U.S. AIR FORCE

USSF

AFRL

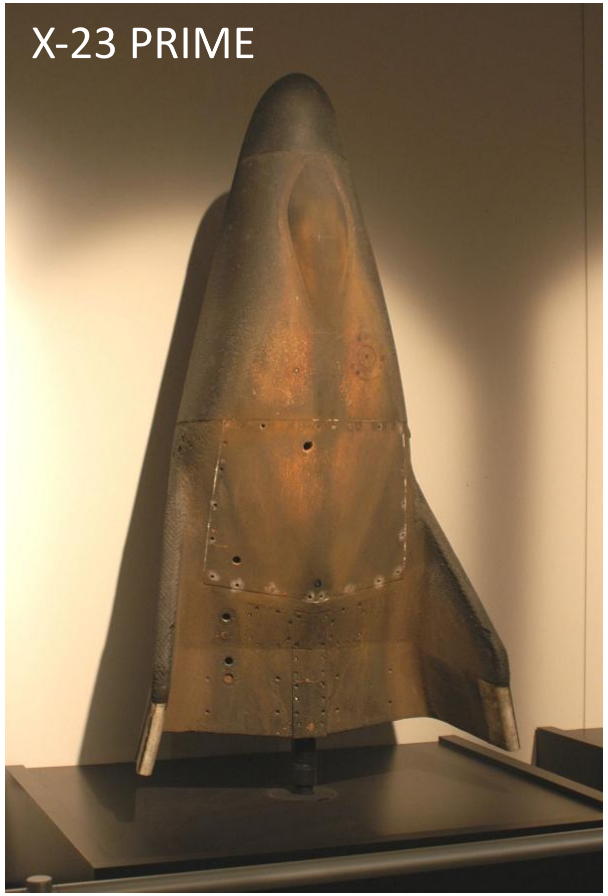
High-Speed Aerodynamics Portfolio
12th Ablation Workshop

Dr. Sarah Popkin

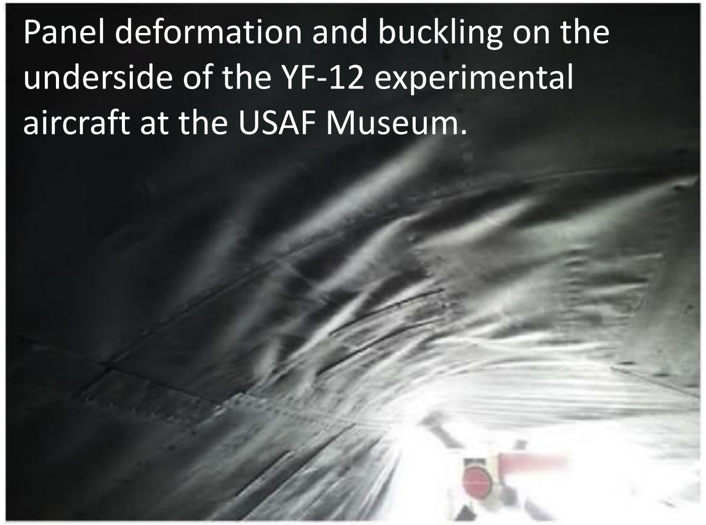
Program Officer, Air Force Office of Scientific Research

9 Nov 2022

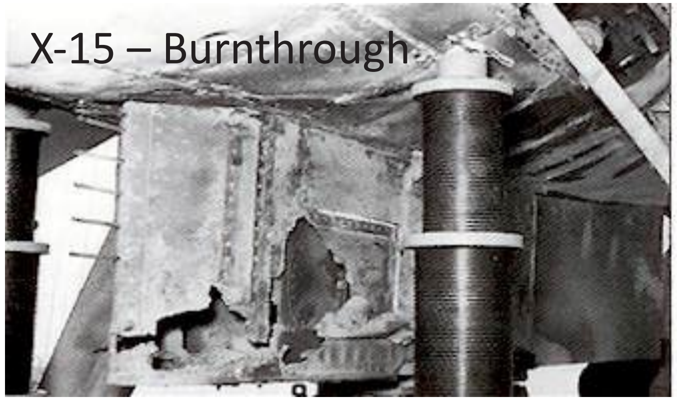
Need for Hypersonic Science


X-23 PRIME

https://www.nationalmuseum.af.mil/Visit/Museum-Exhibits/Fact-Sheets/Display/Article/195893/sv-5d-prime-lifting-body/


Panel deformation and buckling on the underside of the YF-12 experimental aircraft at the USAF Museum.

"Exploring the response of a thin, flexible panel to shock-turbulent boundary-layer interactions," Journal of Sound and Vibration, Vol. 443, January 2019, pp. 74-89

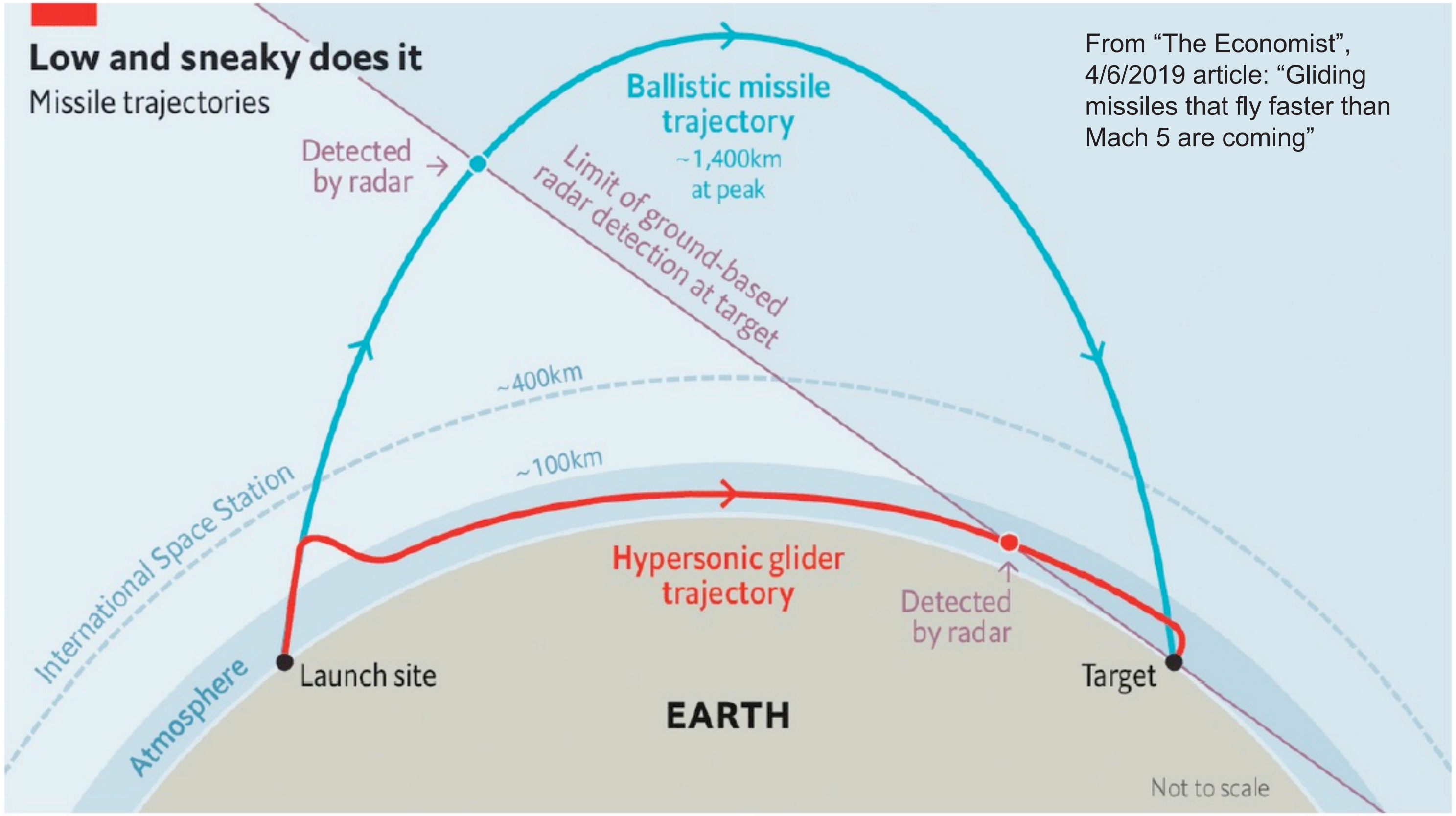

X-15 – Burnthrough


X-15 – Recovered Dummy Scramjet

http://www.ipmsstockholm.org/magazine/2004/03/images/x15_08.jpg

Today's Demand Signal

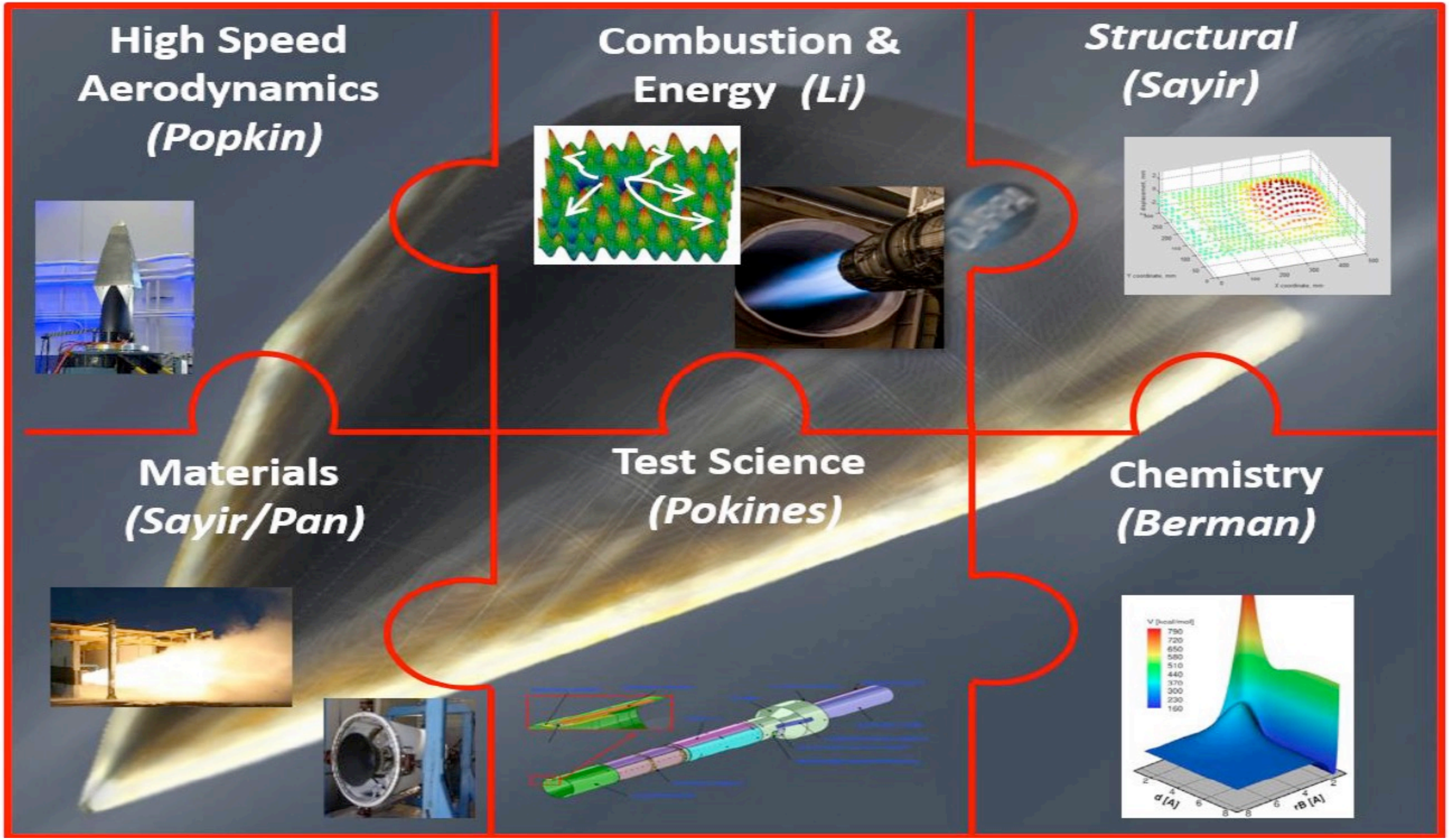
Air Force 2030 Science and Technology Strategy



From "The Economist", 4/6/2019 article: "Gliding missiles that fly faster than Mach 5 are coming"

Recent global surge in hypersonics strongly motivates fundamental understanding

AFOSR Hypersonic Technical Areas, Portfolios and POs



High-Speed Aerodynamics Portfolio

USSF AFRL

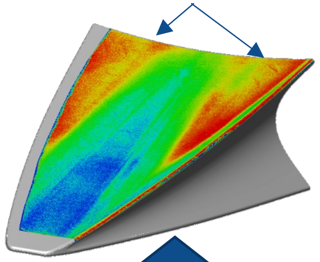
Support scientific foundation for uniquely high-speed aerodynamic and aerothermodynamic phenomenology

Provide forward leaning, thought leadership to emplace foundational discovery through collaborations, publications and workforce development

Boundary Layer Physics

- Laminar, transitional and turbulent physics
- Drives vehicle design due to heating, drag and flap effectiveness

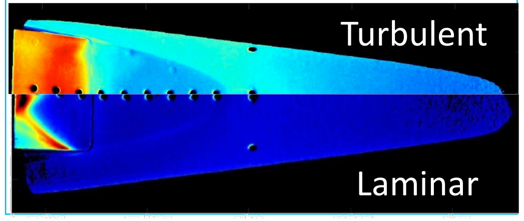
Transition heating



Atmospheric Science

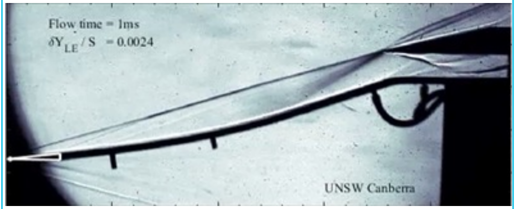
Shock/Boundary Layer Interactions

- Off-nominal boundary layer behavior in the presence of shocks
- Control surface effectiveness and heating



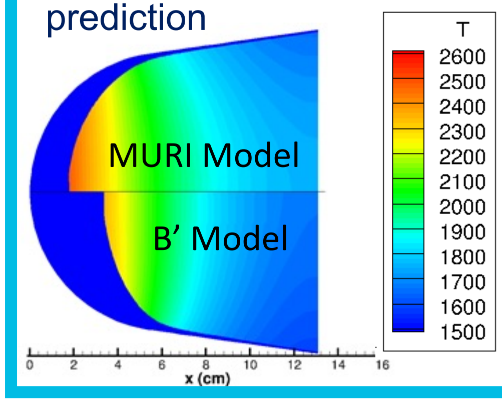
Fluid-Structure Interactions

- Coupled fluid motion with structural vibration
- Vehicle fatigue prediction and coupled impact on boundary layer



Non-Equilibrium Flows

- Dynamic, reactive chemistry when air is ripped apart
- Surface chemistry prediction



Cultivate fundamental science across multiple discipline areas to benefit hypersonic system development

Non-Equilibrium Effects

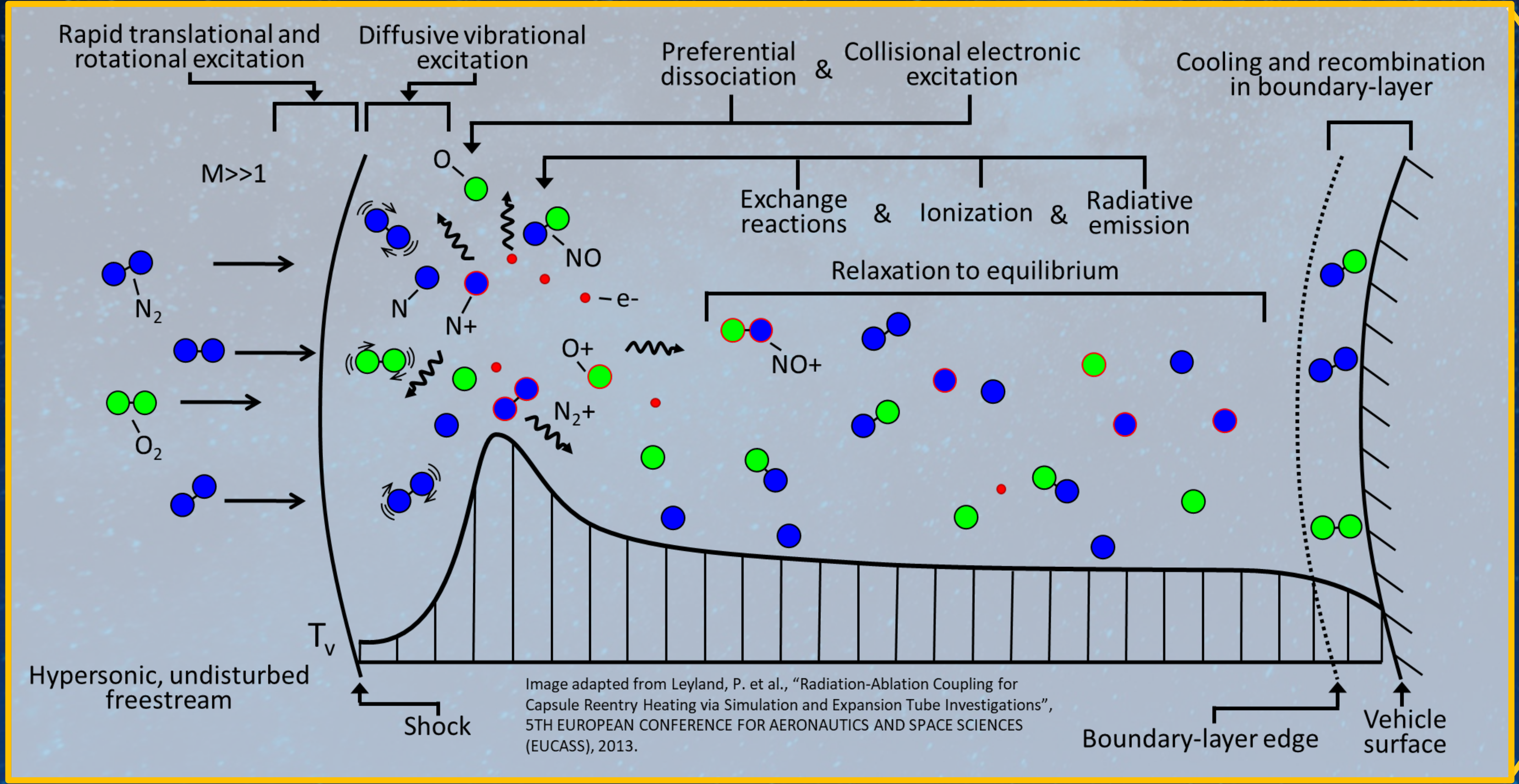
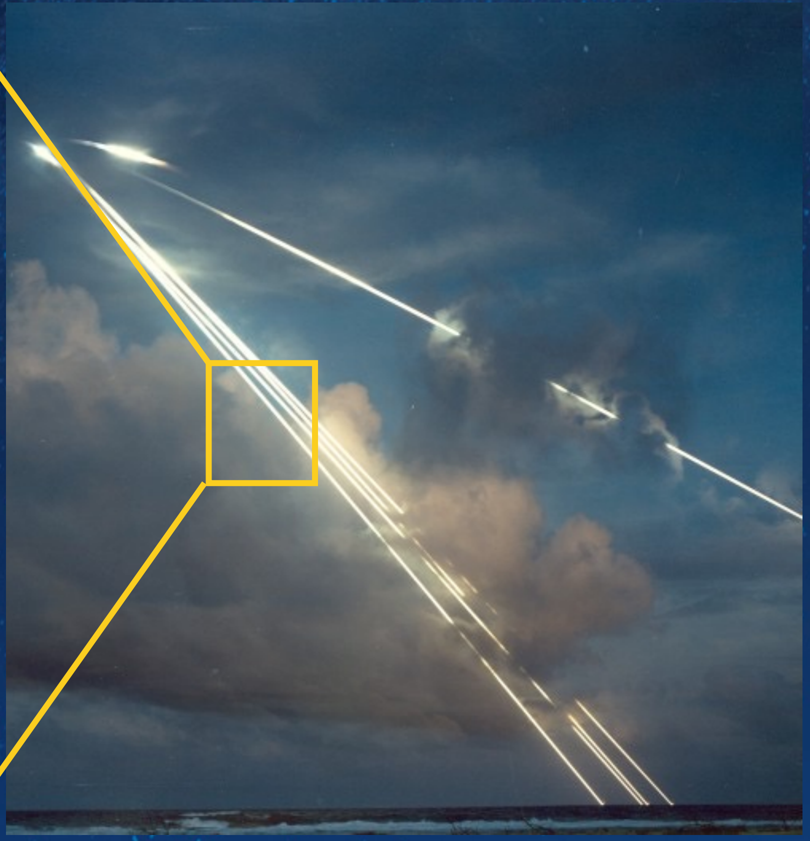


Image adapted from Leyland, P. et al., "Radiation-Ablation Coupling for Capsule Reentry Heating via Simulation and Expansion Tube Investigations", 5TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS), 2013.



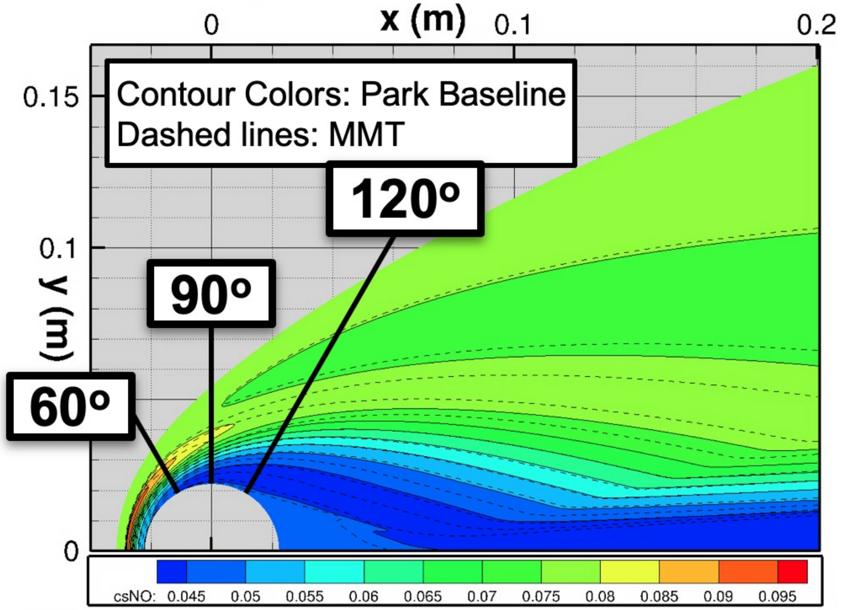
https://www.army.mil/article/169555/smdc_history_nike_x_reentry_measurement_program

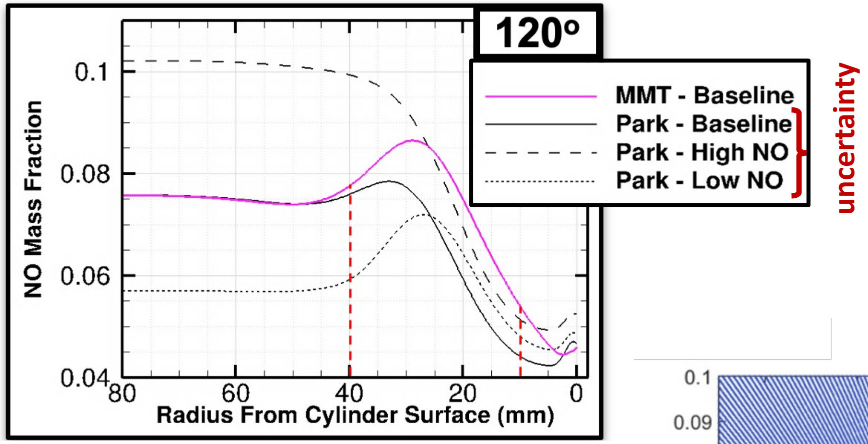
Problem: Today's SOA NE models need experimental validation

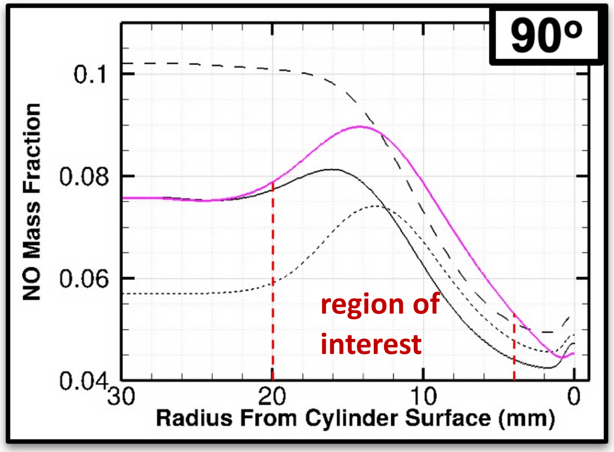
Approach: Identify regions that maximize difference between models, yet minimize uncertainty originating from the freestream

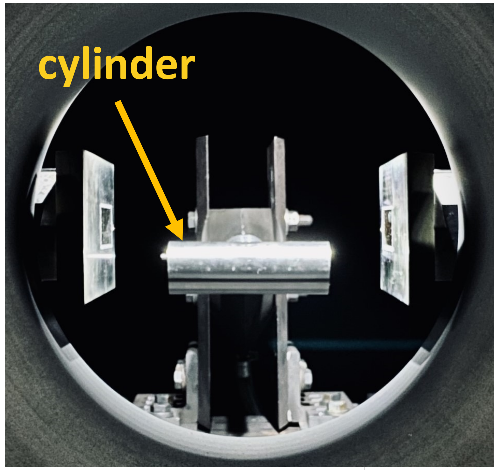
Future: Provide **validated** non-equilibrium model (MMT) to hypersonics community

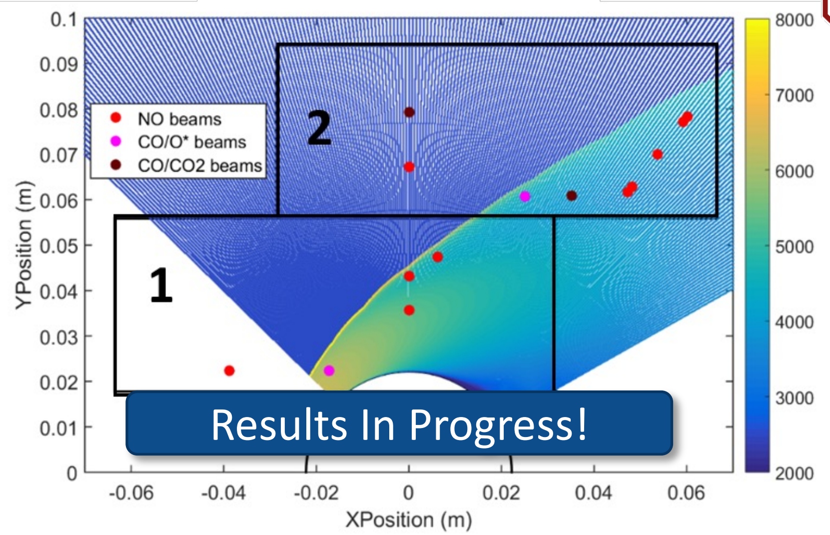
US3D Cylinder Simulations (ρ_{NO})







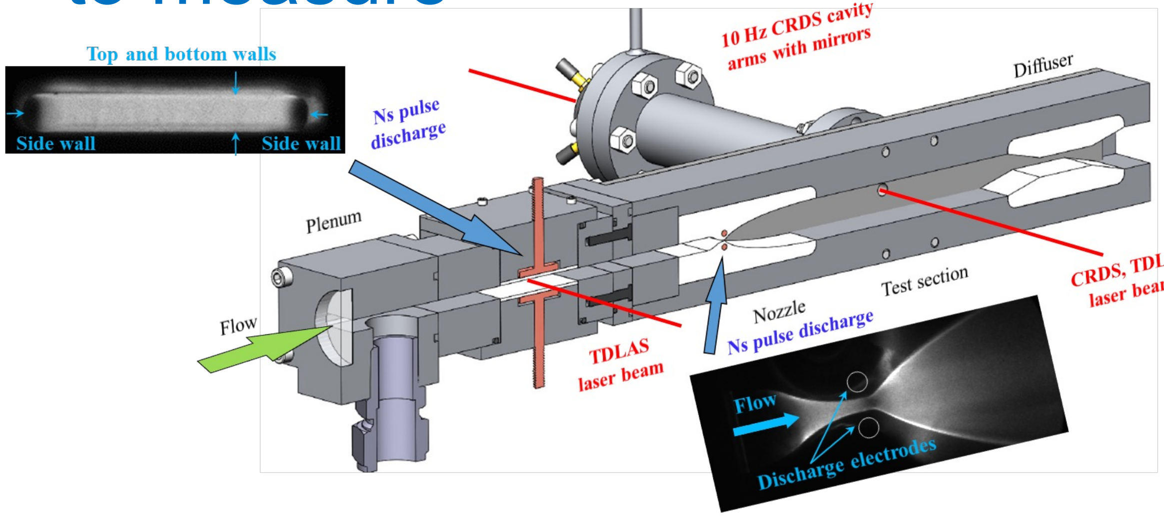




Impact: Validating new non-equilibrium models for faster analysis techniques.

MOTIVATION & APPROACH

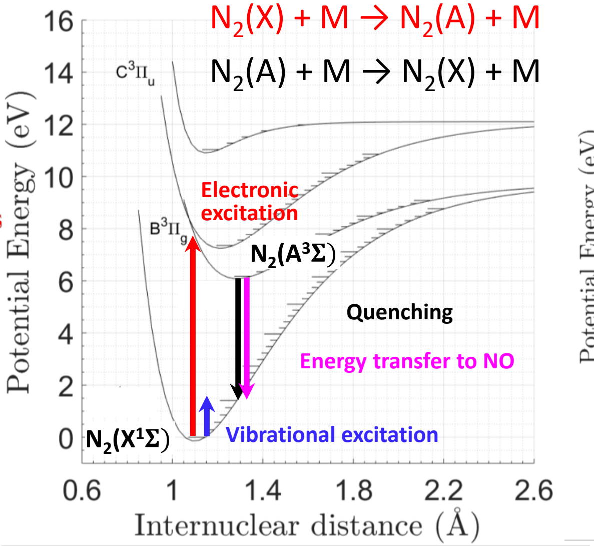
Problem: Critical non-equilibrium species and rates are difficult to measure



$N_2(X,v=0) + M \rightarrow N_2(X,v>0) + M$

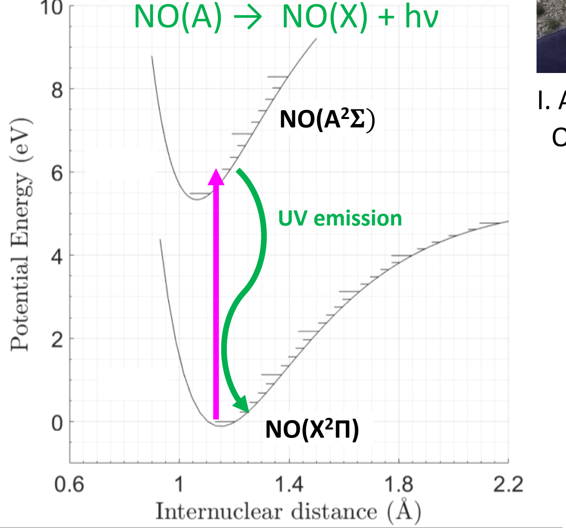
$N_2(X) + M \rightarrow N_2(A) + M$

$N_2(A) + M \rightarrow N_2(X) + M$



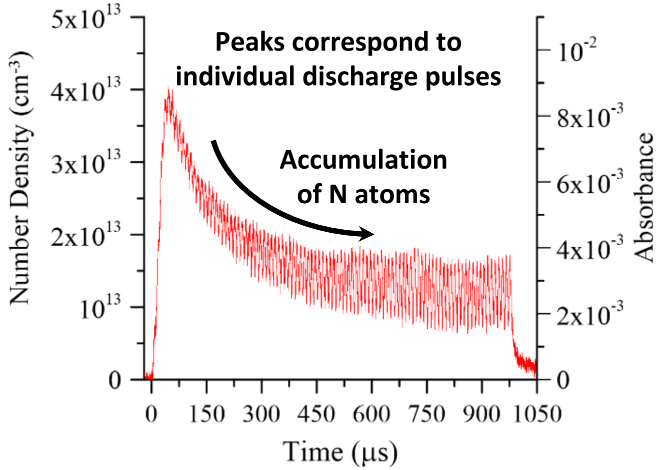
$N_2(A) + NO(X) \rightarrow N_2(X) + NO(A)$

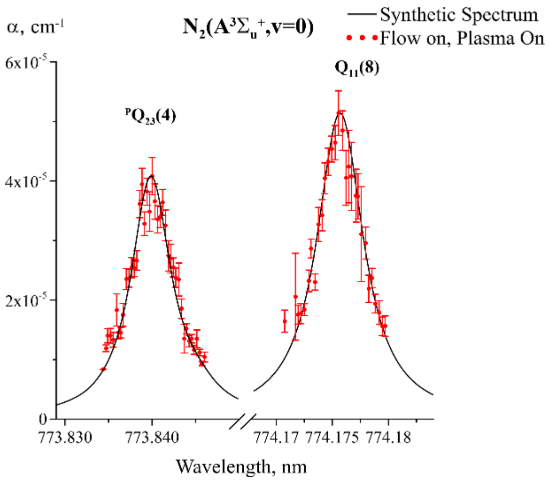
$NO(A) \rightarrow NO(X) + h\nu$

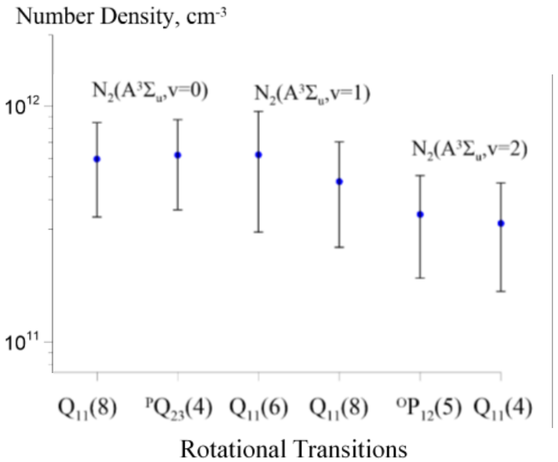


I. Adamovich
Ohio State

RESULTS







Impact: Growing experimental database of relevant non-equilibrium rates

Problem: Inaccurate Ablation Rates

Multiple carbon oxidation mechanisms can occur simultaneously on a single vehicle

Reaction-Limited
1055 K

Oxidation penetrates below the surface

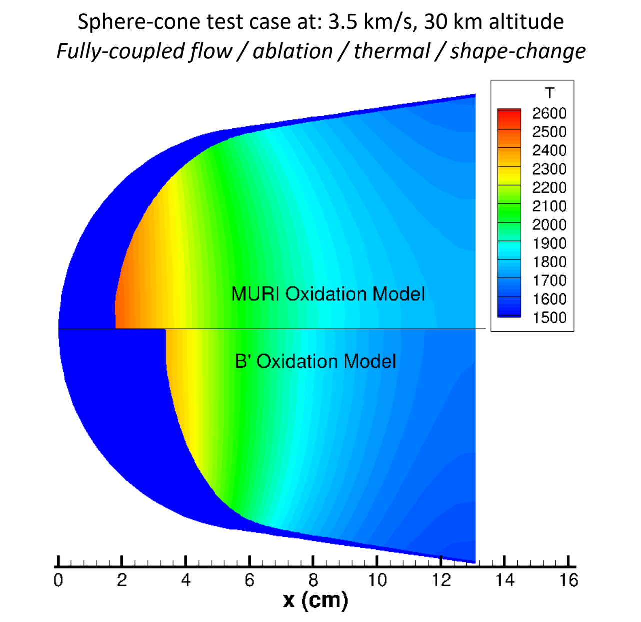
Diffusion-Limited
1465 K

Oxidation occurs at the surface

Mixed-Regime
1225 K

Oxidation occurs at *and* below the surface

Updated models anchored with improved molecular-beam diagnostics



Finite-Rate Oxidation Model for Carbon Surfaces from Molecular Beam Experiments, Savio Poovathingal, Thomas E. Schwartzentruber, Vanessa J. Murray, Timothy K. Minton, and Graham V. Candler, AIAA Journal 2017 55:5, 1644-1658

F. Panerai (YIP), UIUC

G. Candler, U of MN

T. Minton, MSU

T. Schwartzentruber
U of MN

D. Thrular, U of MN

E. Corral, U of A

https://api.army.mil/e2/c/images/2018/08/15/527160/original.jpg

Impact: Unprecedented experimental ablation data tightly coupled with validated simulation

Summary

- Hypersonics is experiencing a resurgence in national importance
- AFOSR is the largest hypersonics basic research funding source in the DoD
- AFOSR funds basic research in aerodynamics, propulsion, materials, chemistry, and test & evaluation
- High Speed Aerodynamics Portfolio
  - Boundary Layer Physics (+ Atmospheric Science)
  - Shock Boundary Layer Interactions
  - Fluid Structure Interactions
  - Non-Equilibrium Effects
- Providing thought leadership in hypersonic basic research and pushing the envelope with high-risk research

What if…

- New computers were built to solve fluid dynamics
- Lightweight magnets
- Efficient thermal energy harvesting + relevant temperatures
- Enable fully flight representative test conditions (new way of flight testing or new kind of ground test technique)
- Sustained flight at higher altitudes and higher speeds
- Controlled shape change in flight
- Reentry flight without heating (ever notice Sci-fi movies where space ships don’t have scorch marks?)

Largest 6.1 national portfolio in this area

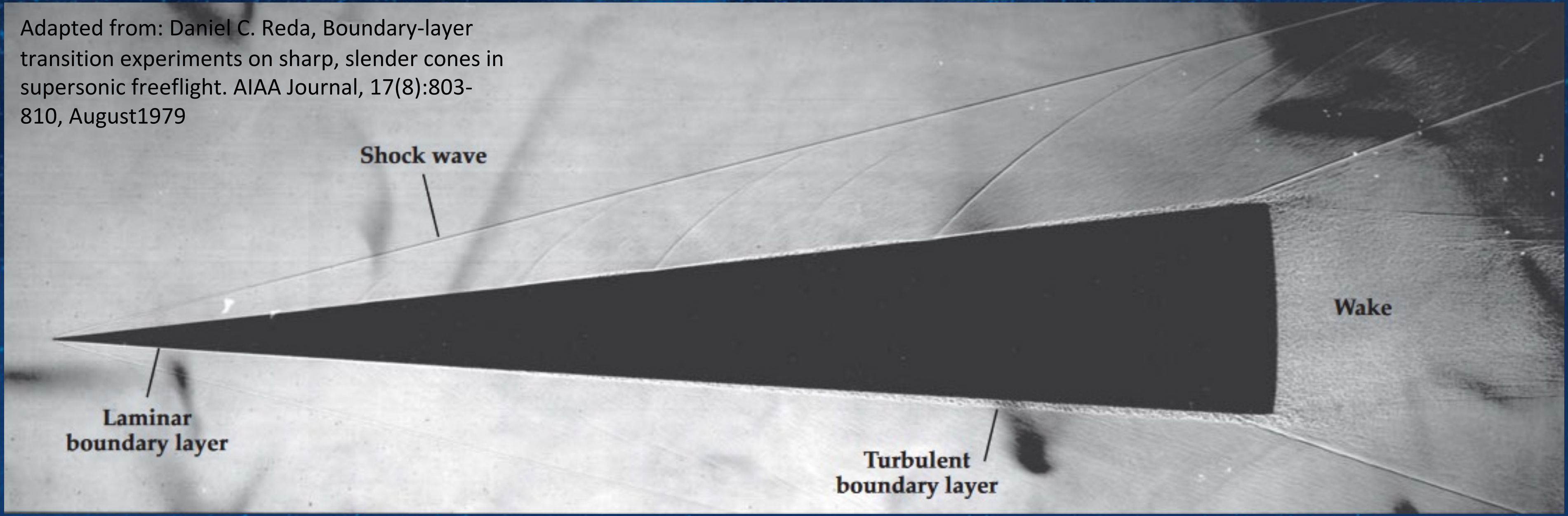
Non-Equilibrium Effects
Fluid Structure Interactions
Shock/Boundary Layer Interactions
Boundary Layer Physics

https://api.army.mil/e2/c/images/2018/08/15/527160/original.jpg

Boundary Layer Physics

The boundary layer is only millimeters high…but it is *very critical* to understand

Adapted from: Daniel C. Reda, Boundary-layer transition experiments on sharp, slender cones in supersonic freeflight. AIAA Journal, 17(8):803-810, August1979



Credit: C. Hader, U of Arizona, Advanced Modeling & Simulation (AMS) Seminar Series NASA Ames Research Center, 2017

Problem: Unacceptable uncertainty on transition prediction in nonlinear region

Approach: Accurate DNS: enable connection of ground tests to flight

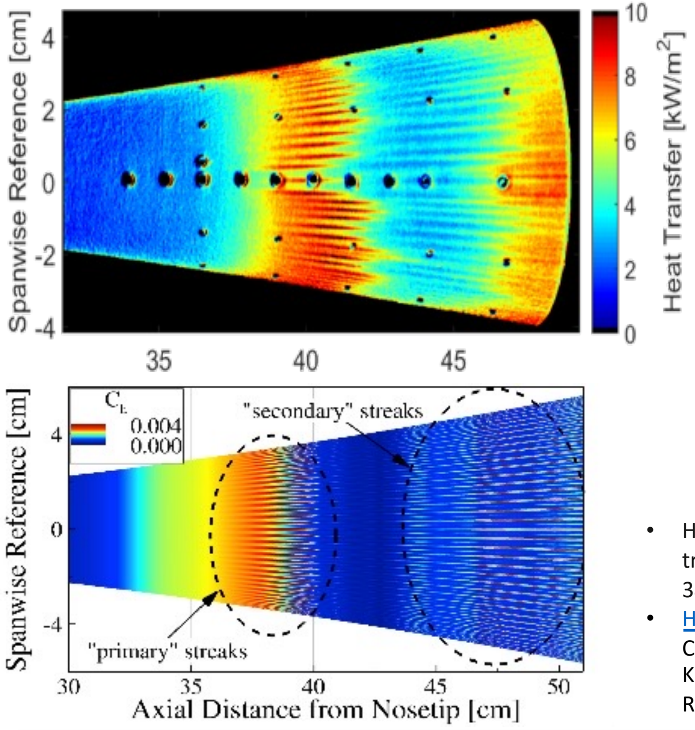
Future: **1)** Predict nonlinear stages for flight via DNS w/ "controlled" & random disturbances

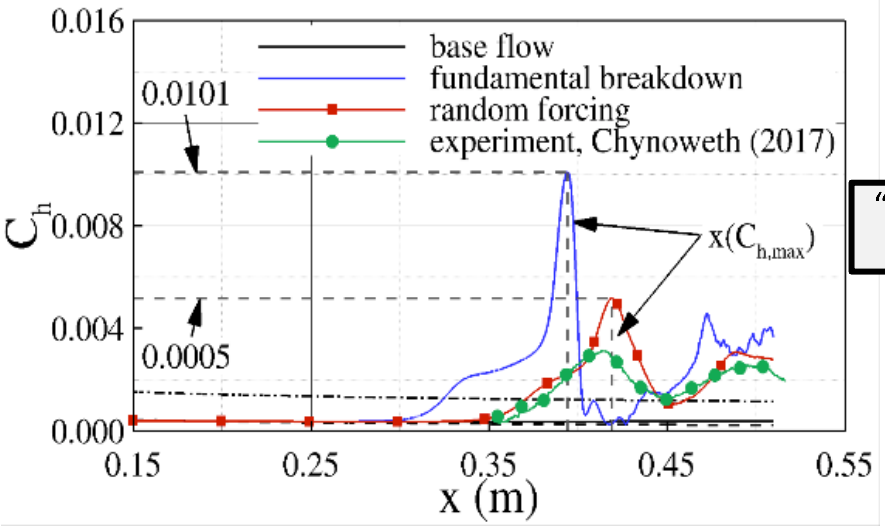
2) Leverage knowledge of nonlinear stages for control/delay transition

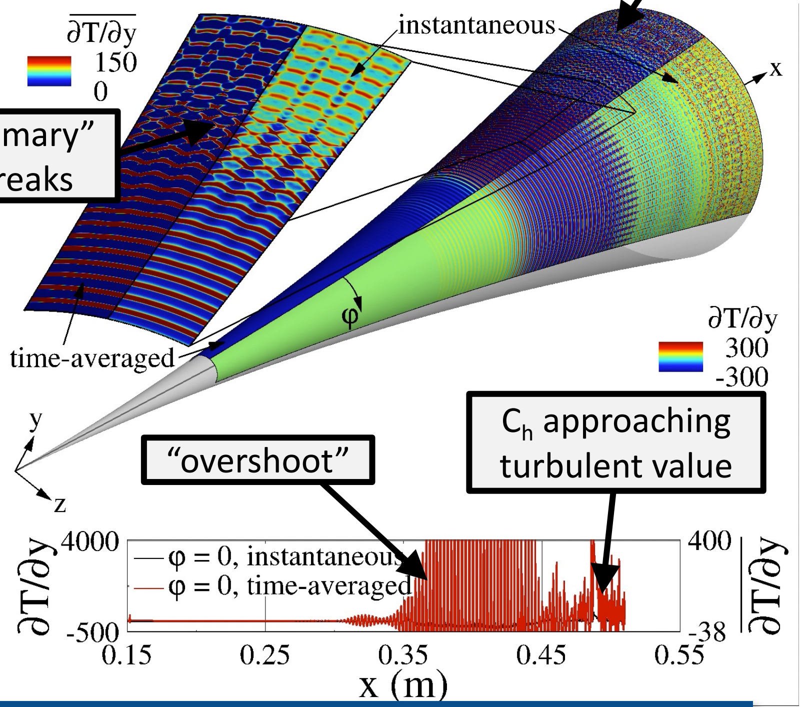
Dr. Roper with Purdue team and Prof. Steve Schneider , Purdue Univ

2018 Prandtl Ring Winner
Hermann Fasel, U of AZ

Good qualitative agreement between experiment and DNS – "Hot Streaks"







- Hader, C., & Fasel, H. (2019). Direct numerical simulations of hypersonic boundary-layer transition for a flared cone: Fundamental breakdown. *Journal of Fluid Mechanics, 869*, 341-384. doi:10.1017/jfm.2019.202
- History and Progress of Boundary-Layer Transition on a Mach-6 Flared Cone, Brandon C. Chynoweth, Steven P. Schneider, Christoph Hader, Hermann Fasel, Armani Batista, Joseph Kuehl, Thomas J. Juliano, and Bradley M. Wheaton, Journal of Spacecraft and Rockets 2019 56:2, 333-346

Impact: Starting to explain and predicting worst heating overshoots due to boundary layer transition

Problem: Inaccurate hypersonic boundary layer transition prediction in **flight**

BOundary Layer Transition (BOLT I) Flight Experiment

Approach:

1) Investigate hypersonic boundary layer **transition mechanisms** on a geometry with relevant features

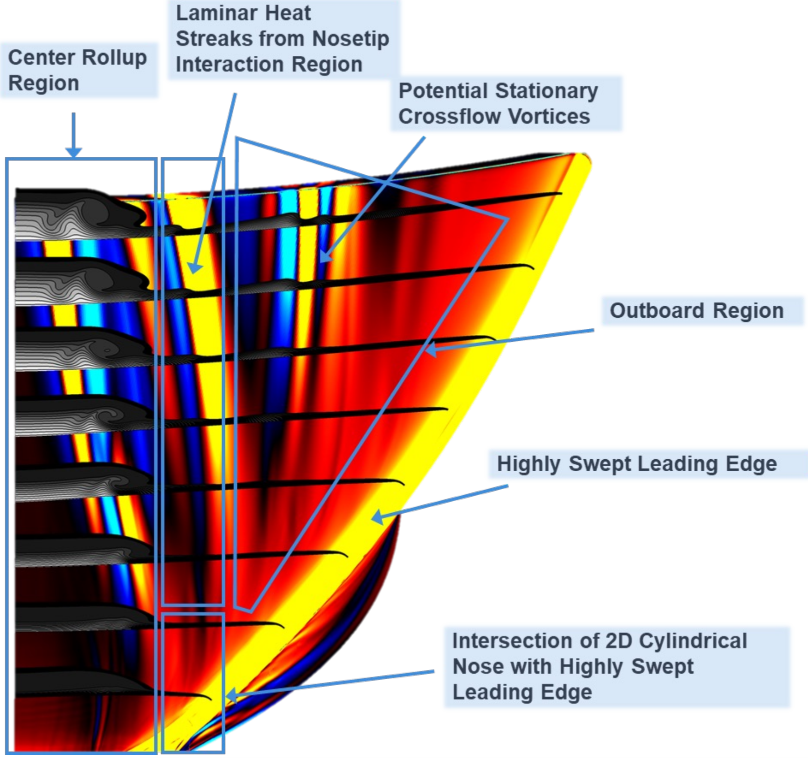
2) Synthesis of computational, experimental and flight test data to challenge predictive techniques

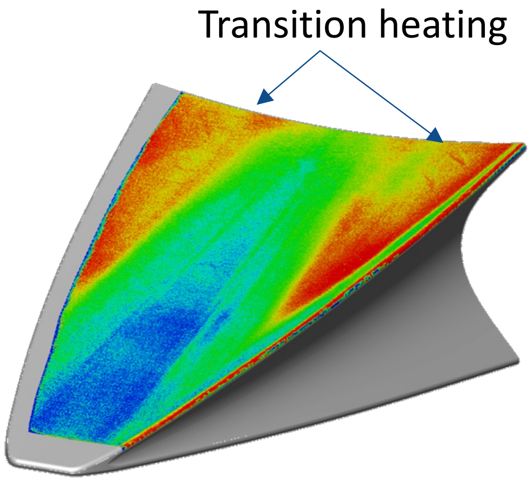
Future: Provide **benchmark 6.1** experiment to boundary layer transition community

TEAM

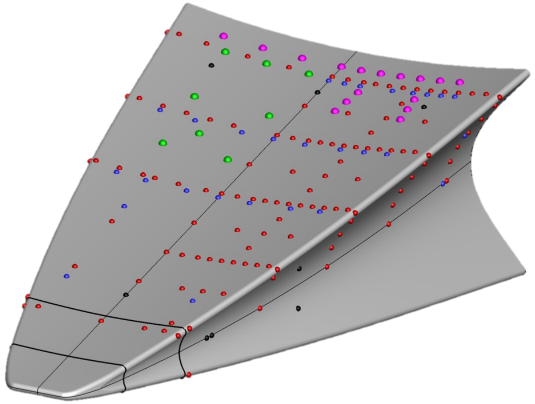
VirtusAero, LLC

DST, Australia





Mach 7 CUBRC heat flux measurements



Informed layout of 237 sensors to chase the science

Flight Test June 2021 from Esrange

Ascent: Mach 5.5, Re/m = 1-18 million

Descent: Mach 7, Re/m = 1-20 million

Impact: Close the gaps to *explain* and *predict* heating due to boundary layer transition

Problem: Inaccurate hypersonic boundary layer turbulence prediction in **flight**

BOundary Layer Turbulence (BOLT II) Flight Experiment

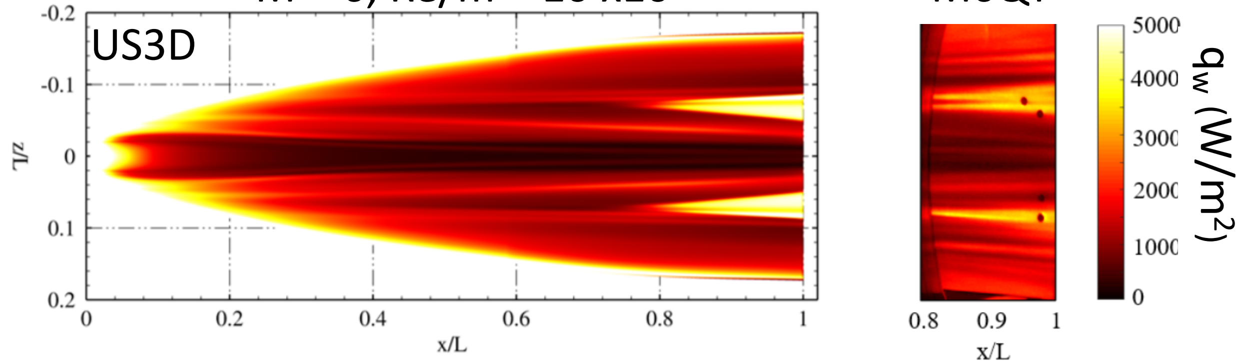
Approach:

1) Investigate hypersonic **turbulent transport mechanisms** which drives heating and skin friction

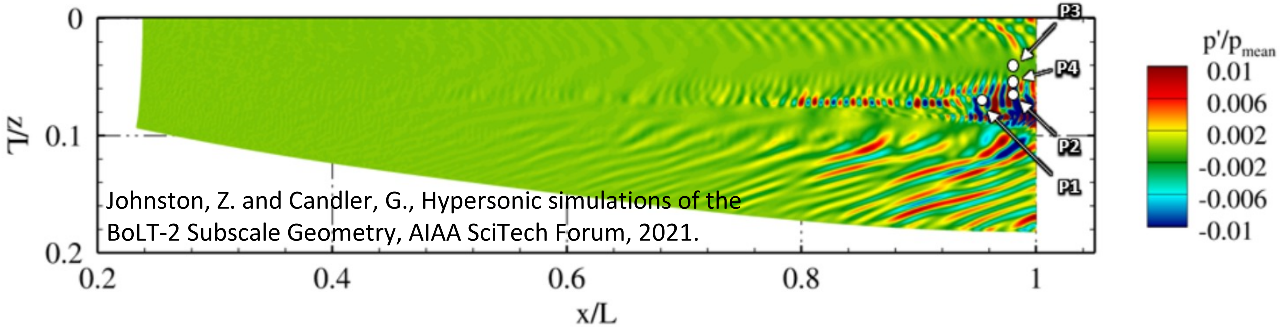
2) Challenge our ability to simulate and ground test hypersonic turbulent boundary layers

Future: Provide **benchmark 6.1** experiment to boundary layer turbulence community

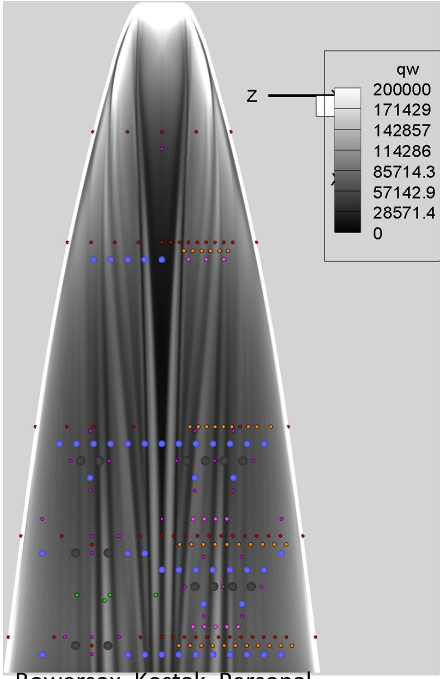
M = 6, Re/m = 10 x10^6 M6QT



Simulated time-dependent DNS of natural transition!



Johnston, Z. and Candler, G., Hypersonic simulations of the BoLT-2 Subscale Geometry, AIAA SciTech Forum, 2021.



Bowersox, Kostak, Personal Correspondance, March 2021.

Informed layout of 280 sensors to chase the science

TEAM

Wallops
Langley
Johnson

Flight Test Fall 2021 from Wallops

Ascent: Mach 5.2, Re/m = 1-20 million

Descent: Mach 5.2, Re/m = 1-35 million

Impact: Close the gaps to *explain* and *predict* heating due to boundary layer turbulence

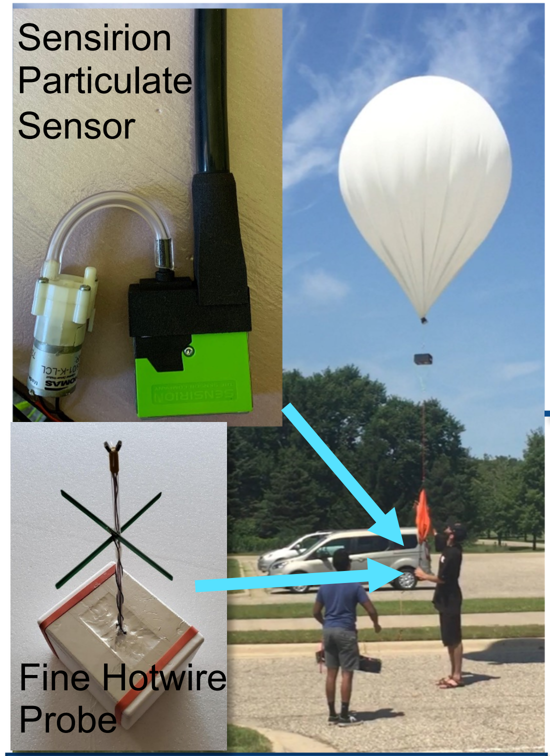
Problem: Unknown impact of atmospheric turbulence and particulates

Balloon
+
Integrated Instruments

Data

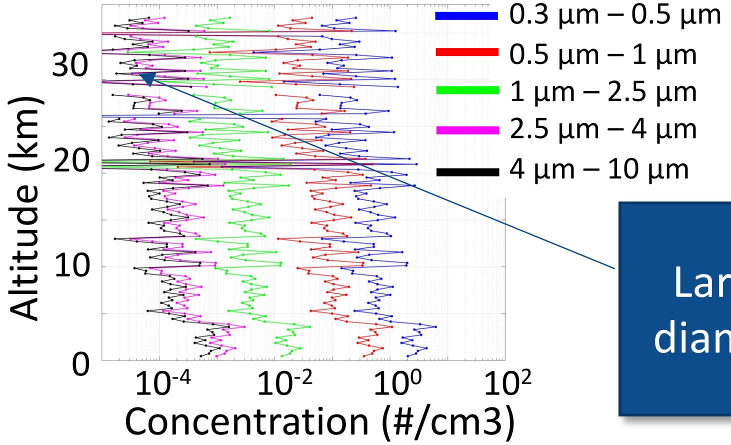
Receptivity
Simulations

MURI TEAM

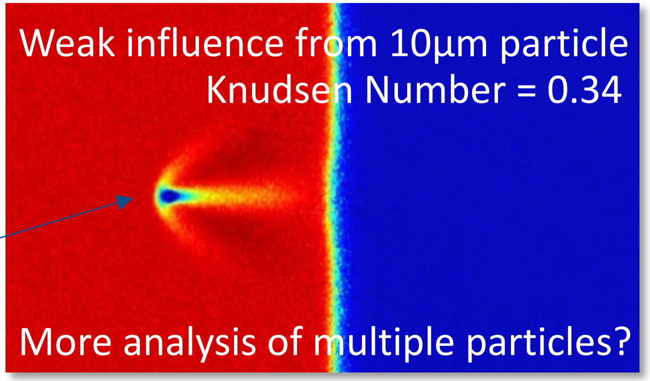


~40 balloon launch campaign to support BOLT!

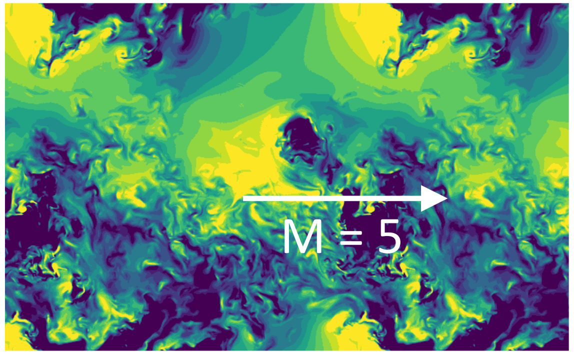
Particulates



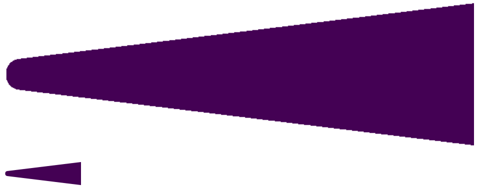
Largest particle diameter ~ 10µm



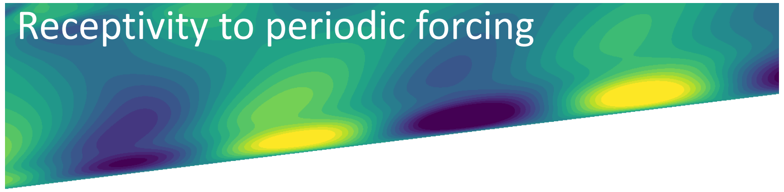
Turbulence

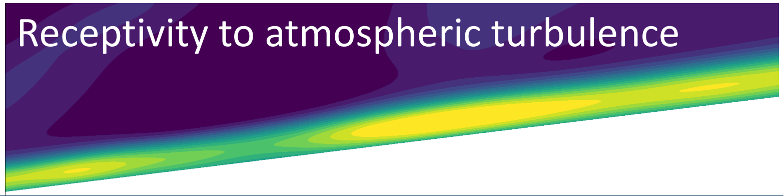


Small scale turbulence



Large scale turbulence

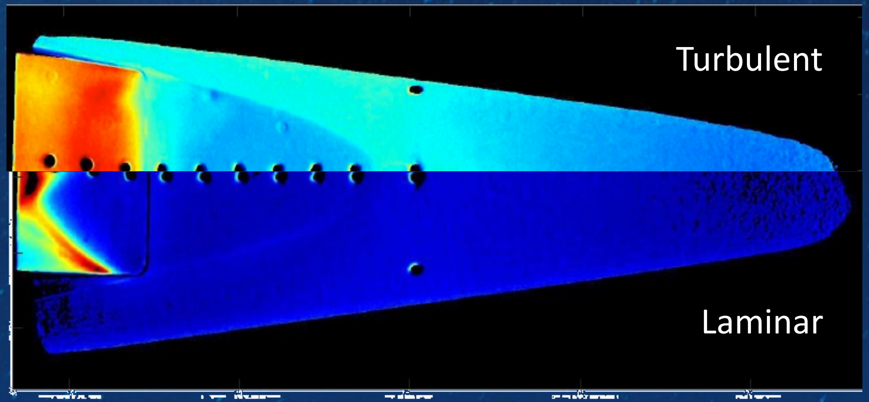




Distinct receptivity to atmosphere

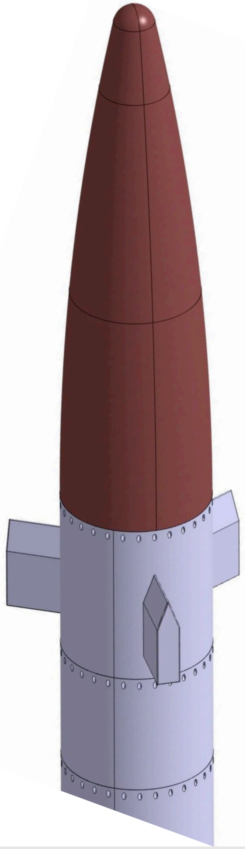
Impact: Provide fundamental understanding of weather effects on hypersonic flight

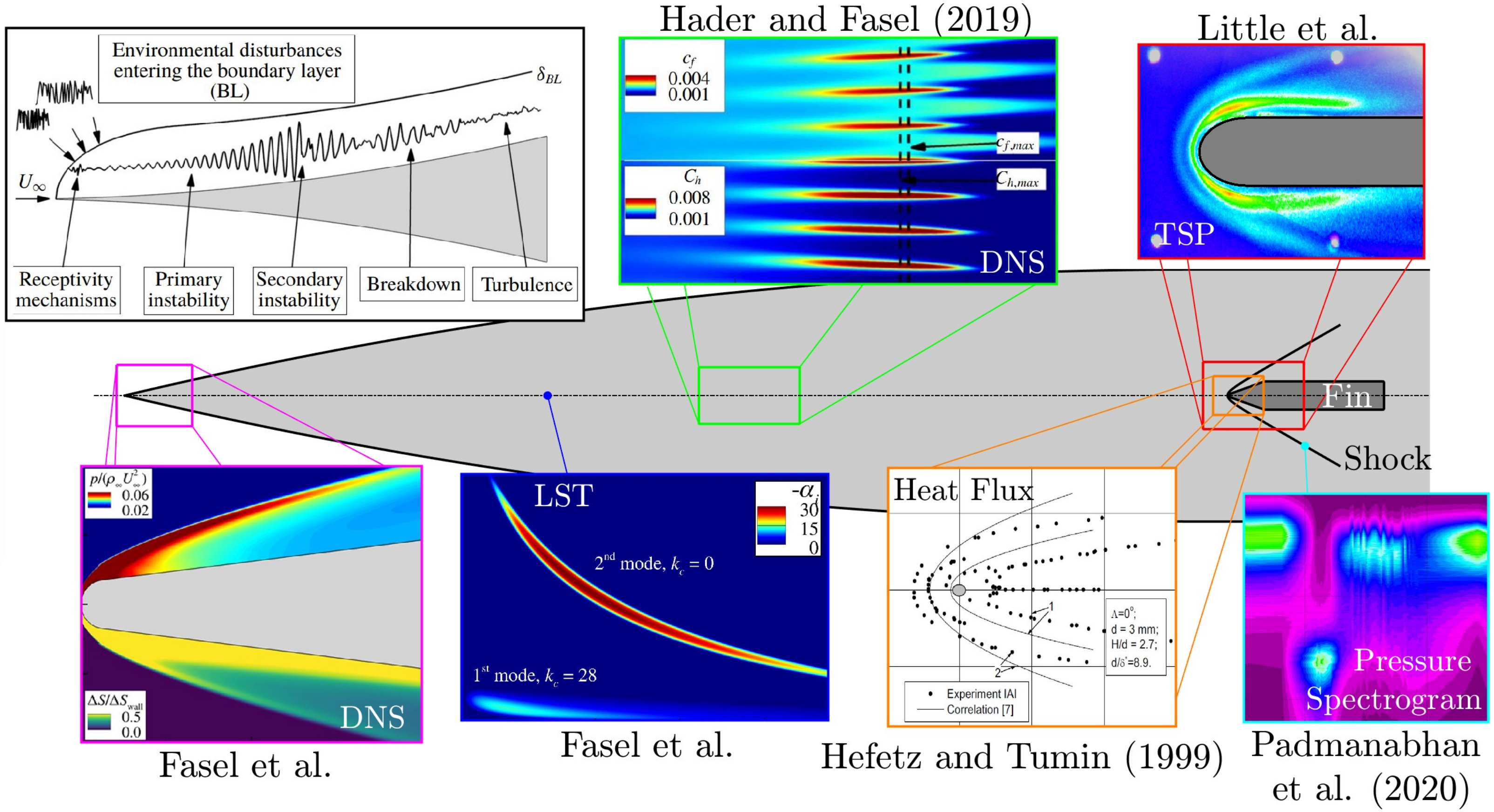
Shock Boundary Layer Interactions



Opportunity: Acquire SBLI flight experiment data

Investigation of 3D Shockwave Boundary Layer Interaction and Related Phenomena for the STORT Flight Program





- Advance the understanding of 3D SBLIs and other phenomena relevant to control surfaces through scientific flight tests, wind tunnel experiments, DNS, stability theory and data analysis.
- Jesse Little (PI), S. Alex Craig, Hermann Fasel and Anatoli Tumin

Fluid Structure Interactions

Problem: Low-frequency loading due to SWBLI leads to large uncertainties in structural lifetimes

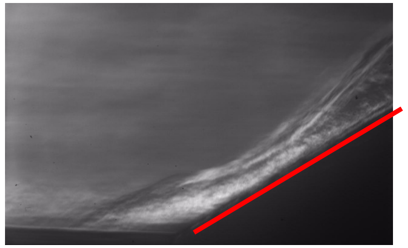
S. Laurence
U. of Md

D. Bodony
UIUC

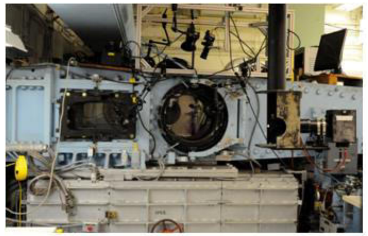
Approach: Isolate key physical phenomena of planar SWBLI-induced fluid-thermal-structural interactions through tightly coupled experimental studies, numerical simulations, and reduced-order modeling

Future: Further advance diagnostic & numerical tools → apply to other hypersonic configurations

High-speed photogrammetry and focused schlieren

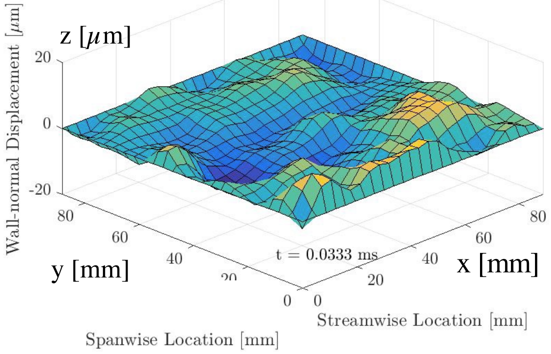


Collaboration with NASA LaRC



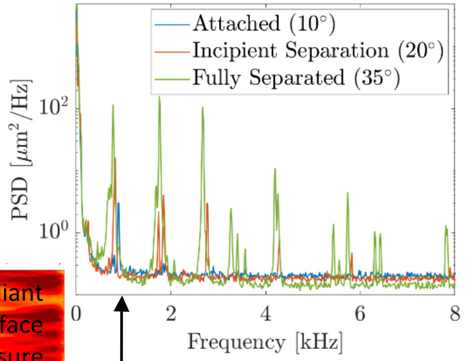
Access to Langley Mach-6 20“ tunnel

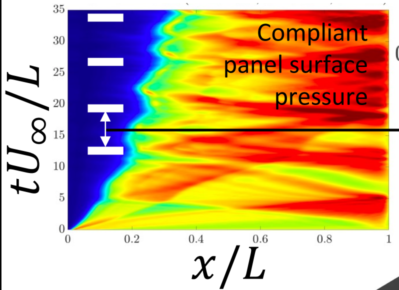
Advanced experimental/ numerical techniques

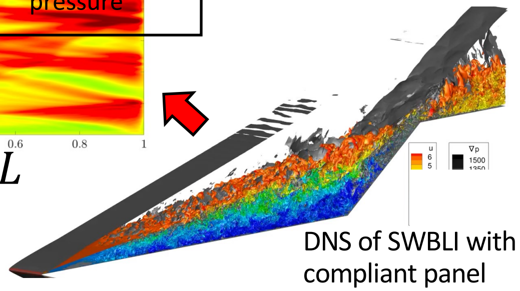


Detailed structural/flow response

Thermal stresses and SWBLI reattachment location dictate panel response





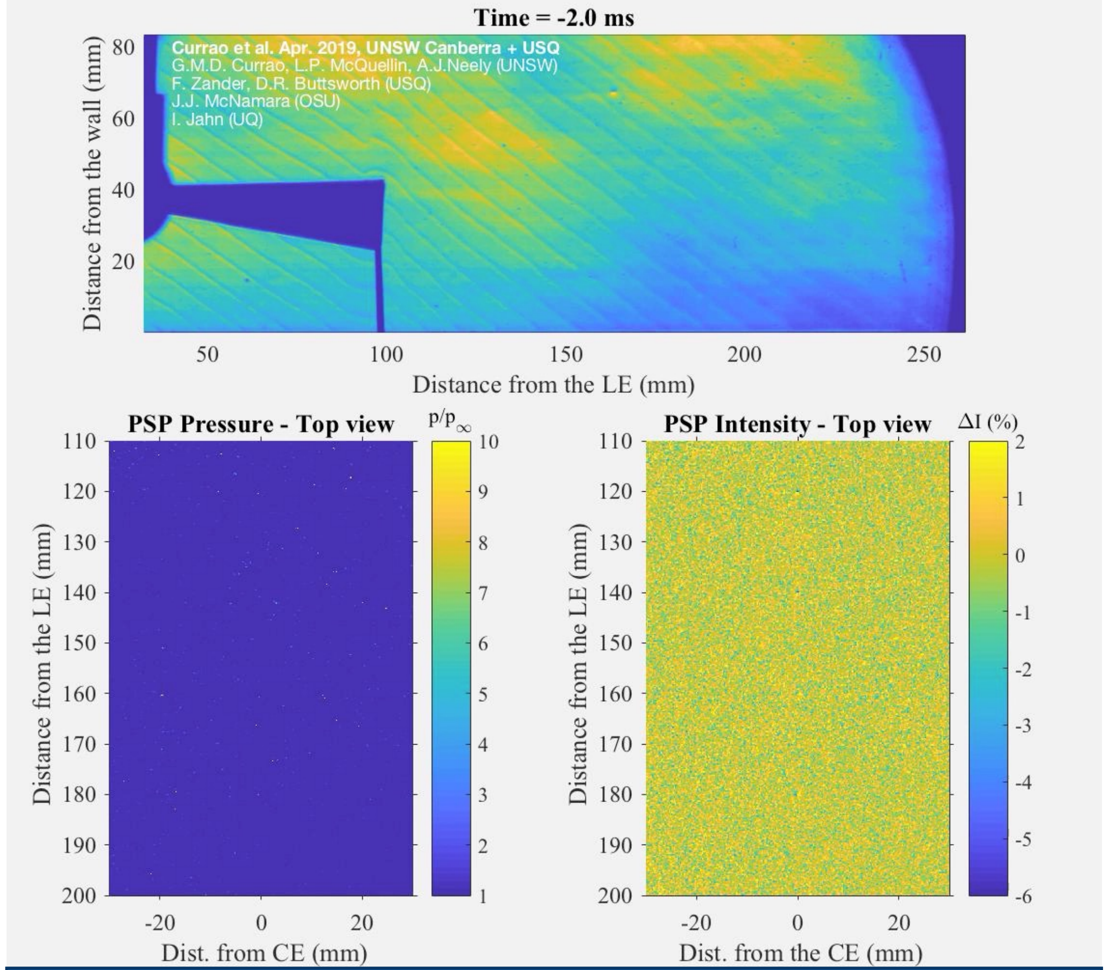


DNS of SWBLI with compliant panel

Impact: Know how to prevent structural failures for hypersonic speeds

Problem: Need canonical cases for FSI community

Moving Shock Unit Case: Rigid



Currao GM, Choudhury R, Gai SL, Neely AJ, Buttsworth DR (2020) Hypersonic Transitional Shock-Wave–Boundary-Layer Interaction on a Flat Plate. *AIAA Journal*, 58(2), 814-829.

Currao GMD, McQuellin LP, Neely AJ, Zander F, Buttsworth DR, McNamara JJ, Jahn I (2019) Oscillating Shock Impinging on a Flat Plate at Mach 6, AIAA-2019-3077.

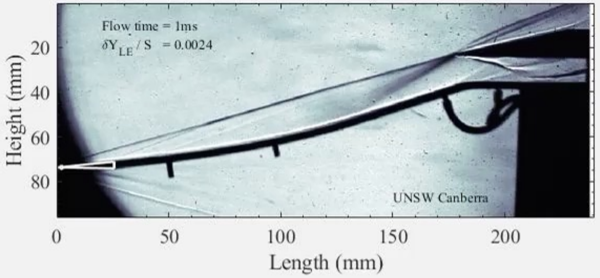
Andrew Neely
UNSW

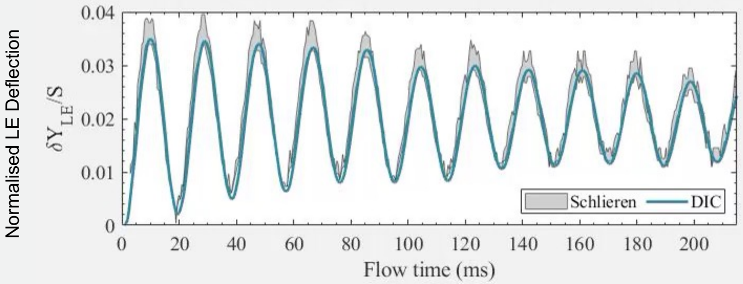
UNSW CANBERRA

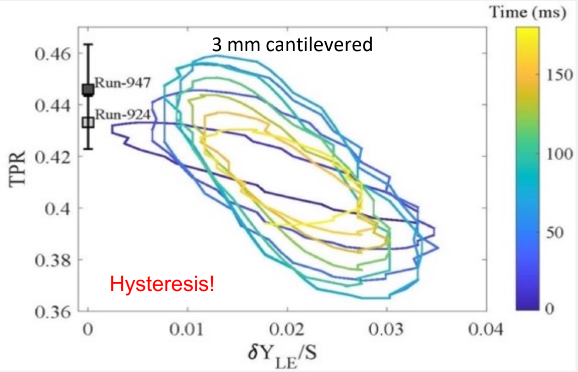
UNIVERSITY OF SOUTHERN QUEENSLAND

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Axial Pressure Gradient Unit Case







Bhattrai, McQuellin, Currao, Neely, Buttsworth (2020) Experimental study of the aeroelastic response and performance of a hypersonic intake, AIAA 2020-2449.