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Upper-limit power for self-guided propagation of intense lasers in plasma

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Outline

- Motivation: why need self-guiding of intense lasers
- Lower-limit laser power for self-focusing
- Upper-limit power and lower-limit density for self-focusing
- Channel or anti-channel is better for self-guiding at high laser power?
- Summary

Self-guiding of intense lasers through a long distance is crucial for many applications

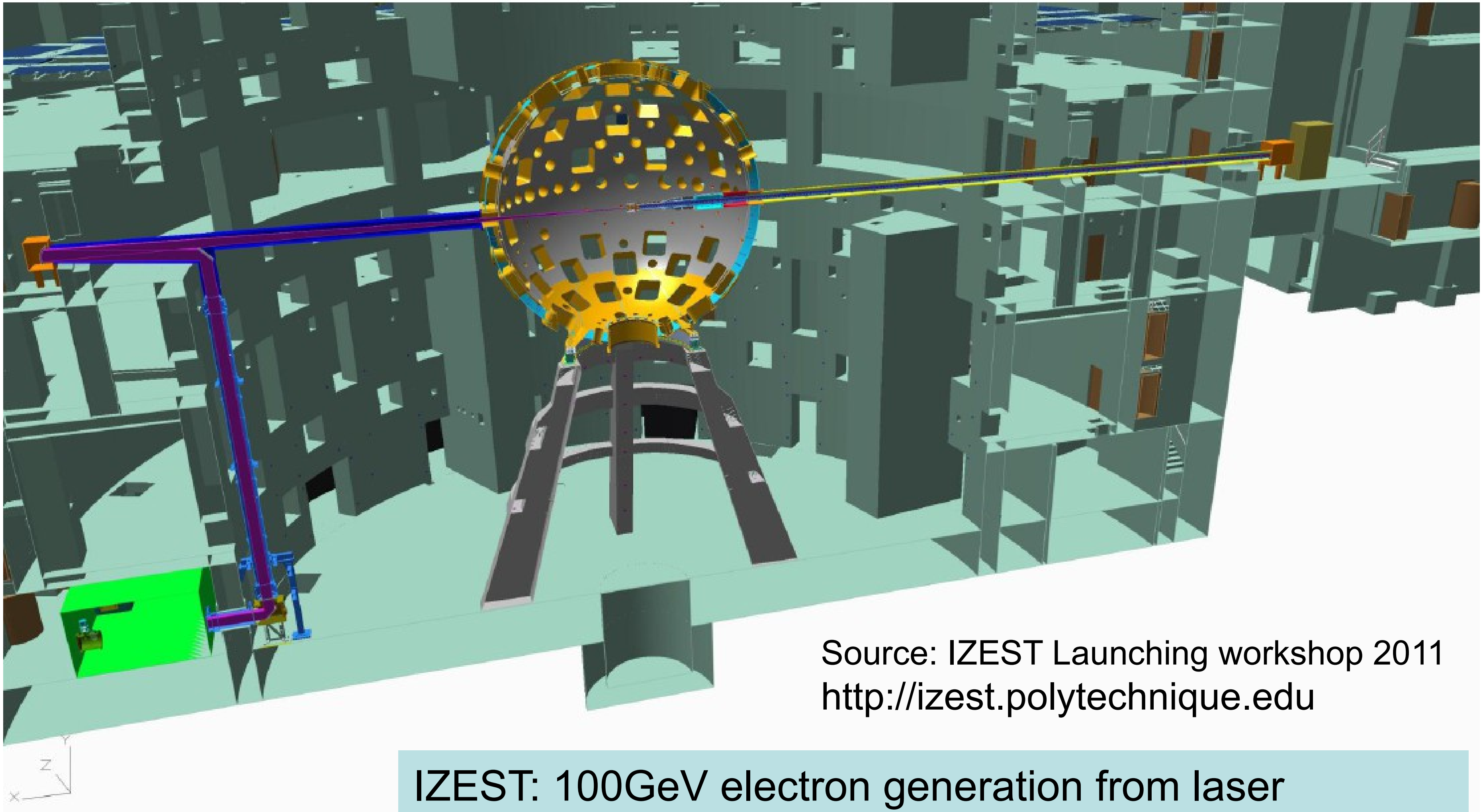
Remote sensing devices using lasers,
Lidar: for **L**ight **d**etection **a**nd **r**anging.

Source: Teramobile

Lightning control using lasers

Source: http://sparkingdawn.com

Self-guiding of intense lasers through a long distance is crucial for LWFA



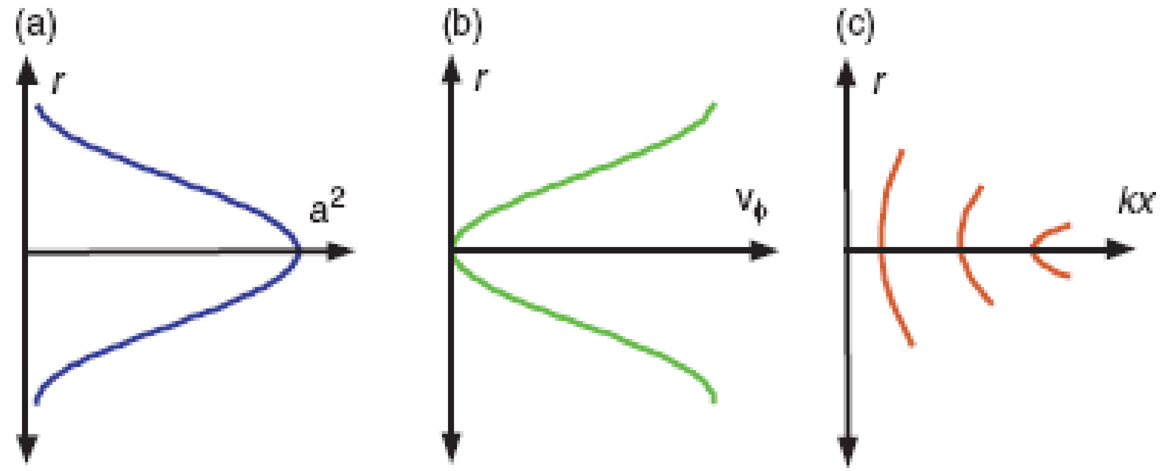
Source: IZEST Launching workshop 2011
http://izest.polytechnique.edu

IZEST: 100GeV electron generation from laser wakefield on PETAL
PETAL: 3.5 kJ, 1053 nm, 0.5 ~10 ps

Self-focusing of lasers in plasma

$$\eta = \sqrt{1 - \frac{4\pi e^2 n_e}{\gamma m_e \varpi_0^2}}$$

$$v_\phi = c/\eta$$



Diffraction spreading

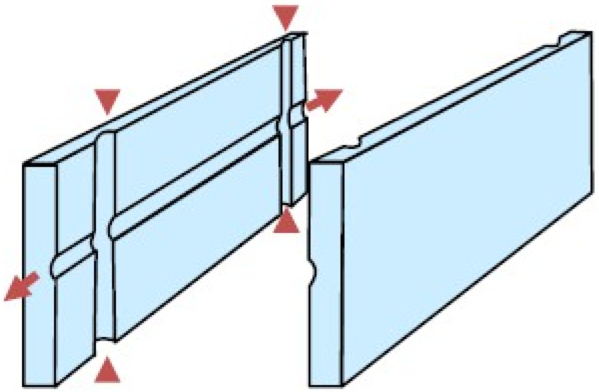
$$\left[\nabla_\perp^2 + 2ik\frac{\partial}{\partial z}\right] a = -\frac{\omega_p^2}{c^2}\frac{|a|^2}{4} a$$

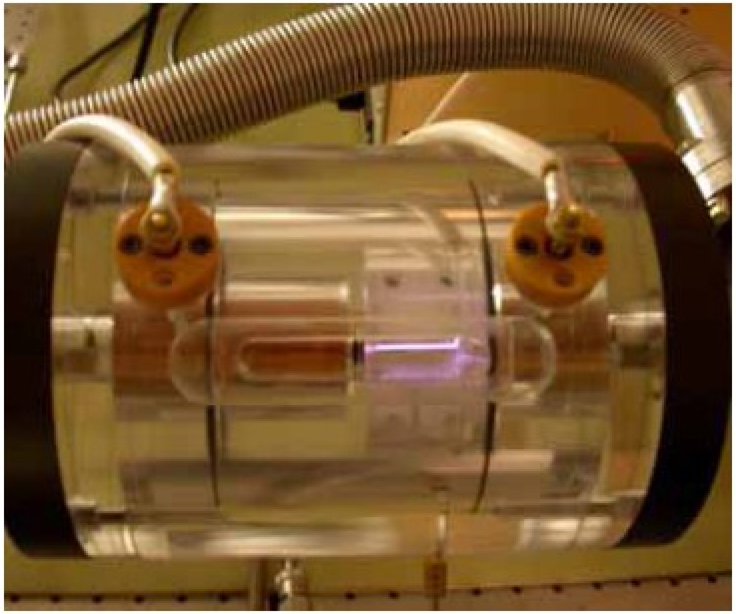
Relativistic and ponderomotive effects

- Usually both relativistic effect (change of electron mass m_e) and transverse ponderomotive force (change of electron density n_e) may lead to laser self-focusing in plasma.

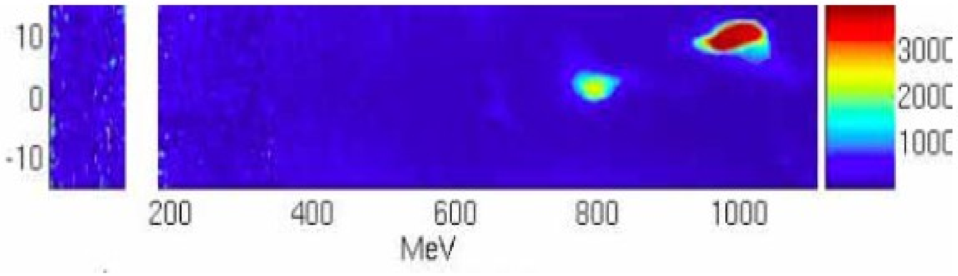
- When $P_0 > P_c = 17(n_c/n_e)$GW, relativistic self-focusing can overcome defocusing, according theory in the weakly relativistic case.

Channels and lasers of ten Pc often adopted in LWFA





GeV beams from gas-filled capillary at LBNL-Oxford



Laser: 40TW 37fs (a=1.4)
Capillary: 312μm diam. , 33mm length
Plasma n_e: 4.3×10^{18} cm^{-3}

W.P. Leemans et al., Nature Physics 2, 696 (2006);

D. J. Spence et al. Phys. Rev. E 63 015401(R) (2001)

Does the self-focusing criterion hold for PW lasers?

■ **Current situation (<=100 TW or a few and ten P_c)**

(a) $P_c = 17(n_0/n_c)$ (GW) is broadly adopted in LWFA designs

(b) Ponderomotive force helps self-focusing

(c) Plasma channels help laser guiding

■ **Our results for PW lasers or tens or hundreds of P_c**

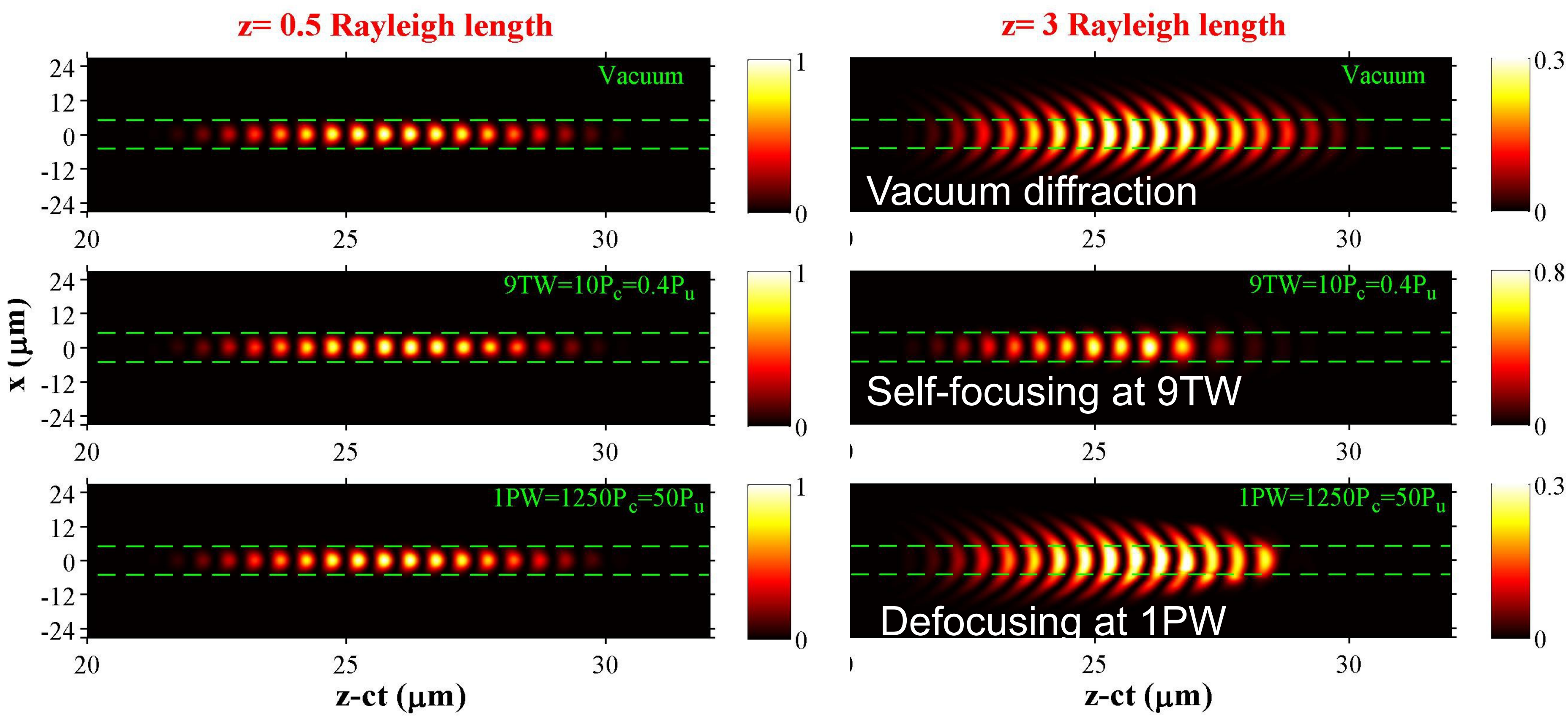
(a) $P_0 > P_c$ is not the enough criterion and there is an upper-limit power P_u, i.e., $P_c < P_0 < P_u$

(b) Ponderomotive force helps defocusing when $P_0 > Pu$

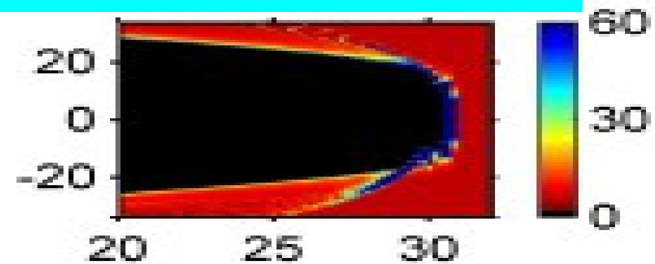
(c) Plasma channels are unfavorable for laser guiding when $P_0 > Pu$

Ponderomotive defocusing of PW lasers (far above P_c)

(2D PIC simulations)



Electron density at 0.5 z_R

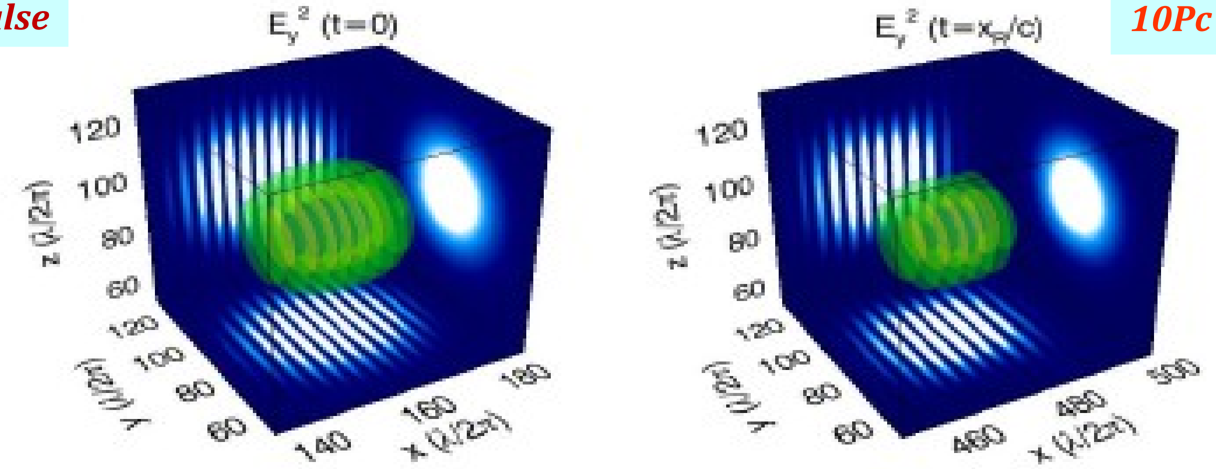


Defocusing is found even for PW lasers, even though self-focusing is found at 9TW.

Similar results are found in 3D PIC simulations

Initial pulse

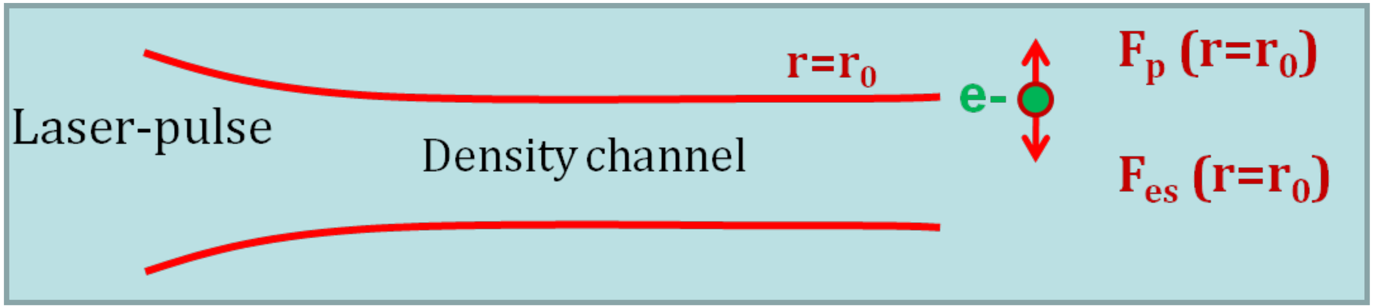
Self-focusing with 10Pc (9.2TW) at z_R



W-M Wang, Z-M Sheng et al., submitted

Both 2D and 3D PIC simulations indicate there is an upper-limit power in addition to the well- known lower-limit critial power Pc= $17(n_0/n_c)$ (GW) **for self-focusing**

Upper-limit power P_u for self-focusing or power threshold for ponderomotive defocusing



Self-guided propagation requires

$$\mathbf{F}_p(r = r_0) + \mathbf{F}_{es}(r = r_0) = 0$$

F_p: transverse ponderomotive force

F_{es}: transverse electrostatic force

r_0: laser beam radius

Upper-limit power P_u for self-focusing or power threshold for ponderomotive defocusing

$$\mathbf{F}_p(r = r_0) + \mathbf{F}_{es}(r = r_0) = ($$

===> $P_u^{3D} =$ $n_0 r_0^4$ [redacted] $n_c \lambda^4$ 3.1 TW **3D geometry**

$P_u^{2D} = 2P_u^{3D}$ **2D slab geometry**

Note that:

$P_c^{3D} = 17(n_c / n_0)$ GW **3D geometry**

P_c^{2D} P_c^{3D} [redacted] $\sqrt{2}$ **2D slab geometry**

P_c: due to the relativistic effect

P_u: due to the ponderomotive force

Lower-limit density n_L for self-focusing

- **For laser self-guiding, it is required that the laser power P satisfies: $P_c<P_0<P_u$**

$P_c<P_u$ => $n_0>0.074n_c(\ ^2/r_0^{\ 2})$

- **A lower-limit density for self-guiding**

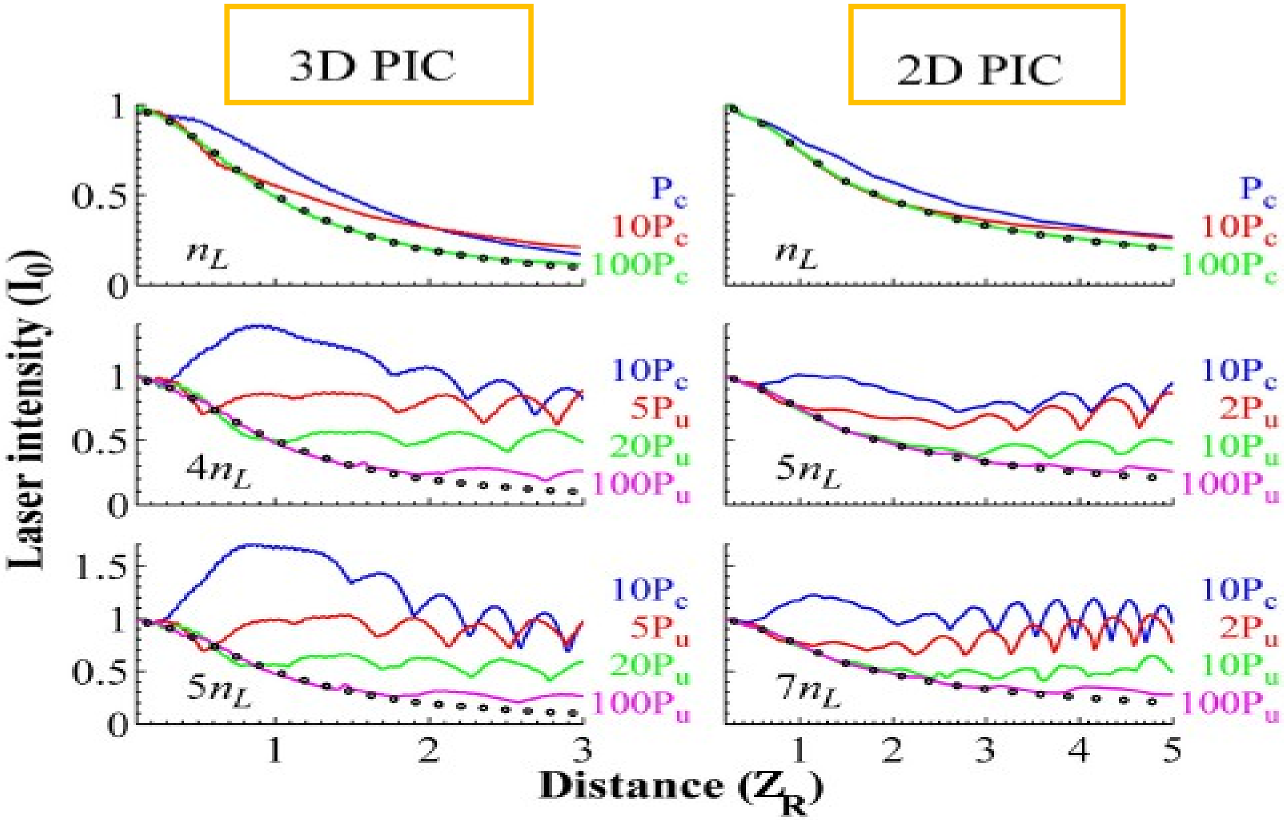
$$n_L = \frac{\lambda^2}{r_0^2} \times 0.074 n_c$$ **3D geometry**

$$n_L = \frac{\lambda^2}{r_0^2} \times 0.044 n_c$$ **2D slab geometry**

- **The relation of Pu and Pc in terms of n_0 and n_L**

$$P_u = \frac{n_0}{n_L}{}^{2}\; P_c$$ **2D or 3D geometry**

Verification of n_L and P_u by PIC simulations



r_0=4um

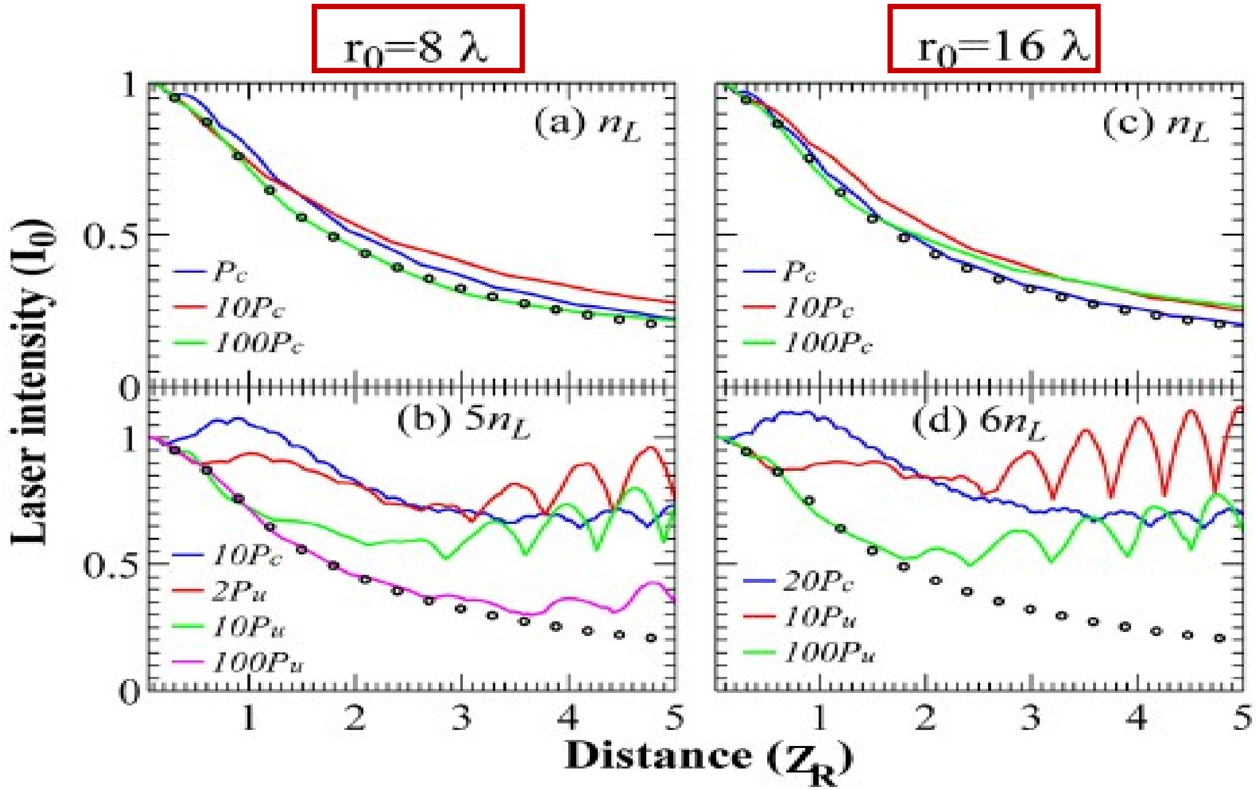
λ=1um

1) $n_0 \leq n_L$, self-focusing never occurs with any laser power;
$n_0 = 4n_L$, self-focusing starts to appear with $P_0 = 10P_c$

2) $P_0 = 5P_u$, ponderomotive defocusing starts to appear obviously;
increasing P_0, the curve approach to the vacuum case

3) 2D results are similar ($4n_L \rightarrow 5n_L$, $5P_u \rightarrow 2P_u$)

2D PIC simulations with larger beam radius r_0

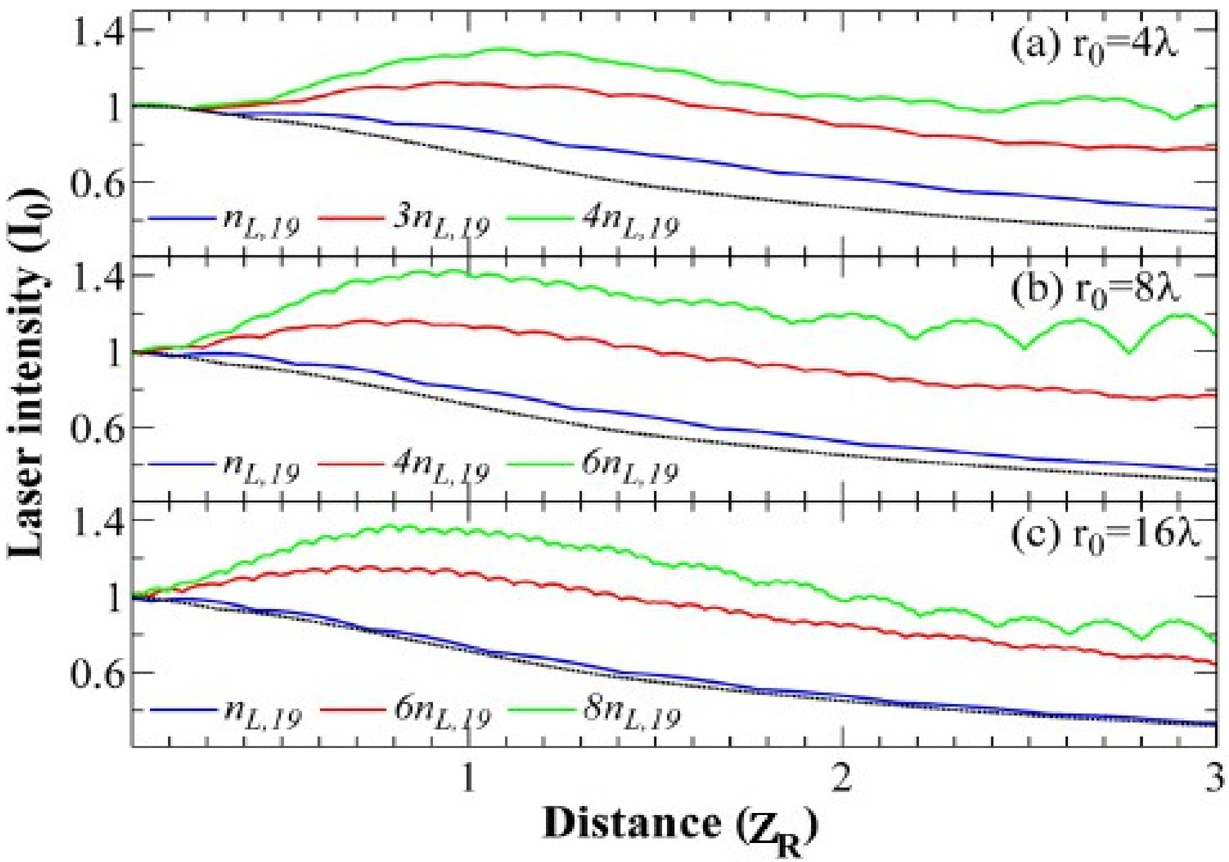


- ***With $n_0=5n_L$ and $6n_L$, self-focusing starts to appear for $r_0=8$ and 16 um***
- ***With $P_0=2P_u$ and 10 P_u, defocusing starts to appear obviously***
- ***Our theory model agrees with simulation better with smaller r_0***

Further examination with given I_0

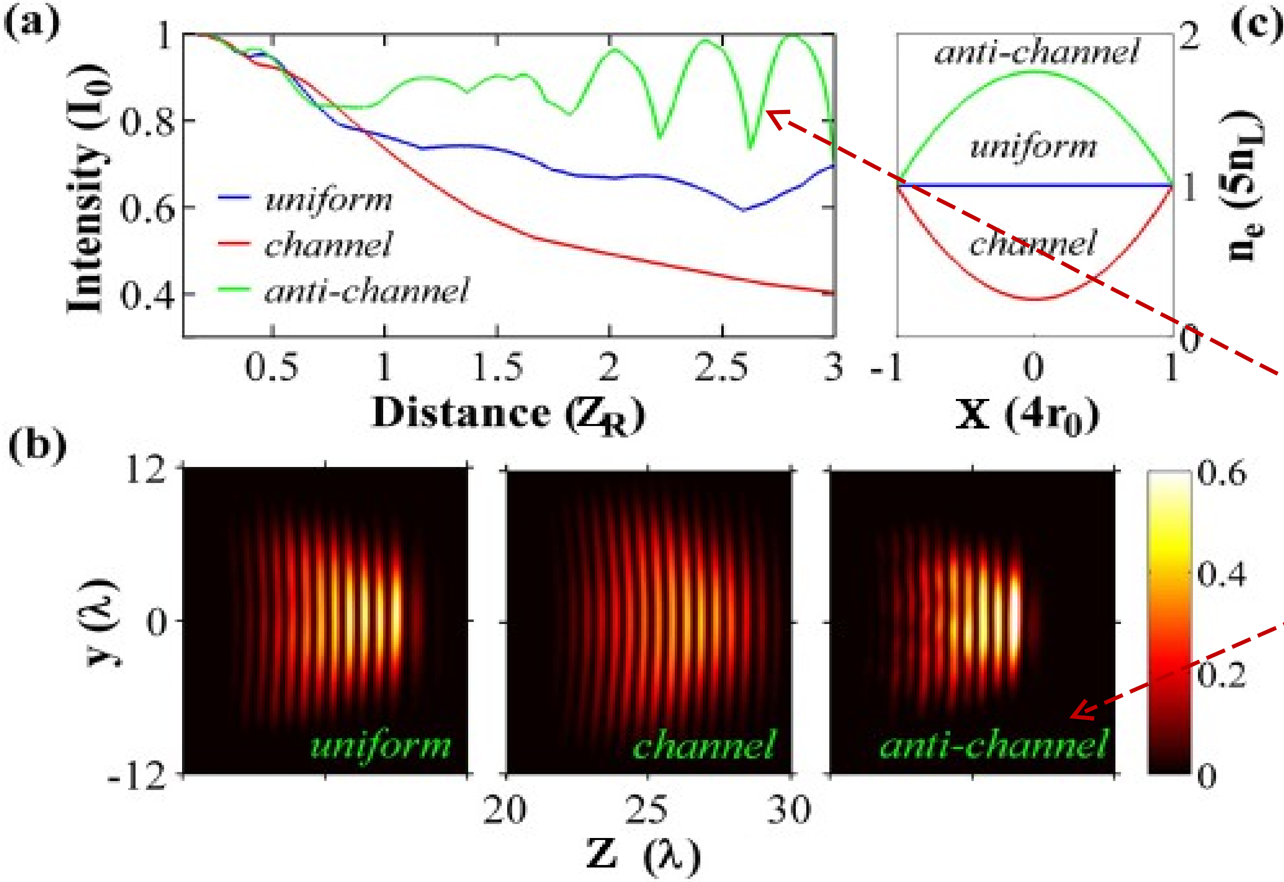
$$P_c \le P_0 \le P_u \Rightarrow \begin{array}{l} n_{L,19} = 0.077 n_c(\lambda^2/r_0^2), \; I_0 = 10^{19}\ \mathrm{Wcm^{-2}} \\ n_{L,21} = 2.5 n_c(\lambda^2/r_0^2), \; I_0 = 10^{21}\ \mathrm{Wcm^{-2}} \end{array}$$

For a given laser intensity, a lower limit density is required for self-guiding.



$I_0 = 10^{19} Wcm^{-2}$

A plasma anti-channel may be preferred for self-guided propagation at high power over Pu



$P_0=2P_u$
$n_0=5n_L$
$r_0=4um$
$\lambda=1um$

Laser pulse in an anti-channel is better for self-guided

This agrees with our theory that there is a lower limit plasma density and higher density is favorable at high laser powers.

Summary

■ We demonstrate that transverse ponderomotive force may lead to defocusing at high laser powers, e.g., PW lasers.

■ Power threshold for ponderomotive defocusing or upper-limit power for self-focusing P_u is given as a function of n_e and r_0. For self-guided propagation, the laser power P should satisfy $P_c<P_0<P_u$

■ A lower-limit density n_L for self-guiding is given.

■ With $P_0>P_u$, a plasma channel is not favorable for laser self-guiding. Instead, an anti-channel may be preferred.

Thank You !