中国科学技术大学
University of Science and Technology of China

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# 大尺度极端火行为基础研究前沿问题

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**火灾科学国家重点实验室**

# 提纲

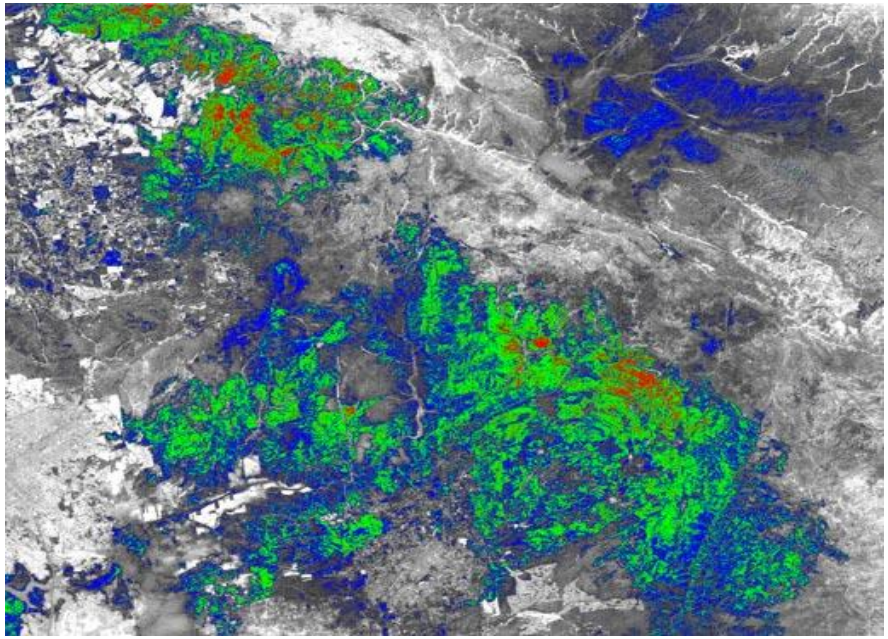
- 研究背景
- 大尺度极端火行为研究现状
- 大尺度极端火行为相互转化
- 大尺度火灾研究挑战

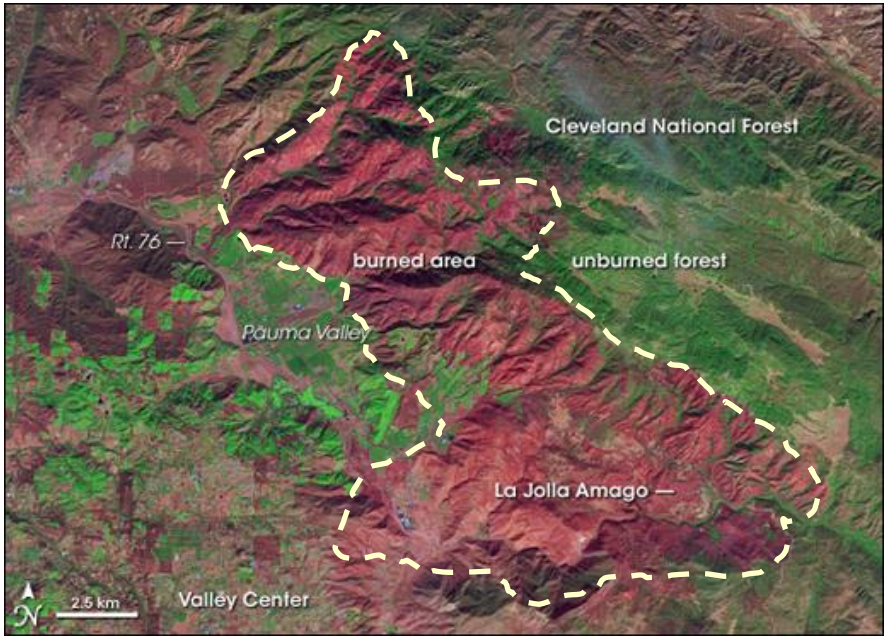
# 1 研究背景

# 国际：大尺度火灾频发

- 美国加州大火
  - ☑ 2003年：过火1134km²
  - ☑ 2007年：过火1970km²，“160倍于广岛核爆”《泰晤士报》

*NASA Satellite Captures San Diego WUI Fire, November 8, 2007， 37.5 by 45 kilometers*
*植被：绿色；城镇区域：蓝色；过火区域：深红色*



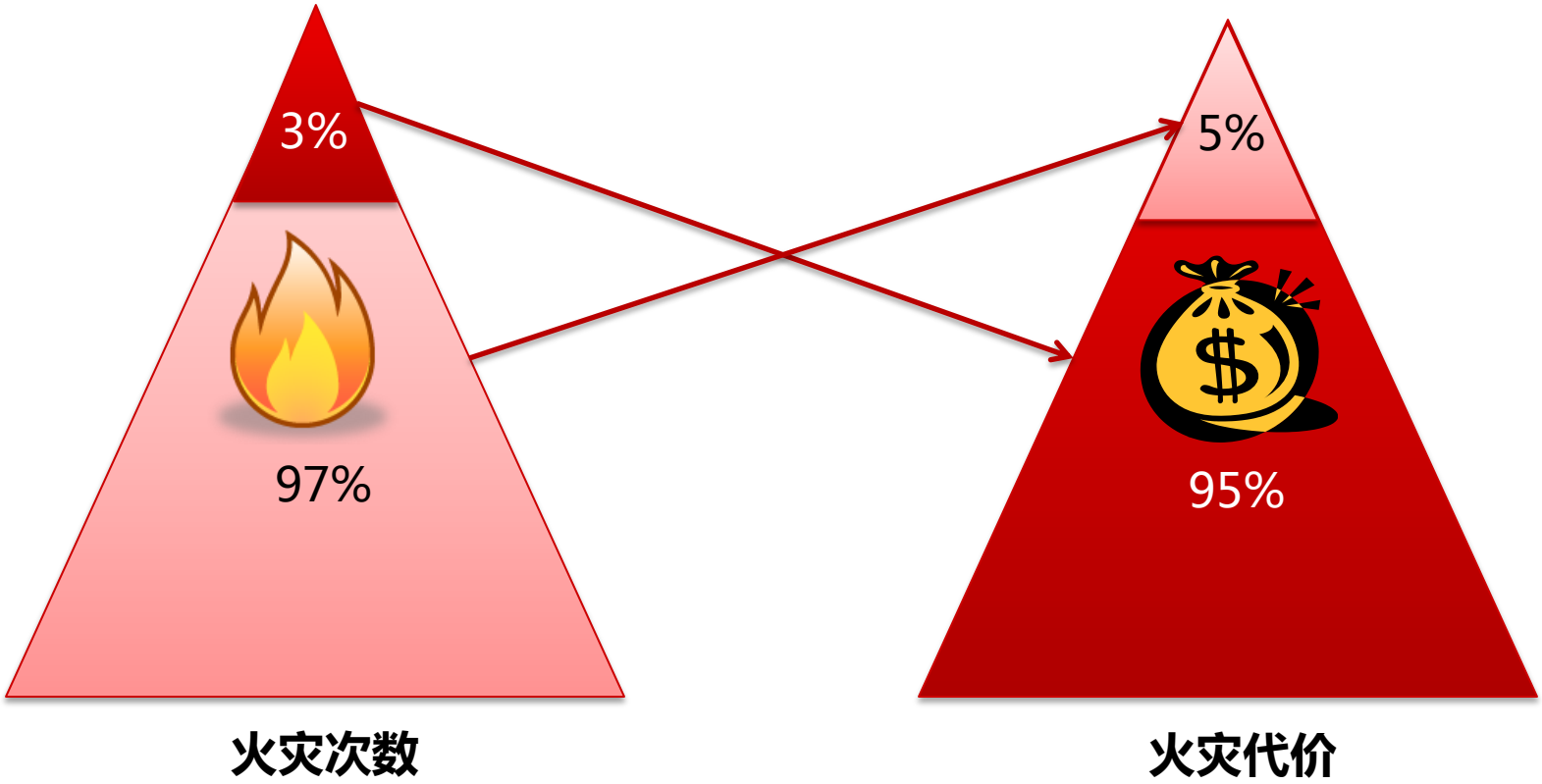



2007年加州圣迭戈县火灾的NASA卫星照片

# 大尺度火灾的重大危害

- **3%大尺度火灾→95%火灾代价**

—— Federal firefighting efforts are very successful, with 97% of fires suppressed at less than 10 acres. About 3% escape to become larger and are responsible for 95% of the nation's firefighting costs. （US National Interagency Fire Center statistics）



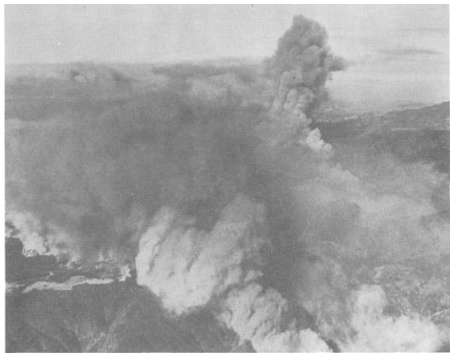
# 研究聚焦：大尺度极端火行为

## 树冠火(Crown fire)


- http://en.wikipedia.org/wiki/Yellowstone_fires_of_1988

☑ **Transition to burn forest fuels at the canopy level**

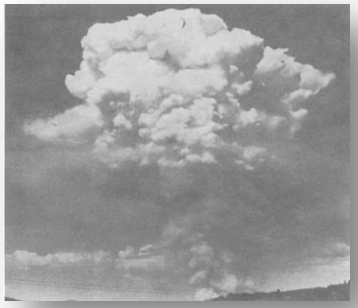
## 狂燃火(Conflagration)

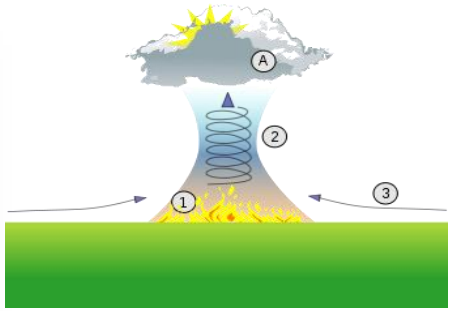


- **[Left]** Countryman, C.M. "Mass Fires and Fire Behavior,", 1964, 53 pp.
- **[Right]** http://www.rivco4.org/web/news/archive/200804/

☑ **Moving fronts with large fire sizes and narrow depth**

## 火暴(Fire storm)






Firestorm-made thermal column. Fire (1) makes hot air (2) to rise forming storm-winds (3) towards the fires.

- **[Left]** Countryman, C.M. "Mass Fires and Fire Behavior," 1964, 53 pp.
- **[Right]** http://en.wikipedia.org/wiki/Fire_storm

☑ **Great convective activity; little outward spread of fire**

## 飞火(Spot fire)


- Koo, E., et al., International Journal of Wildland Fire, 2010. 19(7): p. 818-843.

☑ **Producing numerous ignitions beyond major fire area**

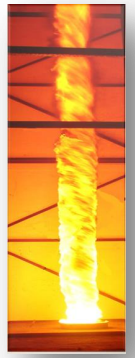
# 研究聚焦：大尺度极端火行为

## 火焰融合(Fire merging)

- **[Left]** Viegas, D.X. Forest fires, 6th ISFEH (Slides)
- **[Right]** Fire merging experiments by group of N. Liu

☑ **Significant interactions among multiple fires**

## 火旋风(Fire whirl)



- **[Left two pictures]** Fire whirls reported in news
- **[Right two pictures]** Fire whirl experiments by group of N. Liu

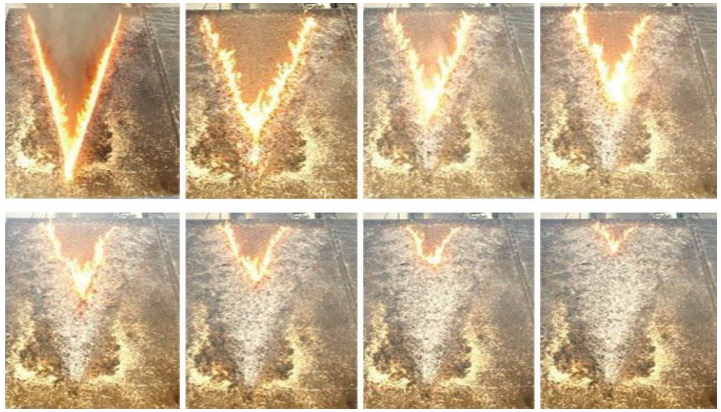
☑ **Concentrated vortex structure with combustion**

## 爆发火(Eruptive fire)

- Dold, J., et al., Some Forest Fire Related Accidents in Europe, DX Viegas (Ed), JRC, Ispra, 2009.

☑ **Typical in canyons or steep slopes; quick acceleration**

## 跳跃火(Jump fire)



- Viegas, D.X., et al. International Journal of Wildland Fire 21(7): 843-856 (2012).

☑ **Merging of fire fronts with a small intersection angle**

# 极端火行为的共性特征

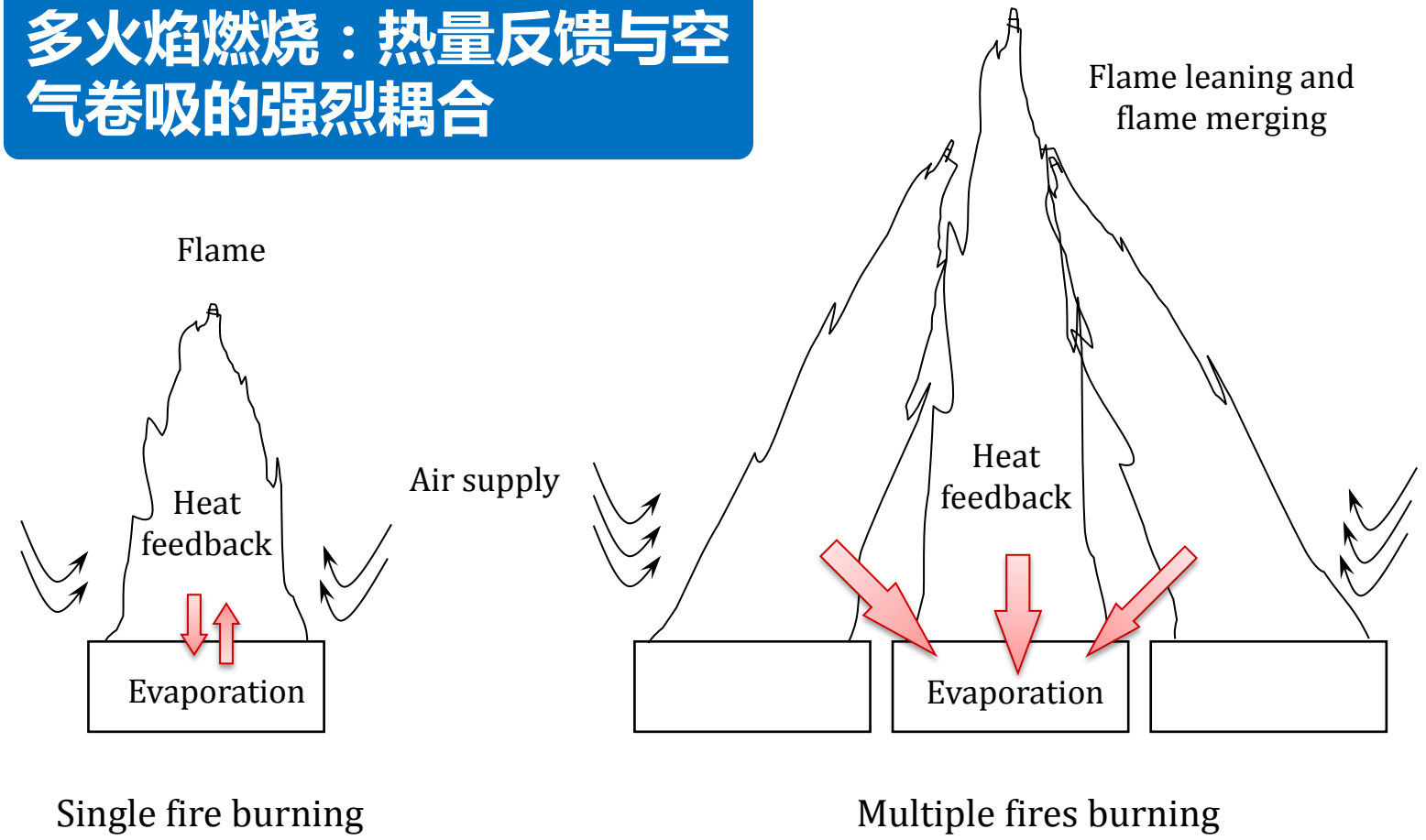
- 诱发过程：包含低强度火在受控机制和燃烧行为两方面的突变

池火向火旋风转变实验，N. Liu

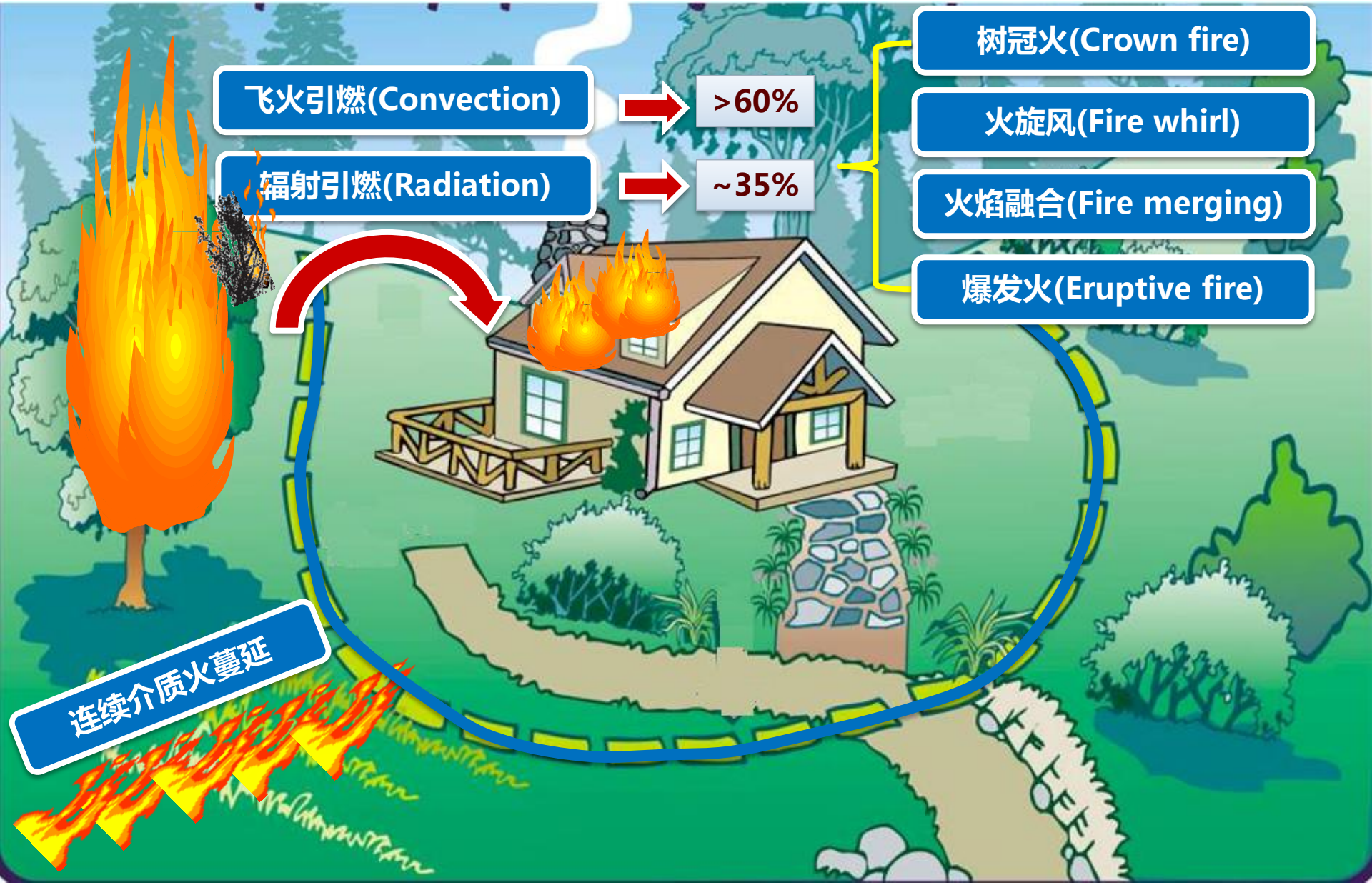
# 极端火行为的共性特征

- 包含显著的传热、流动和燃烧耦合作用

**多火焰燃烧：热量反馈与空气卷吸的强烈耦合**



# 研究聚焦：大尺度极端火行为



# 2 极端火行为研究现状

01 爆发火

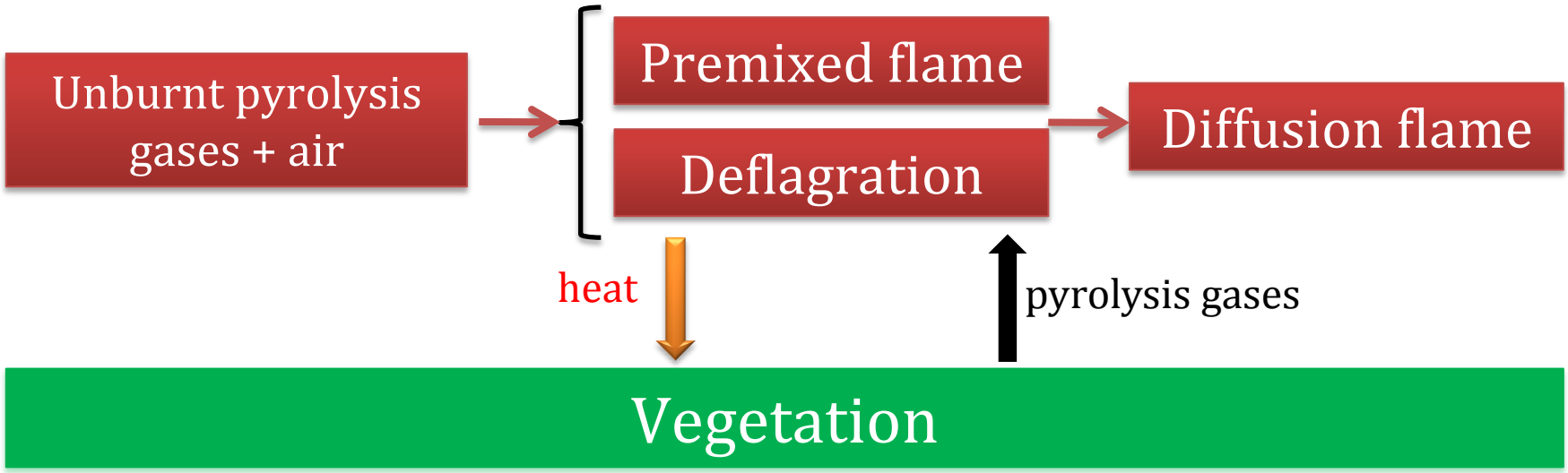
02 火旋风

# 爆发火(Eruptive fire)

- Covering over a wide area of 5-6 hectares within only one minute

- Dold, J., et al., The Palasca Fire, September 2000: Eruption or Flashover?[J]. Some Forest Fire Related Accidents in Europe, DX Viegas (Ed), JRC, Ispra, 2009.

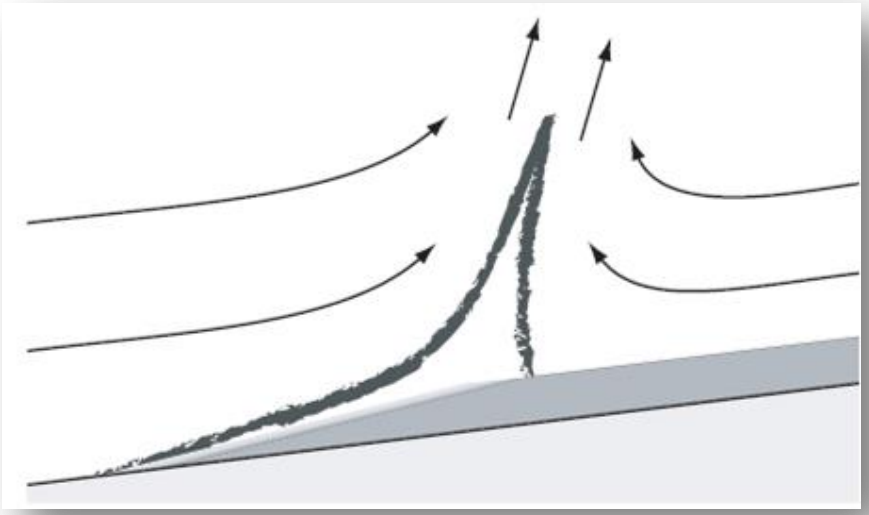
# 爆发火(Eruptive fire)

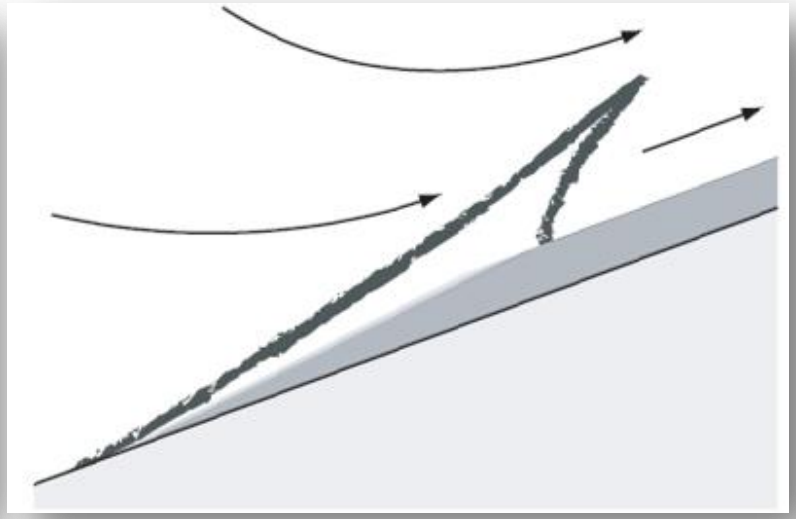



- **可燃气聚集过程：Gas Accumulation**
  - ☑ **热解产生的未燃烧可燃气聚集在局部区域，与空气混合，一旦点燃就形成火爆。**
  - ☑ **热解反应如何与火蔓延过程相互影响？**

- Peuch, E. Wild fire safety: feed back on sudden ignitions causing fatalities. 2007.
- Dold, J., et al., The Palasca Fire, September 2000: Eruption or Flashover? Some Forest Fire Related Accidents in Europe, DX Viegas (Ed), JRC, Ispra, 2009.

# 爆发火(Eruptive fire)



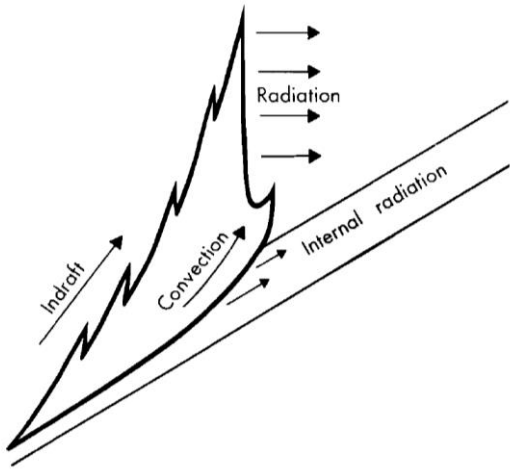


- **对流强化机理**
  - ☑ **风和地形的交互作用产生局部区域特定流场，结合热浮力作用，导致极端火行为发生**
  - ☑ **地形（坡度）如何影响火蔓延过程？**

- Dold, J. and A. Zinoviev, Fire eruption through intensity and spread rate interaction mediated by flow attachment. Combustion Theory and Modelling, 2009. 13(5): p. 763-793.

# 问题：火蔓延传热机制

- **火蔓延传热机制：**
  - ☑ **火焰接触**(direct flame contact)
  - ☑ **对流加热** (convective heating)
  - ☑ **辐射加热** (radiative heating)
  - ☑ **对流冷却** (Convective cooling)
  - ☑ **辐射冷却** (Radiative loss)




- **争议的问题：**
  - ☑ **对流冷却机制**

**—— Albini (CST, 1986): 增加自然对流冷却，模型准确度显著提高**

**—— Mark Finney (IJWF, 2013): 对流加热主导（主要针对树冠火）**


- Albini FA (1986) Wildland Fire Spread by Radiation-a Model Including Fuel Cooling by Natural Convection. *Combustion Science and Technology* **45(1)**, 101-113.
- Finney MA, Cohen JD, McAllister SS, Jolly WM (2013) On the need for a theory of wildland fire spread. *International Journal of Wildland Fire* **22**, 25-36.

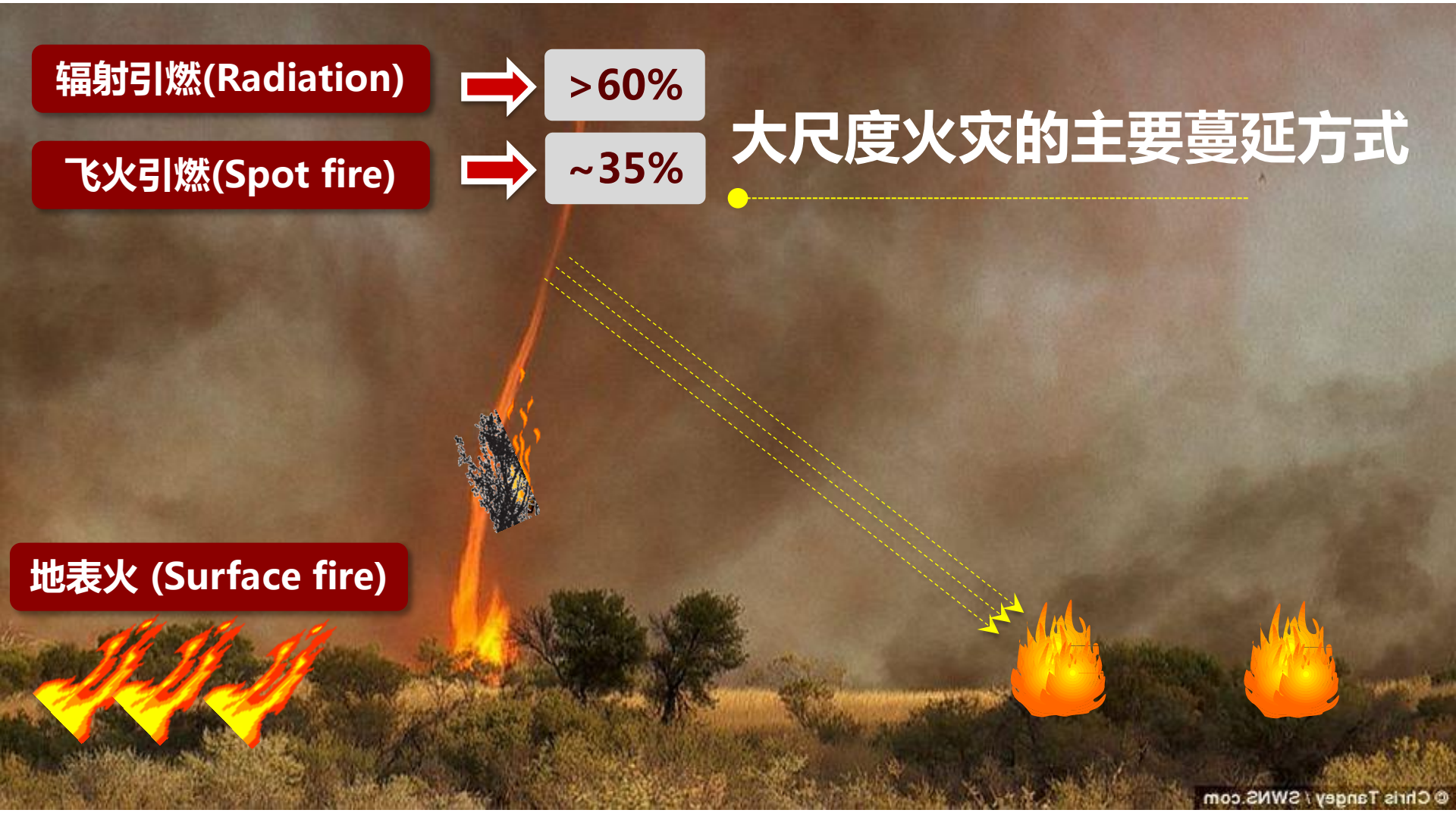
# 2. 火旋风燃烧动力学

辐射引燃(Radiation) ➡ >60%

飞火引燃(Spot fire) ➡ ~35%

大尺度火灾的主要蔓延方式

地表火 (Surface fire)



澳大利亚30m高火旋风（2012.9.18)

# 火旋风(Fire whirl)

**Figure 1-1a** *Japanese painting of the fire whirl during the great Kanto earthquake in Tokyo, 1923. Photo courtesy of Y. Hasemi.*

- **1923年，东京关东大地震**
  - ☑Hifukusho-ato 广场火旋风；38000人丧生

# 火旋风研究现状

理论分析

数值模拟

**定量的实验研究工作匮乏**

燃烧速率，火焰高度，速度场，温度场，辐射热流场

**理论分析很不完善**

主要基于流体力学理论或简单的量纲分析

**数值模拟缺乏可靠子模型**

结论平庸，难以取得机理突破

Howard R. Baum, NIST fellow, Membership in the National Academy of Engineering：**“真正定量实验模拟火旋风的工作只有三篇”**（Combust Theor Model, 2000）

W. K. Chow, Chair Professor of HK PolyU, Chair of AOAFST：**“系统性定量实验工作非常少，对现象本身认识不清晰，难以开展理论研究”**（Journal Fire Sci., 2009）

“(The work by H. W. Emmons, K. Satoh, and K. Saito) are the only studies which have presented quantitative, laboratory-scale data with which to compare a theory for buoyancy-driven flows with circulation.”

# 我们的火旋风研究

**实验研究**

利用丰富的实验测量手段获得不同尺度和外加环量参数条件下火旋风燃烧特性数据

**理论分析**

1. 流体力学，传热学，燃烧学方程及模型
2. 量纲分析、数量级分析和合理近似
3. 与实验数据对比，验证或修正火旋风动力学模型

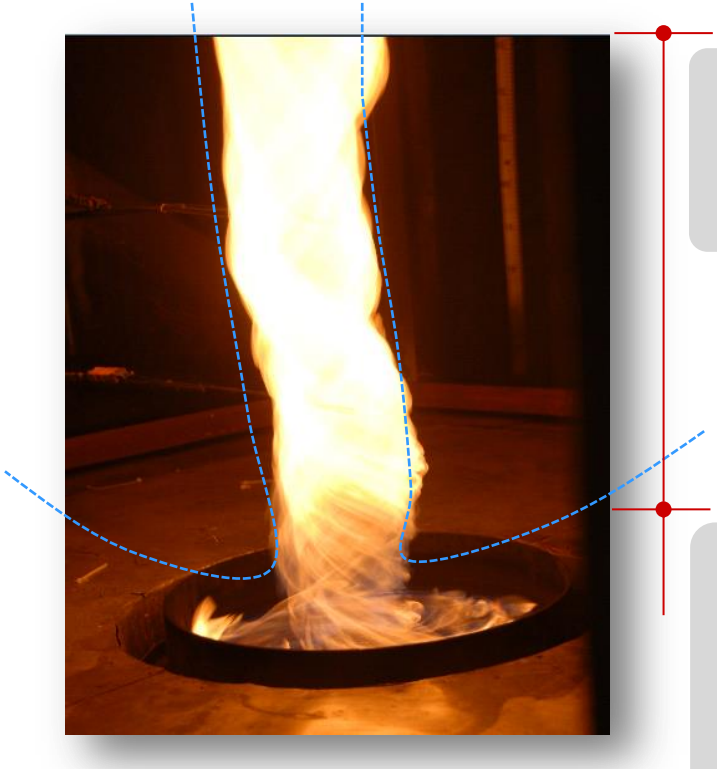
普通浮力池火

**相似与不同**

火旋风

# 火旋风燃烧速率

- Combustion and Flame, 2012, 159(6): 2104-2114.



- 径向压力梯度=离心力
- 稳定涡核结构

- 壁面摩擦力：阻滞旋转
- 径向压力梯度>离心力
- Ekman卷吸边界层

- 火旋风是具有稳定涡核的强对流涡旋
- 燃料表面的对流传热速率大大增强
- 底部边界层：有化学反应的外区和无化学反应的内区

# 火旋风火焰高度

池火
Pool fire

$$H/D = f(\dot{Q})$$

$$\mathrm{Fr} = \frac{u^2}{g \cdot d} \qquad \dot{Q} = \dot{m}\Delta H_c = \rho u \pi d^2 \Delta H_c \Rightarrow \mathrm{Fr} \propto \dot{Q}^2 / d^5$$

$$H/D = -1.02 + 0.235\dot{Q}^{2/5}/D$$ **Heskestad模型**

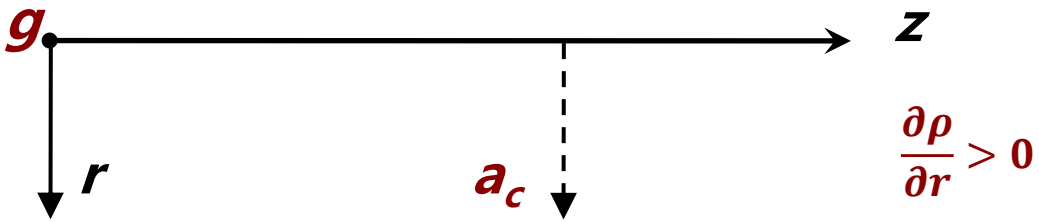
- Proceedings of the Combustion Institute, 2011, 33: 2407-2415.

火旋风
Fire whirl

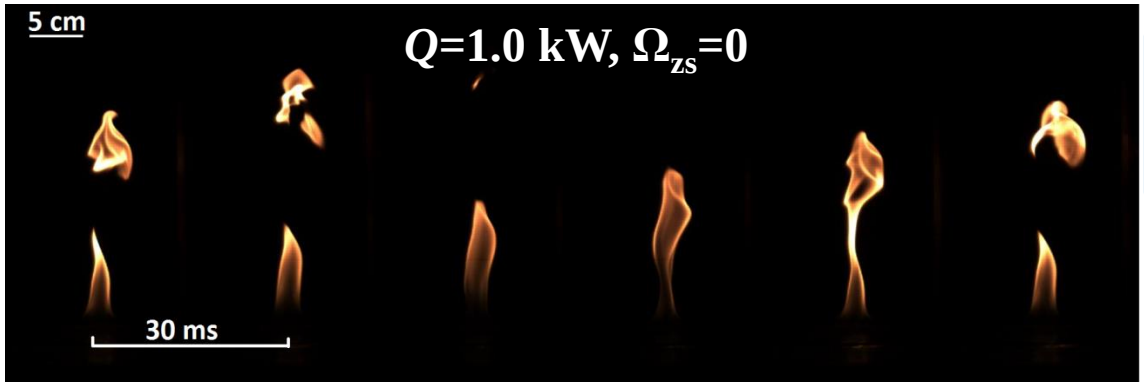
$$H/D = f(\Gamma, \dot{Q})$$

**火旋风火焰高度增加机理：**

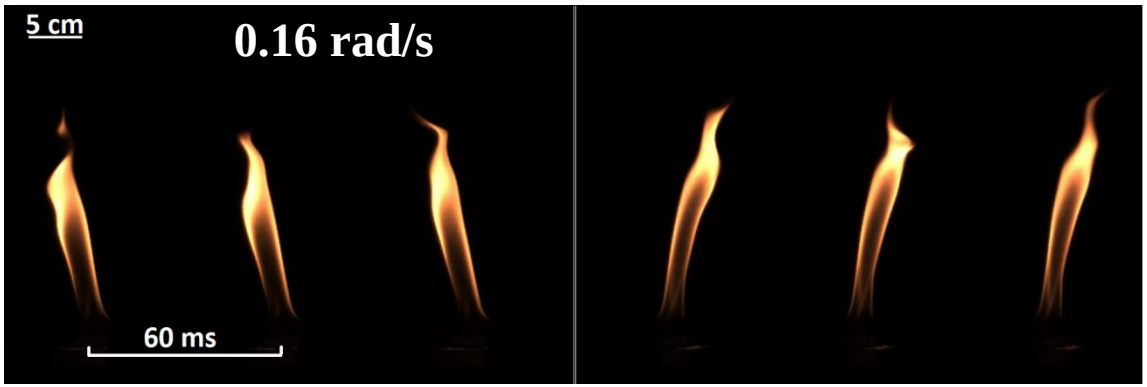
- **旋转**：凝聚相(液体或固体)燃料燃烧速率增大（$\dot{Q}^*$）
- **流场稳定效应**：抑制燃料与氧气的湍流混合（$\Gamma^*$）
  - 径向压力梯度与离心力平衡 $dp/dr = \rho V_\theta^2 / r$
  - 径向离心加速度场中的稳定密度分层

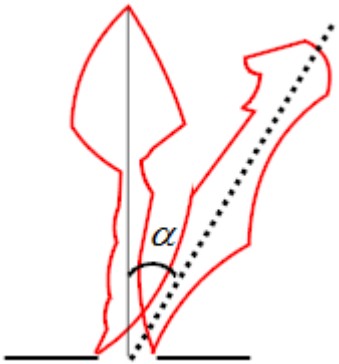


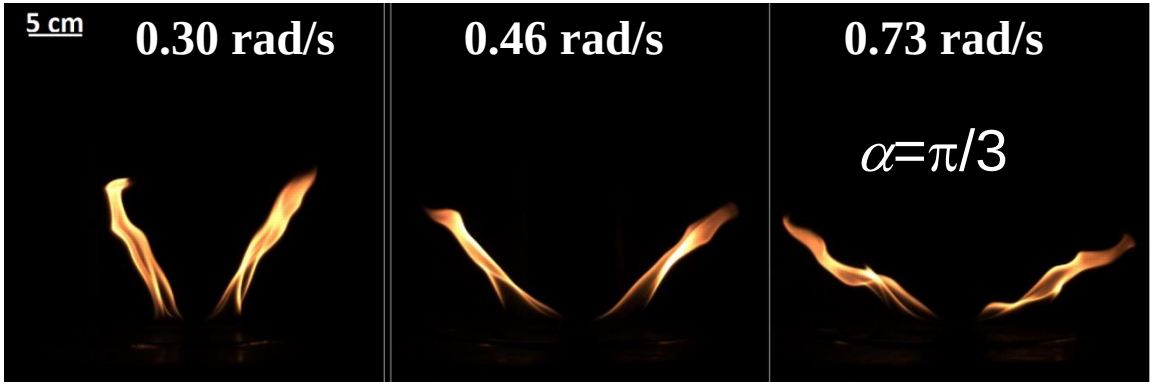
# 火旋风形成前特性

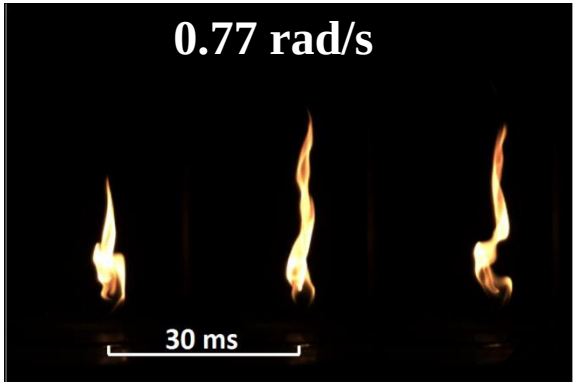



- Proceedings of the Combustion Institute, 2014.



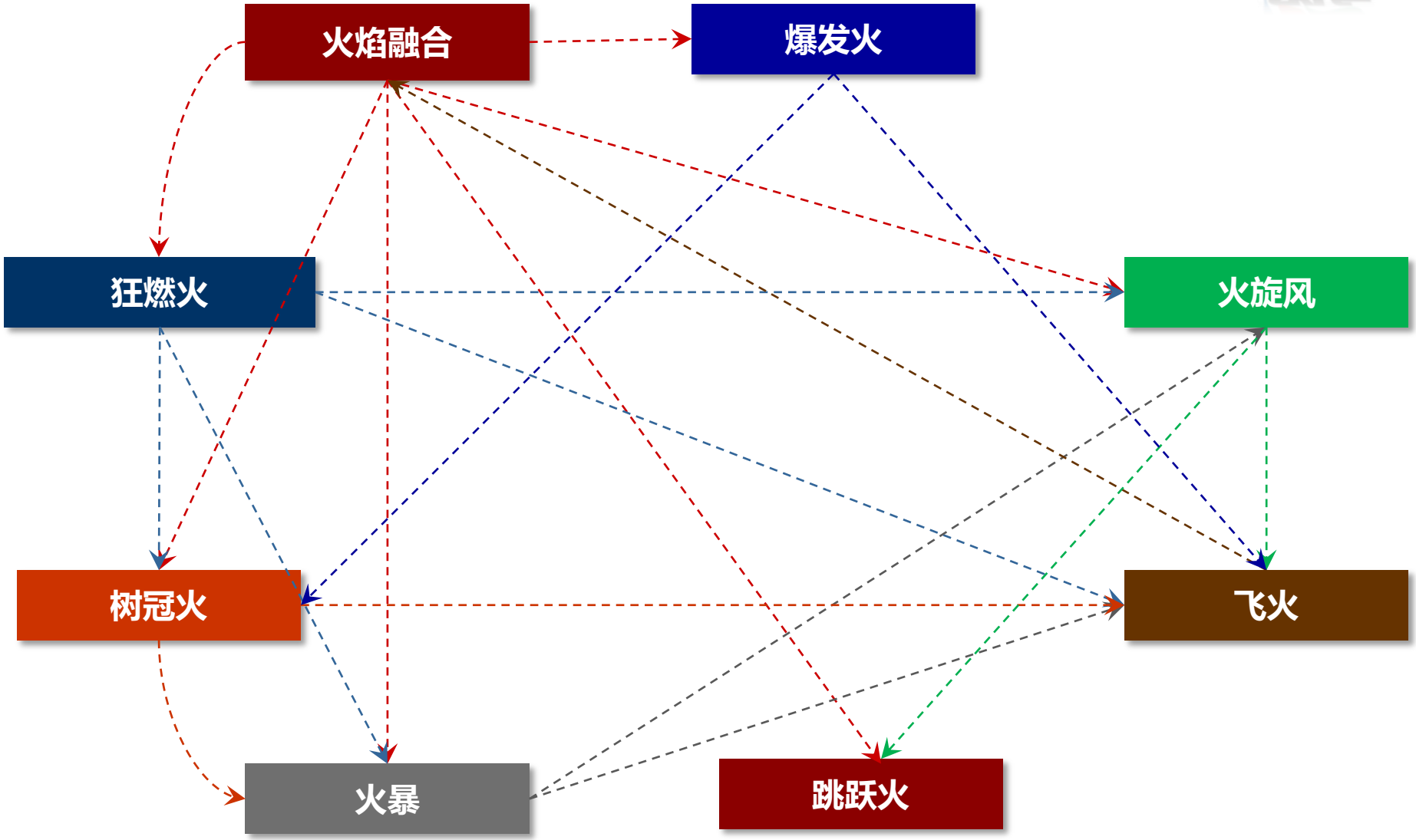
# 火旋风的前沿问题

- Mechanism of moving fire whirl
  - ☑ Role of fluid instability in driving the flame of fire whirl
  - ☑ Critical conditions for moving of fire whirl

Fire whirl observed in Brazil, August, 2010

# 3 极端火行为的相互转化

# 极端火相互转化研究




极端火行为的相互转化

# 4 研究挑战

# 大尺度极端火行为的研究挑战

- 不同稳态极端火行为的物理控制机制与动力学

- 流动、辐射与对流传热和燃烧的耦合机制与行为
- 极端火行为的非线性物理本质与控制条件

# 大尺度极端火行为的研究挑战

- 各类极端火行为之间相互转化的临界条件

- 聚焦：非稳定物理转变机制
- 临界条件：流动与燃烧不稳定性机制

# 大尺度极端火行为的研究挑战

## ●结合实际燃料、大气和地形条件的大尺度火灾发展预测模型

- **应用性模型：实验室建立的物理模型如何扩展到实际的燃料、大气和地形条件？**
- **方法：Scaling law, field experiments, fire case verification**

# 感谢聆听

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