

# *The Dynamics of Gas and Dust Explosions*

Ryan Houim

Associate Professor  
Purdue University

School of Mechanical Engineering  
School of Aeronautics and Astronautics

[rhouim@purdue.edu](mailto:rhouim@purdue.edu)

**Acknowledgements:**

Harsha Chelliah: NSF  
Derek Barbee: AFOSR

**Students:**

Hsiao-Chi Li  
Swagnik Guhathakurta  
Gabriel Goodwin  
Alp Ozgen



School of Mechanical Engineering

# *Unwanted combustion is still a menace to society*

**Imperial Sugare Refinery,  
Port Wentworth GA, 2004**



**Buncefield, UK 2005**

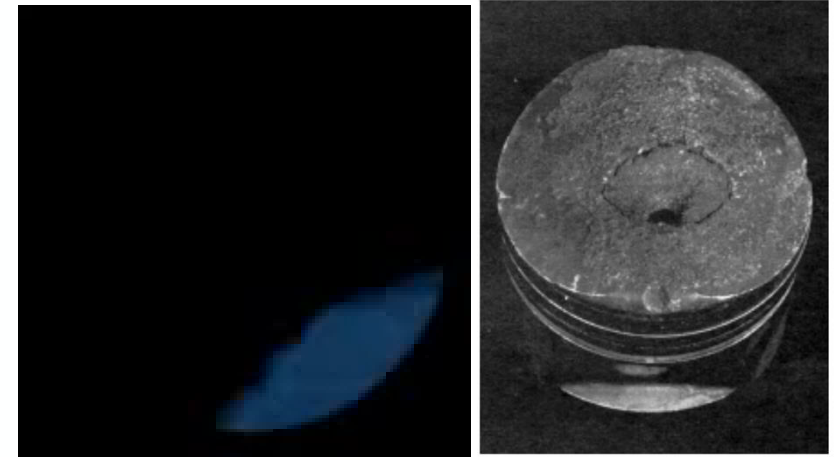
**Color Play Asia incident, June 2015**



- Music festival at a Taipei water park
- Dispersed colored cornstarch dust
- Cornstarch dust cloud ignited by a stage light
- Resulted in 15 deaths and 496 injuries.

**Premature ignition in IC engines (knock)**

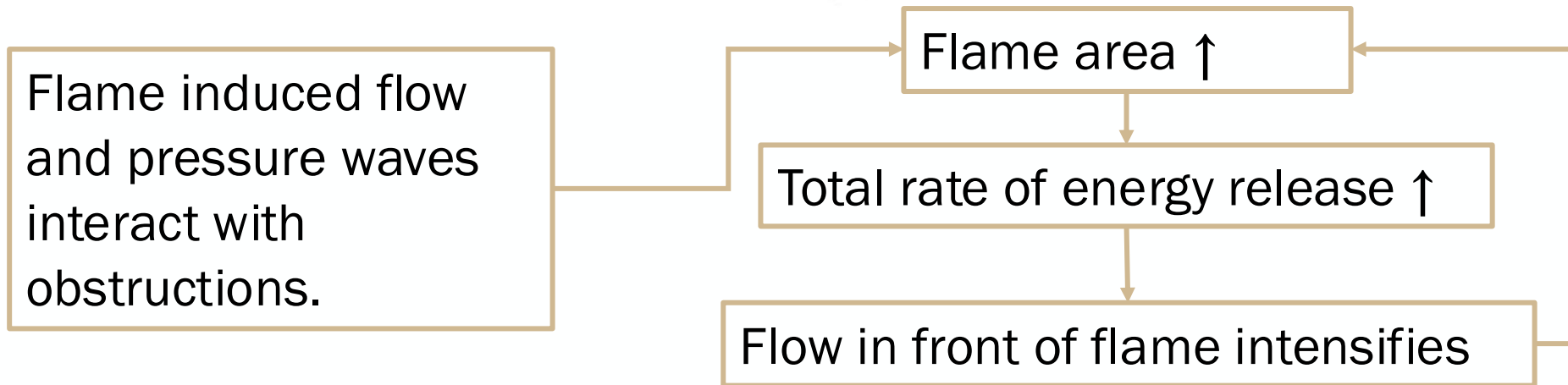
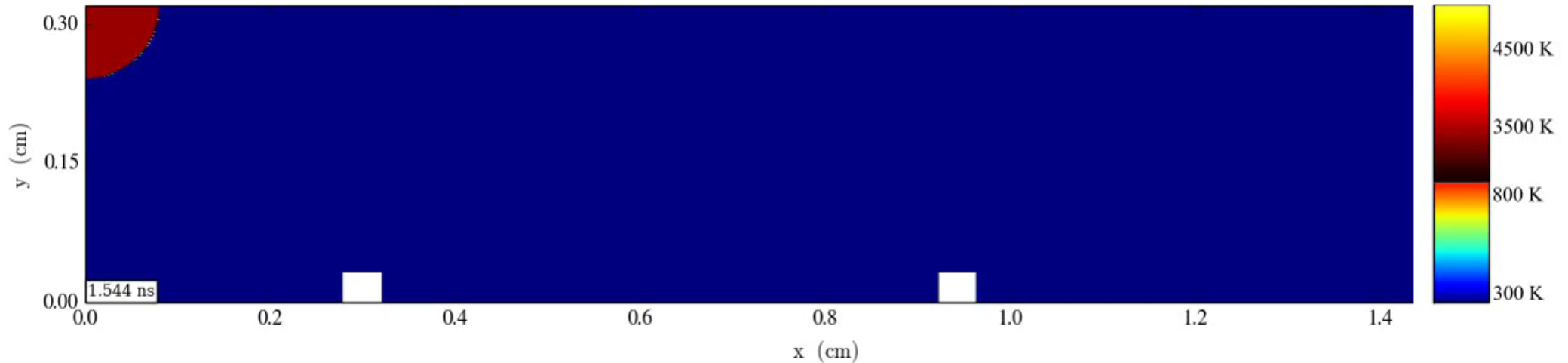
<https://www.youtube.com/watch?v=ytnF89VkUxM>



- Resembles many processes in gas explosions
- Ignition of gas in front of main flame.
- Transition to detonation (super knock) in extreme cases

# Gas phase explosion feedback loop

$C_2H_4/O_2$  premixed flame propagation in an obstacle-laden channel.



Houim, Ozgen, Oran, *Combust. Theor. Model*, 2016

Goodwin, Houim, Oran, *Proc. Combust. Inst.*, 2017

Goodwin, Houim, Oran, *Combust. Flame*, 2016

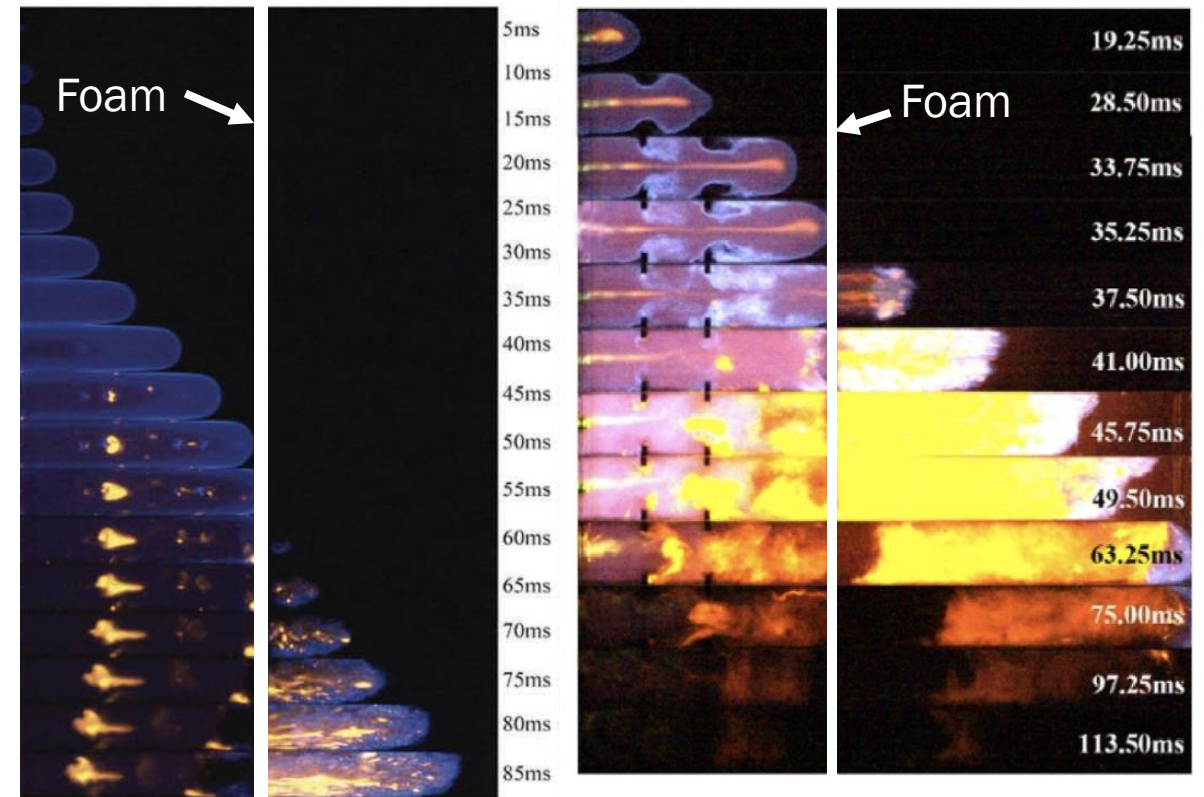
# ***Metal foams are used to quench unwanted flames***

- Placed in piping systems where explosion hazards are a concern.
- Quench flames by extracting sensible energy from the reaction zone.
- Usually characterized by Pores-per-inch (PPI)



# *The quenching performance of foams are dependent on explosion dynamics*

- Duan *et al.*<sup>1,2</sup> performed experiments on quenching of accelerating of CH<sub>4</sub>-air flames
  - Varied placement of the foam, width, PPI, etc.
  - 40 PPI foams quenched all CH<sub>4</sub>-air flames.
- Fong *et al.*<sup>3</sup> found that flame acceleration influence foam performance
  - 60 PPI foams were needed to quench extreme accelerations



Interaction accelerating CH<sub>4</sub>-air flame with a 20 PPI foam (Left) no obstacles [1] and (Right) Two rows of fence-style obstacles [3].

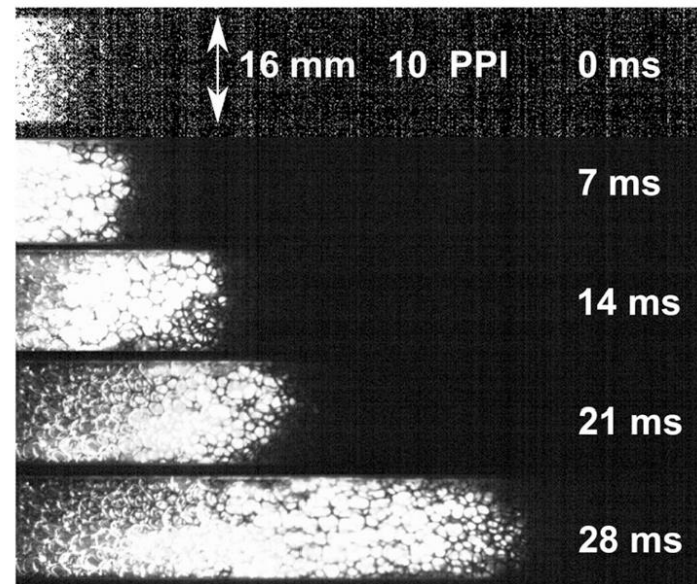
<sup>1</sup>Duan *et al.* *Combust, Sci, Tech.* 2021

<sup>2</sup>Duan *et al.*, *J Loss Prevent Proc Ind.*, 2021

<sup>3</sup>Fong *et al.*, *J Loss Prevent Proc Ind.*, 2022

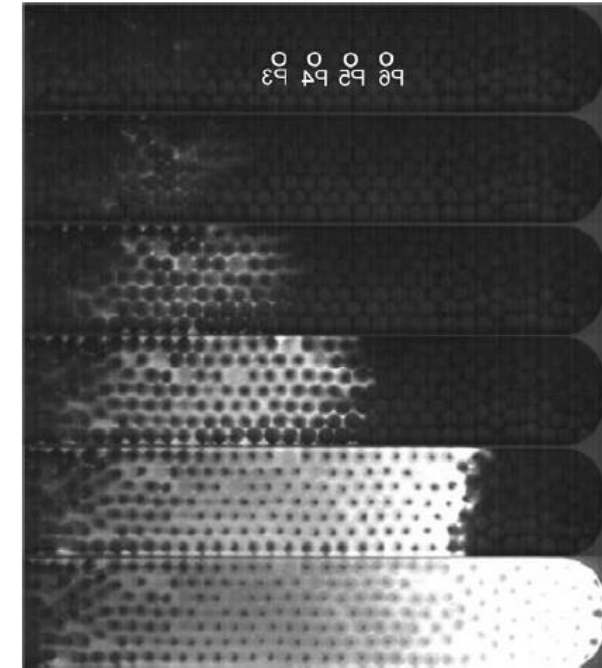
# Experimental results show that poorly chosen foams may exacerbate explosions

- Bivol *et al.*<sup>1</sup> found that 10 PPI foams can accelerate H<sub>2</sub>-air and C<sub>2</sub>H<sub>2</sub>-air flames.
  - *Worsened* explosion and increased pressure.
- Ciccarelli *et al.*<sup>2</sup> found that flames can accelerate to form a shock flame complex inside porous materials.
  - Flame accelerated due to turbulence and jetting-like effect between pores.
  - Pressure piled up near flame to produce a shock.



120 mm

Acceleration of a  $\phi = 0.7$  H<sub>2</sub>-air flame in a 10 PPI foam.<sup>1</sup>



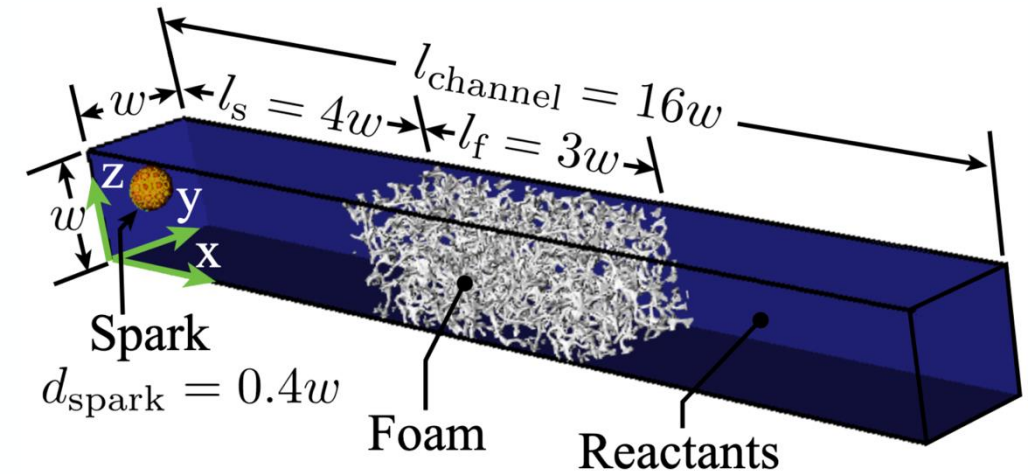
Acceleration of a  $\phi = 1$  H<sub>2</sub>-air flame to a quasi-detonation a porous structure made of solid beads.<sup>2</sup>

<sup>1</sup>Bivol *et al.* *Proc. Safety Environ. Protect.* 2021

<sup>2</sup>Ciccarelli *et al.*, *Proc. Combust. Inst.* 2011

# *Simulations of accelerating flame interacting with a metal foam were performed.*

- Published in Li, Houim, *Combust. Flame*, 2024
- A hemispherical spark ignites a flame that accelerated and interact with a resolved foam.
- Reactants are stoichiometric H<sub>2</sub>-air or H<sub>2</sub>-O<sub>2</sub>
- Foam geometry is embedded using immersed boundary methods.
- Foam surface is rigid, isothermal at 300 K, no-slip, and non-catalytic.
- Detailed chemical reactions\* (11 species and 25 reactions)
- Adaptive mesh refinement using AMReX.
- Governing equations solved using fifth-order MUSCL.

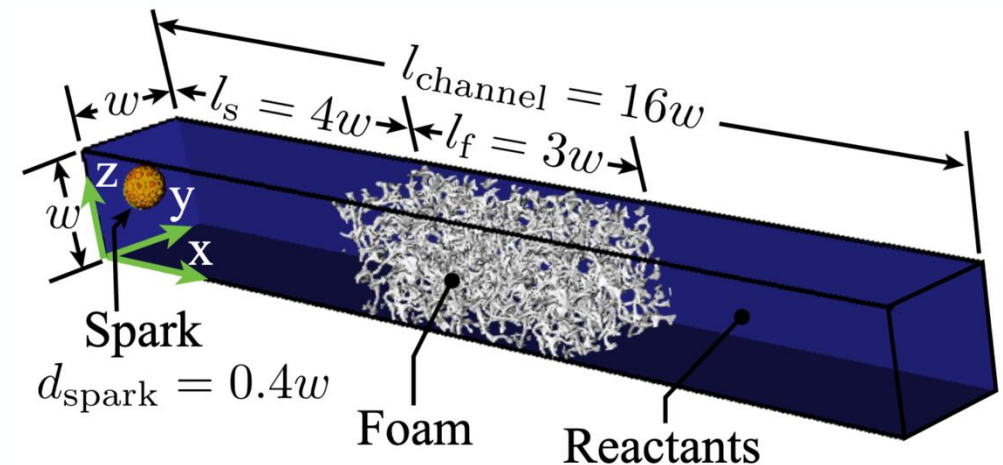
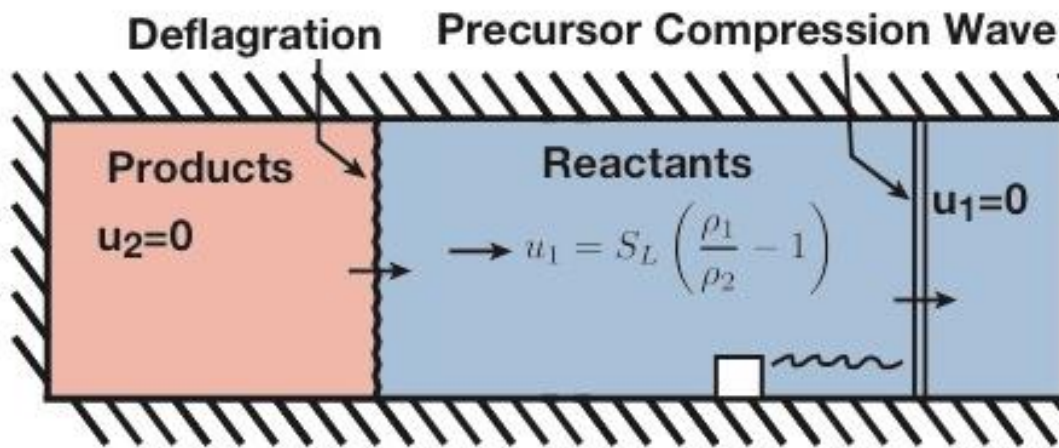


\*Burke et al. *Int. J. Chem. Kin.* 2011

# Six cases simulated to explore channel width, reactant mixture. All lengths scaled by channel width.

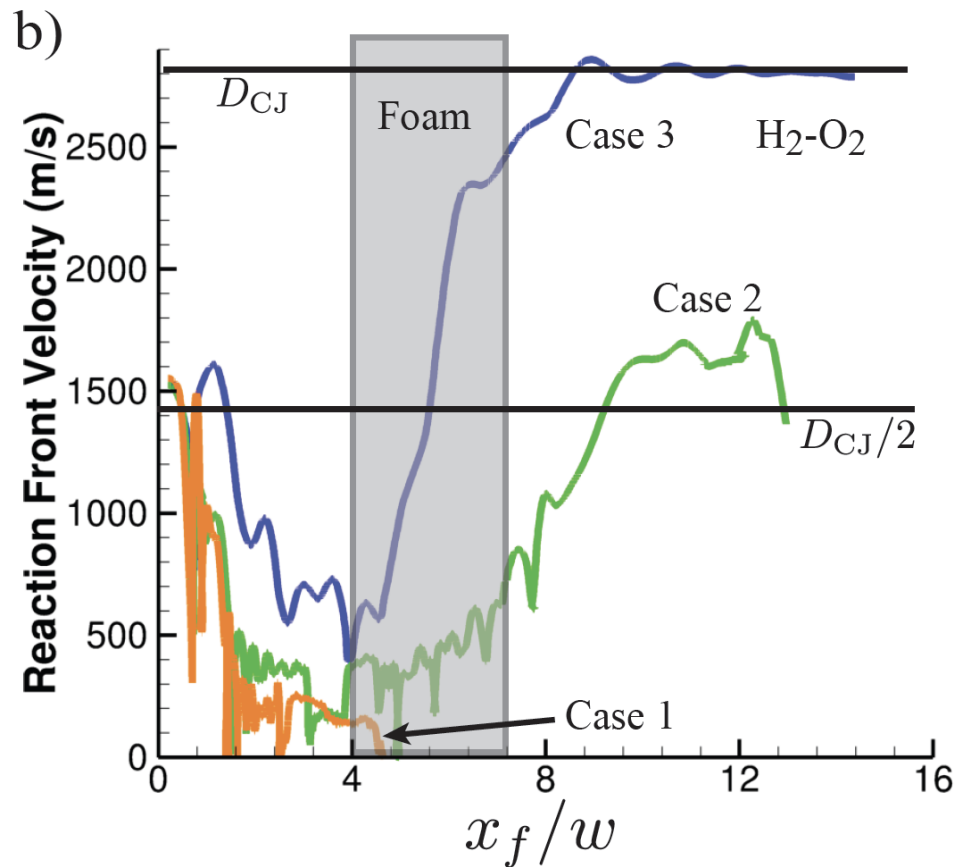
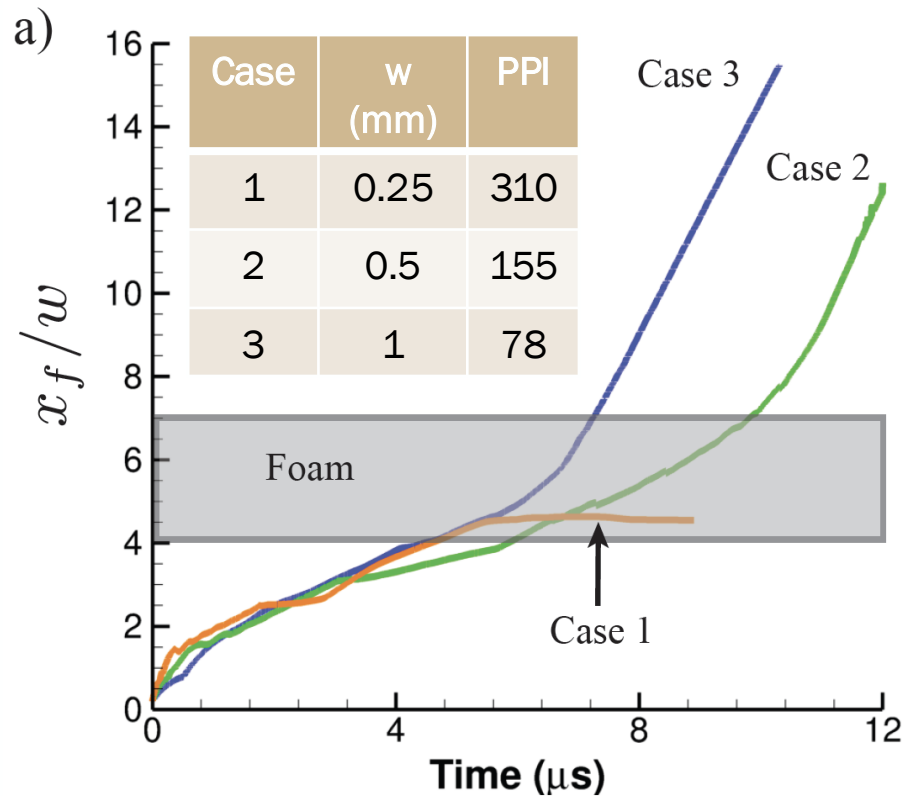
- Laminar flow in unobstructed channel
- All turbulence generated from foam.

Case	Mixture	w (mm)	PPI	$\delta_L/\Delta x$	$d_{\text{strut}}/\Delta x$	$Re_{\text{strut}}$	$Re_w$
1	H <sub>2</sub> -O <sub>2</sub>	0.25	310	244	8.6	17	506
2	H <sub>2</sub> -O <sub>2</sub>	0.5	155	122	8.6	34	1012
3	H <sub>2</sub> -O <sub>2</sub>	1	78	60	8.6	68	2024
4	H <sub>2</sub> -Air	1	78	92	8.6	23	670
5	H <sub>2</sub> -Air	2	39	46	8.6	45	1340
6	H <sub>2</sub> -Air	4	19	22	8.6	90	2680

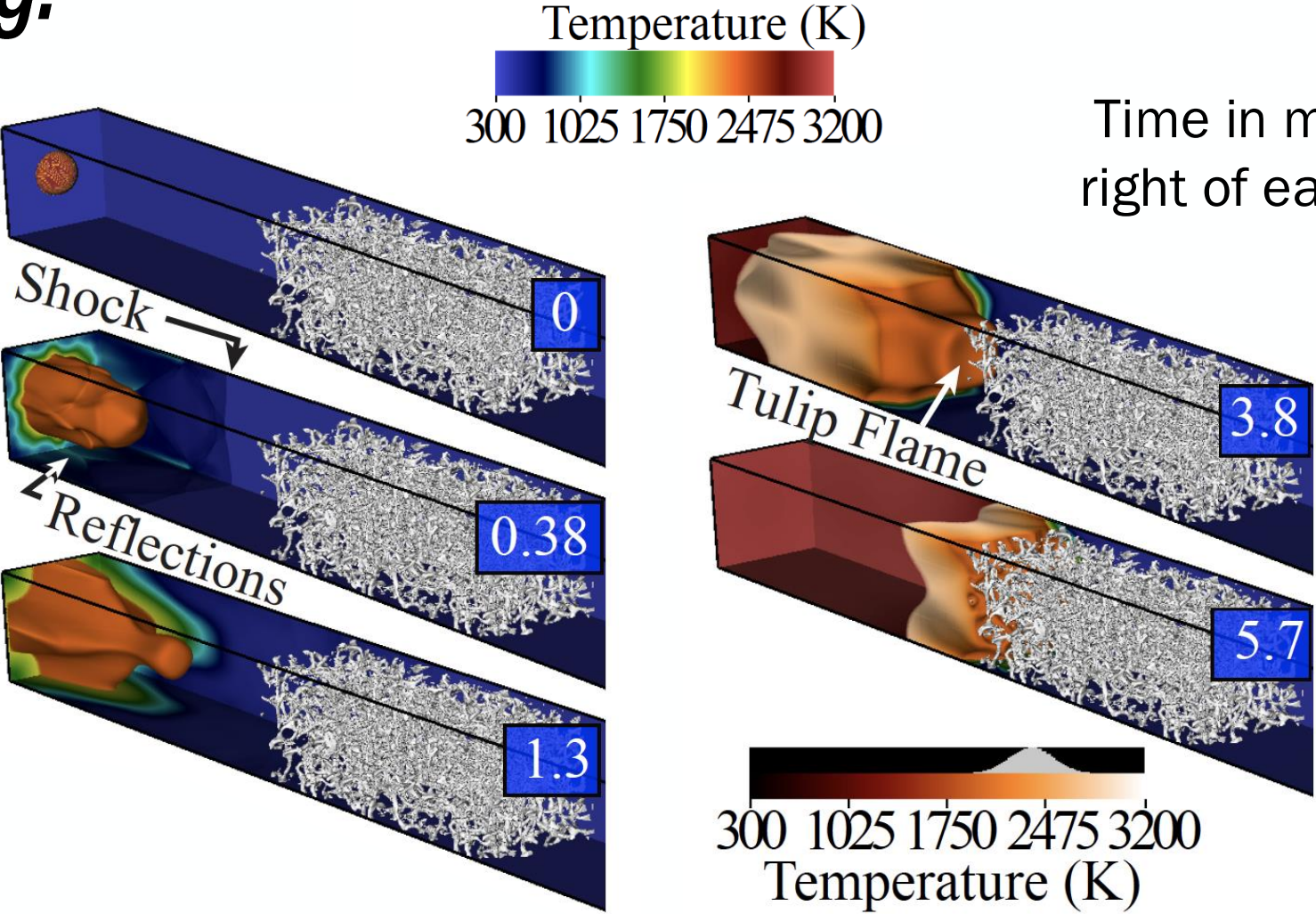


**Results for  $H_2-O_2$  flames show that the foam can either quench the flame, induce massive acceleration, or initiate a detonation.**

$H_2-O_2$

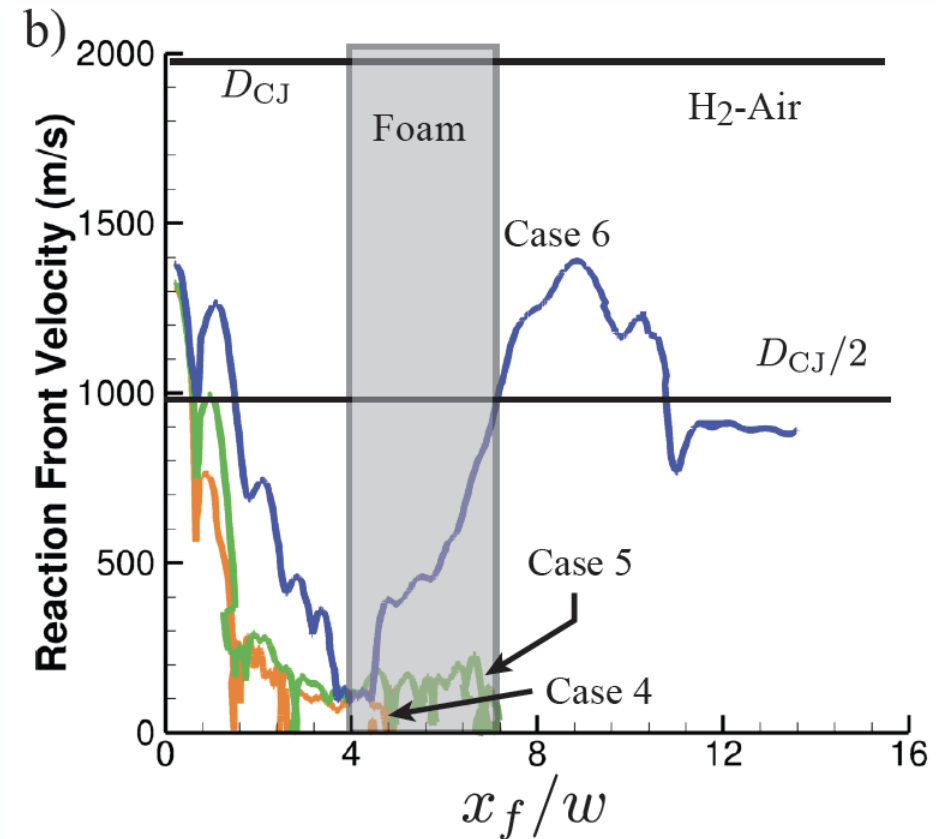
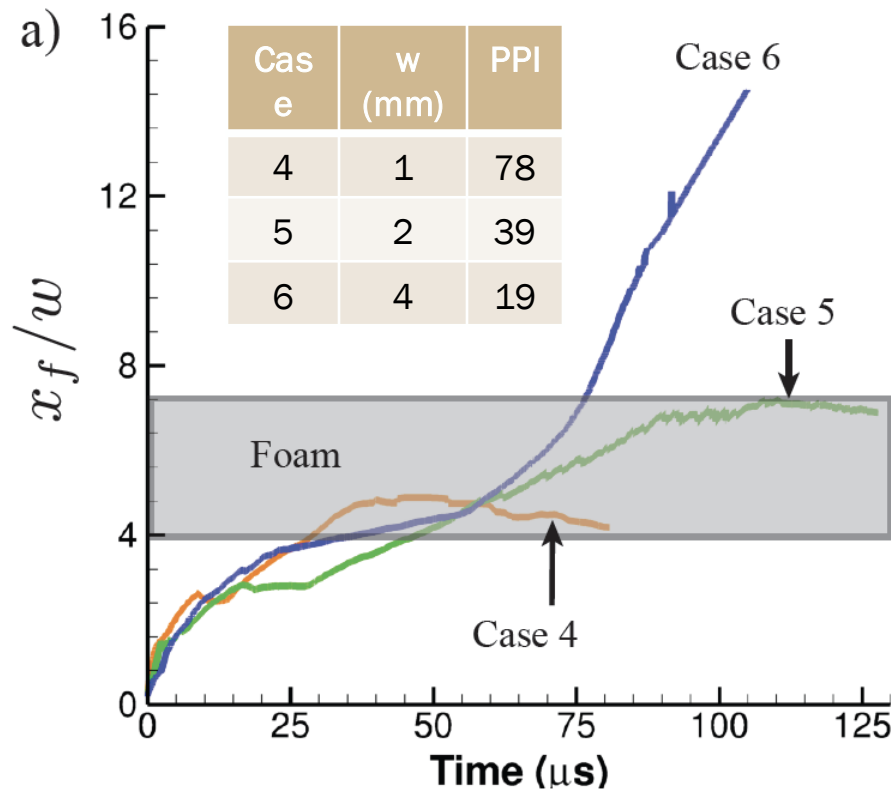


# Results for $H_2-O_2$ flame through a 310 PPI foam show rapid quenching.

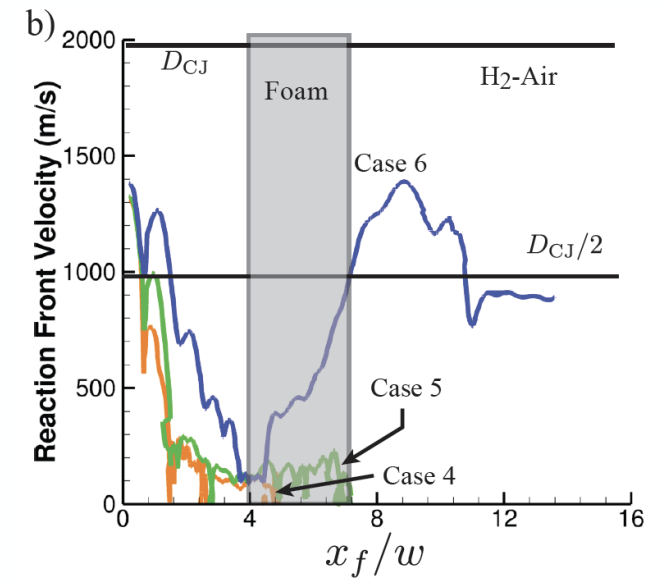
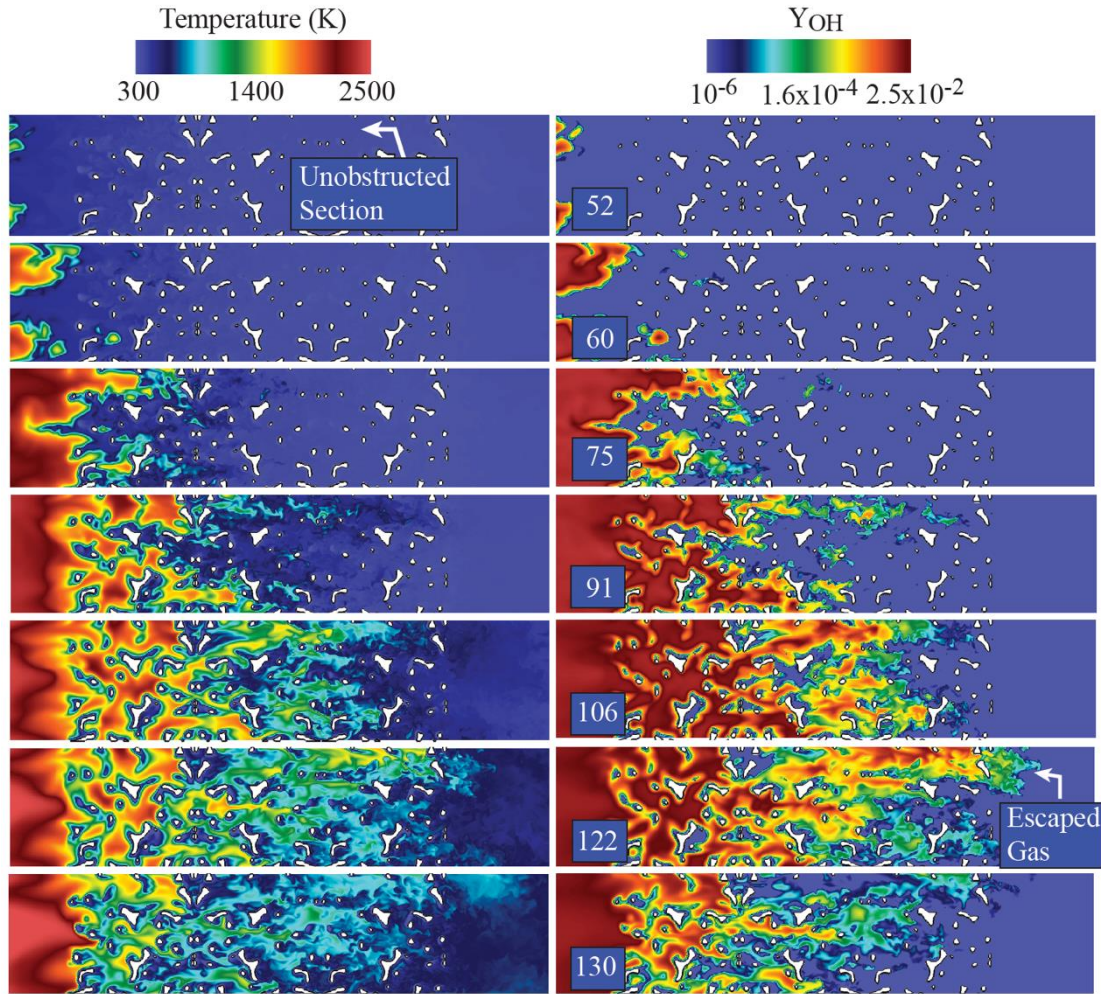


**The results for H<sub>2</sub>-air mixtures (Cases 4-6) show that foams fo ~40 PPI quench the flame. Consistent with Bivol et al.\***

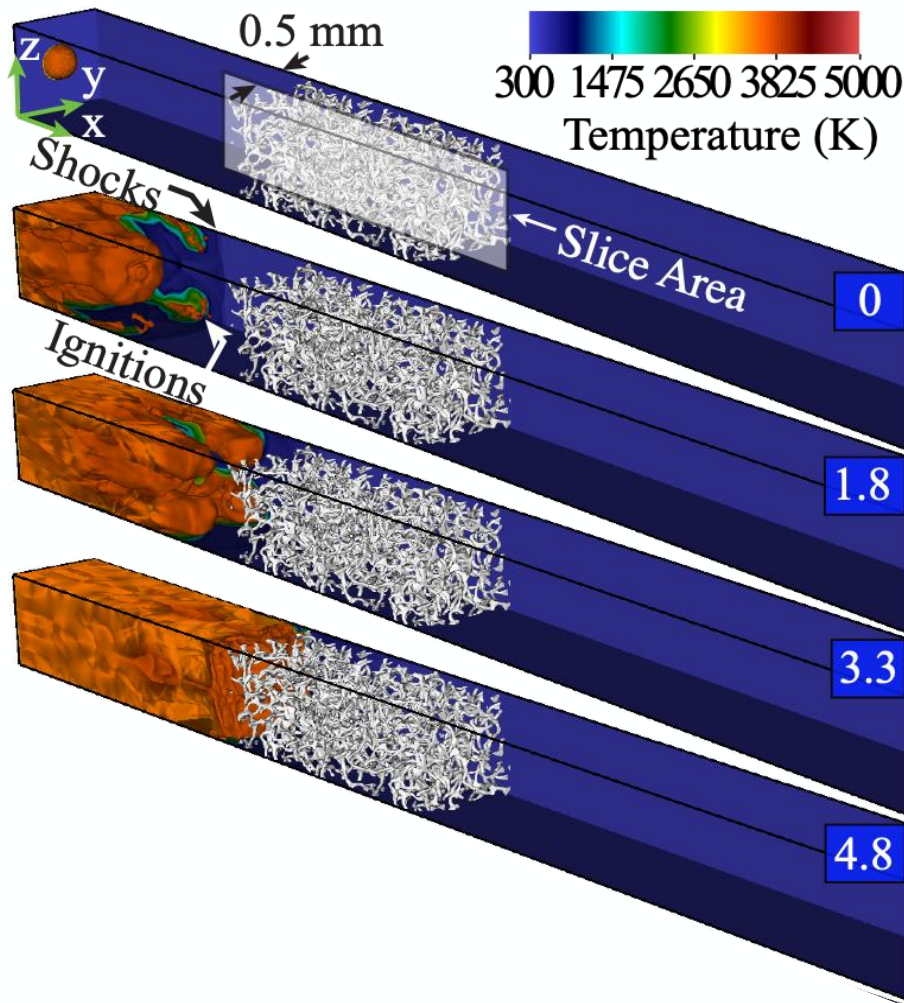
H<sub>2</sub>-air



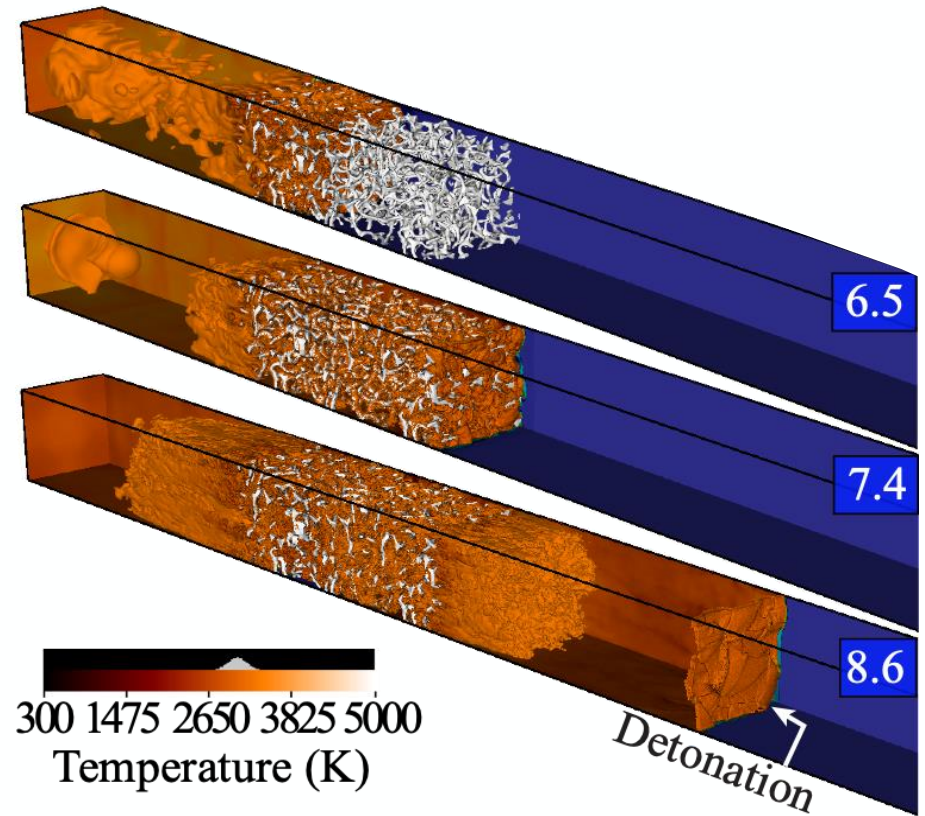
***The H<sub>2</sub>-air flame for Case 5 (39 PPI foam) is barely quenched.***



# The $H_2-O_2$ flame for the 78 PPI foam accelerated and transitioned to detonation.



Time in ms upper right.



*The pressure builds very rapidly and steepens into a shock after the flame enters the foam. This rapidly accelerated the flame.*

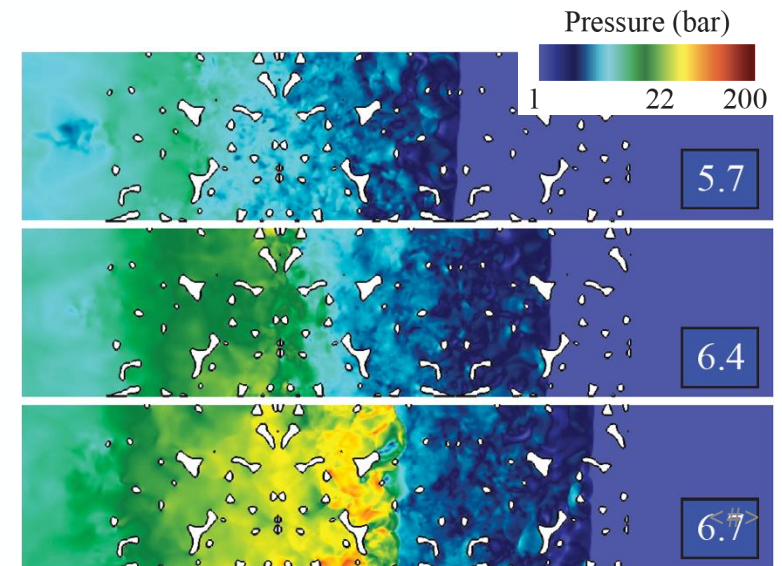
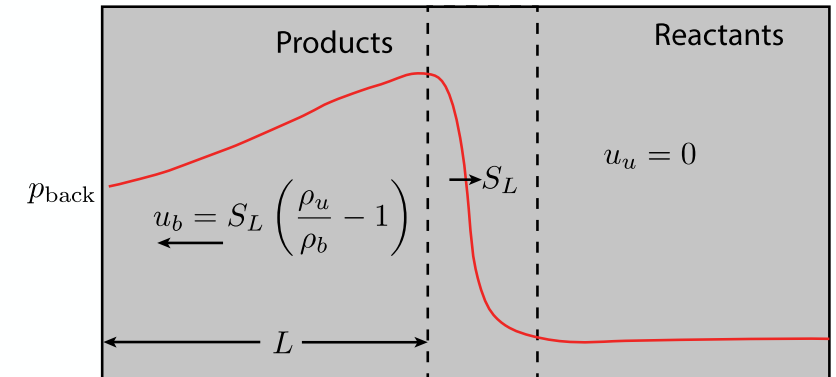


# *Pressure drop across the foam may have a significant contribution to the pressure buildup due to viscous effects and acoustic wave “trapping” in pores.*

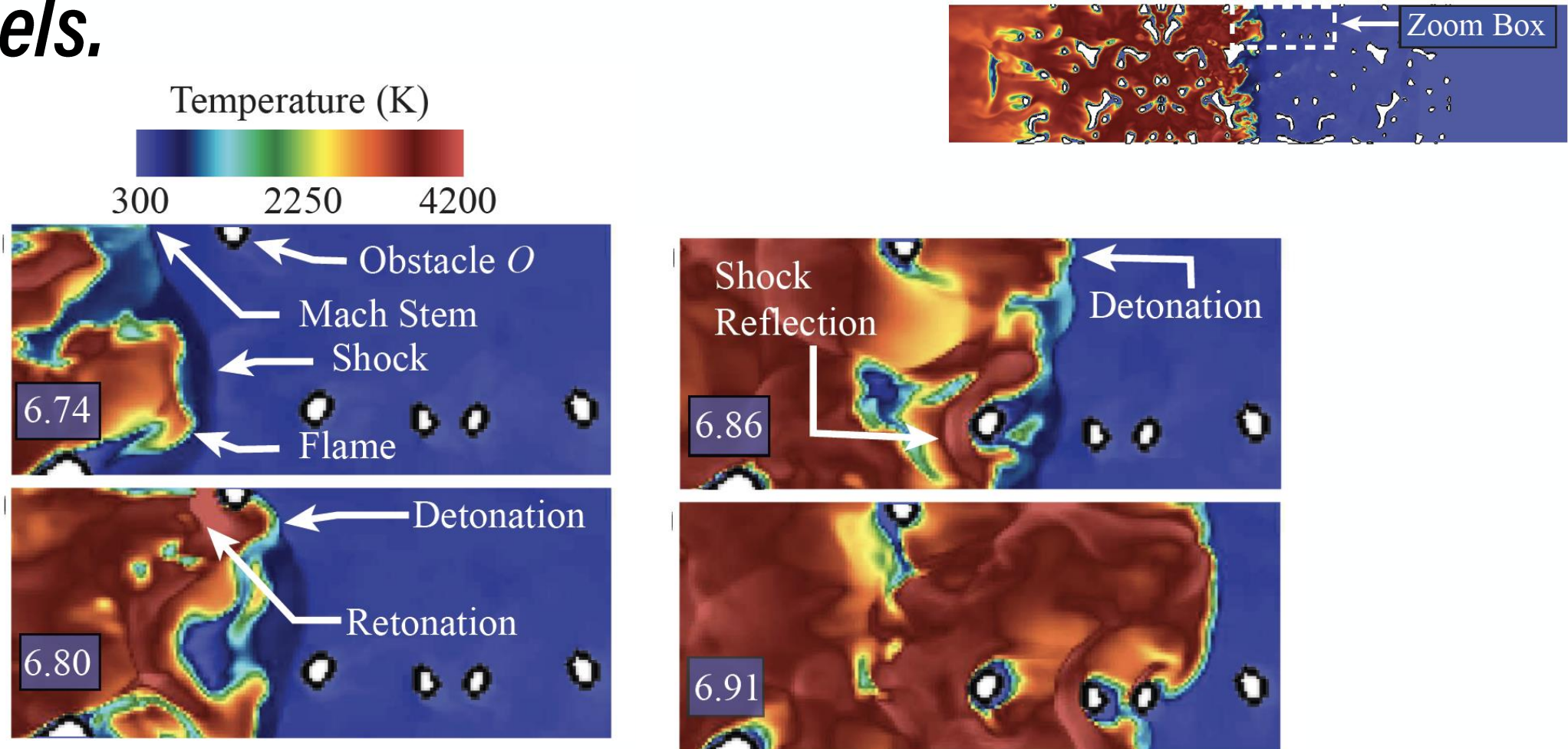
- Consider a scenario where a flame steady propagates inside a foam:
  - No acceleration or compressible flow effects.
- The  $\Delta p$  between the flame and back of the foam can be estimated by a Forchheimer-extended Darcy equation:

$$\frac{\Delta p}{L} = \frac{p_{\text{flame}} - p_{\text{back}}}{L} = f(u_b, \rho_b, \text{foam})$$

- $L \uparrow$  as the flame propagates further into the foam
  - $p_{\text{flame}} \uparrow$  as a result



*The initiation of the detonation is due to a shock wave reflection from a strut, similar to classical obstacle-laden channels.*



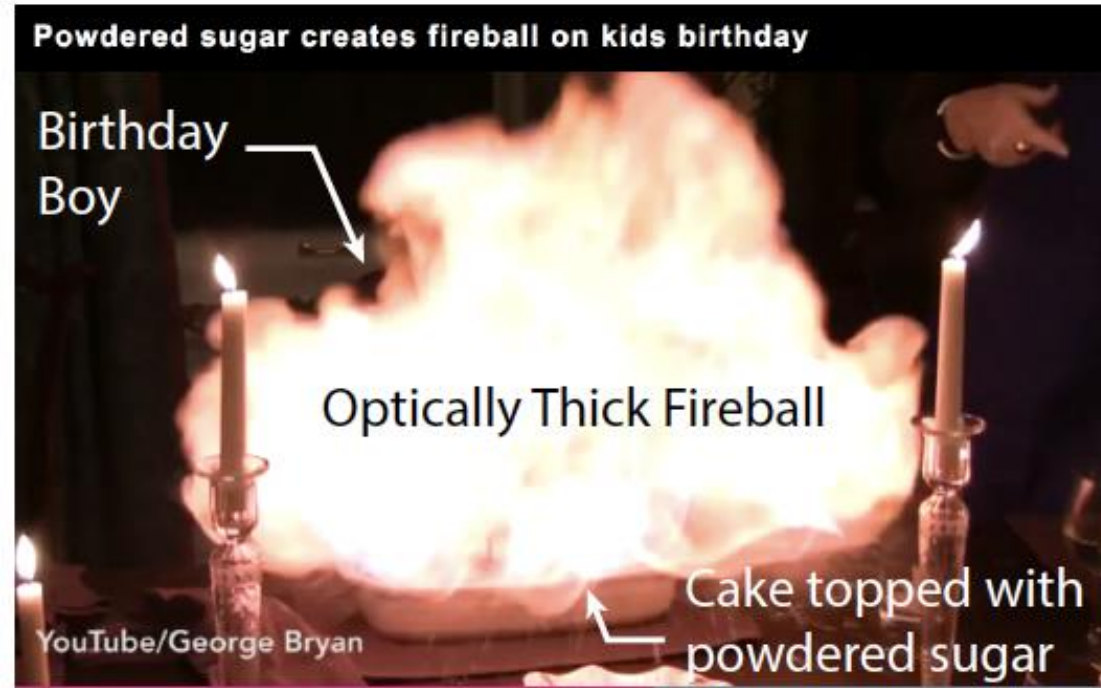
# *Dust “Explosions” can even occur in everyday life*



## **Birthday Cake “Explosion”**

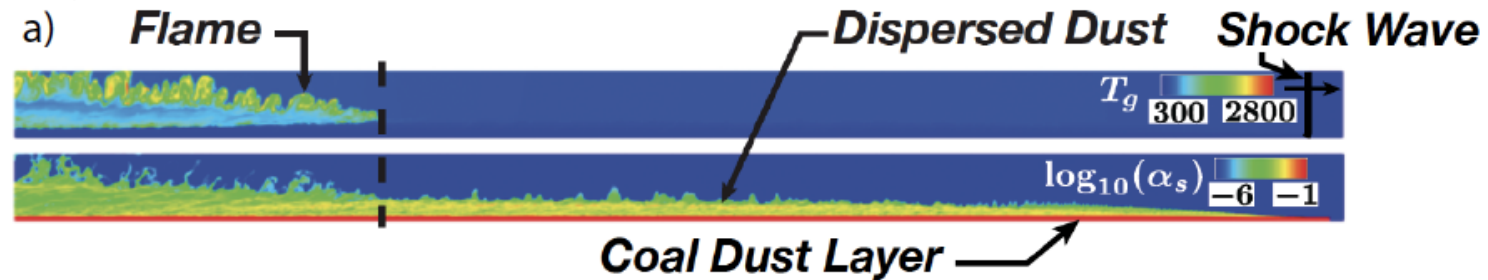
- Viral YouTube video features on “Outrageous Acts of Science”
- Cake topped with loose powdered sugar.
- No injuries! Just surprised people.

# *The influence of radiation on dust explosions is not well understood*



# *The influence of radiation on the initiation and propagation of dust explosions is not well understood.*

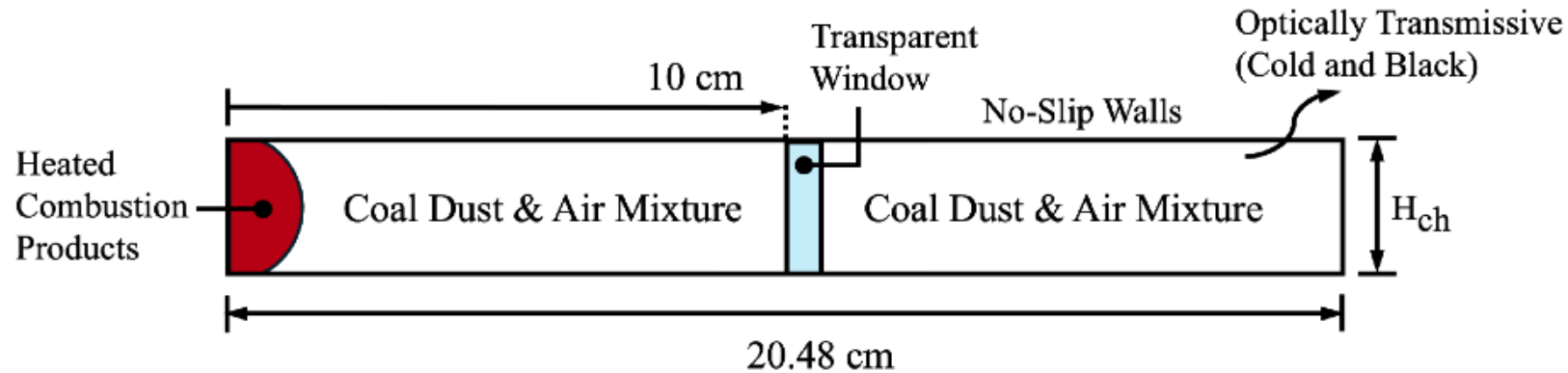
Houim, Oran, ProCI, 2016



- Our earlier work simulated layered dust explosions.
  - Radiation was neglected
  - We received fair criticism.
- Later, we started adding radiation to simpler dust explosion scenarios.
  - We received the opposite criticism.
- A literature survey revealed disagreement on the role of thermal radiation<sup>1</sup>.
  - Some studies show that is important<sup>2-4</sup>
  - Other studies show that it is negligible<sup>5,6</sup>

- 1: Proust, et al. *J. Loss Prevent Proc.*, 45, 2017
- 2: Deshaies and Joulin, *SIAM J. App. Math.*, 46, 1986
- 3: Julien, et al., *Combust Flame*, 162, 2015
- 4: Proust, et al., *26th ICDERS*, 2017
- 5: Qiao and Xu, *CTM*, 16, 2012
- 6: Julien, et al., *J. Loss, Prevent Proc.* 36, 2015.

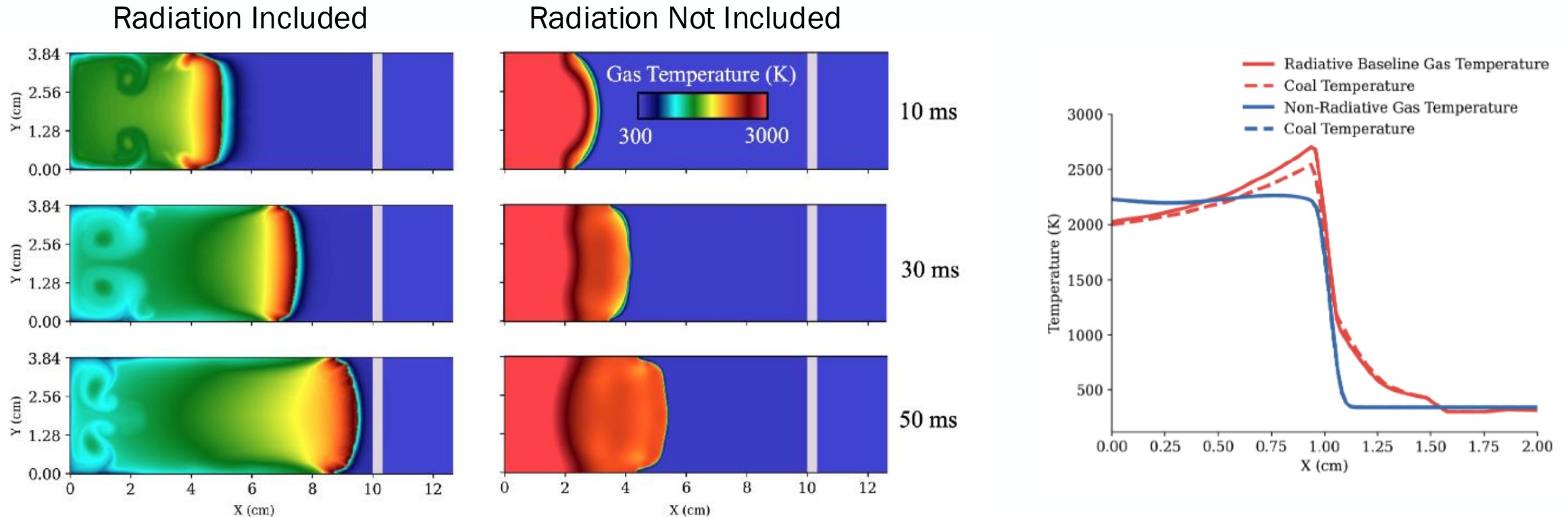
# Can radiation from a burning dust cloud ignite a neighboring dust cloud?



- Chamber filled with coal dust and air
- Transparent window placed in middle that blocks all heat transfer except for radiation.
- Coal dust ignited on left and flame propagated to the right.
- Fully compressible Navier-Stokes equations for multiphase mixtures solved\*.
- Thermal radiation modeled using third-order spherical harmonics with the gray assumption.

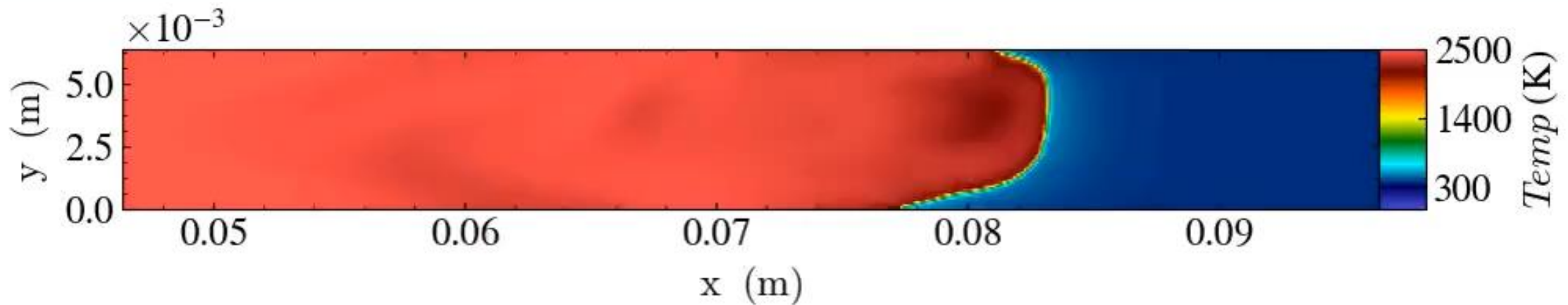
\*Houim, Oran. *J. Fluid Mech.*, 2016

# *Radiation can have a significant impact on the propagation dynamics and structure of dust flames*



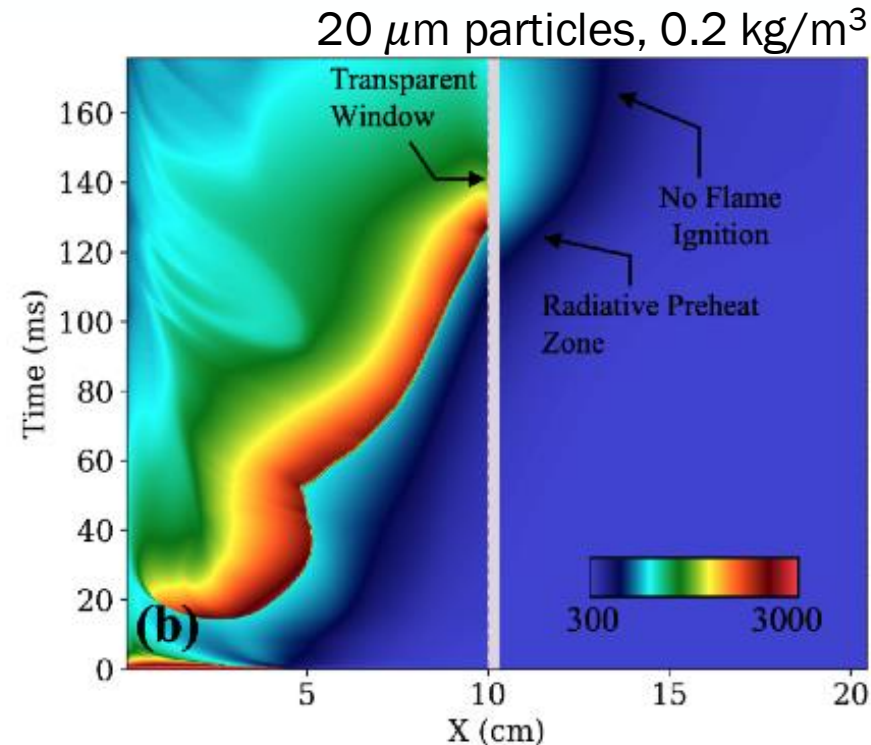
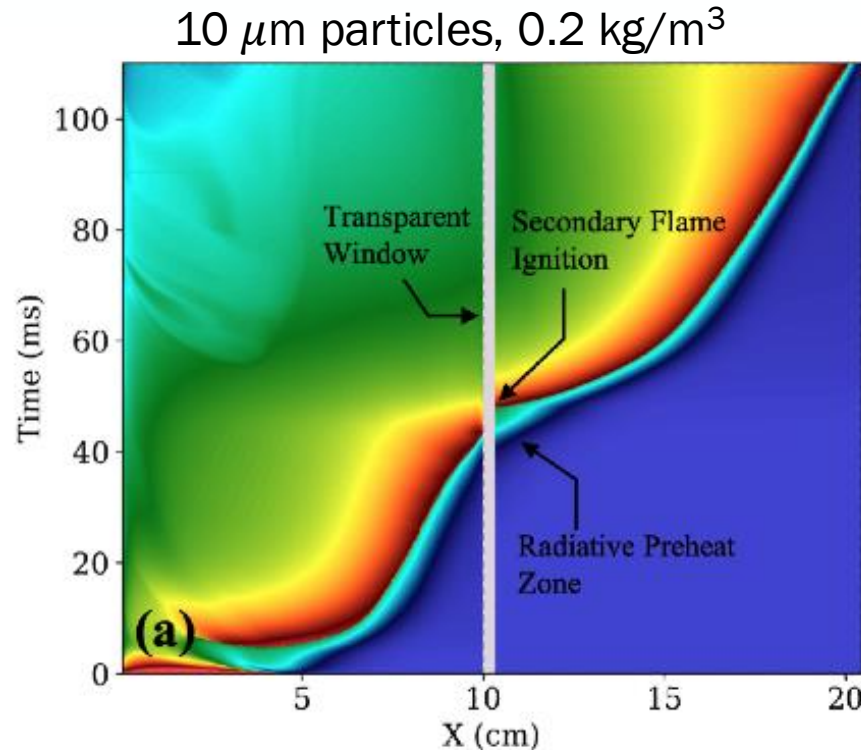
- Radiation produces an elongated preheat zone and overshoot in temperature.
- The product temperature continually lowers due to radiation losses out the sides.

***The computed results show that radiation from the flame in the left can ignite the mixture on the other side of the window.***



- Thermal radiation can cause the flame to jump across the window.

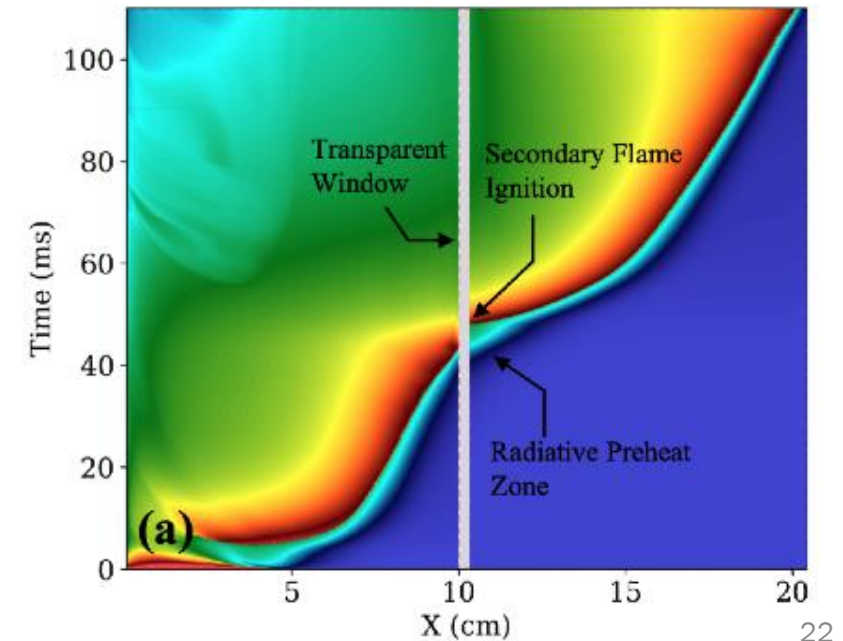
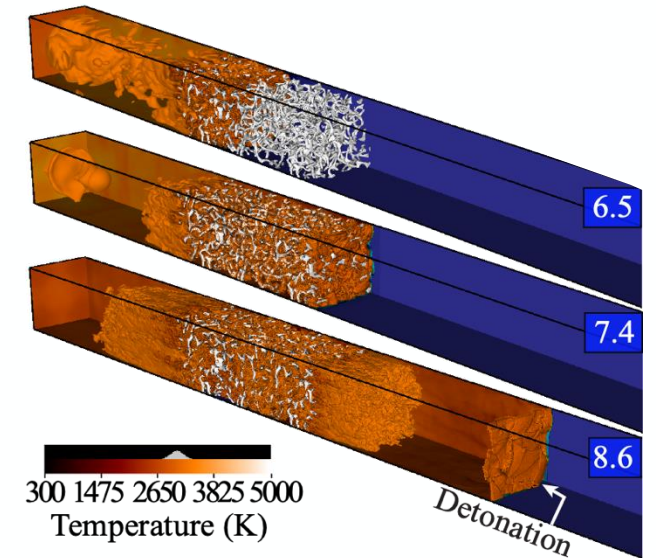
***The computed results show that radiation from the flame in the left can ignite the mixture on the other side of the window.***



- Ignition of the secondary flame is dependent on particle size, dust concentration, channel height, etc.

# Conclusions

- Poorly chosen foams can exacerbate explosions if chosen poorly
  - Accelerate the flame and increase pressure
  - Transition to detonation in extreme cases
- Thermal radiation can have a significant impact on dust flames
  - Changes the flame structure by preheating the particles
  - Radiation from a burning dust cloud can ignite a neighboring cloud.
- Simulations that fully couple compressible flows, combustion, multiphase flow, radiation, etc. are needed to explore these phenomena.

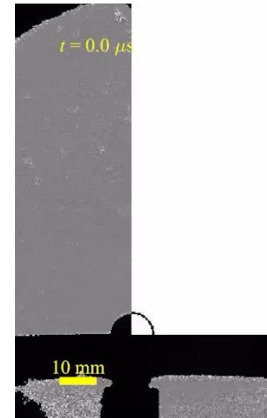


***SPARE***

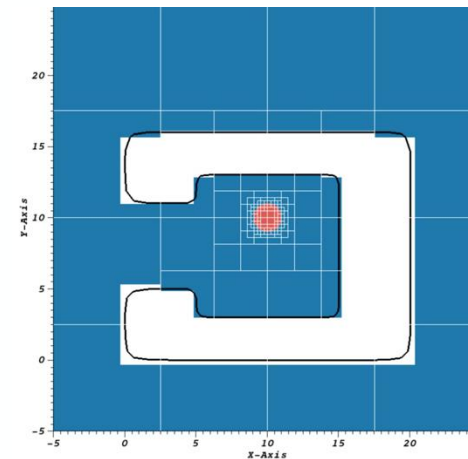
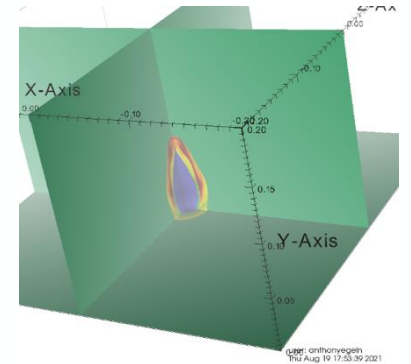
# All simulations use our internally-developed HyBurn code

- Massively-Parallel with adaptive mesh refinement using the AMReX library.
  - Written in hybrid Fortran and C++
- Fully couples compressible reactive gases to granular flows with radiation.
  - Detailed chemistry or simple chemistry.
  - Eulerian and Lagrangian particles.
  - Ideal and non-ideal equations of state.
  - Thermal radiation using filtered spherical harmonics.
  - Explosive burn models.
- Complex geometry using Immersed Boundary Methods
- Extensions being worked on:
  - Multi-material methods for gases, liquids, and solids.
  - Weakly ionized plasma physics.
- Given to collaborators upon request.
- Actively used as Sandia, AFRL/RW, AFRL/RH, and Nevada Nuclear Test Site.

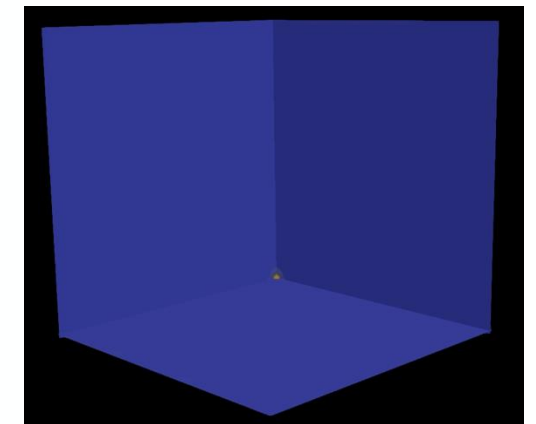
Hemispherical PETN blast



3D initialization of HyBurn from CTH/Tiger



Blast in an open room



Explosive Al particle dispersal