

# An Application of Radiative Opacity to Gravitational Wave Spectroscopy

**Christopher Fontes**

Computational Physics Division  
Los Alamos National Laboratory

*ICTP-IAEA School on Atomic and Molecular  
Spectroscopy in Plasmas*

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# Overview

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- ~10% atomic physics theory and radiative opacity
- ~90% astrophysics: gravitational waves, neutron star mergers, and an application of radiative opacity

# We have entered the age of gravitational wave spectroscopy!

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PRL 116, 061102 (2016)

 Selected for a Viewpoint in *Physics*  
PHYSICAL REVIEW LETTERS

week ending  
12 FEBRUARY 2016



## Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*\*

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of  $1.0 \times 10^{-21}$ . It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a

# Two years later, a stunning observation: gravitational + electromagnetic waves (GW+EM)!

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20

<https://doi.org/10.3847/2041-8213/aa91c9>

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**OPEN ACCESS**



## Multi-messenger Observations of a Binary Neutron Star Merger

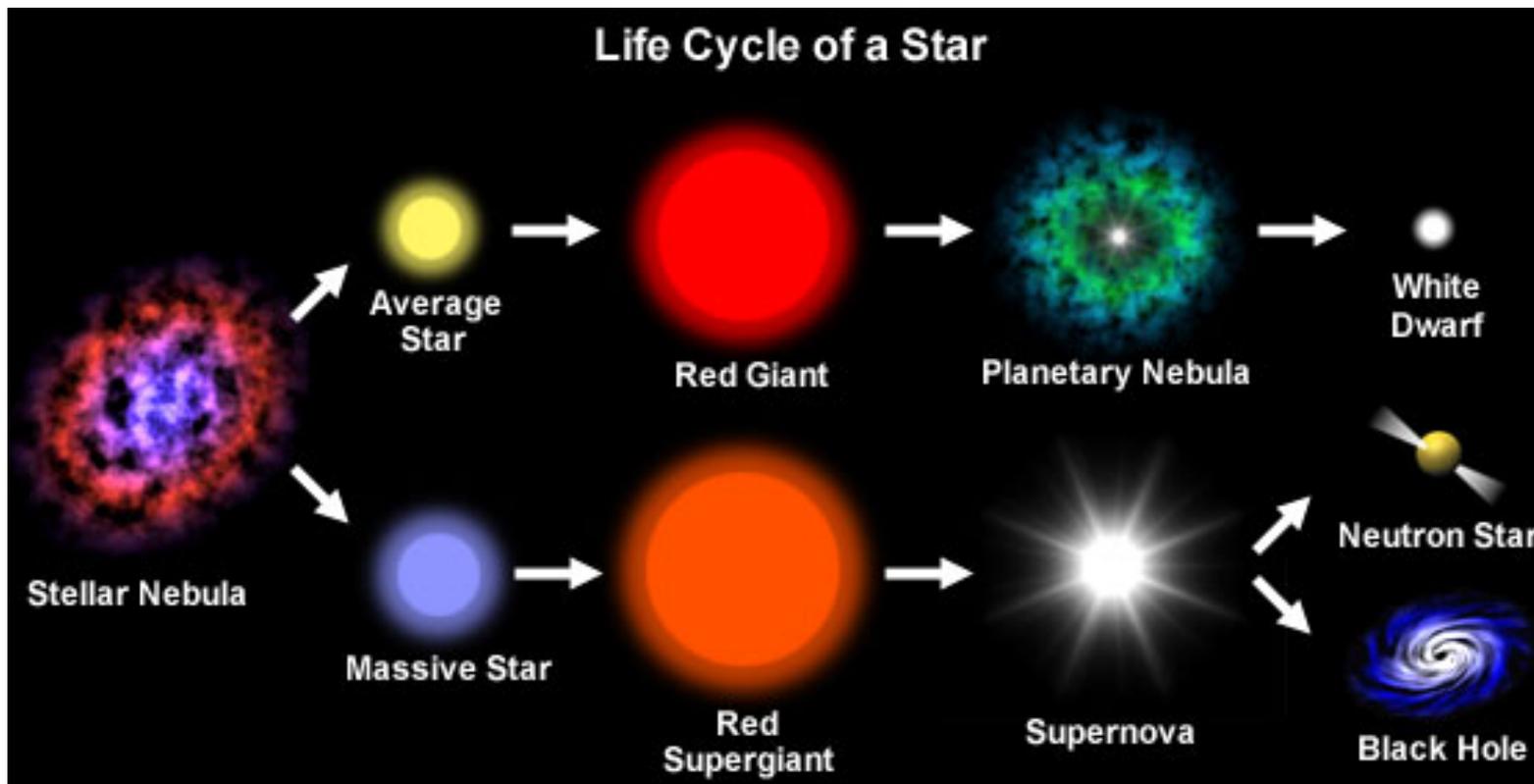
LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc

### Abstract

On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of  $\sim 1.7$  s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky

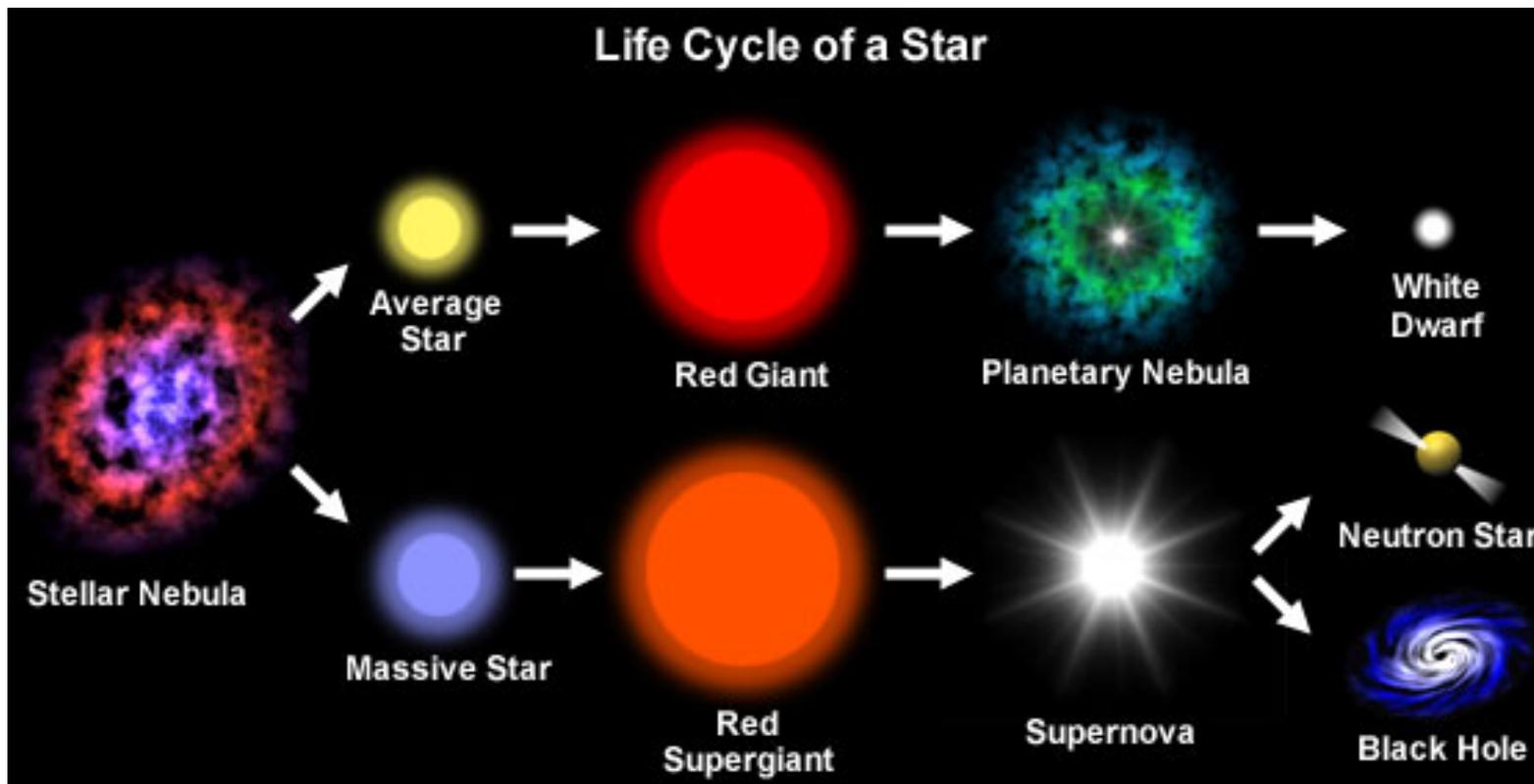
These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of  $r$ -process nuclei synthesized in the ejecta.

# Stellar evolution chart (simplified)



First gravitational wave observation (Sept, 2015)

# Stellar evolution chart (simplified)



GW170817

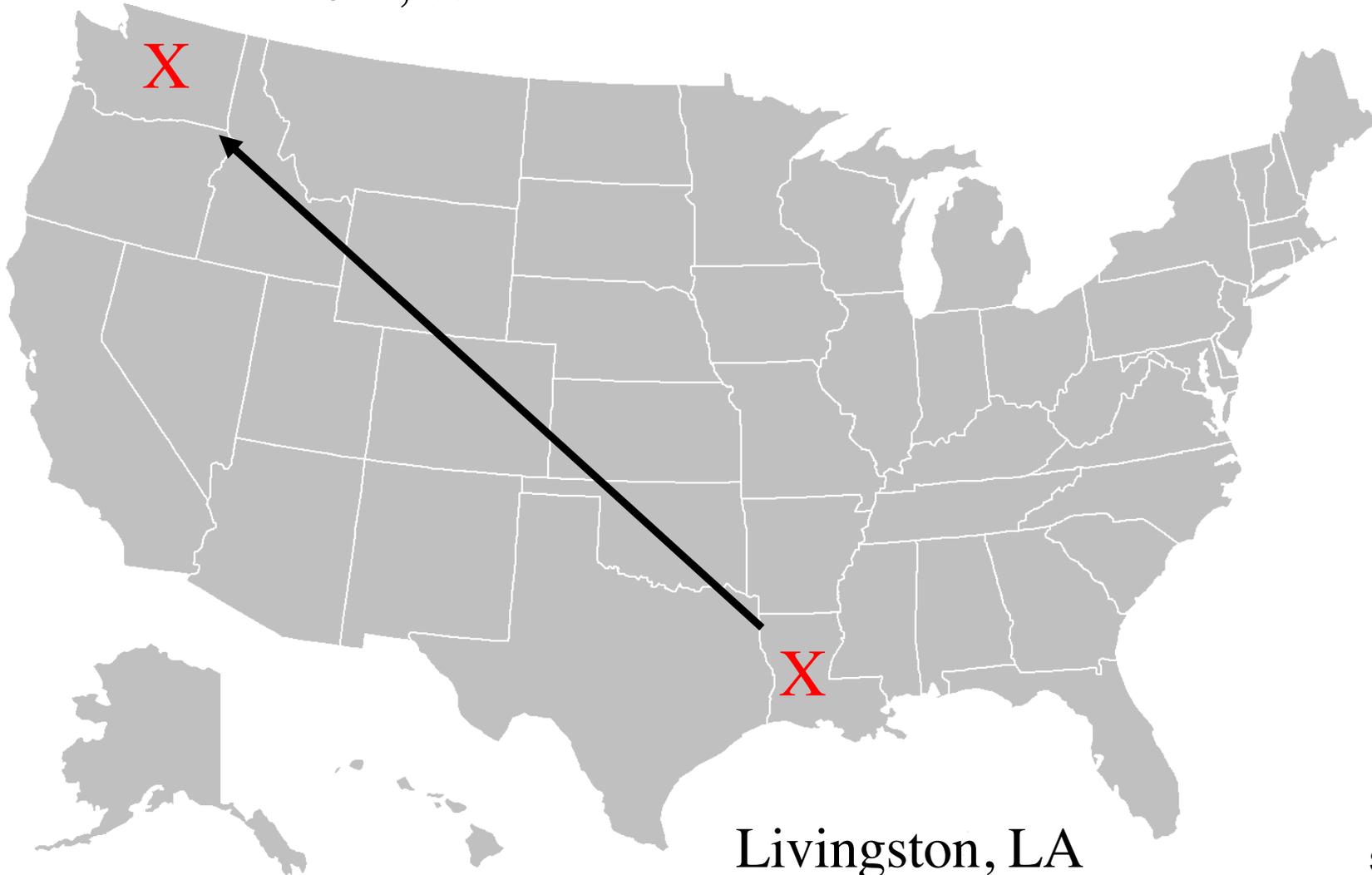
The focus of this talk.  
Observation:  
August, 2017

First gravitational wave observation  
(Sept, 2015)

# First GW LIGO detection (2015) occurred in LA and WA, 0.7 milliseconds apart

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Hanford, WA



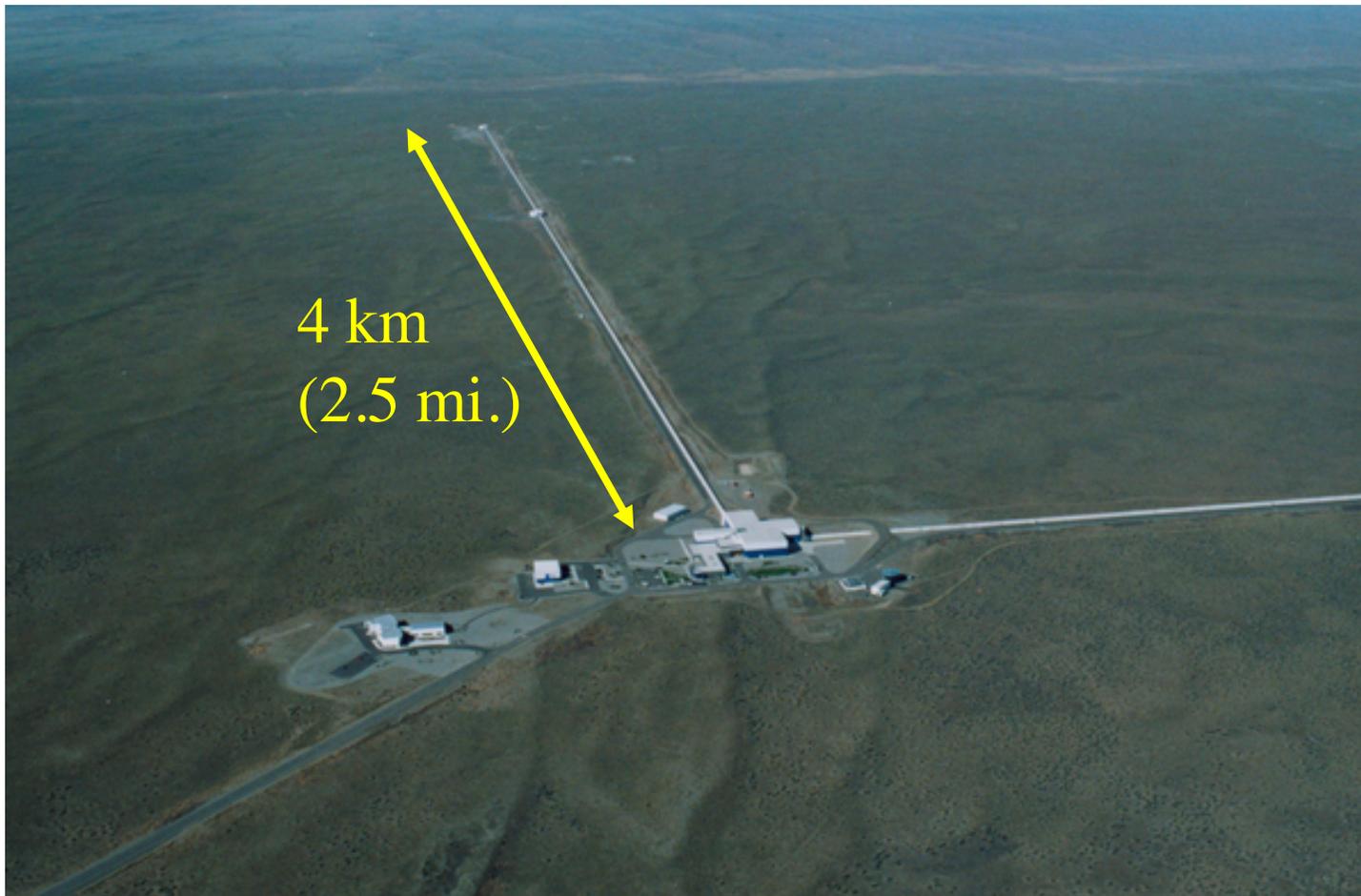
# The Hanford, WA detector site

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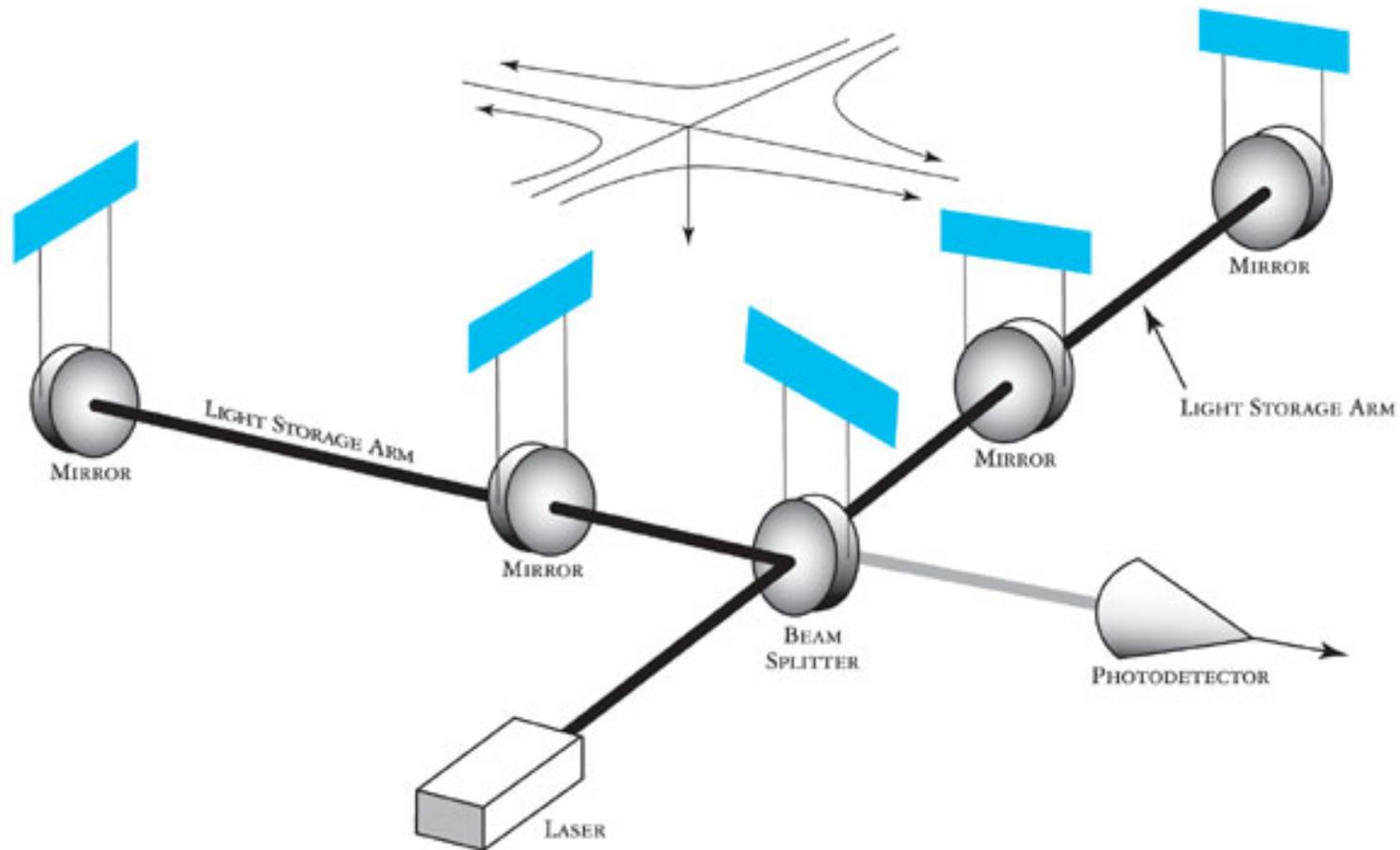


# The Hanford, WA detector site

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# Diagram of LIGO detector



# Gravitational wave spectrum

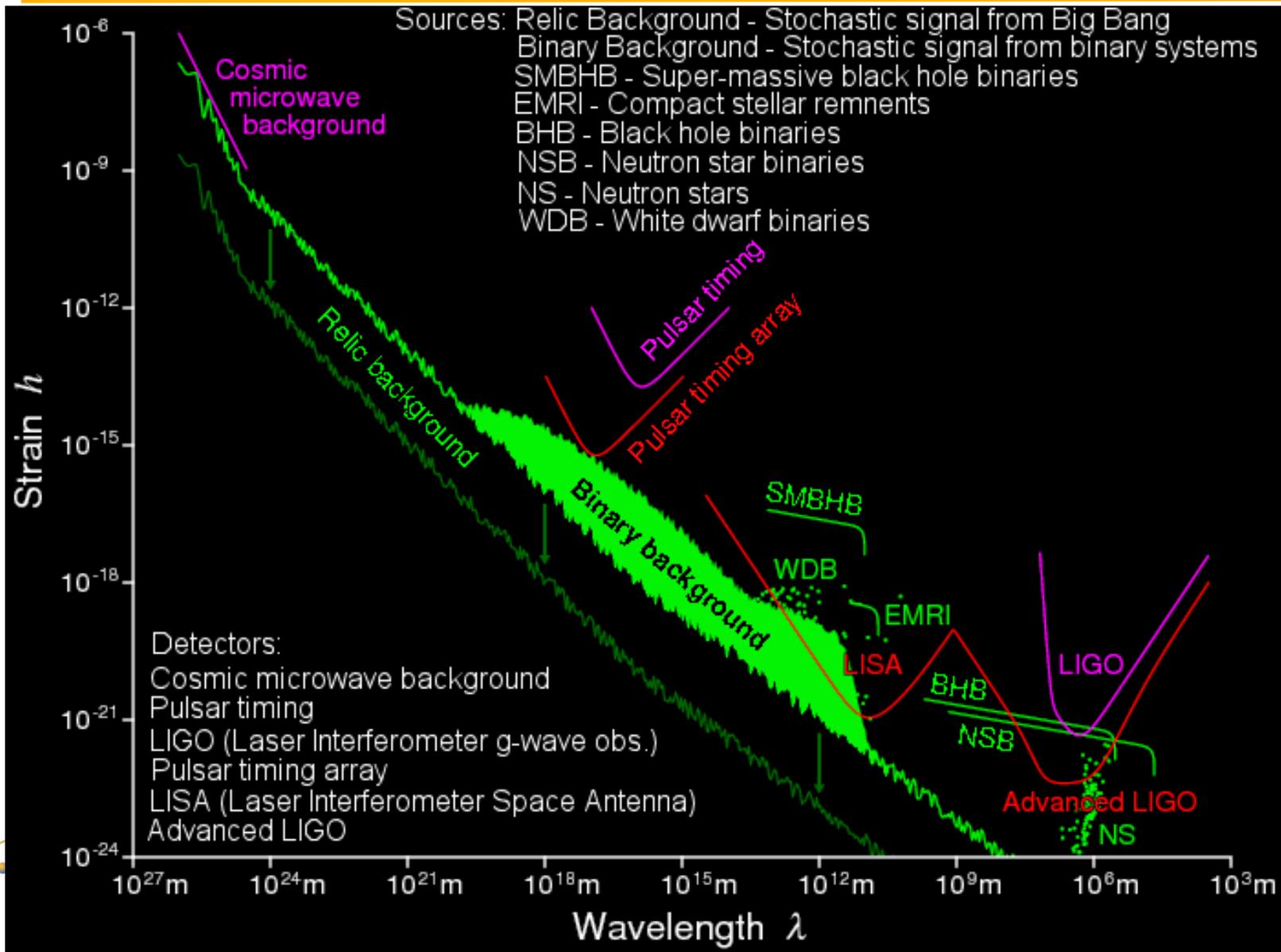


Image:  
T. Creighton

# Gravitational wave spectrum

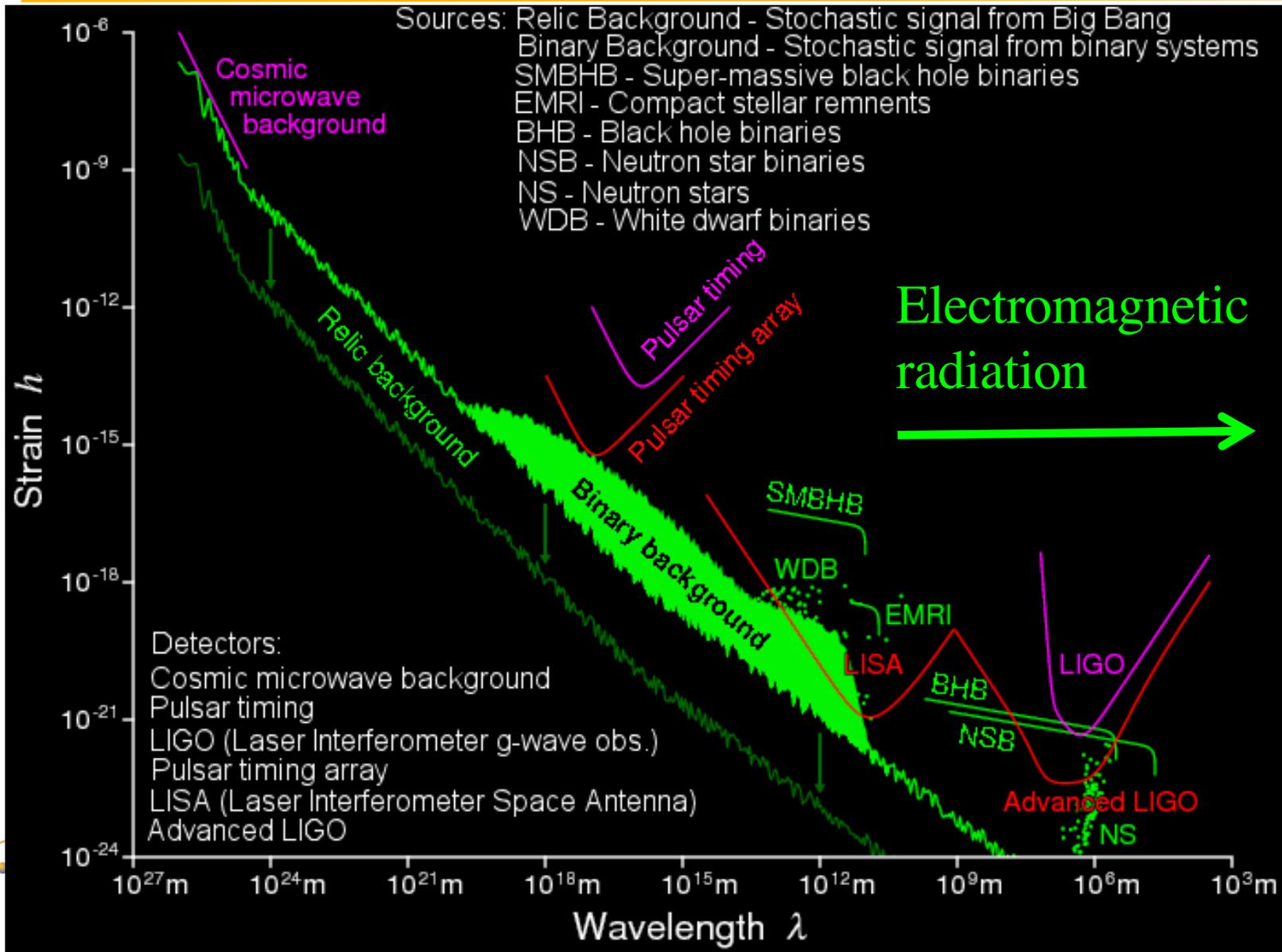
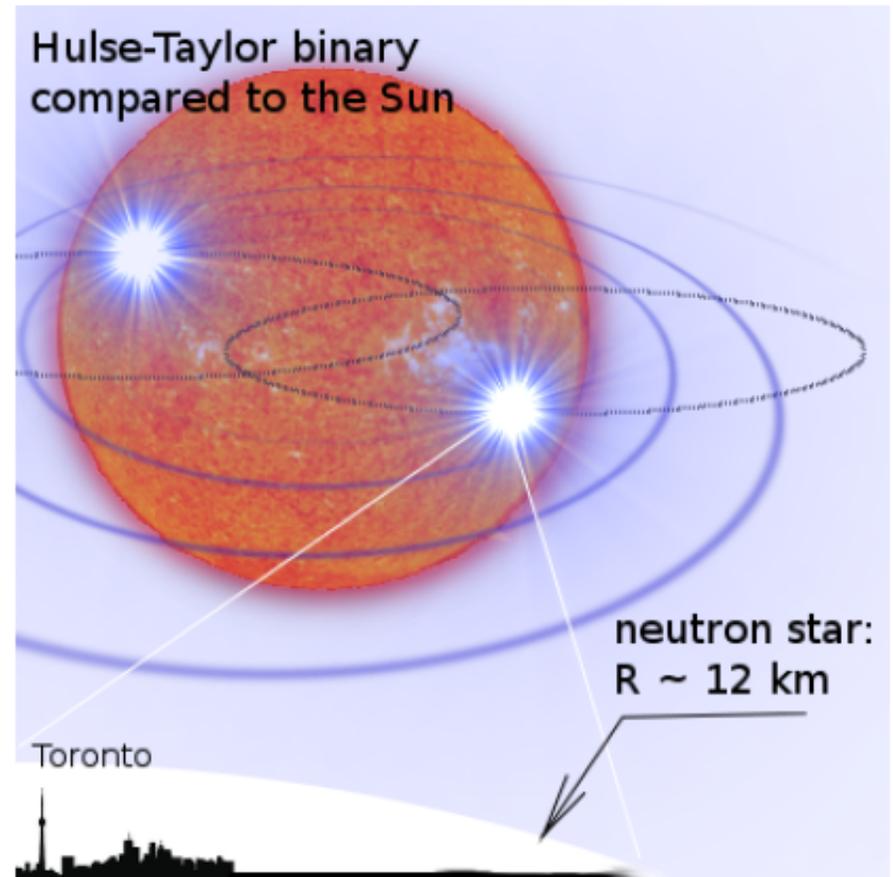


Image:  
T. Creighton

# A brief history of gravitational waves (GWs)

- 1916: Einstein predicted existence of GWs based on general relativity
- 1974: Russell Hulse & Joseph Taylor provided indirect evidence of GWs through observation of first pulsar binary
- 1974: Lattimer & Schramm proposed that such mergers could produce r-process elements in the Galaxy
- 1993: Nobel Prize awarded to Hulse & Taylor



*Image: Oleg Korobkin*

# A brief history of GWs (continued...)

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- 2015-2017: LIGO direct observations of GWs (GW150914, GW151226, GW170104, GW170814) arising from binary BH mergers
- August 17, 2017: LIGO direct observation of GWs from neutron star merger with electromagnetic (EM) counterpart: GW170817 (gamma rays through radio frequencies!)
- October 3, 2017: Nobel prize to be awarded to Weiss, Barish & Thorne for first direct GW observation
- October 16, 2017: Worldwide press release of first GW+EM observation (Nature, Science, ApJ Letters...)



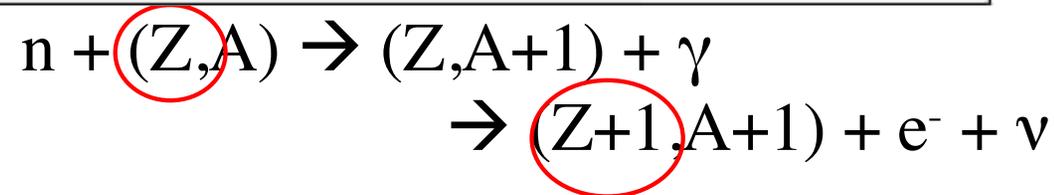
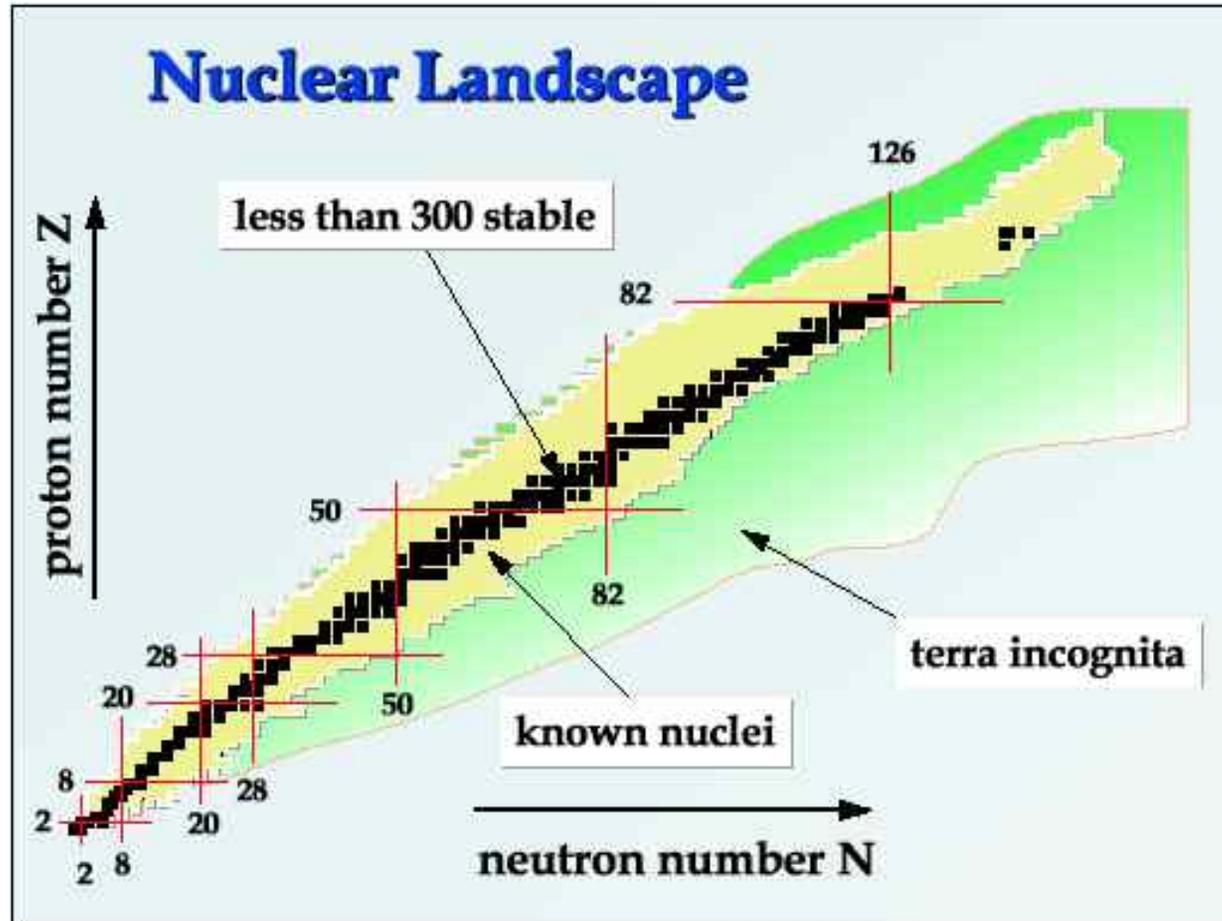
*Image: Dana Berry, SkyWorks Digital, Inc.*

# Why study neutron star mergers (NSMs)?

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- NSMs are suspected to produce short ( $< 2$  seconds) gamma ray bursts (GRBs) [Paczynski (1991)]
- Possibility to observe both gravitational waves (GWs) and electromagnetic (EM) signals from a single event
- NSMs are hypothesized to be the site of the r-process, i.e. the location where heavy nuclei are created from the capture of rapid neutrons (as opposed to s-process for the capture of slow neutrons)

# The r-process: nucleosynthesis via the capture of rapid neutrons



# Another reason to study neutron star mergers

- We can not yet predict the abundance of neutron-rich heavy elements ( $A = N_{\text{protons}} + N_{\text{neutrons}} \geq 130$ ) that is typically observed in the universe (long-standing mystery)

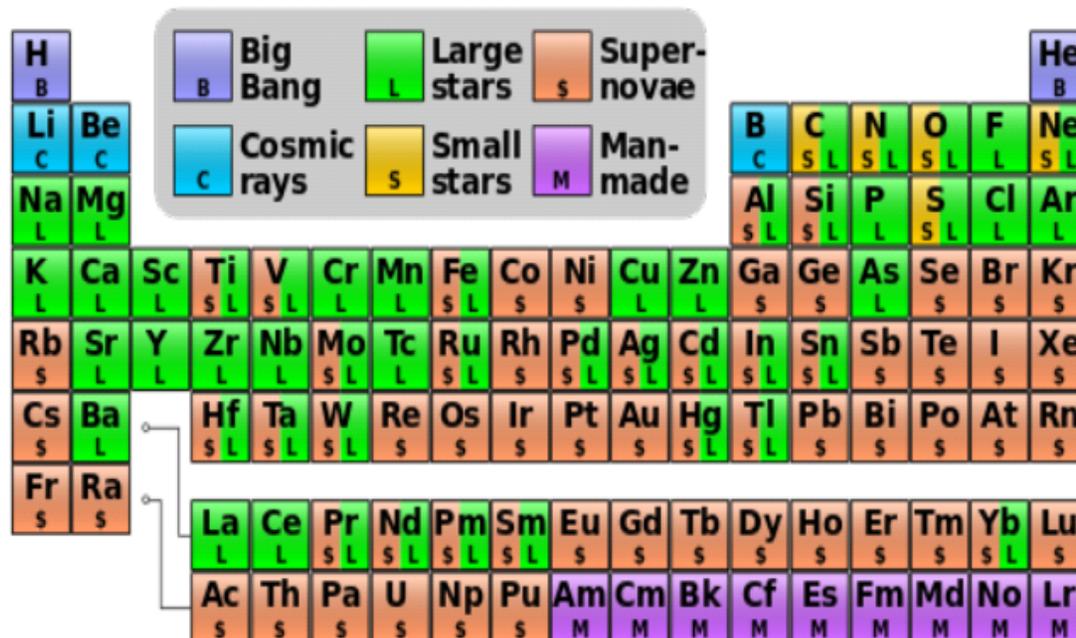
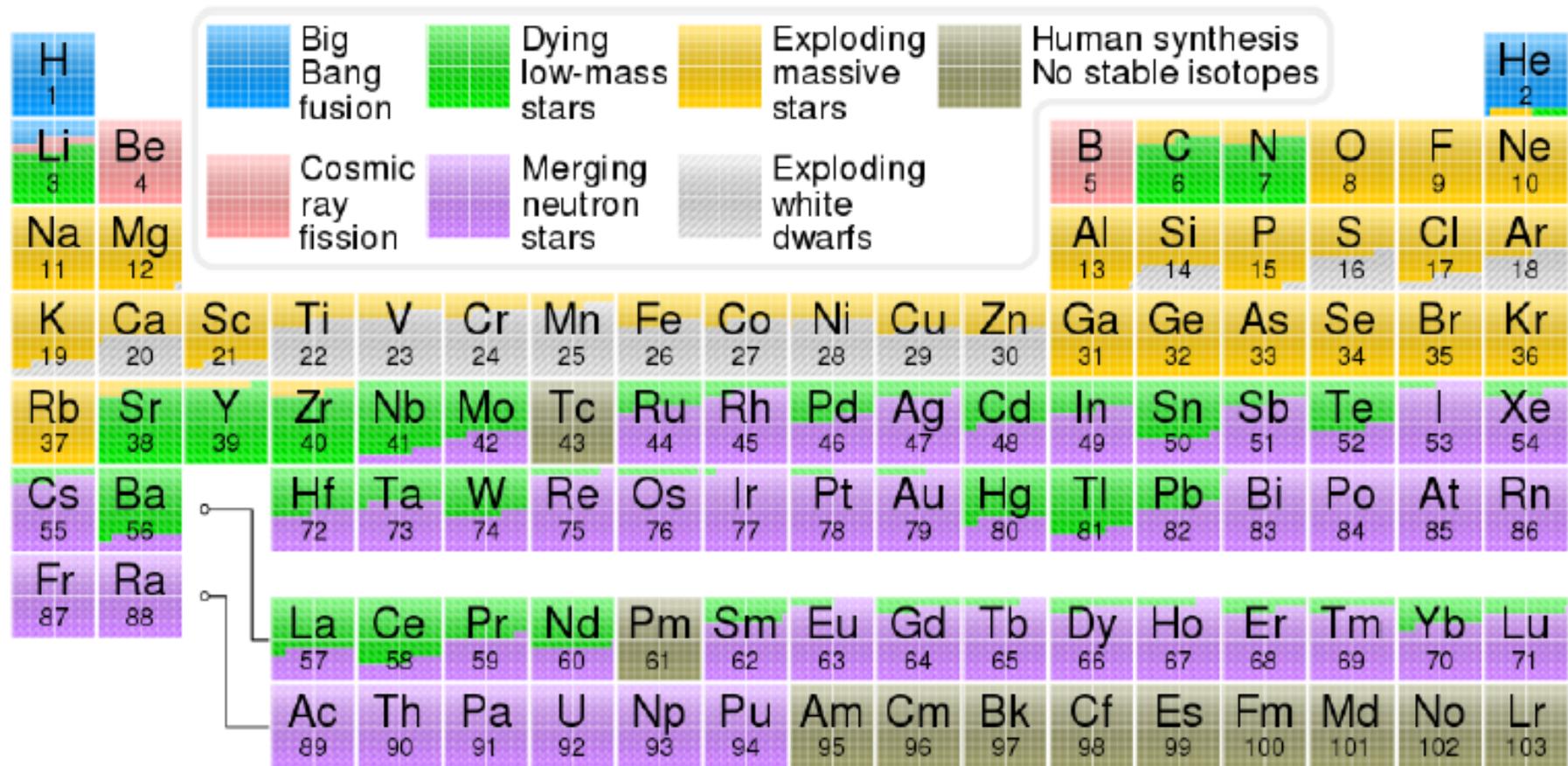


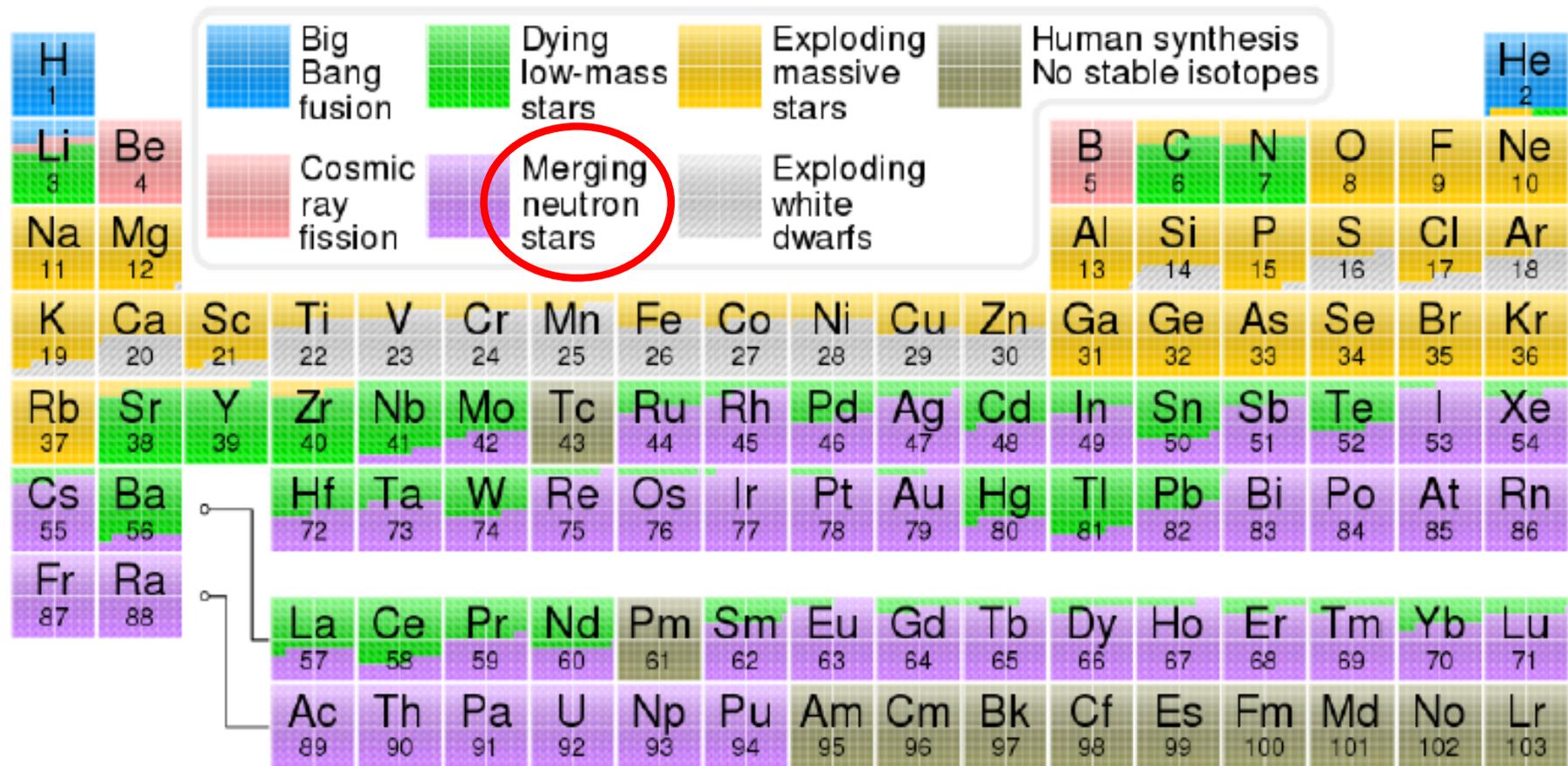
Image: Amanda Bayless



# Origin of elements in the universe (What is the site of the r-process?)



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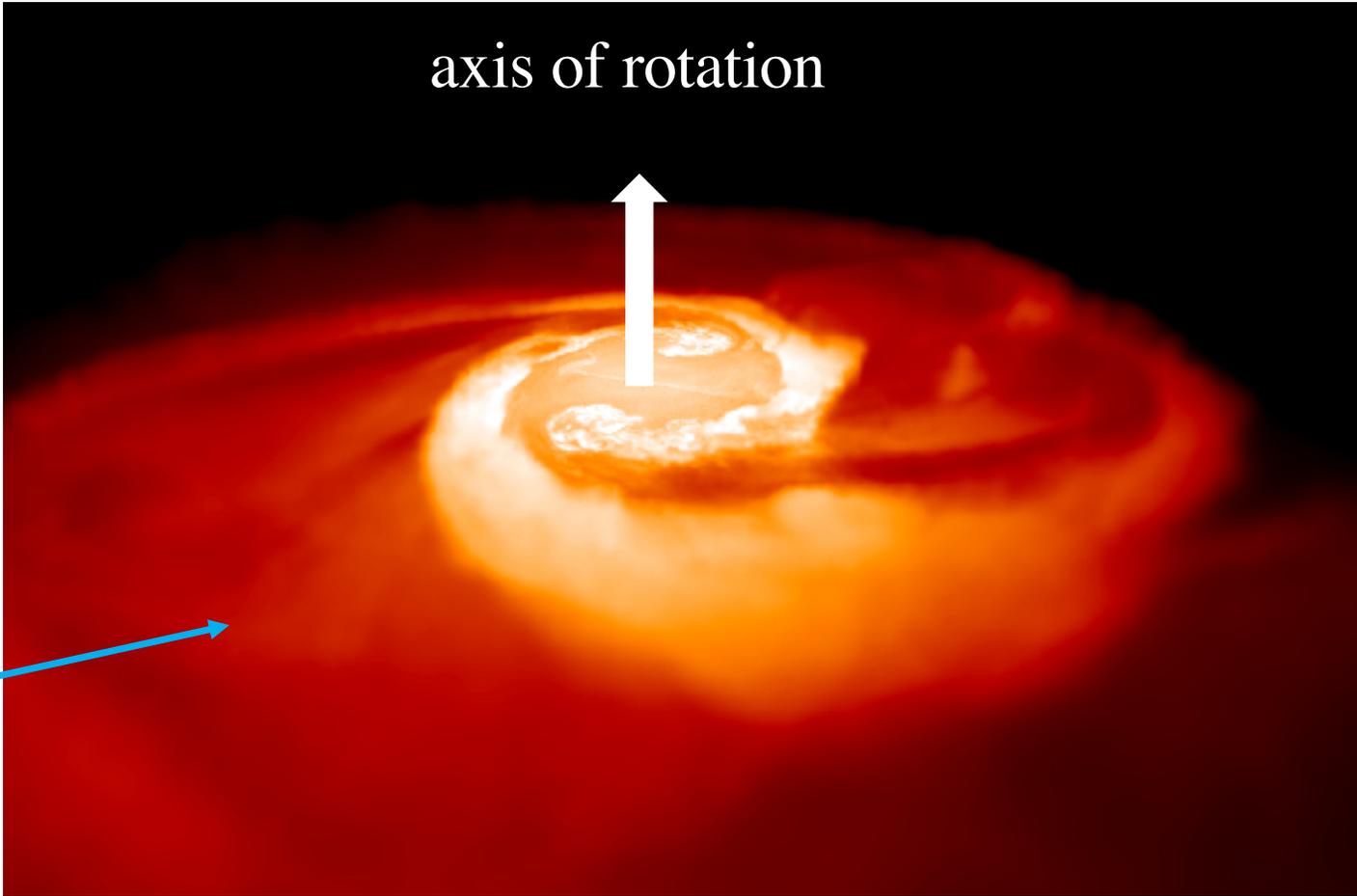


# Some very basic characteristics of neutron star mergers...

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# A double neutron star

$$(\Delta v/c) \sim 0.01$$



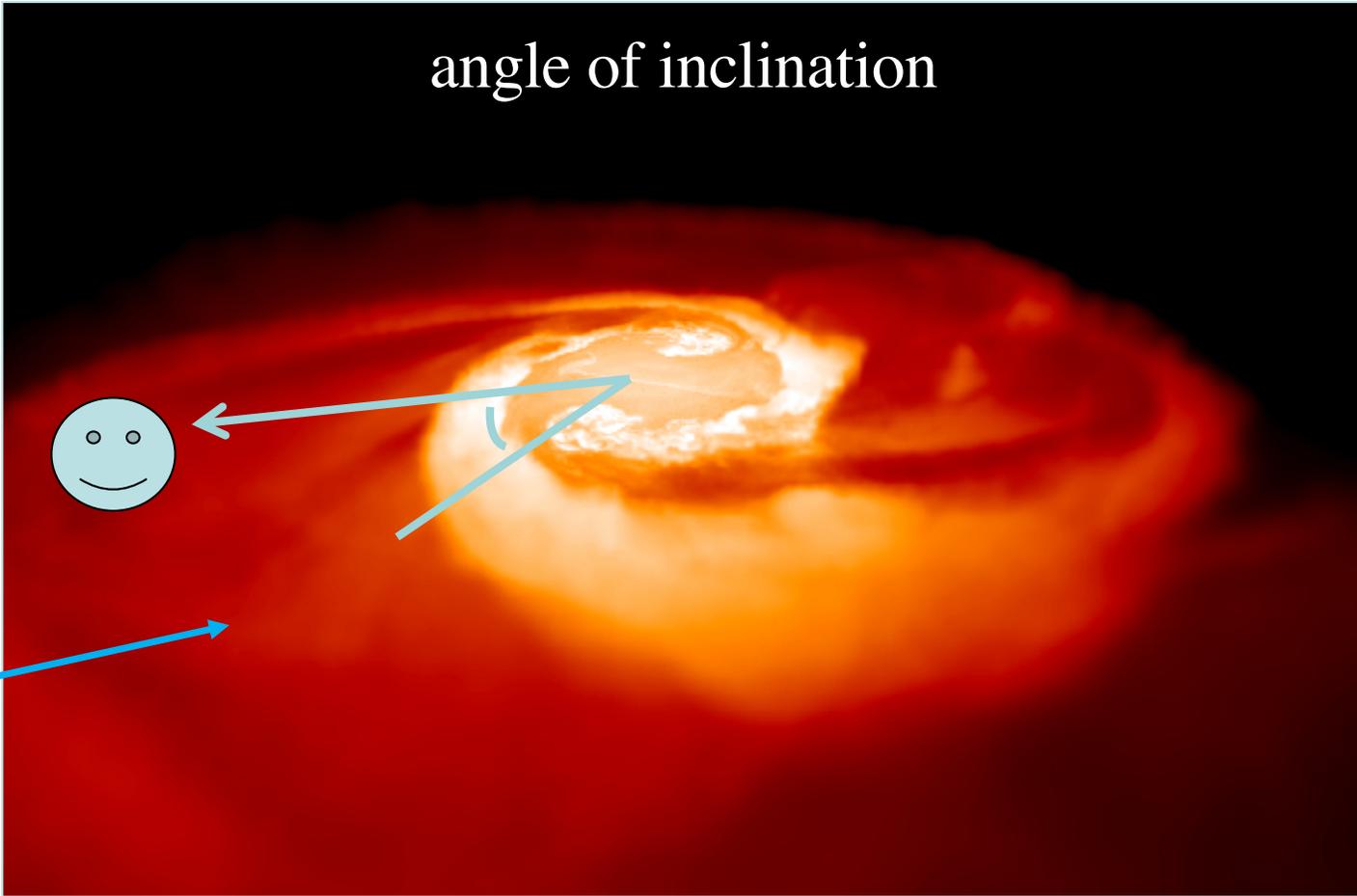
Ejecta composed of heavy elements: lanthanides and actinides!

Massive Doppler shifts!

*courtesy of Stephan Rosswog*

# A double neutron star

$$(\Delta v/c) \sim 0.01$$



Ejecta composed of heavy elements: lanthanides and actinides!

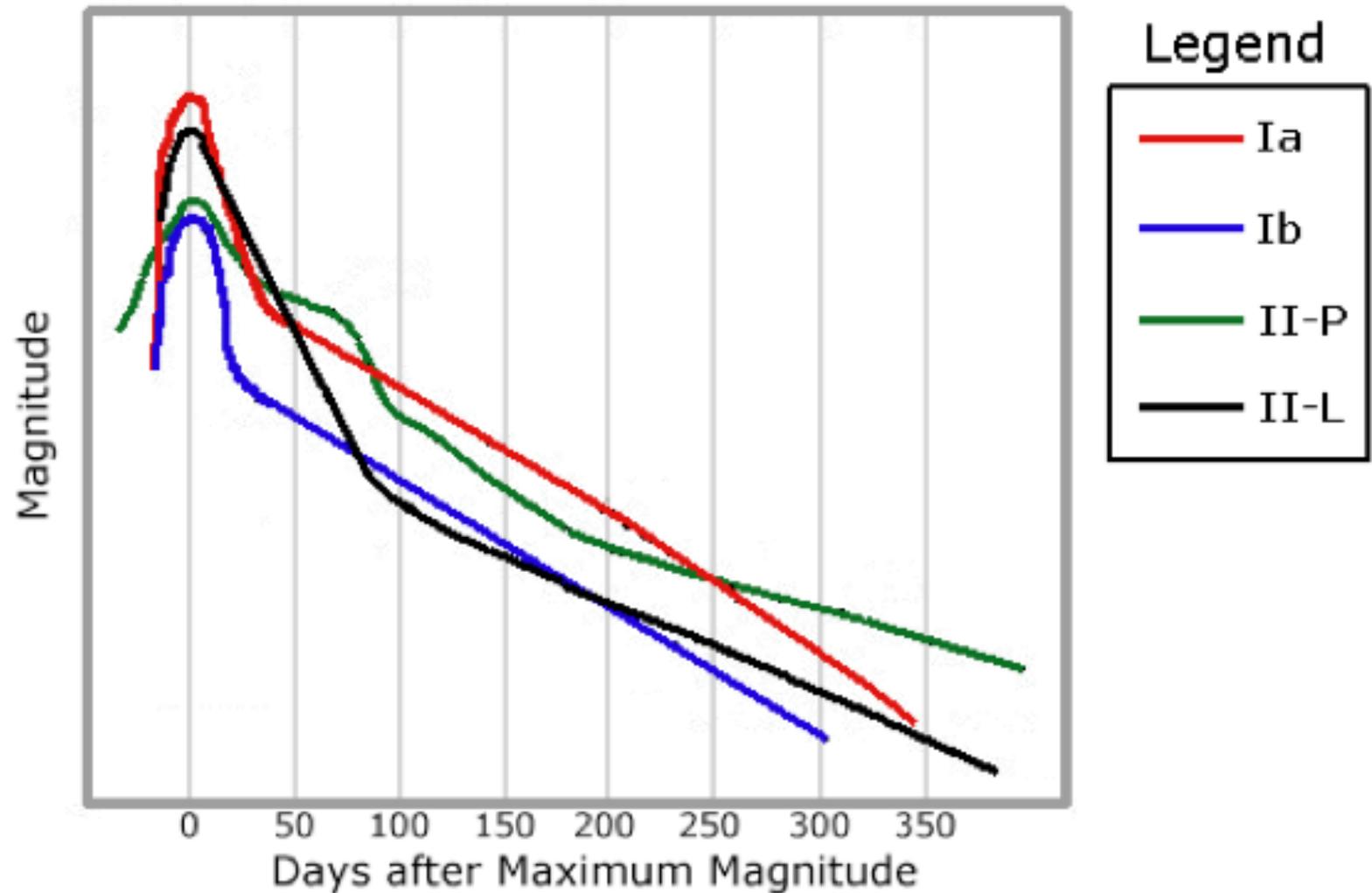
angle of inclination

Massive Doppler shifts!

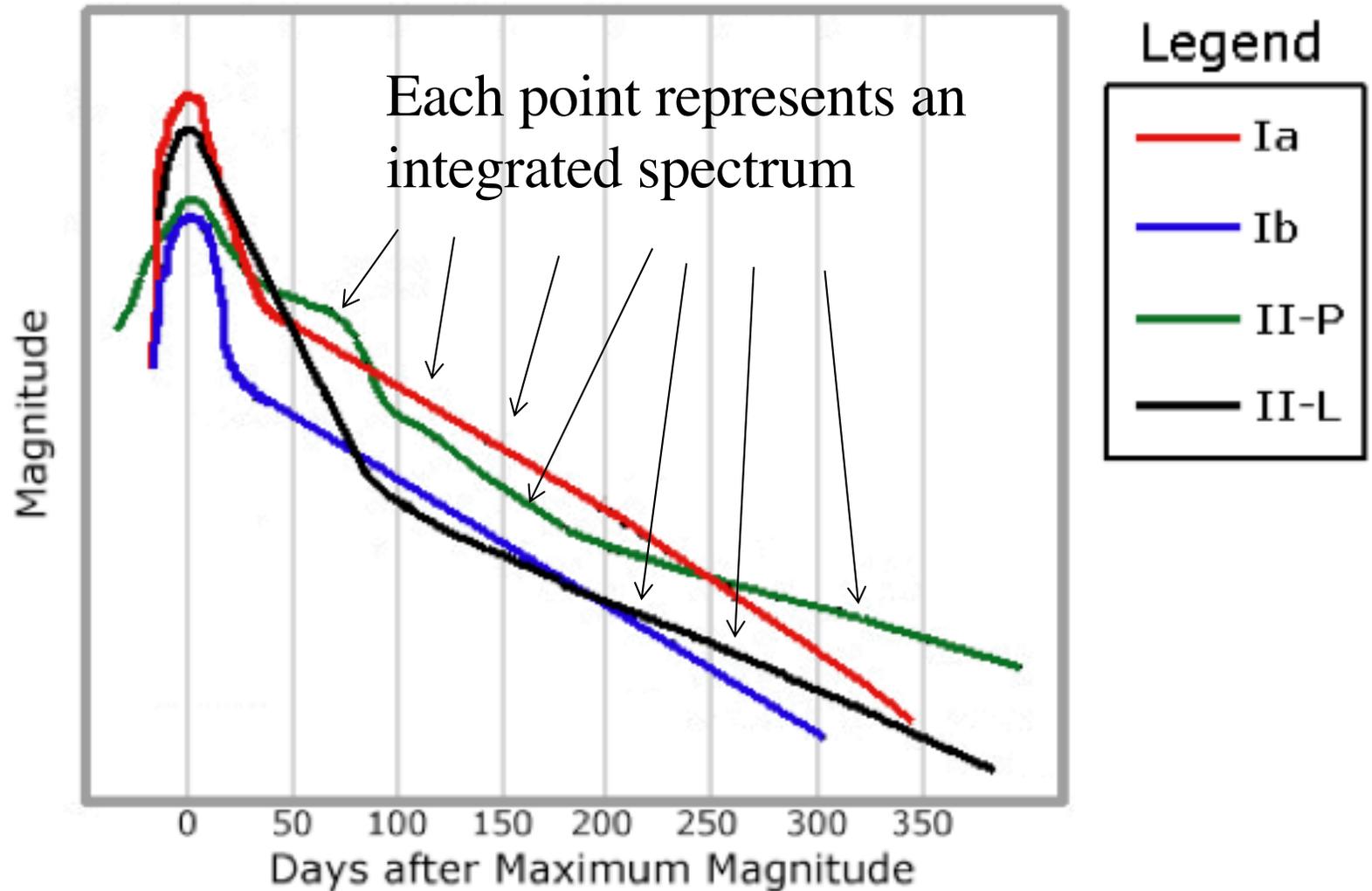
*courtesy of Stephan Rosswog*

# What sort of EM signals are expected from NSMs? First consider supernova light-curve examples.

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# Supernova light-curve examples



# Predicted EM signals from a binary neutron star merger (pre-GW170817 observation)

- Short gamma ray burst (GRB) lasting  $< 2$  seconds
- X-rays produced during the afterglow phase
- UV-Optical-IR emission produced from the “macronova” or “kilonova” involving dynamical ejecta composed of broad range of elements; emission powered by radioactive decay of r-process elements, depends on the opacity of relevant elements

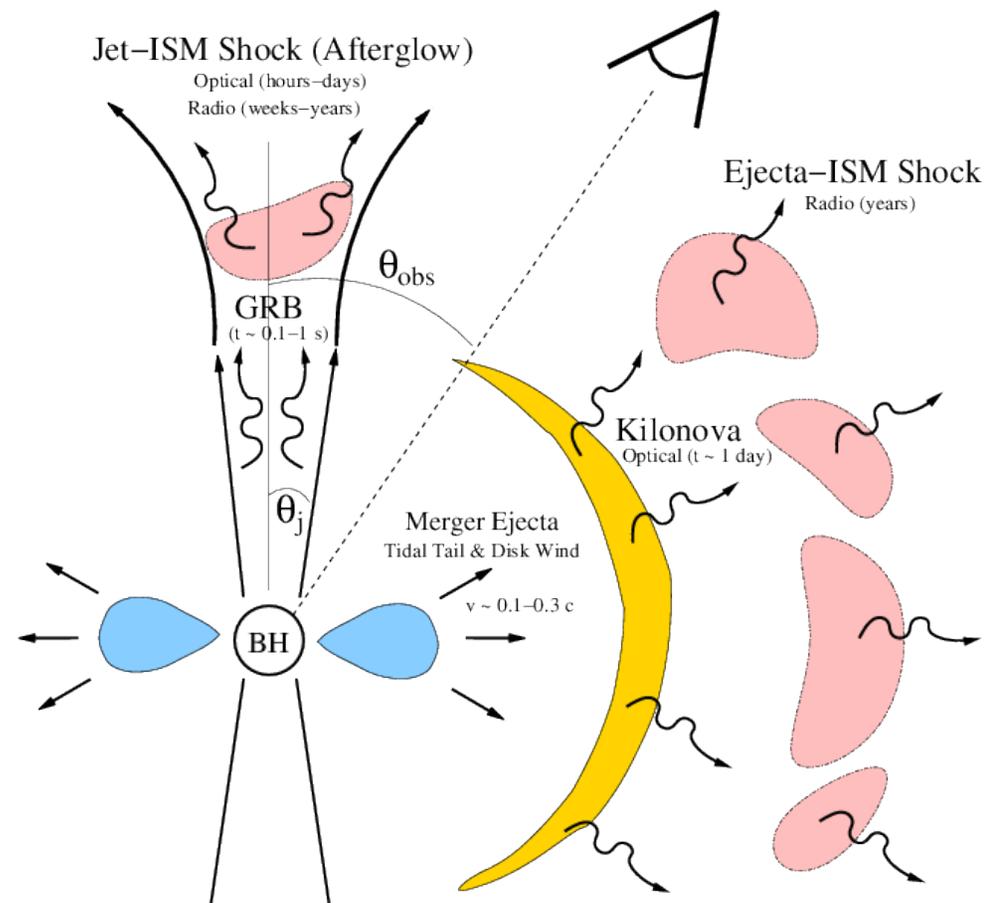


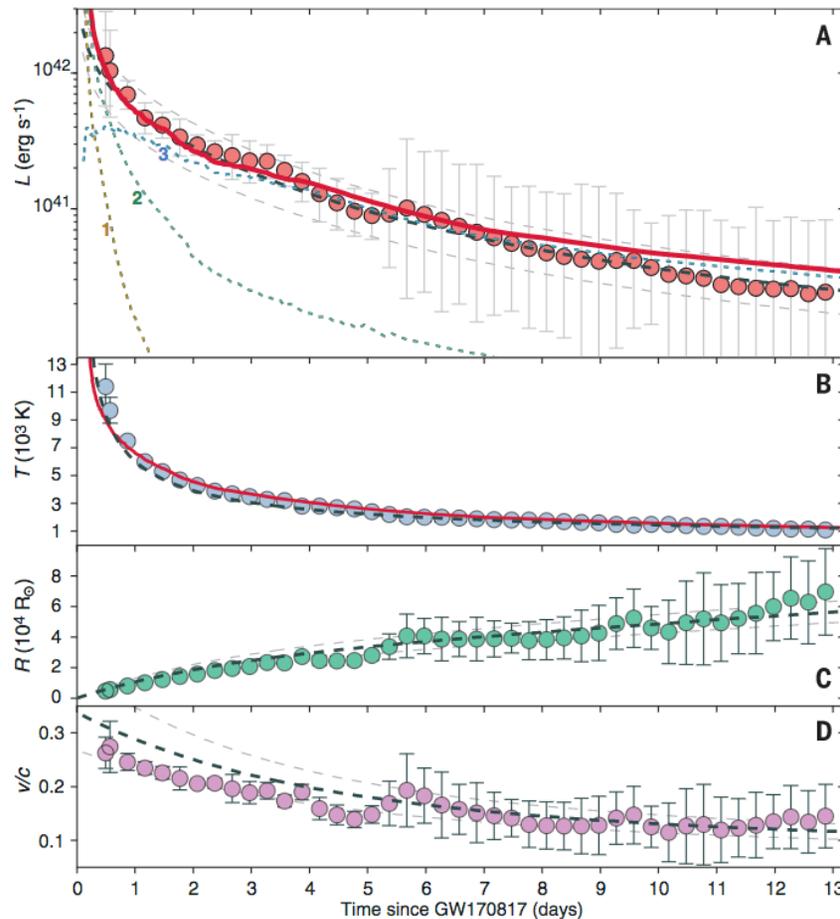
Image: B. Metzger and E. Berger

# NSM light-curve (“macronova” or “kilonova”) predictions

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- Typical modeling predicted a light curve similar in shape to that observed for supernovae, but significantly reduced in peak brightness (1/10 – 1/100 compared to a typical supernova or ~1,000 times brighter than a classical nova)
- Light will be emitted predominantly in the optical-IR range
- We now have *one* observation of a NSM light curve and associated spectrum... (easy to fit in various ways, not yet much opportunity for spectroscopy)

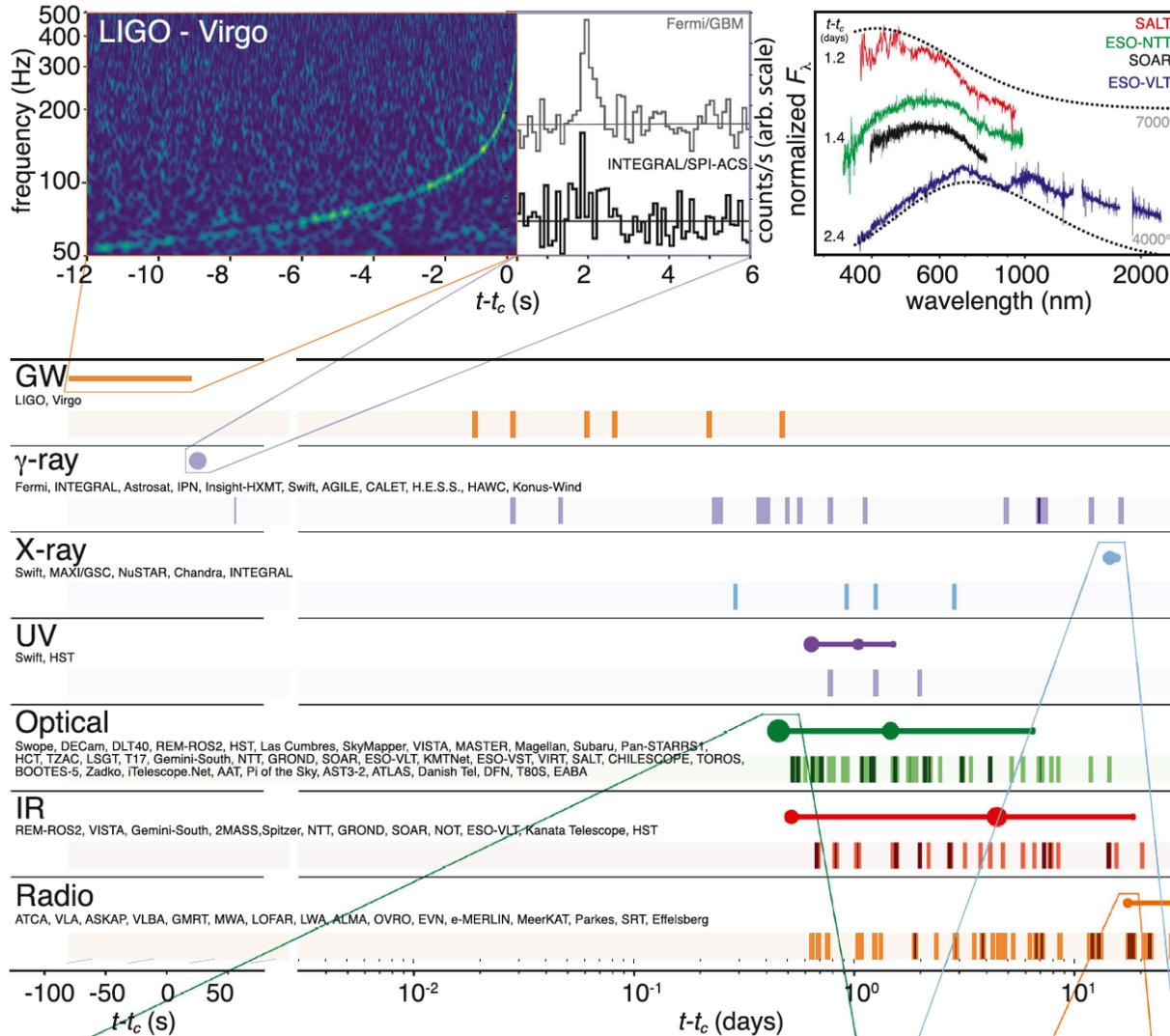
# Light curve for GW170817 displays surprising monotonic decrease with time. Why?



Light curve  
from GW170817

# First GW+EM multi-messenger observation

Abbott et al, ApJL (2017): “Multi-messenger Observations of a Binary Star Merger”



# Post-GW170817 interpretation of NSM observation

- Short (weak) GRB consistent with  $\sim 30^\circ$  viewing angle
- X-ray and radio afterglow delayed in time due to off-axis observation
- Both a blue (lanthanide-free) and red component kilonova resulting from dynamical ejecta and ejecta winds

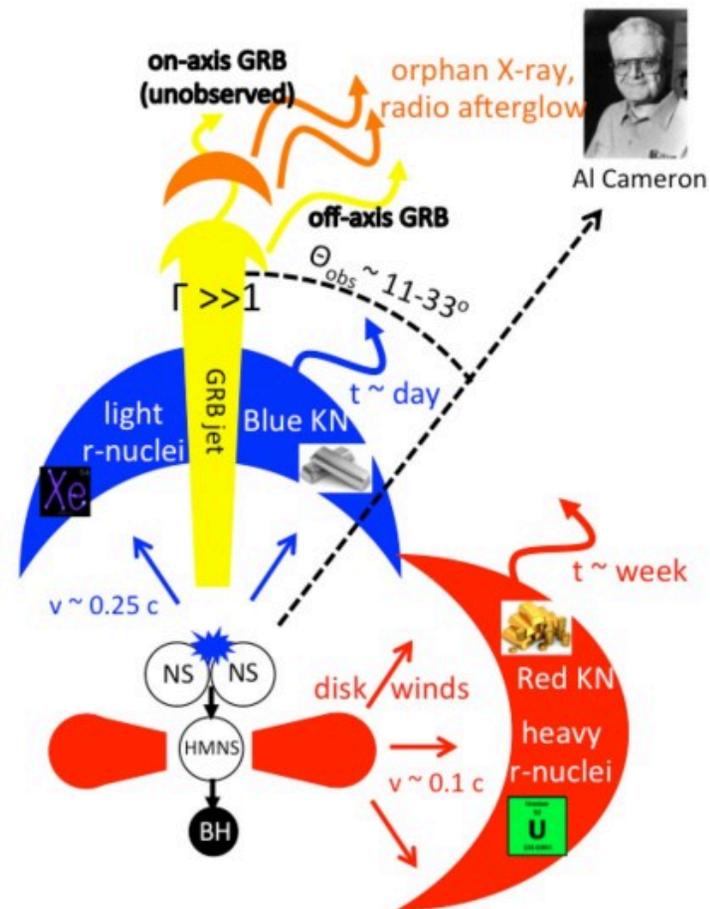
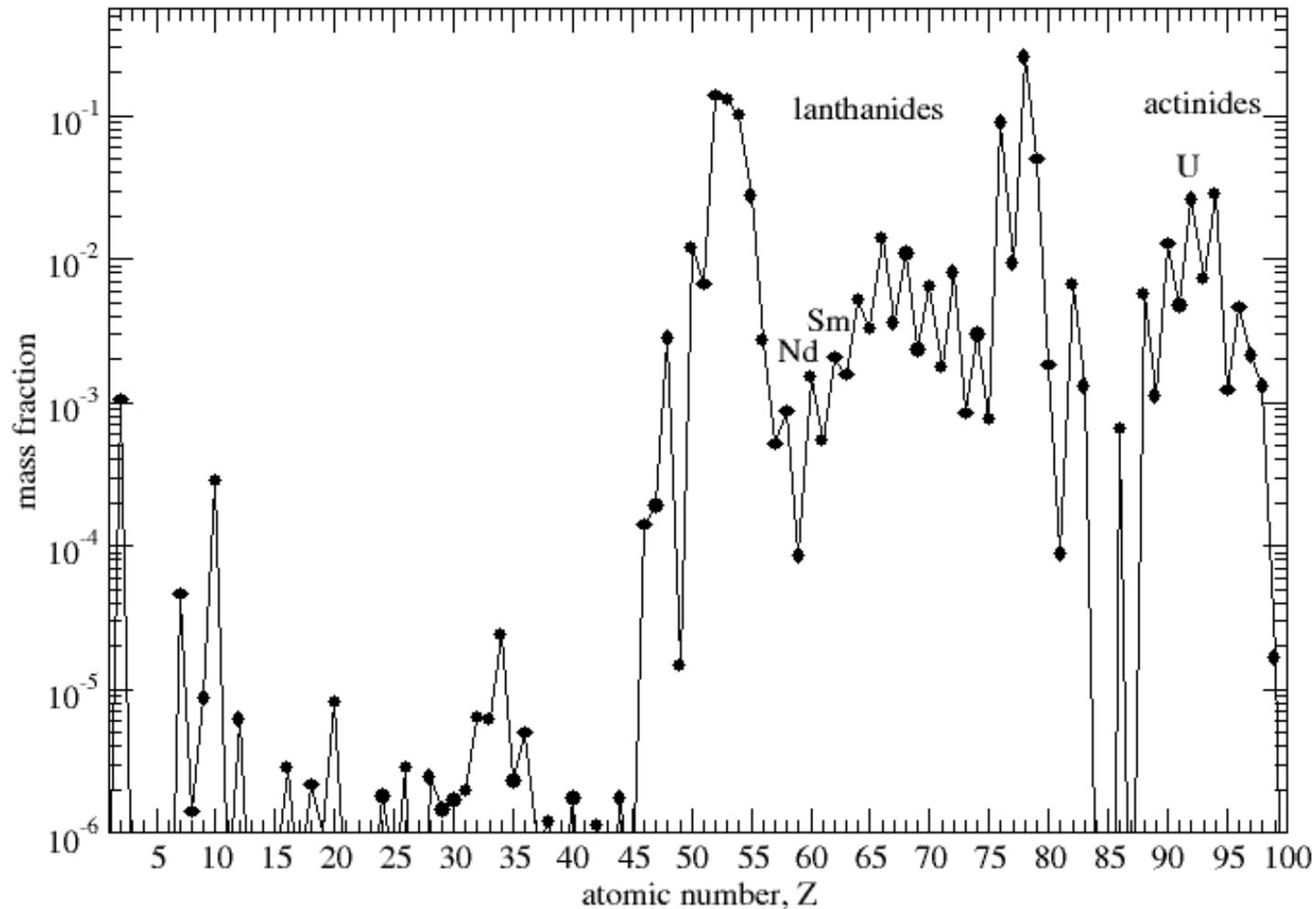


Image: B. Metzger

# Predicted elemental abundances in the ejecta of a neutron star merger (NSM)





# The LANL Suite of Atomic Modeling Codes

[Overview: Fontes et al, JPB 48, 144014 (2015)]

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Atomic Physics Codes → Atomic Models → **ATOMIC**

CATS: Cowan Code

RATS: relativistic

ACE: e<sup>-</sup> excitation

GIPPER: ionization

<http://aphysics2.lanl.gov/tempweb>

fine-structure  
config-average  
UTAs  
MUTAs  
energy levels  
gf-values  
e<sup>-</sup> excitation  
e<sup>-</sup> ionization  
photoionization  
autoionization

LTE or NLTE  
atomic level  
populations  
spectral modeling  
emission  
absorption  
transmission  
power loss

# Conditions for neutron star mergers

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- Initial conditions:  $T \approx 1 \text{ MeV}$ ,  $\rho \approx 10^{14} \text{ g/cm}^3$
- Light curve approaching peak brightness:  $T \approx 1 \text{ eV}$ ,  
 $\rho \approx 10^{-20} - 10^{-10} \text{ g/cm}^3$ ; (if  $\langle Z \rangle \approx 1$ , then  $N_e \approx 10 - 10^{11} \text{ el./cm}^3$ )
- The presence of heavy elements at such cold temperatures requires the calculation of near-neutral ions with many ( $> 60$ ) bound electrons. (Very complicated and difficult to calculate accurately!)
- We calculate radiative opacities for NSM elements under the assumption of local thermodynamic equilibrium (LTE)

# Consider the LTE opacity of cold samarium (Z=62) as an example (Sm<sup>0+</sup> - Sm<sup>3+</sup>)

**PERIODIC TABLE**  
**Atomic Properties of the Elements**

NIST  
National Institute of Standards and Technology  
U.S. Department of Commerce

**Frequently used fundamental physical constants**  
For the most accurate values of these and other constants, visit [physics.nist.gov/constants](http://physics.nist.gov/constants)  
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of <sup>133</sup>Cs

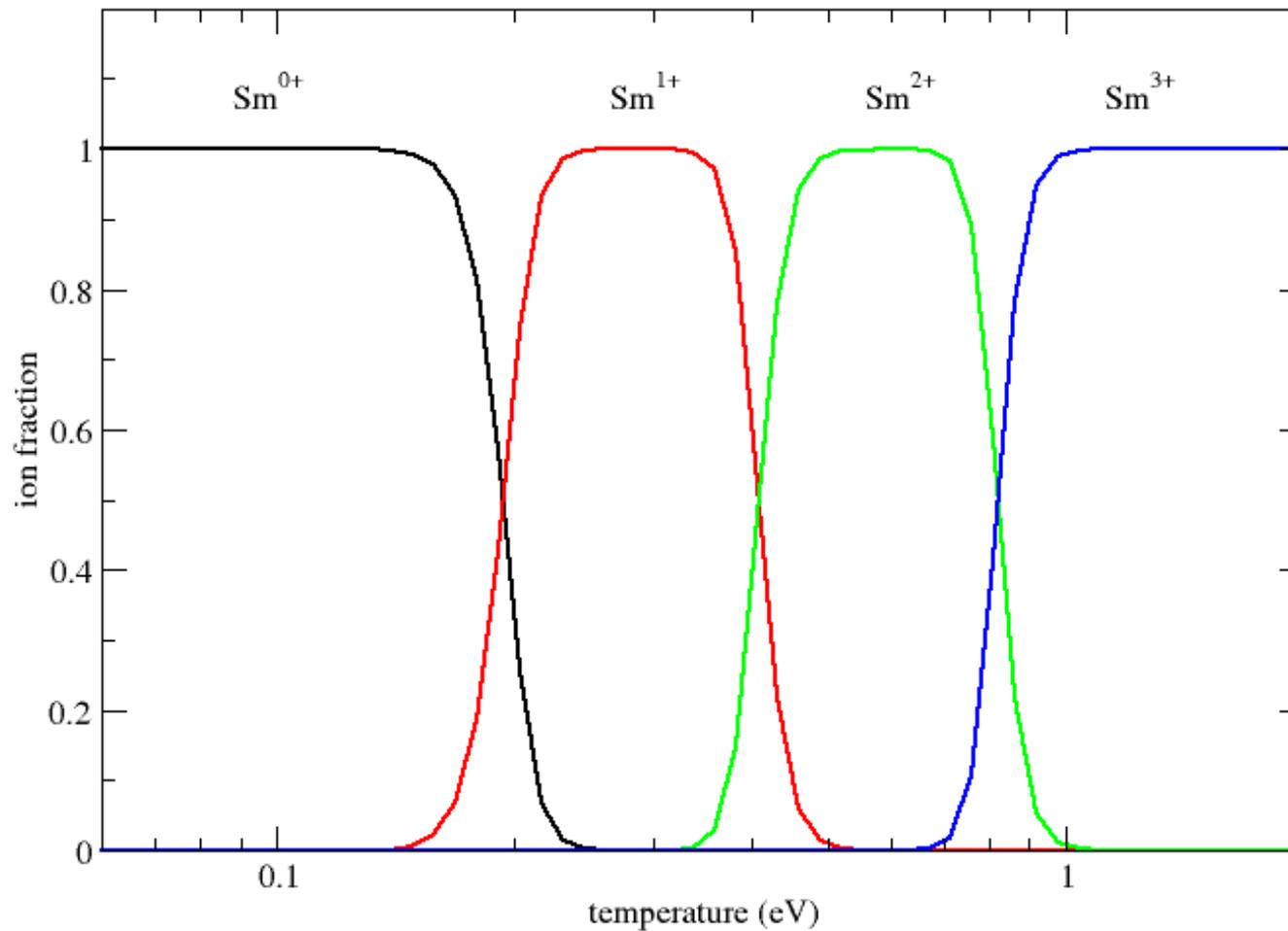
speed of light in vacuum  $c$  299 792 458 m s<sup>-1</sup> (exact)  
Planck constant  $h$  6.6261 x 10<sup>-34</sup> J s ( $h = h/2\pi$ )  
elementary charge  $e$  1.6022 x 10<sup>-19</sup> C  
electron mass  $m_e$  9.1094 x 10<sup>-31</sup> kg  
 $m_e c^2$  0.5110 MeV  
proton mass  $m_p$  1.6726 x 10<sup>-27</sup> kg  
fine-structure constant  $\alpha$  1/137.036  
Rydberg constant  $R_\infty$  10 973 732 m<sup>-1</sup>  
 $R_\infty c$  3,289 842 x 10<sup>15</sup> Hz  
 $R_\infty hc$  13.6057 eV  
 $k$  1.3807 x 10<sup>-23</sup> J K<sup>-1</sup>

	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA												
5	<b>B</b> Boron 10,811 1s <sup>2</sup> 2s <sup>2</sup> 2p	<b>C</b> Carbon 12,0107 1s <sup>2</sup> 2s <sup>2</sup> 2p	<b>N</b> Nitrogen 14,0067 1s <sup>2</sup> 2s <sup>2</sup> 2p	<b>O</b> Oxygen 15,9994 1s <sup>2</sup> 2s <sup>2</sup> 2p	<b>F</b> Fluorine 18,9984032 1s <sup>2</sup> 2s <sup>2</sup> 2p	<b>Ne</b> Neon 20,1797 1s <sup>2</sup> 2s <sup>2</sup> 2p												
6	<b>Al</b> Aluminum 26,9815386 [Ne]3s <sup>2</sup> 3p	<b>Si</b> Silicon 28,0855 [Ne]3s <sup>2</sup> 3p	<b>P</b> Phosphorus 30,973762 [Ne]3s <sup>2</sup> 3p	<b>S</b> Sulfur 32,065 [Ne]3s <sup>2</sup> 3p	<b>Cl</b> Chlorine 35,453 [Ne]3s <sup>2</sup> 3p	<b>Ar</b> Argon 39,948 [Ne]3s <sup>2</sup> 3p												
7	<b>K</b> Potassium 39,0983 [Ar]4s	<b>Ca</b> Calcium 40,078 [Ar]4s	<b>Sc</b> Scandium 44,955912 [Ar]3d <sup>1</sup> 4s	<b>Ti</b> Titanium 47,867 [Ar]3d <sup>2</sup> 4s	<b>V</b> Vanadium 50,9415 [Ar]3d <sup>3</sup> 4s	<b>Cr</b> Chromium 51,9961 [Ar]3d <sup>5</sup> 4s	<b>Mn</b> Manganese 54,938045 [Ar]3d <sup>5</sup> 4s	<b>Fe</b> Iron 55,845 [Ar]3d <sup>6</sup> 4s	<b>Co</b> Cobalt 58,933195 [Ar]3d <sup>7</sup> 4s	<b>Ni</b> Nickel 58,6934 [Ar]3d <sup>8</sup> 4s	<b>Cu</b> Copper 63,546 [Ar]3d <sup>10</sup> 4s	<b>Zn</b> Zinc 65,38 [Ar]3d <sup>10</sup> 4s	<b>Ga</b> Gallium 69,723 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p	<b>Ge</b> Germanium 72,64 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p	<b>As</b> Arsenic 74,92160 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p	<b>Se</b> Selenium 78,96 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p	<b>Br</b> Bromine 79,904 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p	<b>Kr</b> Krypton 83,798 [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p
8	<b>Rb</b> Rubidium 85,4678 [Kr]5s	<b>Sr</b> Strontium 87,62 [Kr]5s	<b>Y</b> Yttrium 88,90585 [Kr]4d <sup>1</sup> 5s	<b>Zr</b> Zirconium 91,224 [Kr]4d <sup>2</sup> 5s	<b>Nb</b> Niobium 92,90638 [Kr]4d <sup>4</sup> 5s	<b>Mo</b> Molybdenum 95,96 [Kr]4d <sup>5</sup> 5s	<b>Tc</b> Technetium (98) [Kr]4d <sup>5</sup> 5s	<b>Ru</b> Ruthenium 101,07 [Kr]4d <sup>7</sup> 5s	<b>Rh</b> Rhodium 102,90550 [Kr]4d <sup>8</sup> 5s	<b>Pd</b> Palladium 106,42 [Kr]4d <sup>10</sup>	<b>Ag</b> Silver 107,8682 [Kr]4d <sup>10</sup> 5s	<b>Cd</b> Cadmium 112,411 [Kr]4d <sup>10</sup> 5s	<b>In</b> Indium 114,818 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p	<b>Sn</b> Tin 118,710 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p	<b>Sb</b> Antimony 121,760 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p	<b>Te</b> Tellurium 127,60 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p	<b>I</b> Iodine 126,90447 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p	<b>Xe</b> Xenon 131,293 [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p
9	<b>Cs</b> Cesium 132,9054519 [Xe]6s	<b>Ba</b> Barium 137,327 [Xe]6s	<b>Hf</b> Hafnium 178,49 [Xe]4f <sup>14</sup> 5d <sup>2</sup> 6s	<b>Ta</b> Tantalum 180,94788 [Xe]4f <sup>14</sup> 5d <sup>3</sup> 6s	<b>W</b> Tungsten 183,84 [Xe]4f <sup>14</sup> 5d <sup>4</sup> 6s	<b>Re</b> Rhenium 186,207 [Xe]4f <sup>14</sup> 5d <sup>5</sup> 6s	<b>Os</b> Osmium 190,23 [Xe]4f <sup>14</sup> 5d <sup>6</sup> 6s	<b>Ir</b> Iridium 192,217 [Xe]4f <sup>14</sup> 5d <sup>7</sup> 6s	<b>Pt</b> Platinum 195,084 [Xe]4f <sup>14</sup> 5d <sup>9</sup> 6s	<b>Au</b> Gold 196,966569 [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s	<b>Hg</b> Mercury 200,59 [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s	<b>Tl</b> Thallium 204,3833 [Hg]6p	<b>Pb</b> Lead 207,2 [Hg]6p	<b>Bi</b> Bismuth 208,98040 [Hg]6p	<b>Po</b> Polonium (209) [Hg]6p	<b>At</b> Astatine (210) [Hg]6p	<b>Rn</b> Radon (222) [Hg]6p	
10	<b>Rf</b> Rutherfordium (261) [Rn]5f <sup>14</sup> 6d <sup>2</sup> 7s <sup>2</sup>	<b>Db</b> Dubnium (268) [Rn]5f <sup>14</sup> 6d <sup>3</sup> 7s <sup>2</sup>	<b>Sg</b> Seaborgium (271) [Rn]5f <sup>14</sup> 6d <sup>4</sup> 7s <sup>2</sup>	<b>Bh</b> Bohrium (272) [Rn]5f <sup>14</sup> 6d <sup>5</sup> 7s <sup>2</sup>	<b>Hs</b> Hassium (277) [Rn]5f <sup>14</sup> 6d <sup>6</sup> 7s <sup>2</sup>	<b>Mt</b> Meitnerium (278) [Rn]5f <sup>14</sup> 6d <sup>7</sup> 7s <sup>2</sup>	<b>Ds</b> Darmstadtium (281) [Rn]5f <sup>14</sup> 6d <sup>8</sup> 7s <sup>2</sup>	<b>Rg</b> Roentgenium (280) [Rn]5f <sup>14</sup> 6d <sup>9</sup> 7s <sup>2</sup>	<b>Cn</b> Copernicium (285) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup>	<b>Uut</b> Ununtrium (284) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p	<b>Uuq</b> Ununquadium (289) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p	<b>Uup</b> Ununpentium (288) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p	<b>Uuh</b> Ununhexium (293) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p	<b>Uus</b> Ununseptium (294) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p	<b>Uuo</b> Ununoctium (294) [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p			

**Legend:**  
■ Solids  
■ Liquids  
■ Gases  
■ Artificially Prepared

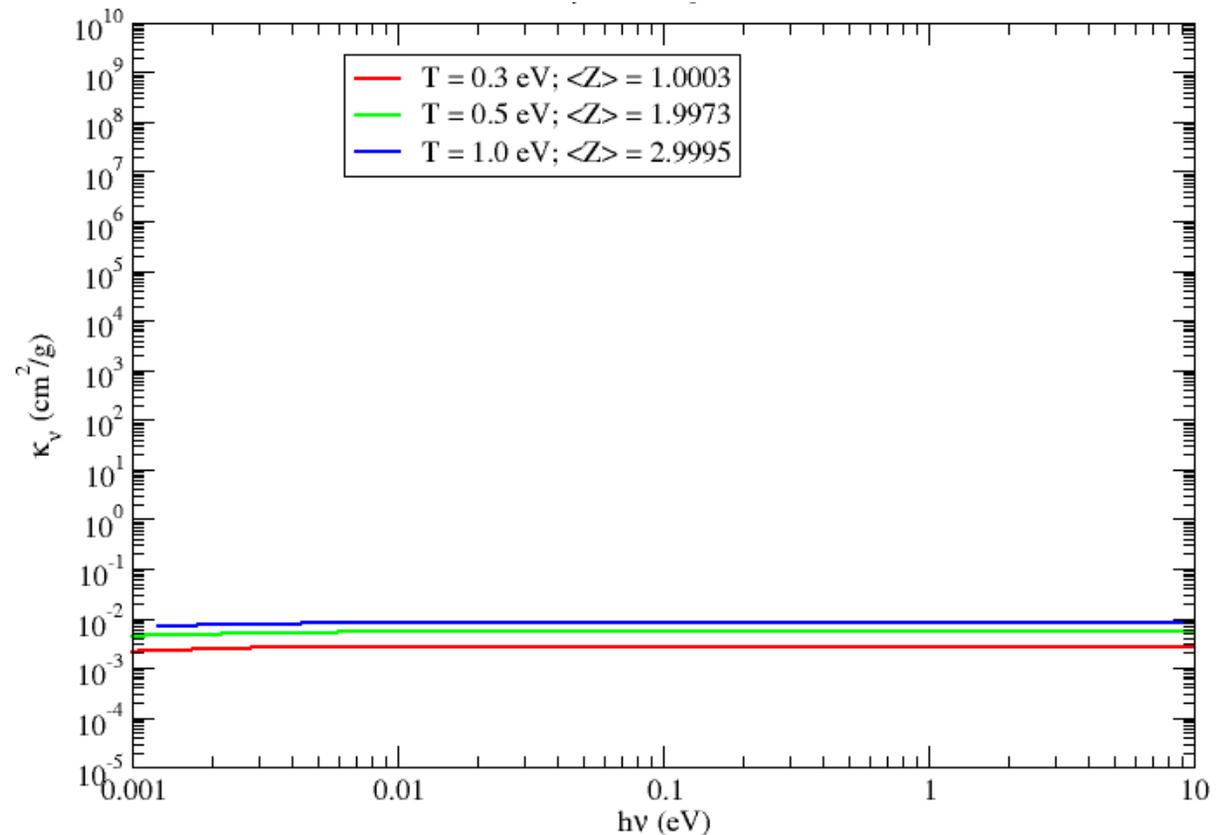
**58 <sup>138</sup>Gd<sup>0</sup>**  
 Symbol: **Ce**  
 Name: Cerium  
 Atomic Number: 140,116  
 Atomic Weight: [Xe]4f<sup>1</sup>5d<sup>1</sup>6s<sup>2</sup>  
 Ground-state Configuration: [Xe]4f<sup>1</sup>5d<sup>1</sup>6s<sup>2</sup>  
 Ionization Energy (eV): 5.5387

# Sm (Z=62) LTE ionization balance ( $\rho = 10^{-13}$ g/cm<sup>3</sup>)



# Consider LTE opacity of Sm ( $Z=62$ ) at $T \sim 0.5$ eV and $\rho = 10^{-13}$ g/cm<sup>3</sup>

- A simple estimate of the opacity: assume Thomson/Compton scattering is the dominant mechanism
- Opacity  $\sim 0.4 \langle Z \rangle / A$  (cm<sup>2</sup>/g)



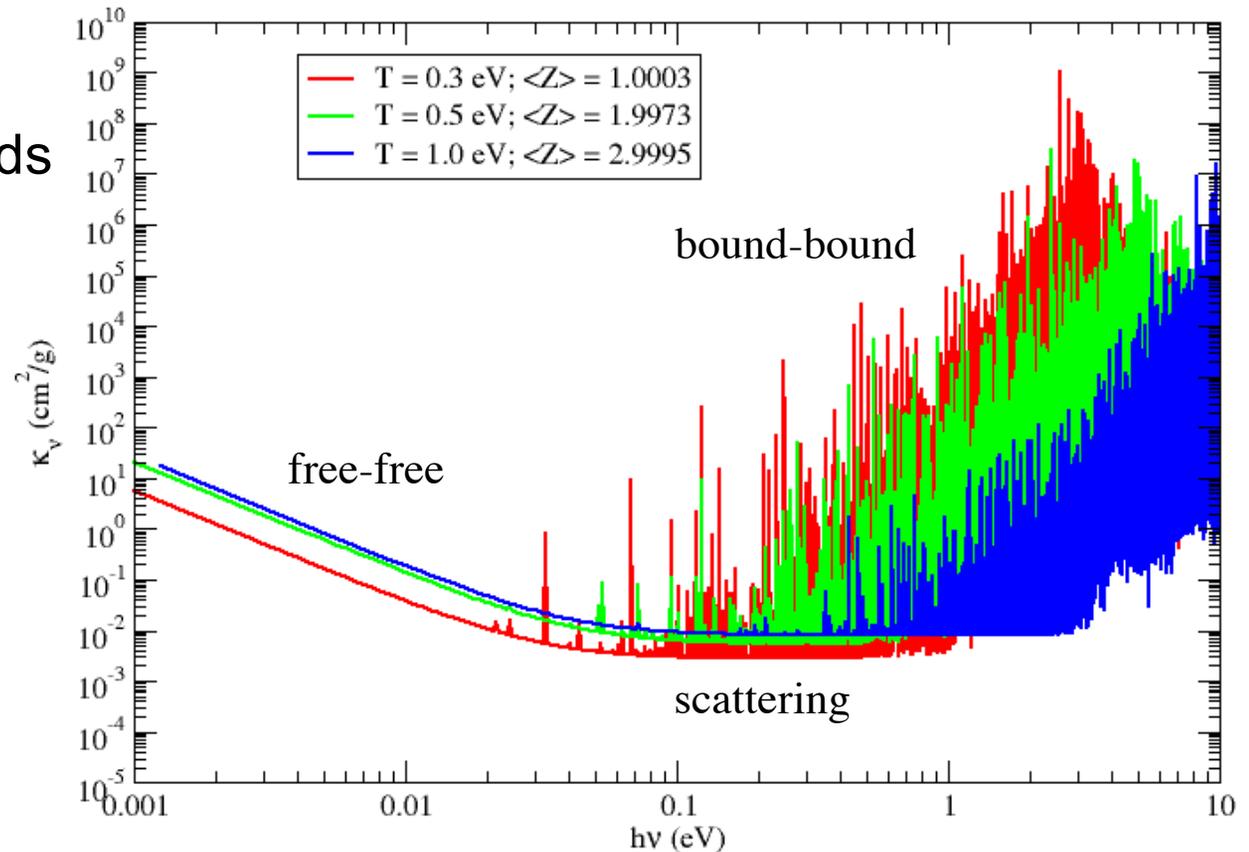
# Consider opacity of Sm (Z=62) at $T \sim 0.5$ eV and $\rho = 10^{-13}$ g/cm<sup>3</sup> (configuration list, assume [Xe] )

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- 25 configurations
- Sm<sup>0+</sup>: 4f<sup>6</sup> 6s<sup>2</sup>, 4f<sup>5</sup> 5d 6s<sup>2</sup>, 4f<sup>6</sup> 5d 6s , 4f<sup>6</sup> 5d<sup>2</sup>, 4f<sup>5</sup> 5d 6s 6p, 4f<sup>6</sup> 5d 6p , 4f<sup>6</sup> 6s 6p
- Sm<sup>1+</sup>: 4f<sup>6</sup> 6s, 4f<sup>6</sup> 5d, 4f<sup>6</sup> 6p, 4f<sup>5</sup> 5d<sup>2</sup>, 4f<sup>5</sup> 5d 6s, 4f<sup>5</sup> 5d 6p, 4f<sup>5</sup> 6s 6p
- Sm<sup>2+</sup>: 4f<sup>6</sup>, 4f<sup>5</sup> 6s, 4f<sup>5</sup> 5d, 4f<sup>5</sup> 6p, 4f<sup>4</sup> 5d, 4f<sup>4</sup> 5d 6s, 4f<sup>3</sup> 5d<sup>2</sup> 6s
- Sm<sup>3+</sup>: 4f<sup>5</sup>, 4f<sup>4</sup> 6s, 4f<sup>4</sup> 5d, 4f<sup>4</sup> 6p
- $\sim 10^5$  energy levels
- $\sim 3.3 \times 10^8$  radiative transitions

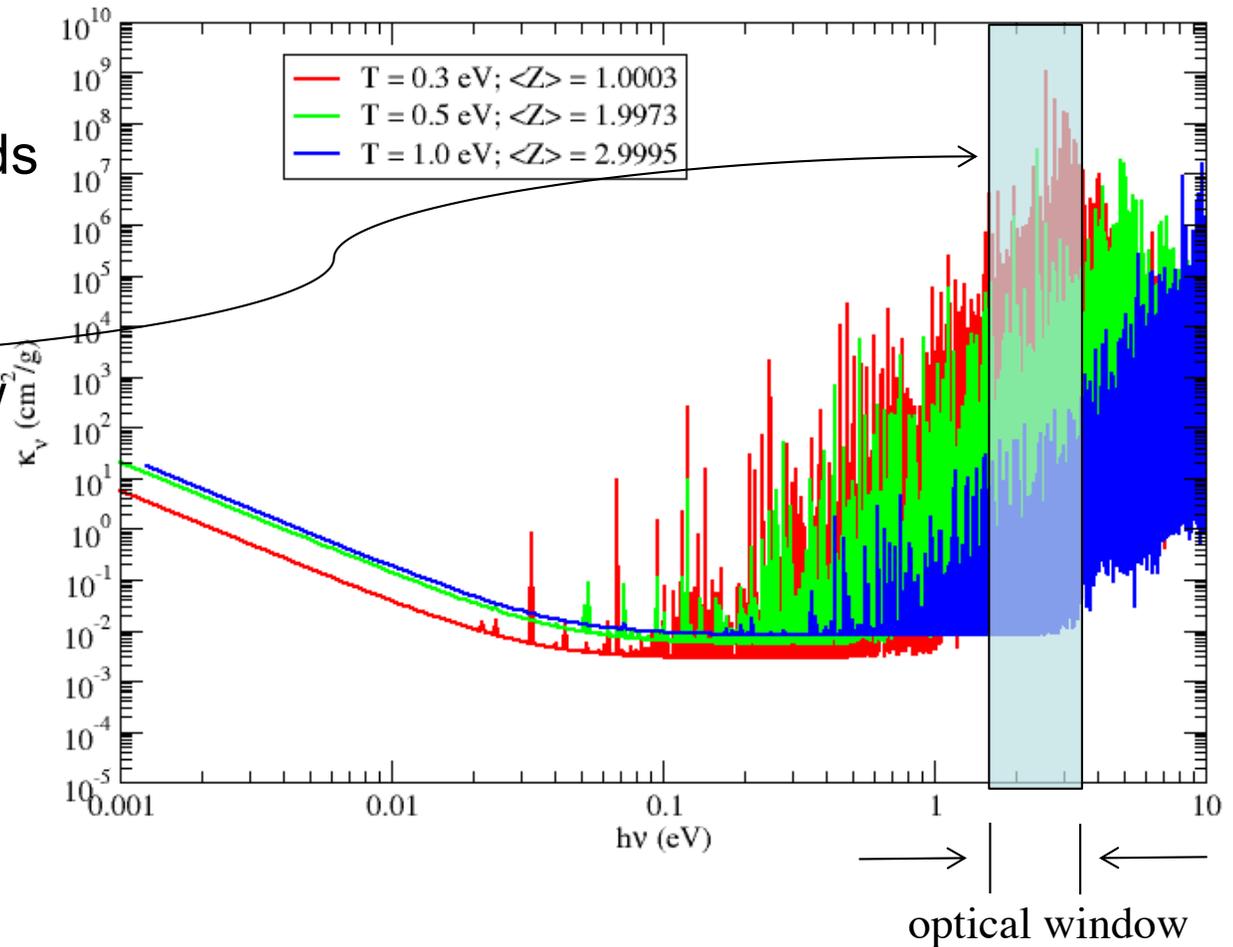
# Consider LTE opacity of Sm ( $Z=62$ ) at $T \sim 0.5$ eV and $\rho = 10^{-13}$ g/cm<sup>3</sup>

- Next, consider detailed bound-electron treatment
- Just 25 configurations leads to 100,000 levels and 330,000,000 lines!

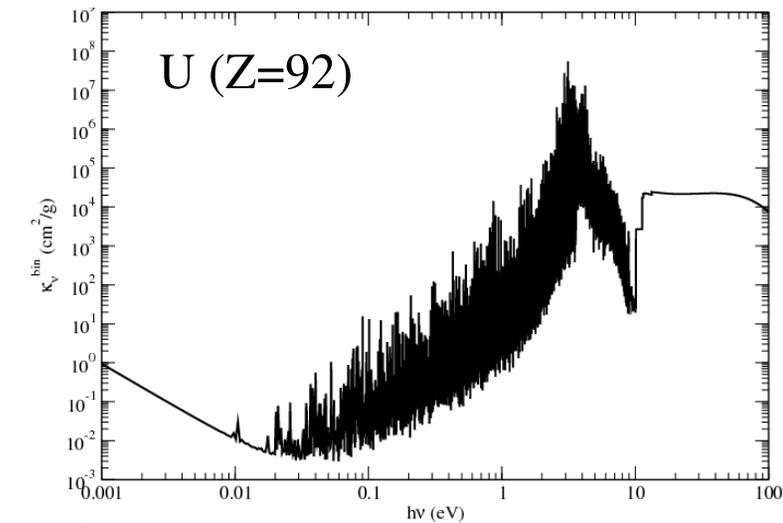
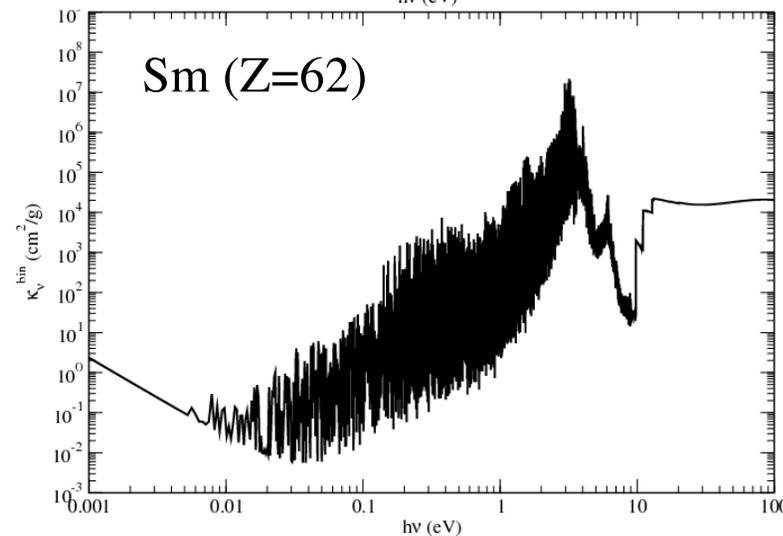
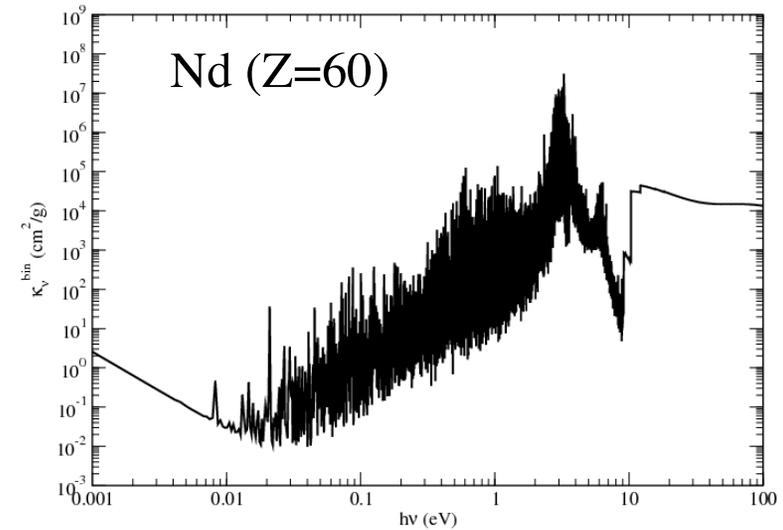
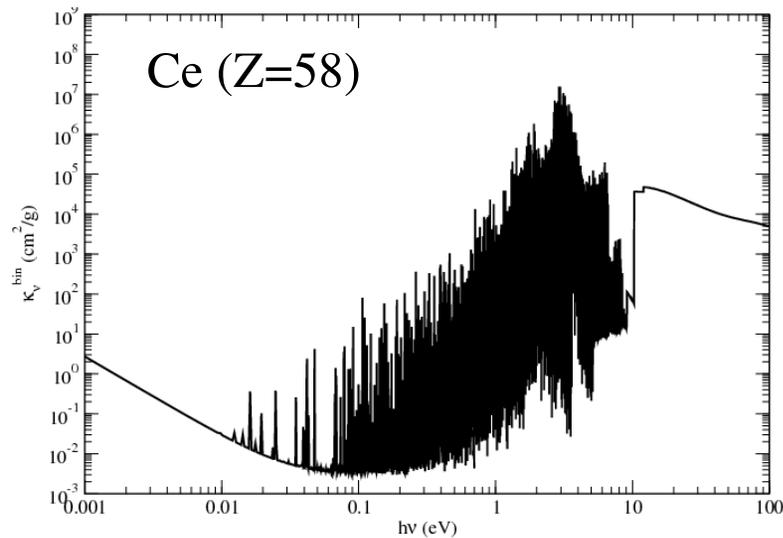


# Consider LTE opacity of Sm ( $Z=62$ ) at $T \sim 0.5$ eV and $\rho = 10^{-13}$ g/cm<sup>3</sup>

- Next, consider detailed bound-electron treatment
- Just 25 configurations leads to 100,000 levels and 330,000,000 lines!
- Visible photons have a low probability of escape  $\rightarrow$  infrared spectroscopy is required to see these objects



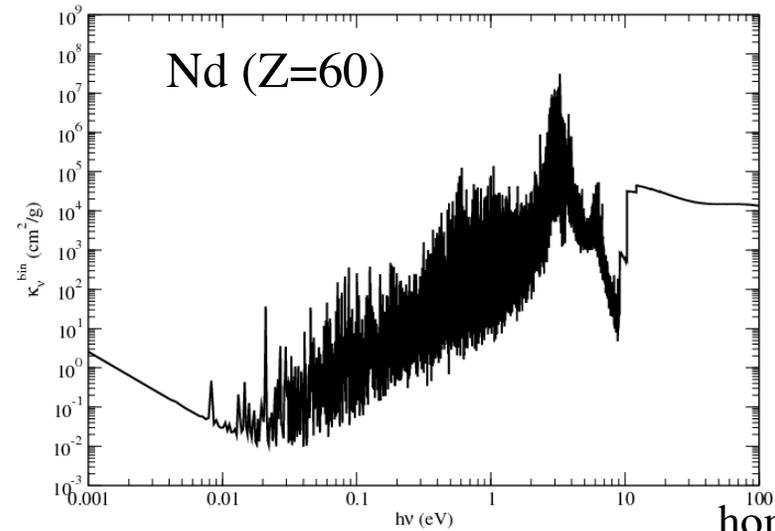
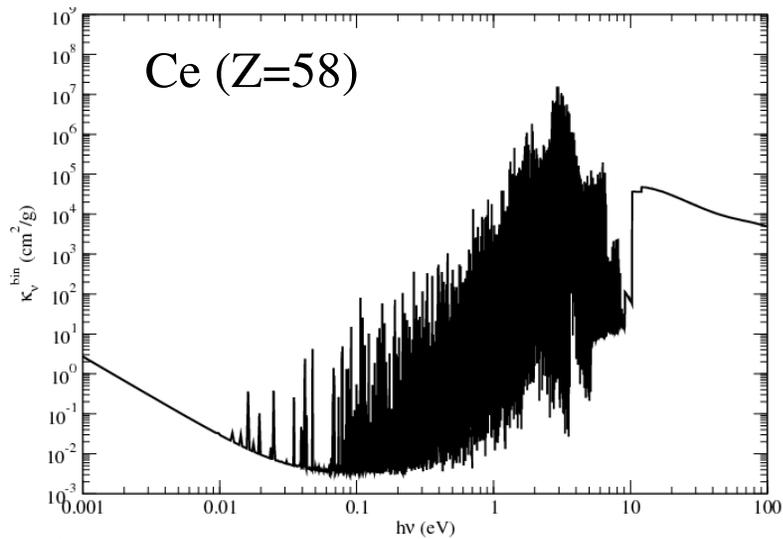
# We have calculated LTE opacities of the lanthanide elements and also uranium



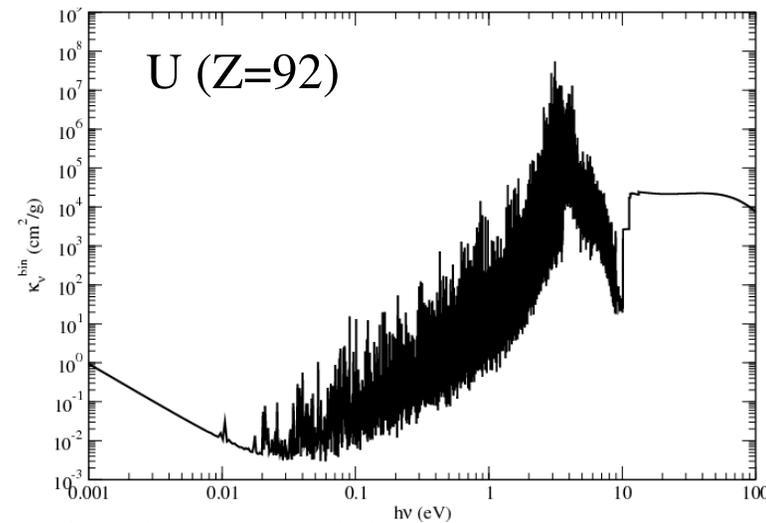
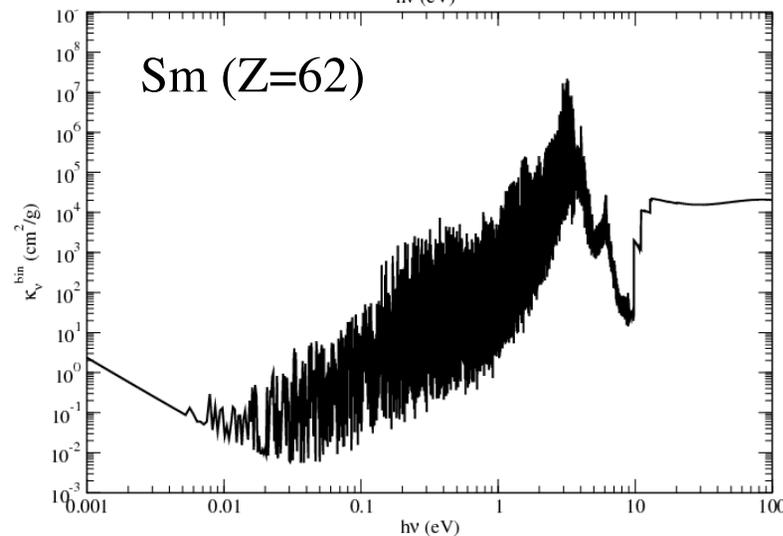
Fontes et al (2019) arXiv(2019):1904.08781

$T = 0.3 \text{ eV (3,481 K)}, \rho = 10^{-13} \text{ g/cm}^3$

# We have calculated LTE opacities of the lanthanide elements and also uranium



← homologues

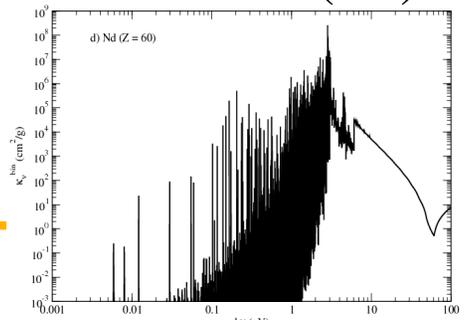
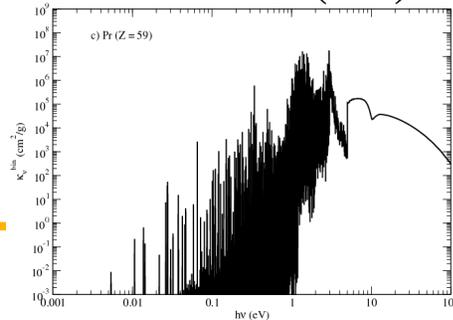
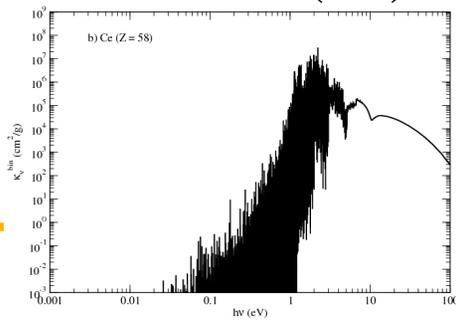
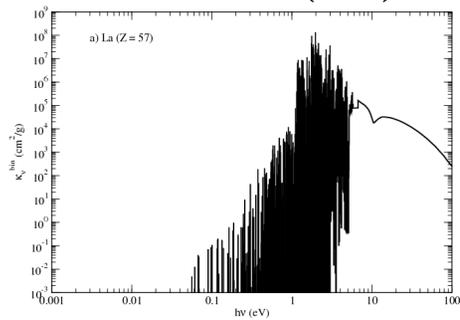


$Z = 57 (4f^0)$

$Z = 58 (4f^1)$

$Z = 59 (4f^3)$

$Z = 60 (4f^4)$

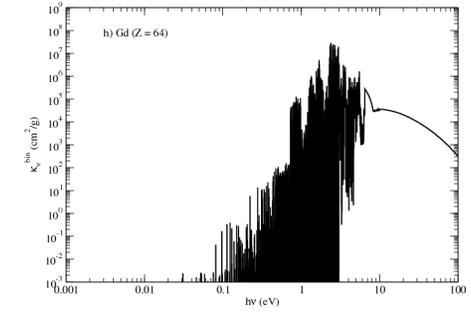
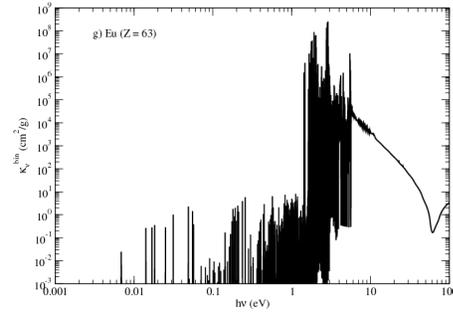
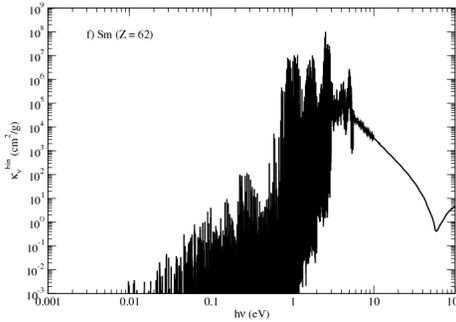
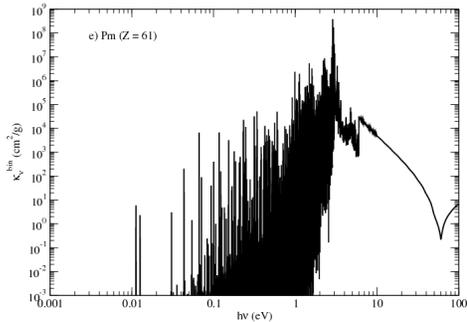


$Z = 61 (4f^5)$

$Z = 62 (4f^5)$

$Z = 63 (4f^7)$

$Z = 64 (4f^7)$

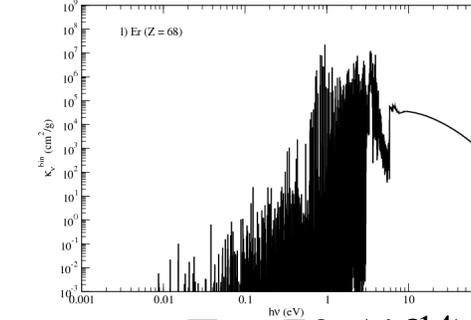
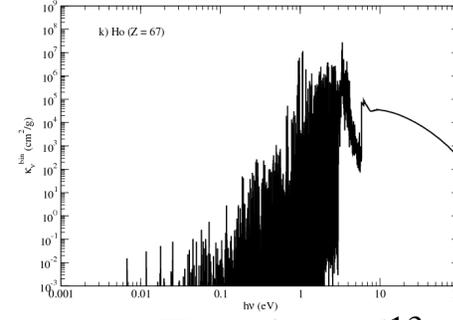
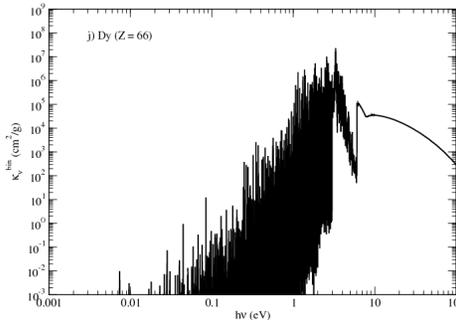
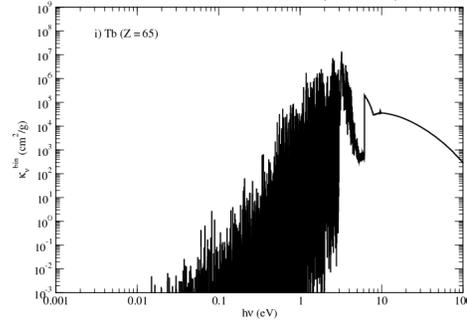


$Z = 65 (4f^9)$

$Z = 66 (4f^{10})$

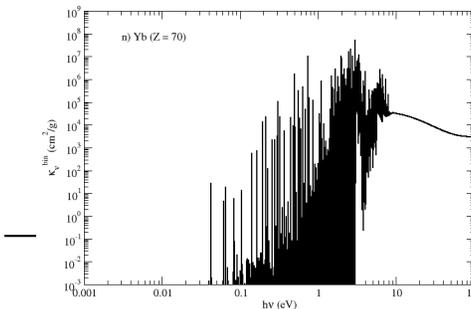
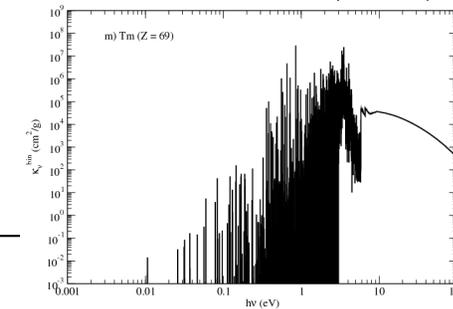
$Z = 67 (4f^{11})$

$Z = 68 (4f^{12})$



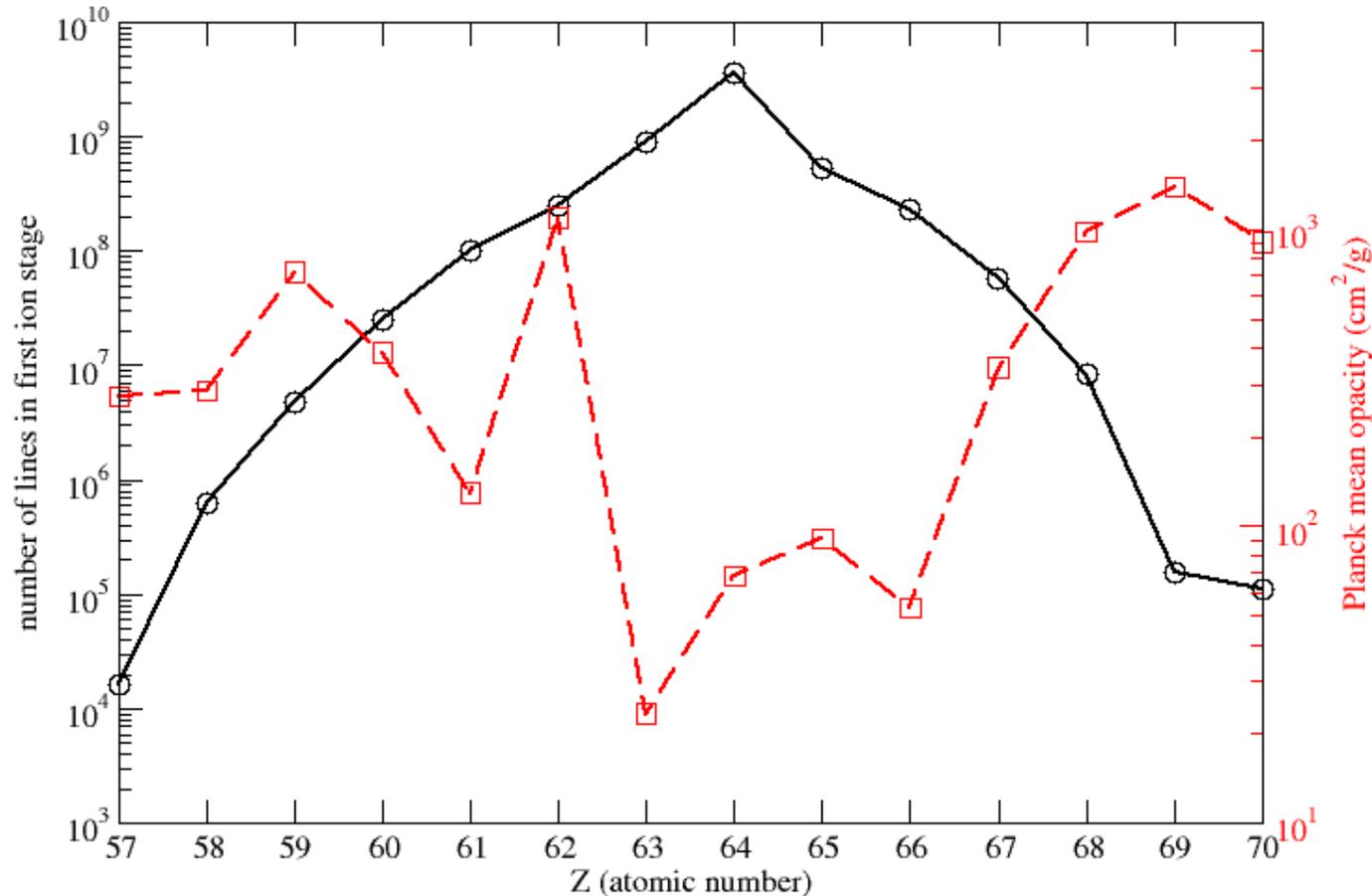
$Z = 69 (4f^{13})$

$Z = 70 (4f^{14})$



$T = 0.1 \text{ eV } (\sim 1,100 \text{ K}); \rho = 10^{-13} \text{ g/cm}^3$   
 (neutral stage is dominant)

# Complexity of bound electrons does not necessarily lead to high opacity



# What does the future hold for observations and modeling of neutron star mergers?

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April 1, 2019

- LIGO is scheduled to restart in ~~September 2018~~ with improved sensitivity... What will be observed???
- Current predictions range from 2-30 observations per year, based on star formation rate of galaxy NGC4993
- Simulations to explain GW170817 have been carried out, but no perfect match: different radiation transport methods, opacities, 1-D vs 2-D geometry, wind + dynamical ejecta, etc. (Need more observations!)
- Important to make opacities available to NSM modeling community; Exploring the creation of an online database with NIST colleagues

# Thank you for your attention!

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