# Observing the Production of Trans-iron Elements

**Erika M. Holmbeck***

NIC XVII School | 13 September 2023

*NHFP Hubble Fellow | eholmbeck.github.io


CARNEGIE SCIENCE | Observatories

# Nuclear Astrophysics

*“ to understand the origin of the chemical elements and isotopes, and the role of nuclear energy generation, in cosmic sources such as stars, supernovae, novae, and violent binary-star interactions ”*

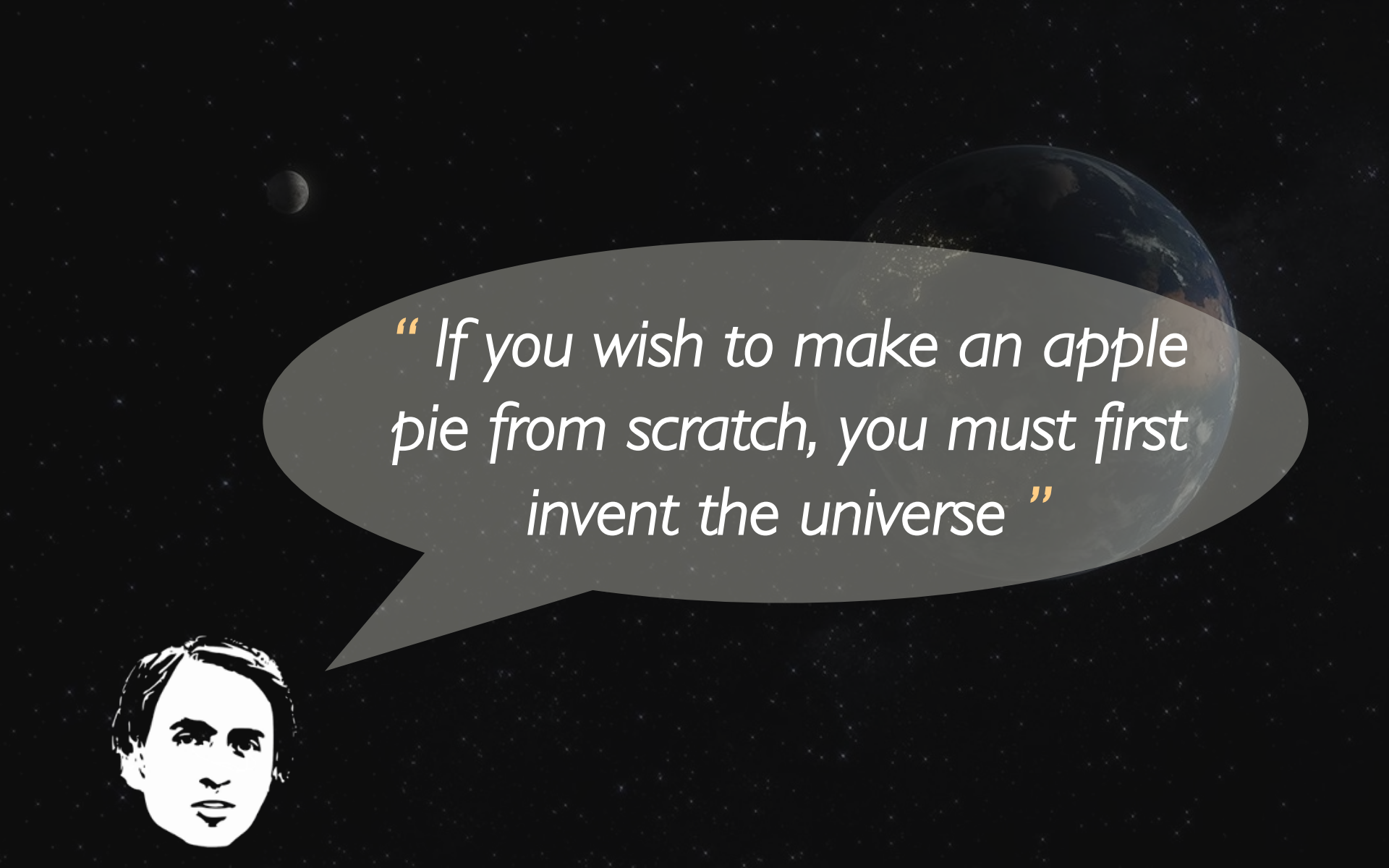
- Wikipedia

# Nuclear Astrophysics

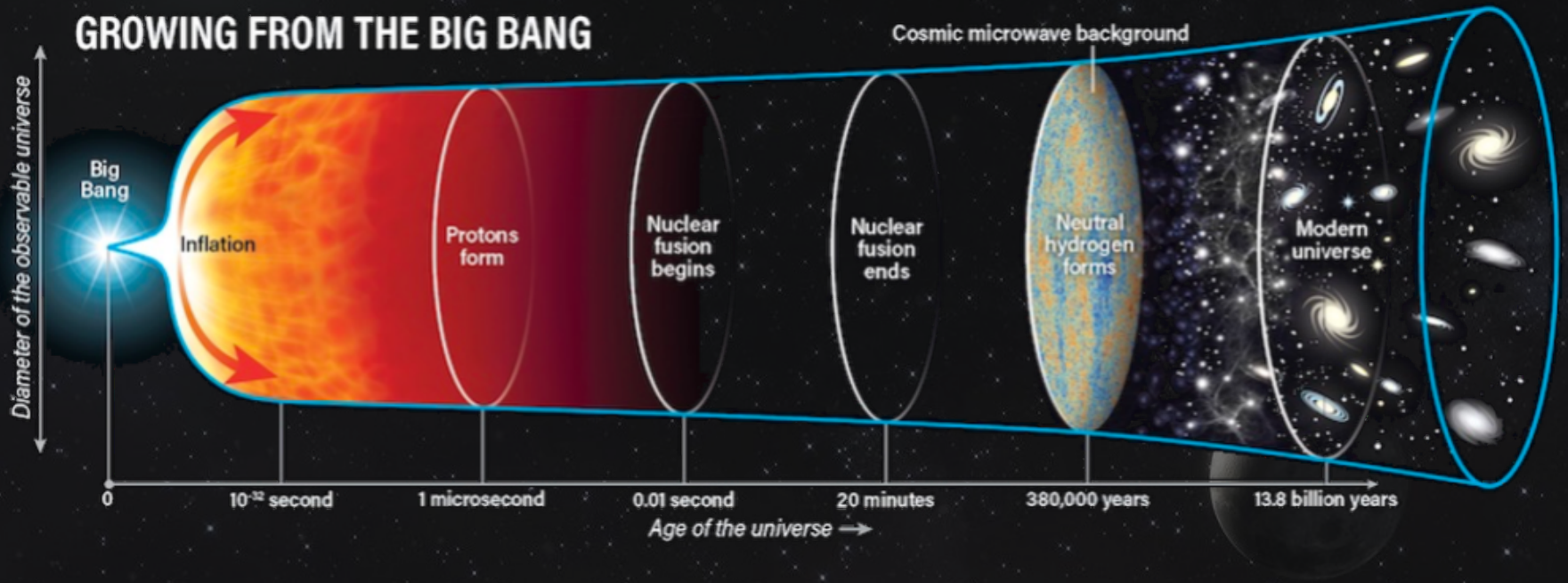
*" to understand the origin of the chemical elements and isotopes, and the role of nuclear energy generation, in cosmic sources such as stars, supernovae, novae, and violent binary-star interactions "*

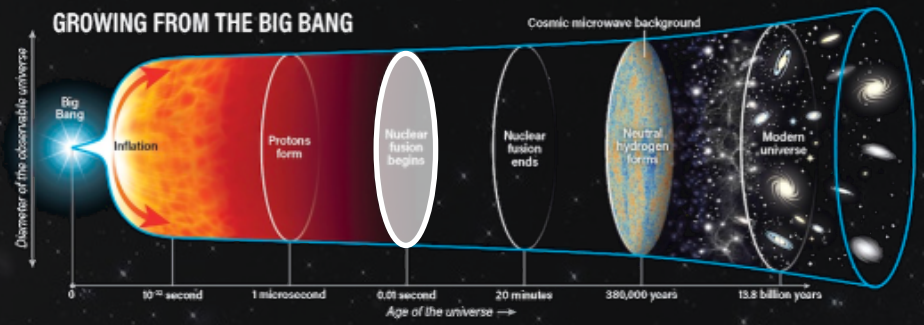
- Wikipedia

*" We are made of star-stuff "*


“ If you wish to make an apple pie from scratch, you must first invent the universe ”

# The Big Bang


GROWING FROM THE BIG BANG
Cosmic microwave background
Diameter of the observable universe
Big Bang
Inflation
Protons form
Nuclear fusion begins
Nuclear fusion ends
Neutral hydrogen forms
Modern universe
0
10⁻³² second
1 microsecond
0.01 second
20 minutes
380,000 years
13.8 billion years
Age of the universe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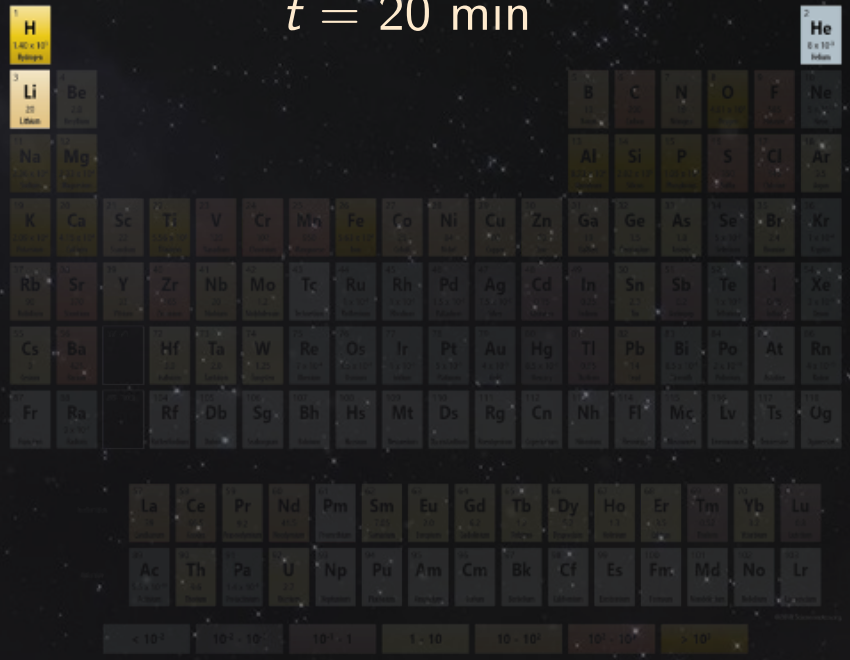
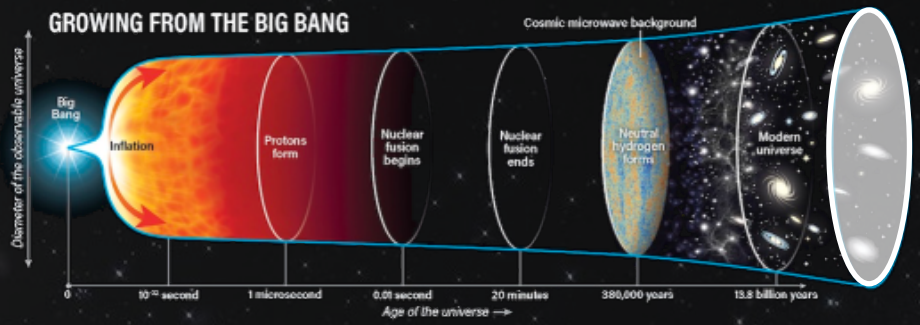
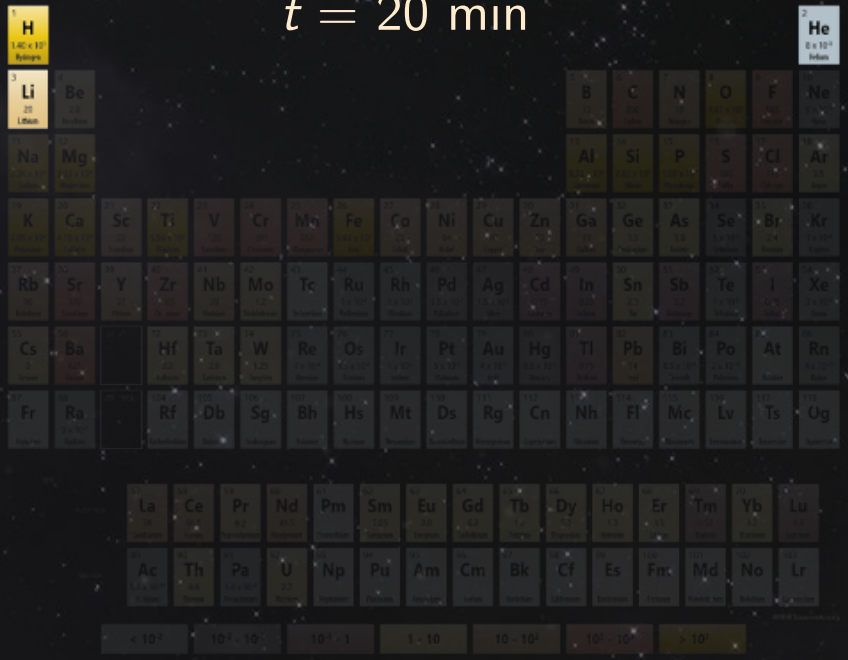
$t = 20$ min

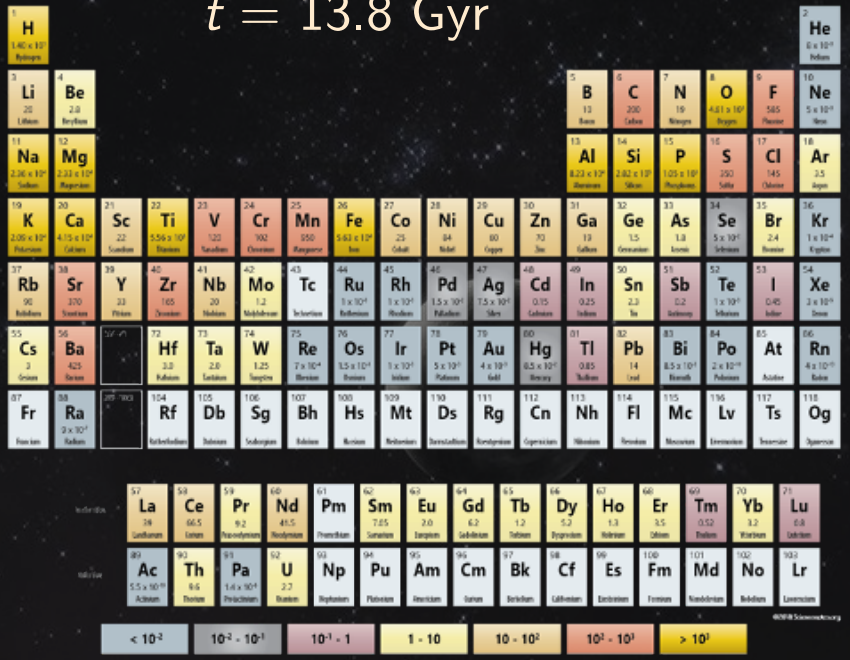


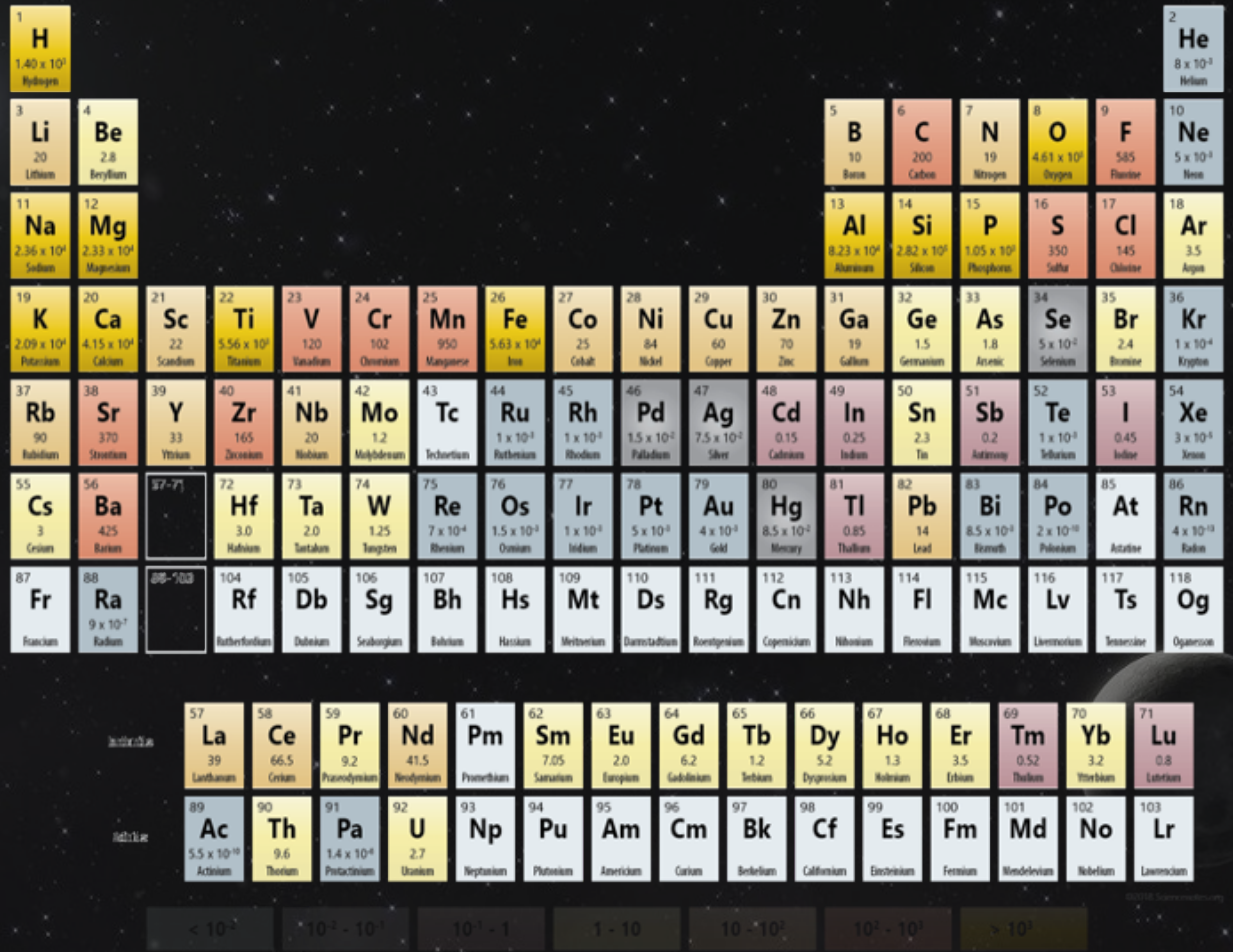



$t = 20$ min

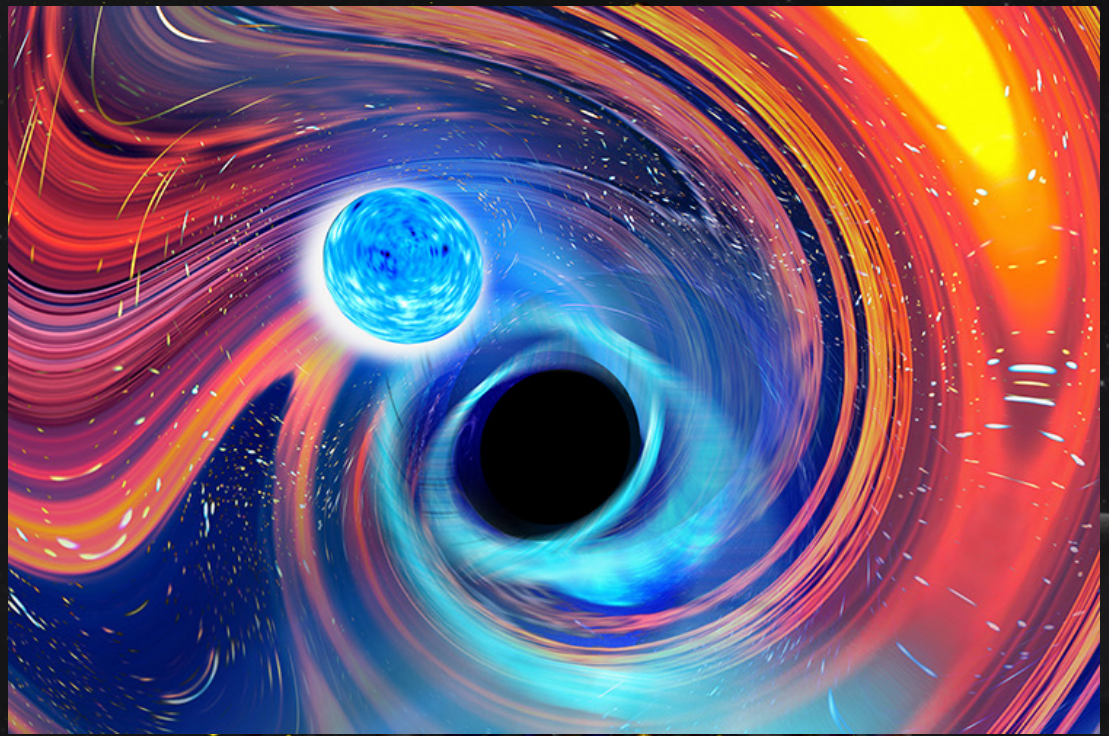


$t = 13.8$ Gyr



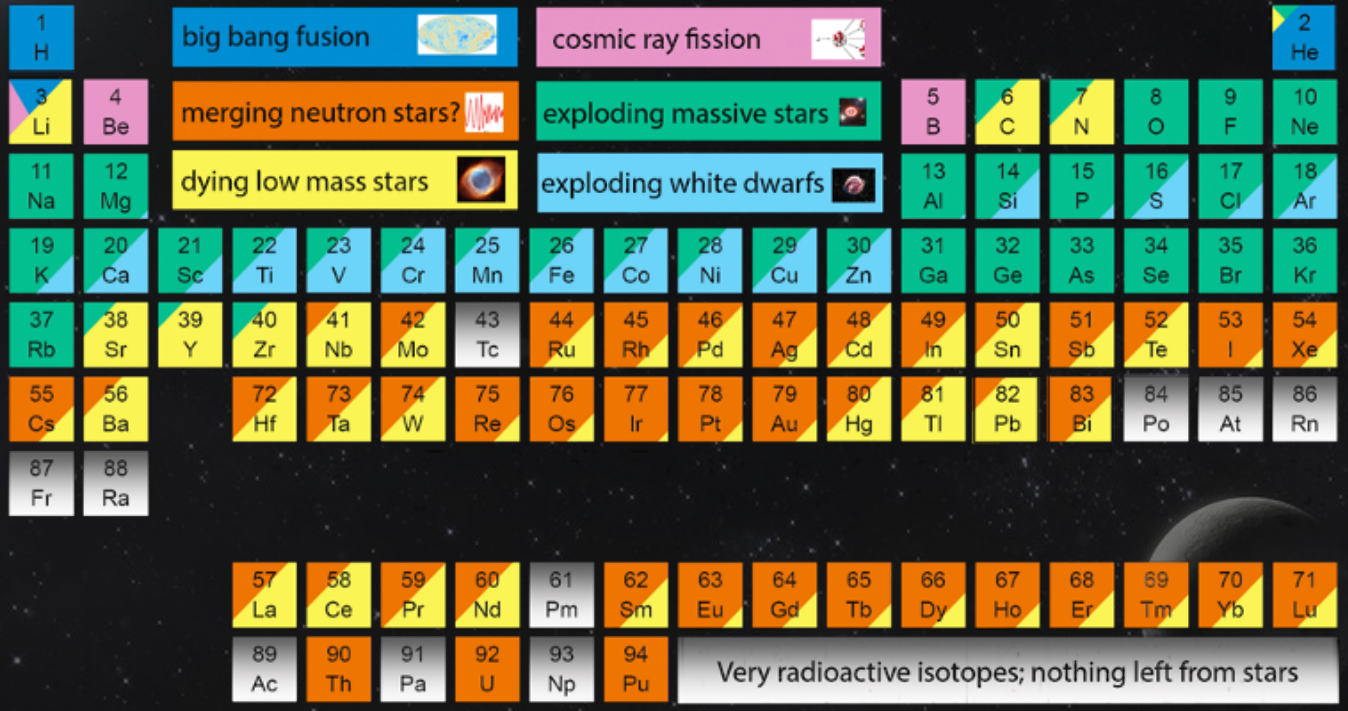

1 H 1.40 x 10³ Hydrogen
2 He 8 x 10⁻³ Helium
3 Li 20 Lithium
4 Be 2.8 Beryllium
5 B 10 Boron
6 C 200 Carbon
7 N 19 Nitrogen
8 O 4.61 x 10⁵ Oxygen
9 F 585 Fluorine
10 Ne 5 x 10⁻⁴ Neon
11 Na 2.36 x 10⁴ Sodium
12 Mg 2.33 x 10⁴ Magnesium
13 Al 8.23 x 10⁴ Aluminum
14 Si 2.82 x 10⁵ Silicon
15 P 1.05 x 10³ Phosphorus
16 S 350 Sulfur
17 Cl 145 Chlorine
18 Ar 3.5 Argon
19 K 2.09 x 10⁴ Potassium
20 Ca 4.15 x 10⁴ Calcium
21 Sc 22 Scandium
22 Ti 5.56 x 10³ Titanium
23 V 120 Vanadium
24 Cr 102 Chromium
25 Mn 950 Manganese
26 Fe 5.63 x 10⁴ Iron
27 Co 25 Cobalt
28 Ni 84 Nickel
29 Cu 60 Copper
30 Zn 70 Zinc
31 Ga 19 Gallium
32 Ge 1.5 Germanium
33 As 1.8 Arsenic
34 Se 5 x 10⁻² Selenium
35 Br 2.4 Bromine
36 Kr 1 x 10⁻⁴ Krypton
37 Rb 90 Rubidium
38 Sr 370 Strontium
39 Y 33 Yttrium
40 Zr 165 Zirconium
41 Nb 20 Niobium
42 Mo 1.2 Molybdenum
43 Tc Technetium
44 Ru 1 x 10⁻³ Ruthenium
45 Rh 1 x 10⁻³ Rhodium
46 Pd 1.5 x 10⁻² Palladium
47 Ag 7.5 x 10⁻² Silver
48 Cd 0.15 Cadmium
49 In 0.25 Indium
50 Sn 2.3 Tin
51 Sb 0.2 Antimony
52 Te 1 x 10⁻³ Tellurium
53 I 0.45 Iodine
54 Xe 3 x 10⁻⁴ Xenon
55 Cs 3 Cesium
56 Ba 425 Barium
57-71
72 Hf 3.0 Hafnium
73 Ta 2.0 Tantalum
74 W 1.25 Tungsten
75 Re 7 x 10⁻⁴ Rhenium
76 Os 1.5 x 10⁻³ Osmium
77 Ir 1 x 10⁻³ Iridium
78 Pt 5 x 10⁻³ Platinum
79 Au 4 x 10⁻³ Gold
80 Hg 8.5 x 10⁻² Mercury
81 Tl 0.85 Thallium
82 Pb 14 Lead
83 Bi 8.5 x 10⁻³ Bismuth
84 Po 2 x 10⁻¹⁰ Polonium
85 At Astatine
86 Rn 4 x 10⁻¹³ Radon
87 Fr Francium
88 Ra 9 x 10⁻⁷ Radium
89-103
104 Rf Rutherfordium
105 Db Dubnium
106 Sg Seaborgium
107 Bh Bohrium
108 Hs Hassium
109 Mt Meitnerium
110 Ds Darmstadtium
111 Rg Roentgenium
112 Cn Copernicium
113 Nh Nihonium
114 Fl Flerovium
115 Mc Moscovium
116 Lv Livermorium
117 Ts Tennessine
118 Og Oganesson
57 La 39 Lanthanum
58 Ce 66.5 Cerium
59 Pr 9.2 Praseodymium
60 Nd 41.5 Neodymium
61 Pm Promethium
62 Sm 7.05 Samarium
63 Eu 2.0 Europium
64 Gd 6.2 Gadolinium
65 Tb 1.2 Terbium
66 Dy 5.2 Dysprosium
67 Ho 1.3 Holmium
68 Er 3.5 Erbium
69 Tm 0.52 Thulium
70 Yb 3.2 Ytterbium
71 Lu 0.8 Lutetium
89 Ac 5.5 x 10⁻¹⁰ Actinium
90 Th 9.6 Thorium
91 Pa 1.4 x 10⁻⁶ Protactinium
92 U 2.7 Uranium
93 Np Neptunium
94 Pu Plutonium
95 Am Americium
96 Cm Curium
97 Bk Berkelium
98 Cf Californium
99 Es Einsteinium
100 Fm Fermium
101 Md Mendelevium
102 No Nobelium
103 Lr Lawrencium
< 10⁻¹
10⁻¹ - 10⁰
10⁰ - 1
1 - 10
10 - 10²
10² - 10³
> 10³

# Elements are created in the lives and deaths of stars



Compact object mergers

# Elements are created in the lives and deaths of stars




Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova

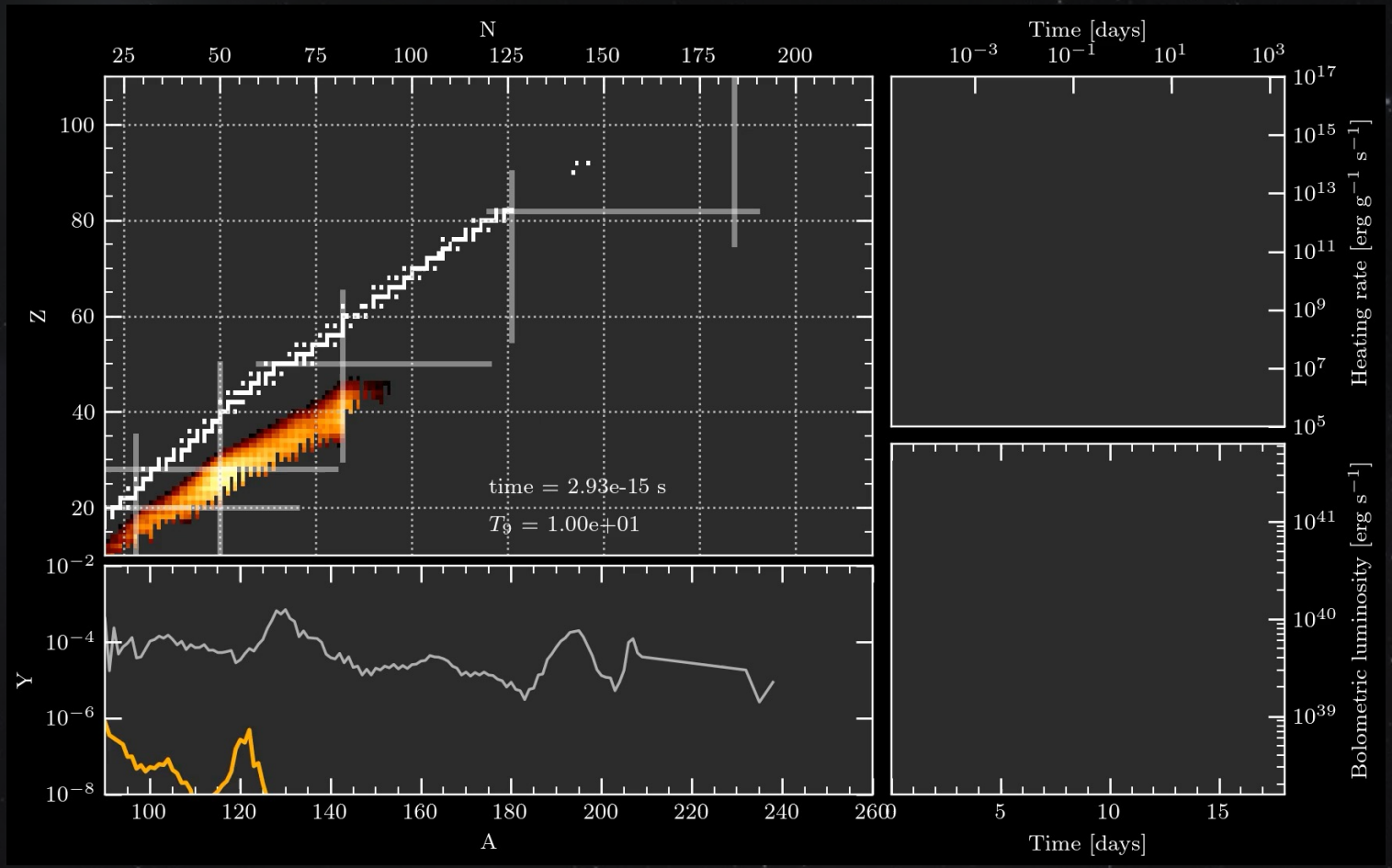
*See lectures by M. Mumpower and W. Aoki*

Elements are created in the ***deaths*** of stars

r-process

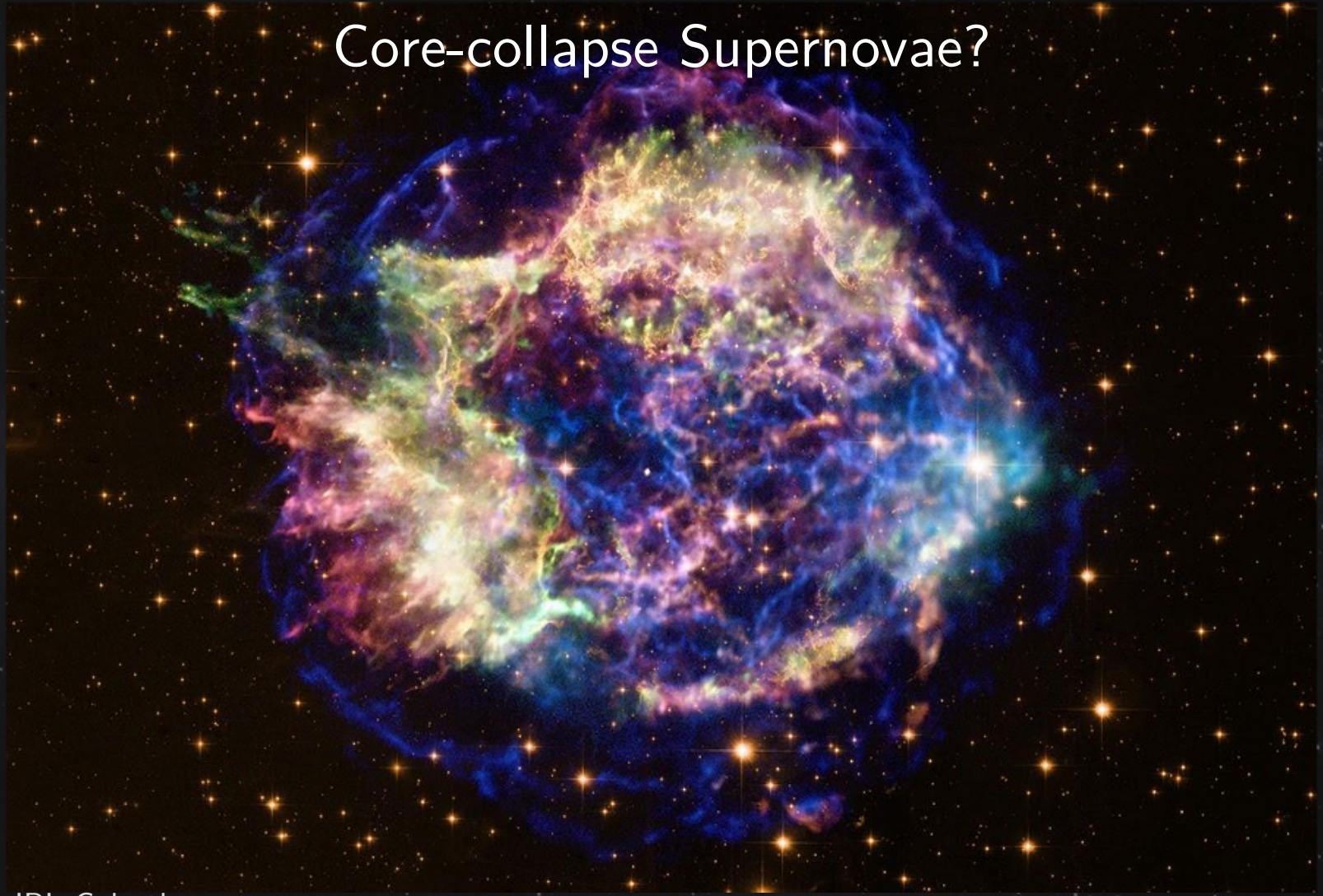
Elements are created in the ***deaths*** of stars

# Rapid neutron-capture nucleosynthesis is a major producer of trans-iron elements, but requires lots of theoretical data



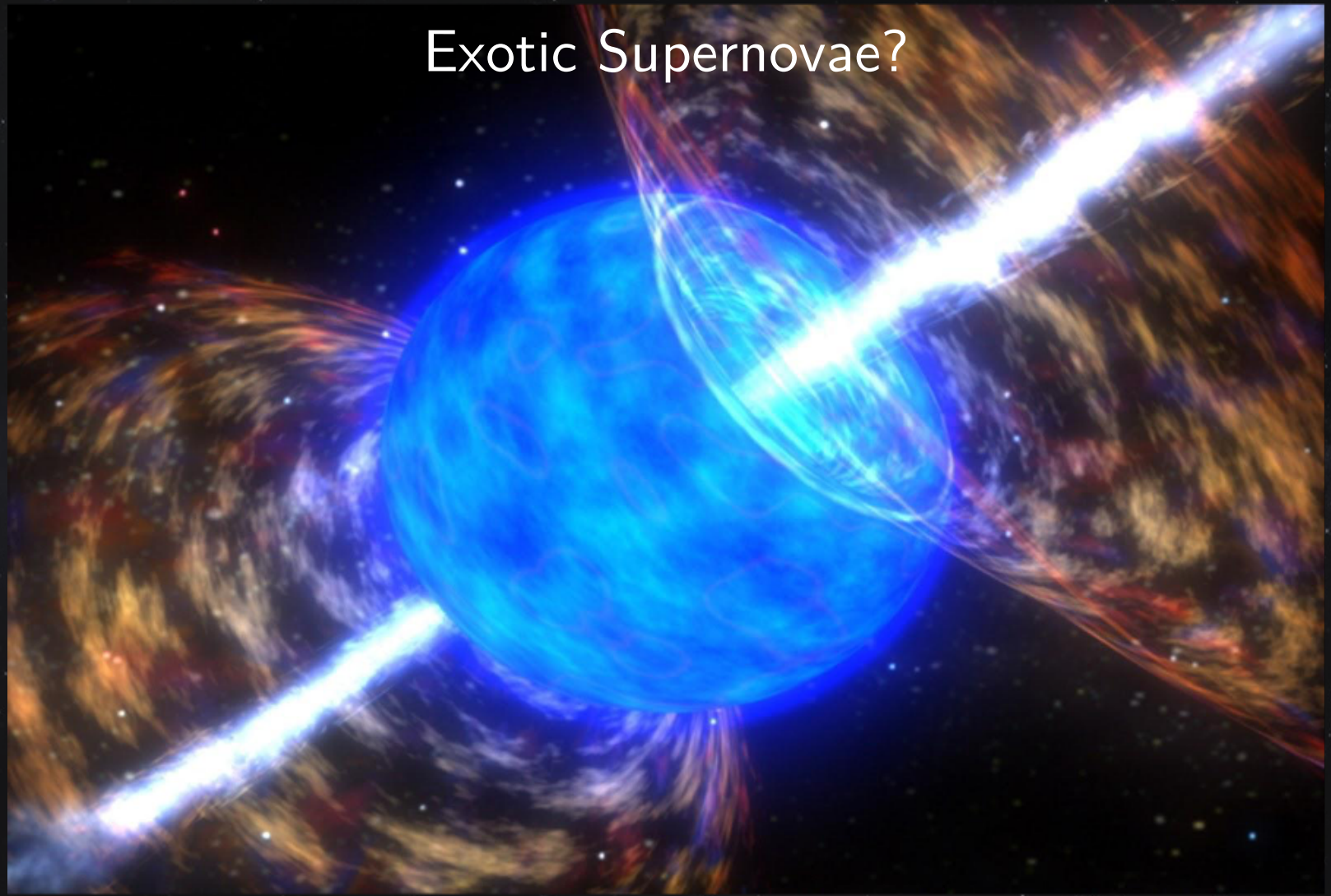

PRISM (Sprouse & Mumpower)

# Core-collapse Supernovae?



NASA / JPL-Caltech

# Exotic Supernovae?



NASA / SkyWork Digital

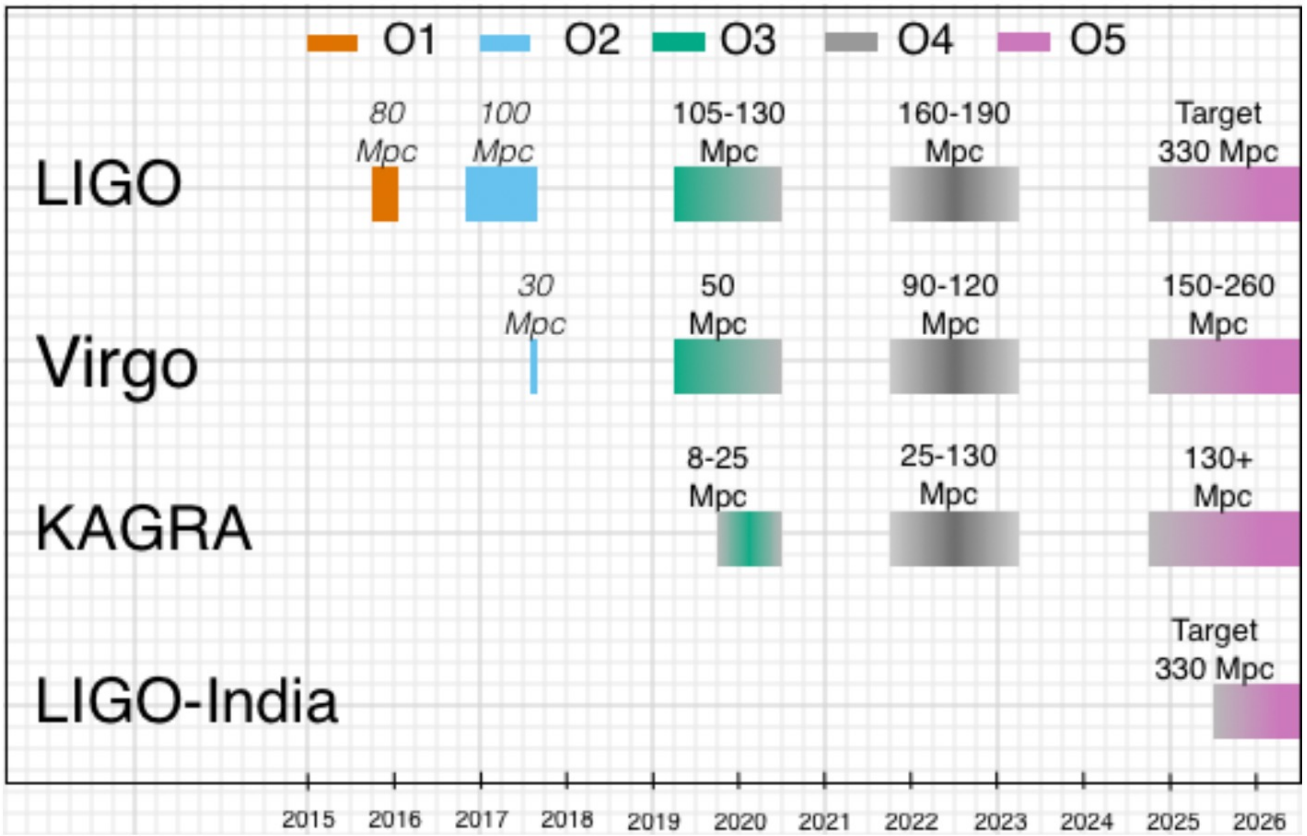
# Neutron Star Mergers

Credit: NASA

# A gravitational wave observatory measures distortions of space by timing the delay in travelled light

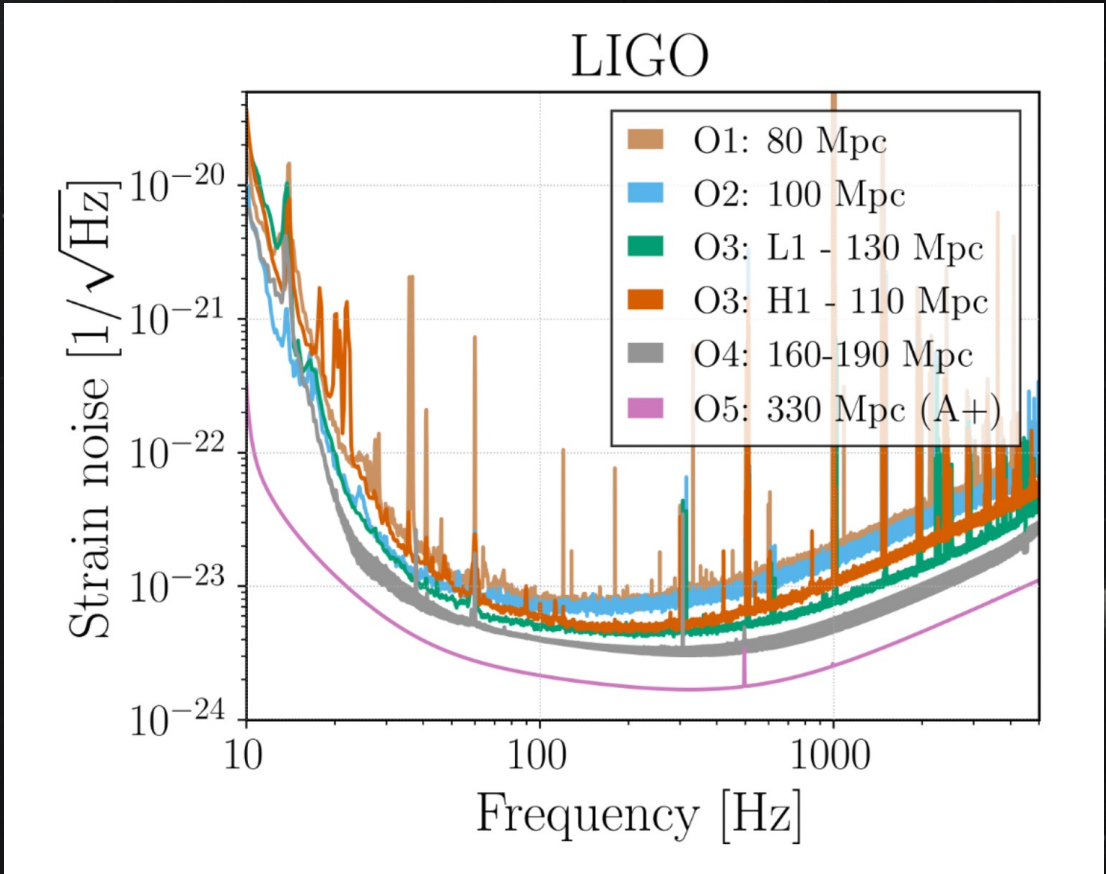

Credit: Caltech

# Past, present, and future observing runs



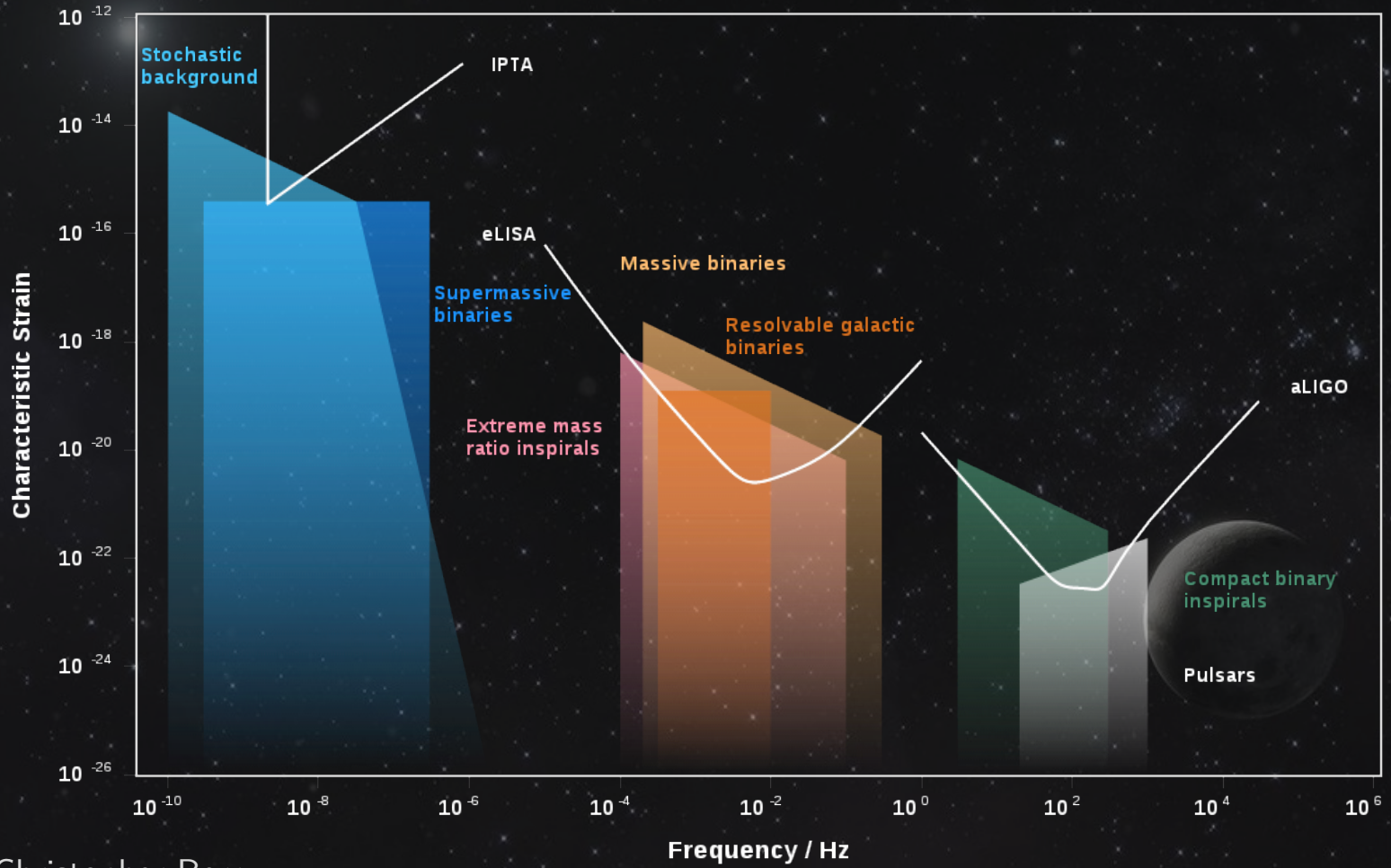

Credit: LVK Collaboration

# LIGO sensitivity



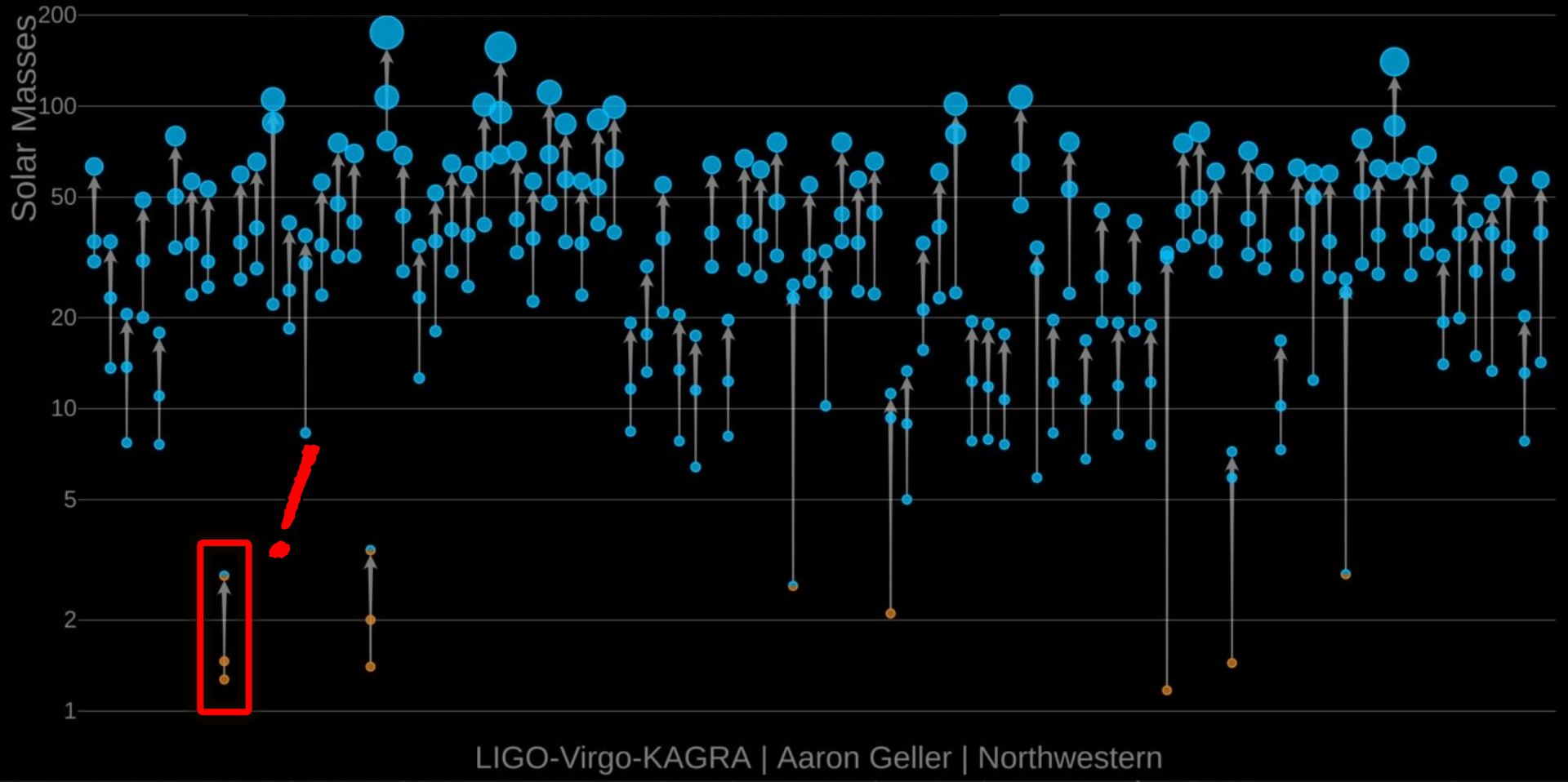

Credit: LVK Collaboration

# What can be detected by gravitational waves?

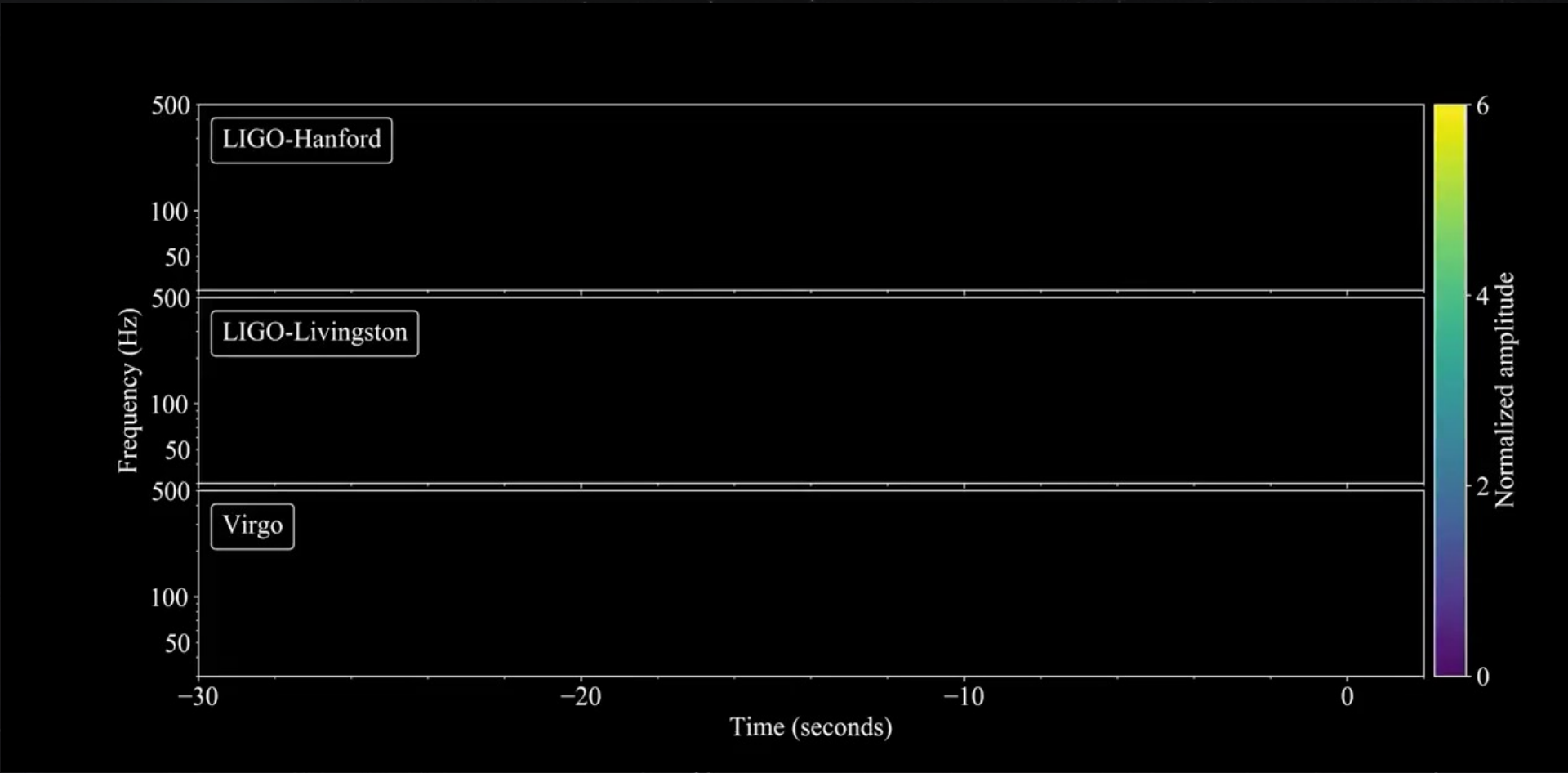



Credit: Christopher Berry

# Masses in the Stellar Graveyard

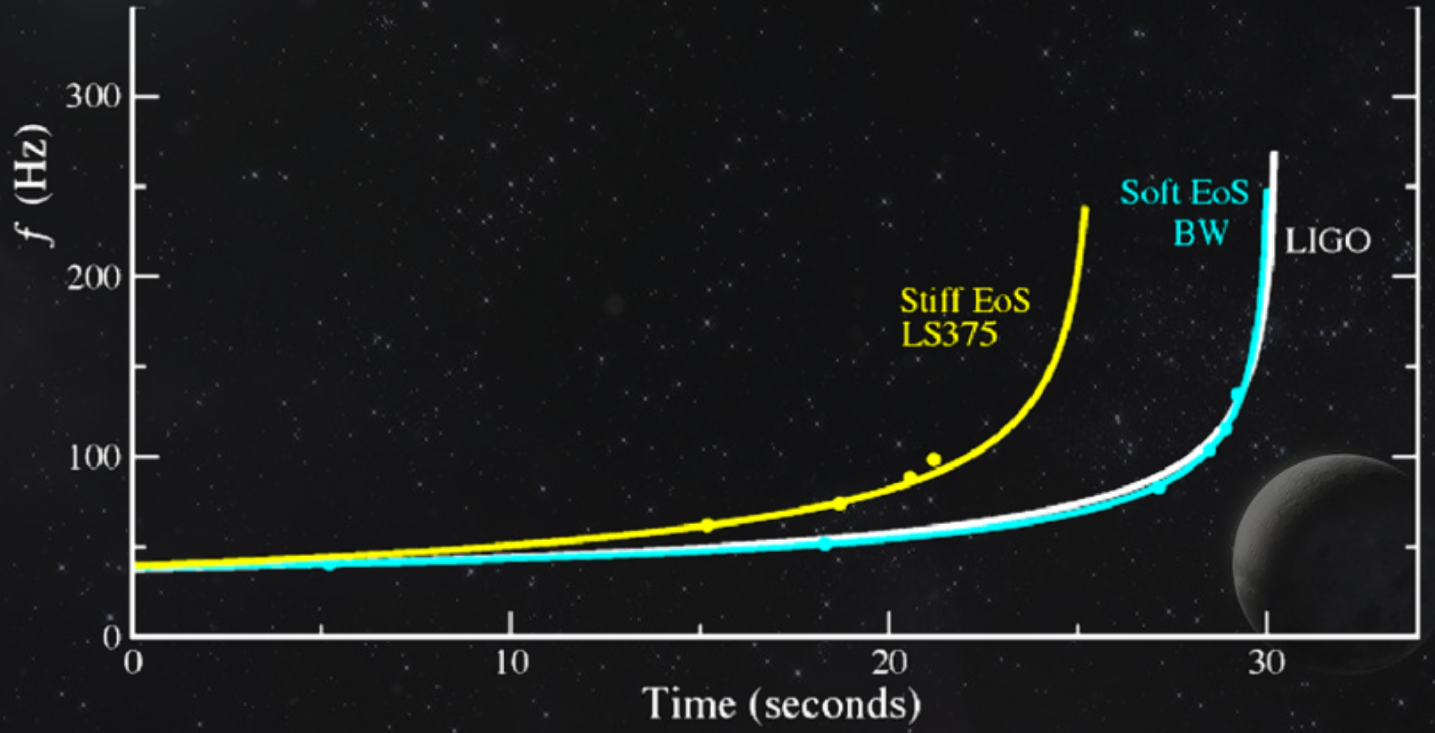


# Observing GW170817 in gravitational waves



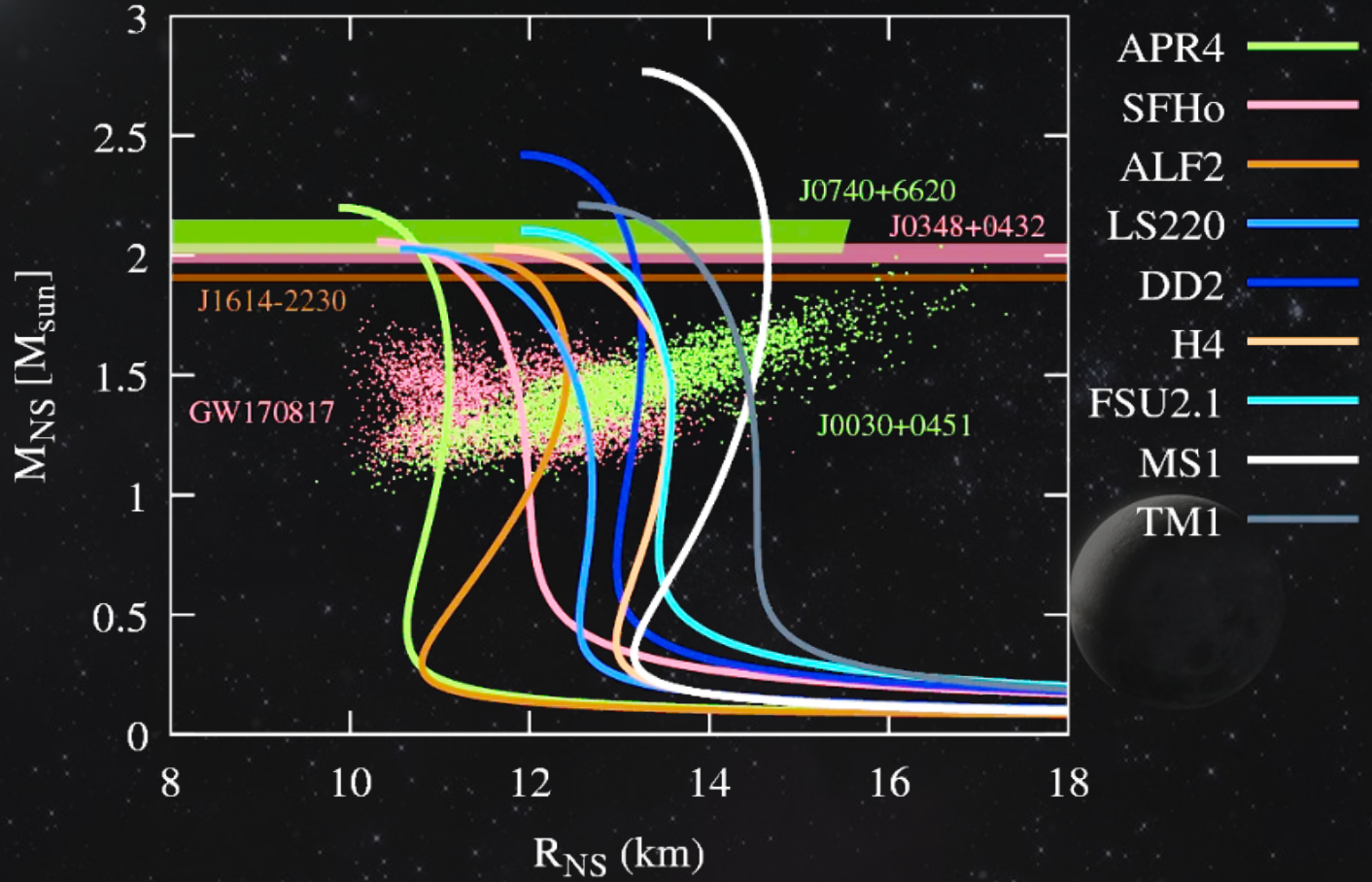

Credit: LIGO-Virgo Collaboration

The shape and duration of the inspiral depends on the neutron star **equation of state**




Mathews+ (2021)

# Graviational waves can help constrain the mass-radius relationship for neutron stars




Kyutoku, Shibata & Taniguchi (2021)

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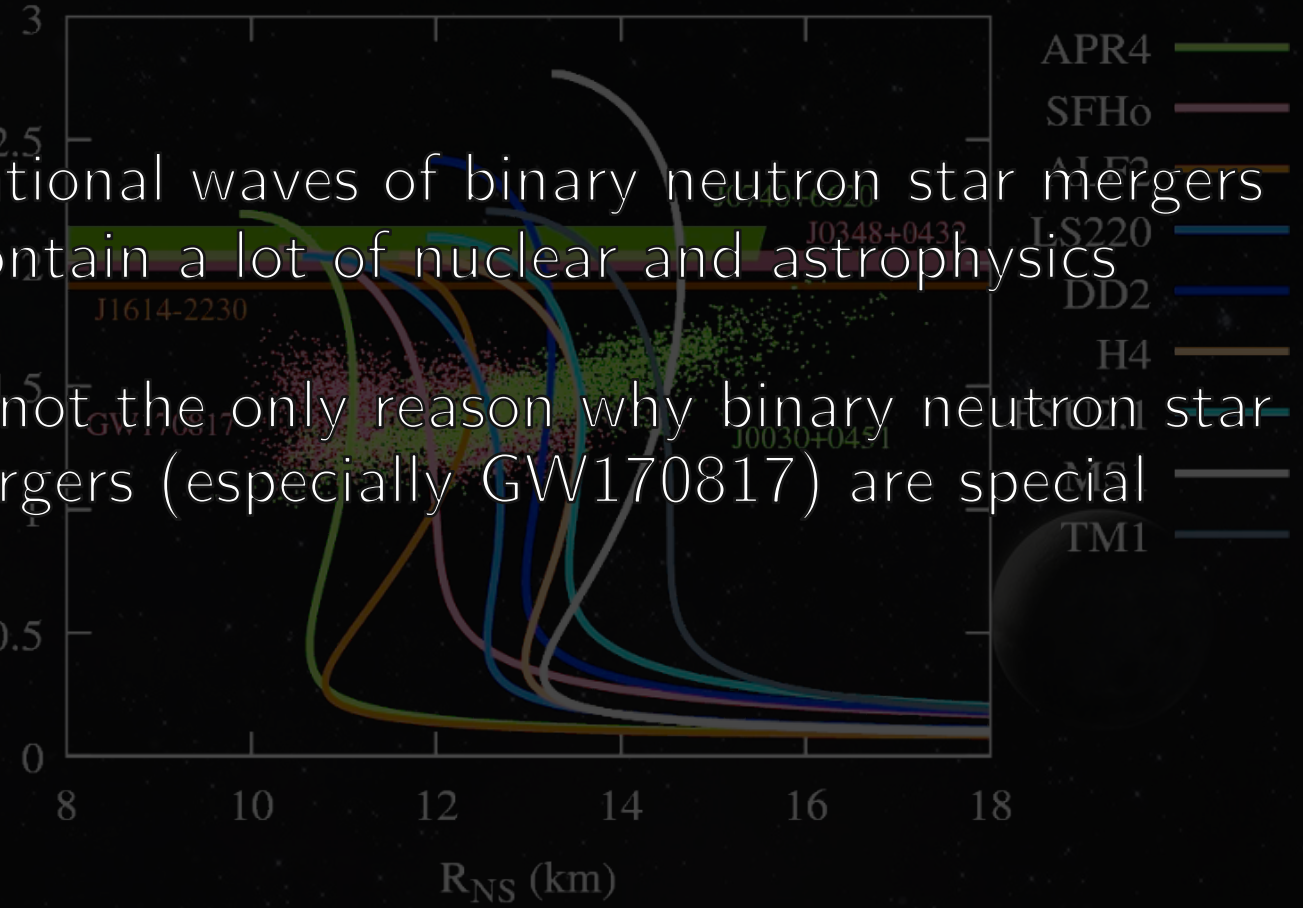
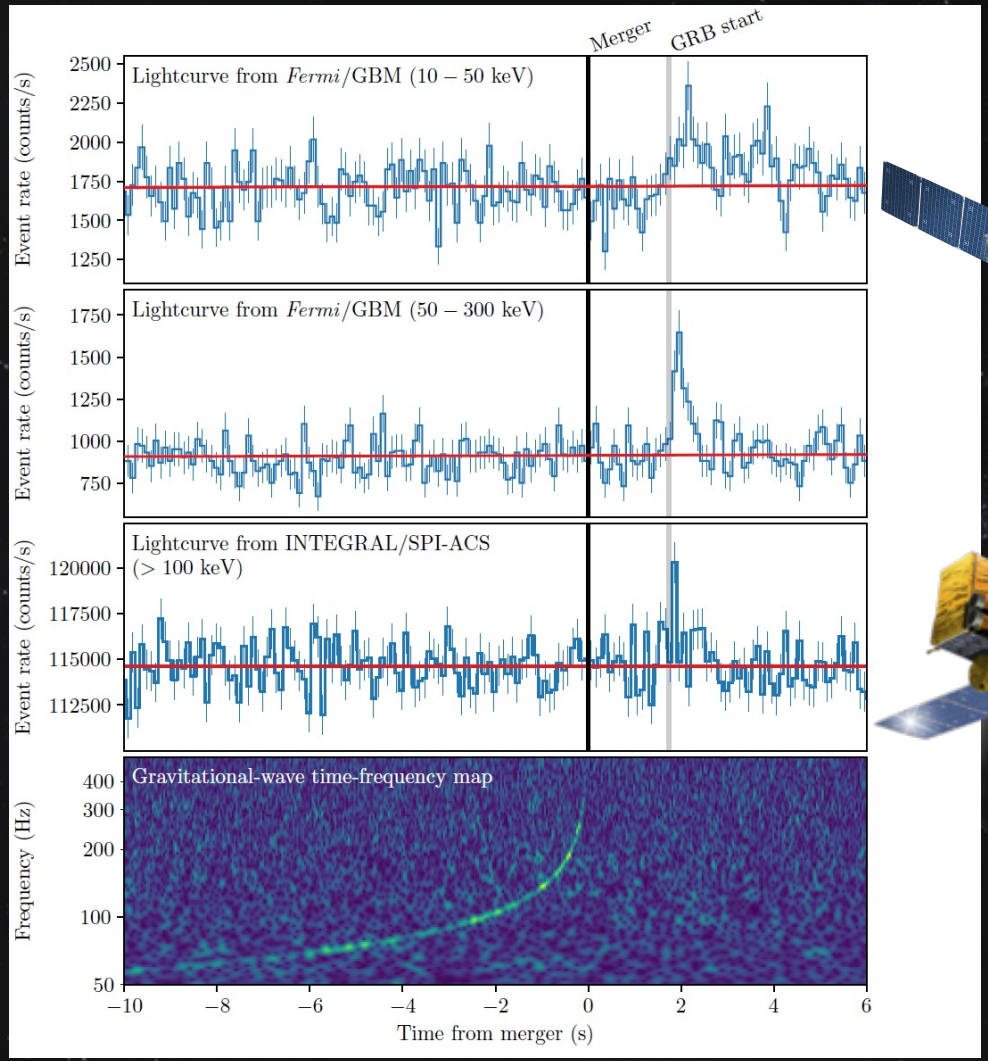



Gravitational waves of binary neutron star mergers contain a lot of nuclear and astrophysics

That's not the only reason why binary neutron star mergers (especially GW170817) are special

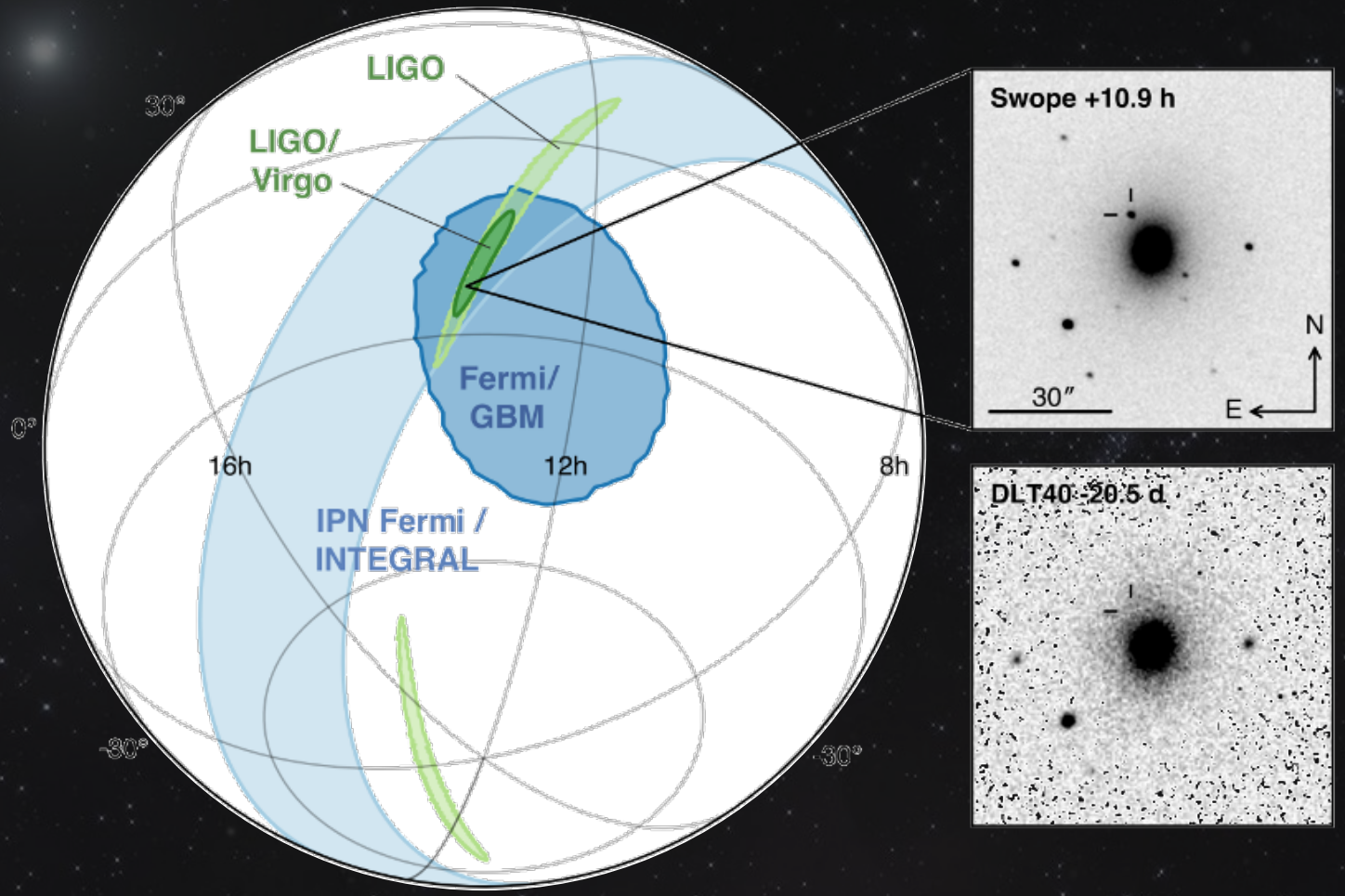
Kyutoku, Shibata & Taniguchi (2021)

# There is a chance to detect *multiple messengers*

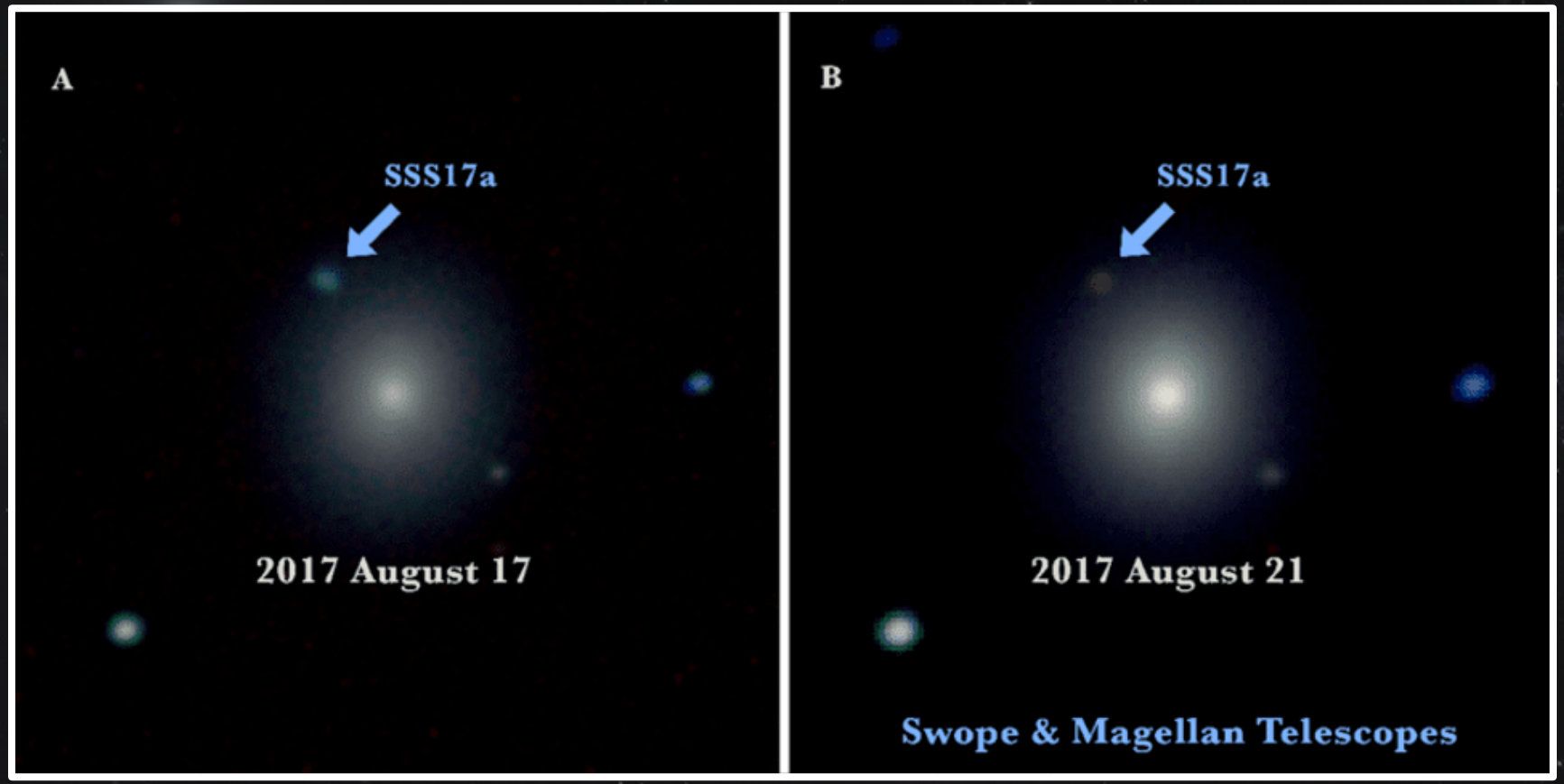



LVK Collaboration (2017)

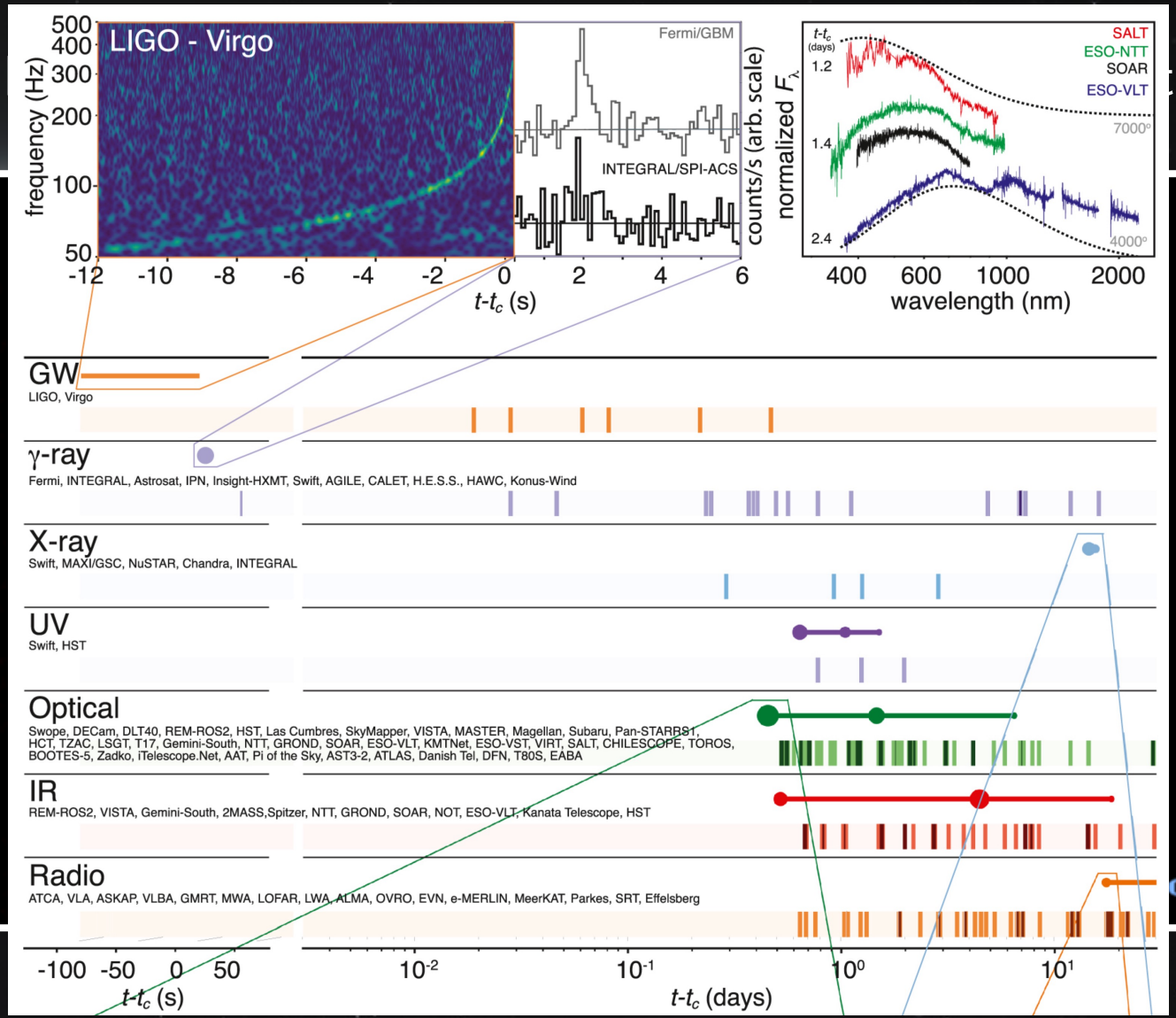
# Finding GW170817 on the sky



# GW170817 and its associated "*kilonova*"




Drout+ (2017)




Stratta & Pannarale (2022)