r-process nucleosynthesis and Kilonovae in the PANDORA project

S. Cristallo

in collaboration with M. Bezmalinovich, D. Vescovi, E. Loffredo

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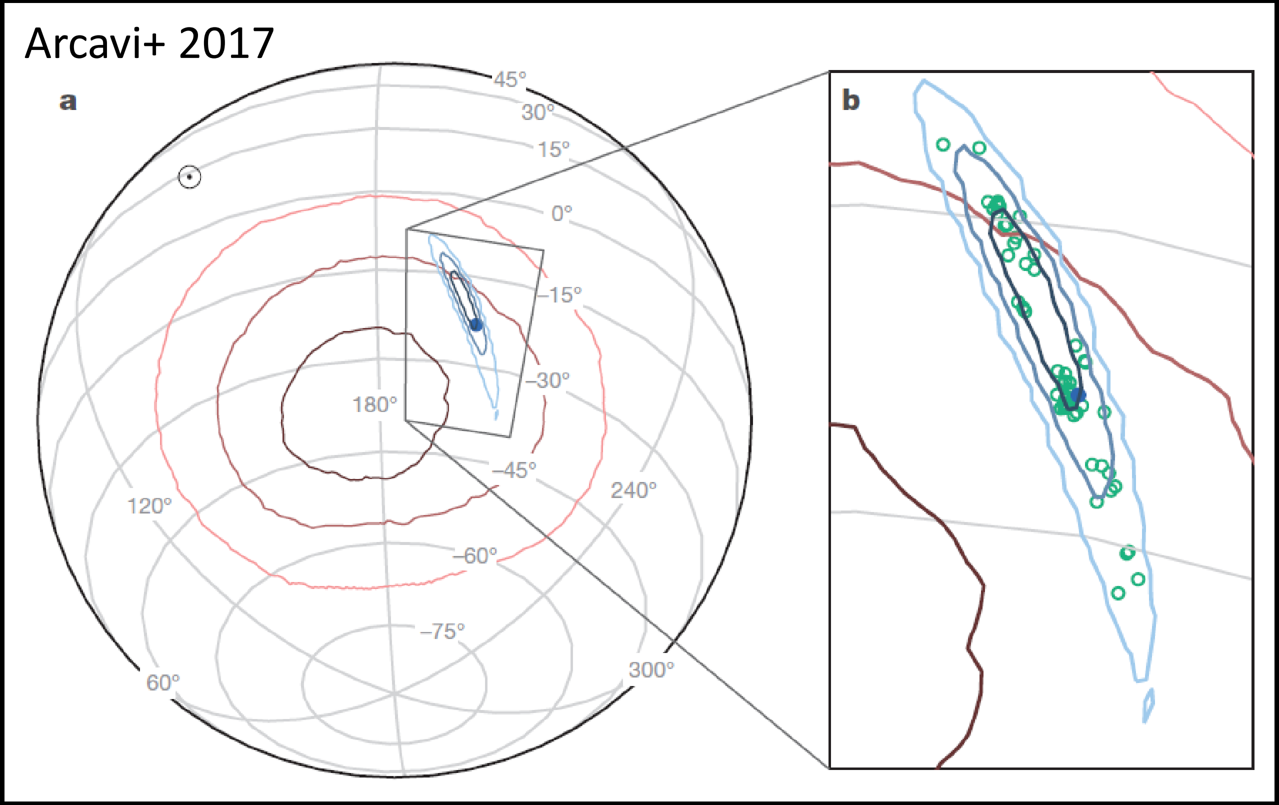
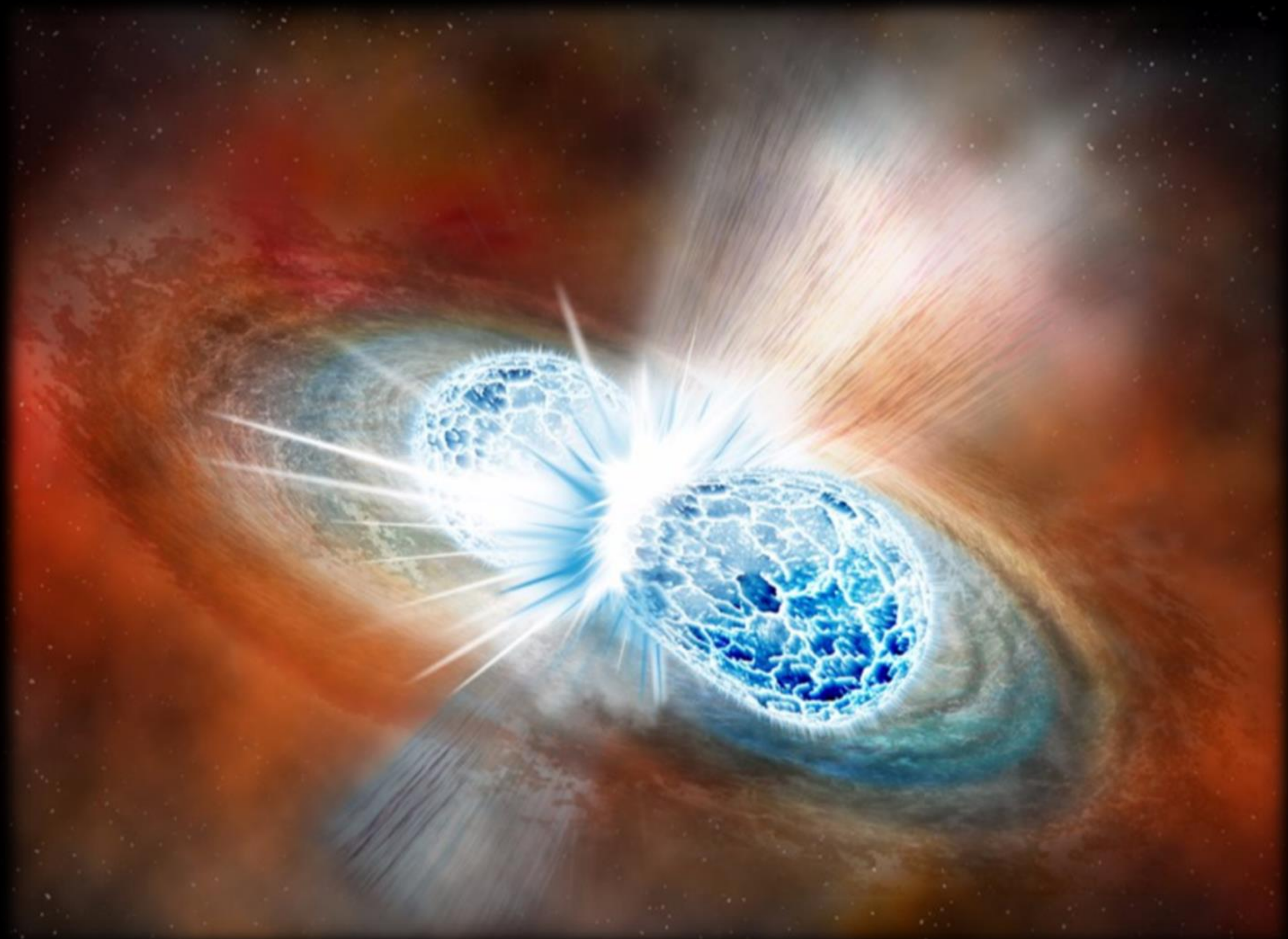
GW170817: «THE» gravitational signal

A revolution similar to Jupiter observations by Galileo…



Hosting galaxy: NGC 4993 (distance ≈44 Mpc)

Neutron Star Mergers (NSMs)



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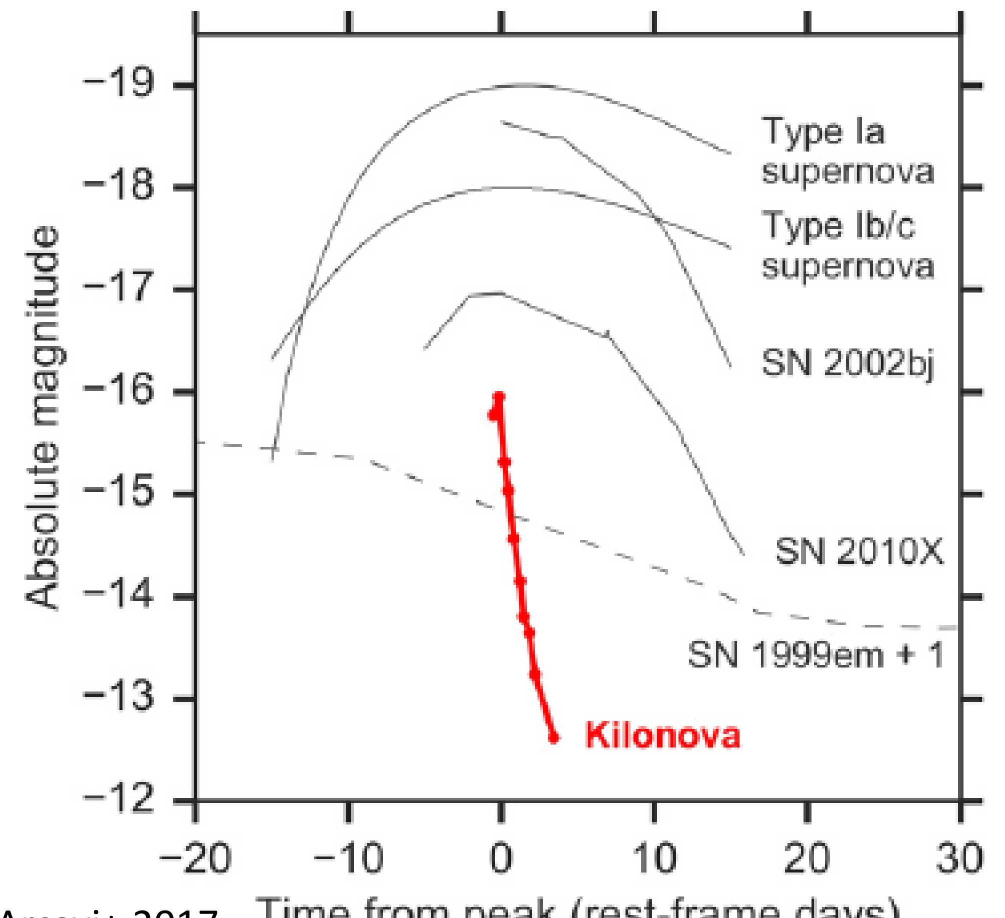
The corresponding Lightcurve

$M_{SUN} \sim +4.5$
$M_{VENUS} \sim -4.5$

Optical flter (r)



Arcavi+ 2017

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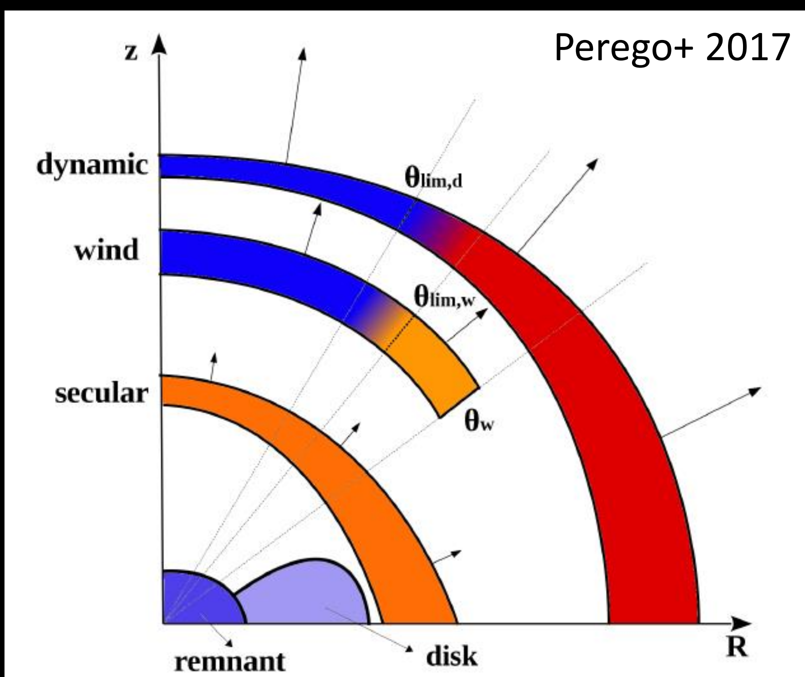
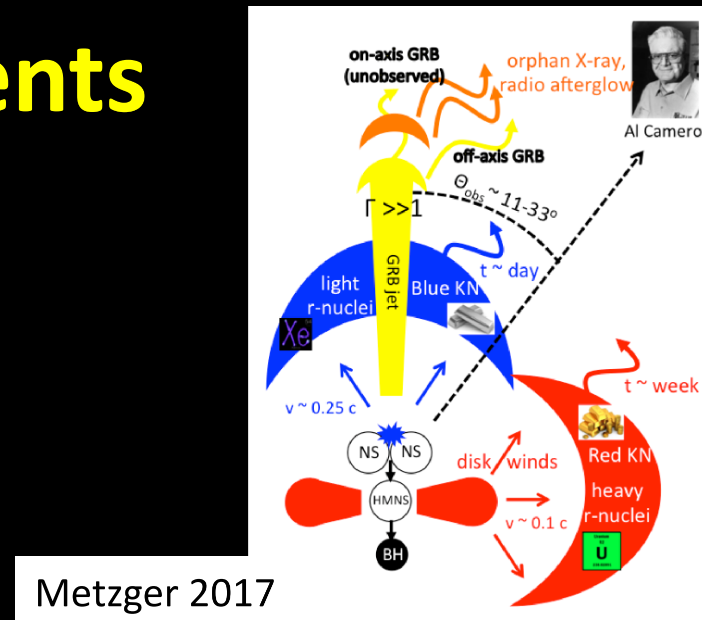
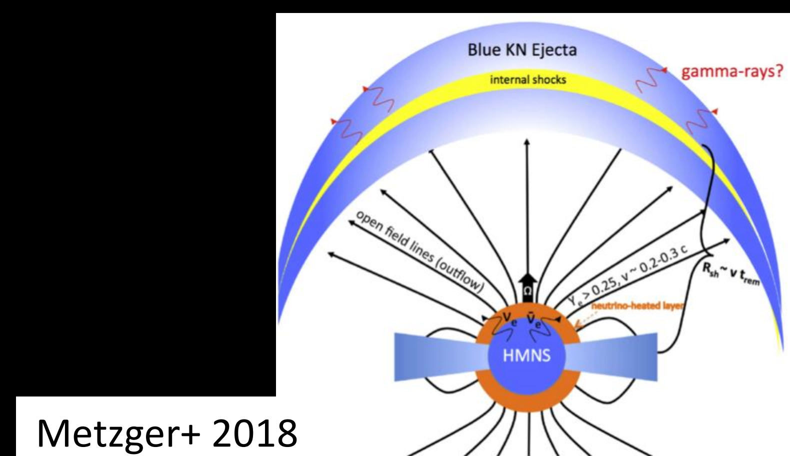
The various components of a NSM



Perego+ 2017



Metzger 2017



Metzger+ 2018

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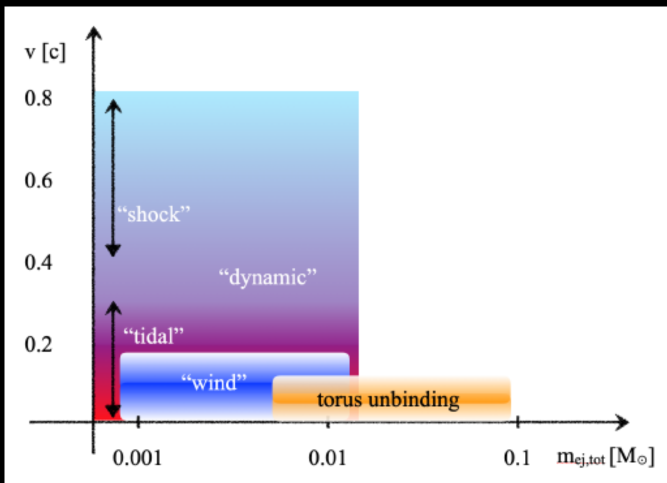
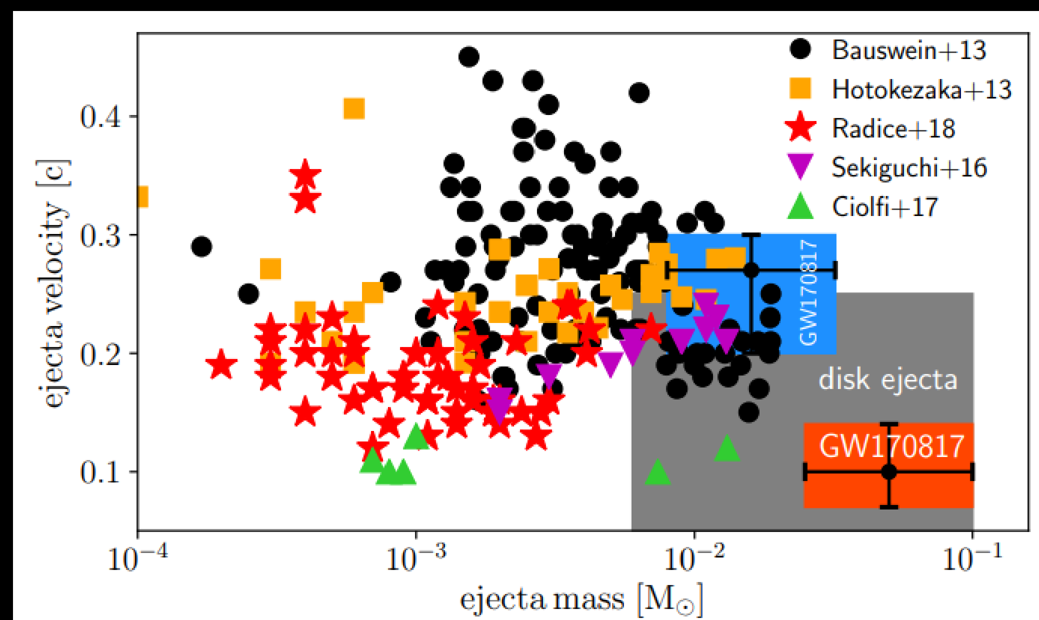
The NSM ejecta

Rosswog & Korobkin 2022



Metzger 2019



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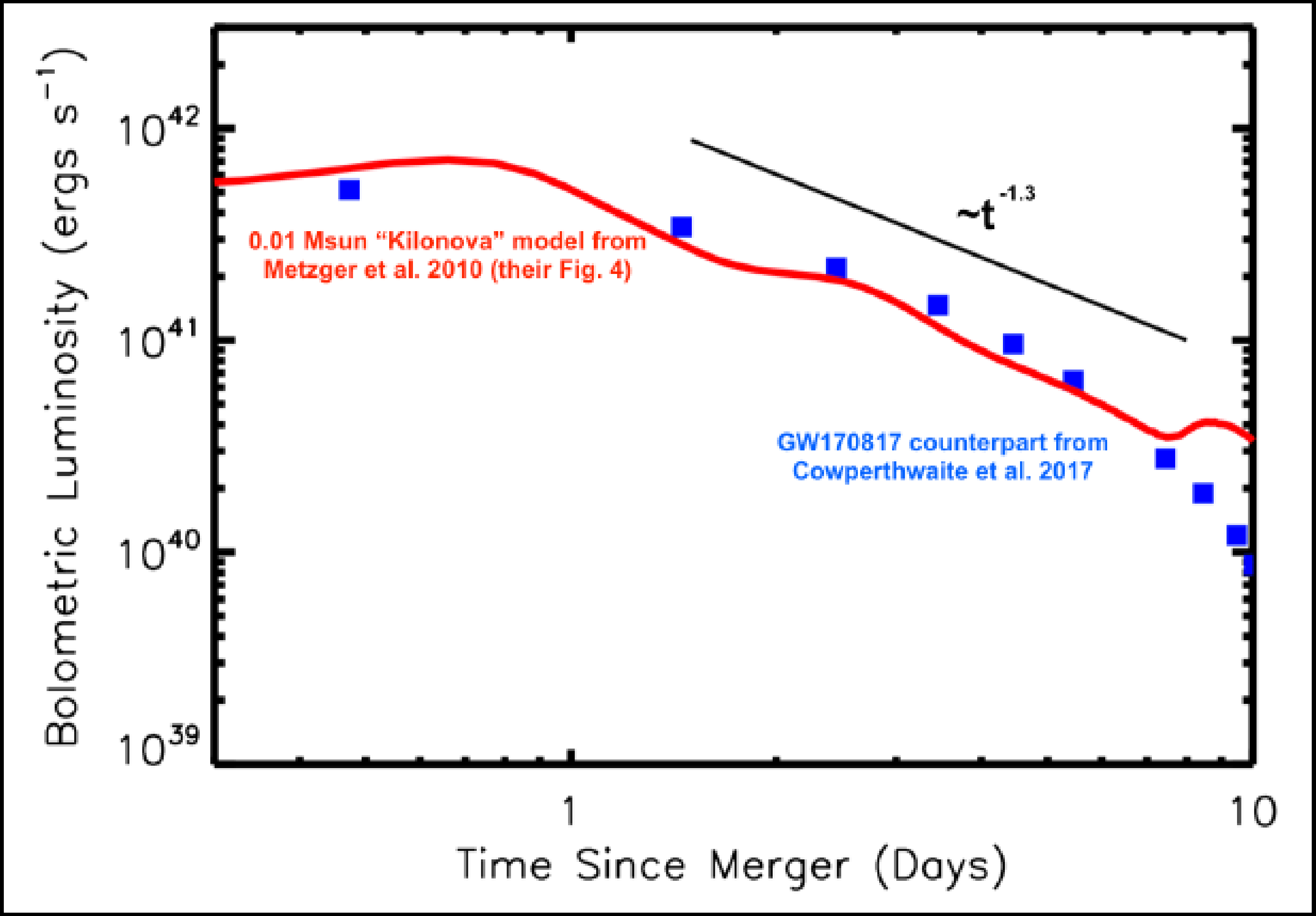
Bolometric curve of GW170817



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

It accounts for the whole energy leaving the «surface» at all wavelenghts

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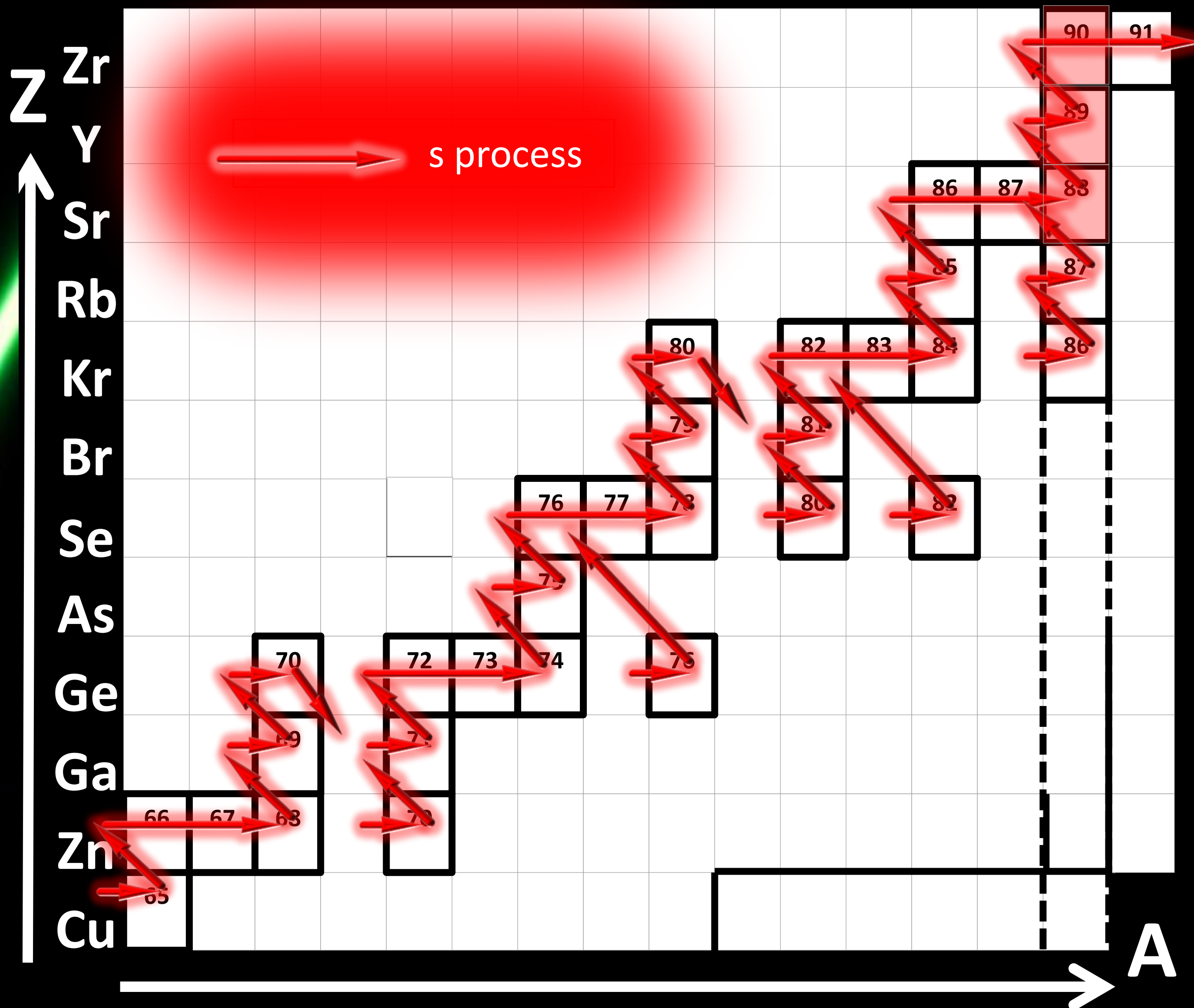

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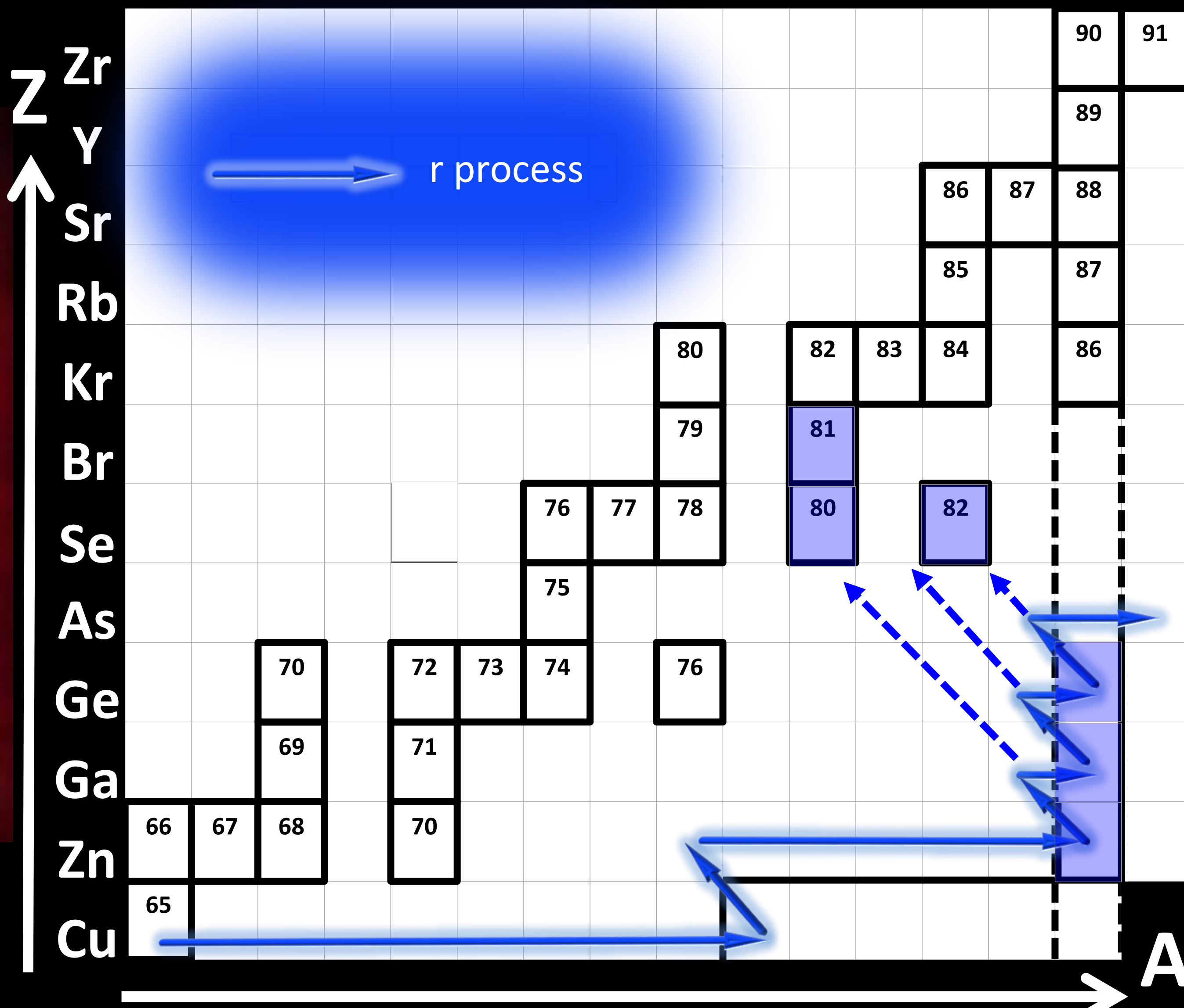

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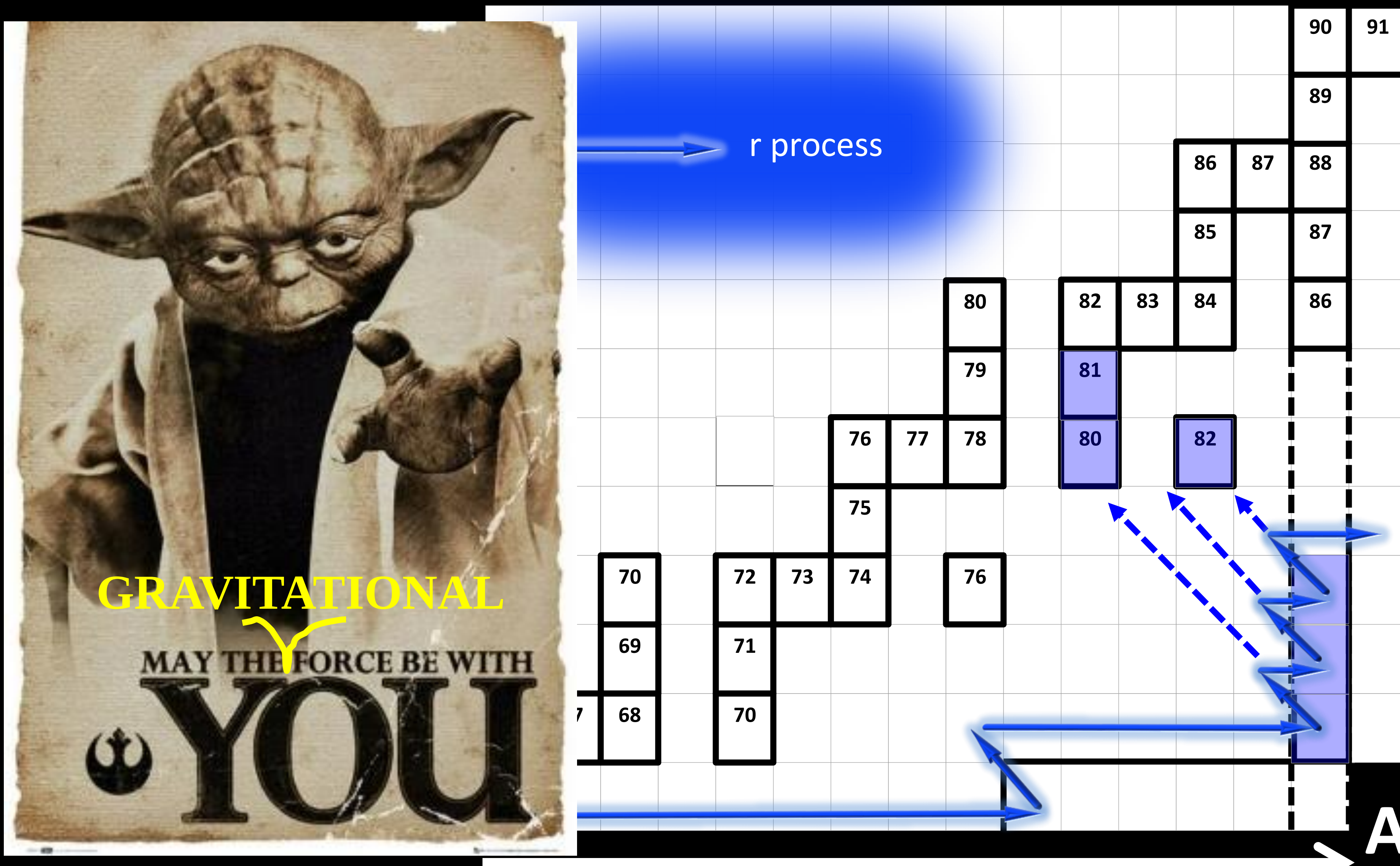

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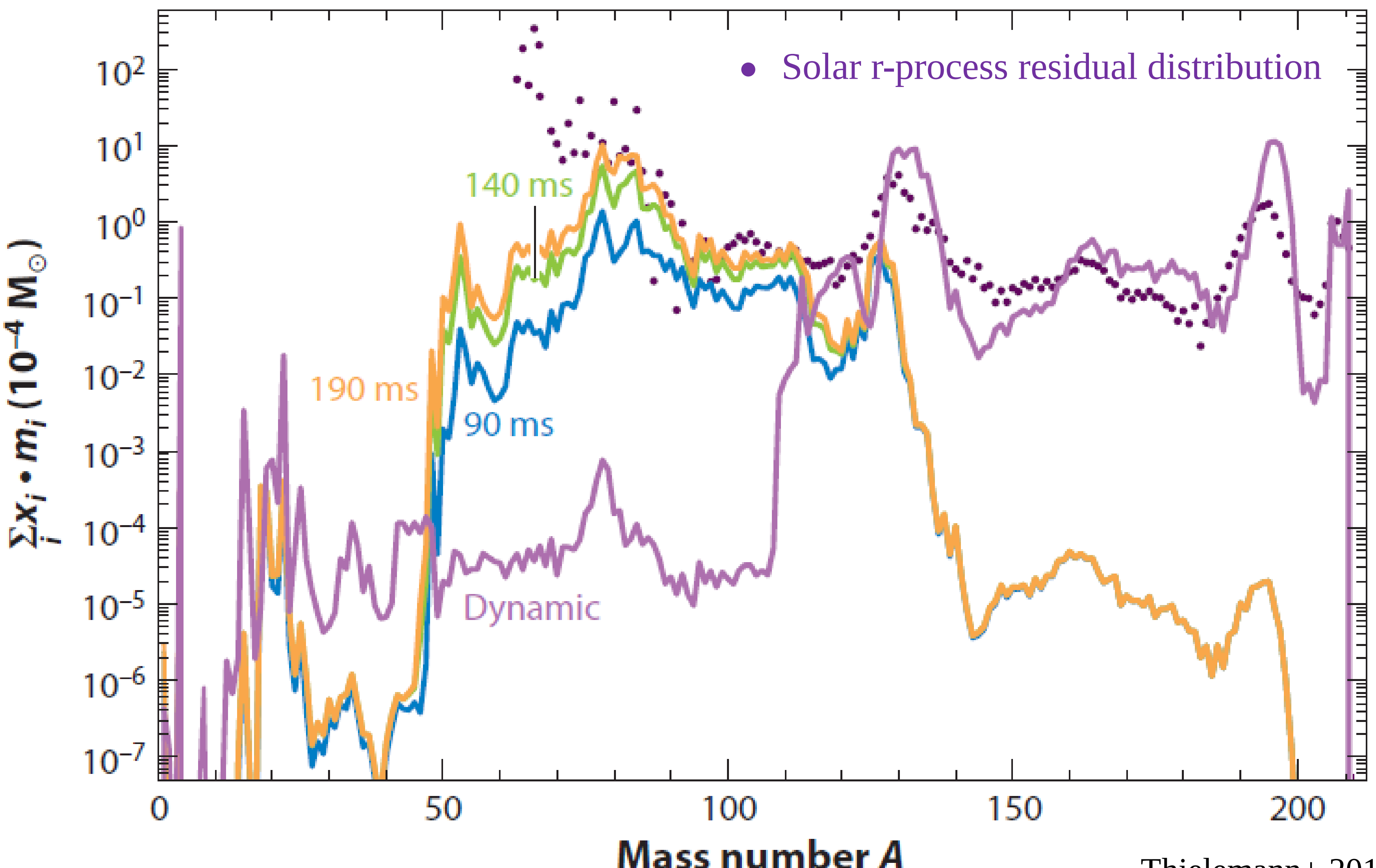

Thielemann+ 2017

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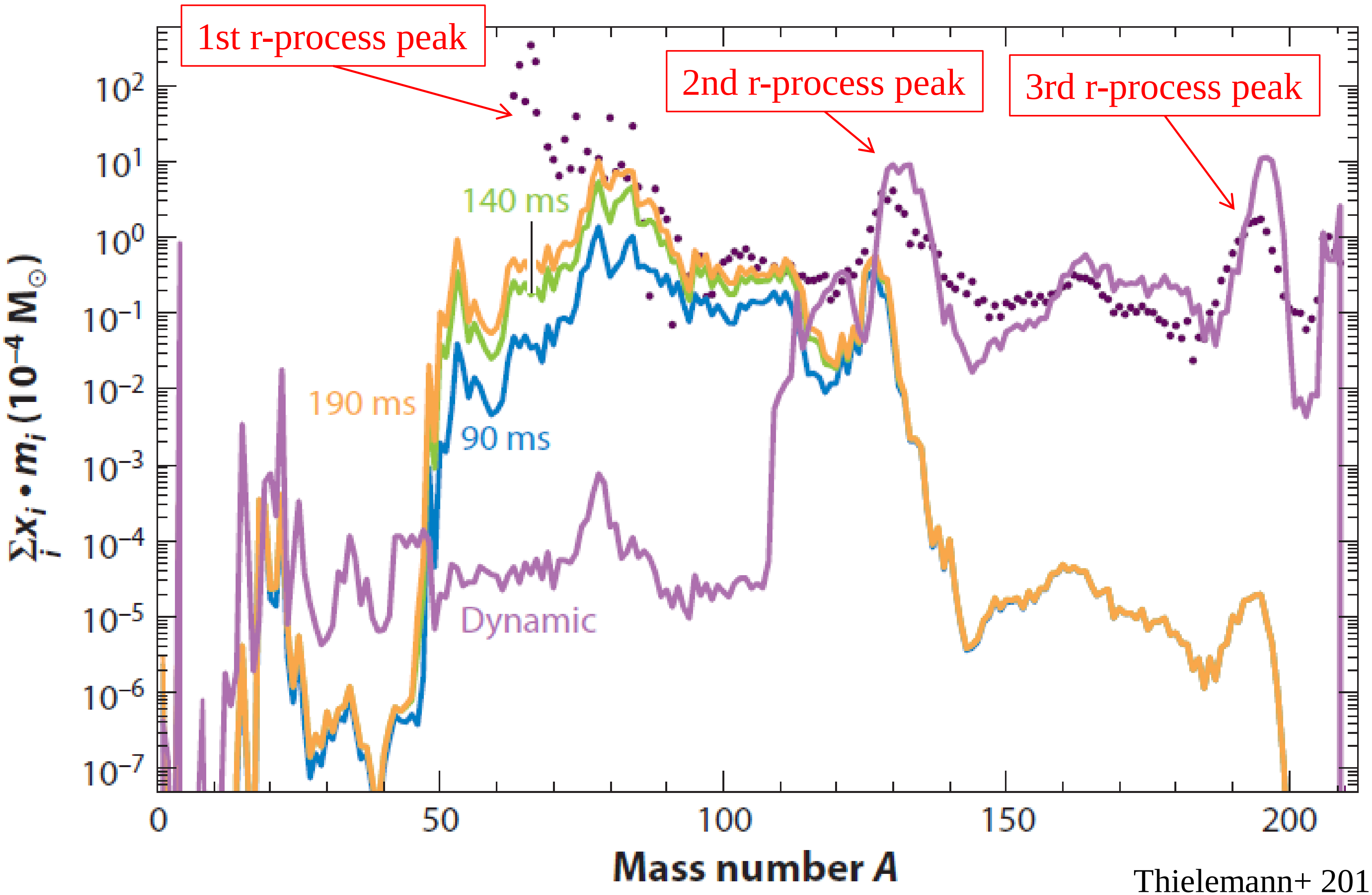

Thielemann+ 2017

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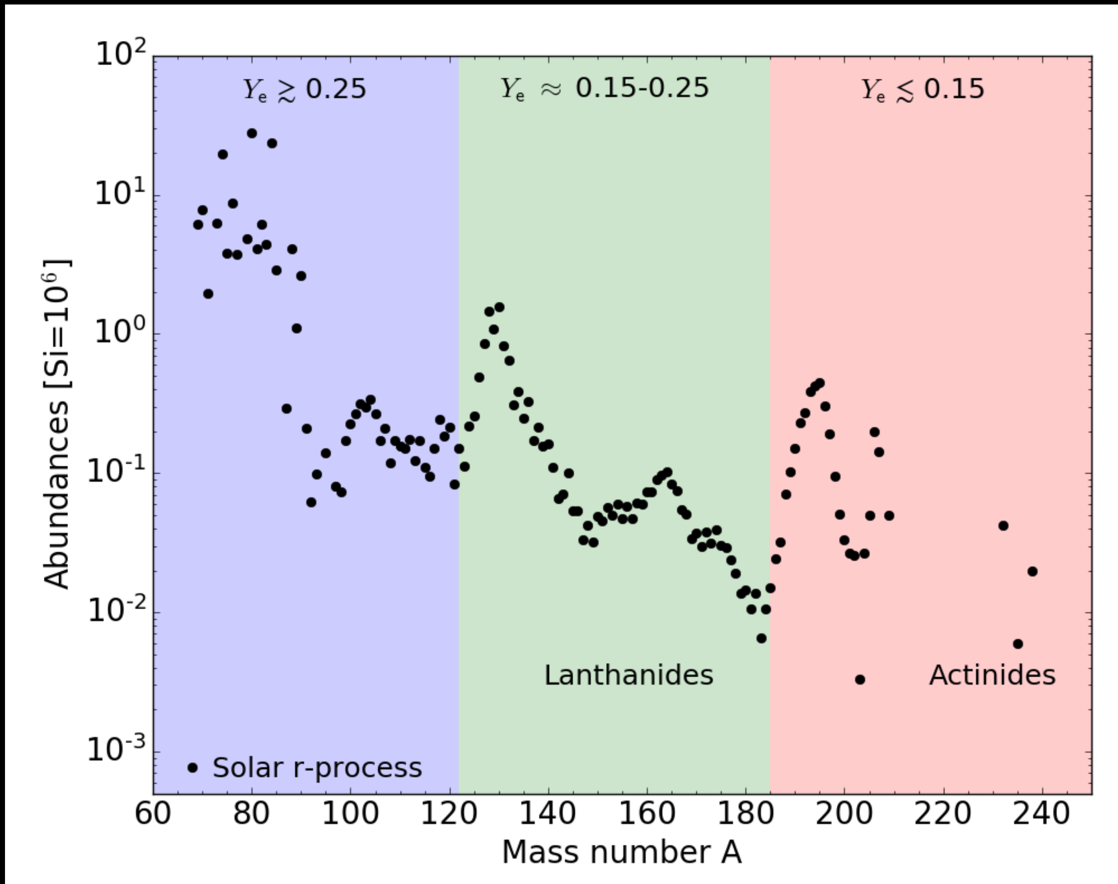
In low entropy environment ($s \sim$ a few tens of k_b /baryon) Y_e is the dominant parameter

- $Y_e \gtrsim 0.25$: 1st peak up to 2nd *r*-process peak
- $0.15 \lesssim Y_e \lesssim 0.25$: 2nd and 3rd *r*-process peaks, but not the 1st
- $Y_e \lesssim 0.15$: robust *r*-process, due to several fission cycles



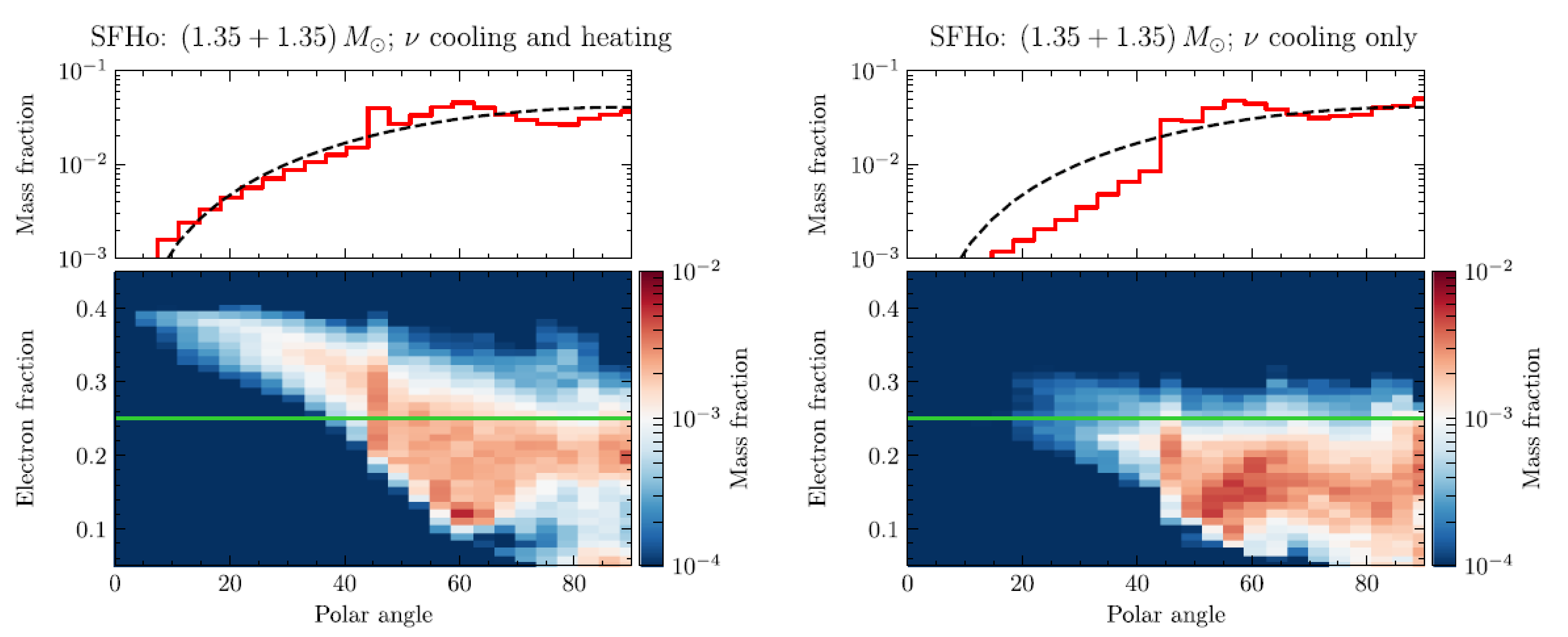
NSM nucleosynthesis

Electron fraction Y_e

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

The role of neutrinos

The presence of neutrinos increases Y_e in the polar direction



Perego+ 2017

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

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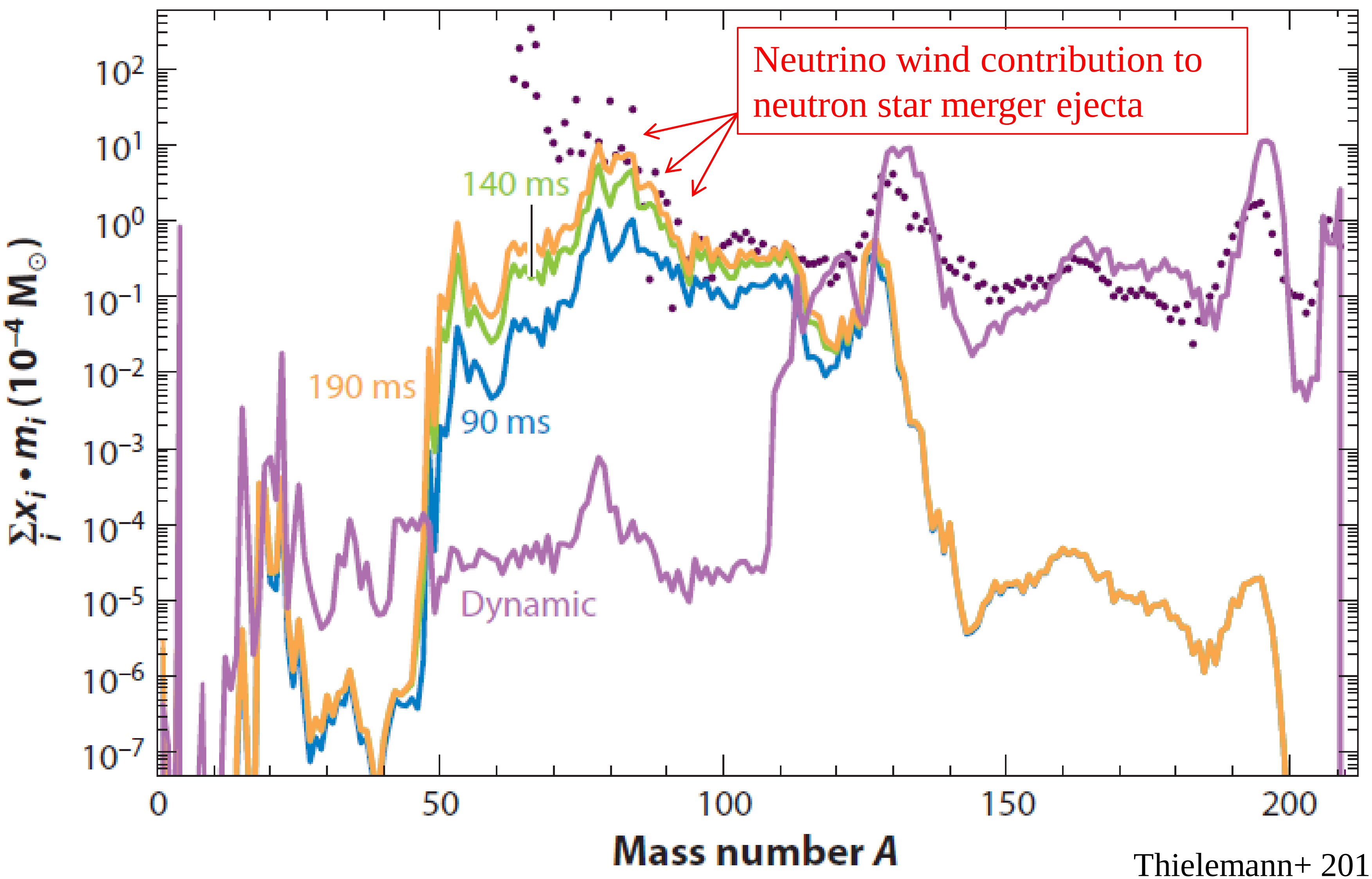

Thielemann+ 2017

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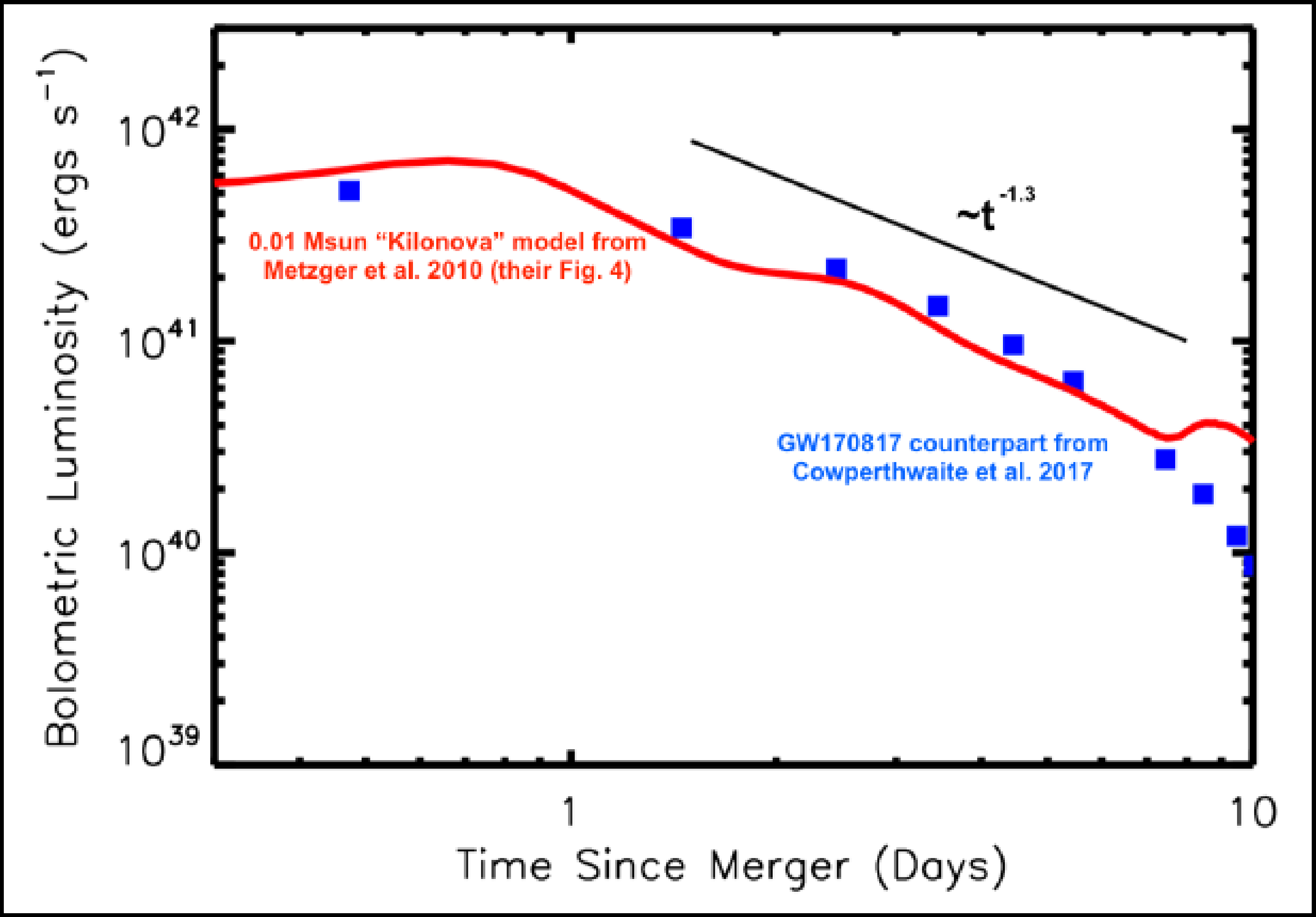
Bolometric curve of GW170817

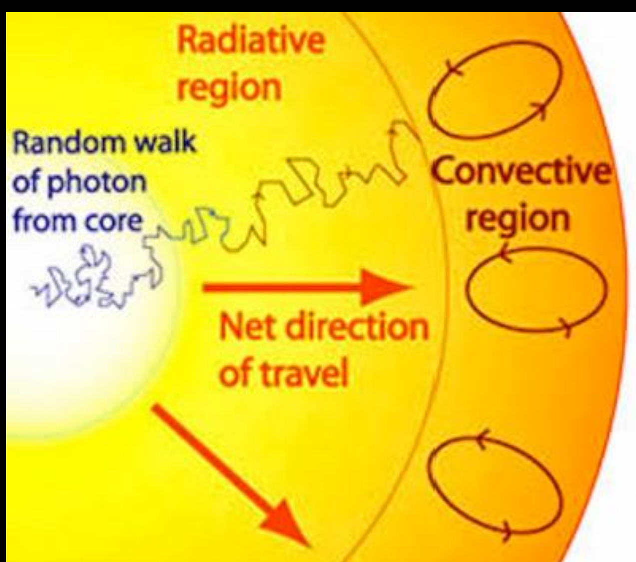


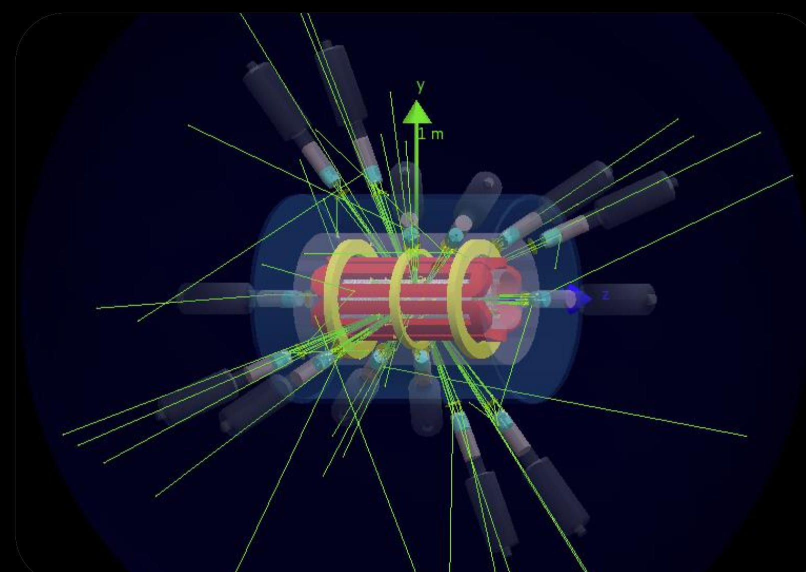
How do photons interact with gas?

It accounts for the whole energy leaving the «surface» at all wavelenghts

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.





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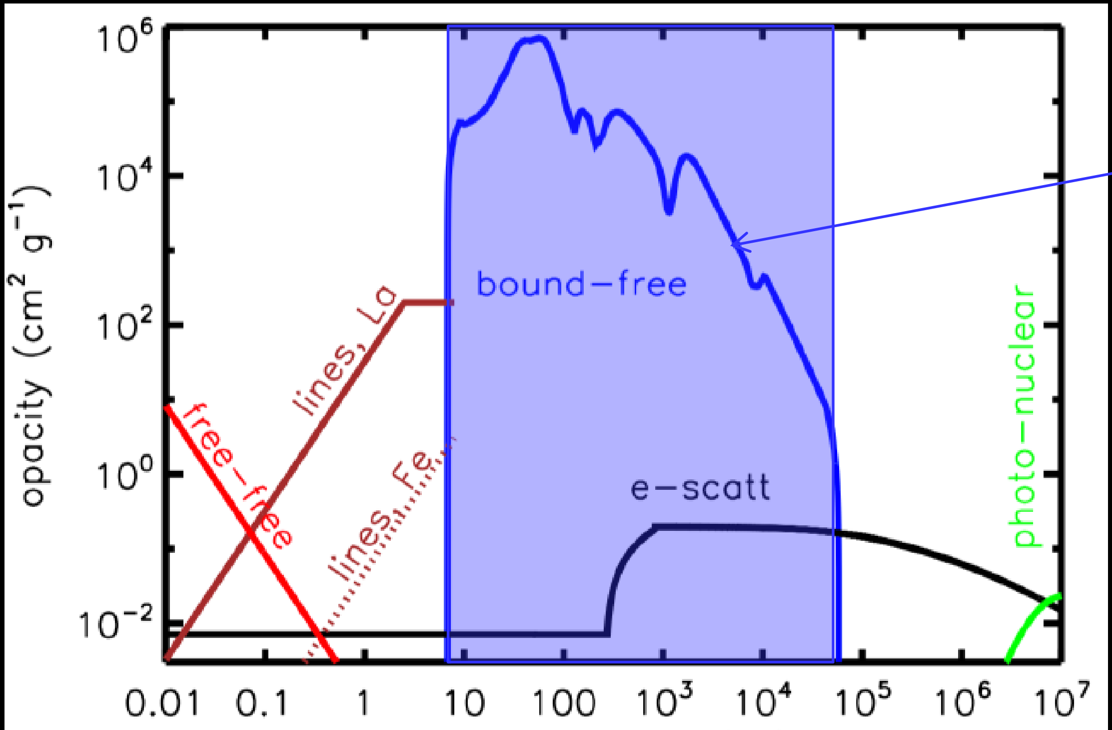
Atomic opacities

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 dominate the opacity (blue line). This prevents radiation from escaping the ejecta at these frequencies.

VERY EARLY TIME KILONOVA

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Atomic opacities

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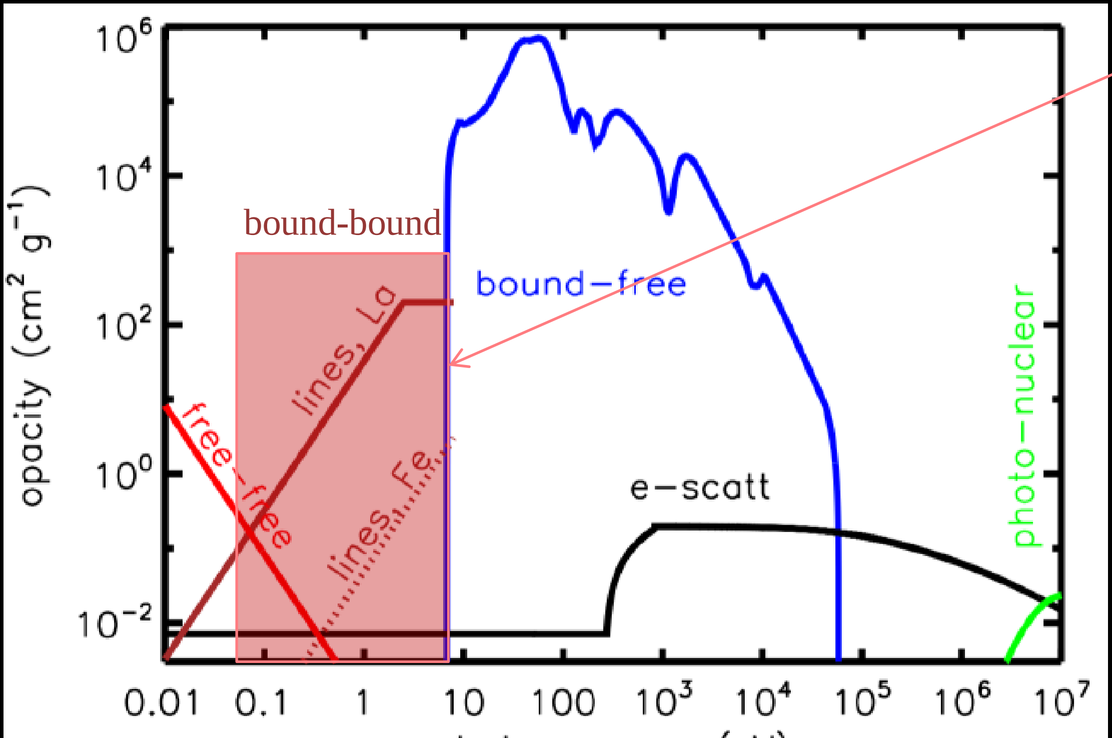


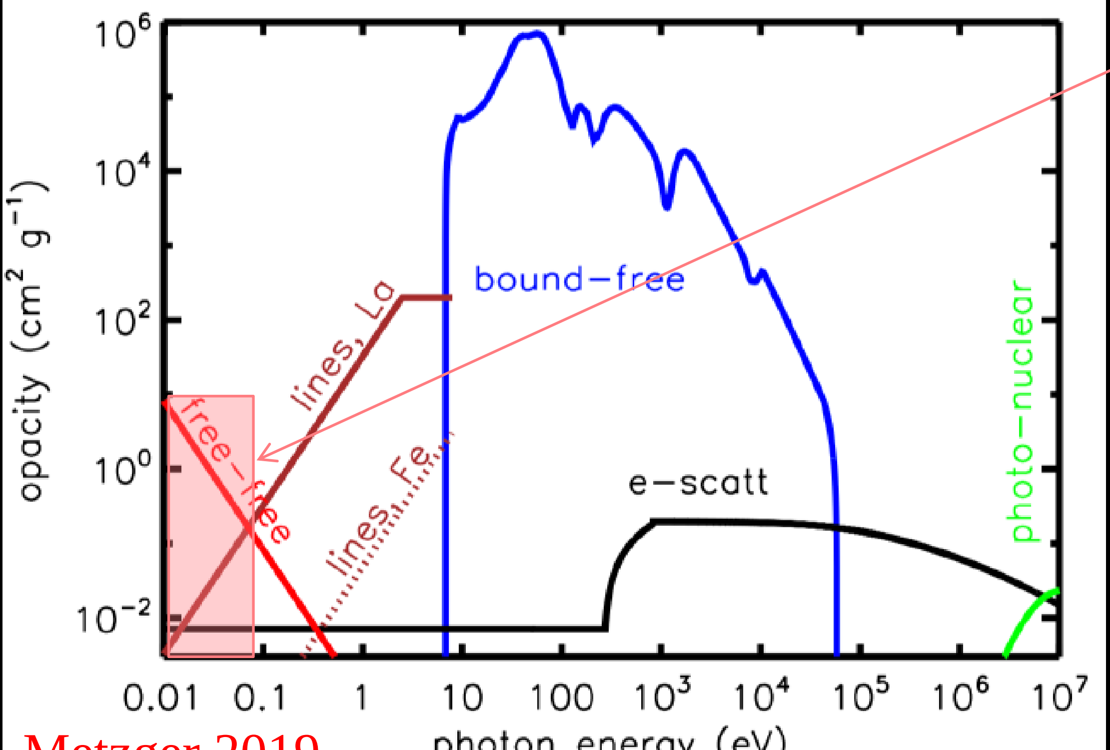
Metzger 2019

At optical/near-IR 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

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

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

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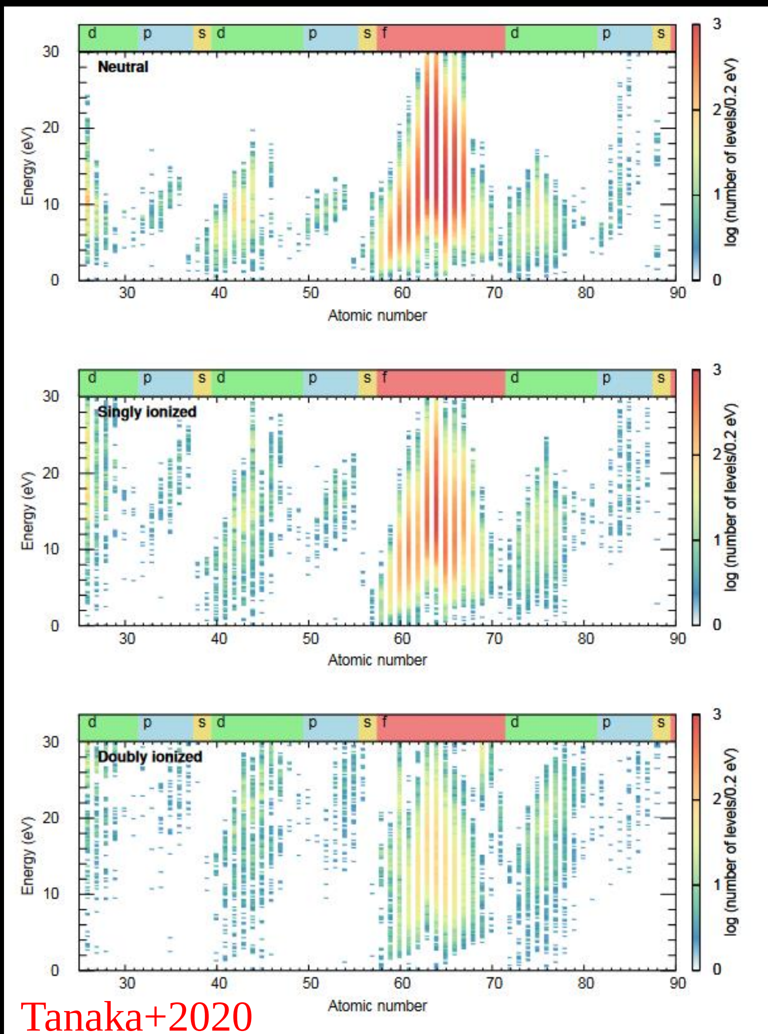
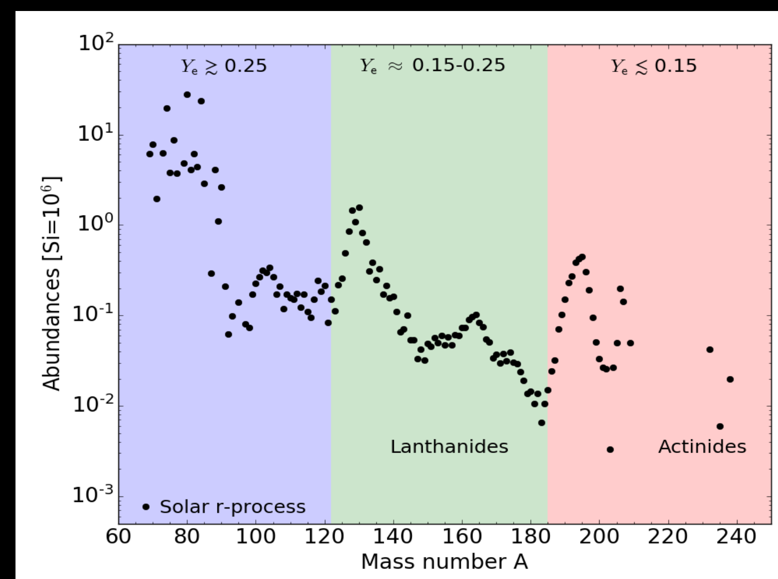
Atomic opacities

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



Tanaka+2020



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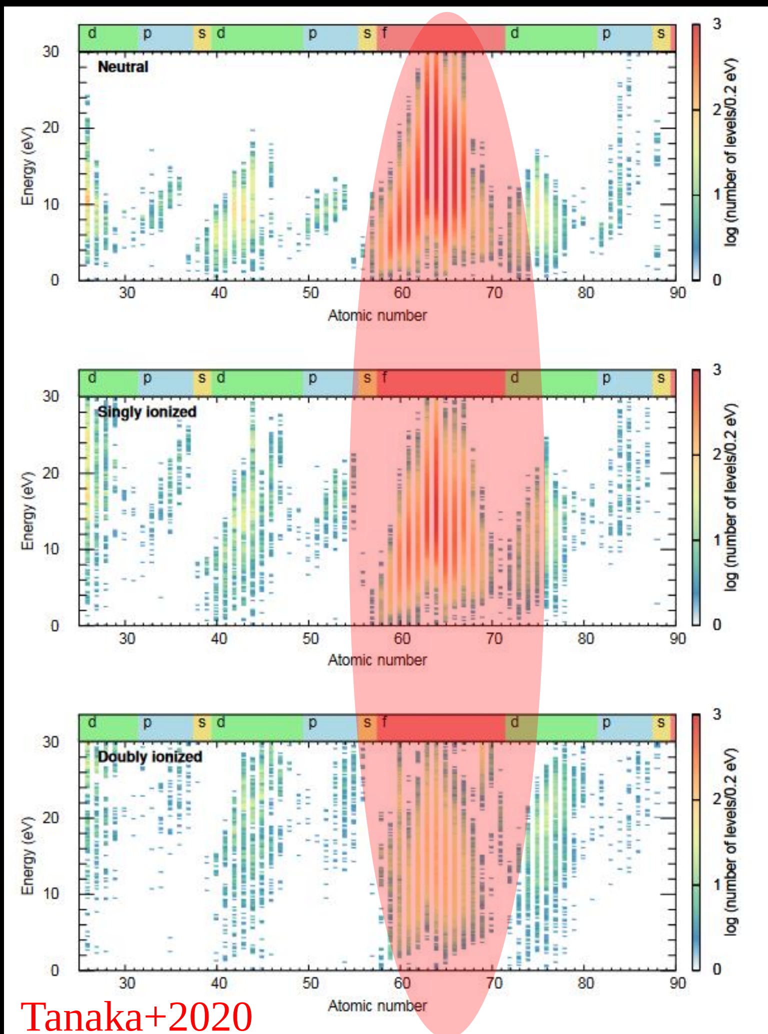
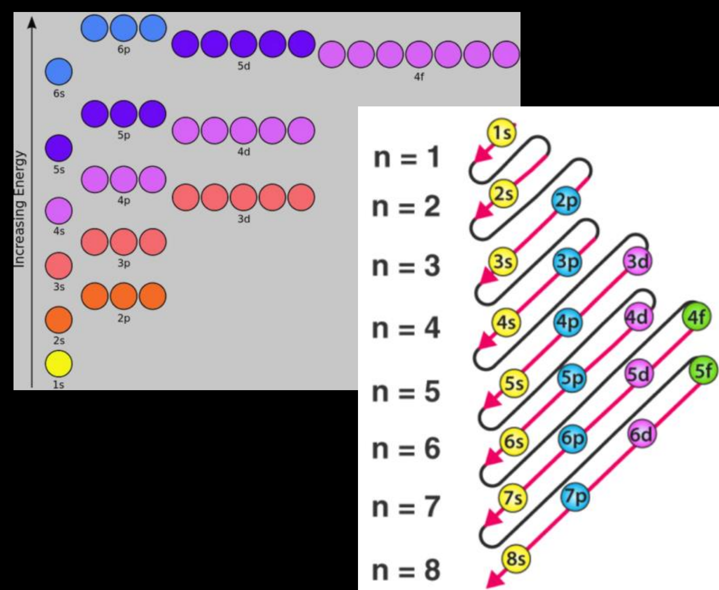
Atomic opacities



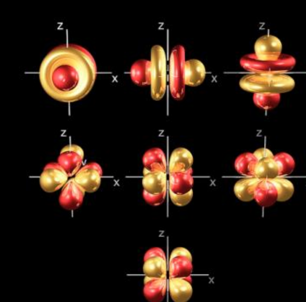
Tanaka+2020

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 IIIA	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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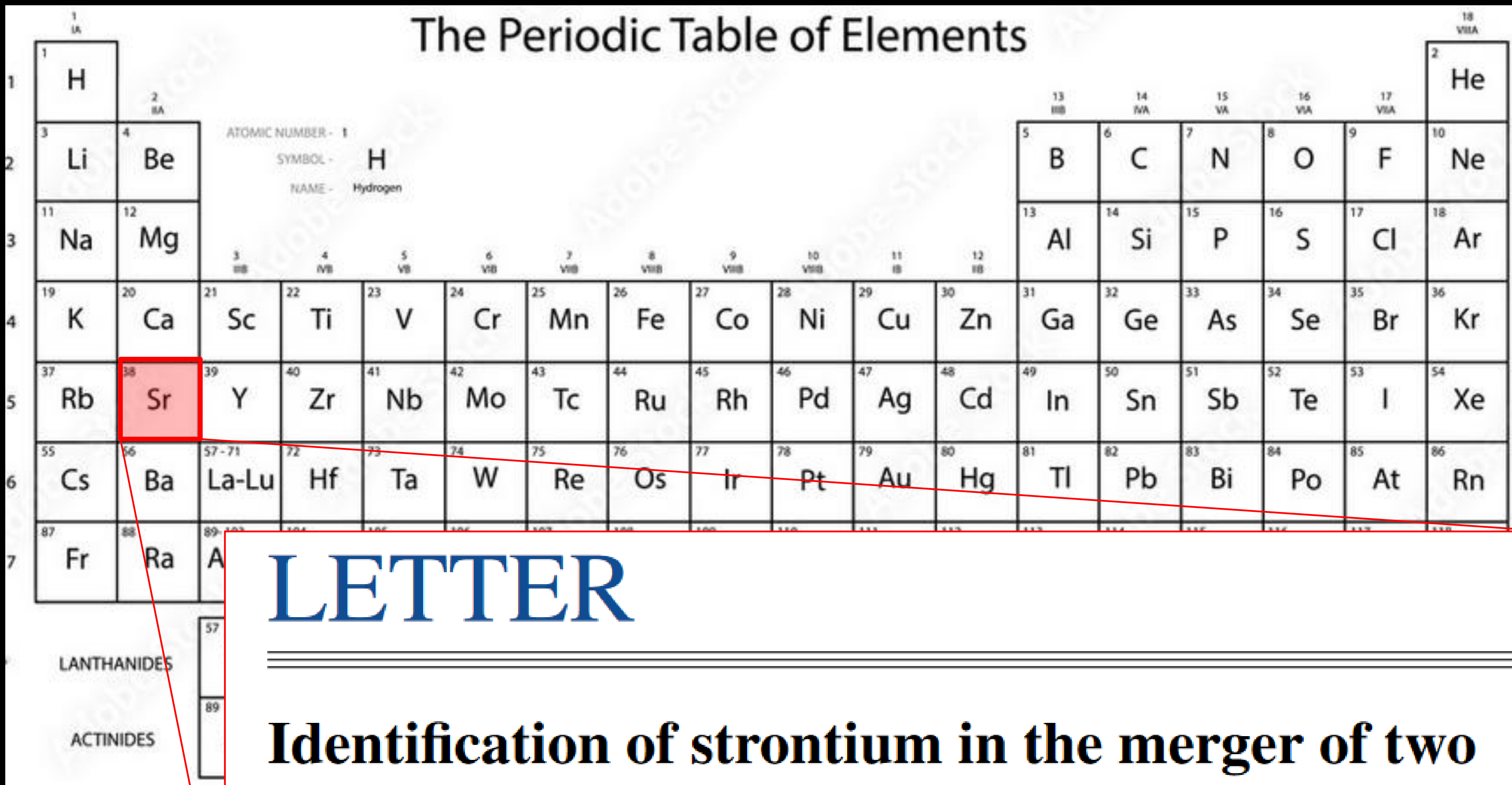

LETTER

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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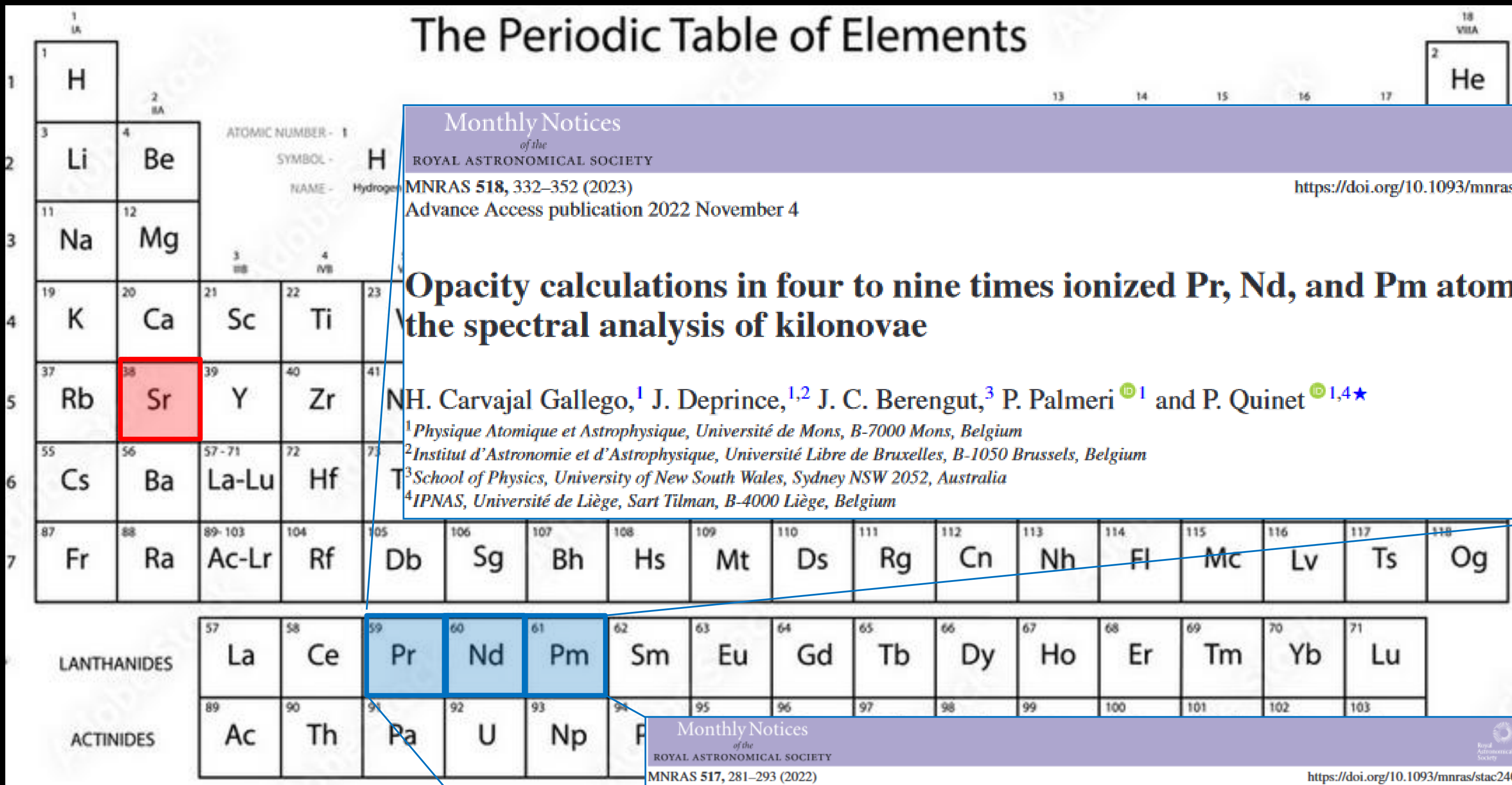

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MNRAS **518**, 332–352 (2023) https://doi.org/10.1093/mnras/stac3129
Advance Access publication 2022 November 4

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

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[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*

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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

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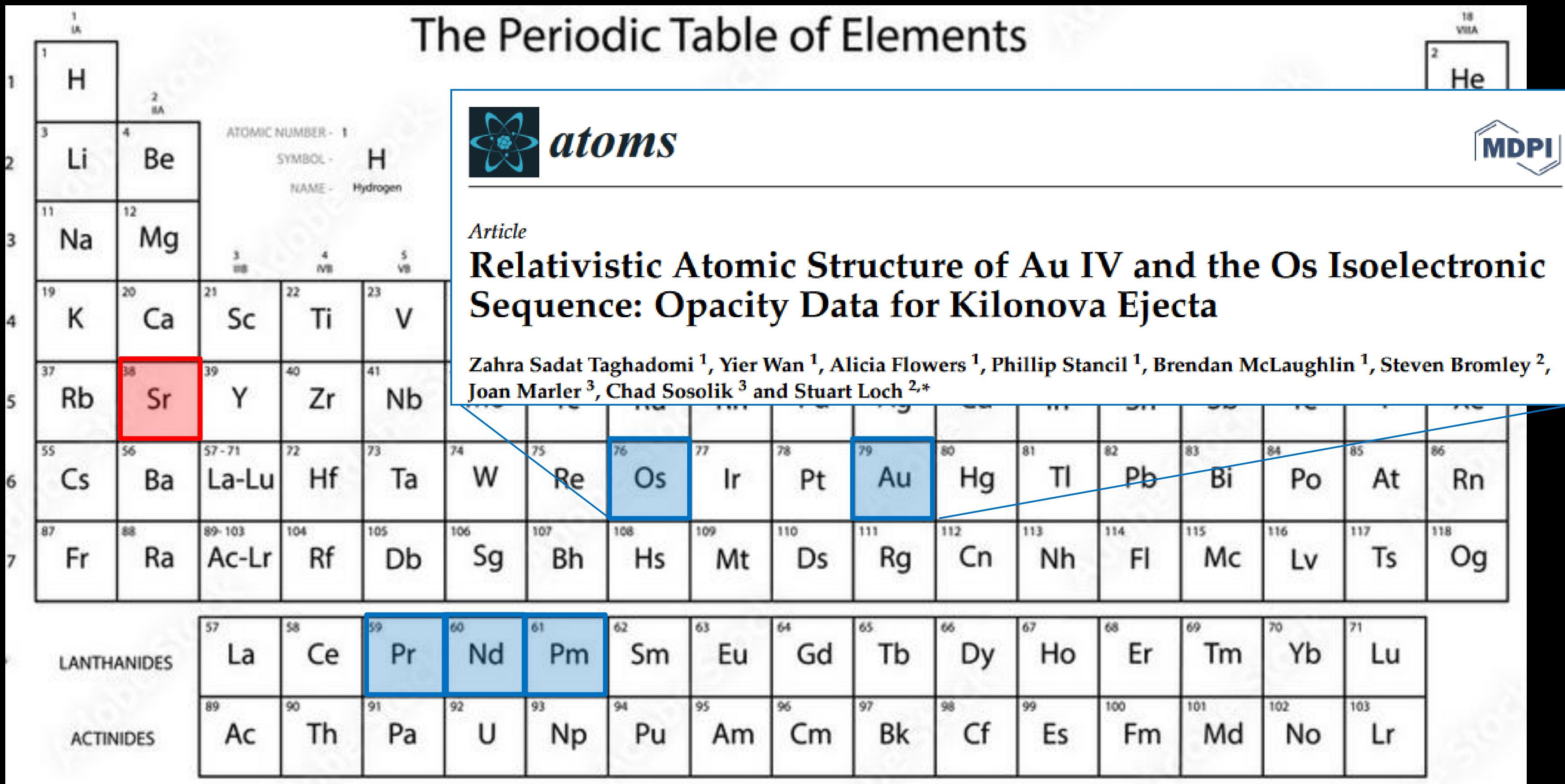
[2] *Astronomical Institute, Tohoku University, Sendai 980-8578, Japan*
[3] *Division for the Establishment of Frontier Sciences, Organization for Advanced Studies, Tohoku University, Sendai 980-8577, Japan*
[4] *National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*
[5] *Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*


The Periodic Table of Elements
ATOMIC NUMBER - 1
SYMBOL - H
NAME - Hydrogen
H
He
Li Be
Na Mg
K Ca Sc Ti V
Rb Sr Y Zr Nb
Cs Ba La-Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Ac-Lr Rf Db Sg Bh Hs Mt Ds Rg Cn Nh Fl Mc Lv Ts Og
LANTHANIDES
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
ACTINIDES
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr
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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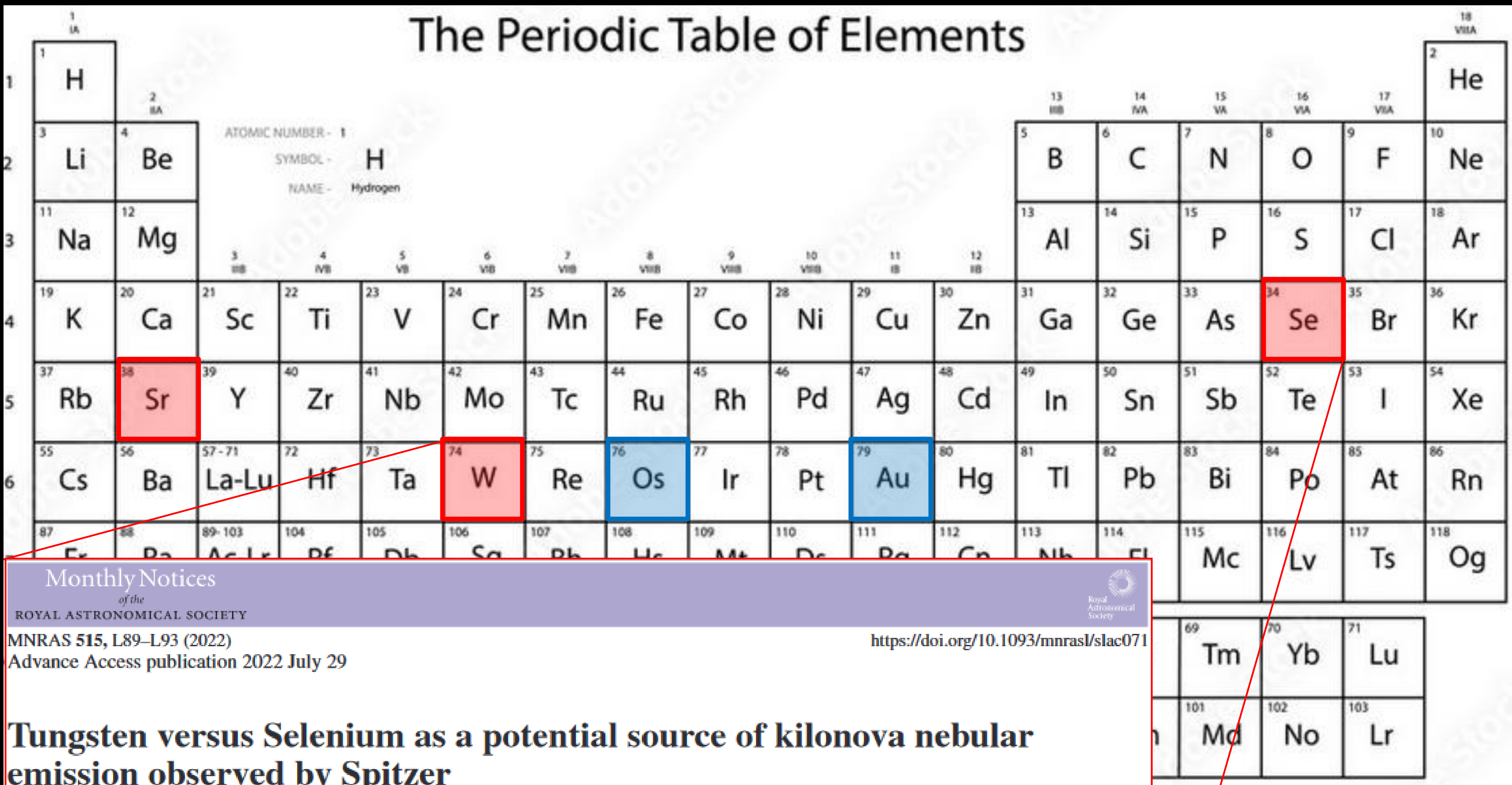

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MNRAS **515**, L89–L93 (2022)
Advance Access publication 2022 July 29

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]

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[2] *Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*
[3] *Astronomical Institute, Tohoku University, Sendai 980-8578, Japan*
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[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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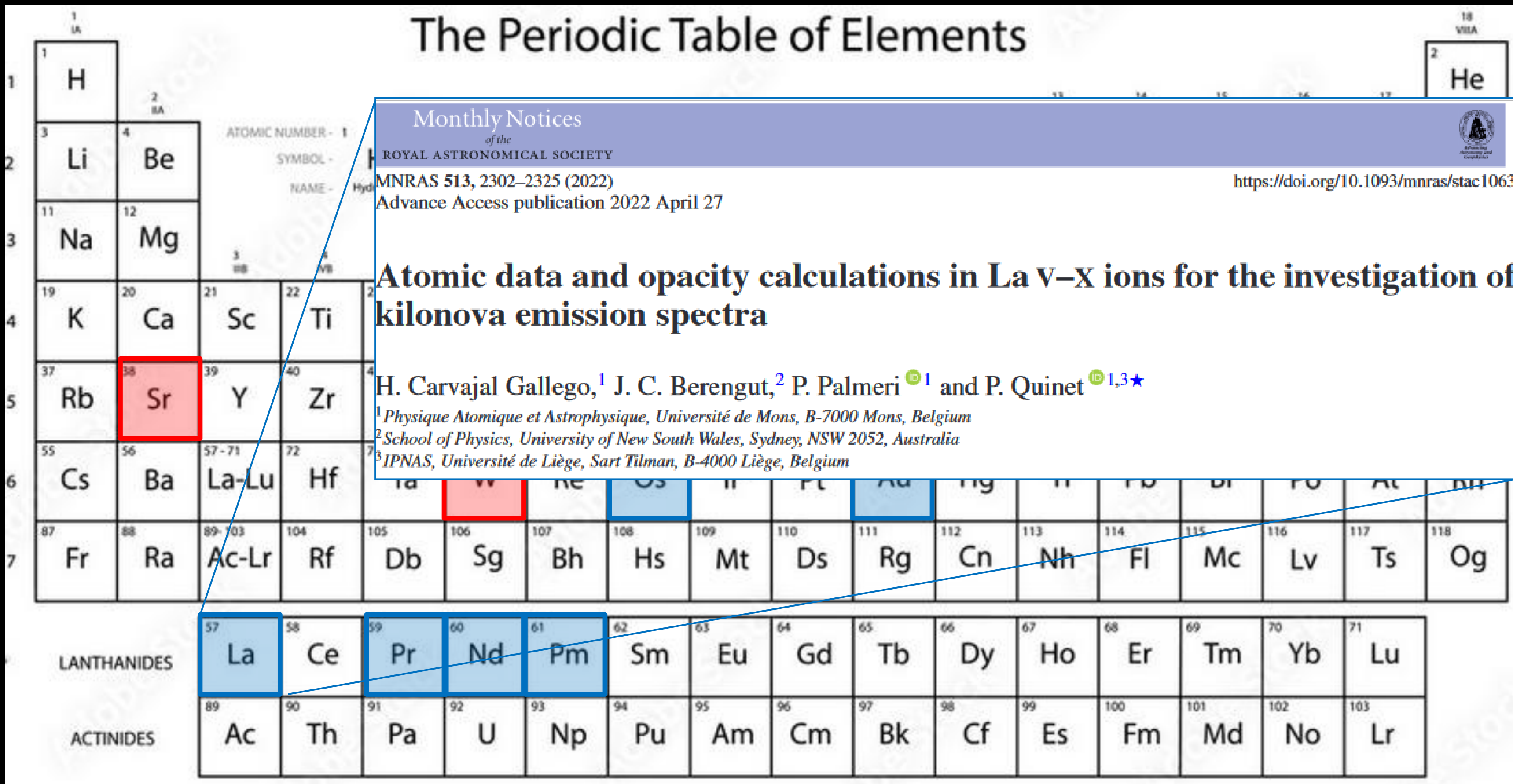

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **513**, 2302–2325 (2022) https://doi.org/10.1093/mnras/stac1063
Advance Access publication 2022 April 27

Atomic data and opacity calculations in La V–X ions for the investigation of kilonova emission spectra

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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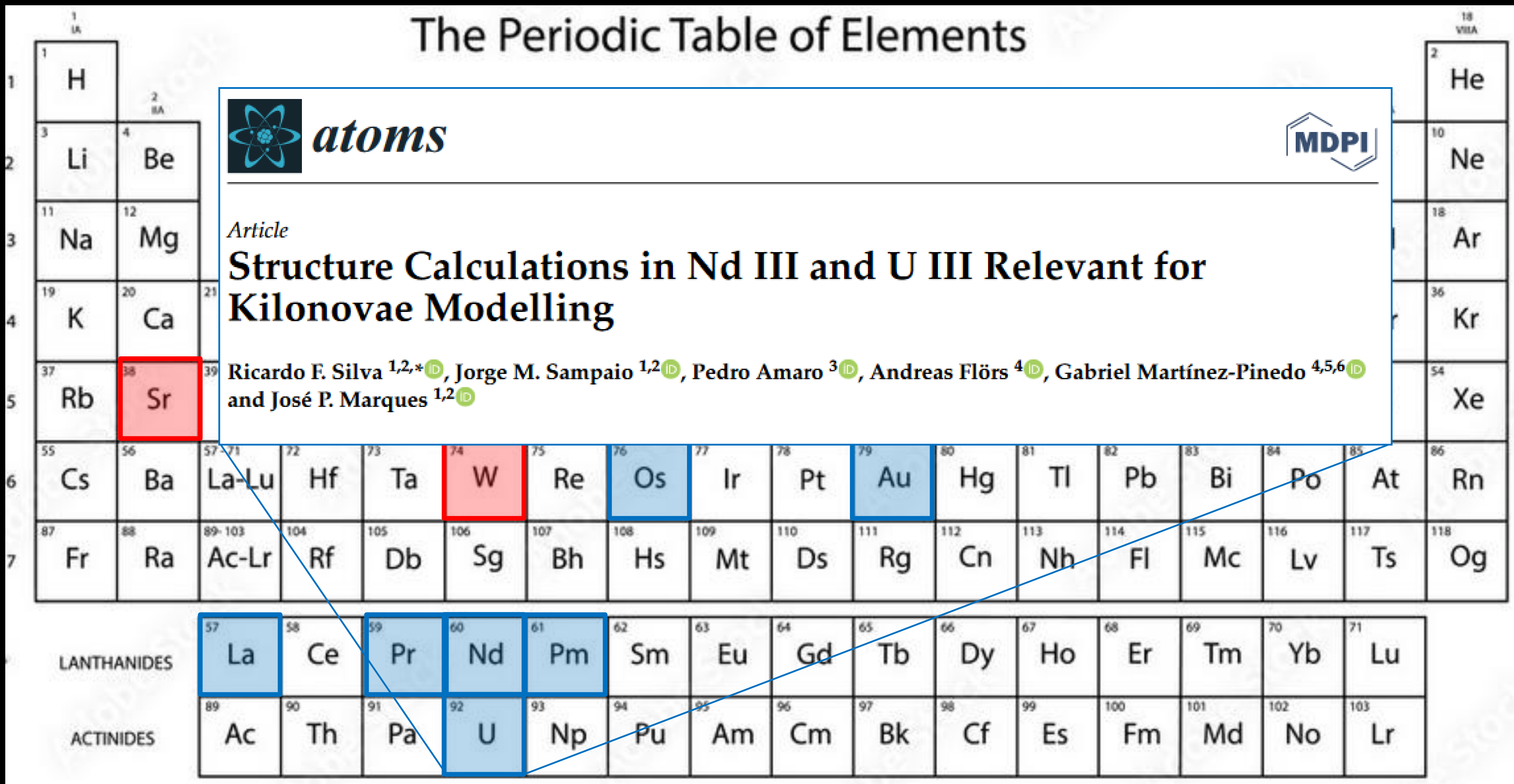

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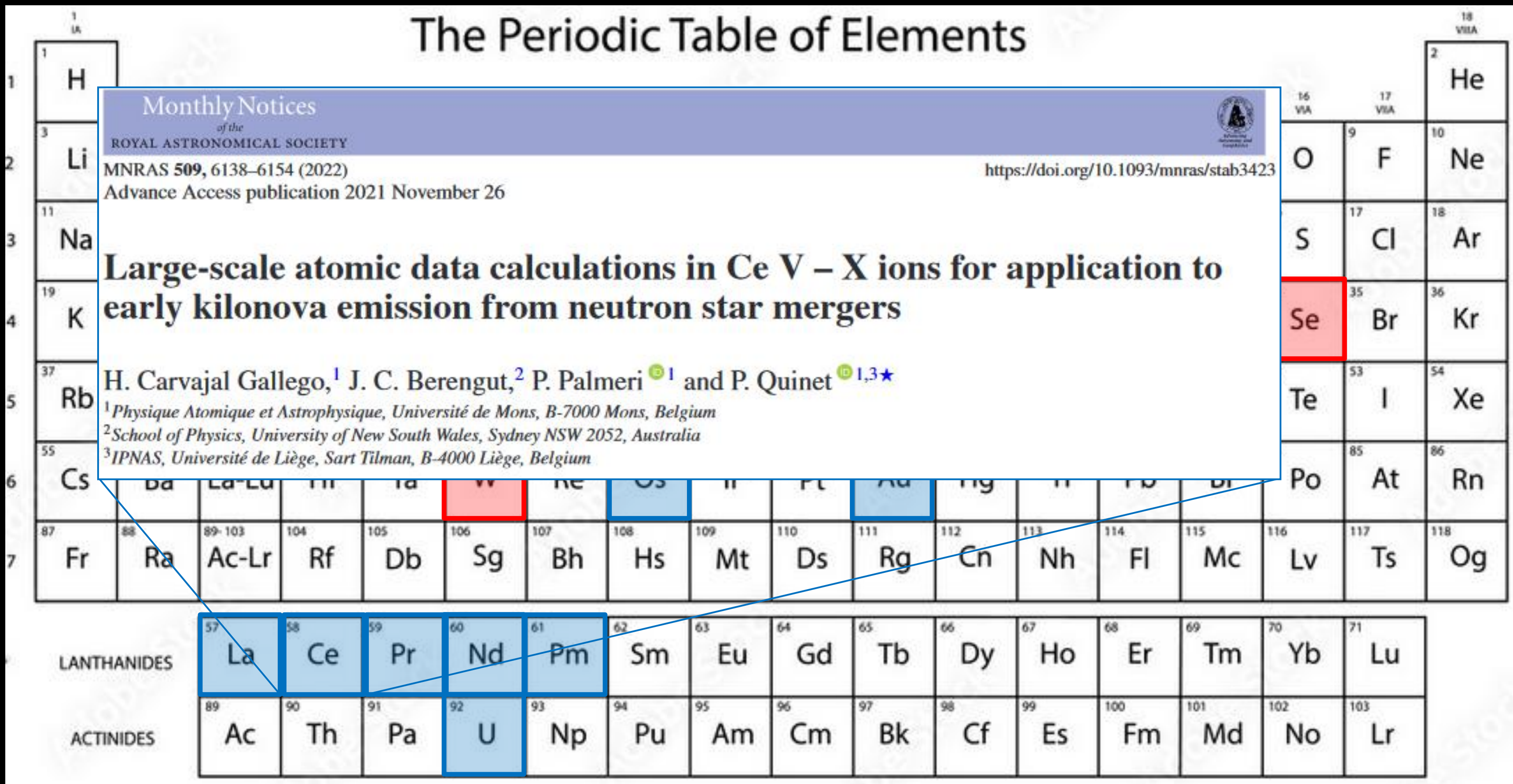

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MNRAS **509**, 6138–6154 (2022) https://doi.org/10.1093/mnras/stab3423
Advance Access publication 2021 November 26

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*
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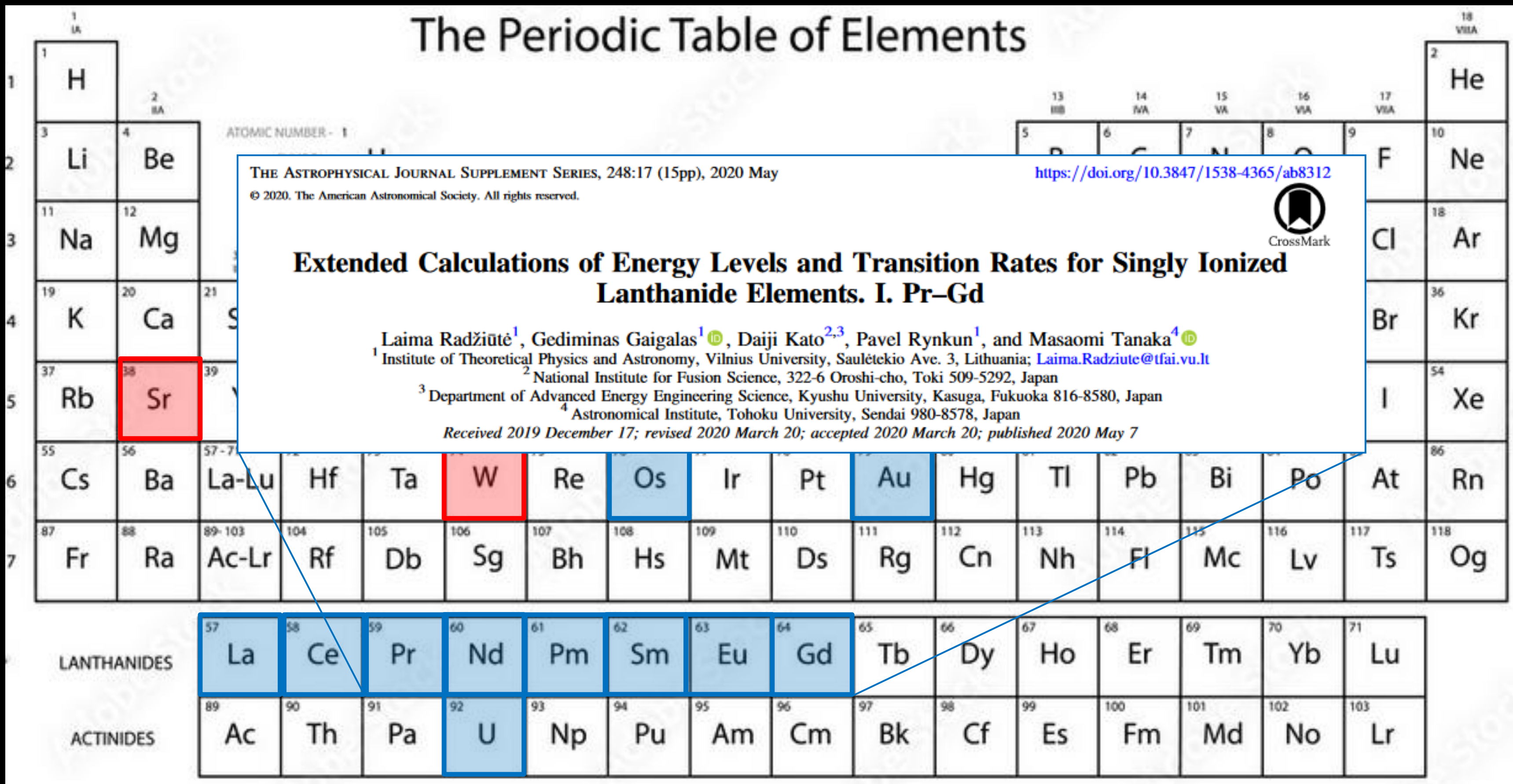

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 248:17 (15pp), 2020 May https://doi.org/10.3847/1538-4365/ab8312

CrossMark

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
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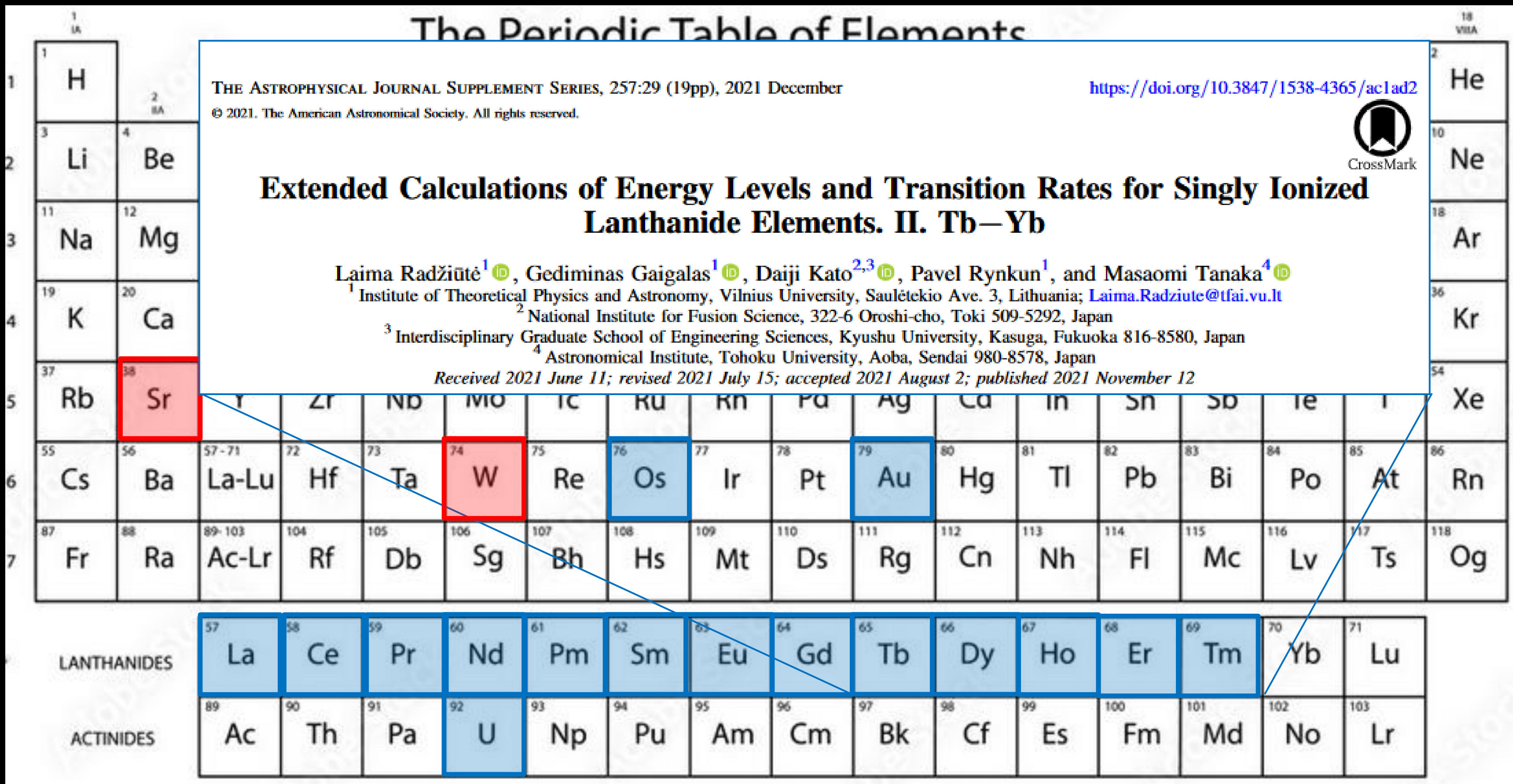

The Astrophysical Journal Supplement Series, 257:29 (19pp), 2021 December
https://doi.org/10.3847/1538-4365/ac1ad2

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
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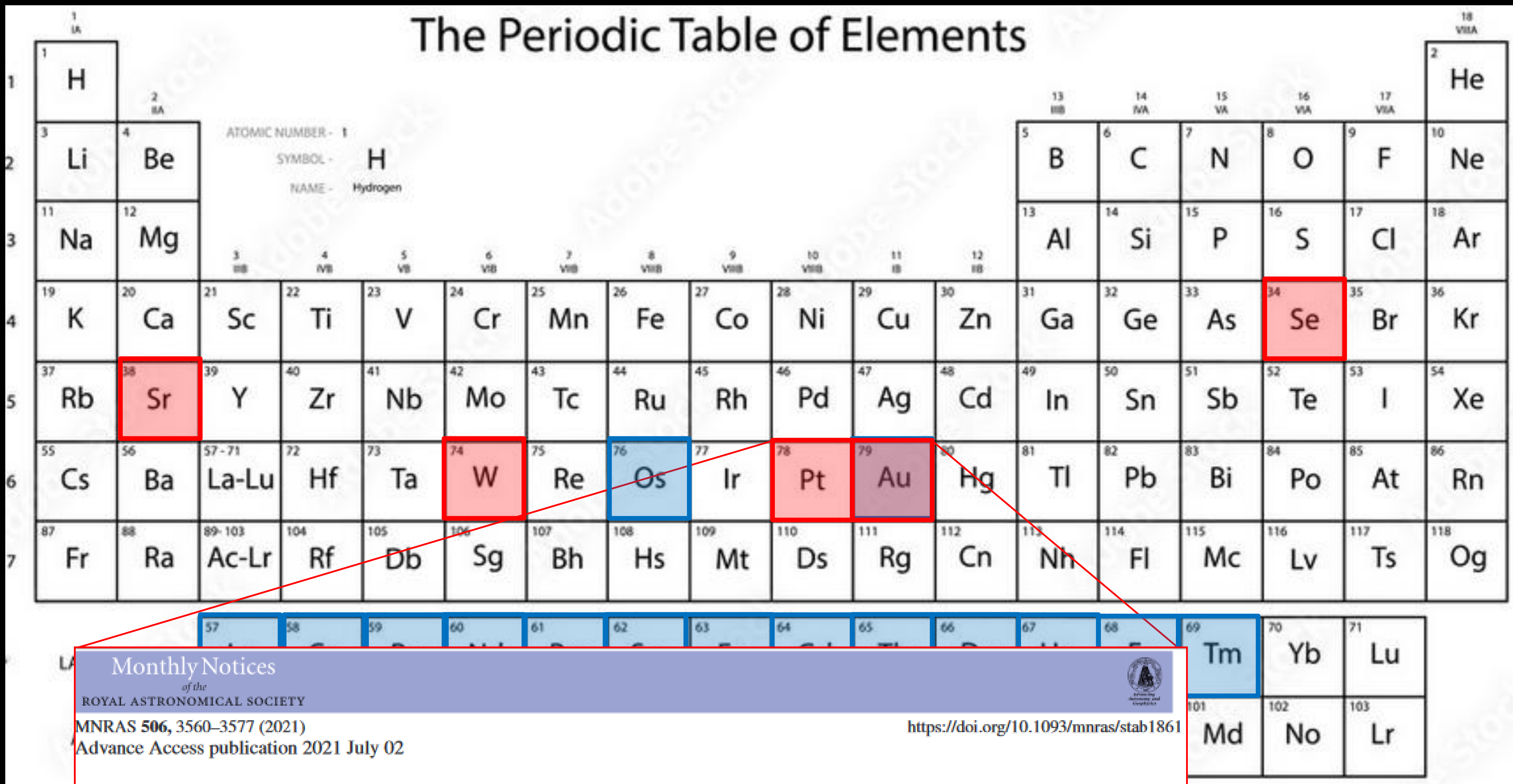

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MNRAS **506**, 3560–3577 (2021)
Advance Access publication 2021 July 02
https://doi.org/10.1093/mnras/stab1861

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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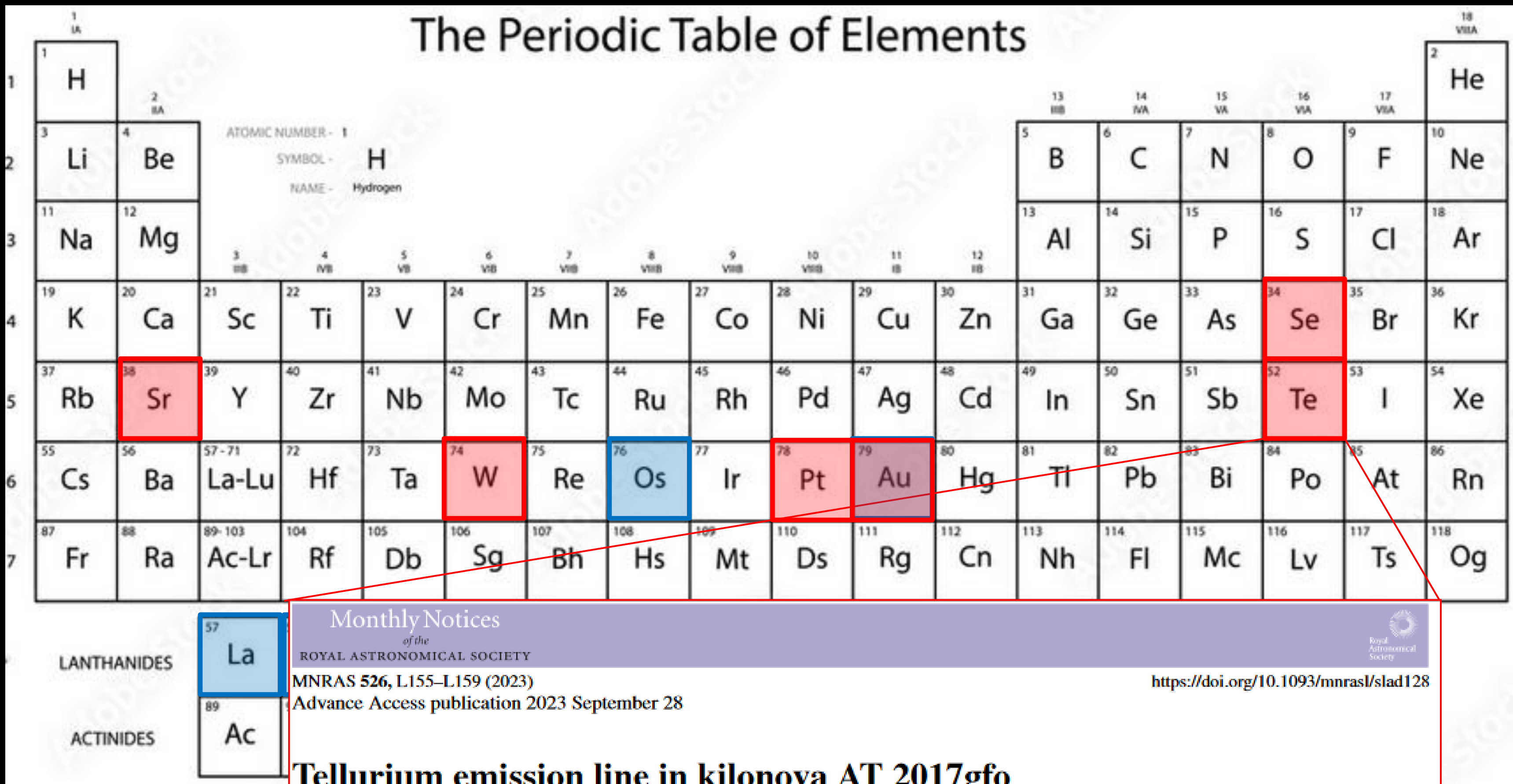

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MNRAS **526**, L155–L159 (2023) https://doi.org/10.1093/mnrasl/slad128
Advance Access publication 2023 September 28

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*
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[5] *Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio Ave. 3, Vilnius 10222, Lithuania*

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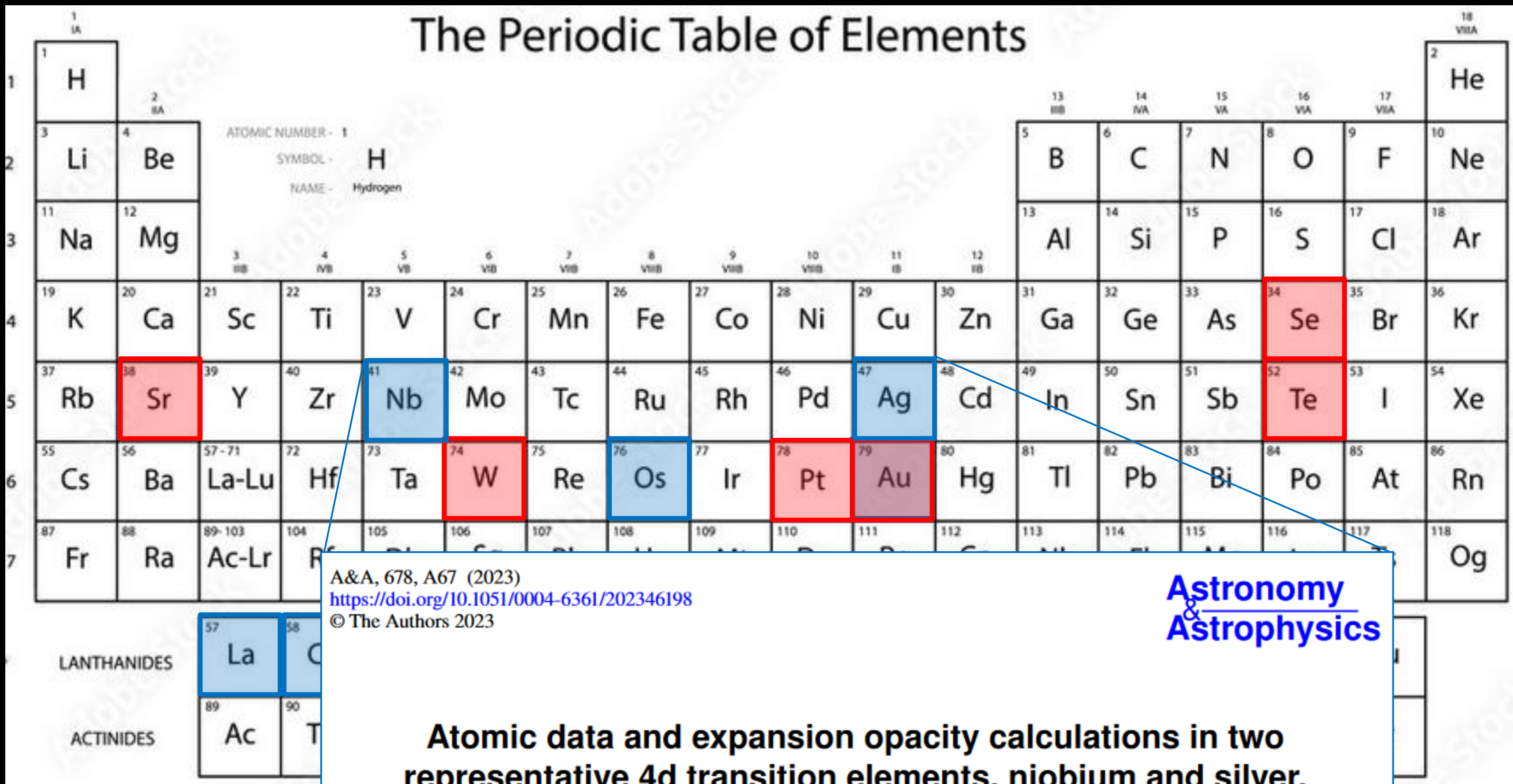

A&A, 678, A67 (2023)
https://doi.org/10.1051/0004-6361/202346198

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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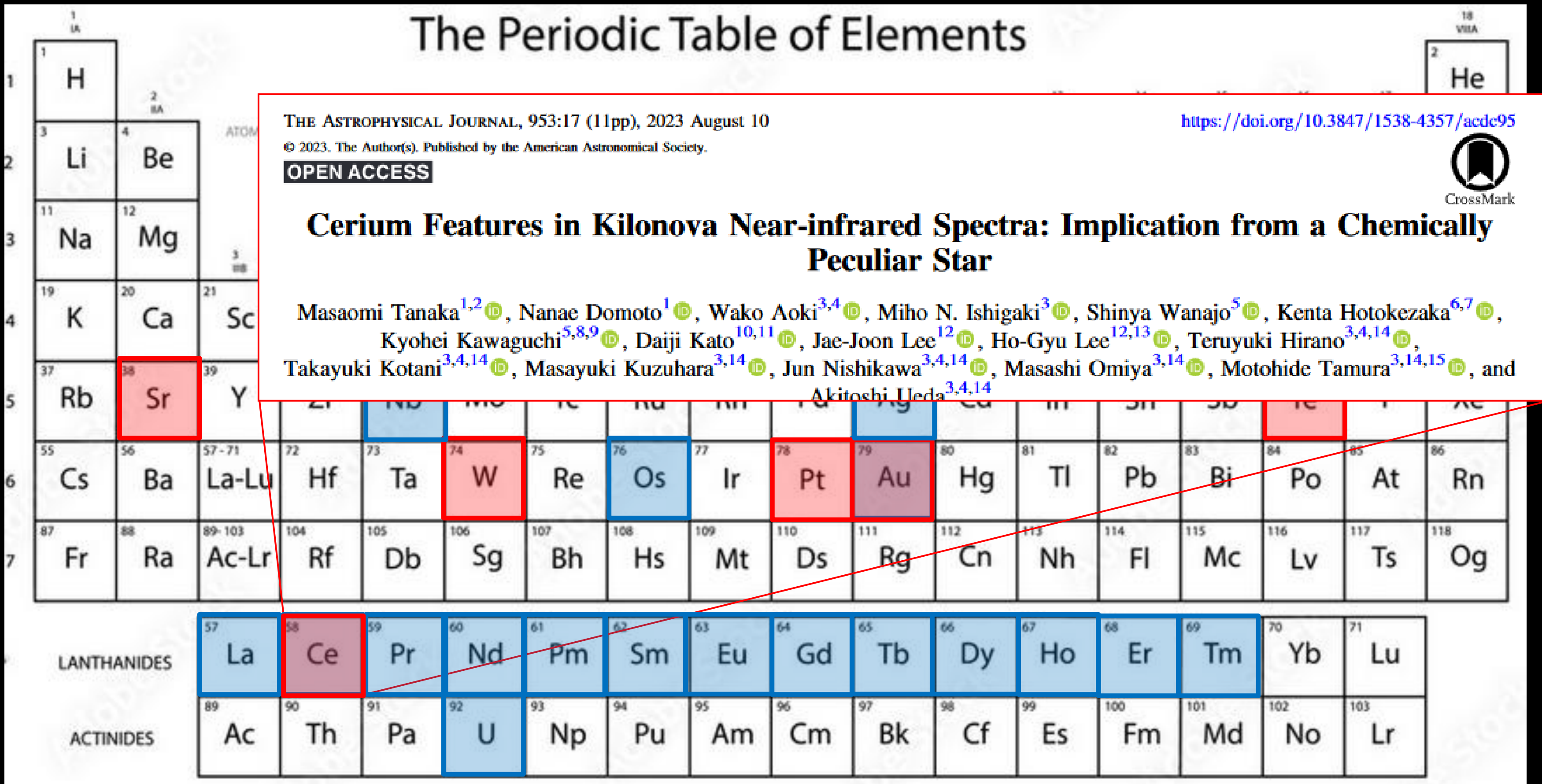

THE ASTROPHYSICAL JOURNAL, 953:17 (11pp), 2023 August 10 https://doi.org/10.3847/1538-4357/acdc95

Cerium Features in Kilonova Near-infrared Spectra: Implication from a Chemically Peculiar Star

Masaomi Tanaka[1,2], Nanae Domoto[1], Wako Aoki[3,4], Miho N. Ishigaki[3], Shinya Wanajo[5], Kenta Hotokezaka[6,7], Kyohei Kawaguchi[5,8,9], Daiji Kato[10,11], Jae-Joon Lee[12], Ho-Gyu Lee[12,13], Teruyuki Hirano[3,4,14], Takayuki Kotani[3,4,14], Masayuki Kuzuhara[3,14], Jun Nishikawa[3,4,14], Masashi Omiya[3,14], Motohide Tamura[3,14,15], and Akitoshi Ueda[3,4,14]

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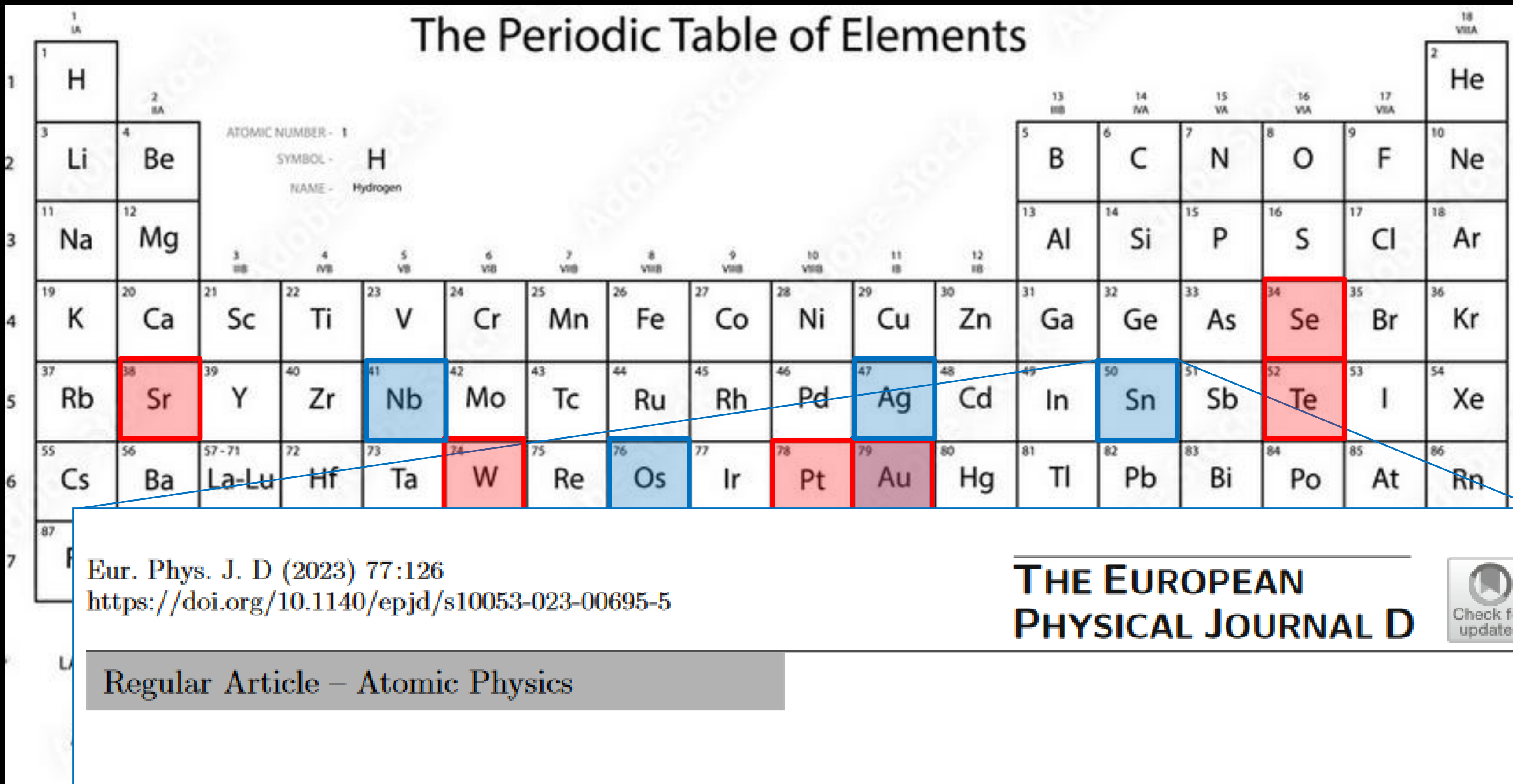

Eur. Phys. J. D (2023) 77:126
https://doi.org/10.1140/epjd/s10053-023-00695-5

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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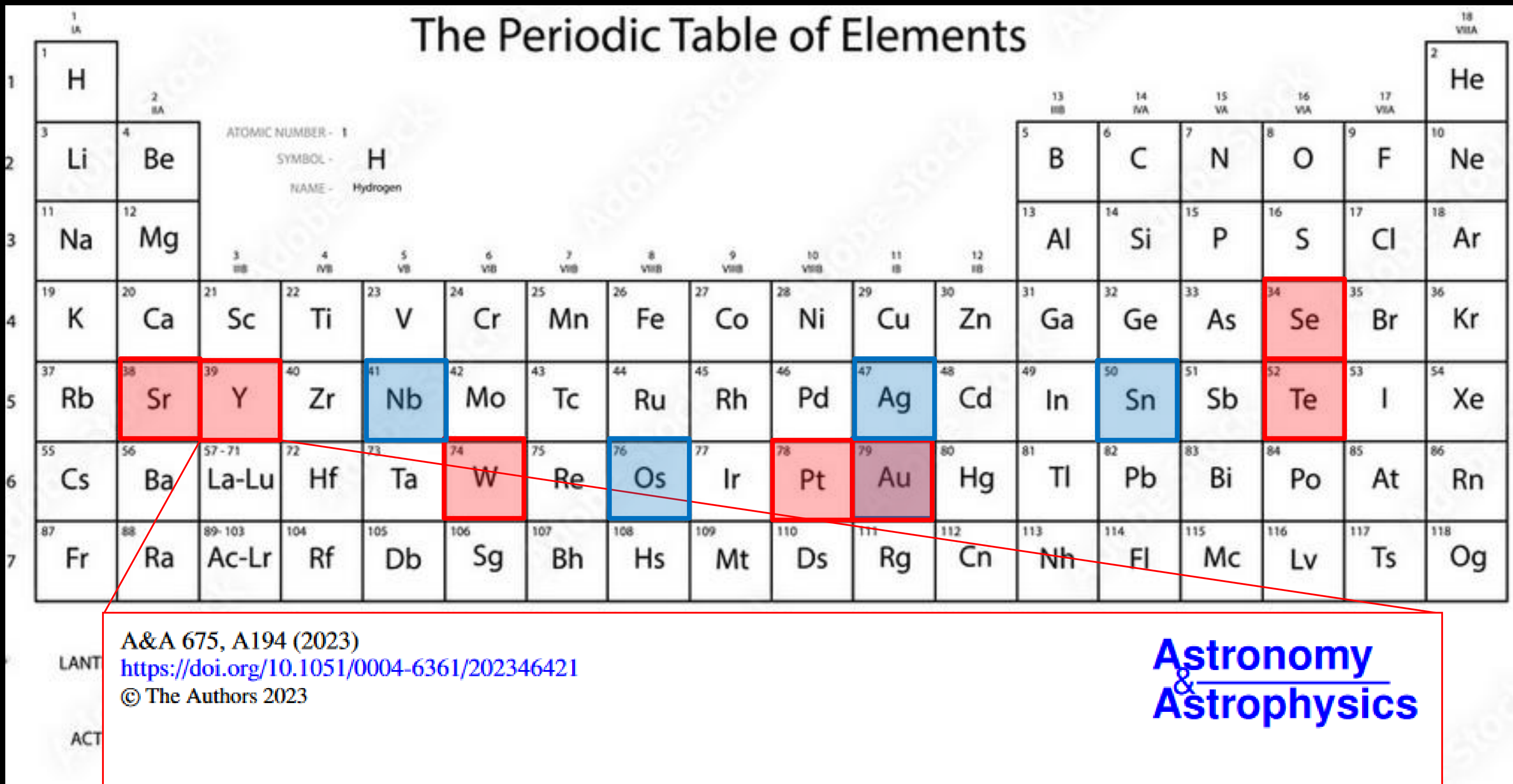

A&A 675, A194 (2023)
https://doi.org/10.1051/0004-6361/202346421

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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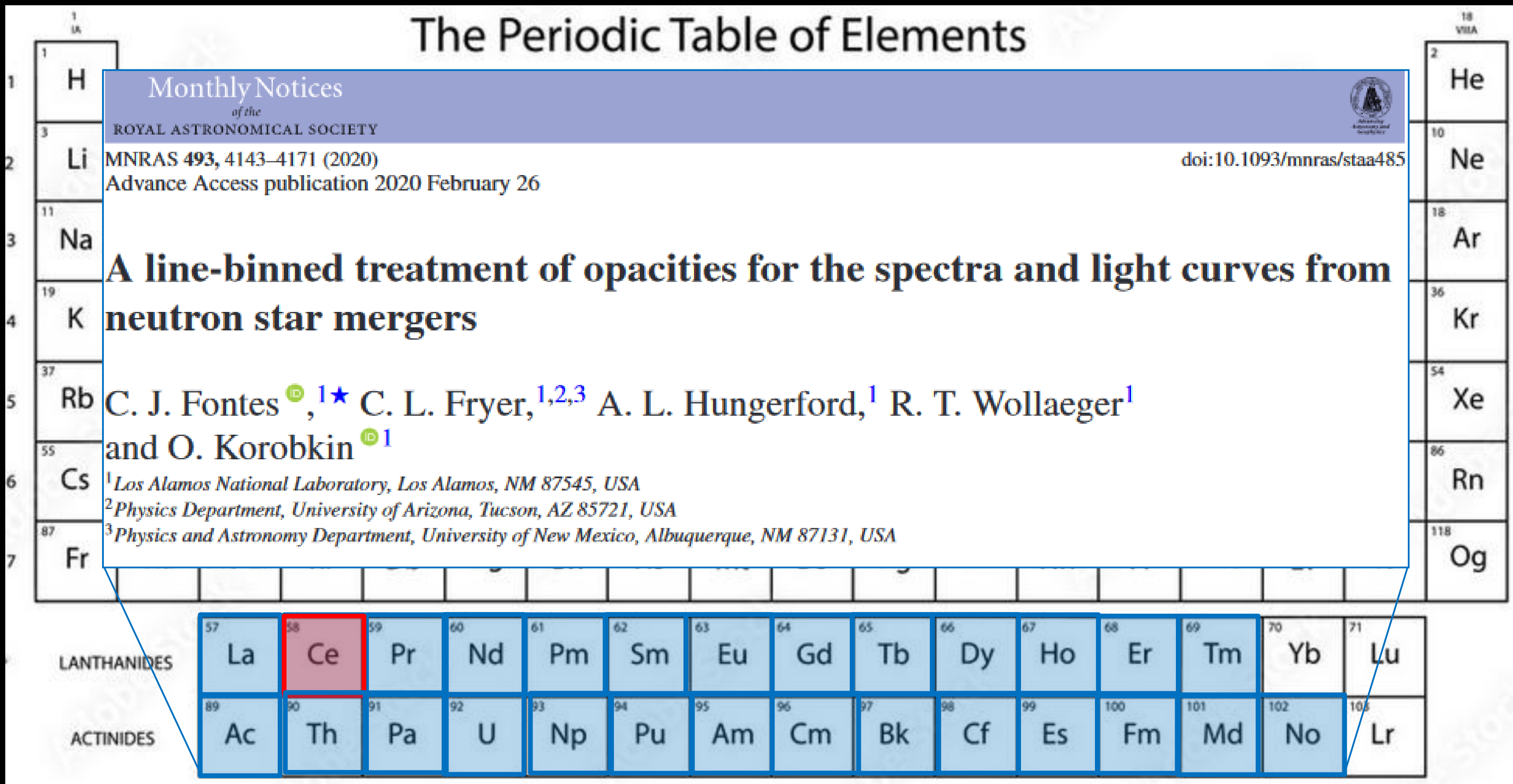

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MNRAS **493,** 4143–4171 (2020) doi:10.1093/mnras/staa485
Advance Access publication 2020 February 26

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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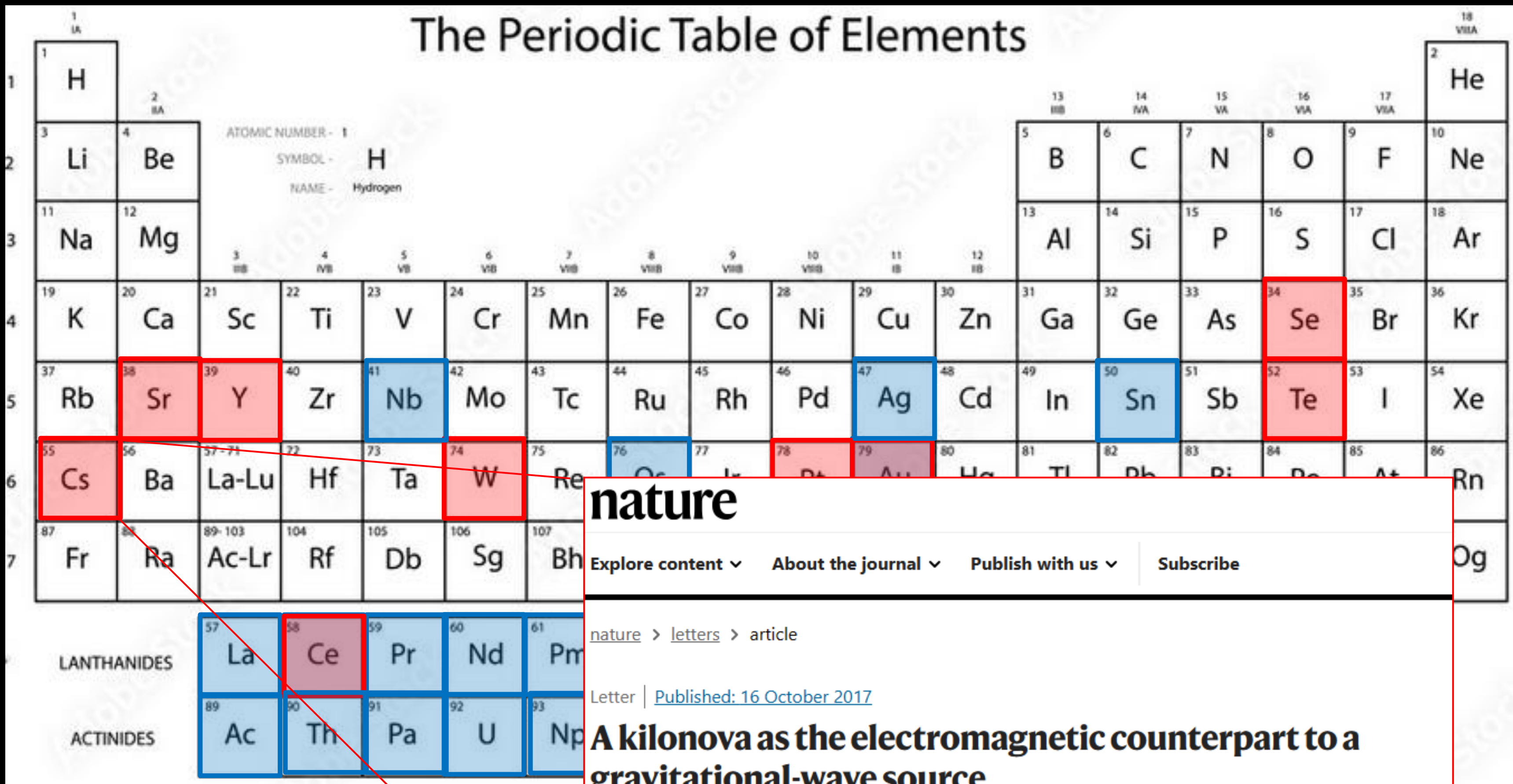

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Letter | Published: 16 October 2017

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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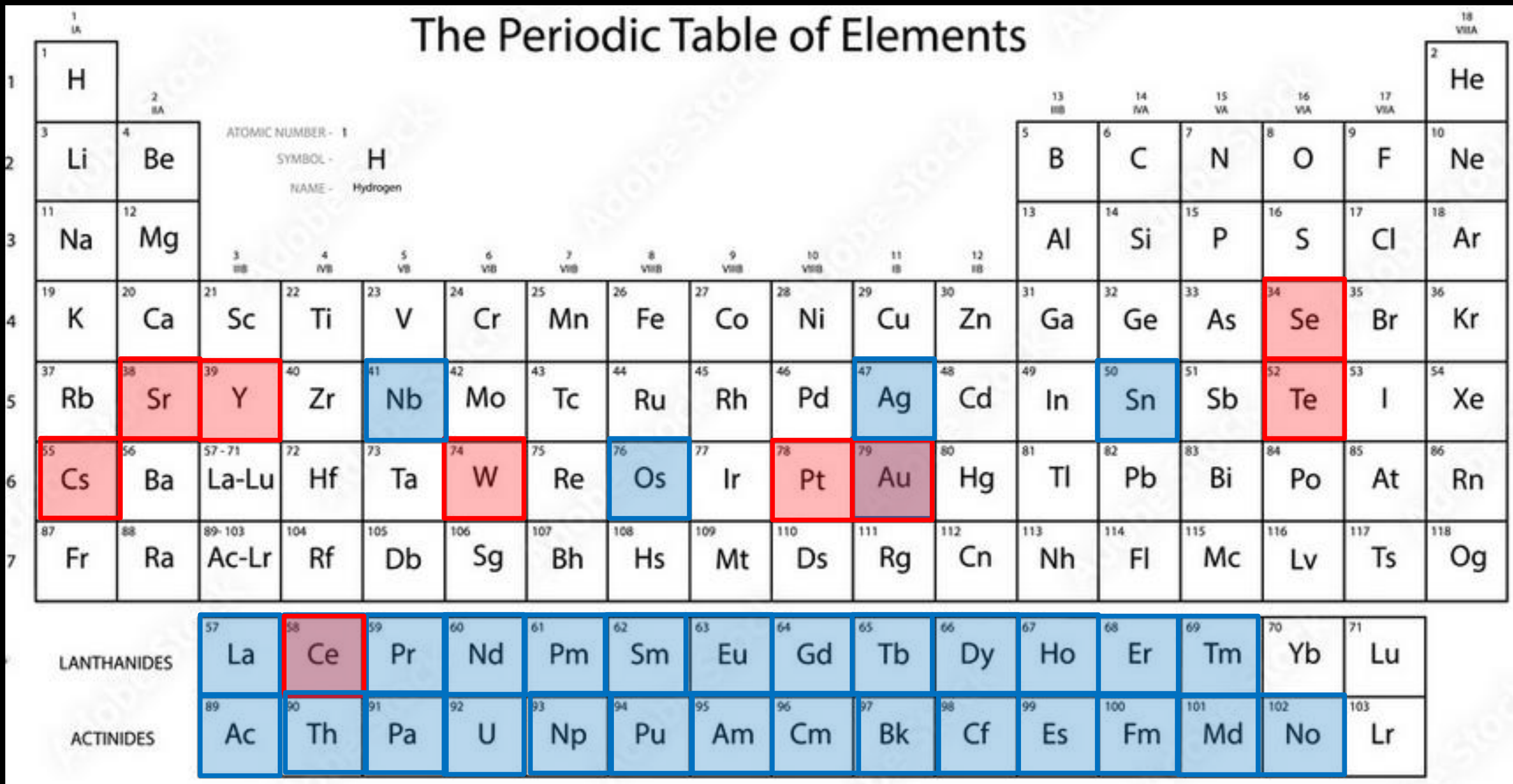


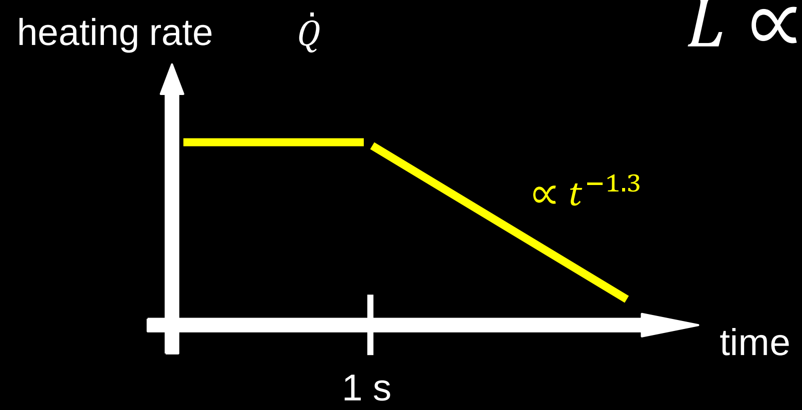
Japan-Lithuania Opacity Database for Kilonova (version 1.1)

Daiji Kato and Izumi Murakami (National Institute for Fusion Science, Japan)
Masaomi Tanaka and Smaranika Banerjee (Tohoku University, Japan)
Gediminas Gaigalas, Laima Kitovienė, and Pavel Rynkun (Vilnius University, Lithuania)

Last input: nuclear heating rates

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

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

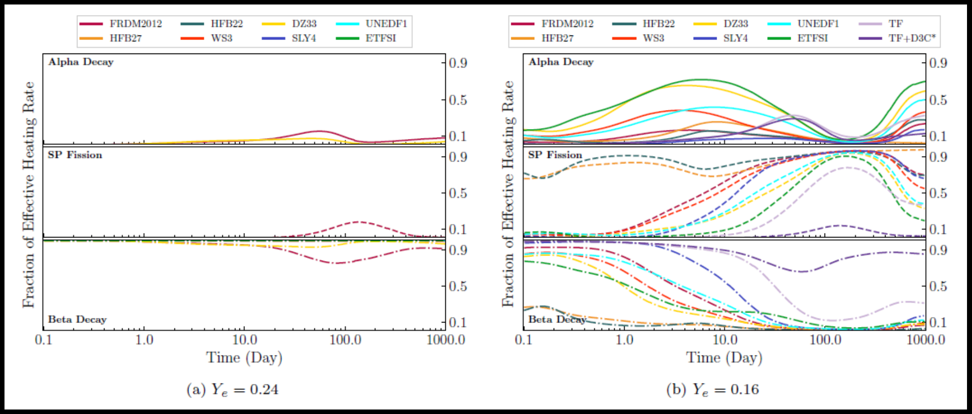


$$Q = M_{initial} - M_{final}$$
$$\lambda = decay\ rate$$

Heating efficiencies

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

...13 free parameters...



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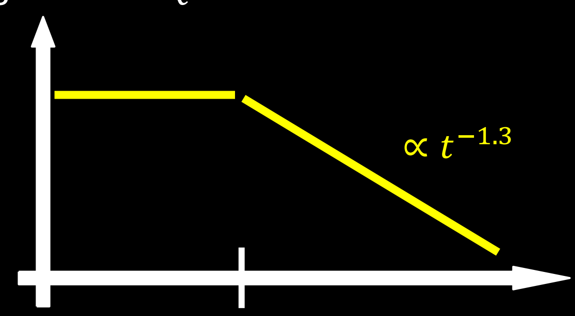

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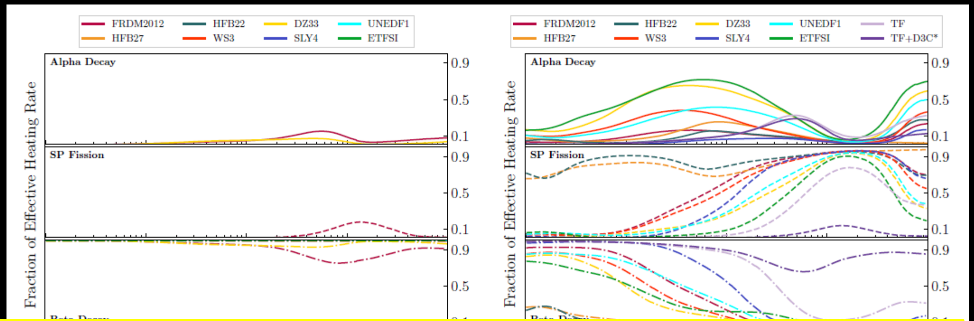
...13 free parameters...



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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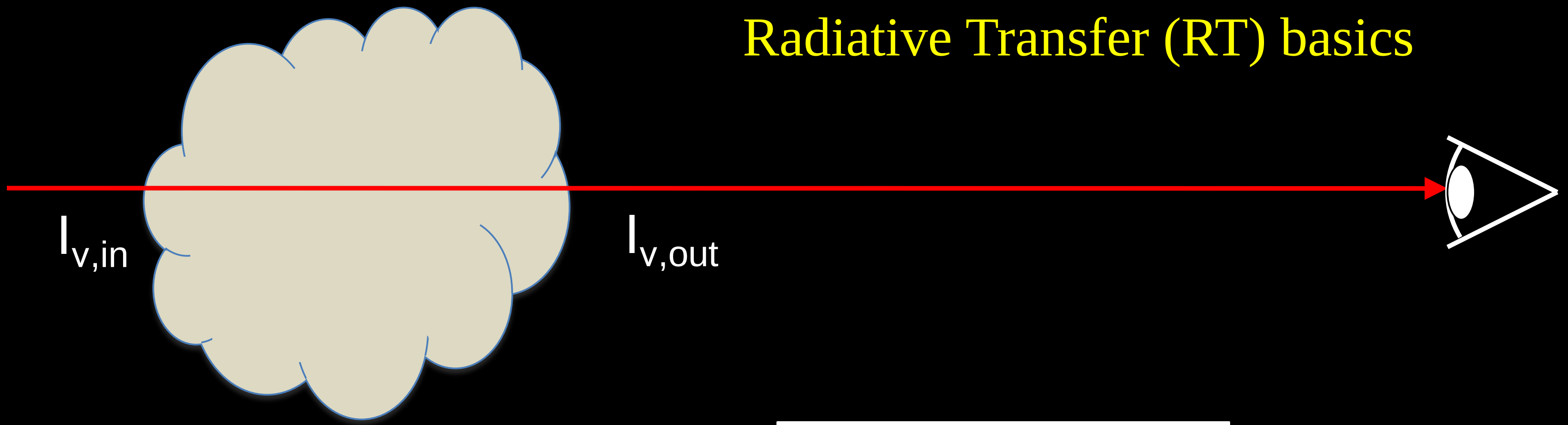
…and finally…

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)

Optical depth is a measure of the extinction coefficient or absorptivity up to a specific stellar layer.

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

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

κ_ν is the frequency-dependent opacity of the medium

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

Photon mean free path

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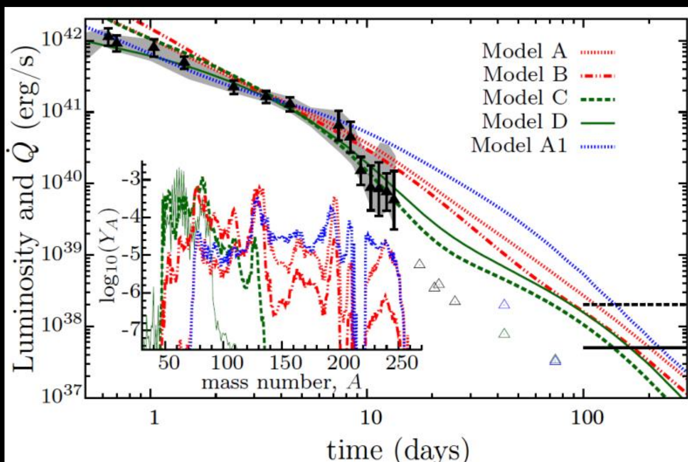
A plethora of KN lightcurves



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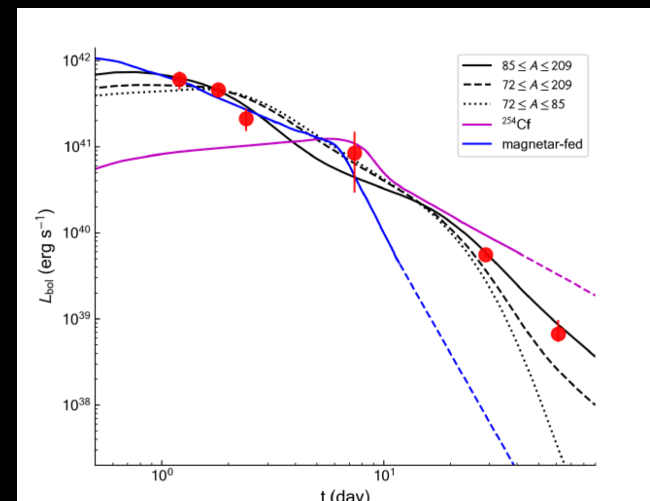
Bulla+2023



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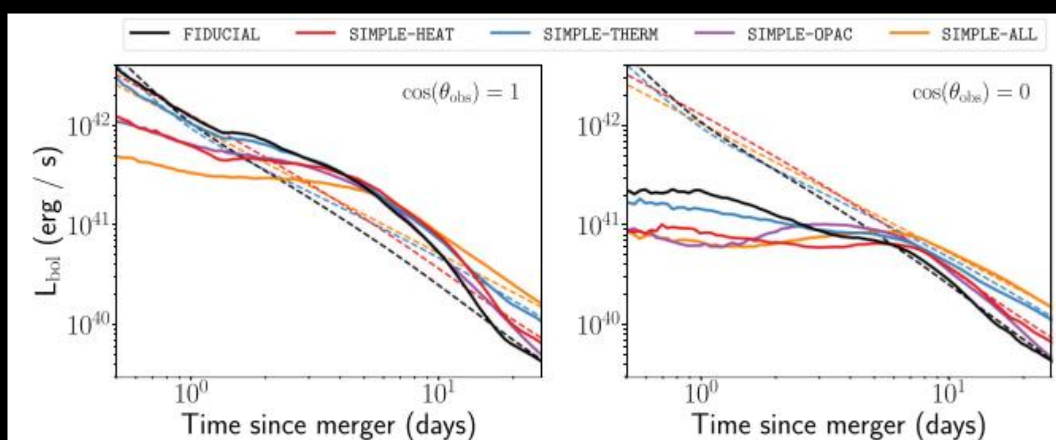

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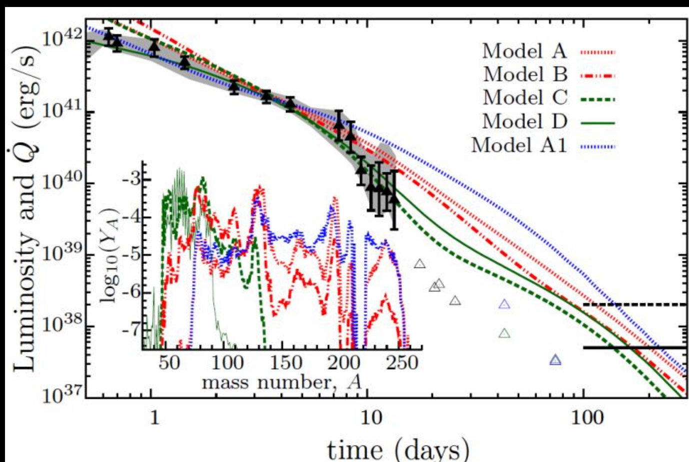
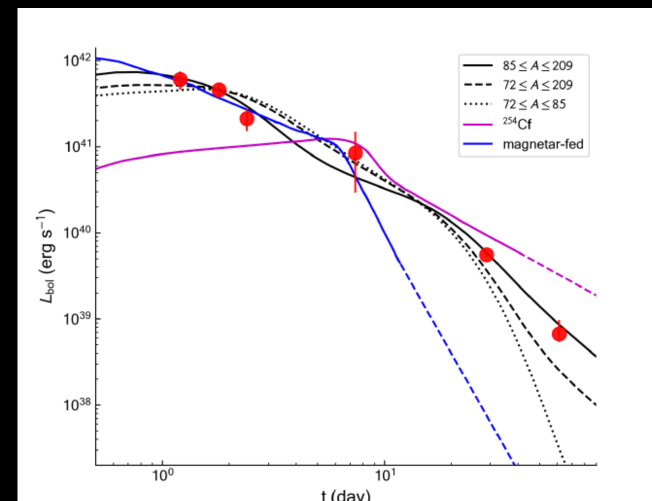
A plethora of KN lightcurves



Wu+ 2019



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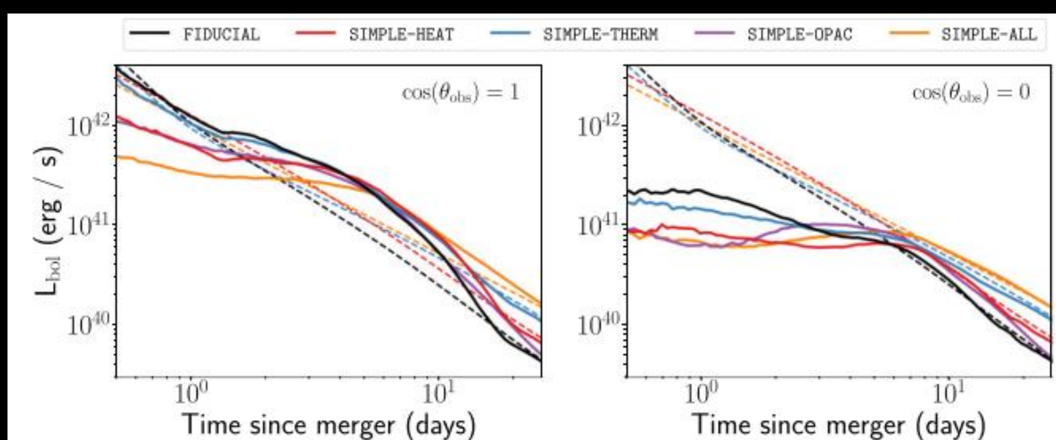

Thanks for the attention