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

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Outline

- Motivation: why do we need self-guided propagation of intense lasers
- Relativistic self-focusing threshold
- Ponderomotive force effect: upper limit power and lower limit plasma density
- Anti-plasma channel for self-guided propagation?
- Summary

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

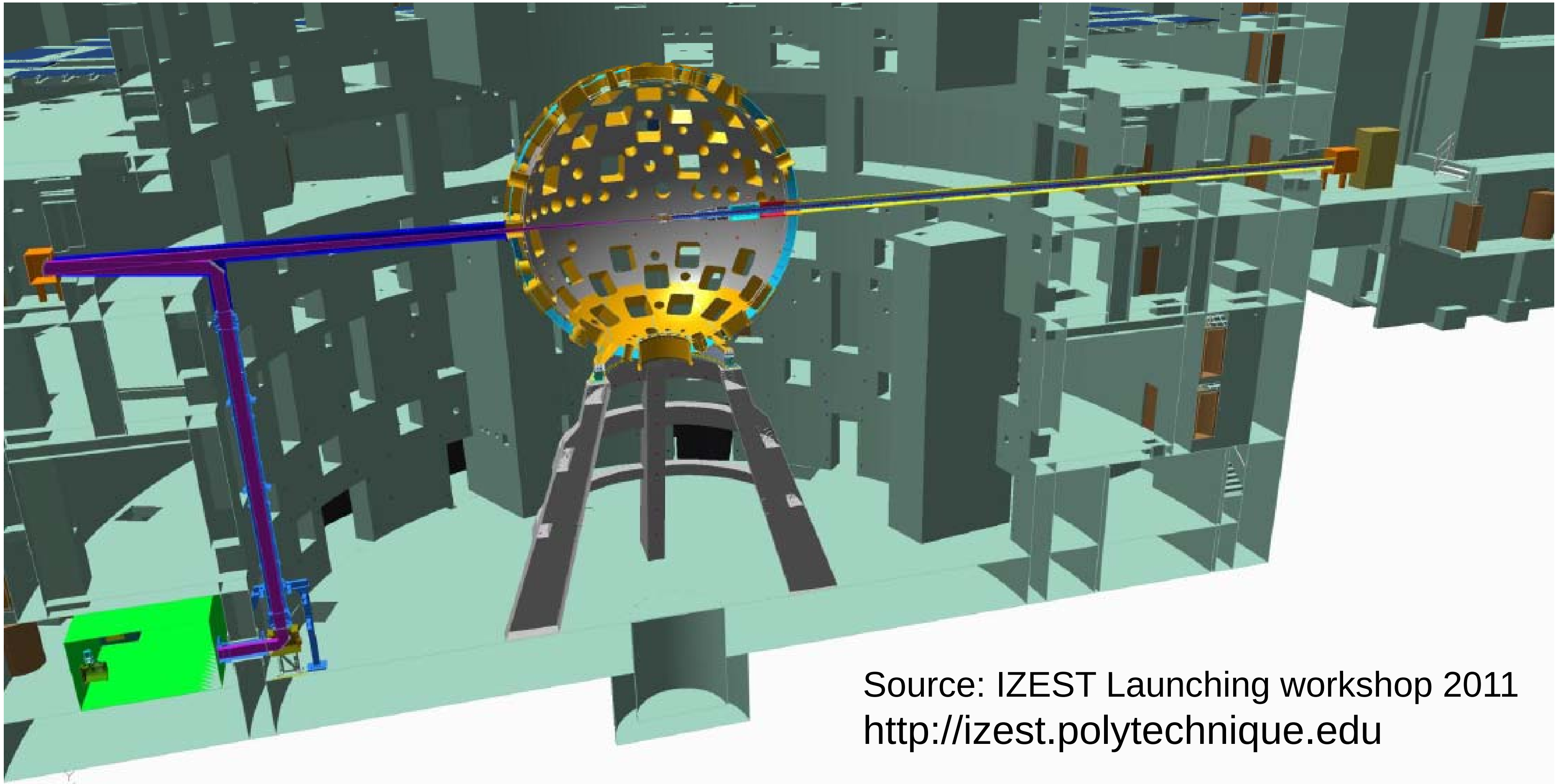
Remote sensing devices using lasers,
Lidar: for **Li**ght **d**etection **a**nd **r**anging.

Source: Teramobile

Lightning control using lasers

Source: http://sparkingdawn.com

Self-guiding of lasers is crucial for many applications



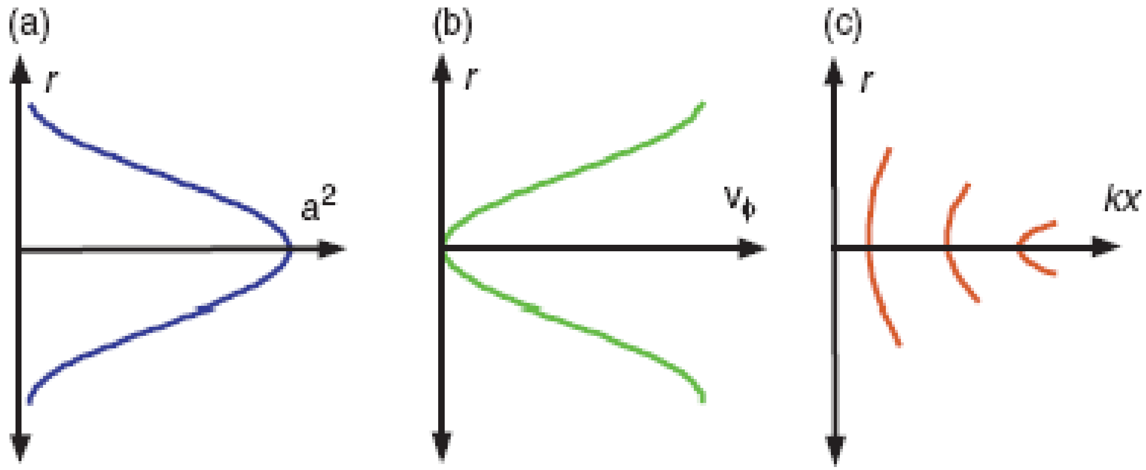
Source: IZEST Launching workshop 2011
http://izest.polytechnique.edu

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 self-focusing

- **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-guiding 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.**

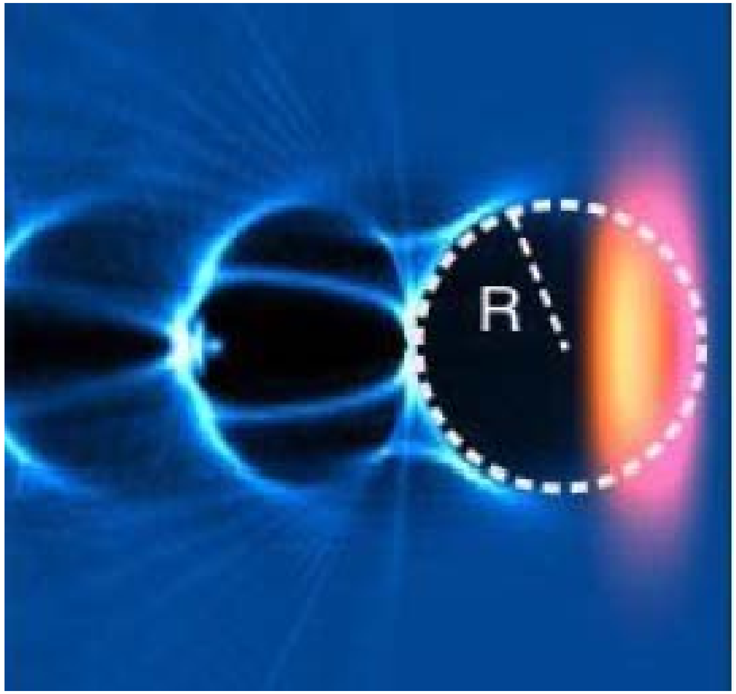
Self-guiding in laser wakefield acceleration

Matched beam spot size in the bubble regime or blowout regime:

$$\boxed{k_p R \simeq k_p w_0 = 2\sqrt{a_0}.}$$

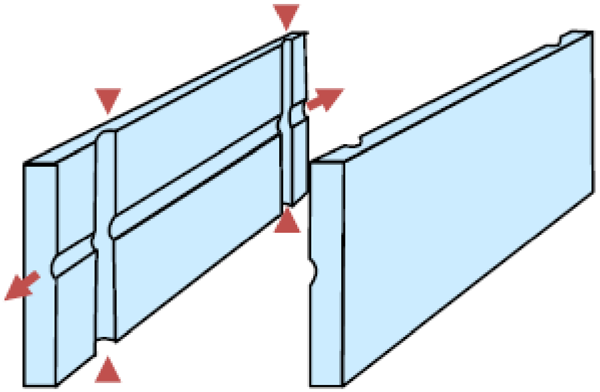
$$a_0 \simeq 2(P/P_c)^{1/3}$$

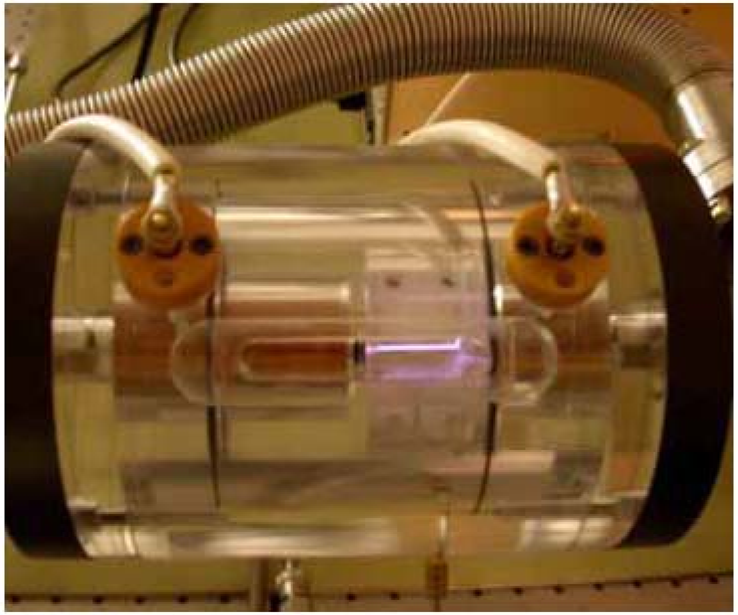
R: the blowout radius
w_0: the laser spot radius
k_p: the plasma wave vector
a_0: the normalized laser peak amplitude
P_c: = $17(n_e/n_c)$ (GW)



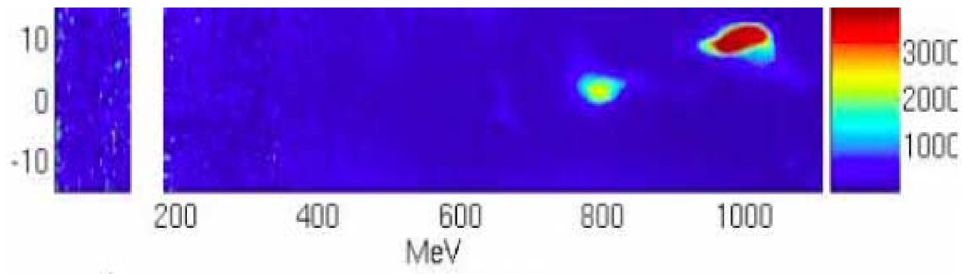
W. LU *et al. Phys. Rev. ST Accel. Beams* ***10, 061301 (2007)***

Plasma channels are often adopted





GeV beams from gas-fill 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);

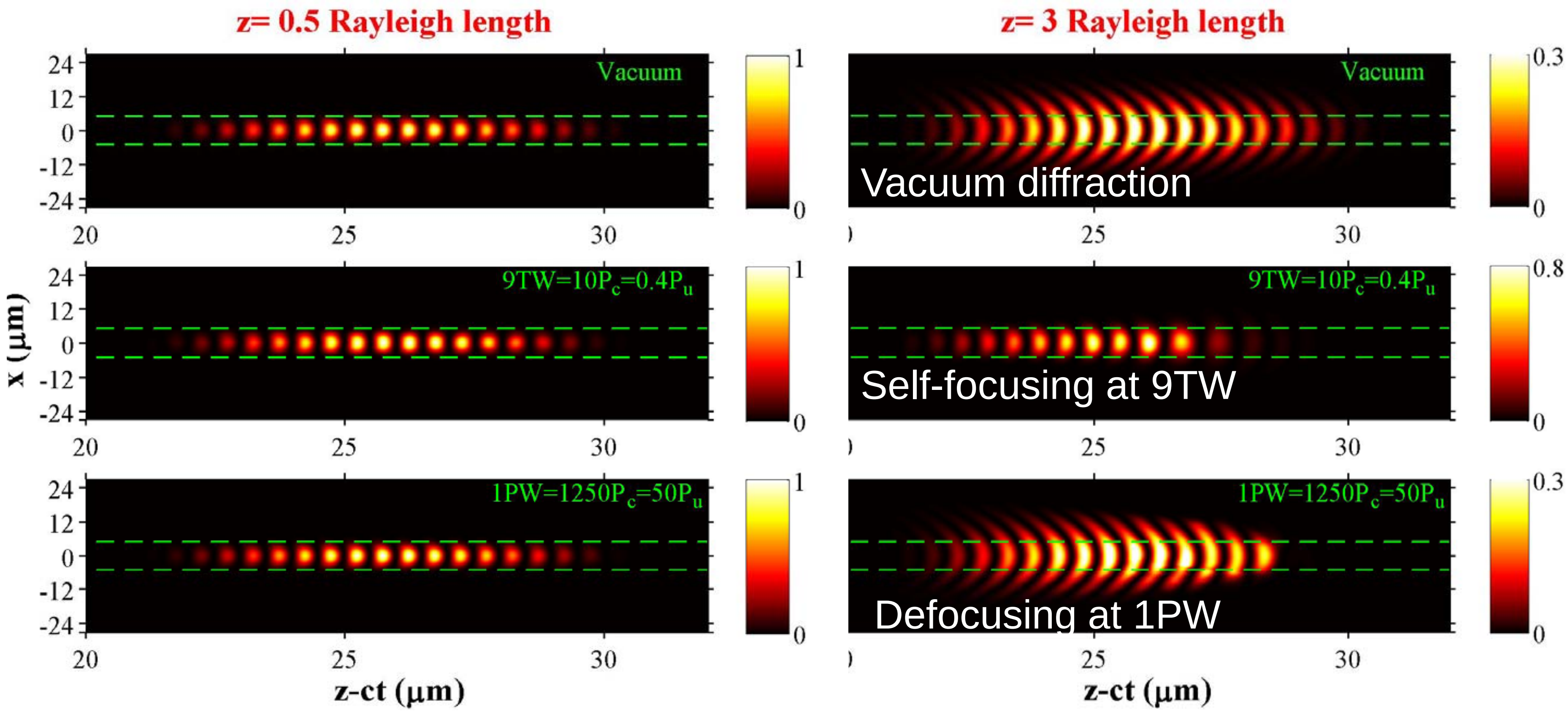
D. J. Spence et al. Phys. Rev. E 63 015401(R) (2001)

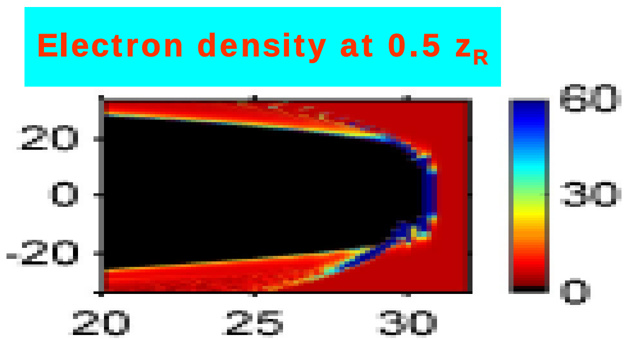
Does the self-focusing criterion holds for PW lasers?

- **Current situation (<=100 TW for most experiments)**
  (a) $P_c = 17(n_e/n_c)$ (GW) is broadly adopted in LWFA designs and experiments, and confirmed in simulations;
  (b) General view: ponderomotive force helps focusing, which produces channel-like plasma density distributions. Often one generates such preformed channels for laser guiding

- **What about for PW lasers or tens or hundreds of P_c for future experiments? Our results indicate that**
  (a) Ponderomotive defocusing may occur
  (b) $P>P_c$ is not enough for self-focusing and there is upper limit power P_u for self-focusing, i.e., $P_c<P<P_u$

Ponderomotive defocusing of PW lasers (far above P_c) (2D PIC simulations)

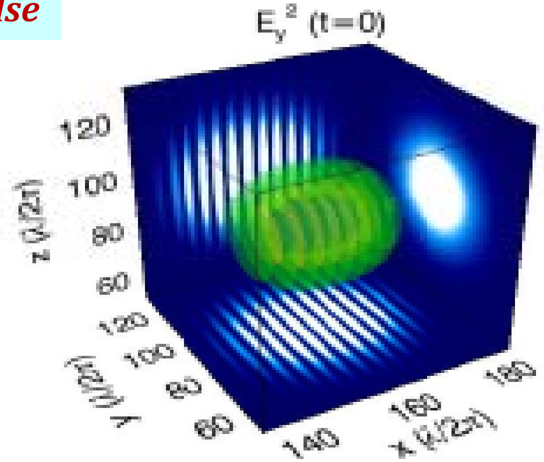




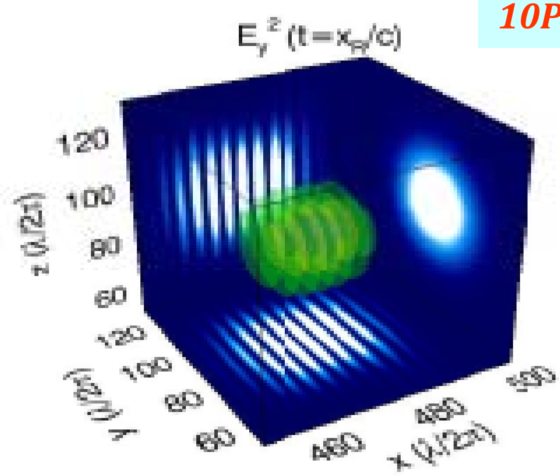
Defocusing is found even for PW lasers, even though self-focusing is found at 9TW.

Similar results are found in 3D PIC simulations

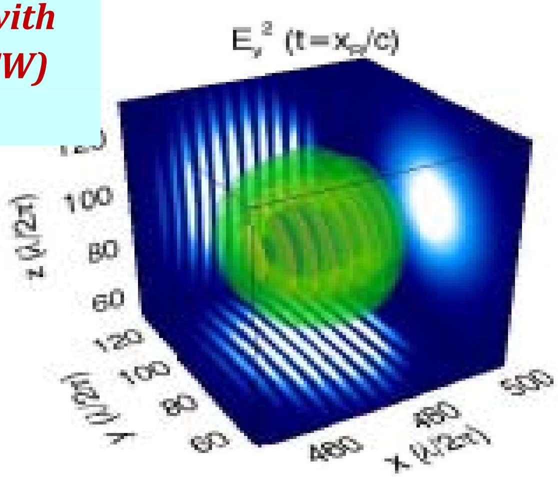
Initial pulse



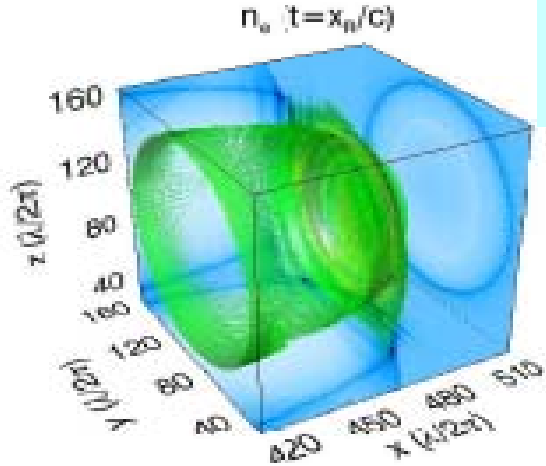
Self-focusing with 10Pc (9.2TW) at z_R



Defocusing with 320Pc (294TW) at z_R



Electron density with 320Pc (294TW) at z_R



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

Similar results are found in 3D PIC simulations

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

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

Self-guided propagation requires

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

F_p: transverse ponderomotive force
F_{es}: transverse Coulomb force
r_0: laser beam radius,
Laser: $e\mathbf{A}/mc^2 = \hat{\mathrm{e}}_y a_0 \sin(\pi\xi/\tau_0)\sin(\omega\xi)\exp(-r^2/r_0^2)$

$$\vec{F}_p = -mc^2\nabla_\perp\gamma, \qquad \vec{F}_{es} = -\hat{e}_r 2\pi n_0 e^2$$

$$\gamma \approx 1 + a^2/2 \quad \text{or} \quad (1+a^2)^{1/2}$$

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

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

$$\Longrightarrow \quad P_u^{3D}=\frac{n_{e0}r_0^4}{n_c\lambda^4}\times 3.1\ \text{TW}$$

3D geometry

$$P_u^{2D}=2P_u^{3D}$$

2D slab geometry

Note that:

$$P_c^{3D}=17(n_c/n_{e0})\ \text{GW}$$

3D geometry

$$P_c^{2D}\rightarrow P_c^{3D}\big/\sqrt{2}$$

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: $P_c<P<P_u$

$$P_c<P<P_u \quad \Rightarrow \quad n_{e0}>0.074n_c(\lambda^2/r_0^2)$$

- A lower-limit density for self-guiding

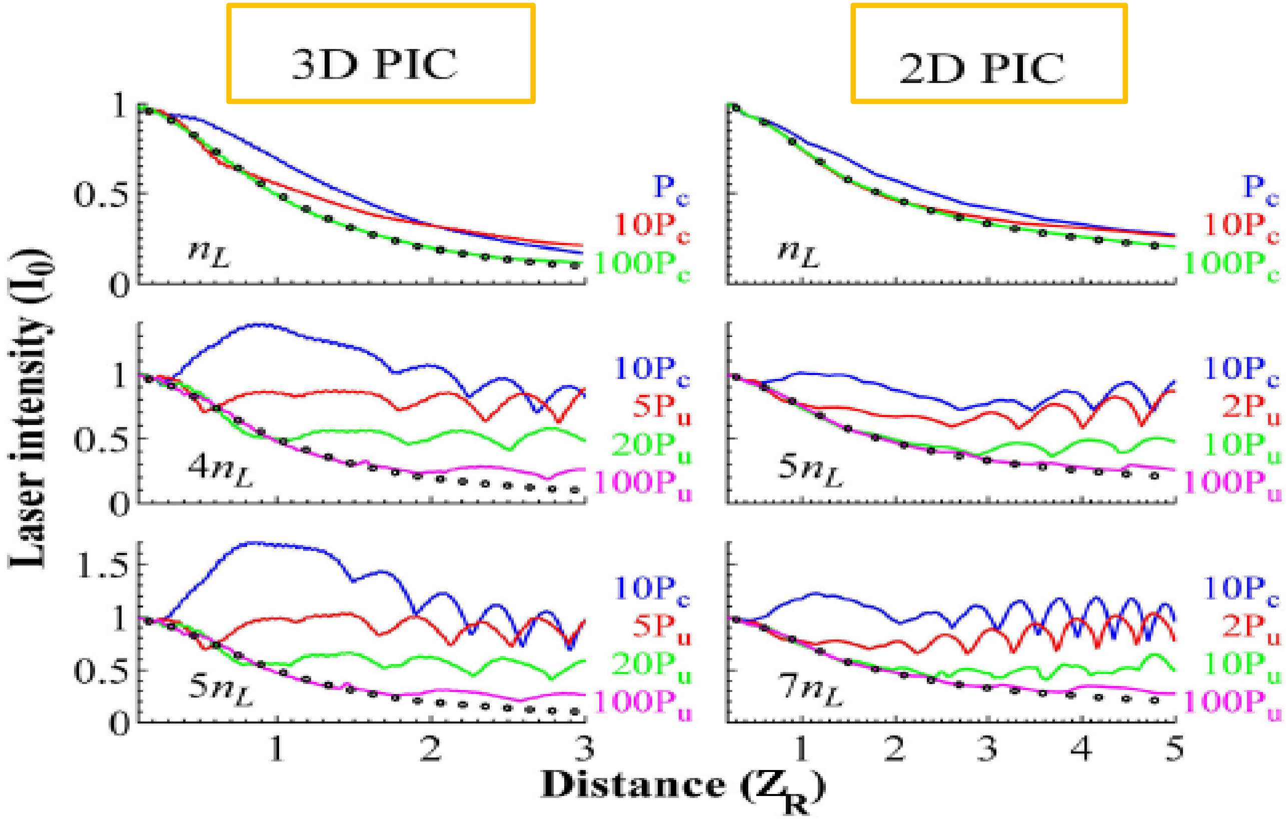
$$n_L = \frac{\lambda^2}{r_0^2} \times 0.074 n_c$$ **3D geometry**

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

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

$$P_u = \left(\frac{n_{e0}}{n_L}\right)^2 P_c$$ **2D or 3D geometry**

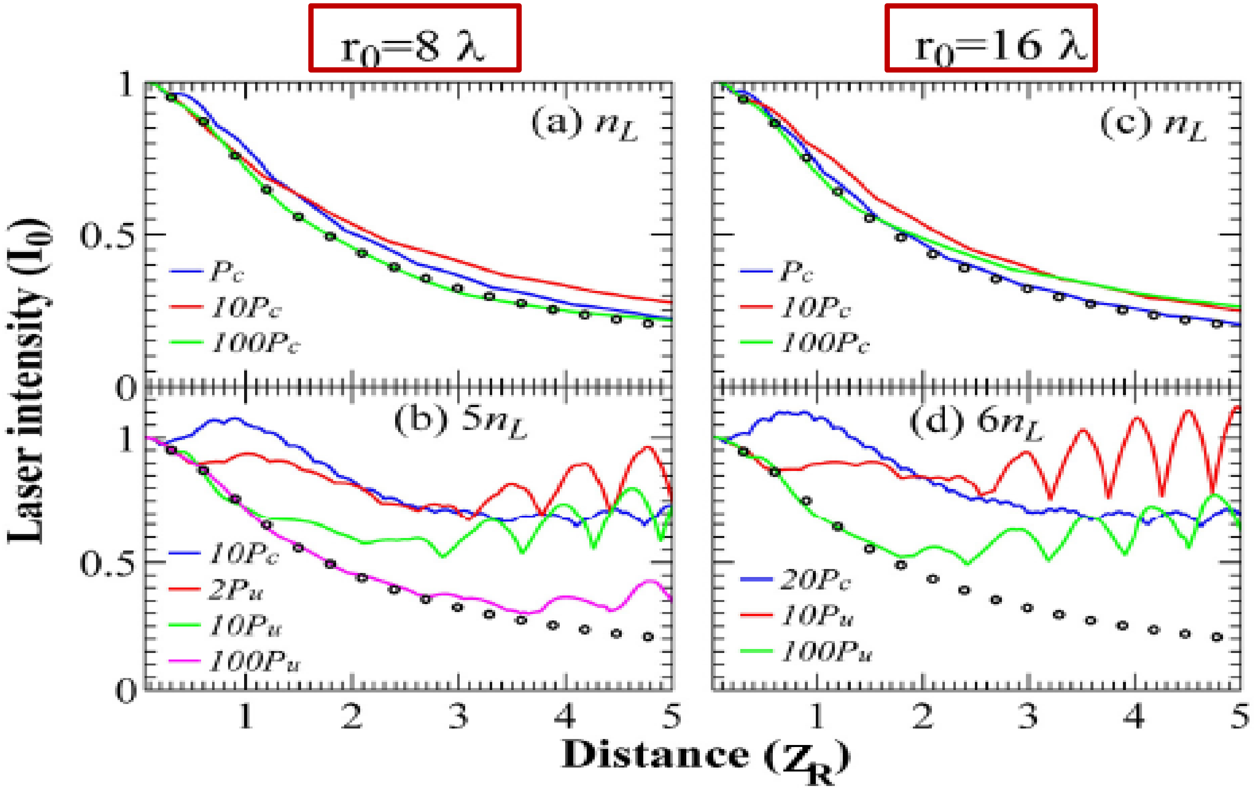
Verification of n_L and P_u by PIC simulations



r_0=4um
λ=1um

1) $n_e \le n_L$, self-focusing never occurs with any laser power;
$n_e=4n_L$, self-focusing starts to appear with $P_0=10P_c$
2) $P_0=5P_u$, ponderomotive-force defocusing starts to appear obviously;
increasing P_0, the laser approaches to the propagation in vacuum
3) 2D PIC results are similar ($4n_L \to 5n_L$, $5P_u \to 2P_u$)

2D PIC simulations with larger beam radius r_0



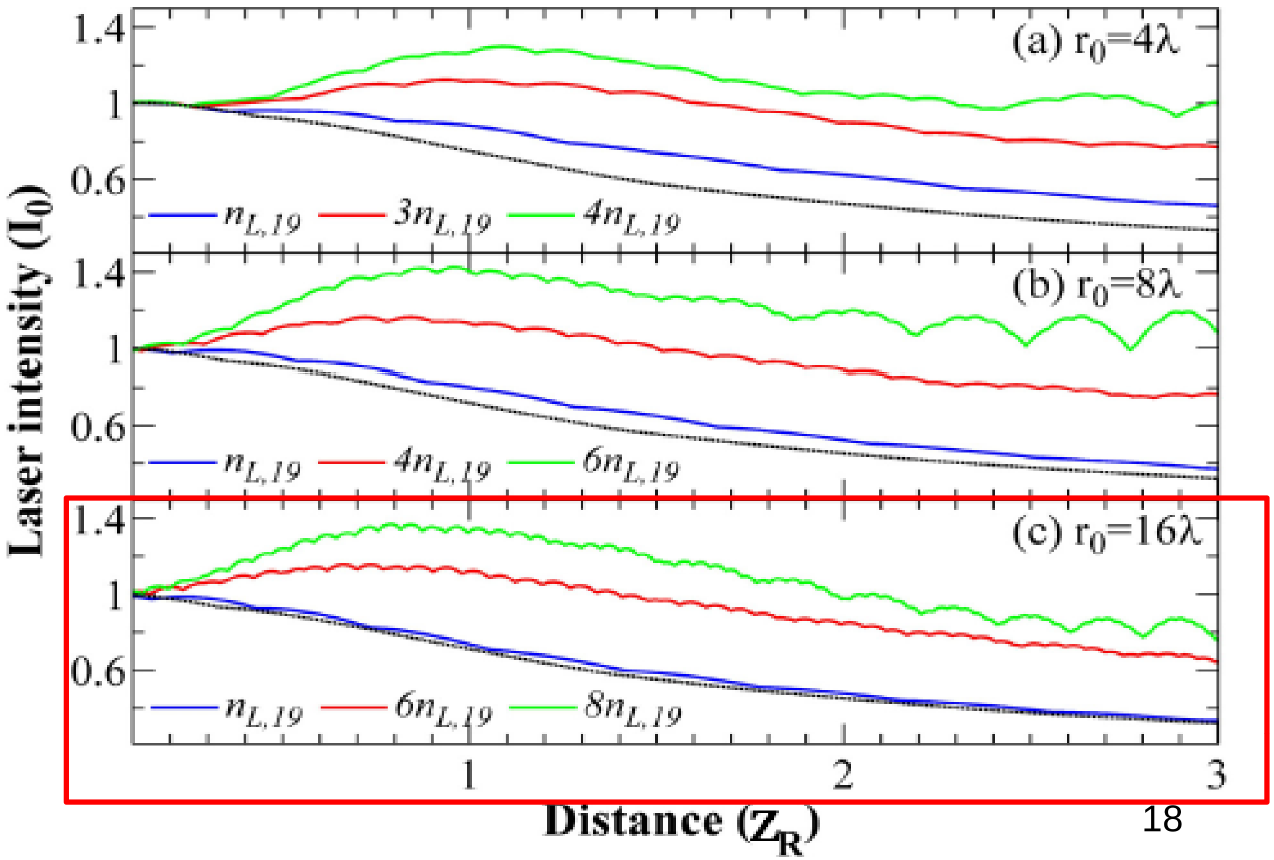
- *With n_{e0}=5n_L and 6n_L, self-focusing starts to appear for r_0=8 and 16 um*
- *With P_0=2P_u and 10 P_u, defocusing starts to appear obviously*
- *Our theory model agrees with simulation better with smaller r_0*

Further examination with given I_0

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

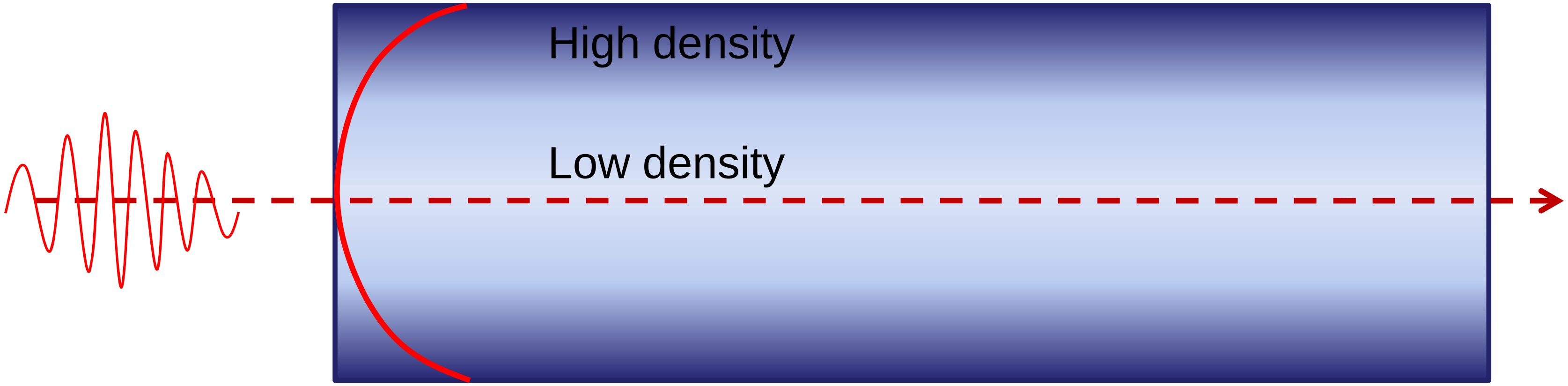
For a given laser intensity, higher densities are favorable for self-guiding.

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

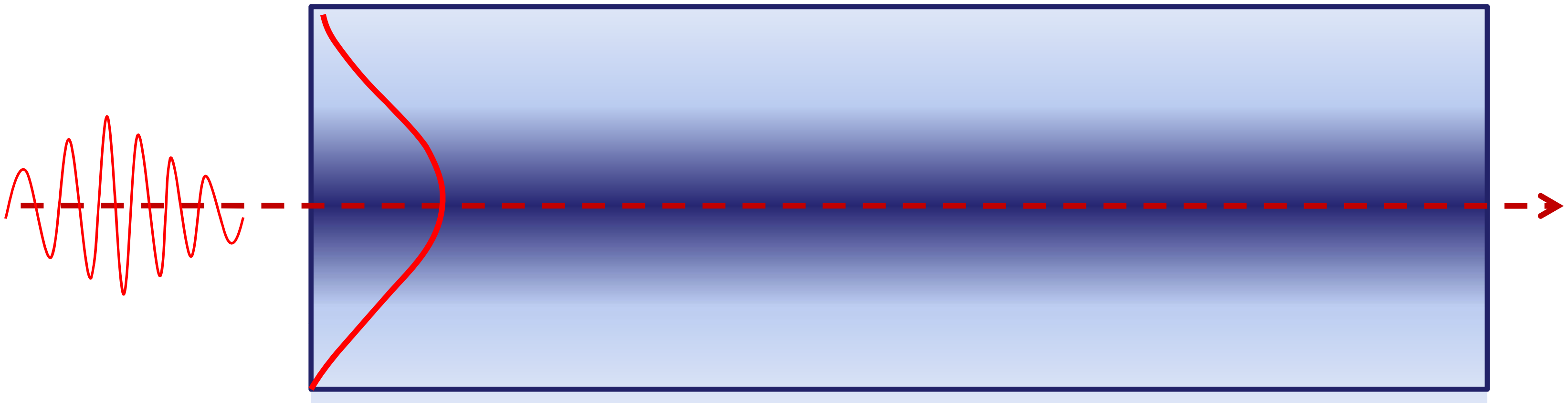


Effect of inhomogeneous plasma

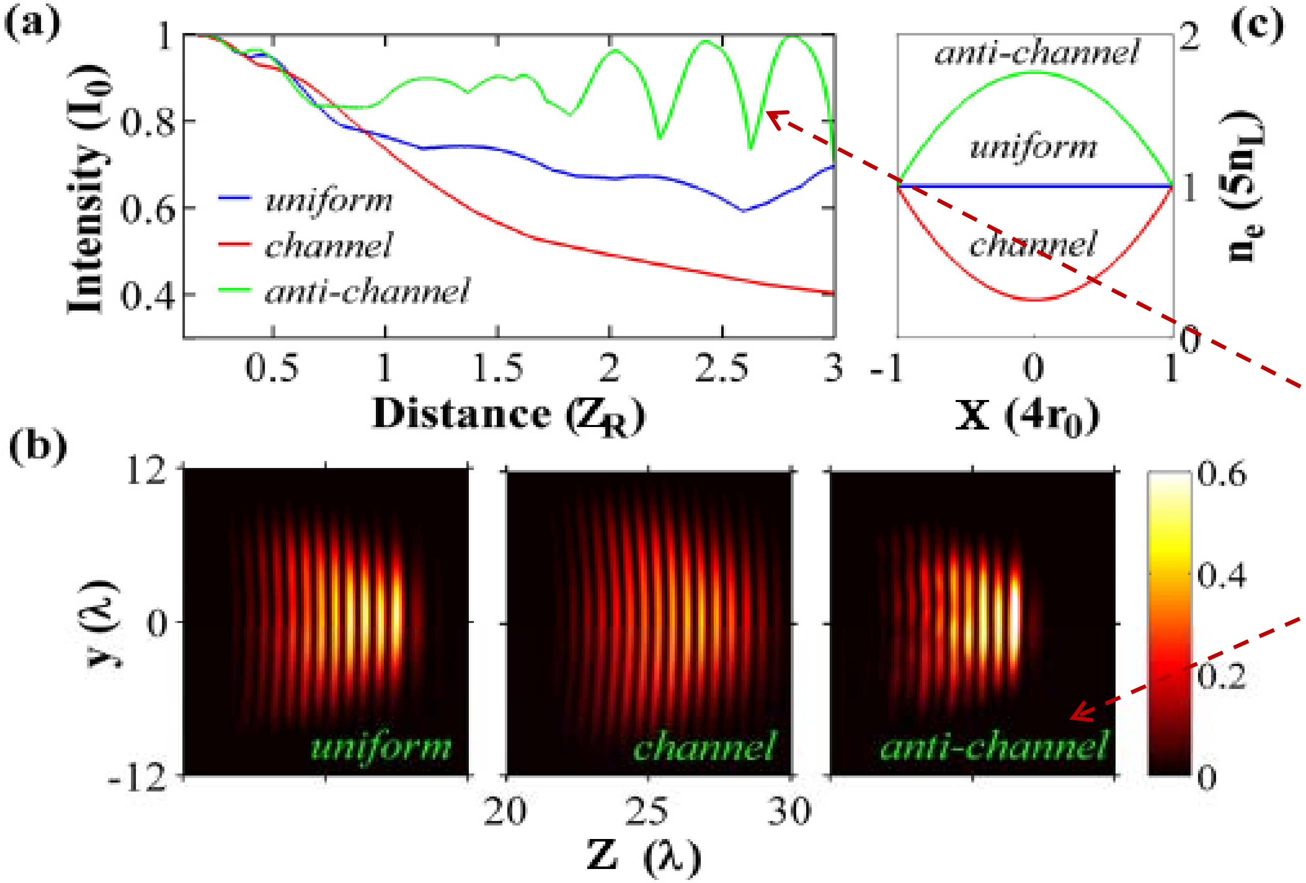
Case 1: normal plasma channel



Case 2: plasma anti-channel



A plasma anti-channel may be preferred for self-guided propagation at high peak power over 1PW



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

The laser pulse in an anti-channel is better self-guided

This agrees with our theory that there is a lower limit of the plasma density for self-guided propagation.

$P_c<P<P_u$ => $n_{e0}>0.074n_c(\lambda^2/r_0^2)$

Summary

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

■ **Power threshold for ponderomotive defocusing or an upper-limit power P_u for self-focusing is given as a function of initial plasma density n_{e0} and laser spot size r_0. In order to have self-guided propagation of laser pulses, the laser power P should satisfy $Pc<P<Pu$.**

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

■ **At or above PW with $P>P_u$, preformed plasma channels may be not favorable for laser self-guiding. In stead, an anti-channel may be preferred.**

Thank You !