Science in the HED regime on NNSA Facilities

The way it worked

NNSA facilities have been used to perform HEDP-related scientific research

- Fundamental programmatic research of material properties
  - **Opacity** (absorption of radiation)
  - **Equation of State** (high-pressure shocks)

Examples are from Nova high-energy laser

Word about measuring material properties "exacting"

- For quantitative measurements one must:
  - Accurately measure the property of interest - *obviously*
  - Precisely measure the state of the system
    - Temperatures, densities, state of equilibrium, radiation field

What was the perspective for science on NNSA facilities?

- Programmatic needs
- Broad-based effort within the program
- Interaction with wider scientific community to promote the effort
- Feedback to program leads to further improved capability

Opacity
interaction of radiation with matter

- Opacity, K_ν, is central to radiation-hydrodynamic simulations
  - Simulations provide guidance when experiments are:
    - Difficult and expensive (Nova, Omega)
    - Difficult and more expensive (next generation facilities)
    - Impossible (astrophysics / NTS)
- Measurements of K_ν in equilibrium are rare
  - Generating equilibrium, LTE, conditions difficult

Opacity: flow of the effort

Experiment

- Started effort to measure K_ν at >100 eV in LTE
- Redesigned experiments to create LTE at 50 eV
- Experimental confirmation of OPAL prediction for Fe
- Measured Ge, Nb opacity in higher Z experiments

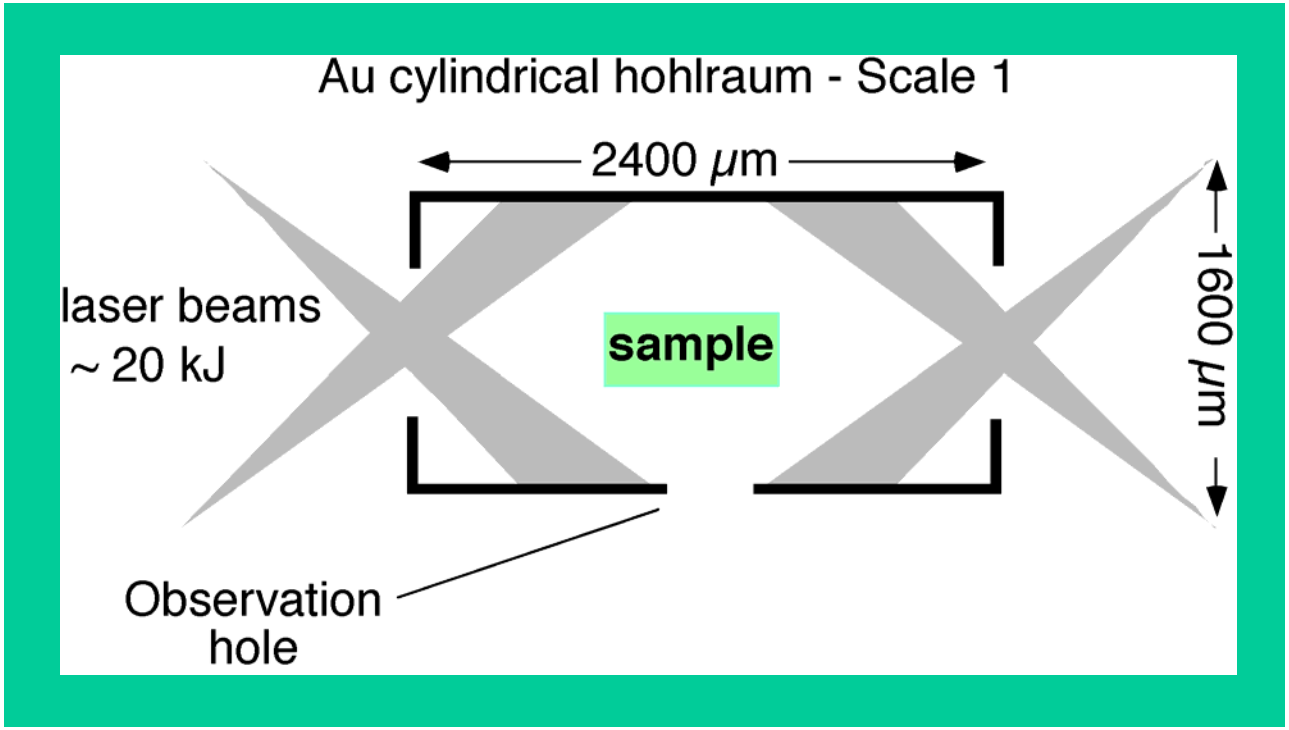
Theory

- Started low-Z opacity code development (OPAL)
- OPAL used to verify the 50 eV environment
- OPAL predicted substantial changes needed for stellar K_ν
- OPAL methodology used for higher Z code, TOPAZ

Over 15 years work provided new experimental and theoretical capability

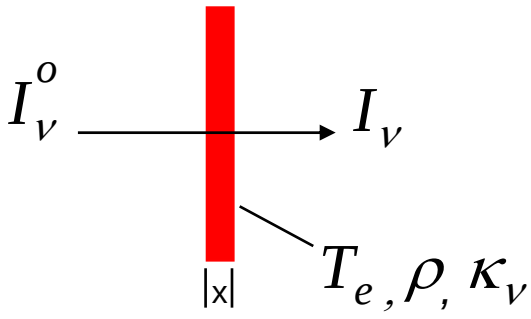
“Laboratory” developed from Inertial Fusion targets: hohlraum (HO)

- Laser irradiated inside of Au HO
- Au plasma emits x-ray
- X-ray irradiate sample

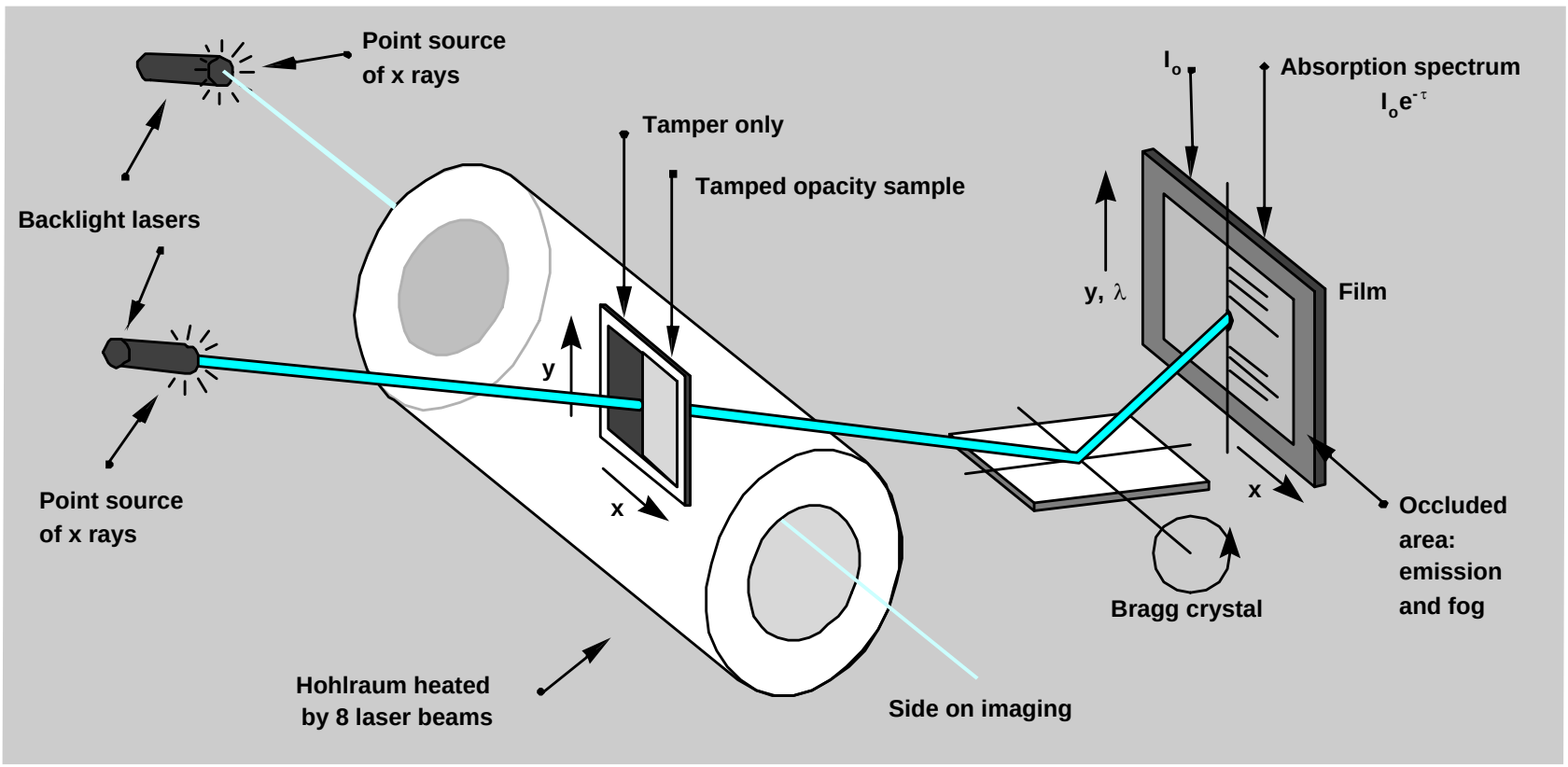


- **Sample was not in LTE due to direct view of hot spots**

Triple-sized holhraum was developed as the LTE laboratory at ~ 60 eV

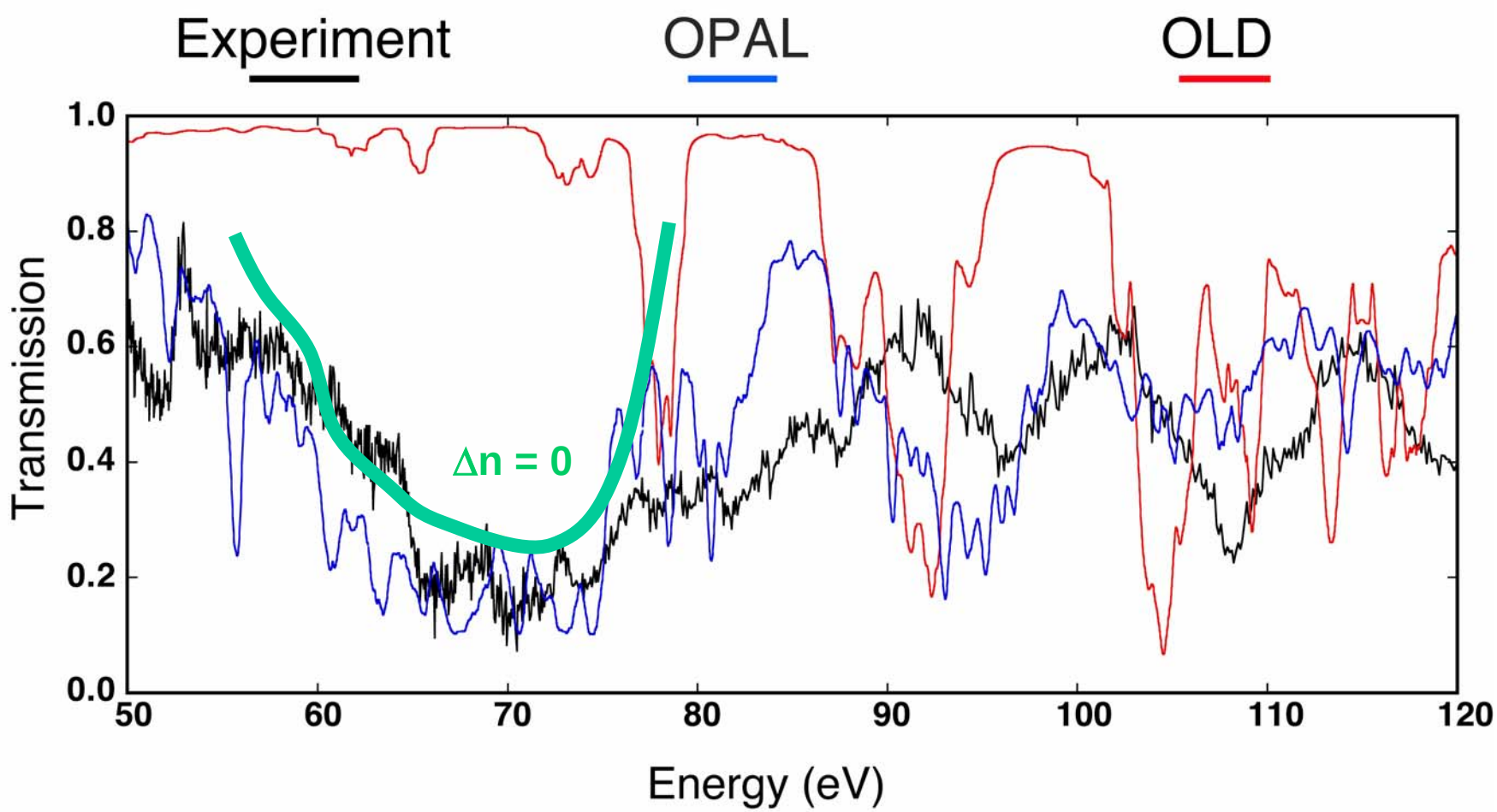


$$I_\nu = I_\nu^o \, e^{-\rho x \mathrm{K}_\nu(\rho, T_e)}$$



Experiment confirmed OPAL opacity code:
Astrophysical issues then resolved using OPAL

- Iron absorption at 20 eV and 0.01 g/cm^3



- **Flow of radiation in stars can be blocked by opacity of Δn = 0**

K_ν effort benefits for NNSA program and the broader community

- Developed technique creating LTE environments
- Developed a low-Z opacity code (OPAL)
  - Researchers (Iglesias & Rogers) amongst the top most-cited at LLNL
  - In top 10 most-cited astrophysical papers for many years
  - Predominant K_ν application for low-Z LTE matter
    - Astrophysics, laboratory experiments, ICF
- Measured K_ν of more complex higher-Z samples: Fe, Ge, Nb
- Developing new higher-Z opacity code (TOPAZ)

Equation of State Studies

- Equation of State (EOS) is the relationship between the pressure, temperature and the density
- EOS is essential for radiation hydrodynamic simulations
- “Slight” error in the EOS can have serious effect on predictive capabilities

Equation of State data at high pressures required to ensure correct simulations

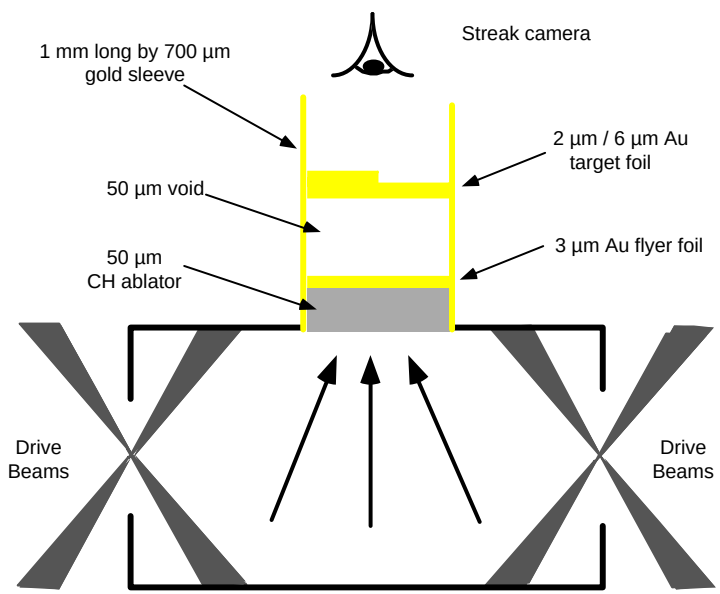
- Required high-pressure EOS laboratory experiments
  - First near GBar shock
- Developed absolute measurements of shock conditions
- Developed cryogenic samples for accurate high-pressure data
- Measured absolute D_2 compressibility
  - *Calculations* not in agreement with data
- Data using different method in disagreement (Sandia)
  - Theorist/modelers still all over map
- Developing alternative techniques

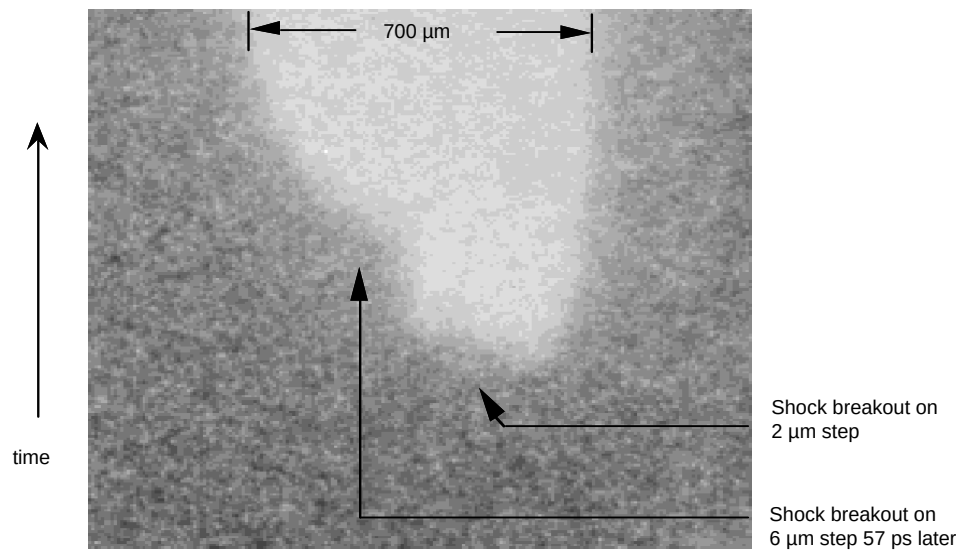
- Case not closed: experiments and theory needed

Hohlraum used to generate shocks
Equation of State (EOS) data determined

- A shock can be used to access a single EOS point in ρ-T space

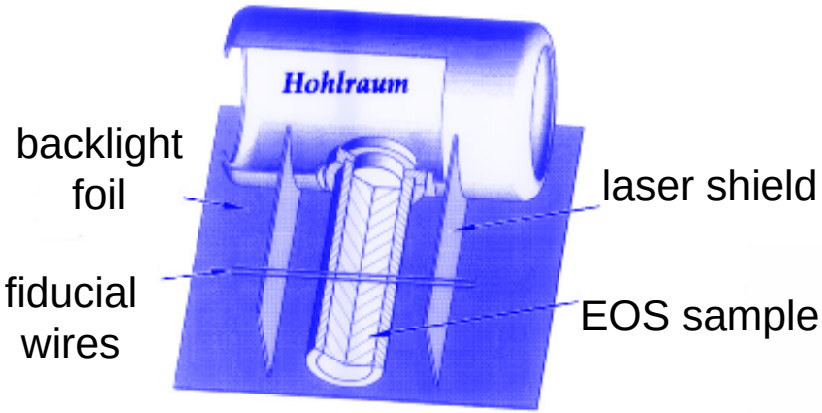
- First determine possibility of creating strong shocks





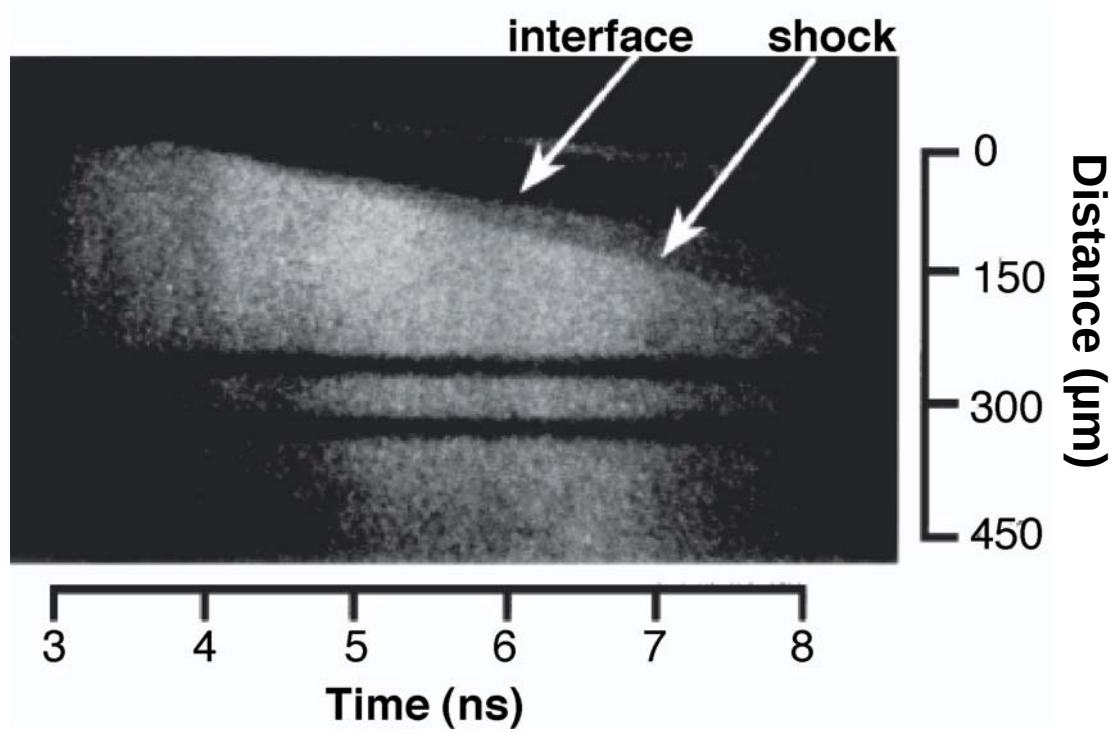
- **~ 0.75 Gbar shock**

Shocks provide absolute EOS when two independent parameters are measured



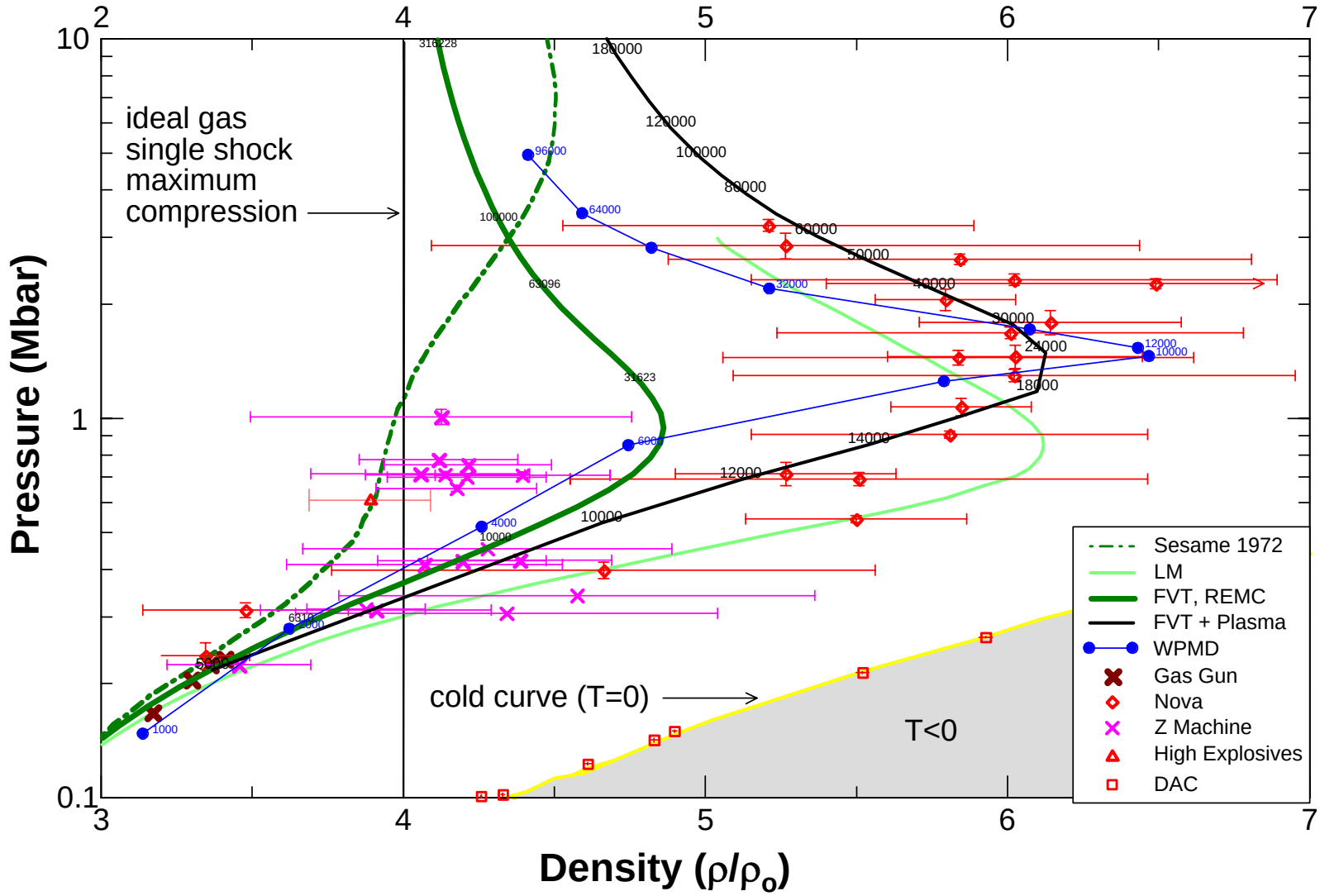
- Transparent material, fiducial markers and backlight allow measure of interface ***and*** shock speeds

- Data from low-Z samples provide tests of EOS tables and previous Mbar experiments



Motivated measurement of D_2 important for ICF and astrophysics

- Similar absolute EOS setup but the results are *stimulating*



EOS effort benefits for NNSA program and the broader community

- PRL and Science articles on D_2 - 257 citations
- Two workshops were dedicated to the subject:
  - 1st not long after publication; 2nd at DOE's request last year
- Data main focus of the 1st WDM Conference and a large fraction of the 2nd WDM Conference.
- “inspired” EOS experiments
  - Laser-based: LANL, Osaka, Ecole Polytechnique, Limeil, NRL, RAL, AWE, and Omega (and NIF, LIL and LMJ planned)
  - Non-laser based: Sandia
- APS Division of Plasmas Physics now has EOS sessions
- Over a dozen theory/modeling groups

Summary

- Science on these large-scale facilities:
  - Starts from programmatic need
  - Requires broad-based effort within the program
  - Incorporates substantial interaction with wider scientific community to promote the effort
  - Feeds back to the program - leading to further improved capability

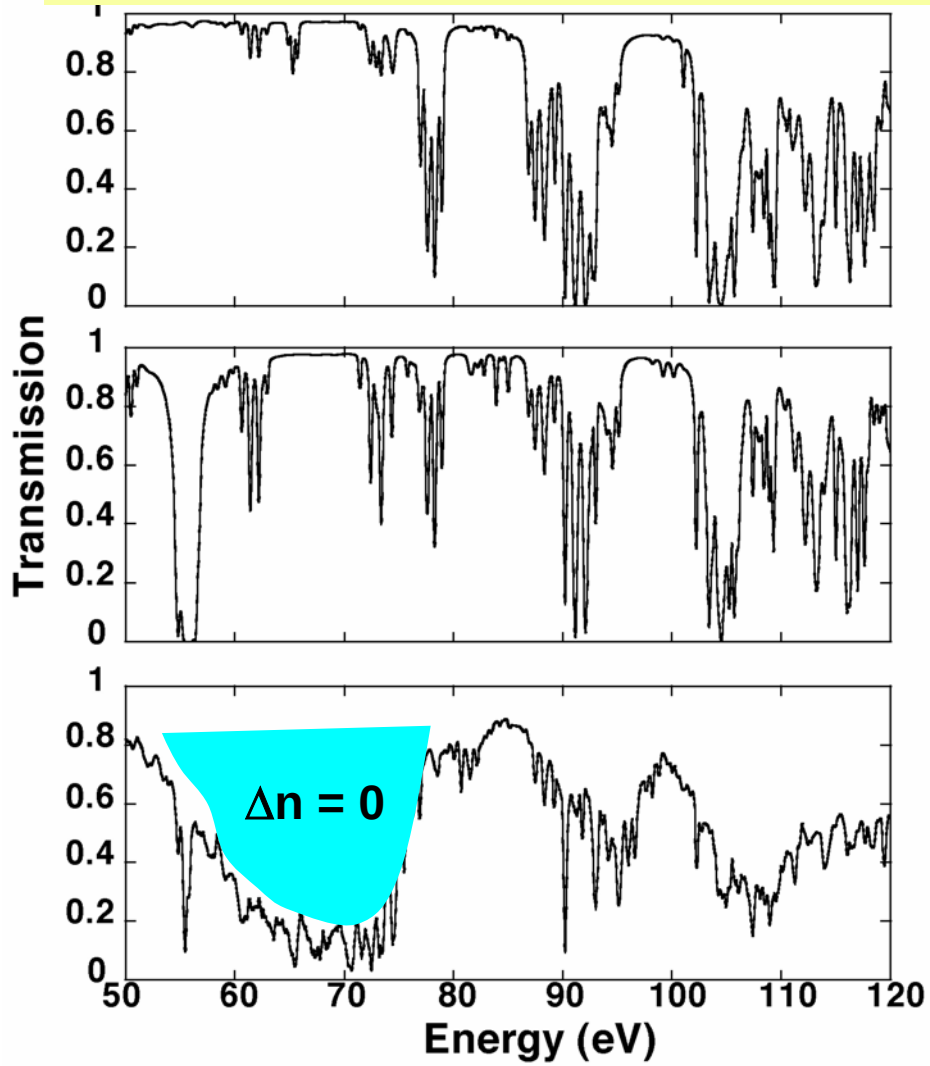
Opacity of low-Z metals important for astrophysical observations: Fe opacity

- Fe transmission for 25 eV and 0.008 g/cm^3

Original

1st improvement

OPAL



HYDROGENIC

NON-HYDROGENIC

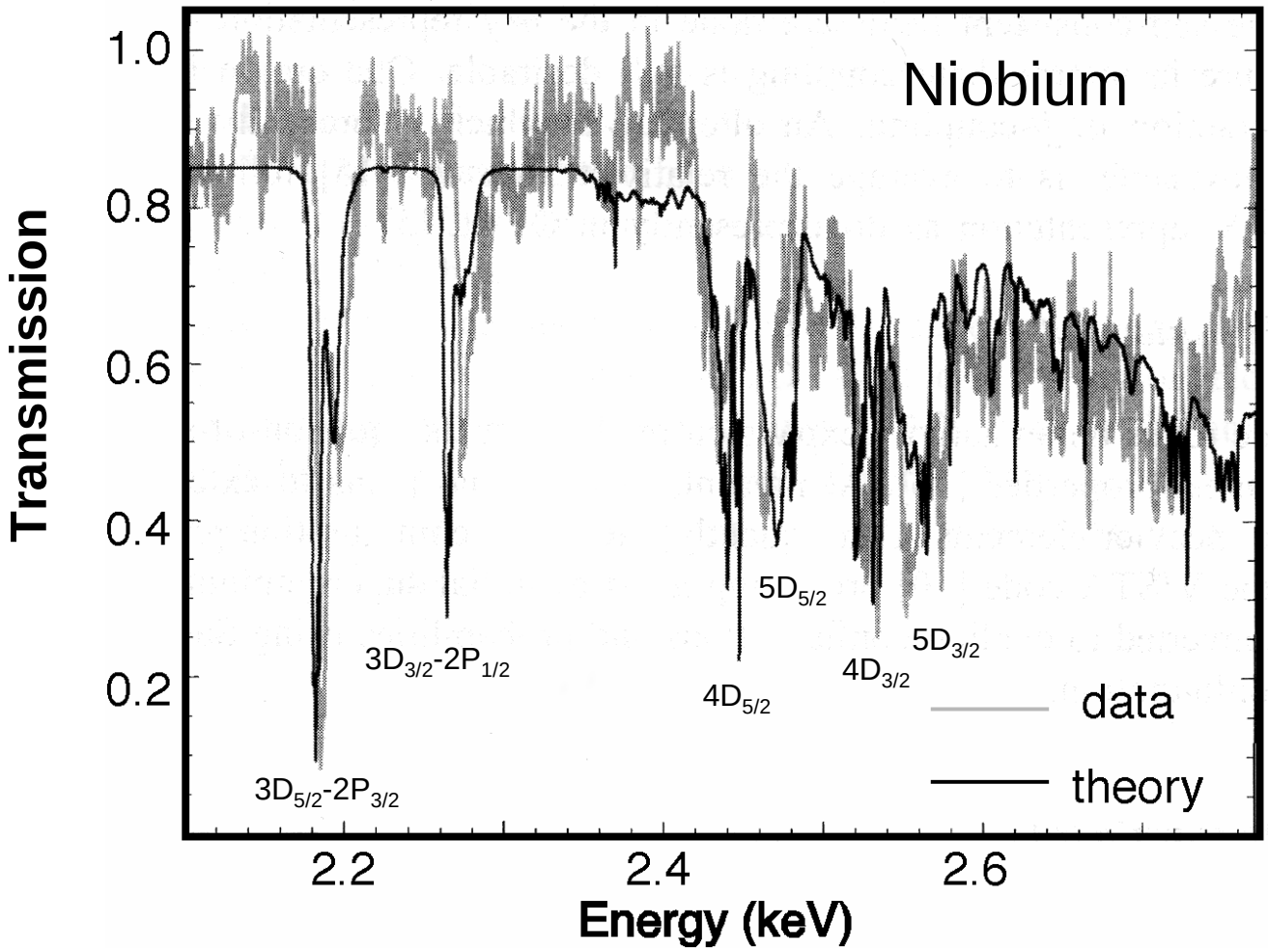
FULL INTERMEDIATE COUPLING

- Rosseland mean at 25 eV is heavily weighted at 3 to 3 transitions, ~ 60-70 eV

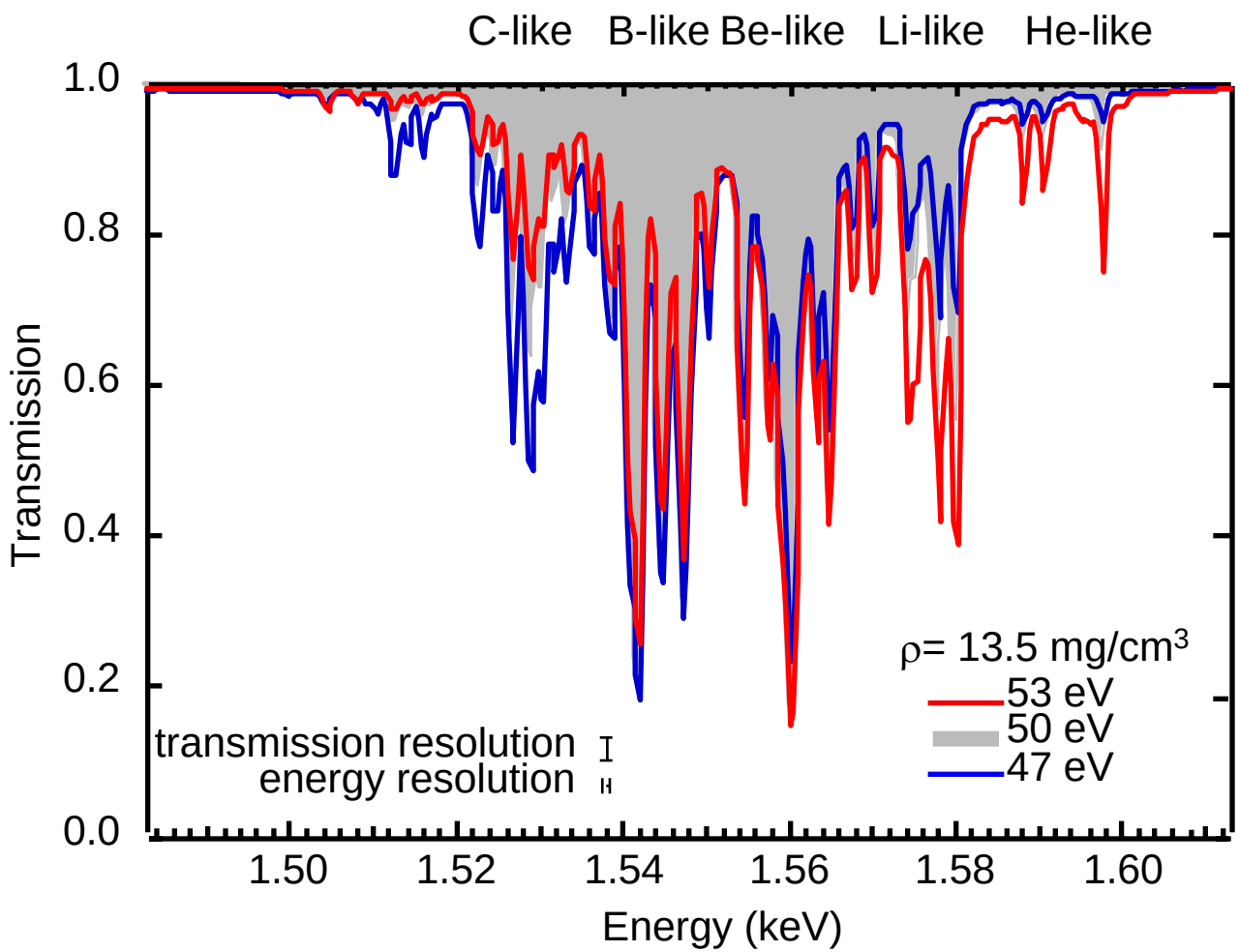
THE END

K_ν-based temperature diagnostic allows higher-Z opacity experiments to test theory

- Use Al / Nb mixture
- Al absorption yields 47 eV; Imaging yields ρ = 0.03 g/cm^3



Use of Al K-shell K_ν to provide an excellent temperature diagnostic



- **Accuracies of ± 3% are obtained in temperature measurements**