### r-process nucleosynthesis and Kilonovae in the PANDORA project

# 5. Cristallo

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

INAF - Osservatorio Astronomico d'Abruzzo



























#### GW170817: «THE» gravitational signal

#### A revolution similar to Jupiter observations by Galileo...



Hosting galaxy: NGC 4993 (distance ≈44 Mpc)









### **Neutron Star Mergers (NSMs)**











### The corresponding Lightcurve











### The various components of a NSM















#### Rosswog & Korobkin 2022

#### v [c] 0.8 0.6 ...shock'' 0.4 ...shock'' 0.2 ...shock'' ...shock''' ...shock'' ..



# The NSM ejecta

#### Metzger 2019











#### **Bolometric curve of GW170817**



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





Italiadomani Piano nazionale Di Rippresa e resilienza









Ministero dell'Università e della Ricerca











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

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











#### The role of neutrinos

#### The presence of neutrinos increases $Y_e$ in the polar direction





















#### **Bolometric curve of GW170817**



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









### **Atomic opacities**

Opacity  $(\kappa_v)$ , 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.













## **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.



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









## **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 optical/near-IR frequencies (brown line), the dominant source of opacity is a dense forest of line transitions. (bound-bound) The magnitude this of 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.



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  $\rho \alpha t^{-3}$  and the fewer number of free electrons as the ejecta cools and recombines.

#### LATE TIME KILONOVA









### **Atomic opacities**



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













## **Atomic opacities**



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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<sup>19</sup> K	<sup>20</sup> Ca	Sc	22 Ti	23 V	24 Cr	Mn	Fe	27 Co	28 Ni	29 Cu	<sup>30</sup> Zn	Ga	32 Ge	<sup>33</sup> As	<sup>34</sup> Se	35 Br	<sup>36</sup> Kr
37 Rb	<sup>38</sup> Sr	<sup>39</sup> Y	<sup>40</sup> Zr	41 Nb	42 Mo	43 Tc	<sup>44</sup> Ru	45 Rh	* Pd	47 Ag	<sup>48</sup> Cd	49 In	<sup>so</sup> Sn	si Sb	<sup>52</sup> Te	53 	<sup>54</sup> Xe
<sup>55</sup> Cs	se Ba	57-71 La-Lu	" Hf	73 Ta	<sup>74</sup> W	<sup>75</sup> Re	76 Os	" Ir	Pt	79 Au	<sup>∞</sup> Hg	<sup>81</sup> TI	<sup>82</sup> Pb	<sup>83</sup> Bi	<sup>84</sup> Po	<sup>85</sup> At	<sup>86</sup> Rn
<sup>87</sup> Fr	Ra	89-103 Ac-Lr	<sup>104</sup> Rf	105 Db	<sup>106</sup> Sg	107 Bh	<sup>108</sup> Hs	109 Mt	Ds	Rg	Cn	<sup>113</sup> Nh	II4 FI	Мс	116 Lv	117 Ts	118 Og
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ACTI	NIDES	89 Ac	°″Th	Pa Pa	92 U	93 Np	94 Pu	95 Am	<sup>%</sup> Cm	97 Bk	<sup>98</sup> Cf	99 Es	Fm	101 Md	102 No	<sup>103</sup> Lr	1











LANTHANIDES

ACTINIDES

#### Identification of strontium in the merger of two neutron stars

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











G. Gaigalas<sup>9</sup>, <sup>1</sup>\* P. Rynkun<sup>9</sup>, <sup>1</sup>\* S. Banerjee, <sup>2</sup> M. Tanaka<sup>9</sup>, <sup>2,3</sup> D. Kato<sup>94,5</sup> and L. Radžiūtė<sup>91</sup>

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<sup>19</sup> K	20 Ca	Sc	22 Ti	23 V	24 Cr	Mn	Fe	27 Co	<sup>28</sup> Ni	29 Cu	<sup>30</sup> Zn	Ga	Ge	<sup>33</sup> As	Se	Br	<sup>36</sup> Kr
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MNRAS 515, L89–L93 (2022) Advance Access publication 2022 July 29



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

Kenta Hotokezaka, <sup>1,2</sup> * Masaomi Tanaka <sup>0</sup> , <sup>3,4</sup> Daiji Kato <sup>5,6</sup> and Gediminas Gaigalas <sup>7</sup>	
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Rb	<sup>™</sup> Sr	<sup>39</sup> Y	<sup>40</sup> Zr	41 Nb	42 Mo	43 Tc	<sup>#</sup> Ru	45 Rh	* Pd	47 Ag	** Cd	49 In	<sup>so</sup> Sn	51 Sb	<sup>52</sup> Te	53 	<sup>54</sup> Xe
SS Cs	<sup>56</sup> Ba	57-71 La-Lu	<sup>22</sup> Hf	73 Ta	74 W	75 Re	76 - 05	<sup>77</sup> Ir	Pt	<sup>79</sup> Au	Hg	<sup>81</sup> TI	<sup>82</sup> Pb	<sup>83</sup> Bi	84 Po	<sup>85</sup> At	<sup>86</sup> Rn
<sup>87</sup> Fr	* Ra	<sup>89-103</sup> Ac-Lr	104 Rf	<sup>105</sup> Db	Sg	107 Bh	108 Hs	109 Mt	Ds	Rg	Cn	Nh	II4 FI	Мс	116 Lv	117 Ts	118 Og
v	Monthly	57 v Notices	58	59	60	61	62	63	64	65	66	67	8	"Tm	<sup>70</sup> Yb	<sup>71</sup> Lu	1
ROY. MNF Adv	AL ASTRONO RAS 506, 35 ance Acces	<sup>the</sup> DMICAL SOCI 560–3577 (20 ss publicati	iety 021) ion 2021 J	July 02						htt	ps://doi.org/	/10.1093/m	Aras/stab180	<sup>101</sup> Md	<sup>102</sup> No	Lr	1

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

J. H. Gillanders<sup>0</sup>,<sup>1</sup>\* M. McCann,<sup>2</sup> S. A. Sim,<sup>1</sup> S. J. Smartt<sup>1</sup> and C. P. Ballance<sup>2</sup>

<sup>1</sup>Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, BT7 1NN Belfast, UK <sup>2</sup>Centre for Theoretical Atomic, Molecular and Optical Physics, School of Mathematics and Physics, Queen's University Belfast, BT7 1NN Belfast, UK









1 LA	-	100		Т	he P	erio	dic 7	Table	e of	Elen	nent	s					18 VIIA
Н	2 84											13 100	14 IVA	15 VA	16 VIA	17 VIA	He
Li	Be	ATOMIC	NUMBER - 1 SYMBOL -	H								<sup>s</sup> B	° C	'N	<sup>8</sup> O	F	<sup>10</sup> Ne
Na	<sup>12</sup> Mg	3	4	5	6	2		9	10		12	<sup>13</sup> AI	<sup>14</sup> Si	15 P	<sup>16</sup> S	<sup>17</sup> CI	<sup>18</sup> Ar
к	20 Ca	21 Sc	22 Ti	23 V	24 Cr	<sup>25</sup> Mn	<sup>26</sup> Fe	27 Co	28 Ni	29 Cu	<sup>30</sup> Zn	Ga	32 Ge	<sup>33</sup> As	<sup>34</sup> Se	35 Br	<sup>36</sup> Kr
Rb	<sup>38</sup> Sr	<sup>39</sup> Y	<sup>40</sup> Zr	41 Nb	42 Mo	43 Tc	<sup>44</sup> Ru	45 Rh	* Pd	47 Ag	48 Cd	49 In	<sup>so</sup> Sn	51 Sb	<sup>s2</sup> Te	53 	54 Хе
S	56 Ba	57-71 La-Lu	<sup>22</sup> Hf	73 Ta	74 W	75 Re	<sup>76</sup> Os	" Ir	Pt	Au	<sup>∞</sup> Hg	81 <b>T</b>	<sup>82</sup> Pb	es Bi	в	×5 At	<sup>86</sup> Rn
Fr	** Ra	89-103 Ac-Lr	<sup>104</sup> Rf	105 Db	<sup>106</sup> Sg	<sup>107</sup> Bh	<sup>108</sup> Hs	Mt	Ds	Rg	Cn	<sup>113</sup> Nh	II4 FI	Мс	Lv	Ts	<sup>118</sup> Og
LANTH	IANIDES	<sup>57</sup> La <sup>89</sup> Ac	M ROYAL . MNRAS Advanc Tell	fonthly N of the ASTRONOMI S <b>526</b> , L155 Xe Access I <b>urium</b>	Notices	3) 2023 Sep	tember 28	, n kilor	nova .	AT 20	17gfo	,	htt	ps://doi.org	/10.1093/m	Annot Society nrasi/slad12	28
			Kenta <sup>1</sup> Resean <sup>2</sup> Astrono <sup>3</sup> Nationa <sup>4</sup> Interdis	a Hotoke ch Center fo omical Institu al Institute f sciplinary G	ezaka, <sup>1</sup> * or the Early tute, Tohoku for Fusion S fraduate Sch	Masao Universe, C University, icience, 322 bool of Eng	omi Tana Graduate So , Aoba, Sen 2-6 Oroshi-o ineering Sci	aka <sup>©</sup> , <sup>2</sup> ] chool of Scie dai 980-857 cho, Toki 50 iences, Kyu	Daiji K ence, Unive 78, Japan 9-5292, Jaj shu Univer	AT 20 ato <sup>3,4</sup> an ersity of Toky pan sity, Fukuok	d Gedin yo, Bunkyo,	ninas G Tokyo 113- , Japan	aigalas <sup>:</sup> 0033, Japa	5 in			

















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1 IA	1			Т	he P	erio	dic 1	<b>Table</b>	of	Elem	nent	s					18 VIIA
н	2														35		He
Li	Be	ATOM	COPEN A	ROPHYSICAI	blished by the	, 953:17 (1 American Ast	1pp), 2023 ronomical Soc	3 August 10						https://do	oi.org/10.3	847/1538-	-4357/acd
Na	<sup>12</sup> Mg	3 108	Cer	ium F	eatur	es in l	Kilono	ova Ne	ar-inf Pe	rared culiar	Spect Star	ra: In	nplicat	tion fr	om a	Chem	Cross
к	°Ca	<sup>21</sup> Sc	Masac	omi Tana Kyohe	ka <sup>1,2</sup> 0, ci Kawag	Nanae D guchi <sup>5,8,9</sup>	omoto <sup>1</sup> ( Daiji	, Wako Kato <sup>10,1</sup>	Aoki <sup>3,4</sup> <sup>1</sup> 10, Jae-	, Miho Joon Le	N. Ishig	aki <sup>3</sup> ®, S o-Gyu L	Shinya W ee <sup>12,13</sup>	Vanajo <sup>5</sup> @ , Teruyu	), Kenta ki Hiran	Hotokez o <sup>3,4,14</sup>	zaka <sup>6,7</sup>
Rb	<sup>™</sup> Sr	39 Y	Takayu	ki Kotan	i <sup>3,4,14</sup> ©,	Masayu	ki Kuzuł		, Jun Ni , Aki	shikawa toshi Ye	1 <sub>12</sub> 3,4,14	Masashi		"", Moi	tohide T	amura <sup>3,1</sup>	<sup>4,15</sup> <sup>0</sup> ,
Cs	56 Ba	57-71 La-Lu	<sup>22</sup> Hf	73 Та	<sup>74</sup> W	<sup>75</sup> Re	<sup>76</sup> Os	" Ir	Pt	Au	<sup>∞</sup> Hg	<sup>81</sup> TI	Pb	Bi	Po	At	<sup>86</sup> Rr
Fr	Ra	<sup>89-103</sup> Ac-Lr	Rf	Db	Sg	Bh	108 Hs	Mt	Ds	III Rg	<sup>112</sup> Cn	<sup>HI3</sup> Nh	II4 Fl	Мс	Lv	Ts	118 Og
LANTH	IANIDES	57 La	<sup>®</sup> Ce	<sup>s9</sup> Pr	<sup>60</sup> Nd	Pm	Sm	63 Eu	Ğd	55 Tb	∞Dy	<sup>67</sup> Ho	Er	۳Tm	<sup>70</sup> Yb	<sup>21</sup> Lu	1
			44	01	03	63	94	36	96	97	QR.	99	100	101	102	103	-









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1 IA	-	200		Т	he P	erio	dic <sup>¬</sup>	Table	e of	Elen	nent	s					18 VIIA
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2 Li	Be	ATOMIC	NUMBER - 1 SYMBOL -	H								<sup>s</sup> B	° c	'N	<sup>8</sup> O	۴	<sup>10</sup> Ne
3 Na	<sup>12</sup> Mg	3	4	S VB	6 VB	2 100	8	9 V08	10 V108		12	<sup>13</sup> Al	<sup>14</sup> Si	<sup>15</sup> P	<sup>16</sup> S	<sup>17</sup> CI	<sup>18</sup> Ar
4 <sup>19</sup> K	°Ca	21 Sc	<sup>22</sup> Ti	23 V	<sup>24</sup> Cr	Mn	Fe	27 Co	28 Ni	<sup>29</sup> Cu	<sup>30</sup> Zn	Ga	<sup>32</sup> Ge	<sup>33</sup> As	<sup>™</sup> Se	<sup>35</sup> Br	<sup>36</sup> Kr
s Rb	<sup>38</sup> Sr	39 Y	<sup>40</sup> Zr	"Nb	42 Mo	43 Tc	<sup>₄</sup> Ru	45 Rh	* Pd	47 Ag	* Cd	<sup>49</sup> In	<sup>so</sup> Sn	si Sb	sz Te	53 	<sup>54</sup> Хе
6 Cs	se Ba	57-71 La-Lu	<sup>n</sup> Hf	73 Ta	24 W	<sup>75</sup> Re	<sup>76</sup> Os	" Ir	Pt	Au	<sup>∞</sup> Hg	<sup>81</sup> TI	<sup>82</sup> Pb	<sup>83</sup> Bi	<sup>84</sup> Po	<sup>85</sup> At	RA
7 F	ur. Phy tps://d	s. J. D loi.org/	(2023) (10.114)	77:126 0/epjd/	5 /s10053	-023-00	)695-5					Тне	EUF	ROPE	AN		

Regular Article – Atomic Physics

### Calculations of multipole transitions in Sn II for kilonova analysis

A. I. Bondarev<sup>1,2,a</sup> , J. H. Gillanders<sup>3</sup>, C. Cheung<sup>4</sup>, M. S. Safronova<sup>4,5</sup>, and S. Fritzsche<sup>1,2,6</sup>



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Finanziato dall'Unione europea NextGenerationEU





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2	Li	Be	ATOMIC	NUMBER - 1 SYMBOL - NAME -	H								<sup>s</sup> B	° C	'N	* 0	F	Ne
3	Na	<sup>12</sup> Mg	3	4	s VB	6 VB	2 V18	8 V18	9 V108	10 V18		12	<sup>13</sup> Al	<sup>14</sup> Si	<sup>15</sup> P	<sup>16</sup> S	<sup>17</sup> CI	Ar
4	к	20 Ca	Sc	22 Ti	23 V	24 Cr	Mn	Fe	27 Co	28 Ni	29 Cu	<sup>30</sup> Zn	Ga	<sup>32</sup> Ge	<sup>33</sup> As	» Se	<sup>35</sup> Br	<sup>36</sup> Kr
37	Rb	<sup>38</sup> Sr	<sup>39</sup> Y	<sup>∞</sup> Zr	Nb	42 Mo	43 Tc	<sup>#</sup> Ru	45 Rh	<sup>46</sup> Pd	47 Ag	<sup>≪</sup> Cd	49 In	<sup>so</sup> Sn	51 Sb	<sup>s2</sup> Te	53 	<sup>54</sup> Xe
6	Cs	<sup>56</sup> Ba	La-Lu	" Hf	73 Ta	74 W	75 Re	<sup>76</sup> Os	" Ir	Pt	Au	<sup>∞</sup> Hg	<sup>81</sup> TI	<sup>82</sup> Pb	Bi	в	<sup>85</sup> At	Rn
7	Fr	Ra	89- 103 Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	<sup>113</sup> Nh	FI	Мс	LV	Ts	Og

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

Astronomy Astrophysics

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

Albert Sneppen<sup>1,2</sup> and Darach Watson<sup>1,2</sup>









1 LA	7			T	he P	erio	dic T	able	e of I	Elem	nent	s					18 VIIA 2
н	Mor	Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY															He
Li	MNRAS 49 Advance A	NRAS 493, 4143–4171 (2020) doi:10.1093/mnras/staa485 dvance Access publication 2020 February 26															Ne
<sup>11</sup> Na	A line	A line-binned treatment of opacities for the spectra and light curves from															<sup>18</sup> Ar
<sup>19</sup> K	neutr	neutron star mergers													<sup>36</sup> Kr		
37 Rb	C. J. F	ontes	<sup>©</sup> ,1★	C. L.	Fryer	,1,2,3	A. L.	Hung	erford	l, <sup>1</sup> R.	T. Wo	ollaeg	ger <sup>1</sup>				s4 Xe
<sup>55</sup> Cs	and O. <sup>1</sup> Los Alama <sup>2</sup> Physics De	s Nationa epartment	DDK111 al Laborate t, Universi	ory, Los A ty of Arize	lamos, NI ona, Tucso	M 87545, m, AZ 852	USA 721, USA										<sup>86</sup> Rn
<sup>87</sup> Fr	<sup>3</sup> Physics an	nd Astrono	omy Depar	tment, Ur	niversity of	f New Me	xico, Albu	querque, 1	NM 87131	, USA		110					Og
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S. J. Smartt<sup>™</sup>, 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 + Show authors







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1 14	1	The Periodic Table of Elements															18 VIIA
н	2 84											13 mit	14	15 VA	16 VIA	17 VIA	He
Li	Be	ATOMIC N	VUMBER - 1 SYMBOL -	н								<sup>s</sup> B	°C	<sup>7</sup> N	* O	۴	<sup>10</sup> Ne
Na	<sup>12</sup> Mg	3 100	4 MB	s VB	6 1/8	2 100	8 V18	9 Vii8	10 V108		12 18	<sup>13</sup> Al	<sup>14</sup> Si	<sup>15</sup> P	<sup>16</sup> S	"CI	<sup>18</sup> Ar
ĸ	<sup>20</sup> Ca	Sc	22 Ti	23 V	<sup>24</sup> Cr	Mn	Fe	27 Co	28 Ni	29 Cu	<sup>30</sup> Zn	Ga	<sup>32</sup> Ge	<sup>33</sup> As	<sup>™</sup> Se	<sup>35</sup> Br	<sup>36</sup> Kr
Rb	<sup>™</sup> Sr	39 Y	<sup>∞</sup> Zr	Nb	42 Mo	43 Tc	<sup>#</sup> Ru	45 Rh	* Pd	47 Ag	<sup>≉</sup> Cd	49 In	<sup>so</sup> Sn	sı Sb	<sup>s2</sup> Te	53 	<sup>54</sup> Xe
cs	<sup>se</sup> Ba	57-71 La-Lu	<sup>n</sup> Hf	73 Ta	74 W	<sup>75</sup> Re	<sup>76</sup> Os	" Ir	Pt	Au	<sup>∞</sup> Hg	<sup>81</sup> TI	Pb	<sup>83</sup> Bi	<sup>84</sup> Po	<sup>85</sup> At	<sup>86</sup> Rn
Fr	** Ra	89-103 Ac-Lr	Rf	Db	<sup>106</sup> Sg	Bh	Hs	Mt	Ds	"" Rg	Cn	<sup>113</sup> Nh	II4 FI	Мс	116 Lv	117 Ts	118 Og
LANTHANIDES		57 La	<sup>ss</sup> Ce	so Pr	<sup>60</sup> Nd	Pm	<sup>62</sup> Sm	63 Eu	<sup>64</sup> Gd	55 Tb	<sup>66</sup> Dy	67 Ho	<sup>68</sup> Er	°″Tm	<sup>70</sup> Yb	<sup>21</sup> Lu	1
		<sup>89</sup> Ac	<sup>∞</sup> Th	Ра	92 U	<sup>93</sup> Np	<sup>94</sup> Pu	95 Am	<sup>**</sup> Cm	97 Bk	<sup>se</sup> Cf	99 Es	<sup>100</sup> Fm	Md	102 No	Lr	1

#### 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 Kitoviene, and Pavel Rynkun (Vilnius University, Lithuania)









### Last input: nuclear heating rates

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

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

**Heating efficiencies** 

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

...13 free parameters...





Zhu+ 2020







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1 s



 $L \propto \dot{Q}M$ 

time

### Last input: nuclear heating rates

heating rate

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

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

**Heating efficiencies** 

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

#### ...13 free parameters...



 $\propto t^{-1.3}$ 

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





Ministero dell'Università e della Ricerca







# ...and finally...



















#### **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.

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

 $\kappa_v$  is the frequency-dependent / opacity of the medium

$$l_{\text{free},v} = \frac{1}{\rho \kappa_v}$$

Photon mean free path

 $\alpha_{\nu} \equiv \kappa_{\nu} \rho$ 





Model A Model B

Model C -----

Model D —

Model A1

100





### A plethora of KN lightcurves



 $(10^{42})^{10^{42}}$  (erg/s)  $\dot{O}_{10^{40}}$ Luminosity  $0^{39}$ 10381 100 150 200250mass number, A $10^{37}$ 1 10 time (days)

Yang+2024









 $10^{0}$ 

 $10^{1}$ 

Time since merger (days)





### A plethora of KN lightcurves



 $10^{0}$ 

 $10^{1}$ 

Time since merger (days)









# Thanks for the attention