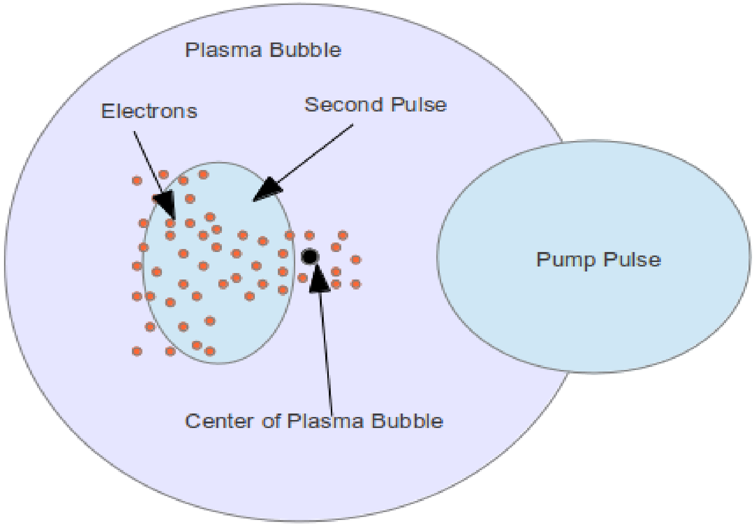
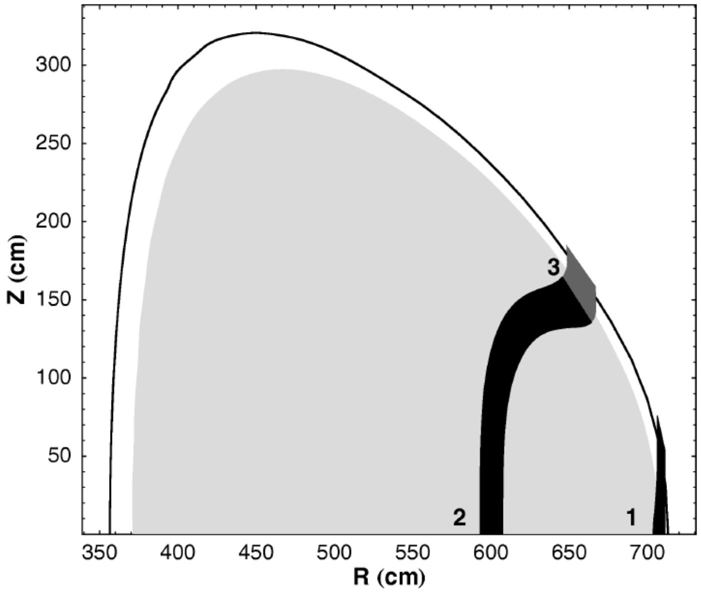
New and Emerging Concepts in Laser-Plasma Acceleration

or

how I learned that more waves is better than fewer

Gennady Shvets, The University of Texas at Austin



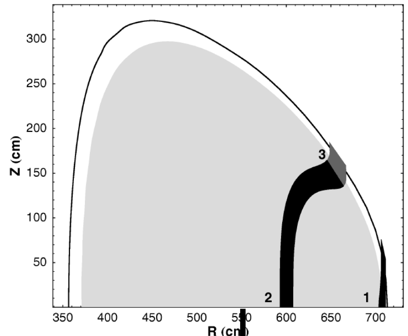


Solved and Unsolved Problems in Plasma Physics, March 28, 2016

The Timeline

Automatic doors into infinite corridor existed during Nat's time there

Alfven eigenmodes & ion Bernstein modes are both needed!



Discover that a tokamak is not a slab → all course work with B. Coppi is invalidated

1992

Meet Nat at the DPP, present an FEL poster on a concept that does not work

1993

MIT: apply for the DOE fellowship to work on alpha channeling

1995

α-channeling work starts on Feb.1, stops in March.

1997

Trip to Nizhny Novgorod → Nat practices his Russian on me and students

1998

Discovery of laser compression in plasma: at least three waves are needed!

2002

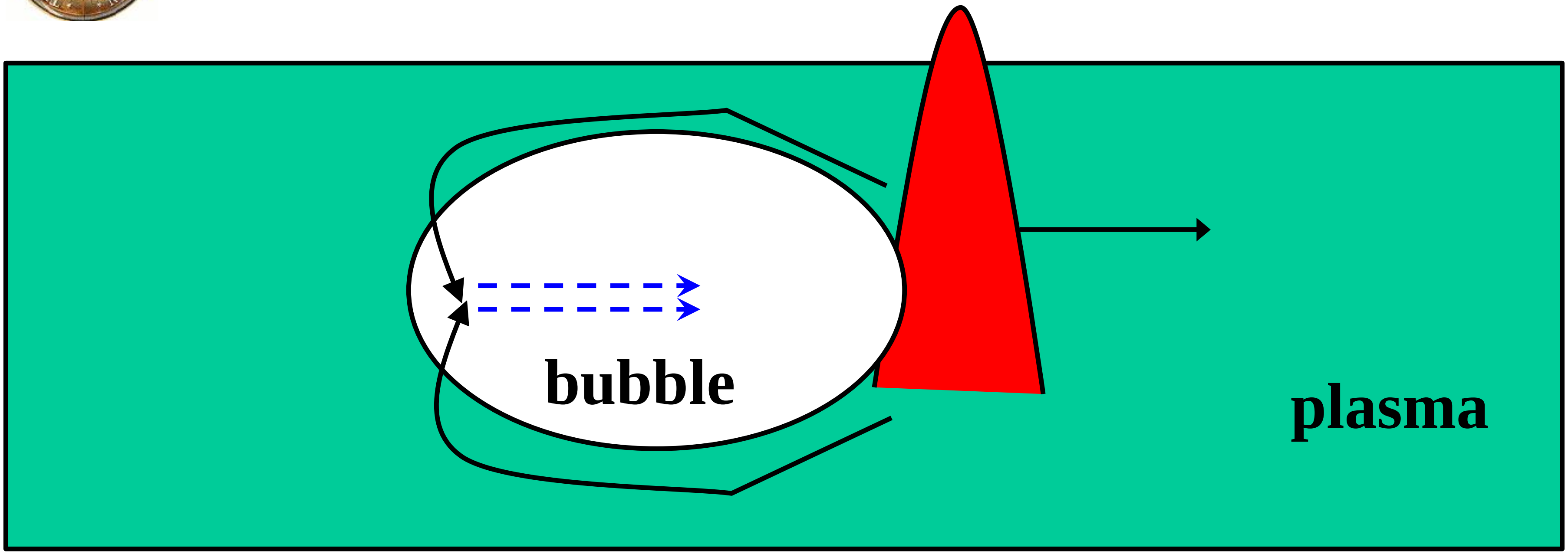
…

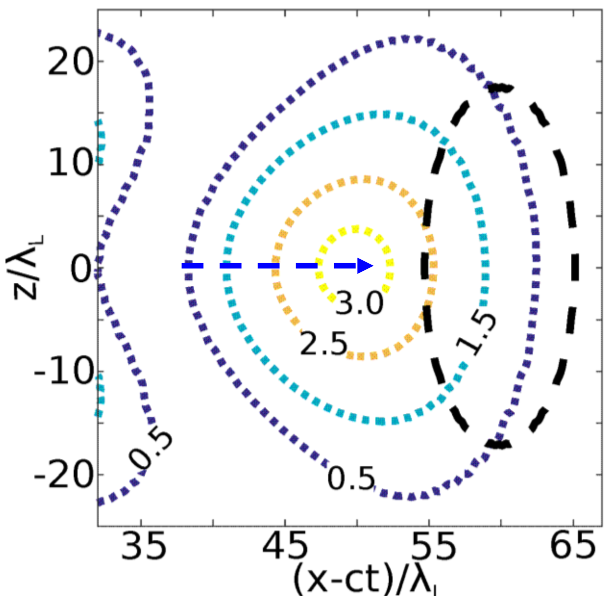
"We'll work on α-channeling and then figure something out"

"Fusion is very deep but not too broad; LP is very broad but not too deep"

"Engineers use fluid descriptions. Physicists go into the phase space!"

Plasma bubble: the workhorse



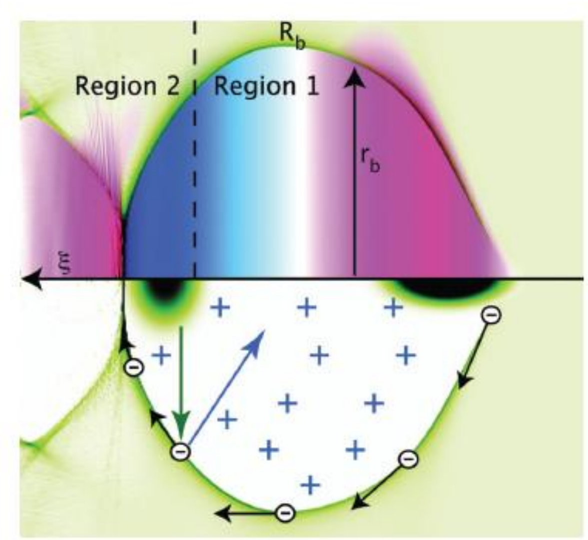


Particle advances inside bubble → gains energy from low-frequency electric field → energy gain is limited by dephasing

$$H_{MF} \approx \frac{p_x}{2\gamma_b^2} - \Psi \rightarrow \Delta p_x = 2\gamma_b^2 \Delta\Psi$$

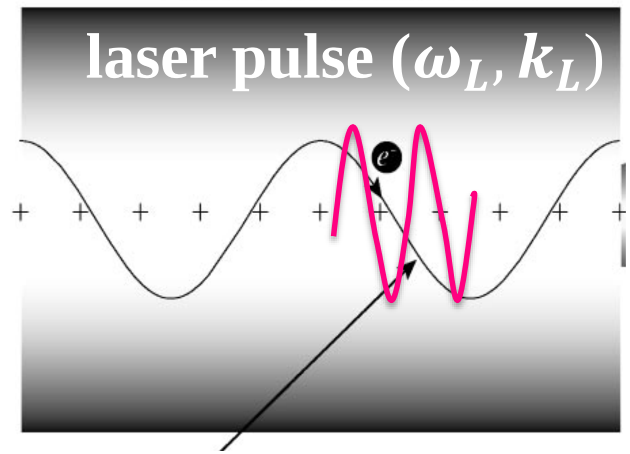
Can we do better??

Electrons motion inside the bubble and Direct Laser Acceleration



Electrons execute betatron motion with frequency ω_β

Transverse energy $\epsilon_\perp$ is reduced due to the conservation of the action $I_\perp = \epsilon_\perp/\omega_\beta$



Betatron motion

Betatron frequency

$$\omega_\beta = \omega_p/(2\gamma)^{1/2}$$

Transverse energy

$$\epsilon_\perp \equiv p_\perp^2/2\gamma m_e + \omega_p^2 m_e^2 z^2/4$$

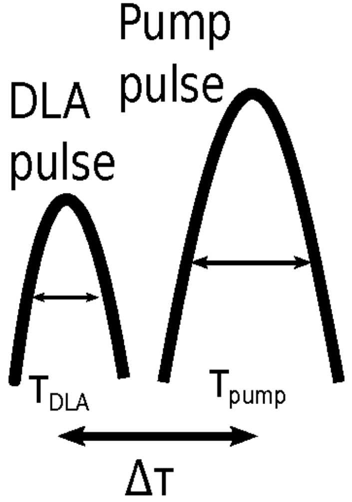
Break the adiabatic invariant by introducing an additional resonant laser pulse → DLA

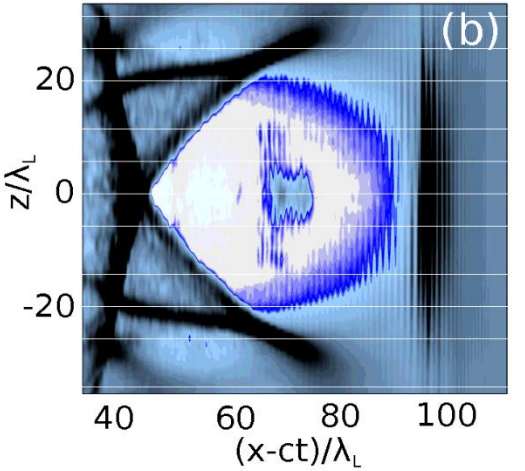
$$\omega_L - k_L v = (2n+1)\frac{\omega_p}{\sqrt{2\gamma}}$$

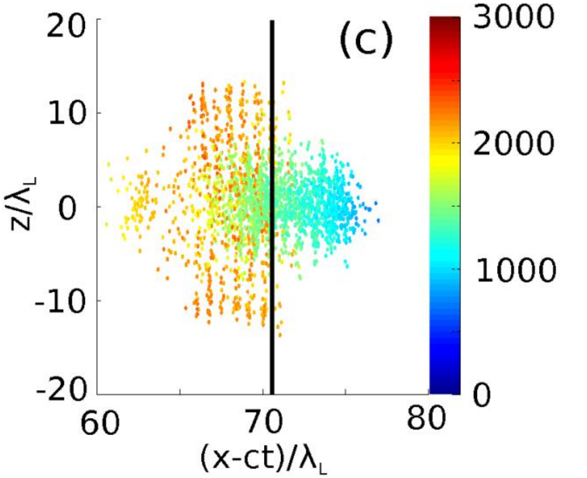
$$\Delta\gamma = \frac{\Delta\epsilon_\perp/mc^2}{1 - c/v_{ph}}$$

Outline of the Talk

- How LWFA and DLA can work together, delay dephasing, and bifurcate the phase space
- How to inject electrons into the plasma bubble and have them experience synergistic DLA/LWFA
- Constant gradient DLA in the decelerating phase of the wake
- Mix-and-match: combining multiple lasers for DLA + LWFA







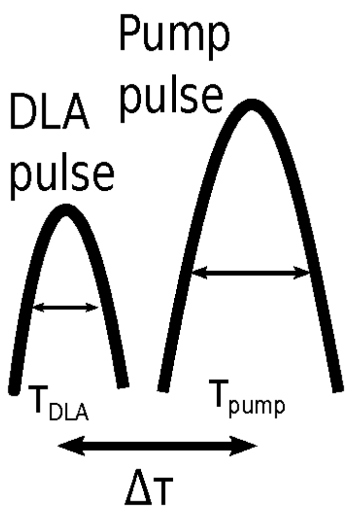
Can LWFA and DLA work together?

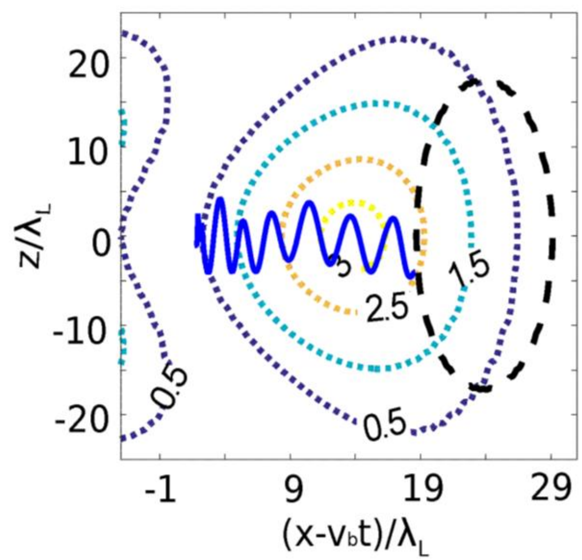
- **DLA's resonance condition can be undone by rapid wakefield acceleration: $\omega_L\left(1 - v_x/v_{ph}\right) = \omega_p/\sqrt{2\gamma}$**
- **DLA requires large $\vec{v}_\perp$ because $A_L \propto \vec{v}_\perp \cdot \vec{A}_L$, but the conservation of $I_\perp$ reduces $|\vec{v}_\perp|$ during acceleration!**

} LWFA is bad for DLA

- **DLA laser pulse can distort the bubble and impede LWF acceleration or electron injection into the bubble**
- **Large amplitude of betatron oscillations may reduce the accelerating gradient experienced inside the bubble**

} DLA is bad for LWFA



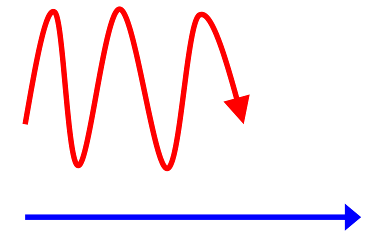


But the benefits of combining the two could be substantial!

X. Zhang, V. Khudik, and GS, PRL **114,** 184801 (2015)
X. Zhang, V. Khudik, A. Pukhov, and GS, PPCF **58,** 034011 (2016)

Benefits of Synergistic Laser Wakefield & Direct Laser Acceleration

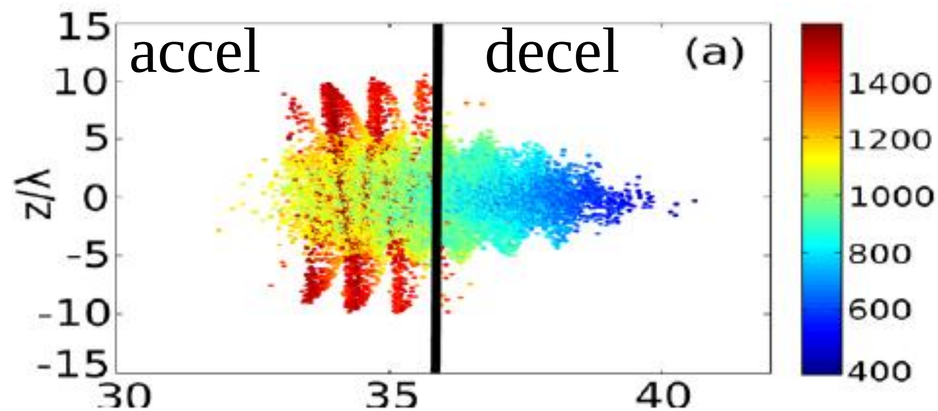
- **Cumulative energy gain from LWFA and DLA**
- **Potentially higher energy gain from LWFA due to delayed dephasing**



- **Large transverse momentum $K = p_\perp/mc$ → efficient source of X-rays and γ −rays up to K^3 harmonic of ω_L**
- **Combining multiple laser pulses (mid-IR + near-IR)**

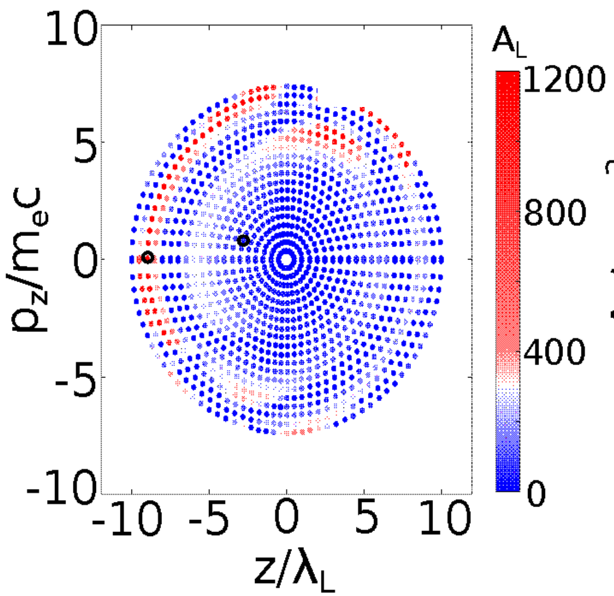
$$\frac{d\zeta}{d(ct)} \approx \frac{1}{2\gamma_b^2} - \frac{1 + \langle p_\perp^2/m_e^2 c^2 \rangle}{\gamma^2}$$

X. Zhang et. al., PRL **114,** 184801 (2015); PPCF **58,** 034011 (2016)

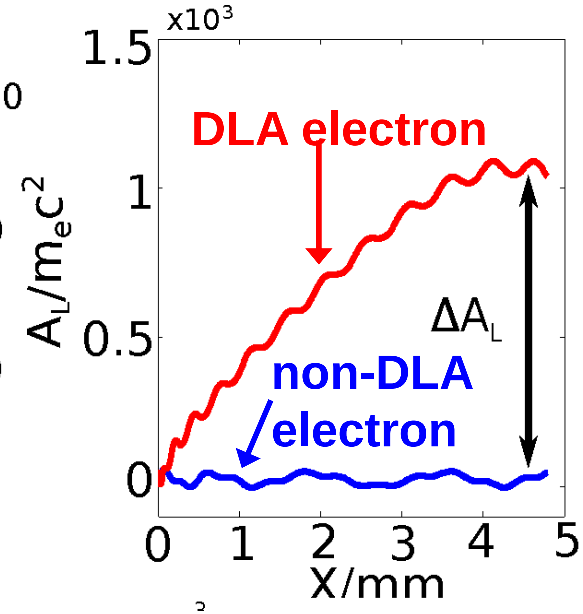


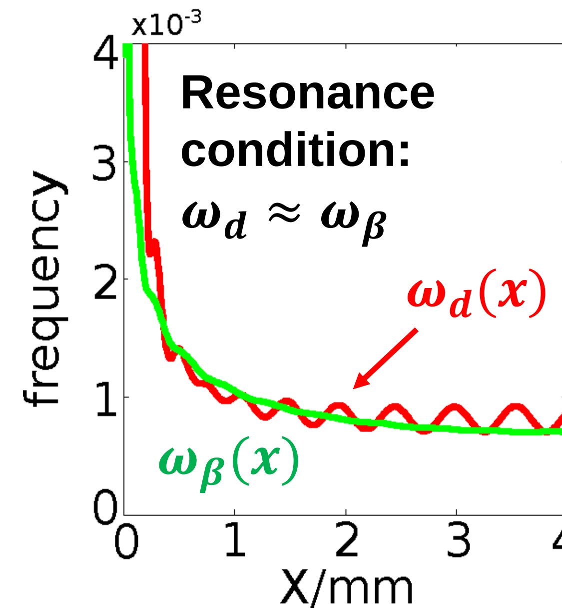
$$\zeta = x - v_b t$$

Synergistic DLA/LWFA: single-particle simulations of a particle swarm



Swarm of initial conditions ($\boldsymbol{p}_\perp, \boldsymbol{r}_\perp$)





$$\omega_d = \omega_L \left(\frac{1 + \langle p_z^2/m^2c^2 \rangle}{2\gamma^2} + \frac{1}{2\gamma_{ph}^2} \right)$$

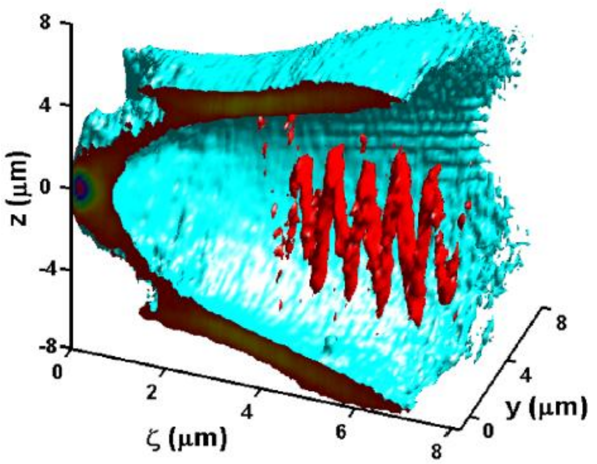
Necessary ingredients of DLA/LWFA synergy:

(a) electron injection with large transverse energy

(b) strong overlap between electrons and the laser

(c) betatron resonance between electrons and the laser

Can DLA happen in a plasma bubble?



Pump pulse creates a bubble

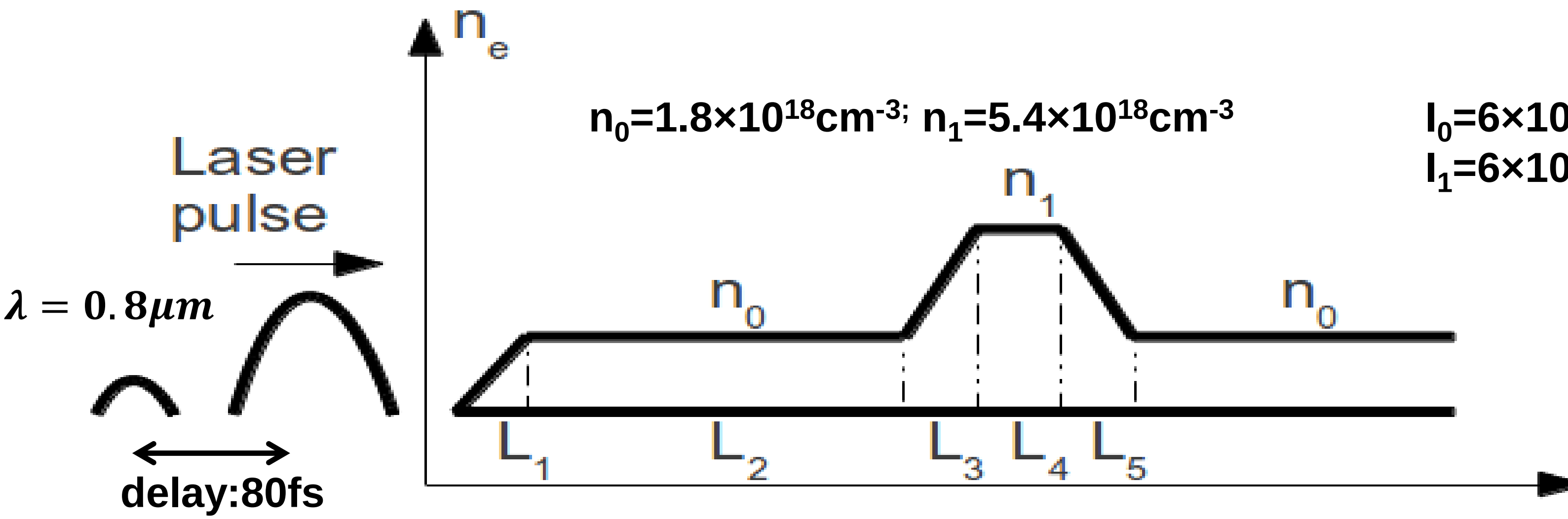
↓

Density bump "shakes" the bubble → side-injection with large $p_{\perp}$ → facilitates DLA

↓

Self-injected electrons interact with the weaker laser pulse delayed by $\Delta\tau$=80fs

Density ramp injection scenario



n_0=1.8×10^{18}cm^{-3}; n_1=5.4×10^{18}cm^{-3}

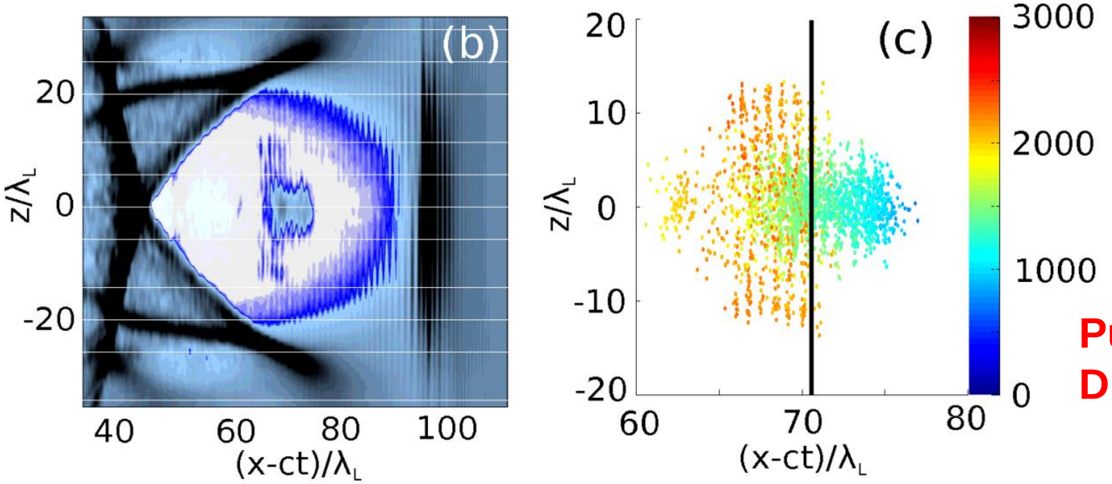
I_0=6×10^{19}w/cm^2; I_1=6×10^{18}w/cm^2

L_2 =1.6mm, $L_3 = L_4 = L_5 \approx 100\mu m$

X. Zhang et. al. PRL **114,** 184801 (2015)

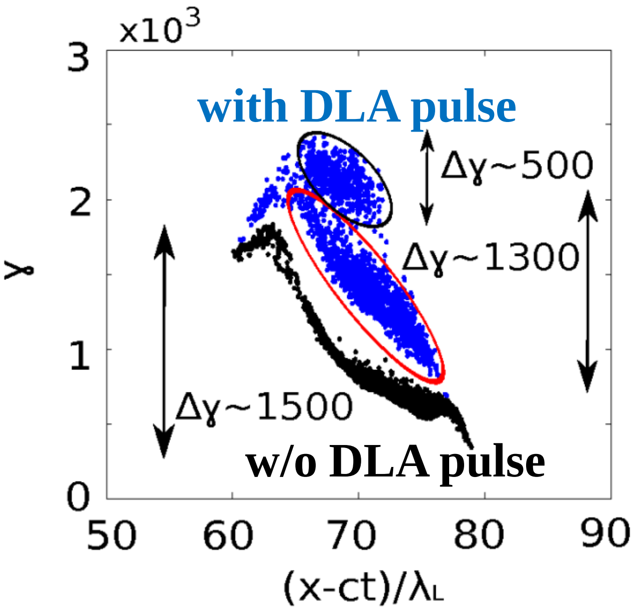
DLA inside a plasma bubble

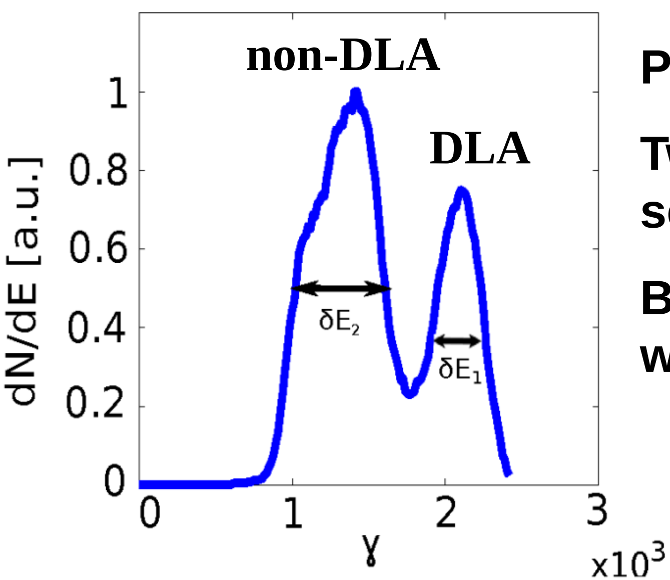
after 1cm propagation



Electrons separated into two groups → DLA electrons with large $p_\perp$ gain more energy and fall behind the non-DLA ones

Pump: $a_L = 5.3, \tau_L = 70fs, w_0 = 20\mu m$
DLA : $a_L = 1.7, \tau_L = 35fs, w_0 = 20\mu m$





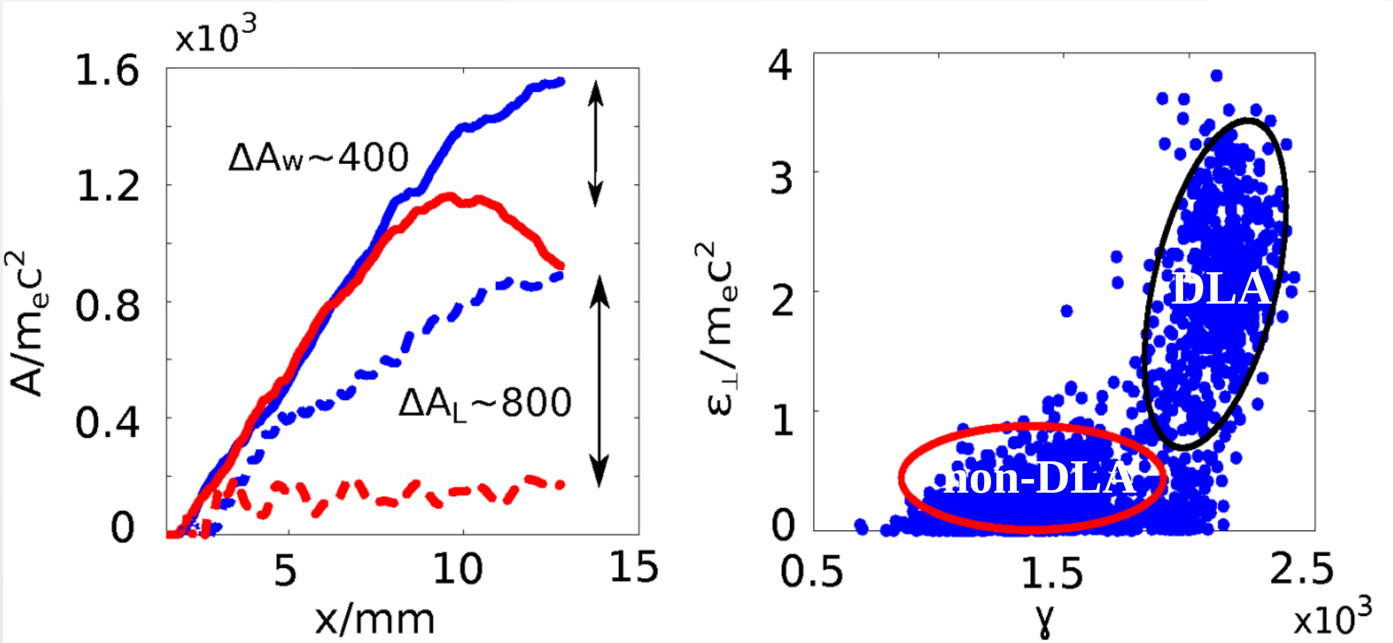
Phase space bifurcation

Two-peak spectrum separated by 400 MeV

Bifurcation is absent without DLA pulse

X. Zhang et. al. PRL **114,** 184801 (2015)

Phase Space Correlations: Key to Synergy



DLA electrons → strong correlation between total energy γmc^2 and transverse energy

$$\epsilon_\perp = \frac{p_z^2}{2\gamma m} + \frac{m\omega_p^2 z^2}{4}$$

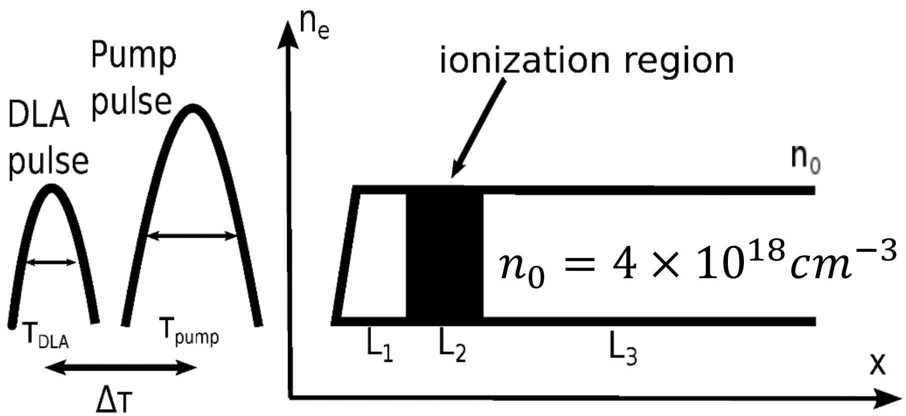
Strong bifurcation in $(\epsilon_\perp, \gamma)$ phase space

Synergy between DLA and LWFA → higher energy gain from the wake for the DLA population ← delayed dephasing!

$$\frac{d\zeta}{d(ct)} \approx \frac{1}{2\gamma_b^2} - \frac{1 + \langle p_\perp^2/m_e^2c^2 \rangle}{\gamma^2}$$

DLA electrons gain extra 200 MeV from the wake and extra 400MeV from the laser (DLA)

DLA is compatible with ionization injection!

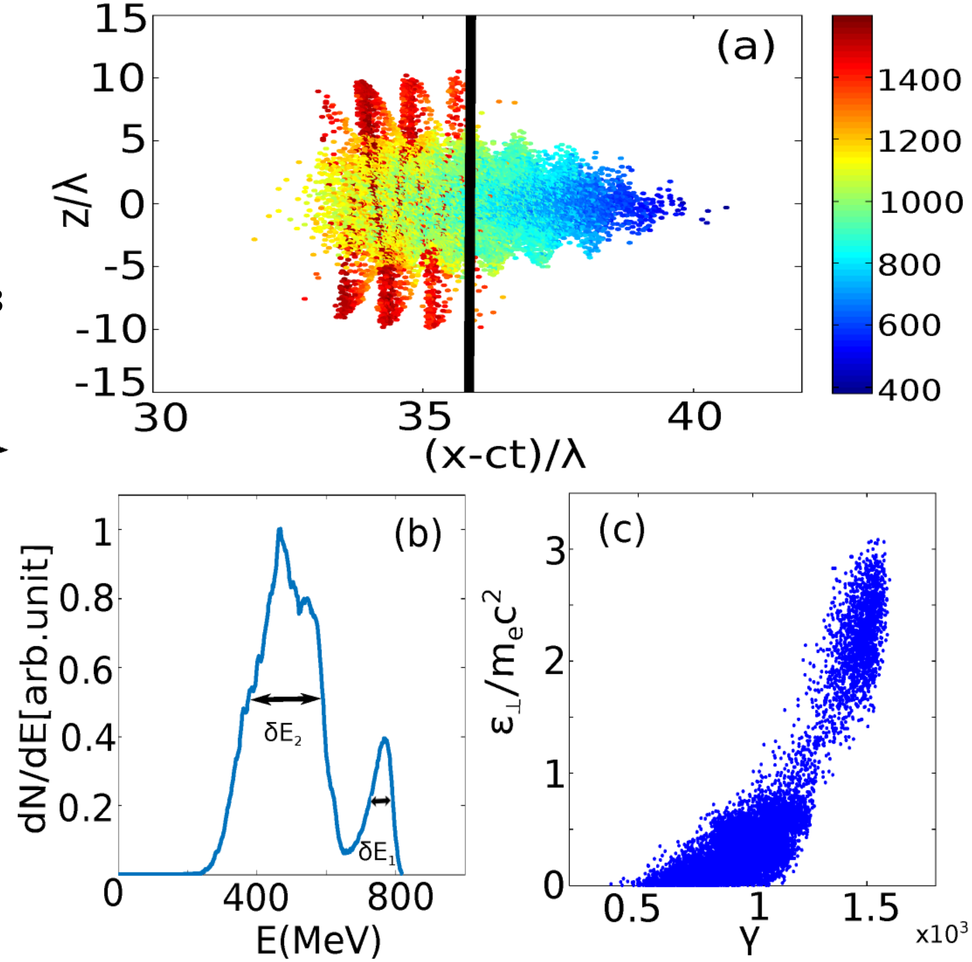


$I_{\text{pump}} = 2.3 \times 10^{19} W/cm^2$

$I_{\text{DLA}} = I_{\text{pump}}/2$

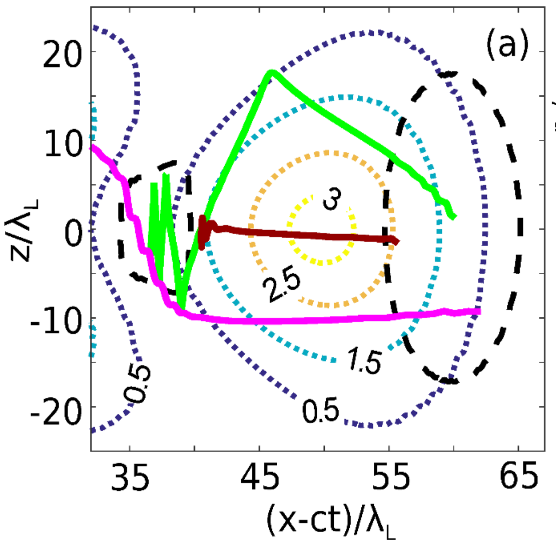
$U_{\text{ion}} = 870eV \rightarrow$ from O^{7+} to O^{8+}

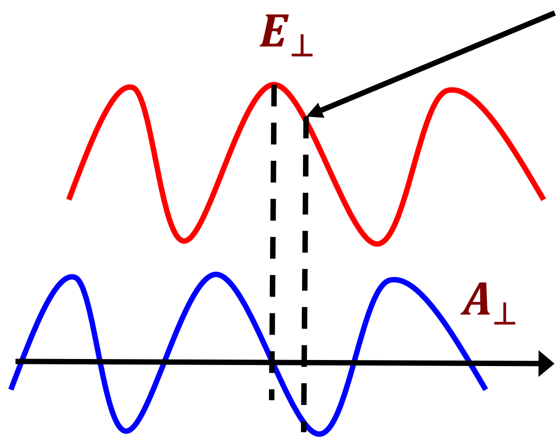
Electrons after 3mm



Off-axis or off-peak phase ionization produces DLA electrons!

Off-peak phase ionization and "ricochet" DLA electrons: real atoms meet meta-atoms

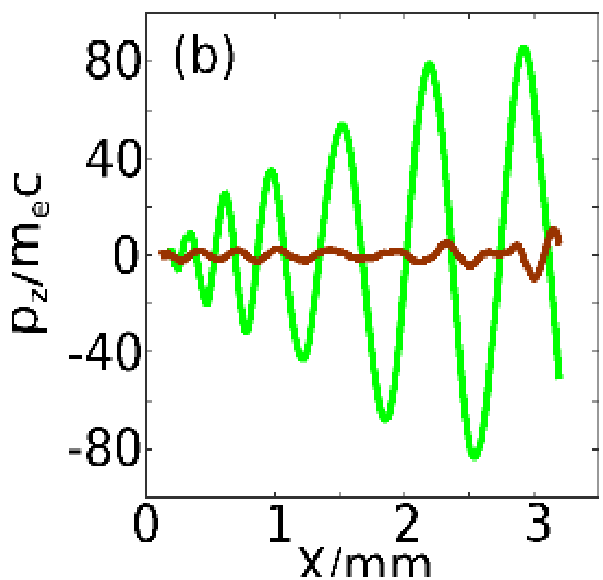


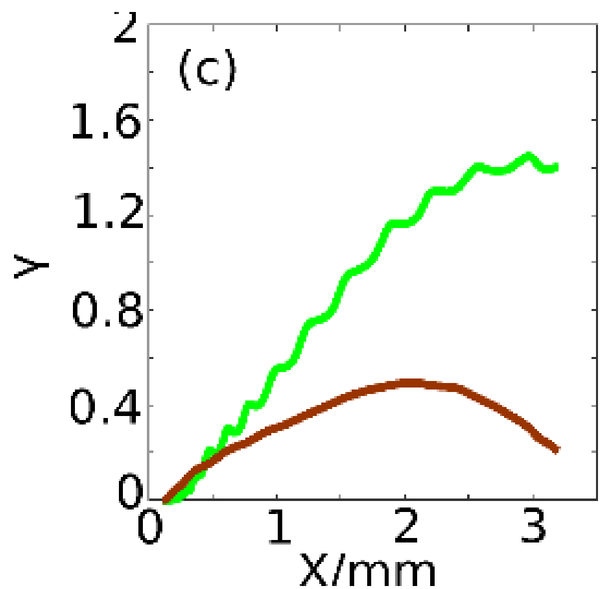


Off-peak ionization phase: electrons leave the laser pulse with finite transverse momentum

$$p_\perp + eA_{\perp/}c = eA_\perp(t_i)/c$$

Phase

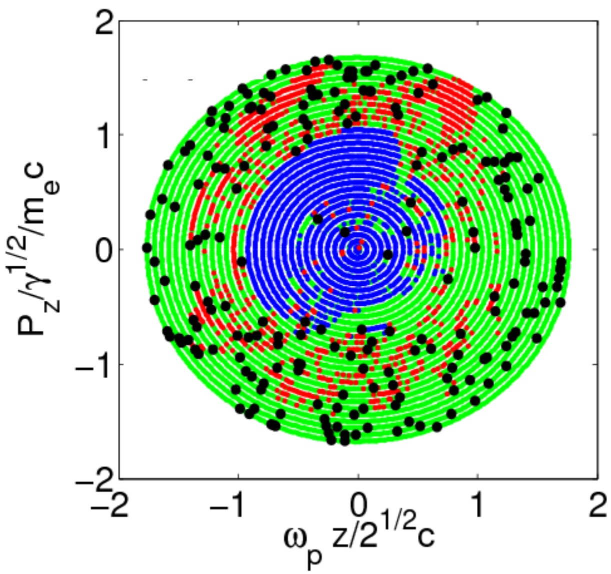


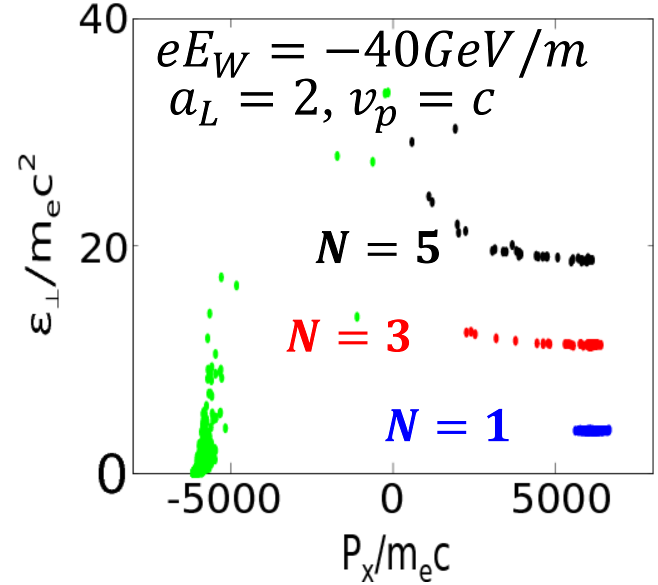


Ricochet electron starts out with large $p_\perp$, interacts with the DLA pulse → gains even larger $p_\perp$ and more energy

One Step Back, Two Steps Forward: Laser Wakefield Decelerator + DLA

Initial conditions



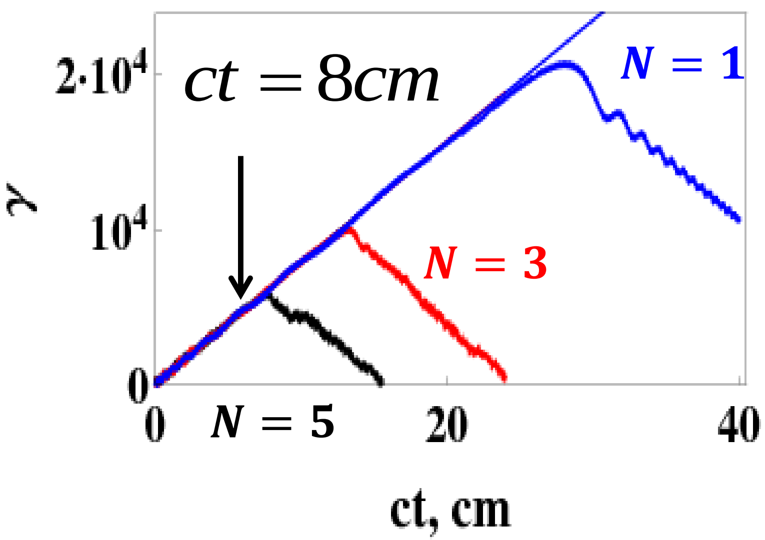


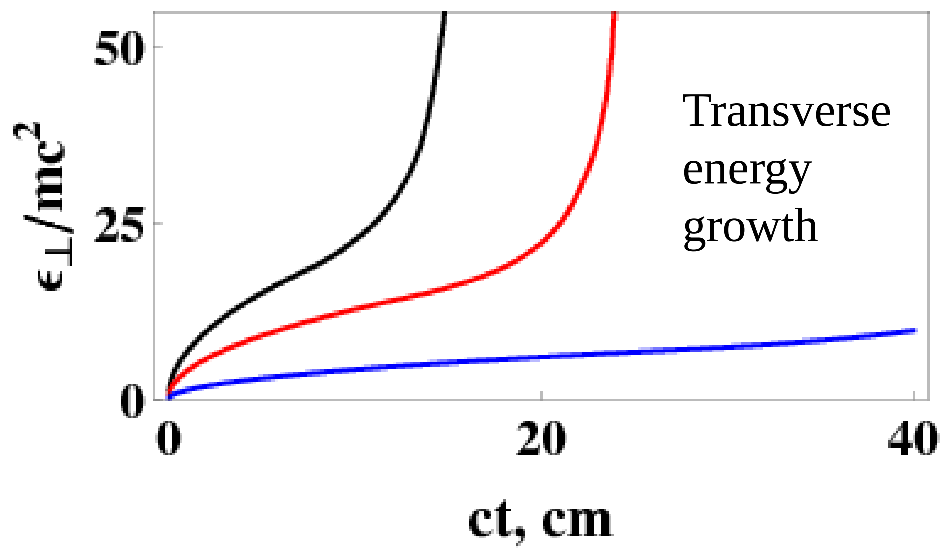
Model: constant **<u>decelerating</u> field E_W**

Multiple DLA harmonics:

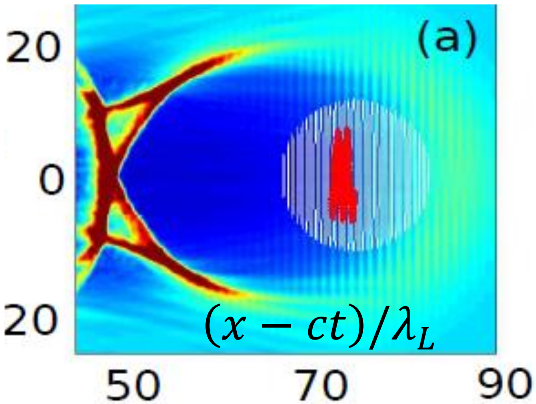
$$\omega_L \frac{1 + \langle p_z^2/m^2c^2\rangle}{2\gamma^2} = $$

$$= N\frac{\omega_p}{\sqrt{2\gamma}}$$

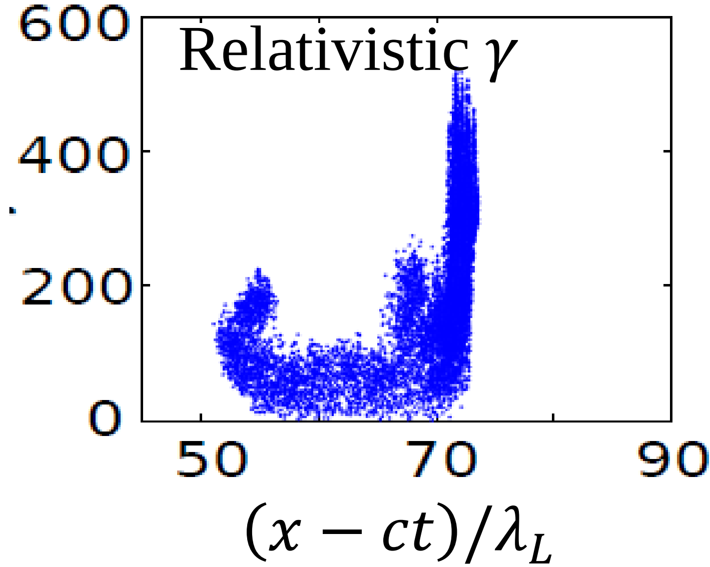


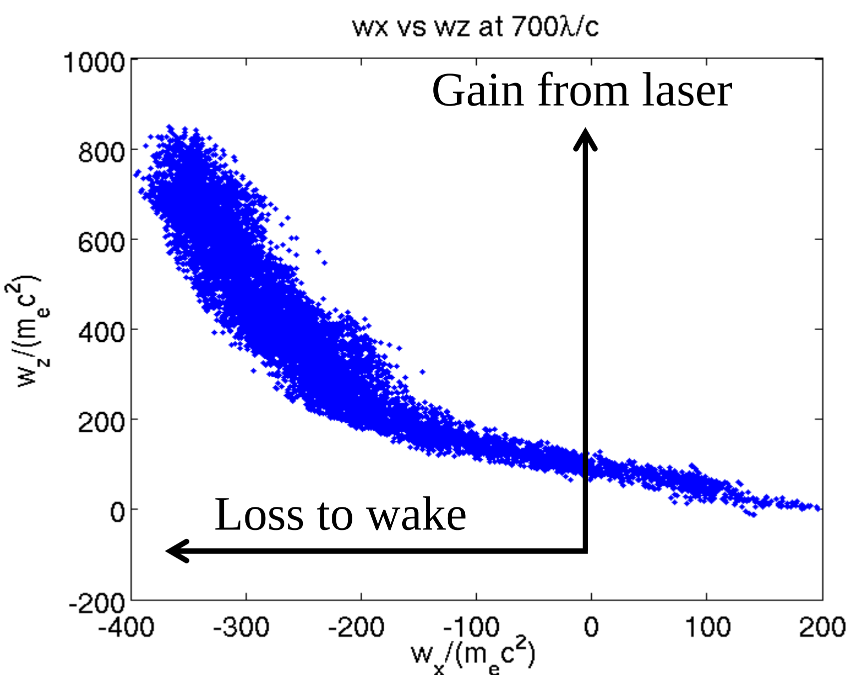


Who needs LWFA if DLA is so great?



$\lambda_1 = 0.8\mu m$ pulse:
$P_1 = 170$TW ($a_1 = 6$)
$\tau_1 = 35$fs, $w_1 = 12\mu$m
$n_0 = 4 \times 10^{18} cm^{-3}$
External injection into the decelerating phase
$p_{x0} = 25 m_e c$





The wake decelerates the electrons, but the DLA accelerates them at more than twice the deceleration rate!

The mix-and-match approach to LA: the case for combining near- and mid-IR lasers

- **Mid-IR lasers produce a large bubble $r_b \sim \lambda_p \sqrt{a_L}$ because less dense plasma is used → large-amplitude betatron oscillations are not a problem**
- **Vector potential $a_L \sim \lambda_L \sqrt{I_L}$ is large for modest laser intensity**
- **External electron injection into a large bubble is easy**
- **Unique opportunity for combining a mid-IR laser pulse ("work horse" that makes a bubble) with an ultra-short solid-state laser pulse ("surgical tool" that injects electrons, excites betatron oscillations, provides DLA)**

Electric field or vector potential?

Ponderomotive potential:

$$a_L^2 \sim \lambda_L^2 I_L$$

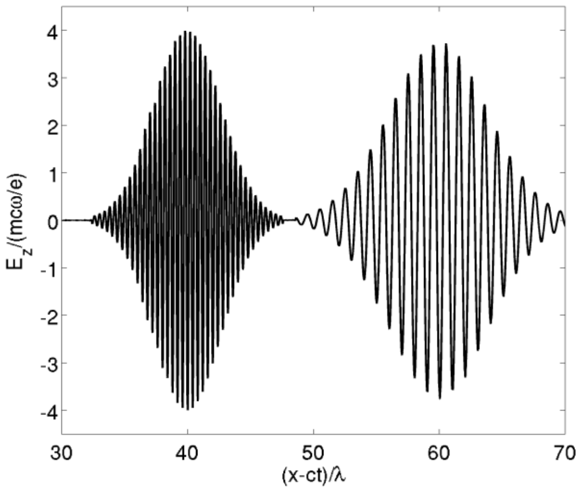
Ionization rate of neutral gasses:

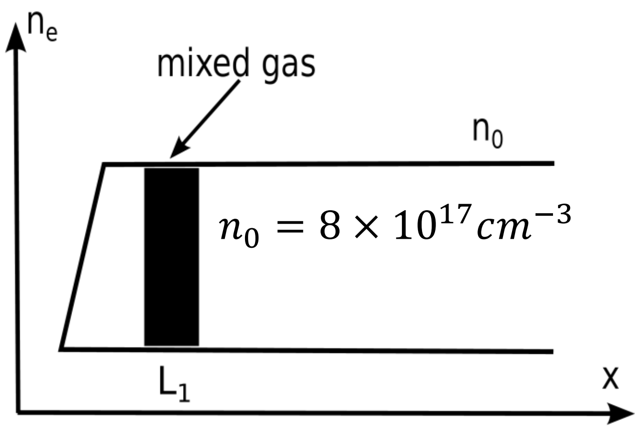
$$E_L \sim \sqrt{I_L}$$

Direct Laser Acceleration gradient:

$$\vec{E}_L \cdot \vec{v}_\beta \sim \sqrt{I_L}$$

Injection, LWFA, and DLA using a sequence of $2.0\mu m$ and a $0.8\mu m$ laser pulses

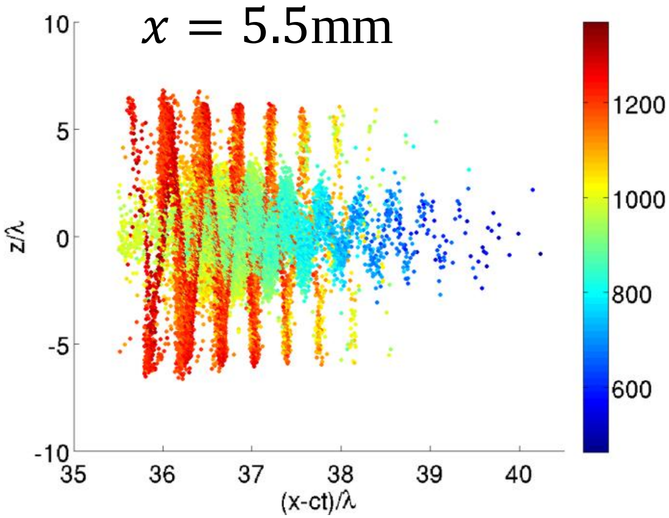


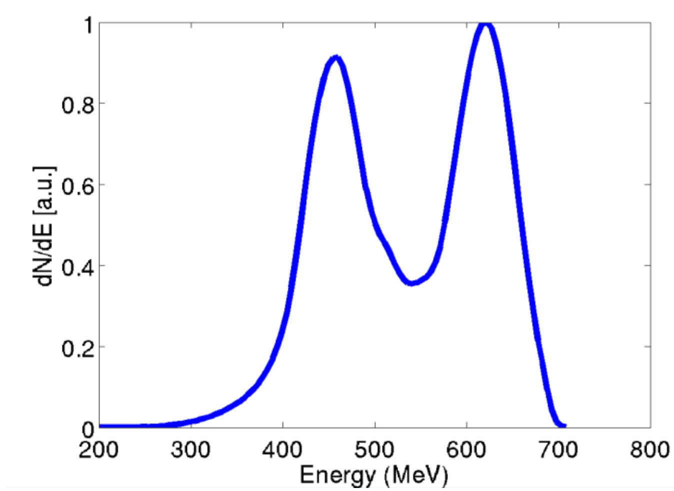


$\lambda_0 = 2\mu m$ **pulse:**
$P_0 = 65\text{TW}\ (a_0 = 3.7)$
$\tau_0 = 45\text{fs},\ w_0 = 30\mu m$

$\lambda_1 = 0.8\mu m$ **pulse:**
$P_1 = 33\text{TW}\ (a_1 = 1.6)$
$\tau_1 = 30\text{fs},\ w_1 = 20\mu m$

Time delay: $\Delta t = 120\text{fs}$



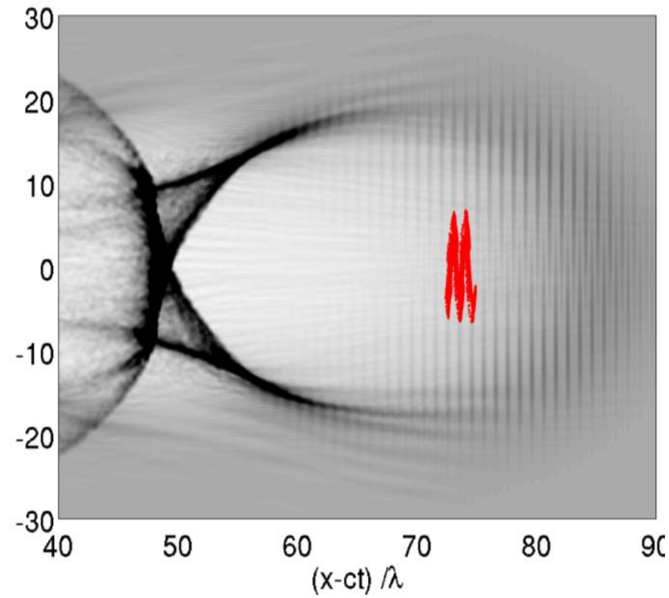


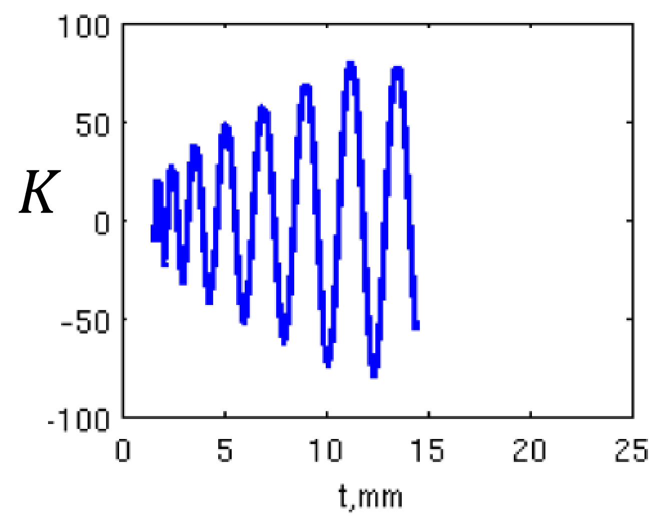
Electrons gain 400MeV from wake and 200MeV from $\lambda = 0.8\mu m$ laser: 1st harmonic DLA

$\omega_L(1 - v_z/v_p) = \omega_\beta$

How the entire LPA paradigm may be changed by Direct Laser Acceleration

- Synchronization of externally injected beam is the key to injecting into the decelerating phase
- The main role of the bubble is not accelerate but to provide focusing field to undulating electrons
- Excellent source of X-ray and Gamma-ray radiation because of the large undulator parameter $K = p_{\perp}/mc$

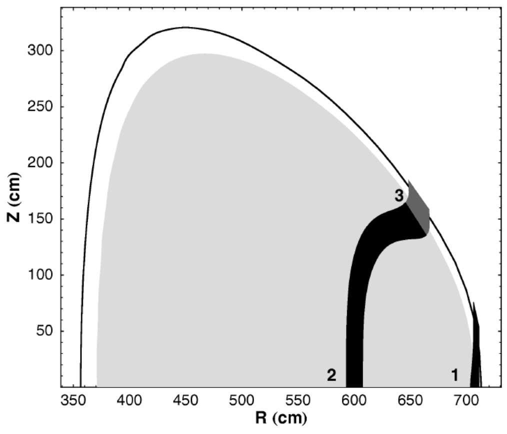


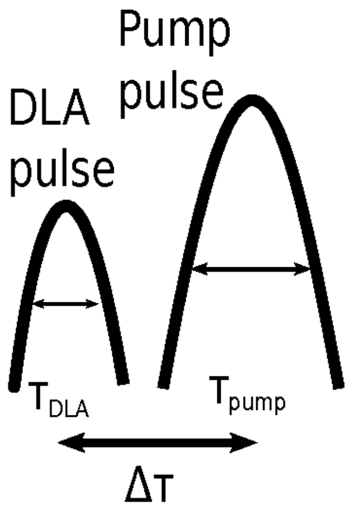


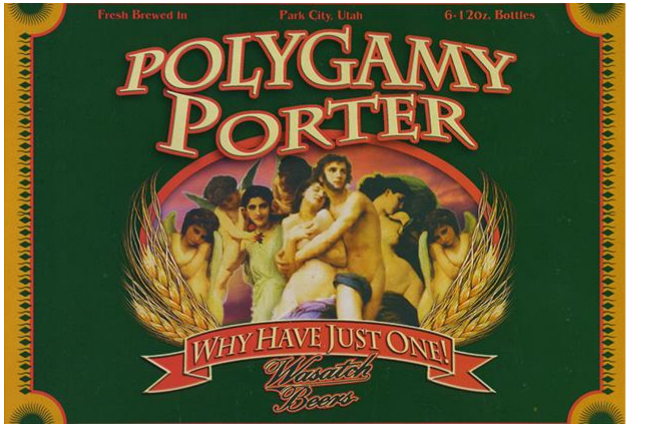
$$\omega_c \sim 2\gamma^2 \omega_\beta \frac{K^3}{1+K^2} \sim K^3 \omega_L$$

Conclusions from this talk: from the least important to the most

When one wave doesn't do the job: bring more!







Watch what you are saying: people are actually listening and following!

"Fusion is very deep but not too broad; LP is very broad but not too deep"

"Engineers use fluid descriptions. Physicists go into the phase space!"

Happy Birthday, Nat!