Turbulent Flames at High Reyolds Number

a) Distributed Combustion = "Near Limit"
b) Piloted Bunsen – Regime Diagram = not very Near
c) JP-8 flames - maybe halfway ?

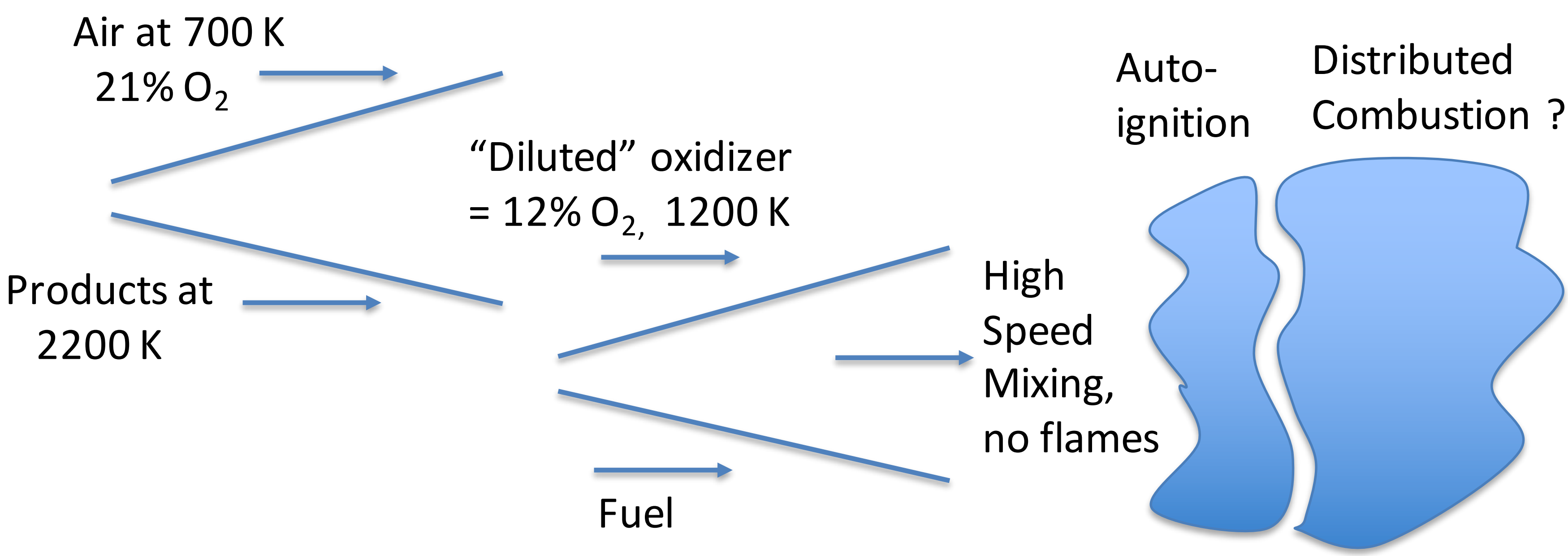
Jim Driscoll

Aaron Skiba, Tim Wabel, Cam Carter

NSF Project CBET-1703543 Dr. Song-Charng Kong
AFOSR Project FA9550-16-1-0028, Dr. Chiping Li

Distributed Turbulent Combustion ←→ Auto ignition

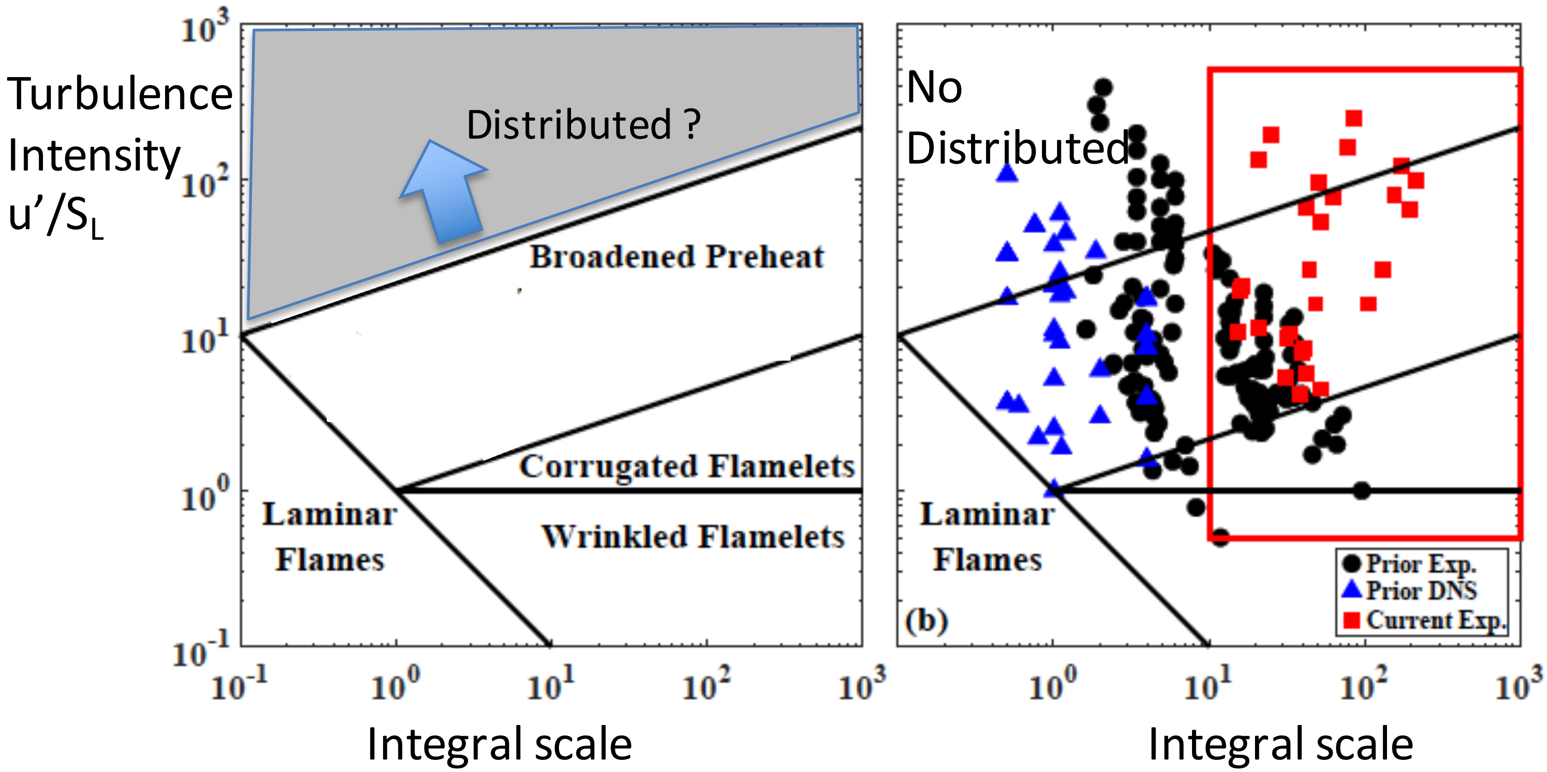
Tianfeng Lu, Jackie Chen, C.K. Law



$$H + O_2 + M \rightarrow HO_2 + M$$

$$DME + HO_2 \rightarrow CH_3OCH_2 + H_2O_2$$

(a) Distributed combustion - not found for piloted Bunsen



Theory

Experiments

not preheated, not diluted, methane only

Distributed Combustion – how to find it ?

Distributed if:

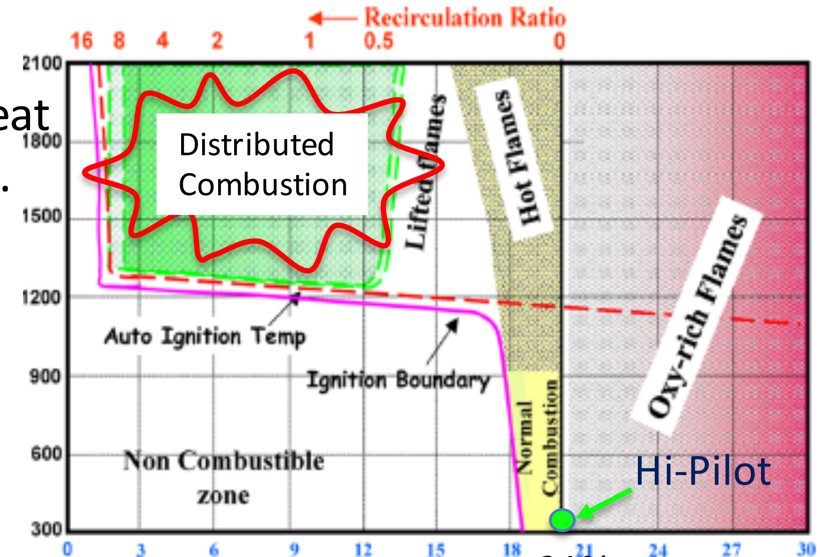
Highly preheated - to 1200 K

Highly diluted with products N_2, CO_2 H_2O

Temperatures rise only from
1200 K to 1700 K

Long residence time = recirculation,
hot walls (Medwell, Dally)

Preheat
Temp.
(K)



21%

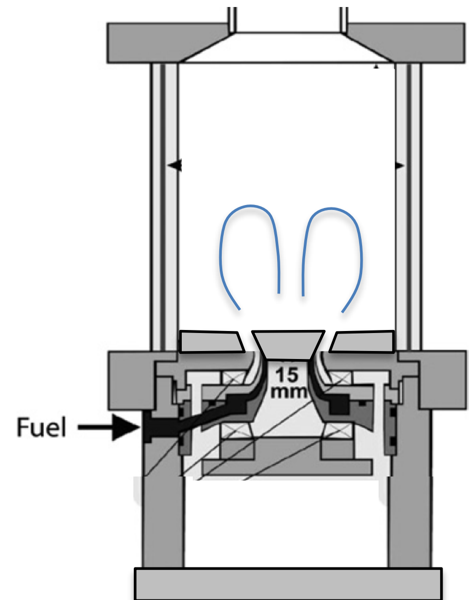
← Dilution = % O_2 in reactants

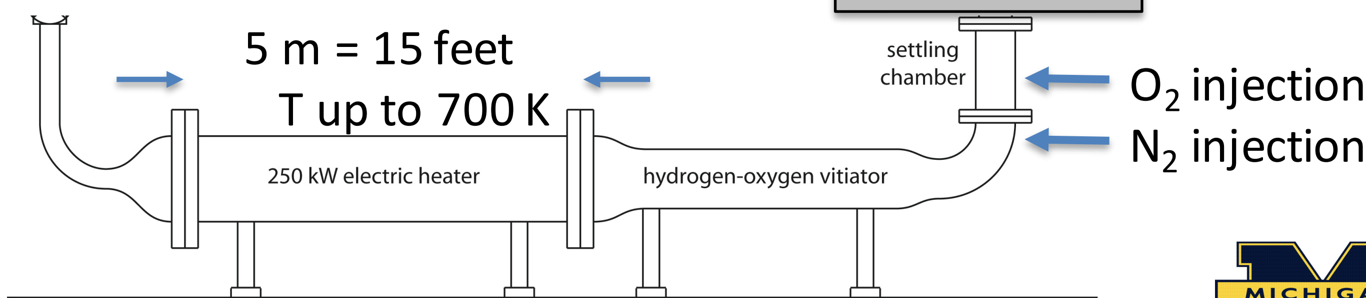
Michigan DISTRIBU - burner

Highly preheated to 1200 K
Highly diluted –
with N_2, CO_2 or H_2O – to 12% O_2
Use vitiator heater - so dilution fraction is well known

Premix chamber - at high velocity to prevent flame formation

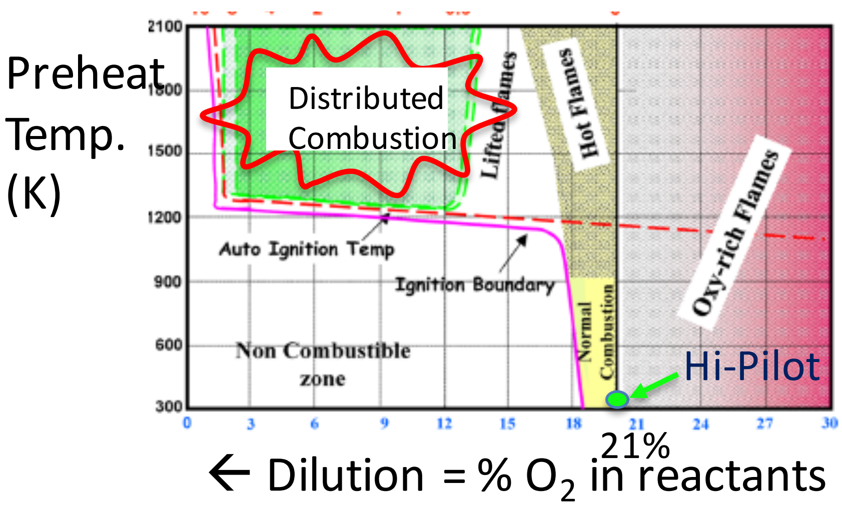
Long residence time, strong mixing
Hot walls



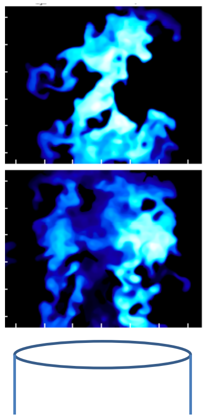


Plan for next year

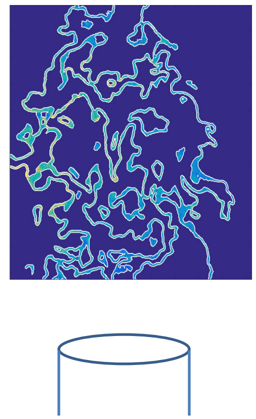
1. Complete Michigan DISTRIBU-burner, achieve distributed combustion
2. Apply our PLIF reaction rate diagnostics (formaldehyde-OH overlap, CH)
3. Measure boundaries of distributed combustion vs. flamelets



b) Piloted Bunsen = unheated, undiluted flame structure



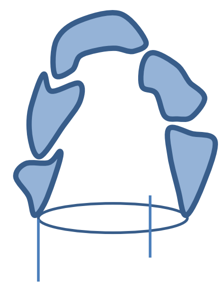
Broadened Preheat Layers (yes)



Fractal-like densely packed (yes)

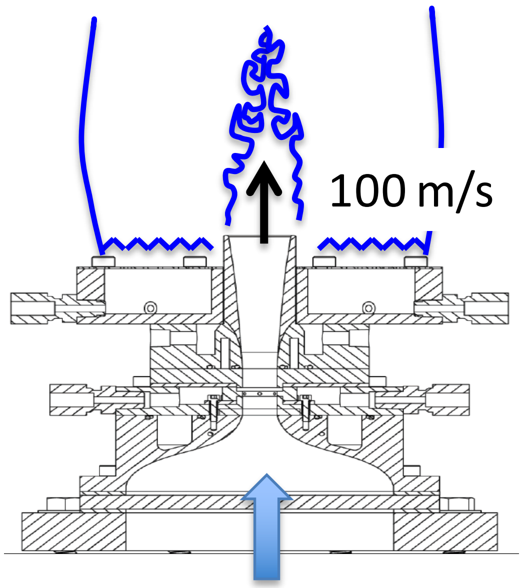
Broken (yes with poor back support)

Thin Wrinkled flamelets (yes)



Distributed (not unless add preheat, dilution, swirl)

Michigan Hi-Pilot Burner - methane, not heated, not diluted



Mean velocity up to 100 m/s

u'/S_L up to 246

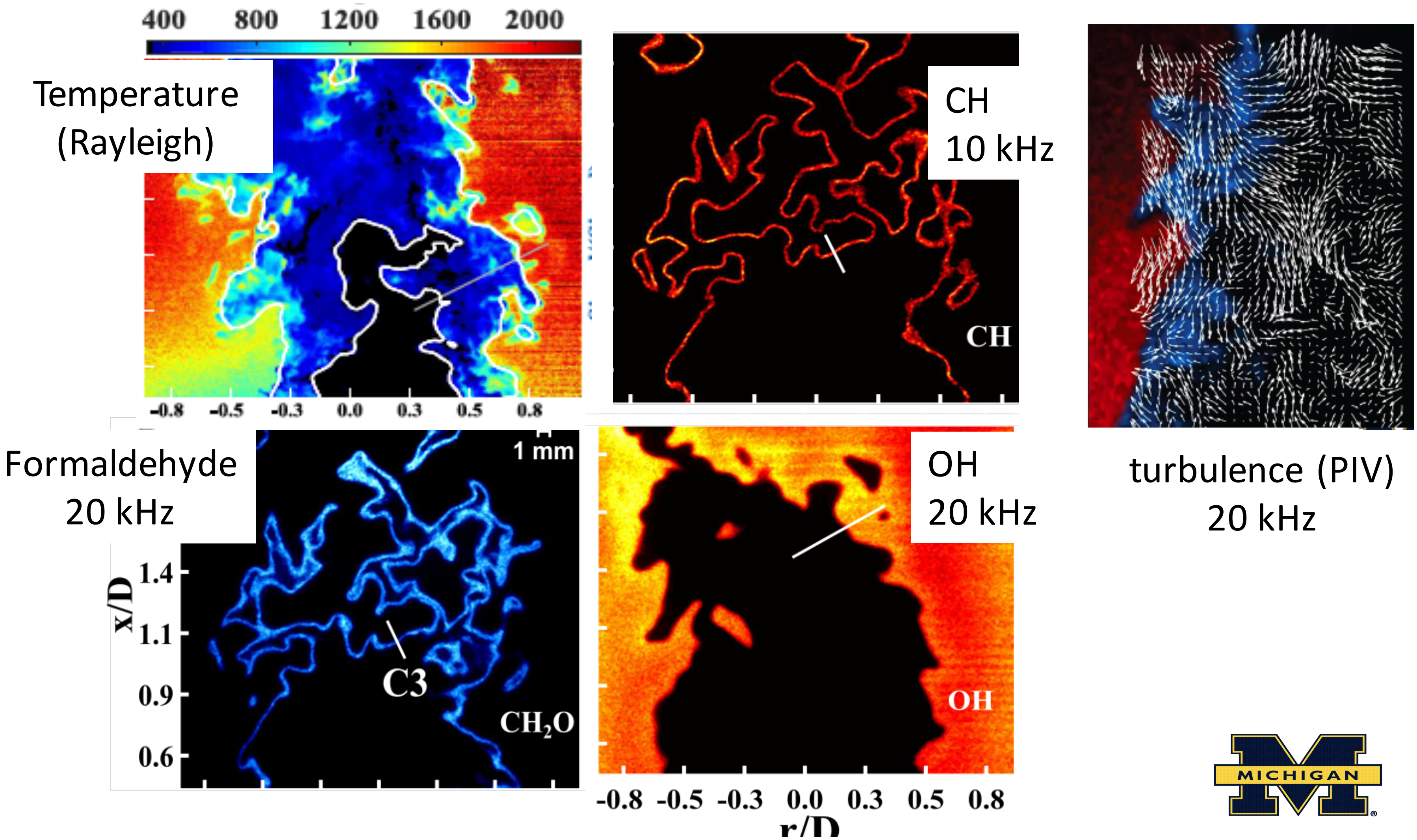
L_x/δ_L up to 215 Re_T = up to 100,000

1. Reactedness structure (temperature) profiles
   Preheat thickness   formald. & Rayleigh
   Reaction layer thickness   CH and overlap
   Turbulence profiles, b.c.'s

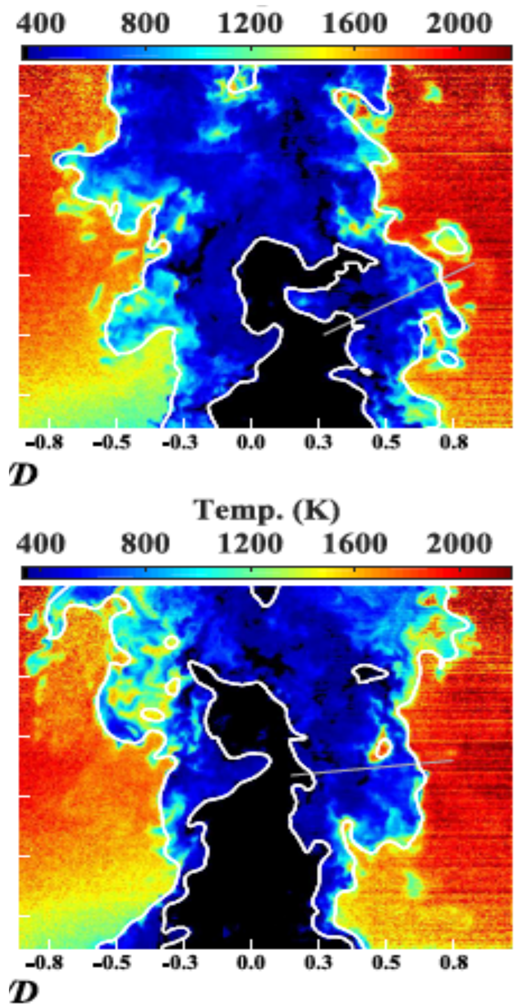
2. Measured Regime Boundary
   Turbulent burning velocity (S_T)

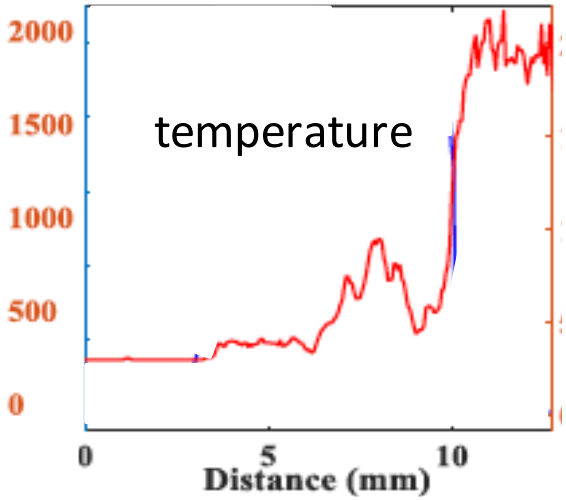
3. "Events" at 20 kHz: pulse burst laser - OH + formald + stereo PIV

High Re METHANE Data Base = temperature, preheat zones, reaction zones, turbulence



Reactedness (Temperature) profiles from Rayleigh



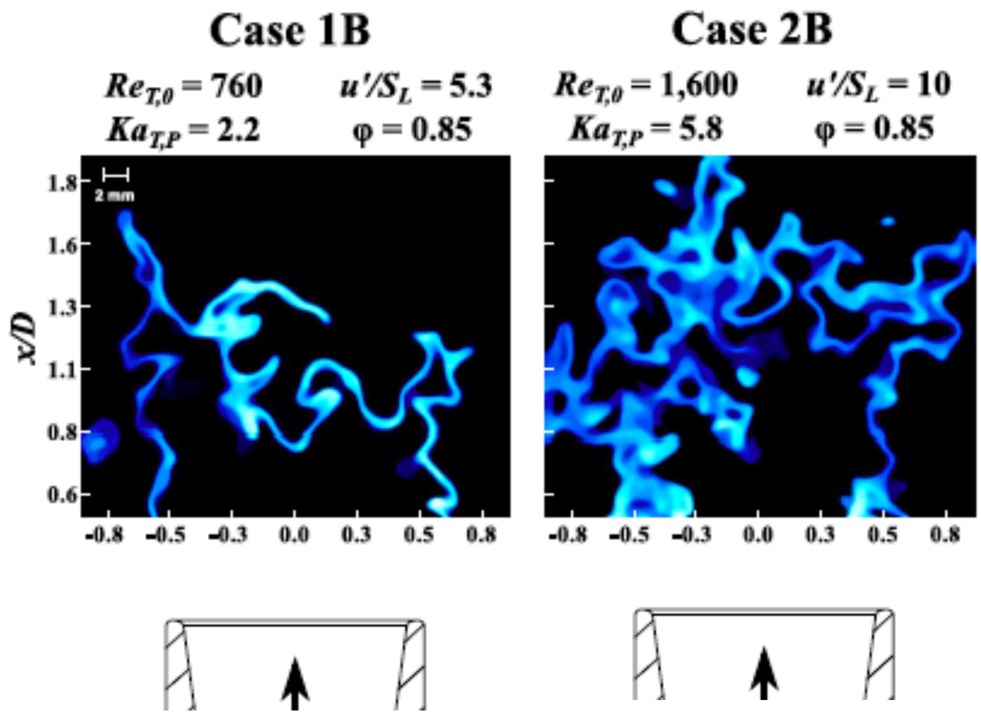


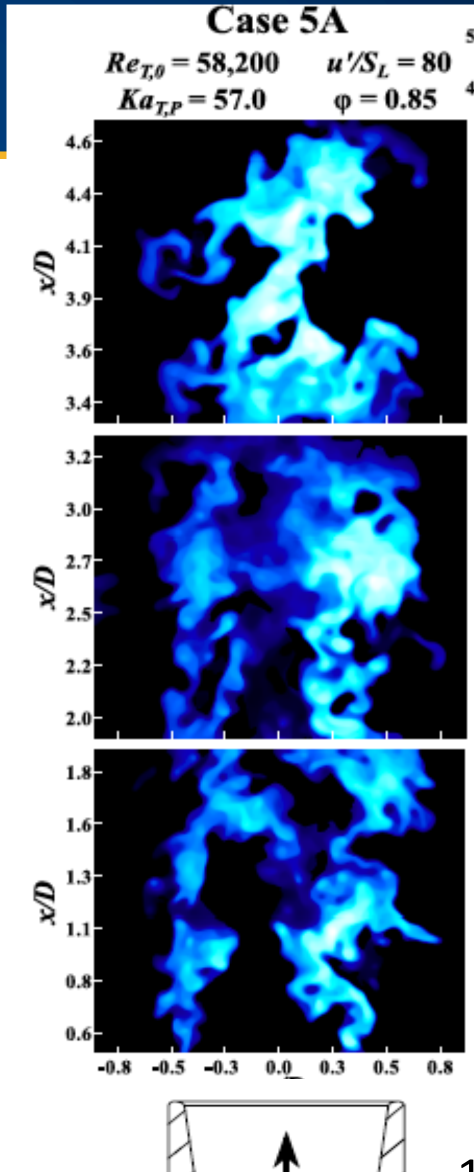
Large blobs
of hot products
convected upstream
by turbulent
diffusion

similar to DNS of
J.H Chen

Preheat layer thickness

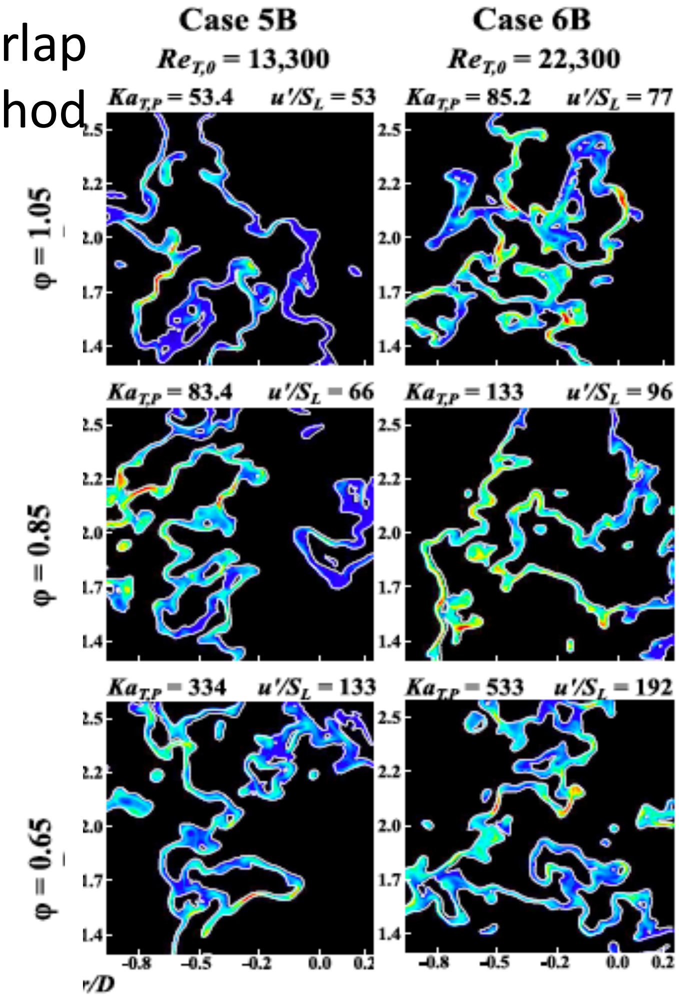
from formaldehyde PLIF
also from Rayleigh



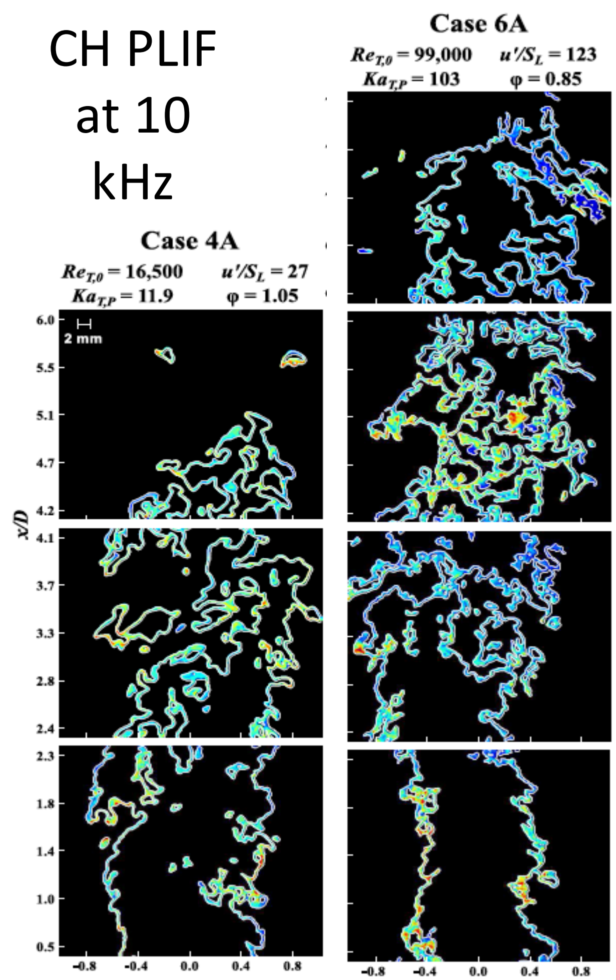


Reaction Layers - from Overlap and CH

Overlap method

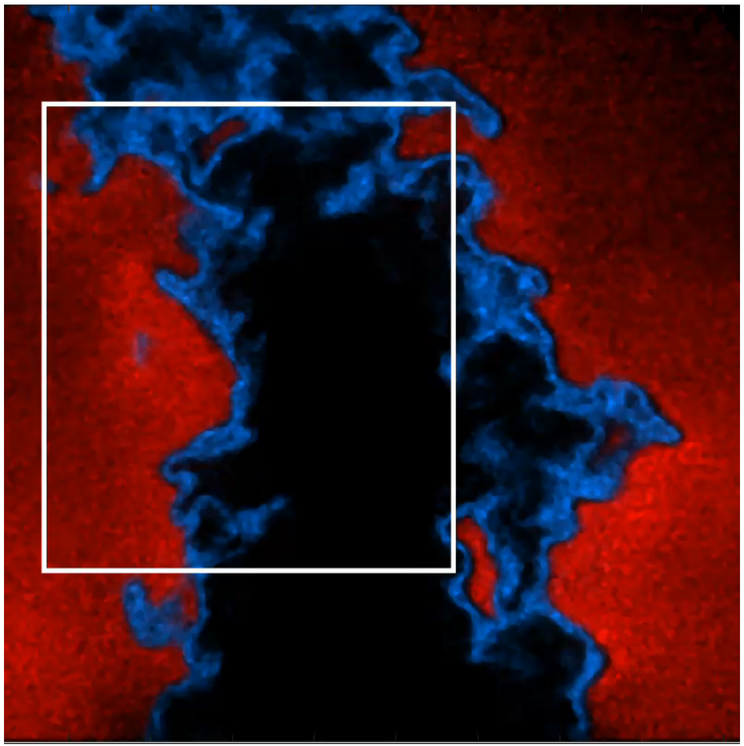


CH PLIF at 10 kHz

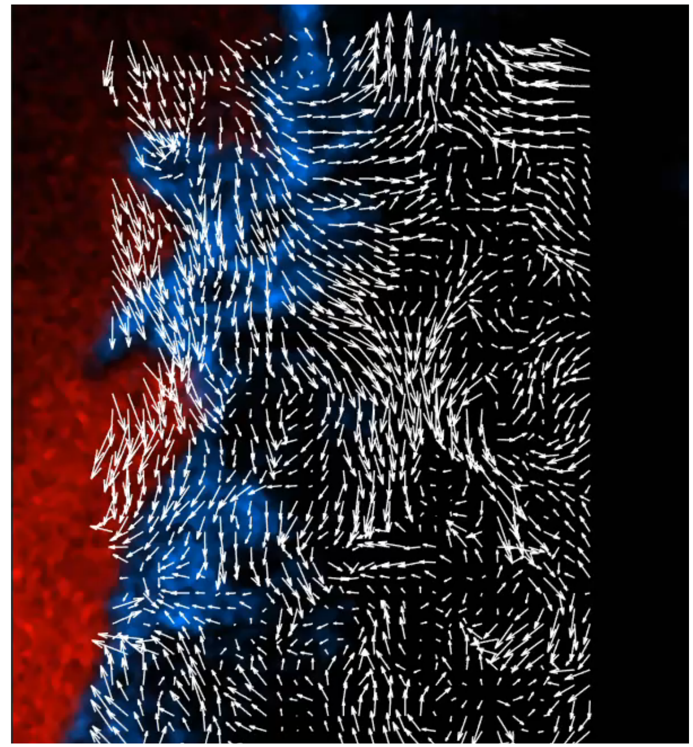


20 kHz Unsteady Events - simul / stereo-PIV / form.-OH

Preheat (blue), Products (red)



Simultaneous Eddies,Velocity



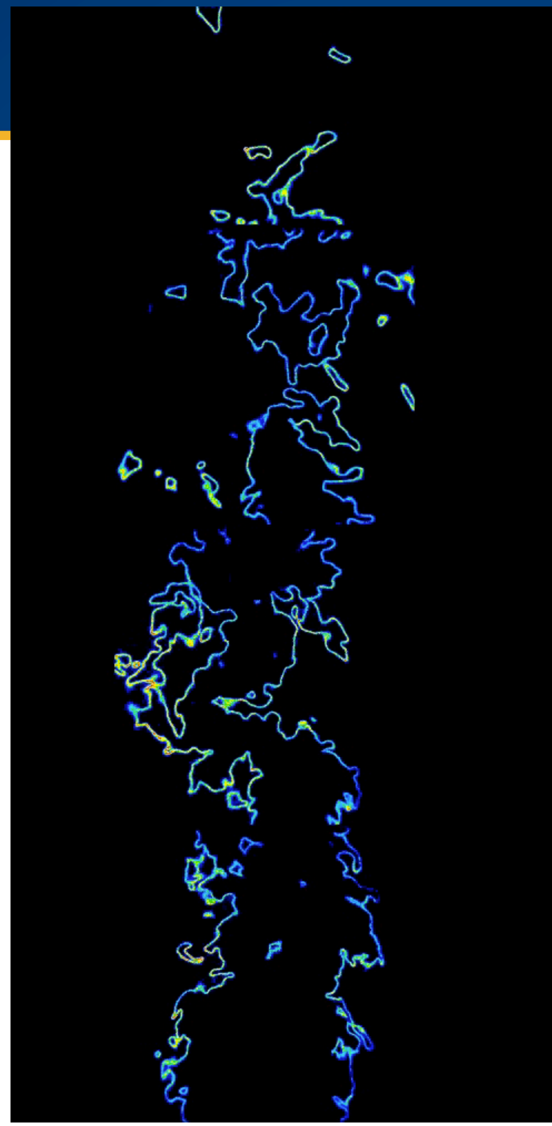
Events: how do large eddies cause Damkohler diffusion of globs of hot gases upstream into reactants ? For what eddy size ?

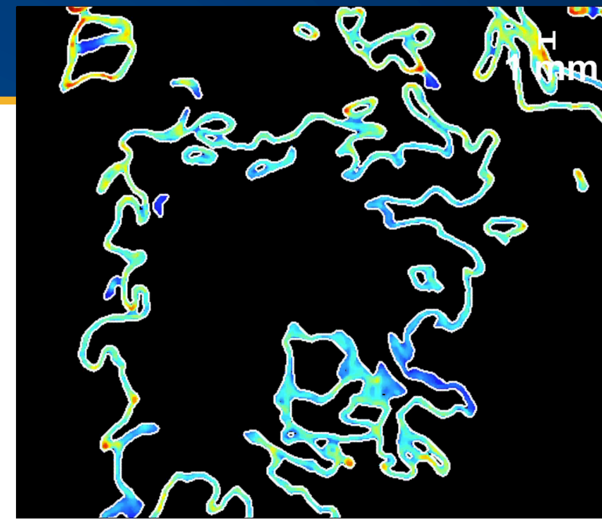
Reaction layers

CH PLIF at 10 kHz

Hi-Pilot Burner

Cam Carter's Lab
Tonghun Lee's
laser at AFRL

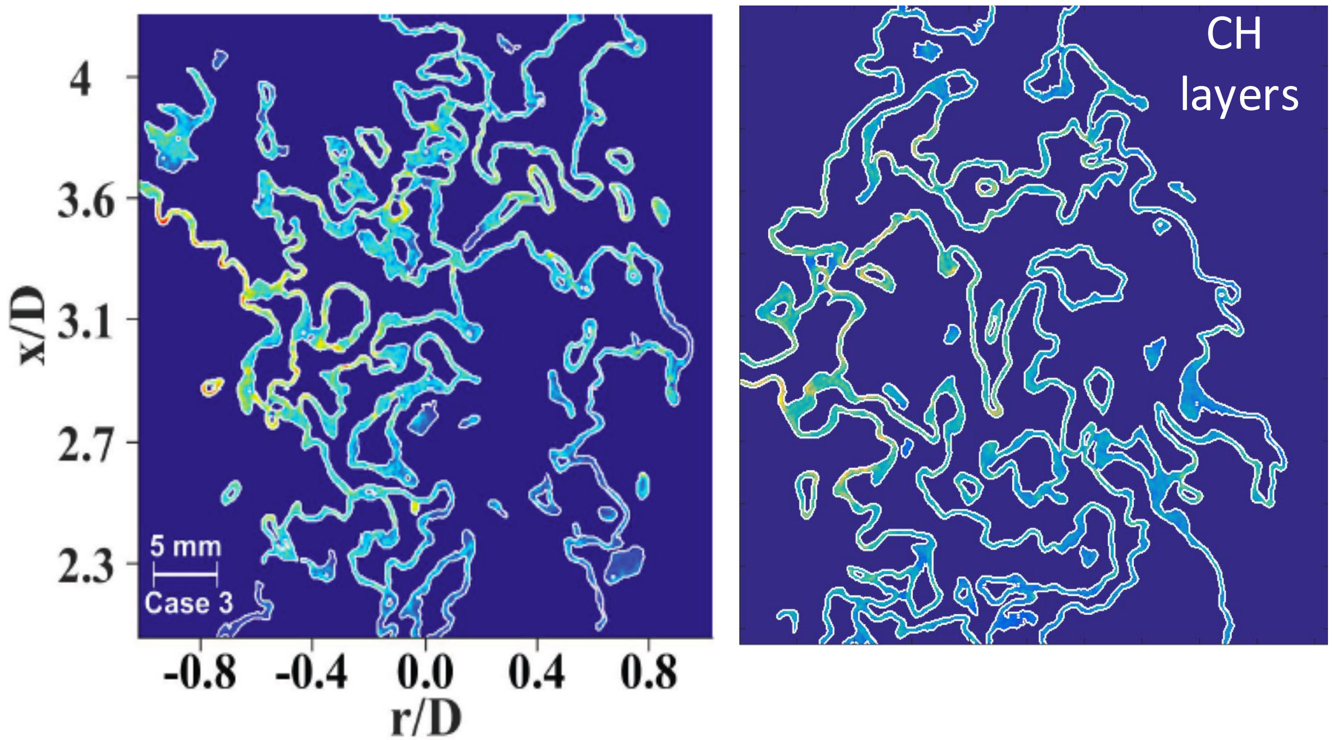




What is the merging rate ?
pocket formation rate ?
extinction rate ?

Why does area never exceed about
five times the unwrinkled area ?

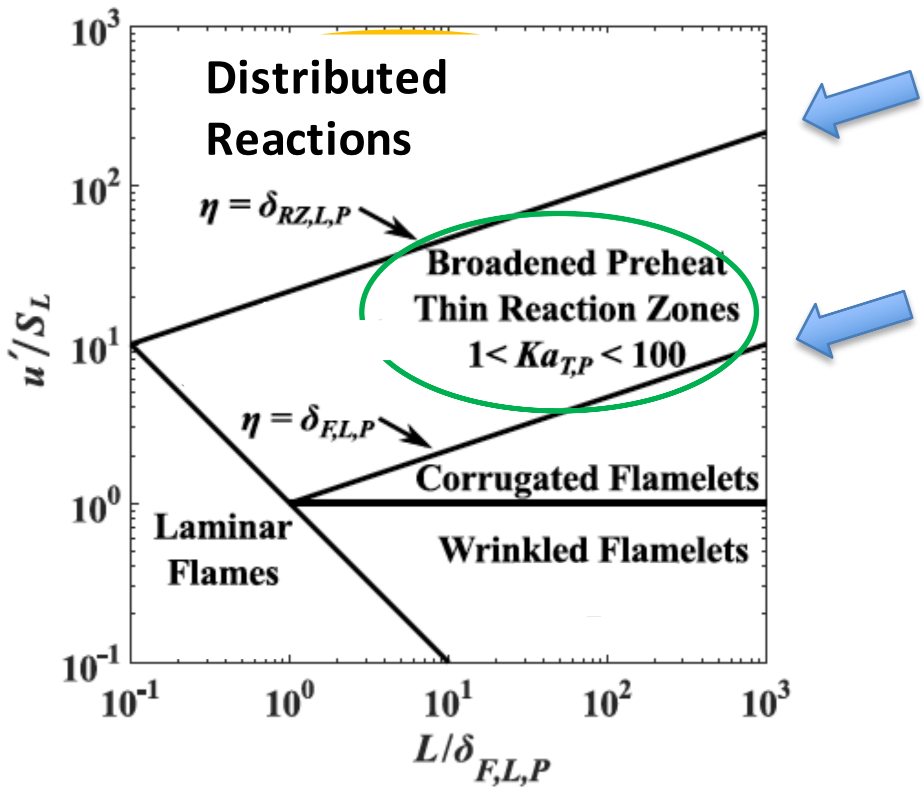
Events - measure the merging rate at high Re



Measured flamelet Merging rate (M)

$$\frac{d\,(\tilde{u}\ \Sigma)}{dx} - \frac{d}{dx}\left(\nu_T\ \frac{d\Sigma}{dx}\right) = K\,\Sigma - \mathrm{M}$$

Predicted Regime Boundaries

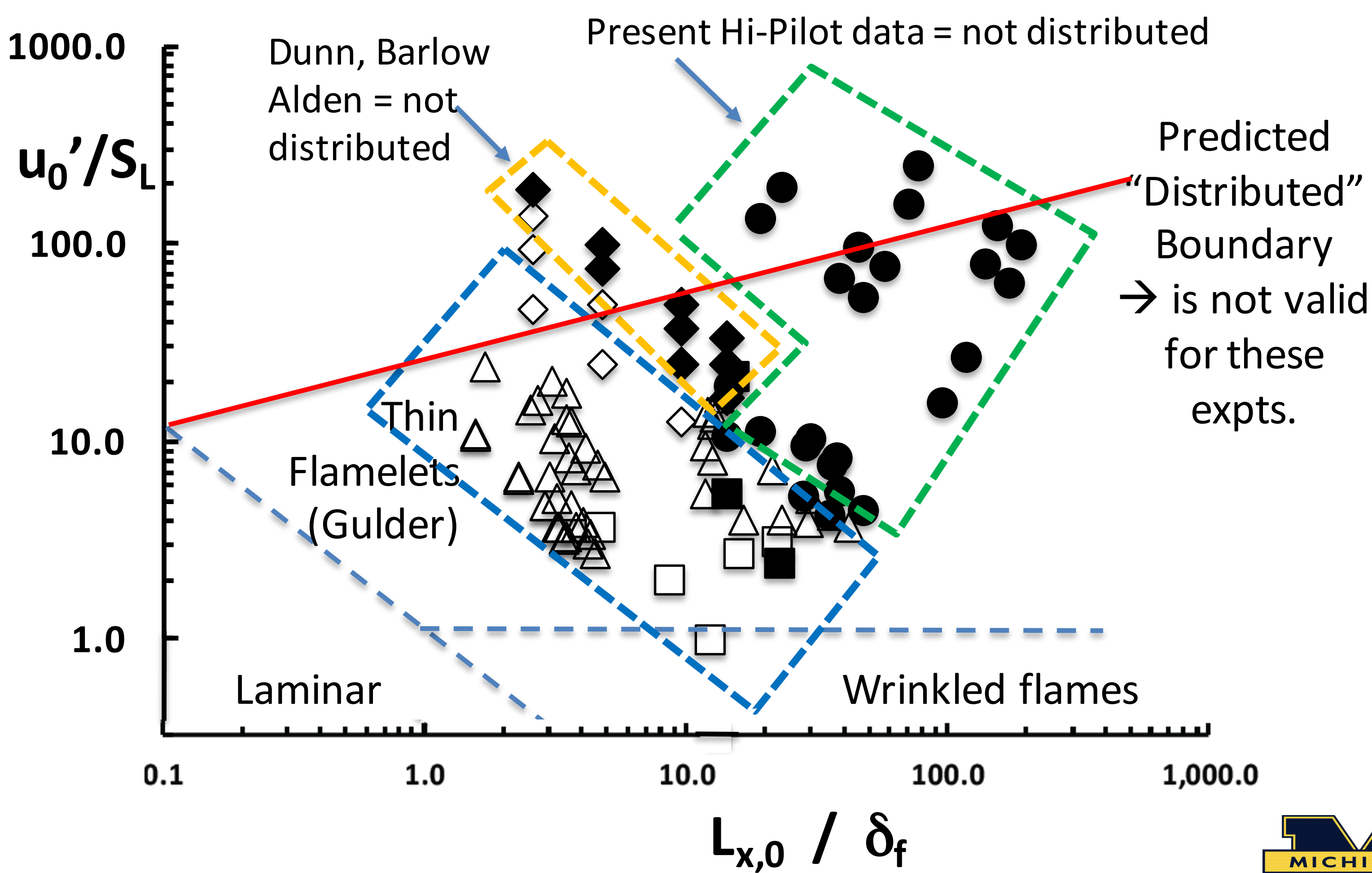


Motivation:

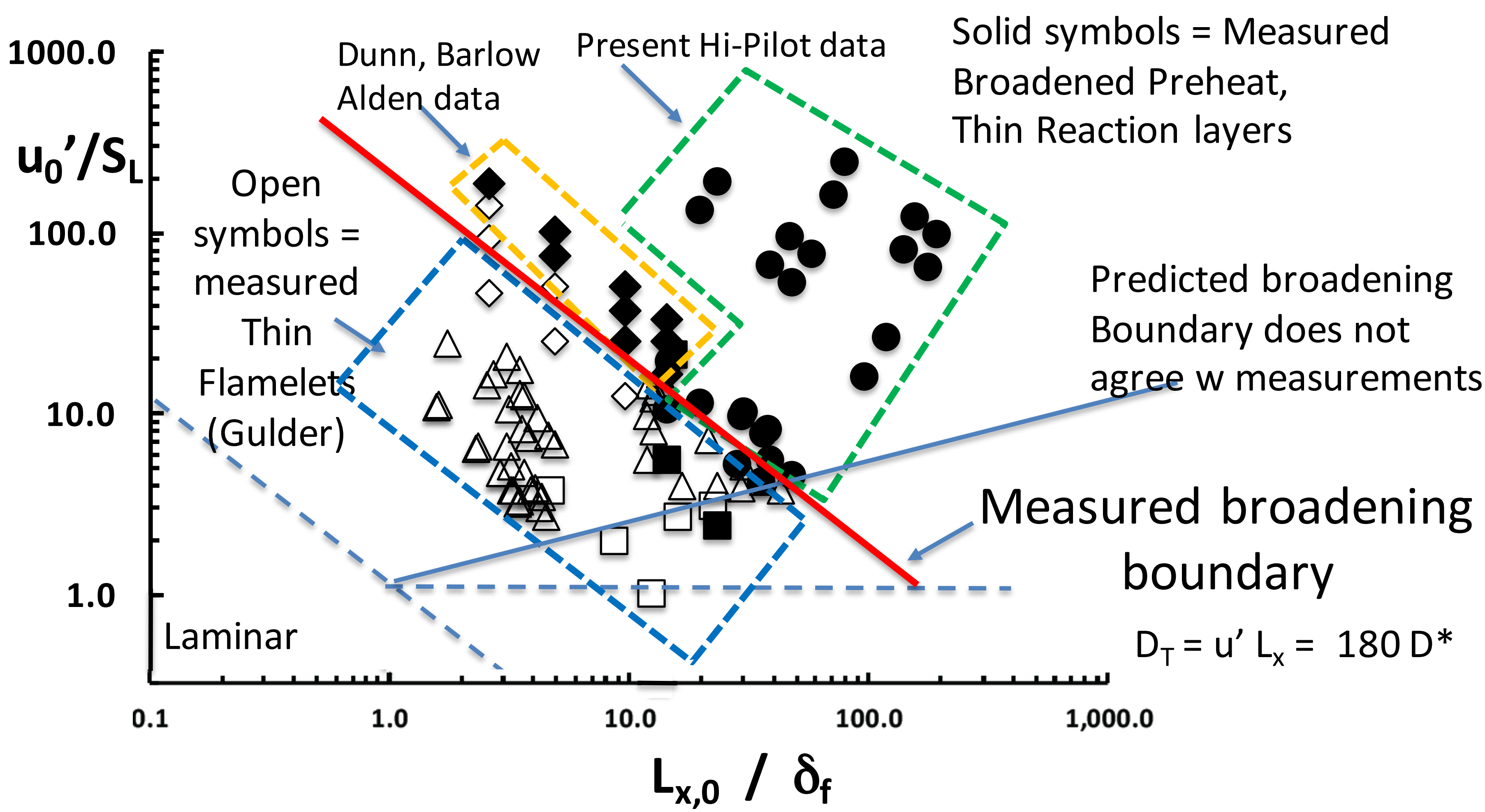
When are models valid ?

Thin flamelet model
Thickened flamelet model
Distributed reaction model

Flamelets not distributed above predicted "distributed" boundary



Measured Regime Diagram - broadening boundary



CONCLUSIONS for METHANE fuel

1. First Hi Re data base - flame structure in “Extreme” turbulence
   $u'/S_L = 240$, $Re_T = 100{,}000$ - completed
   images of temperature, OH, formaldehyde, CH, velocity
   “intense” range = $Re_T = 5{,}000$ = Dunn-Barlow, Alden (Lund)

2. Broadened preheat, thin reaction layers are observed
   Distributed or broken not observed for this expt.

3. Measured Regime Diagram – for piloted bunsen flames only

Two boundaries on the predicted Borghi do not match the Measured Regime Diagram

Broadened preheat layers measured to occur when

$$D_T = u' \, L_x = 180 \, D^*$$

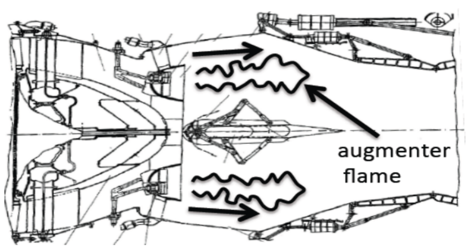
Broken reaction layers not observed in present work - for Karlovitz number up to five times the predicted value

Dunn, Masri see some broken at Ka = ten times predicted

→ Flamelets occur over much wider range than predicted

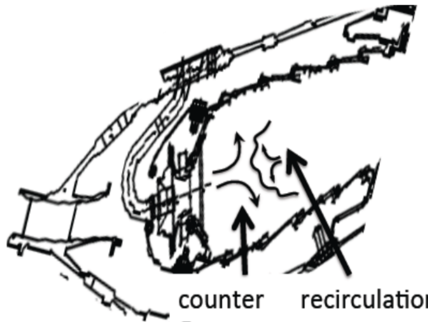
MICHIGAN

Disclaimer - we study TWO out of SEVEN possible geometries



1. Afterburner
large mean velocity
small residence time
not shear dominated

“High-Pilot’
Piloted Bunsen burner
favors flamelets and
hard to extinguish



2. Gas Turbine LPP Combustor
low mean velocity
large residence time

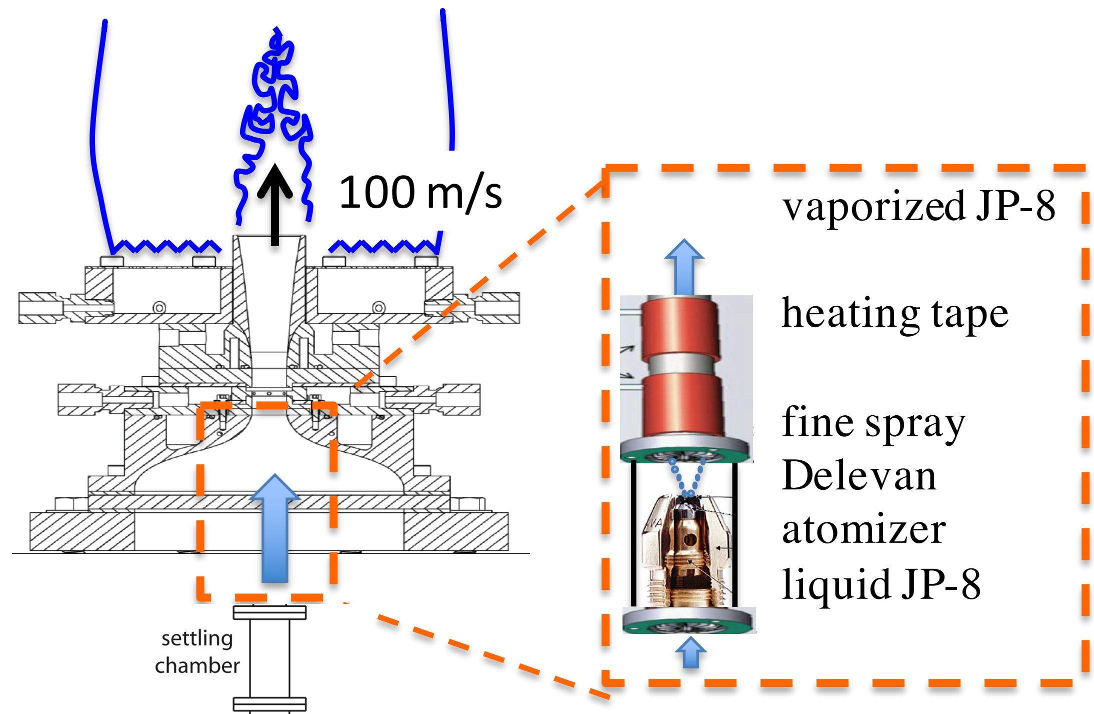
“DISTRIBU-burner”
distributed, flamelets
and extinction ?

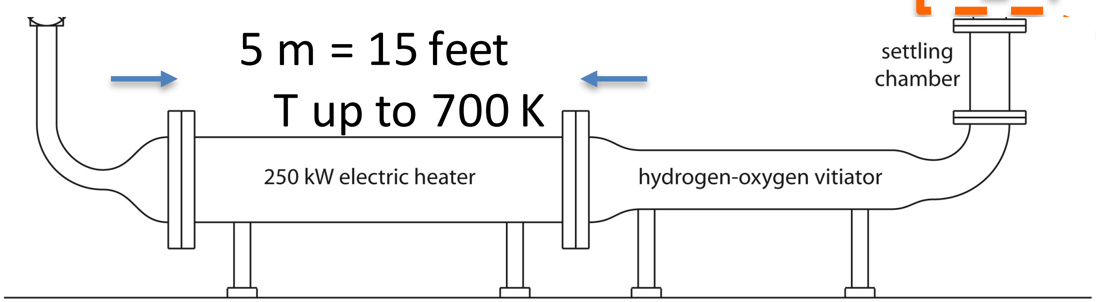
Other geometries:

3. Premixed jet flame:
   is shear dominated
4. Bluff body
5. Counter-flow flames
6. Spherical flame
7. Well stirred reactors

JP-8 Flames - in progress

JP-8 premixed
$Re_T = 20,000$



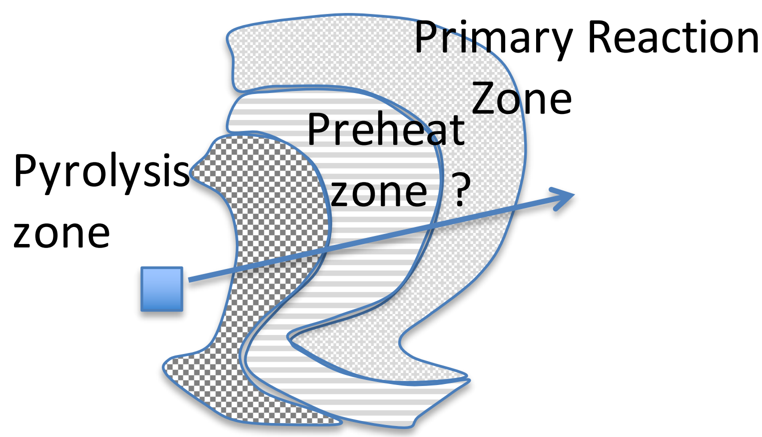


Chemistry in High Re JP-8 Flames

Why study JP-8 chemistry in turbulent flames ?

→ Only turbulent flames (at high Re) provide realistic

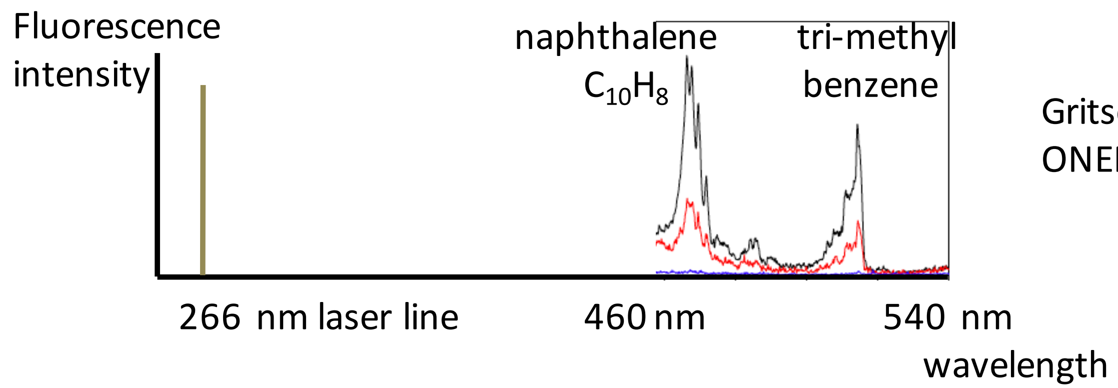
<u>residence times</u> = time for fluid element to cross three layers



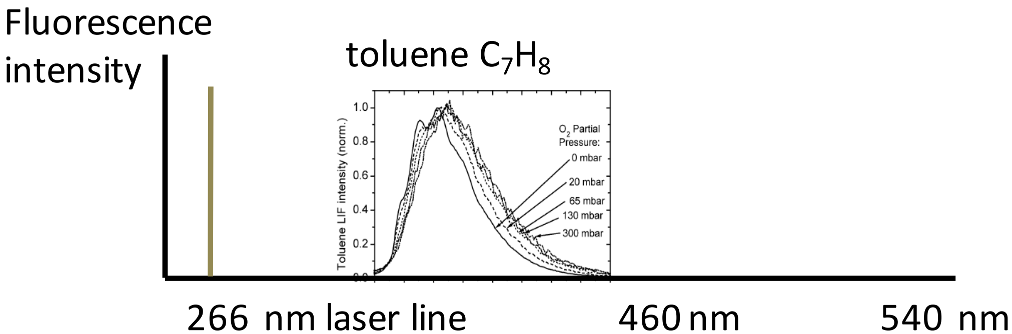
Step 1: PLIF of preheated JP-8 flames at Michigan

PLIF of formaldehyde, OH

PLIF of JP-8 components: naphthalene, toluene, tri-methyl benzene

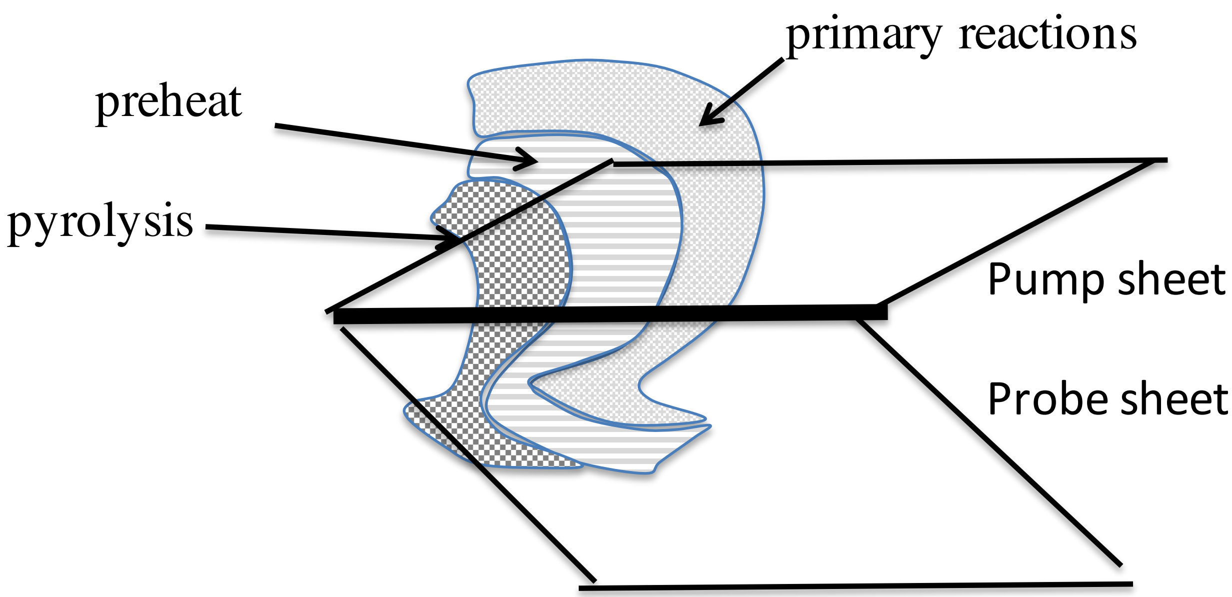


Gritsch ONERA



Sick (Michigan)

STEP 2: Line CARS - of Jim Gord at AFRL

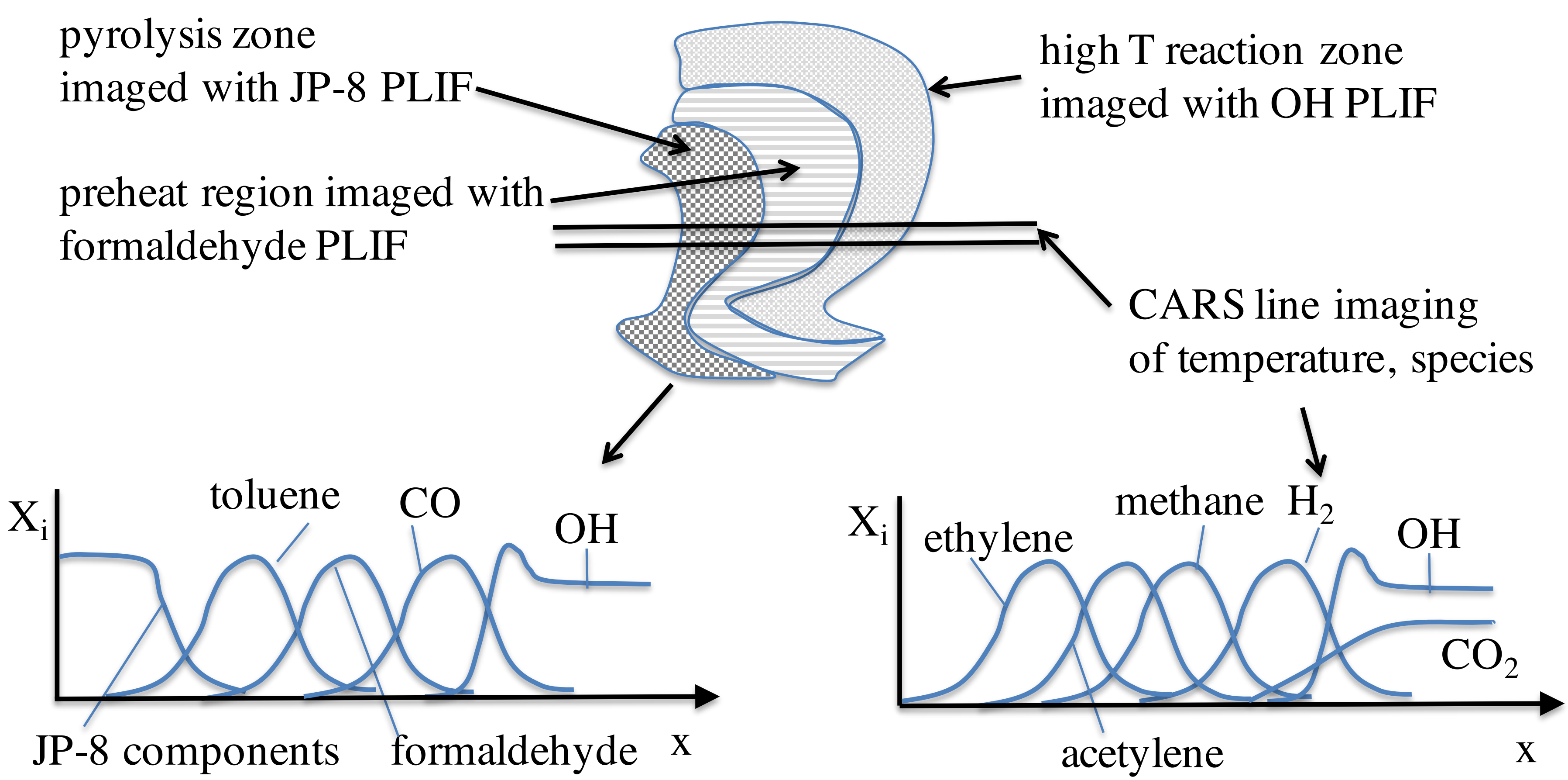


Profiles of 14 species in a vaporized JP-8 flame -

can it be done ?

	Species or temperature		Diagnostic		Location	Ref.
1	hydroxyl	OH	PLIF	2-D image	U. Michigan	1,7
2	formaldehyde	CH_2O	PLIF	2-D image	U. Michigan	1,7
3	JP-8	JP-8	PLIF	2-D image	U. Michigan	8-11
4	carbon monoxide	CO	LIF	line image	U. Michigan	12, 13
5	toluene	C_7H_8	LIF	line image	U. Michigan	14
	temperature	T	PLIF (2-line)	2-D image	U. Michigan	12
	temperature	T	nsec-CARS	line image	AFRL*	15-29
6	hydrogen	H_2	nsec-CARS	line image	AFRL	3
7	methane	CH_4	nsec-CARS	line image	AFRL	17, 19
8	carbon dioxide	CO_2	nsec-CARS	line image	AFRL	18
9	water	H_2O	nsec-CARS	line image	AFRL	17
10	carbon monoxide	CO	nsec-CARS	line image	AFRL	20
,12	nitrogen, oxygen	N_2, O_2	nsec-CARS	line image	AFRL	3
13	acetylene	C_2H_2	nsec-CARS	line image	AFRL	24
14	ethylene	C_2H_4	nsec-CARS	line image	AFRL	28, 29

Chemistry in High Re JP-8 Flames– joint Michigan –AFRL



Fluorescence: 5 species (Michigan)

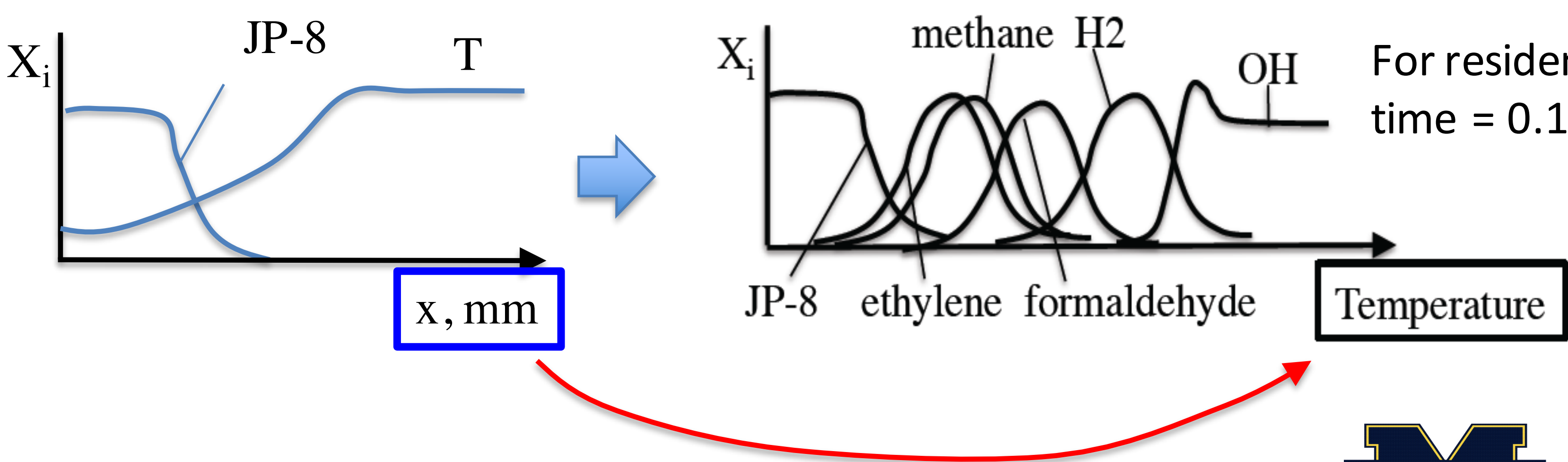
CARS: 9 species (Gord, Meyer)

Chemistry data reduction

Each laser shot (some at 10 Hz, some at kHz)

a) Profile of one species and temperature (CARS or LIF line imaging)

b) Simultaneous 2-D PLIF images of pyrolysis layer, preheat, reaction layer to measure residence time = thickness / normal velocity

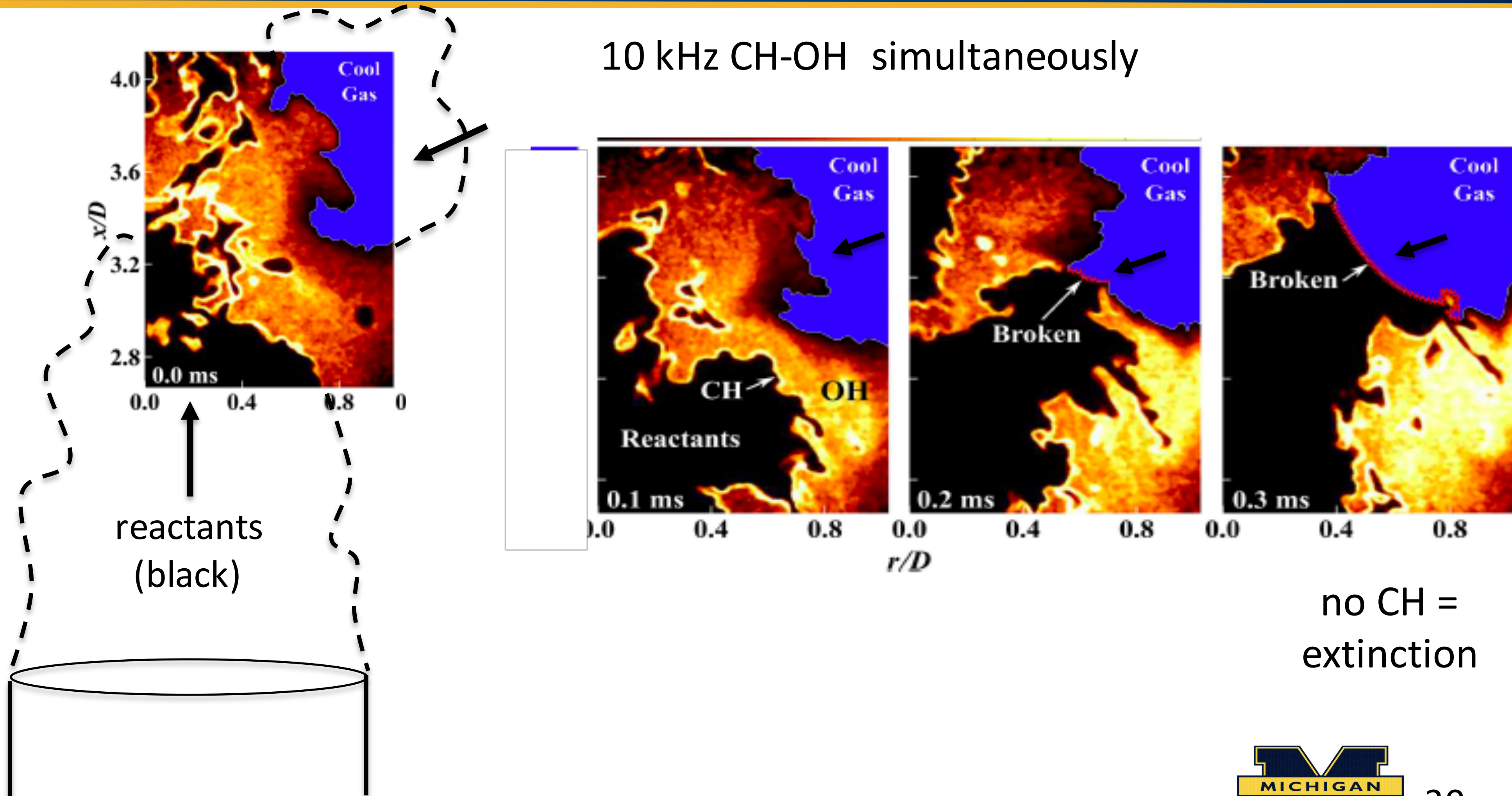


For residence time = 0.1 ms

END

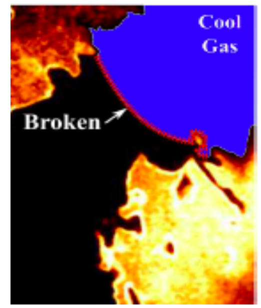
Events: extinction with poor back support

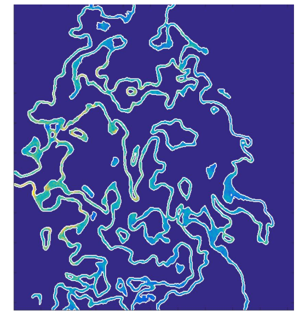
10 kHz CH-OH simultaneously



no CH = extinction

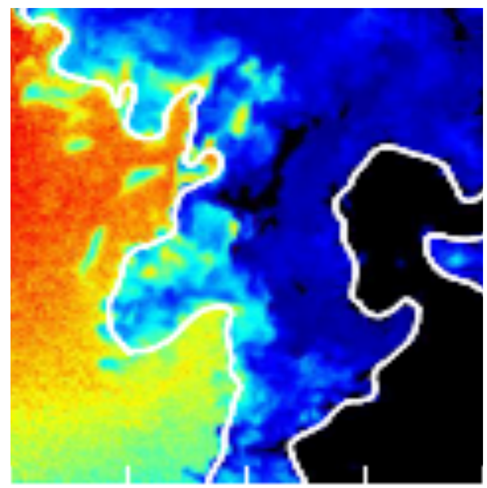
Compare “Events” to DNS of Jackie Chen, John Bell





“area increase” events:

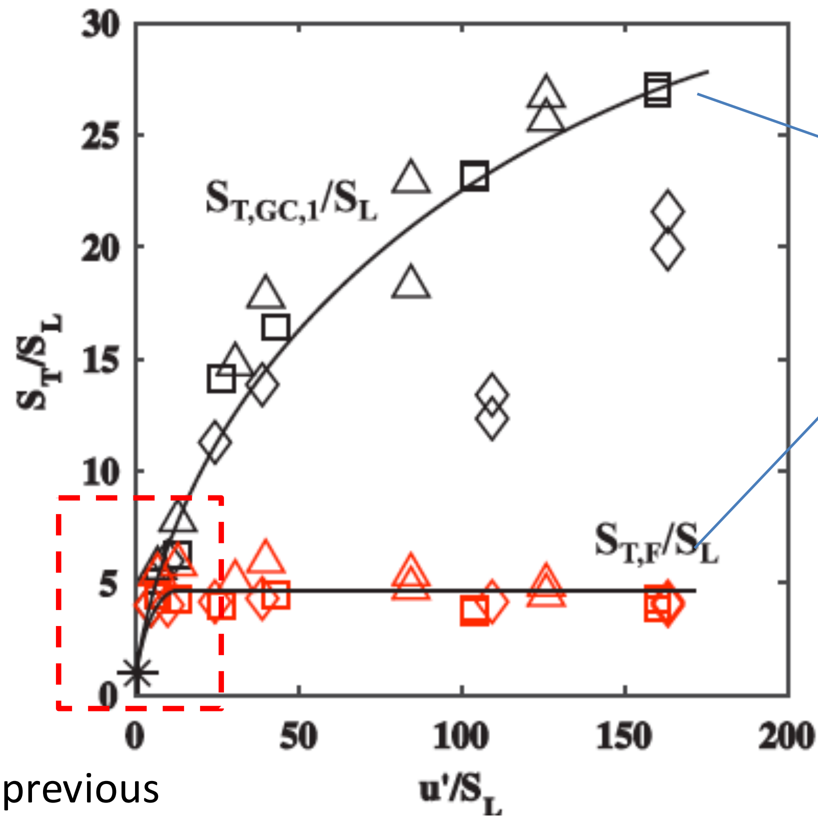
vortex passage, flame stretch,
extinction,
rollup, merging



“Damkohler diffusion” events

globs of hot gases convecting,
broadening the preheat layer

Turbulent Burning Velocity (S_T)



previous data of Gulder

At high Reynolds number, was Damkohler prediction correct ? YES

True measured burning velocity

Wrinkled area / time averaged area

low turbulence = linear variation of S_T

extreme turbulence = square root dependence

$$\frac{S_T}{S_L} = \sqrt{\frac{\alpha_T \ RR}{\alpha_L \ RR}} = \sqrt{\frac{u' \ L_x}{\nu}}$$

For more details: see our recent papers

36th Comb. Symp. Seoul:

"Measurements to Determine **Regimes** of Premixed Flames in Extreme Turbulence",
T. Wabel, A. Skiba, J. Temme, J. F. Driscoll

"**Turbulent Burning Velocity** Measurements: Extended to Extreme Levels of Turbulence"
T. Wabel, A. Skiba, J. F. Driscoll

"Reaction layer visualization: a **comparison of two PLIF techniques** and advantages of kHz-imaging" Skiba, T. Wabel, C. D. Carter, S. Hammack, J. Temme, T.H. Lee, J. F. Driscoll

+ two papers submitted for Journal publication

Conclusions - what happens at extreme levels of turbulence ?

1. **Events:** Merging, extinction, broadening

2. **Preheat layers** - becomes very broadened, Reaction layers – remain thin

3. Stratified flames become broken and distributed (but non-stratified do not)

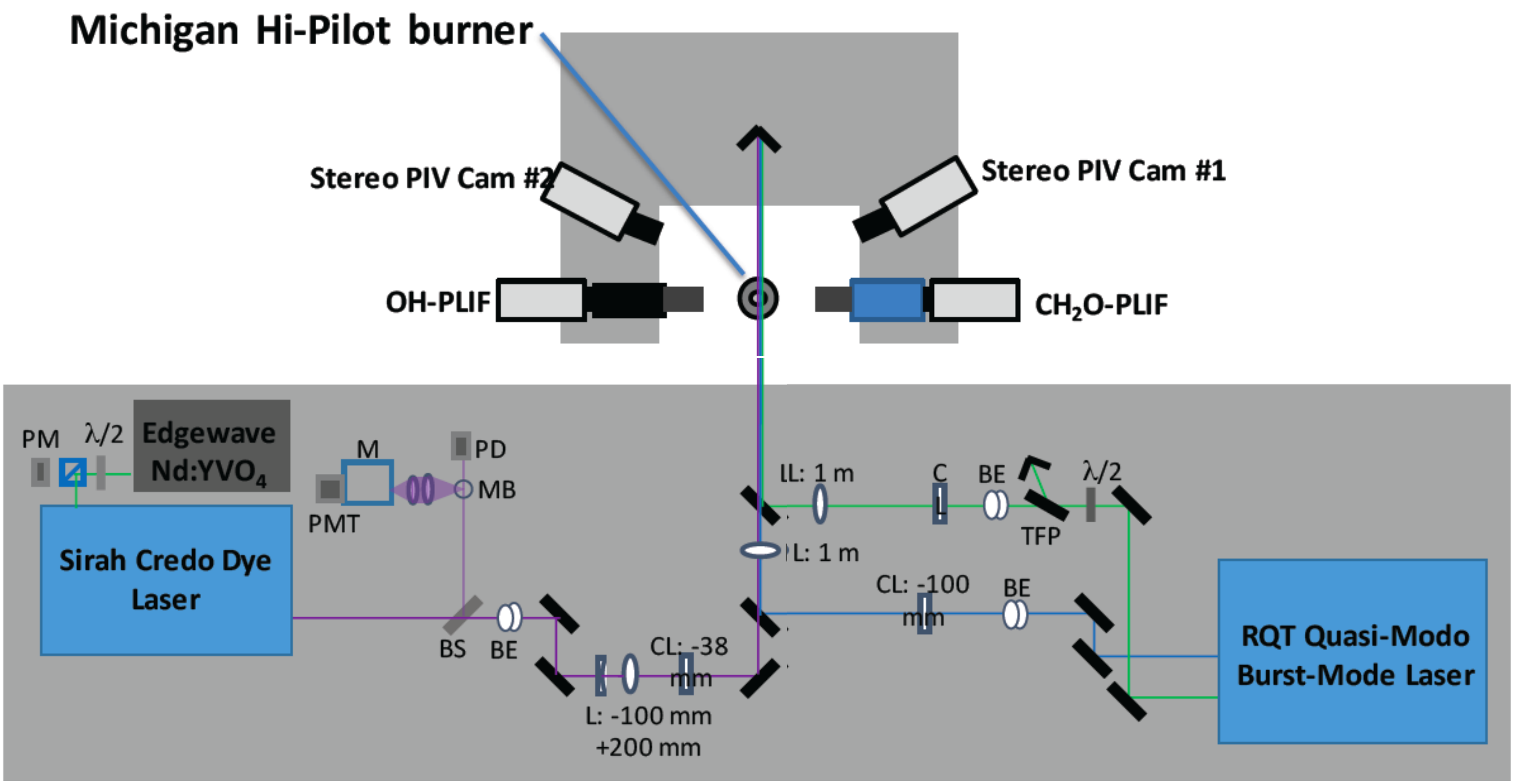
4. Regime of Continuous Thickened Flamelets - is **larger** than predicted by Peters
   Predicted "Broken regime" boundary - is **not** consistent with our data

5. **We measured the boundary** where preheat layers are broadened $D_T > 180\ D^*$

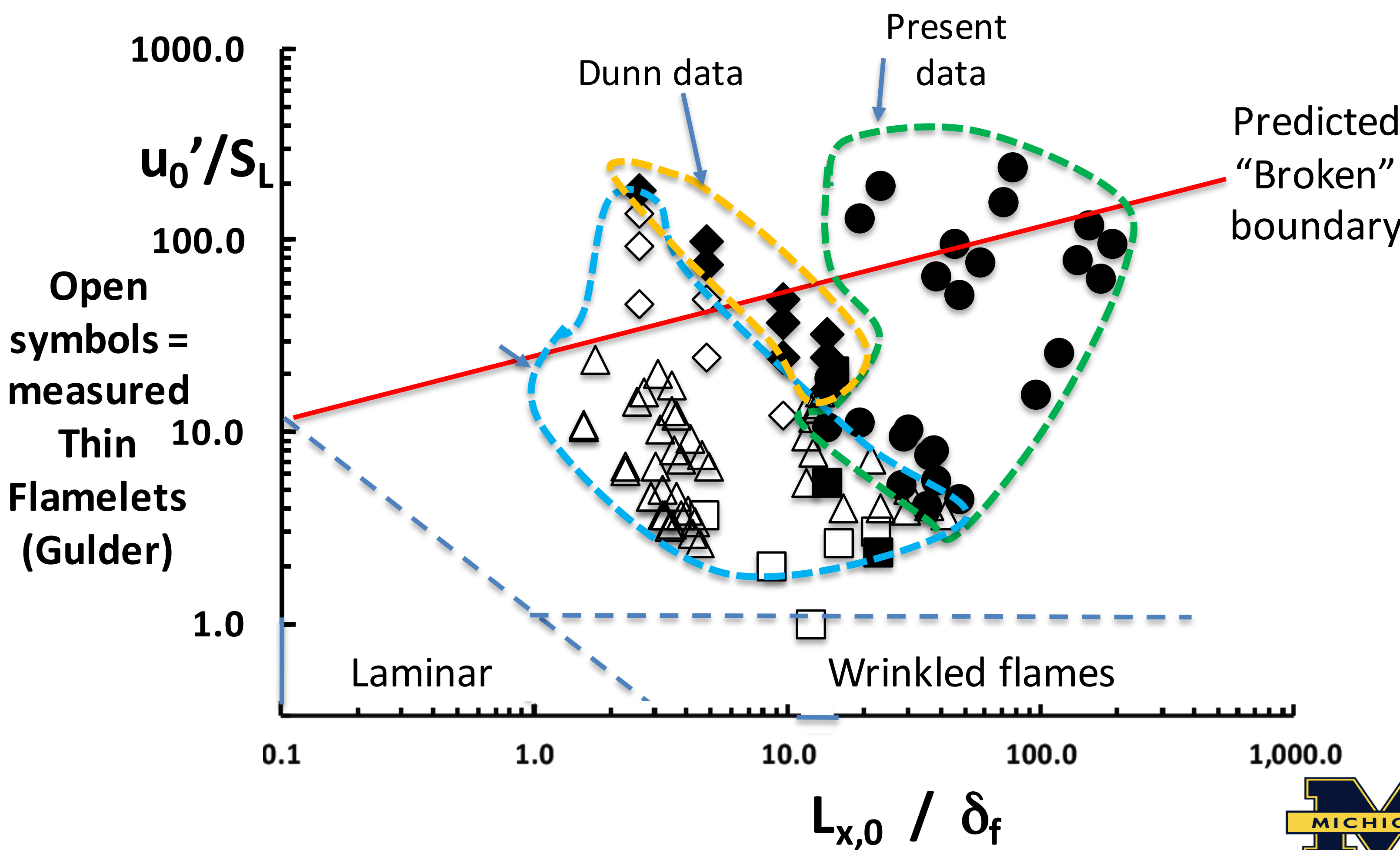
6. **Turbulent burning velocity** at extreme turbulence agrees with Damkohler trends

7. **PLIF of JP-8**, toluene, formaldehyde, OH – careful selection of wavelengths needed

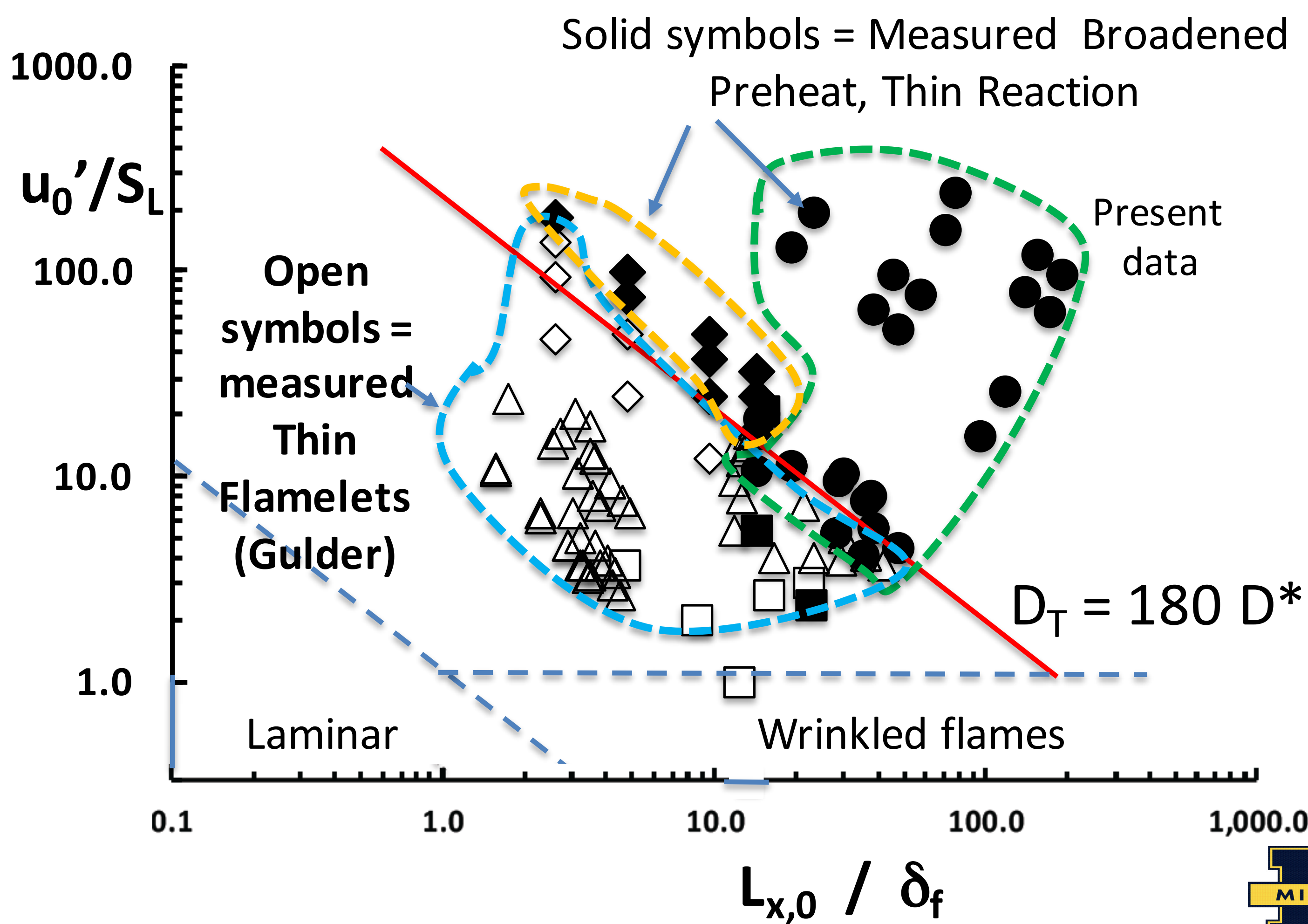
20-40 kHz Pulse Burst Laser and 10 kHz Laser



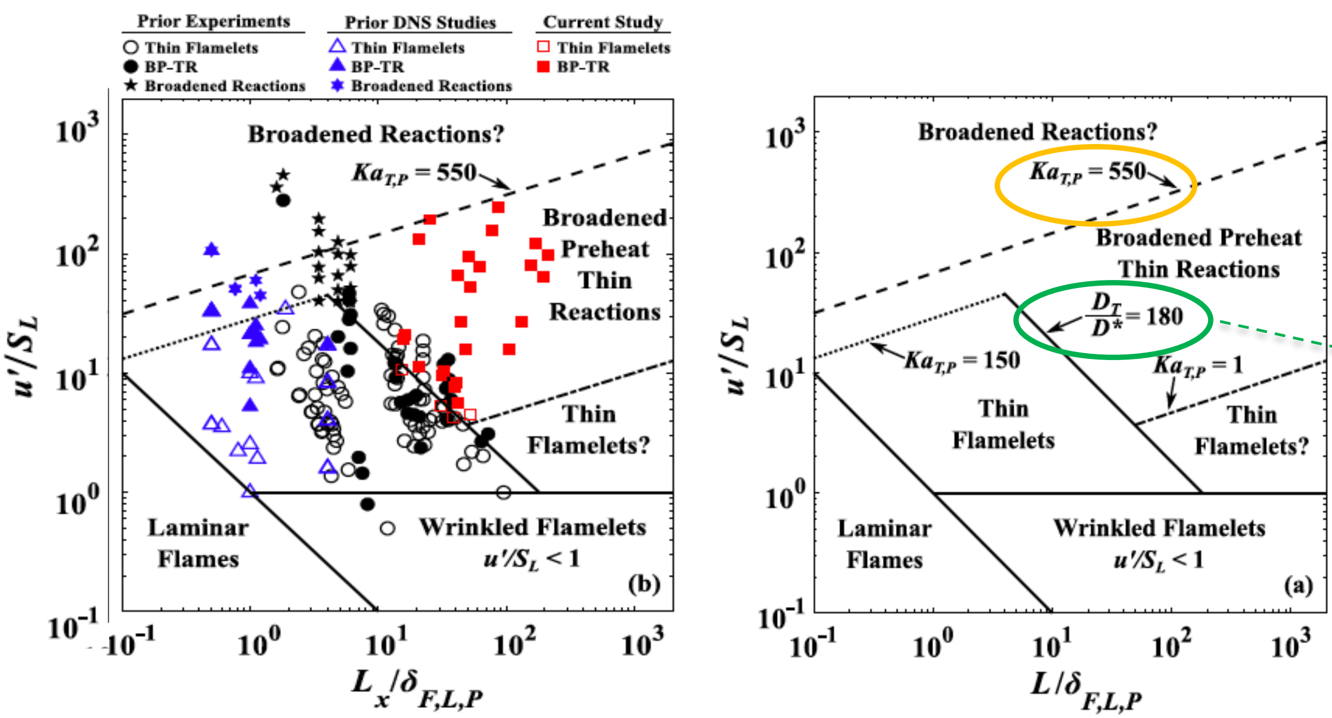
Flamelets are not broken above the predicted "Broken" boundary



Measured Regime Diagram - broadening boundary



Goal #3 Measured Regimes - two measured boundaries do not agree



Broadening of reaction layers → when Ka_P exceeds five times predicted value

Broadening of preheat Layers → when $D_T / D^* = 180$ where $D_T = u' L_x$

Flamelets occur over much wider range than was predicted

Interactions with Drs. Cam Carter, Jim Gord AFRL

Michigan: measured burning velocities, preheat and overlap (reaction) layers (completed)

1. AFRL: Kilohertz CH movies in Hi-Pilot (completed)
2. AFRL: KHz simultaneous CH-OH in Hi-Pilot (completed)
3. Compared CH to Overlap methods (completed)
4. Michigan: Set up JP-8 Hi-Pilot flame (completed)
5. AFRL and Michigan: PIV velocity field (this coming year)
6. AFRL: Run Hi-Pilot on JP-8 for Line CARS (this coming year)

Profiles of 14 species in a vaporized JP-8 flame -

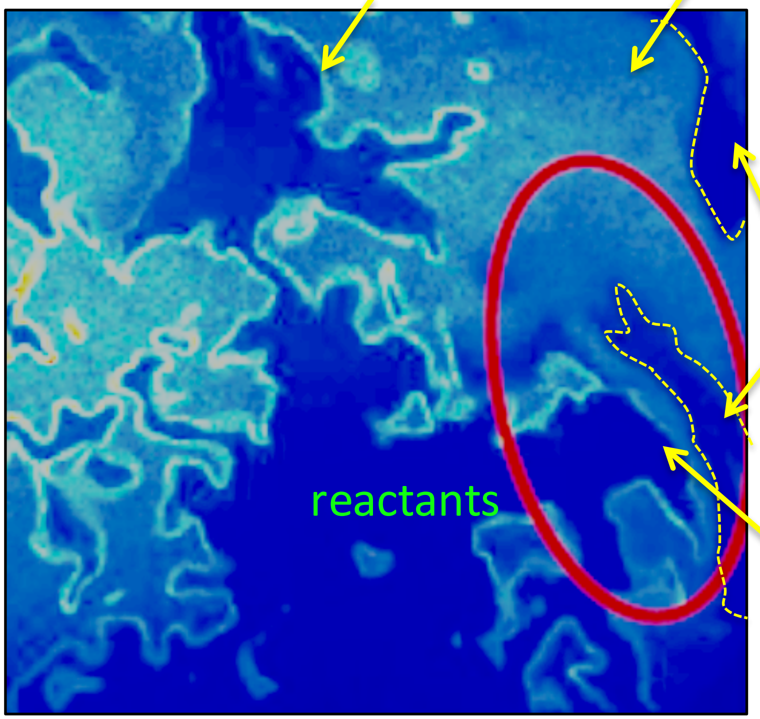
can it be done ?

	Species or temperature		Diagnostic		Location	Ref.
1	hydroxyl	OH	PLIF	2-D image	U. Michigan	1,7
2	formaldehyde	CH_2O	PLIF	2-D image	U. Michigan	1,7
3	JP-8	JP-8	PLIF	2-D image	U. Michigan	8-11
4	carbon monoxide	CO	LIF	line image	U. Michigan	12, 13
5	toluene	C_7H_8	LIF	line image	U. Michigan	14
	temperature	T	PLIF (2-line)	2-D image	U. Michigan	12
	temperature	T	nsec-CARS	line image	AFRL*	15-29
6	hydrogen	H_2	nsec-CARS	line image	AFRL	3
7	methane	CH_4	nsec-CARS	line image	AFRL	17, 19
8	carbon dioxide	CO_2	nsec-CARS	line image	AFRL	18
9	water	H_2O	nsec-CARS	line image	AFRL	17
10	carbon monoxide	CO	nsec-CARS	line image	AFRL	20
,12	nitrogen, oxygen	N_2, O_2	nsec-CARS	line image	AFRL	3
13	acetylene	C_2H_2	nsec-CARS	line image	AFRL	24
14	ethylene	C_2H_4	nsec-CARS	line image	AFRL	28, 29

Extinction events - lead to broken reactions

CH reaction layer = thin bright blue line

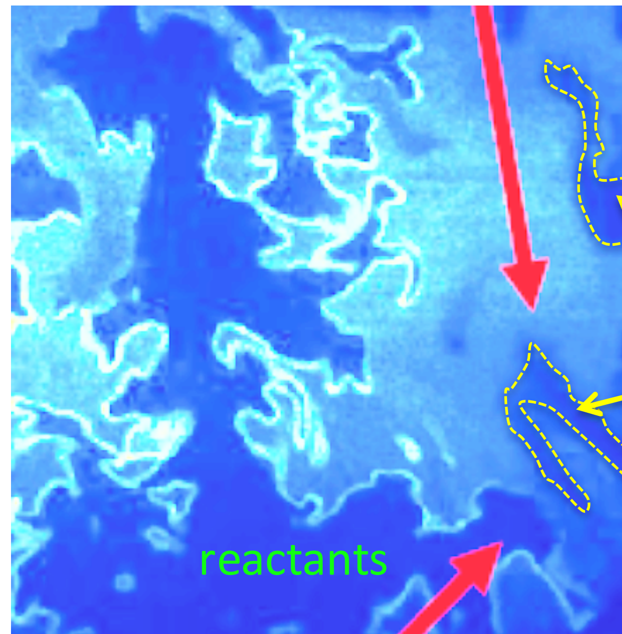
OH products = broad light blue



dark blue = stratified products

Broken reactions

CH-OH method of Cam Carter



dark blue= stratified products

Broken reactions