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THE OPAC CONSORTIUM

THE ENERGETIC TRANSFER OF SUN AND STARS

Sylvaine TURCK-CHIEZE, Service d'Astrophysique/IRFU/DSM/CEA

SEPTEMBER 1ST, 2014

CEA

LABORATORY ASTROPHYSICS

INSTITUT LASERS ET PLASMAS

1905 George Hale develops spectroscopy (stellar composition), redshift, dynamo effect, dielectric recombination…

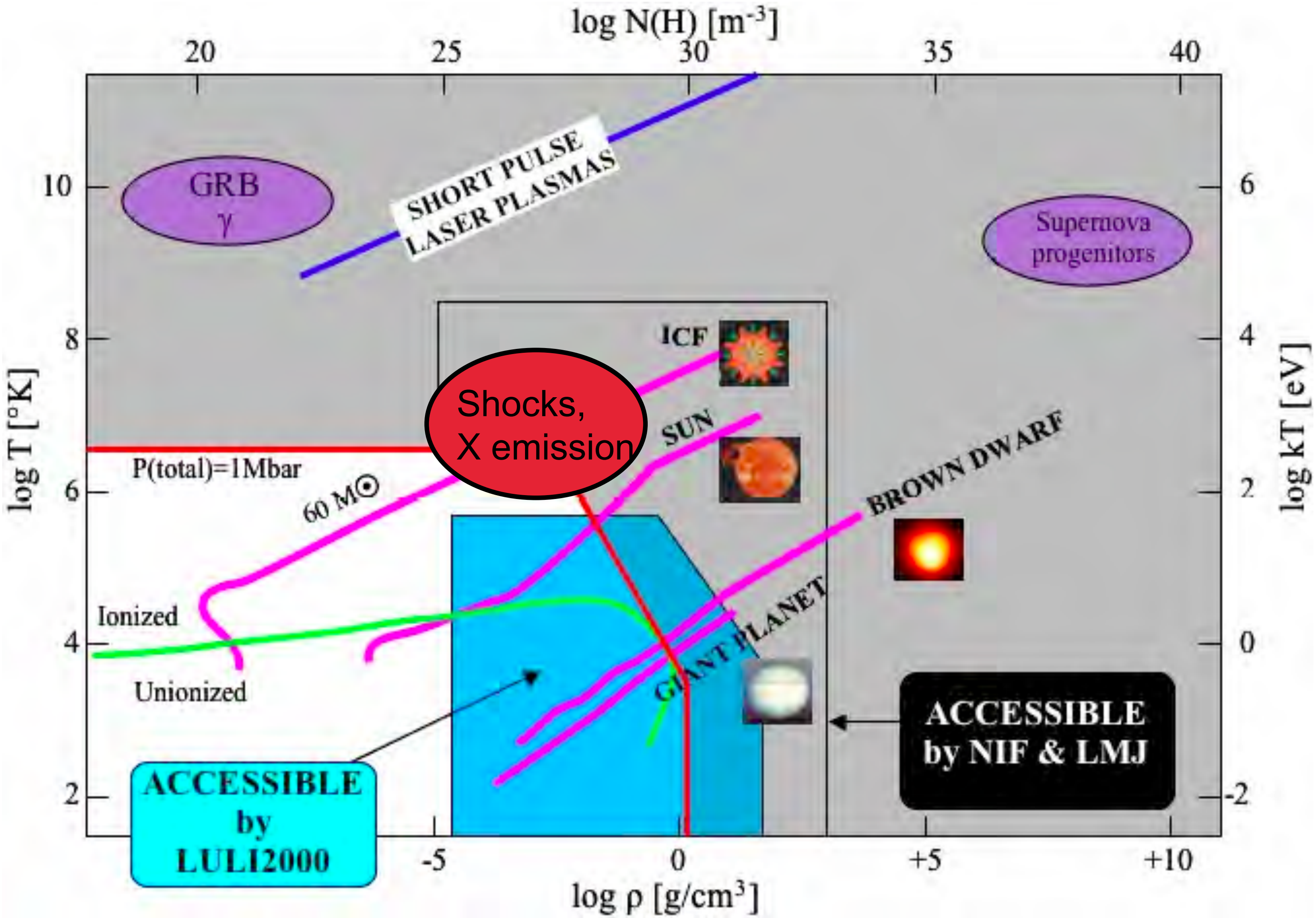
Today Plasma AstroPhysics is accessible with HDE lasers
Stars & Planets… USA / **France** NIF/LMJ England ORION

2003: Creation of the Institute Laser Plasma
2006: Creation of the master "Science of Fusion" ITER / LMJ 30 students /year
two PhD students: Guillaume Loisel (now Post Doc Z machine Albuquerque)
Maelle Le Pennec

We receive support from ANR: ANR OPACITY (lead: STC)

The COST MP 1208 is dedicated to the development of the community around inertial fusion, related physics and science including Laboratory Astrophysics.

LABORATORY ASTROPHYSICS WITH LASER FACILITIES

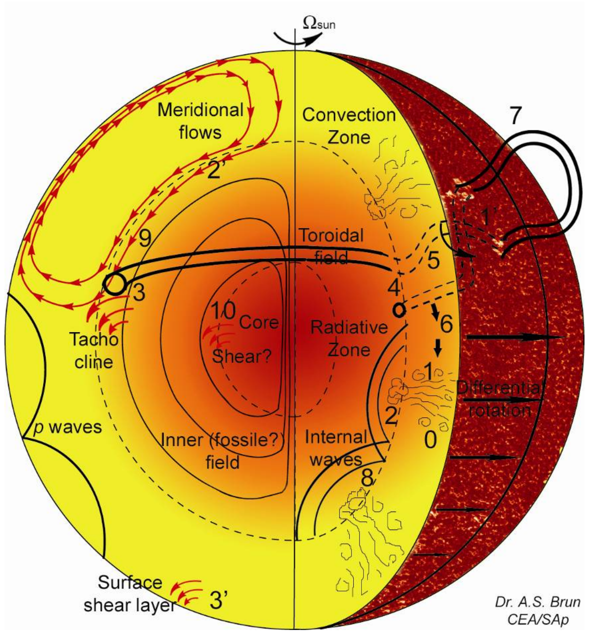


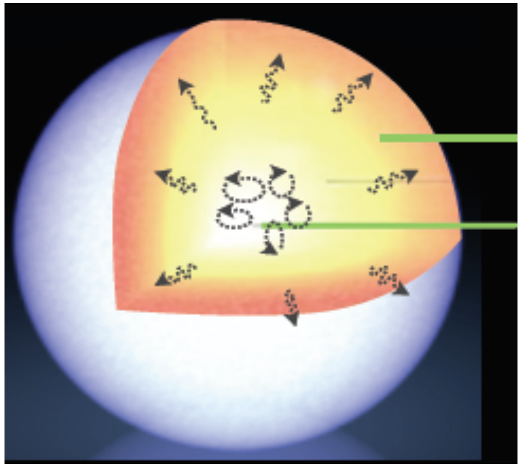
LASER MEGAJOULE AT CEA BORDEAUX

20% of use for the academic community
First shot at the end of this year
First academic shot in 2017-2018

At NIF we prepare an experiment with Los Alamos colleagues on oxygen
And we prepare another one for LMJ

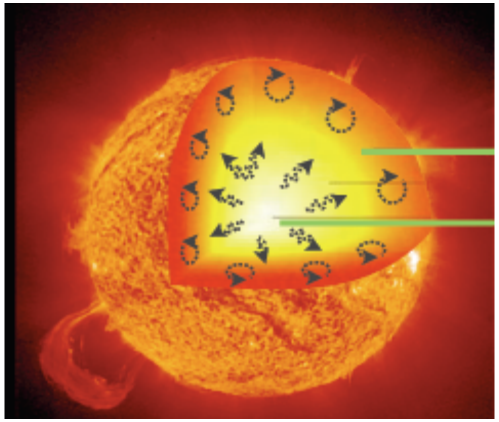
ENERGY TRANSFER by PHOTON interactions in RADIATIVE REGIONS of STARS



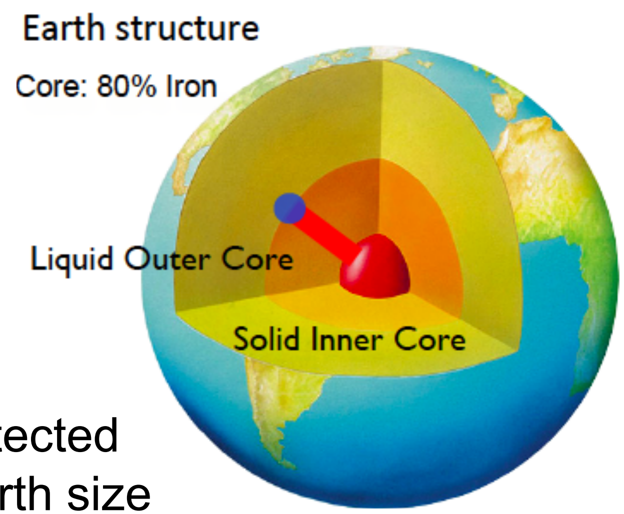


OPACITY (EOS) FOR STARS AND EOS FOR PLANETS

Seismology of Sun and stars / Planet detection



Toward an understanding of the transport of energy and momentum in stars.
SoHO/COROT/KEPLER future PLATO
Turck-Chièze et al. 2004, 2011, 2012,
Basu et al. 2014



Nearly 2000 detected planets, one Earth size detected by KEPLER…

Toward a better determination of the internal structure of the exoplanets.
COROT/KEPLER/ future PLATO
H2/D2: Loubeyre et al. 2012
Fe/SiO2: Benuzzi-Mounaix et al. 2011

EVIDENT RELATIONSHIP
ASTROPHYSICS – INERTIAL FUSION FOR ENERGY

Same kinds of plasmas, similar physical problems:

Equation of state, photon matter interaction on large scales,

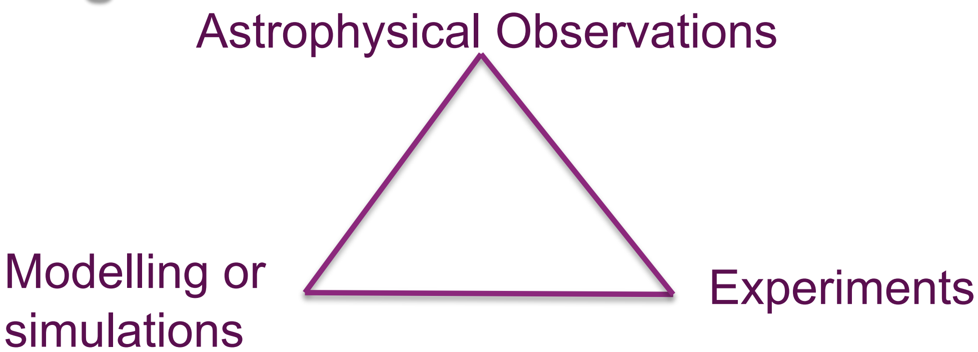
Screening effect in plasma, all kinds of instabilities, shocks….

Any academic validation thanks to experiments and calculations is useful for Astrophysics and Plasma Physics

Results will be used for Fusion both inertial and magnetic

Strong intellectual motivation, high level of competences

High cost but mutual benefits



THE STELLAR OPACITY CALCULATIONS

Extended tables 5000 K < T< some 10^7 K, $10^{-7} < \rho < 10^4$ g/cm^3

21 elements or at least 50 000 calculations to perform

Livermore OPAL and OP for detailed spectra

Validation ? International consortium CEA / Los Alamos

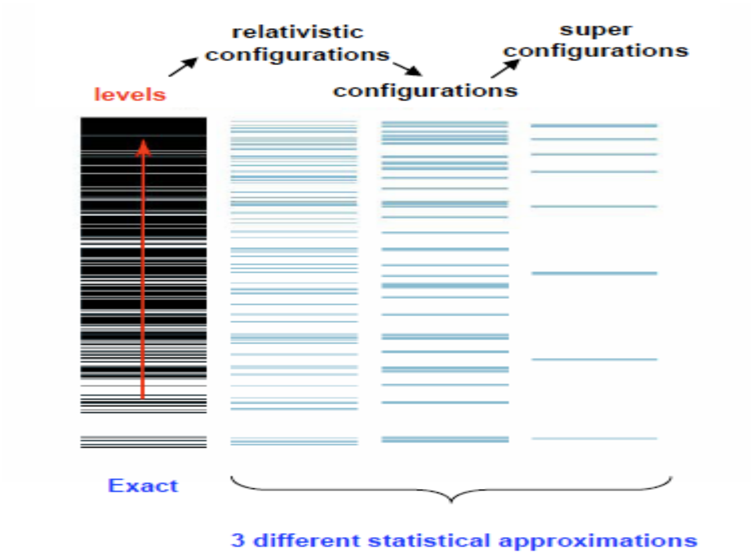
Turck-Chièze et al. 2009, 2011, 2013

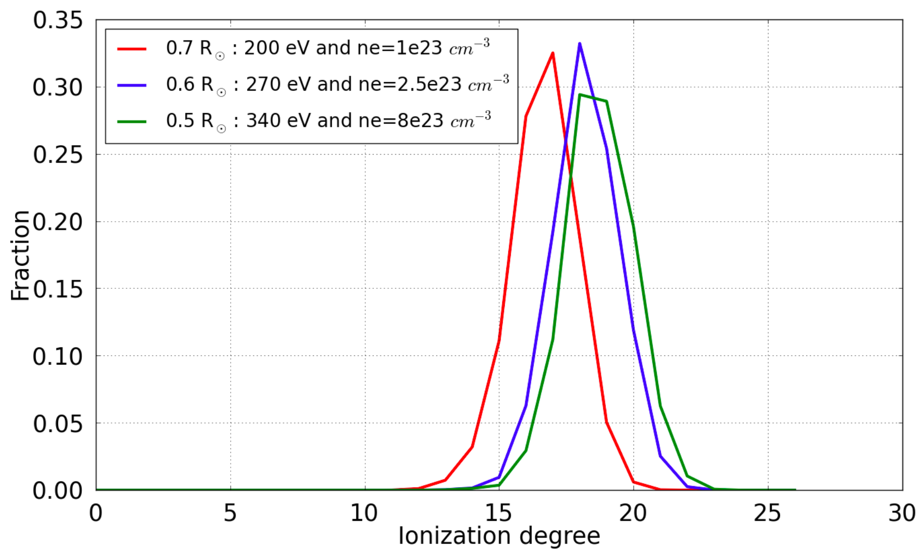
Blancard, Cosse, Faussurier 2011 OPAS, CEA

Porquerot, Gilleron, Pain, Blenski 2011 SCO-RCG, CEA

Bar Shalom, Klapisch, Busquet, Gilles HULLAC,

Colgan, Kilcrease, Fontes, Magee 2013: ATOMIC, Los Alamos





Solar case with the code FLYCHK

Millions to milliards of transitions

Rapidity and Accuracy

Study of the spectral opacities in the radiative zones of stars

The OPAC consortium (France, USA ~30 peoples)
CEA DSM +DAM, CELIA, LOS ALAMOS

Why the opacity calculations coming from OPAL and OP have difficulty to reproduce the mode excitation in massive stars ?

Why do we observe a large difference in the sound speed of the Sun between seismic results and SSM predictions ?

Examination of two cases

- Theoretical and experimental studies of opacity for :
  - The iron opacity bump in the envelopes of pulsating stars of 8 to 20 $M_\odot$: T≈200 000 K and $\rho \approx 10^{-7}$-10^{-6} g/cm^3
  - Solar-type radiative interiors : T > 2.10^6 K and $\rho \approx$ 0.3 à 150 g/cm^3

Unique laser facilities in Europe:

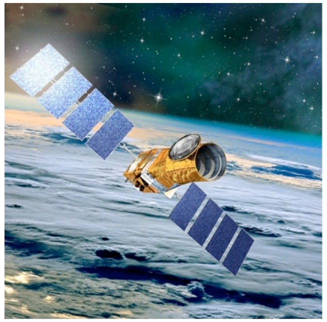
-LULI 2000 (Polytechnique, Palaiseau)

-Laser MégaJoule & PETAL (Bordeaux)

Case I studied on LULI 2000

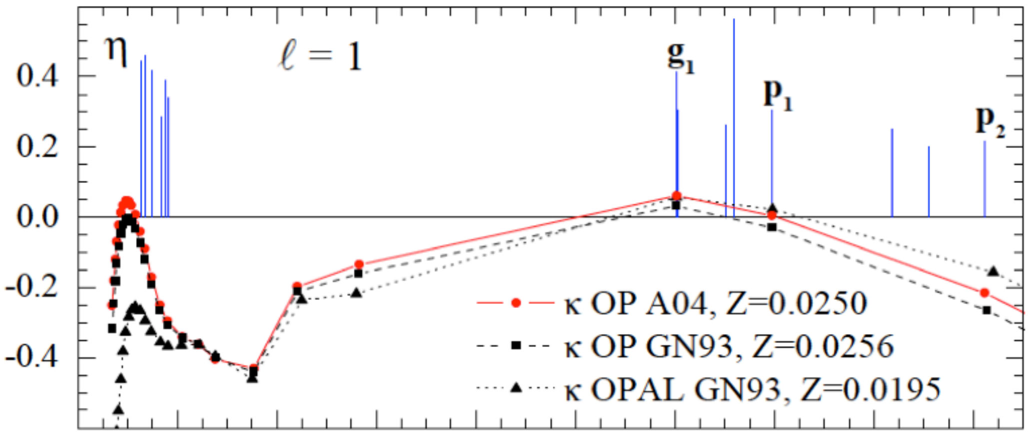
© Palomar Observatory

B-Cephei envelopes



COROT
(©CNES/NASA)

Astrophysical problem



ν, [c/d]

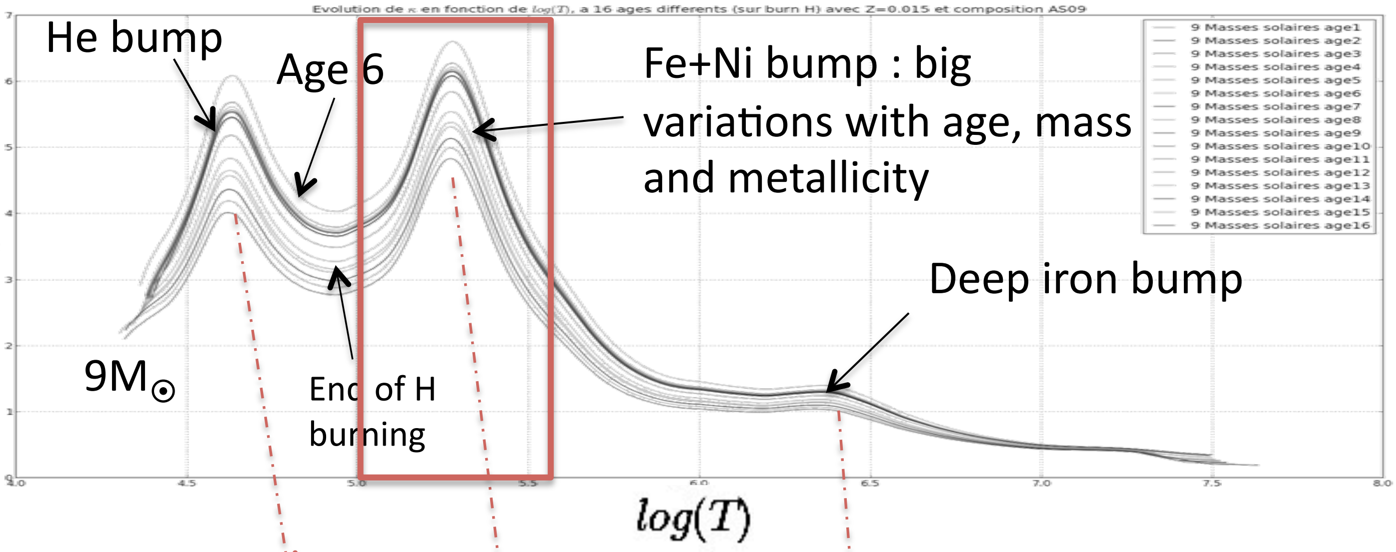
Instability modes : observed modes in blue and calculated modes in red and black (From Zdravkov & Pamyatnykh, 2009)

- Observed modes which are not predicted by stellar models
- These modes are excited by the iron group opacities by κ-mechanism
  - ➤ Understand the differences between OP and OPAL
    - ➤ New calculations from CEA and Los Alamos
    - ➤ Experiments

The iron bump : example of a 9M$_\odot$star

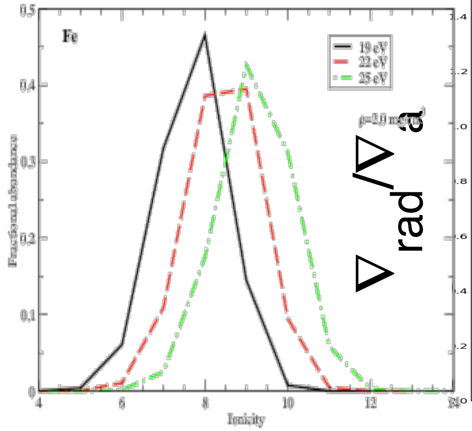
MESA

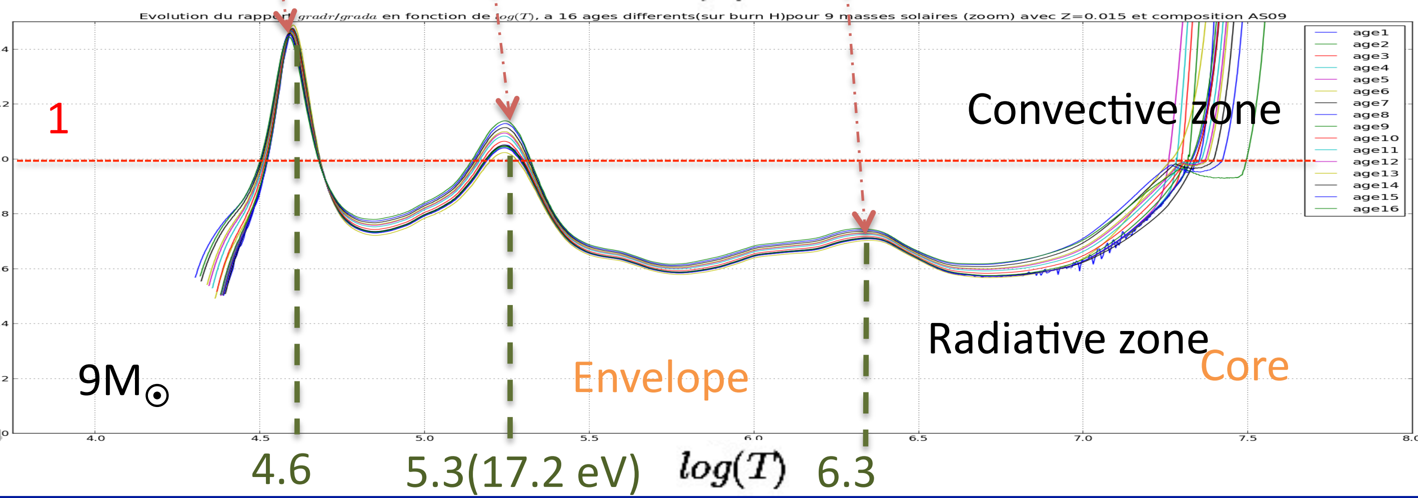
Le Pennec & Turck-Chièze, 2013



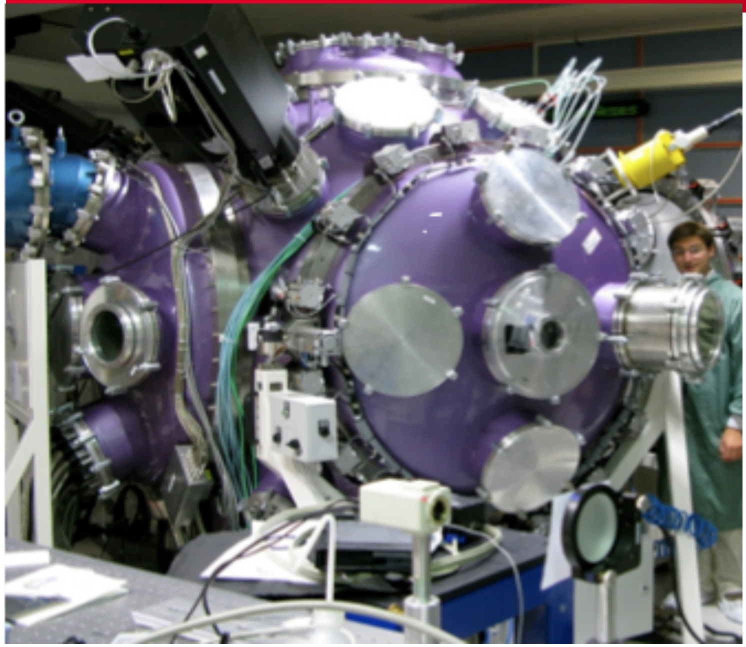
Schwarzschild criteria

$$\nabla_{rad} > \nabla_{ad}$$



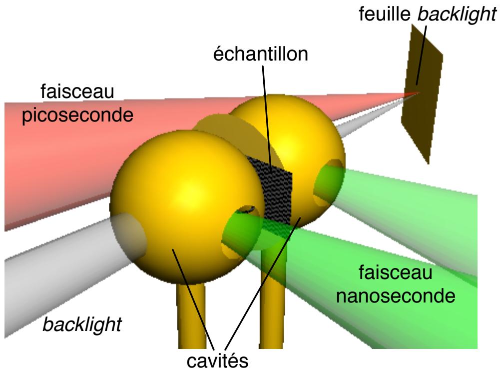


STELLAR ENERGY TRANSFER: XUV EXPERIMENTS



laser of 170J 0.517 μm 0.6 -0.9ns
+ pico second laser 12J 10-20 ps

LTE experimental principle
ns laser + ps laser



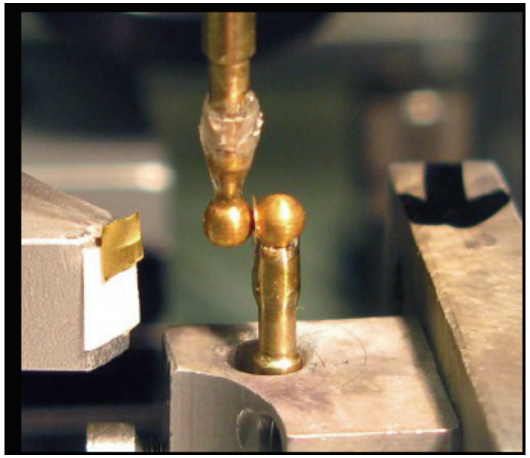
T=23 eV (1 eV= 11600 K)
Rho= some 10^{-3} g/cm^3

ΔT=15%
$\Delta\rho$=15%

Spectral transmission:

$$\tau_\nu = \frac{I_\nu}{I_{\nu,0}} = e^{-\int \kappa_\nu \rho dr}$$

Loisel et al. 2009 LULI2000
Turck-Chièze et al. 2011, 2013, 2014



$$\frac{1}{\kappa_R} = \frac{\int d\nu \frac{1}{\kappa_\nu^{tot}} \frac{dB_\nu}{dT}}{\int d\nu \frac{dB_\nu}{dT}} = \frac{\int d\nu \frac{1}{\kappa_\nu^a (1 - e^{\frac{-h\nu}{kT}}) + \kappa^d} \frac{dB_\nu}{dT}}{\int d\nu \frac{dB_\nu}{dT}}$$

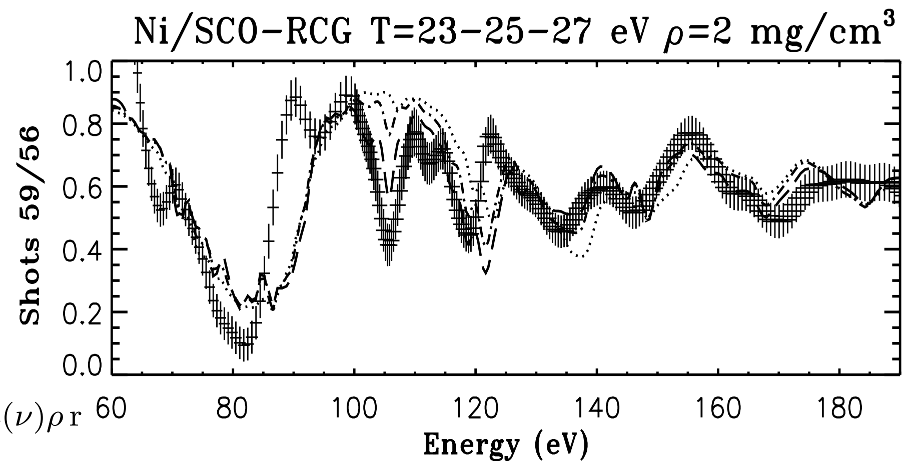
$$\frac{1}{\kappa_R} = \int_0^\infty \frac{W_R(u) du}{\kappa'(u)}$$

$$W_R(u) = \frac{15 u^3 e^{-u}}{\pi^4 1 - e^{-u}}$$

$$u = \frac{h\nu}{kT}$$

Experiments : results on NICKEL

T_{exp}= 24± 3eV
ρ_{exp}= 2 ± 1 mg/cm^3

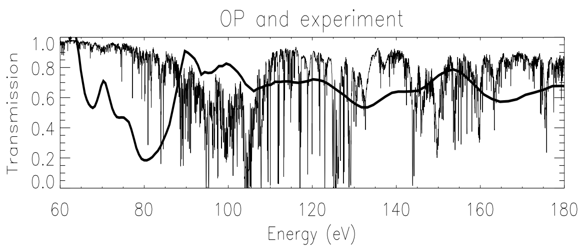


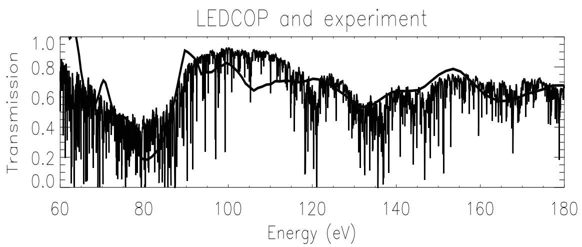
Experience & SCO-RCG
(23eV, 2mg)

Turck-Chièze et al., 2013
Turck-Chièze et al., 2014

1eV=11604 K

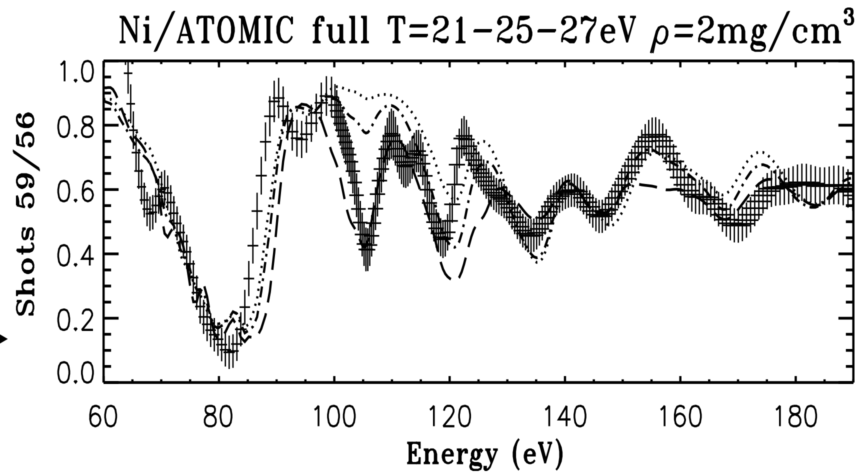
$$T(\nu) = \frac{I_\nu}{I_\nu \, \mathrm{ref}} = \exp^{-\kappa(\nu)\rho \, r}$$



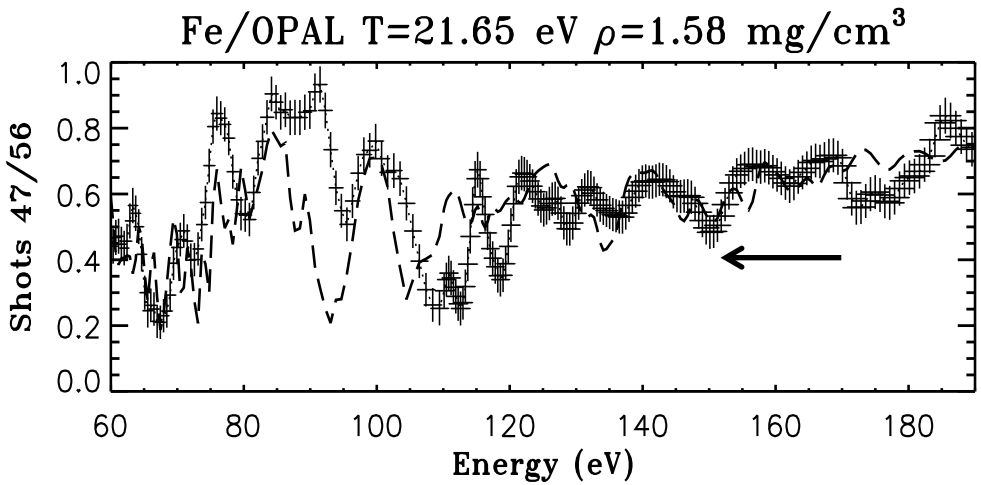


Experience & OP
← (23eV, 2mg)

Experience &
ATOMIC →

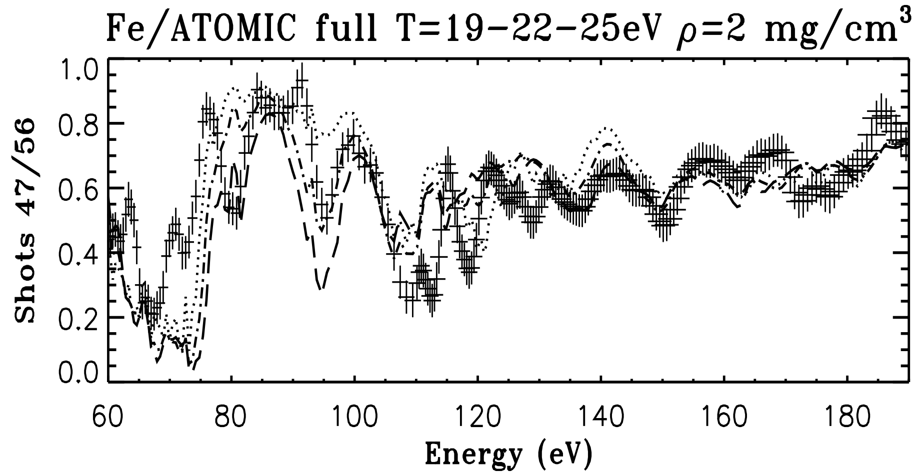


Experiments : results on IRON



Experience & OPAL
(21.65 eV, 1.58mg)

Experience & SCO-RCG, ATOMIC
(23 eV, 2mg)



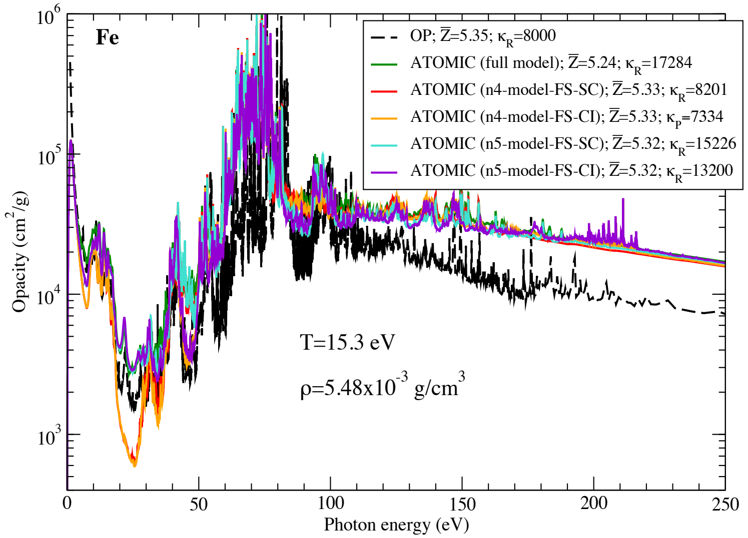
- Increase of the performance of the calculators→ Better opacity
- In the present situation : hybrid codes are good compromises
- Still two elements to exploit (Copper and Chromium)

Turck-Chièze et al., 2014

Turck-Chièze, Gilles, Le Pennec et al., 2014, ApJ, soon on ADS
Le Pennec et al., 2014a, Phys. Rev. E, in prep.

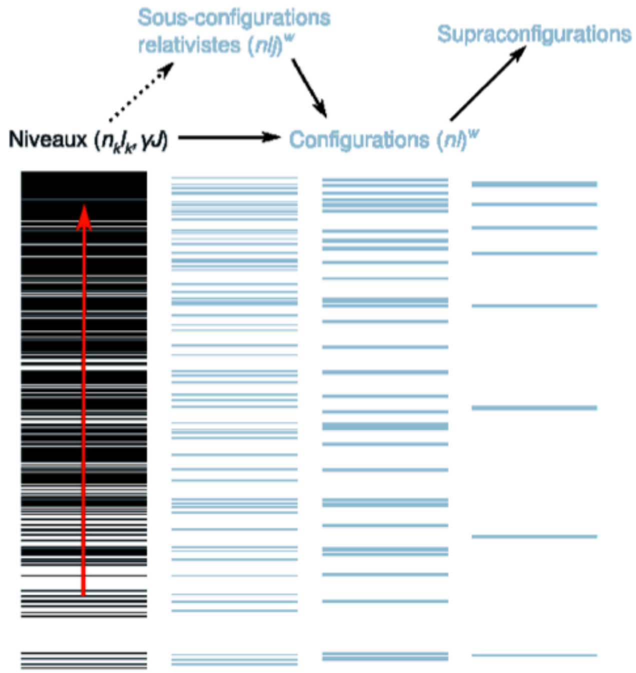
New calculations : comparisons

Turck-Chièze, Gilles, Le Pennec et al. ,HEDP,2013



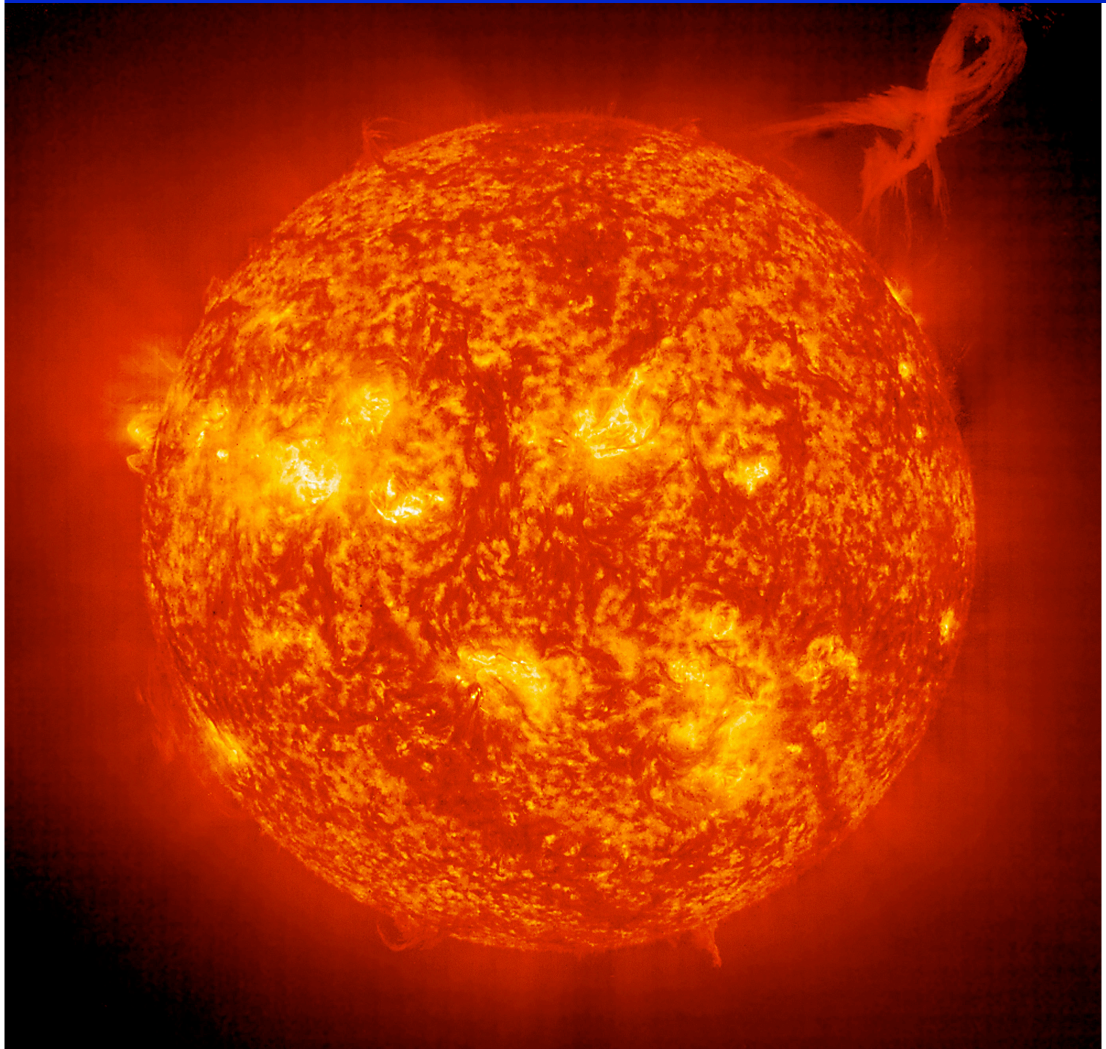
Comparisons at 15.3 eV and ρ=5.48 x 10^{-3} cm^{-3} (Turck-Chièze et al. 2014) between several ATOMIC options

➤ Hybrid codes SCO-RCG and ATOMIC Combines detailed treatment with statistical treatment in function of the transition



- Nickel : differences up to a factor 8 in Rosseland mean in the iron bump for OP
- Iron : differences up to a factor 2 in Rosseland mean values but still in discussion

Part II

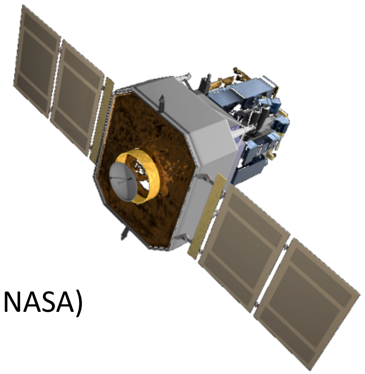


© NASA/ESA

Sun

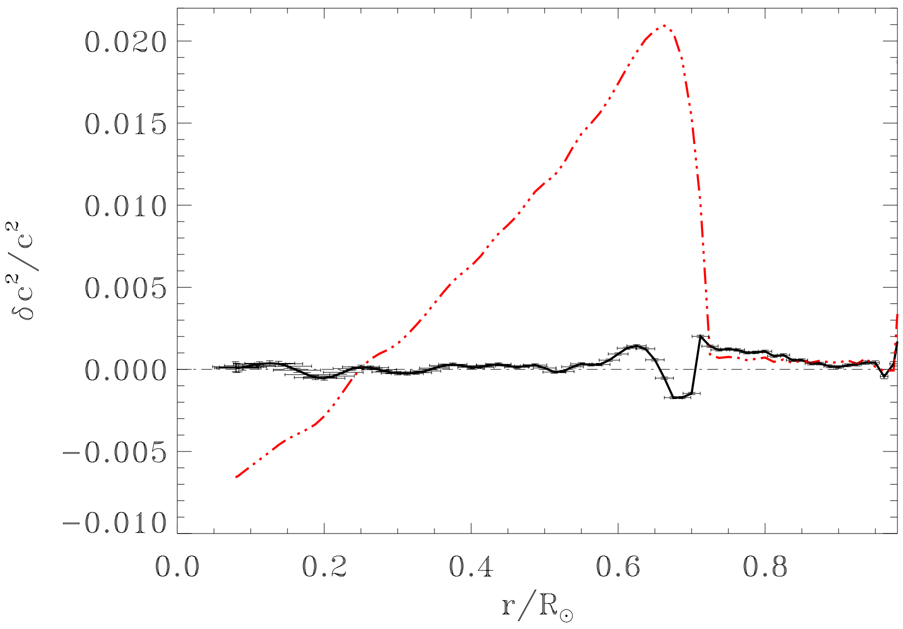
&

Solar-type stars



NASA SOHO (© NASA)

Problem to solve for Sun and solar-like stars



Relative difference between the squared of the sound speed coming from seismology (SoHO) and the standard model (red). The seismic model is in black continuous line with error bar coming from seismic observations. Adapted from Turck-Chièze et al. 2011

Discrepancies between the seismic observations, neutrinos and SSM predictions

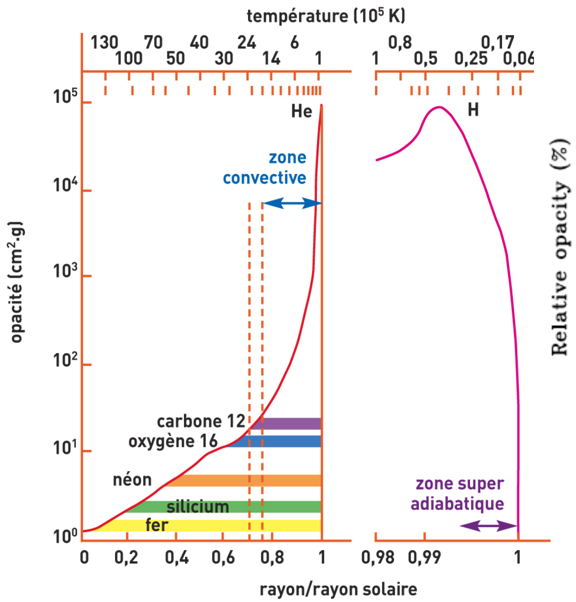
- Macroscopic processes in the radiative zone not taken into account in the energetic balance of the Sun ?

Turck-Chièze, Piau & Couvidat 2011, Lopes & Turck-Chièze, ApJ lett 2014

$\Delta E/E < 5\%$; core fluctuations $\Delta T/T < 0.05\%$

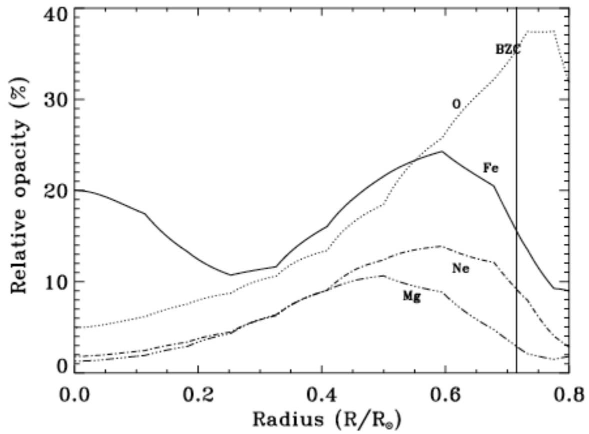
- Radiative transfer calculations not correctly taken into account
  - Rosseland mean value ?
  - Treatment of the radiative acceleration which limits gravitational settling and leads to incorrect internal abundances

The contributors to opacity

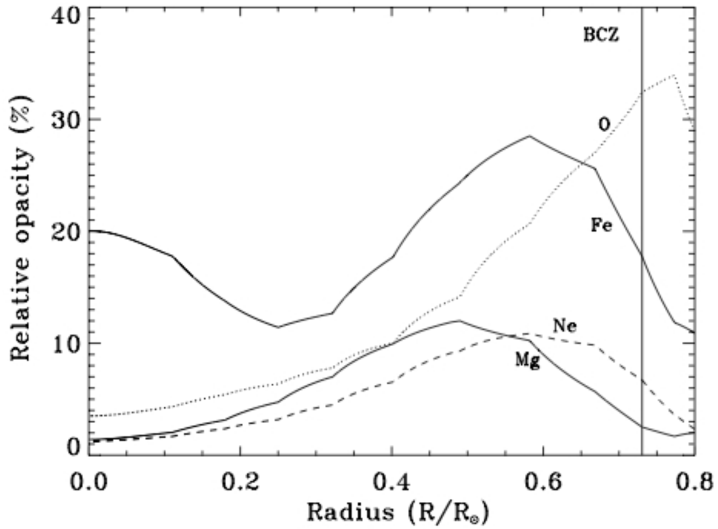


Rosseland mean evolution along the solar profile. from Turck-Chièze et al. 1993

GN 1993



Asplund et al.2009



Z/X from 0.025 to 0.018

Relative contribution of the most important heavy element to the total opacity (including H and He) for the internal conditions of the Sun, using OPAL opacities (Turck-Chièze et al. 2010)

The most important contributors to global opacity

- Hydrogen
- Helium

most abundant

- Iron
- Oxygen
- Silicon

only few % but individually contributing up to 30%

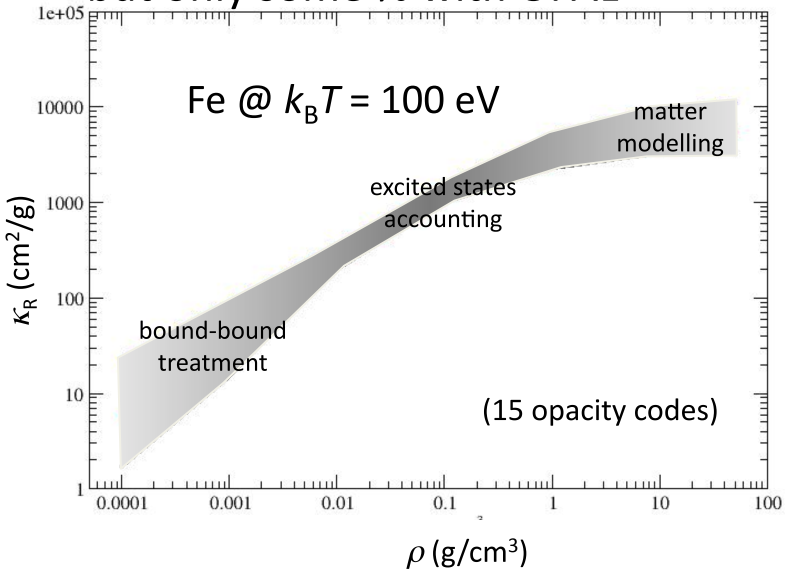
Reliability? No experimental validation until now on plasma effects and atomic physics...

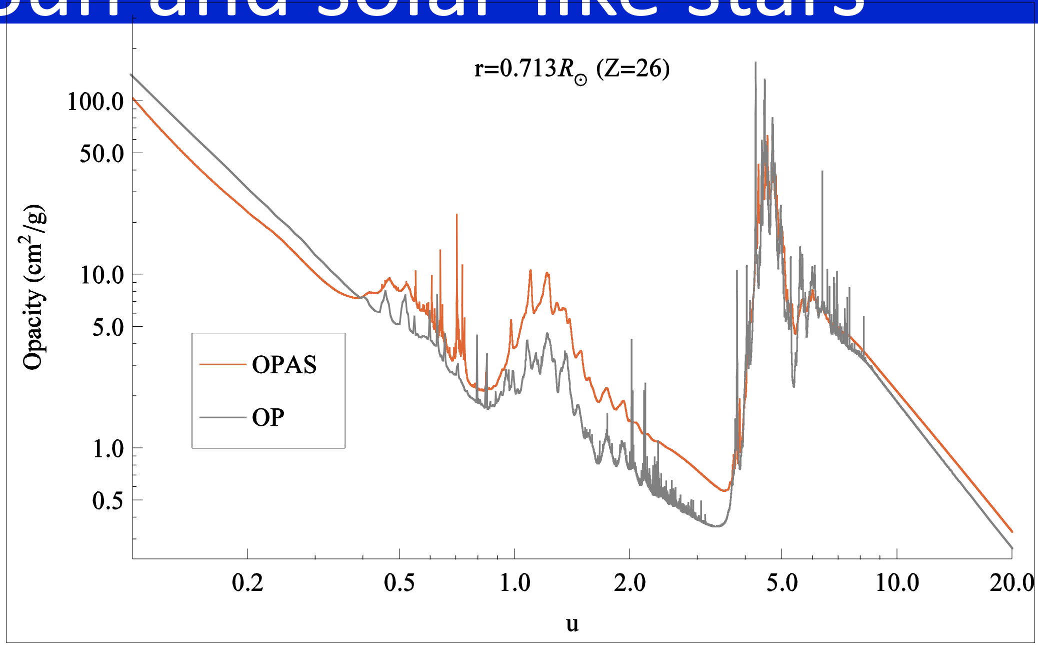
The OPAS code: new calculations for Sun and solar-like stars

Blancard, Cosse, Faussurier 2011

22 elements, 21142 points
1 Tbytes of information
32 billions of lines

First results large differences with OP but only some % with OPAL





Reliability? No experimental validation until now on plasma effects and atomic physics...

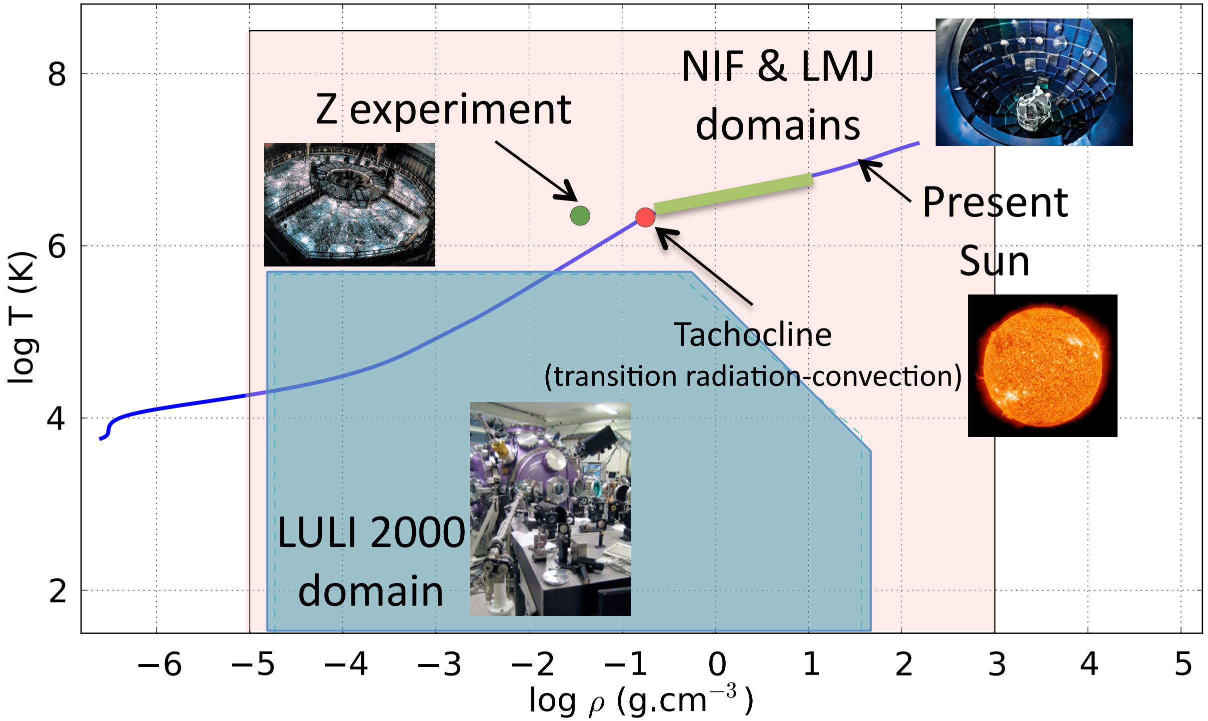
Experimental Challenge : Reproducing solar conditions at LTE

Solar radius ($r/R_\odot$)	T (eV)	Ne (cm^{-3})
0.5	340	8×10^{23}
0.55	295	7.8×10^{23}
0.6	270	2.5×10^{23}
0.7	200	1×10^{23}

Temperature and free electron density at different depths of the Sun (MESA models and Couvidat et al., 2003)

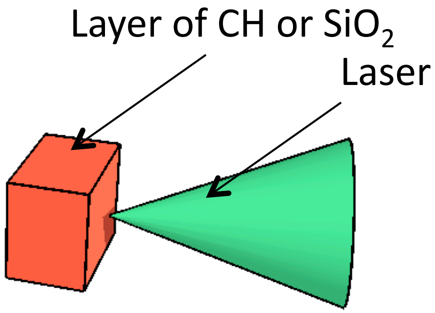
Domain of temperature and density of the Sun, the National Ignition Facility (LLNL, USA) (pink). The green point represent the conditions reached by the Z pinch experiments on iron : 4 x 10^{22} cm^{-3} and 195 eV. Adapted from the NRC Report : High Energy Density Physics : The X-Games of Contemporary Science

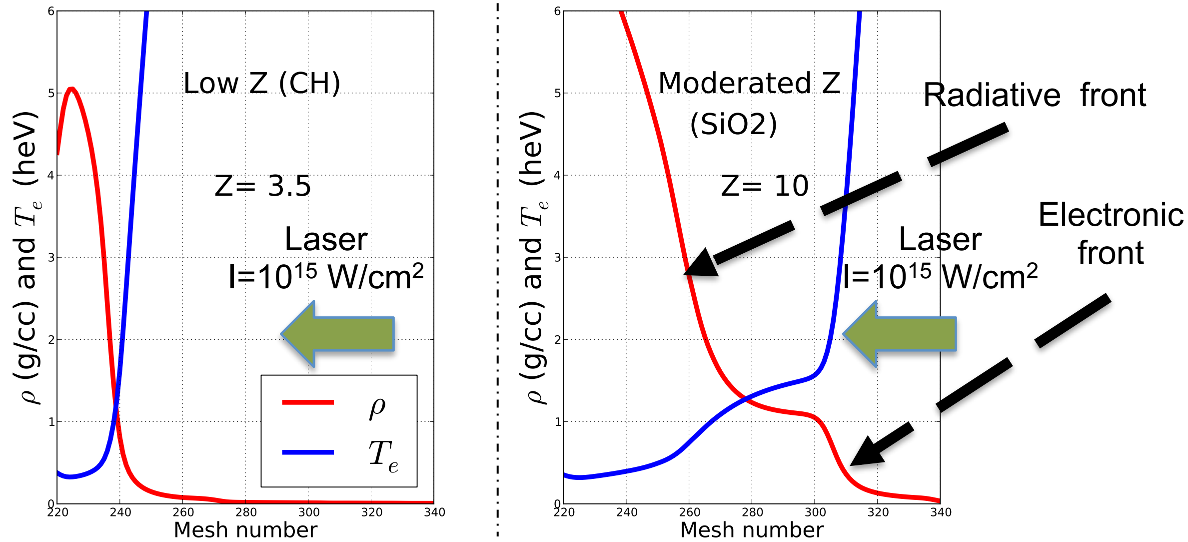
1eV=11604 K



Double Ablation Front (DAF)

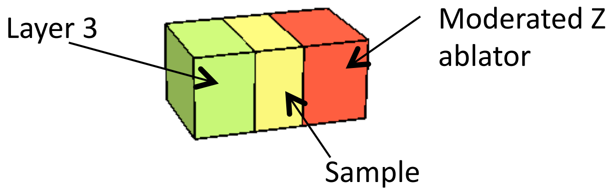
Le Pennec et al. 2014





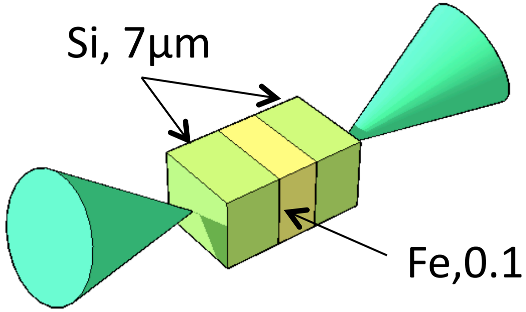
- The energetic photons emitted in the corona (high T, high ρ) are absorbed in the opaque region at the base of the thermal wave, creating an additional ablation front
- Use to limit gradients in the sample

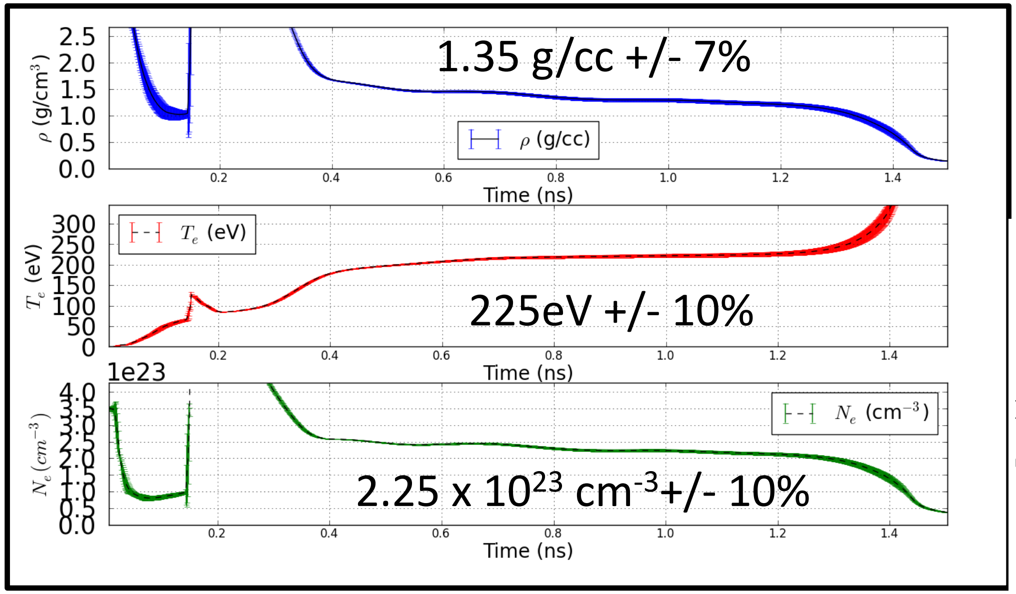
Sanz et al., 2009
Drean et al., 2010
Yañez et al., 2011

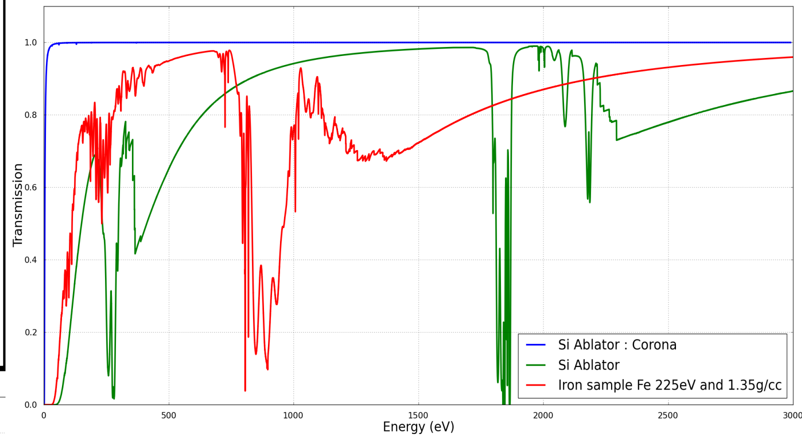


Results : two symmetrical lasers irradiation

Two quads : $I_1 = I_2 = 1.5 \times 10^{15}$ W/cm^2

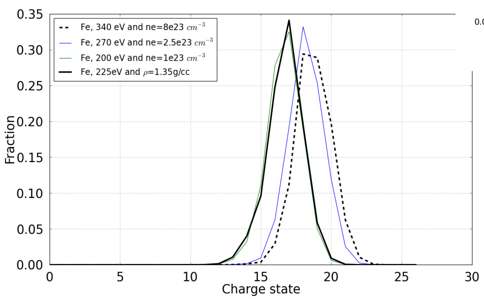






Expected transmission

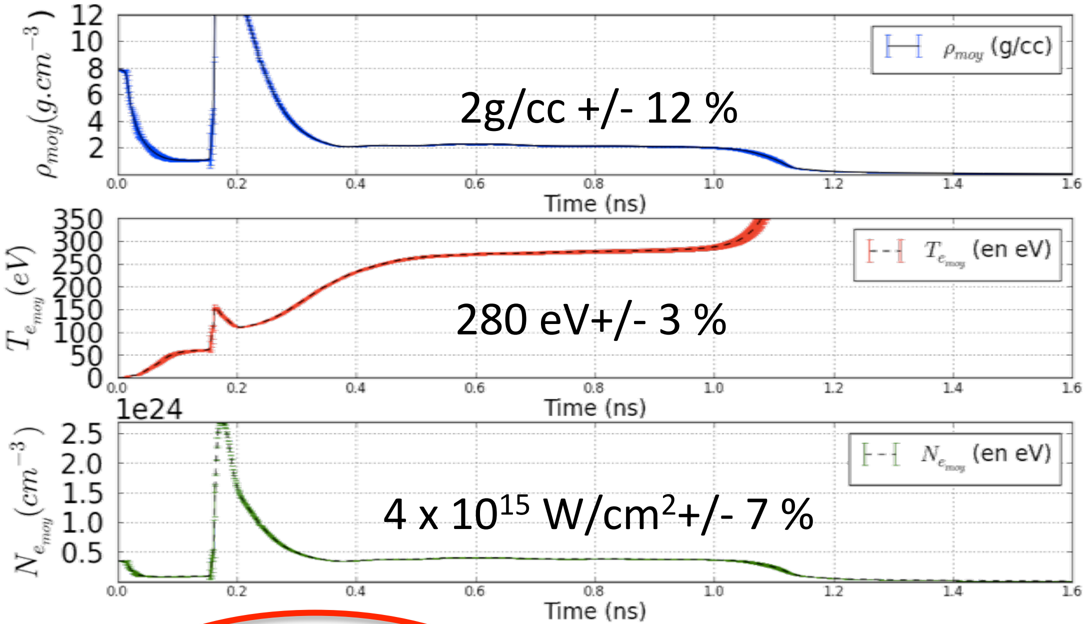
Spatial gradient in the sample
- ρ : 6%
- T : 5%
- N_e : 5%

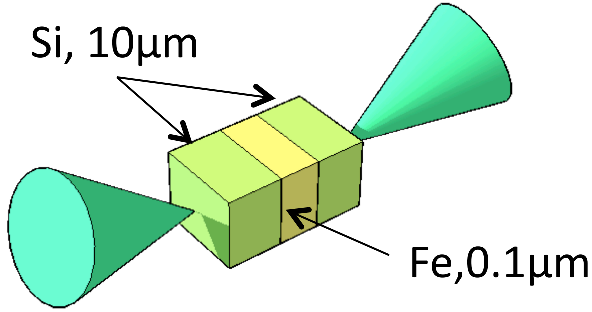


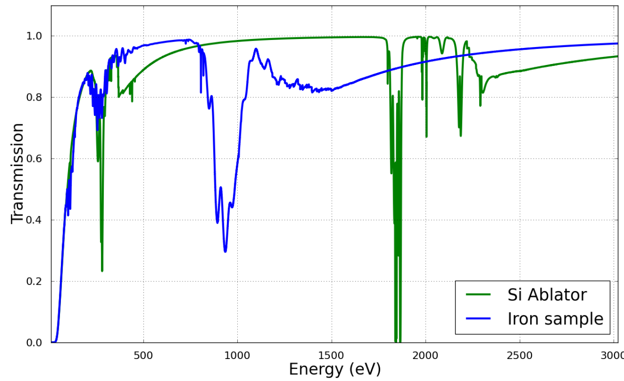
← *Charge state distribution*

Results : two symmetrical lasers irradiation

Two quads : $I_1=I_2=4 \times 10^{15}$ W/cm^2







Expected transmission

Spatial gradient in the sample
- ρ : 1.5%
- T : 1.5%
- N_e : 1.6%

SUMMARY

- **Discrepancies between seismic observations and predictions given by OP and OPAL lead us to investigate the opacities of the stellar radiative zones.**
- **Still 2 years for our ANR**

- **Our work on the iron bump in ß-Cephei shows that :**

➤ A revision of iron and nickel calculations is necessary
➤ All transitions must be included (not often done)
➤ Experiments show a reasonable agreement with ATOMIC and SCO-RCG calculations.
➤ Increase is waited for nickel, iron case in discussion, new tables will be prepared

- **For Sun and solar-type radiative interiors :**
- New tables will be available soon but we need to qualify them
- We study a new approach to create density and temperature conditions of half of the solar radiative zone.
- A proposal on NIF is in preparation, another one will be done for LMJ

- **This activity is important for asteroseismology** as one needs to know if the model hypotheses and ingredients are correct to determine the age of stars and …

- **In parallel we need to continue to observe the solar radiative zone to add new constraints: improving accuracy is extremely useful + time dependent**