Space-based Combustion Experiments "Group Combustion" aboard Kibo on the ISS

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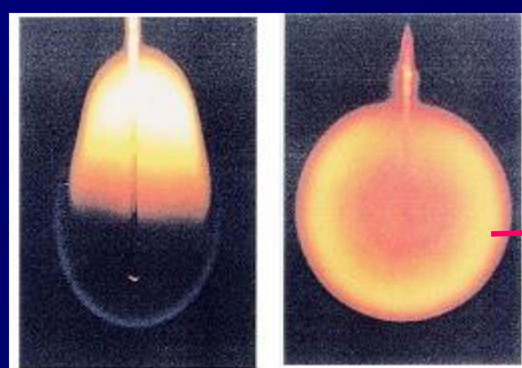
Spray combustion

Fuel droplet in 1G

d_0=0.01 mm

Negligible gravity effect

Single droplet combustion



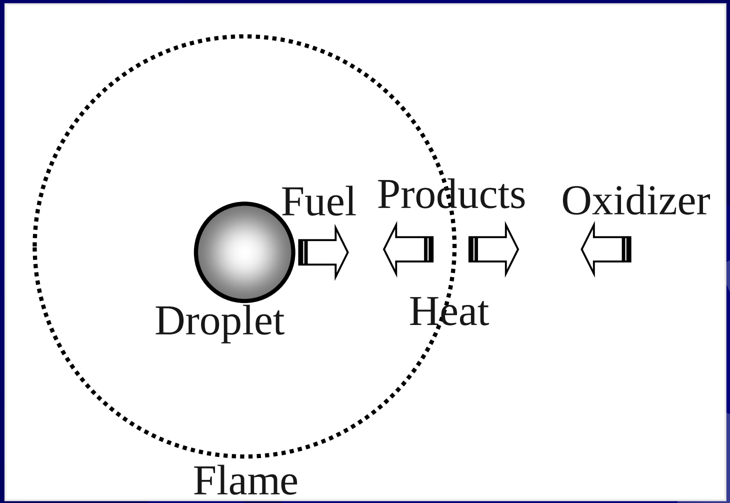
Fuel droplet in μG

d_0=1mm

Negligible gravity effect

Gravity effect	1G	μG
	Significant!	Negligible

Droplet combustion in microgravity

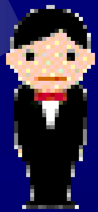


Spherically-symmetry one-dimensional combustion

Candle flame

UNOOSA Hypergravity/Microgravity Webinar, May 26, 2021

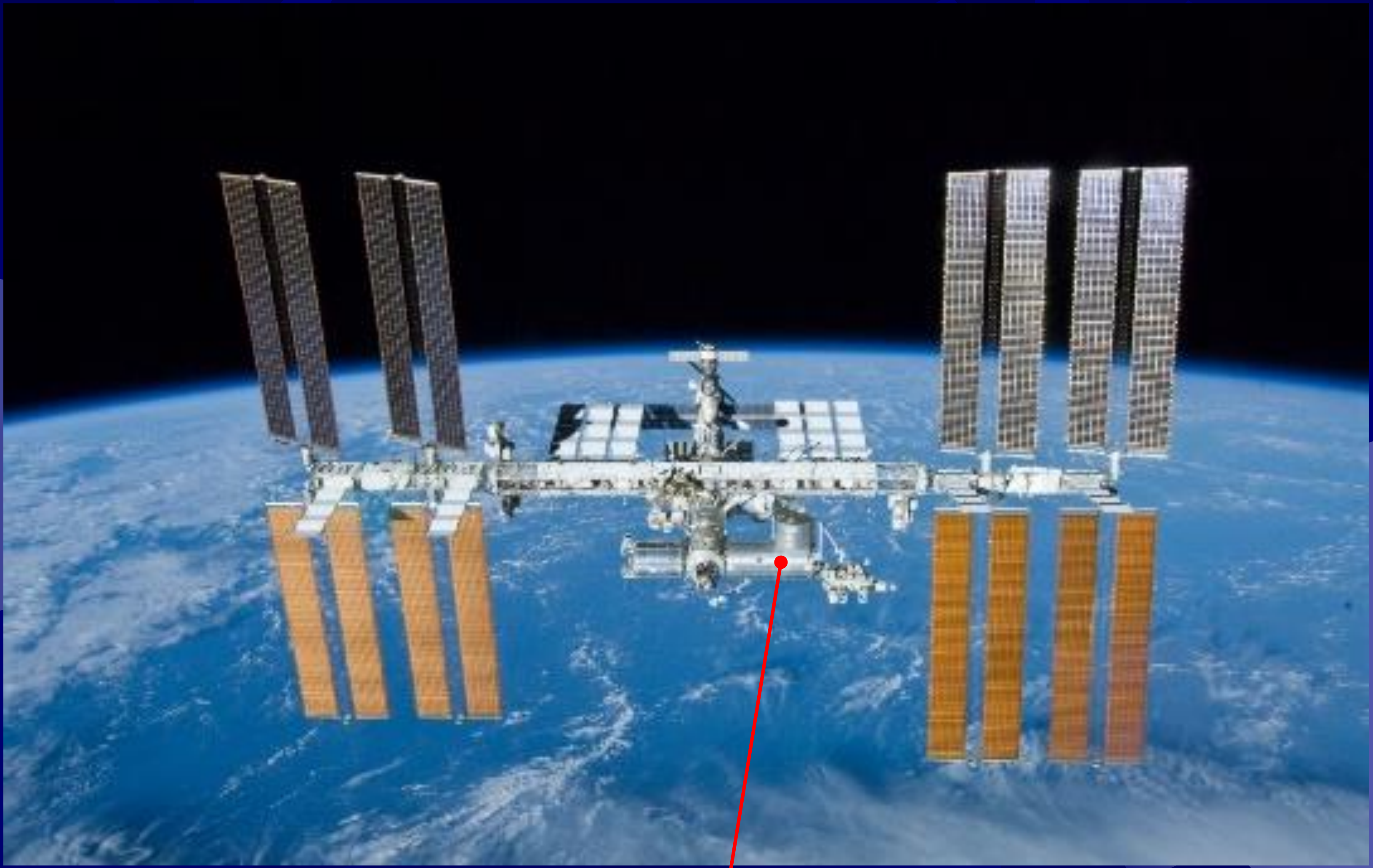
Space-based Combustion Experiments "Group Combustion" aboard Kibo on the ISS



- Masato Mikami : Yamaguchi Univ.

YAMAGUCHI UNIVERSITY

International Space Station (ISS)



Japanese Experiment Module
“Kibo”

Source: JAXA/NASA

Combustion research is hot in Space!

Combustion research using CIR in Destiny/ISS

- FLEX (2009-2013), FLEX-ICE (2013), FLEX-2J (2015), Cool Flames (2016)
- ACME (2018-2019),
- SoFIE (2019-2021),

Combustion research in Kibo/ISS

- Group Combustion (2017)（PI: Mikami)
- Atomization (2018)(PI: Umemura)
- FLARE (2021)(PI: Fujita)
- L3-Flame (2022)(PI: Maruta)
- Group Combustion-2 (2023)（PI: Mikami)

Combustion Experiments in KIBO

JASMA

Group Combustion

PI: Prof. Masato MIKAMI
(Yamaguchi Univ.)

Elucidation of Flame Spread and Group Combustion Excitation Mechanism of Randomly Distributed Droplet Clouds
in 2017
Group Combustion-2 from 2023

ATOMIZATION

PI: Prof. Akira UMEMURA
(Nagoya Univ.)

Detailed validation of the new atomization concept derived from drop tower experiments -Aimed at developing a turbulent atomization simulator
in 2018

FLARE

PI: Prof. Osamu FUJITA
(Hokkaido Univ.)

Fundamental Research on International Standard of Fire Safety in Space -base for safety of future manned mission
in 2021

L3-FLAME

PI: Prof. Kaoru MARUTA
(Tohoku Univ.)

Low-speed low-Lewis-number counterflow flame experiment for unified combustion limit theory
in 2022

PI M. Mikami
CI T. Seo

CI H. Nomura
CI Y. Suganuma

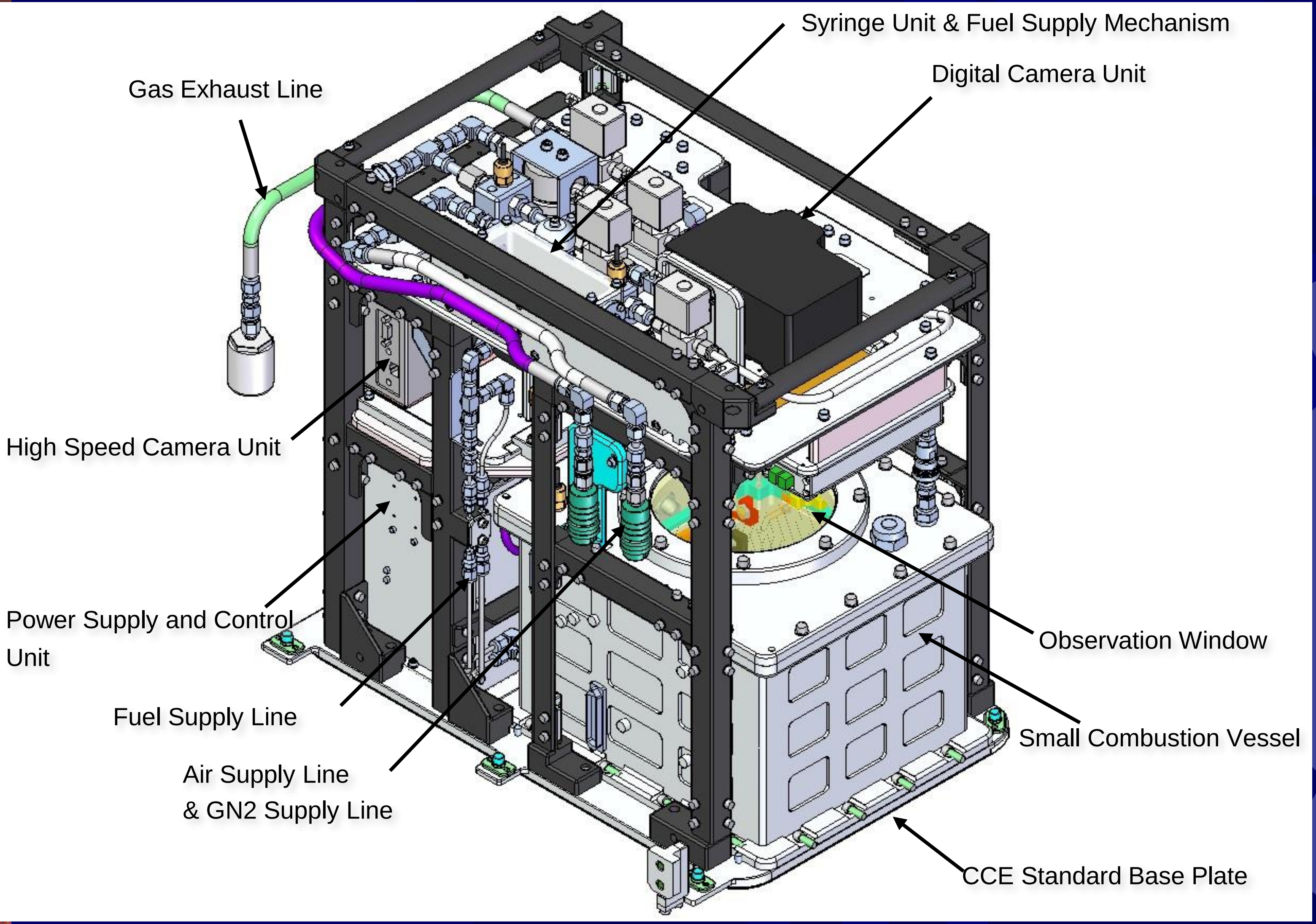
CI O. Moriue

CI A. Umemura

CI T. Sakashita
CI M. Kikuchi
CI T. Suzuki

NASA GRC
CI D.L. DIETRICH

Group Combustion Experiment Module (GCEM)



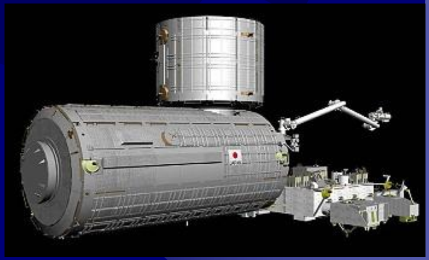
Delivery of GCEM to "Kibo" aboard ISS

H-2B rocket

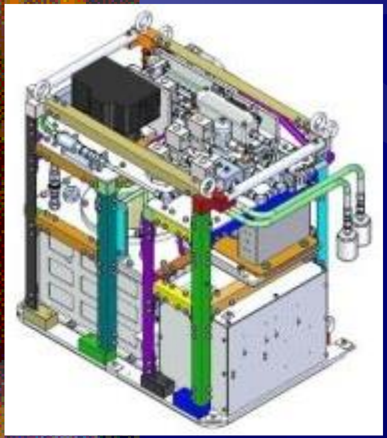
Transfer vehicle "Kounotori"

Docking of "Kounotori" to ISS by robot arm

ISS



Japanese Experiment Module "Kibo"



GCEM

Aug 2015 GCEM was launched by Japanese rocket H2B and delivered to ISS by Kounotori.

July 2016 The rest appratus was launched by US Space-X rocket and delivered to ISS by Dragon.

Transfer vehicle "Dragon"

Source: JAXA/NASA

Assembly of GCEM and CCE by Astronaut Takuya Onish in 2016

Source: JAXA

Installation of CCE to MSPR aboard “Kibo”/ISS

Source: JAXA

Feb 17 2017 First combustion experiment aboard KIbo

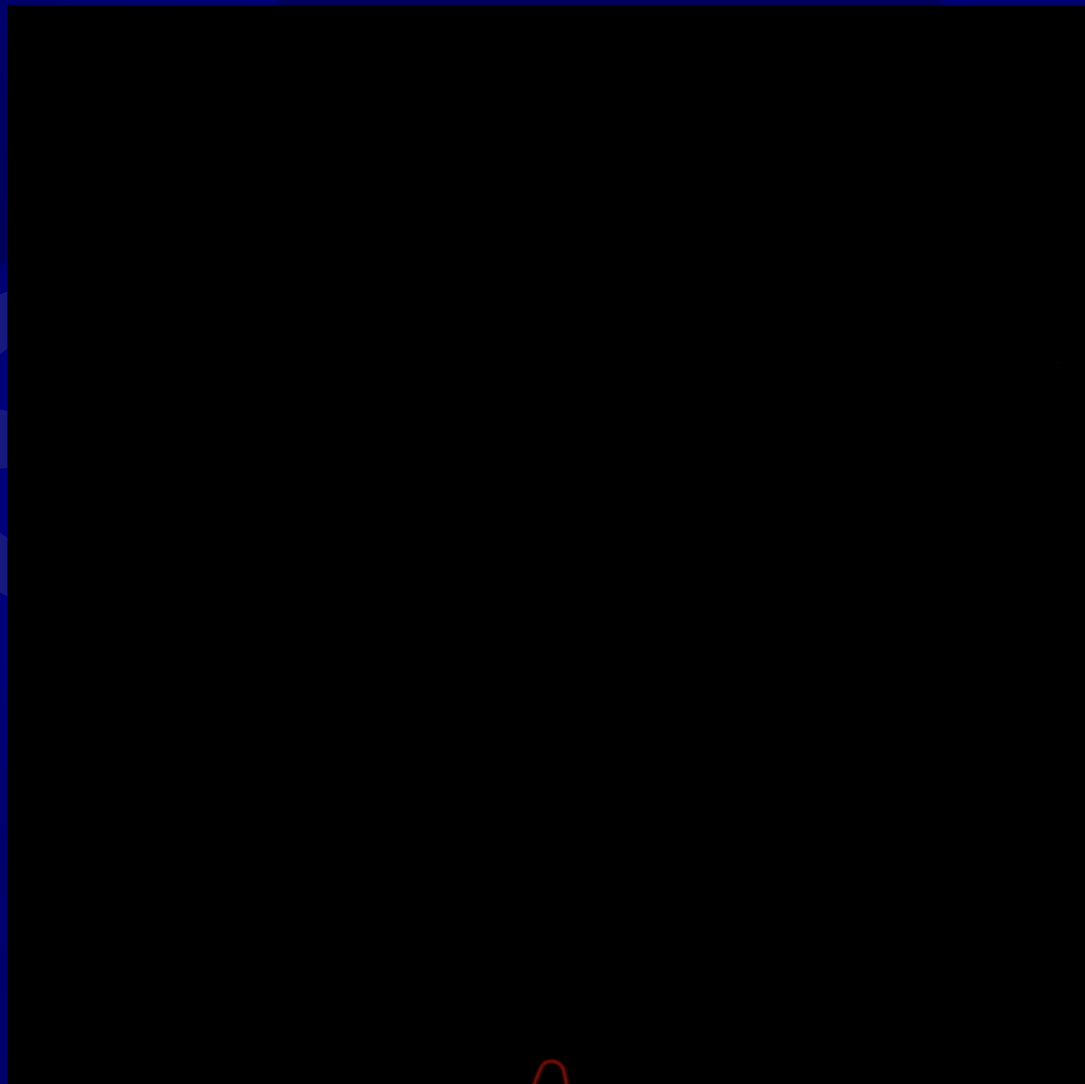
Feb - July 150 test conditions

Experiment operation at JAXA

Source : JAXA

Group-combustion excitation through flame spread

Number of droplets M=97, Initial droplet diameter d_0=1.03 mm



✸Background

(droplet combustion and spray combustion)

Liquid fuel combustion
- Spray combustion -

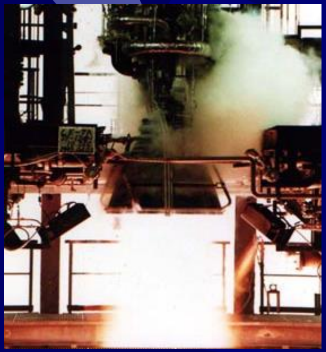
Mazda

Diesel engine

The Jet Engine

Jet engine

Gas turbine



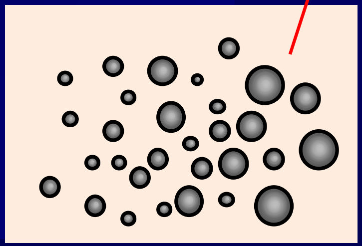
JAXA

Liquid rocket motor

Industrial furnace

Stable combustion

Group combustion
of fuel spray
(droplet cloud)

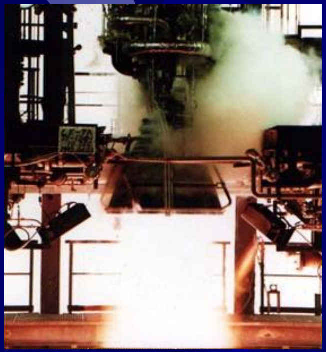


Fuel spray
(droplet cloud)

Spray combustion and droplet combustion

Diesel engine

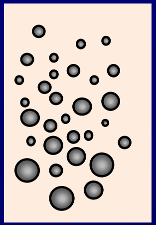
Jet engine
Gas turbine



Rocket motor
(liquid oxygen)

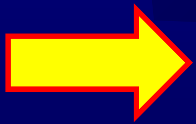
Industrial furnace

Spray combustion

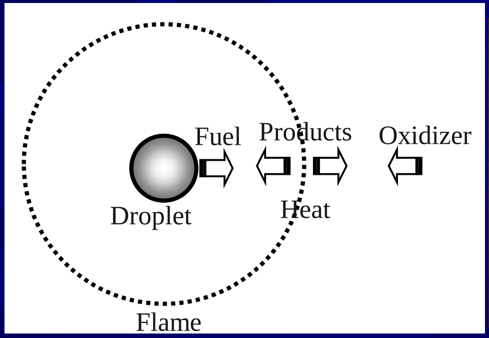


Droplet cloud

Fundamental research



Droplet combustion in microgravity



Spherically-symmetry one-dimensional combustion

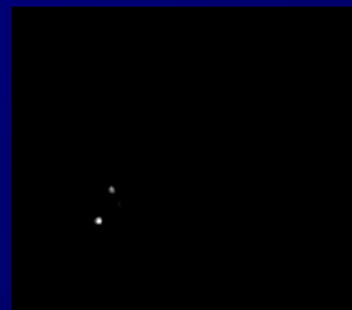
Existence of steady-state solution

From droplet combustion toward spray combustion

Flame spread of
droplet array

2000-2003
in drop tower

Flame spread of
droplet cloud element



2004-2016
in drop tower

Flame spread over
randomly distributed droplet cloud

2017
aboard “Kibo”/ISS

Single-droplet
combustion

from 1950’s
in drop tower μG

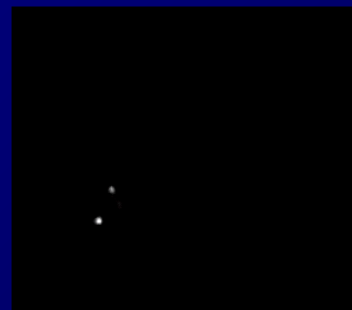
Spray combustion

From droplet combustion toward spray combustion

Flame spread of droplet array

2000-2003
in drop tower

Flame spread of droplet cloud element



2004-2016
in drop tower

Flame spread over randomly distributed droplet cloud

2017 aboard "Kibo"/ISS

Percolation model

Single-droplet combustion
from 1950's
in drop tower μG

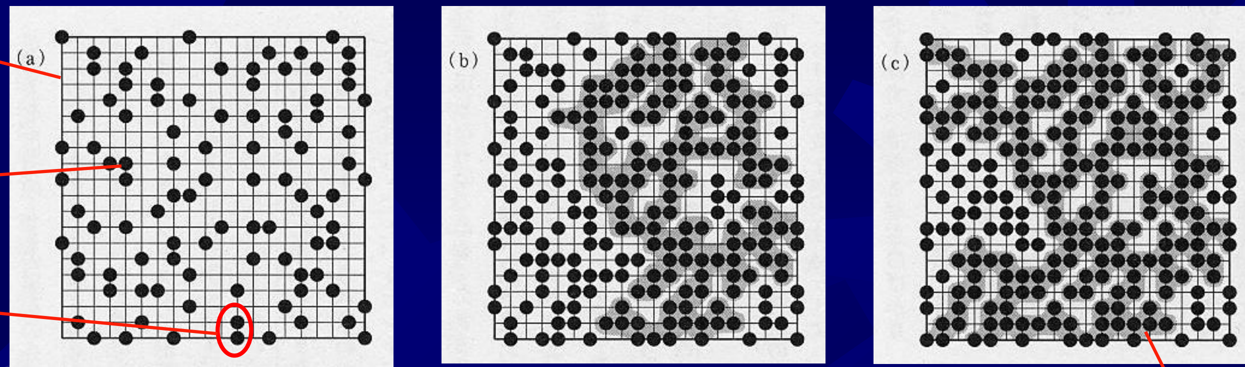
Spray combustion

Percolation Theory

Lattice

Particle

Cluster



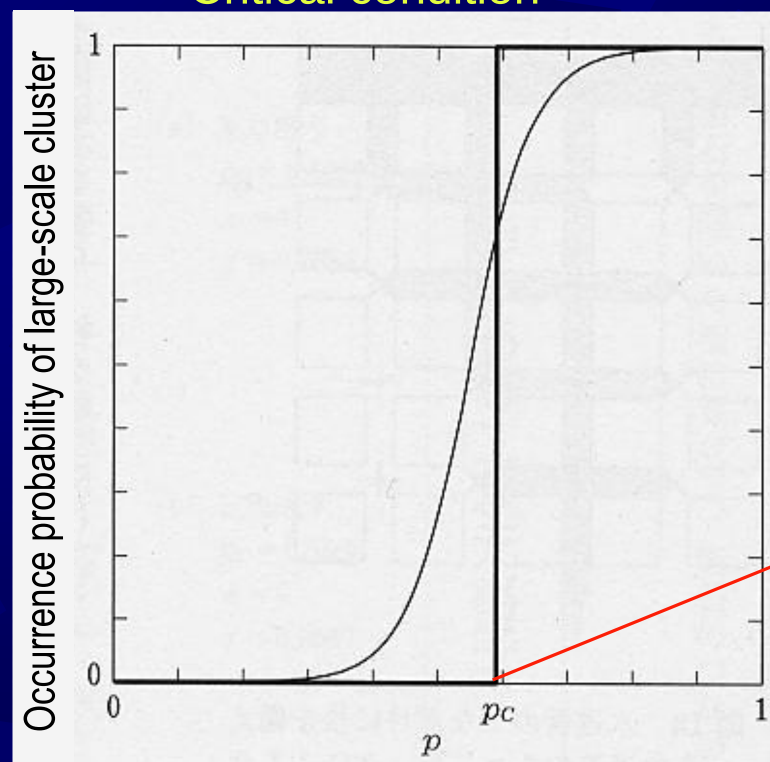
Occupation fraction p=0.266

p=0.598
Critical condition

p=0.665

Large-scale cluster

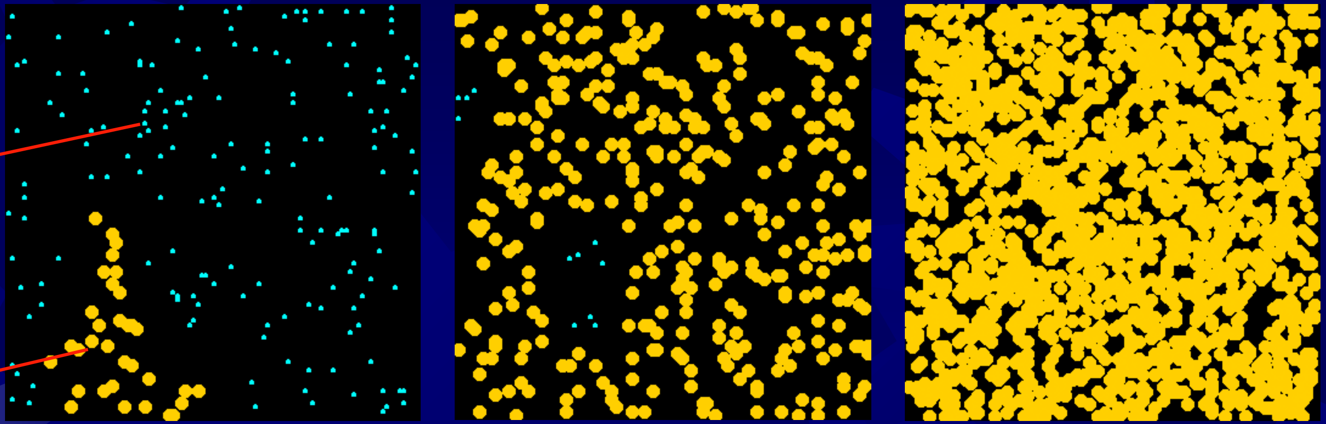
Local connection rule determines macroscopic behavior of randomly distributed particle cloud

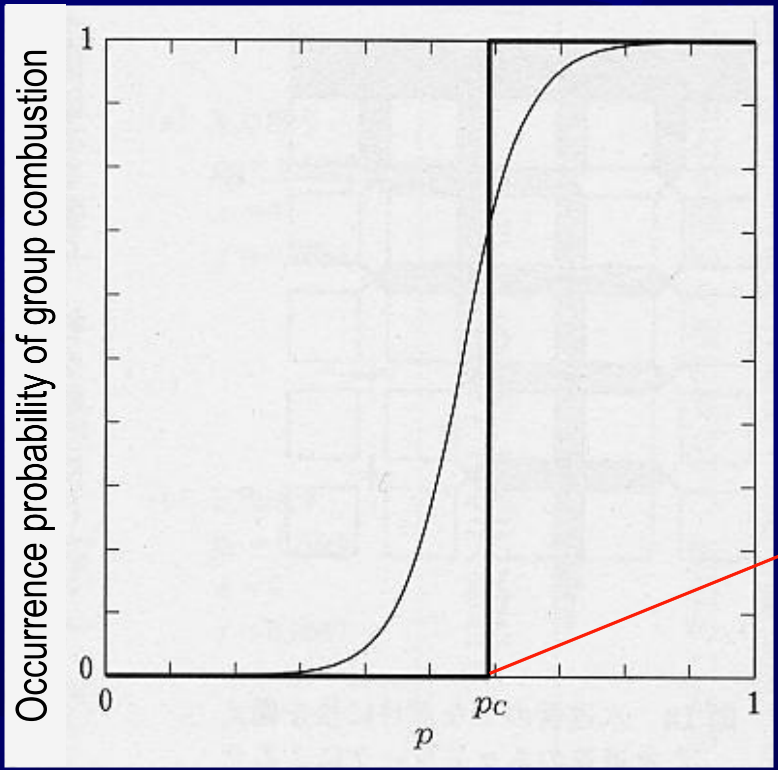


Occupation fraction

Critical occupation fraction

Application of Percolation Theory to Spray Combustion

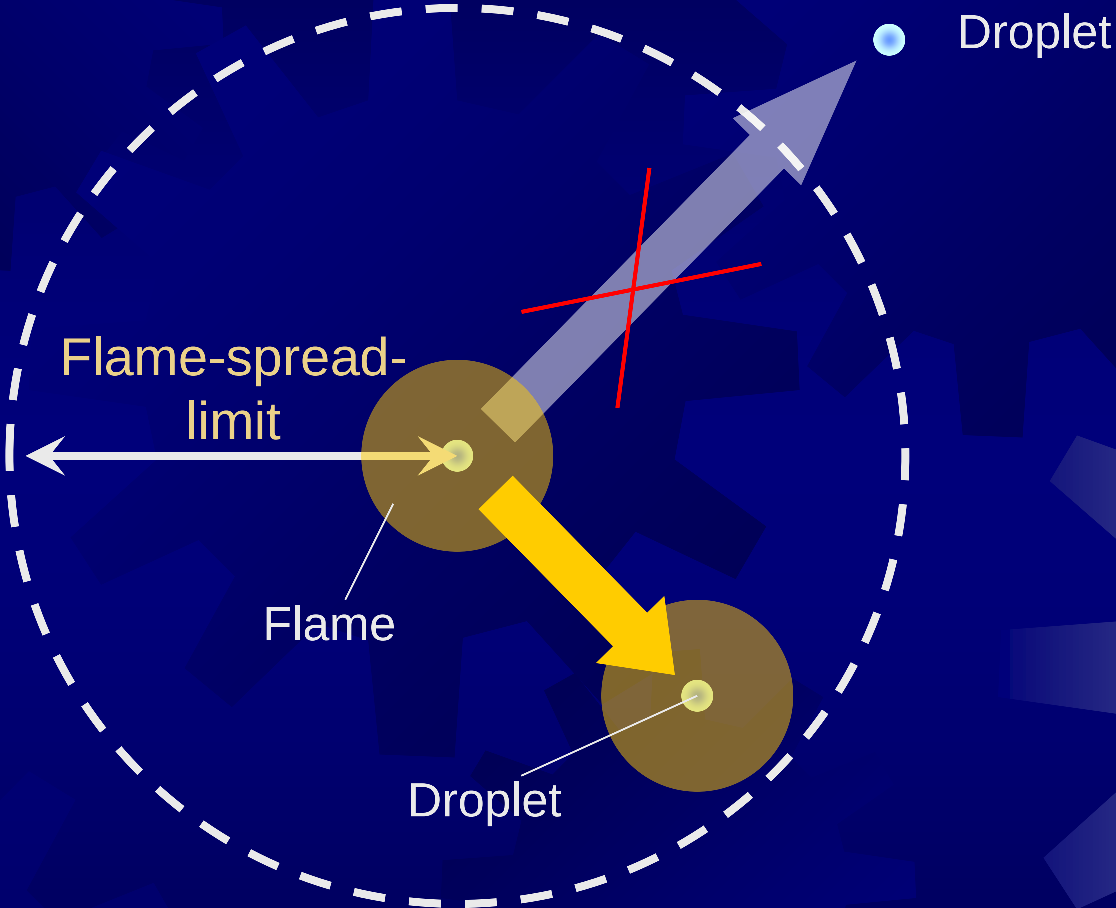




Local flame-spread rule determines macroscopic group combustion behavior of randomly distributed droplet cloud

Percolation model of flame spread in randomly distributed droplet cloud considering flame-spread-limit distance

Mikami et al, MST 30, 2018

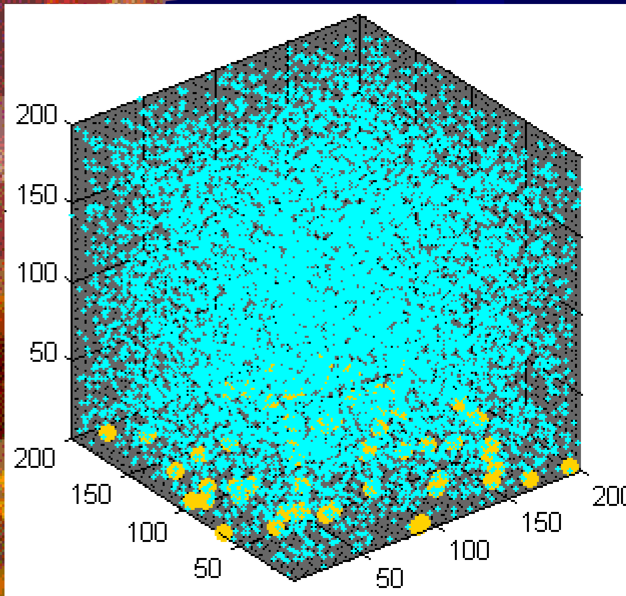


Flame-spread-limit distance $(S/d_0)_{limit}$ =14
(n-decane droplet array in microgravity)

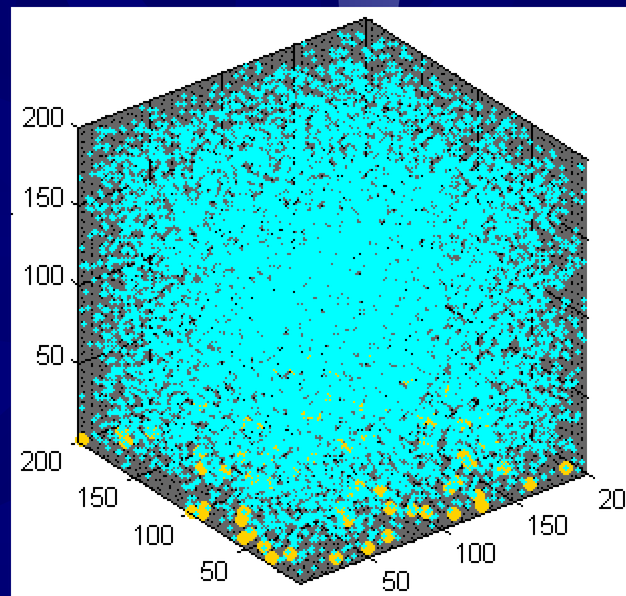
Mikami et al, 2006

Calculation of flame spread in randomly distributed droplet cloud

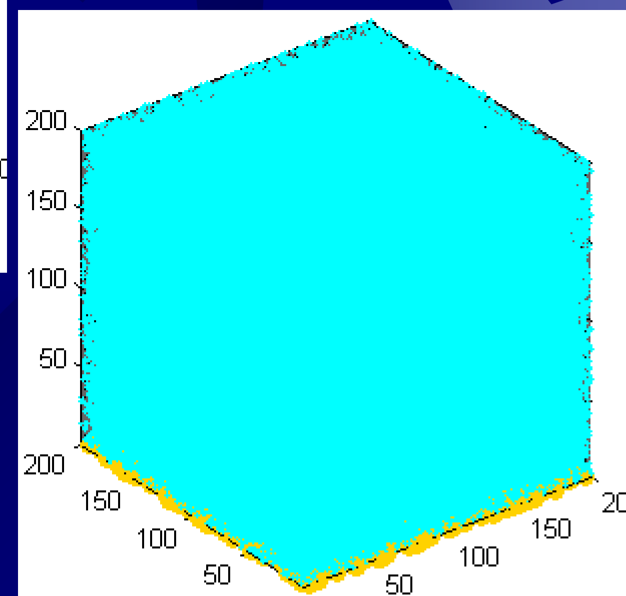
Mikami et al, MST 30, 2018



Dilute spray
large $(S/d_0)_m$



Critical condition

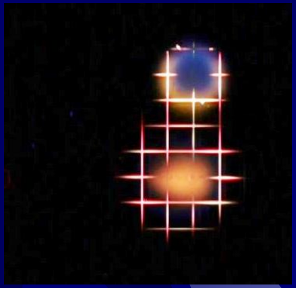


Dense spray
small $(S/d_0)_m$

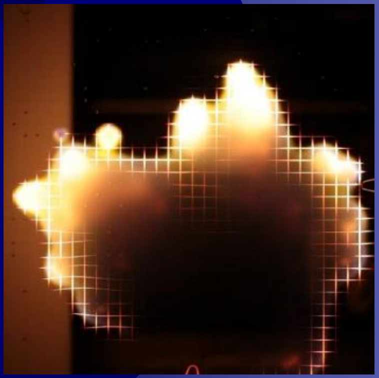
Local flame-spread rule determines macroscopic group combustion behavior of randomly distributed droplet cloud

Flame-spread experiments “Group Combustion” aboard “Kibo” to study local flame-spread rule and group combustion behavior

- Droplet-cloud element
  to study local flame-spread rule
  (Yoshida et al., PROCI 37, 2019)



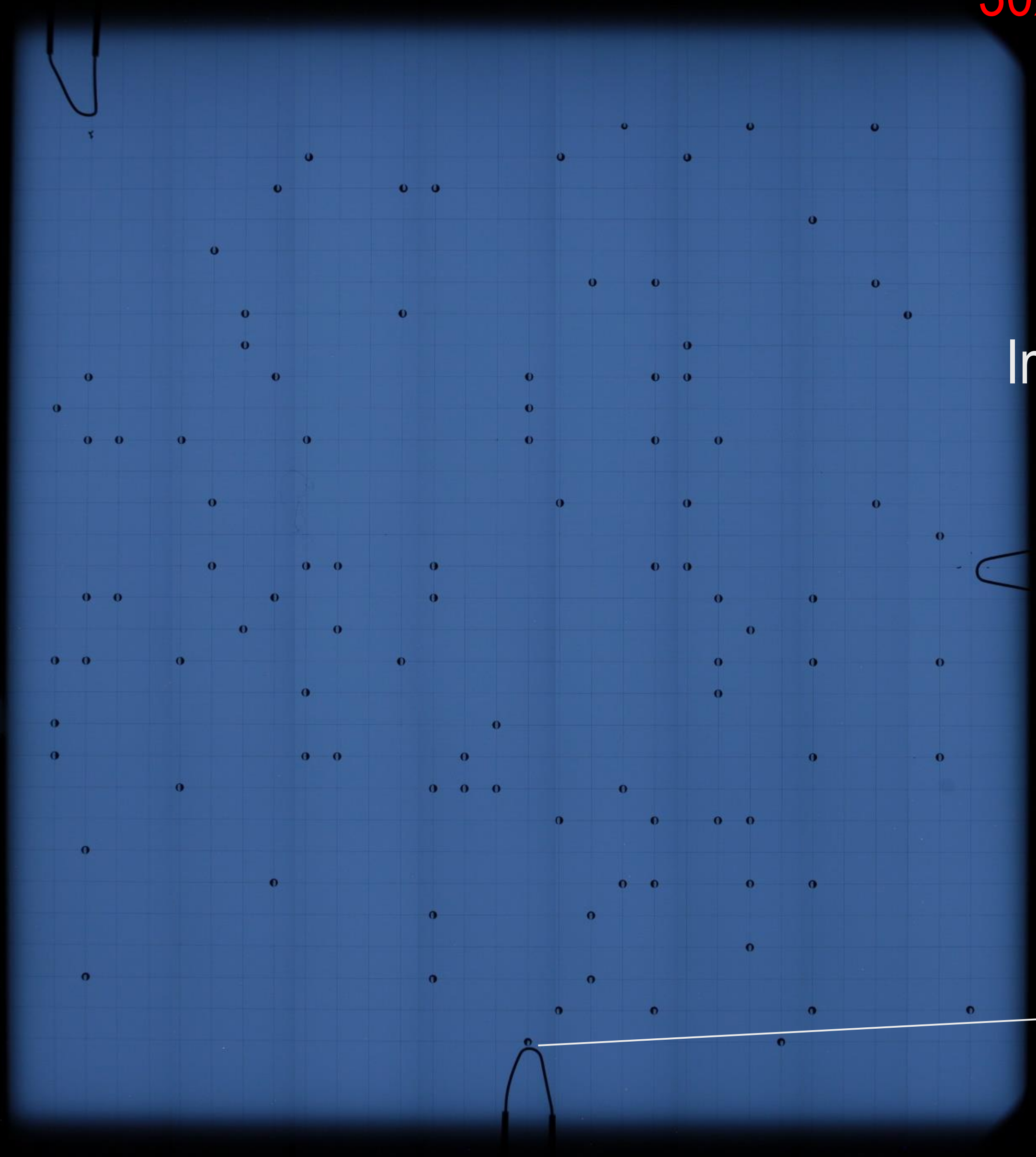
- Randomly distributed droplet cloud
  with about 100 droplets
  to check group combustion behavior
  and local flame-spread behavior
  (Mikami et al., MST 30, 2018,
  Mikami et al., PROCI 33, 2021)



Droplet arrangement in “Group Combustion”aboard Kibo/ISS

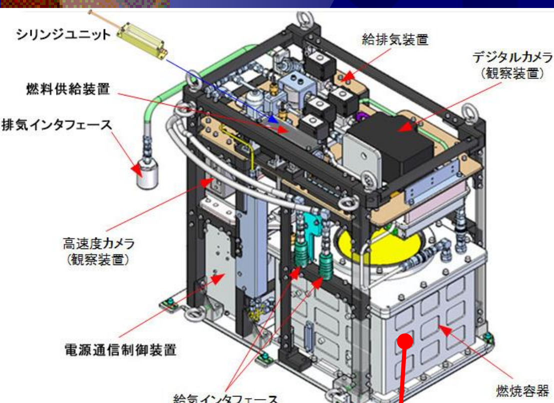
30x30 SiC fiber lattice
(4 mm interval)

Number of droplets
M=67-152
Initial droplet diameter
d_0=0.9-1.2 mm

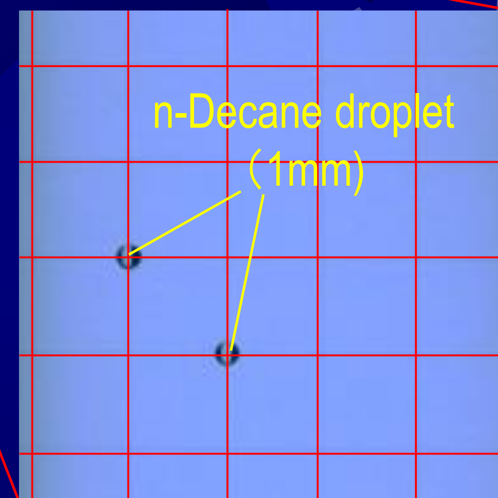


Droplet cloud on SiC fiber lattice

GCEM



Droplet cloud generation and combustion inside the chamber



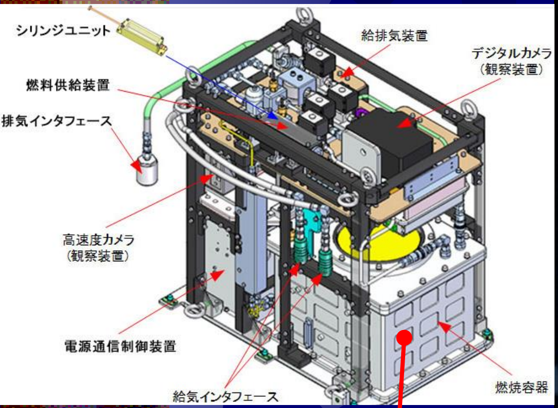
4 mm interval

14 μm SiC fiber lattice

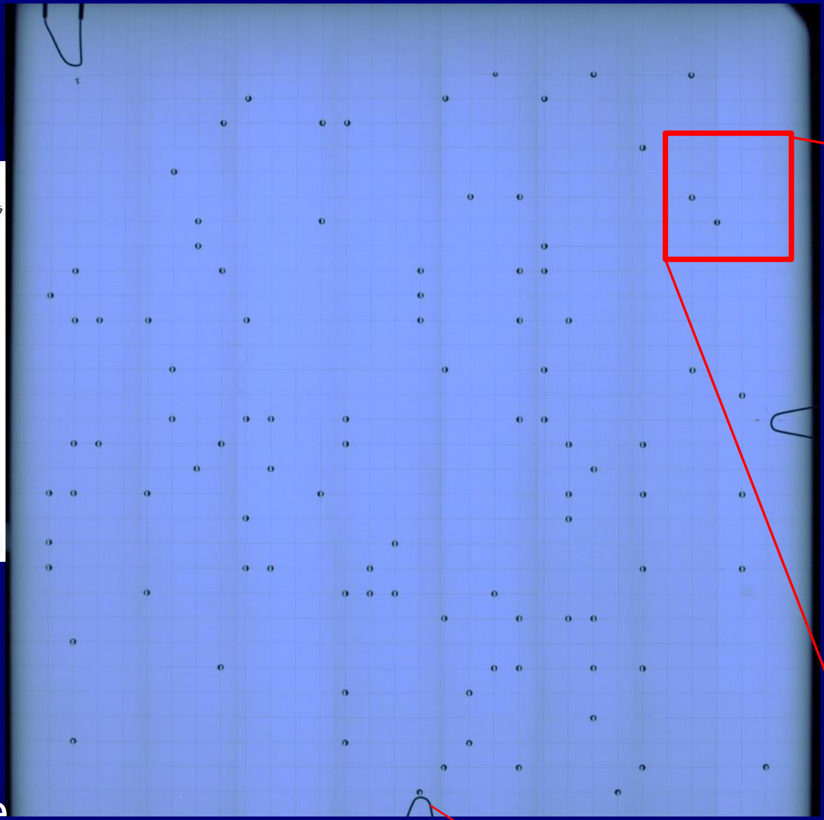
(30 × 30)

Droplet cloud on SiC fiber lattice

GCEM



Droplet cloud generation and combustion inside the chamber



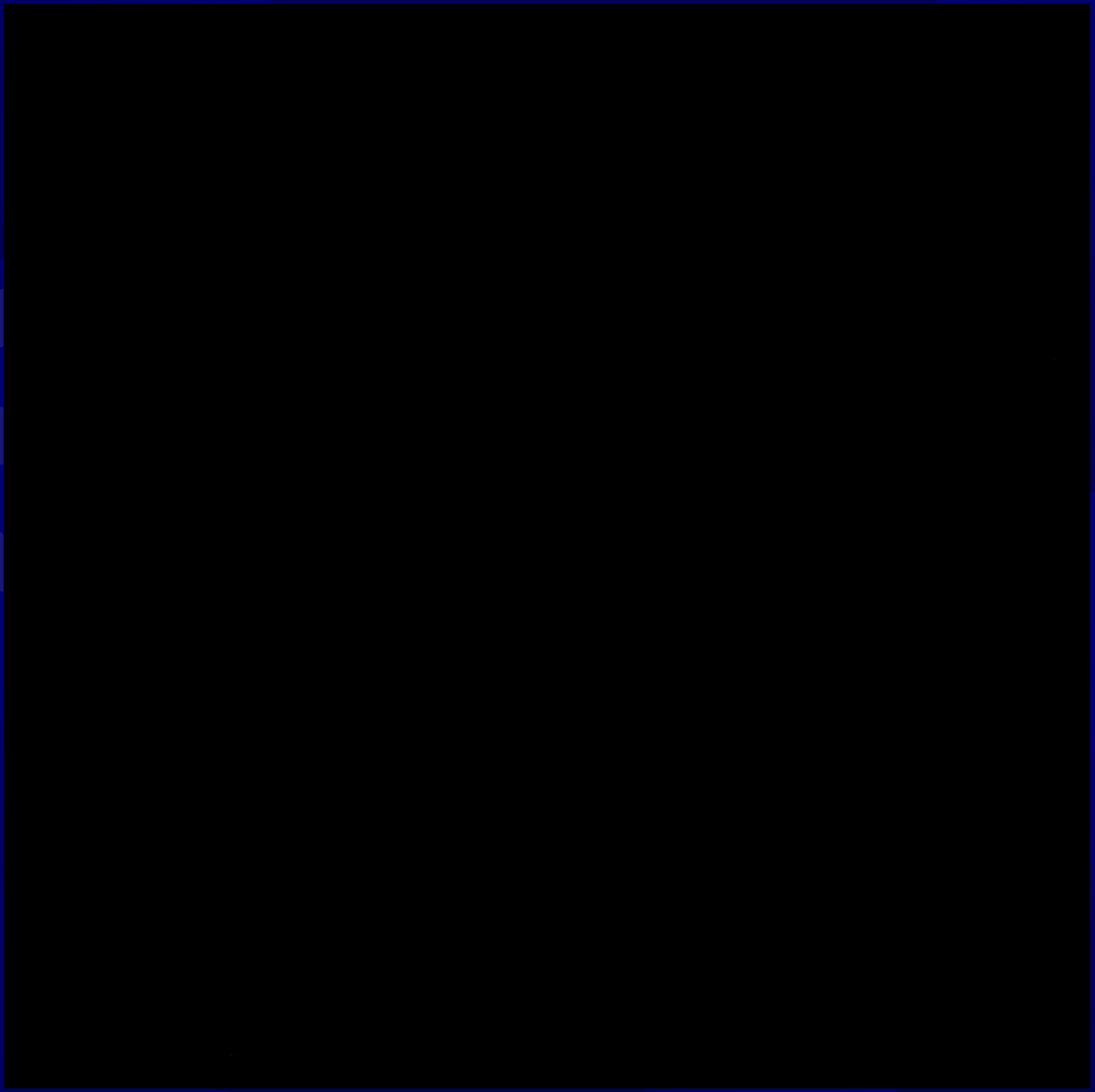
4 mm interval

14 µm SiC fiber lattice

（30 × 30）

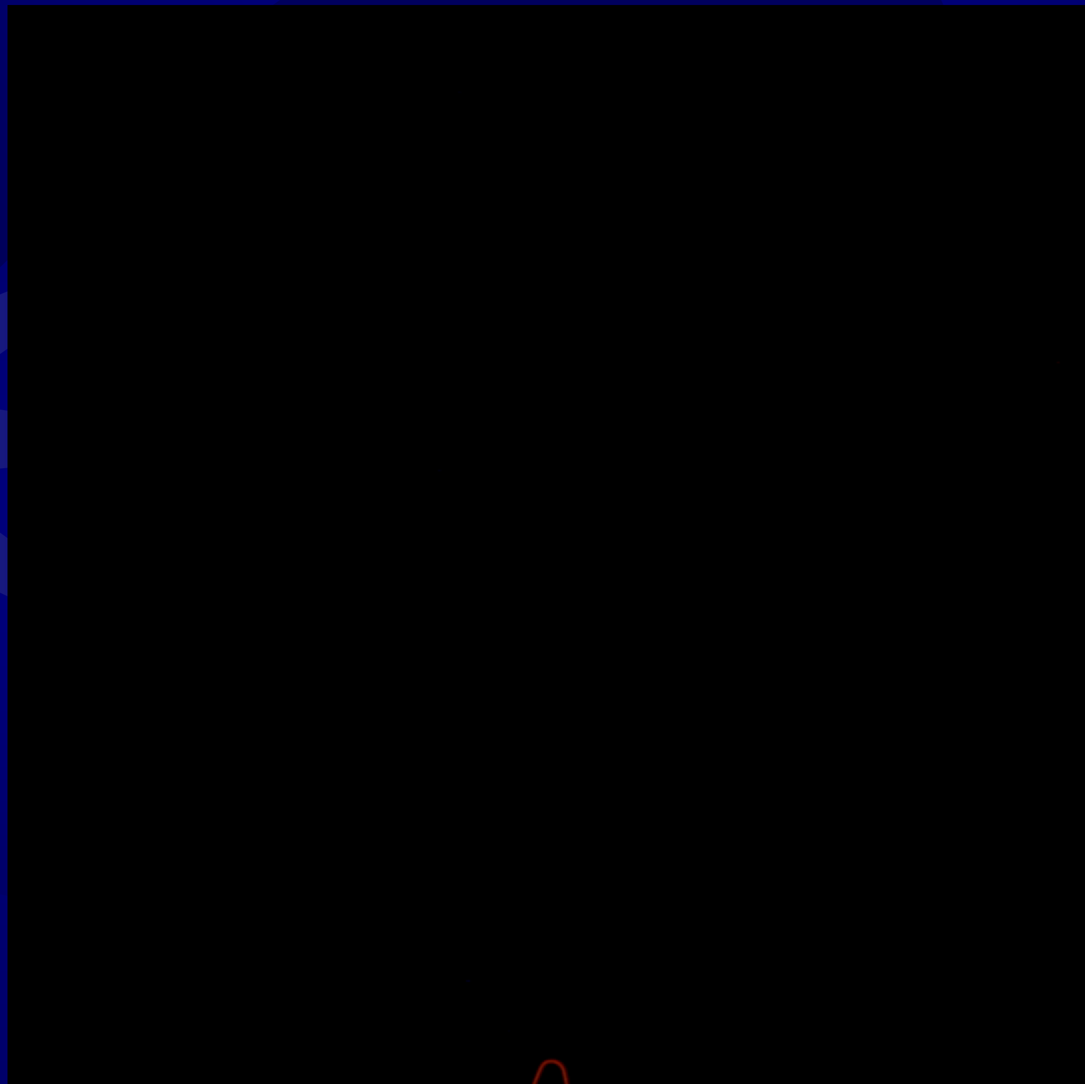
Group-combustion excitation through flame spread

Number of droplets M=152!!, Initial droplet diameter d_0=1.05 mm



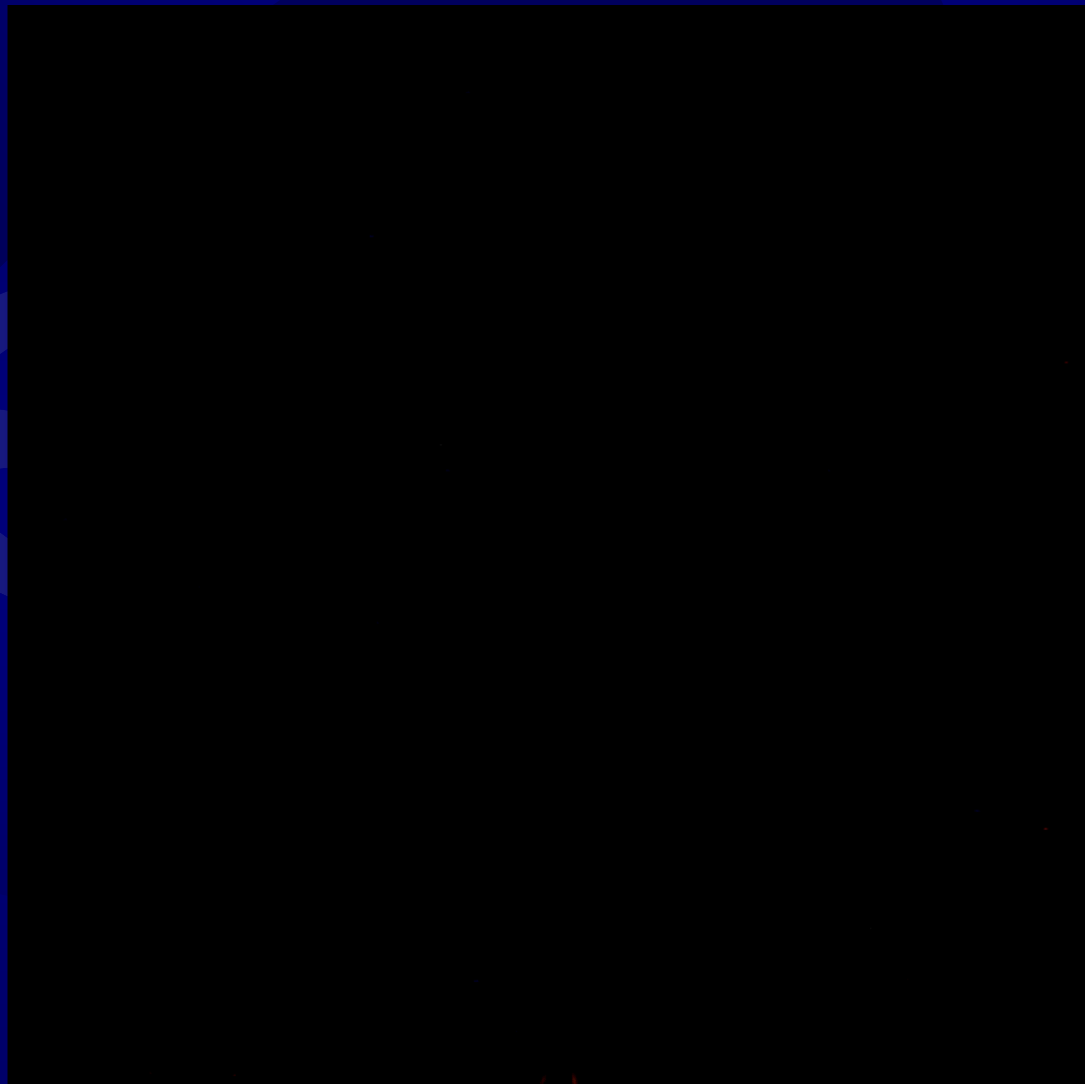
Group-combustion excitation through flame spread

Number of droplets M=97, Initial droplet diameter d_0=1.03 mm



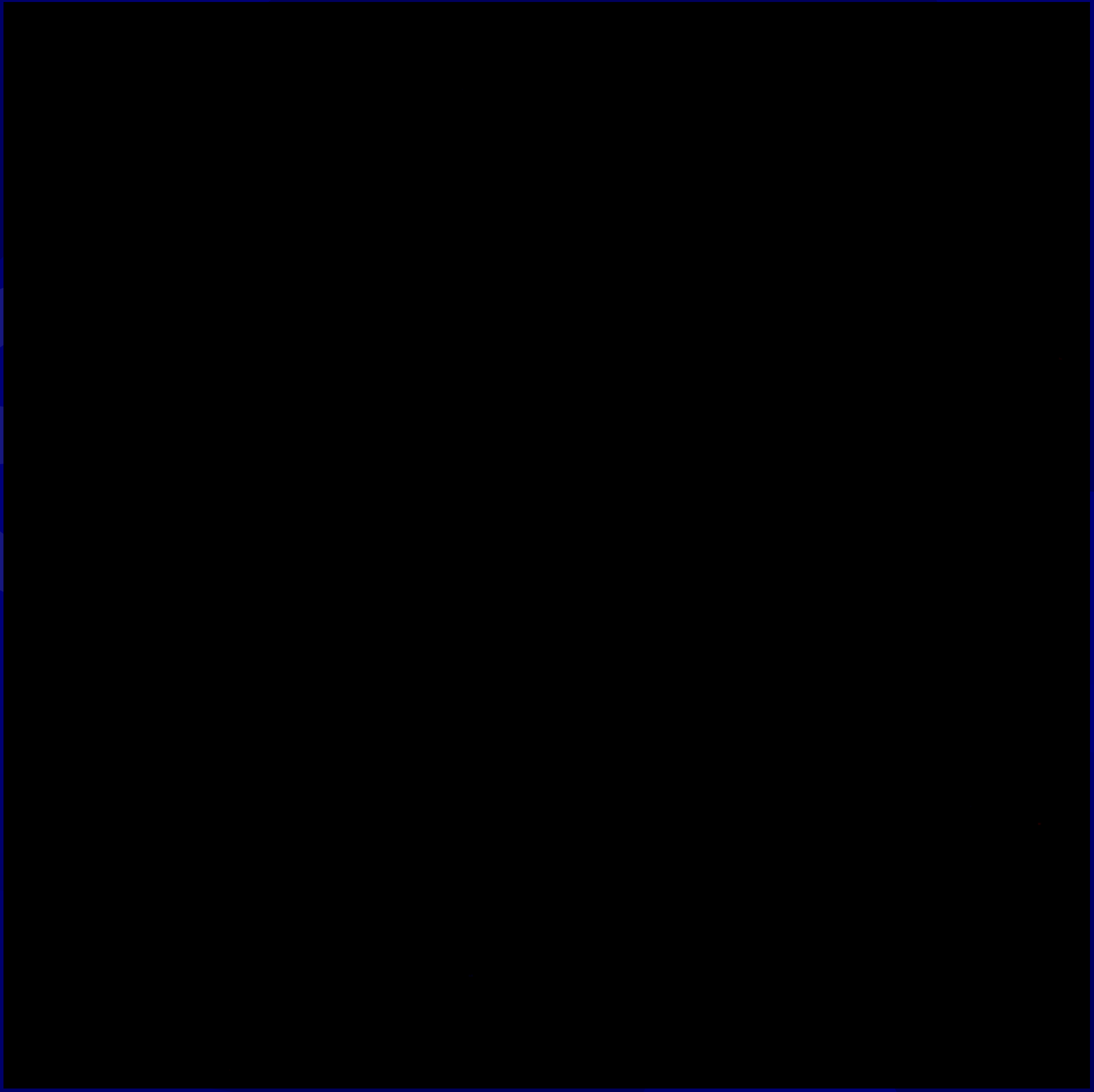
Partial combustion (outside the group-combustion excitation limit (GCEL))

Number of droplets M=67, Initial droplet diameter d_0=0.91 mm



Anomalous combustion behavior 1 near GCEL

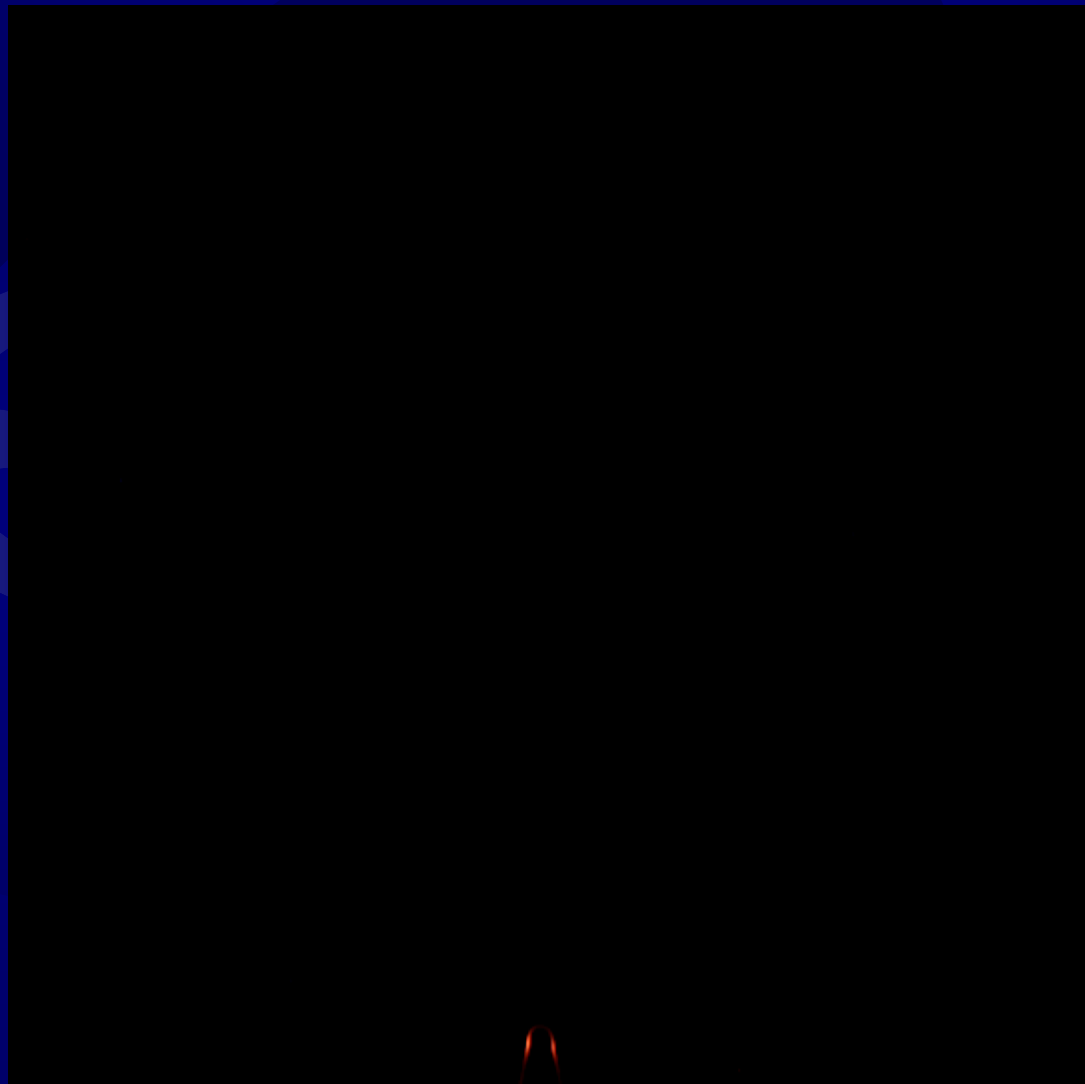
Number of droplets M=67, Initial droplet diameter d_0=1.01 mm



Complicated flame spread, a large-scale ignition

Anomalous combustion behavior 2 near GCEL

Number of droplets M=67, Initial droplet diameter d_0=1.10 mm



Slow flame propagation in burned area

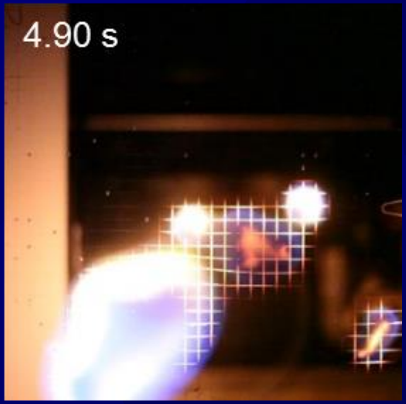
Summary

- Successfully conducted “Group Combustion” experiments aboard Kibo/ISS
- Group-combustion excitation through flame spread
- Sensitive flame-spread behavior to the initial condition
- Unexpected anomalous phenomena appearance

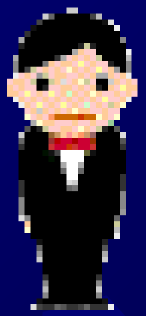
Future Research

“Group Combustion-2” in 2023

- Study the role of cool flame in the anomalous combustion phenomena during flame spread over droplet cloud near the group-combustion-excitation limit (GCEL)
- Measure cool flame in flame spread over droplet cloud near GCEL



Thank you for your attention!



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http://www.nainen.mech.yamaguchi-u.ac.jp/mikami/

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