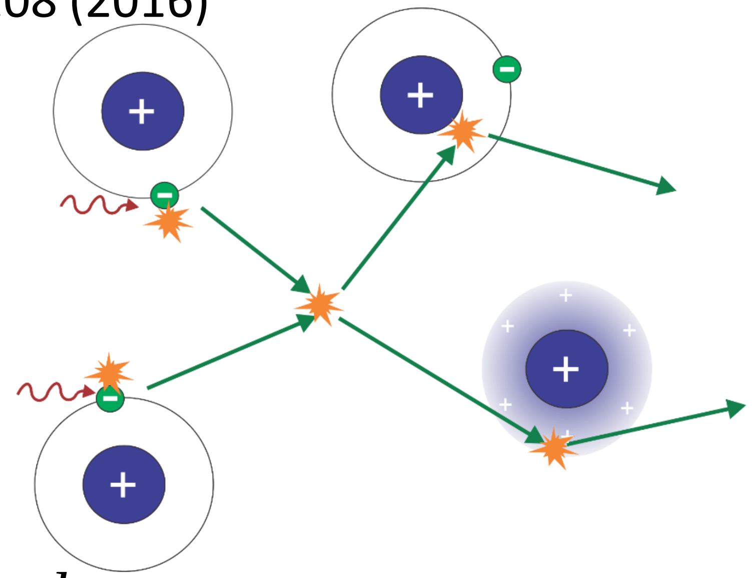


Spectra at 100m



Quantum Many-Body Equations for Coulomb Scattering

K. Schuh et al., PRE **88**, 063102 (2013); PRE **89**, 033103 (2104); PRE **93**, 013208 (2016)



- Assume ions are stationary

$$i\hbar \frac{d}{dt} f_s = \sum_{\vec{k}} \Omega^*_{s\vec{k}} P^*_{s\vec{k}} - \Omega_{s\vec{k}} P_{s\vec{k}}$$

$$i\hbar \frac{d}{dt} f_{\vec{k}} = N\left[\Omega_{s\vec{k}} P_{s\vec{k}} - \Omega^*_{s\vec{k}} P^*_{s\vec{k}}\right] - \frac{e}{\hbar} \vec{\nabla}_{\vec{k}} f_{\vec{k}} \vec{E}$$

[redacted]

$$i\hbar \frac{d}{dt} P_{\vec{k}\vec{k}'} = \left[\epsilon_{\vec{k}} - \epsilon_{\vec{k}'}\right] P_{\vec{k}\vec{k}'} - \frac{e}{\hbar} \vec{\nabla}_{\vec{k}} P_{\vec{k}\vec{k}'} \vec{E} + \Omega_{s\vec{k}} P_{s\vec{k}'} - \Omega^*_{s\vec{k}'} P^*_{s\vec{k}}$$

$$H_{el-el} = \frac{1}{2} \sum_{\vec{q},\vec{k},\vec{k}'} a^\dagger_{\vec{k}} a^\dagger_{\vec{k}'} a_{\vec{k}+\vec{q}} a_{\vec{k}-\vec{q}} W(q)$$

Requires solution of Quantum Boltzmann Equation

Long Wavelength Scaling of Critical Parameters

Critical Power:

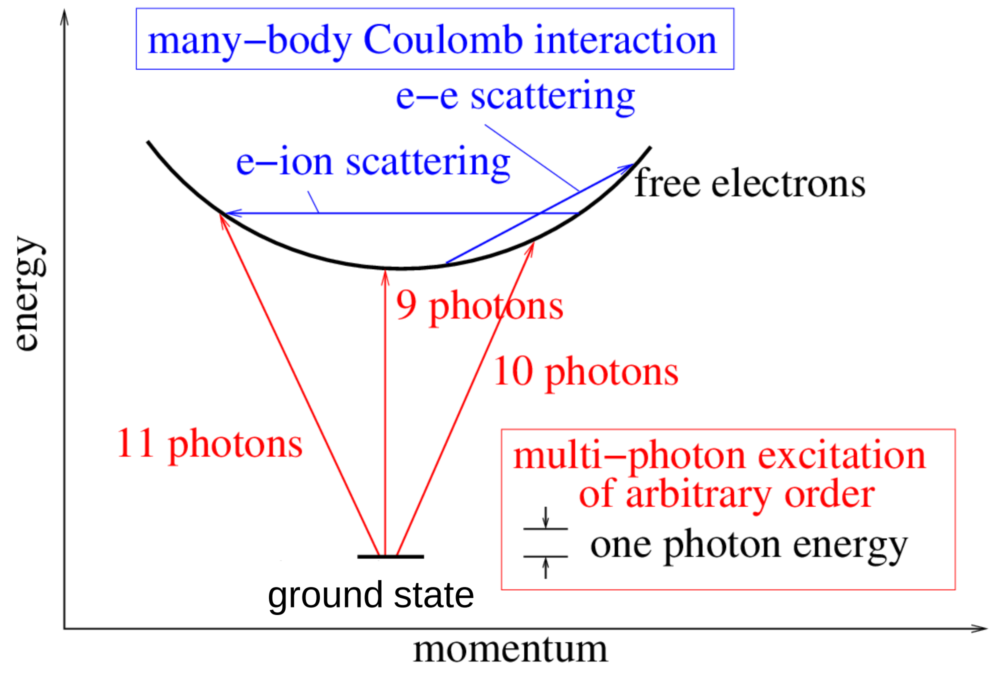
$$P_{\text{crit}} = \frac{0.3\lambda^2}{nn_2}$$

Ionized Electron Polarization

$$P_{\text{pl}} = -f(t)\frac{e^2\mu_0}{m}\lambda^2 E$$

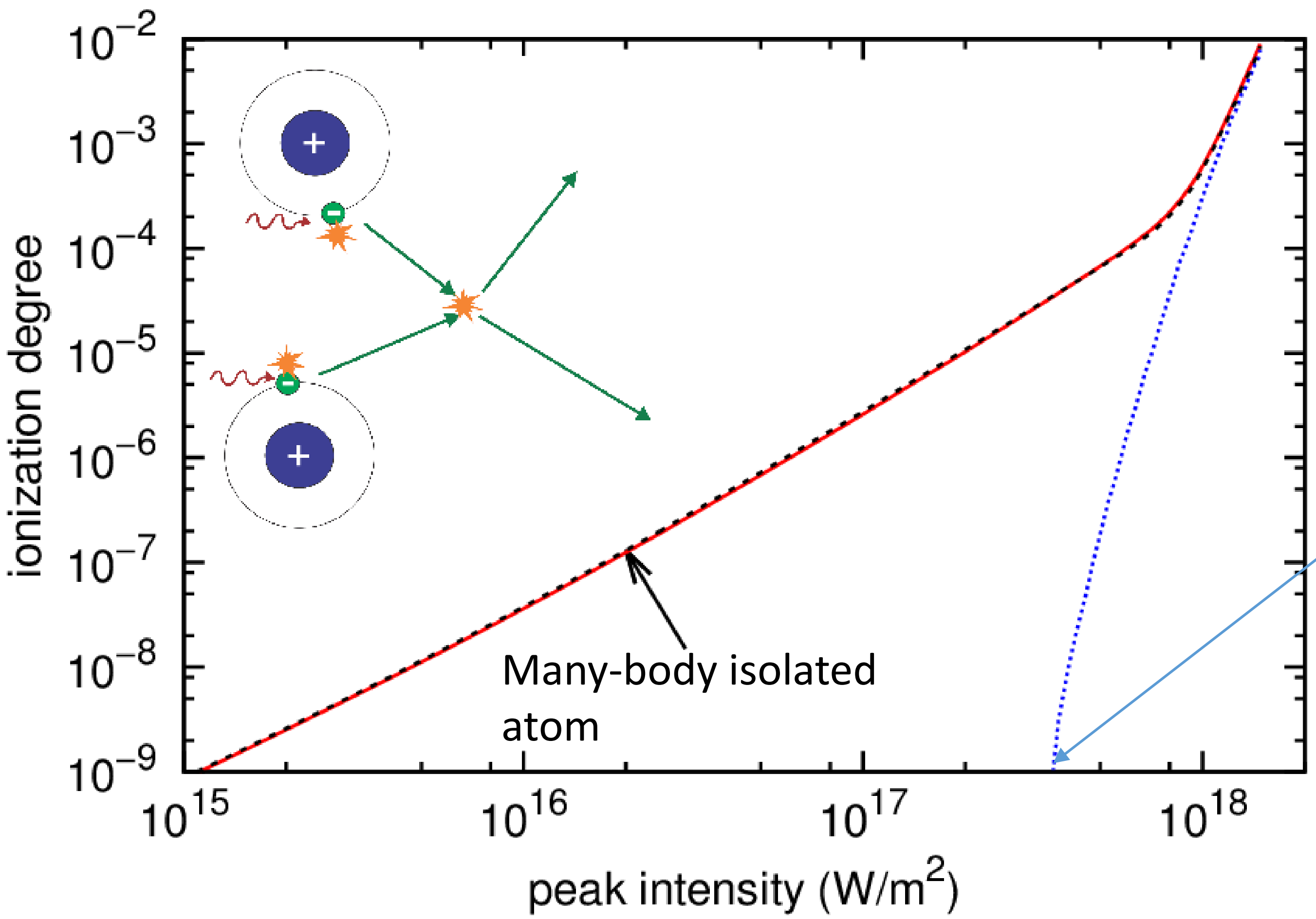
Ionized Electron Density

$$n_{\text{pl}} = -f(t)\frac{e^2\mu_0}{2m}\lambda^2$$



Self-Channeling of High Power LWIR Pulses in Atomic gases

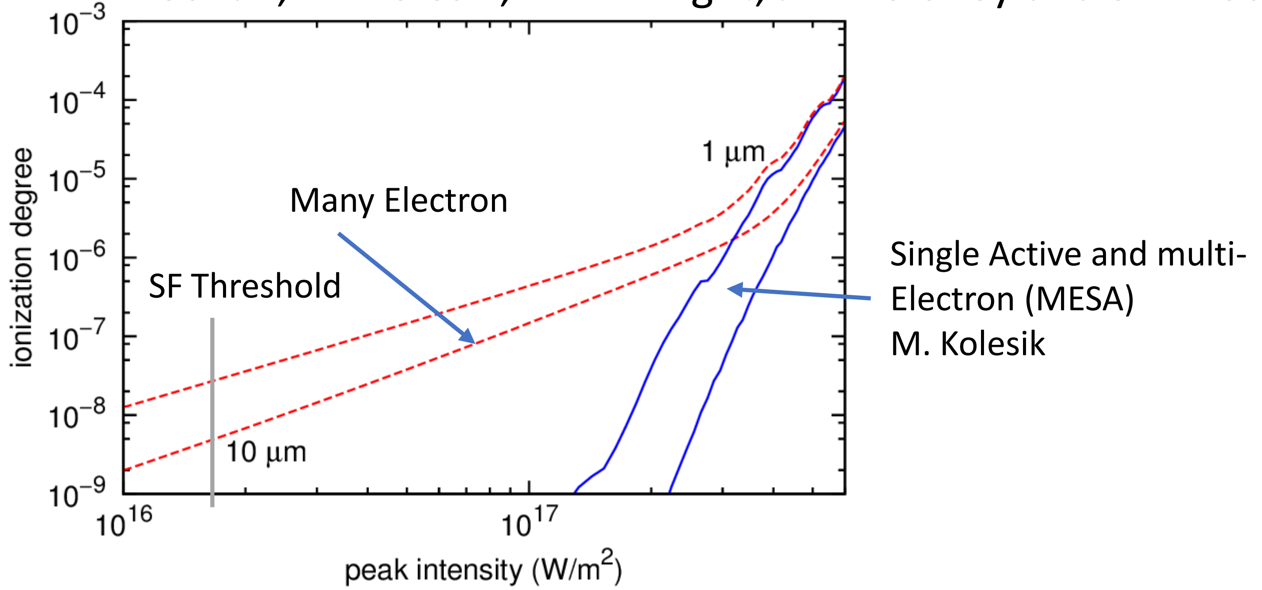
K.Schuh, M. Kolesik, E.M. Wright, J.V Moloney and S.W Koch, PRL, **118** 063901 February 10 (2017)

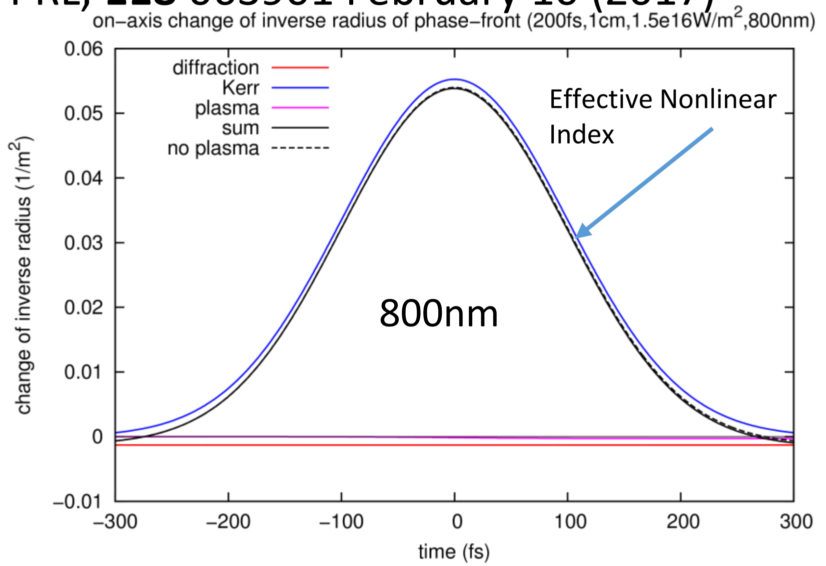


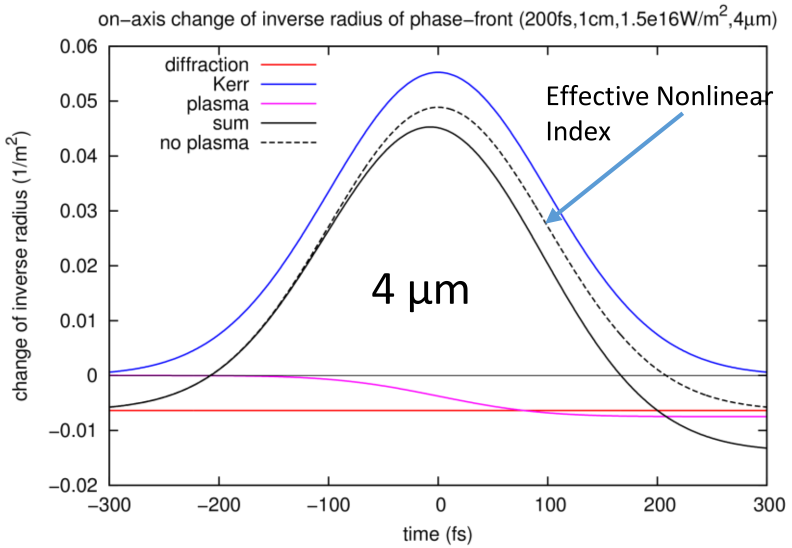
Single and multi-electron ionization threshold

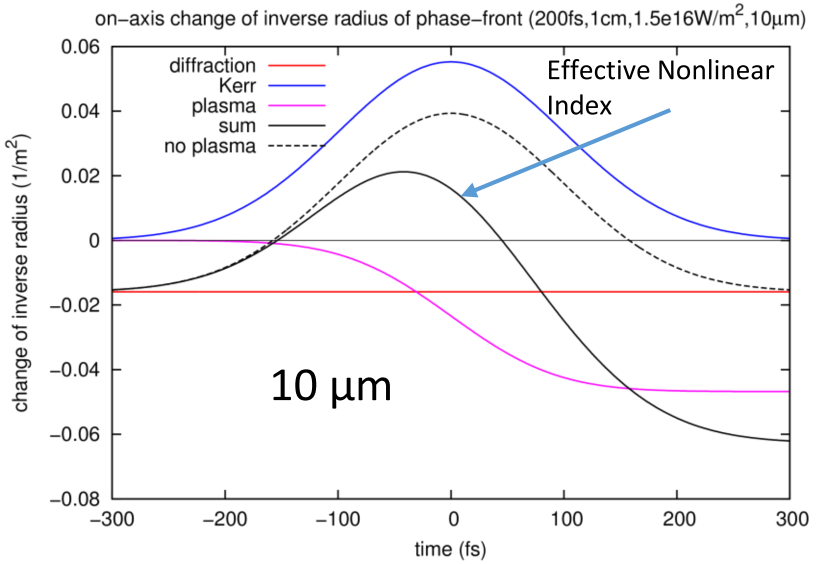
Many-Body Interactions of Weakly Ionized Electrons

K.Schuh, M. Kolesik, E.M. Wright, J.V Moloney and S.W Koch, PRL, **118** 063901 February 10 (2017)





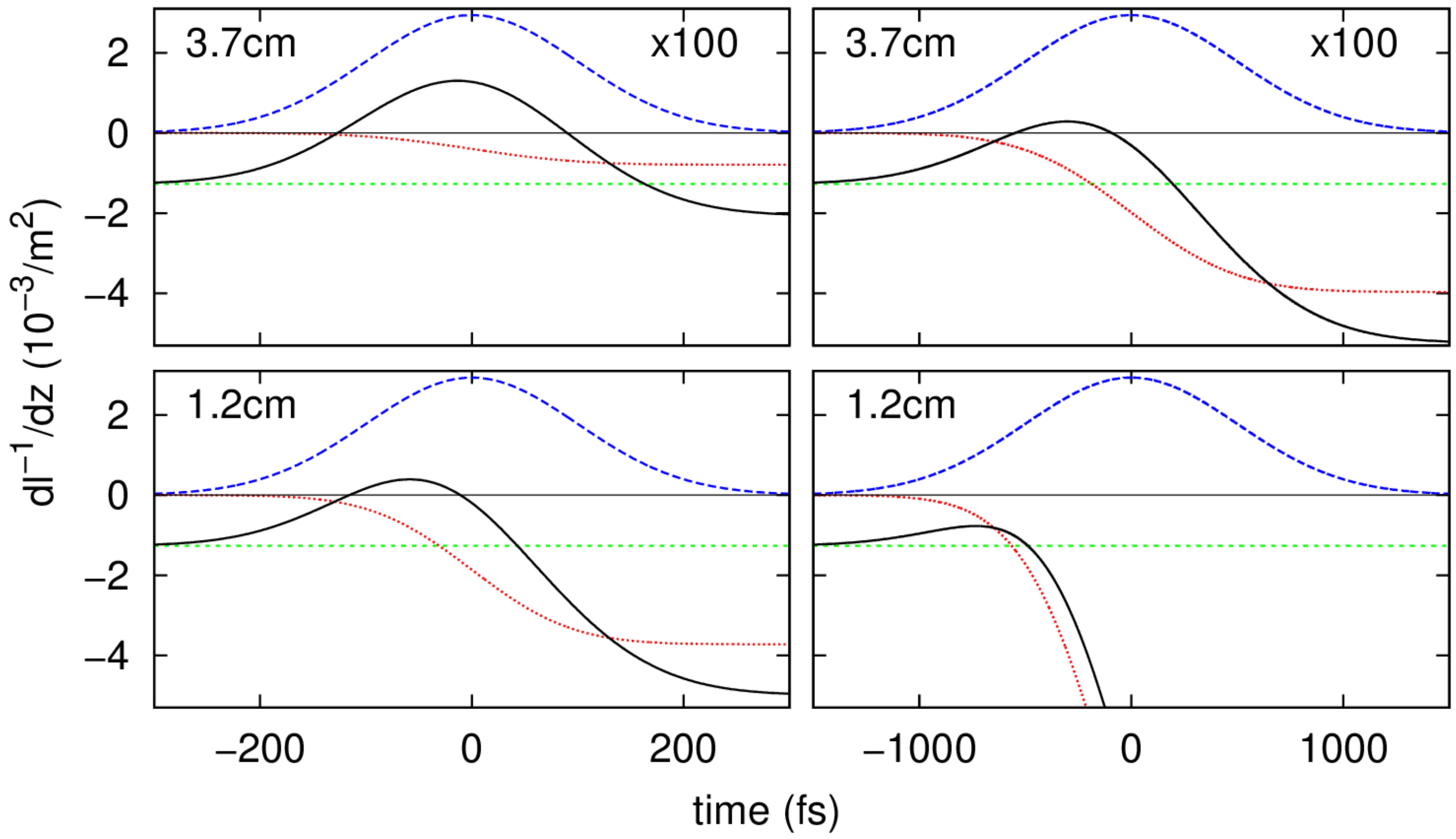




Physics of beam confinement – Dynamical Index Suppression

- K.Schuh et al., PRL **118,** 063901 (10 Feb. 2017)

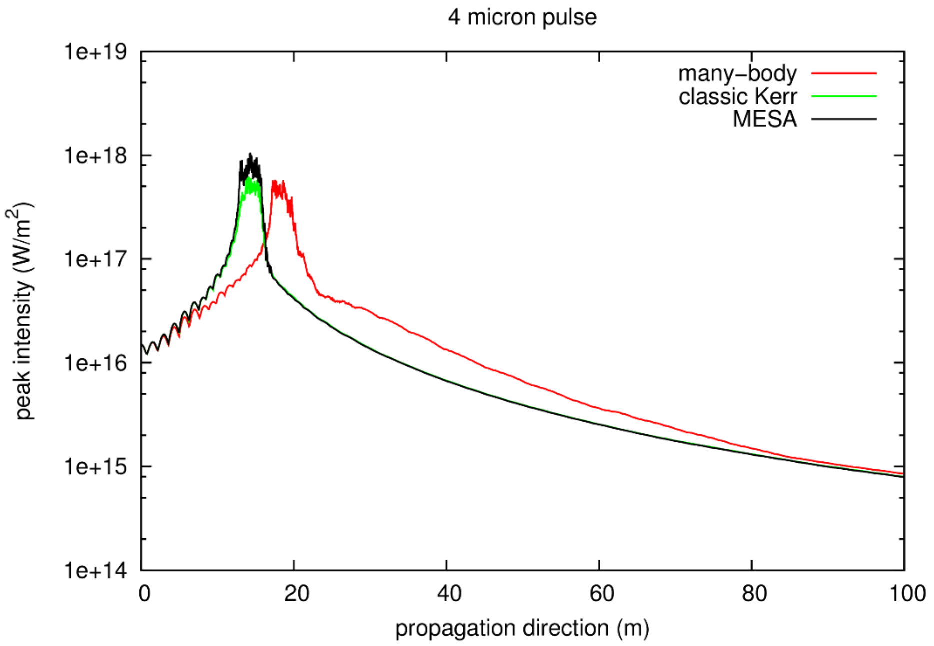
- Hold power fixed but shrink waist – turns off effective Kerr lensing (10μm)

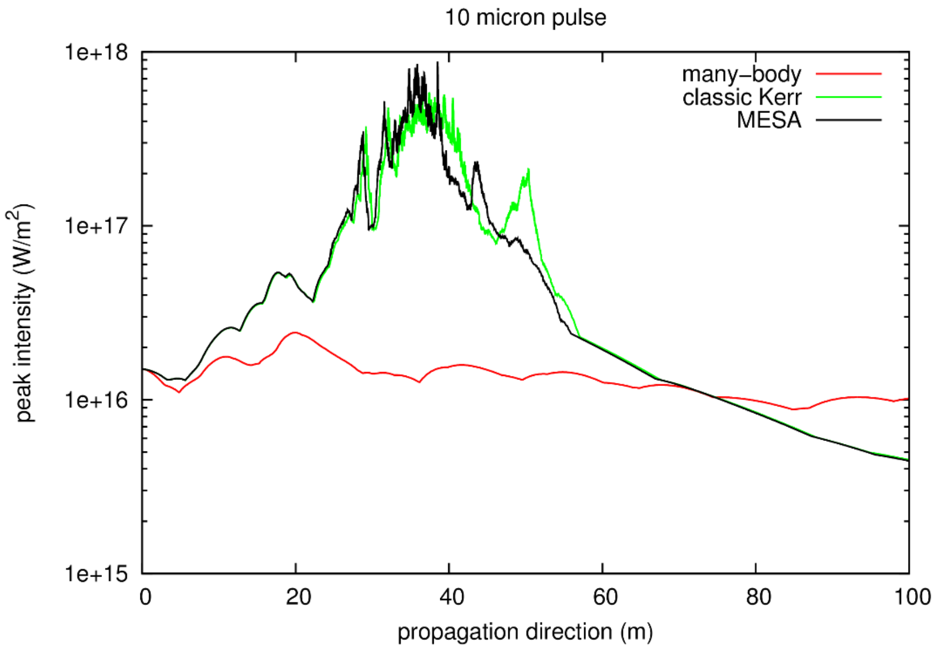


- Beam confinement sensitive to launch conditions and cumulative ionization

Propagation Characteristics at 4 and 10µm

- K.Schuh et al., PRL **118,** 063901 (10 Feb. 2017)
- Use Argon as test medium – no molecular contributions; n_2 comparable to air electronic





Prediction:

- Weak positive lens keeps waist collimated but no localized filament

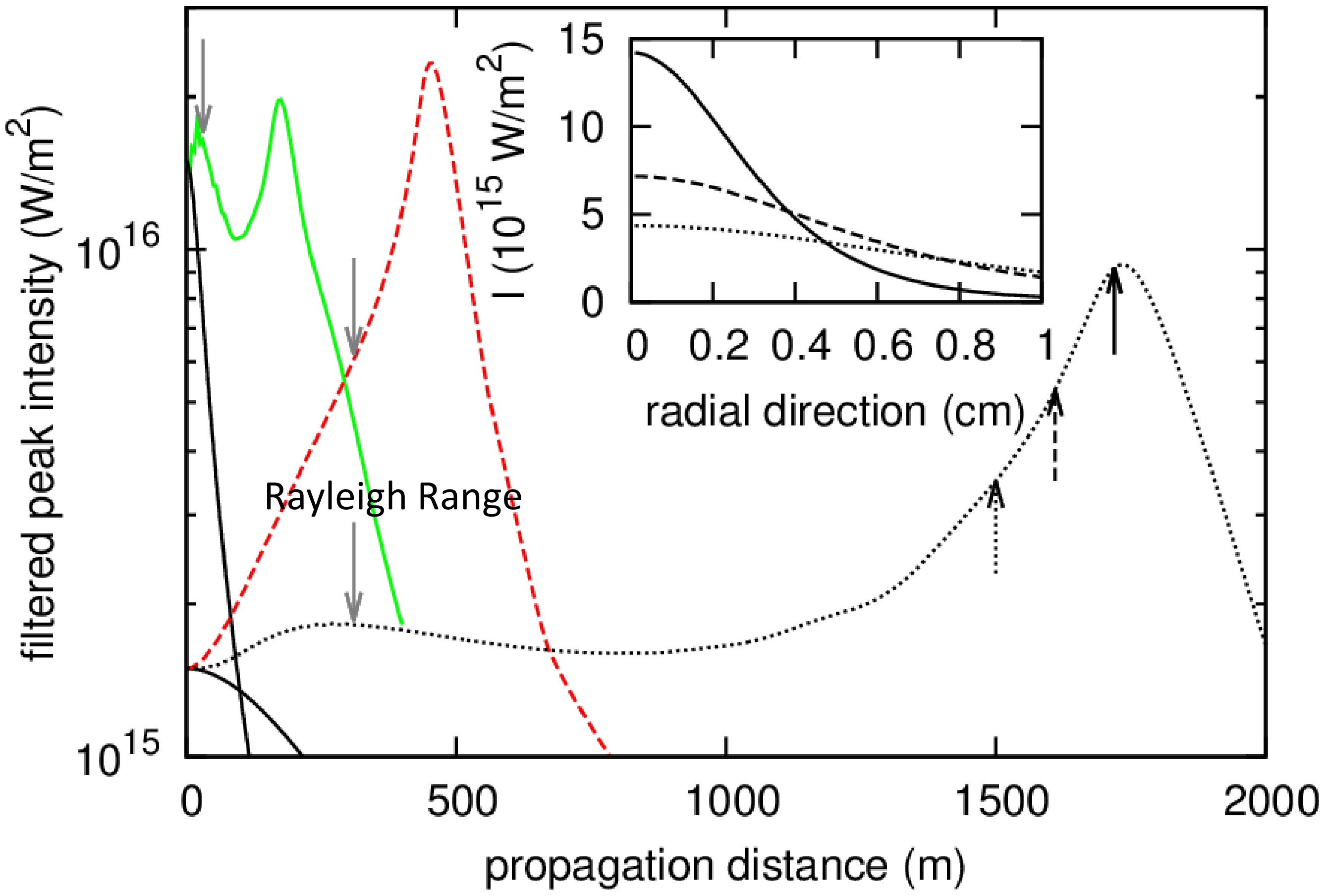
Long Range Multi-Joule Pulse Delivery

K.Schuh, M. Kolesik, E.M. Wright, J.V Moloney and S.W Koch, PRL, **118** 063901 February 10 (2017)

- Cumulative ionization (plasma) dispersion weakens effective Kerr lens

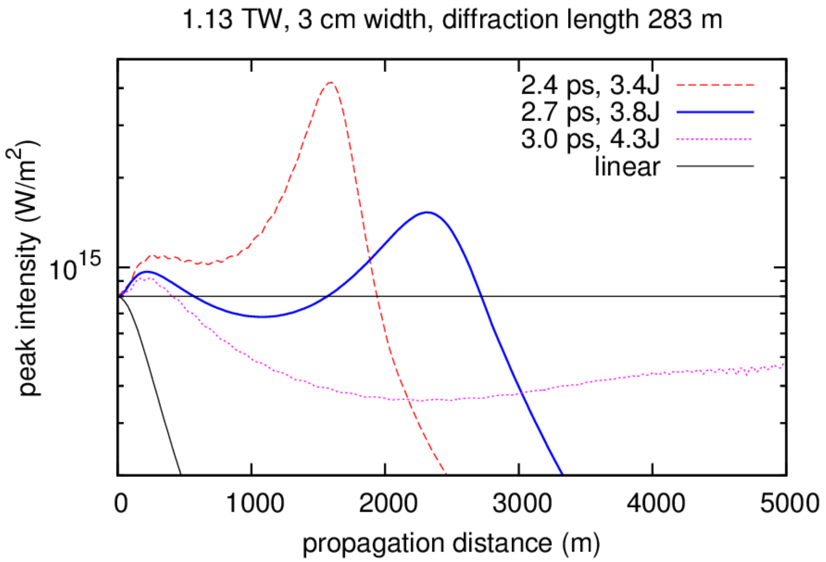
Beam characteristics at 10 μm

1. 100 fs pulse – filament (red dashed)
2. 1 ps pulse - Self-trapped whole beam self-channeling (black dashed).
3. Weak self-focusing compression beyond 1.5 km

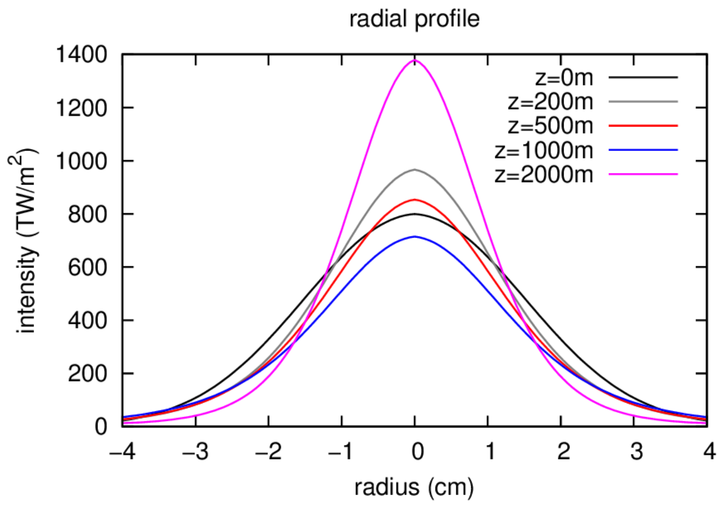


Multi-Kilometer Air Propagation at 10µm

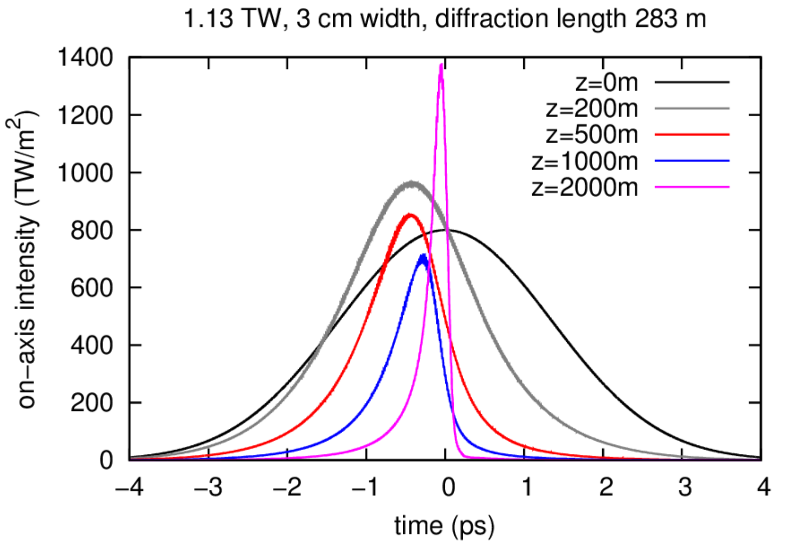
- Fix peak power above critical
- Increase energy (pulse duration)
- Longer (higher energy) pulses tend to suppress strong focus but self-trap over longer ranges.



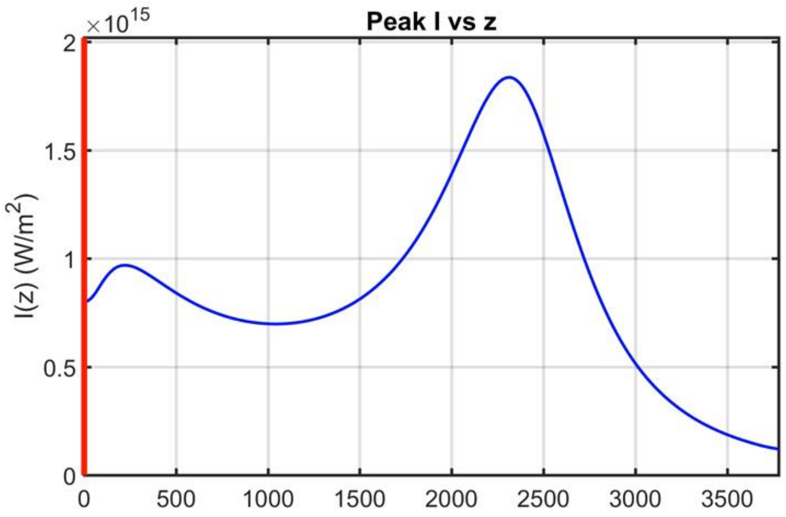
Whole beam radial compression beyond 2km

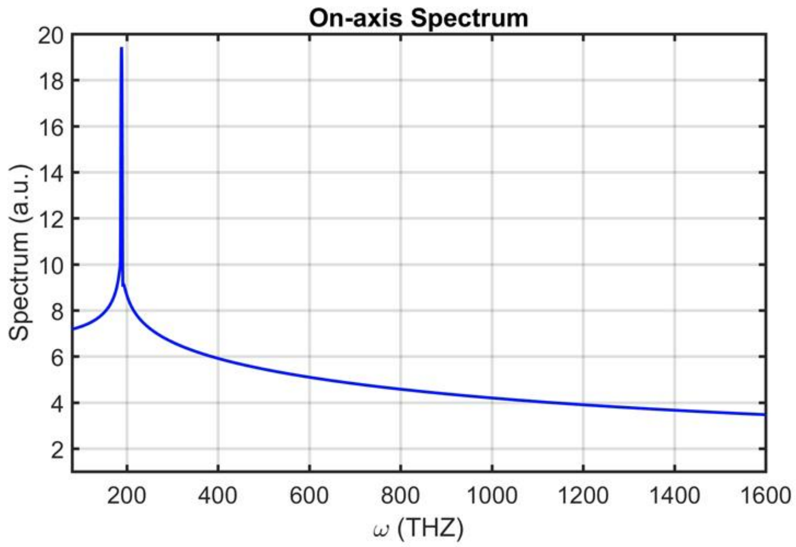


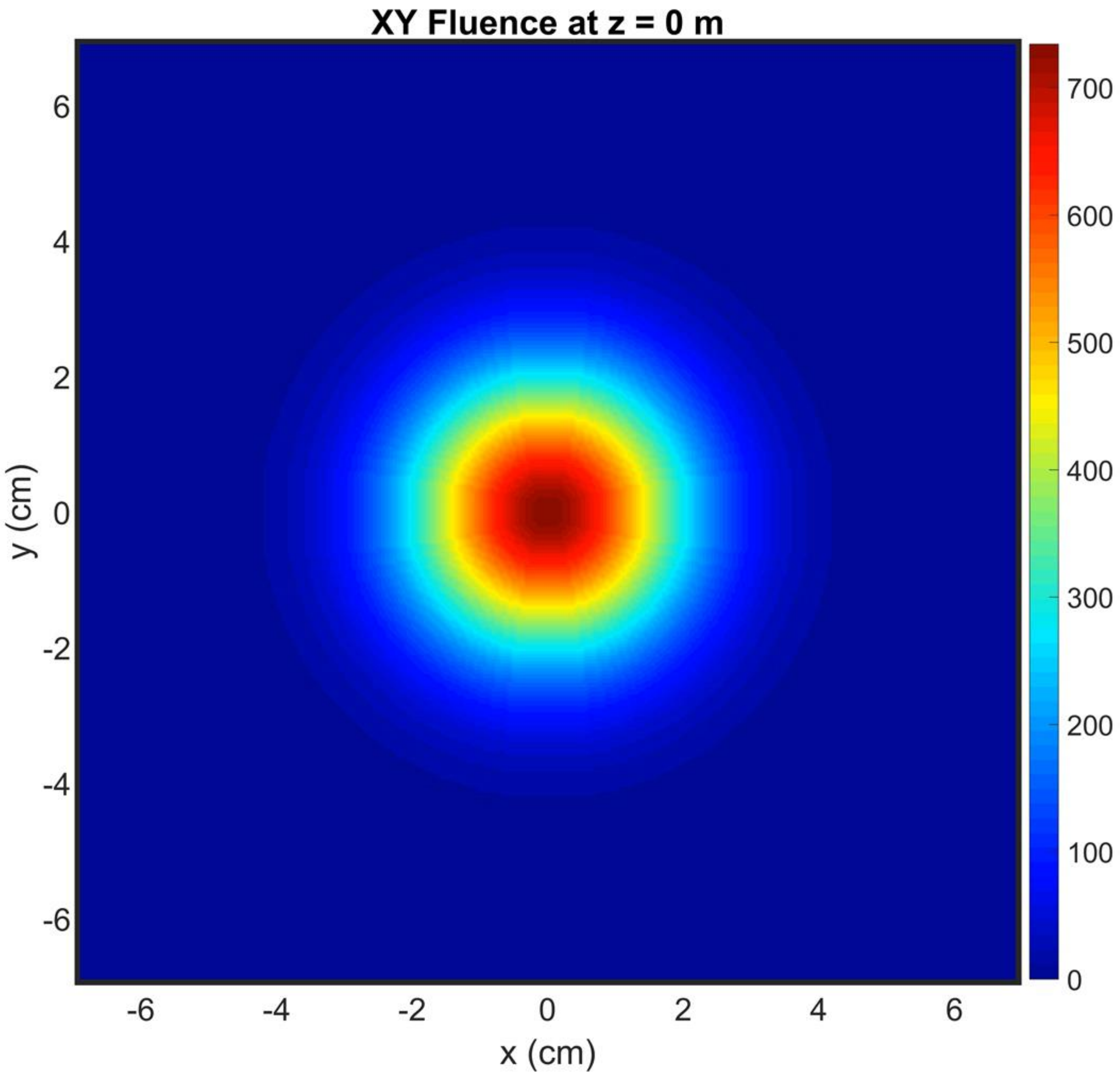
Strong pulse compression in time



Whole Beam Self-trapping

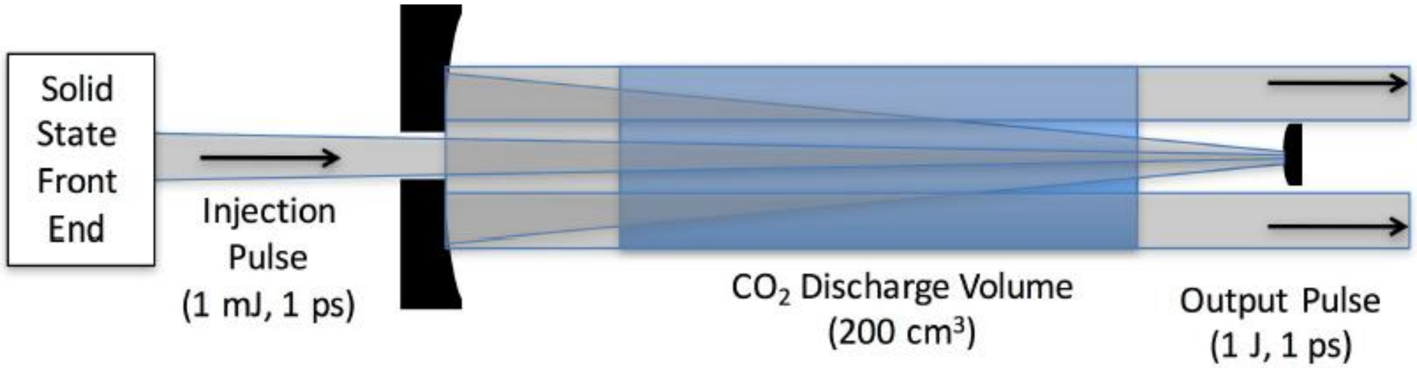


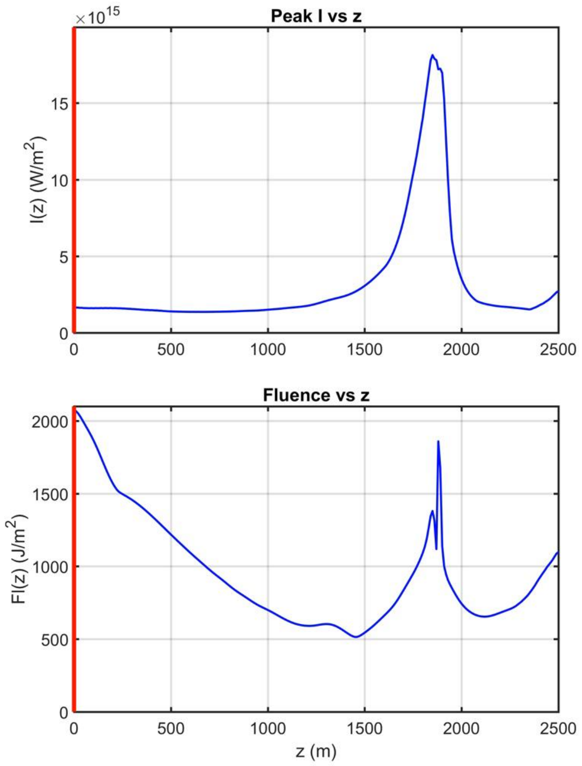


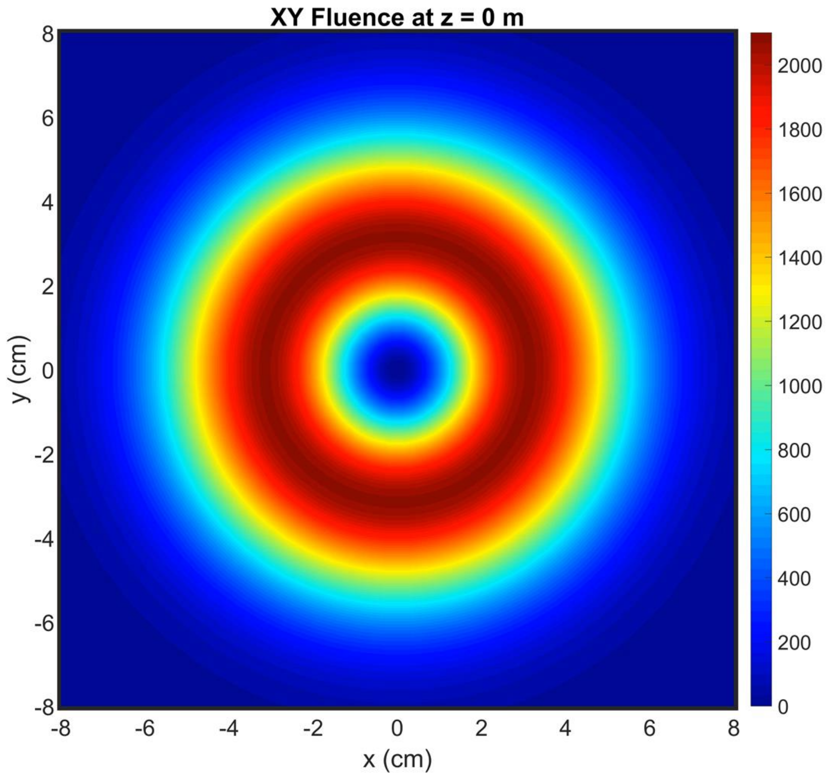


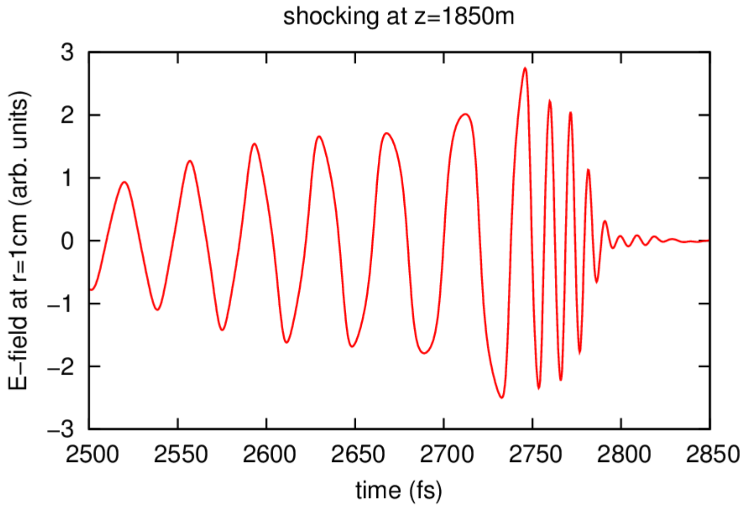
Non-Gaussian Vortex Beams

- D. Gordon et al Proc. SPIE Vol 9835, (2016)









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Summary and Conclusion

- Recurrent carrier shocks maintain light bullet ~ 100's meters.
- Carrier shock and blow-up singularity act in concert to maintain solitonic leading edge – envelope description invalid.
- Anomalous dispersion and absorption around 4.3μm limits propagation
- Potential to create very long thermal waveguides
- Many-body effects enable self-trapping over multiple kilometers
- Pulse stays trapped over tens of(>20) Rayleigh ranges of the launched beam.
- Currently developing a nonlinear HITRAN database