Multi-Terawatt Long Wavelength mid-IR Atmospheric Light Bullets

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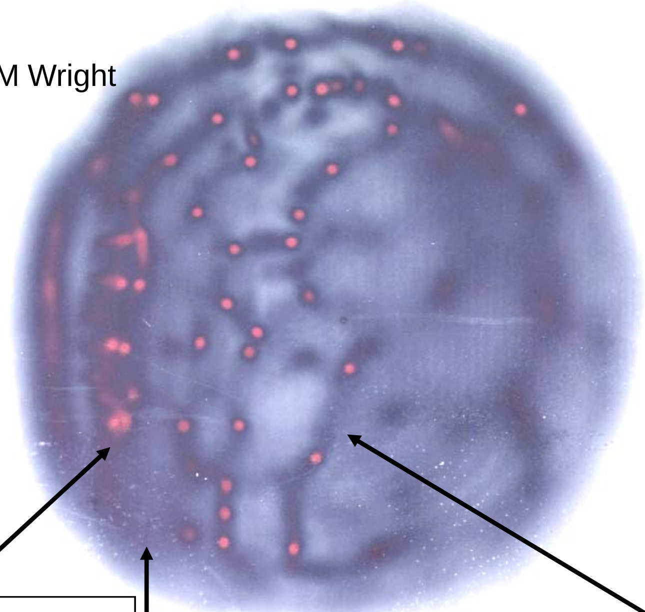
Talk Outline

- Introduction
- Filament Modeling Hierarchy
- Multi-TW Mid-IR Light Bullet
- 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

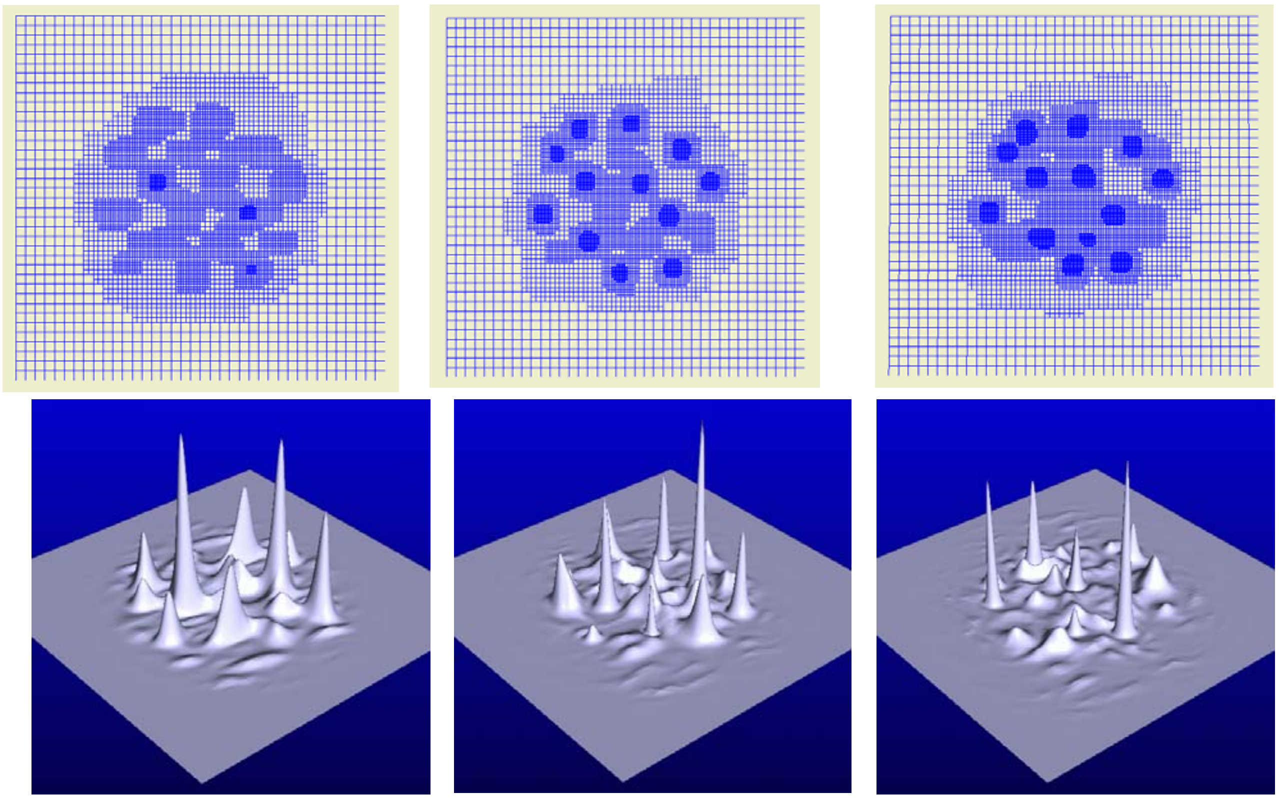
Intense self-focused filaments

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).

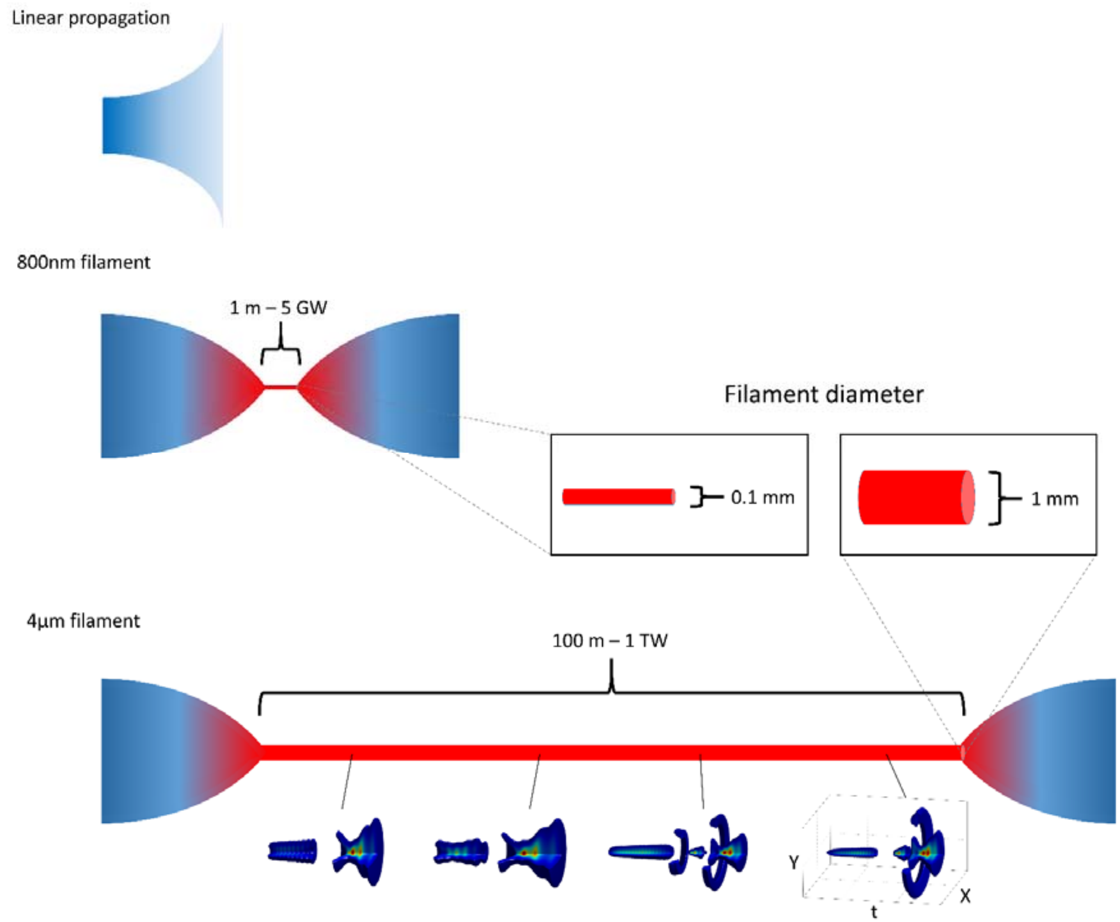
Adaptive Mesh GNLSE Parallel Solver

Dynamic regriding in space and time – Multiple light strings



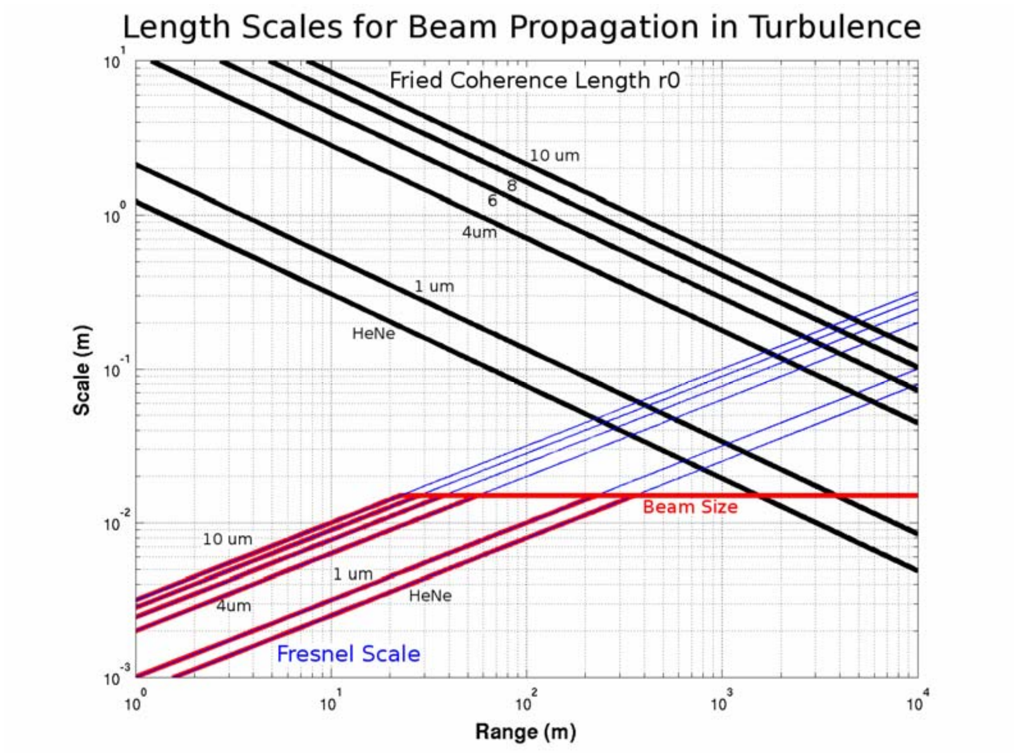
M. Mlejnek, M. Kolesik, J.V. Moloney, E.M. Wright, *PRL,* **83**(15) pp. 2938-2941 (1999).

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 can beat diffraction limitation

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Filament Modeling Hierarchy

Nonlinear Envelope Equation – Generalization of Nonlinear Schrödinger Equation
- Computational workhorse for near-IR filament propagation

Dispersion operator

$$\frac{\partial \mathcal{E}}{\partial z} = \frac{i}{2}\left[\nabla_\perp^2 \mathcal{E} + D\mathcal{E}\right] + k_0\left[T^2 N_{Kerrr}(\mathcal{E}) + T N_{NLL}(\mathcal{E}) + N_{Plasma}(\mathcal{E},\rho)\right]$$

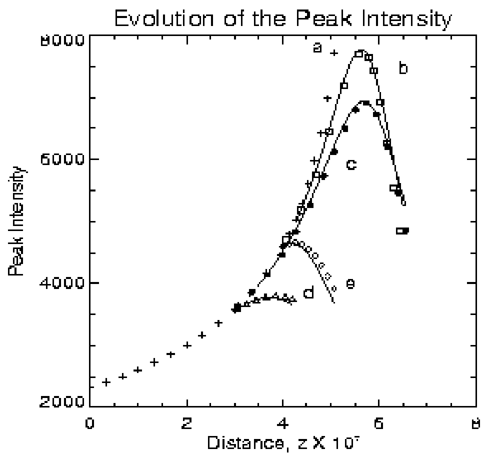
$$\nabla_\perp^2 = \Delta_\perp = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \qquad N_{Kerr}(\mathcal{E}) = i\frac{\omega_0}{c} n_2 \left((1-a)|\mathcal{E}|^2 + a\int_{-\infty}^{t} R(t-\tau)|\mathcal{E}|^2\, d\tau\right)\mathcal{E}$$

$$N_{NLL}(\mathcal{E}) = -\frac{\beta_K}{2}\left[1 - \frac{\rho}{\rho_{nt}}\right]|\mathcal{E}|^{2K-2}\,\mathcal{E} \qquad N_{Plasma}(\mathcal{E},\rho) = -\frac{\sigma}{2}(1 + i\omega\tau_c)\rho\mathcal{E}$$

J.V. Moloney and A.C. Newell, “Nonlinear Optics”, *Perseus* (2004)

NLSE in the limit of weak Normal GVD

Luther, Newell and Moloney, Physica D, Vol. 74, p59 (1994)

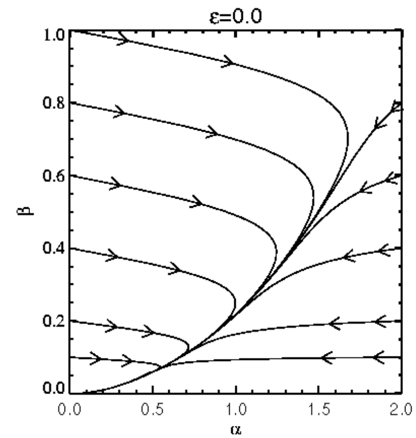


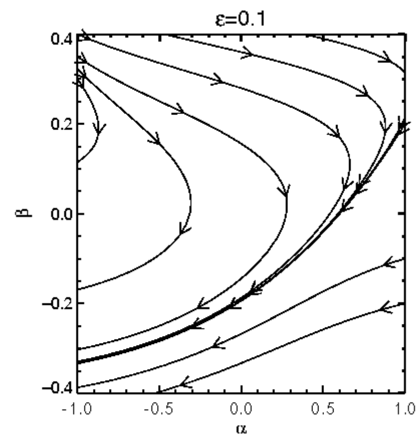
Self-similar form of
Collapse Singularity

$$A(\tau,\zeta,t) = g(\tau)\chi(\zeta)e^{-i\frac{\alpha}{4}\zeta^2 + i\tau}$$

$$\xi = g\rho, \quad \tau = \int^{z} g^2 dz'$$

$$\alpha = \frac{g_\tau}{g}, \quad \beta = \frac{1}{4}(\alpha_\tau + \alpha^2)$$





$$g(t) = 1\Big/\sqrt{z(t) - z_0(t)}$$

$$g_\tau = \alpha g$$

$$\alpha_\tau = 4\beta - \alpha^2$$

dispersion

$$\beta_\tau = -av(\beta) - \varepsilon(a - \alpha^2/4 - \beta)$$

Conclusion: ε no matter how small arrests the collapse via pulse splitting!

Scalar UPPE Model (Unidirectional)

Unidirectional Pulse Propagating Equation (z-UPPE)

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

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

Plasma-related current

Accurate chromatic dispersion

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

<u>Carrier based approach, no envelope approximations used</u>

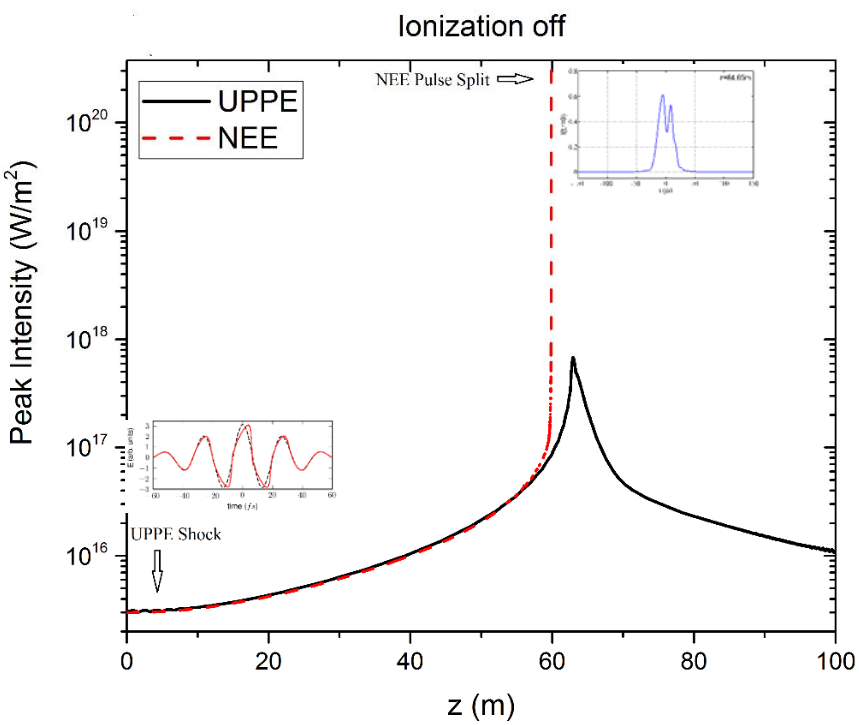
VOLUME 89, NUMBER 28 PHYSICAL REVIEW LETTERS 31 DECEMBER 2002

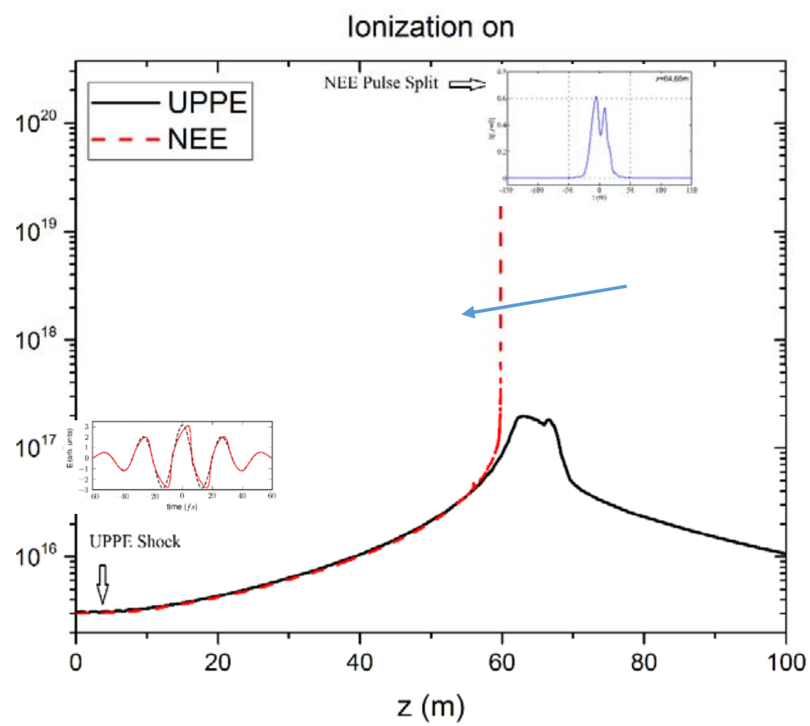
Unidirectional Optical Pulse Propagation Equation

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

UPPE Carrier Shock Regularization – No HOKE or ~~Ionization~~ Regularization Necessary

- Long wavelength limit of NLSE supports Luther et al. analysis (1994)





Weak dispersion of ionized electrons works in conjunction Intrinsic GVD

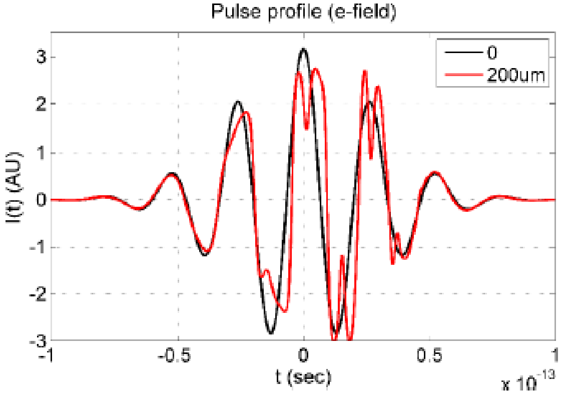
Modified Kadomtsev-Petviashvili (MKP1)

- Canonical Full Field Propagator for long wavelength USPs

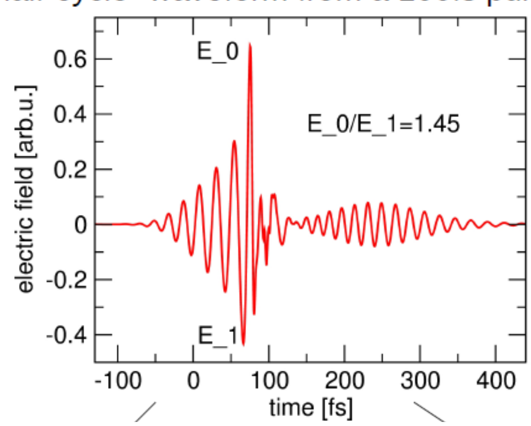
$$\partial_\tau \left[\partial_z E(r,z,\tau) + \frac{4n_2}{c} E^2 \partial_\tau E - a\partial_\tau^3 E \right] + bE = \frac{c}{2n(\omega_R)} \Delta_\perp E$$

- 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 (2011)
- 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

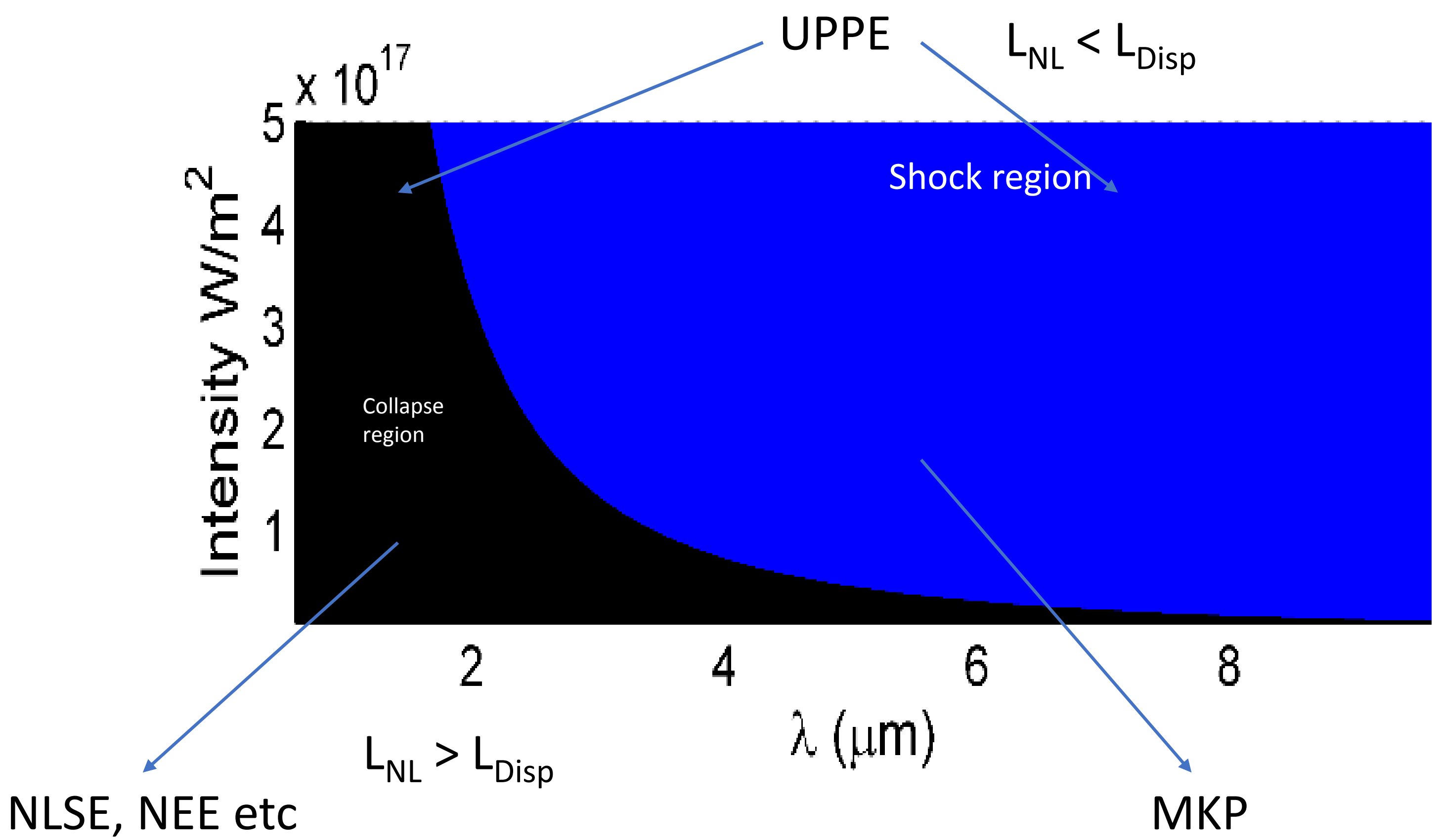
Carrier shock in Diamond at 8µm



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



Shock Regularization is Universal for Long Wavelengths



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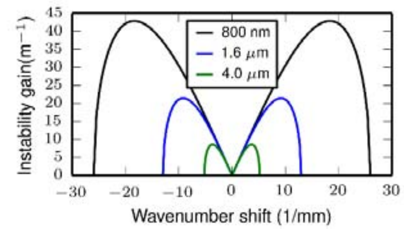
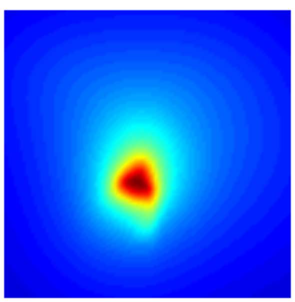
Advantages of multi-TW mid-IR pulses

- ❑ Modulational instability suppressed.

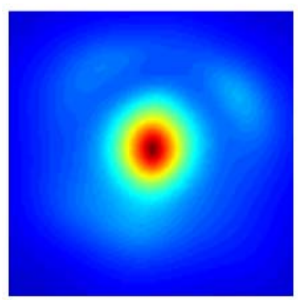


- ❑ Resistant to filamentation
- ❑ Beam stabilization - Shock initiated harmonic walk-off

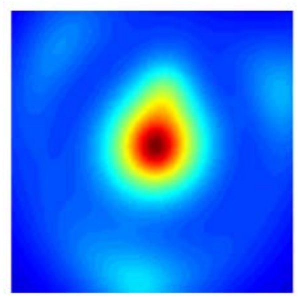
Initial beam waist: 1.5 cm, Total Power = 7 TW Energy = 265 mJ



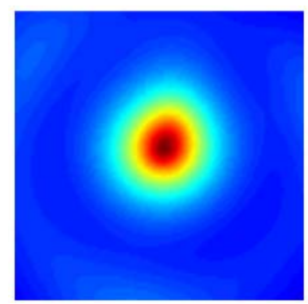
Z = 20 m



z= 30m



z=40m



z=50m

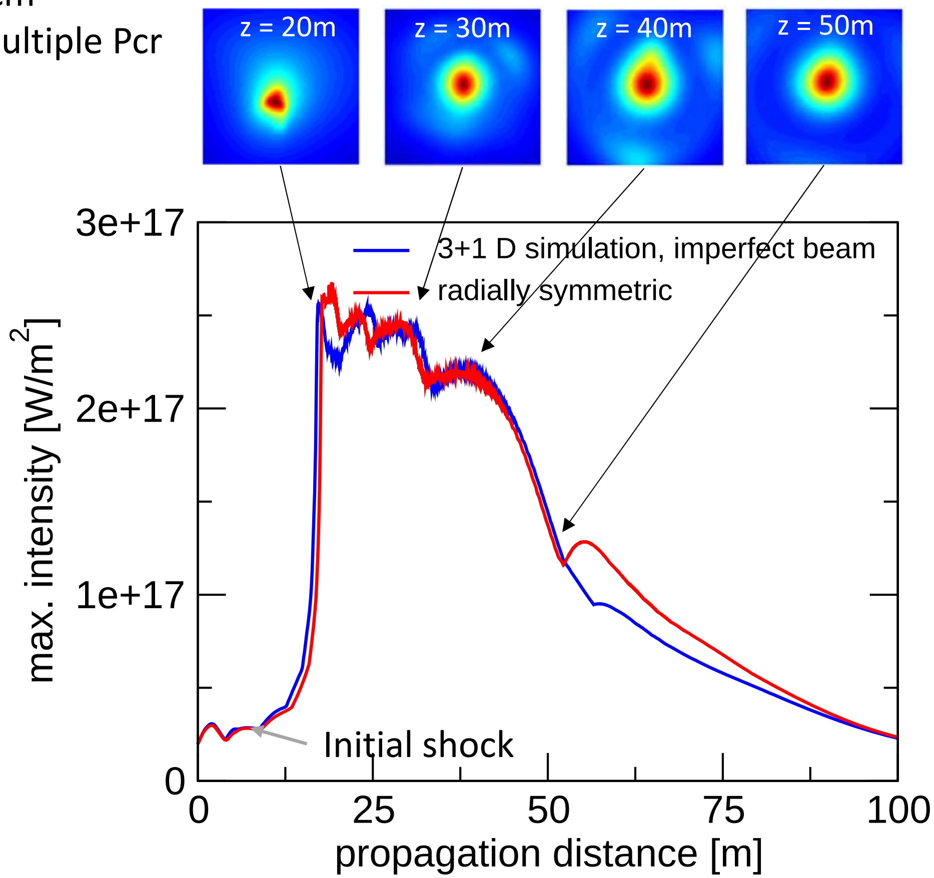
Multi-TW Mid-IR Light Bullet (4 μm)

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

- ❑ 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

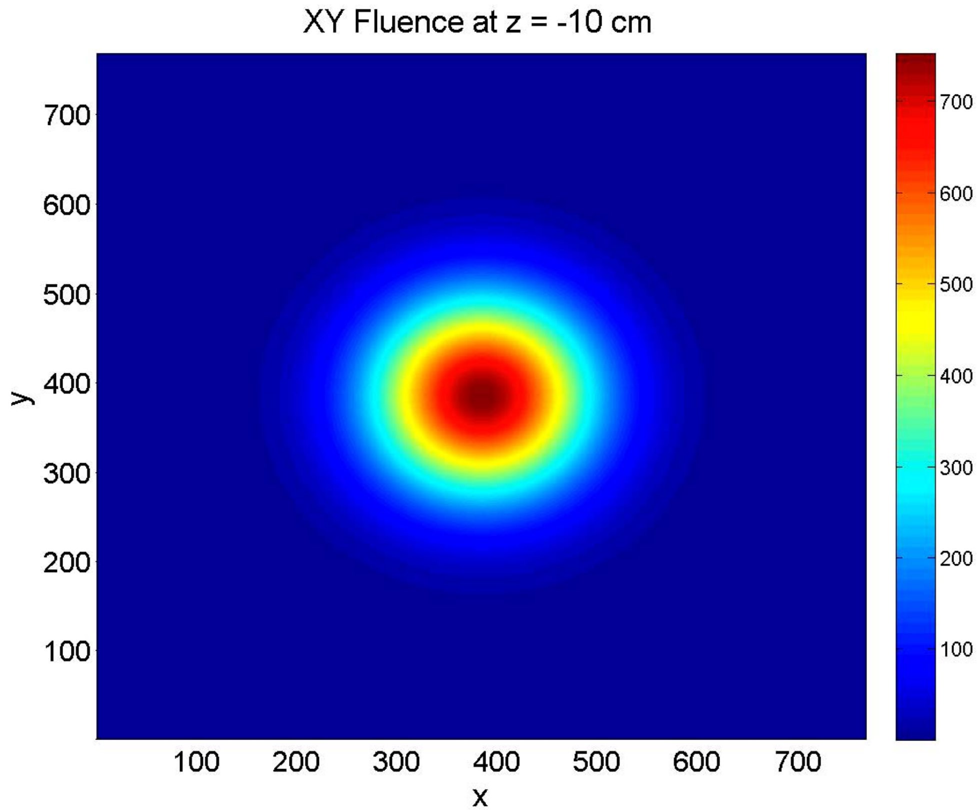
Waist = 1cm
Power = multiple Pcr
λ = 4μm
τ = 30fs

XY fluence (normalized)



Energy Fluence of 7 TW 4 μm Pulse

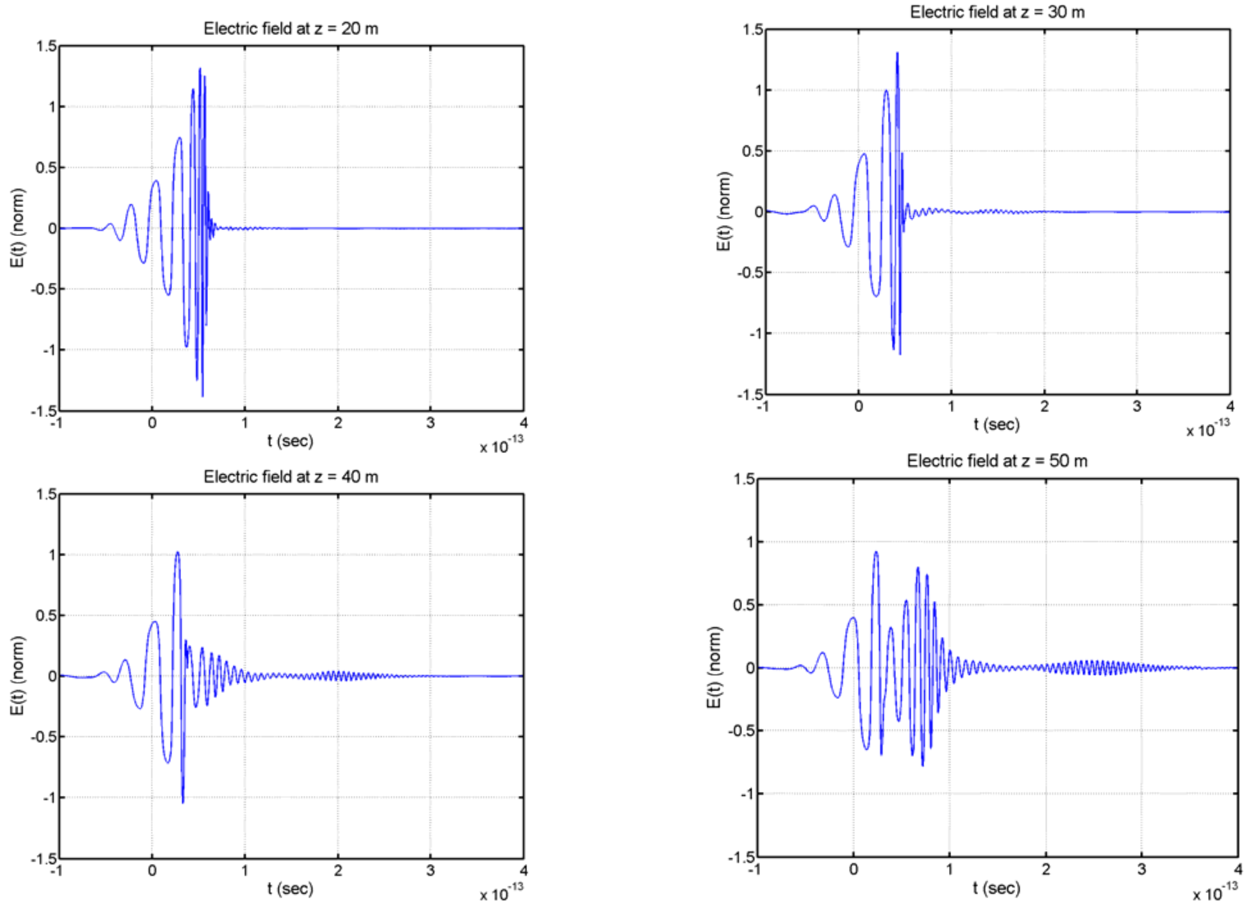
- Large initial transverse perturbation added to the beam to test robustness



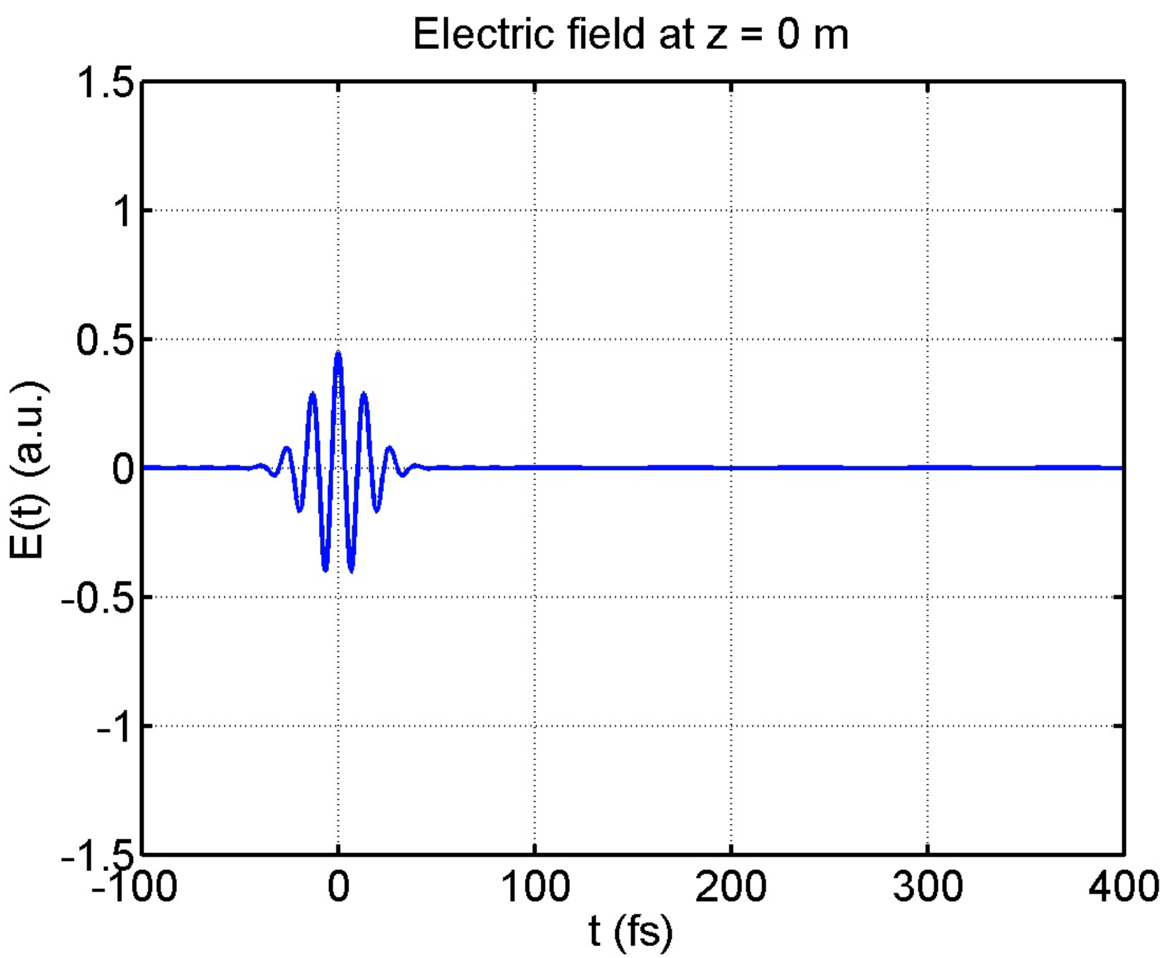
Light Bullet Dynamics

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

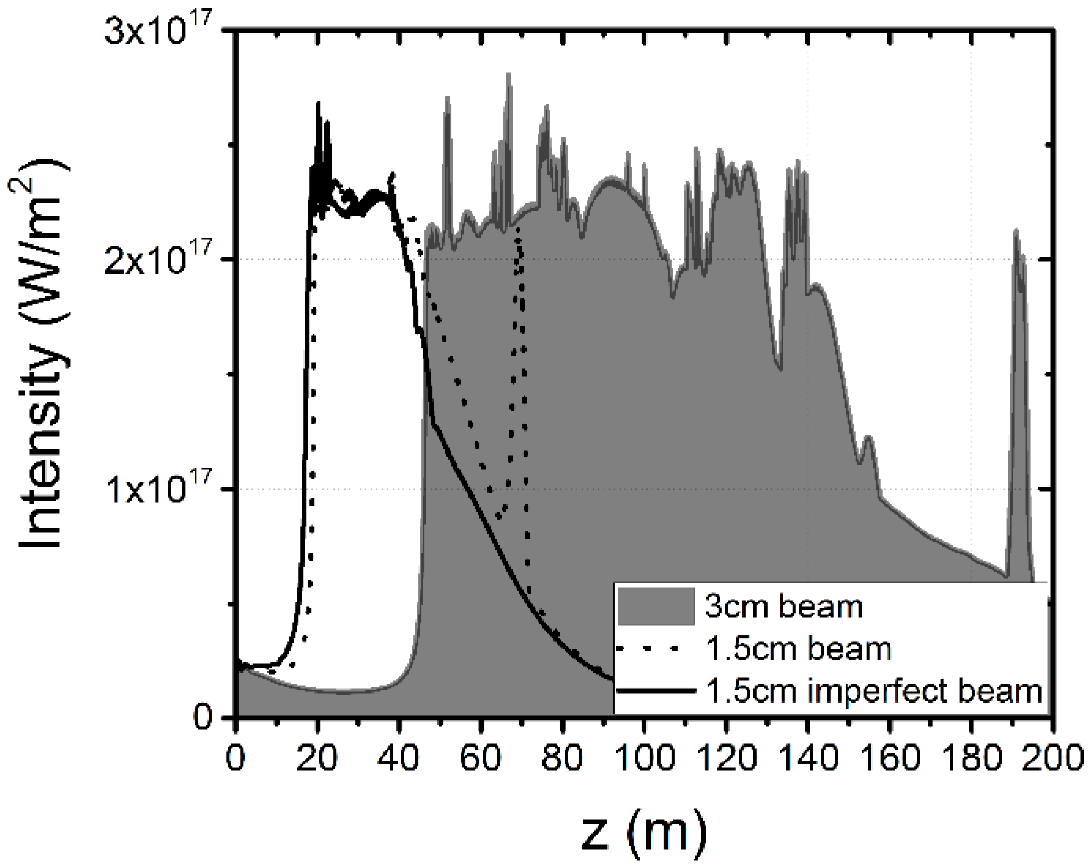
1D slice captured approximately by 1D mKdV with opposite sign for dispersion coefficient – nonintegrable case – P. Jakobsen



Harmonic walk-off (movie)

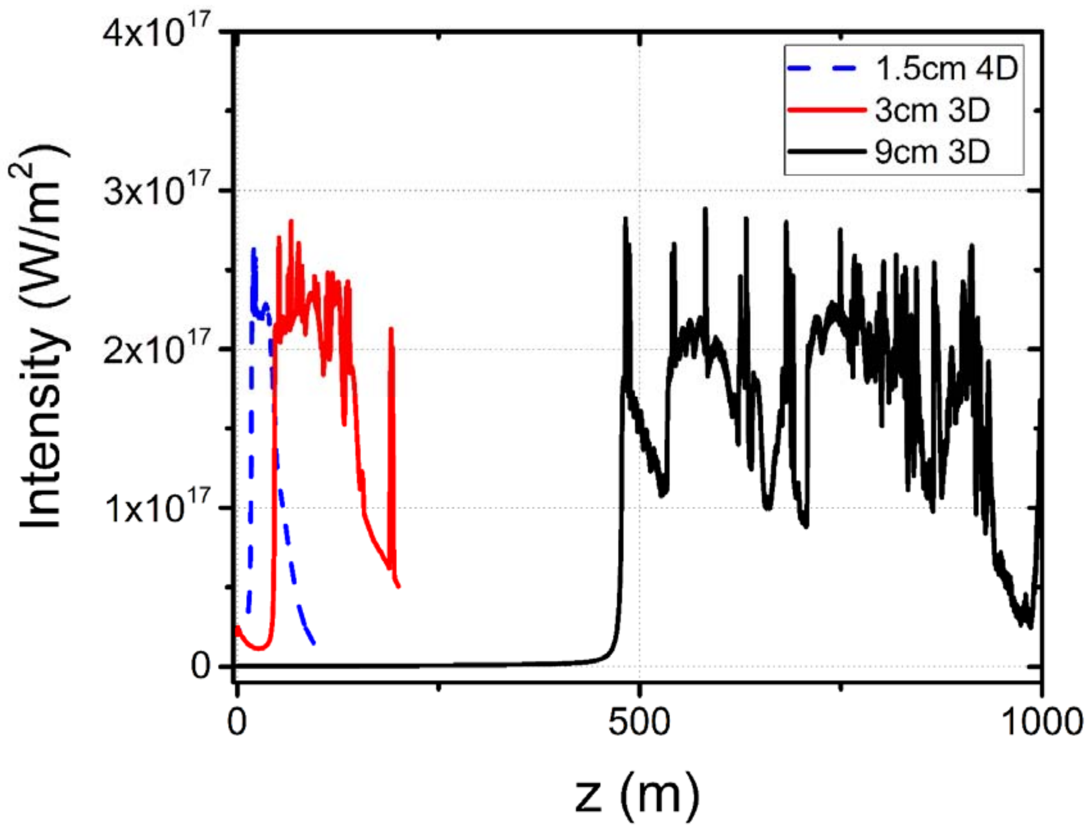


Scaling Propagation Distance (4 μm)



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

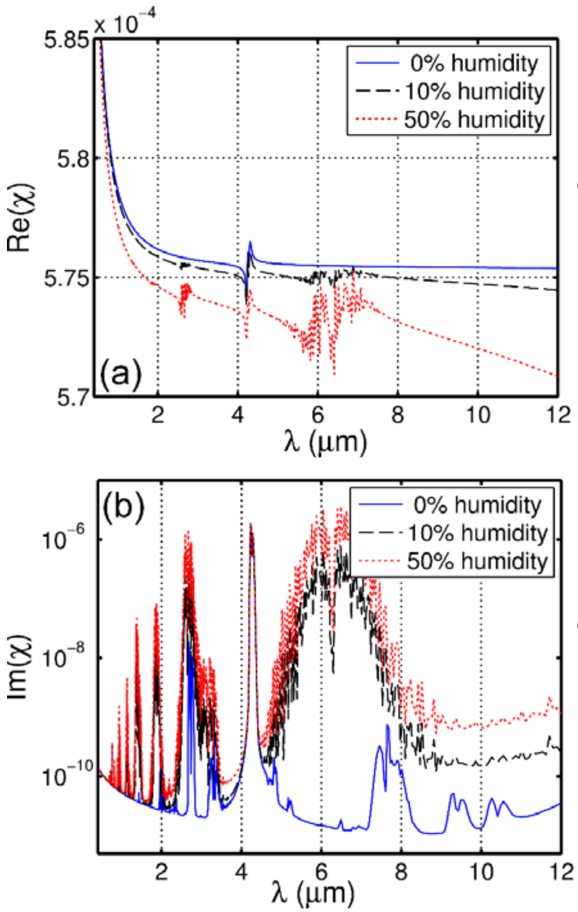
P. Paniagotopoulos et al. PRA (in press) (2016)



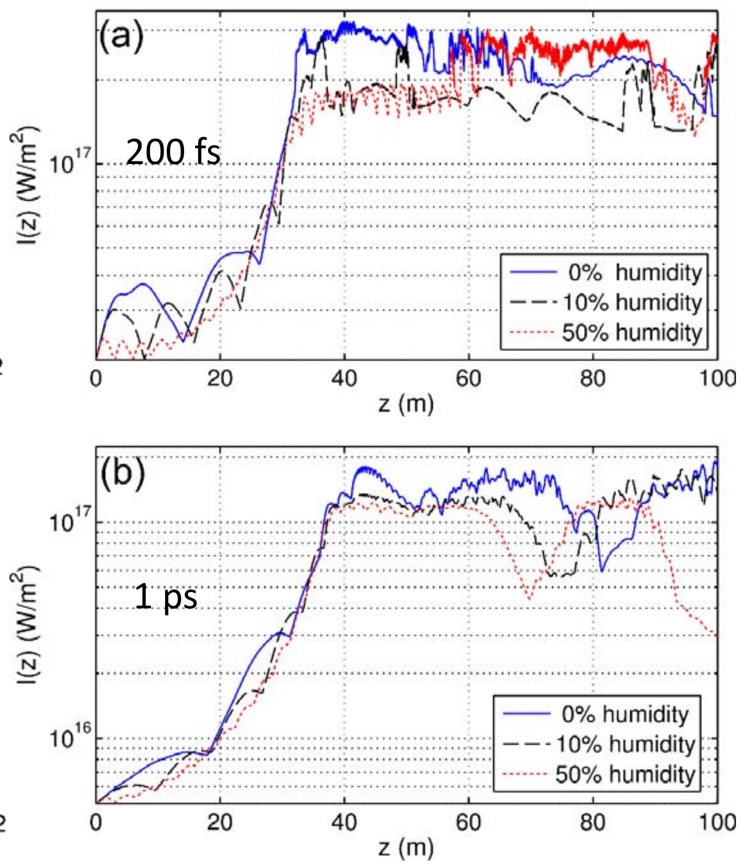
10 µm Pulse Propagation in a Realistic Atmosphere

P. Panagiotopoulos et al. JOSA B (2016). Expt n_2 measurement: Sergei Tochitsky 16:30 talk today

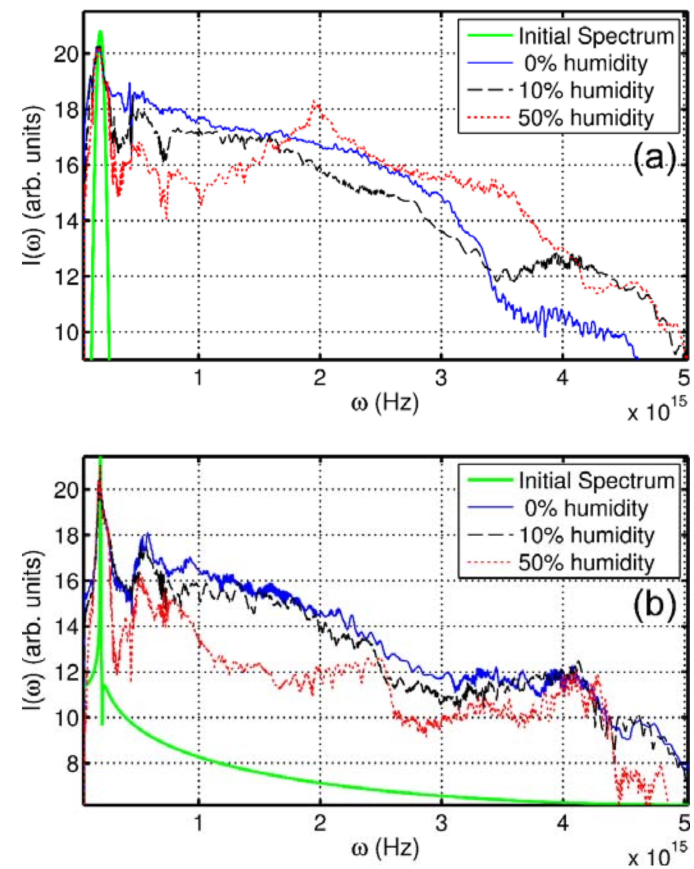
HITRAN Database



Peak Power over 100m



Spectra at 100m



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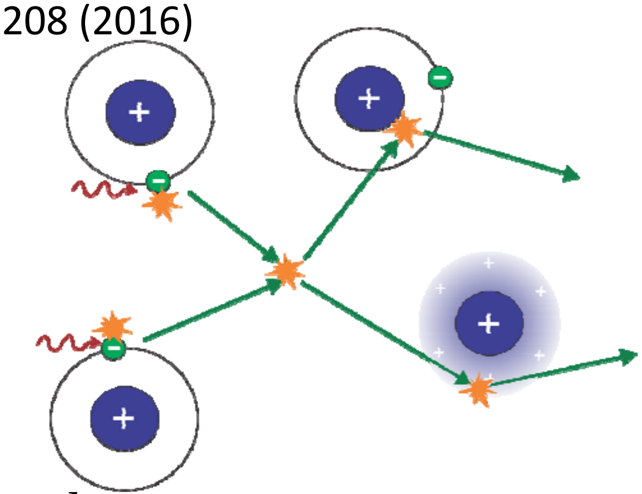
Quantum Many-Body Equations for Coulomb Scattering

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

- Assume ions are stationary



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

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

$$i\hbar \frac{d}{dt} P_{s\vec{k}} = \left[\epsilon_s - \epsilon_{\vec{k}}\right] P_{s\vec{k}} + \Omega^*_{s\vec{k}} \left[f_{\vec{k}} - f_s \right] - \frac{e}{\hbar} \vec{\nabla}_{\vec{k}} P_{s\vec{k}} \vec{E} + \sum_{\vec{k}' \neq \vec{k}} \Omega^*_{s\vec{k}'} P_{\vec{k}'\vec{k}} + i\hbar \frac{d}{dt} P_{s\vec{k}} \Big|_{\text{e-e}}$$

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

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

Requires solution of Quantum Boltzmann Equation

Long Wavelength Scaling of Critical Parameters

Critical Power:

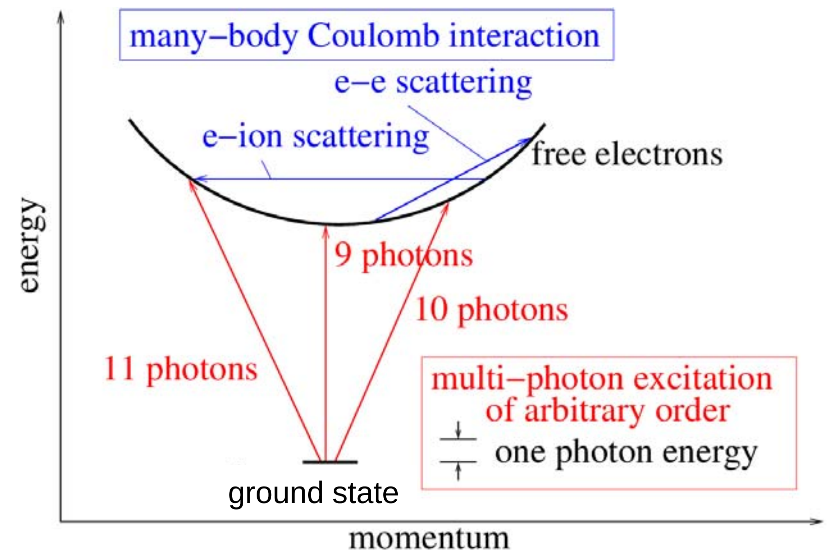
$$P_{\text{crit}} = \frac{0.3\lambda^2}{nn_2}$$

Ionized Electron Polarization

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

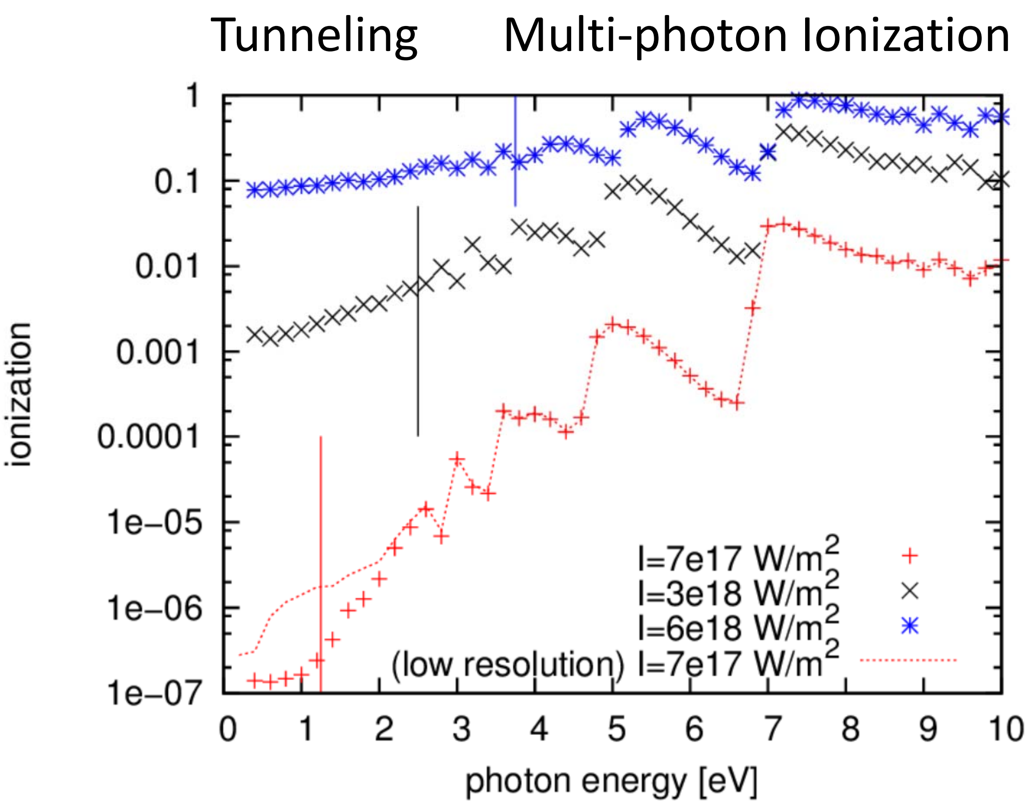
Ionized Electron Density

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

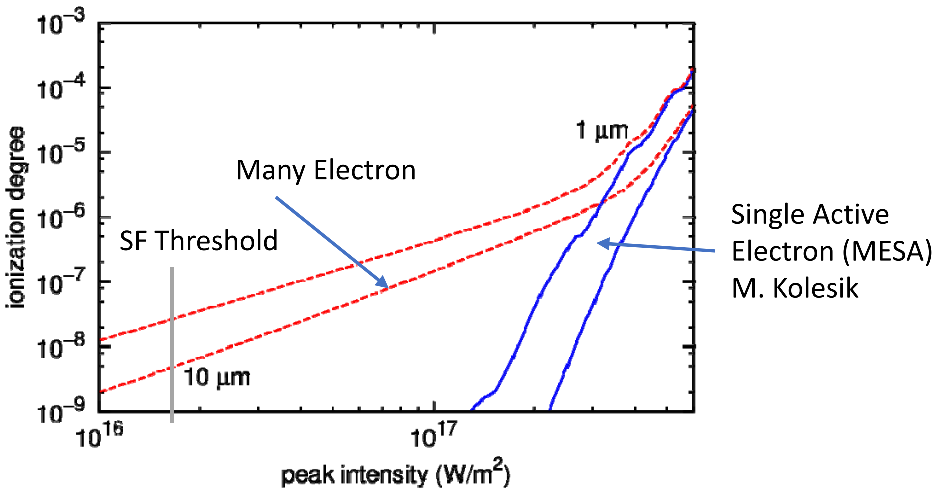


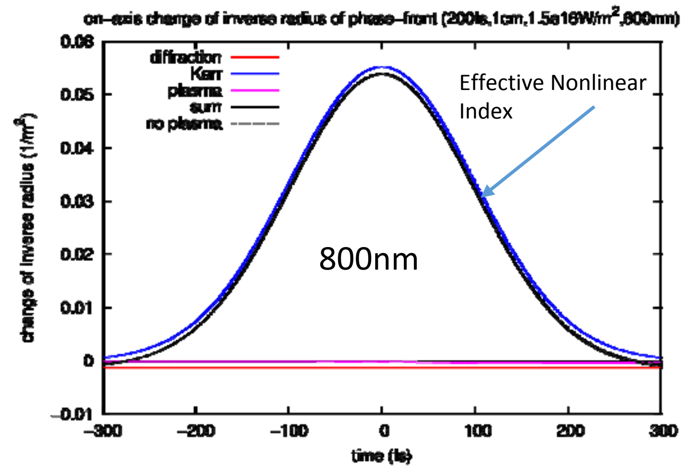
Quantum Many-Body -Tunneling and Multi-Photon Regime

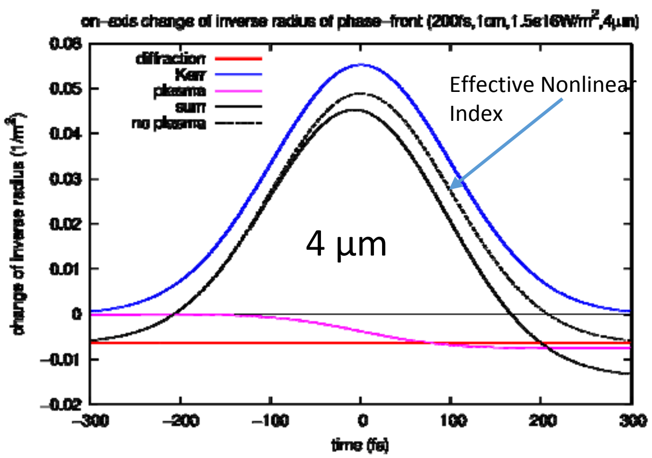
- Vertical lines indicating a Keldysh parameter of 1
- Tunneling regime
  - (left of vertical lines)
  - Weak dependency of ionization on photon energy
- Multi-photon regime
  - Strongly increasing ionization with increasing photon energy
  - Photon resonances

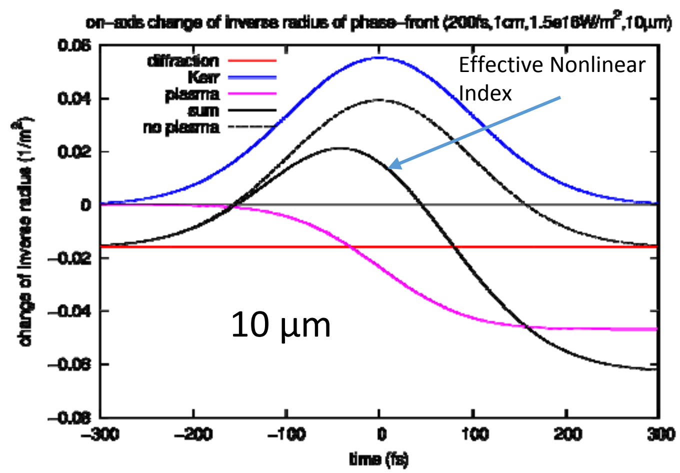


Many-Body Interactions of Weakly Ionized Electrons

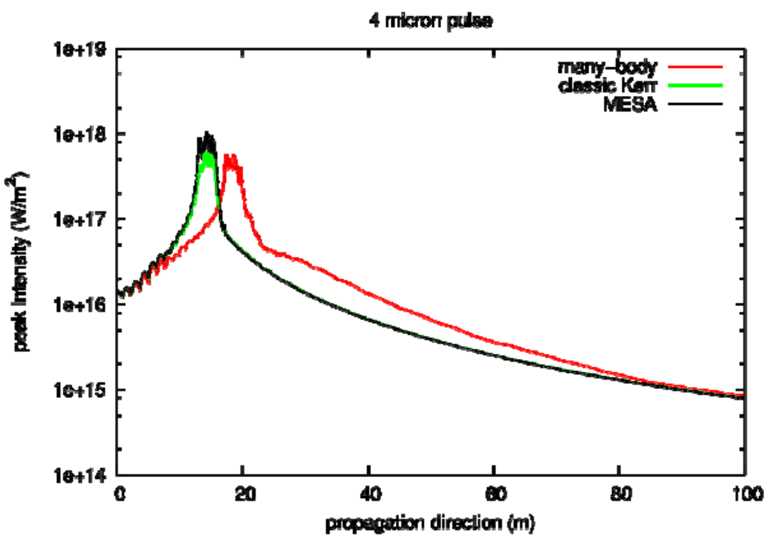


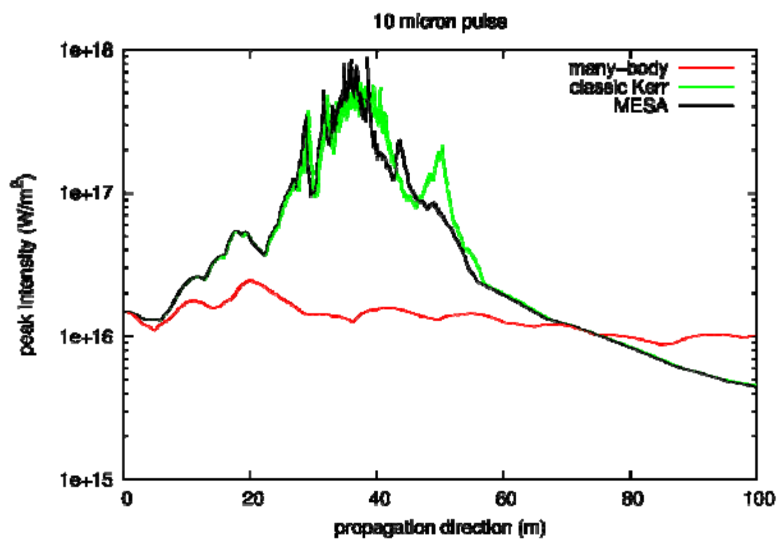






Propagation Characteristics at 4 and 10μm

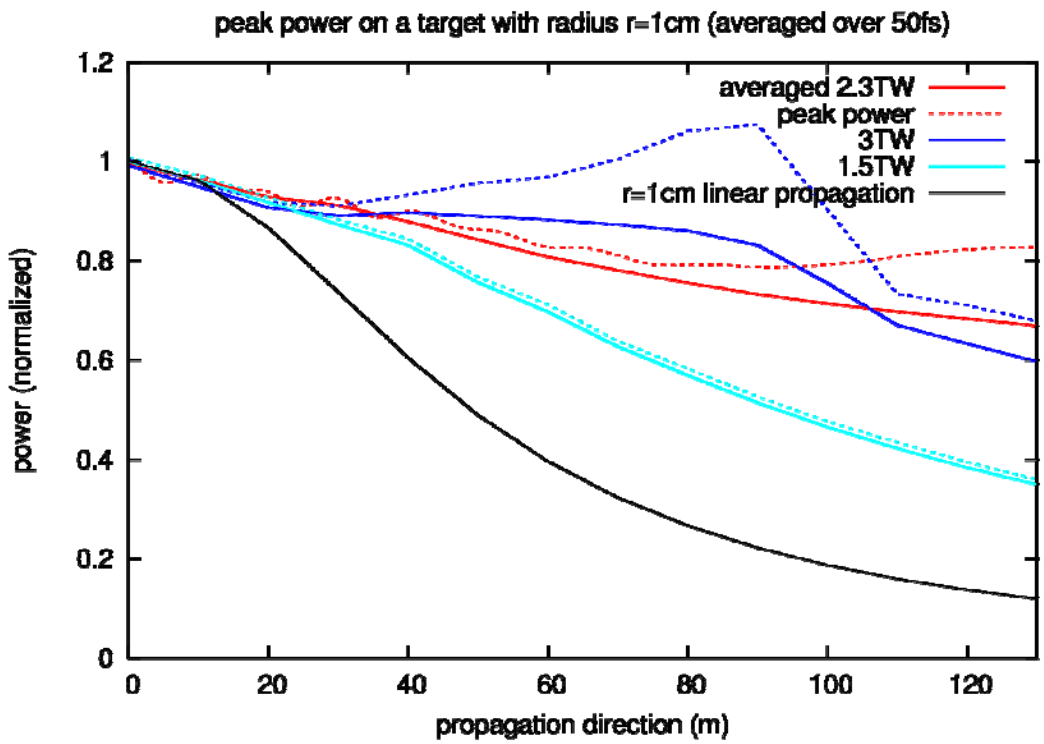




Prediction:

- Weak positive lens keeps waist colimated but no localized filament

10 μm Peak Power Delivered to a 1 cm Target at 120m



- Preliminary experimental evidence for weak self-trapping at 10μm – Sergei Tochitsky (UCLA)

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Summary and Conclusion

- Mid-IR light bullet transports multiple TW in a single filament
- Recurrent carrier shocks maintain light bullet ~ 100's meters.
- Experiments in mid-IR just beginning – source limitation
- Carrier shock and blow-up singularity act in concert to maintain solitonic leading edge – envelope description invalid.
- Potential to create very long thermal waveguides in air.
- Many-body effects offset filamentation at 10µm – main broad beam
- Very recent experiment at Brookhaven National lab on 10µm filamentation