Stellar opacities and radiative accelerations

Experiences – Theory - Applications

AFE 2019

Georges Alecian (LUTH)

Gerard Massacrier (CRAL)

Franck Delahaye (LERMA)

Morgan Deal (LESIA- Univ. Porto)

Francis LeBlanc (Univ. Moncton, Canada)

Connor Ballance (QUB, UK)

Nigel Badnell (Strathclyde Univ. Glasgow, UK)

Michel Koenig (LULI)

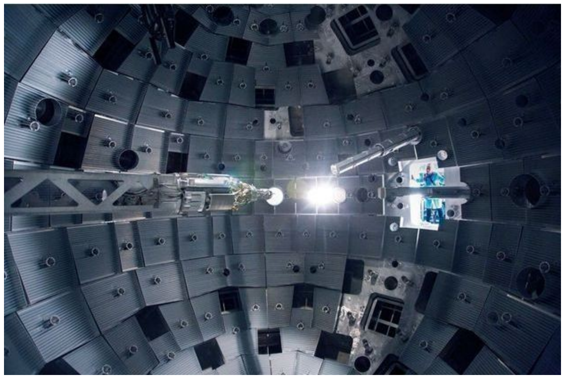
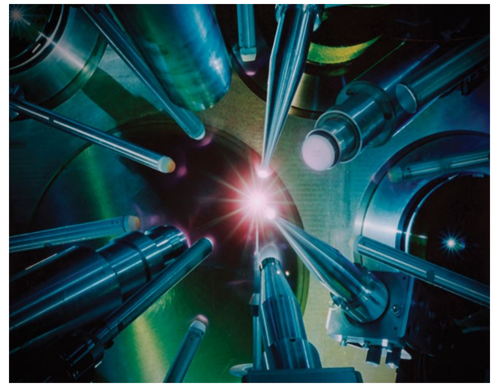
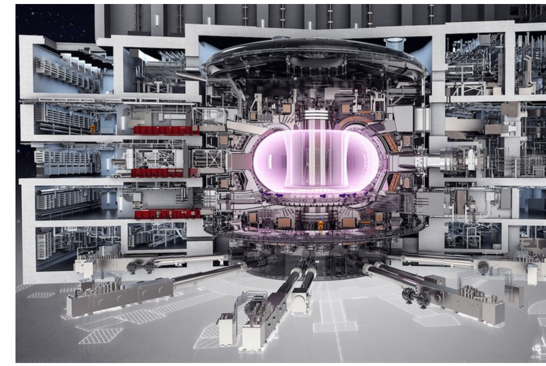
Bruno Albertazzi (LULI)

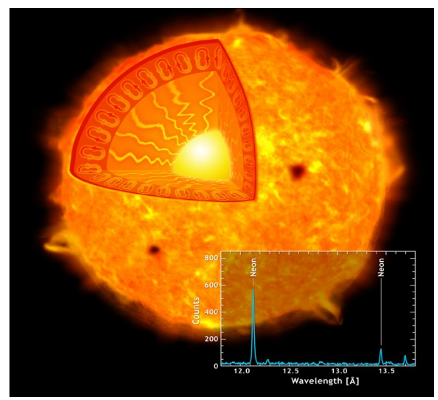
Patrick Renaudin (CEA)

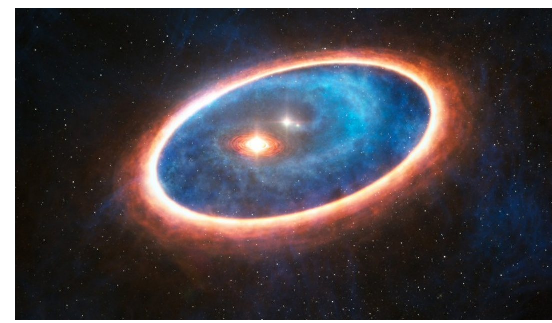
Shinsuke Fujioka (ILE, Japan)

A quantitative comparison of opacities calculated using the distorted-wave and R-Matrix methods

Opacities





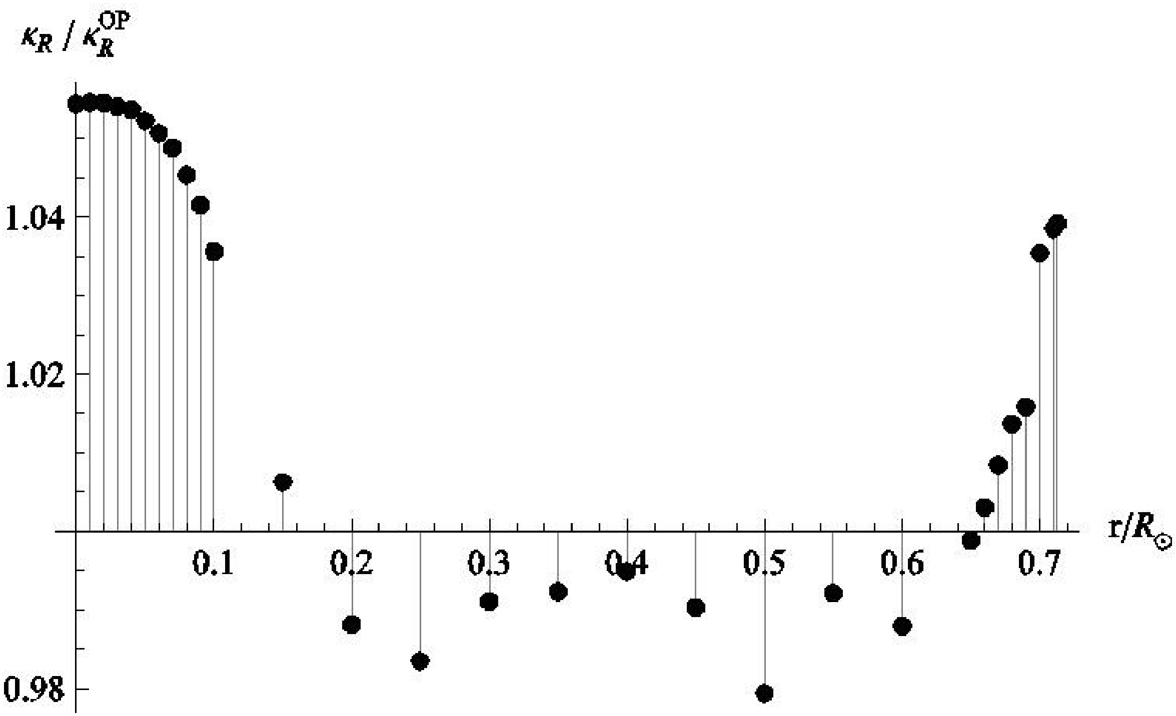
Opacity is a quantity which determines the transport of radiation through matter, and is of importance for many problems in physics and Astronomy. In order to calculate opacities one requires atomic data for a large number of processes involving absorption and scattering of radiation.“ (M.J. Seaton, J.Phys.B. 1987, 20 6363)

Atomic data & Opacities – Theory

The Opacity Project for Stellar Opacities – 2 Releases

2011 OPAS (CEA)

- New Rosseland mean opacities for solar mixture



2005 – Badnell N.R., Bautista M.A. et al. MNRAS 360, Issue 2, 458

- Including inner-shells

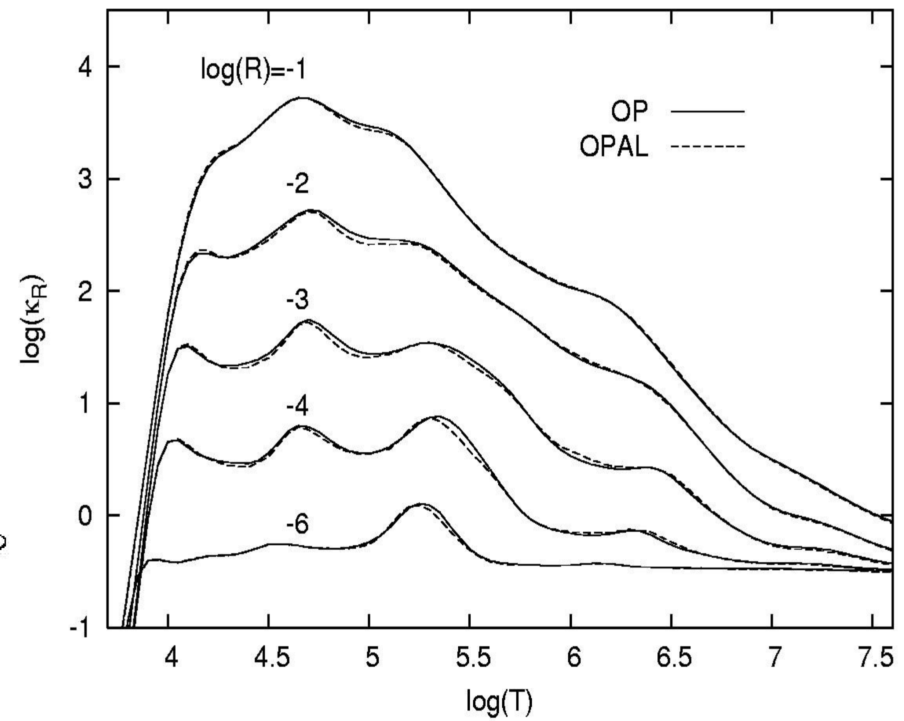
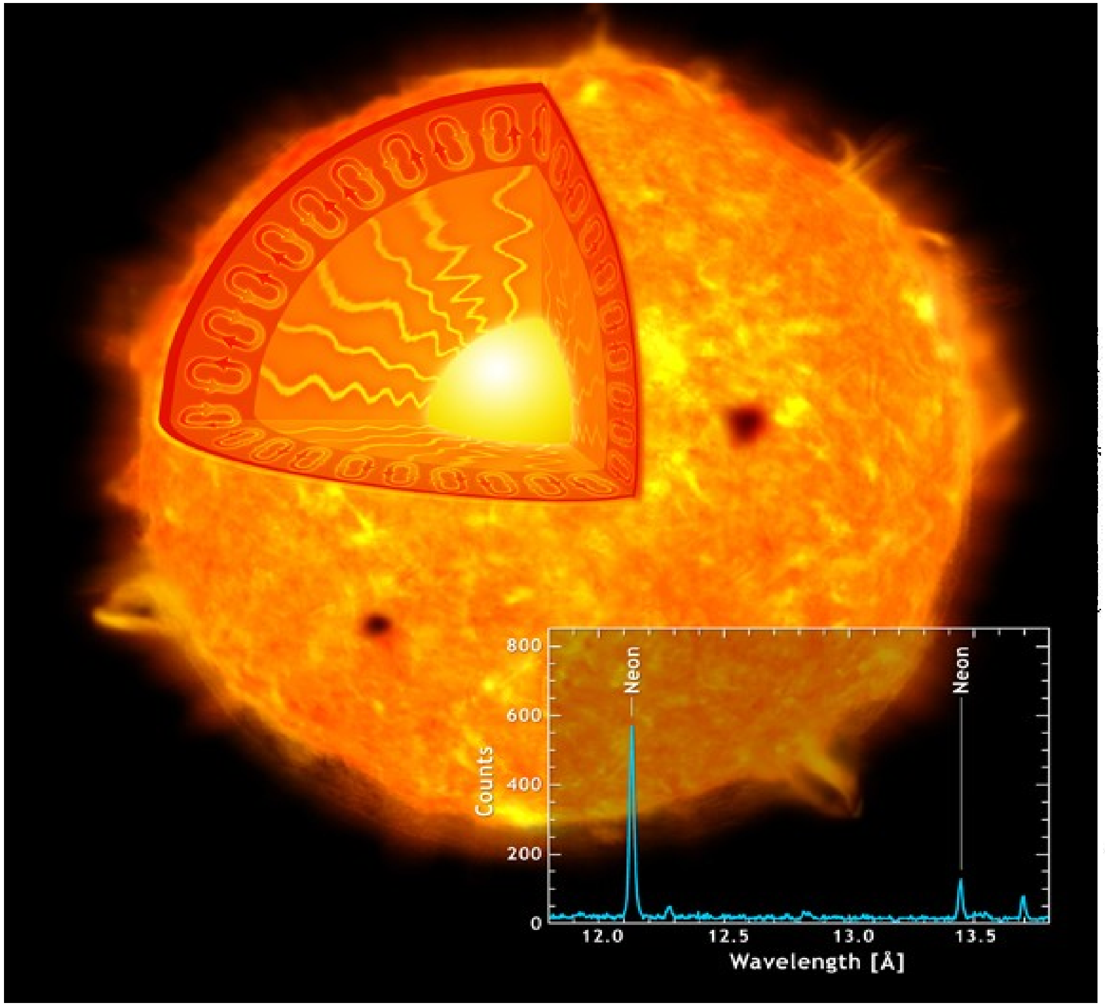
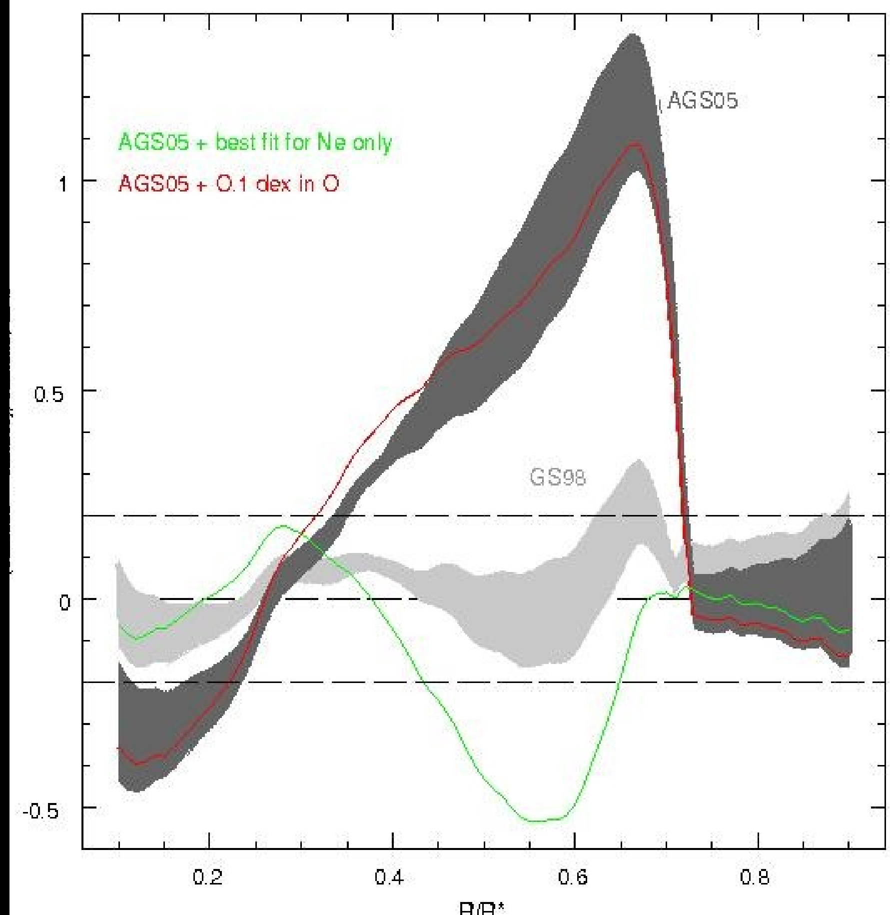


Figure 2. Rosseland-mean opacities from OP and OPAL for the S92 mix.

What is the composition of the Sun?
The solar problem is 14 yrs old !

Rosseland mean: OP vs OPAL vs OPAS — Success or Failure on Solar abundances?



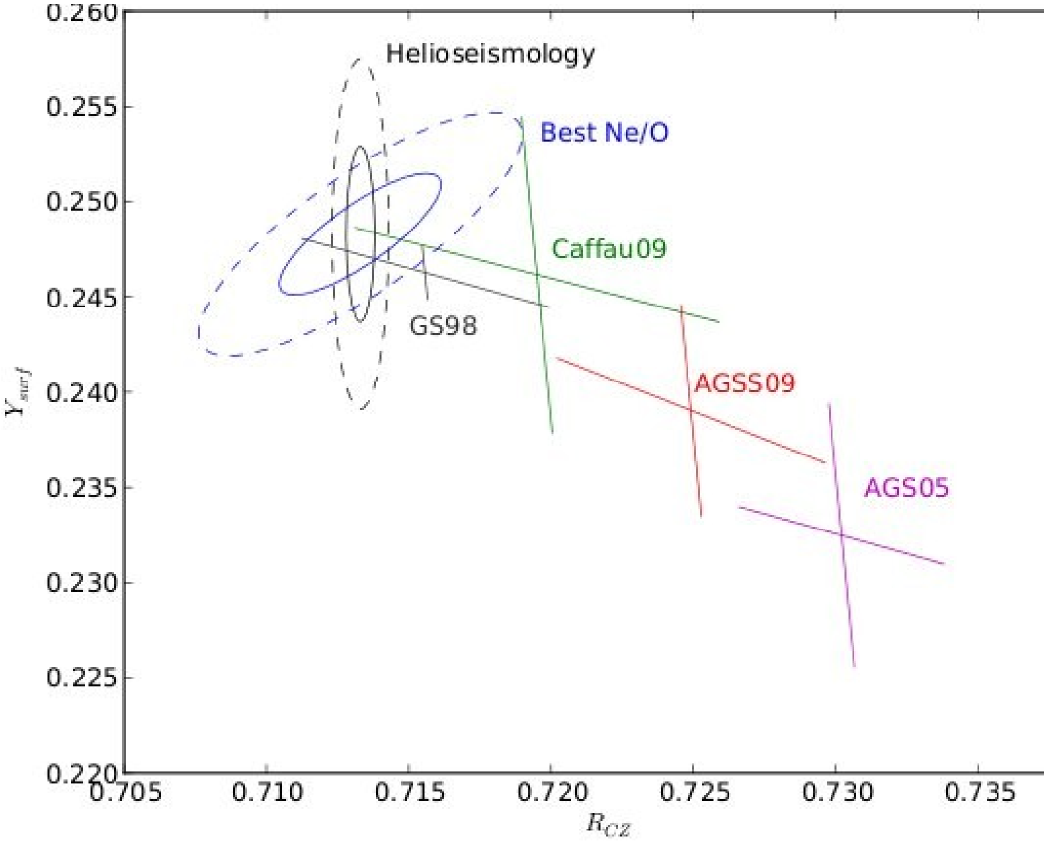


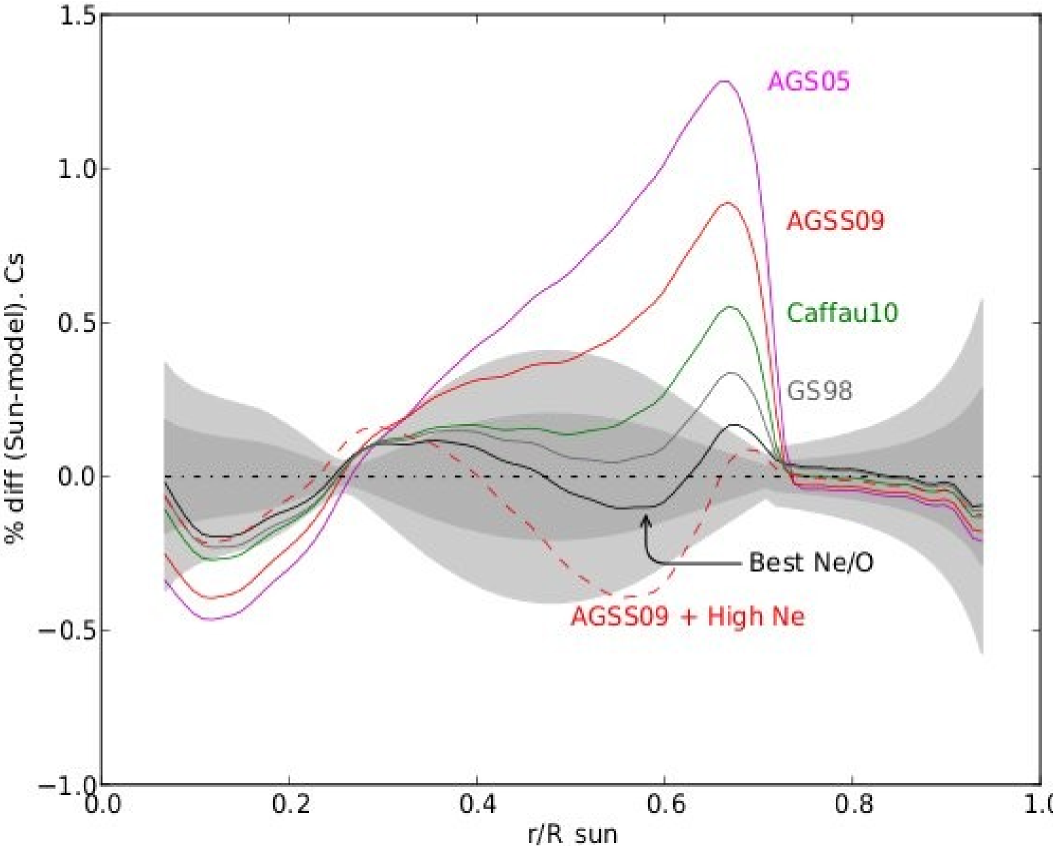
Delahaye, Pinsonneault, Pinsonneault & Zeippen 2010

New Composition => Solar models Fail≠Observation: Compensate drop in [CNO] = increase κ

The IPOPv2 - Results and New challenges ...

Success or Failure on Solar abundances?

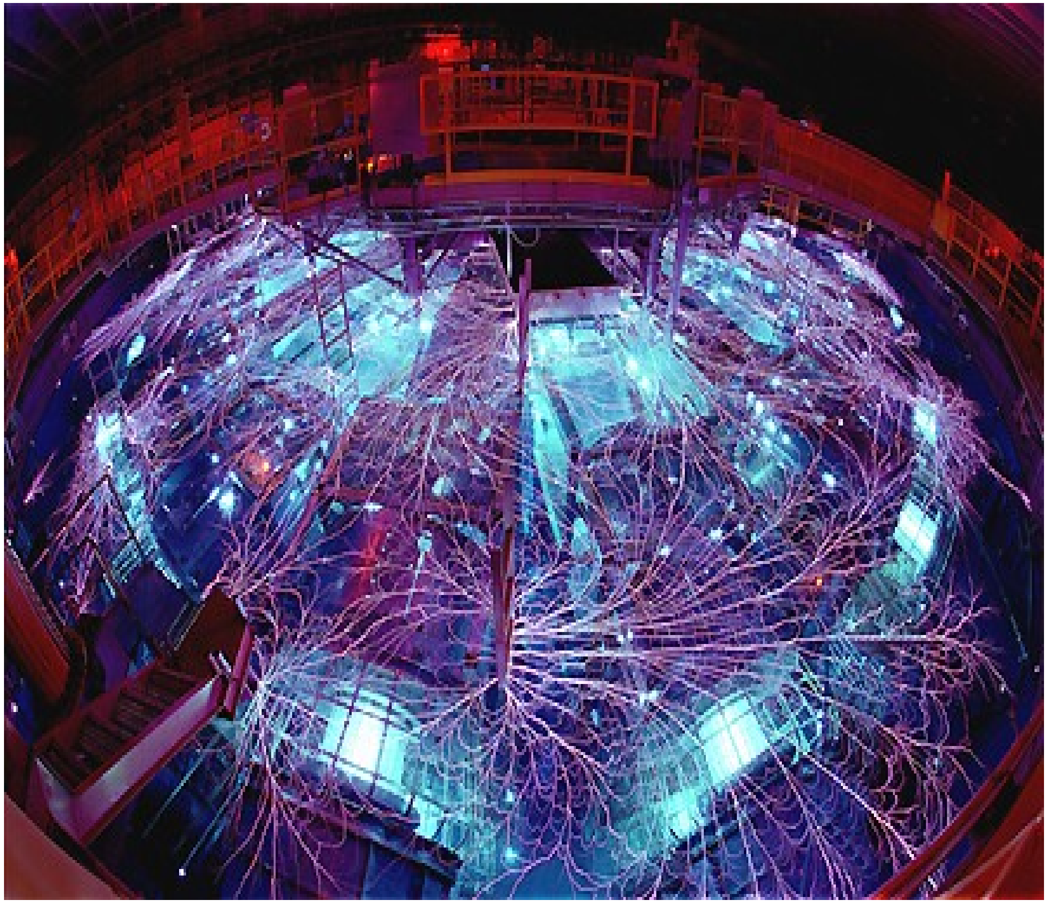


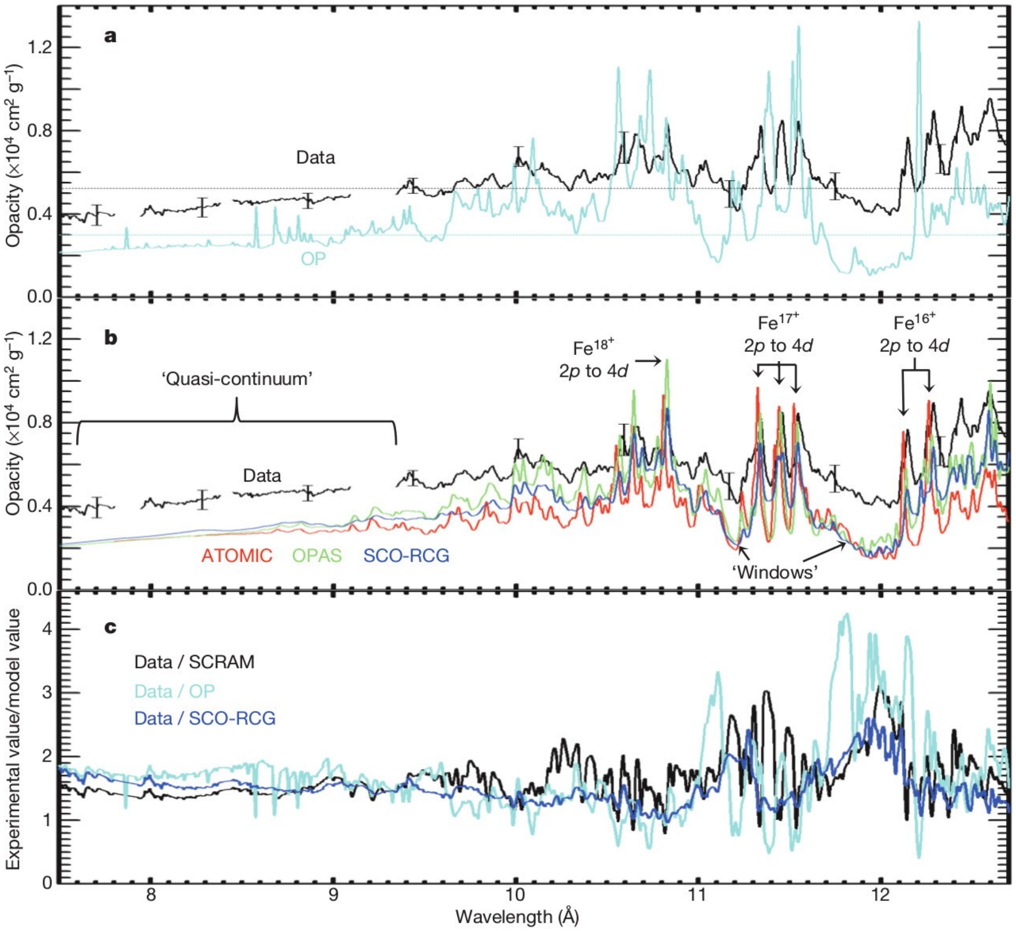


Delahaye, Pinsonneault, Pinsonneault & Zeippen 2010

Experiments

Fe experiment at Sandia – Bailey et al. 2015, Nature (doi:10.1038/nature14048)





Comparisons of iron opacity spectra with multiple models at the solar radiation/convection zone boundary temperature. Fe at Te=182eV or 2.11×10^{6} K, ne=3.1×10^{22} cm^{-3}
Bailey et al. 2015

+

Radiative accelerations

Opacities and radiative accelerations

Stellar Structure

Radiative equation $$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\rho\kappa_R}{T^3}\frac{L}{4\pi r^2}$$

Rosseland mean $$\frac{1}{\kappa_R} = \int \frac{1}{\kappa_\nu(total)} f_\nu d\nu$$

tot=total – bf=Bound-Free
ff=Free-Free bb=Bound-Bound

$$\kappa_{tot}(\nu) = \kappa_{bb}(\nu) + \kappa_{bf}(\nu) + \kappa_{ff}(\nu)$$

$$\kappa_\nu(total) = \sum_k \kappa_\nu(k) + \kappa_{scat}$$

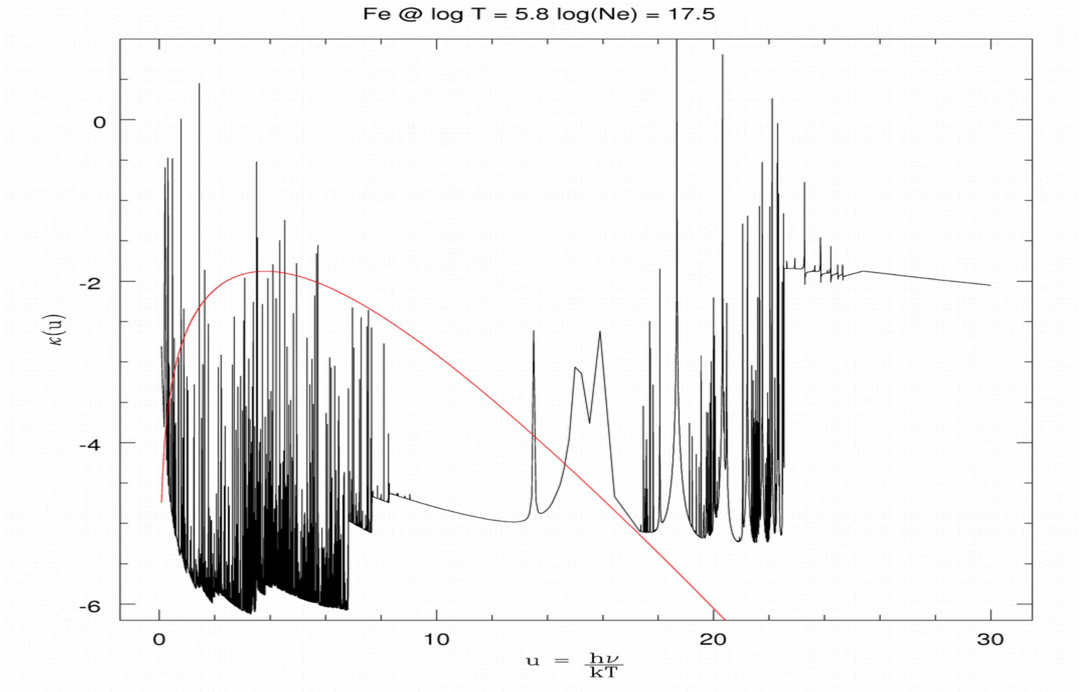
$$\kappa_\nu(total) = \sum_k \kappa_\nu(k) + \kappa_{scat}$$

$$f_\nu = \frac{15h^5\nu^4}{4\pi^4 k_B^5 T^5}\frac{e^{h\nu/k_B T}}{(e^{h\nu/k_B} - 1)^2}$$

Micro-diffusion

Radiative Acceleration $$g_{rad}(k) = \frac{F}{c}\frac{M}{M(k)}\kappa_R\gamma(k)$$

Absorption due to the element k $$\gamma(k) = \int \frac{\kappa_\nu(k)}{\kappa_\nu(total)} f_\nu d\nu$$



Radiative accelerations

Semi-analytic approximations « SVP »

$$g_{tot} = \frac{\sum_i w_i N_i \left(g_{i,bb} + a_i \left(\frac{\chi}{1+\chi} \right)^{b_i} g_{i,cont} \right)}{\sum_i w_i N_i}$$

$$g_{i,bb} = q\varphi_i^* \left(1 + \xi_i^* C_i\right) \times \left(1 + \frac{C_i}{b\psi_i^{*2}}\right)^{\alpha_i}$$

Without correction:

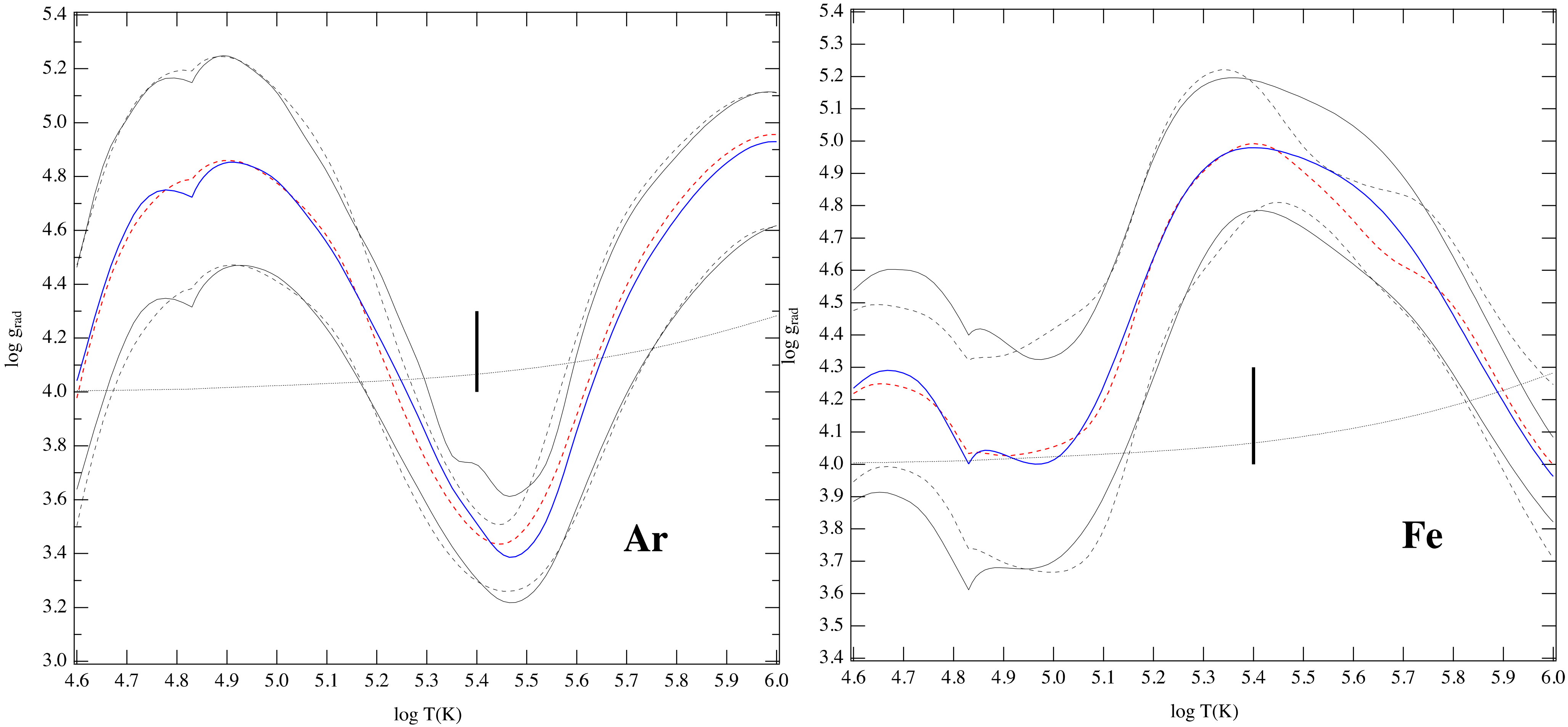
$a_i = 1$

$b_i = 0$

$\alpha_i = -1/2$

Radiative Accelerations – SVP vs OP

SVP vs OP : need new Atomic data!



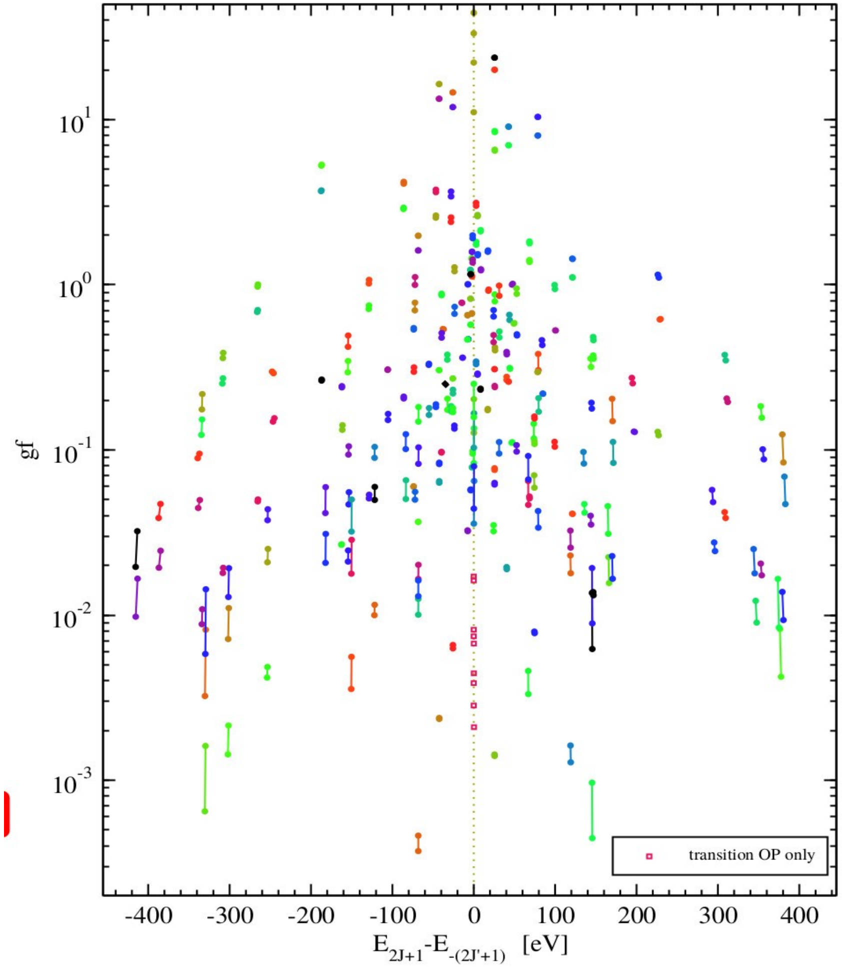
Radiative acceleration from SVP(dash line) method compared to The Opacity Project results (solid) for a $2M_{sun}$ star depending on depth (log T) for 3 different content (0.1, 1 and 1 Solar content) for Ar on left and Fe on Fe

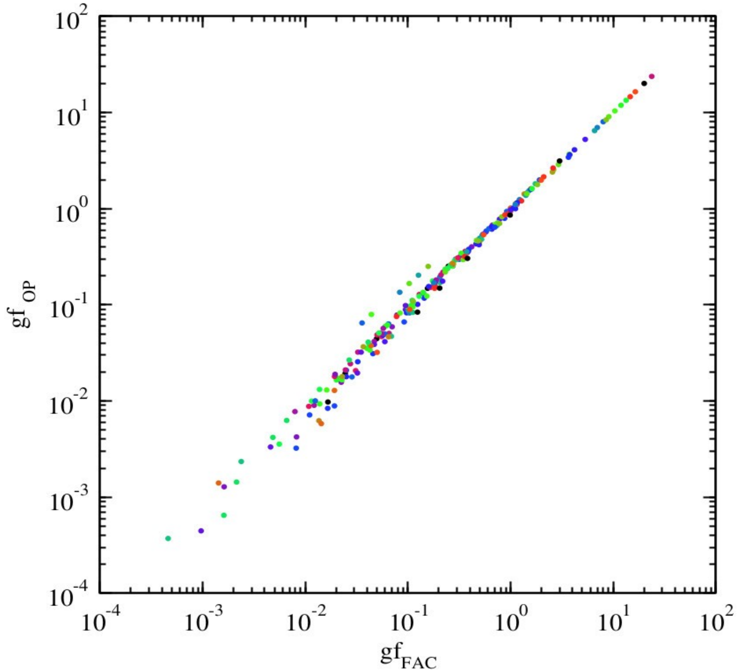
Atomic Calculations – FAC vs AS

New atomic data

FeXVI (11 el.) **comparison between FAC and OP transitions**

each pair of bullets links the points (ΔE,gf) of a
transition as computed through FAC and OP
(assuming FAC and OP levels are well matched)

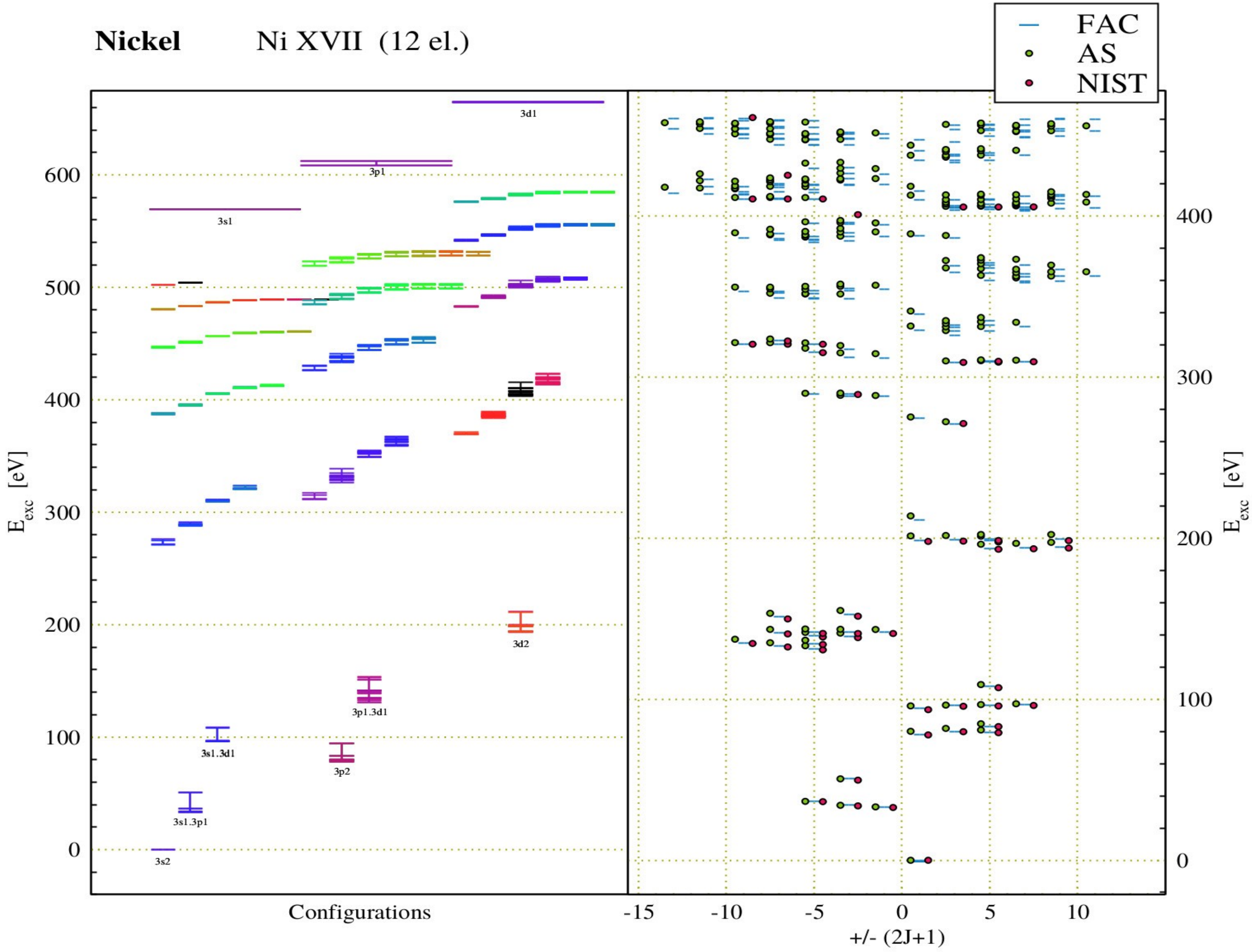




l'Observatoire de Paris | University of Strathclyde Glasgow | Institute of Laser Engineering Osaka University | Queen's University Belfast | cea | UPMC Sorbonne Universités | cnrs

Atomic Calculations – FAC vs AS

New atomic data



SVP

Interiors: recent improvement of *SVP* tables

SVP methods can be implemented in existing numerical codes for stellar evolution: already done for TGEC (*Theado et al, 2009)*, and CESTAM (*Deal et al. 2018*).

- Details of the method & data may be found online:
  - **See the website http://gradsvp.obspm.fr (significant update by the beginning of 2020)**
  - **New *SVP* tables for a large number of stellar masses (1 to 10 solar mass stars) will be available shortly (in collaboration with F. LeBlanc, Moncton, Canada)**
  - **Source codes (fortran) will also be available (possibly next year)**

Where are we heading?

Experiment – Theory - Application

- *New set of atomic data FAC vs AS for Fe and Ni*
- *New The Opacity set of data (atomic, opacities and radiatives accelerations)*
- *OP routines for opacities and radiative accelerations already parallelized need to implement them now*
- *Implementation of 'on the fly' opacities and radiative acceleration in YREC (Yale Rotational Evolutionary Code)*
- *New implementation/improvement of SVP*
- *New experiments to confirm or contest SANDIA results – (GEKKO laser-PI F. Delahaye)*

What Next: new experiment

Open L-shell

At 180 eV (SANDIA exp.) Cr and Fe are in open L-shell configuration while Ni is closed

- NIF working on Fe at 180 eV

Our Proposal: Same iso-electronic sequence at lower T (30 to 80 eV) Si
Can we model O-like, F-like and Ne-like opacities?

- Test our hability to model O-like, F-like and Ne-like ions using the different approaches (Rmatrix and Distorted Wave)

- Get confirmation or not on the SANDIA experiment

- Get new opacity measurements at different T and for different Element
  → New data point to improve theory

Measure opacities for light ions
- LULI / ILE proposal Opacities at T in [30 – 80 eV] – Ne in [10^{19} – 10^{22} cm^{-3}] for light Elem. up to Ni

New Challenges for Opacities

Fe experiment at Sandia – Nagayama et al. Phys. Rev. 2019

Reasons behind s

- missing BF ?

- Broadening ?

- EOS ?

- Experiment ?

PHYSICAL REVIEW LETTERS **122,** 235001 (2019)

Editors' Suggestion | Featured in Physics

Systematic Study of *L*-Shell Opacity at Stellar Interior Temperatures

T. Nagayama,[1] J. E. Bailey,[1] G. P. Loisel,[1] G. S. Dunham,[1] G. A. Rochau,[1] C. Blancard,[2] J. Colgan,[3] Ph. Cossé,[2] G. Faussurier,[2] C. J. Fontes,[3] F. Gilleron,[2] S. B. Hansen,[1] C. A. Iglesias,[4] I. E. Golovkin,[5] D. P. Kilcrease,[3] J. J. MacFarlane,[5] R. C. Mancini,[6] R. M. More,[1,*] C. Orban,[7] J.-C. Pain,[2] M. E. Sherrill,[3] and B. G. Wilson[4]

[1]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*
[2]*CEA, DAM, DIF, F-91297 Arpajon, France*
[3]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[4]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[5]*Prism Computational Sciences, Madison, Wisconsin 53711, USA*
[6]*University of Nevada, Reno, Nevada 89557, USA*
[7]*Ohio State University, Columbus, Ohio 43210, USA*

(Received 7 March 2019; published 10 June 2019)

The first systematic study of opacity dependence on atomic number at stellar interior temperatures is used to evaluate discrepancies between measured and modeled iron opacity [J. E. Bailey *et al.*, Nature (London) **517**, 56 (2015)]. High-temperature (> 180 eV) chromium and nickel opacities are measured with ±6%–10% uncertainty, using the same methods employed in the previous iron experiments. The 10%–20% experiment reproducibility demonstrates experiment reliability. The overall model-data disagreements are smaller than for iron. However, the systematic study reveals shortcomings in models for density effects, excited states, and open *L*-shell configurations. The 30%–45% underestimate in the modeled quasicontinuum opacity at short wavelengths was observed only from iron and only at temperature above 180 eV. Thus, either opacity theories are missing physics that has nonmonotonic dependence on the number of bound electrons or there is an experimental flaw unique to the iron measurement at temperatures above 180 eV.

New Challenges for Opacities

Fe experiment at Sandia – Nagayama et al. Phys. Rev. 2019

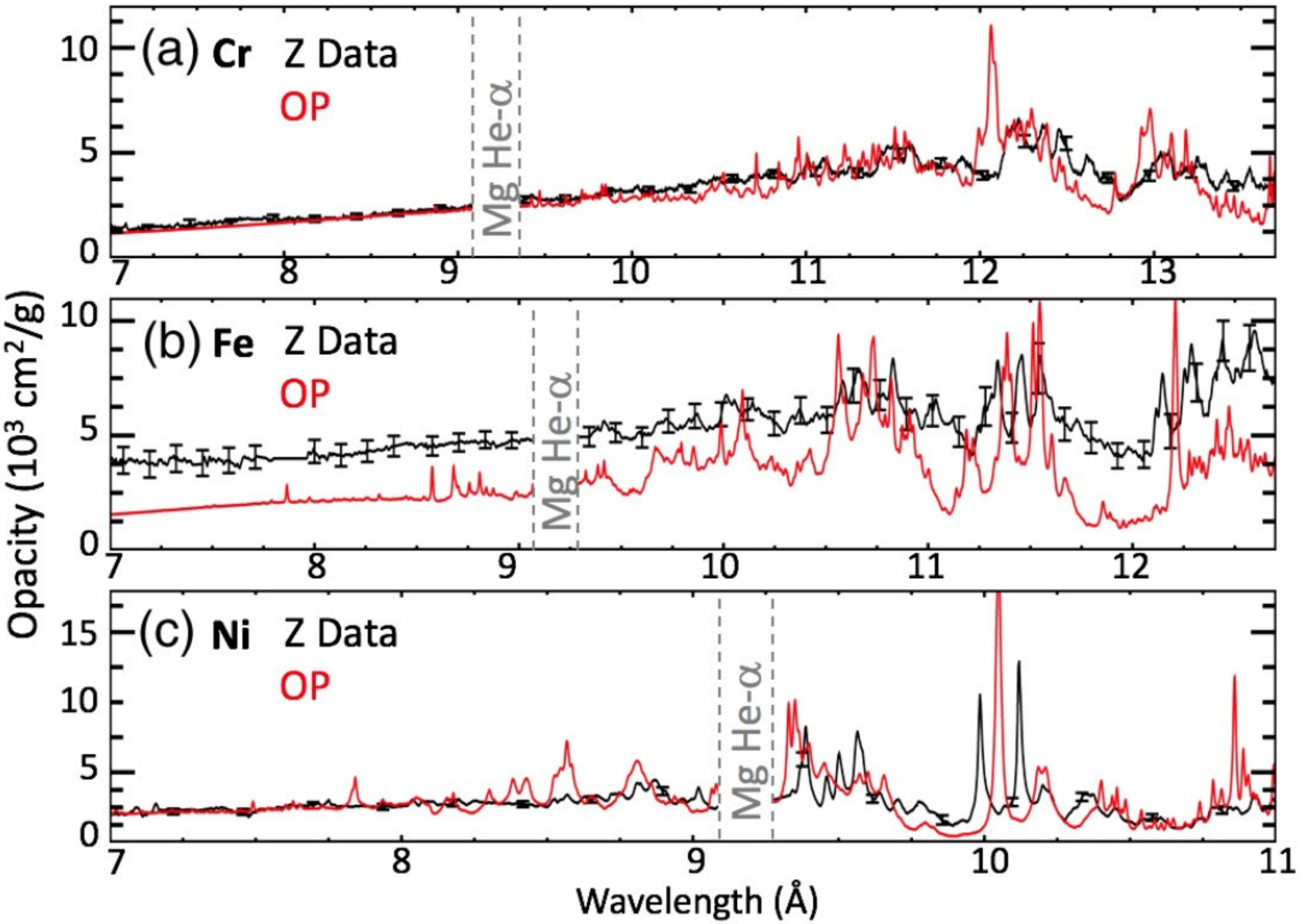
Reasons behind sucl

- missing BF ?

- Broadening ?

- EOS ?

- Experiment ?
Fig 3



New Challenges for Opacities

Fe experiment at Sandia – Nagayama et al. Phys. Rev. 2019

Reasons behind such

- missing BF ?

- Broadening ?

- EOS ?

- Experiment ?
Fig 3