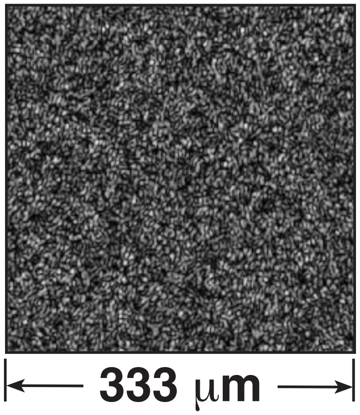
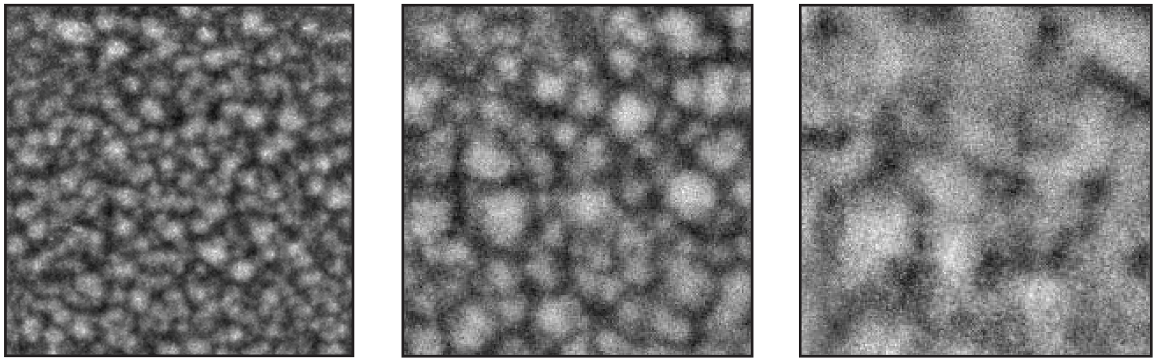
Rayleigh–Taylor Growth Measurements of 3-D Modulations in Nonlinear Regimes

SG8 DPP
laser modulation
(input)



X-ray radiographs at


4 ns **6 ns** **10 ns**

V. A. Smalyuk
University of Rochester
Laboratory for Laser Energetics

47th Annual Meeting of the
American Physical Society
Division of Plasma Physics
Denver, CO
24–28 October 2005

Summary

The measured nonlinear Rayleigh–Taylor growth is in good agreement with theoretical models

- Direct-drive, planar through-foil radiography is analyzed in real and Fourier spaces.
- Nonlinear velocities and spectral shapes are consistent with Haan-model* predictions.
- Late nonlinear growth is relatively insensitive to initial conditions.
- The self-similar regime** of bubble size distributions was observed with the modulation σ_{rms} growing as $\alpha_\sigma g t^2$, with $\alpha_\sigma = 0.027$.

⇨ Bubble front $\alpha_B \simeq \sqrt{2} \cdot \alpha_\sigma = 0.04$ is consistent with Haan's saturation parameter $\left(S_k = \frac{2}{Lk^2}\right)$ and previous classical RT results.

---

*S. Haan, Phys. Rev. A <u>39</u>, 5812 (1989).

**U. Alon *et al.*, Phys. Rev. Lett. <u>74</u>, 534 (1995).

Contributors

R. Betti, V. N. Goncharov, J. A. Delettrez,
D. D. Meyerhofer, S. P. Regan, and T. C. Sangster

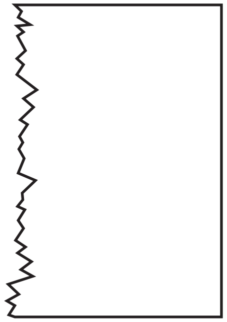
University of Rochester
Laboratory for Laser Energetics

O. Sadot, D. Shvarts

Nuclear Research Center
Negev, Israel

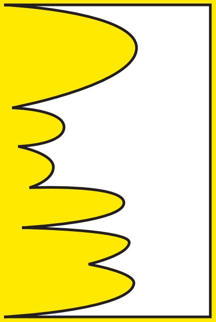
The Rayleigh–Taylor instability has linear, nonlinear, and turbulent stages

Linear stage



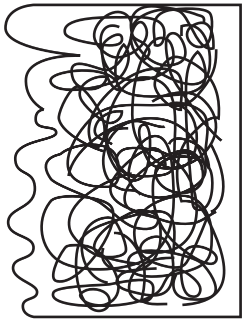
Small-amplitude modulations grow exponentially in the linear regime.

Nonlinear stage



Bubbles compete and merge in the nonlinear regime.

Turbulent-mixing stage



Chaotic mixing is characteristic in the turbulent regime of classical Rayleigh–Taylor instability.

E14124

In the Haan saturation model, 3-D broadband modulations saturate at $S_k = \frac{2}{Lk^2}$*

- For a single-mode modulation Z_k the saturation level is 0.1 λ

$$S_k = 0.1\ \lambda$$

- For broadband modulations saturation, the σ_{rms} of modes near Z_k is 0.1 λ

$$\sqrt{\sum_{k-\delta k}^{k+\delta k} S_k^2} = 0.1\ \lambda$$

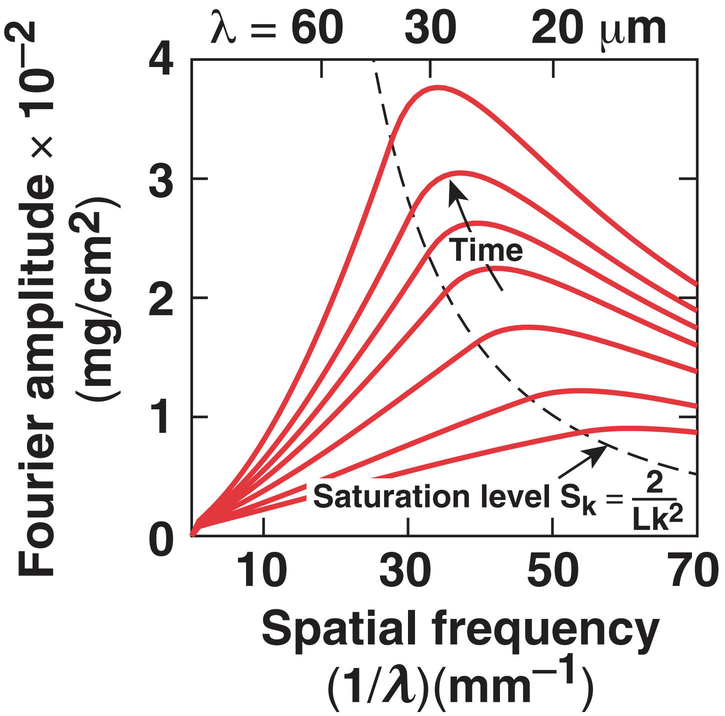
- $S_k = \frac{\in}{Lk^2}$, where $\in = 2$

---

*S. Haan, Phys. Rev. A 39, 5812 (1989).

In the Haan saturation model,* the Fourier amplitudes of broadband modulations saturate at $S_k = \frac{2}{Lk^2}$

- Fourier amplitudes grow exponentially up to the saturation levels $\boxed{S_k = \frac{2}{Lk^2}}$
- Subsequent growth is linear in time with velocities $\boxed{Vs = S_k \times \gamma\ (k)}$ [γ (k) is the linear growth rate].
- The shape of the late modulation spectrum is relatively insensitive to the initial modulation spectrum and to growth history (growth rates).

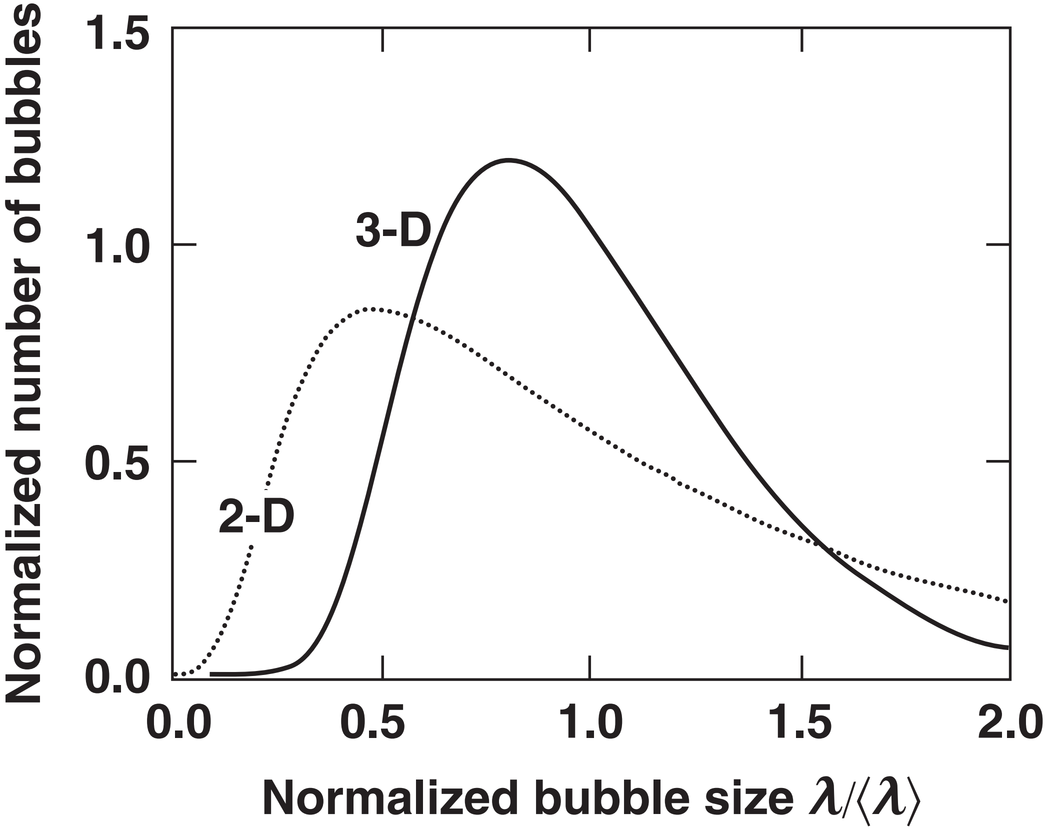


E13606b

---

*S. Haan, Phys. Rev. A <u>39</u>, 5812 (1989).

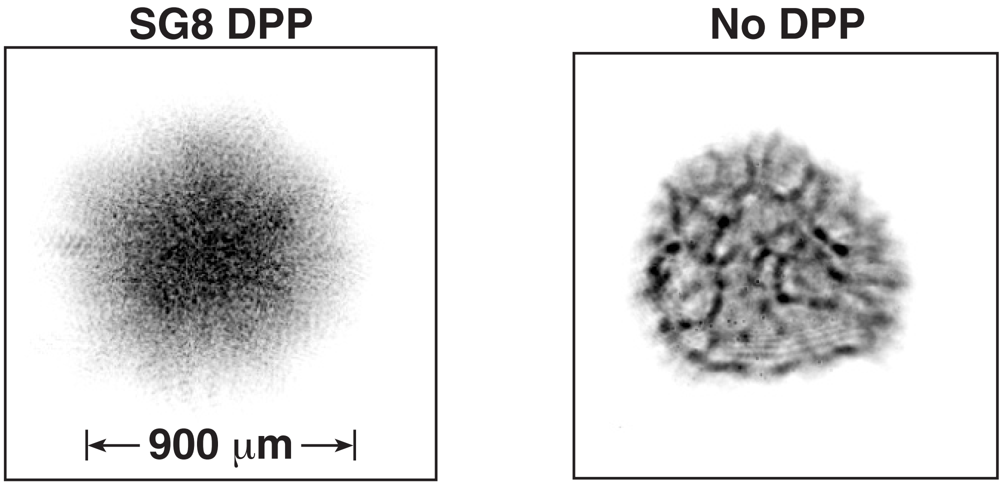
In real-space analysis, bubble competition models predict that bubble size distributions evolve in self-similar regimes*

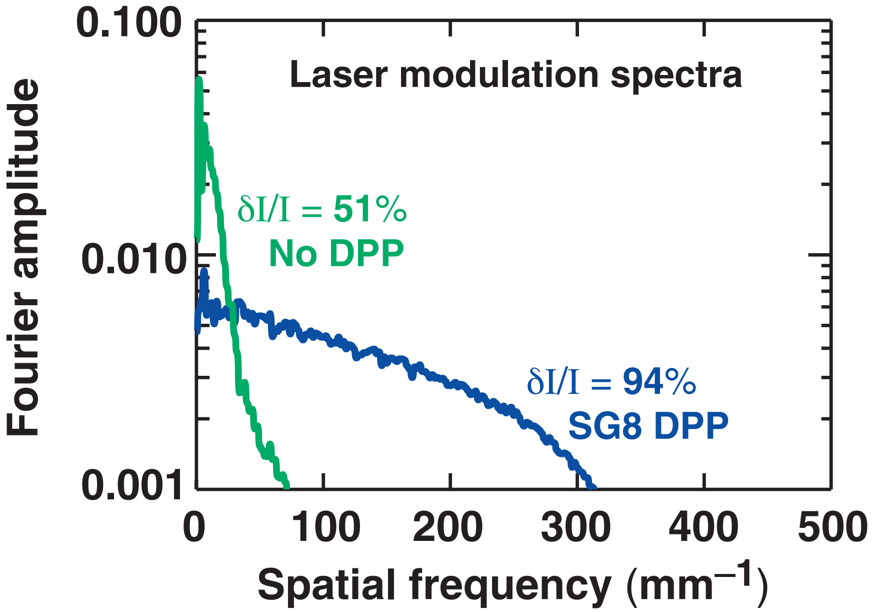


---

*U. Alon *et al.*, Phys. Rev. Lett. 74, 534 (1995).
*D. Oron *et al.*, Phys. Plasmas 8, 2883 (2001).

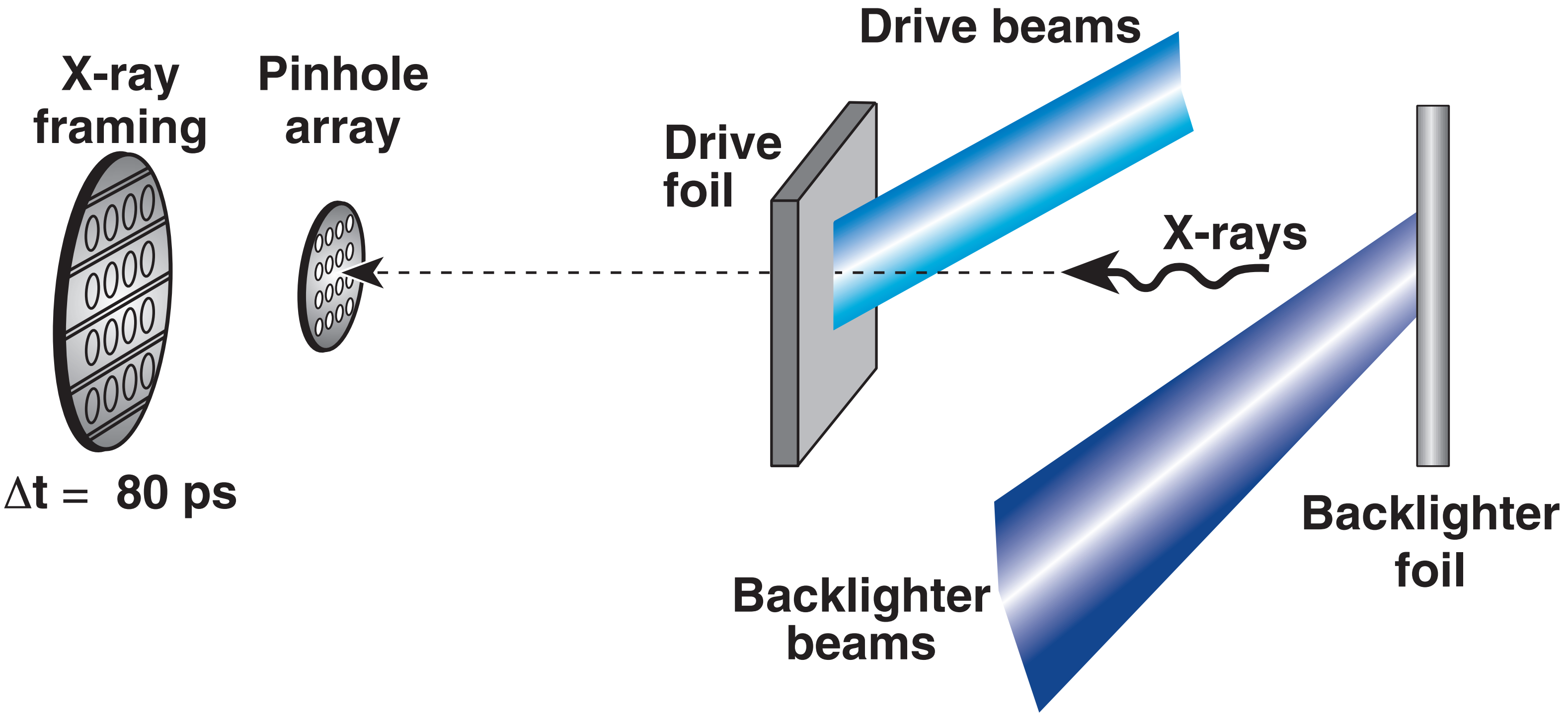
Initial seeds for the Rayleigh–Taylor instability were produced by laser imprinting





RT Growth Measurements

X-ray framing cameras are the primary diagnostics of instability growth

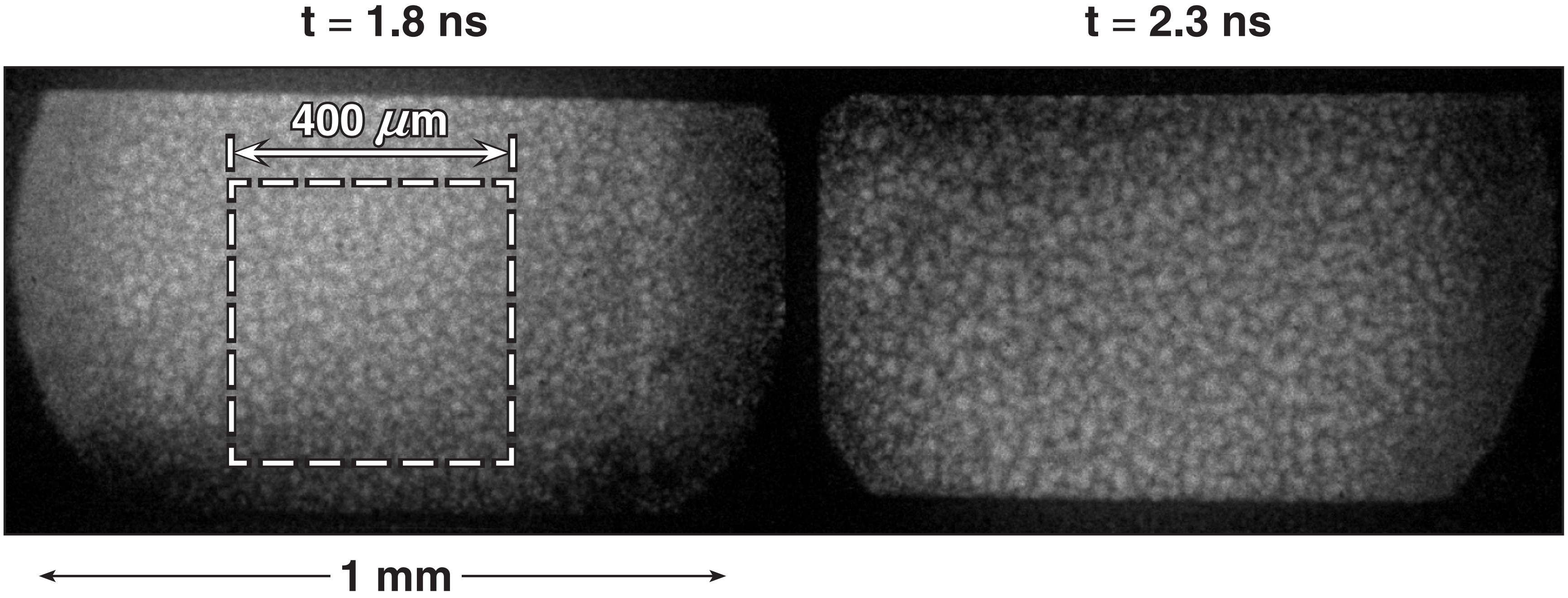


$\Delta t = 80$ ps

- 20-μm thick foils driven by 3-ns pulses at 2×10^{14} W/cm^2
- 50-μm thick foil driven by 12-ns pulses at 5×10^{13} W/cm^2

Thin Target, Early-Time Experiment

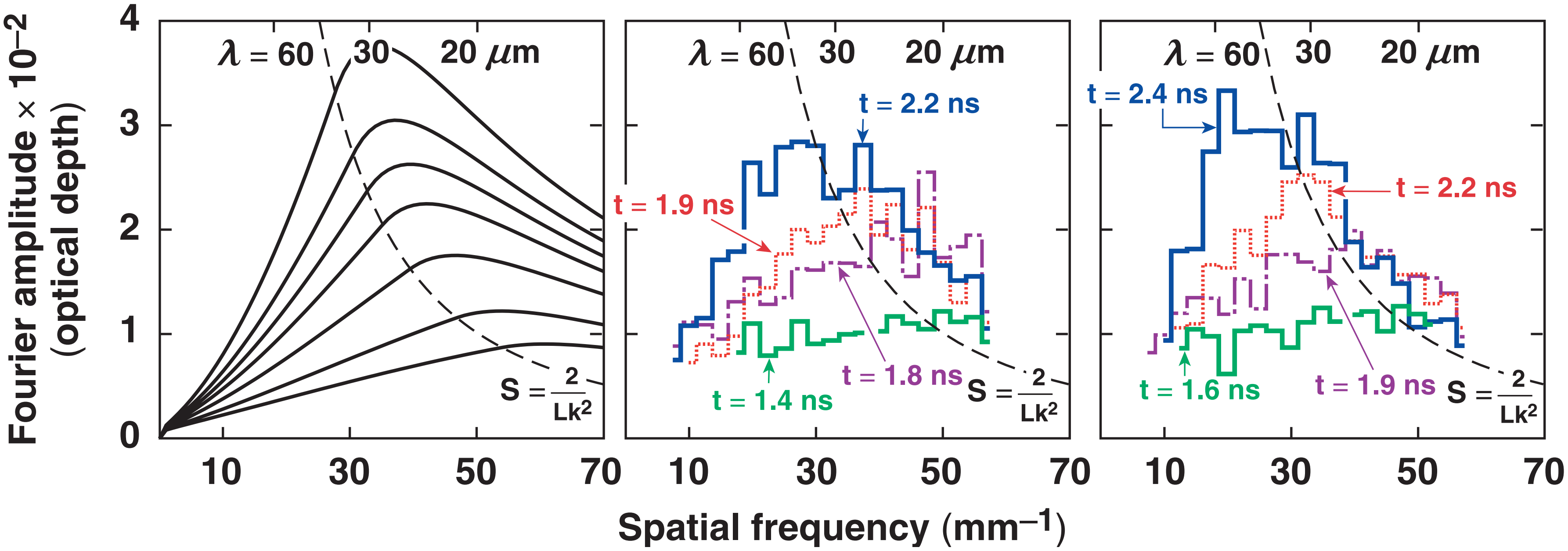
The growth of imprinted broadband modulations has been measured with a spatial resolution of 10 μm



- 20-μm thick CH foils were driven with 3-ns square laser pulses at 2×10^{14} W/cm^2.
- Fourier amplitudes were obtained by taking azimuthal averages of the 2-D Fourier images.

Thin Target, Early-Time Experiment

The measured spectral evolution is in agreement with Haan's saturation level, evolving toward longer wavelengths*



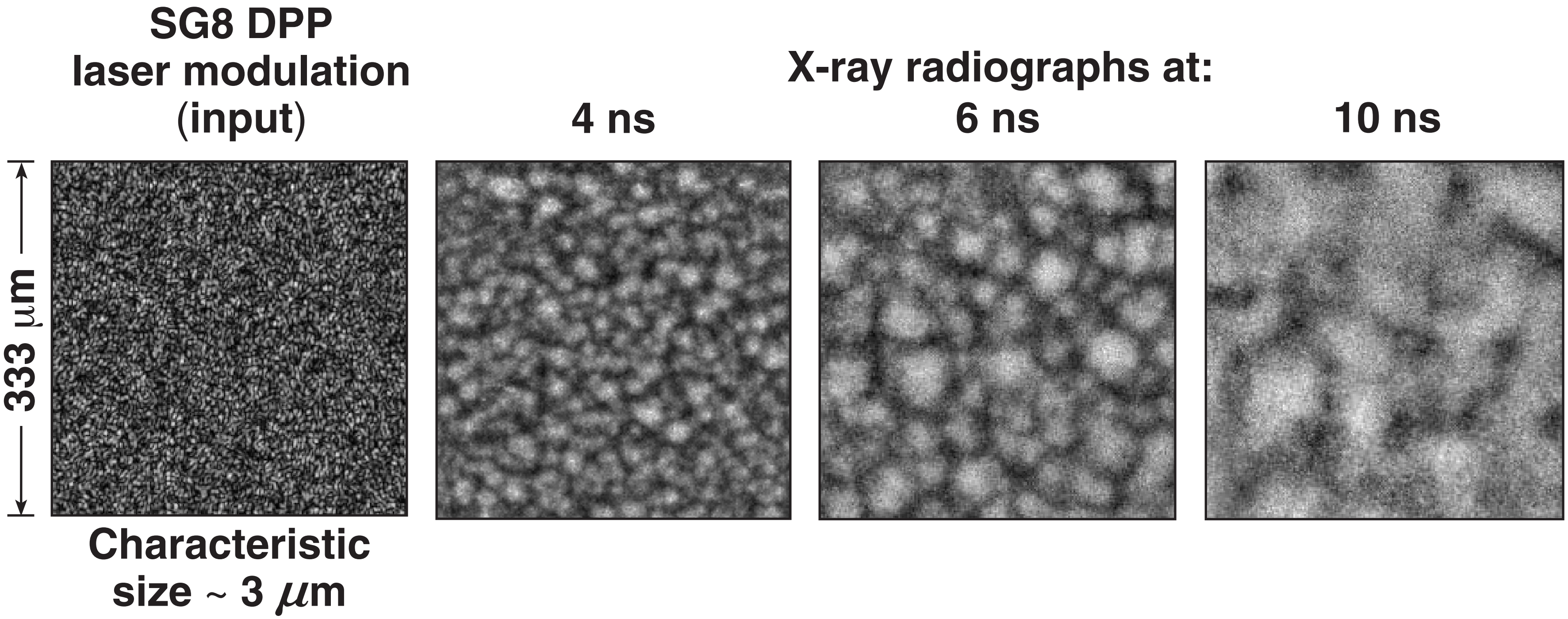
- **Questions left:**
  1. What are the post-saturation velocities?
  2. When do bubble competition and merger happen?

---

*V. A. Smalyuk *et al.*, Phys. Rev. Lett. 81, 5342 (1998).

Thick Target, Late-Time Experiment

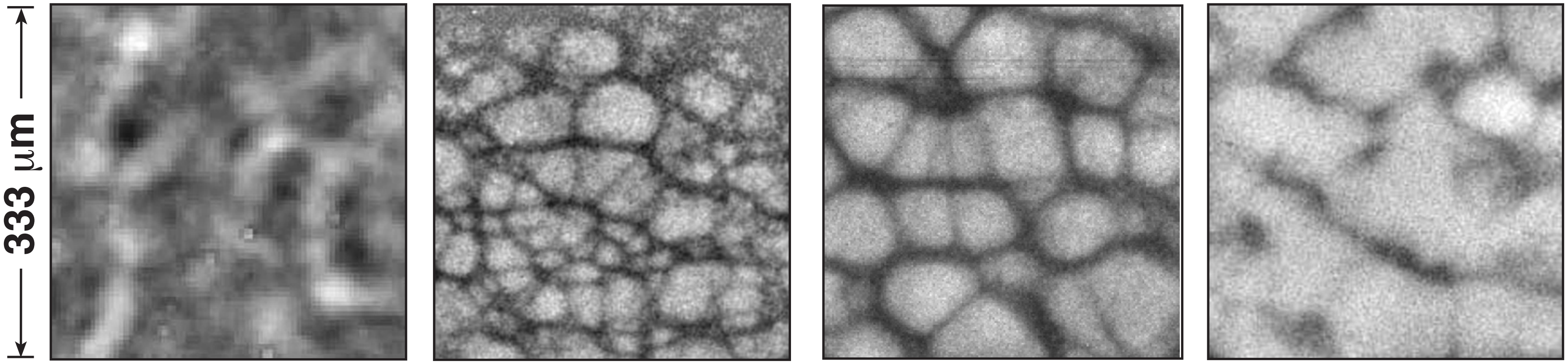
Broadband modulations become larger as they grow nonlinearly



- 50-μm-thick CH foils were driven with 12-ns-square laser pulses at 5 × 10^{13} W/cm^2

E13611a

The late nonlinear evolution is relatively insensitive to initial conditions



No DPP, laser modulation (input)

X-ray radiographs at:

4 ns

5 ns

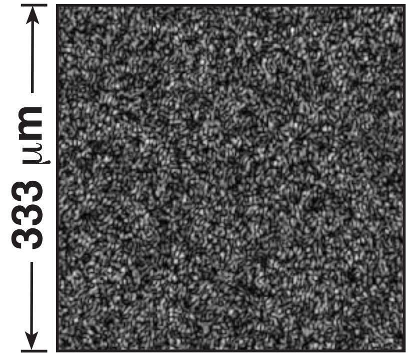
8 ns

Characteristic size ~ 30 μm

- **50-μm thick CH foils were driven with 12-ns-square laser pulses at 5 × 10^{13} W/cm^2**

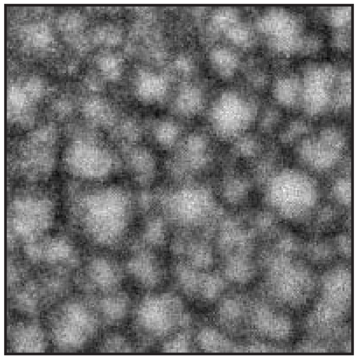
The nonlinear evolution is relatively insensitive to initial conditions

SG8 DPP
laser modulation

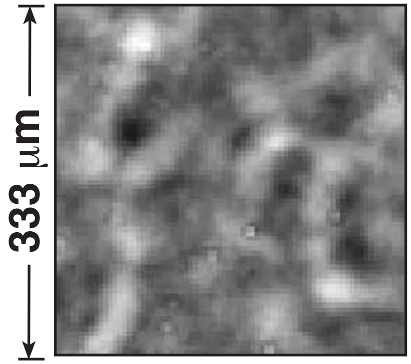


Characteristic size ~ 3 µm

X-ray radiograph
at ~6 ns

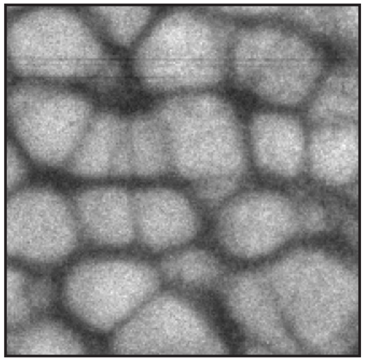


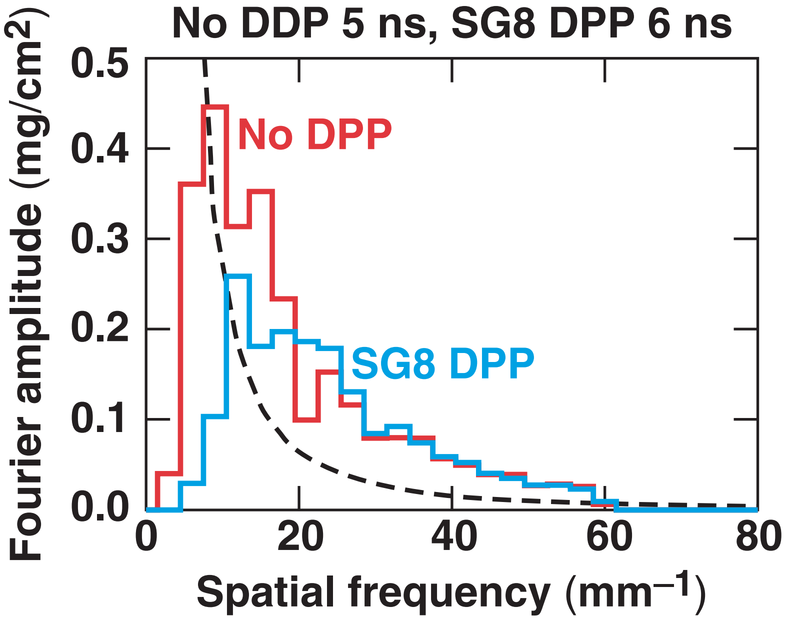
No DPP
laser modulation



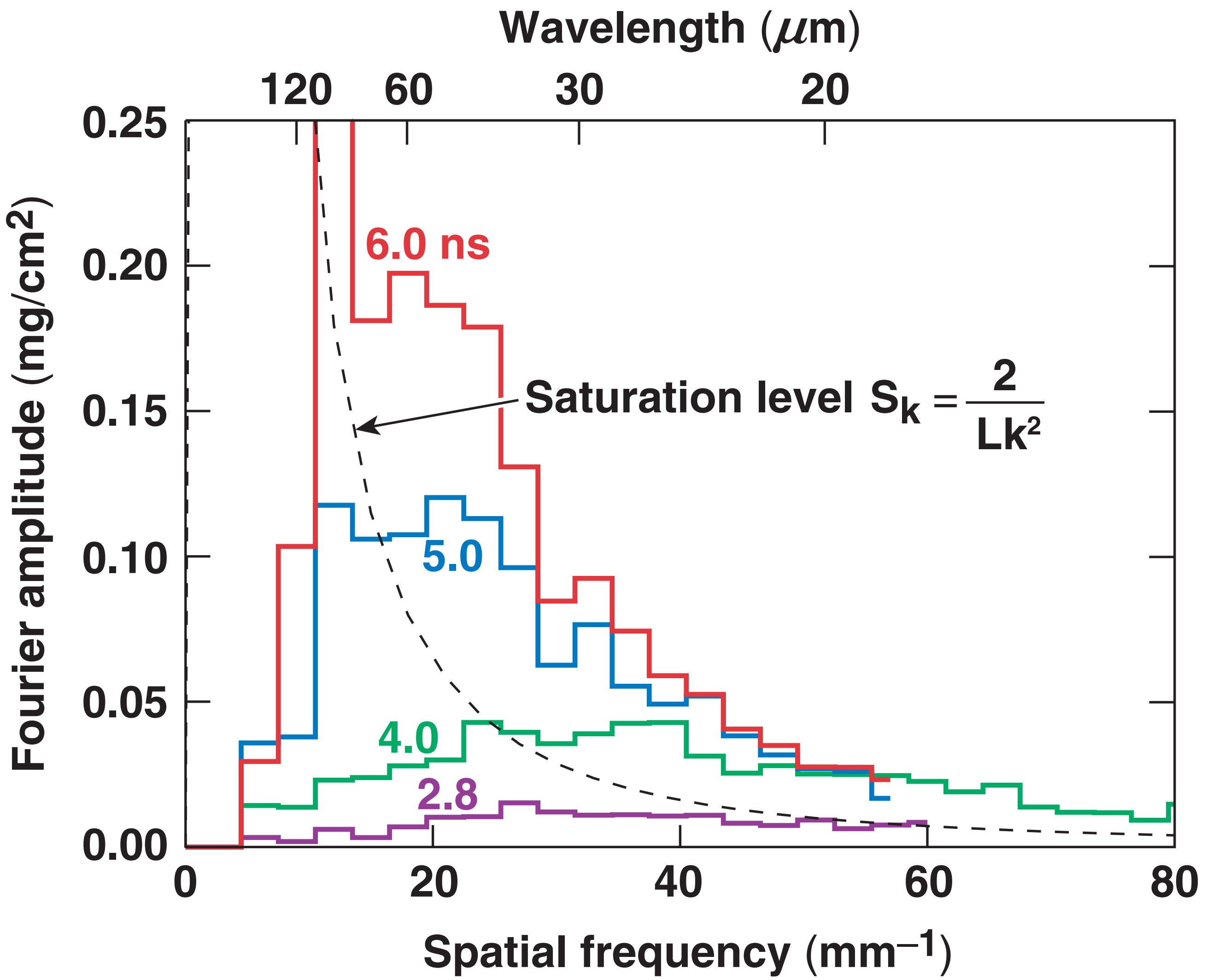
Characteristic size ~ 30 µm

X-ray radiograph
at ~5 ns



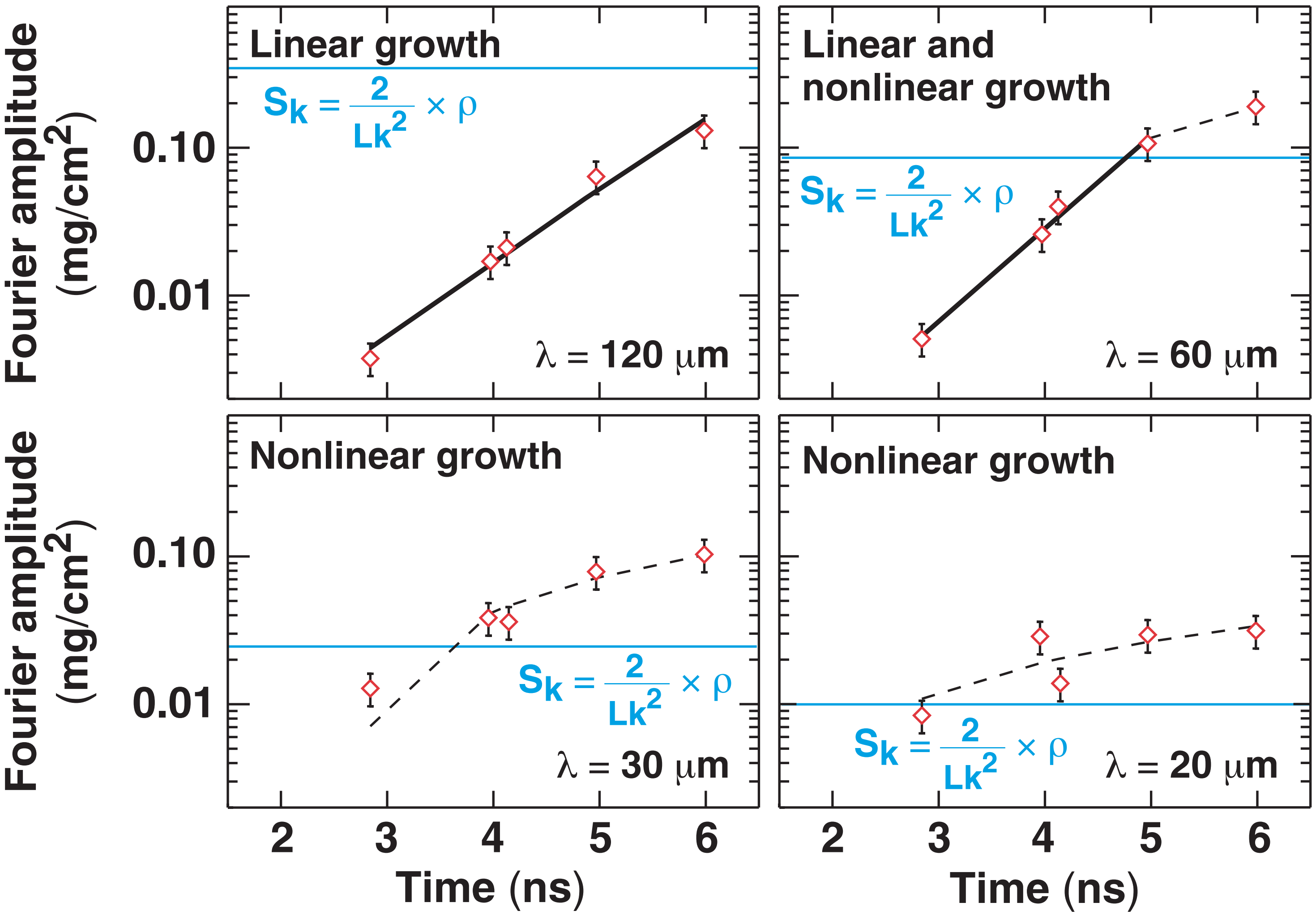


The modulation spectra shift to longer wavelengths as they grow, similar to Haan model predictions



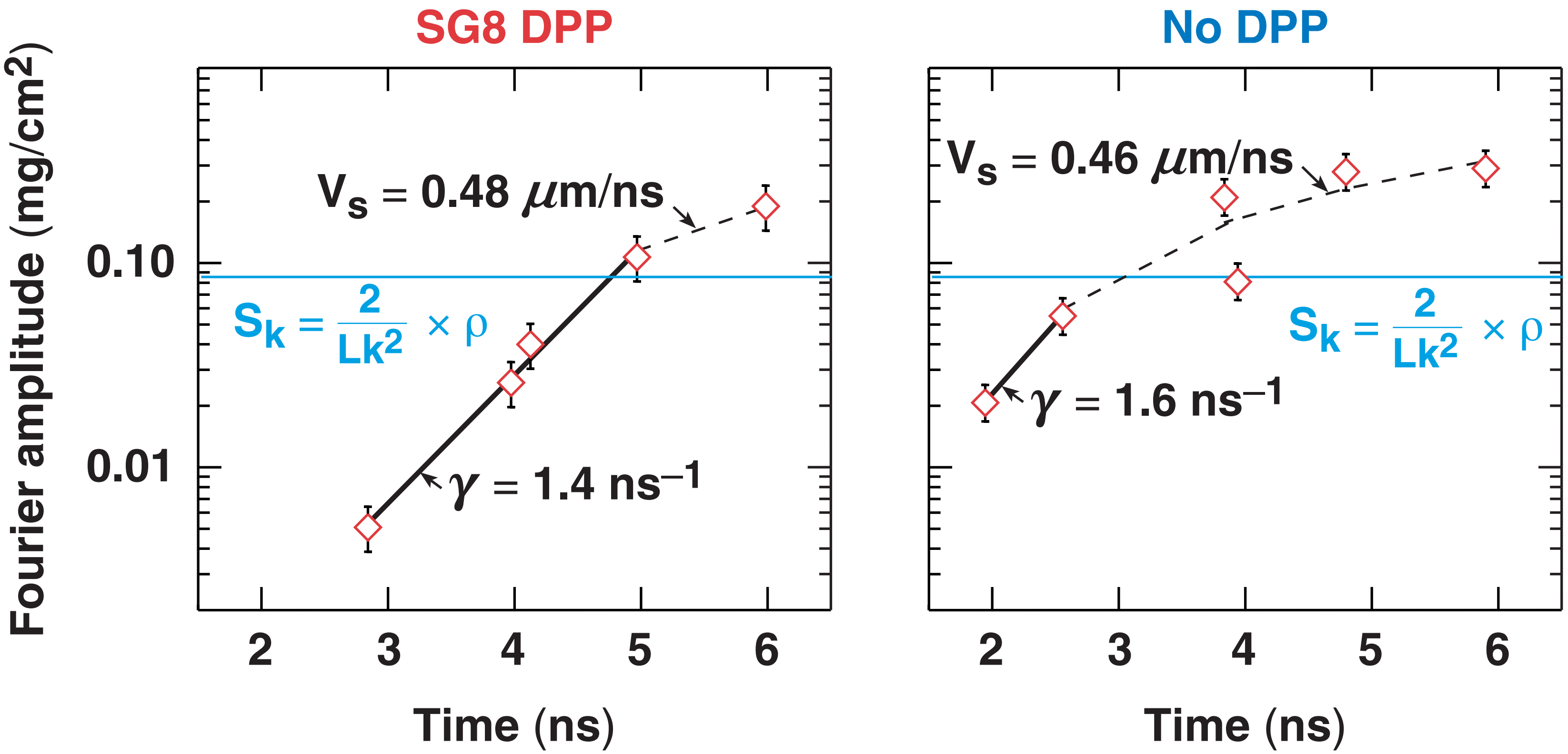
E13612a

Nonlinear velocities and growth rates were determined by fitting the experimental data at various wavelengths



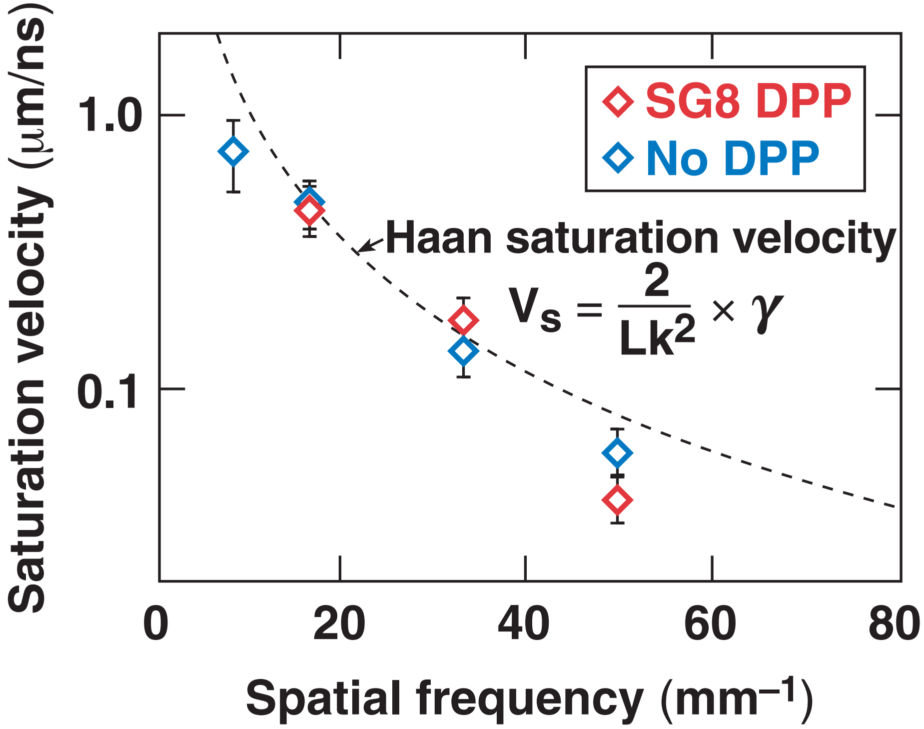
- Initial modulations were imprinted using a beam with SG8 DPP.

Saturation levels, pre-saturation growth, and post-saturation growth are insensitive to the initial spectrum



E14199

Measured nonlinear velocities are in good agreement with Haan model predictions*



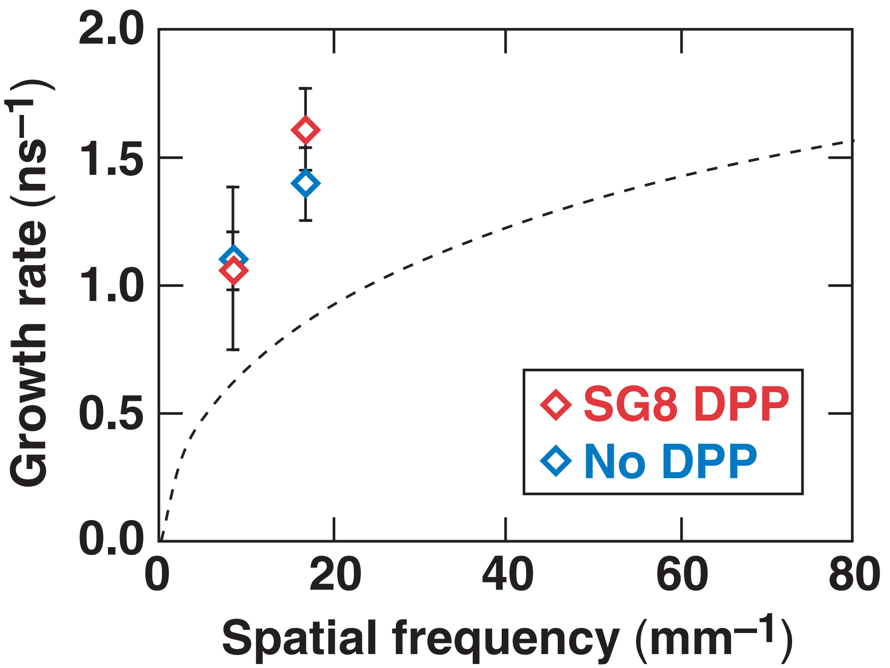
$$V_s = \frac{2}{Lk^2} \times \gamma$$

- Betti–Goncharov growth rate $\gamma = 0.94\sqrt{\frac{kg}{1+kL_m}} - 1.5\,V_a\,k$

---

*V. A. Smalyuk *et al.*, to be published in Phys. Rev. Lett. (2005).

The measured growth rates of longer-wavelength modes are higher than single-mode predictions



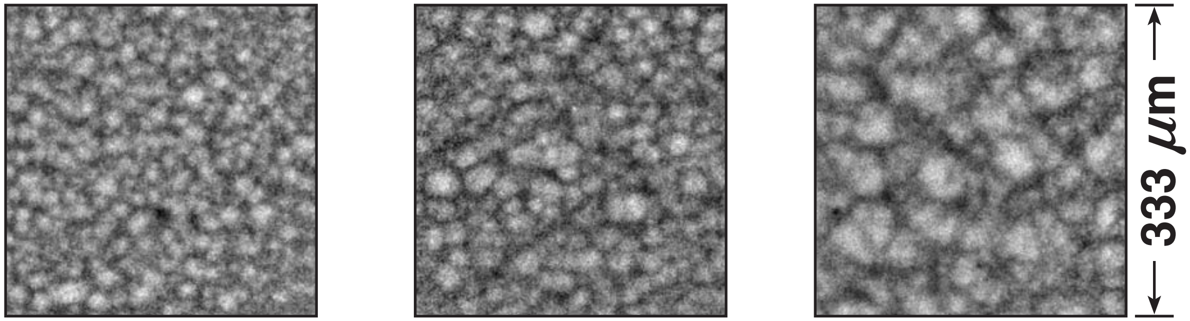
- Betti–Goncharov growth rate $\gamma = 0.94\sqrt{\frac{kg}{1 + kL_m}} - 1.5\,V_a\,k$
- S. W. Haan* and D. Ofer *et al.*** predict no significant mode coupling in the ablative case.
- J. Sanz *et al.*† predicted enhanced mode coupling in the ablative case compared to the classical case.

---

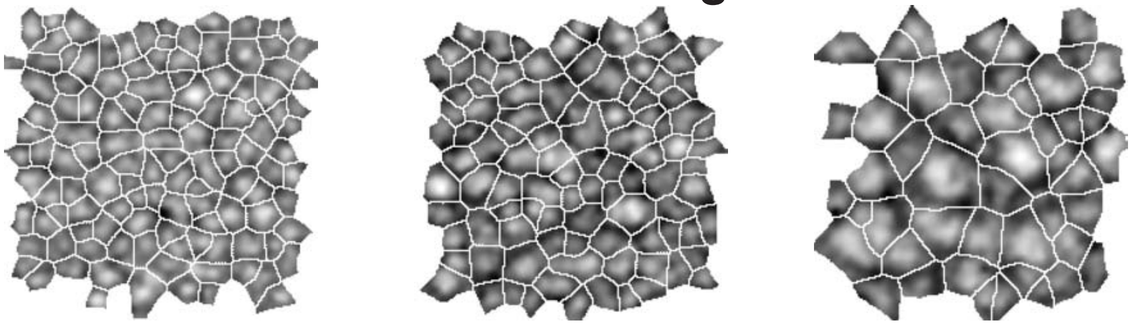
*S. W. Haan, Phys. Fluids B 3, 2349 (1991), **D. Ofer *et al.*, Phys. Plasmas 3, 3073 (1996),
†J. Sanz *et al.*, Phys. Rev. Lett. 89, 195002 (2002).

Real-space bubble competition models describe Rayleigh–Taylor evolution more naturally

Raw images



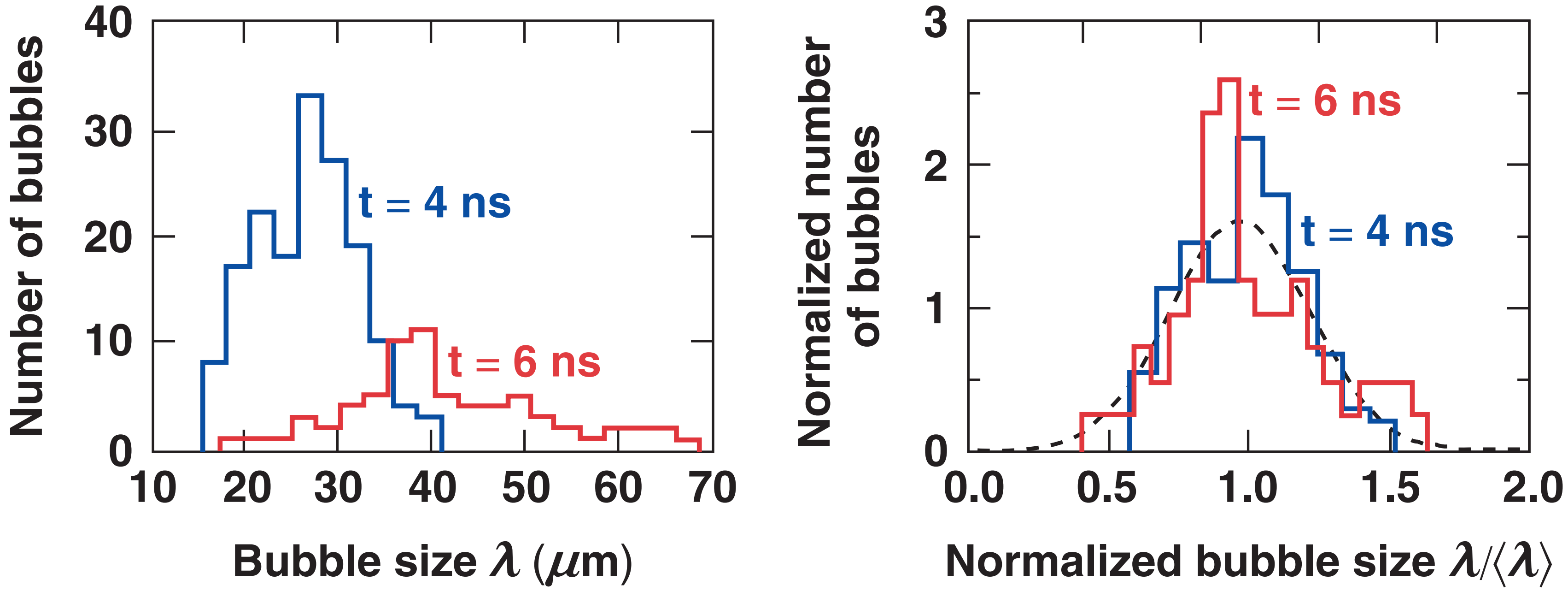
Processed images



---

*O. Sadot *et al.*, LO1.003

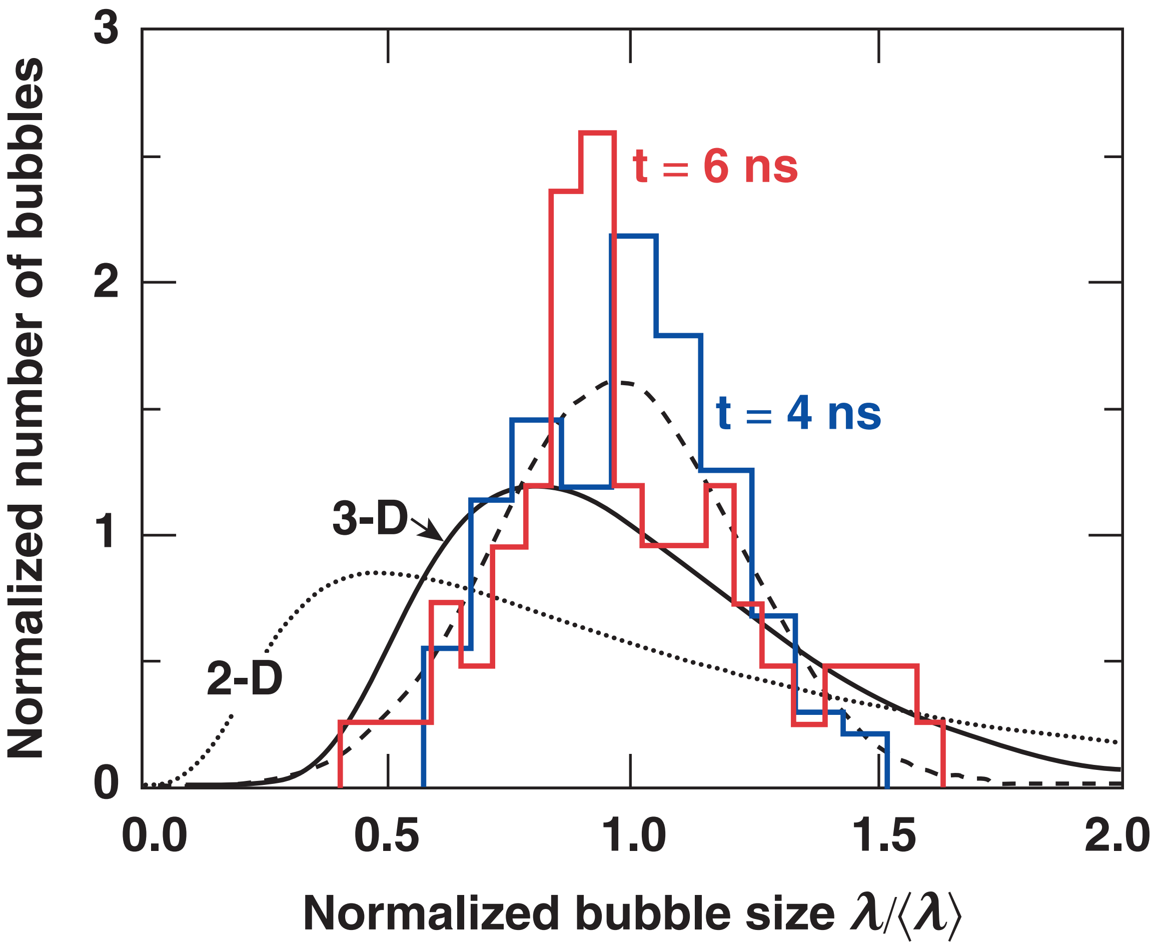
The nonlinear bubble evolution is self-similar in the nonlinear regime



Measured distributions were fit with a normal distribution function.

$$f\left(\frac{\lambda}{\langle\lambda\rangle}\right) = \frac{1}{\sqrt{2\pi}\,C_\lambda}\exp\left[-\frac{\left(\frac{\lambda}{\langle\lambda\rangle}-1\right)^2}{\sqrt{2}\,C_\lambda^2}\right], \qquad C_\lambda = 0.24 \pm 0.01.$$

Measured bubble size distributions are in better agreement with 3-D models than with 2-D models*

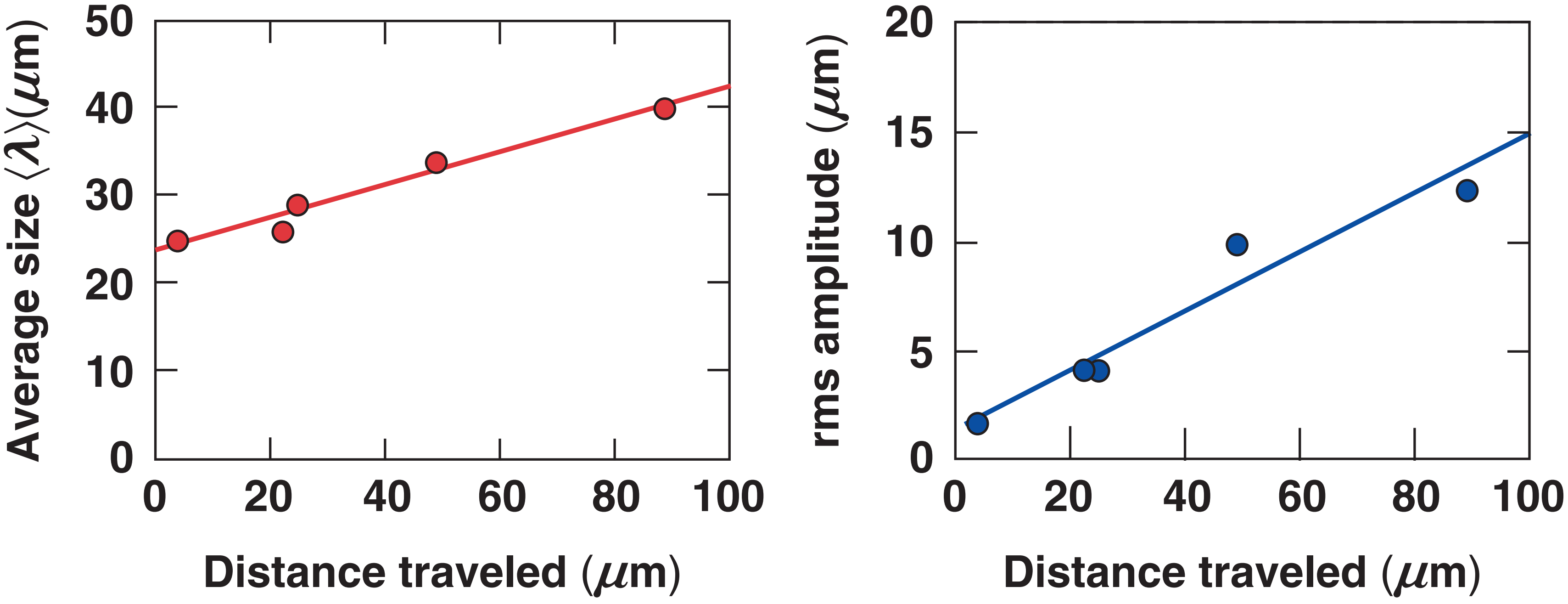


---

*D. Oron *et al.*, Phys. Plasmas 8, 2883 (2001).

In the self-similar regimes, both the average bubble size and rms amplitude grow linearly with the distance traveled

Real-Space Analysis



- **The modulation σ_{rms} grows as $\alpha_\sigma gt^2$, with $\alpha_\sigma = 0.027 \pm 0.003$.**

Measured bubble-front evolution is consistent with $\alpha_B \sim 0.04$

- $h_{bubble} \simeq \sqrt{2}\,\alpha_\sigma \cdot gt^2 = 0.04\ gt^2$
- Haan model

  $S_k = \dfrac{2}{Lk^2}$ is consistent with $\alpha_B \sim 0.035$

  if $S_k = \dfrac{4}{Lk^2}$ is consistent with $\alpha_B \sim 0.07$
- Measured ablative RT α_B is similar to classical RT α_B.*

---

*G. Dimonte *et al*., Phys. Plasmas 12, 056301 (2005).

The bubble merger is evident from the evolution of the same area of the target*

---

*O. Sadot *et al.*, LO1.003

Summary/Conclusions

The measured nonlinear Rayleigh–Taylor growth is in good agreement with theoretical models

- Direct-drive, planar through-foil radiography is analyzed in real and Fourier spaces.
- Nonlinear velocities and spectral shapes are consistent with Haan-model* predictions.
- Late nonlinear growth is relatively insensitive to initial conditions.
- The self-similar regime** of bubble size distributions was observed with the modulation σ_{rms} growing as $\alpha_\sigma gt^2$, with $\alpha_\sigma = 0.027$.

⇨ Bubble front $\alpha_B \simeq \sqrt{2} \cdot \alpha_\sigma = 0.04$ is consistent with Haan's saturation parameter $\left(S_k = \dfrac{2}{Lk^2}\right)$ and previous classical RT results.

---

*S. Haan, Phys. Rev. A <u>39</u>, 5812 (1989).

**U. Alon *et al.*, Phys. Rev. Lett. <u>74</u>, 534 (1995).