Atomic recipes for astronomical transients...
...and relative experimental setups!

S. Cristallo

INAF – Osservatorio Astronomico d'Abruzzo (Italy)

INFN – Sezione di Perugia (Italy)

Collaborators: M. Bezmalinvich, D. Vescovi, E. Loffredo, A.Perego, A. Fiore, S. Giuliani, A. Pidatella

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Outline

- The «ingredients» of a kilonova lightcurve
- The importance of atomic opacities
- The PANDORA experiment

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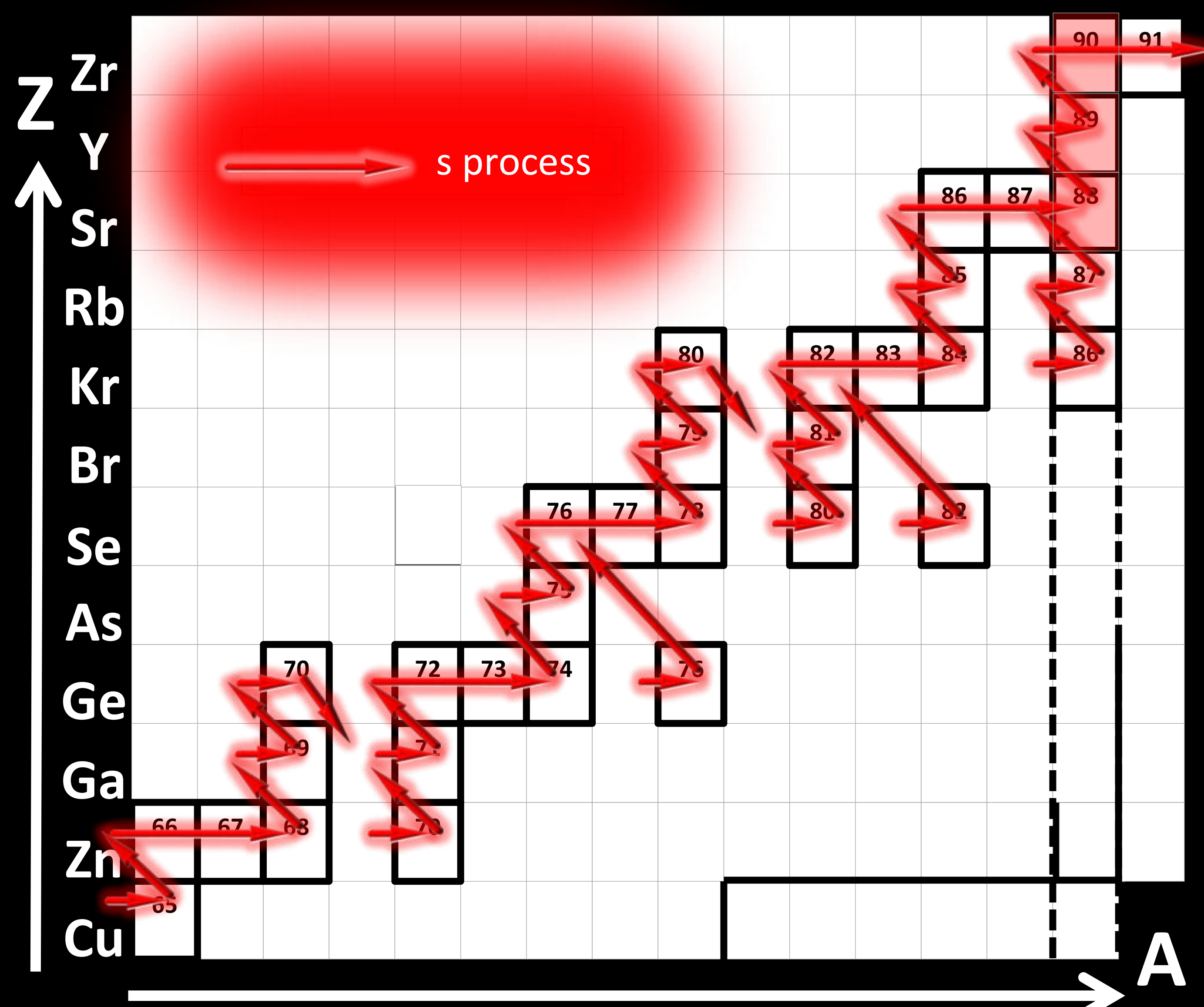

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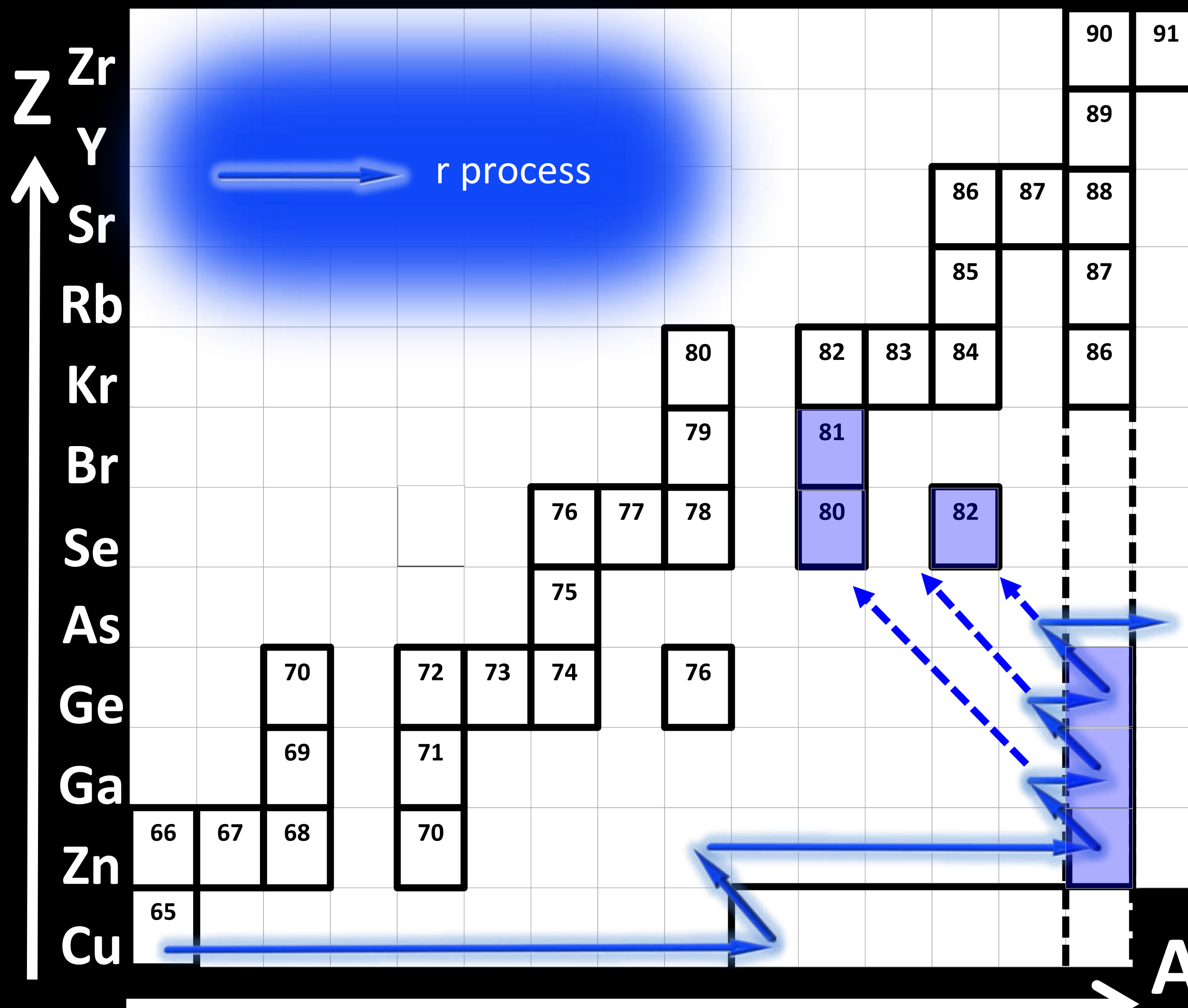

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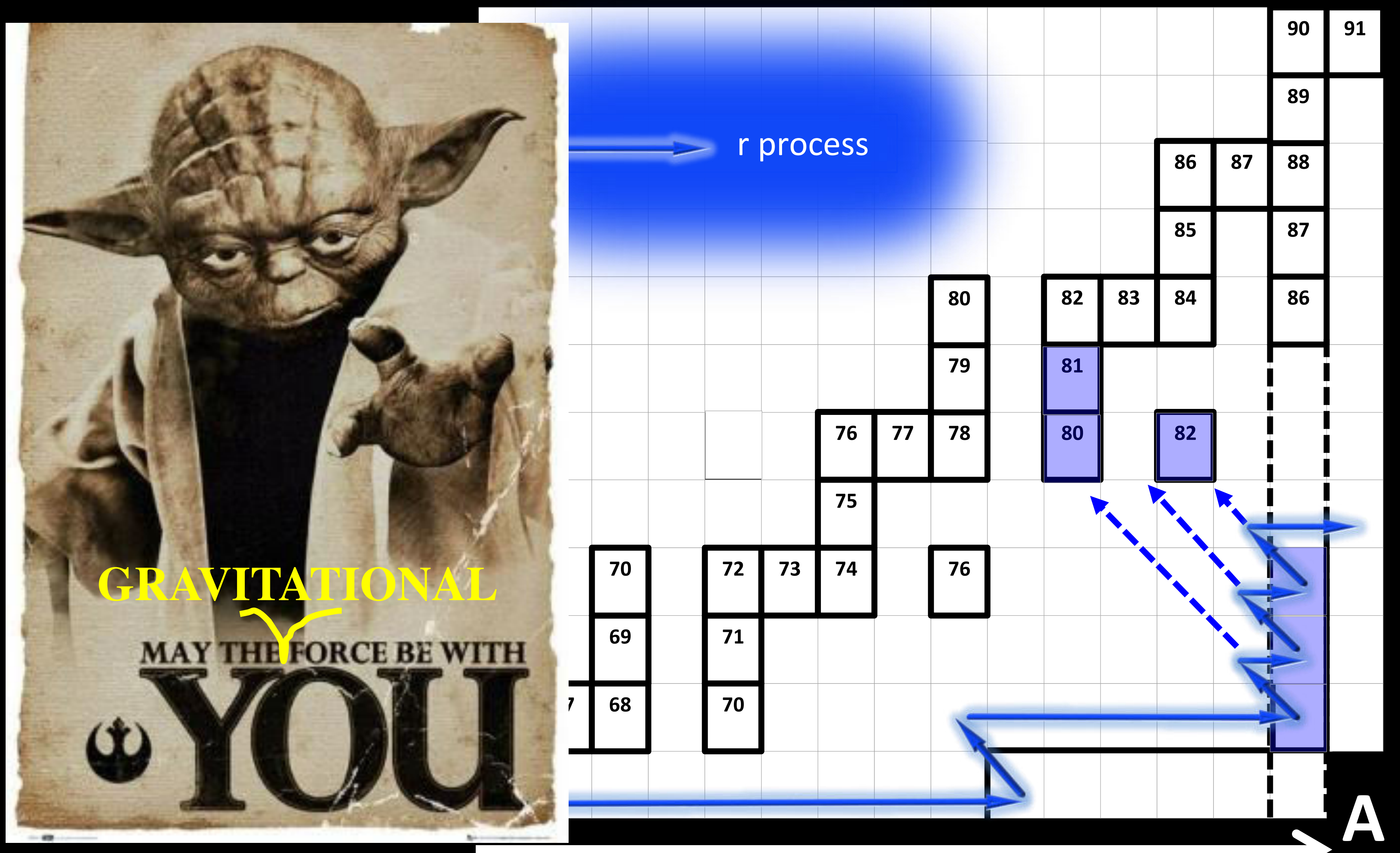
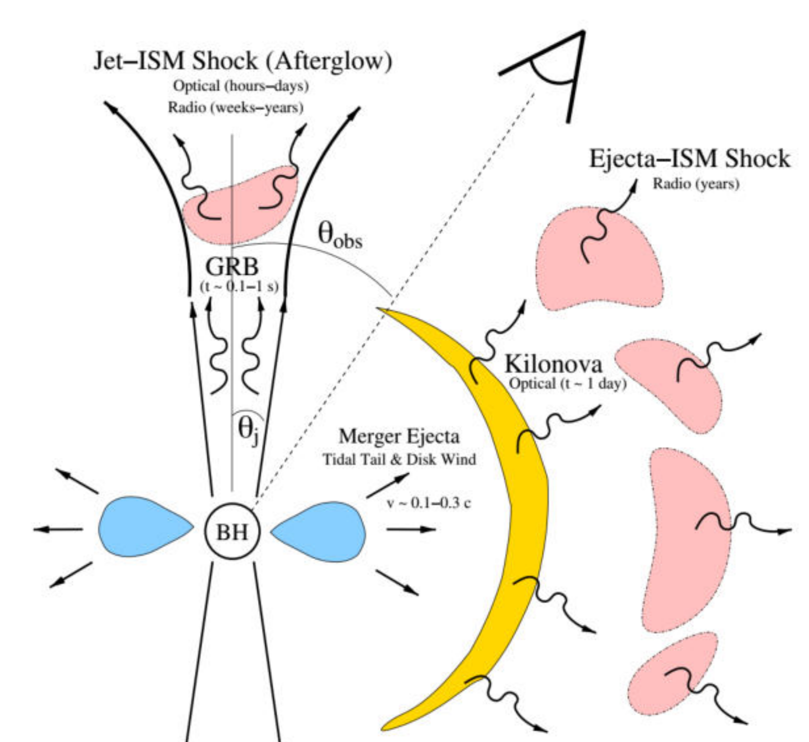


A **KILONOVA (KL)** arises from a *translucent* stage of the expanding ejecta, when thermal radiation can escape. Its energy results from a balance between thermalization processes and the warm-up due to nuclear fissions and decays (α and β).



Metzger & Berger 12

Basic ideas:

1. <u>radioactive decay</u> of freshly sinthesized *r*-process elements in the expanding ejecta (0.1-0.2c) release **nuclear energy;**
2. thermalization of high energy decay products with ejecta;
3. **diffusion** of thermal photons during ejecta expansion;
4. thermal emission of photons at photosphere.

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Key ingredients

1. **Numerical relativity simulations of BNS mergers**: physical trajectories are needed to determine the physical conditions to which matter is exposed during a BNS (fix velocity and mass of the ejecta);
2. **r-process nucleosynthesis calculations:** r-process yields are needed to properly compute KLs because, depending on the chemical species, different types of KLs can be obtained;
3. **Heating efficiencies**: thermalization of high-energy decay radiation directly affects the luminosity of a kilonova;
4. **Heavy element atomic opacities**: a fundamental input to properly compute KLs are atomic opacities, which regulate the interaction between the emerging radiation and the expanding plasma;
5. **Radiative transfer code**: last but not least, a tool combining all the aforelisted inputs is needed to properly determine local thermodynamic variables.

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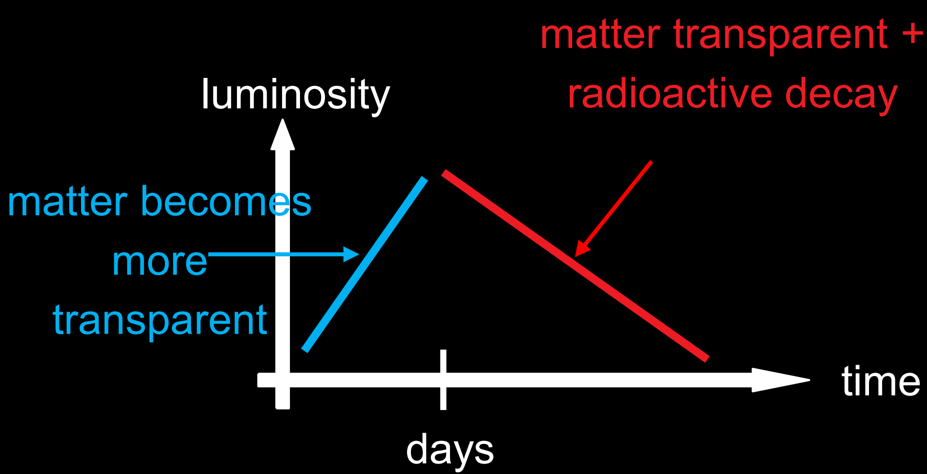
The transition from blue-KN to red-KN



Stefan-Boltzmann´s law:

$$L = 4\pi R^2 \sigma T^4$$

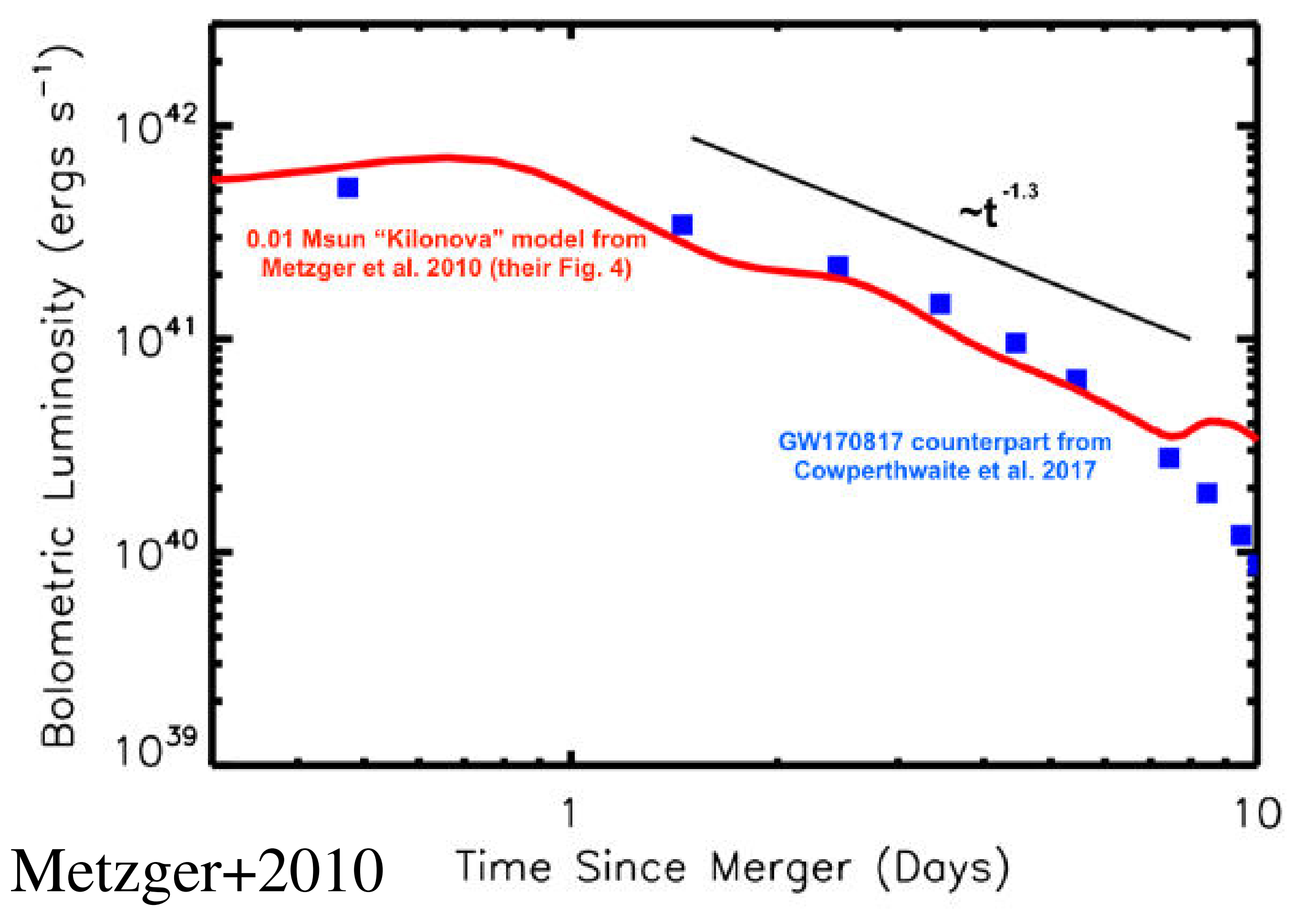
$\sigma = 5.67 \times 10^{-5}$ erg cm^{-2} K^{-4} s^{-1}

$Y_e \gtrsim 0.25$	$Y_e \lesssim 0.25$
weak *r*-process (A<130)	robust *r*-process (A>130)
"blue transients" peaking after ~ 1 day	"red transients" peaking after ~ 1 week

Y_e measures of the neutron richness

$$Y_e = \frac{n_{e^-} - n_{e^+}}{n_b} = (1 + n_n/n_p)^{-1}$$

A kilonova lightcurve



Bolometric curve of at2017gfo

The *bolometric luminosity* is a measure of the total radiation emitted at all wavelengths.

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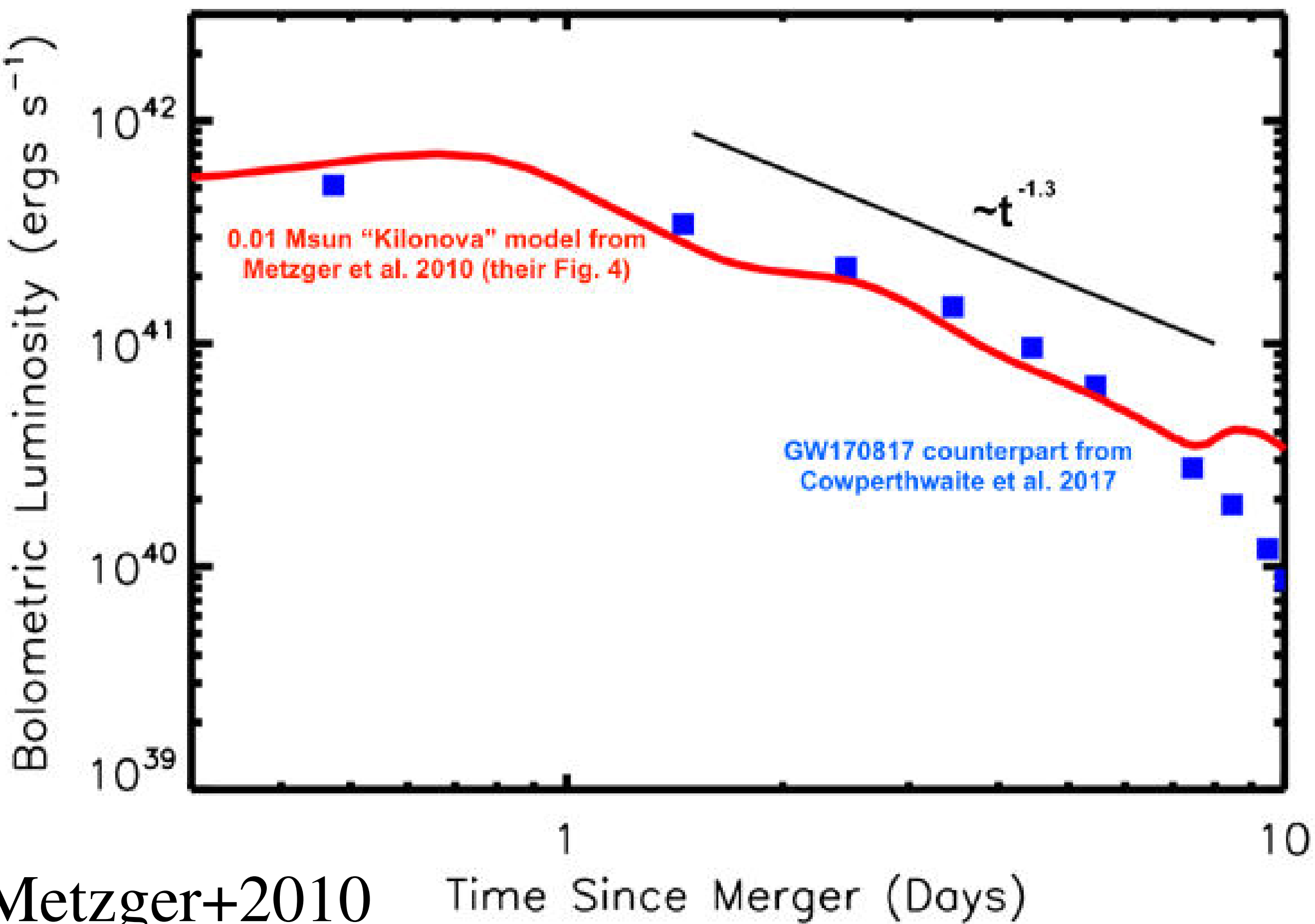


Metzger+2010

Bolometric curve of at2017gfo

Rebrightening in the IR: which is the cause?

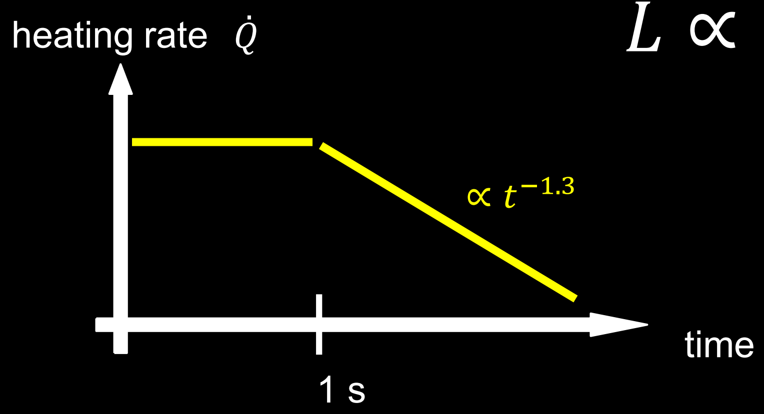
The *bolometric luminosity* is a measure of the total radiation emitted at all wavelengths.

Nuclear heating rate

$$\dot{Q}_{r-process} = \sum_{i \in reactions} Q_i \lambda_i$$

$$Q = M_{initial} - M_{final}$$
$$\lambda = decay\ rate$$

$$L \propto \dot{Q} M$$



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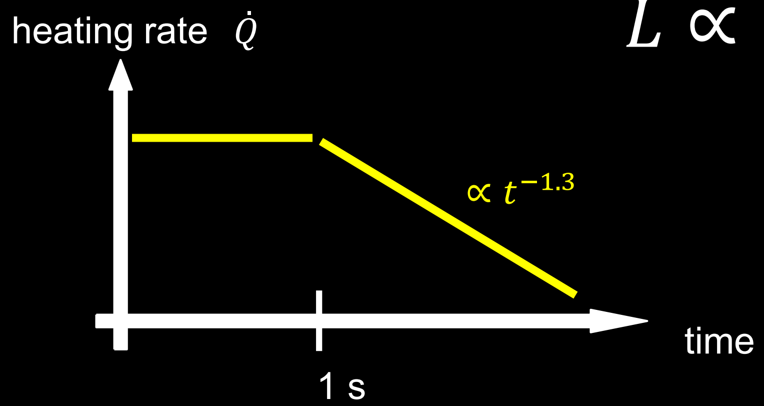

$$L \propto \dot{Q} M$$

Heating efficiencies

$$\frac{d\varepsilon}{dt} = \dot{\varepsilon}_0 \left(\frac{1}{2} - \frac{1}{\pi}\arctan\left[\frac{t-t_0}{\sigma}\right]\right)^{\alpha} \left(\frac{1}{2} + \frac{1}{\pi}\arctan\left[\frac{t-t_1}{\sigma_1}\right]\right)^{\alpha_1} + C_1 e^{-t/\tau_1} + C_2 e^{-t/\tau_2} + C_3 e^{-t/\tau_3} \quad (2)$$

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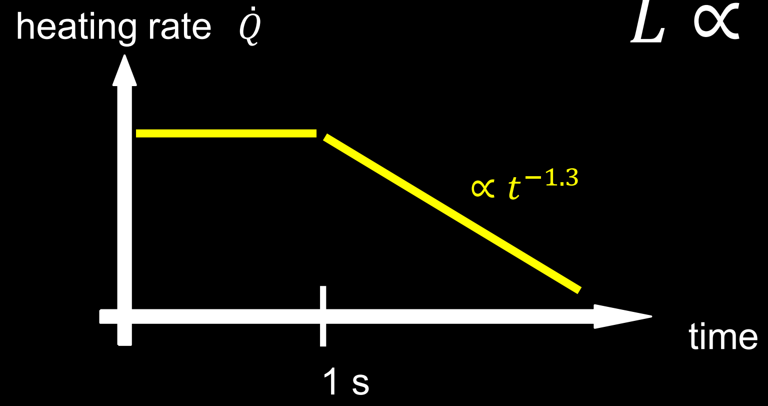

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…13 free parameters…

With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.
[J. VON NEUMANN]

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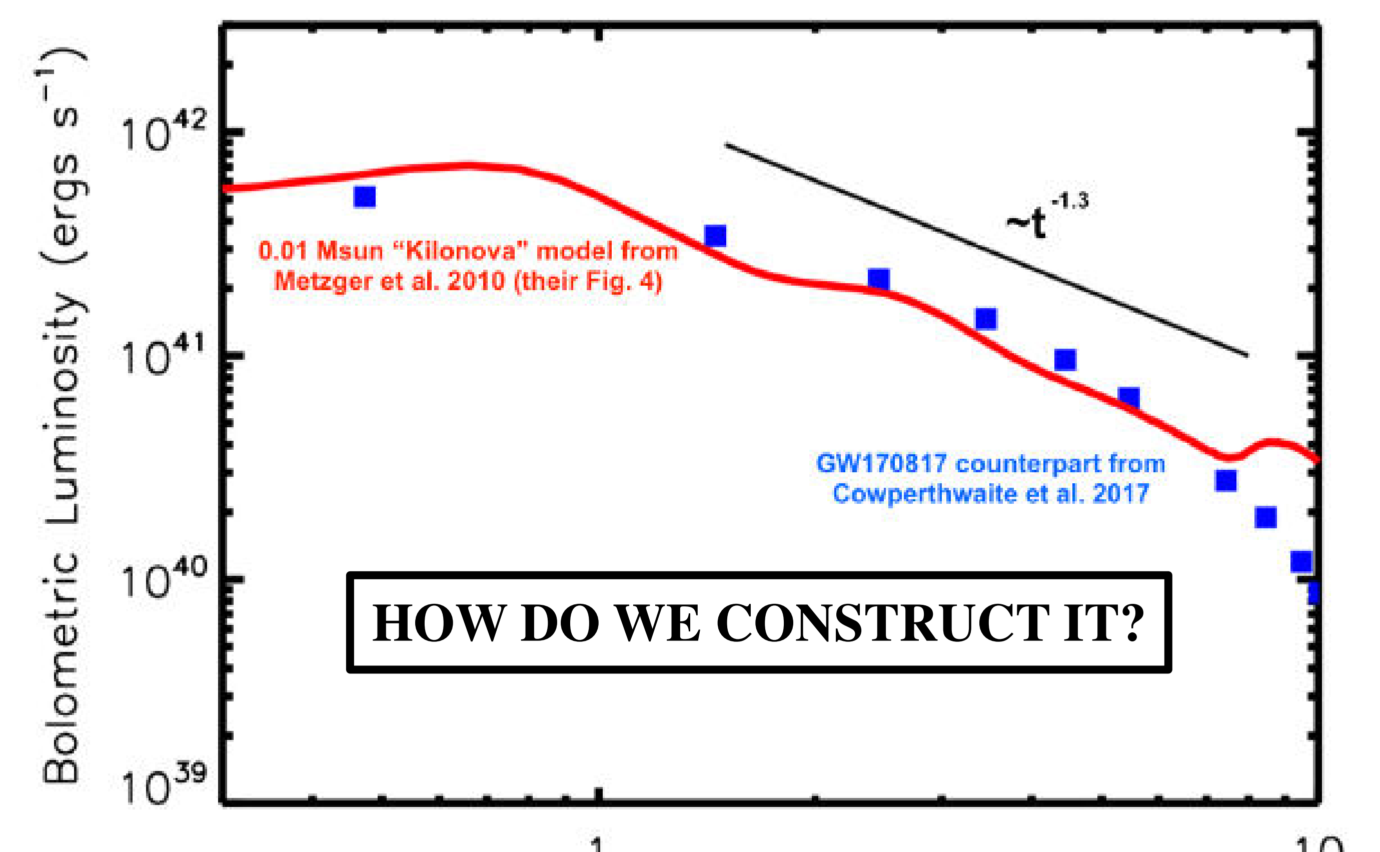
A kilonova lightcurve



Metzger+2010

Bolometric curve of at2017gfo

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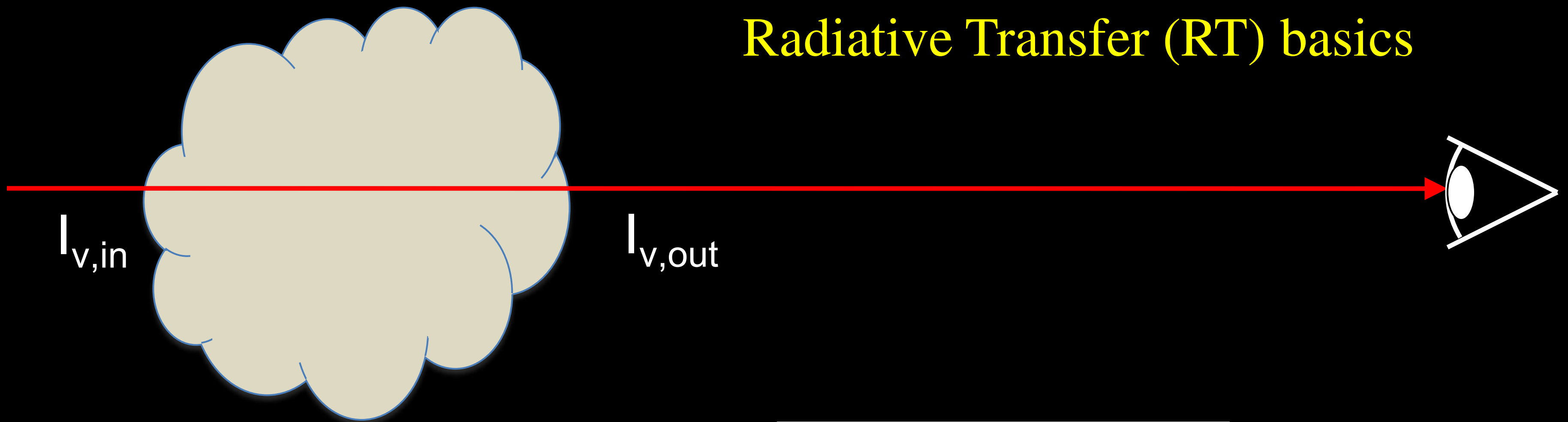
Radiative Transfer (RT) basics



Basic quantity: *intensity*

$$I(\Omega,\nu) = \frac{\text{erg}}{\text{scm}^2\text{Hzster}}$$

Definition of *mean intensity:*

$$J(\nu) = \frac{1}{4\pi}\oint_{4\pi} I(\Omega,\nu)d\Omega = \frac{\text{erg}}{\text{s cm}^2\text{Hz ster}}$$

Definition of *flux:*

$$\vec{F}(\nu) = \oint_{4\pi} I(\Omega,\nu)\vec{\Omega}d\Omega = \frac{\text{erg}}{\text{scm}^2\text{Hz}}$$

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RT equation

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = S_\nu - I_\nu$$

Optical depth

Source function (emissivity to absorption ratio)

$$\tau_\nu(D) = \int_0^D \alpha_\nu(s)\,\mathrm{d}s$$

$$\alpha_\nu = \kappa_\nu \rho$$

κ_ν is the frequency-dependent opacity of the medium

$$l_{\mathrm{free},\nu} = \frac{1}{\rho\kappa_\nu}$$

Photon mean free path

Radiative Transfer (RT) basics

The ejecta is extremely hot immediately after the merger. This thermal energy cannot initially escape as radiation because of its high optical depth at early times:

$$\tau \simeq \rho\kappa R = \frac{3M\kappa}{4\pi R^2} \simeq 70 \left(\frac{M}{10^{-2} M_\odot}\right) \left(\frac{\kappa}{1\,\mathrm{cm}^2\,\mathrm{g}^{-1}}\right) \left(\frac{v}{0.1c}\right)^{-2} \left(\frac{t}{1\,\mathrm{day}}\right)^{-2}$$

and the correspondingly long photon diffusion timescale through the ejecta:

$$t_{\mathrm{diff}} \simeq \frac{R}{c}\tau = \frac{3M\kappa}{4\pi c R} = \frac{3M\kappa}{4\pi c v t}$$

Radiative Transfer (RT) basics

Radiation can escape when the diffusion timescale is equal to the expansion timescale, when the lightcurve peaks:

$$t_{\rm peak} \equiv \left(\frac{3M\kappa}{4\pi\beta vc}\right)^{1/2} \approx 1.6\,{\rm d}\,\left(\frac{M}{10^{-2}M_\odot}\right)^{1/2}\left(\frac{v}{0.1c}\right)^{-1/2}\left(\frac{\kappa}{1\,{\rm cm^2\,g^{-1}}}\right)^{1/2}$$

The corresponding luminosity is:

$$L_{\rm peak} \sim 1.1\varepsilon\times10^{41}\frac{\rm erg}{\rm s}\left(\frac{k_\gamma}{\rm cm^2g^{-1}}\right)^{-\alpha/2}\left(\frac{v}{0.1c}\right)^{\alpha/2}\left(\frac{M}{0.01{\rm M_\odot}}\right)^{1-\alpha/2}$$

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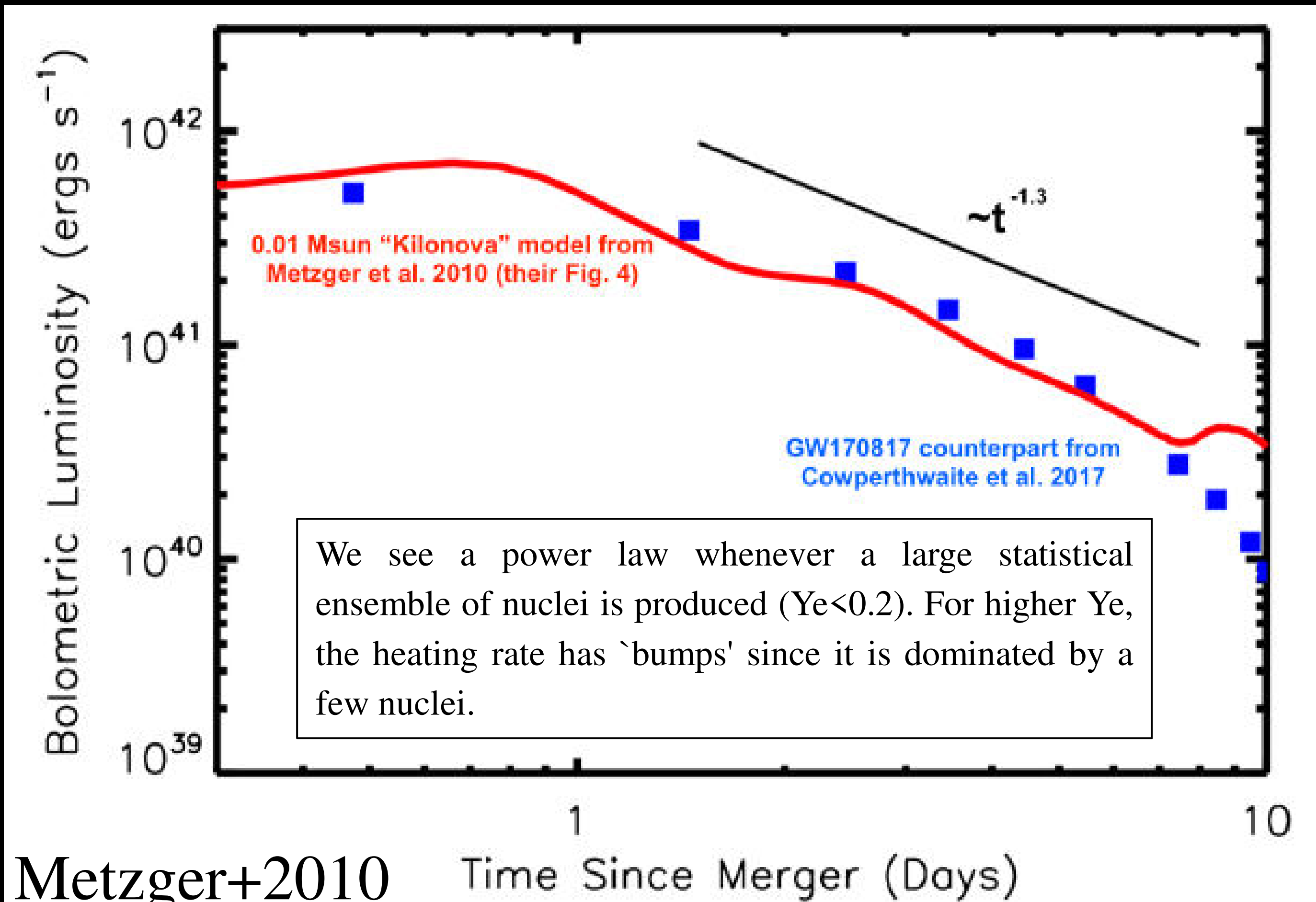
In these formulas, κ is assumed **CONSTANT in time** and independent from chemical abundances (and, therefore, **independent from the frequency**).

HOWEVER, opacity **heavily depends on the wavelenghts** and **evolves with time** by reflecting changes in density and temperature (and, THUS, ionization/excitation states).

A kilonova lightcurve



We see a power law whenever a large statistical ensemble of nuclei is produced (Ye<0.2). For higher Ye, the heating rate has `bumps' since it is dominated by a few nuclei.

Metzger+2010

Bolometric curve of at2017gfo

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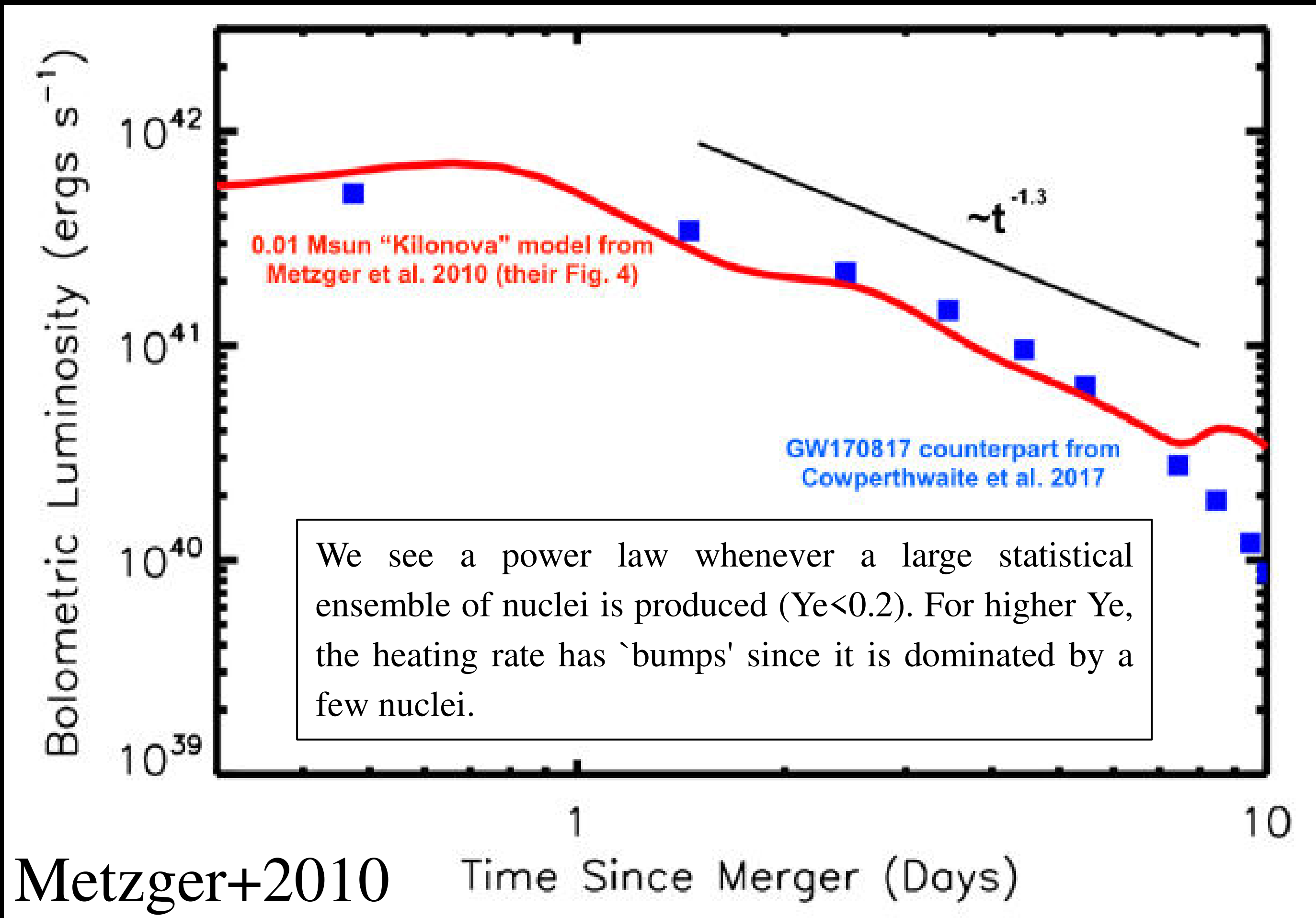
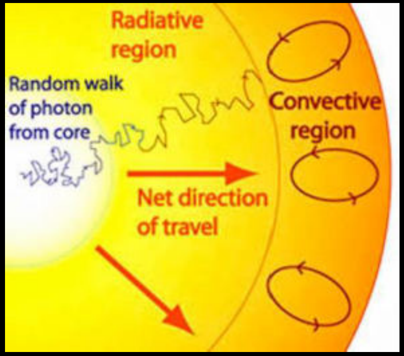


Bolometric curve of at2017gfo

Chemical abundances come from network calculations.
But the question is: how do they interact with radiation?

Atomic opacities

Opacity (κ_ν), which is proportional to the plasma atomic level population and to radiative process cross sections, regulates the energy exchange between radiation and plasma, via multiple absorption-scattering processes through the radiative transport, and arises from the blending of millions of atomic line transitions.



According to the famous 'drunkard's walk' problem, the distance a drunk, making random left and right turns, gets from the lamp post is his typical step size times the square root of the number of steps he takes: $D \approx d_{feet} * (N_{steps})^{0.5}$.

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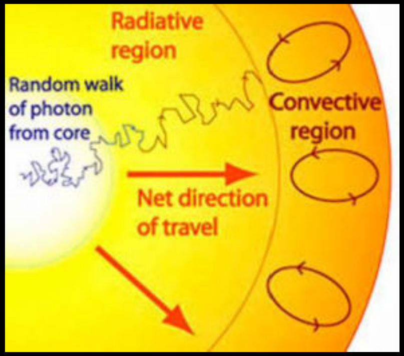

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TAKE HOME MESSAGE FOR STUDENTS:

tonight check how many steps you need to return to your room at Waldwirt Hotel!!!

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Absorption Coefficient

$$\boxed{\alpha_\nu = \mathcal{N}_l \left(1 - \frac{\mathcal{N}_u g_l}{\mathcal{N}_l g_u}\right) \frac{\pi e^2}{mc} f_{lu}\phi(\nu) \qquad (cm^{-1})}$$

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State wavefunction

Radiative transition data

Number of electrons in the upper and lower states

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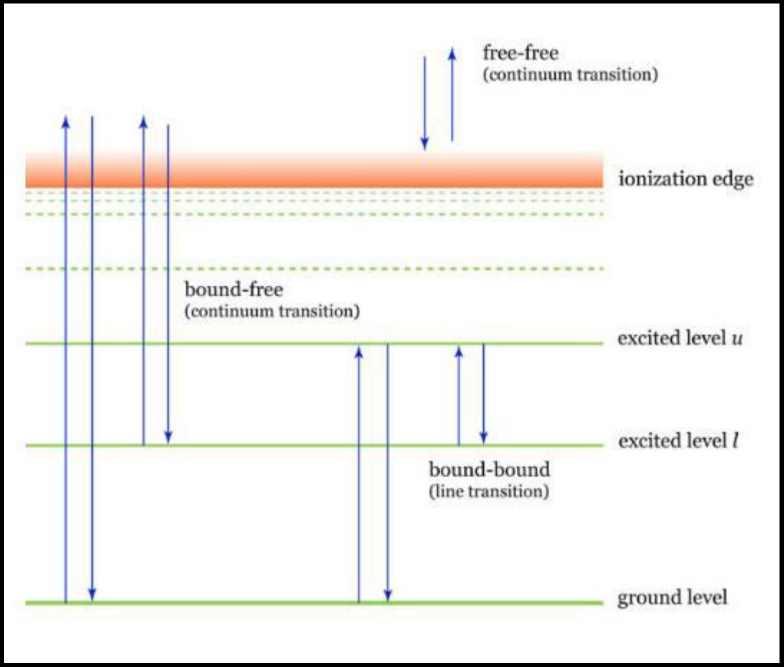

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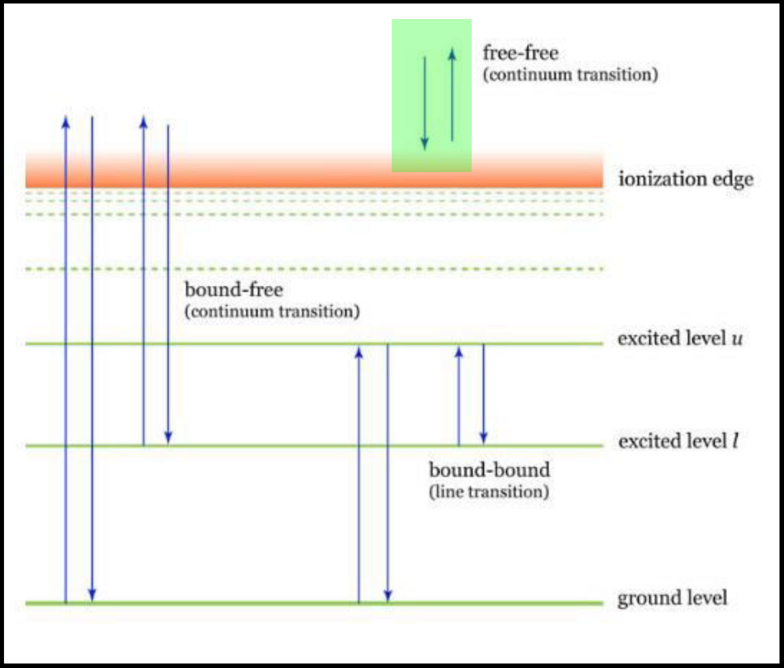
Number of electrons in the upper and lower states

Free-free transitions



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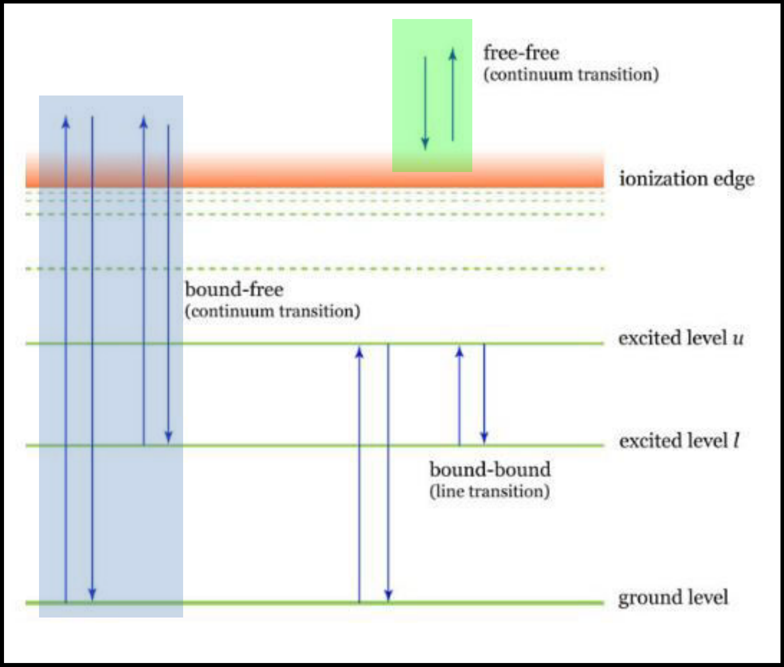
State wavefunction

Radiative transition data

Number of electrons in the upper and lower states

Free-free transitions

Bound-free transitions



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State wavefunction

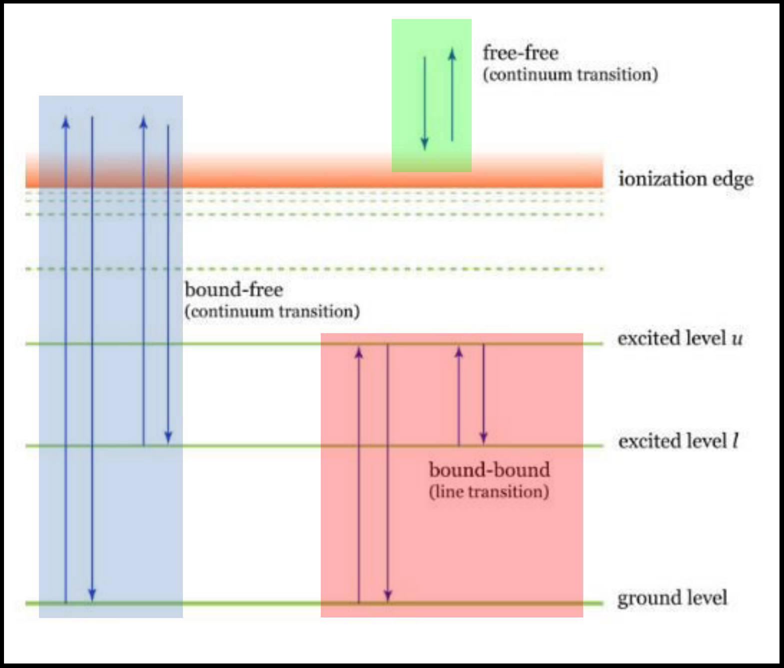
Radiative transition data

Number of electrons in the upper and lower states

Free-free transitions

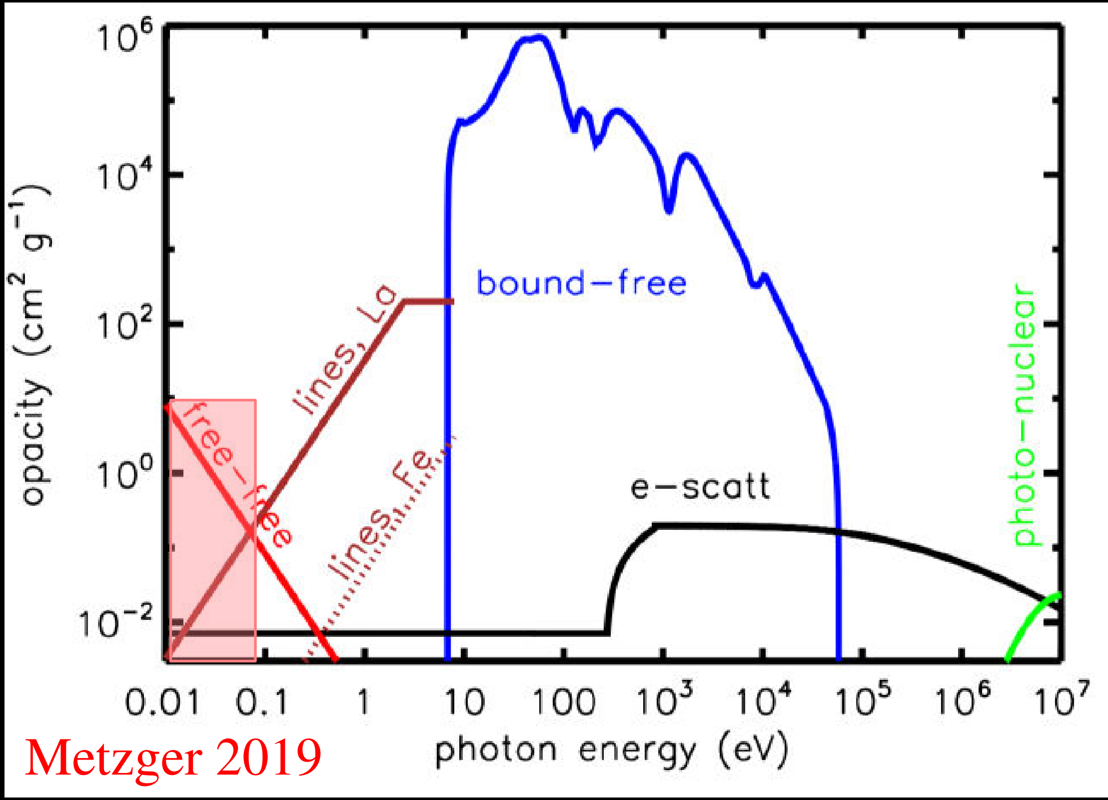
Bound-free transitions

Bound-bound transitions



Atomic opacities

Kilonova emission is centered in the optical/IR band, as this is the first spectral window through which the expanding merger ejecta becomes transparent.



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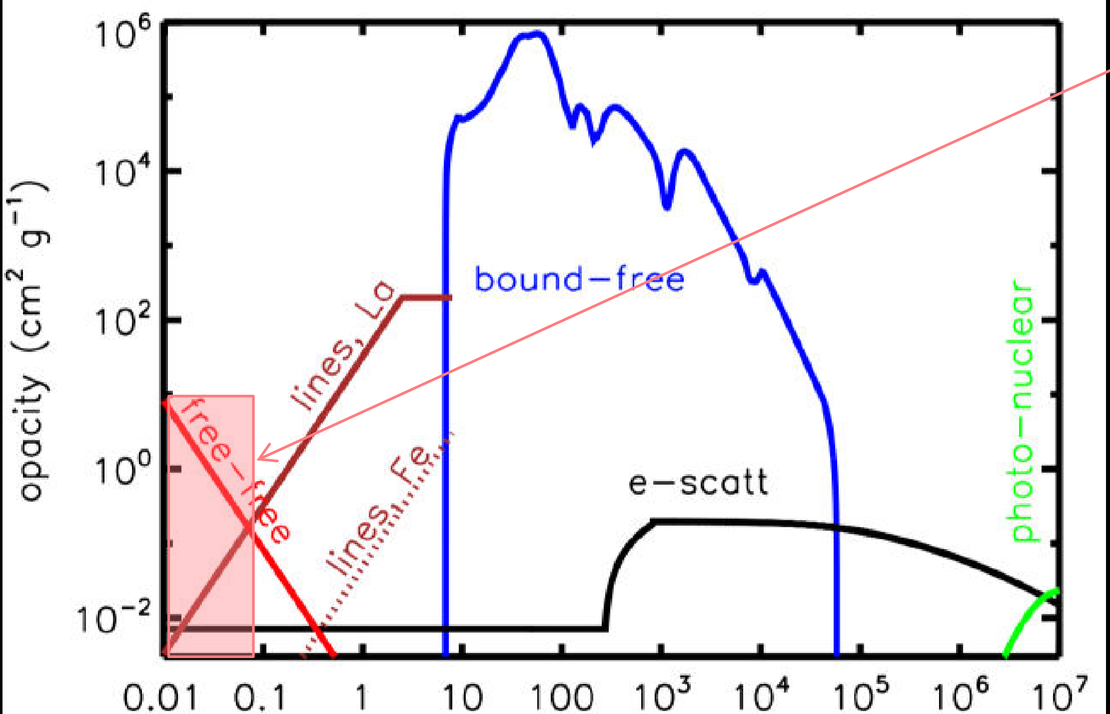


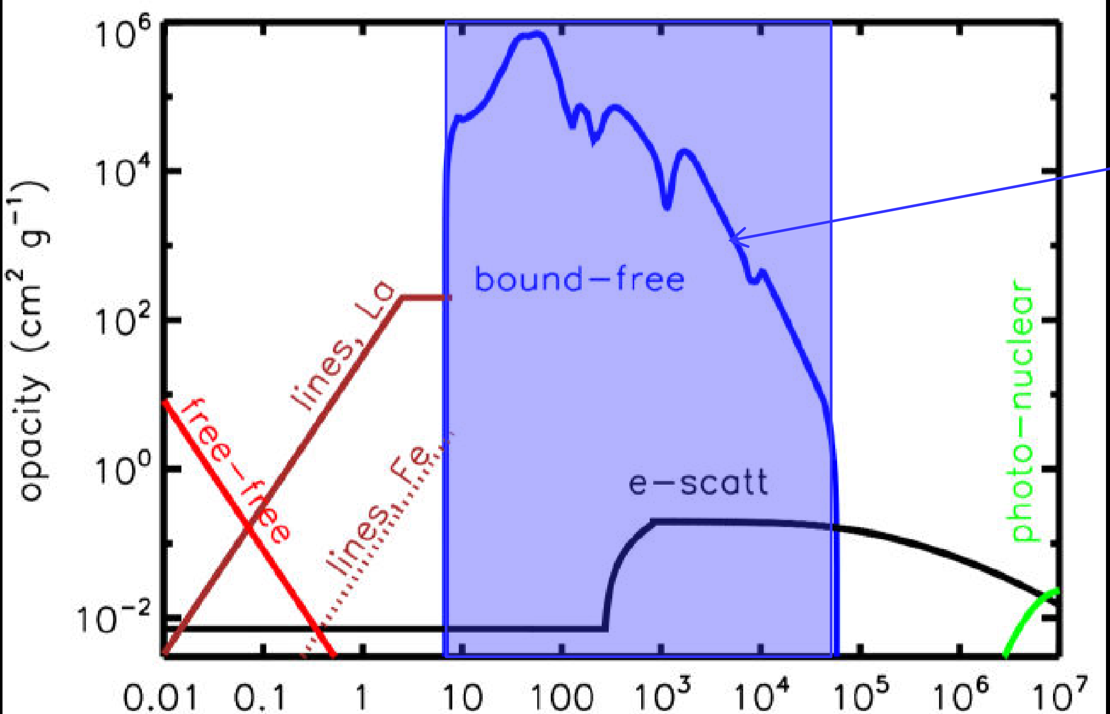
Metzger 2019

At the lowest frequencies (radio and far-IR), free-free absorption from ionized gas dominates (red line). As the ejecta expands, the free-free opacity will decrease rapidly due to the decreasing density $\rho \propto t^{-3}$ and the fewer number of free electrons as the ejecta cools and recombines.

LATE TIME KILONOVA

Atomic opacities

Kilonova emission is centered in the optical/IR band, as this is the first spectral window through which the expanding merger ejecta becomes transparent.



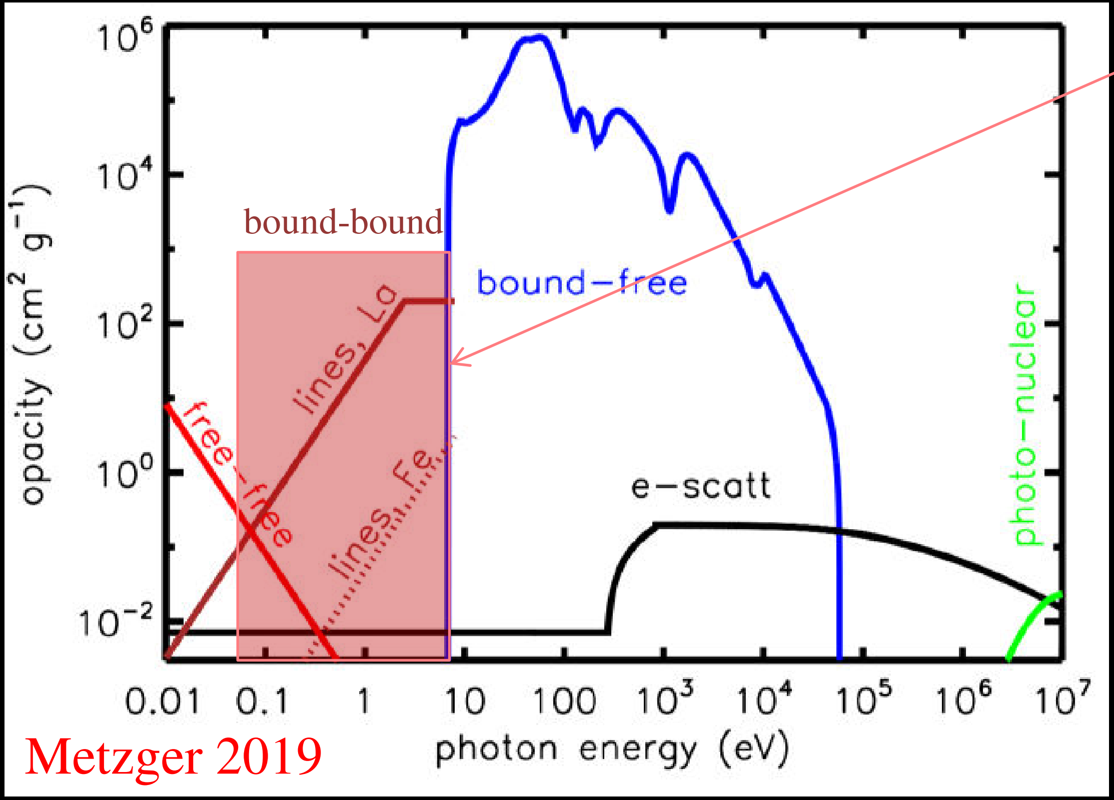
Metzger 2019

Throughout the far UV and X-ray bands, bound-free transitions of the ejecta dominates the opacity (blue line). This prevents radiation from escaping the ejecta at these frequencies.

VERY EARLY TIME KILONOVA

Atomic opacities

Kilonova emission is centered in the optical/IR band, as this is the first spectral window through which the expanding merger ejecta becomes transparent.



At near-IR/optical frequencies (brown line), the dominant source of opacity is a dense forest of line (bound-bound) transitions. The magnitude of this opacity is determined by the strengths and wavelength density of the lines, which in turn depend sensitively on the ejecta composition.

0.5d - 5d KILONOVA

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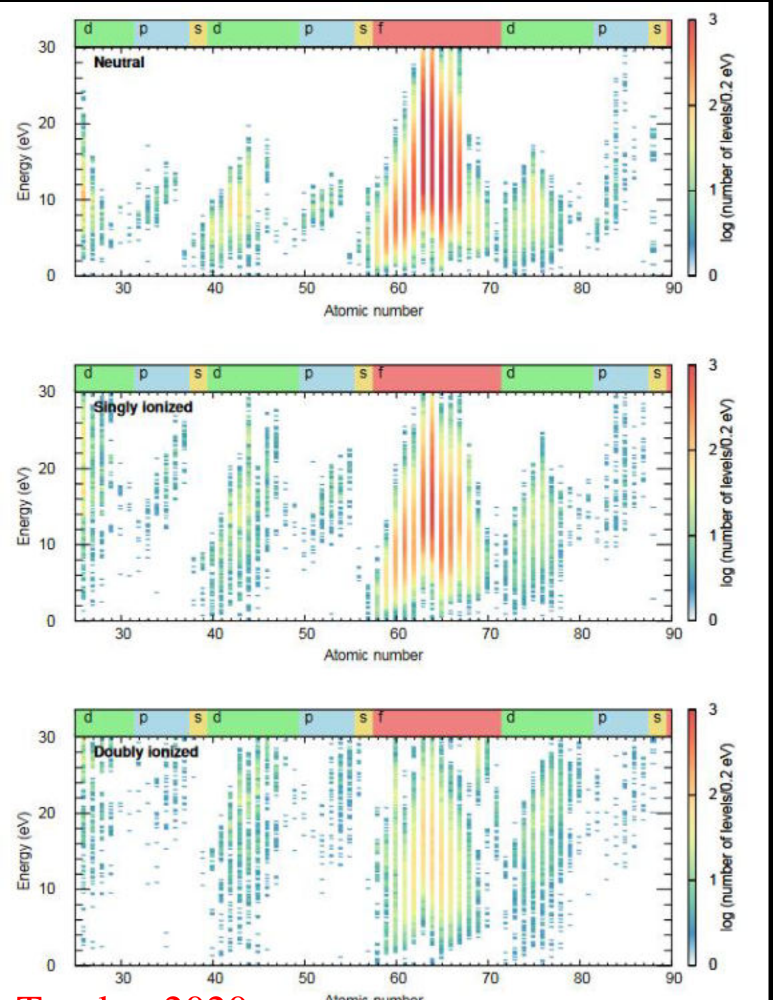
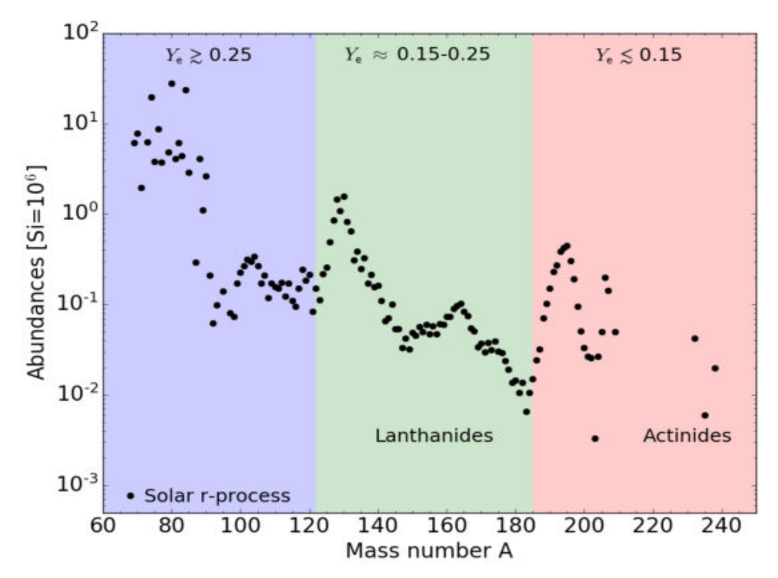
Atomic opacities



Tanaka+2020

Chemical elements contribute to the global opacity with very different contributions, basing on their **electronic configuration** and their **abundance**.



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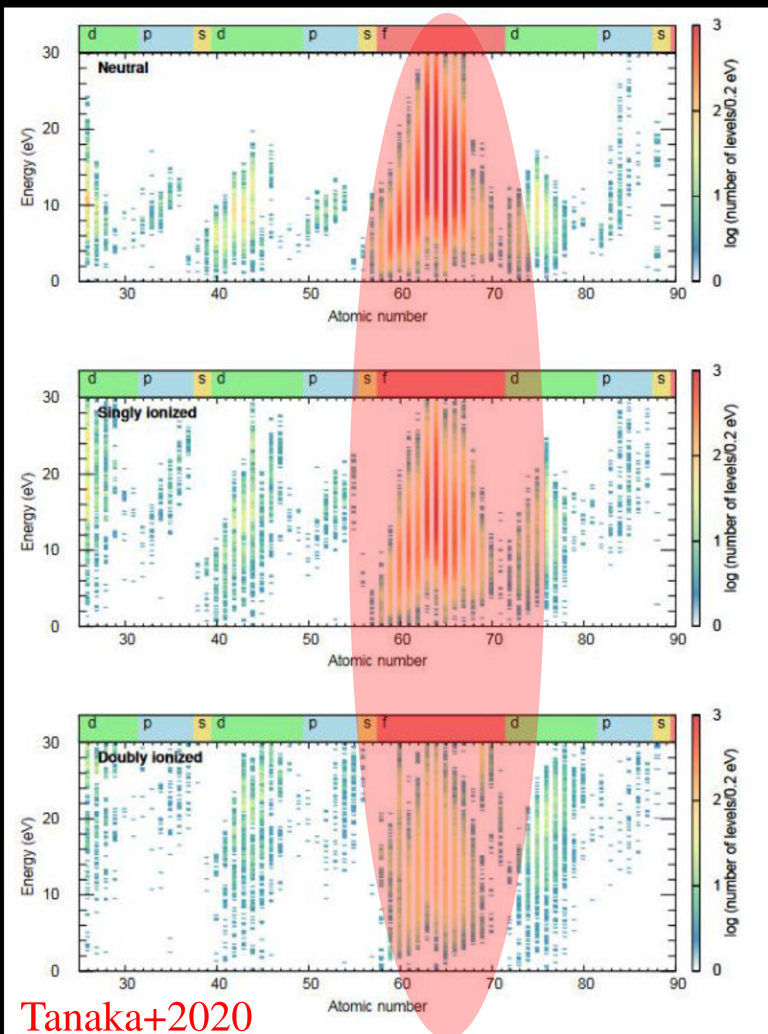
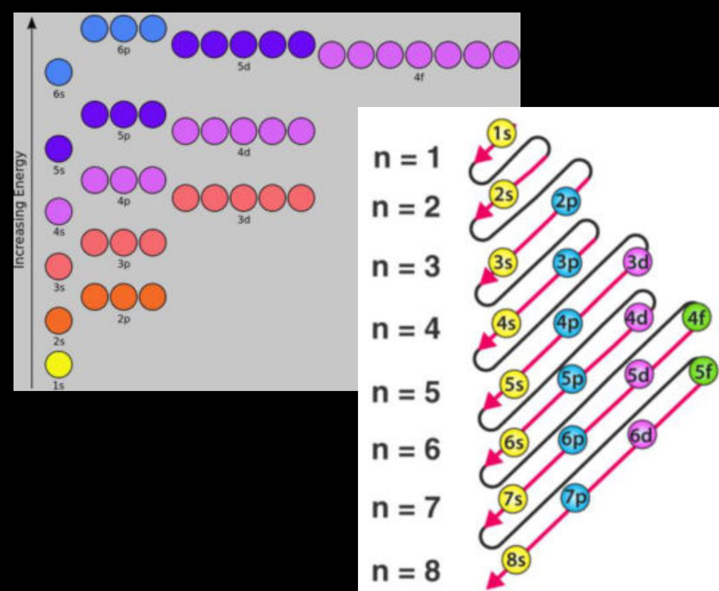
Atomic opacities



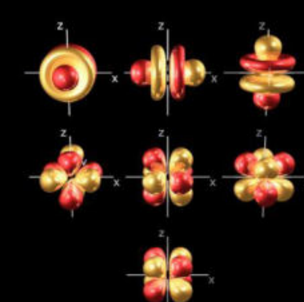
Tanaka+2020

Chemical elements contribute to the global opacity with very different contributions, basing on their **electronic configuration** and their **abundance**.

In particular, open f-shell elements (lanthanides) have larger opacities than the elements with other outermost electron shells.



f-shell orbitals



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The Periodic Table of Elements

ATOMIC NUMBER - 1
SYMBOL - H
NAME - Hydrogen

	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIB	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57-71 La-Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89-103 Ac-Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

LANTHANIDES	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
ACTINIDES	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

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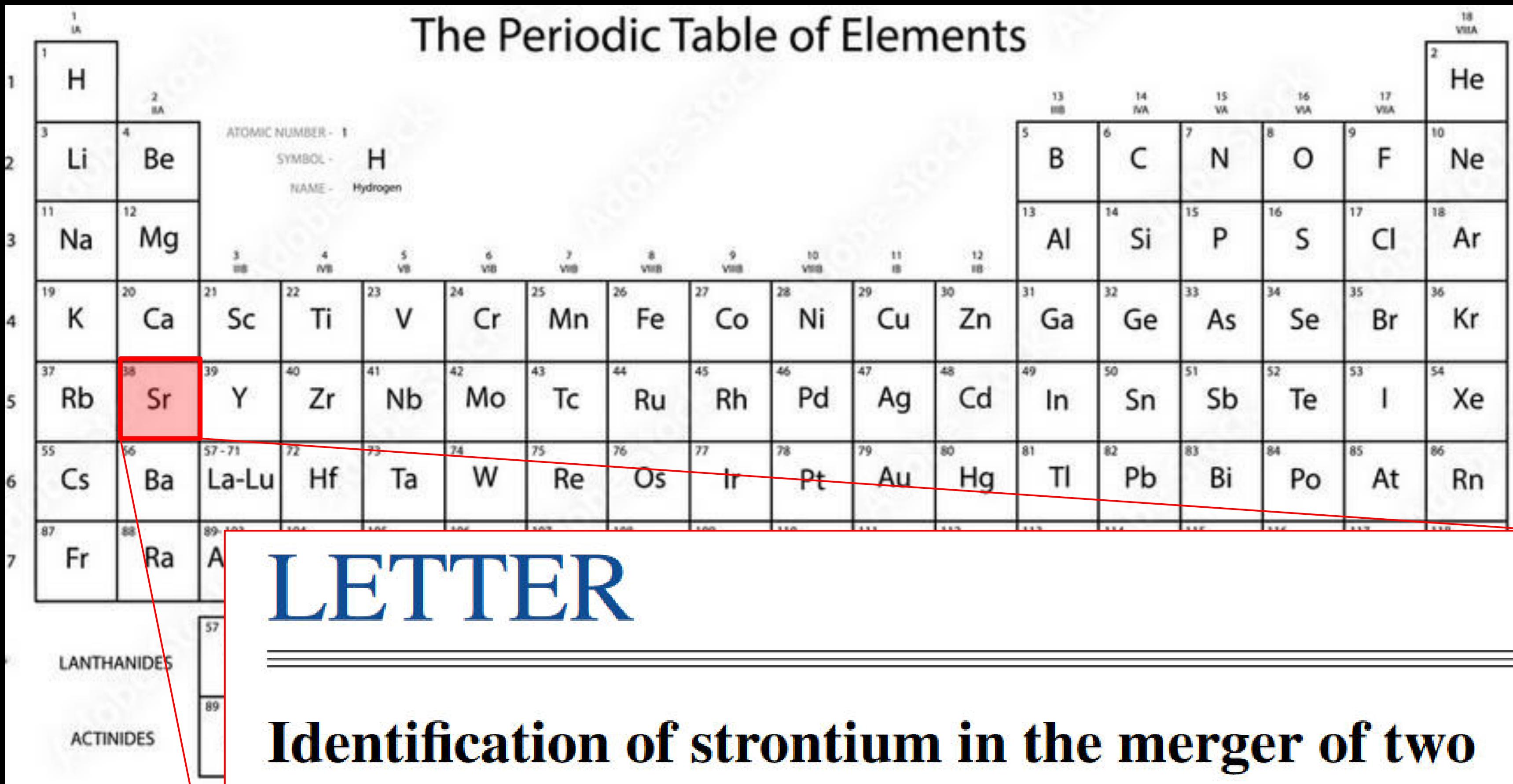

LETTER

Identification of strontium in the merger of two neutron stars

Darach Watson[1,2], Camilla J. Hansen[3,*], Jonatan Selsing[1,2,*], Andreas Koch[4], Daniele B. Malesani[1,2,5], Anja C. Andersen[1], Johan P. U. Fynbo[1,2], Almudena Arcones[6,7], Andreas Bauswein[7,8], Stefano Covino[9], Aniello Grado[10], Kasper E. Heintz[1,2,11], Leslie Hunt[12], Chryssa Kouveliotou[13,14] Giorgos Leloudas[1,5], Andrew Levan[15,16], Paolo Mazzali[17,18], Elena Pian[19] [See end for affiliations]

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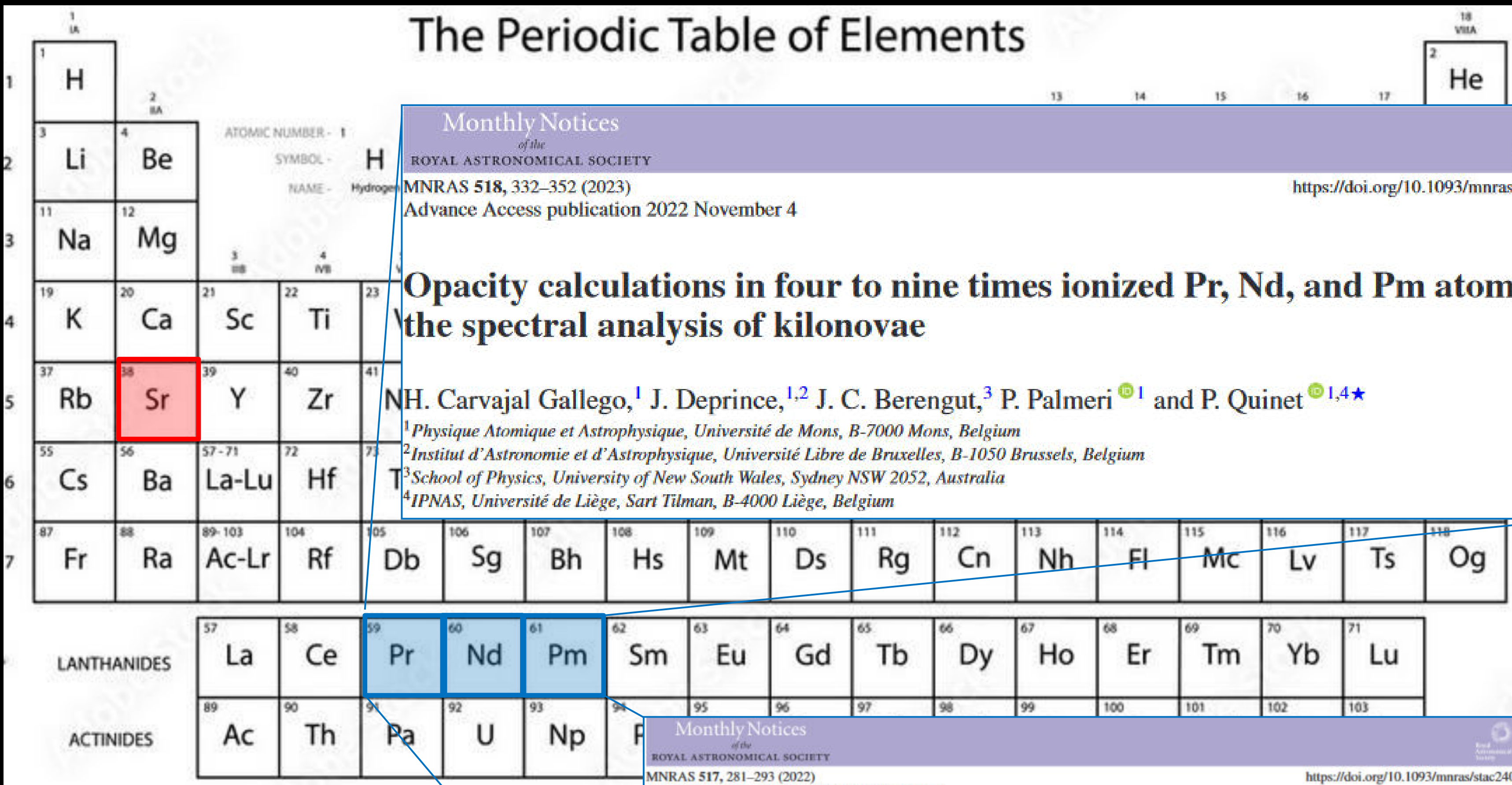

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MNRAS **518**, 332–352 (2023) https://doi.org/10.1093/mnras/stac3129
Advance Access publication 2022 November 4

Opacity calculations in four to nine times ionized Pr, Nd, and Pm atoms for the spectral analysis of kilonovae

H. Carvajal Gallego,[1] J. Deprince,[1,2] J. C. Berengut,[3] P. Palmeri[1] and P. Quinet[1,4★]
[1]*Physique Atomique et Astrophysique, Université de Mons, B-7000 Mons, Belgium*
[2]*Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, B-1050 Brussels, Belgium*
[3]*School of Physics, University of New South Wales, Sydney NSW 2052, Australia*
[4]*IPNAS, Université de Liège, Sart Tilman, B-4000 Liège, Belgium*

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **517**, 281–293 (2022) https://doi.org/10.1093/mnras/stac2401
Advance Access publication 2022 September 1

Theoretical investigation of energy levels and transitions for Pr IV

G. Gaigalas,[1★] P. Rynkun,[1★] S. Banerjee,[2] M. Tanaka,[2,3] D. Kato[4,5] and L. Radžiūtė[1]
[1]*Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio Ave. 3, LT-10257 Vilnius, Lithuania*
[2]*Astronomical Institute, Tohoku University, Sendai 980-8578, Japan*
[3]*Division for the Establishment of Frontier Sciences, Organization for Advanced Studies, Tohoku University, Sendai 980-8577, Japan*
[4]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*
[5]*Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*

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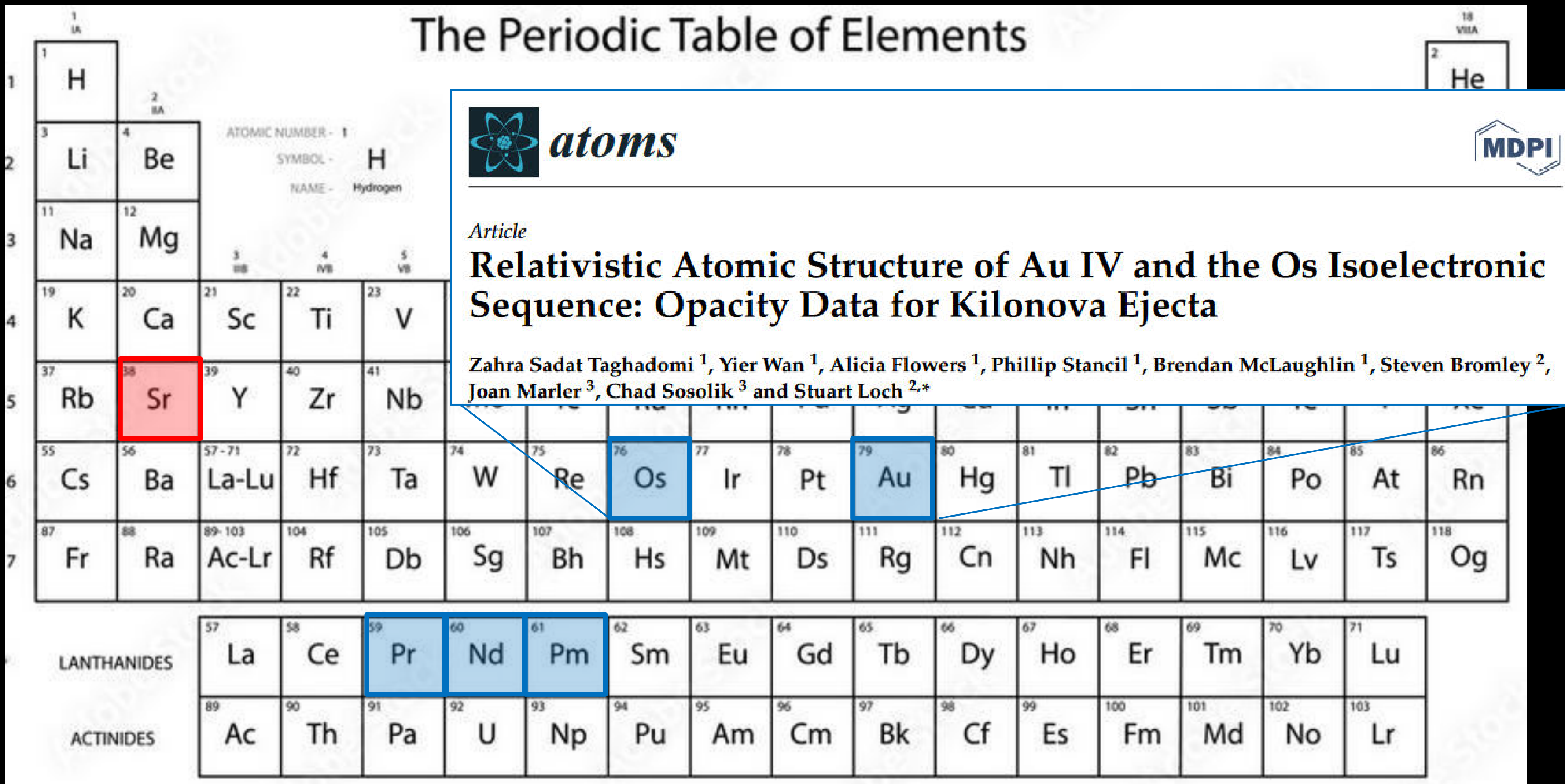

atoms MDPI

Article

Relativistic Atomic Structure of Au IV and the Os Isoelectronic Sequence: Opacity Data for Kilonova Ejecta

Zahra Sadat Taghadomi [1], Yier Wan [1], Alicia Flowers [1], Phillip Stancil [1], Brendan McLaughlin [1], Steven Bromley [2], Joan Marler [3], Chad Sosolik [3] and Stuart Loch [2,*]

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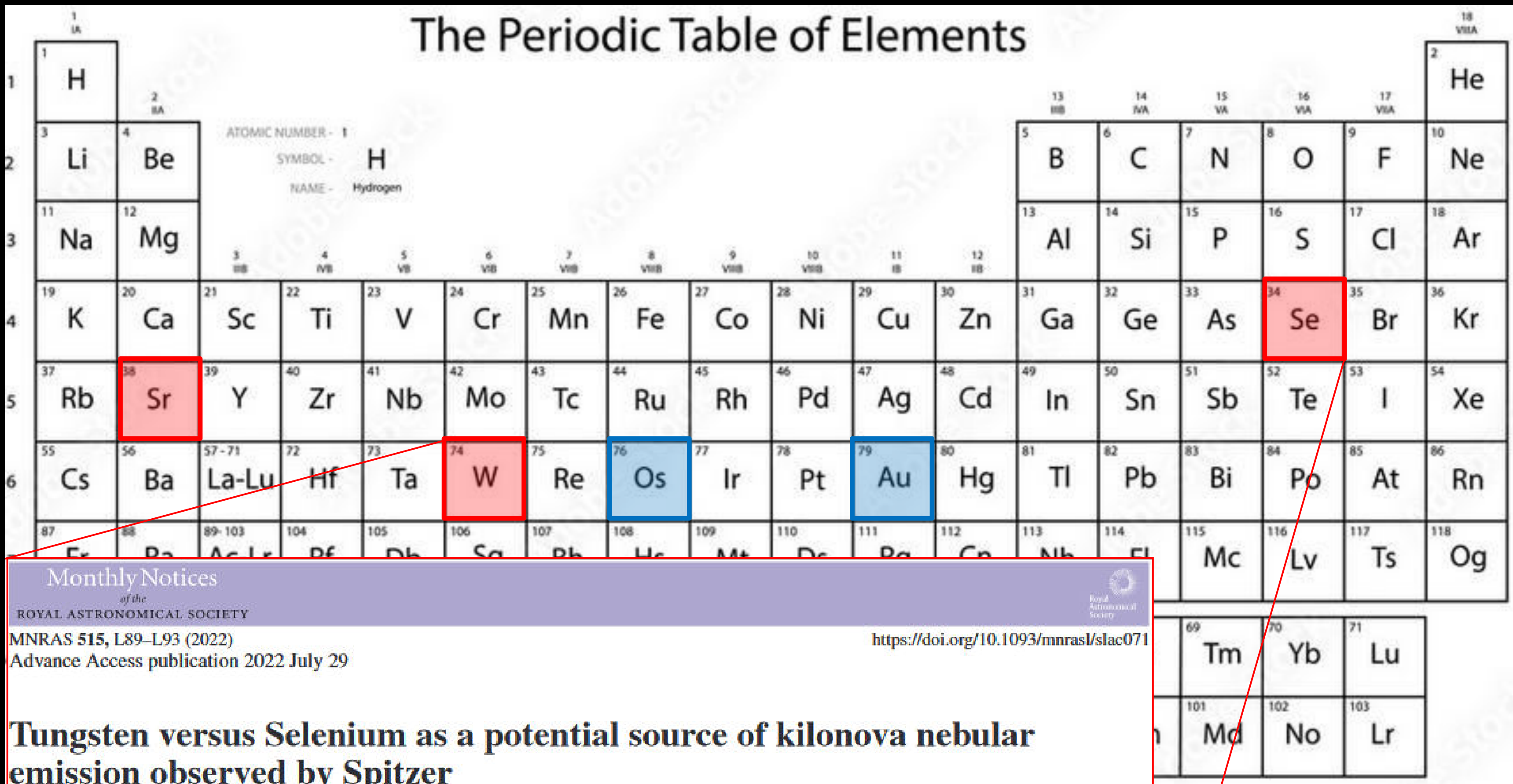

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MNRAS **515**, L89–L93 (2022)
Advance Access publication 2022 July 29
https://doi.org/10.1093/mnrasl/slac071

Tungsten versus Selenium as a potential source of kilonova nebular emission observed by Spitzer

Kenta Hotokezaka,[1,2★] Masaomi Tanaka,[3,4] Daiji Kato[5,6] and Gediminas Gaigalas[7]

[1] *Research Center for the Early Universe, Graduate School of Science, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
[2] *Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*
[3] *Astronomical Institute, Tohoku University, Sendai 980-8578, Japan*
[4] *Division for the Establishment of Frontier Sciences, Organization for Advanced Studies, Tohoku University, Sendai 980-8577, Japan*
[5] *National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*
[6] *Department of Advanced Energy Engineering Science, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*
[7] *Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio Ave. 3, Vilnius, Lithuania*

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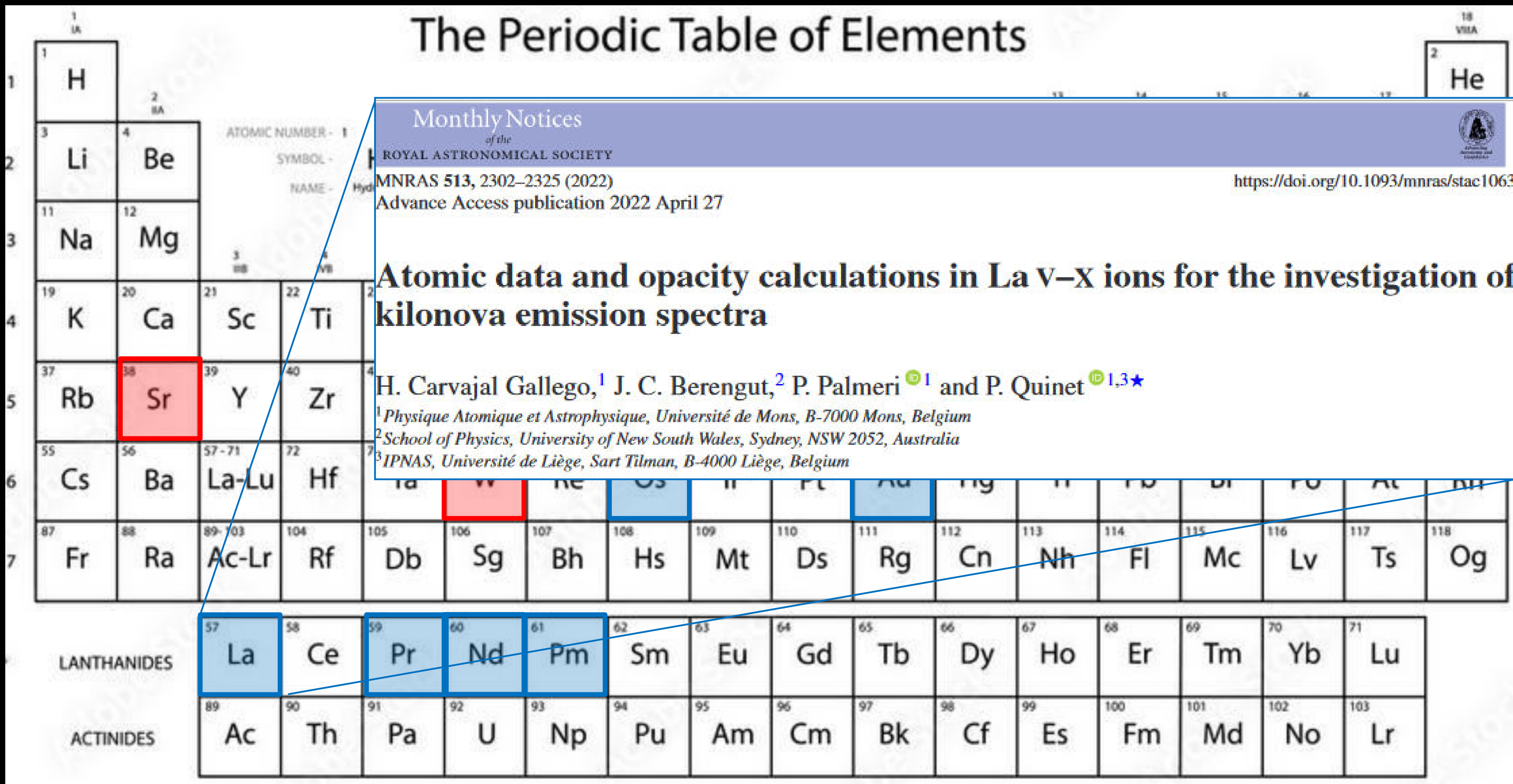

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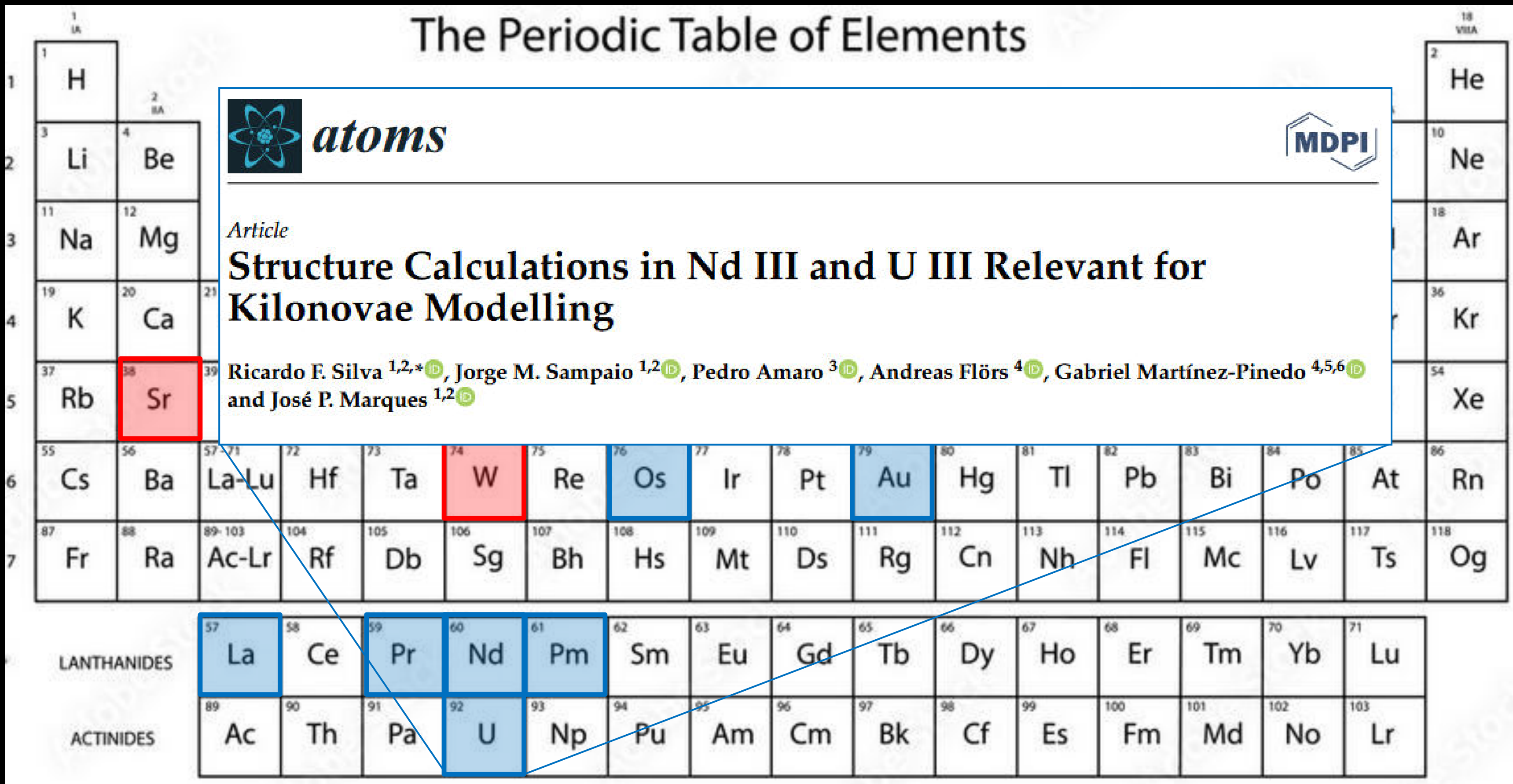
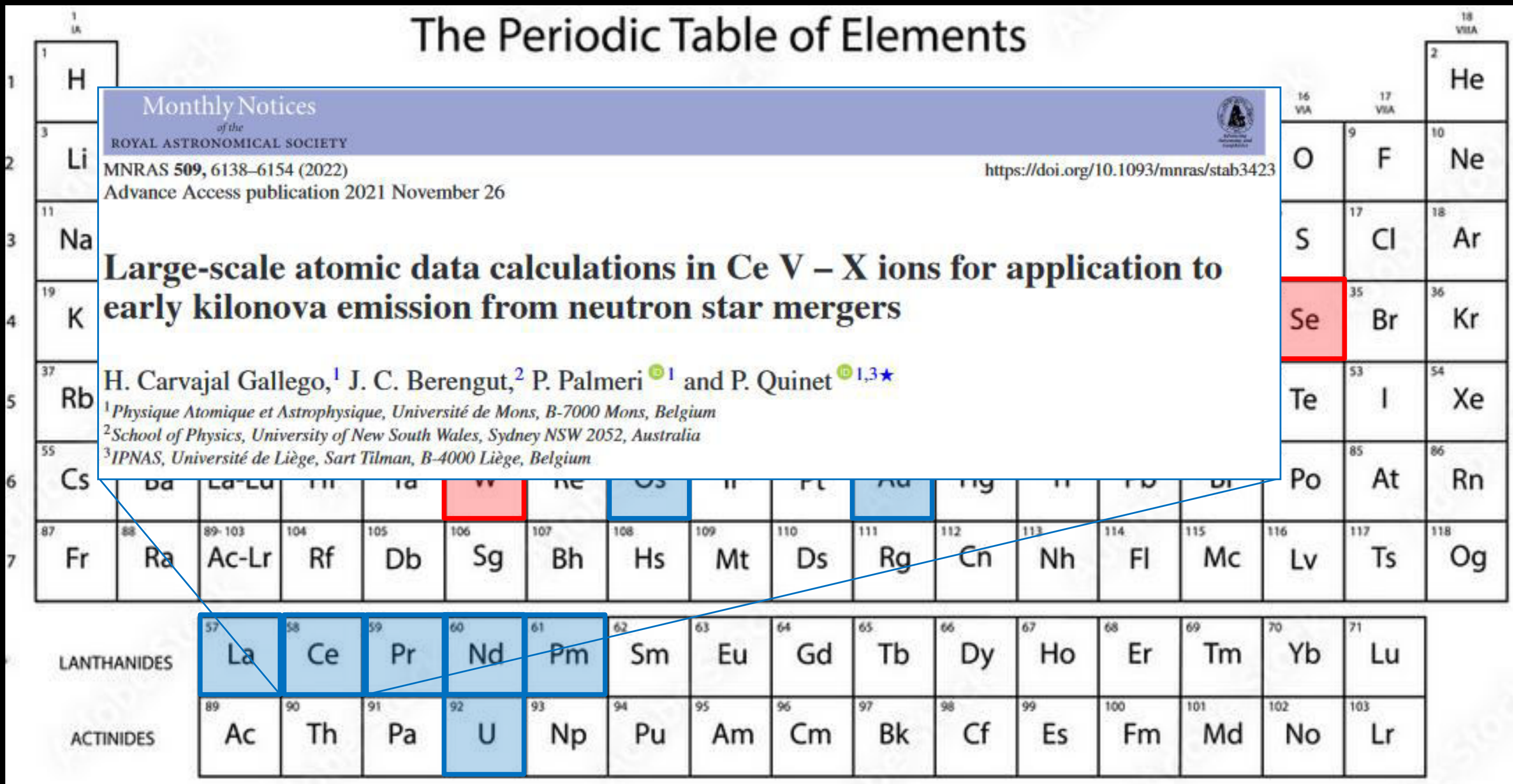


atoms
MDPI

Article

Structure Calculations in Nd III and U III Relevant for Kilonovae Modelling

Ricardo F. Silva [1,2,*], Jorge M. Sampaio [1,2], Pedro Amaro [3], Andreas Flörs [4], Gabriel Martínez-Pinedo [4,5,6] and José P. Marques [1,2]



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MNRAS **509**, 6138–6154 (2022) https://doi.org/10.1093/mnras/stab3423
Advance Access publication 2021 November 26

Large-scale atomic data calculations in Ce V – X ions for application to early kilonova emission from neutron star mergers

H. Carvajal Gallego,[1] J. C. Berengut,[2] P. Palmeri[1] and P. Quinet[1,3★]
[1] *Physique Atomique et Astrophysique, Université de Mons, B-7000 Mons, Belgium*
[2] *School of Physics, University of New South Wales, Sydney NSW 2052, Australia*
[3] *IPNAS, Université de Liège, Sart Tilman, B-4000 Liège, Belgium*

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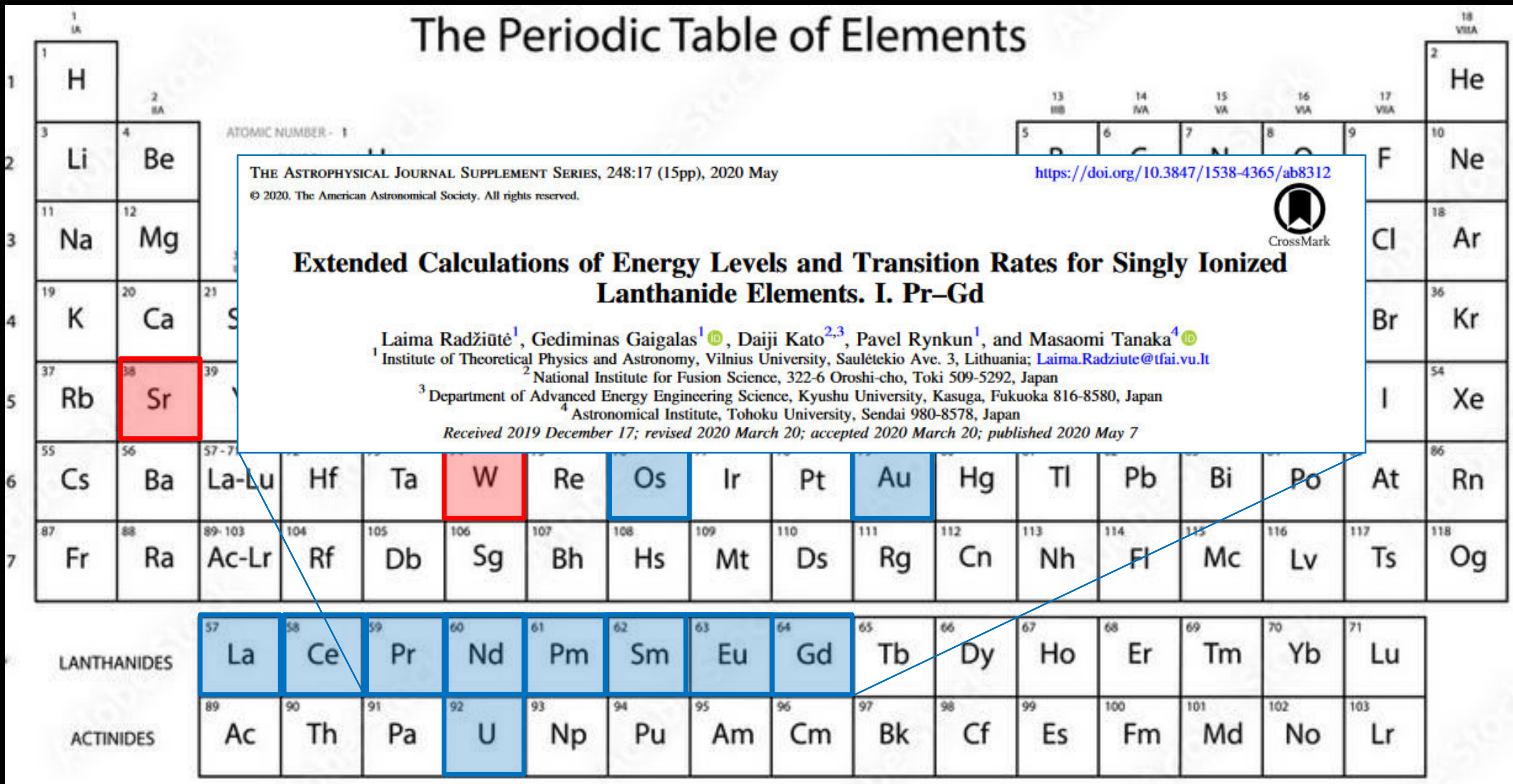
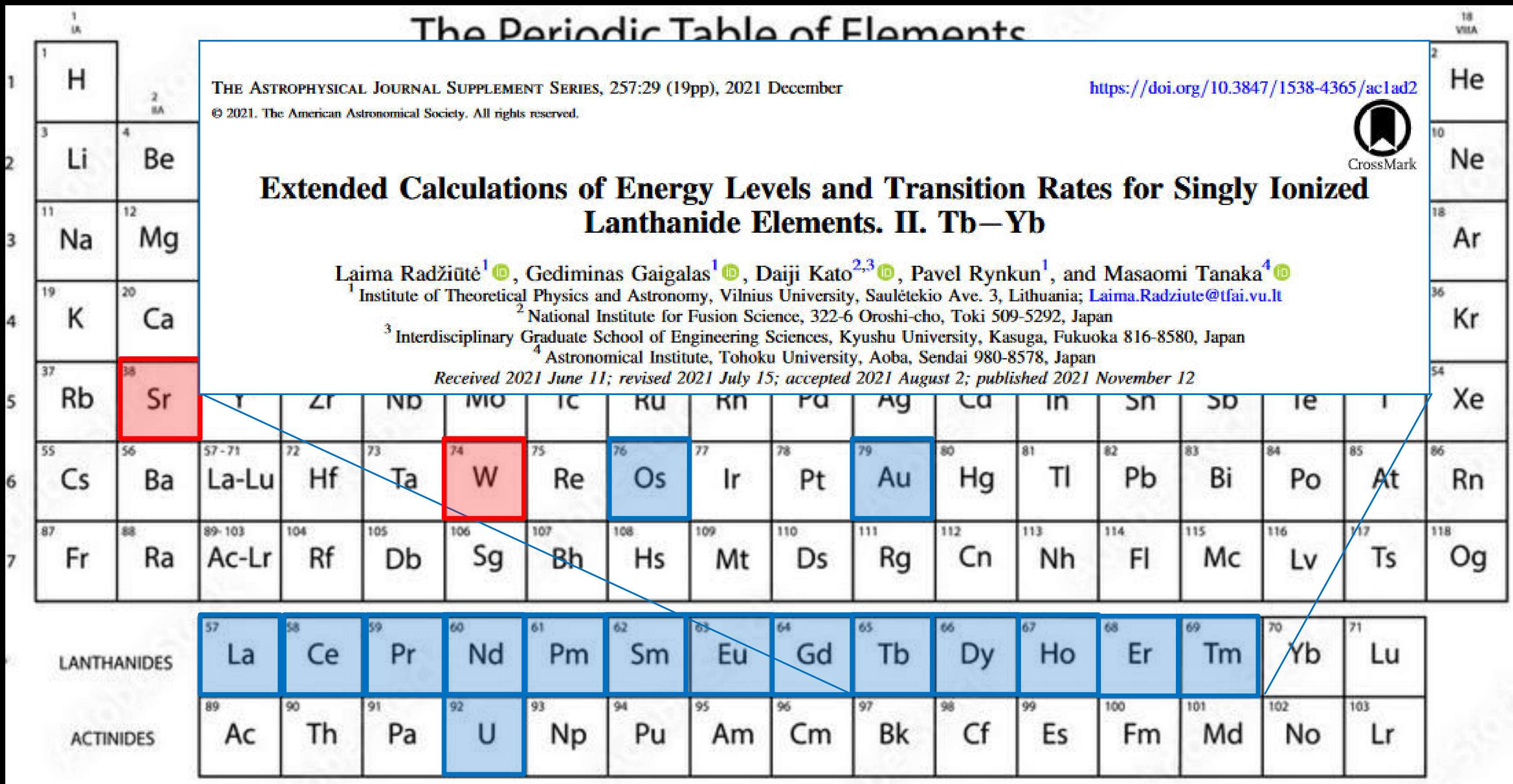


The Astrophysical Journal Supplement Series, 248:17 (15pp), 2020 May
https://doi.org/10.3847/1538-4365/ab8312

Extended Calculations of Energy Levels and Transition Rates for Singly Ionized Lanthanide Elements. I. Pr–Gd

Laima Radžiūtė[1], Gediminas Gaigalas[1], Daiji Kato[2,3], Pavel Rynkun[1], and Masaomi Tanaka[4]
[1] Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio Ave. 3, Lithuania; Laima.Radziute@tfai.vu.lt
[2] National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
[3] Department of Advanced Energy Engineering Science, Kyushu University, Kasuga, Fukuoka 816-8580, Japan
[4] Astronomical Institute, Tohoku University, Sendai 980-8578, Japan
Received 2019 December 17; revised 2020 March 20; accepted 2020 March 20; published 2020 May 7



The Astrophysical Journal Supplement Series, 257:29 (19pp), 2021 December
https://doi.org/10.3847/1538-4365/ac1ad2

Extended Calculations of Energy Levels and Transition Rates for Singly Ionized Lanthanide Elements. II. Tb—Yb

Laima Radžiūtė[1], Gediminas Gaigalas[1], Daiji Kato[2,3], Pavel Rynkun[1], and Masaomi Tanaka[4]
[1] Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio Ave. 3, Lithuania; Laima.Radziute@tfai.vu.lt
[2] National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
[3] Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan
[4] Astronomical Institute, Tohoku University, Aoba, Sendai 980-8578, Japan
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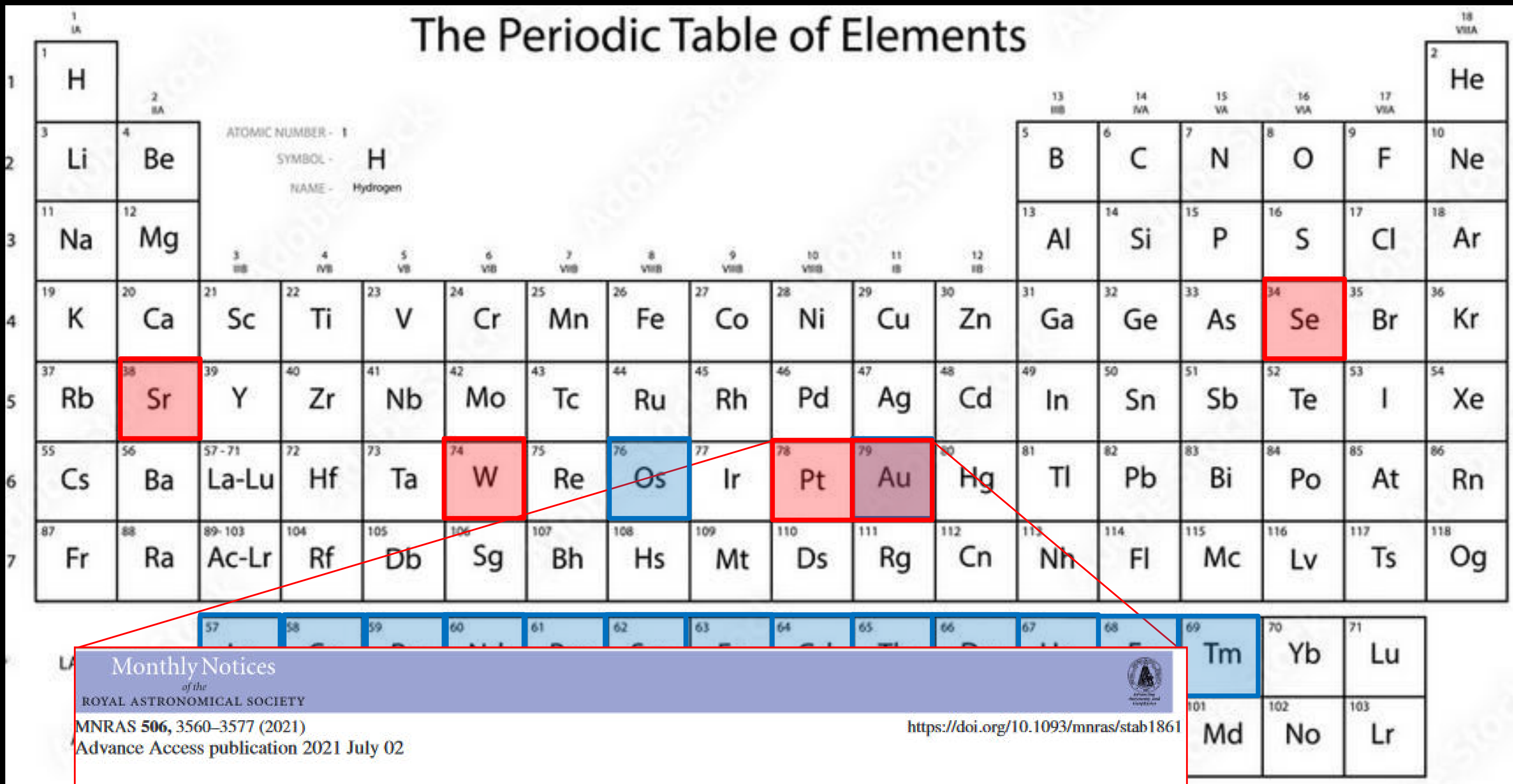

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MNRAS **506**, 3560–3577 (2021)
Advance Access publication 2021 July 02

https://doi.org/10.1093/mnras/stab1861

Constraints on the presence of platinum and gold in the spectra of the kilonova AT2017gfo

J. H. Gillanders,[1★] M. McCann,[2] S. A. Sim,[1] S. J. Smartt[1] and C. P. Ballance[2]

[1] *Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, BT7 1NN Belfast, UK*
[2] *Centre for Theoretical Atomic, Molecular and Optical Physics, School of Mathematics and Physics, Queen's University Belfast, BT7 1NN Belfast, UK*

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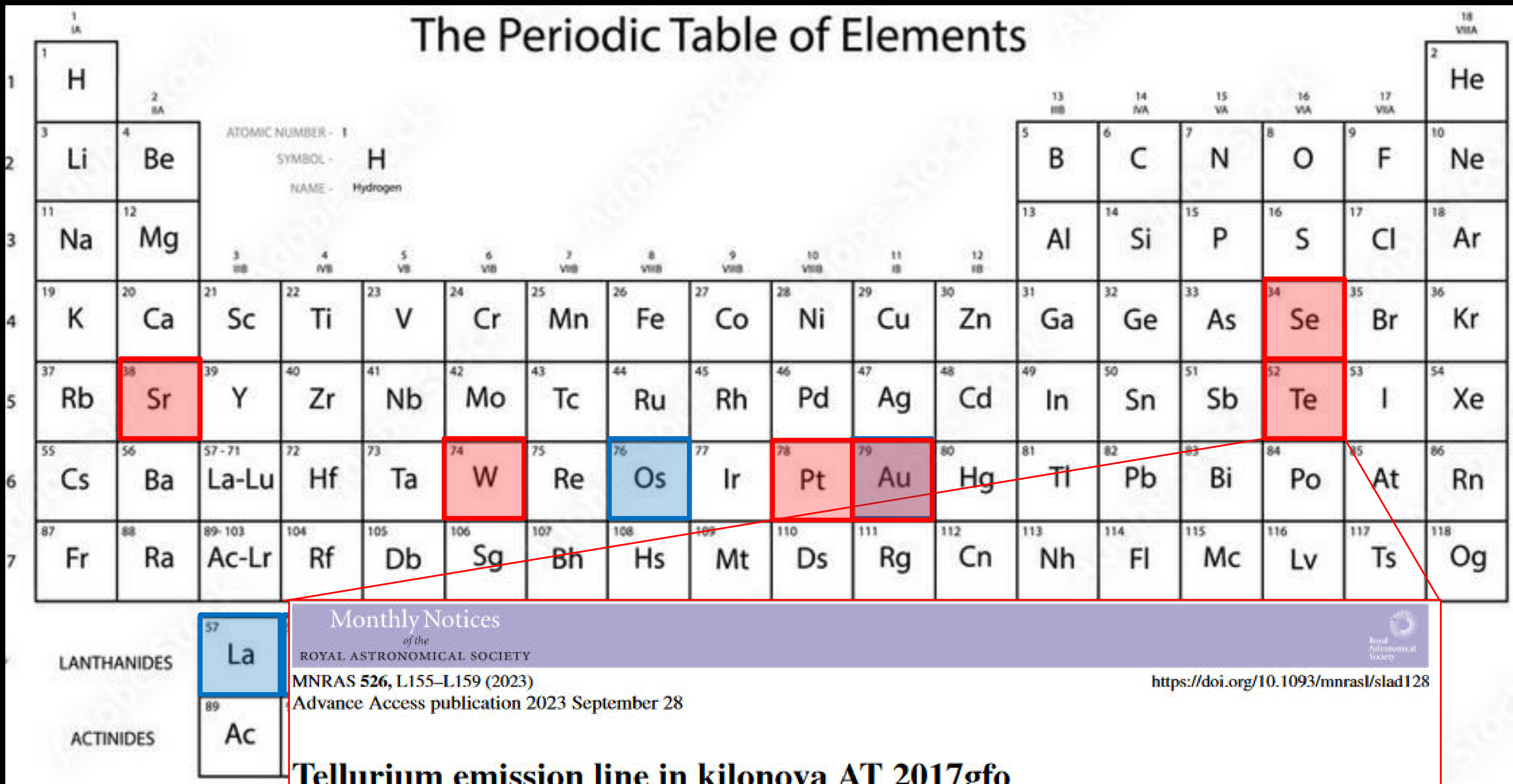

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MNRAS **526**, L155–L159 (2023) https://doi.org/10.1093/mnrasl/slad128
Advance Access publication 2023 September 28

Tellurium emission line in kilonova AT 2017gfo

Kenta Hotokezaka,[1★] Masaomi Tanaka [2] Daiji Kato[3,4] and Gediminas Gaigalas[5]

[1] *Research Center for the Early Universe, Graduate School of Science, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
[2] *Astronomical Institute, Tohoku University, Aoba, Sendai 980-8578, Japan*
[3] *National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*
[4] *Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Fukuoka 816-8580, Japan*
[5] *Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio Ave. 3, Vilnius 10222, Lithuania*

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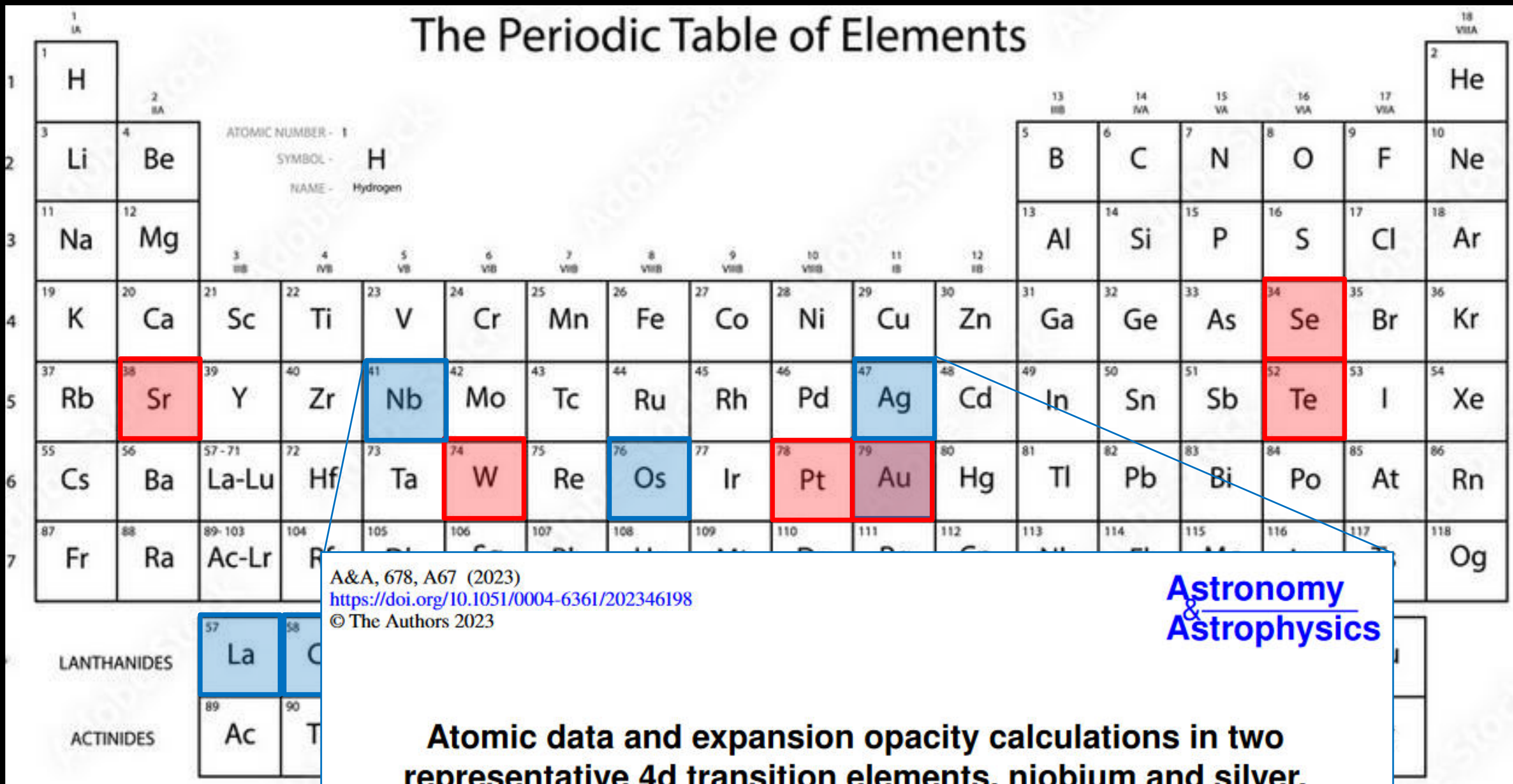

A&A, 678, A67 (2023)
https://doi.org/10.1051/0004-6361/202346198

Astronomy & Astrophysics

Atomic data and expansion opacity calculations in two representative 4d transition elements, niobium and silver, of interest for kilonovae studies★

S. Ben Nasr[1], H. Carvajal Gallego[1], J. Deprince[1,2], P. Palmeri[1], and P. Quinet[1,3]

[1] Physique Atomique et Astrophysique, Université de Mons, 7000 Mons, Belgium
e-mail: sirine.bennasr@umons.ac.be; sirinamarouan@gmail.com; pascal.quinet@umons.ac.be
[2] Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, CP 226, 1050 Brussels, Belgium
[3] IPNAS, Université de Liège, Sart Tilman, 4000 Liège, Belgium

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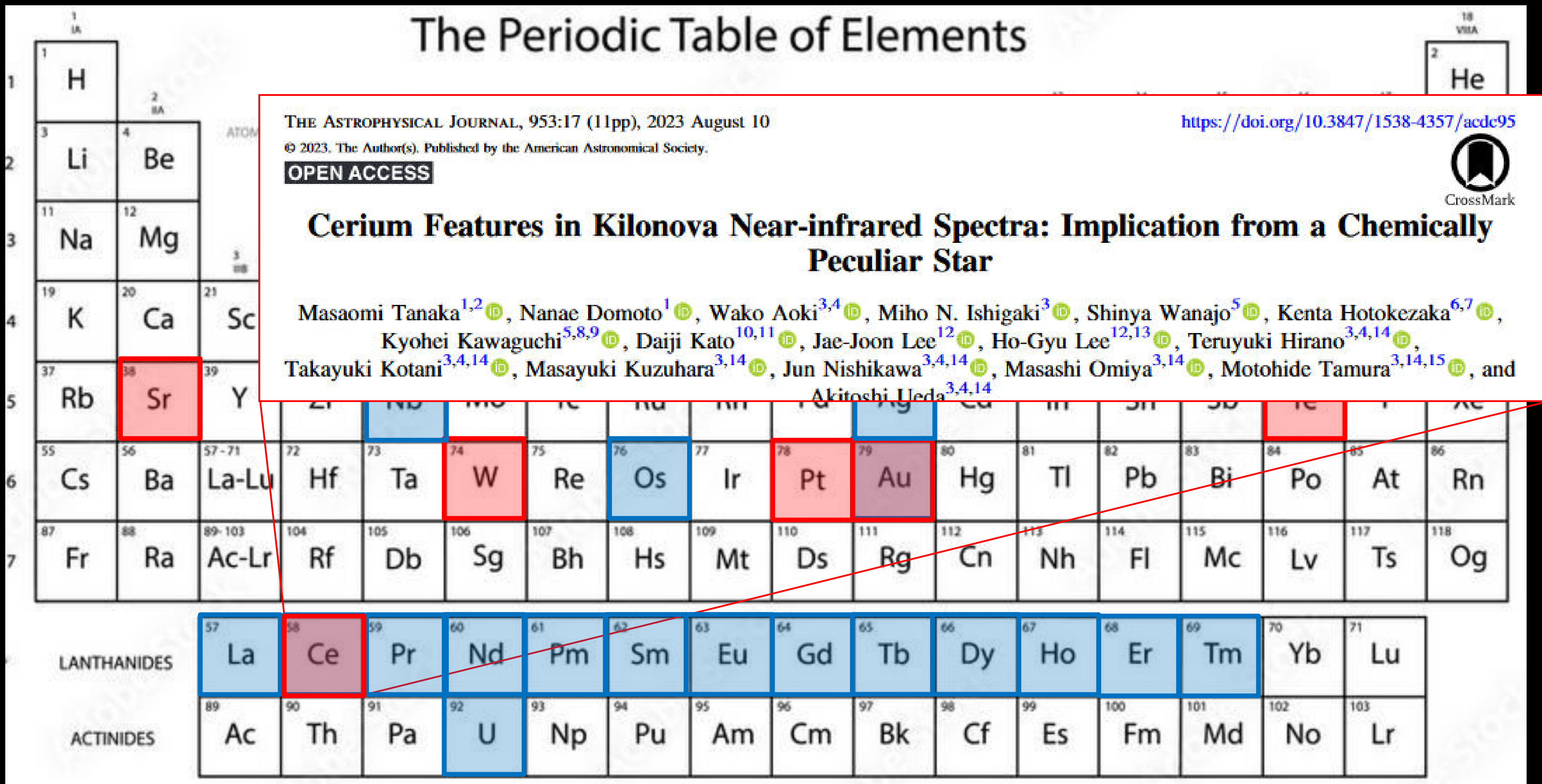

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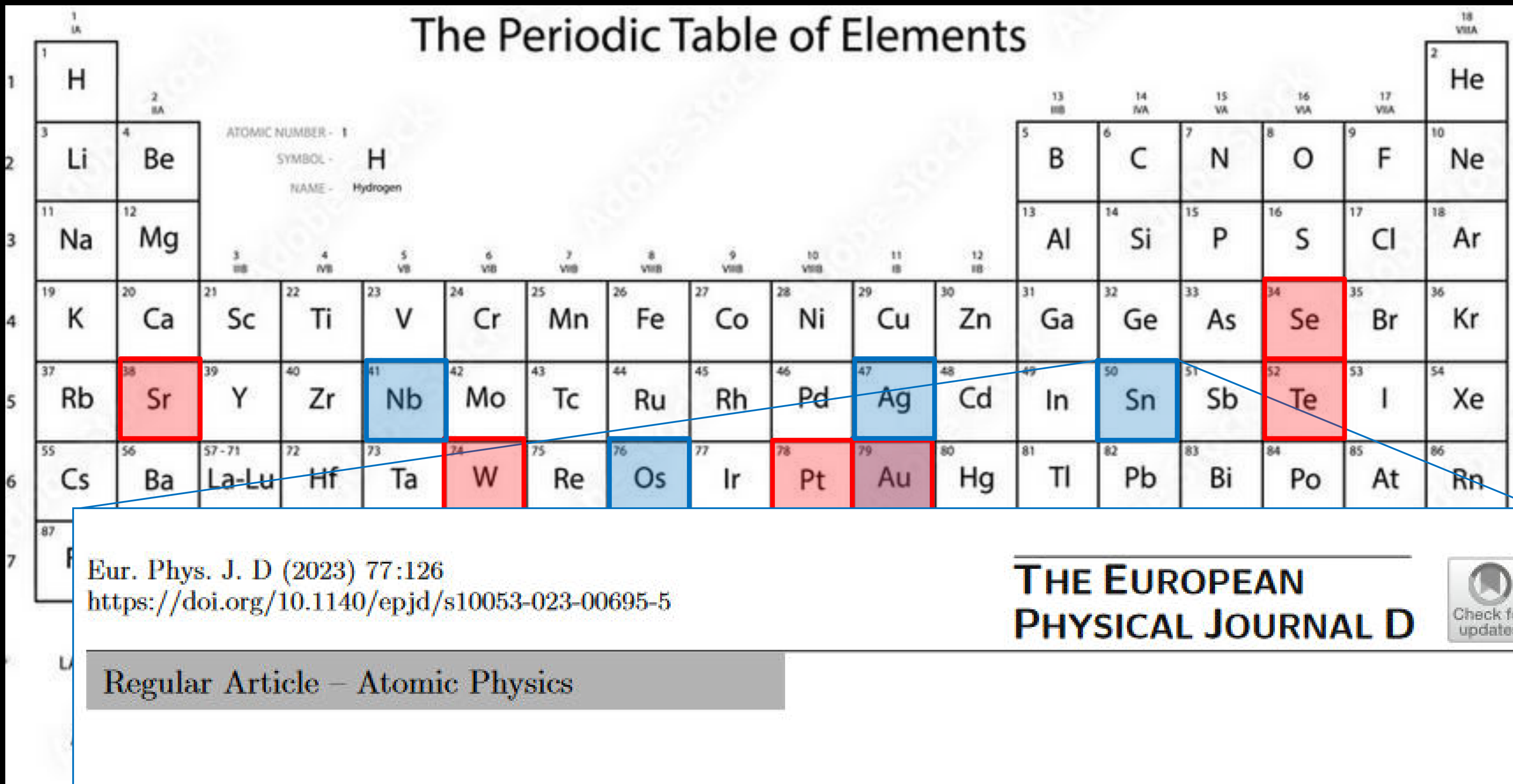

Eur. Phys. J. D (2023) 77:126
https://doi.org/10.1140/epjd/s10053-023-00695-5

THE EUROPEAN PHYSICAL JOURNAL D

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Regular Article – Atomic Physics

Calculations of multipole transitions in Sn II for kilonova analysis

A. I. Bondarev[1,2,a], J. H. Gillanders[3], C. Cheung[4], M. S. Safronova[4,5], and S. Fritzsche[1,2,6]

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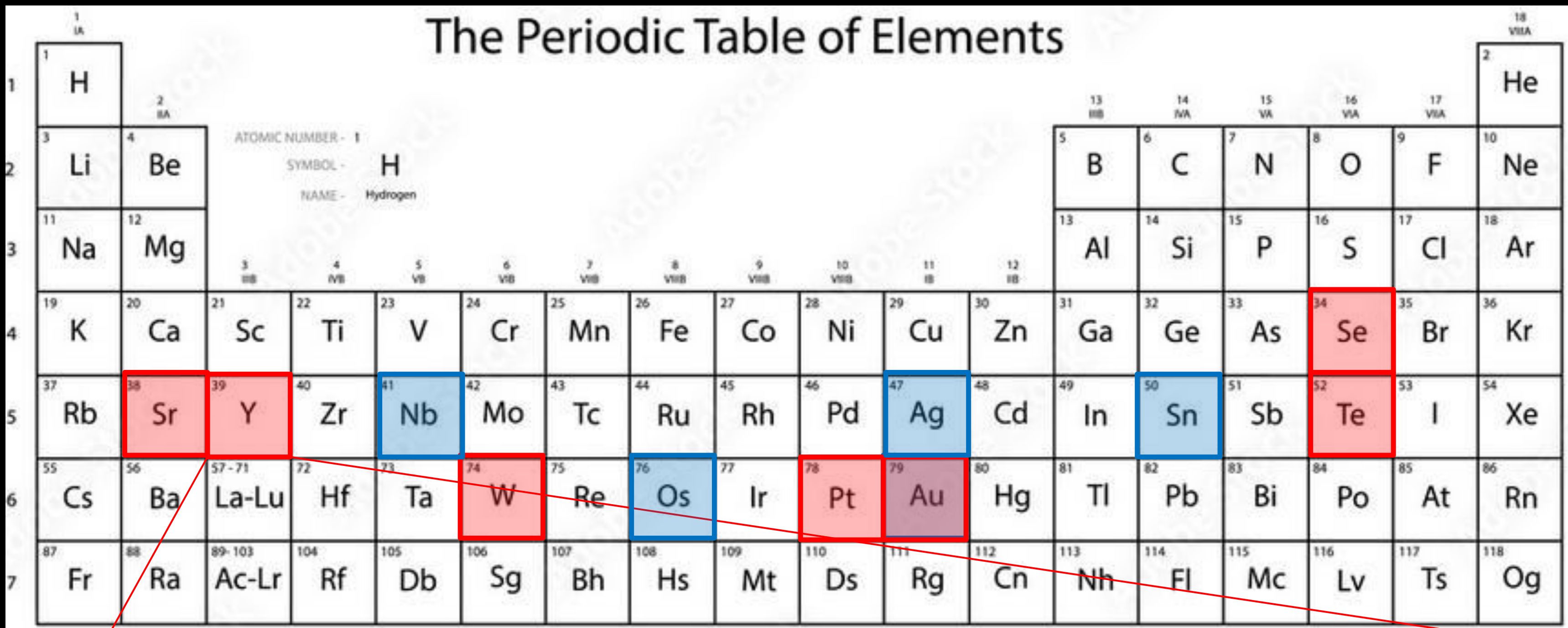

A&A 675, A194 (2023)
https://doi.org/10.1051/0004-6361/202346421

Astronomy & Astrophysics

Discovery of a 760 nm P Cygni line in AT2017gfo: Identification of yttrium in the kilonova photosphere

Albert Sneppen[1,2] and Darach Watson[1,2]

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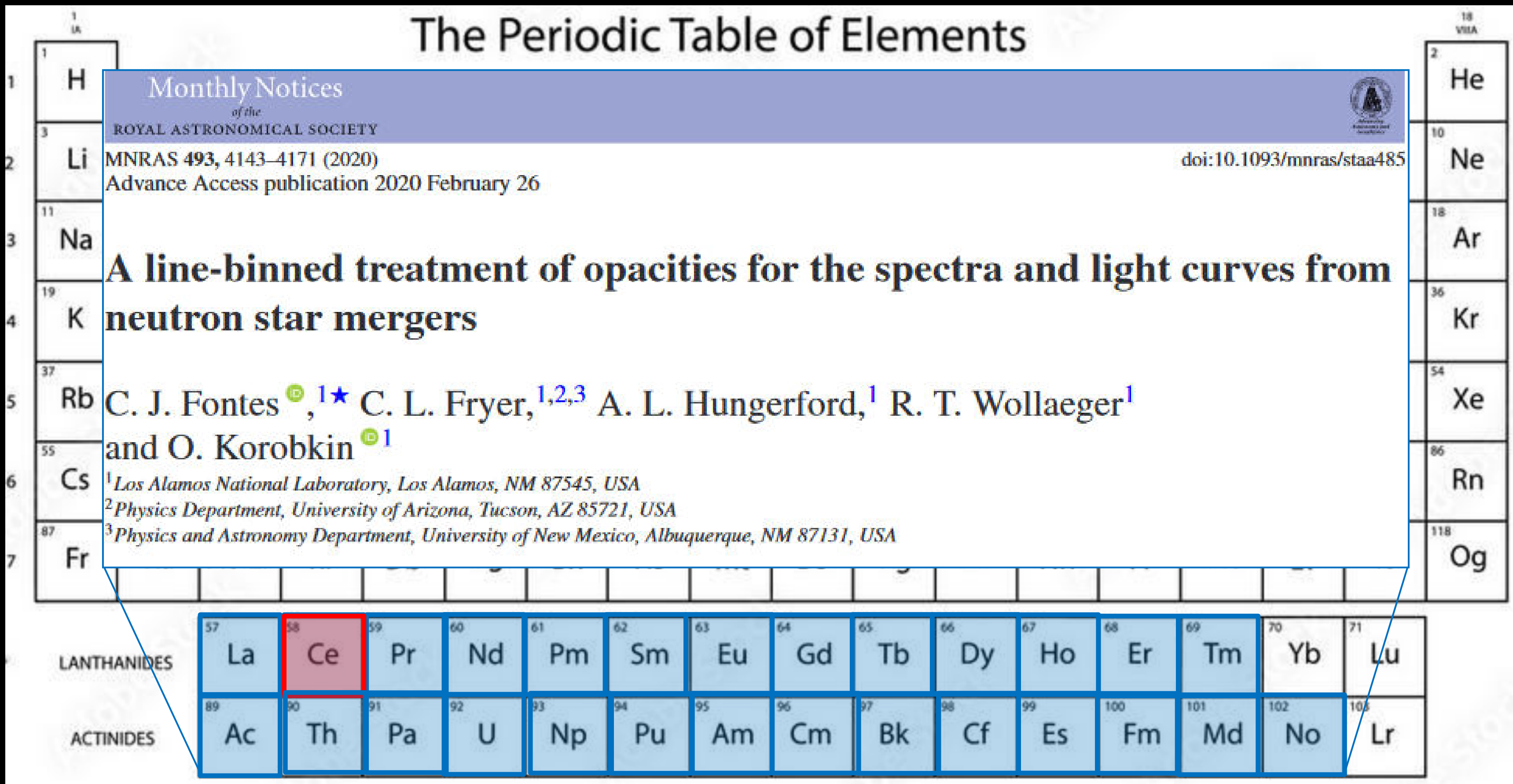

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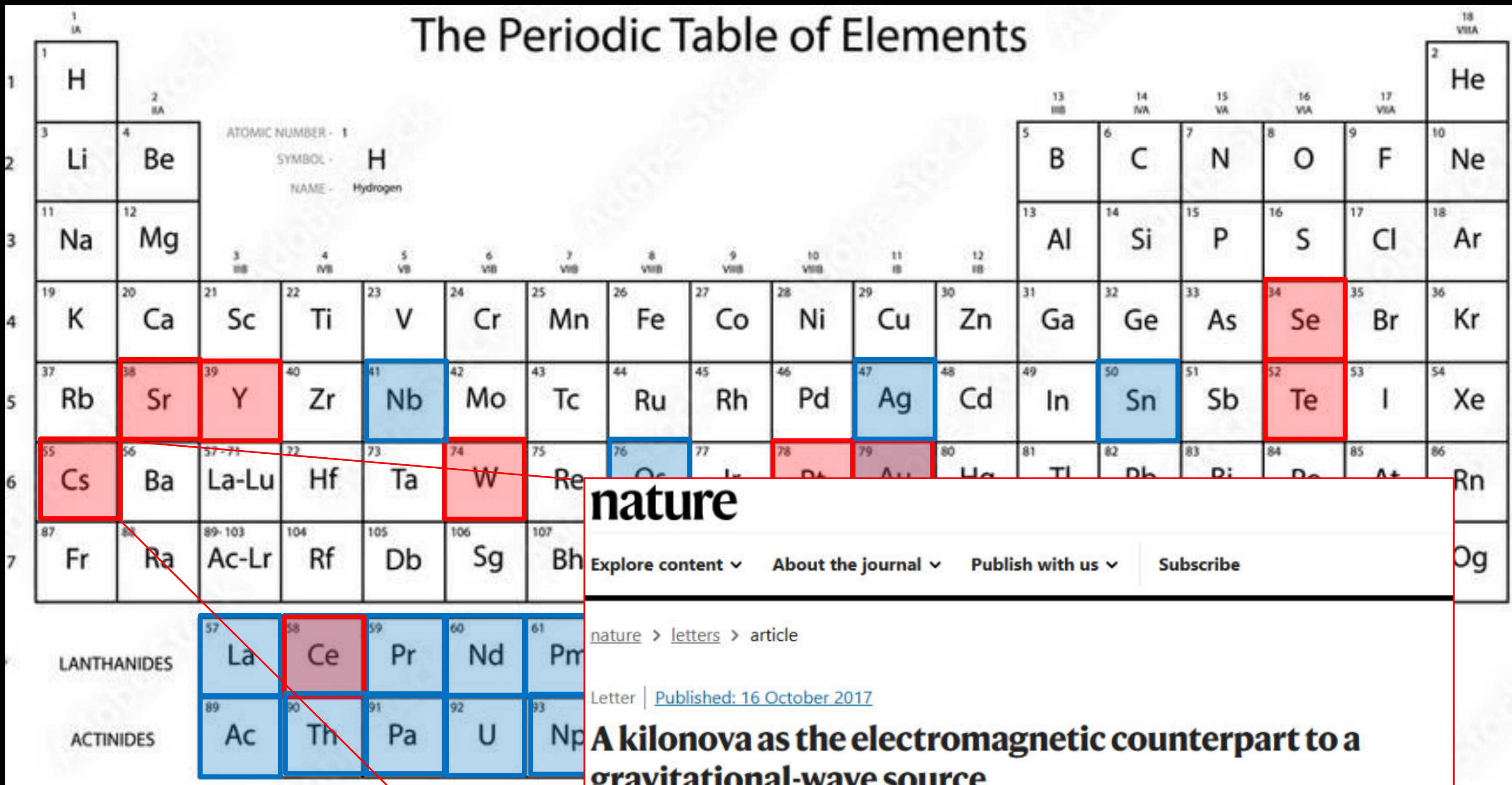
MNRAS **493,** 4143–4171 (2020) doi:10.1093/mnras/staa485
Advance Access publication 2020 February 26

A line-binned treatment of opacities for the spectra and light curves from neutron star mergers

C. J. Fontes,[1★] C. L. Fryer,[1,2,3] A. L. Hungerford,[1] R. T. Wollaeger[1] and O. Korobkin[1]

[1] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[2] *Physics Department, University of Arizona, Tucson, AZ 85721, USA*
[3] *Physics and Astronomy Department, University of New Mexico, Albuquerque, NM 87131, USA*



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Letter | Published: 16 October 2017

A kilonova as the electromagnetic counterpart to a gravitational-wave source

S. J. Smartt, T.-W. Chen, A. Jerkstrand, M. Coughlin, E. Kankare, S. A. Sim, M. Fraser, C. Inserra, K. Maguire, K. C. Chambers, M. E. Huber, T. Krühler, G. Leloudas, M. Magee, L. J. Shingles, K. W. Smith, D. R. Young, J. Tonry, R. Kotak, A. Gal-Yam, J. D. Lyman, D. S. Homan, C. Agliozzo, J. P. Anderson, ... O. Yaron

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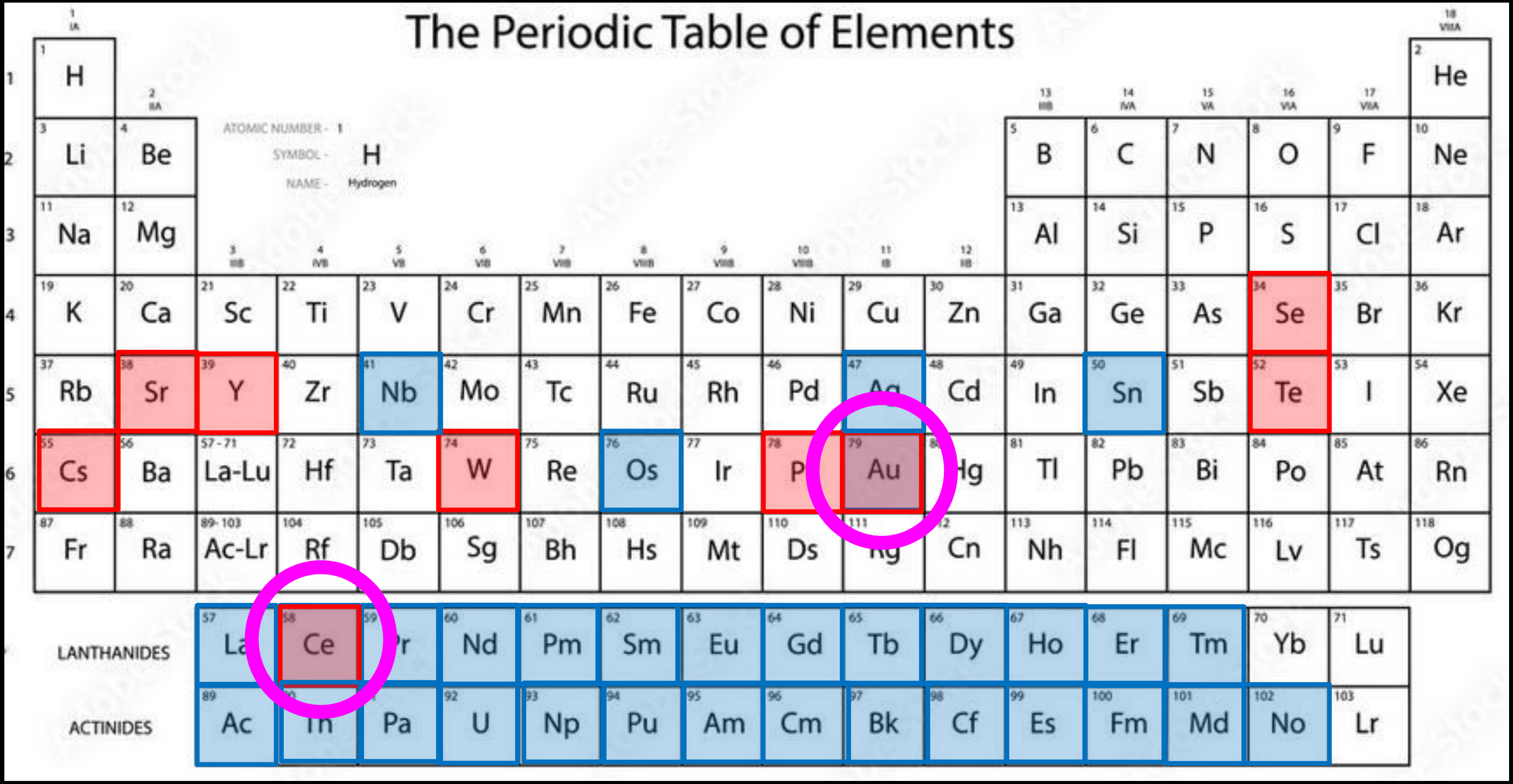

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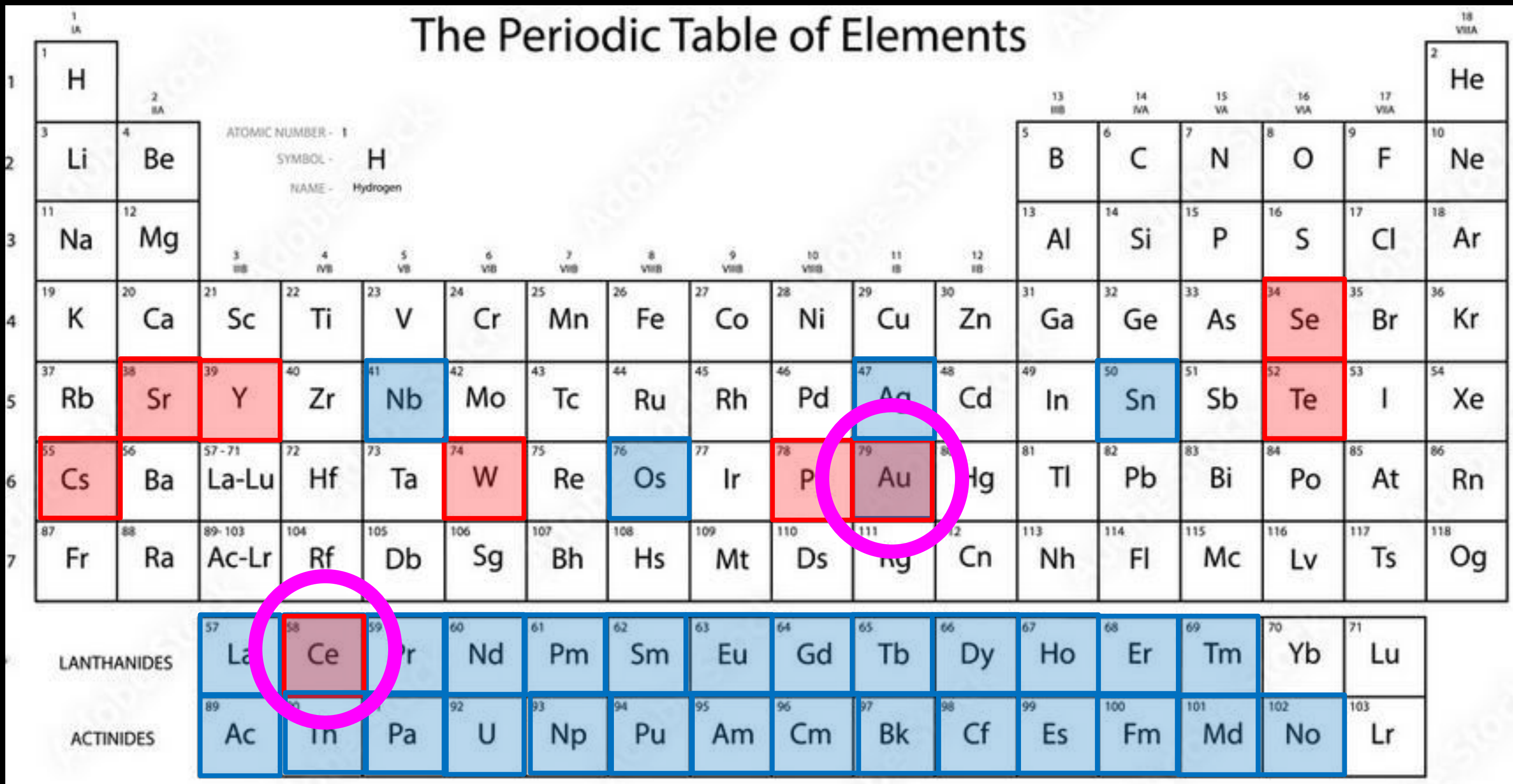

Without considering the various degree of ionization of each element!

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INAF ISTITUTO NAZIONALE DI ASTROFISICA Osservatorio Astronomico d'Abruzzo

Theoretical approach

GRASP

General Relativistic Atomic Structure Package

Based on

- ✓ Relativistic Multi-Configuration Dirac-Hartree-Fock (MCDHF)
- ✓ Breit and Quantum ElectroDynamics (QED) corrections

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General Relativistic Atomic Structure Package

- ✓ Electron configurations for atomic data
- ✓ Spectroscopic labels
- ✓ Atomic data needed for:

1. Wavelengths of emission lines;
2. E1 and M1 spontaneous emission rates (transition probabilities).

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M. Bezmalinovich PhD Thesis

Opacity estimation

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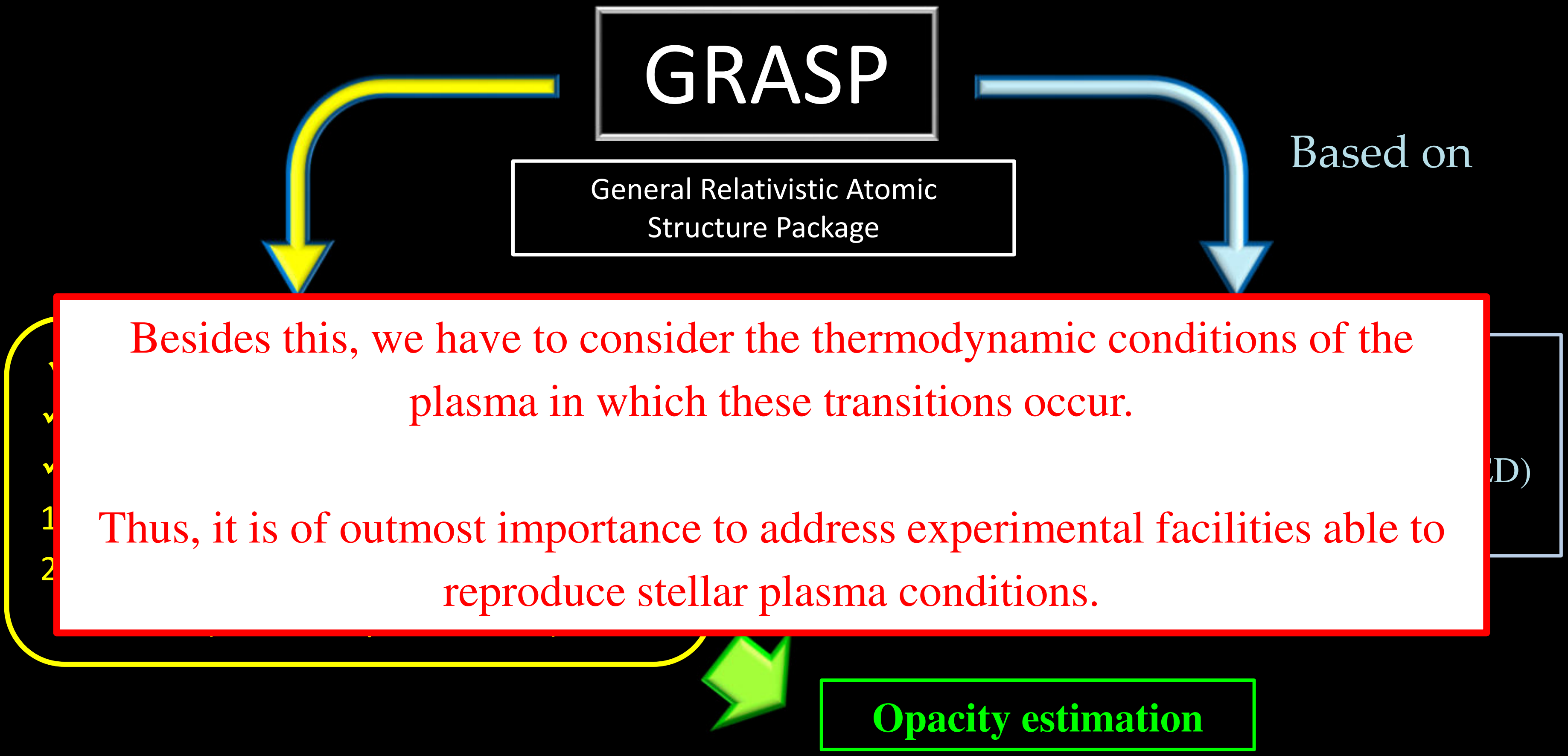
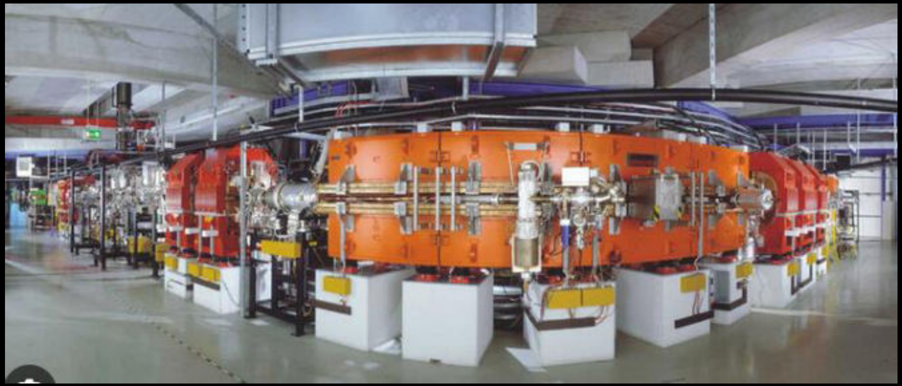
Theoretical approach

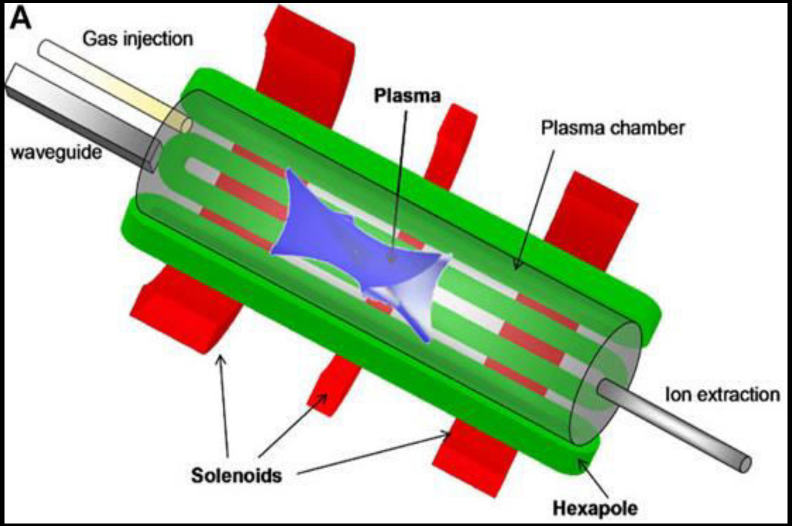


Besides this, we have to consider the thermodynamic conditions of the plasma in which these transitions occur.

Thus, it is of outmost importance to address experimental facilities able to reproduce stellar plasma conditions.

Ion Storage Rings vs. Plasma Traps





The storage ring approach is based on the investigations of a single charge state at a time.

A plasma trap reproduce stellar-like conditions where a Charge State Distribution (CSD) of the ions is established.

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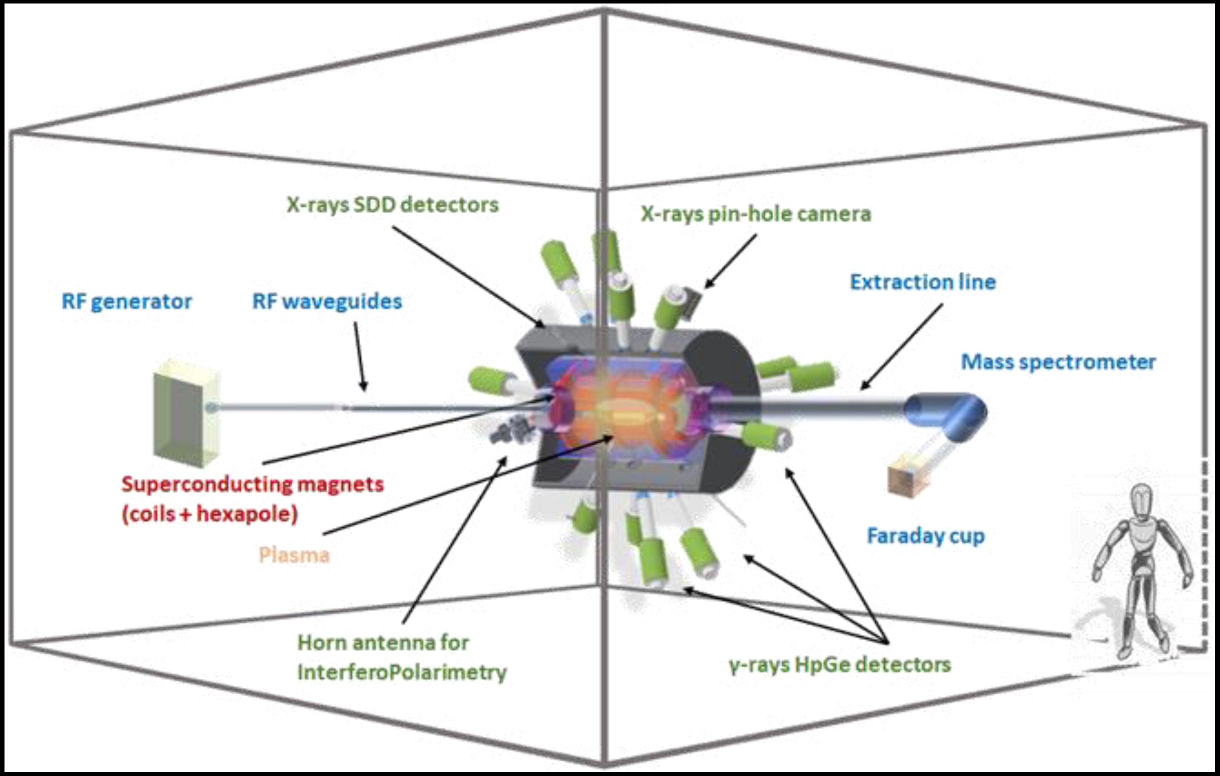
Plasmas for Astrophysics Nuclear Decays Observation and Radiation for Archaeometry

PANDORA



INFN - Laboratori Nazionali del Sud (Catania)

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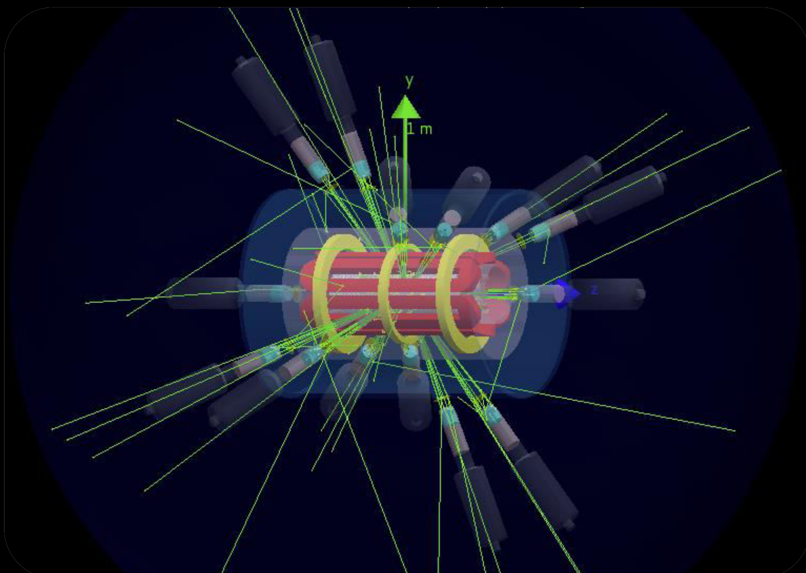
PANDORA

Mascali+2021



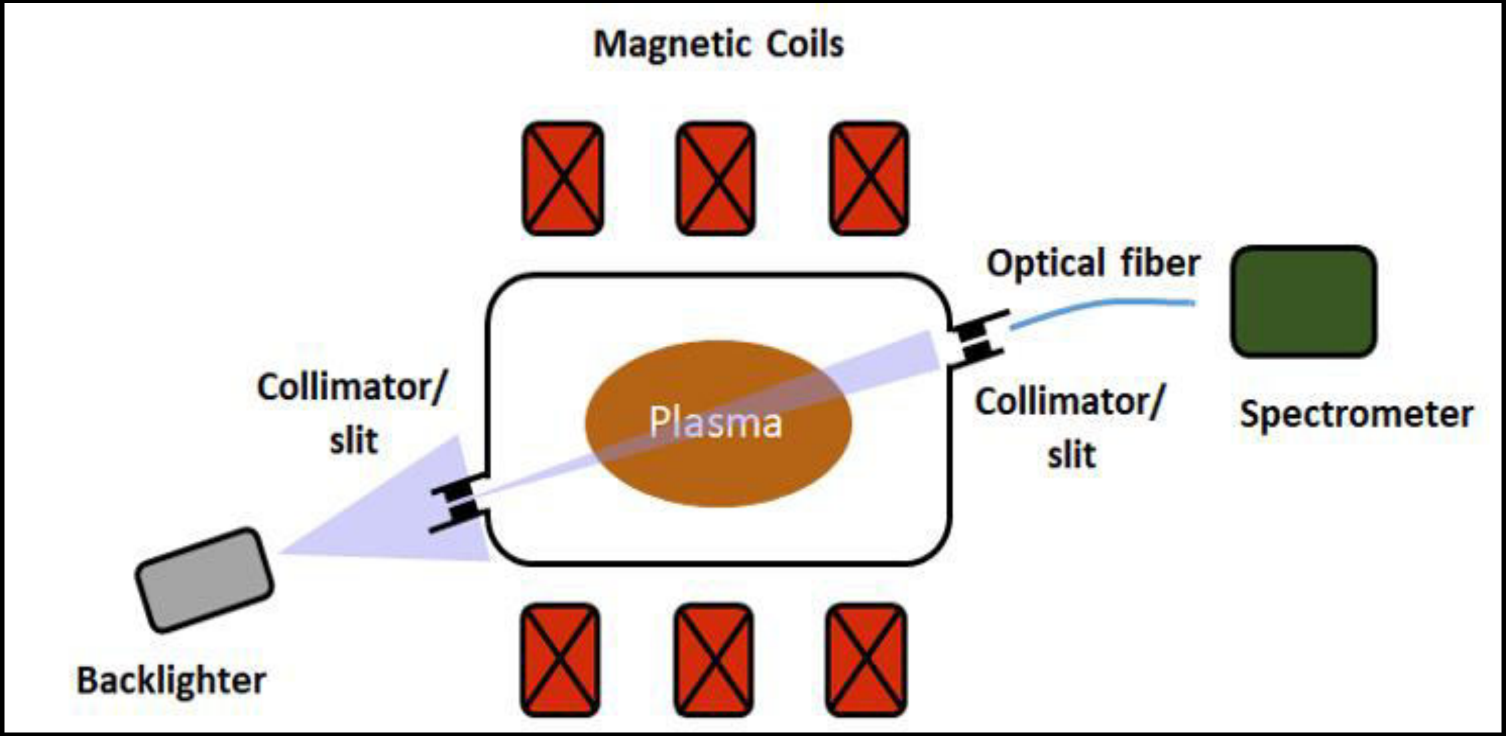
1) **Superconducting Magnetic Plasma Trap:** the plasma is generated via the **electron cyclotron resonance (ECR)** mechanism, sustained via microwave, and confined by the magnetic trap;
2) **HpGe Array:** it consists of 14 detectors to measure the γ rays emitted after β-decays;
3) **Plasma Diagnostics System:** it consists of RF, optical and X ray spectrometers allowing direct correlation of β-decay rate to plasma density and temperature

It could *"add unique research capability"* in Astrophysics and Nuclear Astrophysics in laboratory:

1) **for the first time, β-decay measurements in plasmas (^{176}Lu, ^{134}Cs, and ^{94}Nb);**

2) **plasma opacity measurements in conditions similar to kilonovae ejecta.**

PANDORA and Neutron Stars



The plasma, enriched with a single heavy element, is irradiated with a (white) calibrated source with an emissivity larger than plasma's one. Then, by means of a spectrometer, the spectral characteristics of the chemical elements are derived.

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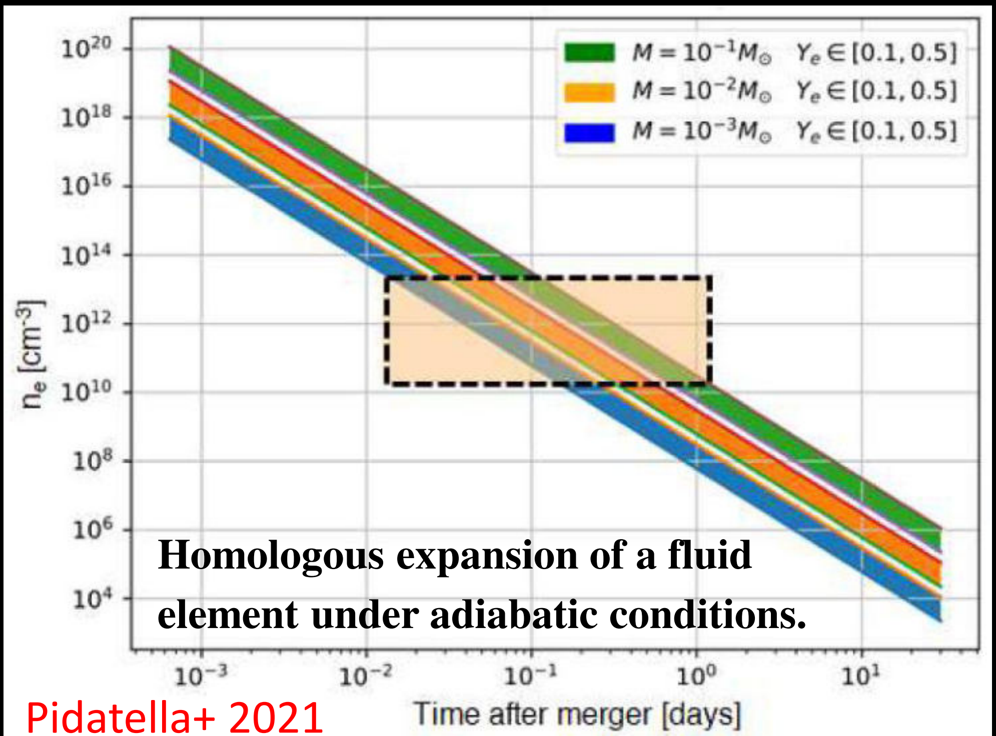
PANDORA and Neutron Stars



Pidatella+ 2021

PANDORA will have a dense and hot plasma, made of multi-charged ions in a cloud of energetic electrons, which is confined in a so-called minimum-B magnetic profile, and heated by microwave power, according to the electron cyclotron resonance (ECR) mechanism.

- n_e: 10^{10} - 10^{13} cm^{-3}
- T_e: few eV

PANDORA plasma parameters fit better the conditions of early-stage kilonova emission, i.e., between 10^{-2} – 1 days after merger.

This early phase of the signal (blue-kilonova emission) has its peak at optical frequencies, more likely due to the ejecta's light component featuring a low degree of opacity.

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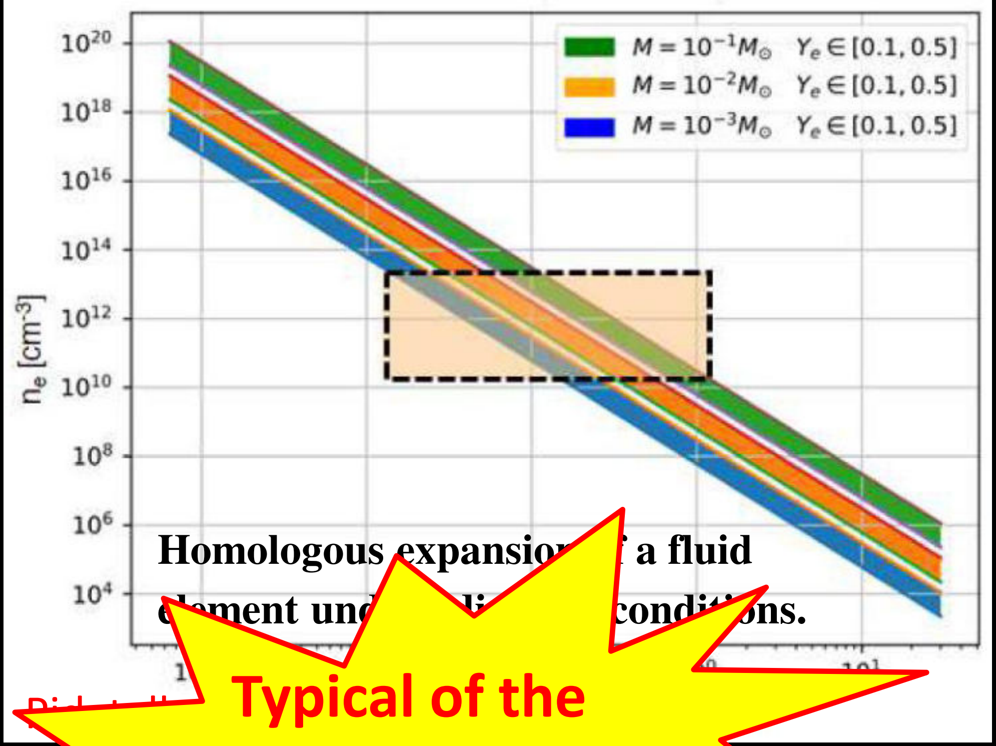
PANDORA and Neutron Stars



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- n_e: 10^{10} - 10^{13} cm^{-3}
- T_e: few eV

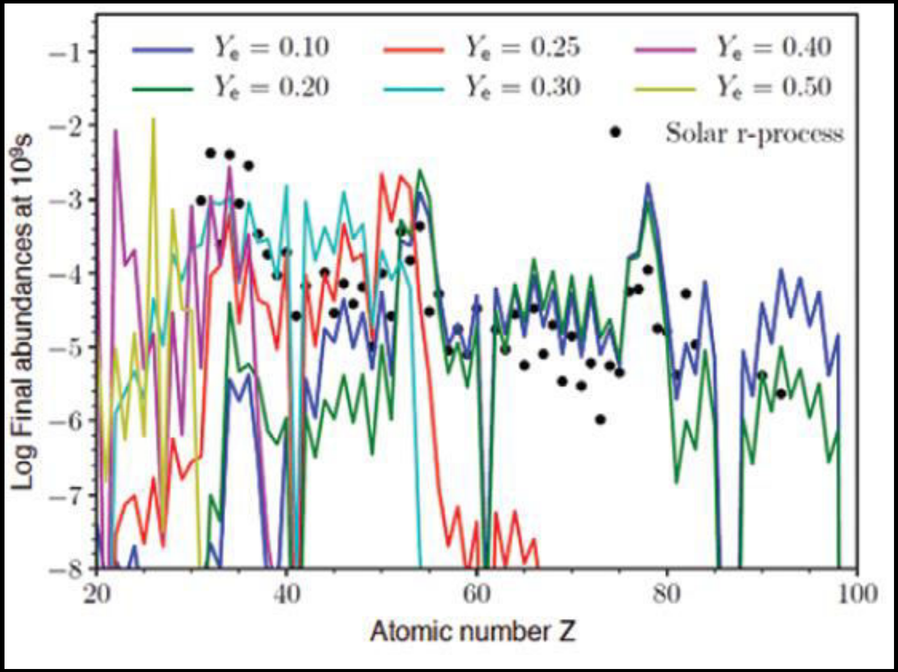
Typical of the blue-kilonova phase!!

PANDO ... er the conditions of early-stage kilonova emission, ... erger.

This ... gnal (blue-kilonova emission) has its peak at optical freque... ...y due to the ejecta's light component featuring a low degree of opacity.

PANDORA and Neutron Stars

Main atomic abundances in the astrophysical environment, according to *r*-process nucleosynthesis, have been determined to constrain relevant elements for in-laboratory measurements.

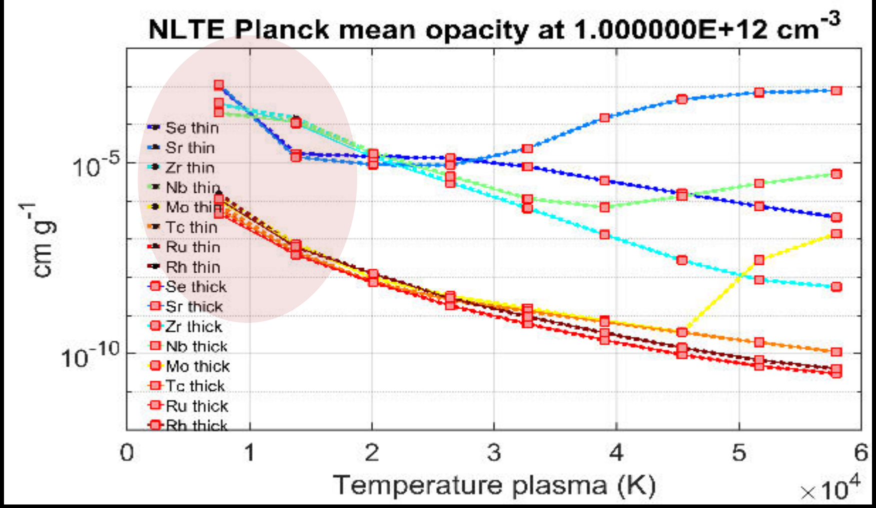


Light r-process elements dominate for Ye>0.25 (typical value expected for early-days blue kilonovae).

<u>Following step</u>: determination of the suitability of plasma species for experiments basing on their contribution to opacity.

PANDORA and Neutron Stars

First phase of PANDORA: considered elements going from selenium to rhodium as eligible for the experimental campaign. Thus, single-species self-emitting plasmas made of Se, Sr, Zr, Nb, Mo, Tc, Ru, and Rh have been considered.



Opacity can differ of several orders of magnitudes:

- ejecta enriched in light r-process elements have relatively low opacity ($\kappa<1$ cm g^{-1}), radiating optical light that fades in days;
- heavy r-process elements enlarges the opacity ($\kappa\approx 10$ cm g^{-1}), with redder light curves lasting even for weeks.

Se-Sr-Zr-Nb exhibit larger mean opacity at the temperature condition of early-epochs kilonova ($<2\cdot 10^4$ K).

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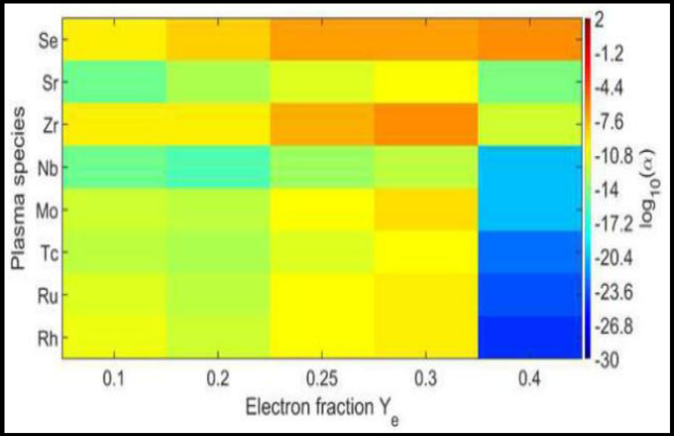
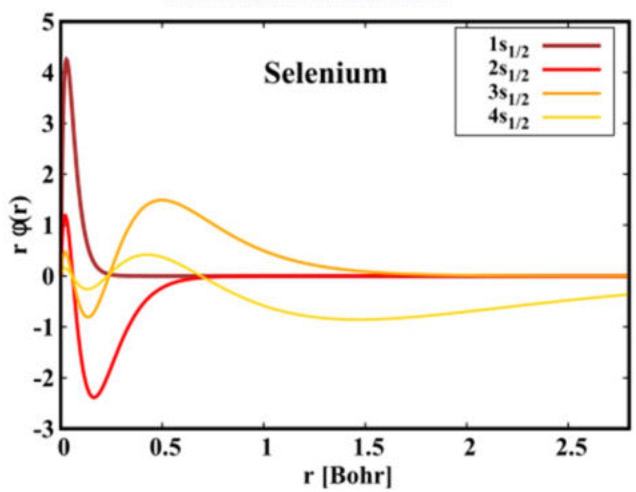


In view of these numerical results, it is useful to define a mean opacity weighted on abundances at a given Y_e. For Y_e 0.25 and T typical of blue-kilonova emission, **selenium** plasma as one of the most favoured for the experiment.

M. Bezmalinovich
PhD Thesis

^{34}Se orbitals wavefunctions



Recall the state wavefunction

$$\phi(\mathbf{x}) = \frac{1}{r}\begin{pmatrix} P(n\kappa;r)\chi_{\kappa m}(\theta,\varphi) \\ \mathrm{i}Q(n\kappa;r)\chi_{-\kappa m}(\theta,\varphi) \end{pmatrix}$$

Selenium electron configuration

[Ar] $3d^{10}4s^{2}4p^{4}$

Se ground state

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PANDORA and Neutron Stars

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Tungsten versus Selenium as a potential source of kilonova nebular emission observed by Spitzer

Kenta Hotokezaka,[1,2★] Masaomi Tanaka ,[3,4] Daiji Kato[5,6] and Gediminas Gaigalas[7]

[1] Research Center for the Early Universe, Graduate School of Science, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan

[2] Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan

[3] Astronomical Institute, Tohoku University, Sendai 980-8578, Japan

[4] Division for the Establishment of Frontier Sciences, Organization for Advanced Studies, Tohoku University, Sendai 980-8577, Japan

[5] National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

[6] Department of Advanced Energy Engineering Science, Kyushu University, Kasuga, Fukuoka 816-8580, Japan

[7] Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio Ave. 3, Vilnius, Lithuania

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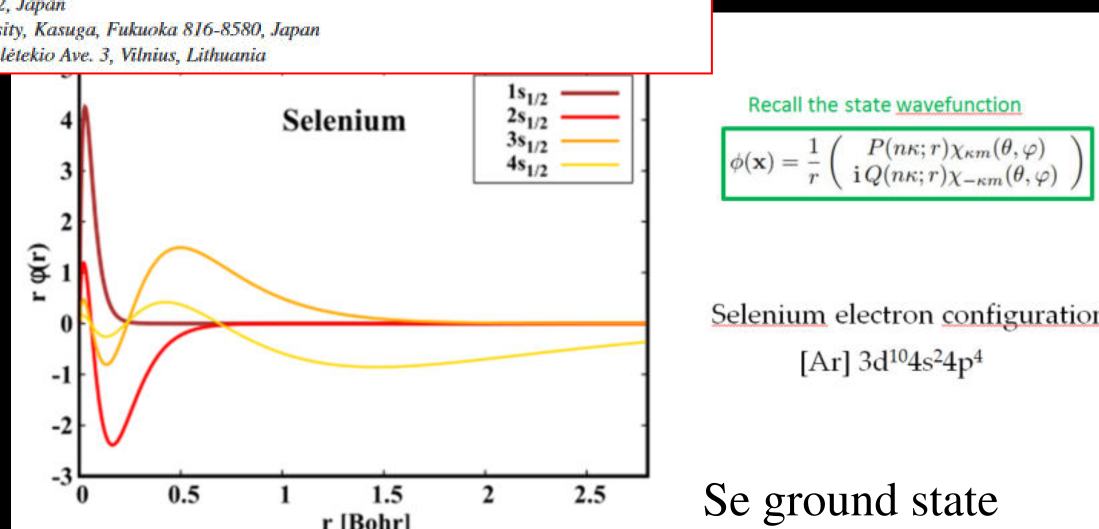
M. Bezmalinovich

PhD Thesis



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sergio.cristallo@inaf.it; diego.vescovi@inaf.it

THAT’S ALL FALKS!!!