An Application of Radiative Opacity to Gravitational Wave Spectroscopy

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ICTP-IAEA School on Atomic and Molecular Spectroscopy in Plasmas

Trieste, May 6-10, 2019

Overview

- ~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!

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) 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 1.0×10^{-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

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 ~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.

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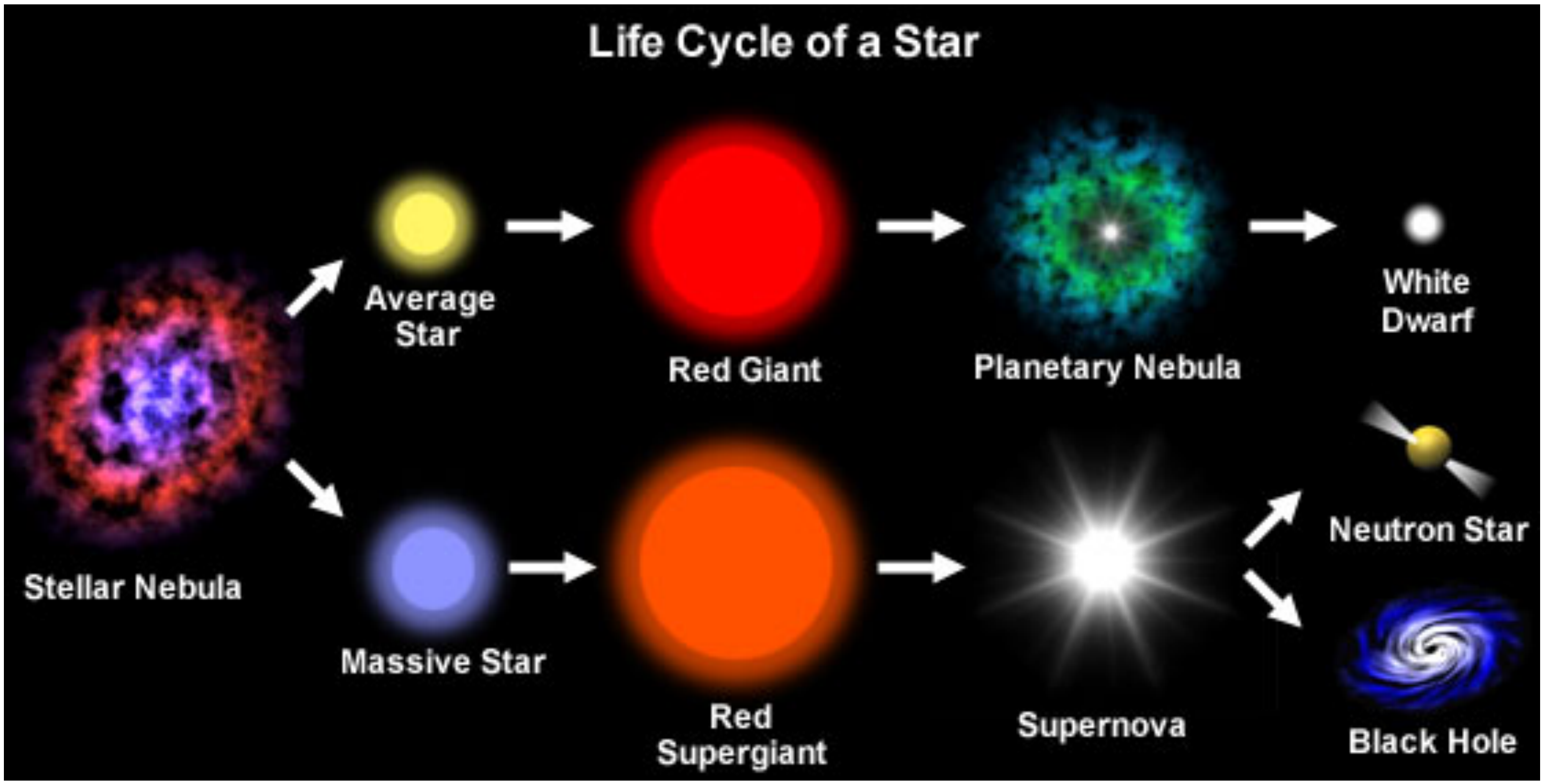
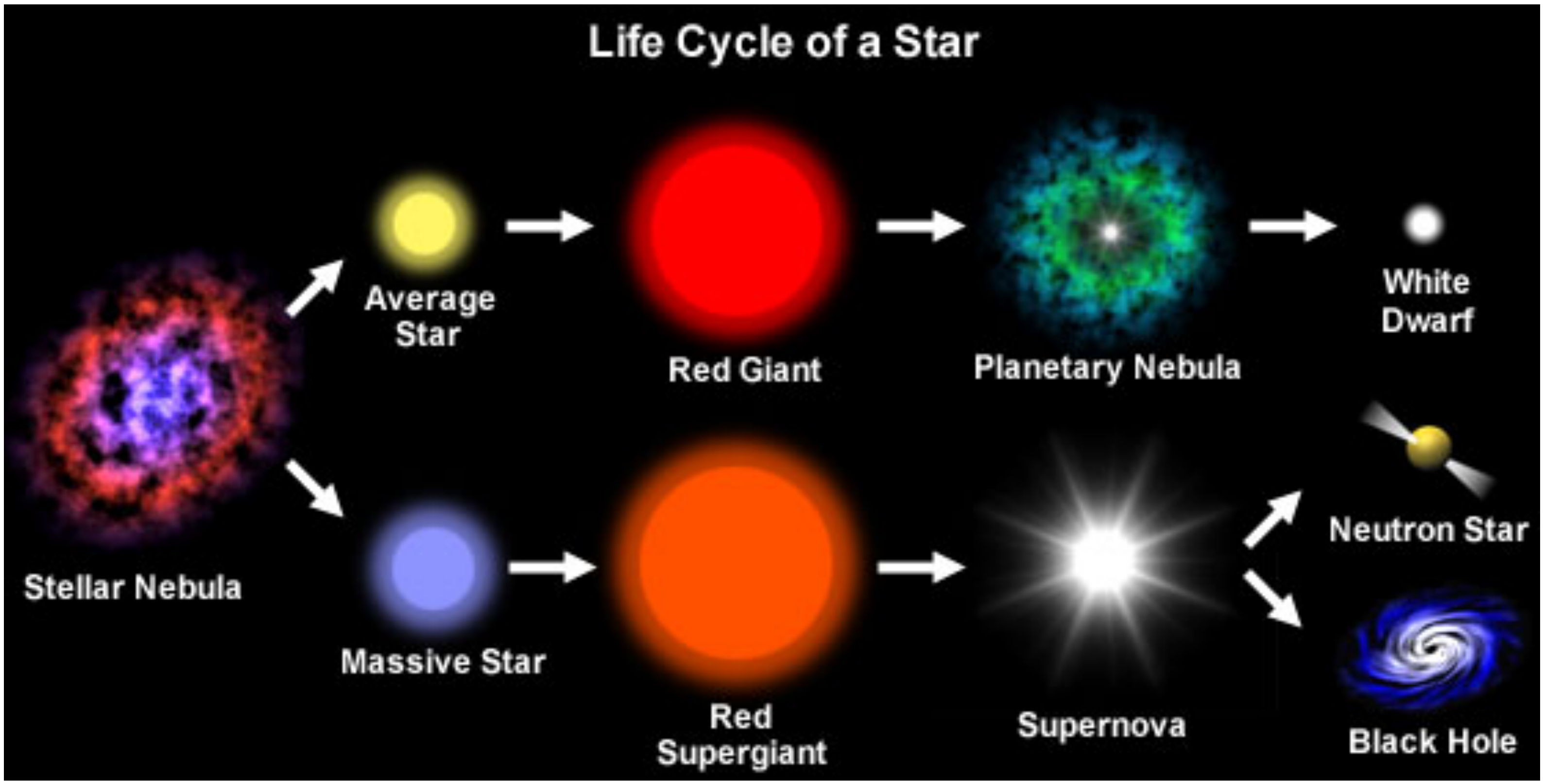
Stellar evolution chart (simplified)



First gravitational wave observation (Sept, 2015)

Stellar evolution chart (simplified)

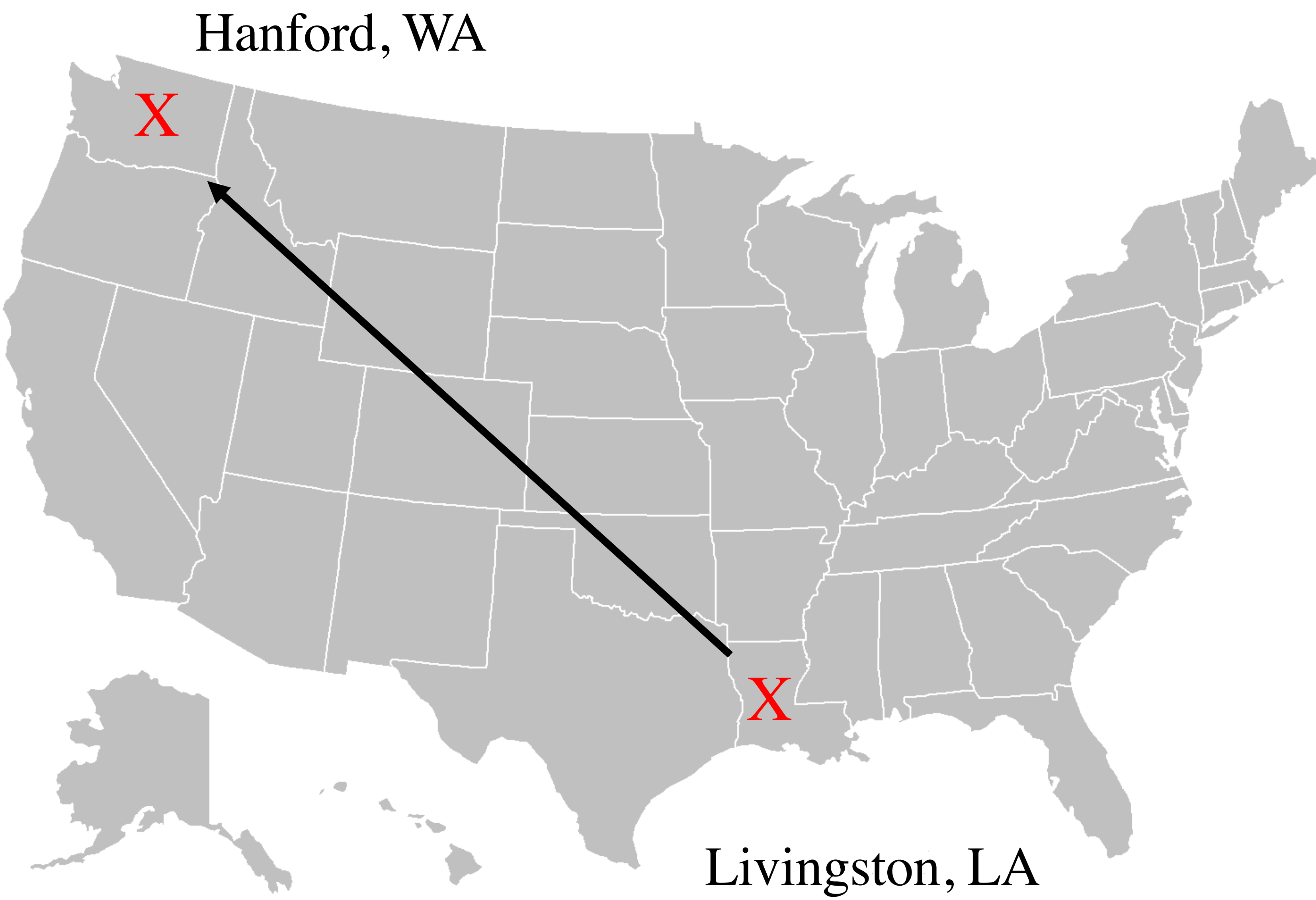


GW170817

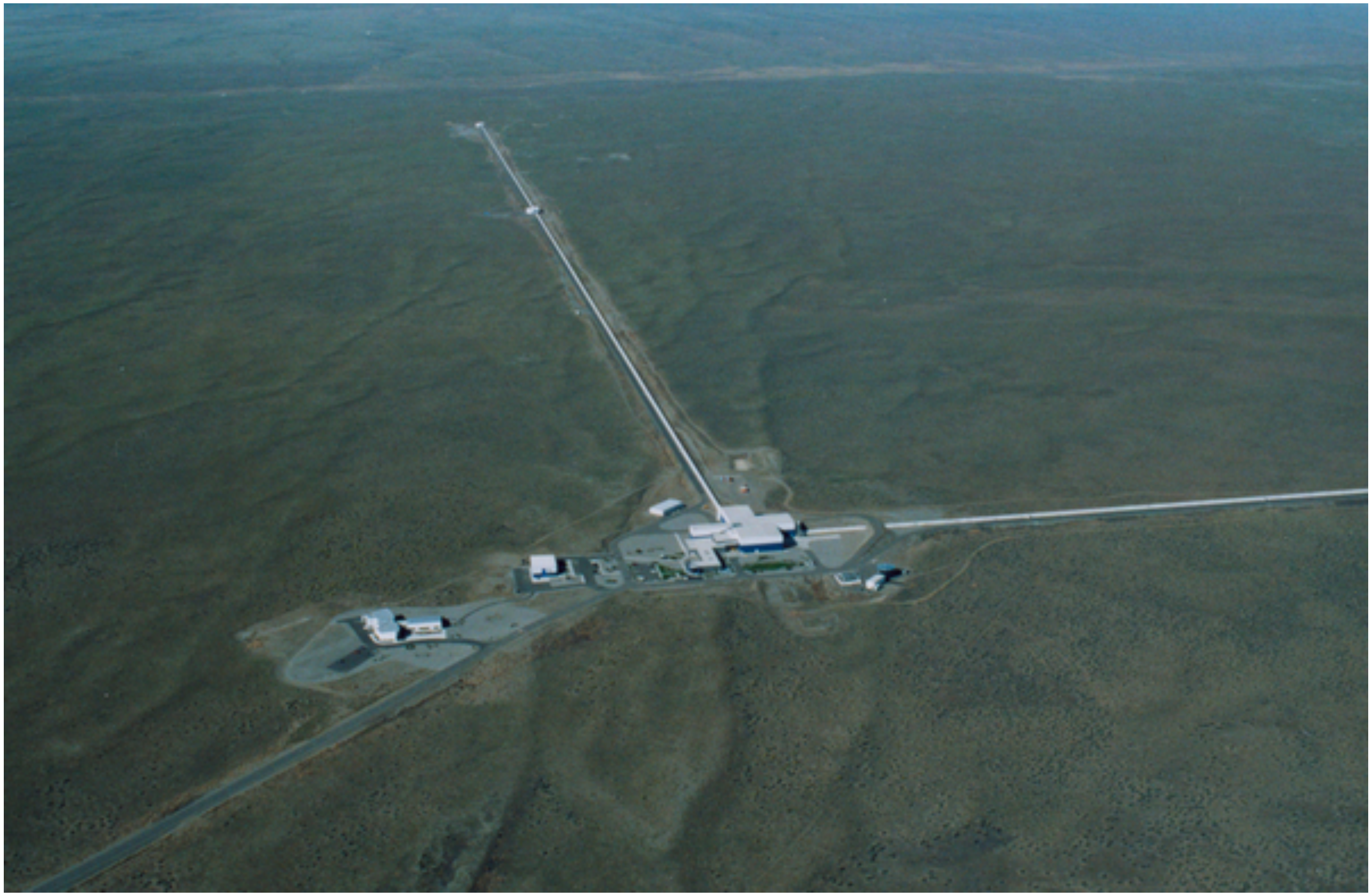
The focus of this talk. Observation: August, 2017

First gravitational wave observation (Sept, 2015)

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

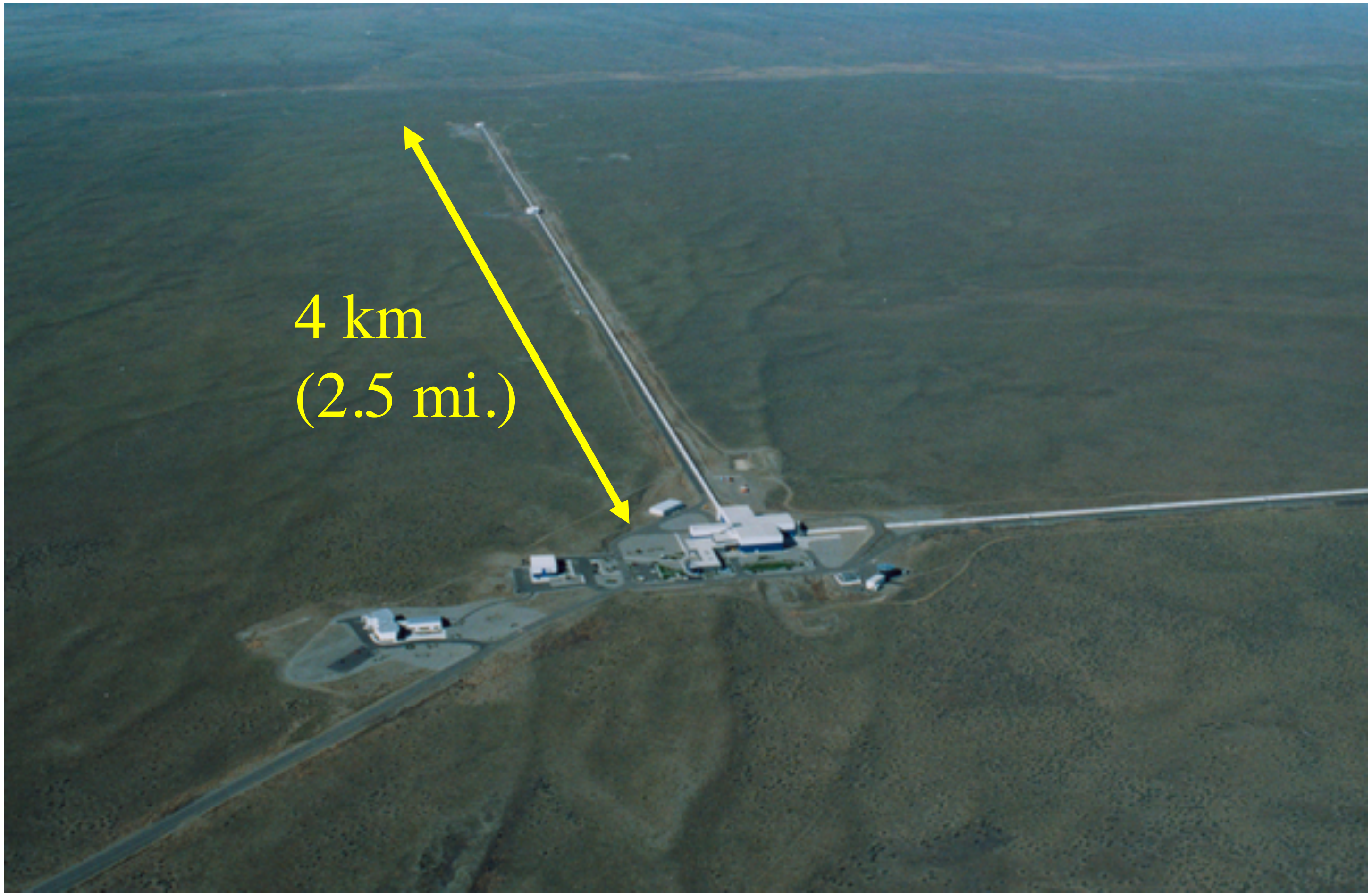


The Hanford, WA detector site



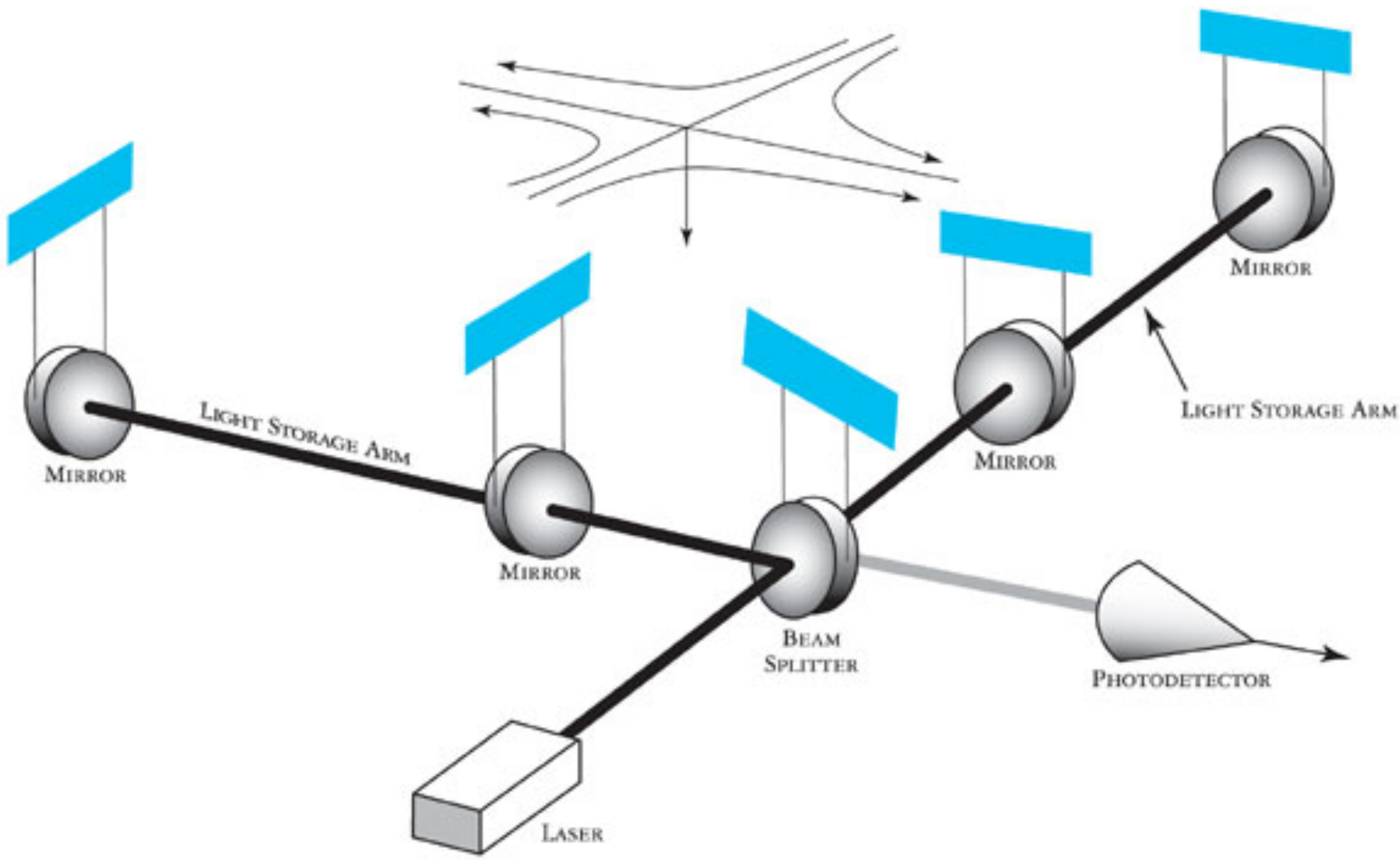
Credit: Caltech/MIT/LIGO Lab

The Hanford, WA detector site



Credit: Caltech/MIT/LIGO Lab

Diagram of LIGO detector



Credit: California Institute of Technology

Gravitational wave spectrum

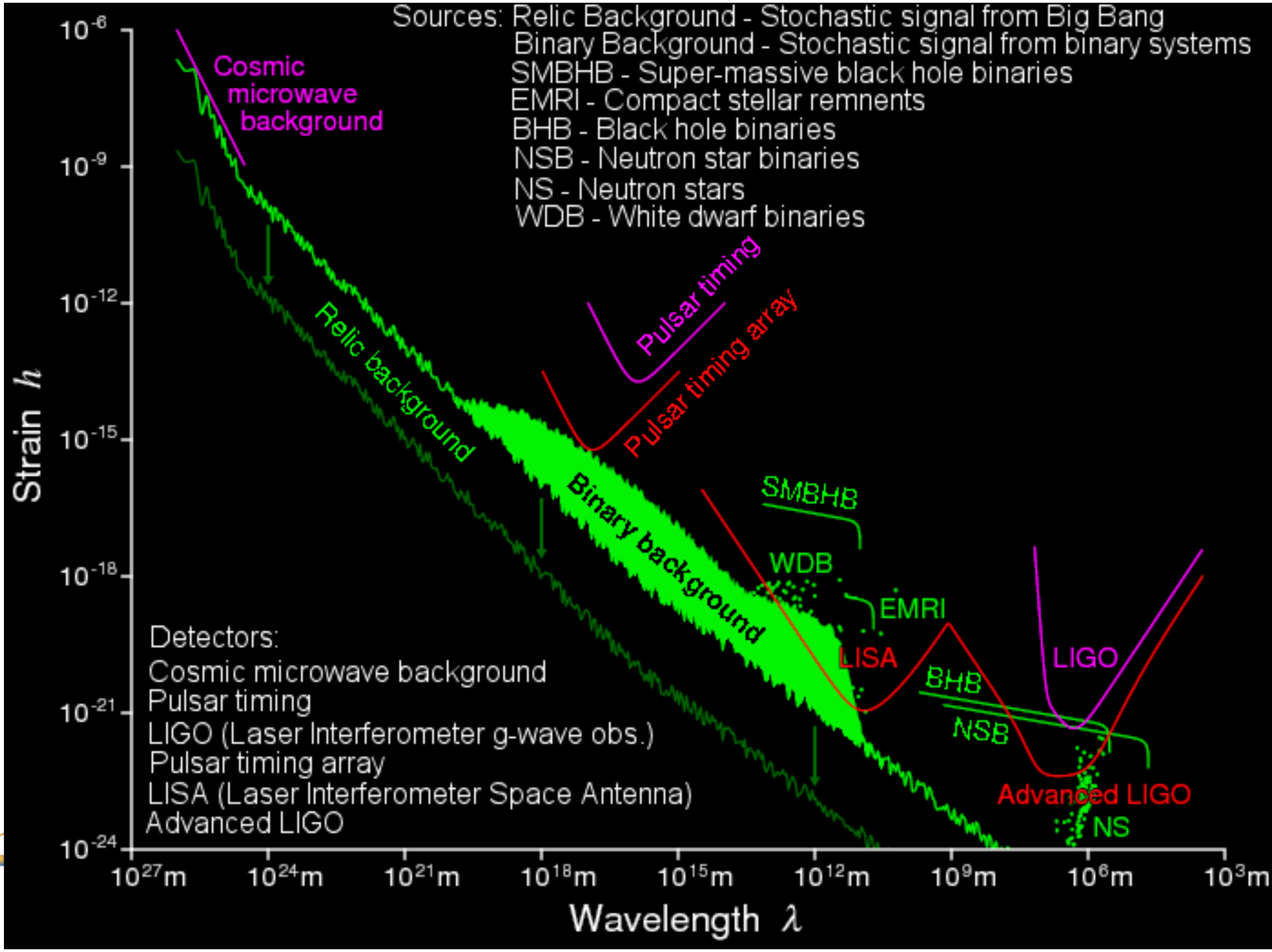


Image: T. Creighton

Gravitational wave spectrum

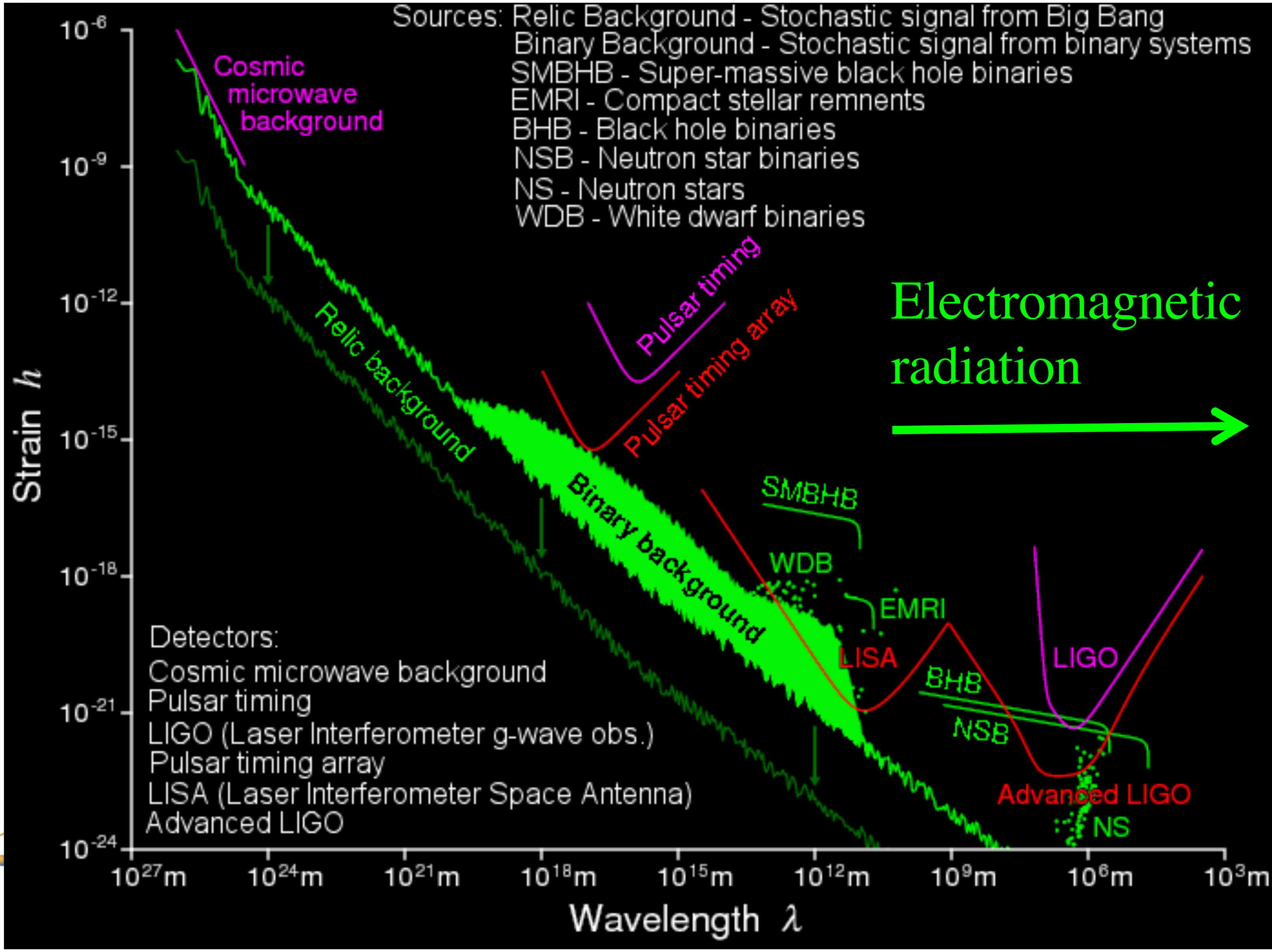


Image: T. Creighton

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

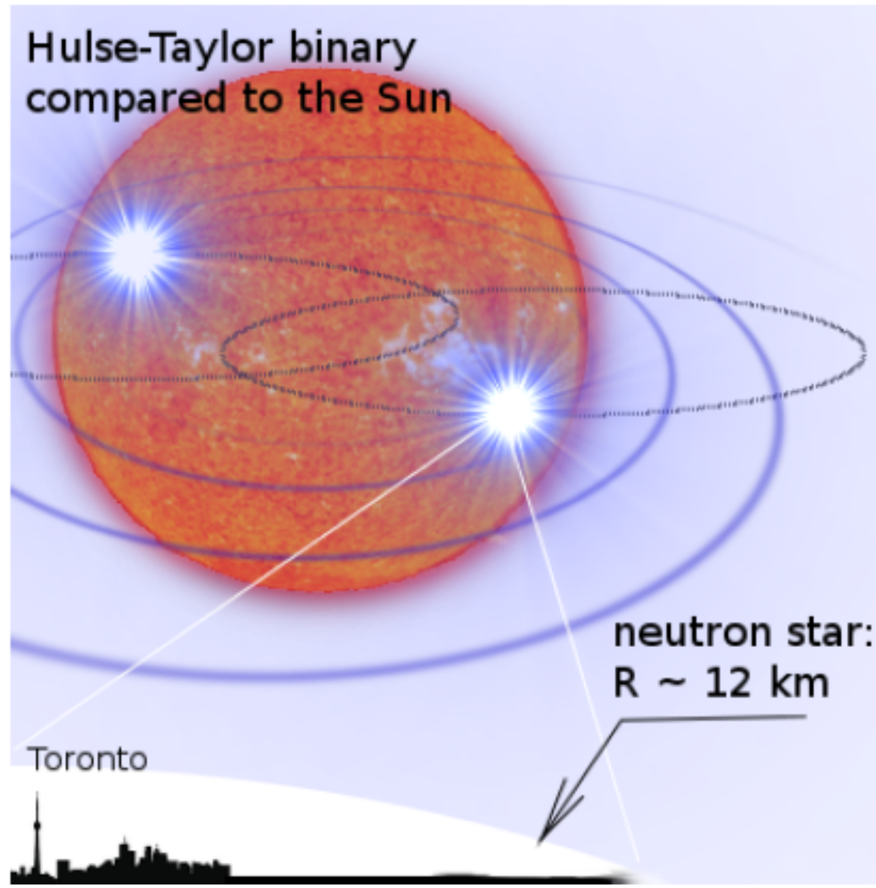


Image: Oleg Korobkin

A brief history of GWs (continued...)

- 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...)

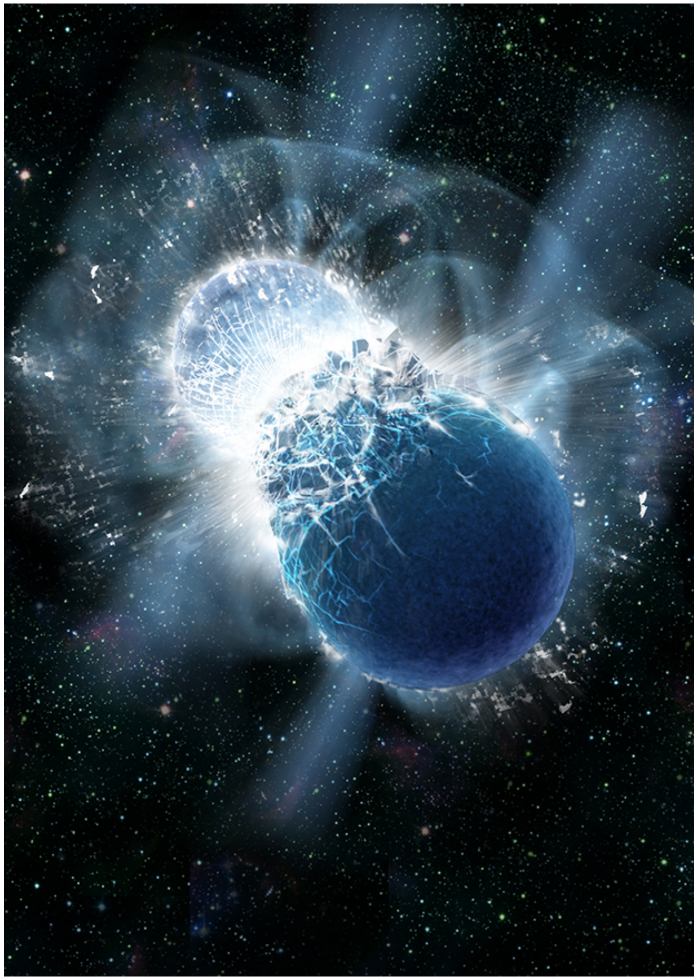
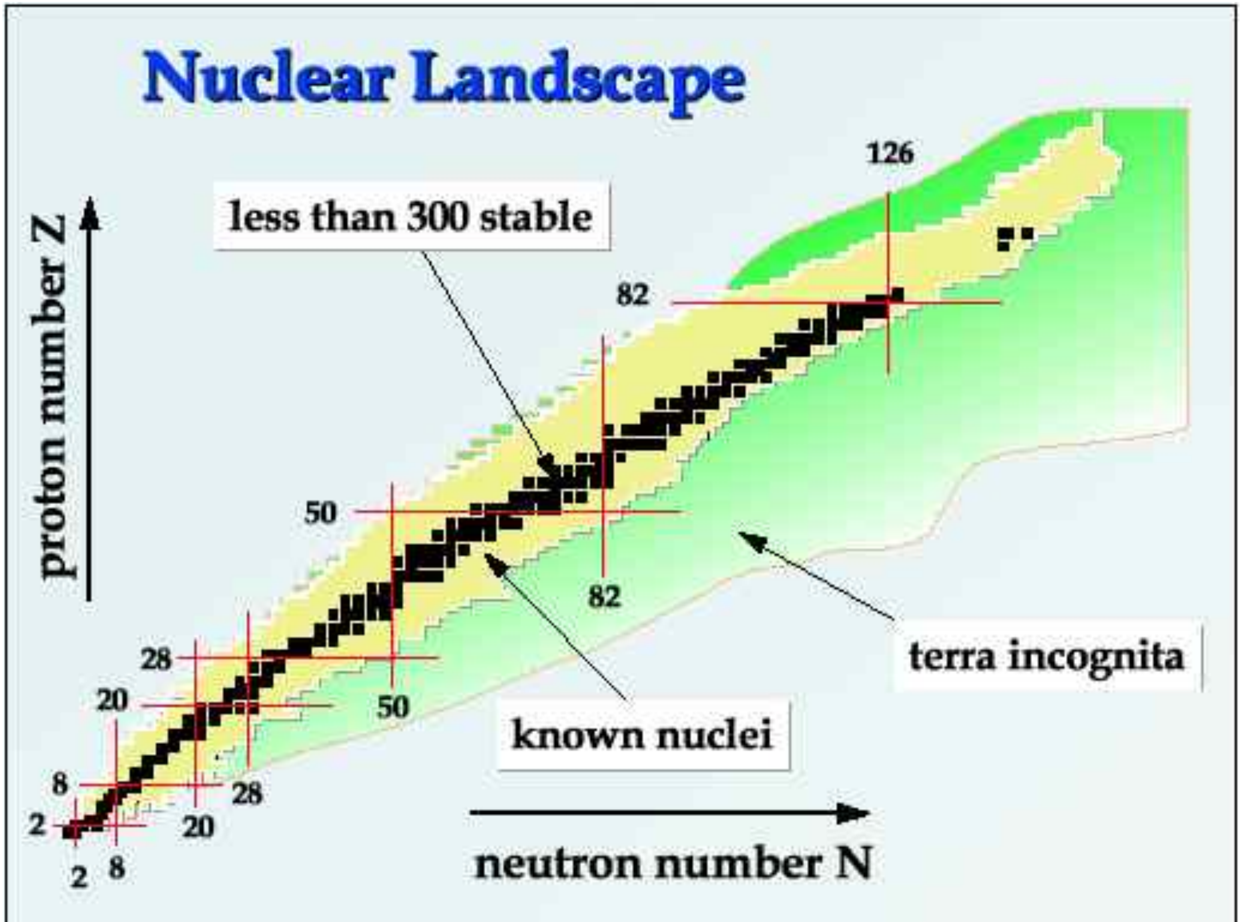


Image: Dana Berry, SkyWorks Digital, Inc.

Why study neutron star mergers (NSMs)?

- 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



$$n + (Z,A) \rightarrow (Z,A+1) + \gamma$$
$$\rightarrow (Z+1,A+1) + e^{-} + \nu$$

Another reason to study neutron star mergers

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

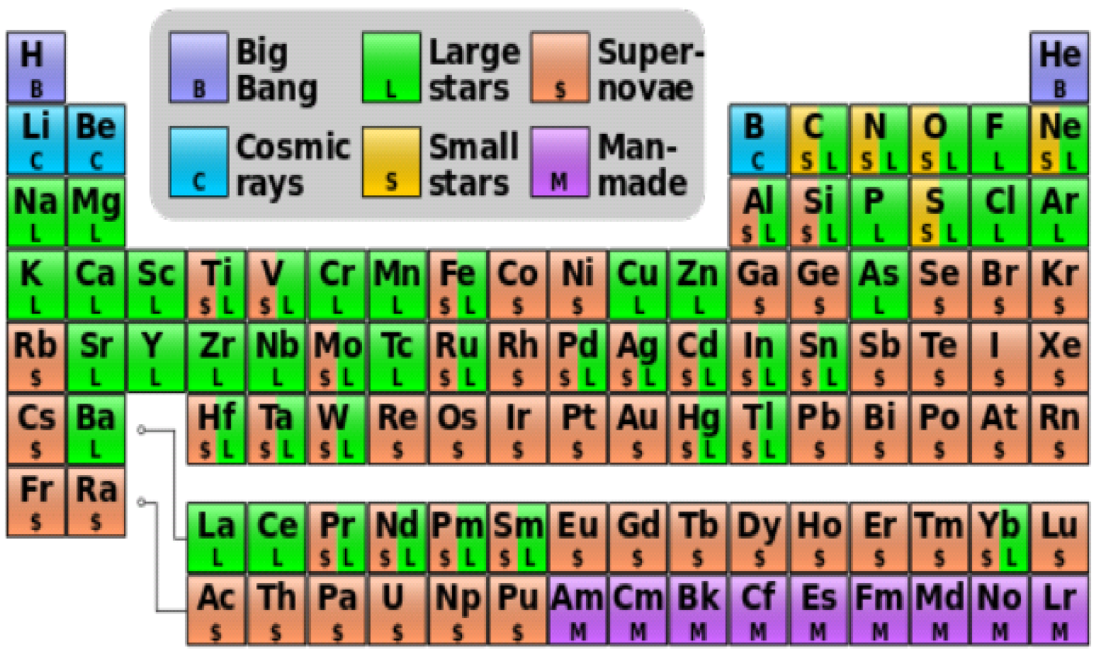


Image: Amanda Bayless

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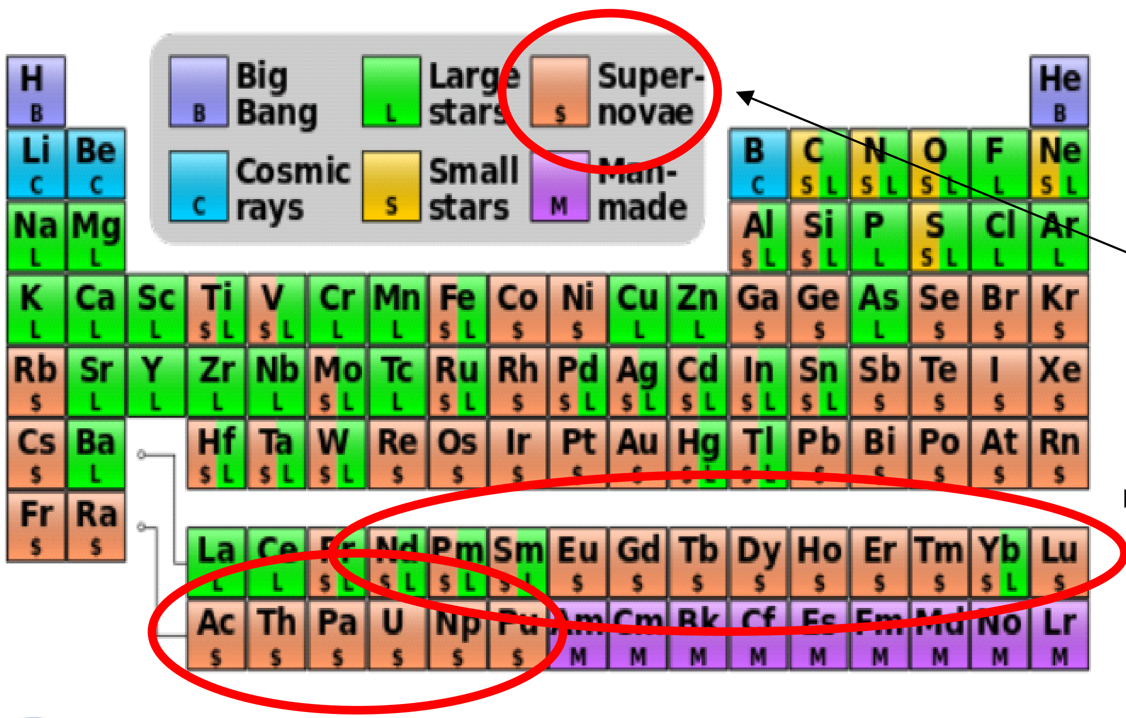

Don't believe everything you read on the internet!

Image: Amanda Bayless

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

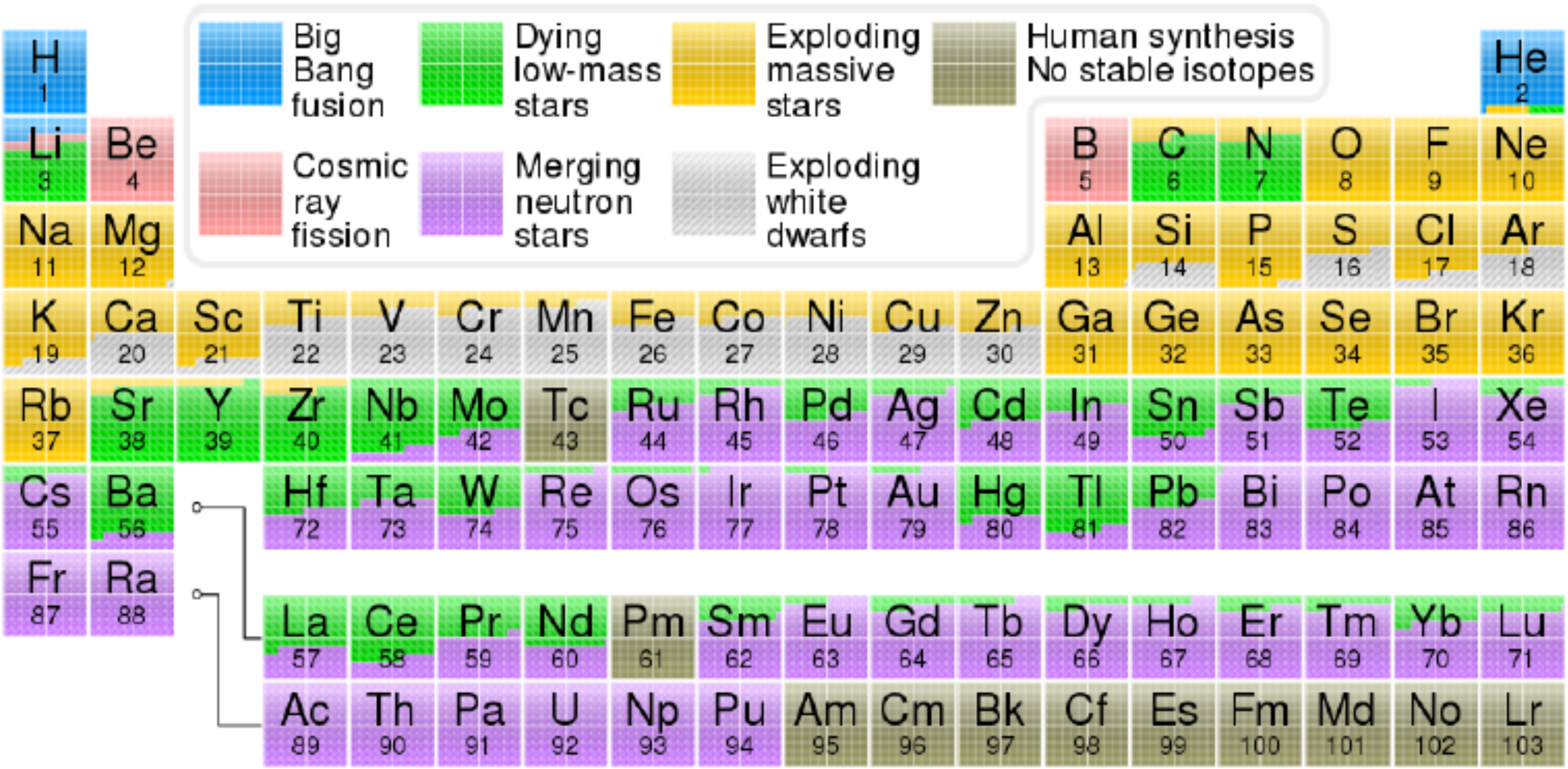

Image: J. Johnson

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

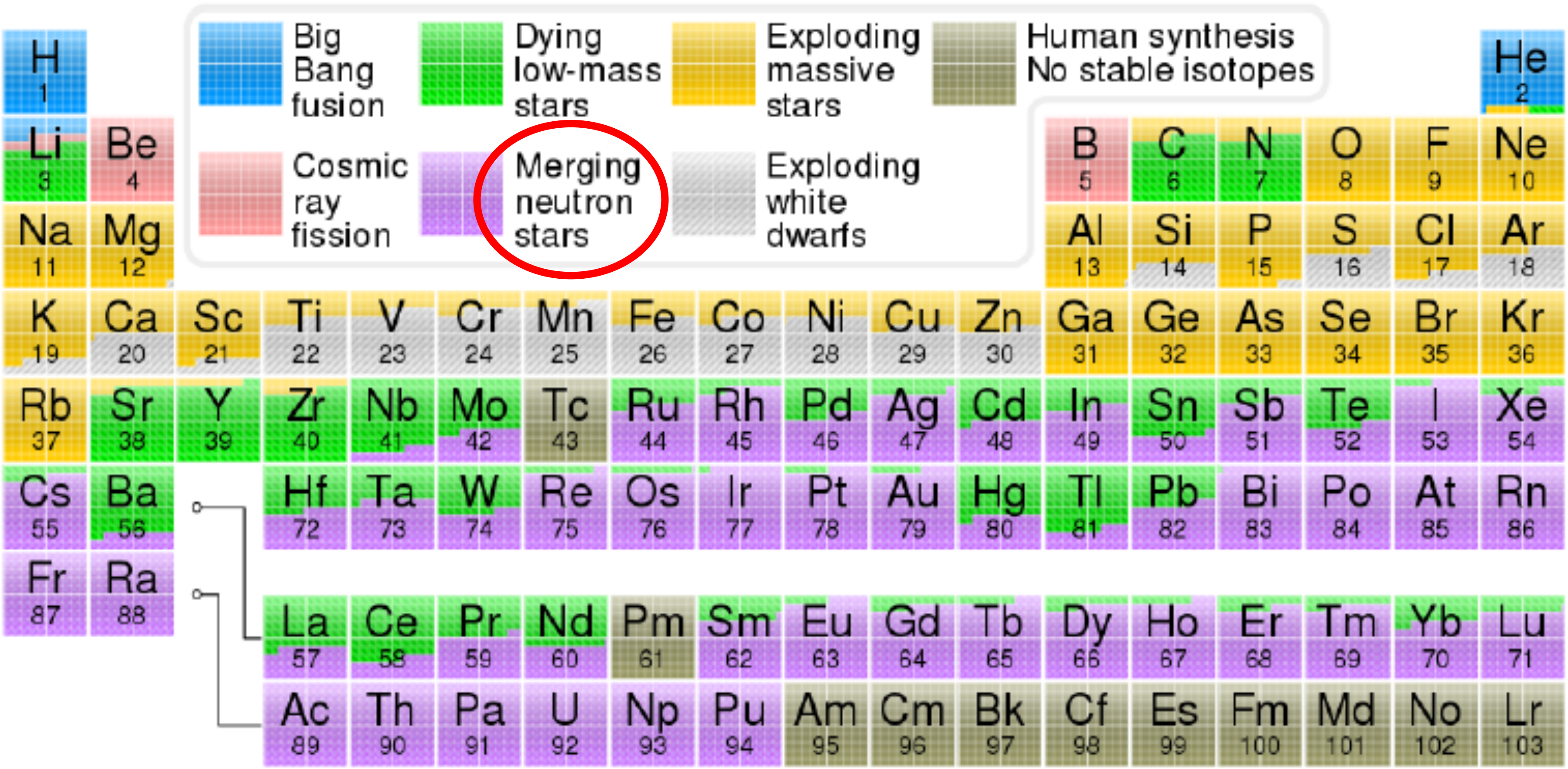


Image: J. Johnson

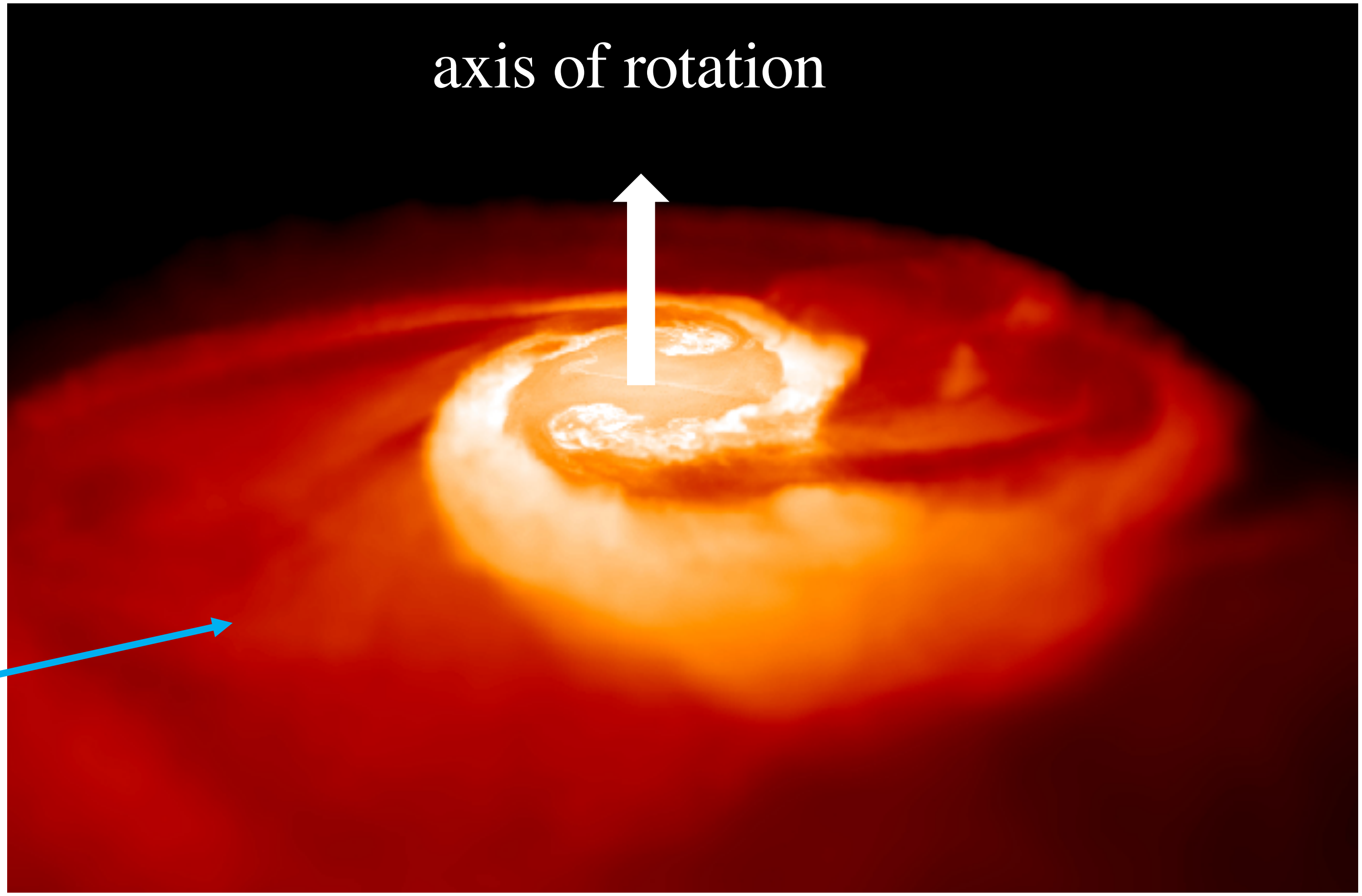
Some very basic characteristics of neutron star mergers...

A double neutron star

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

Massive Doppler shifts!

Ejecta composed of heavy elements: lanthanides and actinides!



courtesy of Stephan Rosswog

A double neutron star

(Δv/c) ~ 0.01

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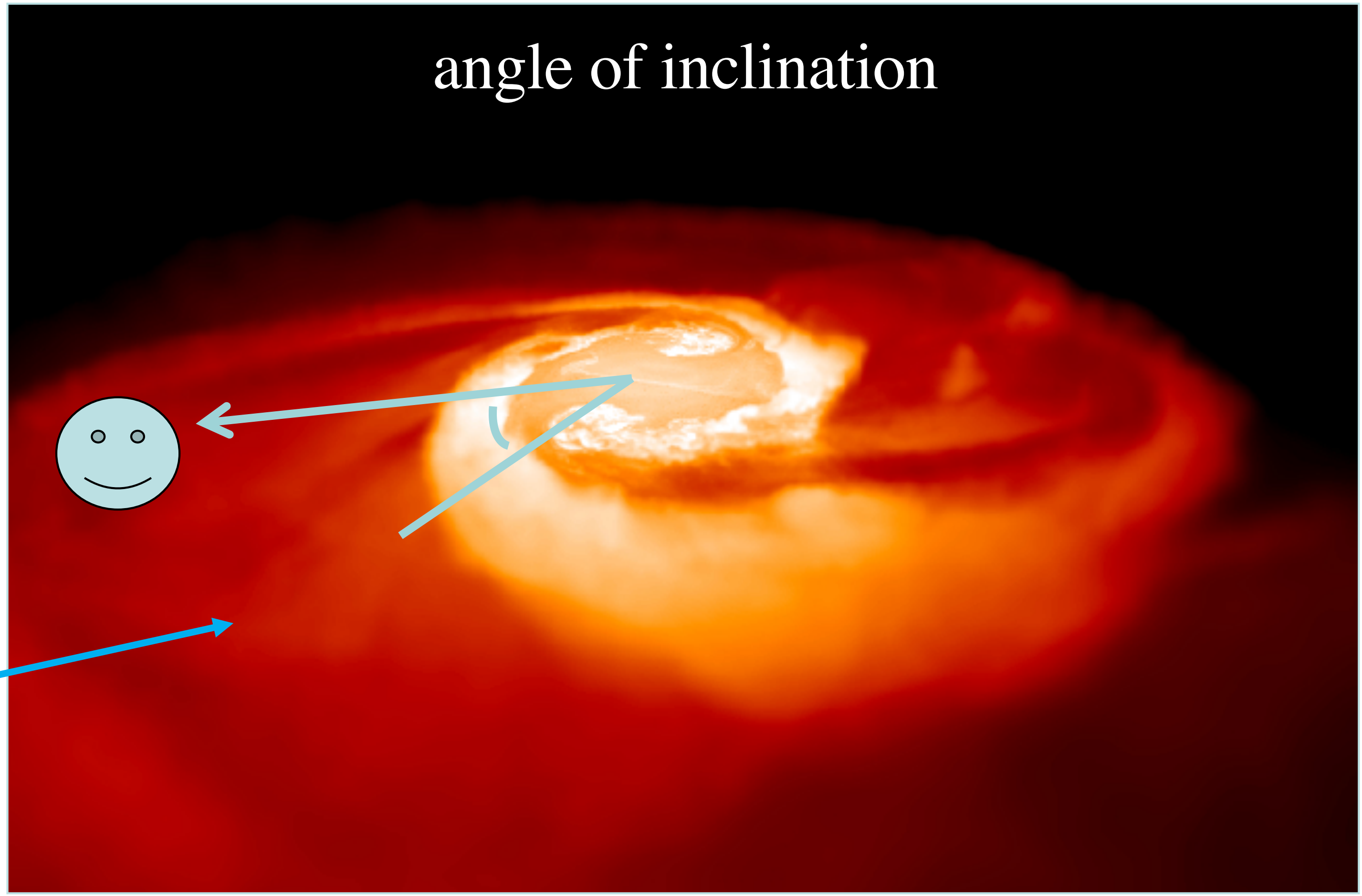
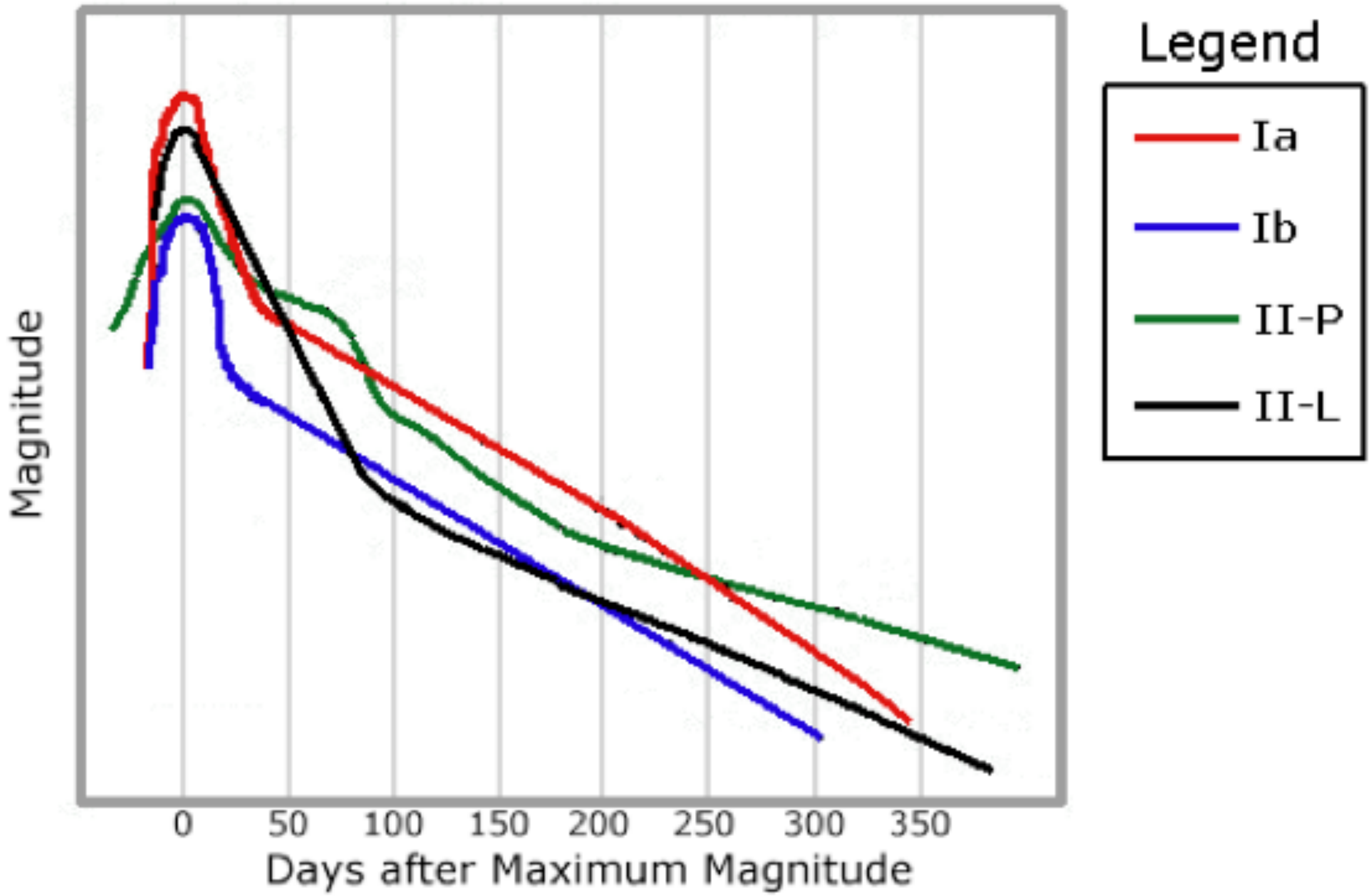
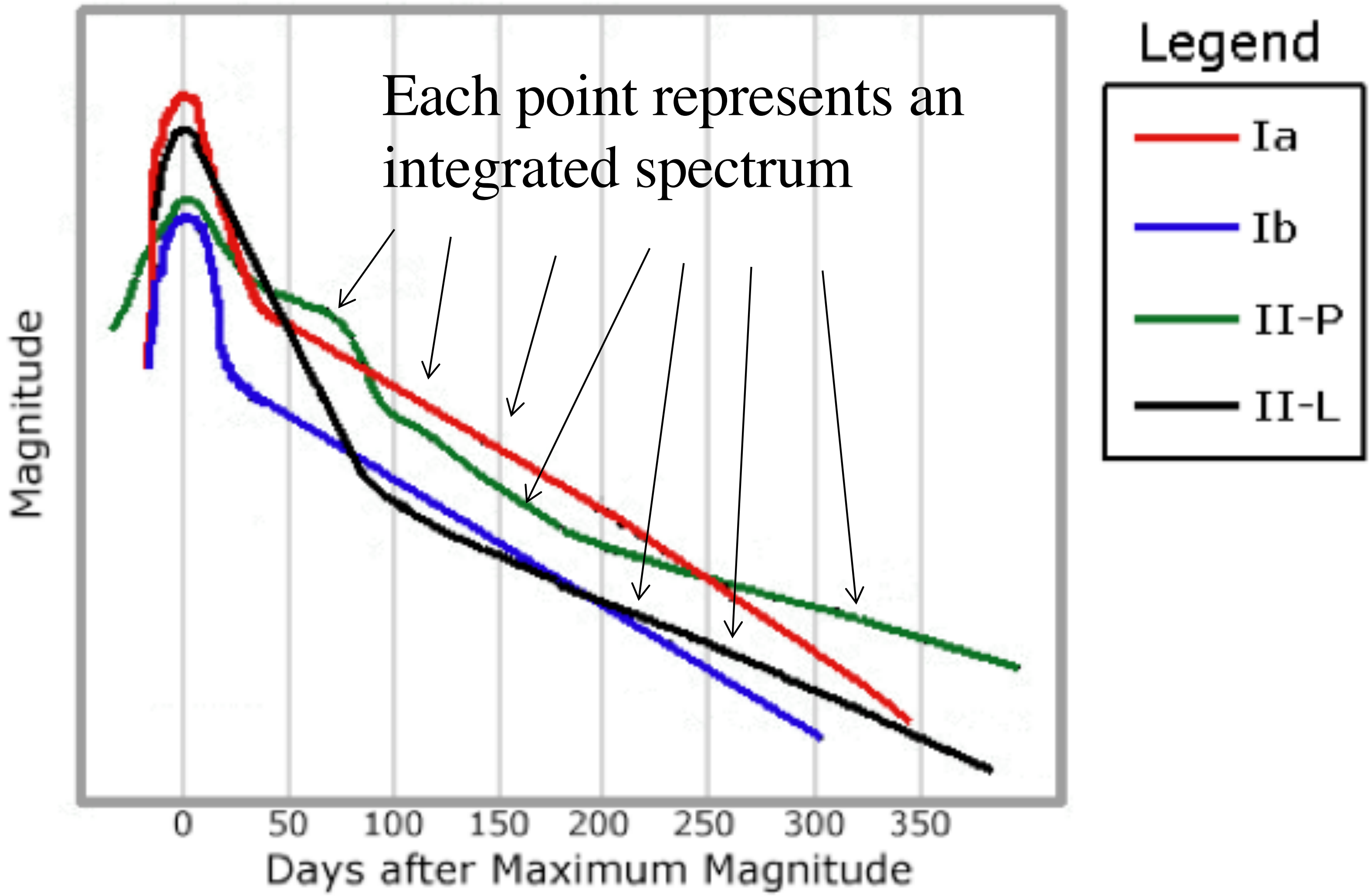


courtesy of Stephan Rosswog

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



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

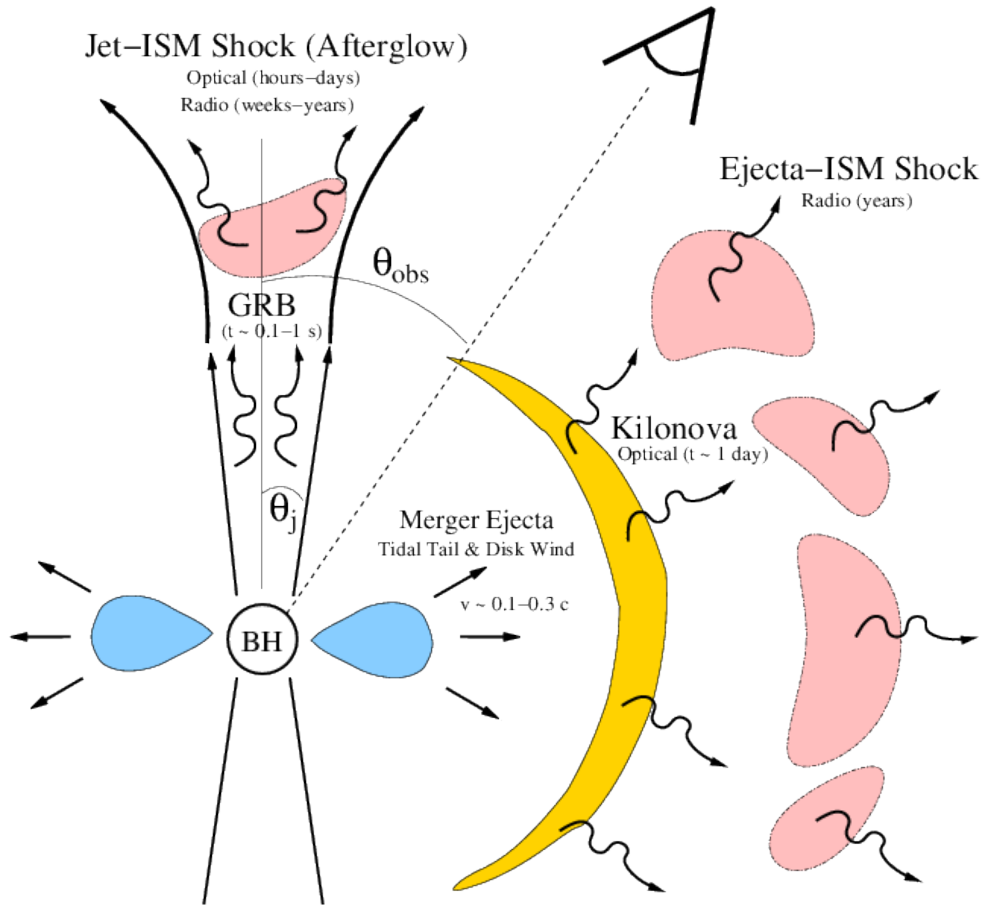
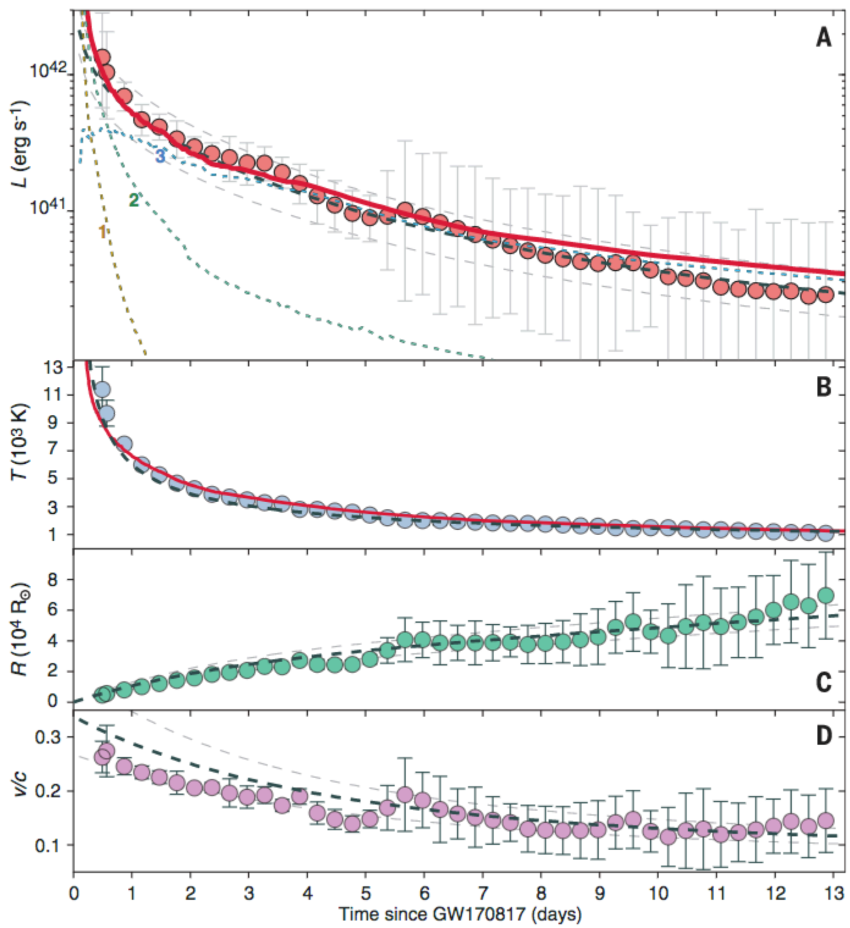


Image: B. Metzger and E. Berger

NSM light-curve ("macronova" or "kilonova") predictions

- 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?

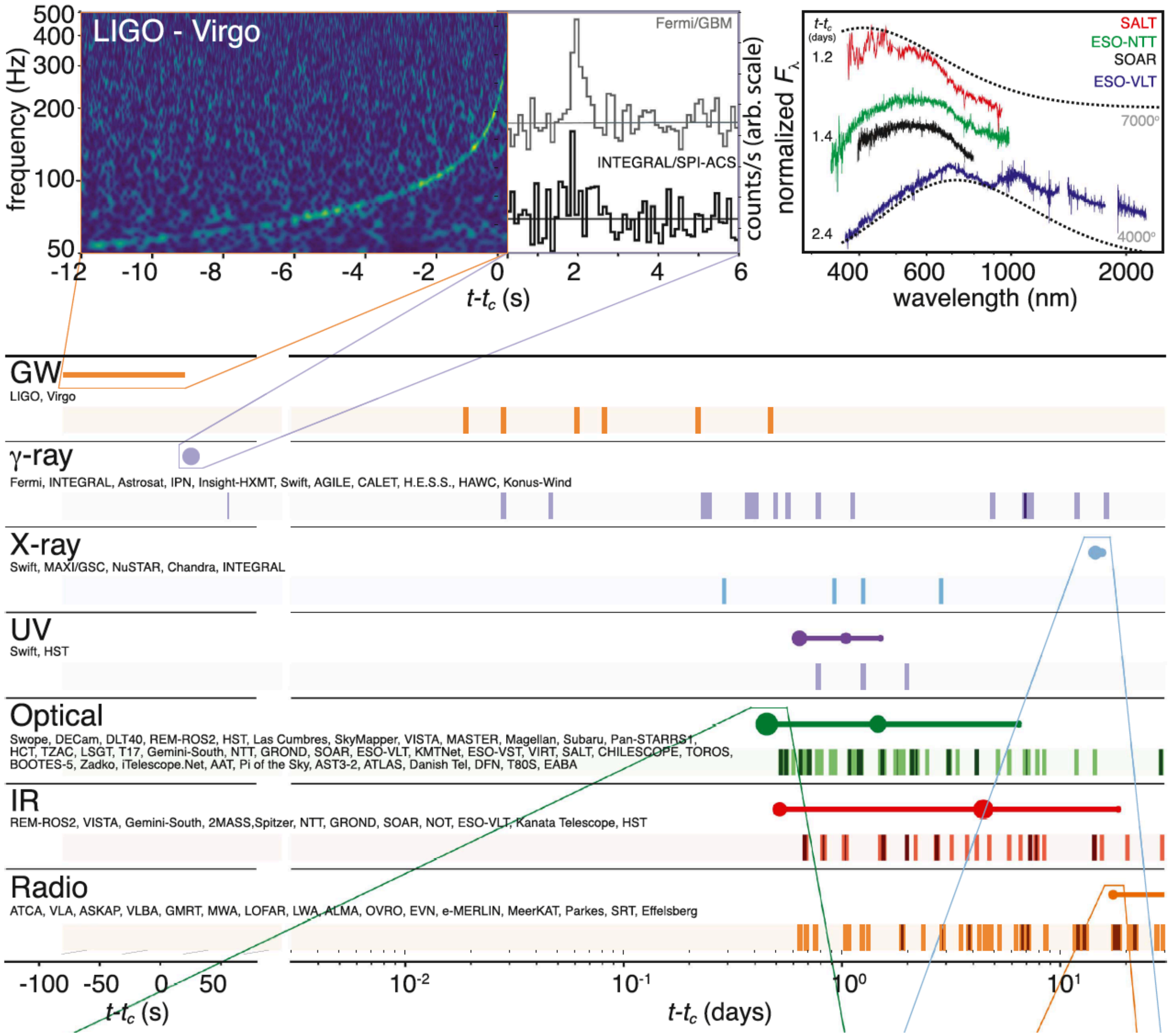


Light curve from GW170817

Image: M.M. Kasliwal, Science (2017)

First GW+EM multi-messenger observation

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



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Post-GW170817 interpretation of NSM observation

- Short (weak) GRB consistent with ~30^{o} 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

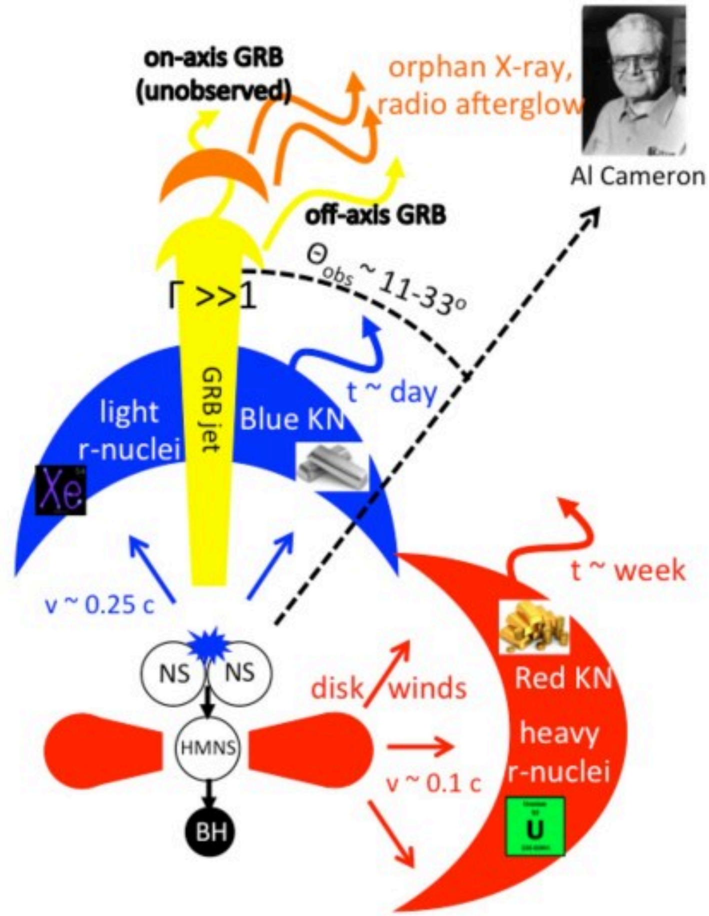

Image: B. Metzger

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

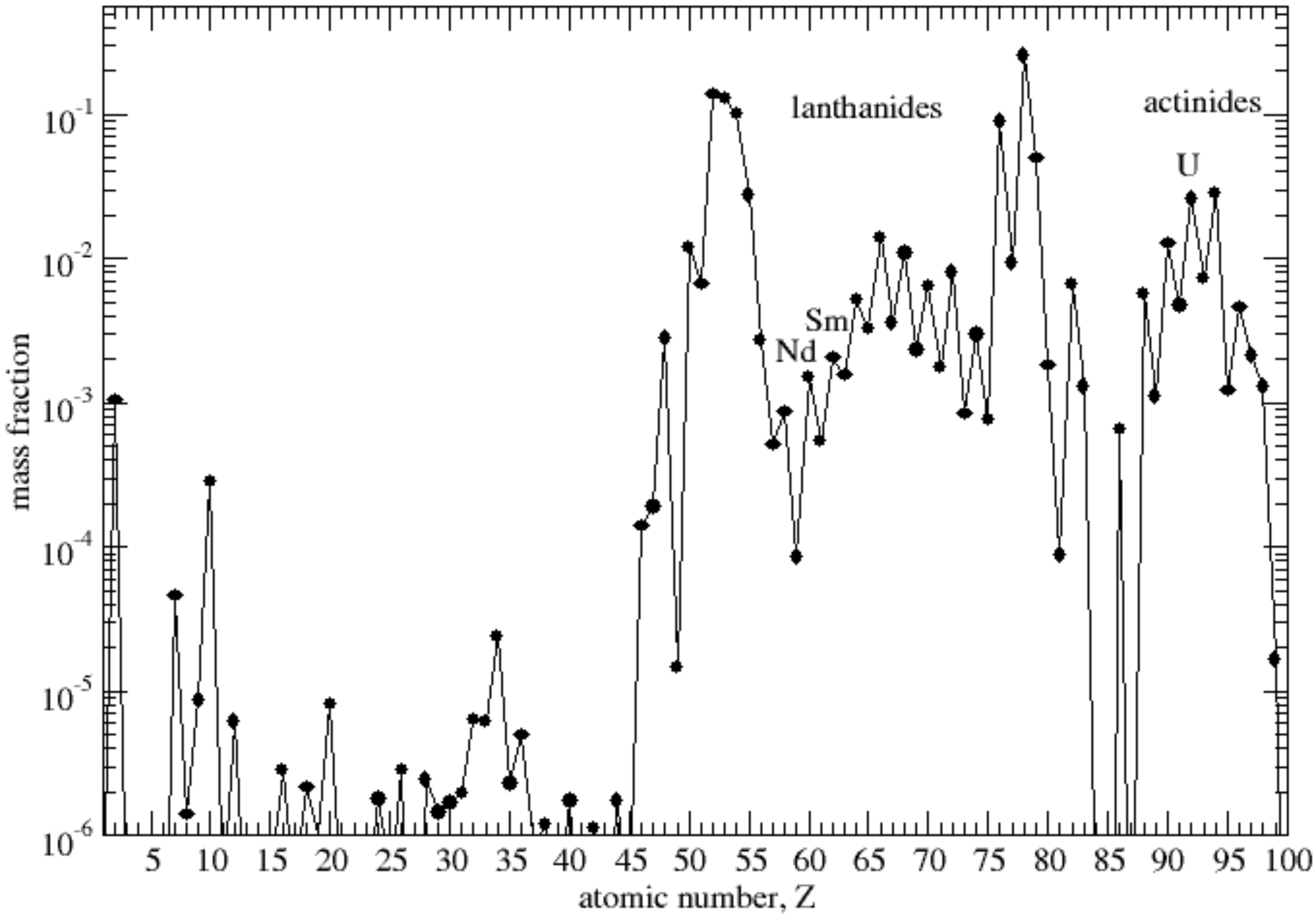
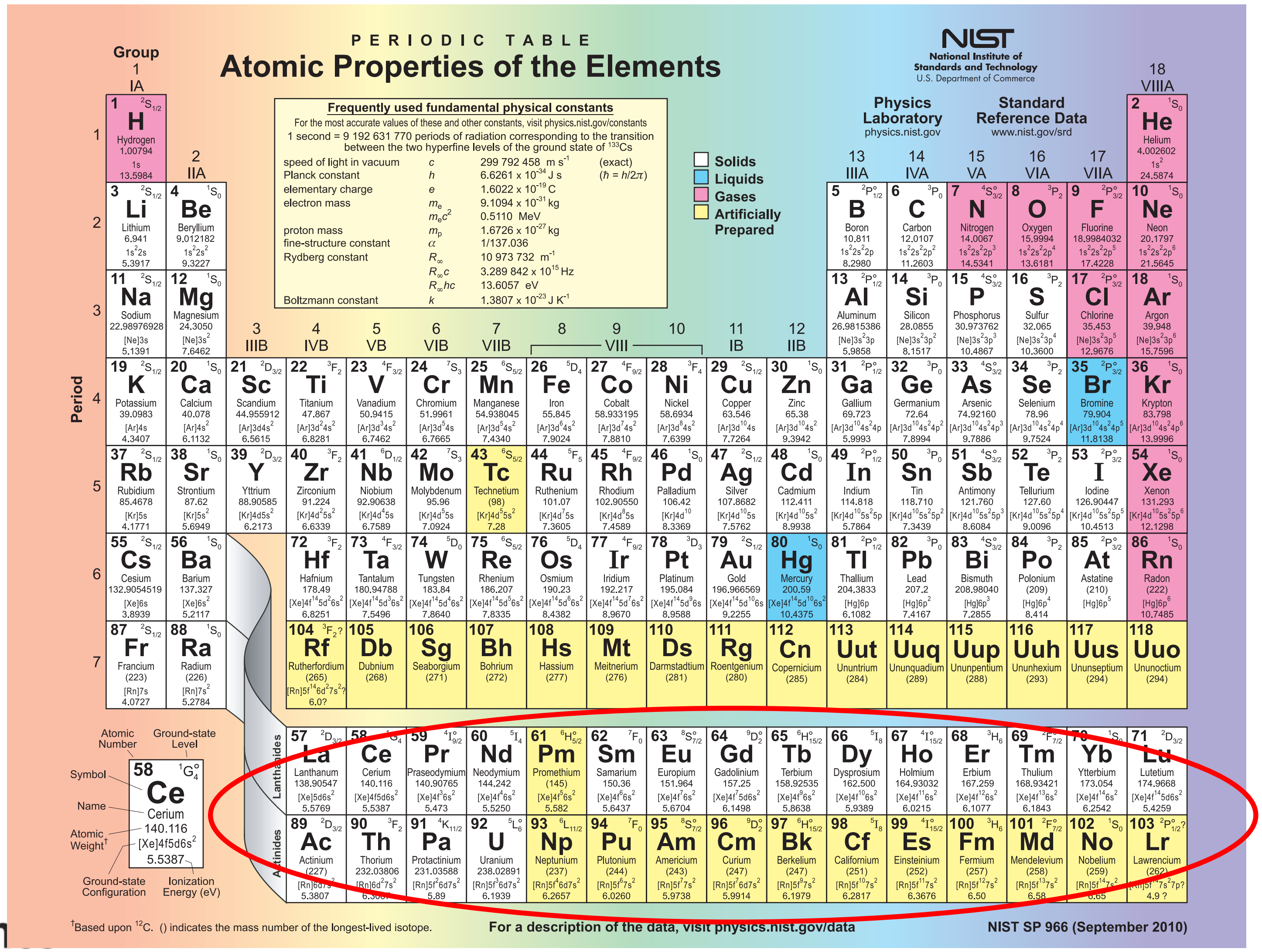


Image: O. Korobkin & S. Rosswog

Let's calculate some opacities: the lanthanides and actinides



The LANL Suite of Atomic Modeling Codes
[Overview: Fontes et al, JPB 48, 144014 (2015)]

Atomic Physics Codes → Atomic Models → ATOMIC

CATS: Cowan Code

RATS: relativistic

ACE: e^- excitation

GIPPER: ionization

http://aphysics2.lanl.gov/tempweb

fine-structure
config-average
UTAs
MUTAs
energy levels
gf-values
e^- excitation
e^- ionization
photoionization
autoionization

LTE or NLTE
atomic level
populations

spectral modeling
emission
absorption
transmission
power loss

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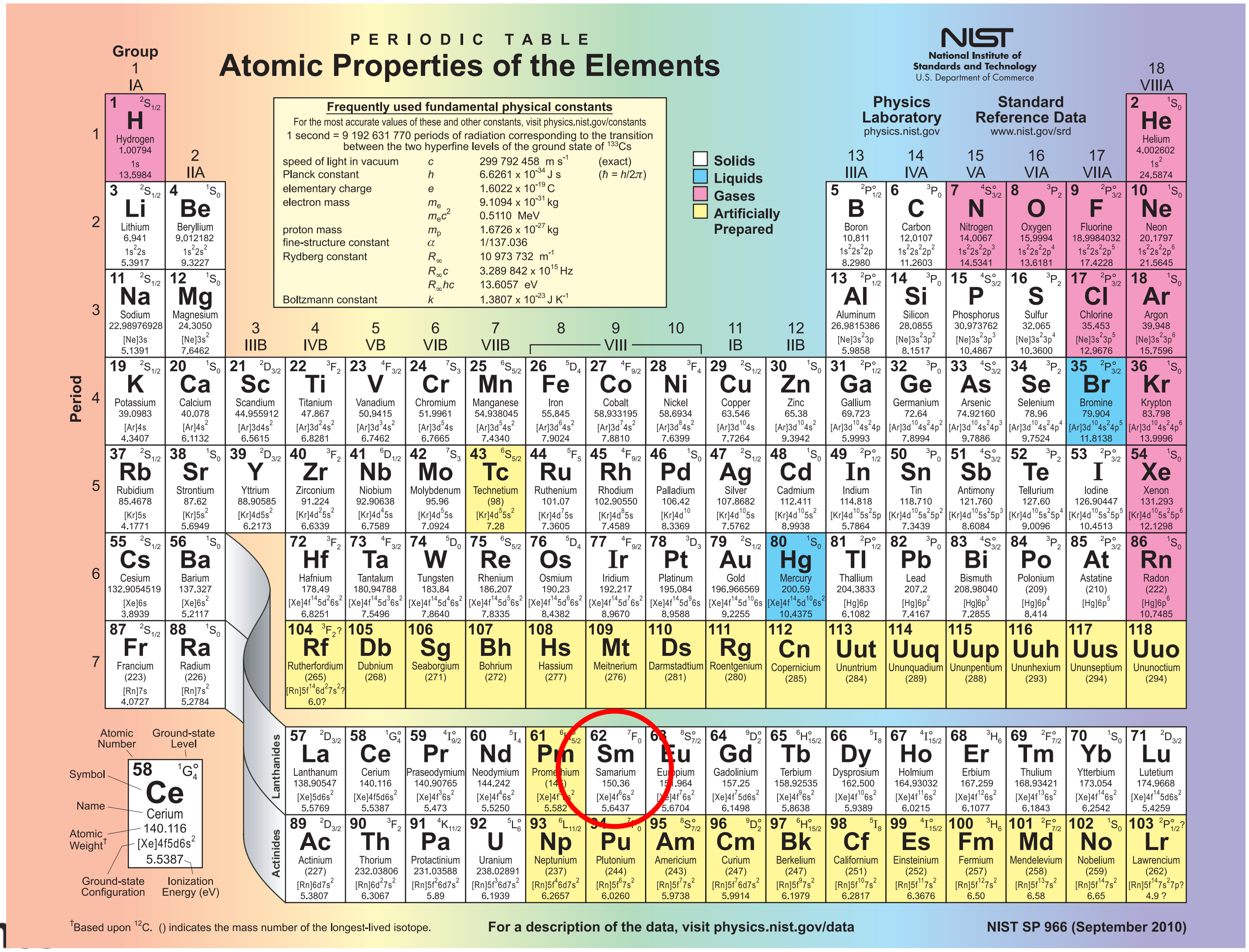
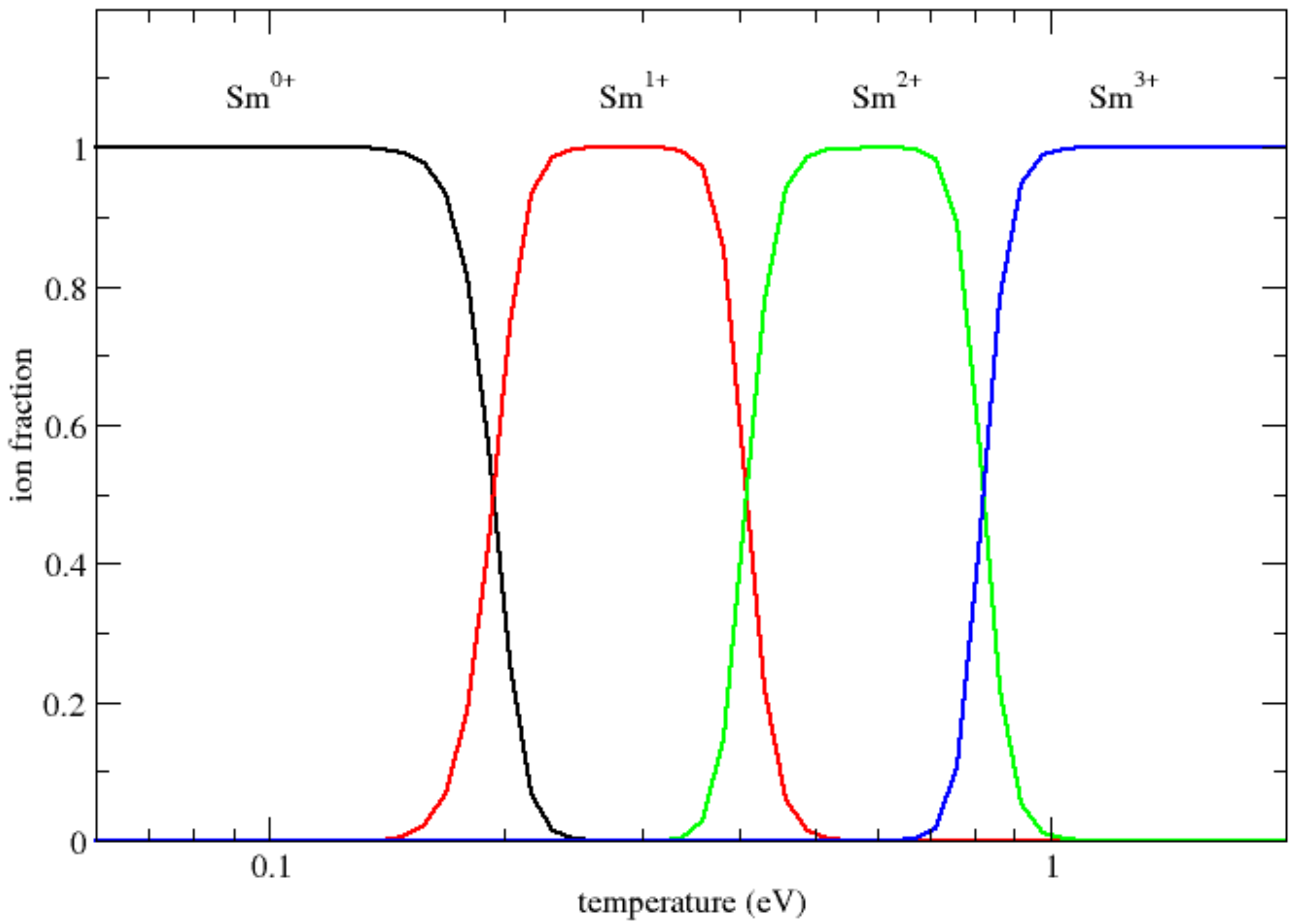
Conditions for neutron star mergers

- Initial conditions: T ≈ 1 MeV, $\rho \approx 10^{14}$ g/cm^3
- Light curve approaching peak brightness: T ≈ 1 eV, $\rho \approx 10^{-20} - 10^{-10}$ g/cm^3; (if <Z> ≈ 1, then $N_e \approx 10 - 10^{11}$ 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^{0+} - Sm^{3+})

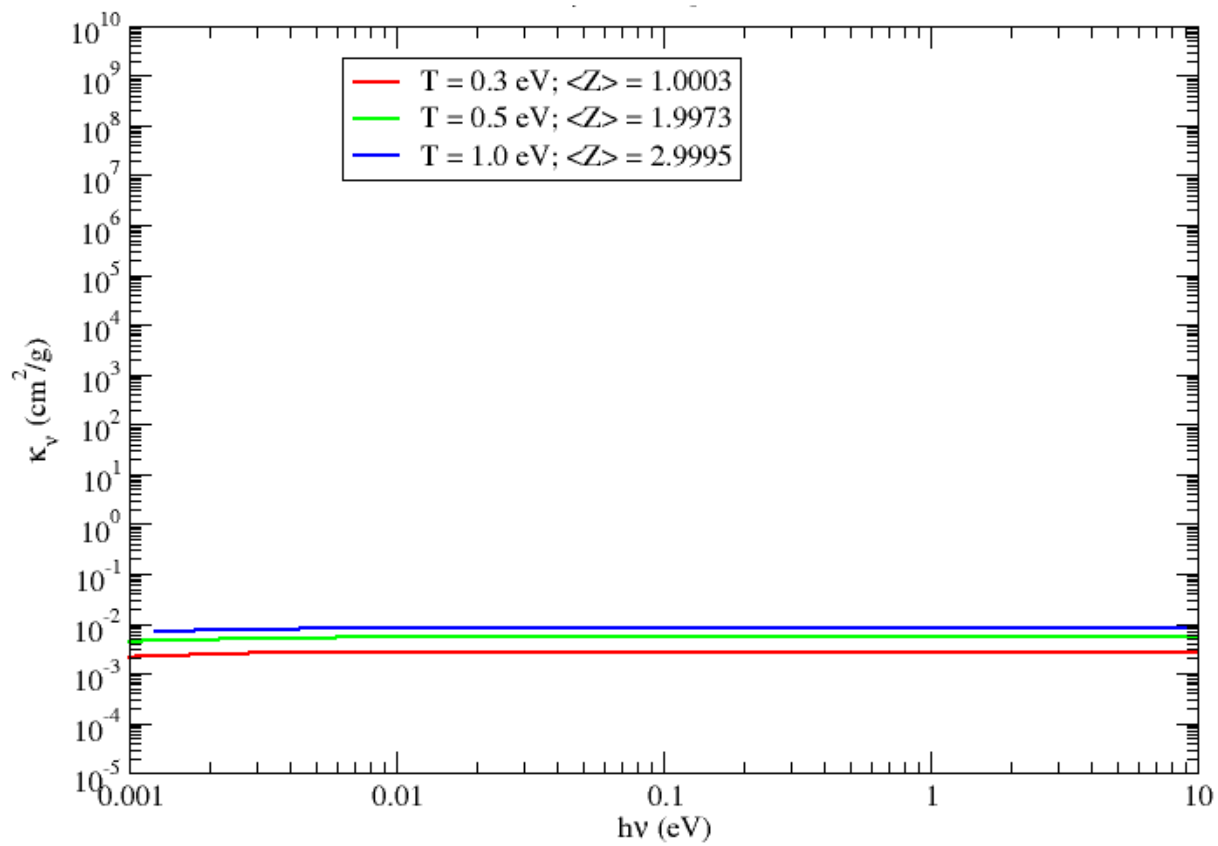


Sm (Z=62) LTE ionization balance ($\rho = 10^{-13}$ g/cm^3)



Consider LTE opacity of Sm (Z=62) at T ~ 0.5 eV and ρ = 10^{-13} g/cm^3

- A simple estimate of the opacity: assume Thomson/Compton scattering is the dominant mechanism
- Opacity ~ 0.4 <Z>/A (cm^2/g)

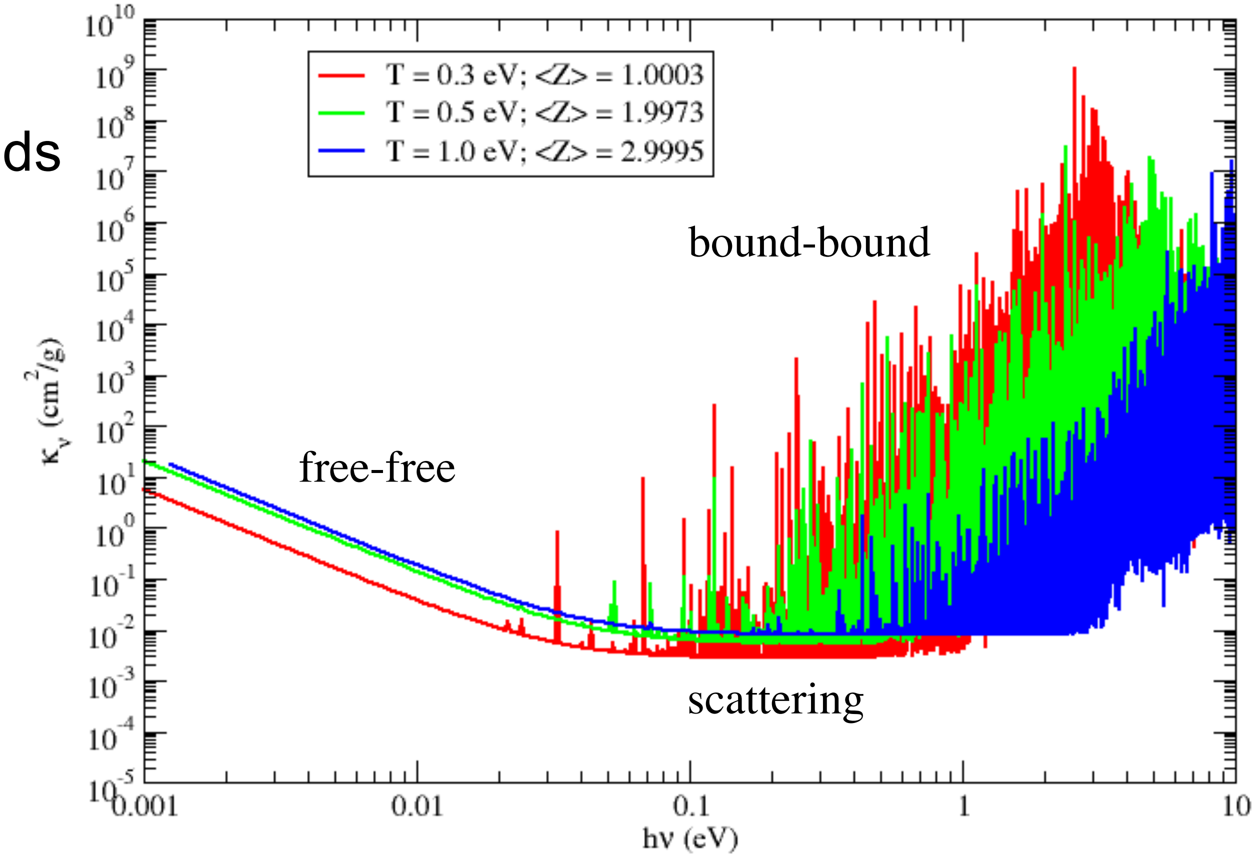


Consider opacity of Sm (Z=62) at T ~ 0.5 eV and $\rho = 10^{-13}$ g/cm³ (configuration list, assume [Xe])

- 25 configurations
- Sm^{0+}: $4f^6\ 6s^2$, $4f^5\ 5d\ 6s^2$, $4f^6\ 5d\ 6s$, $4f^6\ 5d^2$, $4f^5\ 5d\ 6s\ 6p$, $4f^6\ 5d\ 6p$, $4f^6\ 6s\ 6p$
- Sm^{1+}: $4f^6\ 6s$, $4f^6\ 5d$, $4f^6\ 6p$, $4f^5\ 5d^2$, $4f^5\ 5d\ 6s$, $4f^5\ 5d\ 6p$, $4f^5\ 6s\ 6p$
- Sm^{2+}: $4f^6$, $4f^5\ 6s$, $4f^5\ 5d$, $4f^5\ 6p$, $4f^4\ 5d$, $4f^4\ 5d\ 6s$, $4f^3\ 5d^2\ 6s$
- Sm^{3+}: $4f^5$, $4f^4\ 6s$, $4f^4\ 5d$, $4f^4\ 6p$
- ~ 10^5 energy levels
- ~ 3.3×10^8 radiative transitions

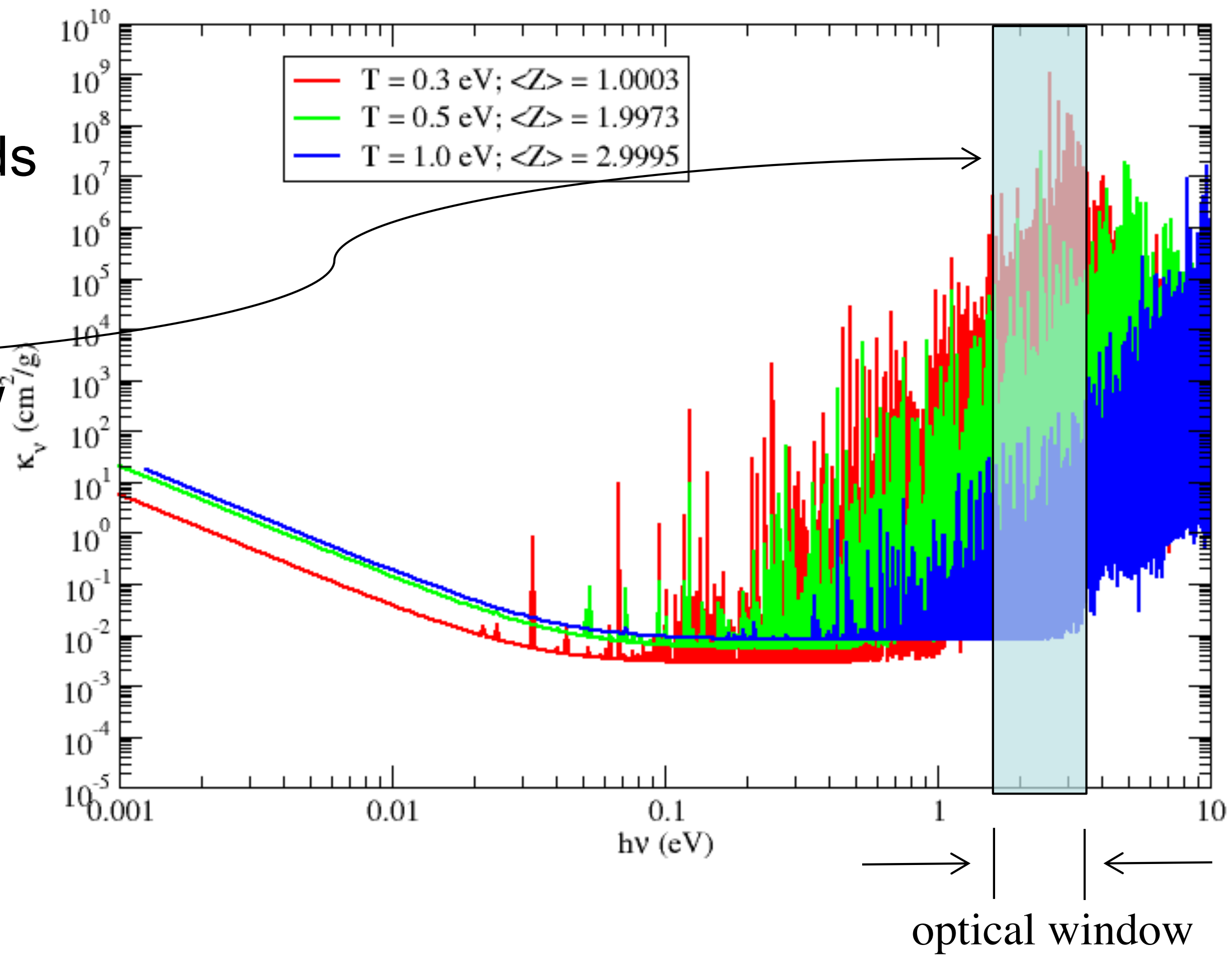
Consider LTE opacity of Sm (Z=62) at T ~ 0.5 eV and ρ = 10^{-13} g/cm^3

- 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 ~ 0.5 eV and ρ = 10^{-13} g/cm^3

- 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 ➔ infrared spectroscopy is required to see these objects



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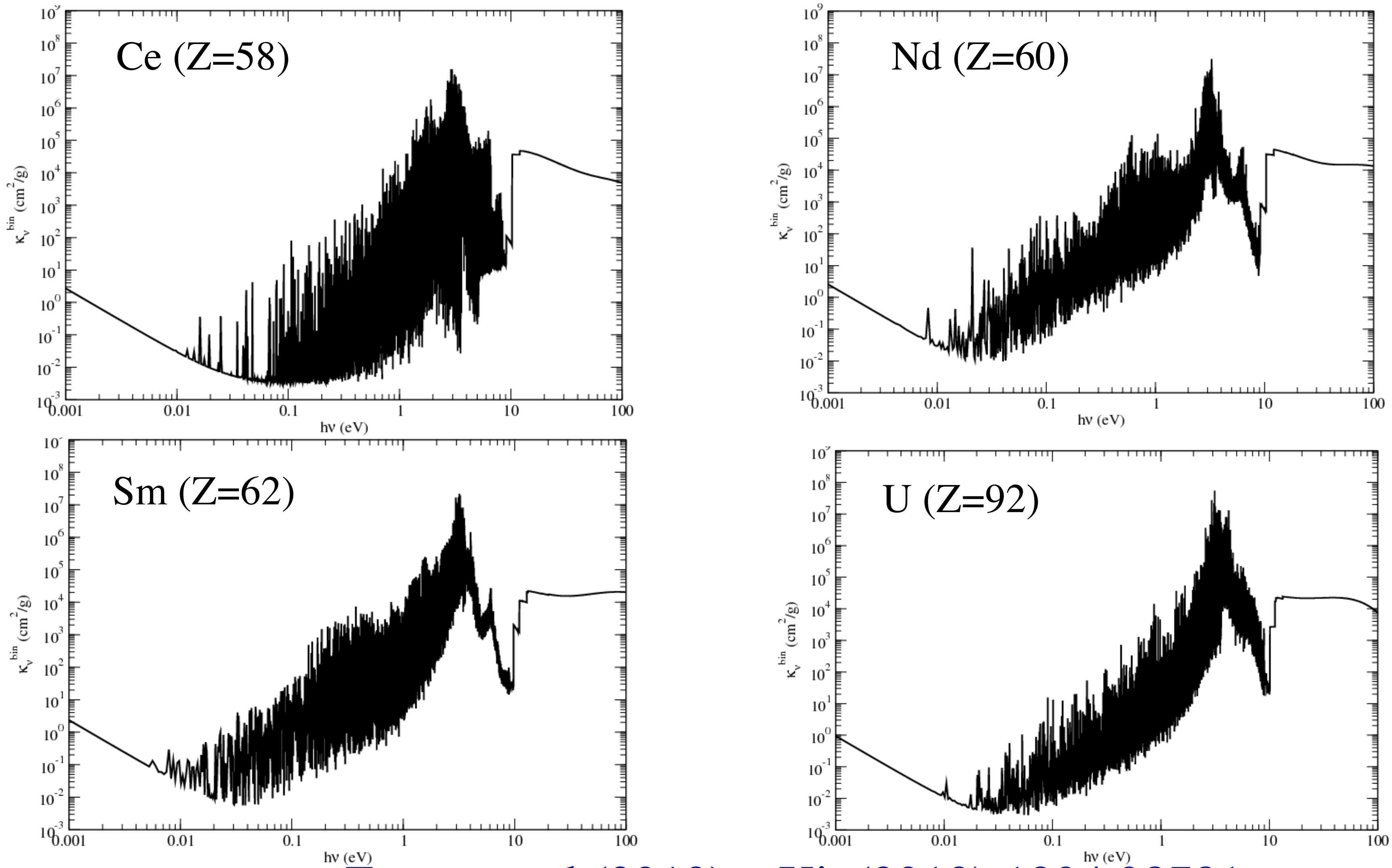
We have calculated LTE opacities of the lanthanide elements and also uranium



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

T = 0.3 eV (3,481 K), ρ = 10^{-13} g/cm^3

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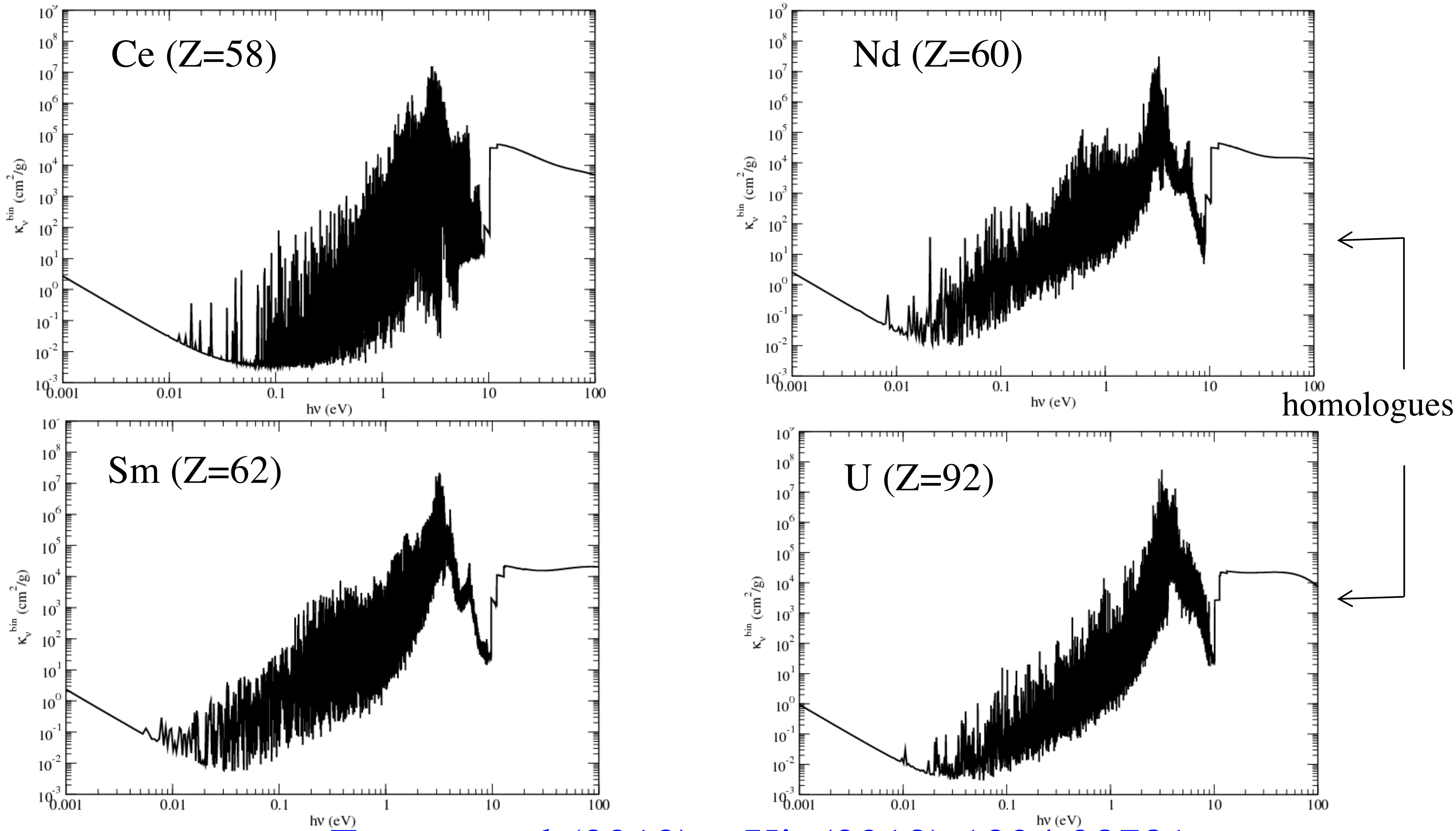
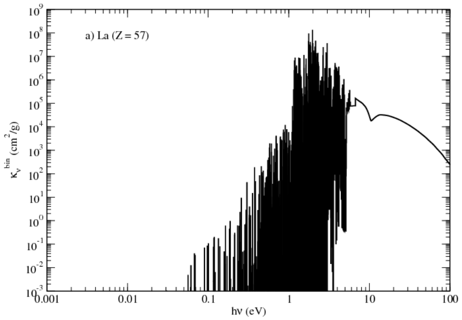


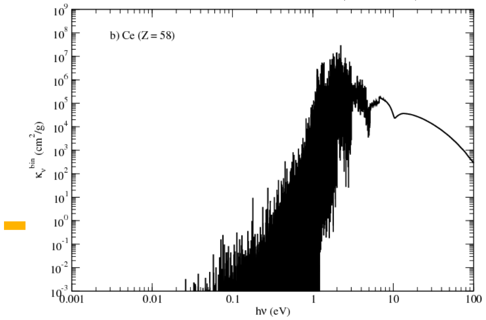
Fontes et al (2019) arXiv(2019):1904.08781

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

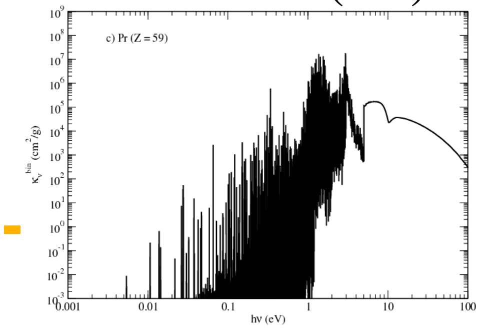
Z = 57 ($4f^{0}$)



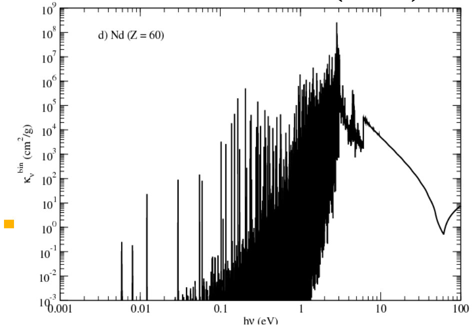
Z = 58 ($4f^{1}$)



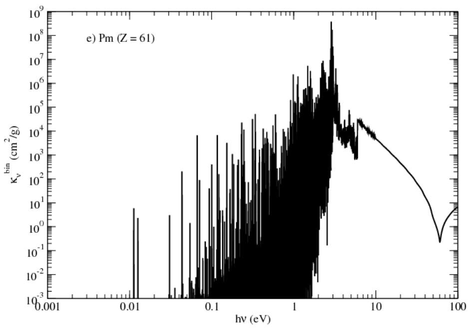
Z = 59 ($4f^{3}$)



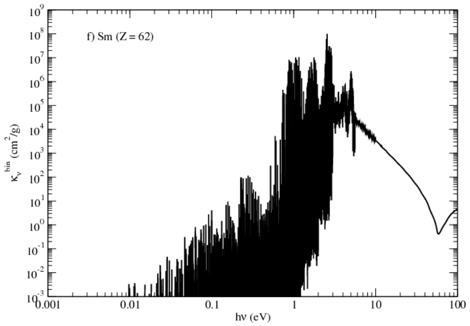
Z = 60 ($4f^{4}$)



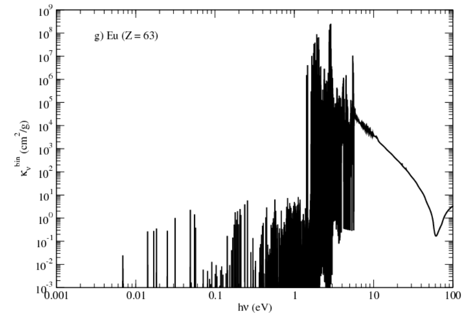
Z = 61 ($4f^{5}$)



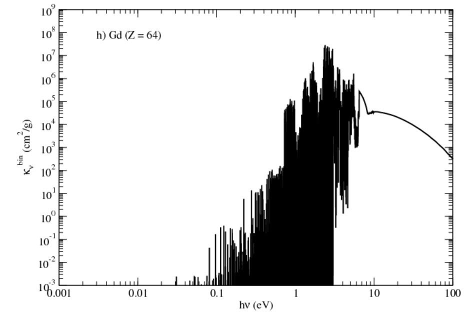
Z = 62 ($4f^{5}$)



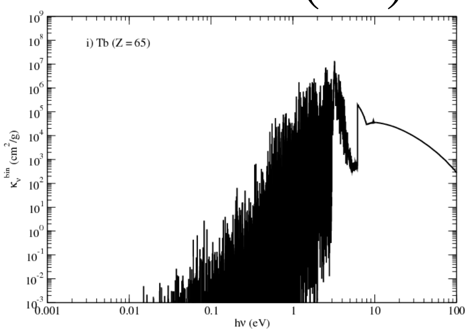
Z = 63 ($4f^{7}$)



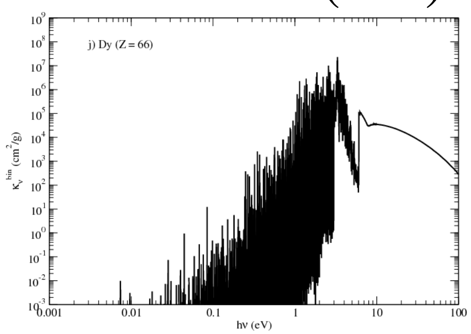
Z = 64 ($4f^{7}$)



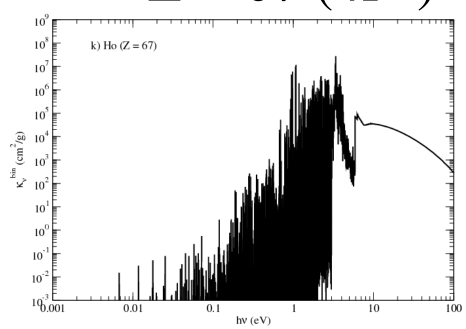
Z = 65 ($4f^{9}$)



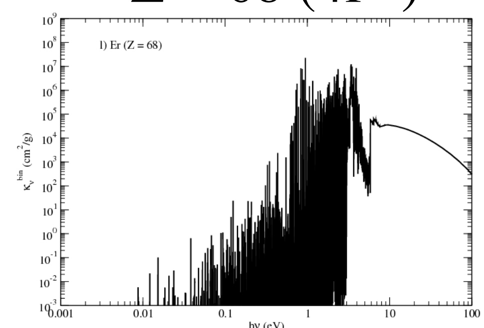
Z = 66 ($4f^{10}$)



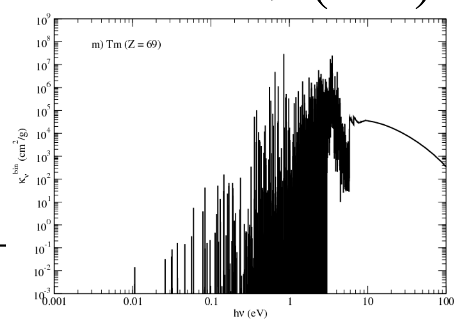
Z = 67 ($4f^{11}$)



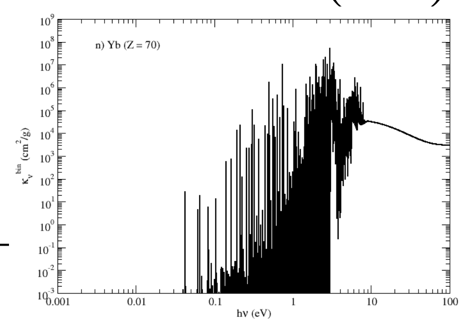
Z = 68 ($4f^{12}$)



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



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



T = 0.1 eV (~1,100 K); $\rho = 10^{-13}$ g/cm^3

(neutral stage is dominant)

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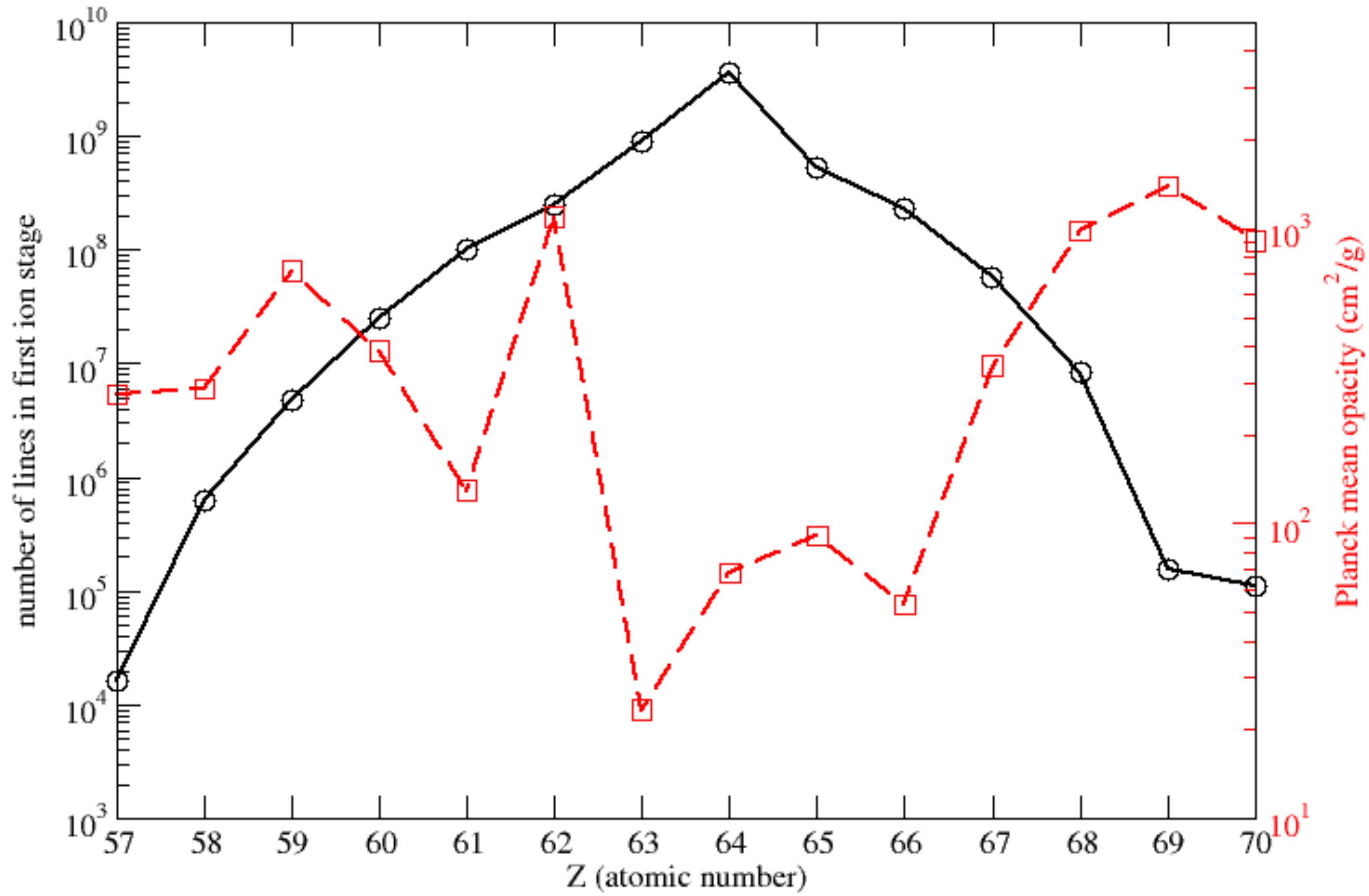
Complexity of bound electrons does not necessarily lead to high opacity



$T = 0.1$ eV (~1,100 K); $\rho = 10^{-13}$ g/cm^3

(neutral stage is dominant)

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

- LIGO is scheduled to restart in ~~September 2018~~ April 1, 2019 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!