### 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





Italiadomani Piano nazionale Di Ripresa e resilienza











Italiadomani Di Rippesa e resilienza





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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 ( $\alpha$  and  $\beta$ ).



Basic ideas:

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









#### Key ingredients

- 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.









#### The transition from blue-KN to red-KN











### A kilonova lightcurve



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







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### A kilonova lightcurve



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### **Nuclear heating rate**











### **Nuclear heating rate**



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



#### Heating efficiencies

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









### **Nuclear heating rate**



#### Heating efficiencies

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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]









### A kilonova lightcurve



Bolometric curve of at2017gfo



















### **RT** equation

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

#### **Optical depth**

#### Source function (emissivity to absorption ratio)

$$\tau_{\nu}(D) = \int_{0}^{D} \alpha_{\nu}(s) \, \mathrm{d}s$$
$$\alpha_{\nu} = \kappa_{\nu}\rho$$

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

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

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:

$$t_{\rm diff} \simeq \frac{R}{c} \tau = \frac{3M\kappa}{4\pi cR} = \frac{3M\kappa}{4\pi cvt}$$









#### Radiative Transfer (RT) basics

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

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

The corresponding luminosity is:

$$L_{\text{peak}} \sim 1.1\varepsilon \times 10^{41} \frac{\text{erg}}{\text{s}} \left(\frac{k_{\gamma}}{\text{cm}^2 \text{g}^{-1}}\right)^{-\alpha/2} \left(\frac{\nu}{0.1c}\right)^{\alpha/2} \left(\frac{M}{0.01 \text{M}_{\odot}}\right)^{1-\alpha/2},$$









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In these formulas,  $\kappa$  is assumed <u>CONSTANT in time</u> and independent from chemical abundances (and, therefore, <u>independent from the frequency</u>). 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



Bolometric curve of at2017gfo









### A kilonova lightcurve



Bolometric curve of at2017gfo

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









## **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.



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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TAKE HOME MESSAGE FOR STUDENTS:

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









### **Absorption Coefficient**

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









### **Absorption Coefficient**

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Number of electrons in the upper and lower states

State wavefunction

Radiative transition data









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### **Absorption Coefficient**



Number of electrons in the upper and lower states

State wavefunction

Radiative transition data

Free-free transitions











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 $(cm^{-1})$ 

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State wavefunction

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Free-free transitions

**Bound-free transitions** 











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State wavefunction

Radiative transition data

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.











## **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**

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 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.



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



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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LANTHANIDES

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#### 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>9</sup><sup>1</sup>

Astronomical Institute, Tohoku University, Sendai 980-8578, Japan

Division for the Establishment of Frontier Sciences, Organization for Advanced Studies, Tohoku University, Sendai 980-8577, Japan National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

<sup>5</sup>Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan

















Deservatorio Astronomico d'Abruzzo

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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> M	Iasaomi Tanaka <sup>9</sup> , <sup>3,4</sup> Daiji Kato <sup>5,6</sup> and Gediminas Gaigalas <sup>7</sup>
<sup>1</sup> Research Center for the Early Univ.	erse, Graduate School of Science, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
<sup>2</sup> Kavli IPMU (WPI), UTIAS, The Un	iversity of Tokyo, Kashiwa, Chiba 277-8583, Japan
<sup>3</sup> Astronomical Institute, Tohoku Univ	versity, Sendai 980-8578, Japan
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<sup>&</sup>lt;sup>4</sup>Division for the Establishment of Frontier Sciences, Organization for Advanced Studies, Tohoku University, Sendai 980-8577, Japan

<sup>&</sup>lt;sup>5</sup>National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

<sup>&</sup>lt;sup>6</sup>Department of Advanced Energy Engineering Science, Kyushu University, Kasuga, Fukuoka 816-8580, Japan

<sup>&</sup>lt;sup>7</sup>Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio Ave. 3, Vilnius, Lithuania









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

J. H. Gillanders<sup>1</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>

Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, BT7 INN Belfast, UK Centre for Theoretical Atomic, Molecular and Optical Physics, School of Mathematics and Physics, Queen's University Belfast, BT7 INN Belfast, UK









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INAF ISTITUTO NAZIONALE DI ASTROPISICA Deservatorio Astronomico d'Abruzzo

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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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37 Rb	<sup>38</sup> Sr	39 Y	<sup>40</sup> Zr	Nb	<sup>42</sup> Mo	43 Tc	<sup>#</sup> Ru	45 Rh	* Pd	47 Ag	<sup>≉</sup> Cd	49 In	<sup>so</sup> Sn	<sup>51</sup> Sb	<sup>s2</sup> Te	53 	<sup>54</sup> Xe
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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>









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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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"Na	<sup>12</sup> Mg	3 100	4	s VB	6 VB	2 108	a VIIB	9 VII8	10 V108	11	12 18	<sup>13</sup> Al	<sup>14</sup> Si	<sup>15</sup> P	<sup>16</sup> S	<sup>17</sup> CI	<sup>18</sup> Ar
<sup>19</sup> K	20 Ca	<sup>21</sup> 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>34</sup> Se	Br	<sup>36</sup> Kr
Rb	<sup>38</sup> Sr	39 Y	<sup>∞</sup> Zr	Nb	<sup>42</sup> Mo	43 Tc	<sup>#</sup> Ru	45 Rh	* Pd	47 A.a.	<sup>≉</sup> Cd	49 In	<sup>so</sup> Sn	sı Sb	<sup>s2</sup> Te	<sup>53</sup>	<sup>54</sup> Xe
SS Cs	se Ba	57-71 La-Lu	" Hf	73 Ta	74 W	<sup>75</sup> Re	<sup>76</sup> Os	" Ir	78 P	Au	łg	<sup>81</sup> TI	Pb	<sup>83</sup> Bi	<sup>84</sup> Po	<sup>85</sup> At	Rn
<sup>87</sup> Fr	<sup>≋</sup> Ra	89-103 Ac-Lr	<sup>104</sup> Rf	105 Db	Sg	Bh	108 Hs	Mt	Ds	ny ny	Cn	<sup>113</sup> Nh	II4 Fl	Мс	116 Lv	Ts	118 Og
LANTH	IANIDES	57 Lä	<sup>ss</sup> Ce	<sup>59</sup> /r	<sup>∞</sup> Nd	Pm	<sup>62</sup> Sm	63 Eu	Ğd	55 Tb	∞Dy	<sup>67</sup> Ho	<sup>68</sup> Er	۳Tm	<sup>70</sup> Yb	Lu	1
ACTI	NIDES	<sup>89</sup> Ac	În	Ра	92 U	<sup>93</sup> Np	Pu	Am	<sup>∞</sup> Cm	P7 Bk	<sup>98</sup> Cf	99 Es	Fm	Md	102 No	103 Lr	







INAF ISTITUTO NAZIONALE DI ASTROFISICA Osservatorio Astronomico d'Abruzzo



Without considering the various degree of ionization of each element!









## Theoretical approach



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

corrections









## Theoretical approach



General Relativistic Atomic Structure Package Based on

- 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).

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

corrections









## Theoretical approach



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- Electron configurations for atomic data
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- Breit and Quantum ElectroDynamics (QED) corrections

#### M. Bezmalinovich PhD Thesis

**Opacity estimation** 









## Theoretical approach



General Relativistic Atomic Structure Package Based on

D)

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.









# Plasmas for Astrophysics Nuclear Decays Observation and Radiation for Archaeometry PANDORA



#### INFN - Laboratori Nazionali del Sud (Catania)









## PANDORA



- 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;
- 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,  $\beta$ -decay measurements in plasmas (<sup>176</sup>Lu, <sup>134</sup>Cs, and <sup>94</sup>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.

![](_page_63_Picture_0.jpeg)

![](_page_63_Picture_2.jpeg)

![](_page_63_Picture_3.jpeg)

![](_page_63_Picture_4.jpeg)

## **PANDORA and Neutron Stars**

![](_page_63_Figure_6.jpeg)

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<sup>10</sup> - 10<sup>13</sup> cm<sup>-3</sup>  
□  $T_e$ : 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.

![](_page_64_Picture_0.jpeg)

![](_page_64_Picture_2.jpeg)

![](_page_64_Picture_3.jpeg)

![](_page_64_Picture_4.jpeg)

## **PANDORA and Neutron Stars**

![](_page_64_Figure_6.jpeg)

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<sup>10</sup> - 10<sup>13</sup> cm<sup>-3</sup> □  $T_e$ : few eV

er the conditions of early-stage kilonova emission,

gnal (Dive-kilonova emission) has its peak at optical due to the ejecta's light component featuring a low degree of

![](_page_65_Picture_0.jpeg)

![](_page_65_Picture_2.jpeg)

![](_page_65_Picture_3.jpeg)

![](_page_65_Picture_4.jpeg)

## **PANDORA and Neutron Stars**

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

![](_page_65_Figure_7.jpeg)

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.

![](_page_66_Picture_0.jpeg)

![](_page_66_Picture_2.jpeg)

![](_page_66_Picture_3.jpeg)

![](_page_66_Picture_4.jpeg)

## **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.

![](_page_66_Figure_7.jpeg)

## Opacity can differ of several orders of magnitudes:

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

Se-Sr-Zr-Nb exhibit larger mean opacity at the temperature condition of earlyepochs kilonova ( $<2.10^4$  K).

![](_page_67_Picture_0.jpeg)

![](_page_67_Picture_2.jpeg)

![](_page_67_Picture_3.jpeg)

![](_page_67_Picture_4.jpeg)

## **PANDORA and Neutron Stars**

![](_page_67_Figure_6.jpeg)

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.

![](_page_67_Figure_8.jpeg)

r [Bohr]

![](_page_68_Picture_0.jpeg)

![](_page_68_Picture_2.jpeg)

![](_page_68_Picture_3.jpeg)

![](_page_68_Picture_4.jpeg)

## **PANDORA and Neutron Stars**

of the ROYAL ASTRONOMICAL SOCIETY MNRAS 515, L89-L93 (2022) Advance Access publication 2022 July 29

https://doi.org/10.1093/mnrasl/slac0

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

Kenta Hotokezaka.<sup>1,2</sup>\* Masaomi Tanaka<sup>9,3,4</sup> Daiji Kato<sup>5,6</sup> and Gediminas Gaigalas<sup>7</sup> Research Center for the Early Universe, Graduate School of Science, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan <sup>2</sup>Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan <sup>3</sup>Astronomical Institute, Tohoku University, Sendai 980-8578, Japan <sup>4</sup>Division for the Establishment of Frontier Sciences, Organization for Advanced Studies, Tohoku University, Sendai 980-8577, Japan

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

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

Institute of Theoretical Physics and Astronomy, Vilnius University, Saulétekio Ave. 3, Vilnius, Lithuania

#### **M. Bezmalinovich** PhD Thesis

![](_page_68_Figure_14.jpeg)

al results, it is useful to eighted on abundances and T typical of blueium plasma as one of experiment.

Recall the state wavefunction  $\phi(\mathbf{x}) = \frac{1}{r}$ 

 $P(n\kappa; r)\chi_{\kappa m}(\theta, \varphi)$ iQ(n\kappa; r)\chi\_{-\kappa m}(\theta, \varphi)

Selenium electron configuration [Ar] 3d<sup>10</sup>4s<sup>2</sup>4p<sup>4</sup>

Se ground state

![](_page_69_Picture_0.jpeg)

![](_page_69_Picture_2.jpeg)

![](_page_69_Picture_3.jpeg)

![](_page_69_Picture_4.jpeg)

### Advertisement!!!

![](_page_69_Picture_6.jpeg)

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

### THAT'S ALL FALKS!!!

![](_page_70_Picture_1.jpeg)