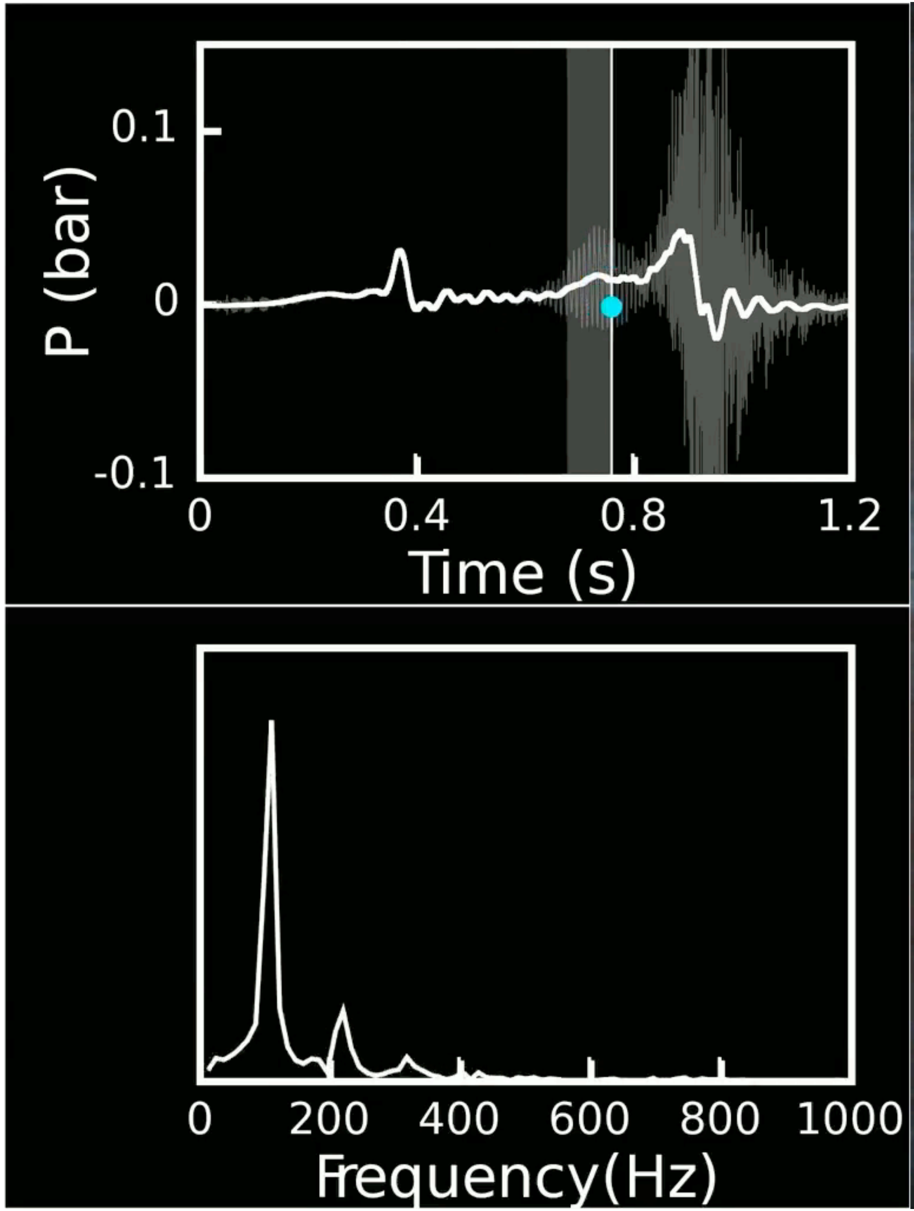
Spherical Flame Acceleration in Lean Hydrogen-Air Flames

C.R. Bauwens, J.M. Bergthorson, and S.B. Dorofeev

6th International Conference on Hydrogen Safety
Yokohama, Japan
October 21st, 2015

Accidental Explosions



Motivation – Accidental Explosions

- Flame propagation velocity key parameter to determine pressure that develop
- Cell formation can significantly increase propagation velocity
- Need a better understanding of how cells form and growth with flame
- Limited data on atmospheric pressure flames, especially at large-scale
  - Bradley et al. 2001, Kim et al., 2015

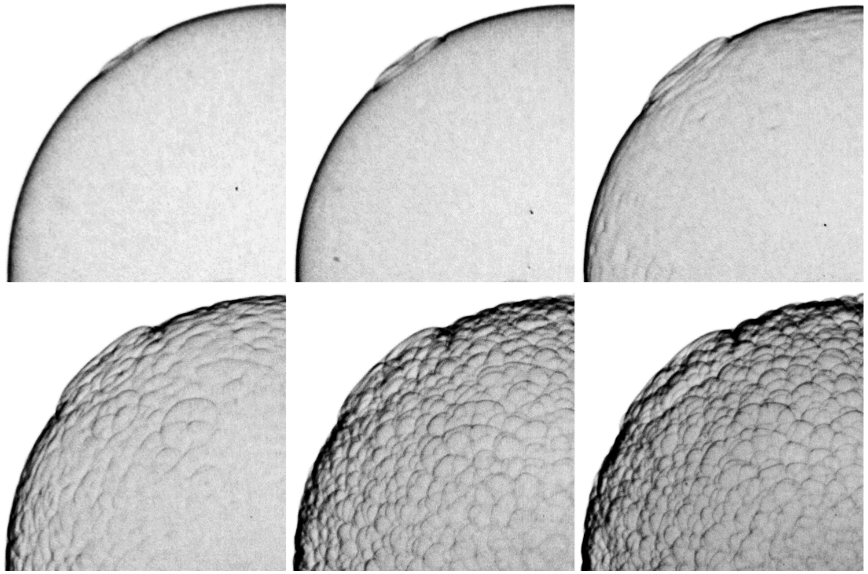
Background – Darrieus-Landau Instability

- Intrinsic instability due to expansion of burned gas

- Extensively studied
  - Experimentally
    - Manton et al. (1952), Bradley and Harper (1994), Clanet and Searby (1998), Law et al. (2005)…
  - Analytically
    - Darrieus (1938), Landau (1944), Markstein (1964), Istratov & Librovich (1969), Pelce and Clavin (1982), Bechtold and Matalon (1987)…

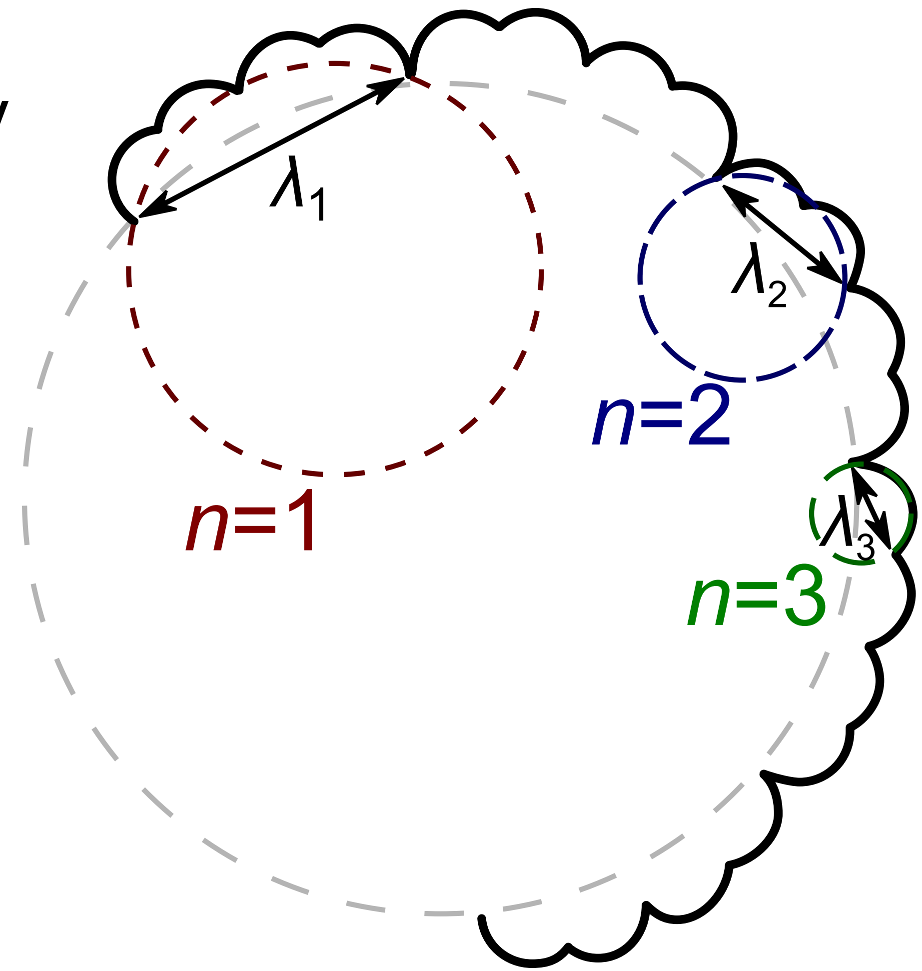
Background – Spherical Flames

- Initially flame stabilized by curvature and stretch
- At a critical radius, R_0, cells spontaneously form on flame surface
- Cell formation accompanied by rapid flame acceleration



Background – Spherical FA

- Acceleration continues indefinitely with increasing radius
- Self-similar theory
  Gostintsev et al. (1988)
  - Correlated large scale data
  - Found: $R = R_0 + At^{\alpha}$
  - Acceleration mechanism explained using fractal argument



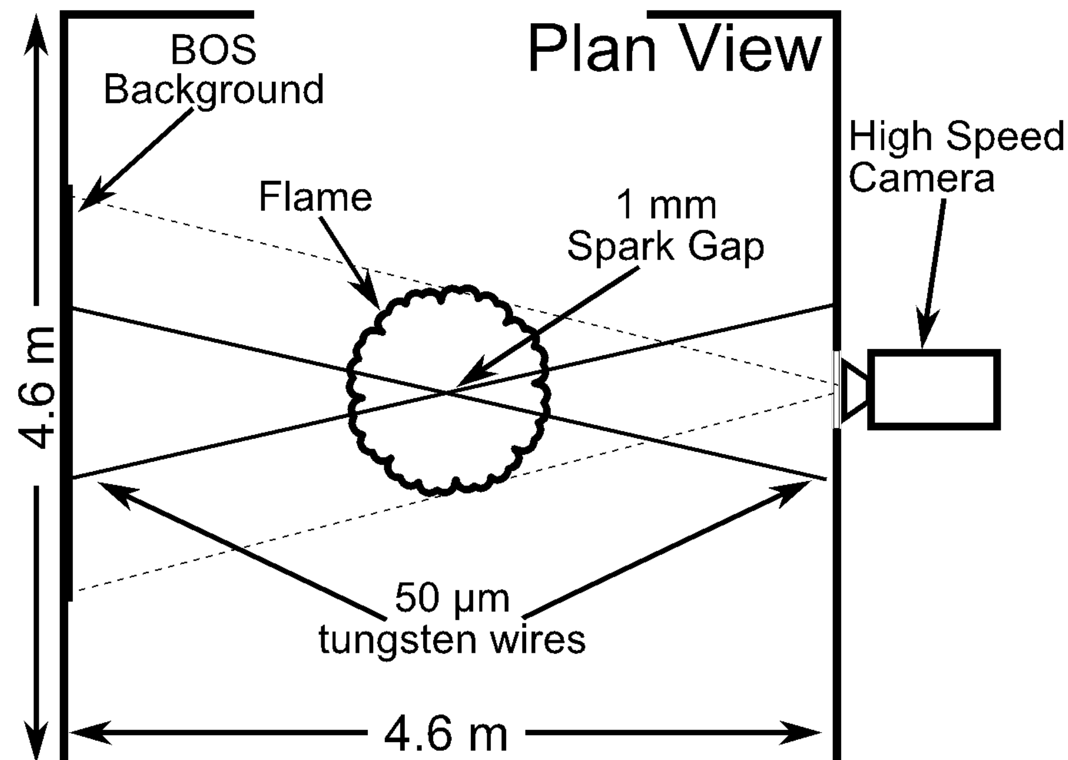
Present Study – Hydrogen-Air

- Why lean hydrogen-air?
  - Strong thermal-diffusive instability
    - Small critical radius
  - Larger increases in flame speed for the same flame size

- Examined lean hydrogen-air concentrations
  - $\phi = 0.3 - 0.6$

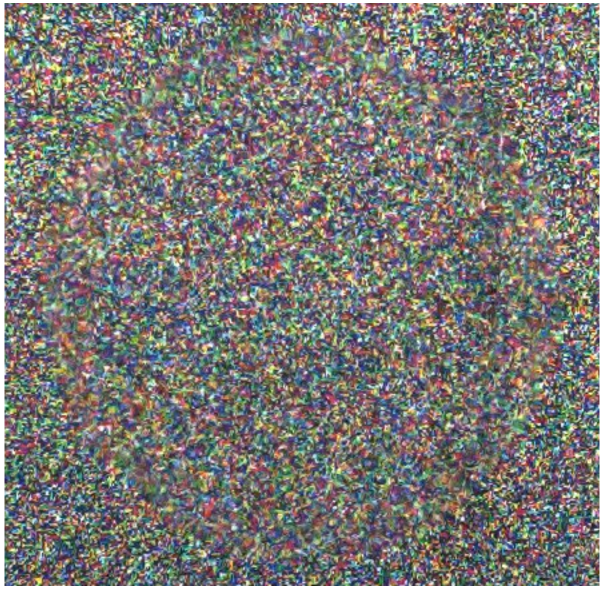
Experimental Setup

- 64 m^3 vented enclosure ($4.6 \times 4.6 \times 3\ m^3$)
- Constant pressure
- Quiescent mixtures
- Weak ignition source



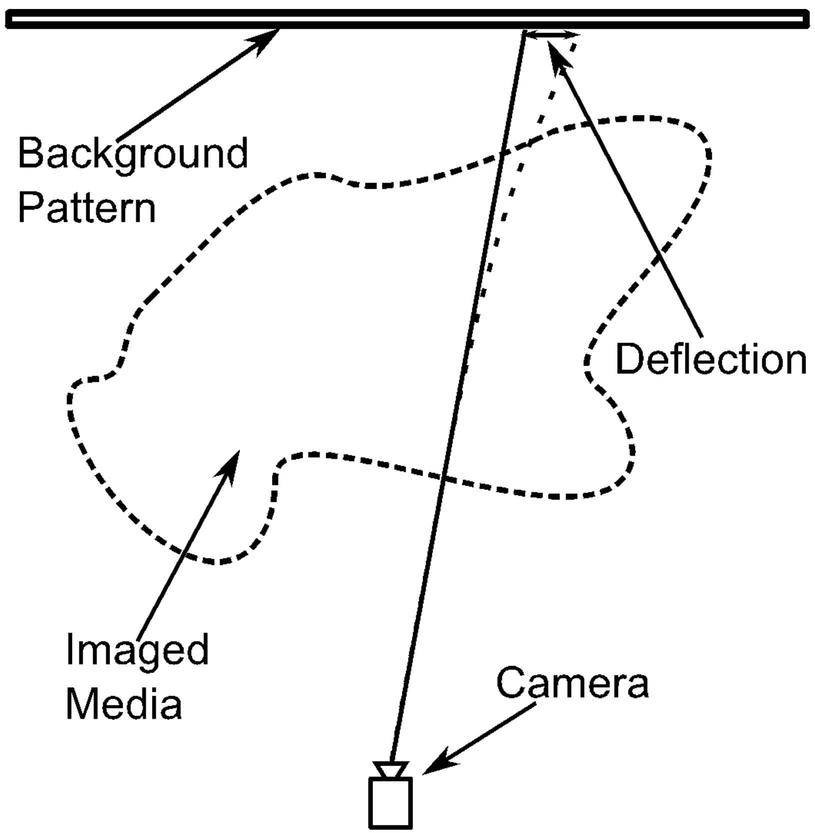
Visualizing Hydrogen-Air Flames

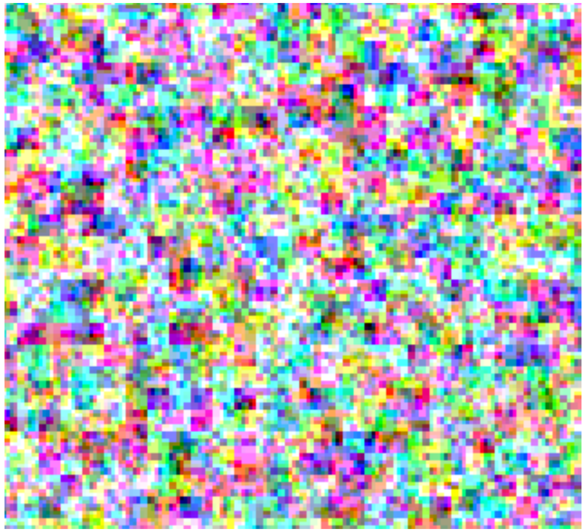
- Direct optical measurements not possible
- Traditional schlieren not feasible at large scale
- Alternate method needed



Hydrogen Flame Image

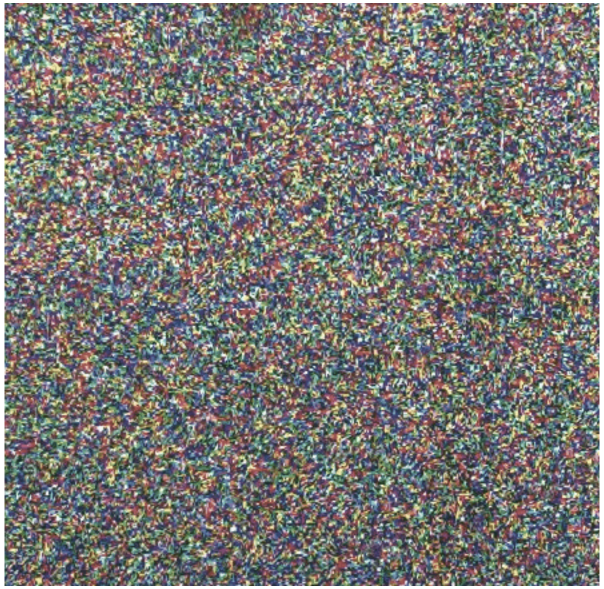
Background Oriented Schlieren



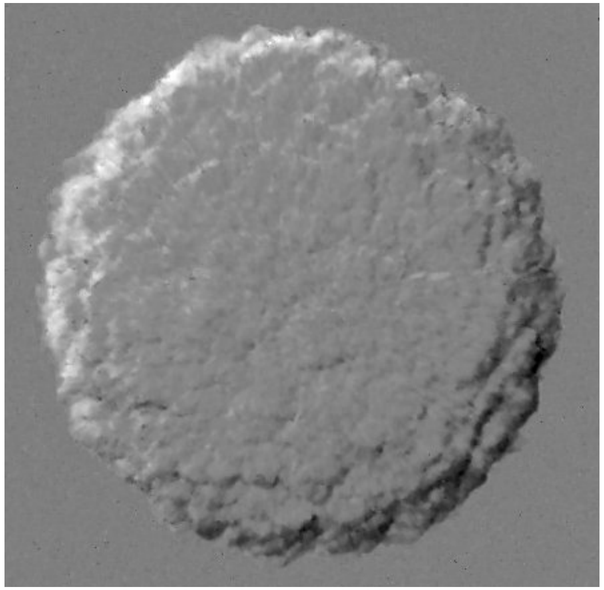


Background Pattern

Background Oriented Schlieren

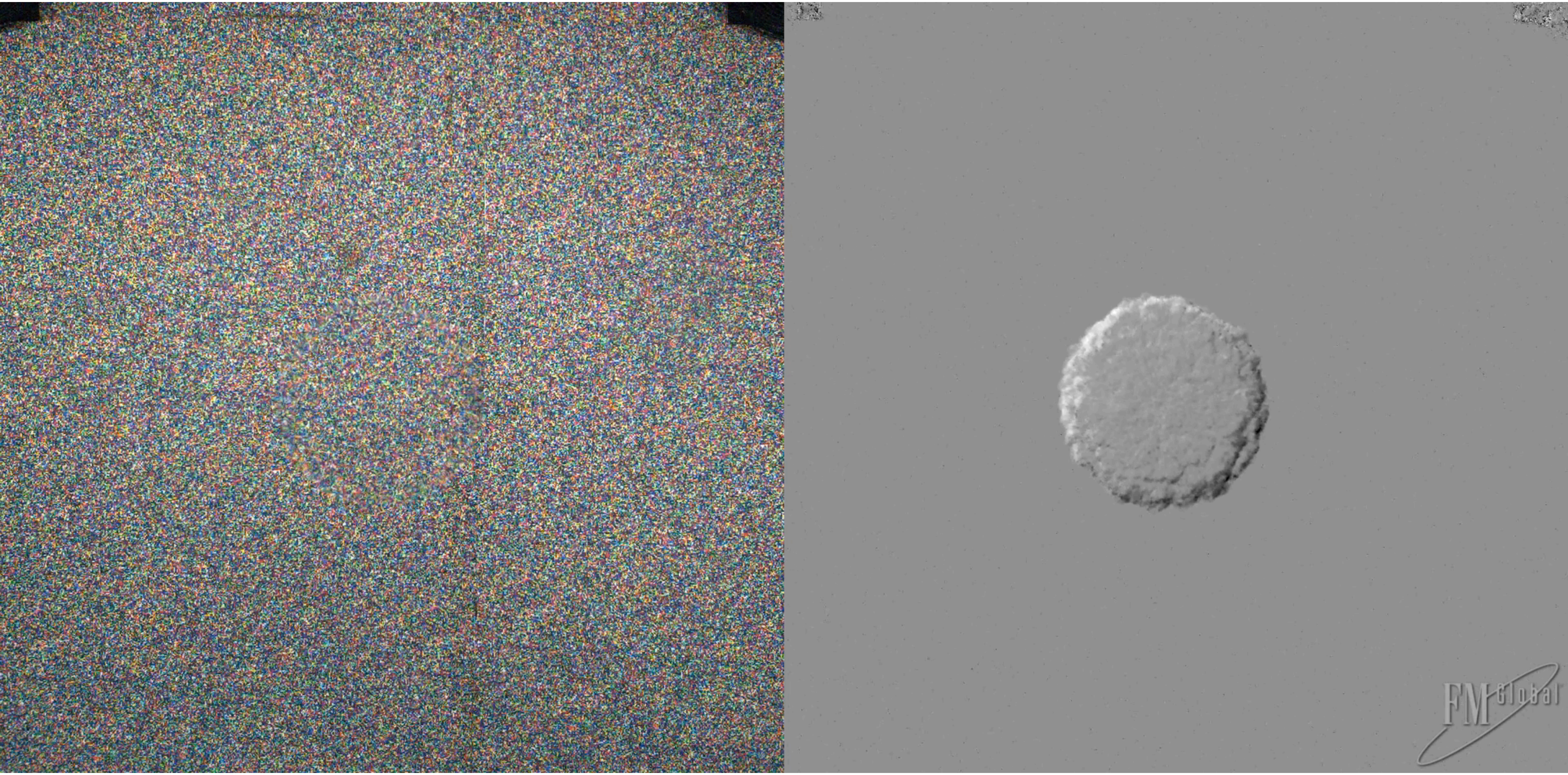


Raw Images



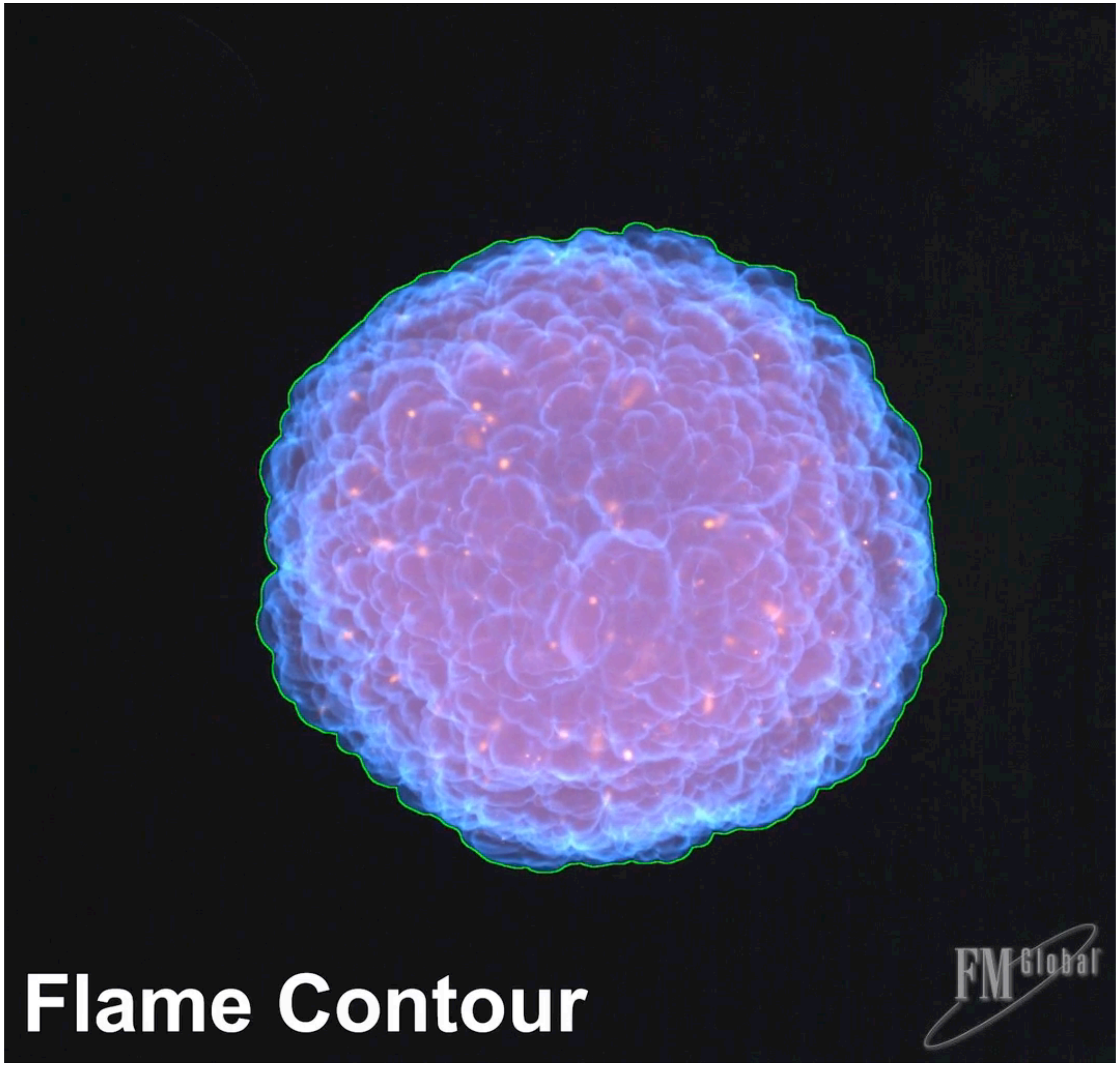
BOS Image

Background Oriented Schlieren



Front Tracking

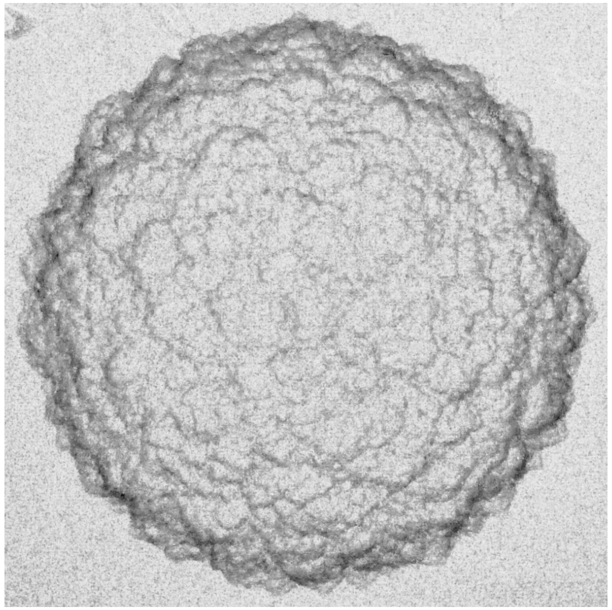
- Maximize images into virtual open shutter
- Difference images across multiple frames
- Calculate radius from flame cross-section

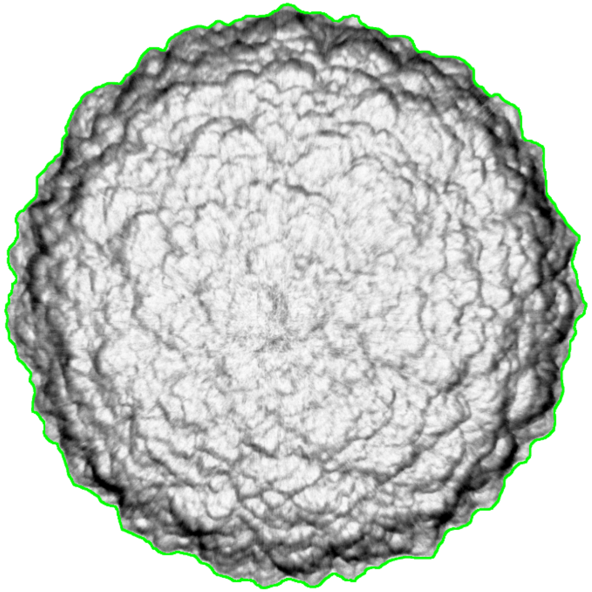


Temporal Smoothing

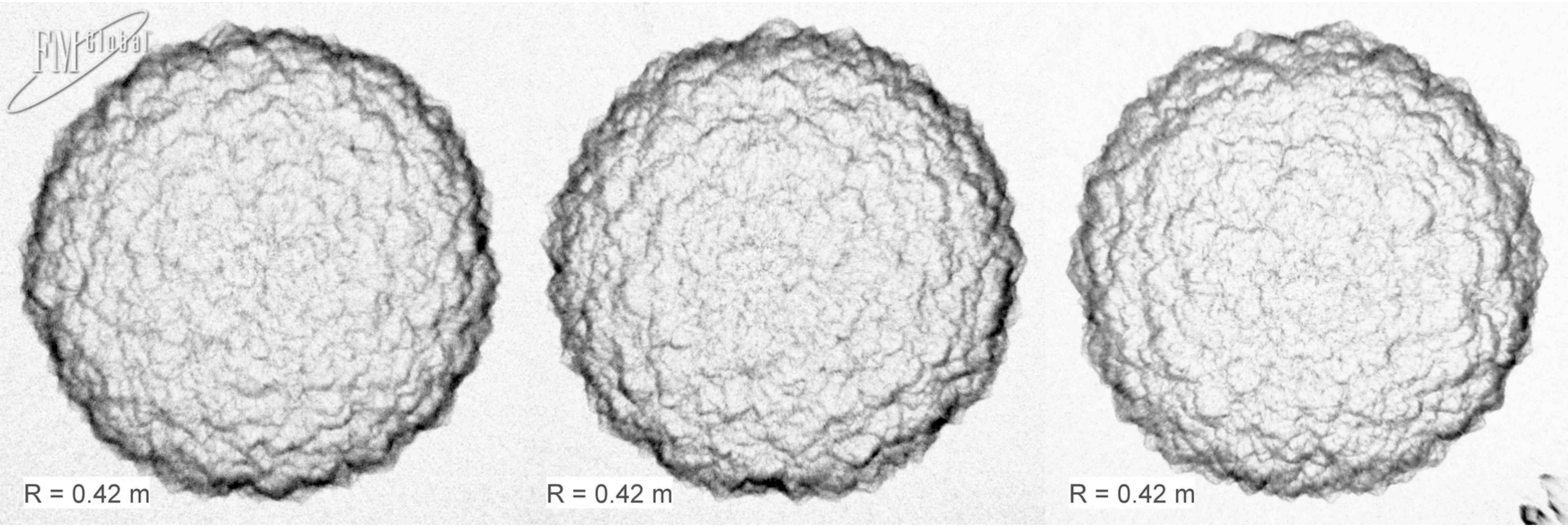
- Average flame surface over time (multiple images)

- Resize flame to a common length scale to eliminate motion blur





Effect of Concentration



$\phi = 0.33$ $\phi = 0.46$ $\phi = 0.57$

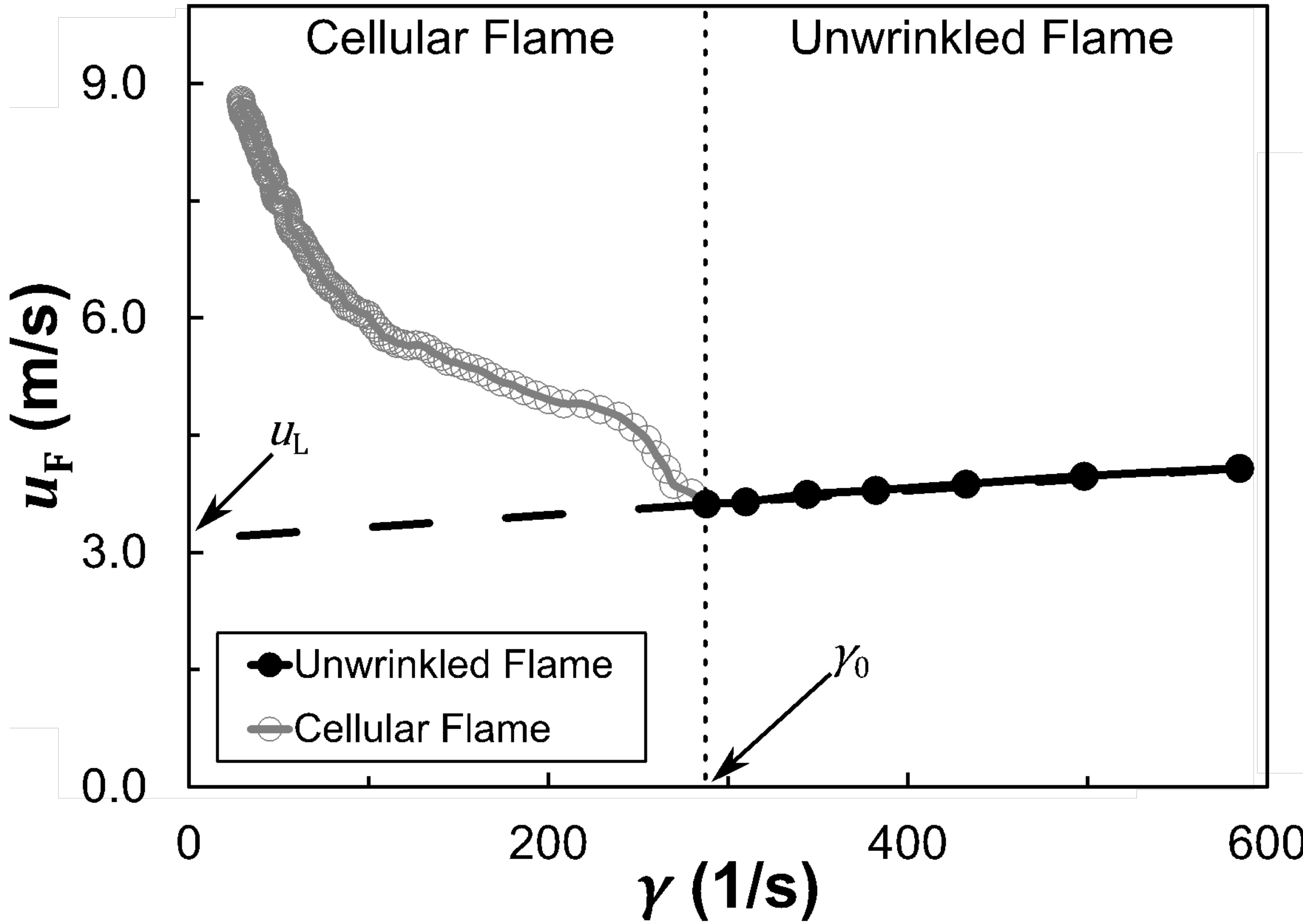
Results – Hydrogen-air $\phi = 0.49$

- Plot of flame speed vs. stretch rate

$$\gamma = \frac{2}{R}\frac{dR}{dt}$$

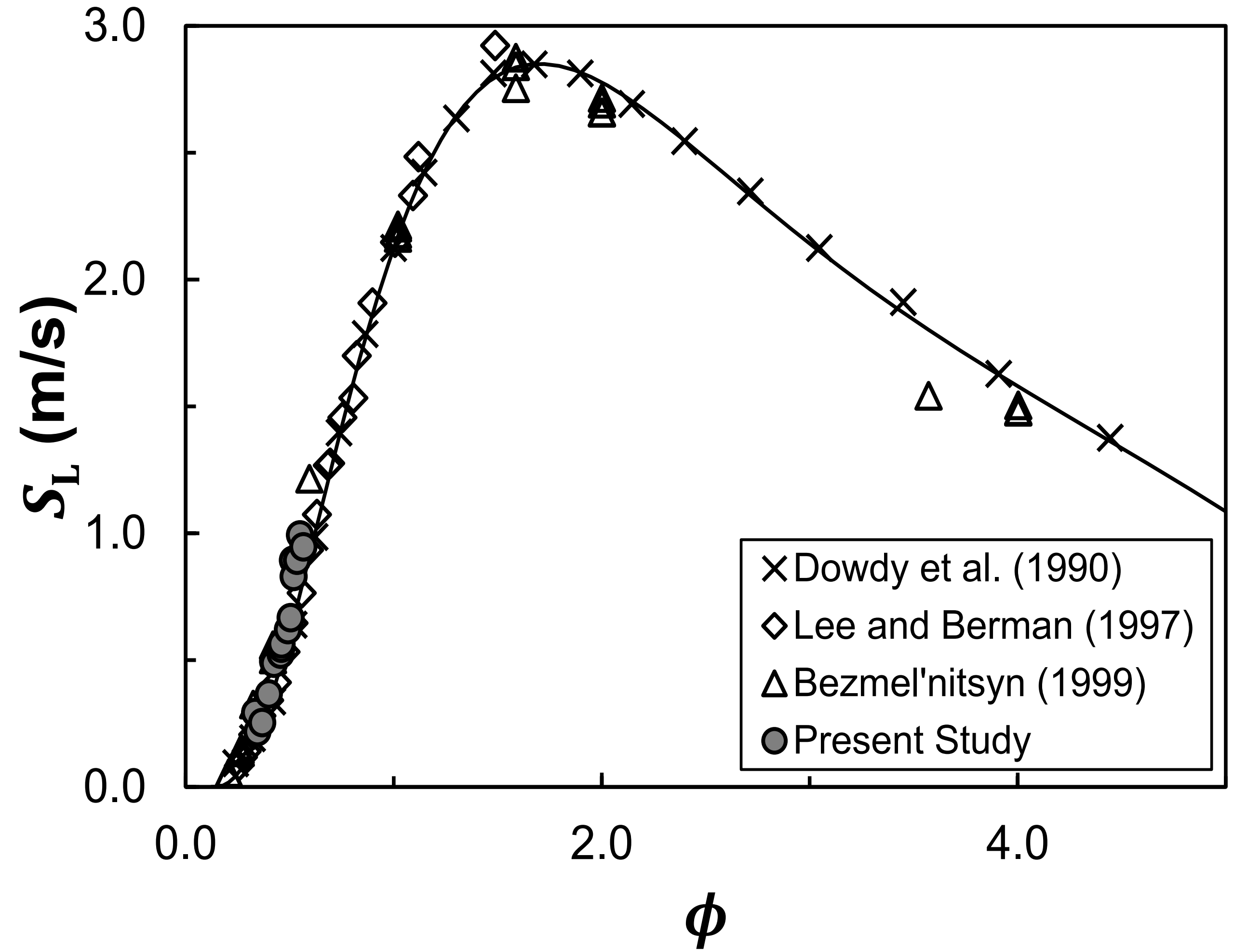
- Linear stretch extrapolation to obtain LBV

- Critical radius, R_0, from γ_0



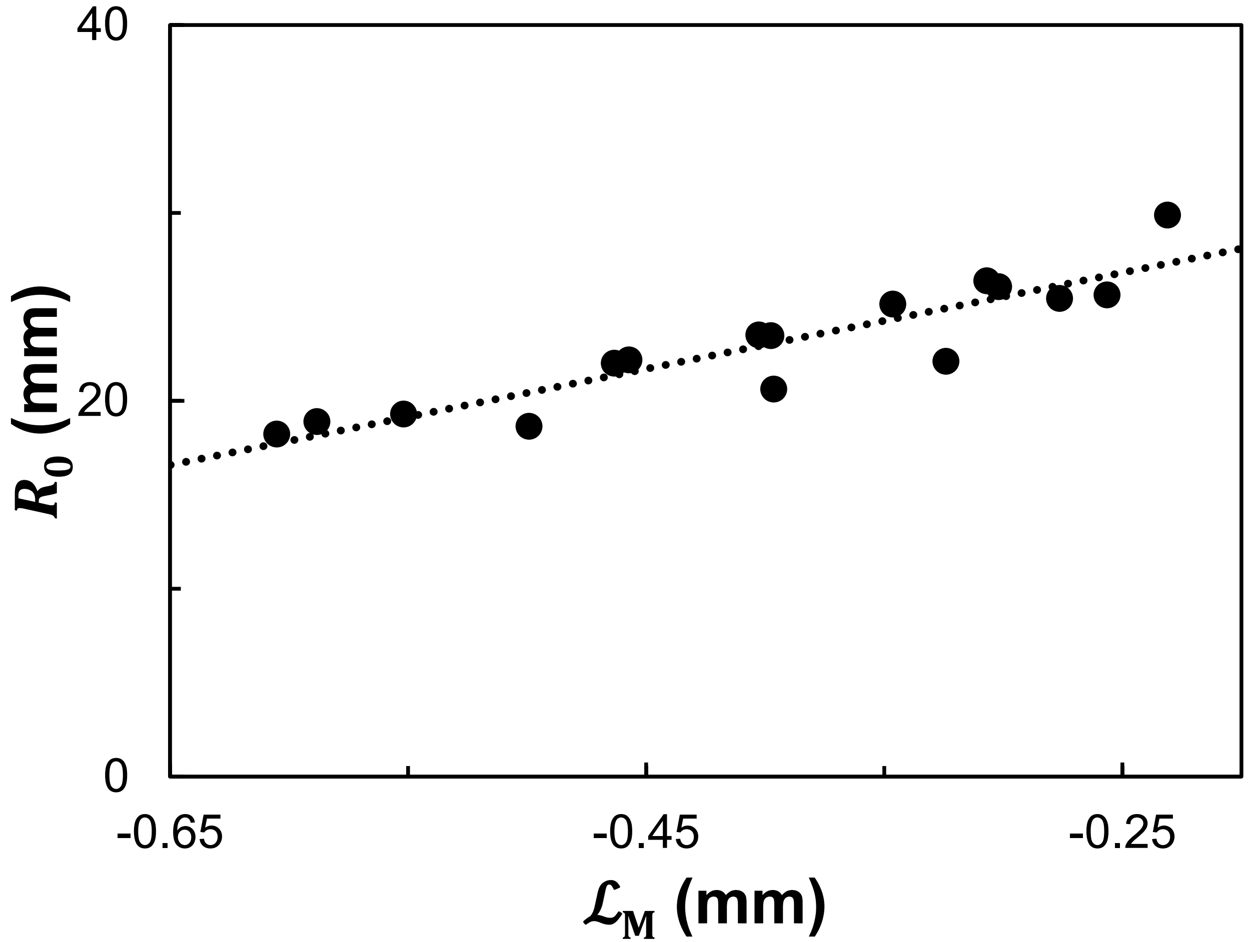
Results

- Laminar burning velocity
  - Good agreement with past studies



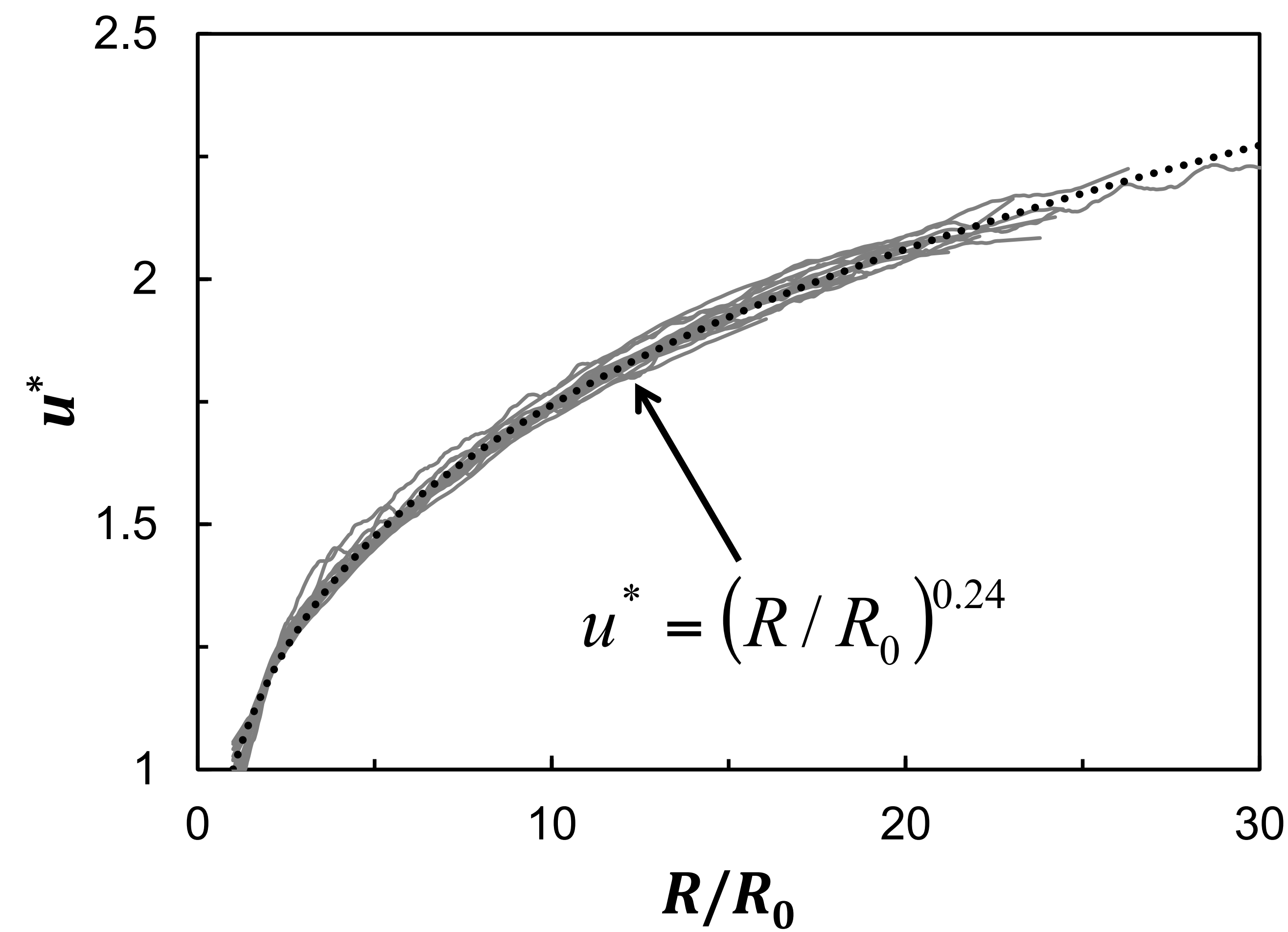
Results

- Critical radius
  - R_0 decreased linearly with $\mathcal{L}_\mathrm{M}$ (and ϕ)



Discussion

- Flame self-acceleration
  - Normalized curves all collapse to single relation
  - No oscillations observed

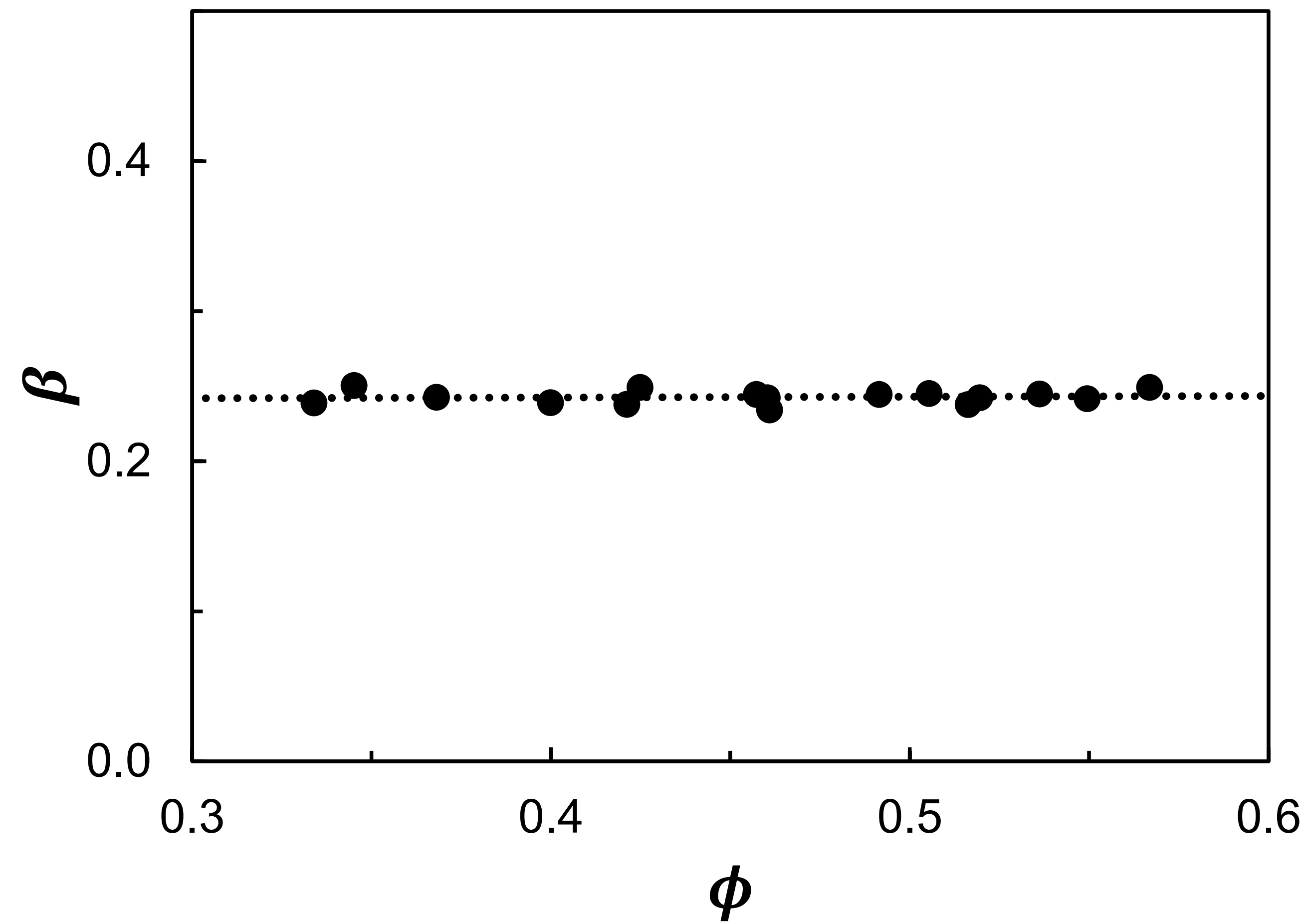


Discussion

- Fractal excess constant across full range

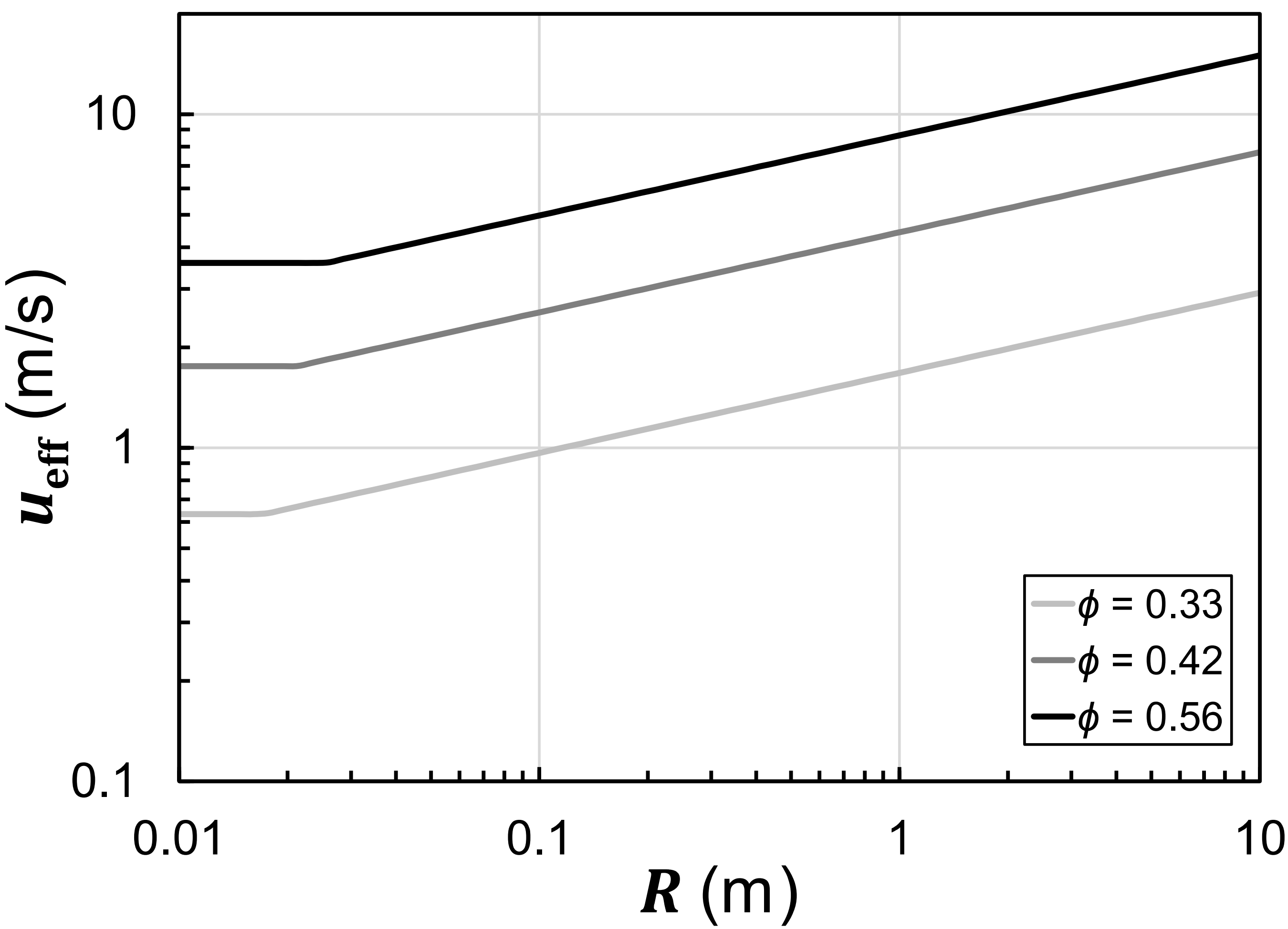
$$\beta = 0.243 \pm 0.005$$

- Equivalent to fractal exponent $\alpha = 1.32$



Discussion

- Flame self-acceleration results in large increase in u_{eff}
- Flame velocity doubles when $\mathrm{R}/\mathrm{R}_0 = 16$ $(\mathrm{R} = 0.3 – 0.5 \text{ m})$



Summary/Conclusions

- BOS used to characterize flame acceleration
  - Laminar burning velocities agrees with existing data
  - Critical radius decreases with concentration
  - Fractal excess constant across full range of concentrations studied
- Flame self-acceleration must be considered when modeling lean hydrogen-air flames at large scale
  - Laminar burning velocity alone will significantly under-predict flame speed

Questions?