High-accuracy Laboratory Atomic Spectroscopy for Astrophysics

CompAS annual meeting 2025
Lund University

Henrik Hartman and collaborators
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https://mau.se/en/persons/henrik.hartman/

Collaborators

Laboratory spectroscopy (Malmö and Lund universities):
Hampus Nilsson, Namrata Nath, Madeleine Burheim, Rickard du Rietz (Malmö),
Lars Engström, Hans Lundberg (Lund)

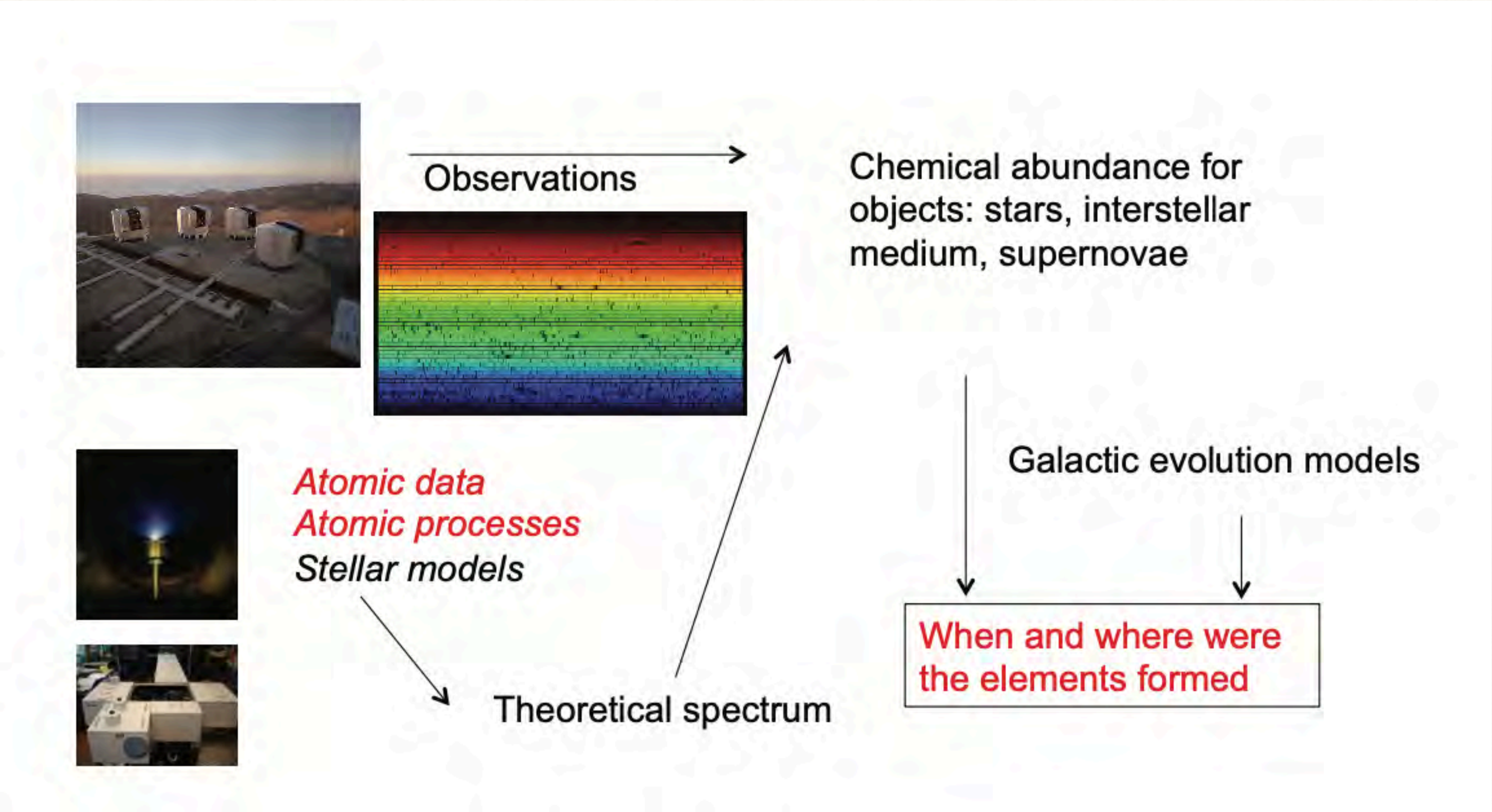
Calculations (GRASP2k and ATSP2k):
Per Jönsson, Jörgen Ekman, Stefan Gustafsson (Malmö), Gediminas Gaigalas (Vilnius)

DESIREE
Paul Martini, Henning Schmidt (Stockholm), Uldis Berzins (Riga), Janis Snickeris (Gothenburg)

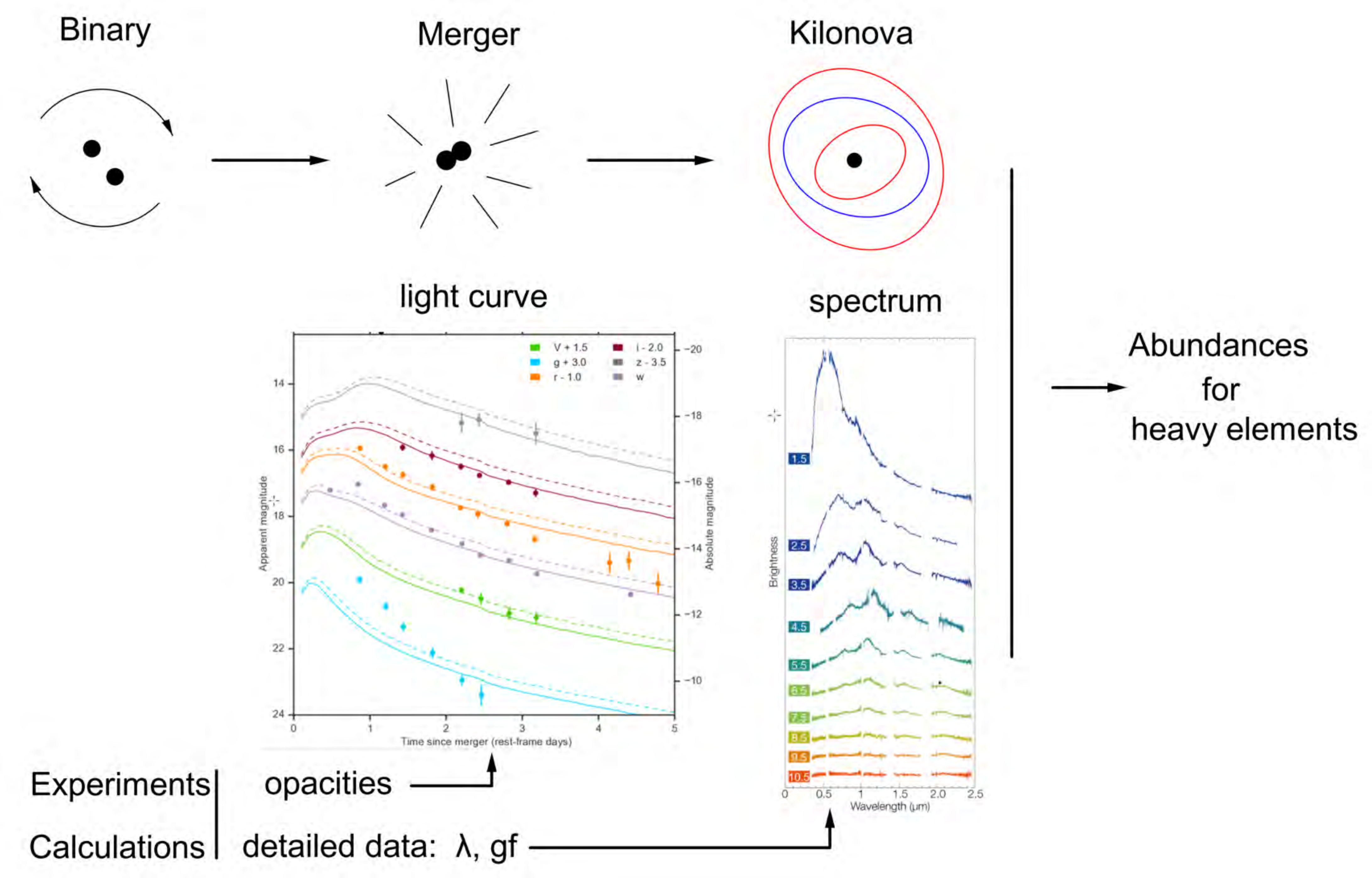
Collaborations:
LUMCAS: Henrik Jönsson, Nils Ryde, Brian Thorsbro, Tomas Brage
CompAS, Imperial College London, NIST, Valladolid University, Uppsala University

Vetenskapsrådet
Gyllenstiernska Krapperupsstiftelsen
CARL TRYGGERS STIFTELSE FÖR VETENSKAPLIG FORSKNING

Principle of abundance analysis



Binary merger and kilonovae



Different needs of atomic radiative data

The need of atomic data in terms of parameters and quality is dependent on the application:

Stellar abundances - individual lines: wavelength, accurate oscillator strengths, line structure (hyperfine structure)

Exoplanet atmosphere detection - wavelength, approximate line strength

Kilonova light curves - broad opacity, completeness

Kilonova spectra - rather accurate wavelength, rather accurate strengths

The near-infrared region (1-5 microns) is particularly empty of atomic data.
This was the case for the ultraviolet region before the *Hubble Space Telescope* launch in 1990s.

Oscillator strengths *f* and transition rates *A*

The important parameter for quantitative astrophysical analysis is

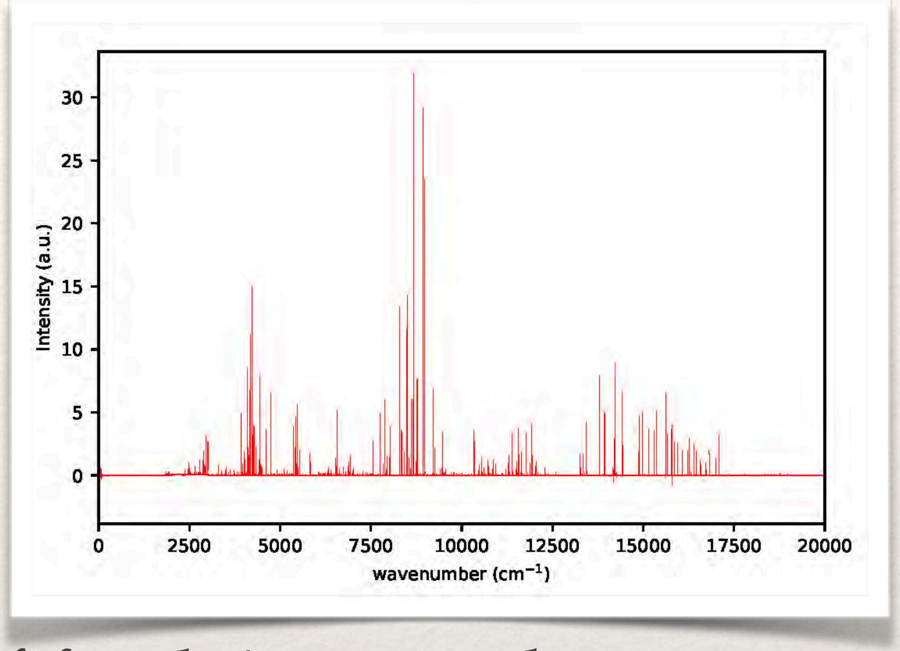
- oscillator strength f for absorption (e.g. stellar atmospheres) or
- transition rate/probability A (emission sources, e.g. nebulocites and low-density plasmas)

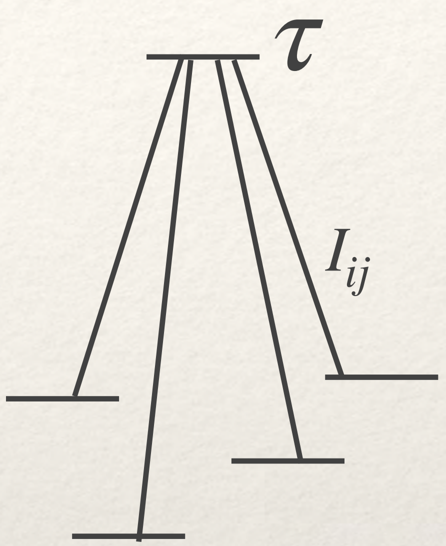
Experimental measurements of f and A are similar:

- Oscillator strength f can be measured from absorption in a plasma from Absorption $\propto n_l \cdot g_l \cdot f$
- transition rate A is measured from emission measurements and derived from Emission $\propto n_u \cdot g_u \cdot A_u$
- To derive absolute f and A, the population must be known.

Oscillator strengths *f* and transition rates *A*

$$A = \frac{BF_{ul}}{\tau_u} \qquad \text{where } BF_{ul} = \frac{I_{ul}}{\sum_l I_l}$$





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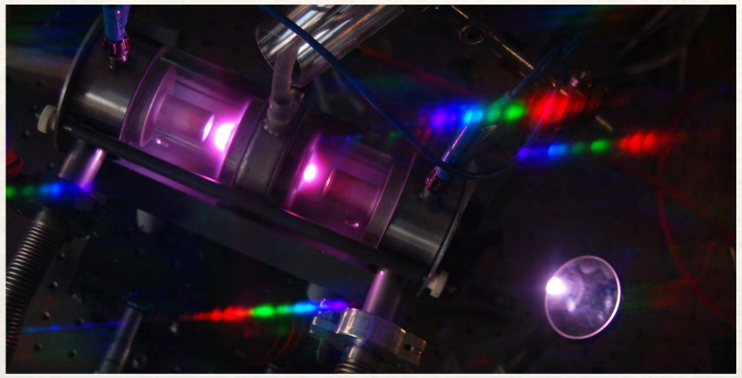
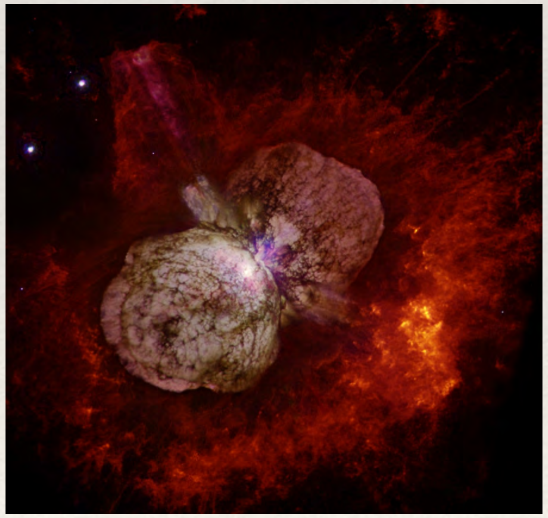
Our Laboratory Astrophysics program



FTS and HCDL,
emission

LIF laboratory, Physics@LU
Lifetimes

Soleil synchrotron
VUV absorption

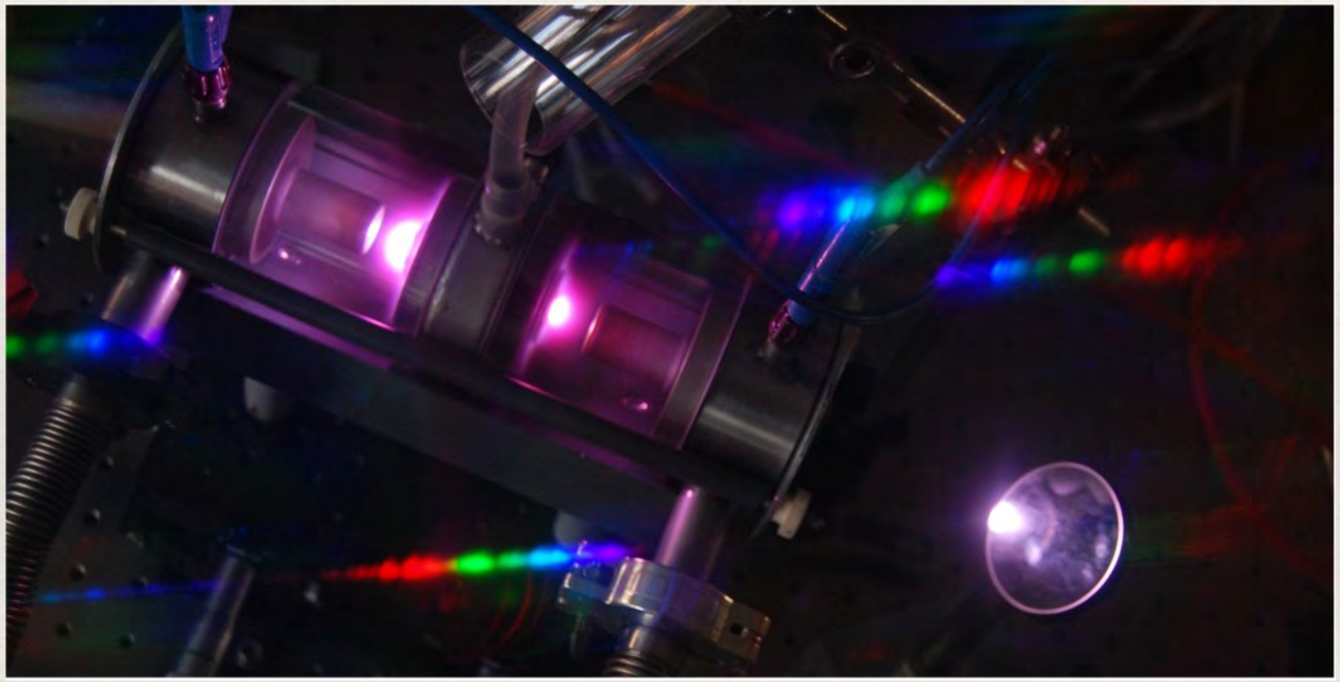


Eta Carinae, HST and JWST
Forbidden lines

DESIREE Stockholm University
Metastable lifetimes

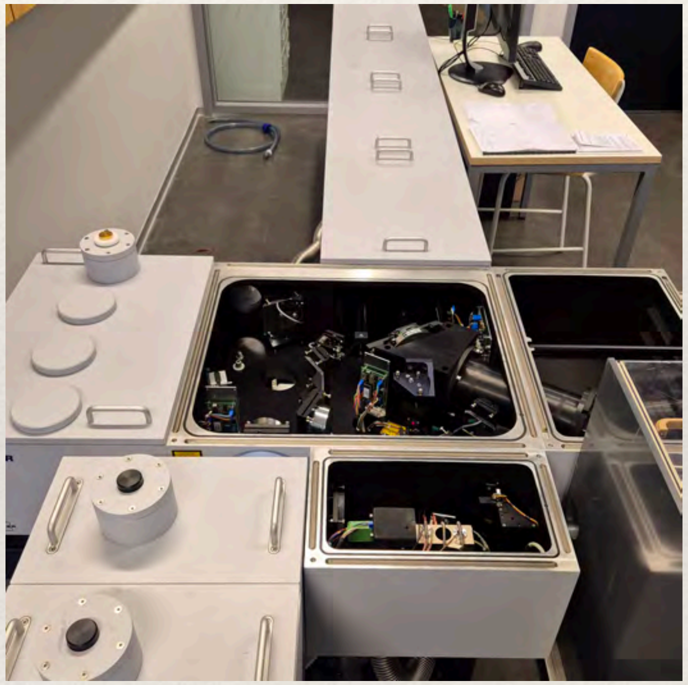
Emission intensity measurements

Light source
Hollow cathode discharge lamp



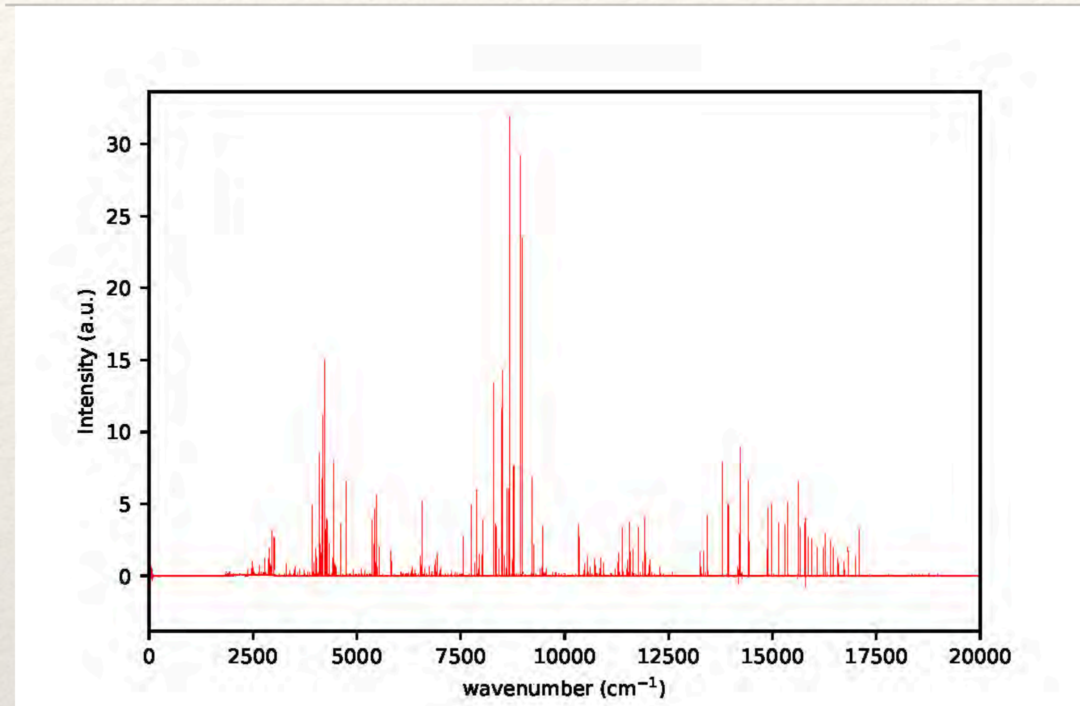
Plasma with neutral and singly ionized atoms

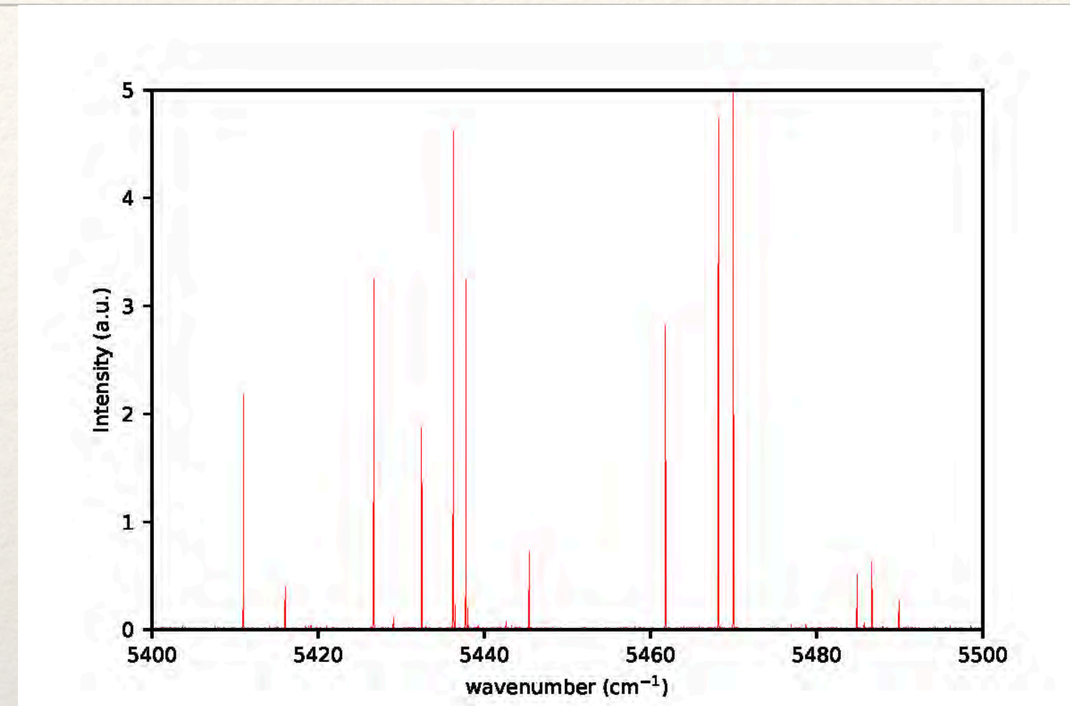
Detector
Fourier transform spectrometer

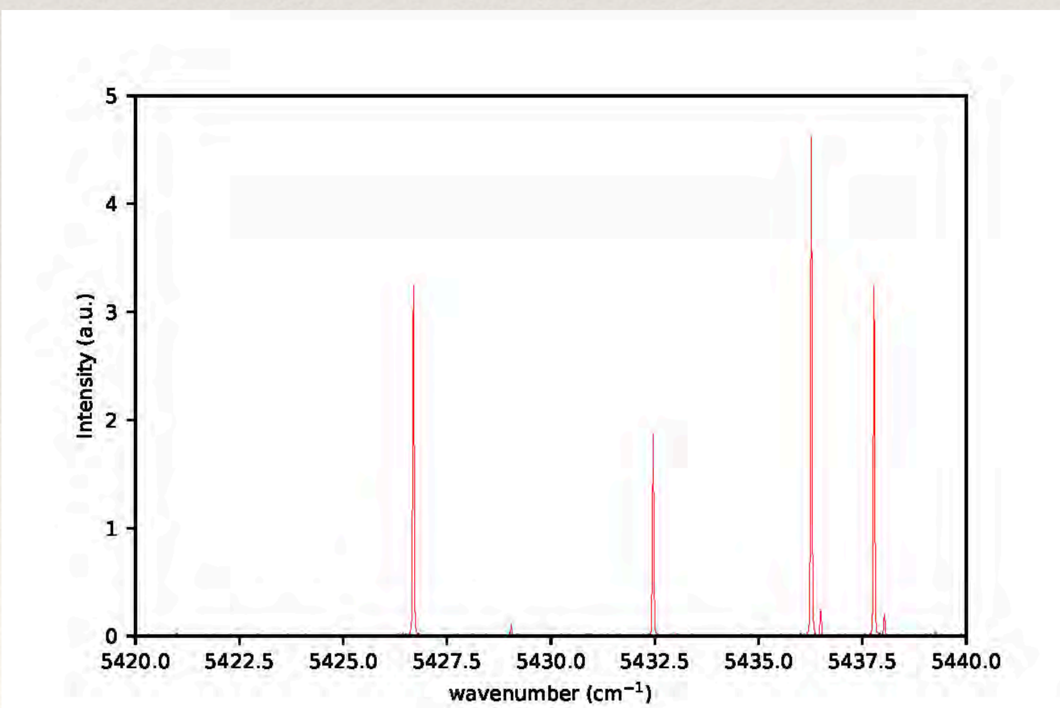


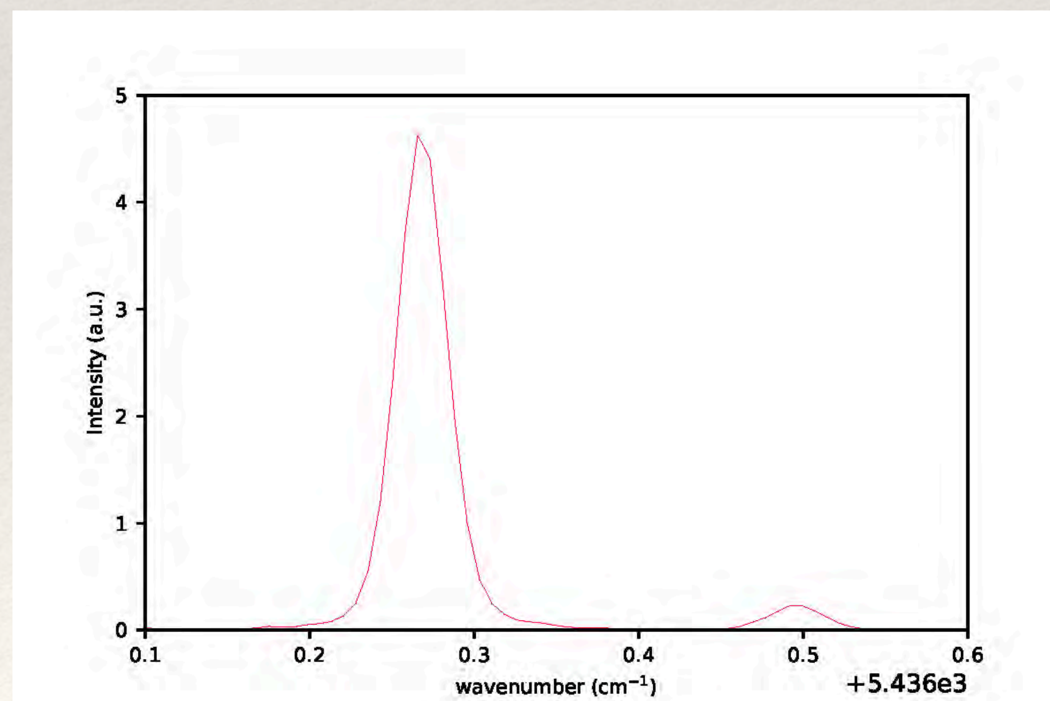
Near-IR and optical wavelengths
Resolving power $R=10^6$
Wavelength calibration about $1:10^7$

Emission spectrum of a Cerium discharge



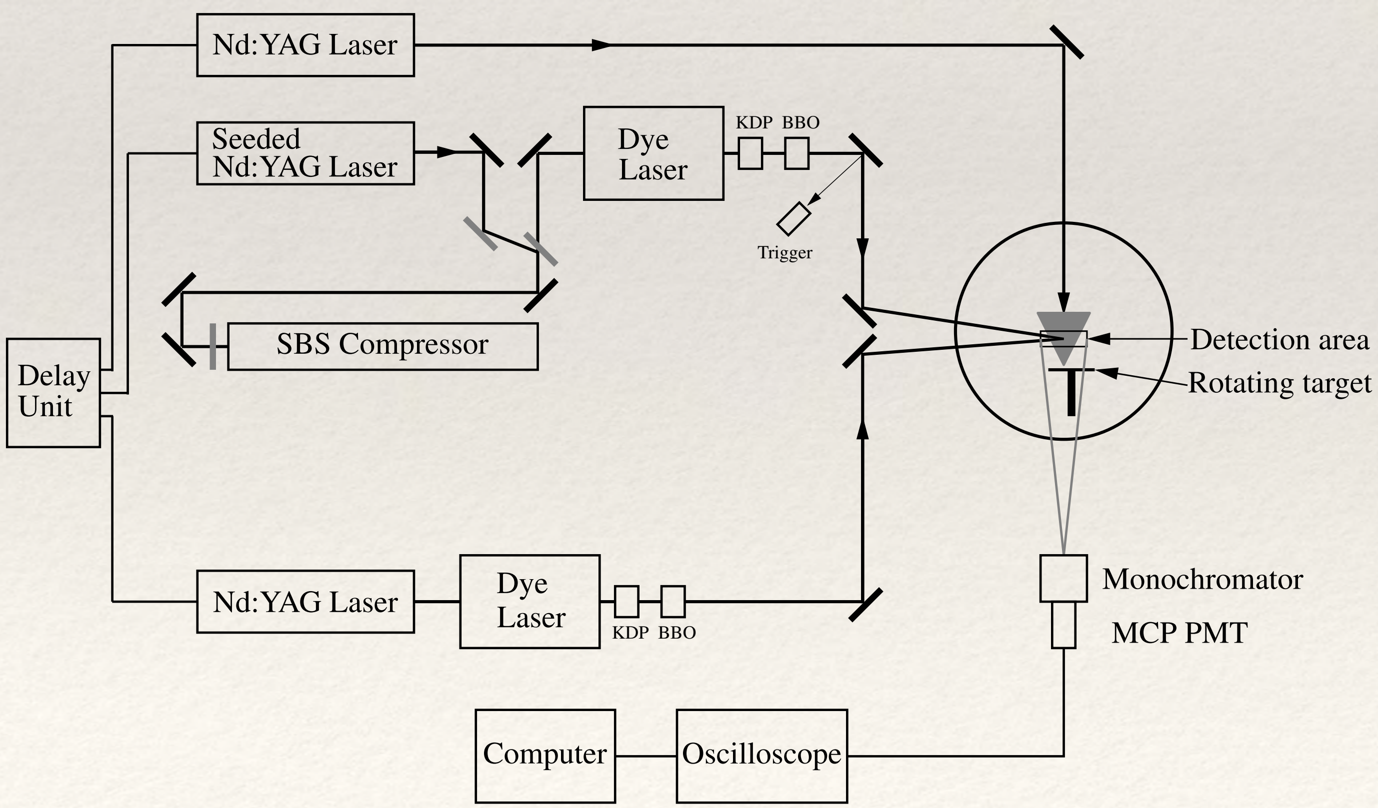


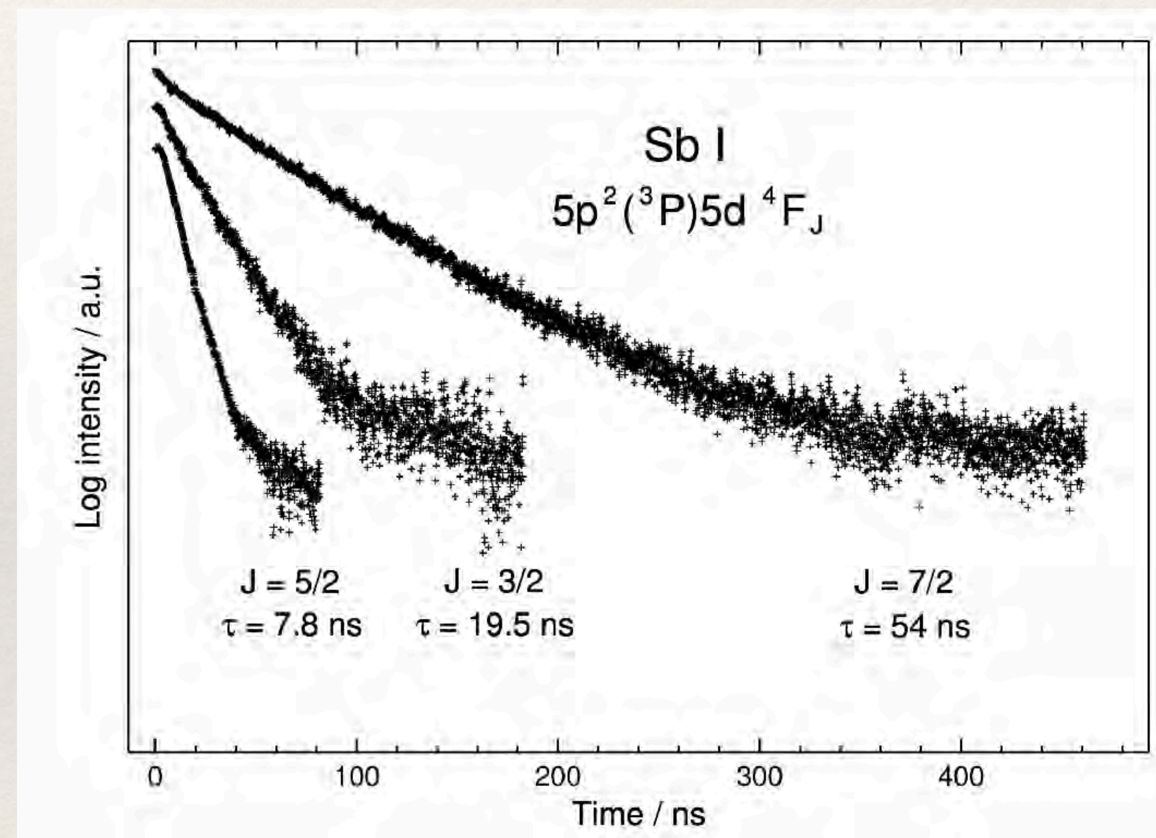




Spectra by M.Burheim

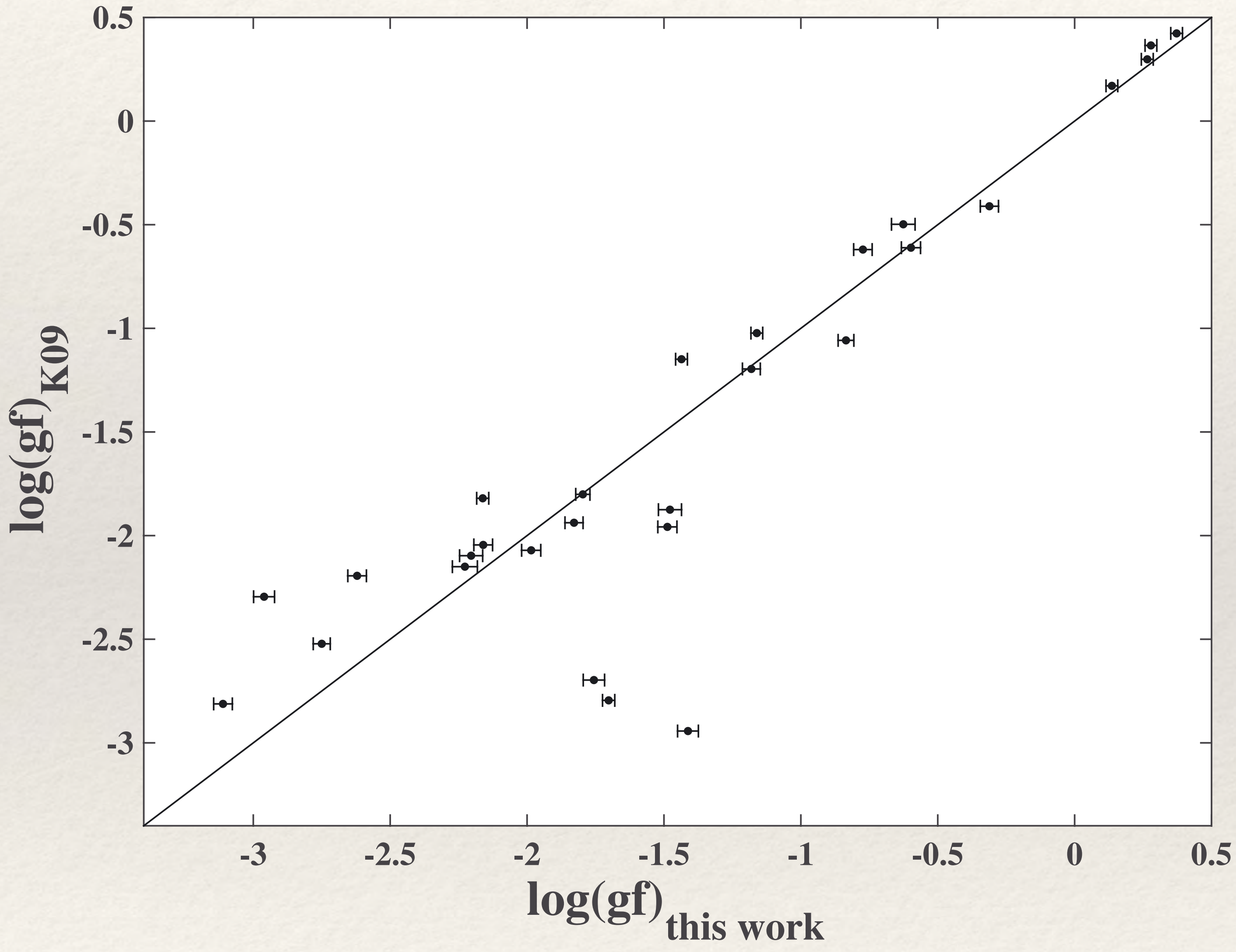
Laser induced plasma probed with short pulses (1ns)





Hartman et al, (2010)

Results for Sc I

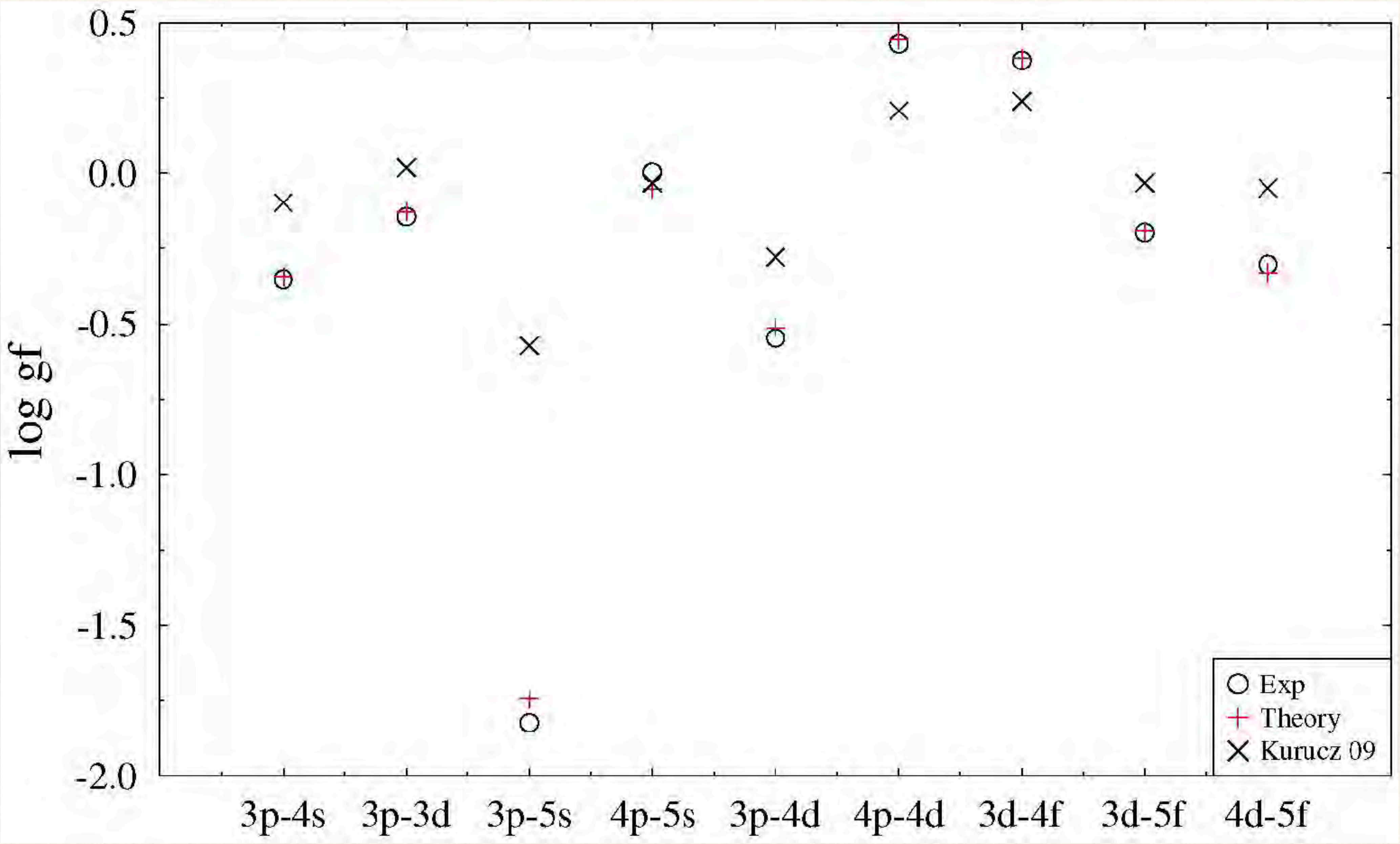


The experimental results are compared to the calculations by Kurucz (2009)

Lifetimes and spectra for Y I and La I have been measured are being analysed
They share a similar atomic structure

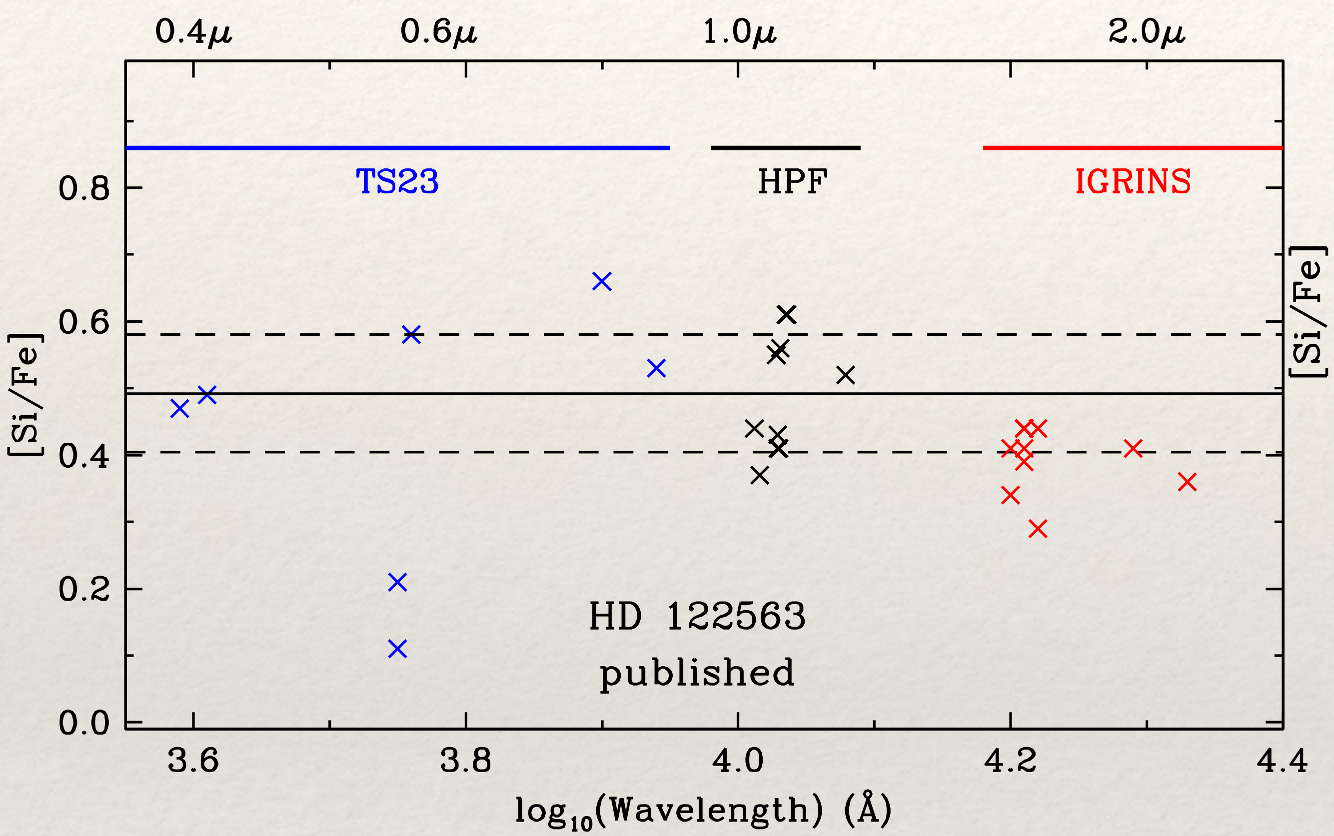
Pehlivan et al., (2015)

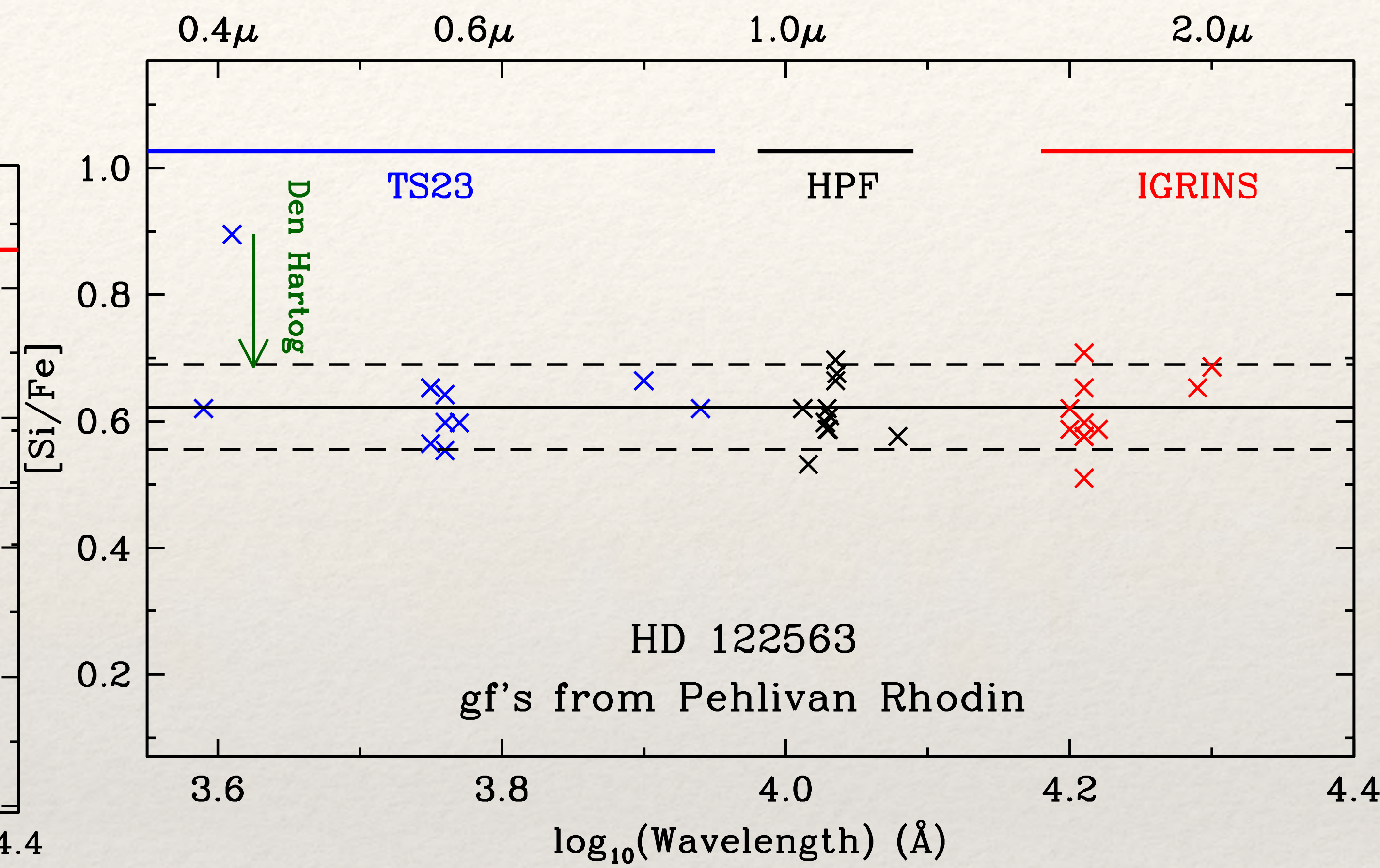
Results for Magnesium, Mg I



Mg I (Pehlivan Rhodin, et al., 2017)

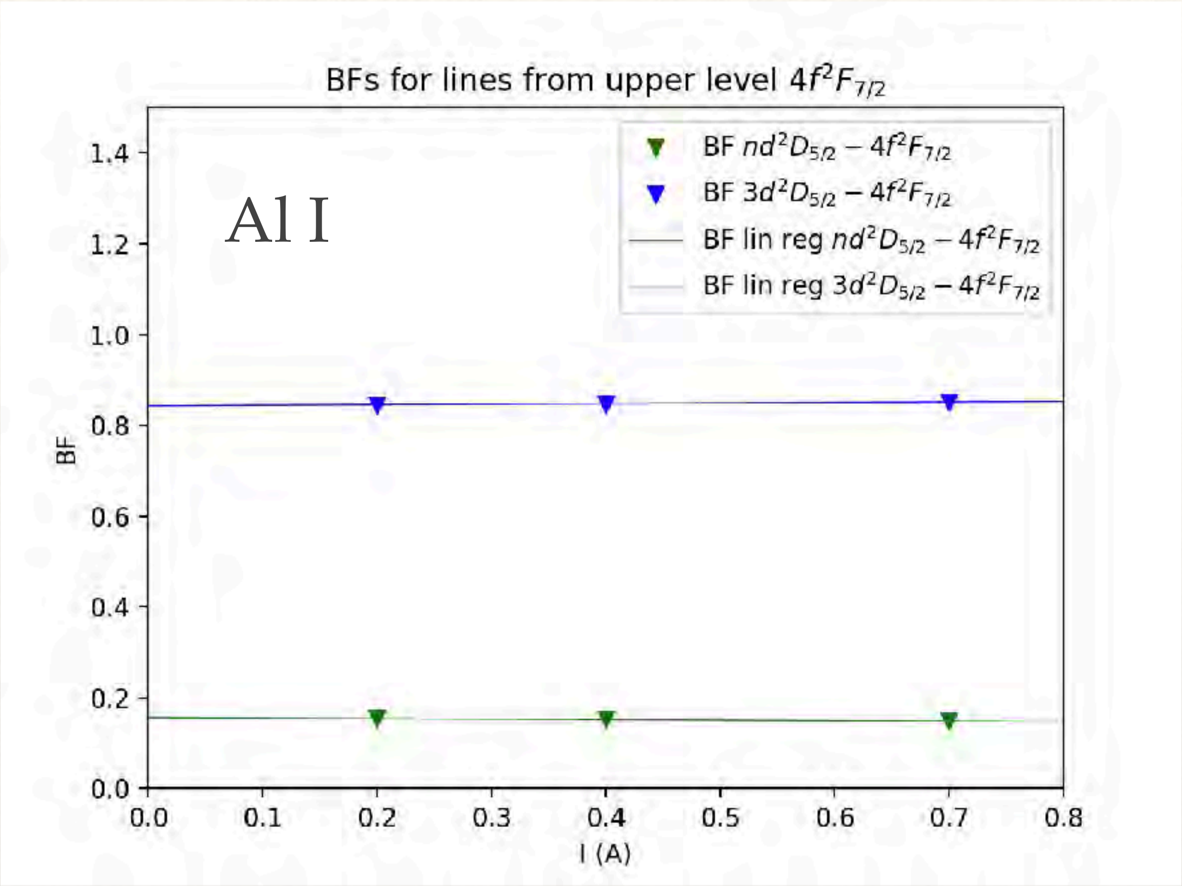
Results Si I and II

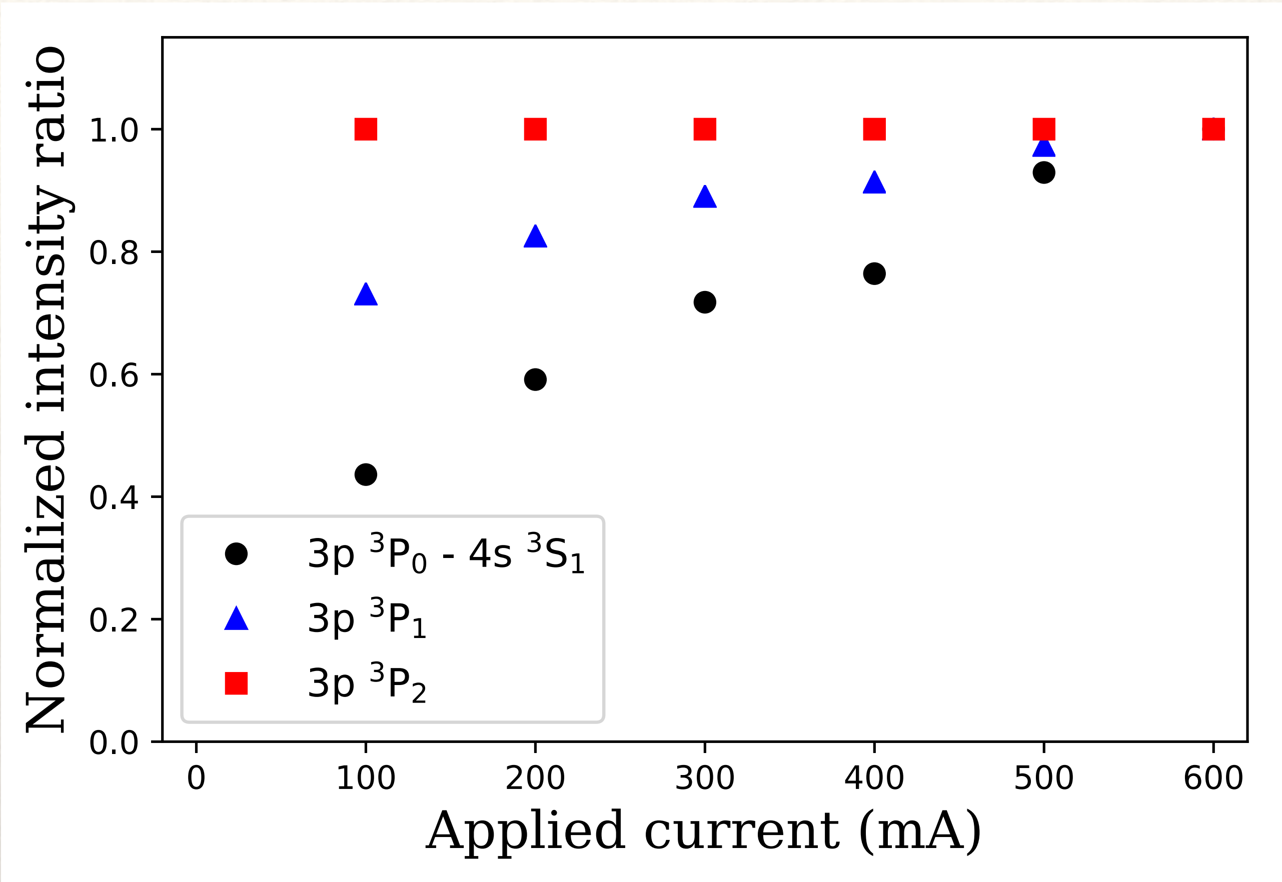




C. Sneden, private communication
Pehlivan Rhodin et al., 2024

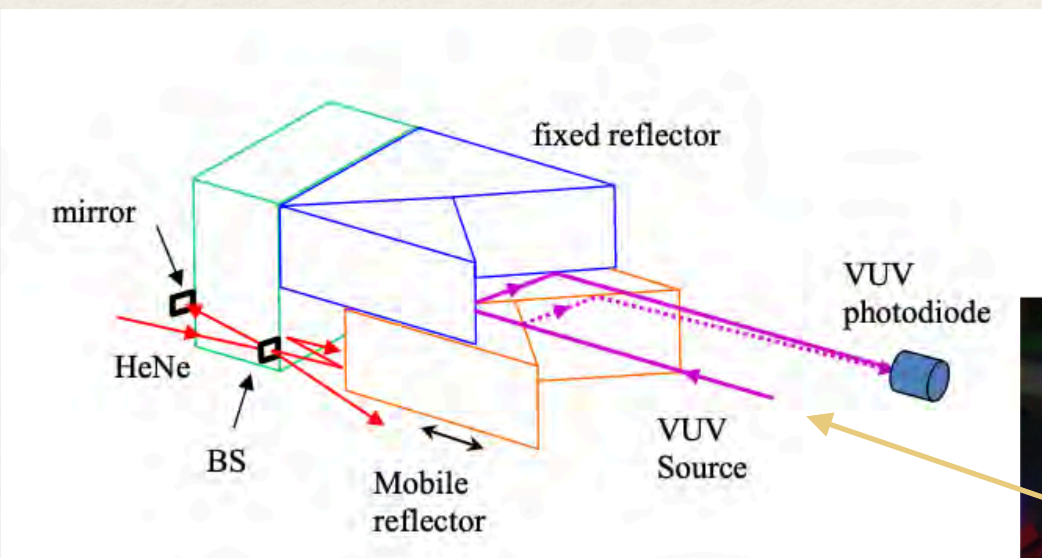
Radiative transfer effect in the discharge - self absorption

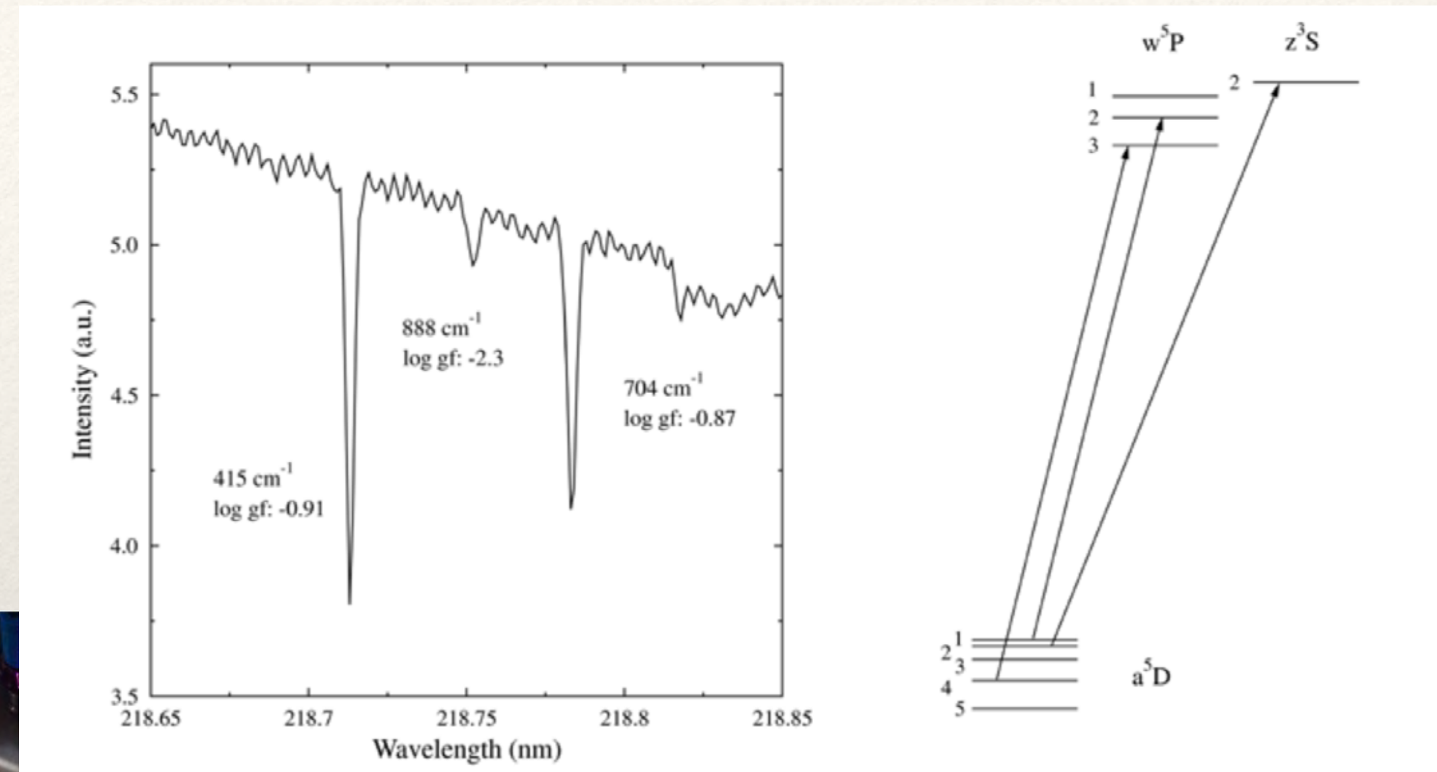


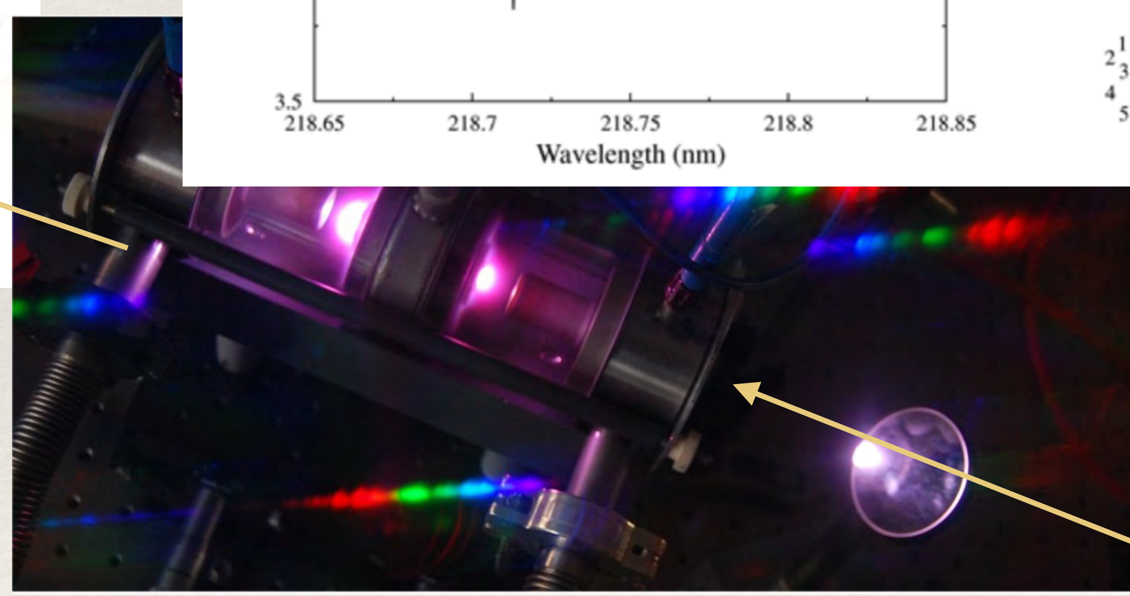


Burheim et al. 2023

Absorption measurements using synchrotron light







Parity forbidden lines: M1 and E2

An important class of infrared lines are parity forbidden transitions (E2 and M1), observed in nebula and low density plasmas.

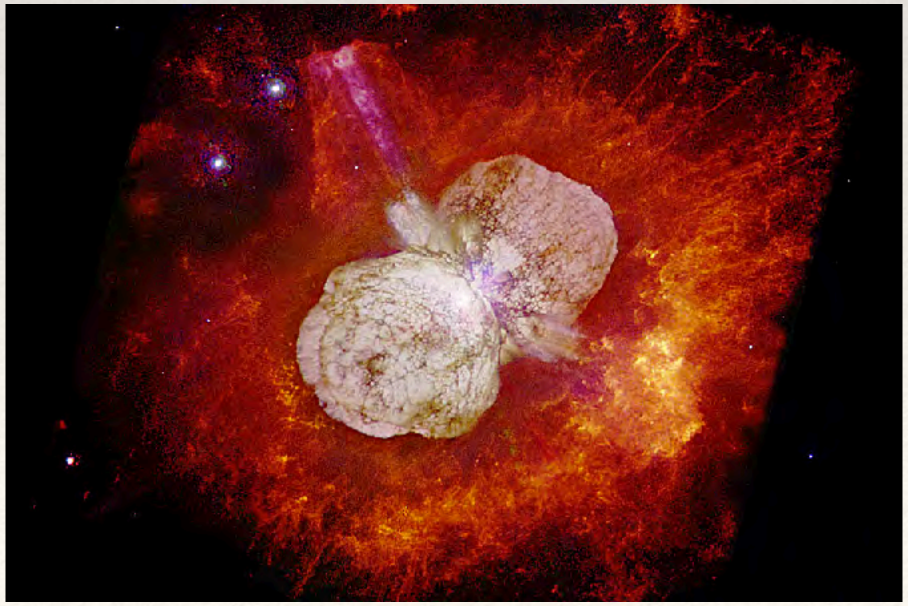
Low transition rates (A is around 1 s^{-1})

Long radiative lifetimes (several seconds)

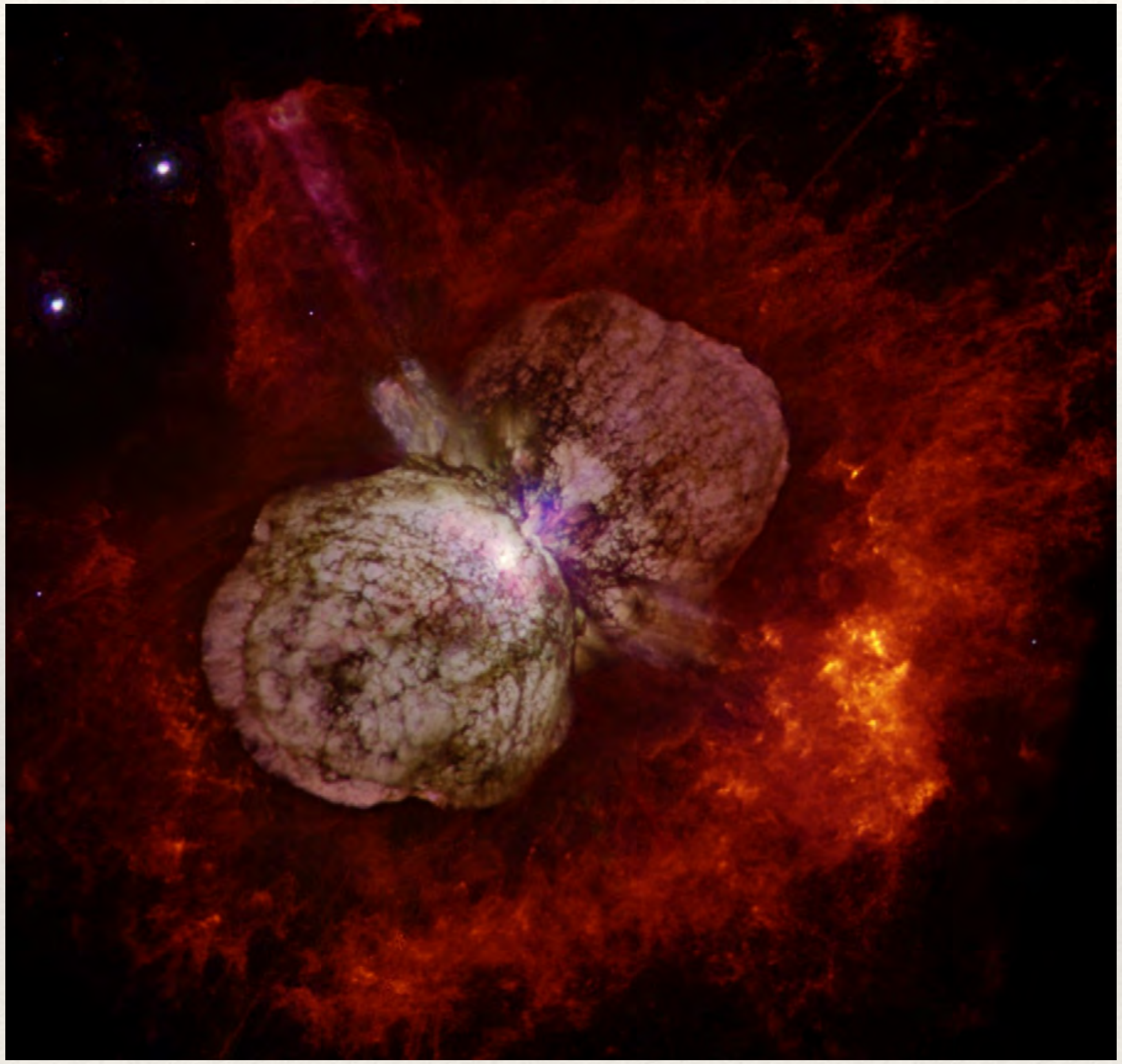
Sensitive to collisions

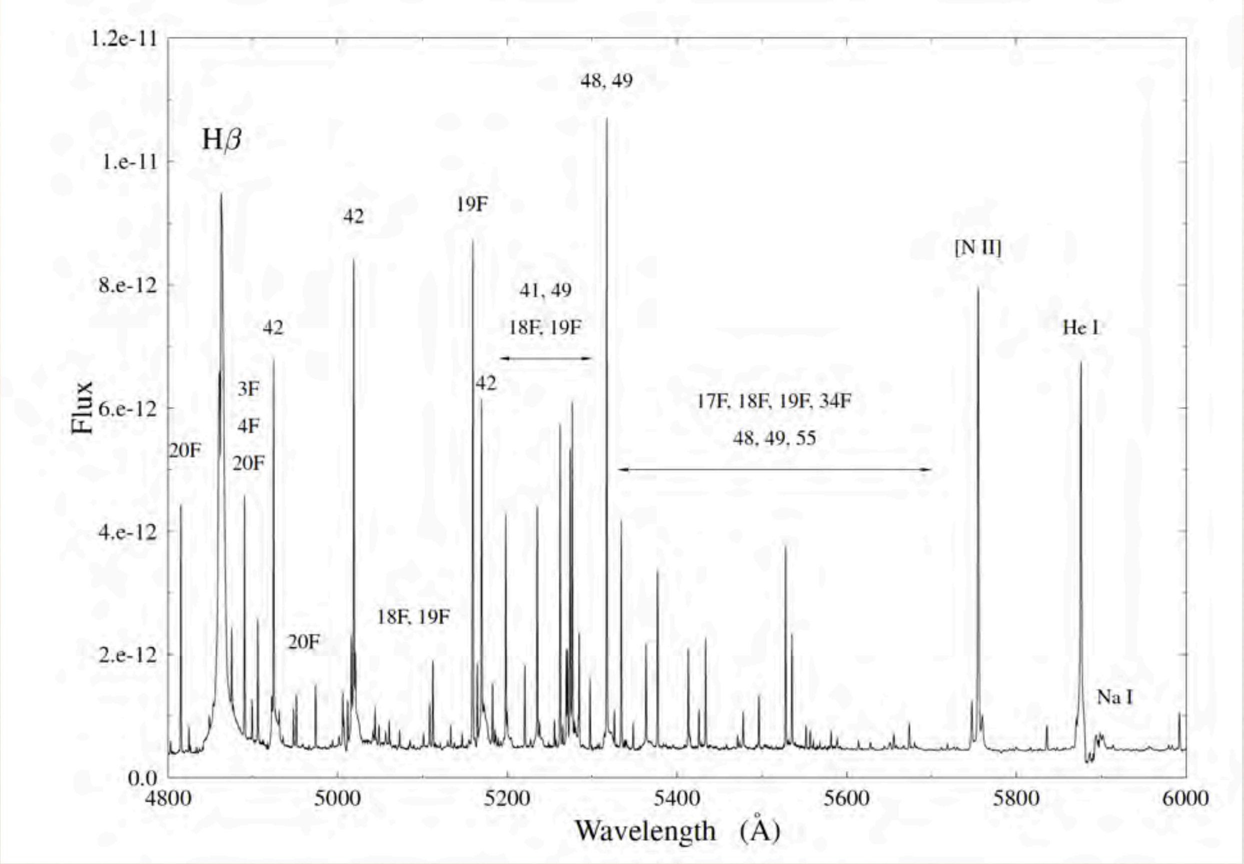
$$A = \frac{BF_{ul}}{\tau_u} \quad \text{where BF} = \frac{I_{ul}}{\sum_l I_l}$$

Have relied on calculated transition rates, but can be measured using Laser Induced fluorescence methods at storage rings (e.g. DESIREE @ Stockholm university, Sweden) combined with astronomical observations of low-density plasmas (Eta Carinae).



Eta Carinae - a true astrophysical laboratory

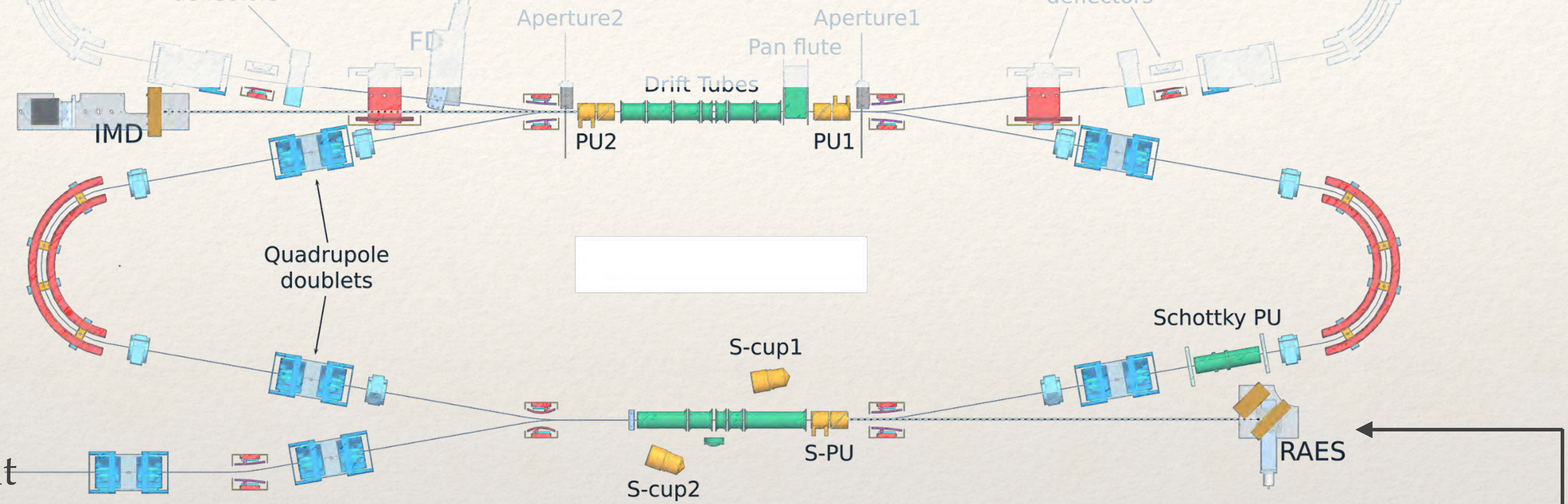


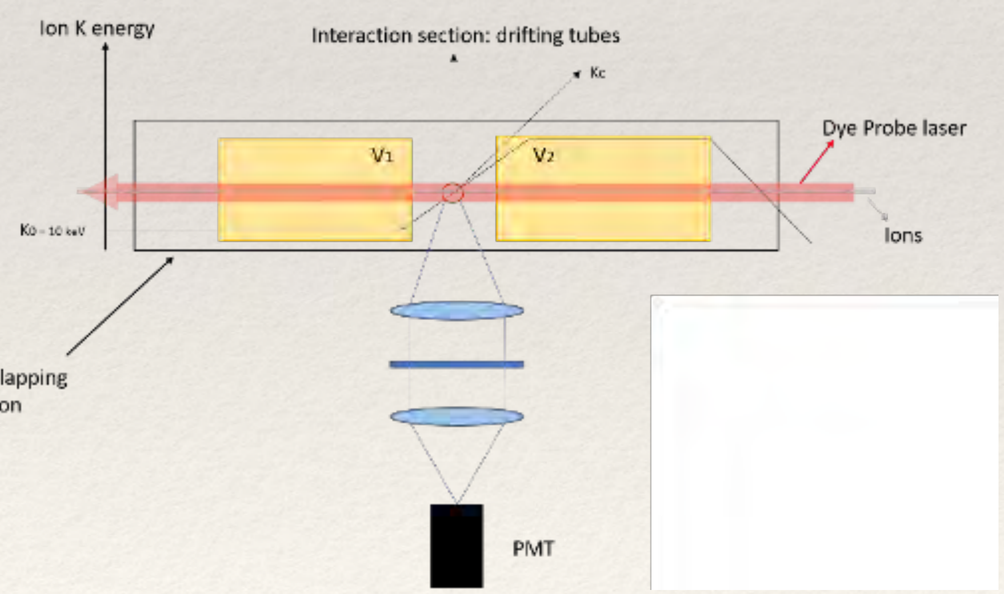


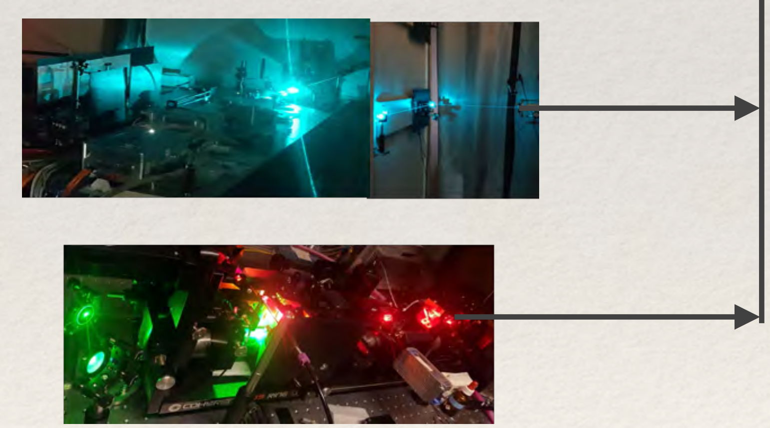
Hubble Space Telescope provide UV and optical spectra, and an accepted proposal for JWST will provide infrared spectra of the full nebulosity next year.

DESIREE - electrostatic storage ring

Ions input



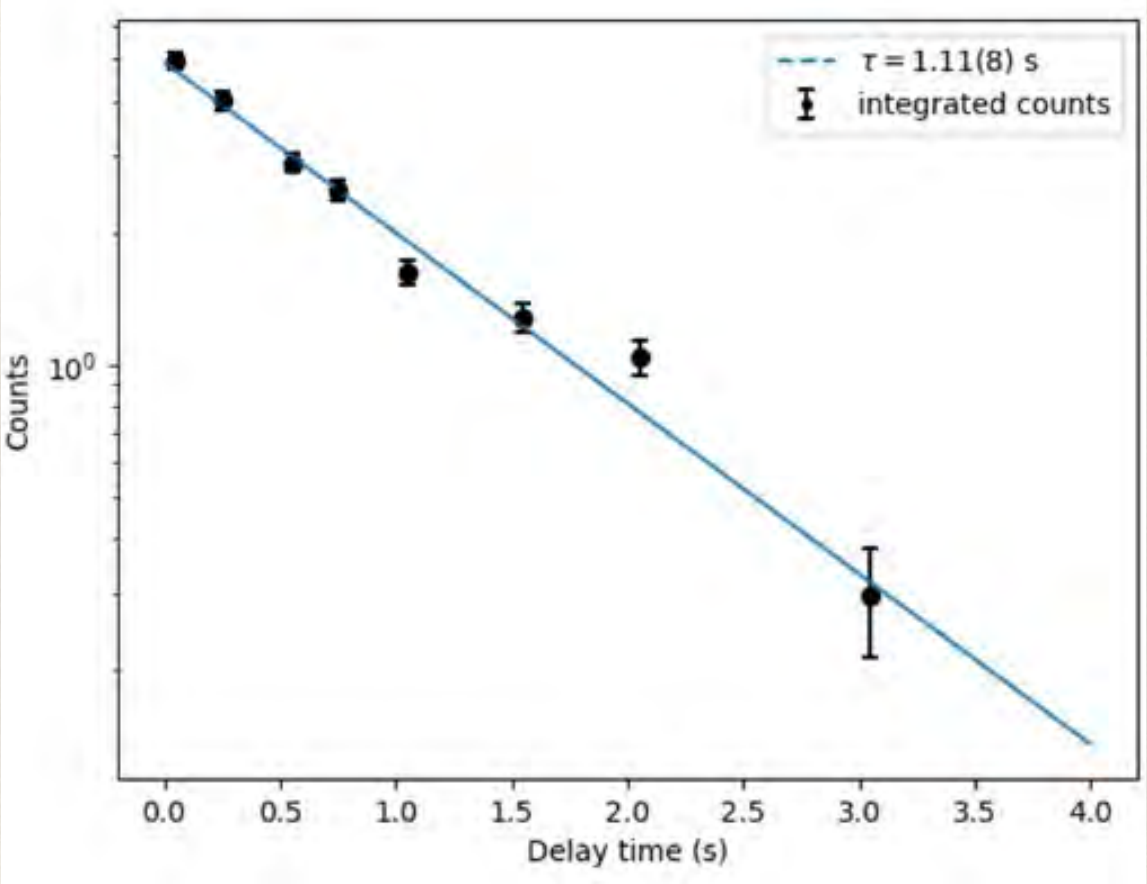




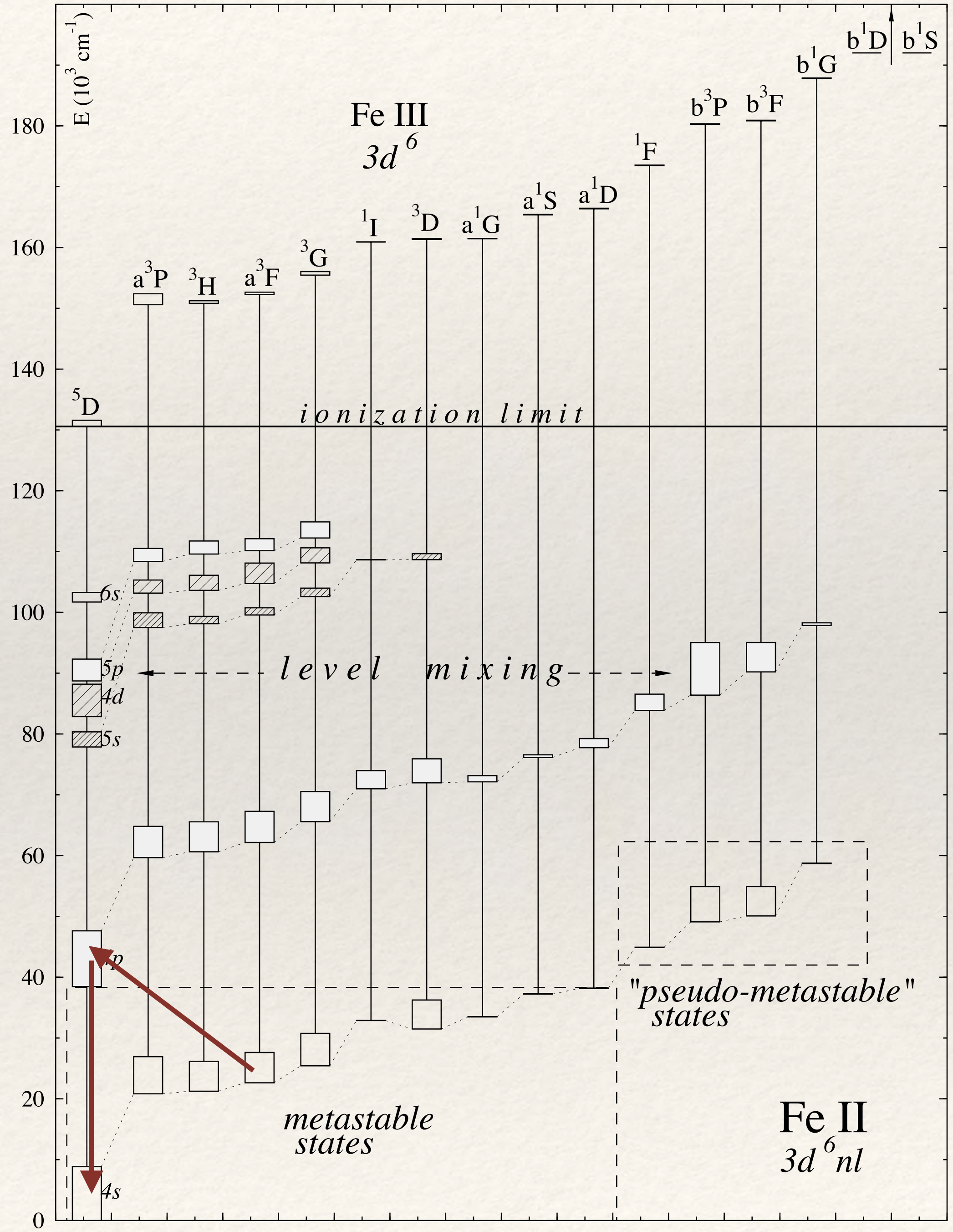
https://www.desiree-infrastructure.com/

Laser Probing Technique

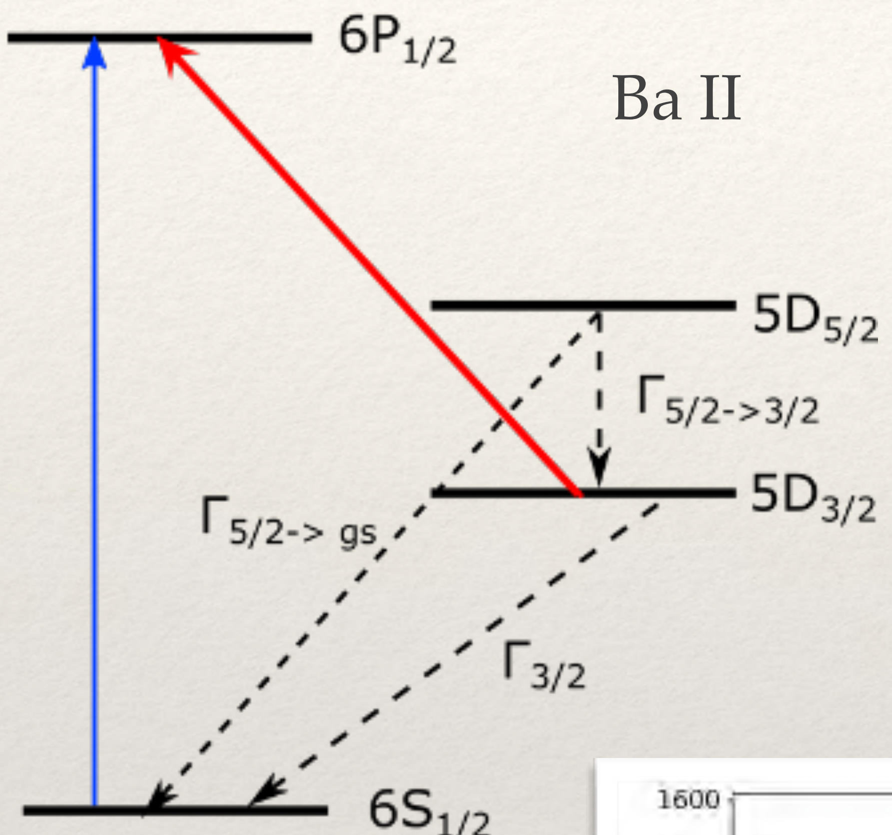
Complex ions, e.g. Fe II

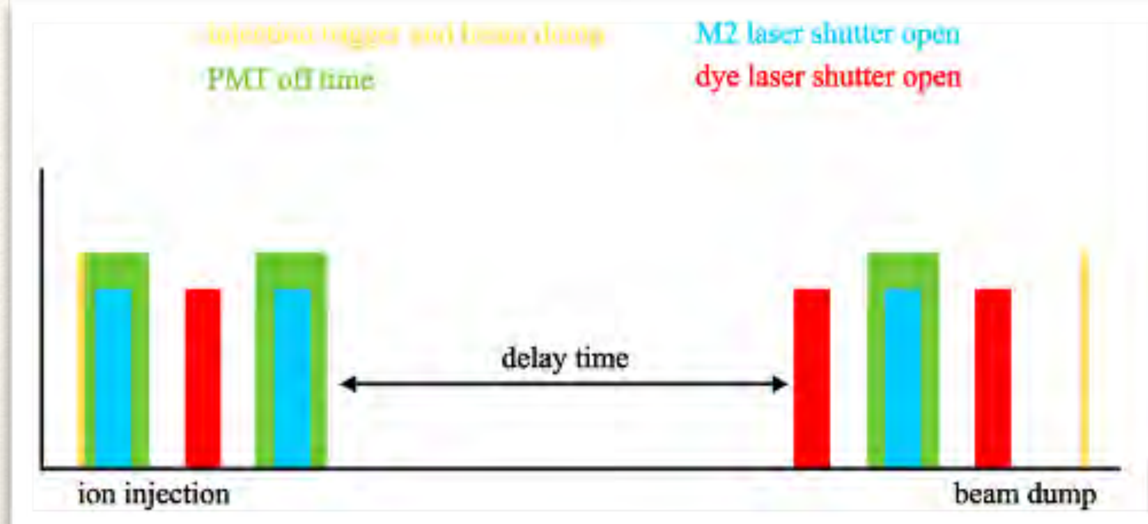


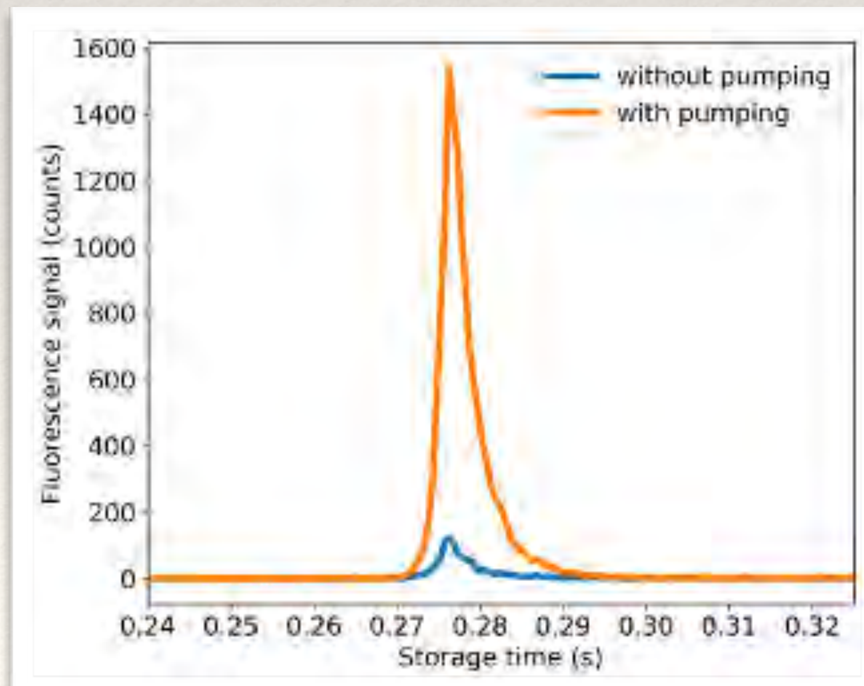
Snickeris et al (in prep)

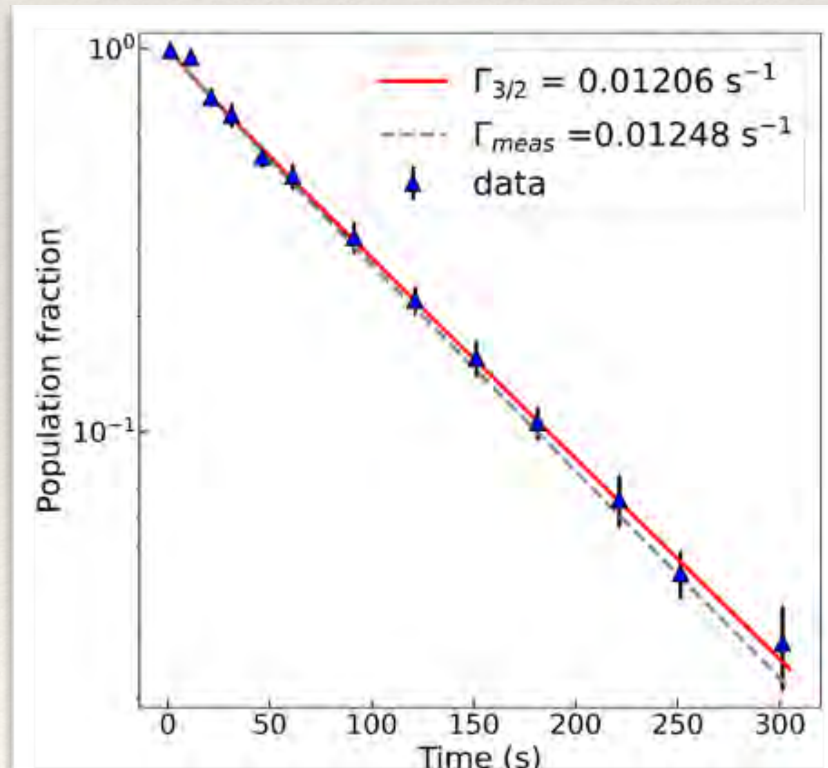


Laser Probing Technique





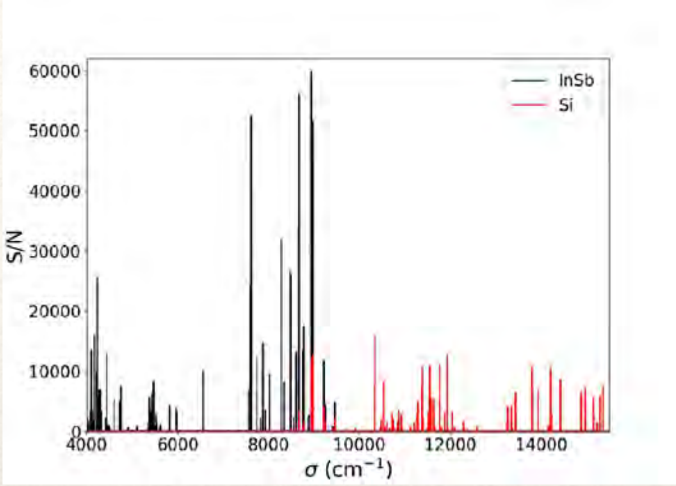


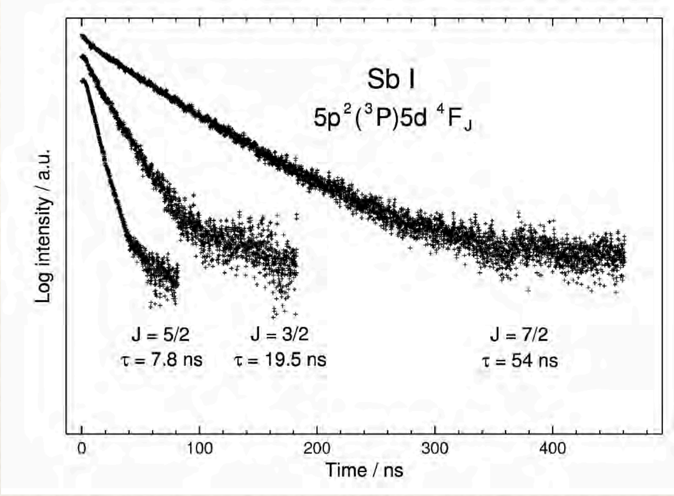


Martini et al, in prep

Uncertainties

Remember: $A_{ul} = \frac{BF_{ul}}{\tau_u}$





Uncertainties for experimental data:

Branching fractions: 0-30%

Radiative lifetimes: 1-15%

Experimental A- or f-values can be obtained with uncertainties down to 5%, both for optical and near-IR E1 transitions and forbidden M1/E2

Summary

Accurate experimental line data is derived for selected sets of transitions, to an accuracy down to a few percent. Different techniques are used and combined. The majority of line intensities are to be provided by calculations, and the combination is important to provide accurate, 'complete' sets of data for astrophysical applications.

Near-infrared (and optical) experimental data has been provided for Mg I, Sc I, Al I and Si I+II

Analysis in progress: Y I, La I, Zr I and Zr II.

Metastable lifetimes : Ba II, Sr II, Fe II are measured, and Ca II, Ni II, Ce II planned

We investigate an approach to apply a tuning technique to merge the theoretical and experimental linelists.