



# ***Overview of Recent EAST Testing, Modeling & Analysis***

Image taken 1962

**12<sup>th</sup> IWSTT, JAXA Kakuda Space Center**

**Presented by: Aaron Brandis**

**AMA Inc, NASA Ames Research Center**

April 12, 2018



- This presentation contains work for a large number of NASA'S Entry Systems Modelling (ESM) team members & affiliates, including:
  - NASA Ames:
    - Brett Cruden, Rich Jaffe, David Schwenke, Khalil Bensassi, Jeff Hill
  - NASA Langley:
    - Tom West
  - University of Minnesota:
    - Durgesh Chandel, Graham Candler

# Shock Layer Radiation at NASA Ames

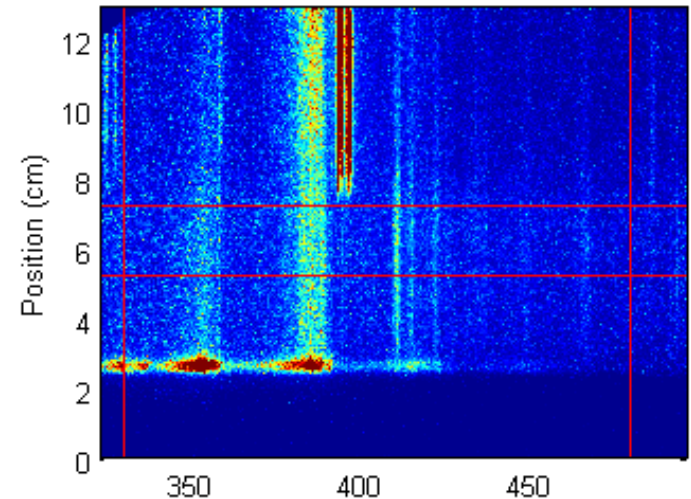


- **Background:** Complex aerothermal and thermochemical phenomena of planetary entry define convective and radiative heating. A spacecraft's TPS mitigates heat transfer to substructure. Successful TPS design relies on verifiable characterization of these phenomena in the anticipated flight environment.
- **Approach:** EAST simulates high-enthalpy, real-gas phenomena encountered by hypersonic vehicles entering planetary atmospheres by spectrally imaging a the flow behind a moving shock wave.
- **Goal:** Validate aerothermal models (DPLR & NEQAIR), inform model improvements, reduce uncertainty and quantify design uncertainties.
- **Recent Relevant Projects:** MSL & Mars 2020, InSight, OSIRIS-REx, Orion EFT-1 & EM-1 and New Frontiers



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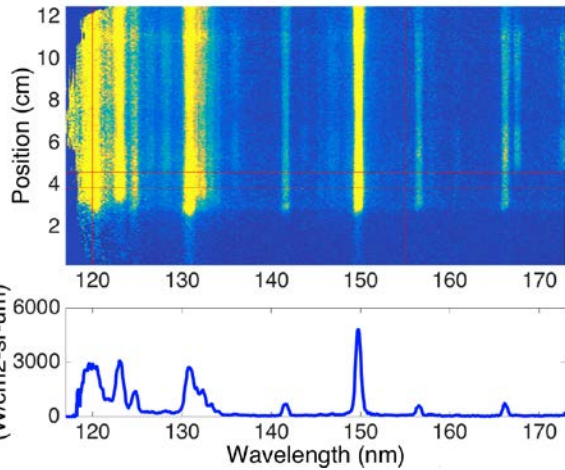
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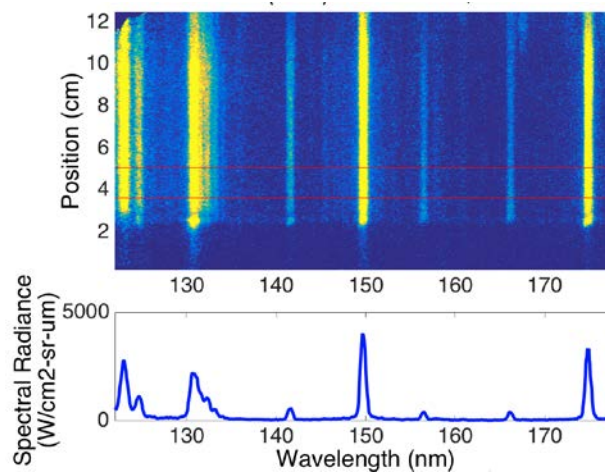
# Radiance Obtained in Different Spectral Regions



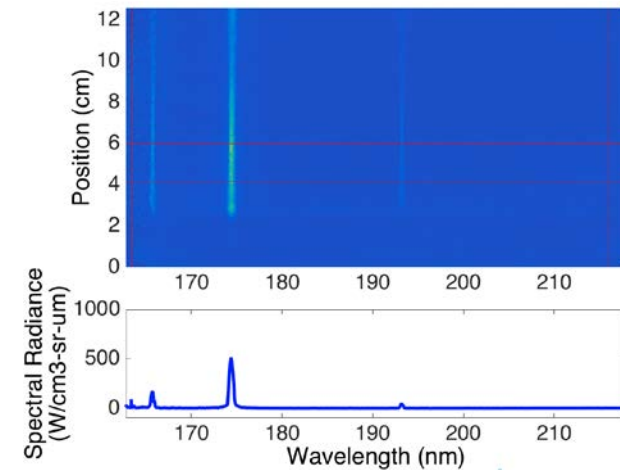
## Deeper VUV



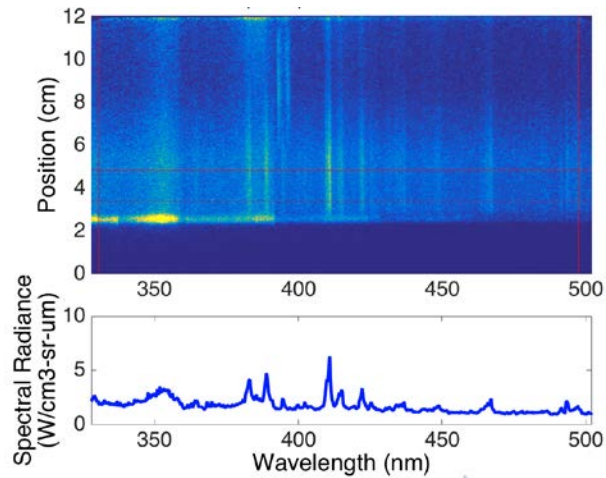
## VUV



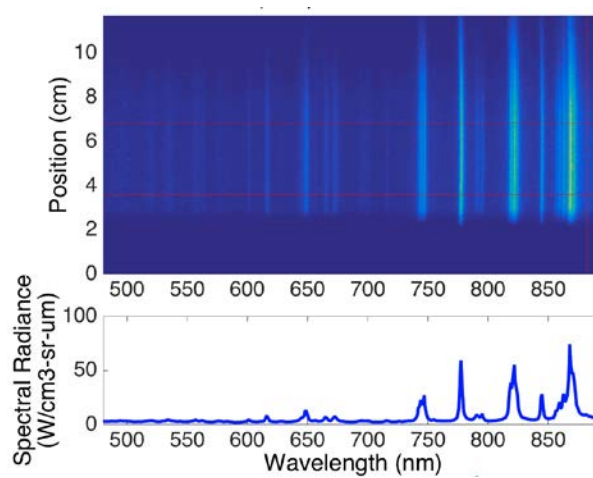
## VUV/UV



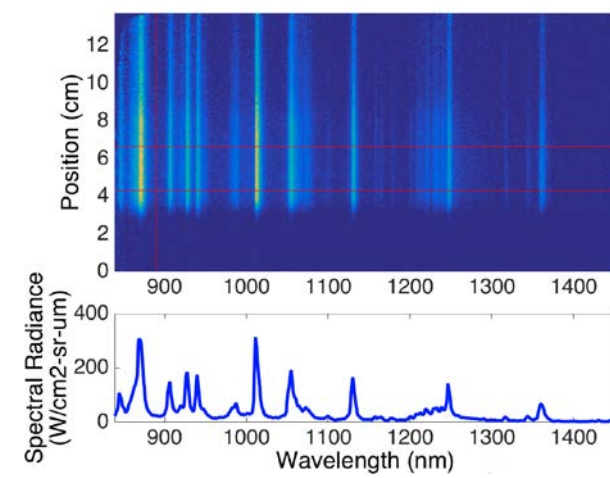
## UV/Vis



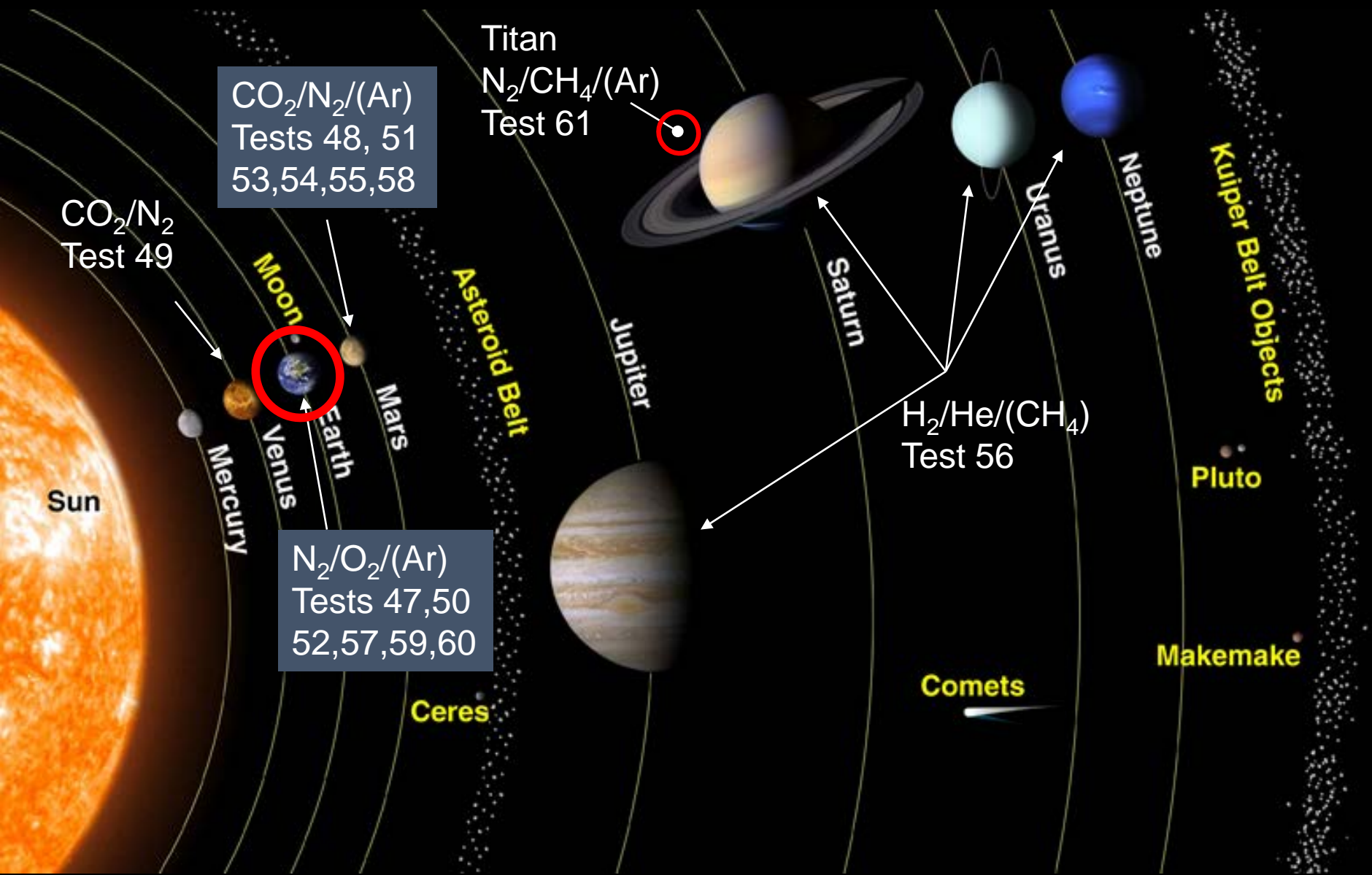
## Vis/NIR



## NIR/IR



# Planetary Atmospheres



# Recent Significant Achievements

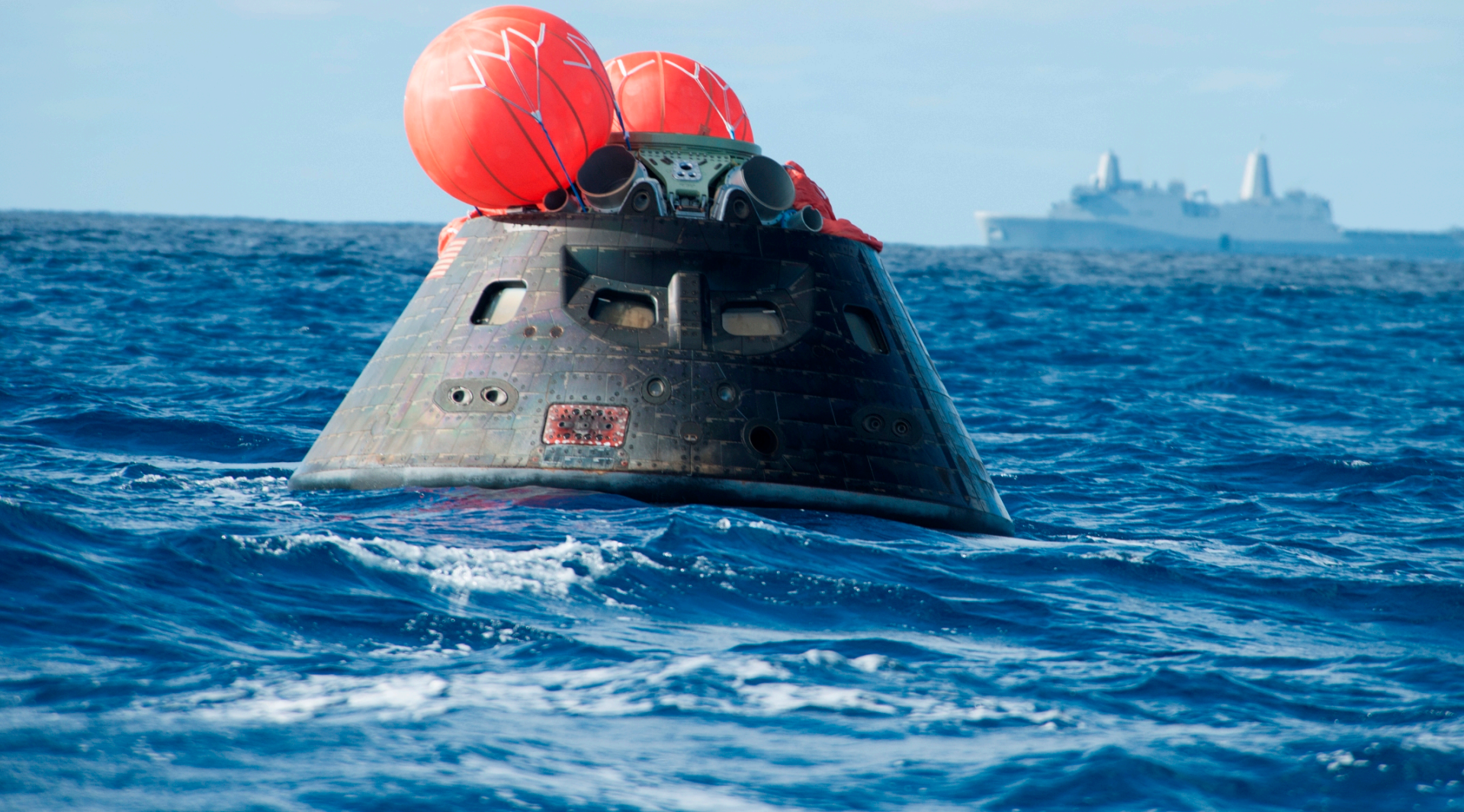


- **Margin Policies**
  - Rigorous approach to radiation margin developed for Earth re-entry **Orion: EM1**
  - Similar approach applied to Mars entry **Mars 2020**
- **FT1 Radiometer Discrepancy**
  - Significant under-prediction of FT1 radiation with baseline simulations
  - EAST testing allowed for the construction of a new model **Orion: FT1, EM1**
  - Model updates show good agreement with FT1 data
- **Titan Radiation Discrepancy** **New Frontiers: Dragonfly**
  - Radiation predictions for Titan entry have historically greatly over-predicted shock tube measurements
  - Newly measured radiation is substantially larger compared to literature experiments
  - Good agreement with simulations observed for peak radiance, while discrepancy in decay rate is still present
- **New Validation Data for Martian Entries** **Future Mars missions**
  - TDLAS measurement provides new avenues for understanding Martian reaction kinetics
- **Backshell Radiation** **Mars 2020, Orion, InSight**
  - ESM research implementing and validating backshell radiation for both Mars/Venus and Earth entries has directly influenced mission design – leading to EAST expansion testing

Recent EAST testing has driven significant model improvements and multiple infusions with flight projects



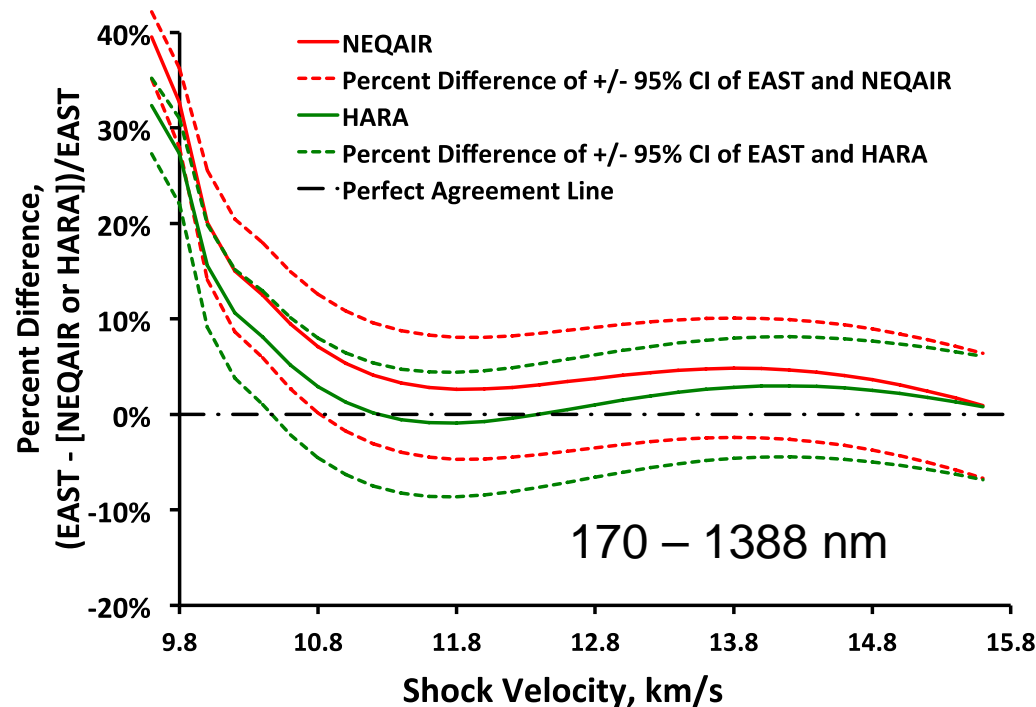
# Investigation of Earth Entry Radiation



# Equilibrium Summary



- Uncertainty for model predictions of EAST as a function of velocity for Earth entry up to 15.5 km/s.
- 1 Standard deviation in scatter of EAST: 17%.
- Disagreement of models w.r.t. to mean EAST result from 11 – 15.5 km/s on average [9.0%, -6.3%].

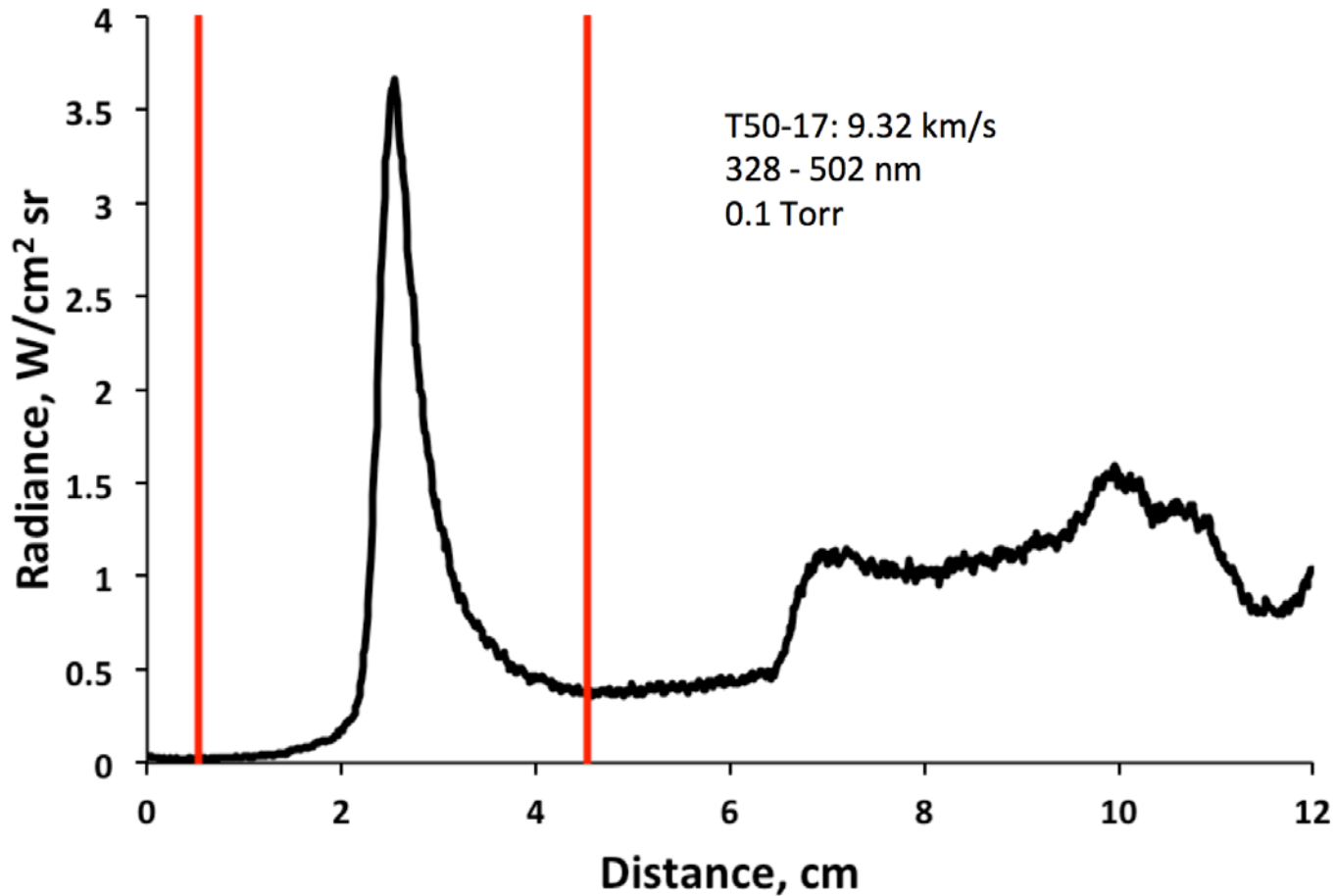




# Non-equilibrium Metric

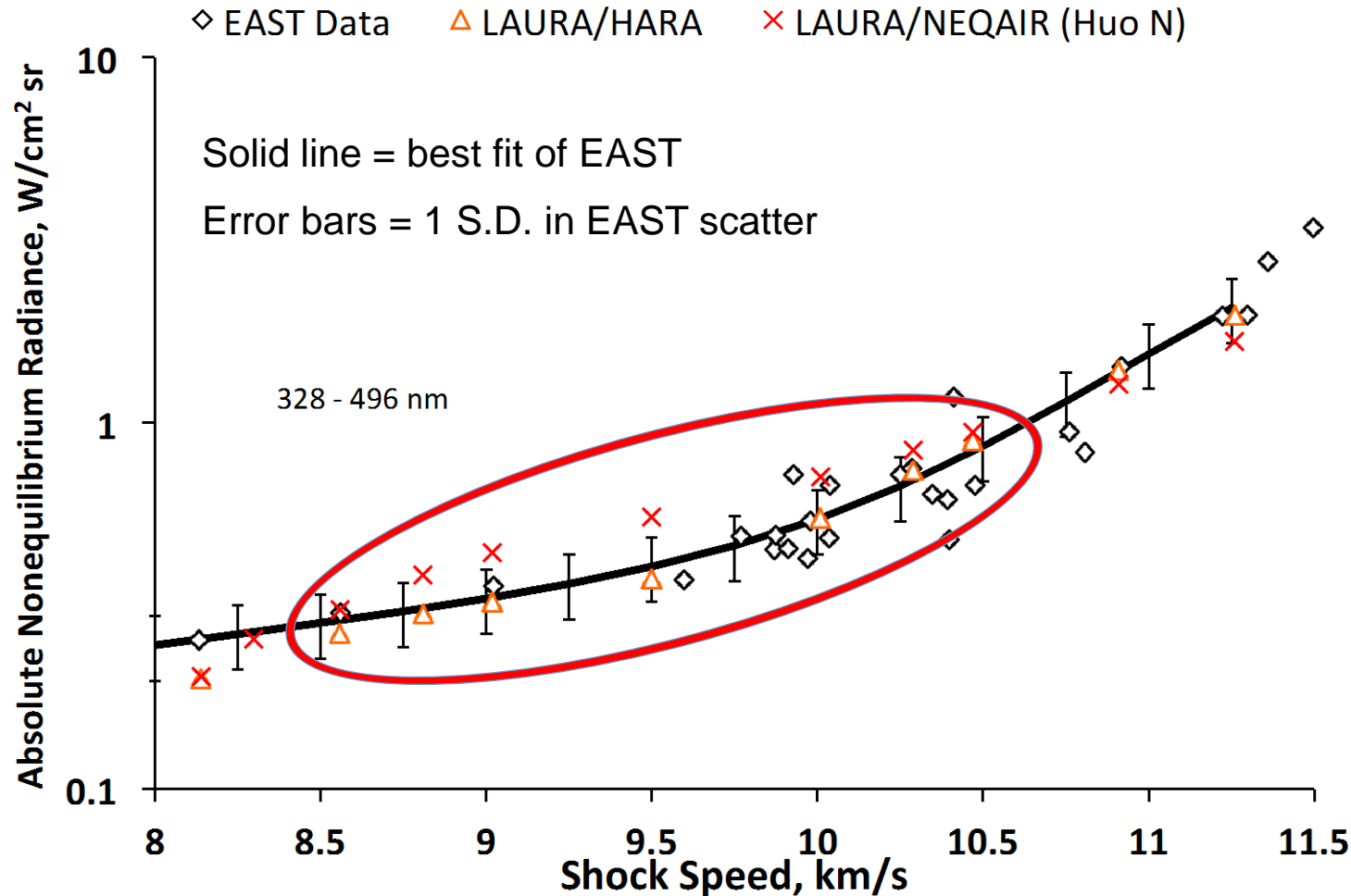


## Absolute Non-Equilibrium Radiance



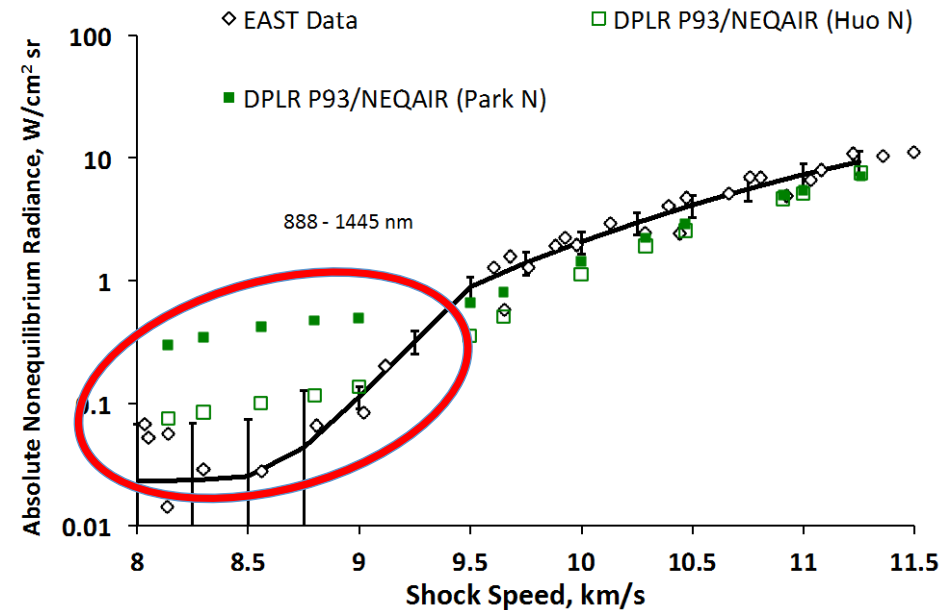
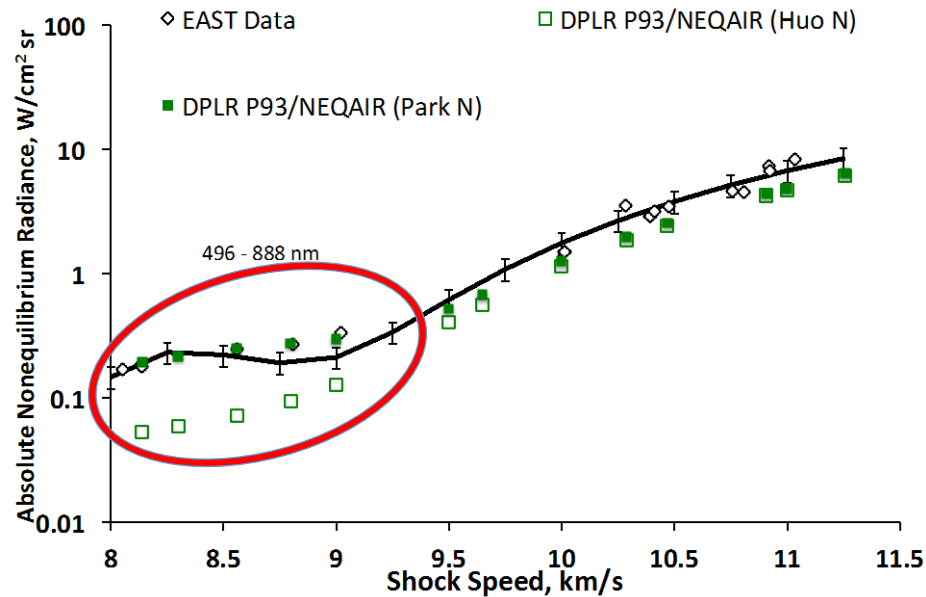
Integrate radiance  $\pm 2$ cm either side of shock front.  
Normalized by shock tube diameter

# Simulations vs EAST: UV



- In the UV, NEQAIR and HARA show a difference between 8.5 and 10.5 km/s when based on the same (LAURA) flowfield

# Using EAST to Validate Excitation Models

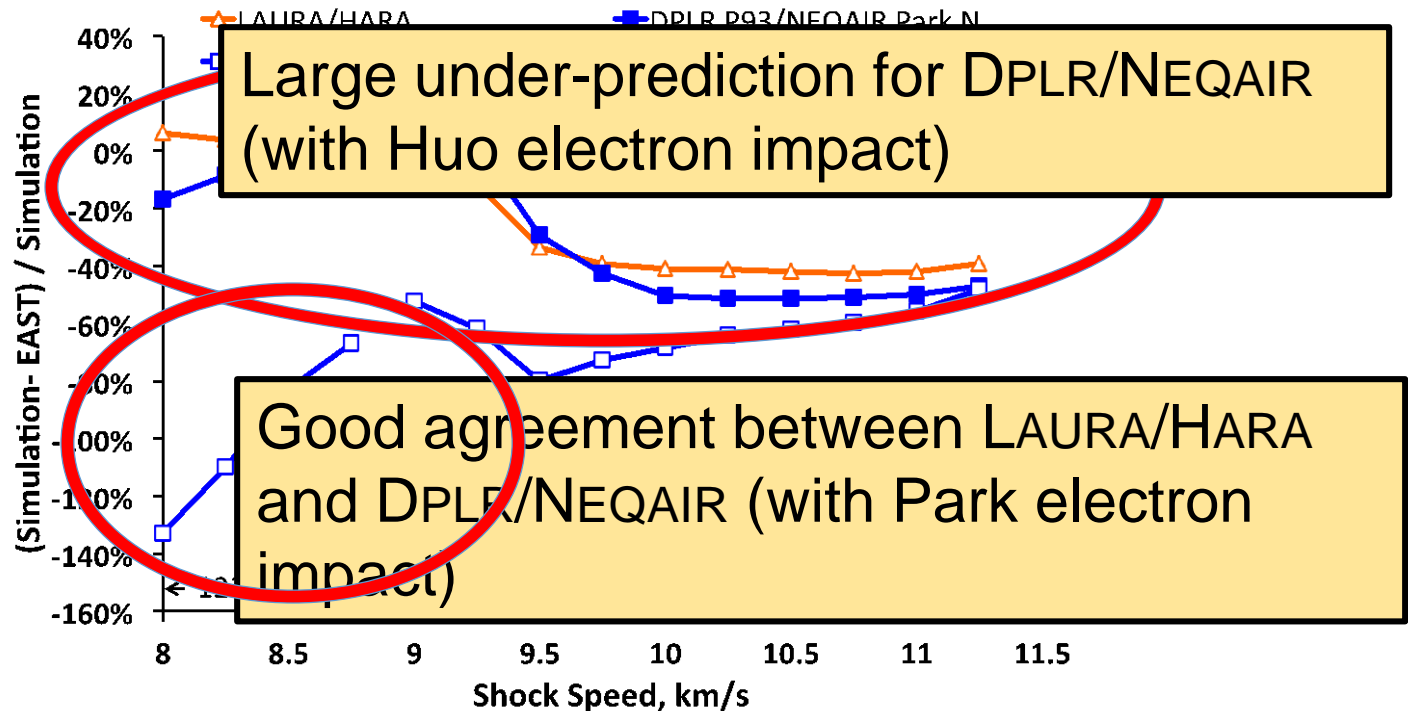


- In the Vis/NIR, the nitrogen electronic impact excitation rates from Park match well with EAST, while there is an under-prediction with those from Huo
- Other spectral regions show the inverse, such as the IR, with better agreement observed using the Huo data

# Overall Summation

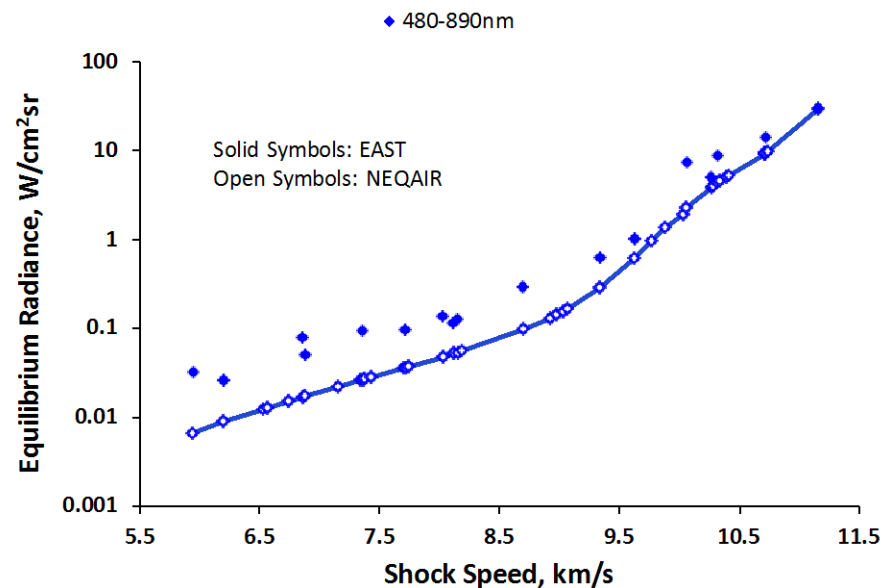
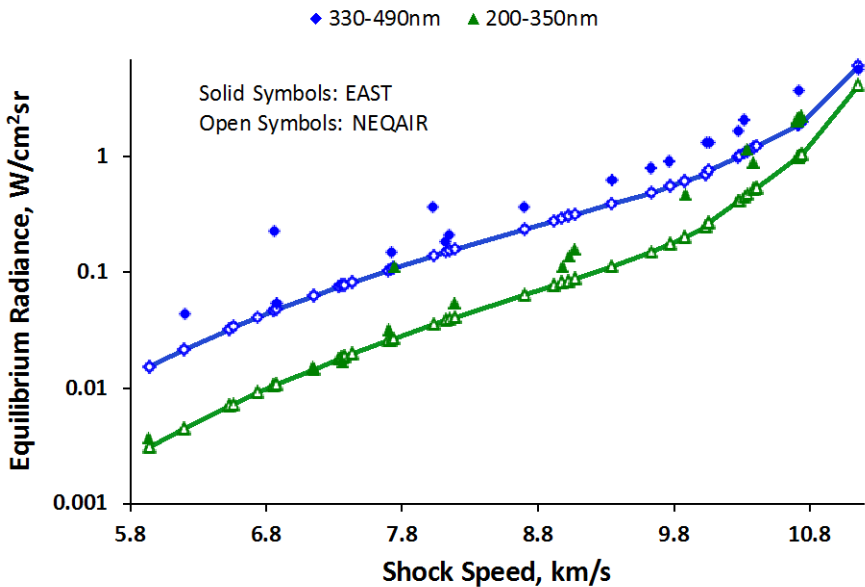
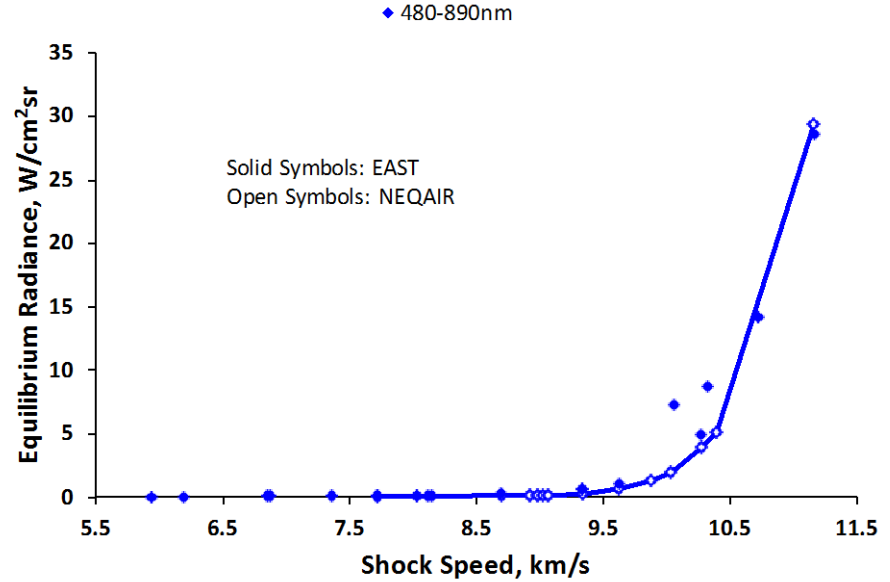
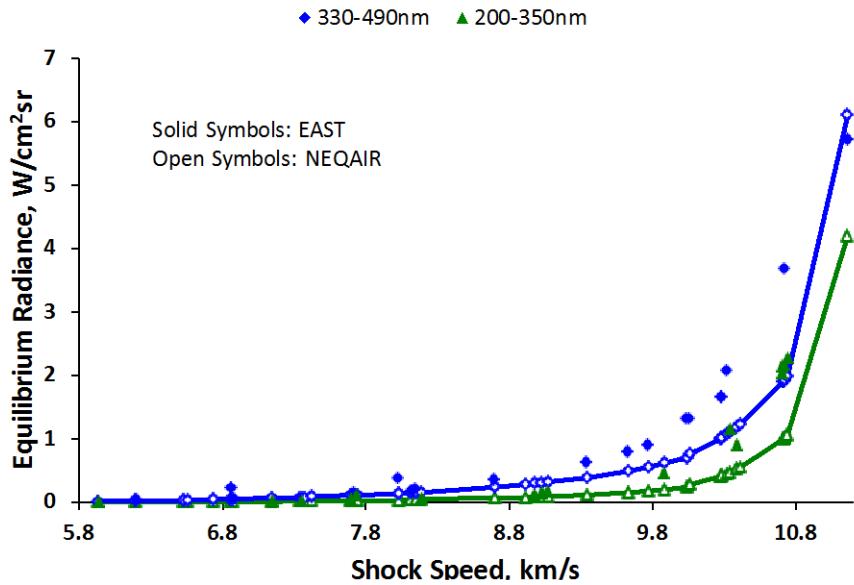


- The summation of the weighted discrepancies (overall difference) is shown below.

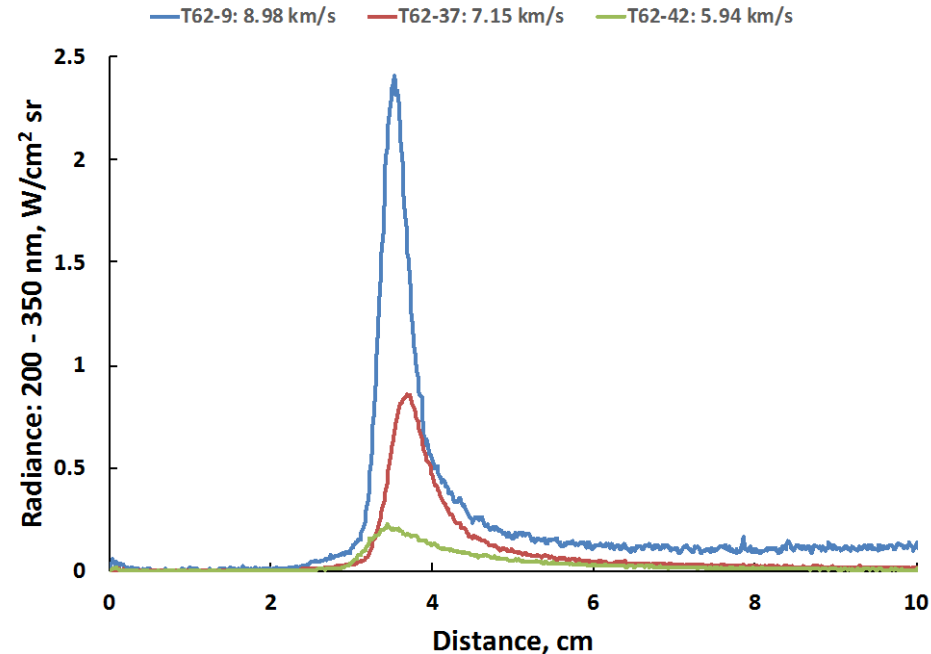
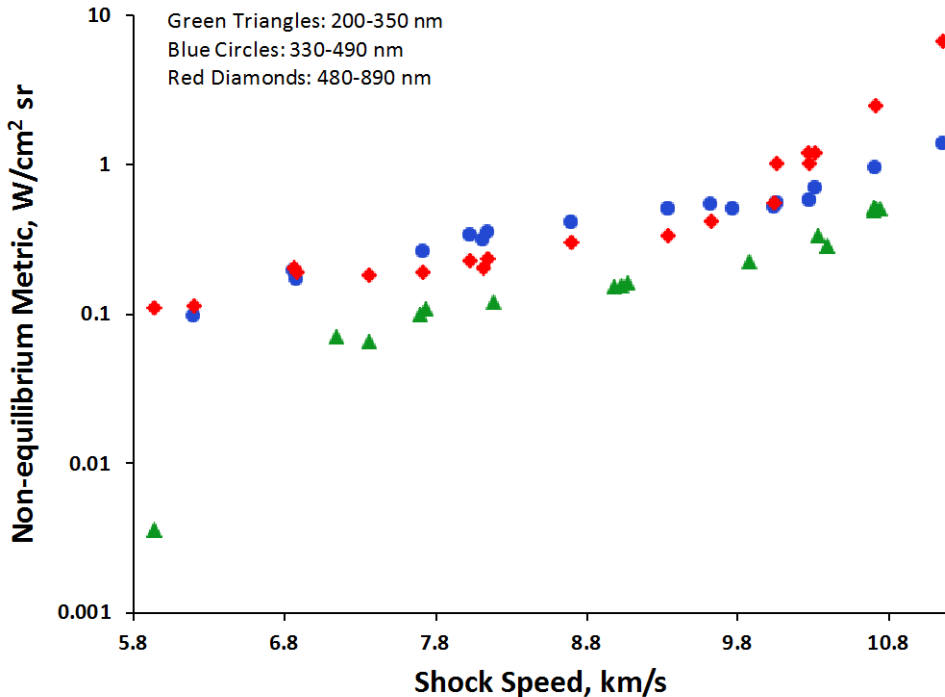


- Large differences at lower speeds, where non-equilibrium is more significant
- Improving agreement between the codes as shock speed is increased

# Equilibrium EAST: N<sub>2</sub> & 0.2Torr



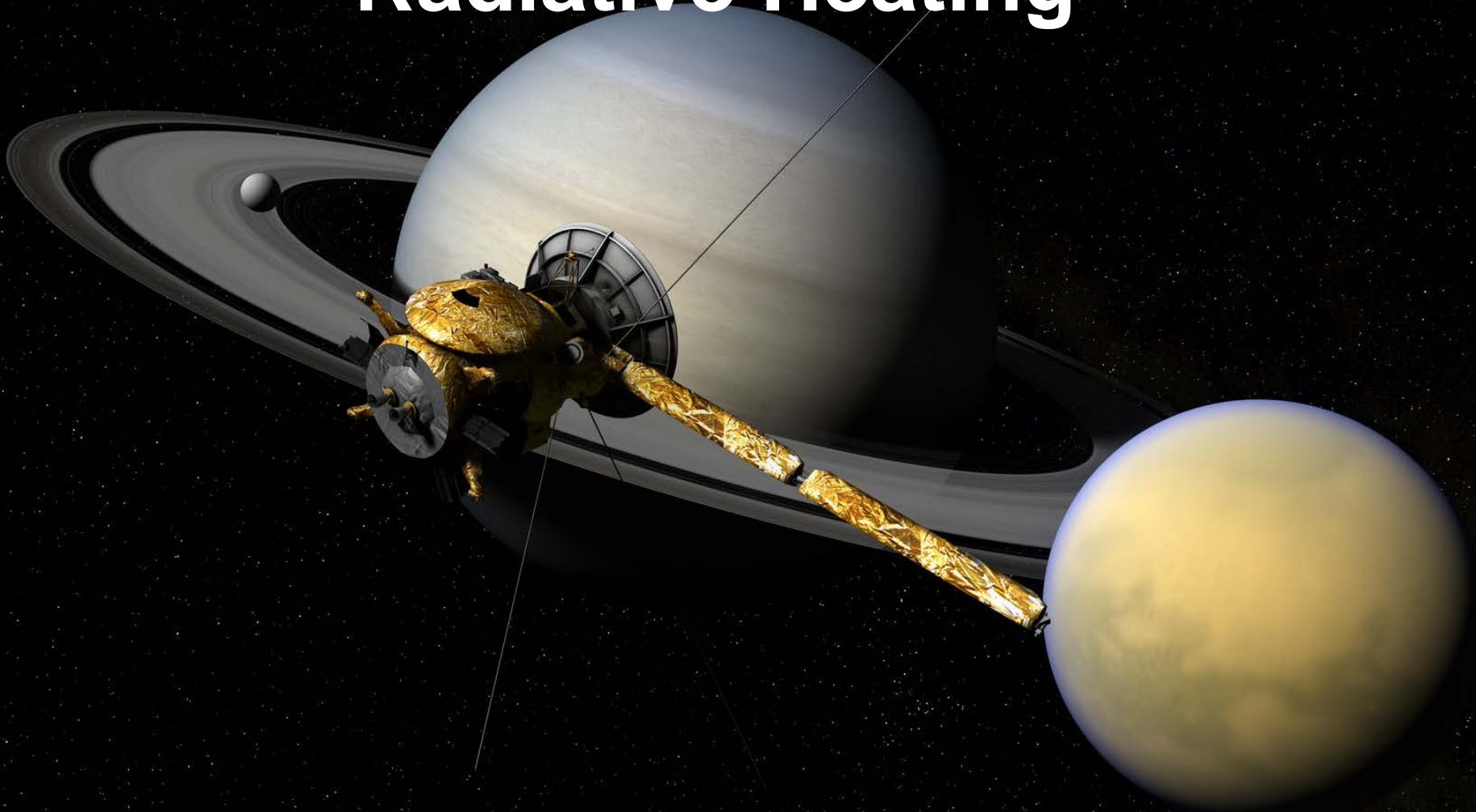
# Nonequilibrium EAST: N<sub>2</sub> & 0.2Torr



- Goal is to provide a fundamental database for validation of N<sub>2</sub> models, such as dissociation.
- Identify benchmark datasets.
- The insights gained from examining this dataset can then be applied to our air flight simulation capability.



# Titan Atmospheric Entry Radiative Heating



# Previous Titan Radiation Studies



- The joint NASA/ESA Cassini/Huygens mission resulted in significant efforts to understand radiative heating for Titan.
- Post flight simulations were conducted assuming a Boltzmann distribution of cyanogen (CN) excited states
  - If this were to be the case, Huygens may have burnt up during entry
- Consequently, experiments were performed in shock tubes and QSS/CR models developed.
- Reasons to believe there were issues with previously reported Titan (pre-upgrade) EAST data.
- Current interest in heading to Titan with two New Frontiers proposals
- Warranted to update published data due to improvements available with the current EAST set up

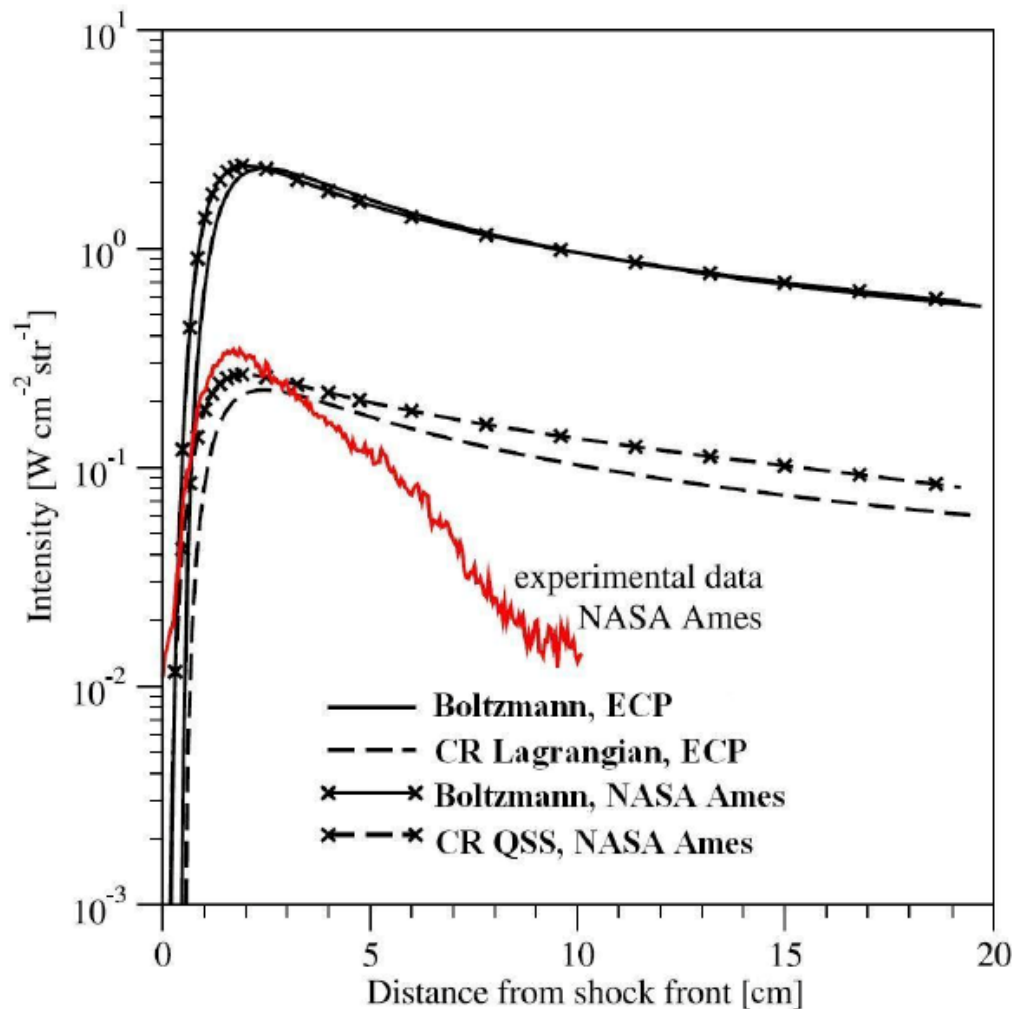




# Previous Titan Radiation Studies

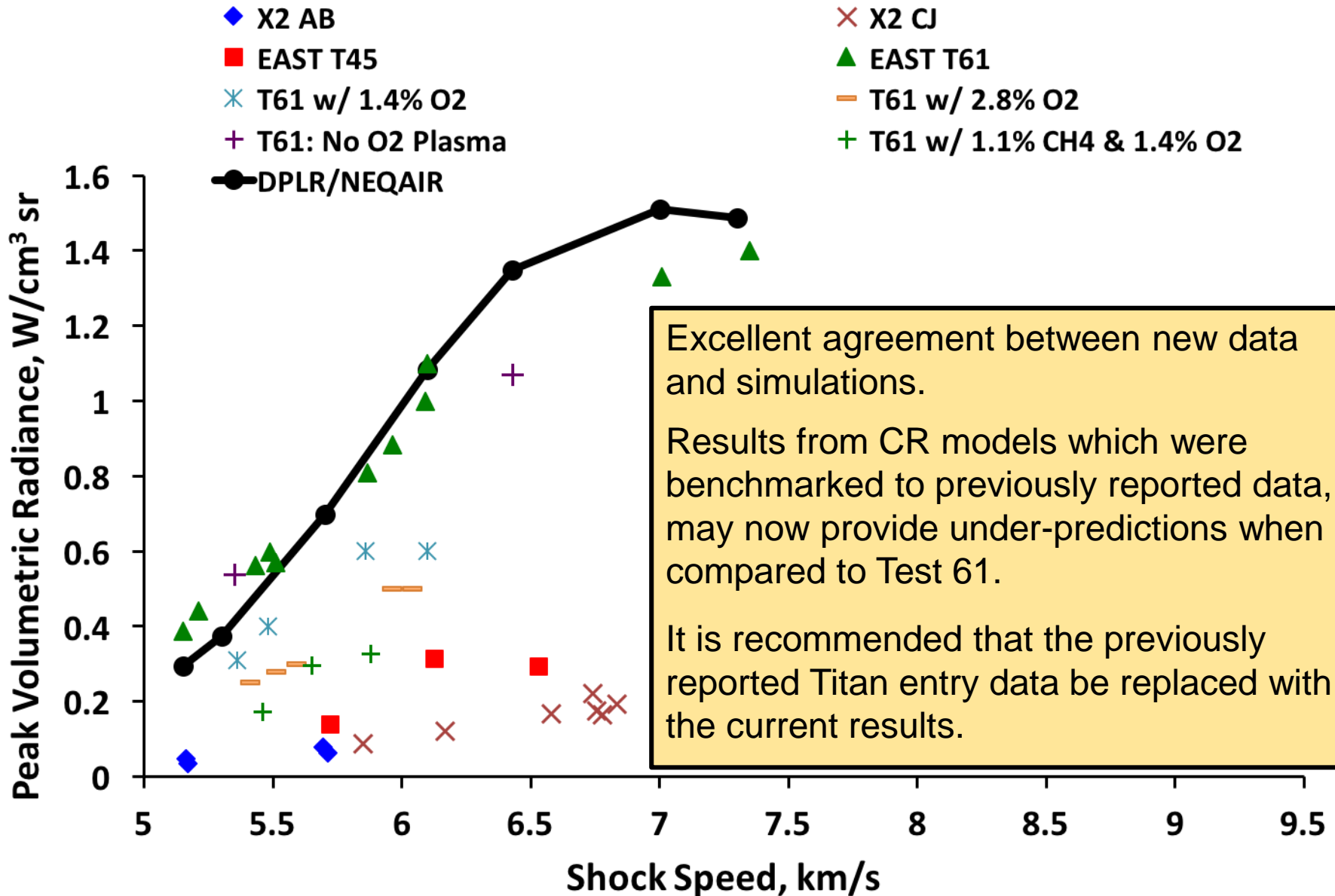


5.15 km/s, 98% N<sub>2</sub> : 2% CH<sub>4</sub>, 0.1 Torr,  
400 – 430nm. EAST T43-25



- Test 43 & 45 from EAST (2003 to 2005)
- Boltzmann predictions shown to substantially over-predict
- CR models deemed to adequately match peak (within a factor of ~2)
- Simulations showed slower decay rate than experiment

# Understanding The New EAST T61 Data



Excellent agreement between new data and simulations.

Results from CR models which were benchmarked to previously reported data, may now provide under-predictions when compared to Test 61.

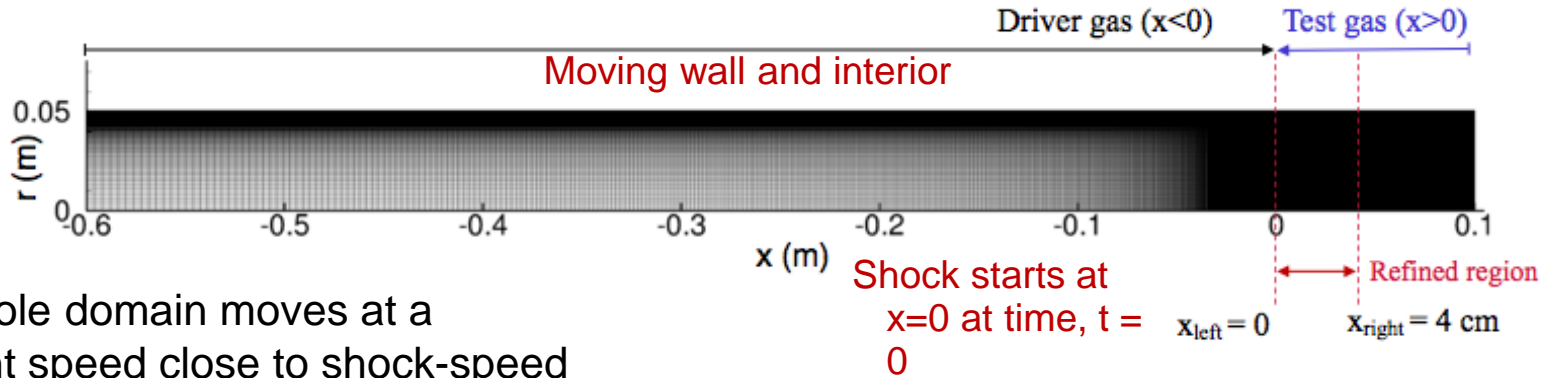
It is recommended that the previously reported Titan entry data be replaced with the current results.



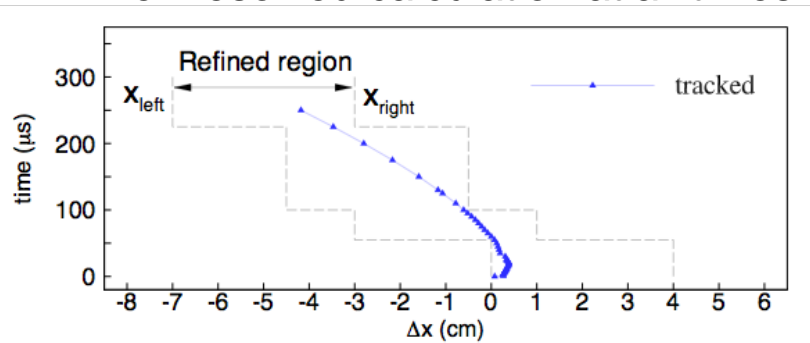
# CFD SIMULATIONS OF EAST

- One of the main uses of EAST data is to extract or infer reaction rates
- This is a difficult task, as many inter-connected reactions occur simultaneously.
- However, in order to better understand the extraction of rates, there are two main avenues we are taking:
  - Doing simplified chemistry tests in EAST, e.g. Pure CO, CO<sub>2</sub>, N<sub>2</sub>
  - Understanding the influence the shock tube has on the state of the shocked test gas
- We need to disconnect the influence of shock tube effects on the test gas non-equilibrium excitation and relaxation from the actual kinetics
- Furthermore, in order to probe and analyze the results from the upcoming expansion testing in EAST, we **NEED** a facility model.
  - There are no analogous CFD tricks to play for expansion (ie blunt body simulations for compression)

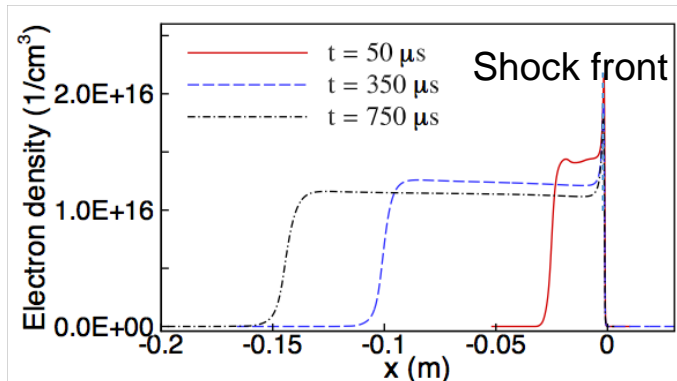
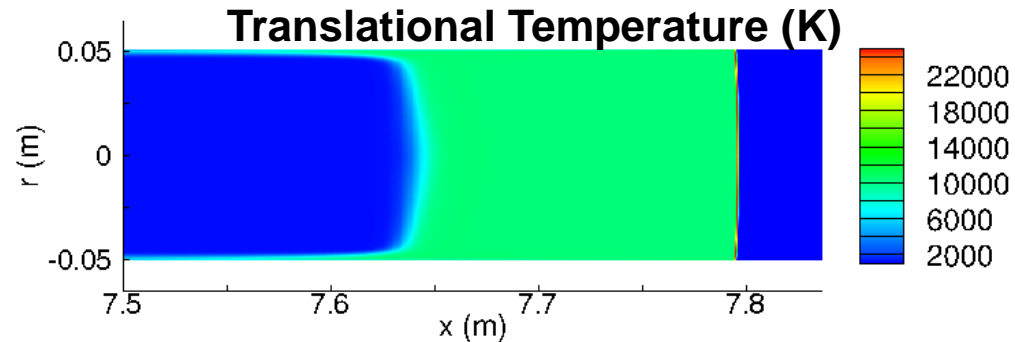
# US3D Simulations of EAST at UMN



- The whole domain moves at a constant speed close to shock-speed
- Shock tracking is used to ensure a well-resolved calculation at all times



- Shock starts at 26.3 km/s (goes to 10.5 km/s within 5  $\mu\text{s}$ )
- After  $t = 50 \mu\text{s}$  (10.4 km/s to 10.1 km/s over a period of 350  $\mu\text{s}$ )

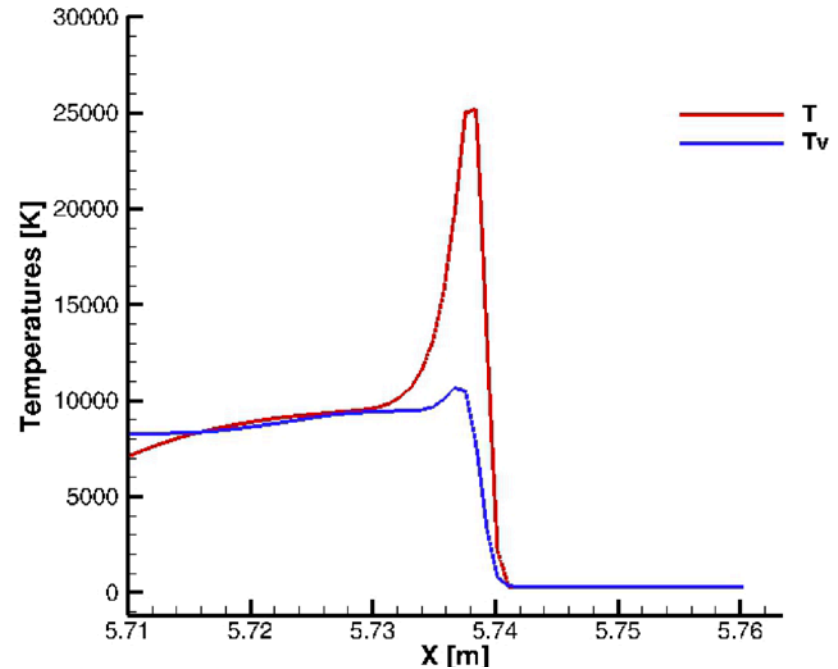


$u_s = 10.00 \text{ km/s}$   
Electron density increasing behind shock, as is seen in EAST

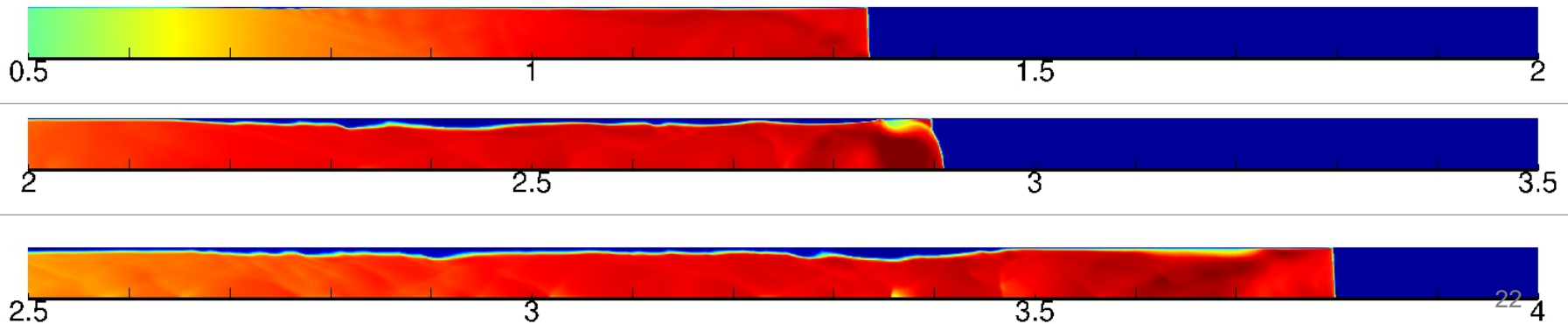
# COOLFluid Simulations of EAST (Khalil Bensassi)



- 2-D axisymmetric finite volume solver, second order in space and time.
  - The US3D simulation was first order in time
- Modeling the entire length of EAST, as opposed to the moving grid method used by US3D



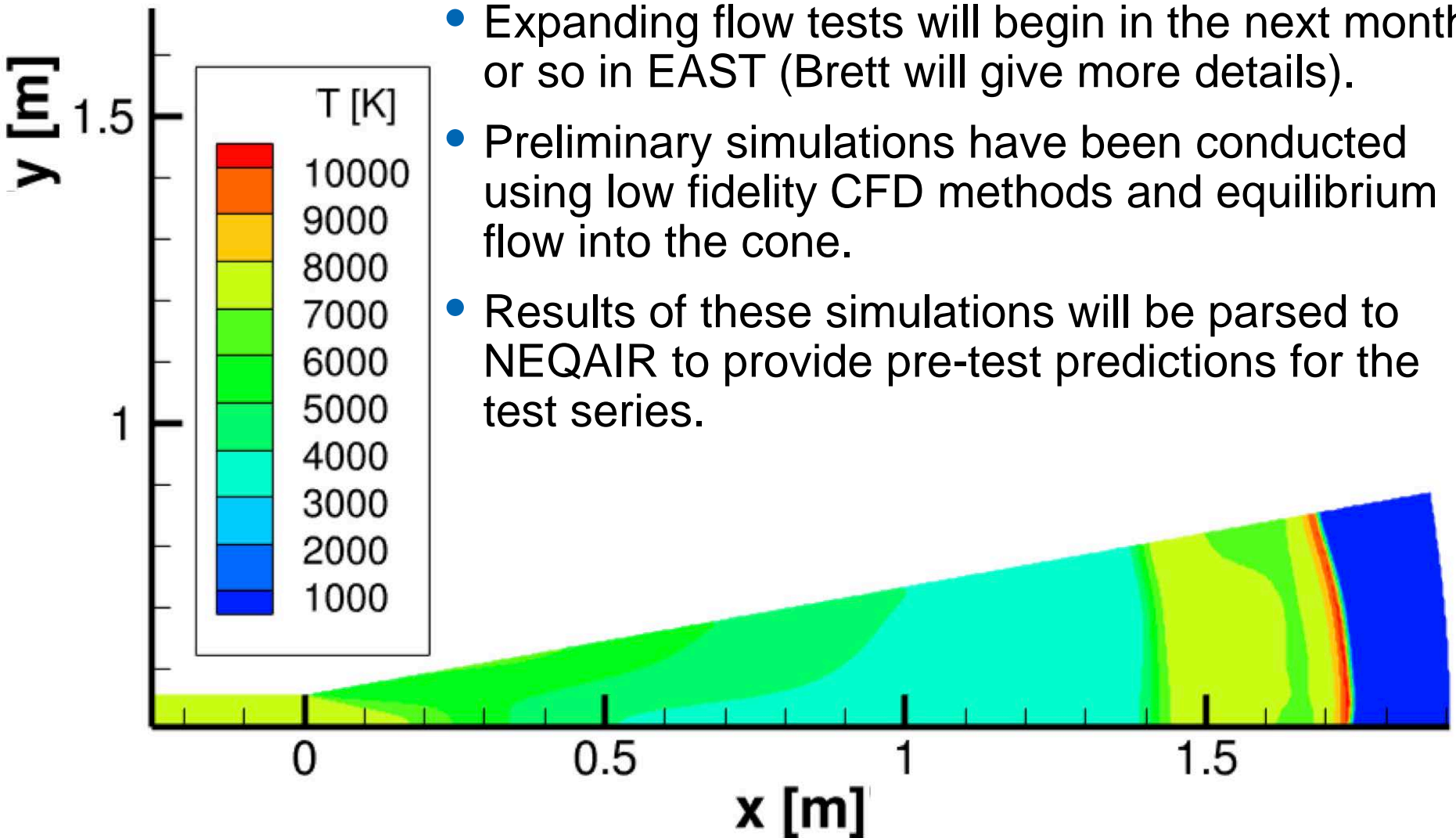
u : 0 2000 4000 6000 8000 10000





# **First Steps to Aftbody Validation Data**

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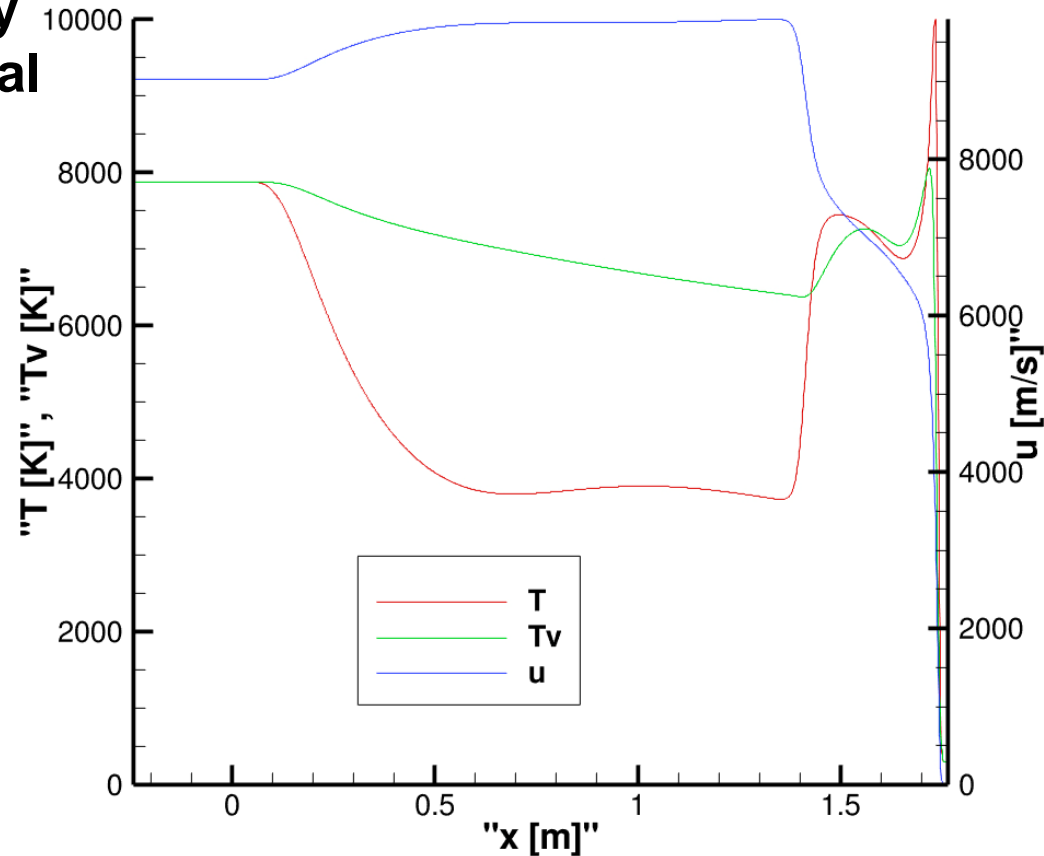




# First Steps to Aftbody Validation Data



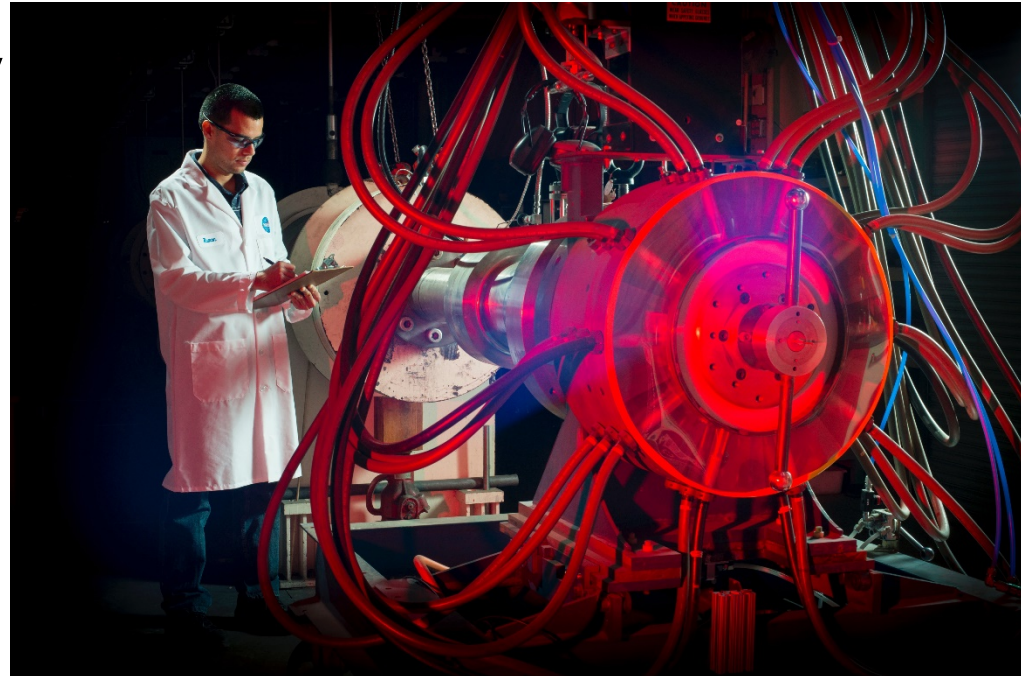
- **Symmetry line plot of velocity and translation and vibrational temperature.**
- **Simulations show a compressive region just behind the shock front.**
- **Large expanding flow region identified beginning 0.6m behind the shock.**



# Future EAST Plans



- What's in the pipeline for future EAST testing?
  - Using carbon/hydrogen based test gases (e.g. acetylene,  $C_2H_2$ ) to mimic ablation species
  - At present, outer planets testing has been performed with just H/He, when in reality there is also some  $CH_4$ 
    - This could drastically effect the formation of ions/electrons
  - More tests in the 24" tube facility with an aim to improve lower speed Earth and Mars tests
    - Focus on lower density regimes.



# Acknowledgements



- EAST Facility Operations
  - Mark McGlaughlin, facility manager
  - Ramon Martinez
  - Rick Ryzinga
- NASA Radiation Group
  - Brett Cruden
  - Chris Johnston
- Project Management
  - Michael Wright/Michael Barnhardt, Entry Systems Modeling

# Conclusions



- EAST Facility is a nation-unique facility capable of achieving flight-similar conditions for entry vehicles
- Analysis with NEQAIR and DPLR, combined with the data from EAST have been used to quantify the nature and magnitude of radiative heating for re-entry problems
  - Multi-purpose crewed vehicle/Orion, MSL, Mars 2020, New Frontiers proposals
  - Informs accuracy of predictive models
  - Allowed reduction of aerothermal margin for radiative heating
- Benchmark datasets from recent EAST Earth re-entry test campaigns have been identified.
  - Data can be found at:
    - <https://data.nasa.gov/docs/datasets/aerothermodynamics/EAST/index.html>

National Aeronautics and  
Space Administration

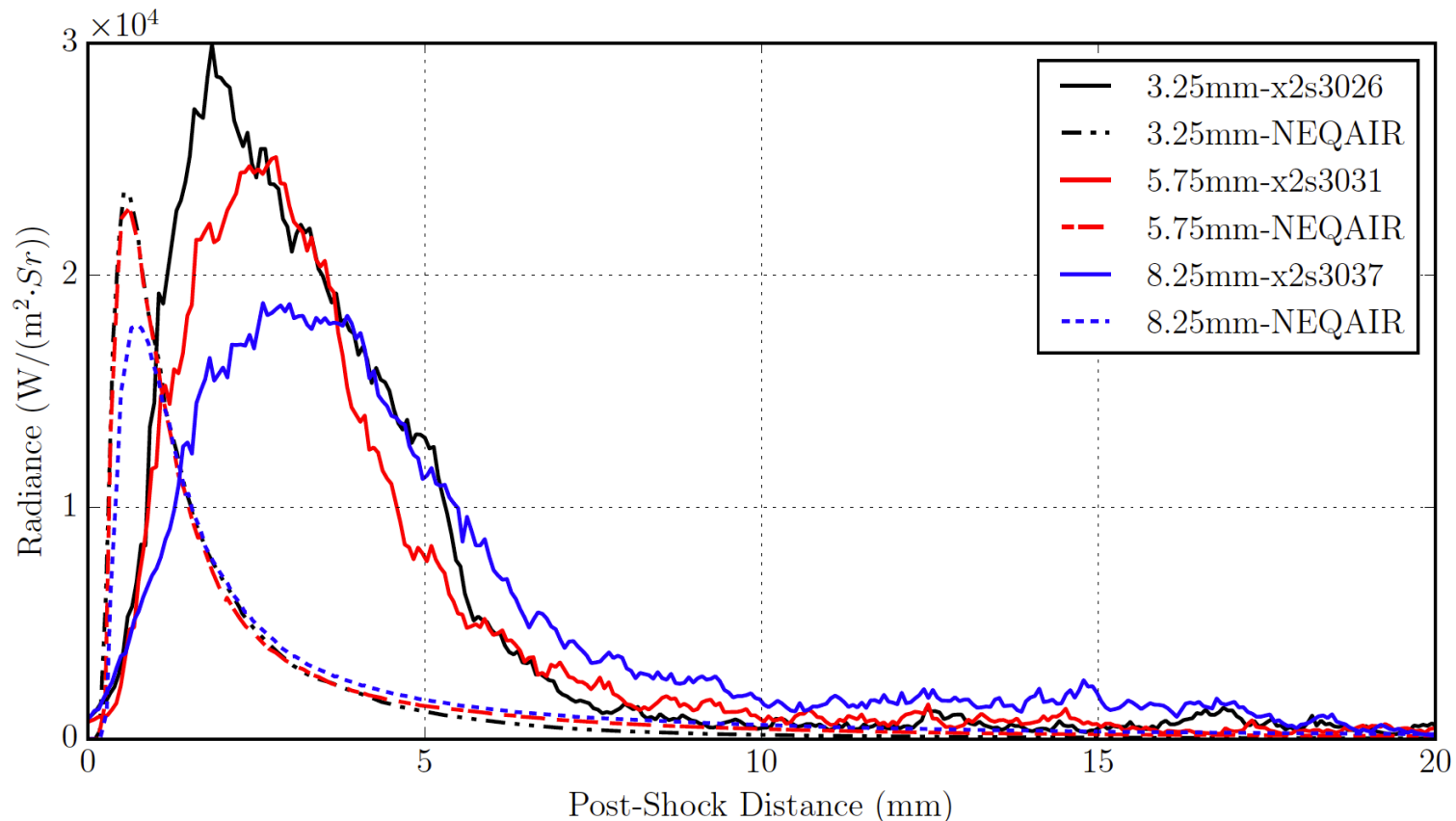


Ames Research Center  
Entry Systems and Technology Division

# First Steps to Aftbody Validation Data (Han Wei)



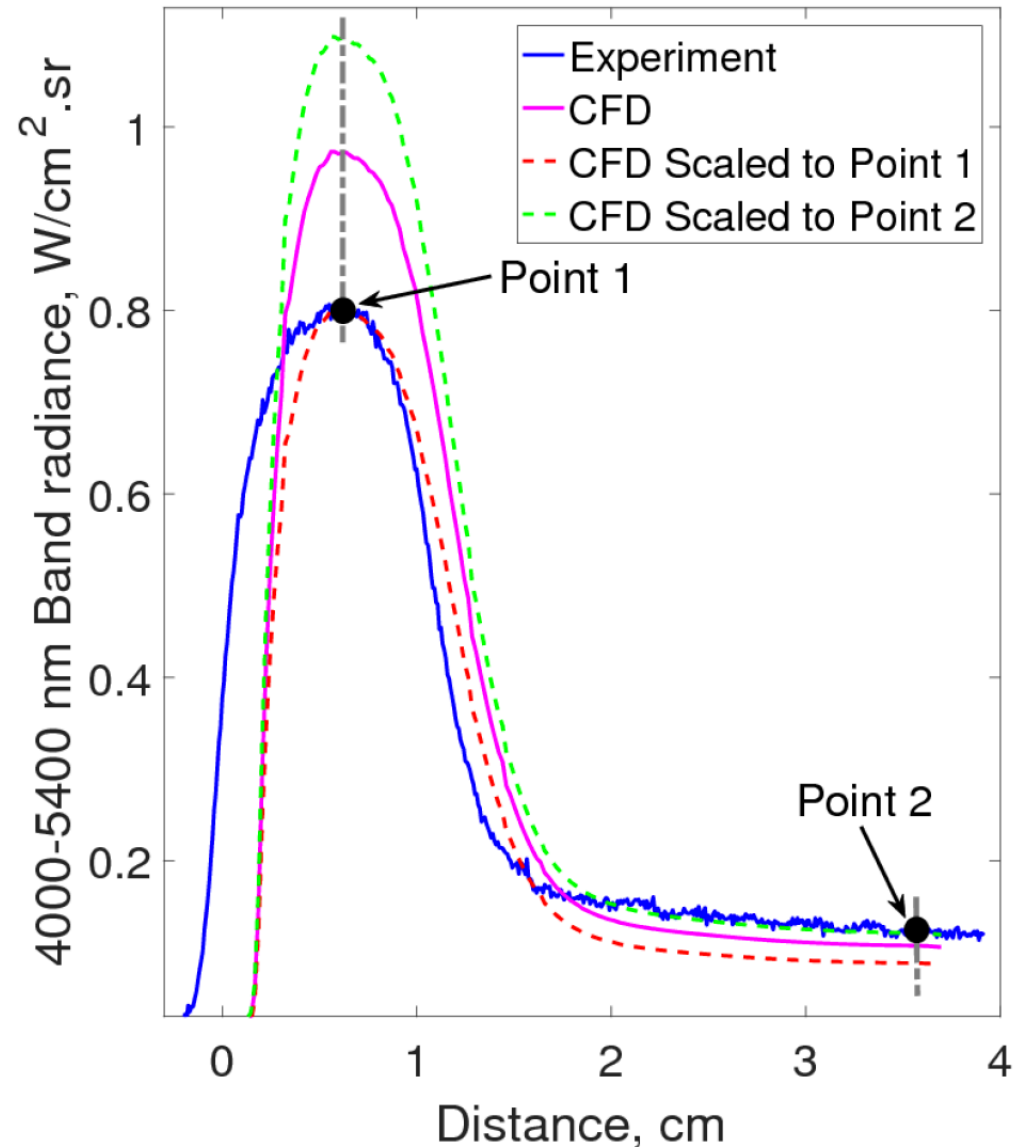
- Tests over a wedge model have been conducted in the X2 facility at the University of Queensland for both Air and CO<sub>2</sub>.
- Plot below shows comparison of simulations with X2 data for an expanding Air flow integrated over the 149 nm N line



# First Steps to Aftbody Validation Data (Sangdi Gu)



- Plot to the right shows a comparison of simulations with X2 for MWIR CO<sub>2</sub>.
- The scale factors required across conditions tested vary between approximately 0.8 and 3.
- Questions remain with regards to the accuracy of the quoted freestream conditions.
  - The test gas goes through an unsteady expansion then through a nozzle before arriving at the wedge.





- Large number of EAST experiments
  - Great for statistical analysis, but problematic for identifying representative shots for detailed analysis
  - Provide more accessible data for future code validations and facility-to-facility comparisons
- Benchmark experiments are the ones in closest agreement to line of best fit and with the best experimental characteristics
- Data is reported in different formats for analysis, and all the information needed to simulate EAST is provided
- Data can be found at:
  - <https://data.nasa.gov/docs/datasets/aerothermodynamics/EAST/index.html>



# Recent Testing – CO<sub>2</sub>/Ar

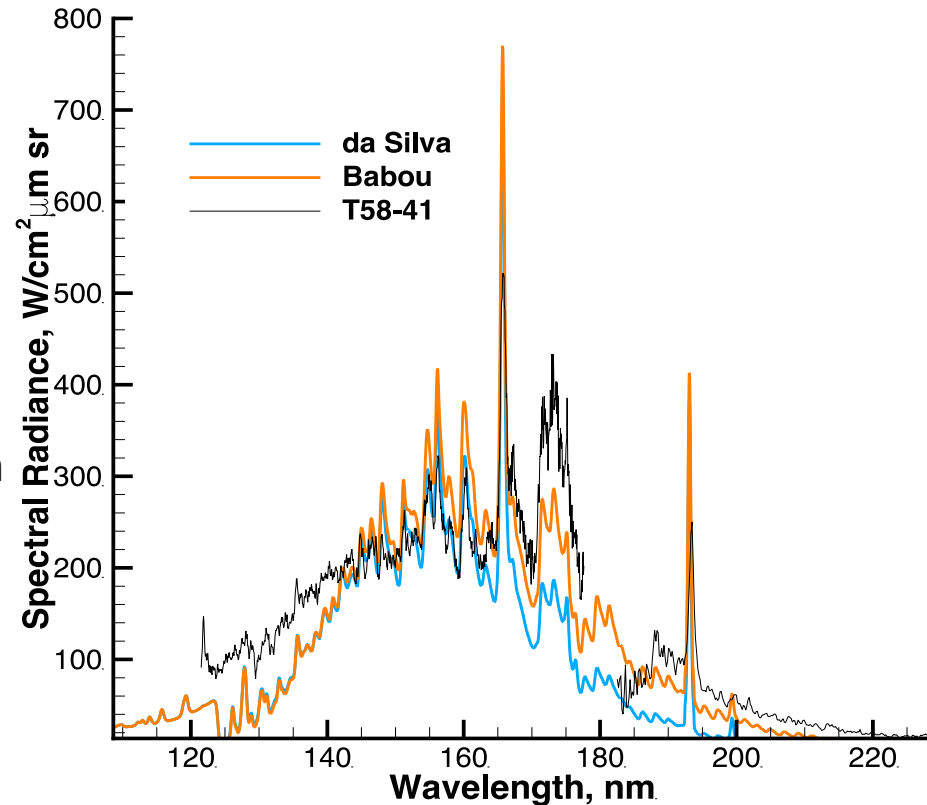


- Particular interest for Mars and Venus entries

- Several EAST tests have helped develop/confirm equilibrium radiation models and CO<sub>2</sub> reaction kinetics.

- However, results remain somewhat ambiguous

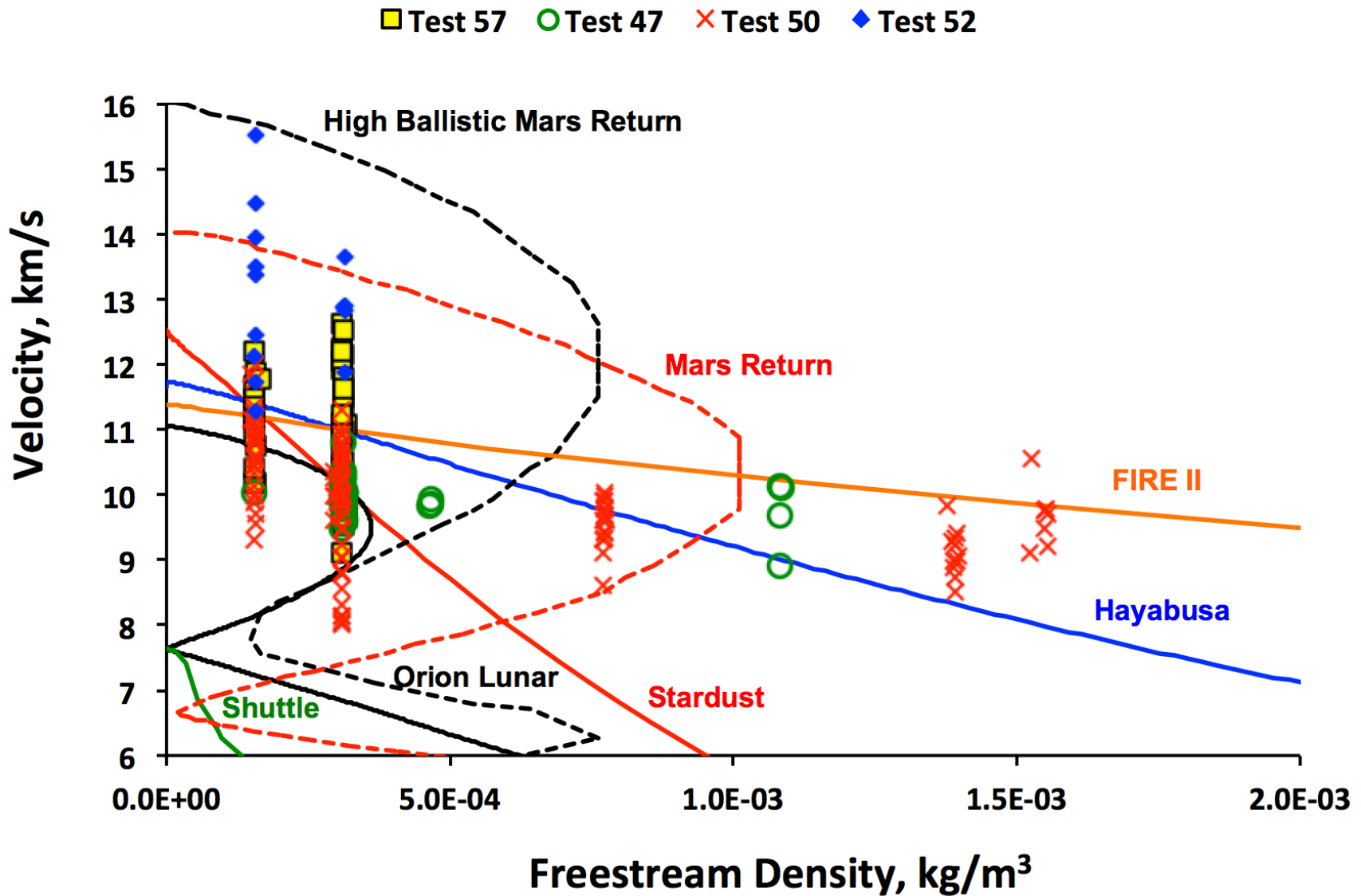
- e.g. HARA and NEQAIR use two distinct CO 4<sup>th</sup> Positive models are used
- Under different conditions or assumption one is observed to agree better than the other
- The choice of spectroscopic database influences inferring reaction rates from EAST data



- Hybrid spectral database might provide better solution

- Possible test series to repeat with TDLAS and/or with 24" tube

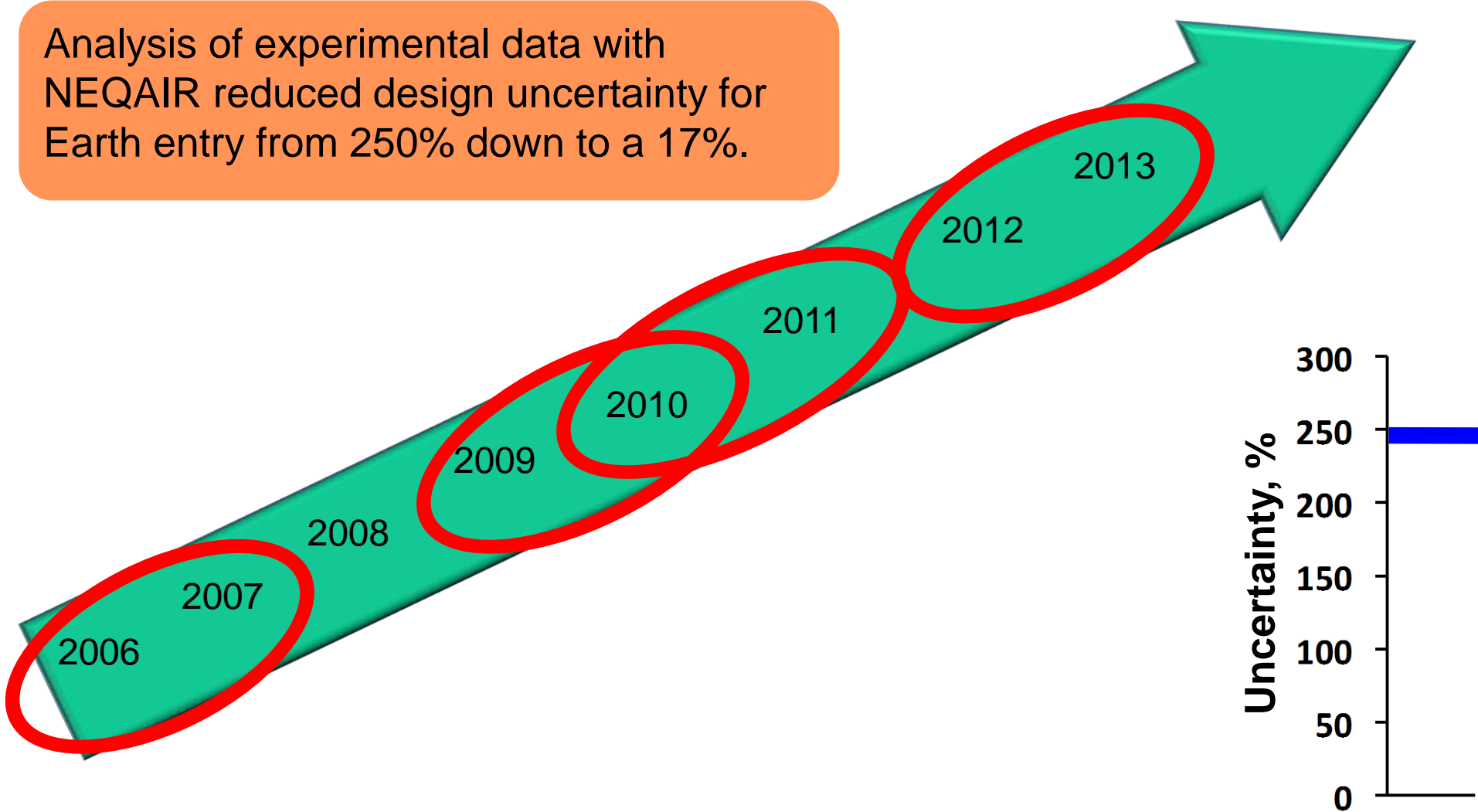
# Recent EAST Earth Testing Conditions



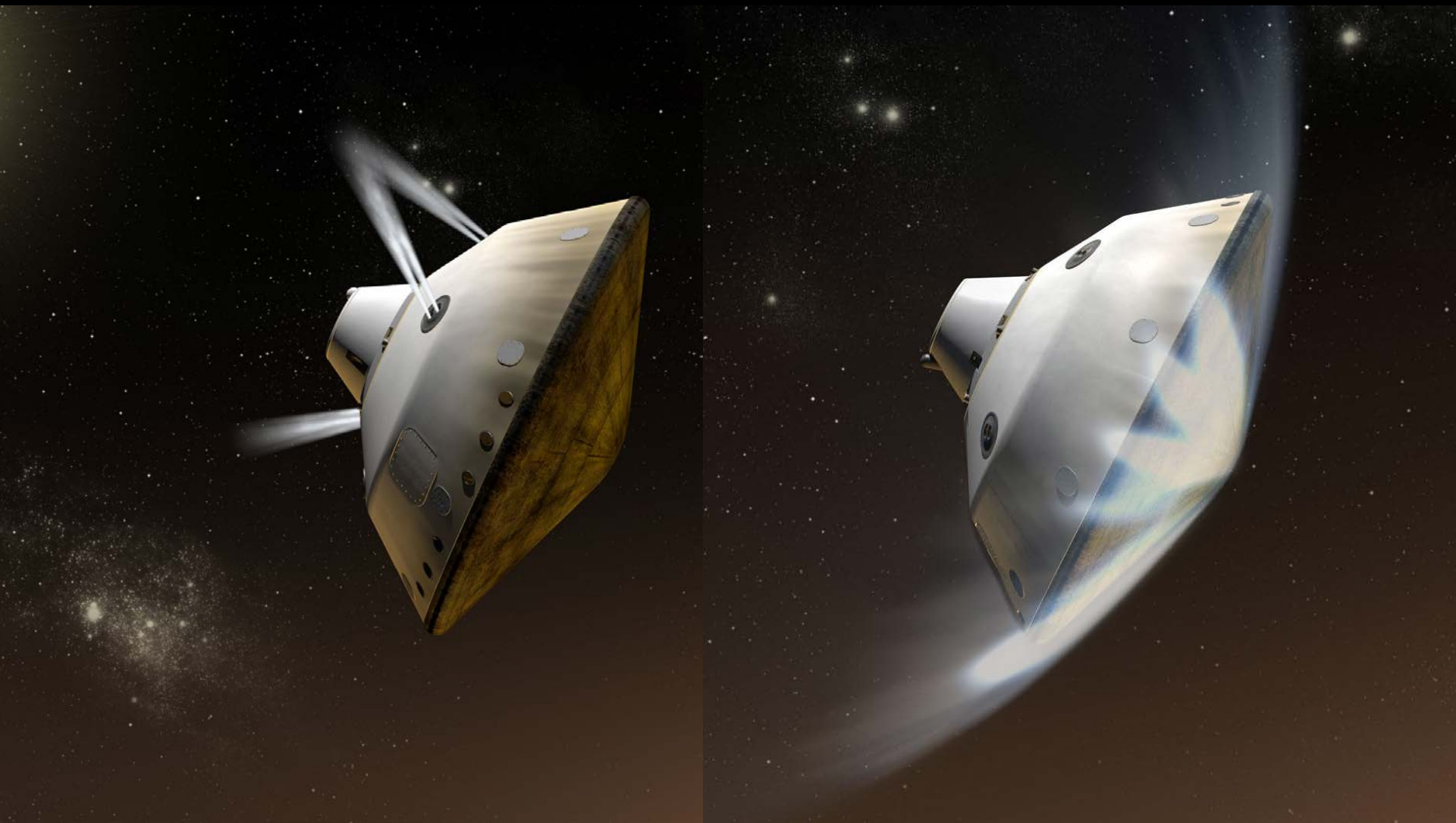
# Improvement of Uncertainty for Earth Equilibrium Radiation



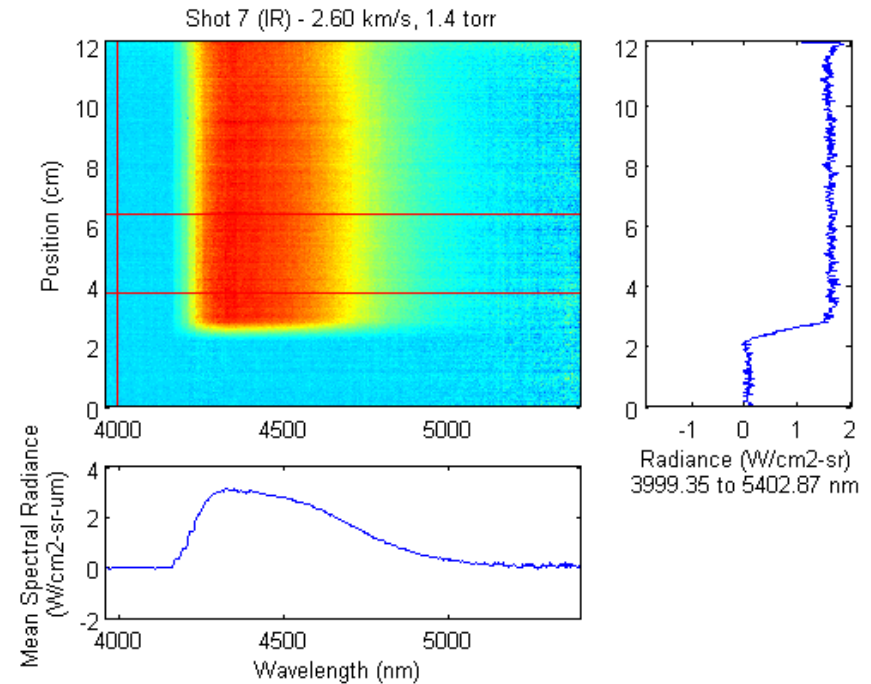
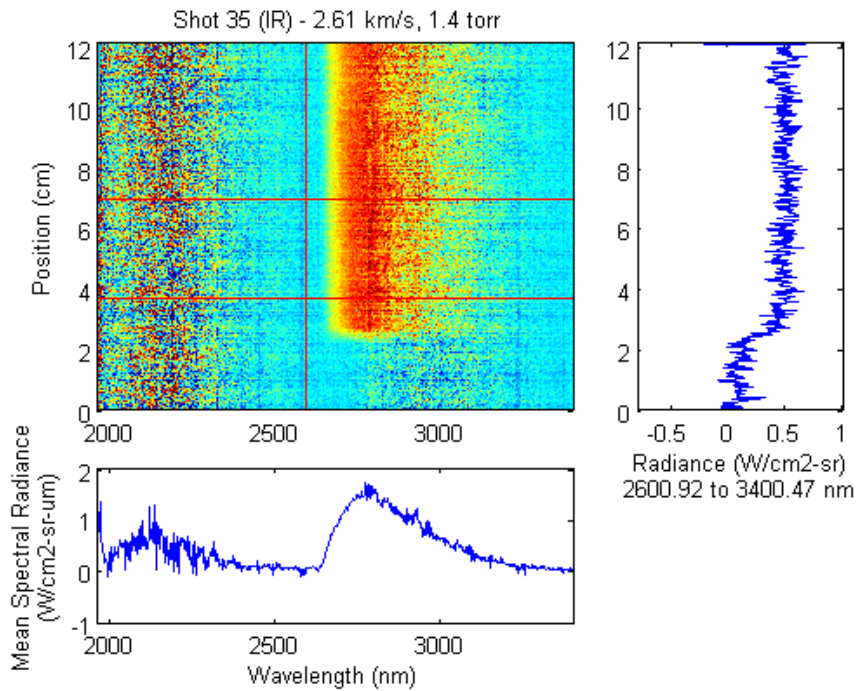
Analysis of experimental data with NEQAIR reduced design uncertainty for Earth entry from 250% down to a 17%.



# Radiative Heating for Mars Exploration

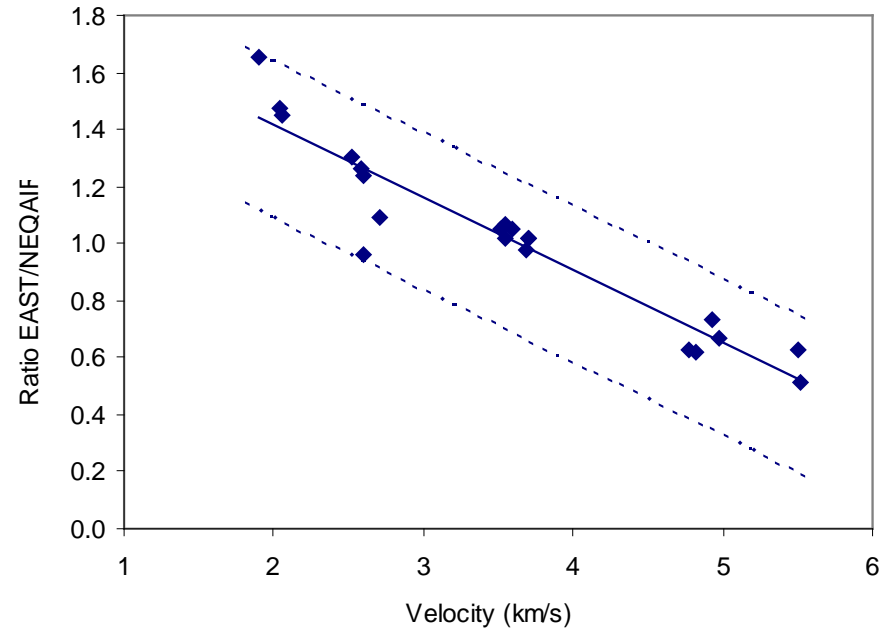
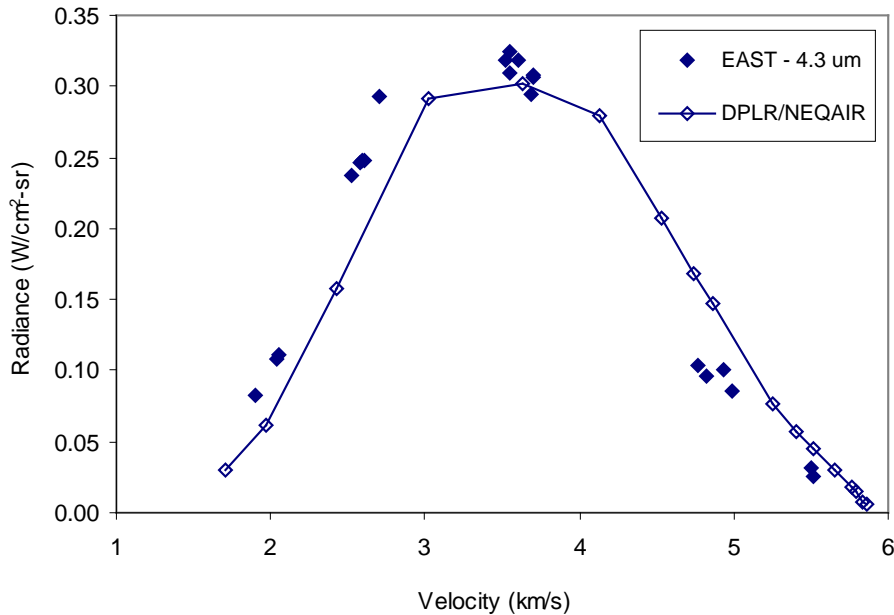


# EAST Experiments – Later Trajectory

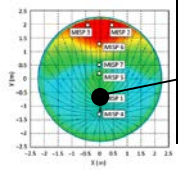


- Condition of 2.6 km/s and 1.4 Torr corresponds to  $t = 95.2$ s point of MSL Entry
- In this condition
  - No non-equilibrium zone observed
  - No radiation observed in UV/VUV. Visible is weak
  - Both  $2.7 \mu\text{m}$  and  $4.7 \mu\text{m}$  bands of  $\text{CO}_2$  are observed

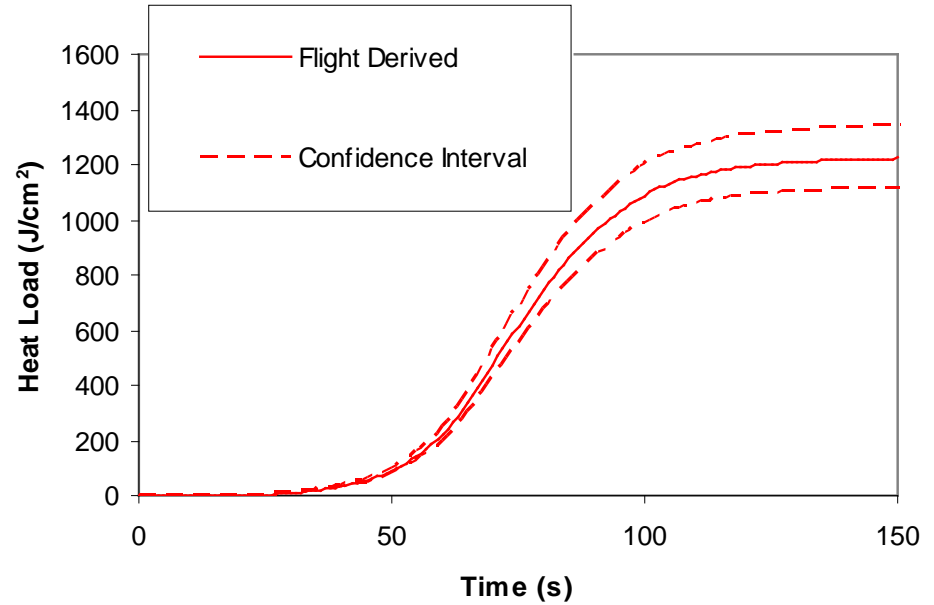
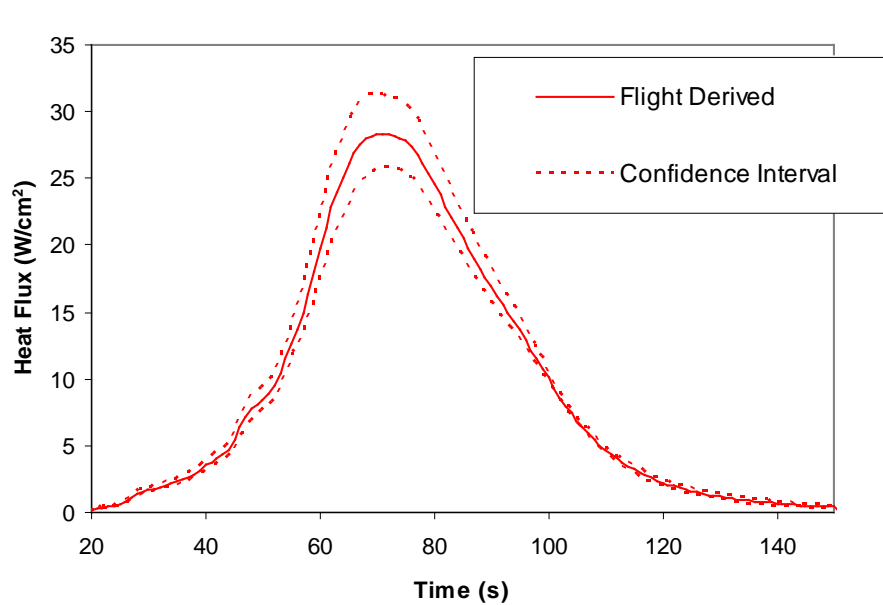
# Validation – 4.3 $\mu\text{m}$



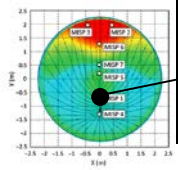
- The 4.3  $\mu\text{m}$  band is matched, but appears shifted by  $\sim 0.2$  km/s
  - This shift is larger than facility velocity uncertainties
  - We speculate that it may be related to uncertainties in the chemical kinetic model
- Corresponding mean uncertainty:
  - +50% at low velocity, -50% at high velocity
  - Almost zero at peak radiation



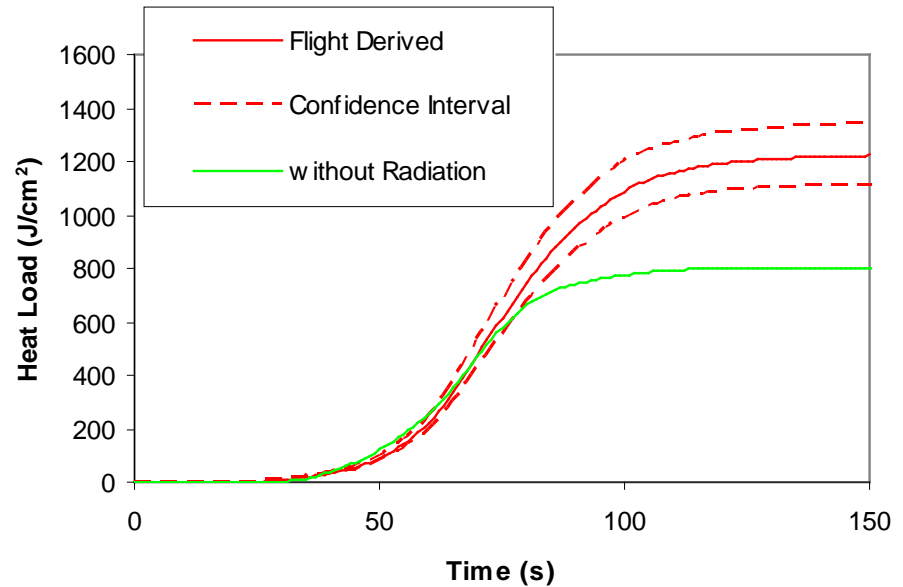
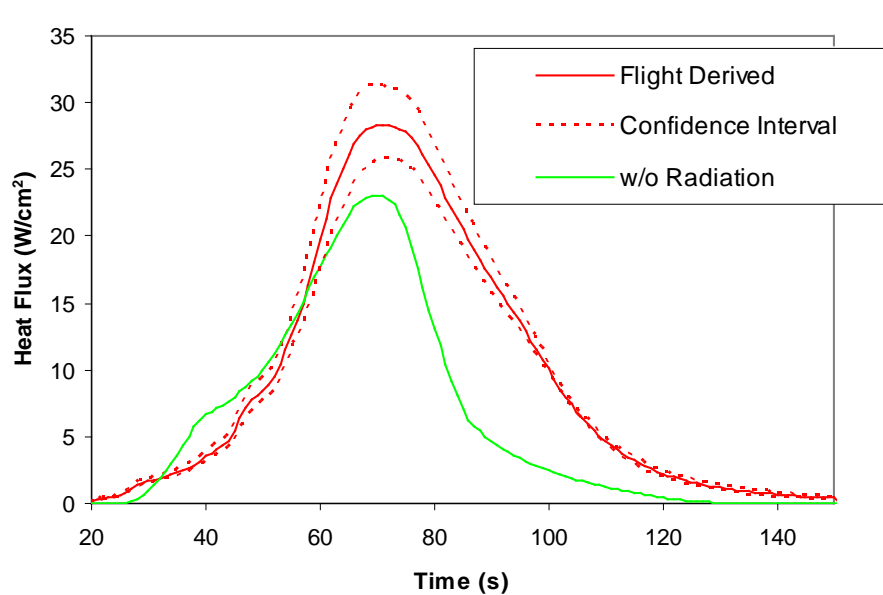
# Flight Derived Heating



- Confidence intervals are based on using a Monte Carlo analysis
- Heat load can be more relevant for heat shield sizing

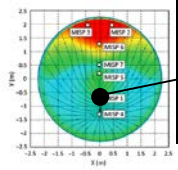


# Comparison to Flight Data

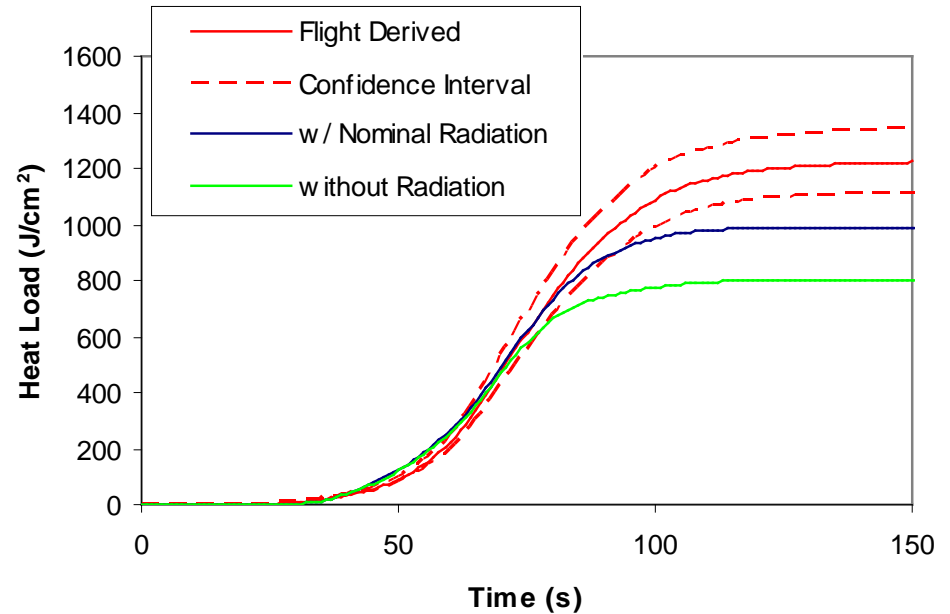
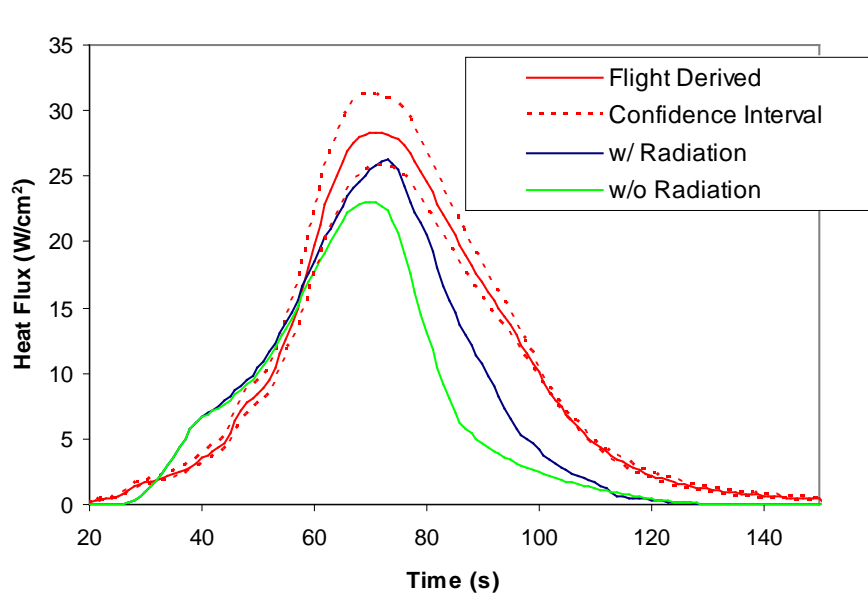


- Confidence intervals are based on using a Monte Carlo analysis
- Heat load can be more relevant for heat shield sizing
- Using convection only, the heat flux is under-predicted significantly
- Heat load is under-predicted by 400 J/cm<sup>2</sup>, or 33%





# Impact of Radiation



- Including radiation calculated by NEQAIR reduces heat flux discrepancy by approximately half
  - Heat load under-prediction reduced to 19%
- Peak heat flux is just within confidence interval at peak heating

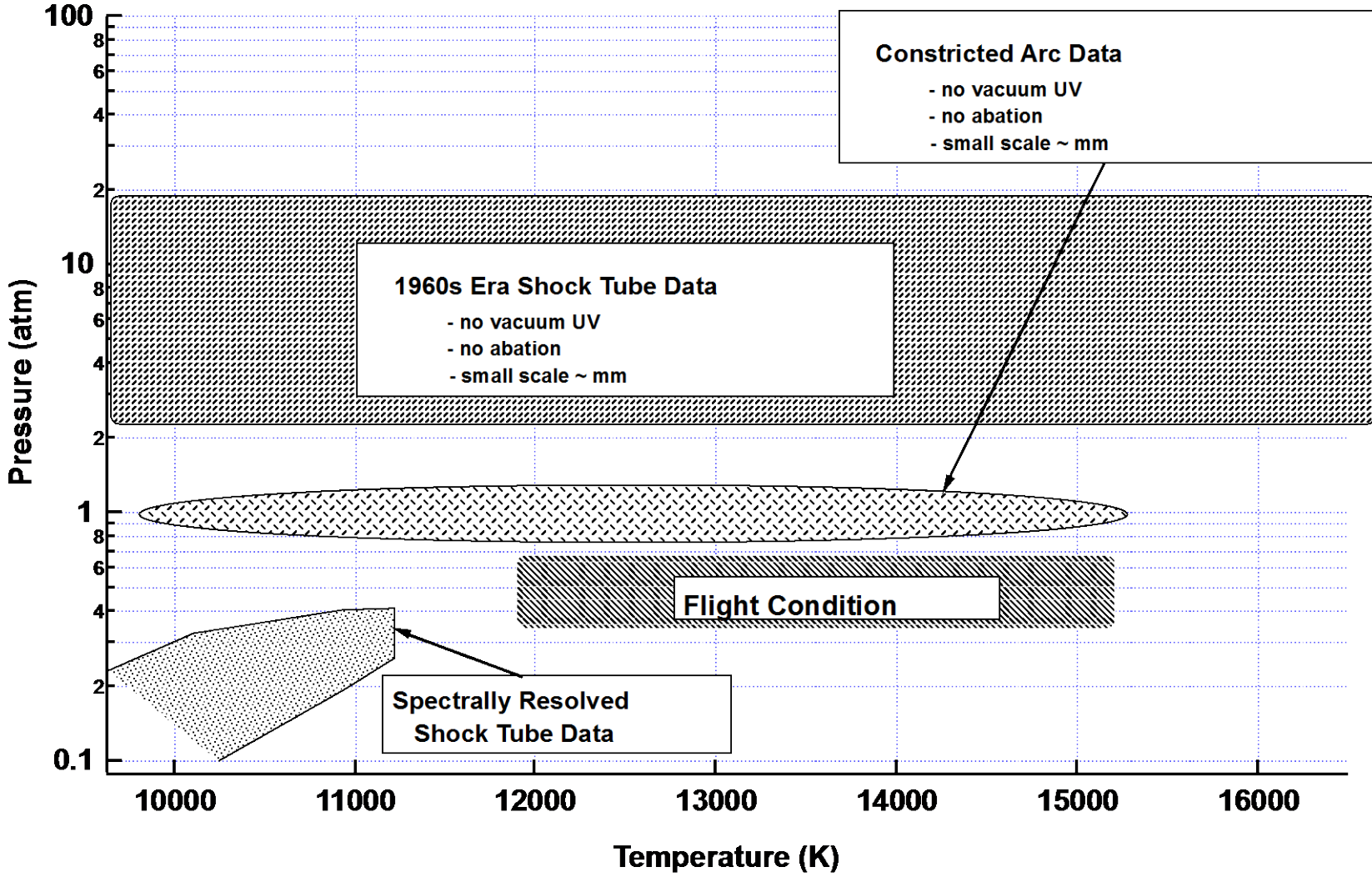


# High Speed Earth Return

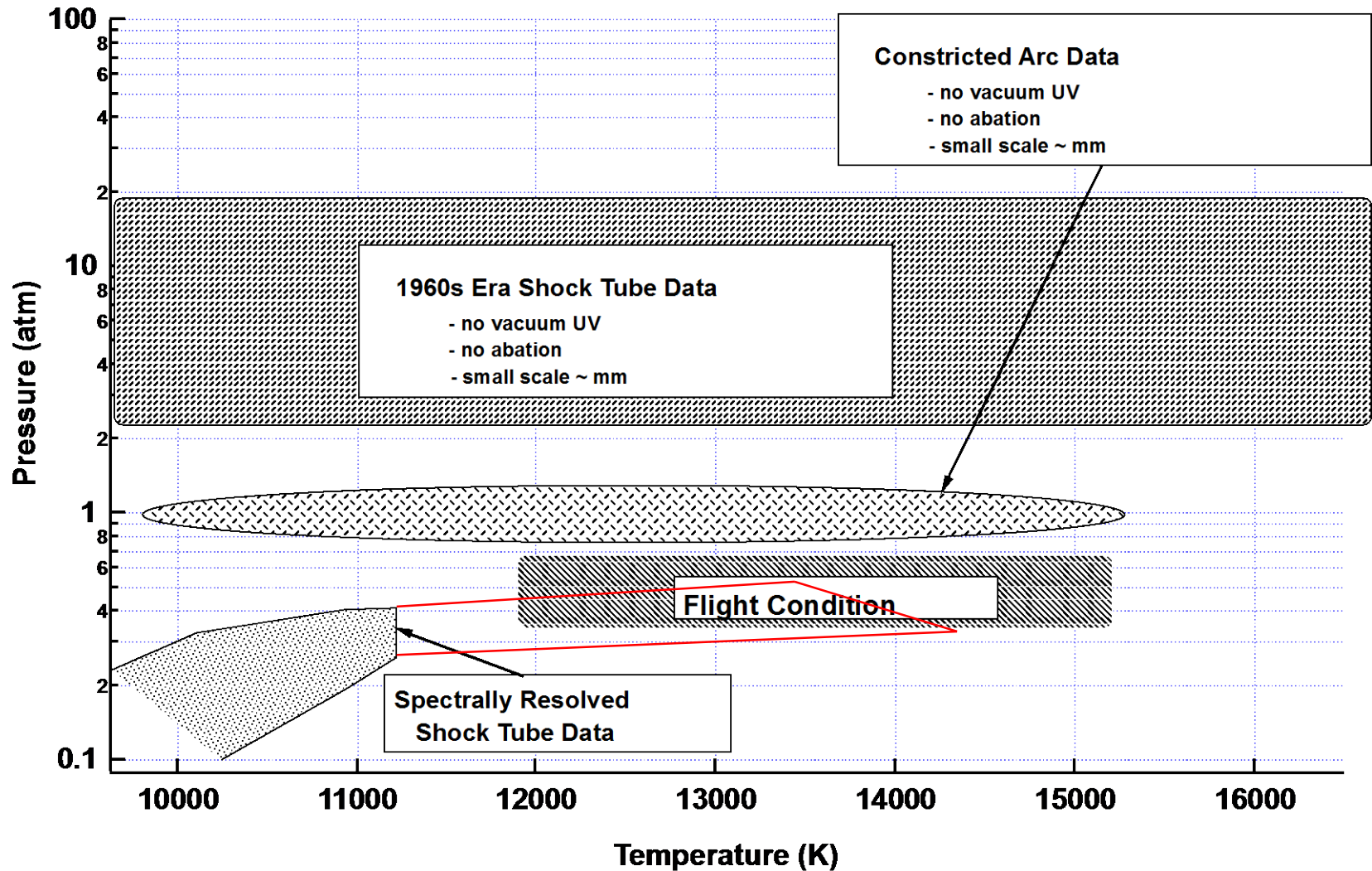
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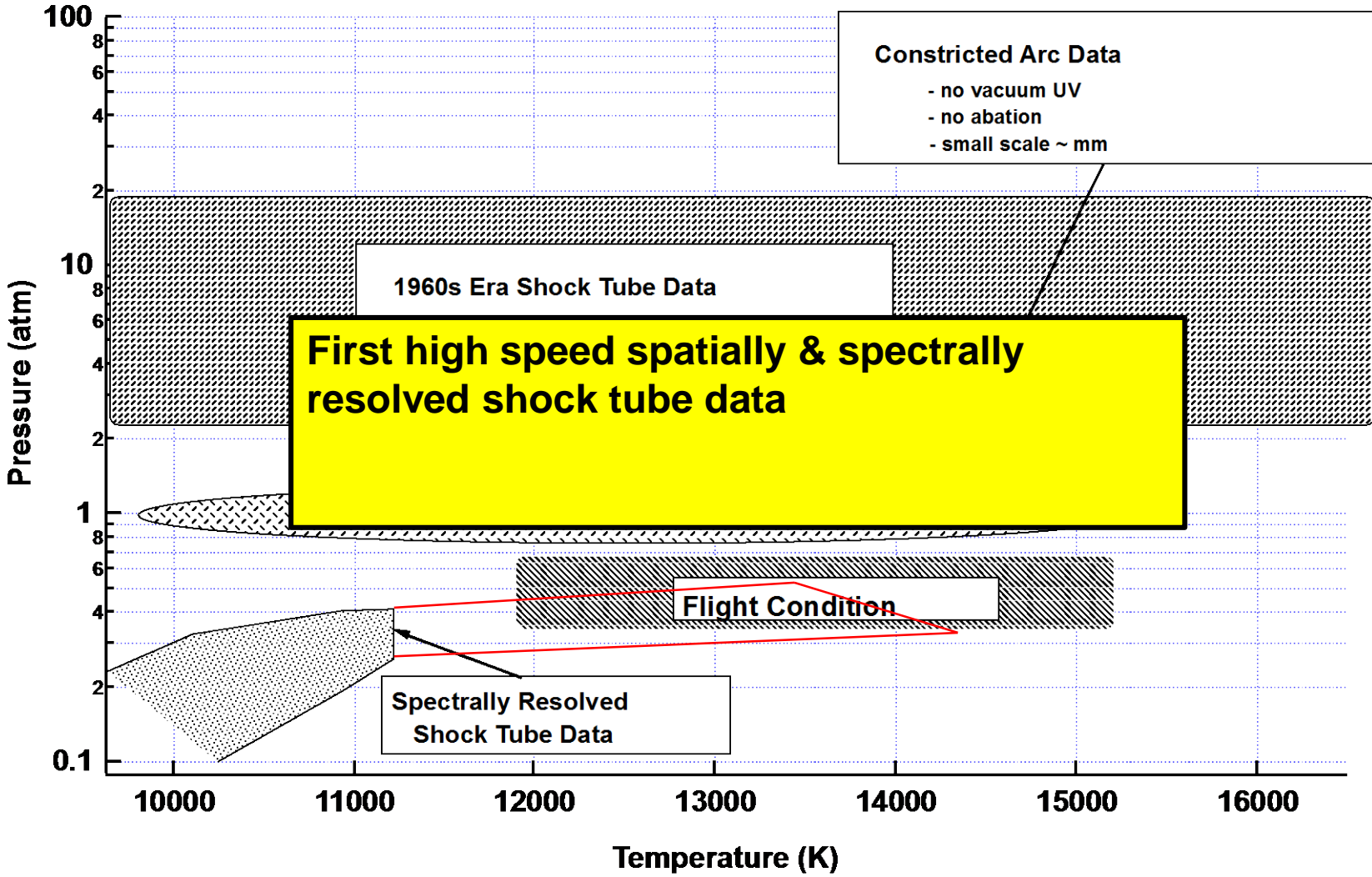
# High Speed Earth Entry Data



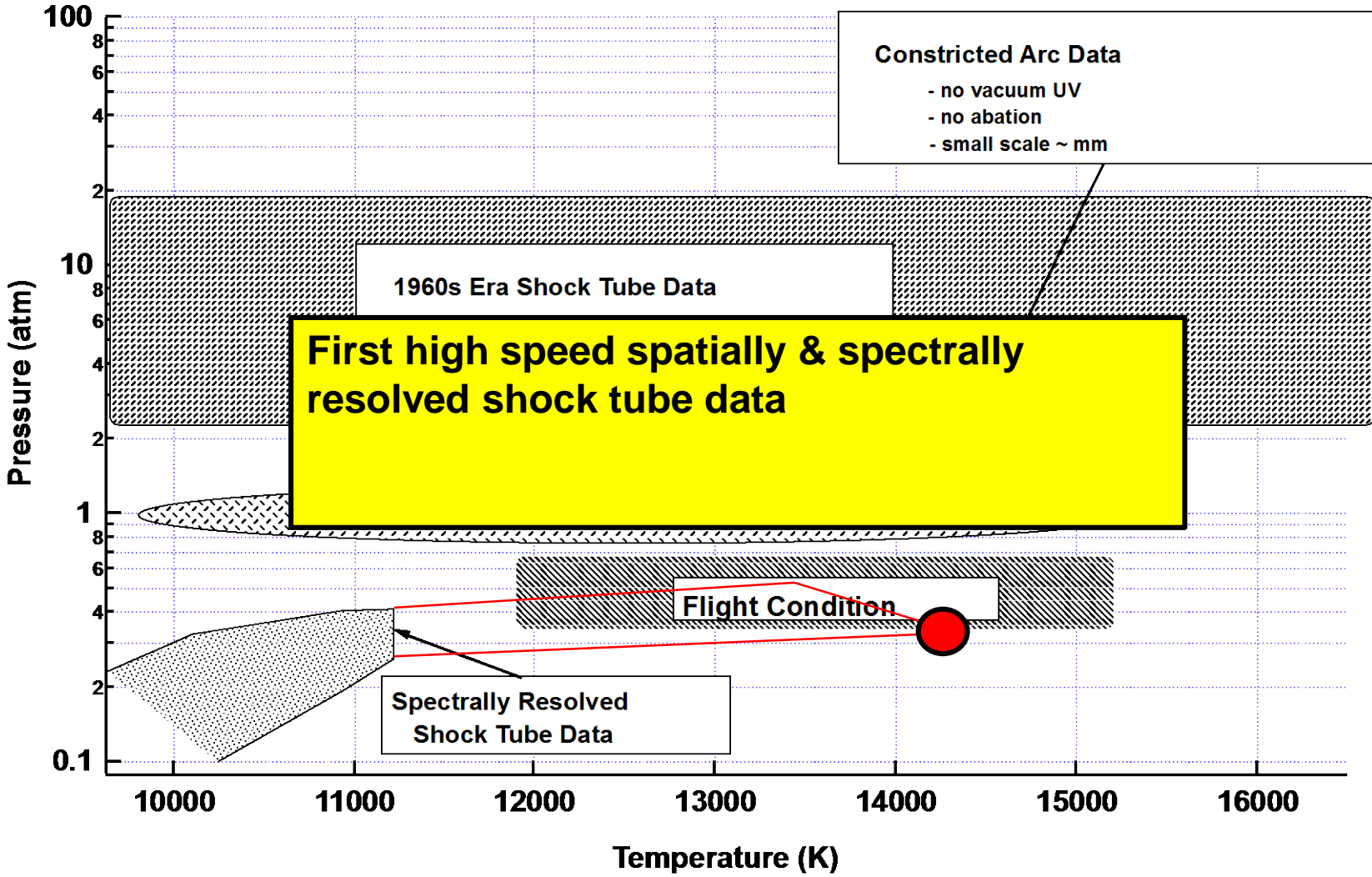
# High Speed Earth Entry Data



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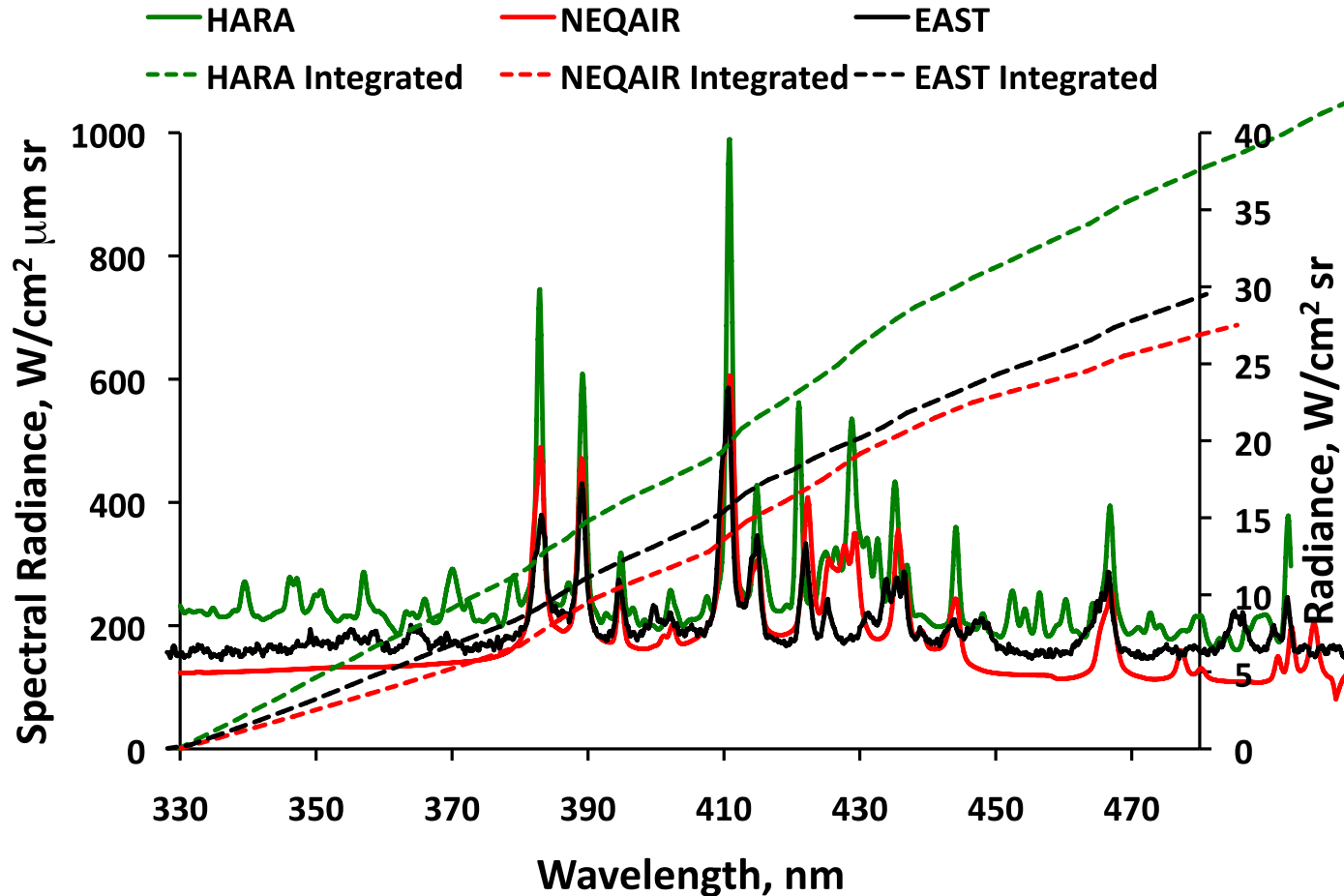
# High Speed Earth Entry Data



# Spectral Comparison 15.5 km/s: UV/Vis



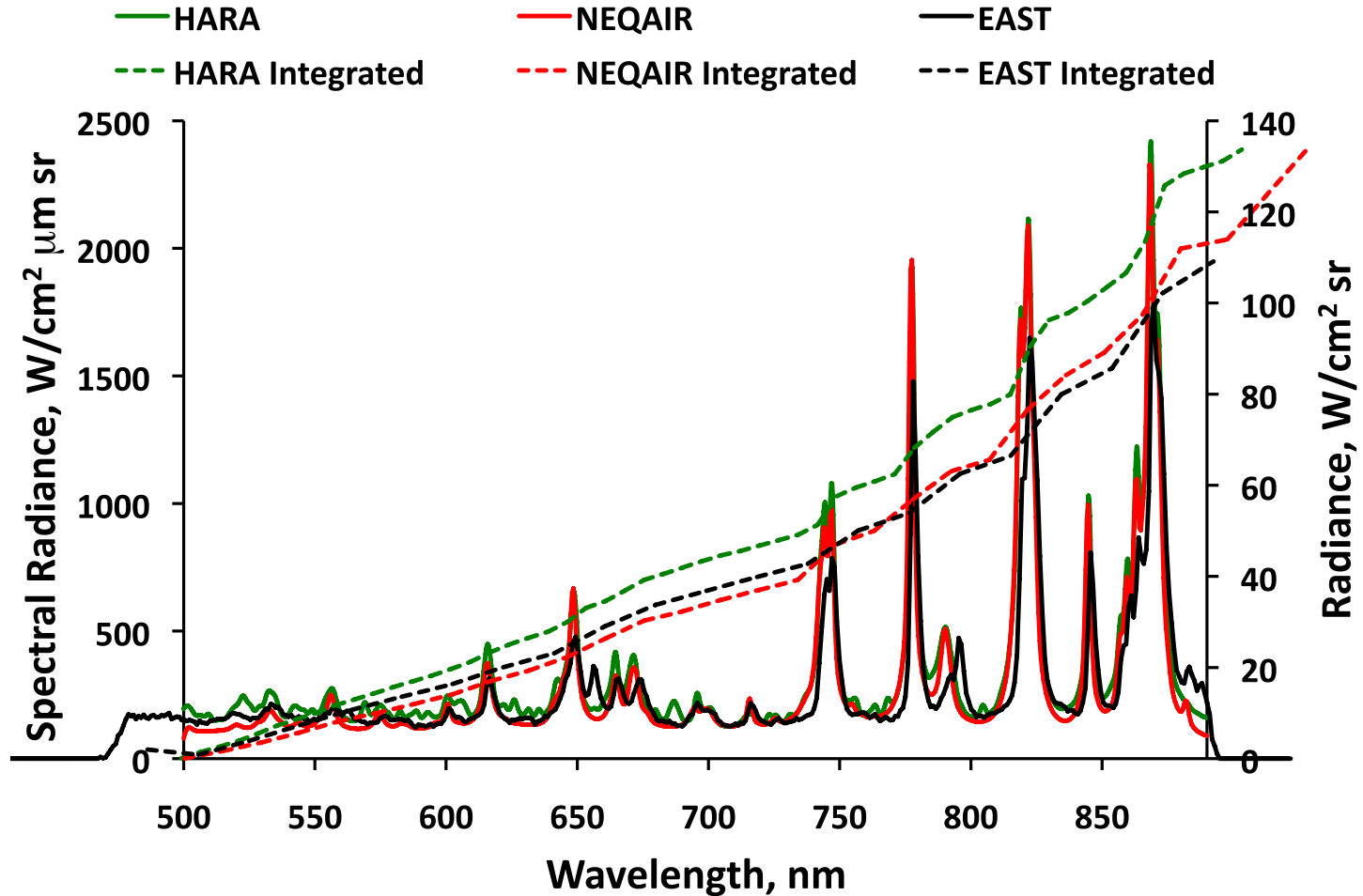
Good agreement for both codes in UV/Vis within 30%



# Spectral Comparison 15.5 km/s: Vis/NIR

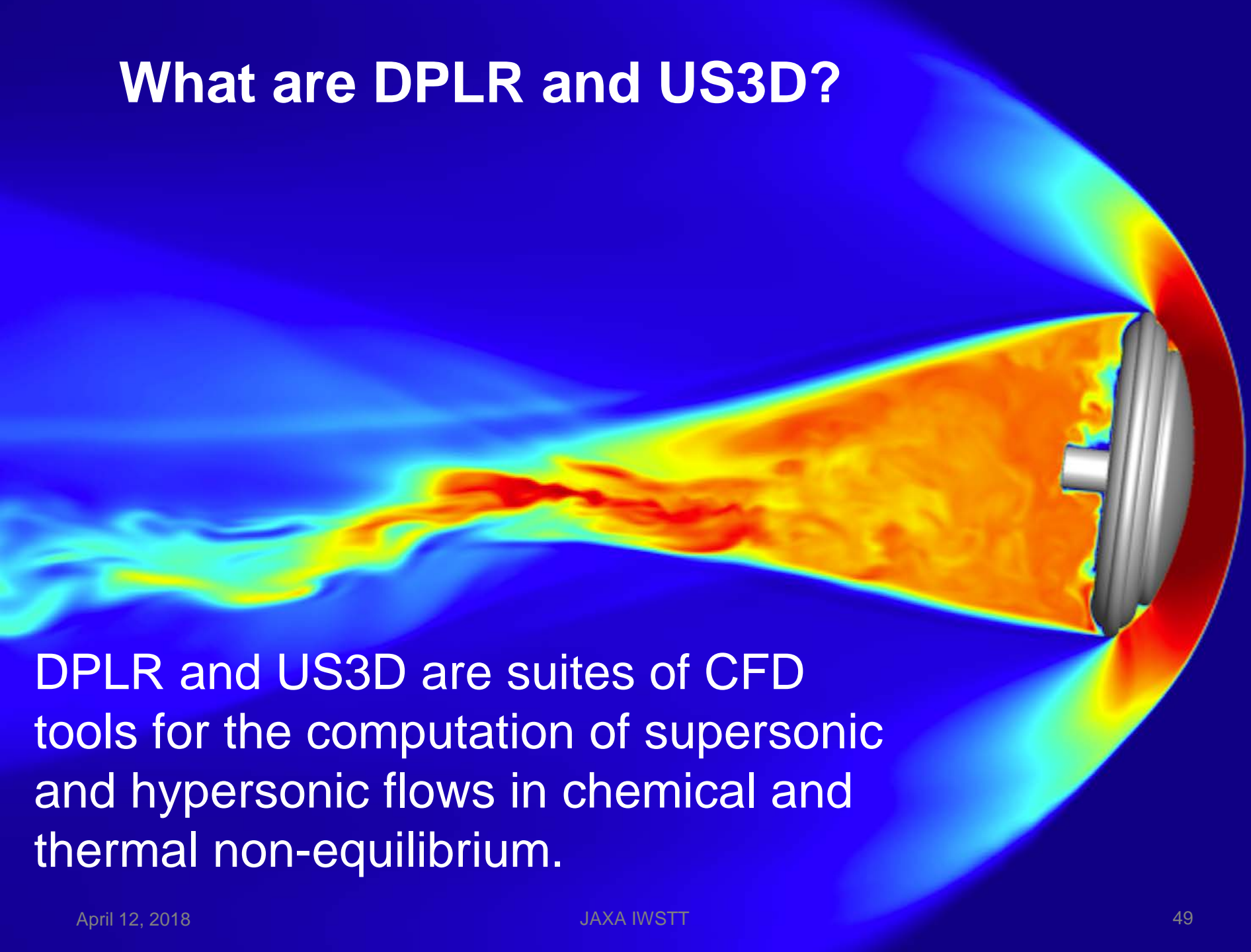


Excellent agreement for both codes in Vis/NIR within 20%





# What are DPLR and US3D?



DPLR and US3D are suites of CFD tools for the computation of supersonic and hypersonic flows in chemical and thermal non-equilibrium.

# What is NEQAIR?

A satellite is shown in space, oriented horizontally. It has a long, thin antenna extending to the left. The main body of the satellite is covered in a gold thermal blanket. A large, white, circular antenna is visible on the left side of the satellite. The background is a dark blue space filled with stars, and a large, orange, spherical object is partially visible on the right side.

NEQAIR was NASA's first radiative heating code and has been the go-to-tool for 30 years

NEQAIR computes spectra and radiative heating based on a given flow-field