U3A* Technology and Science Group
Talk 2023
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From massive stars to the gold in your body – The lives of neutron star mergers

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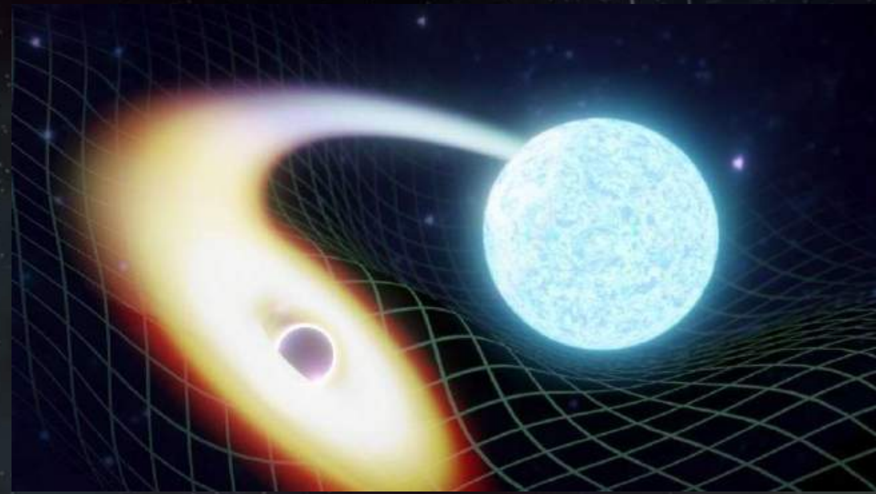
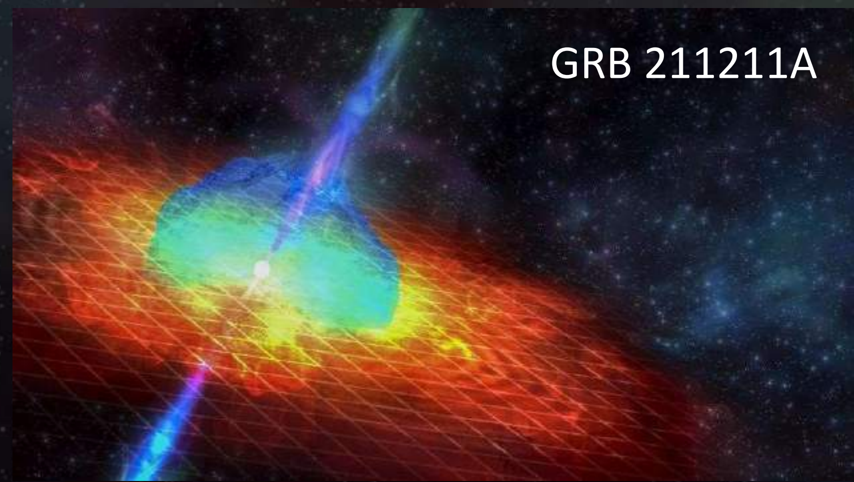
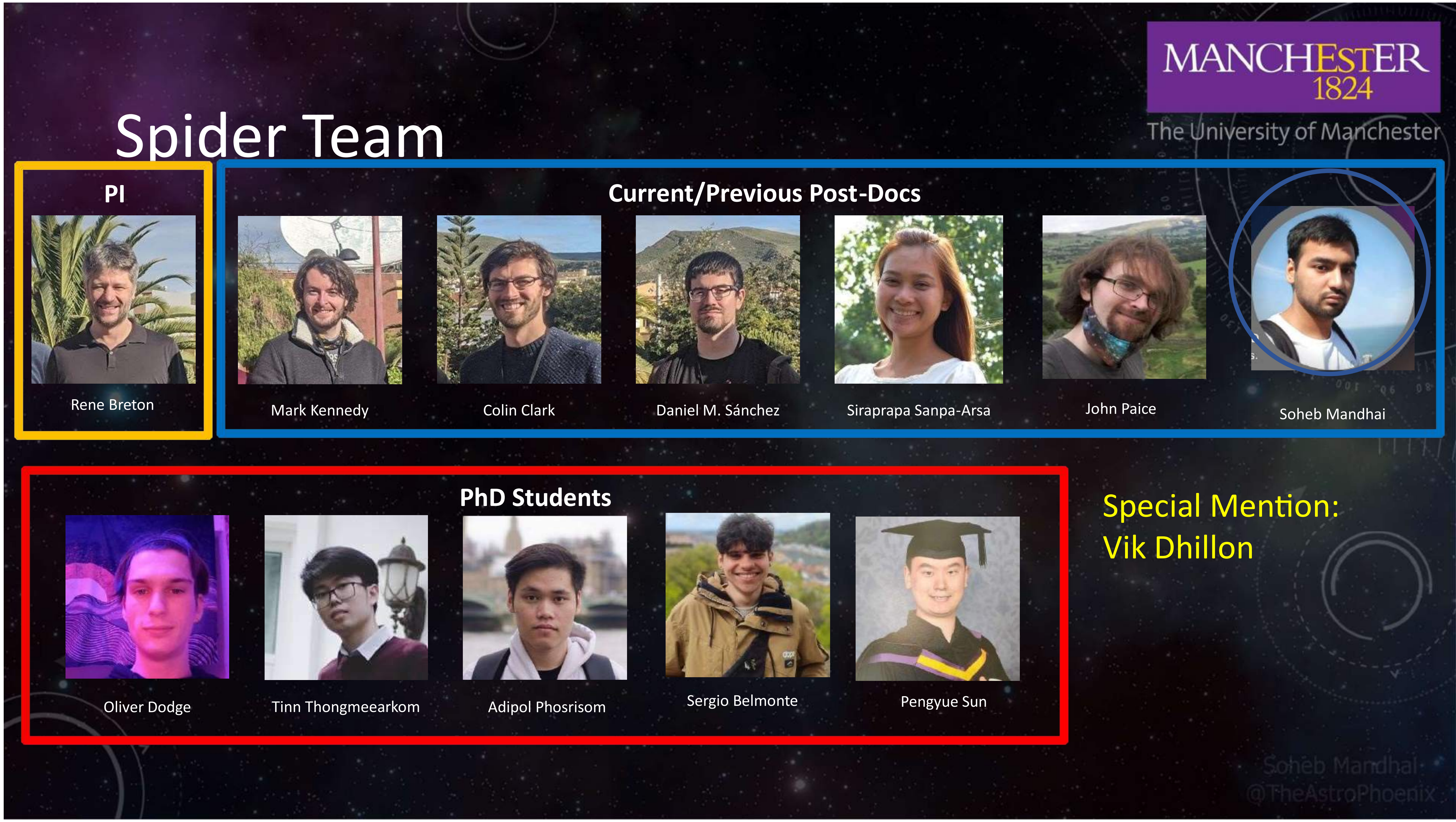
About Me!

- Post-Doc: Spiders Group, The University of Manchester
- PhD: University of Leicester
- Thesis Topic: Electromagnetic Counterparts of Gravitational Waves
- Hobbies: Digital Art, Crafting, 3D Modelling (Blender)/Printing, Game Development, Learning Japanese, and Anime
- Created art for press releases!



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Special Mention:
Vik Dhillon
Soheb Mandhai
@TheAstroPhoenix

In this talk…

- Connection between us and the stars
- Neutron stars and their role in the universe
- Gravitational Waves
- Surveys/Missions/Observations

Questions to ponder:

1. Why is there gold on Earth?
2. How are heavy elements created?
3. What can we learn from gravitational waves and their follow-up?

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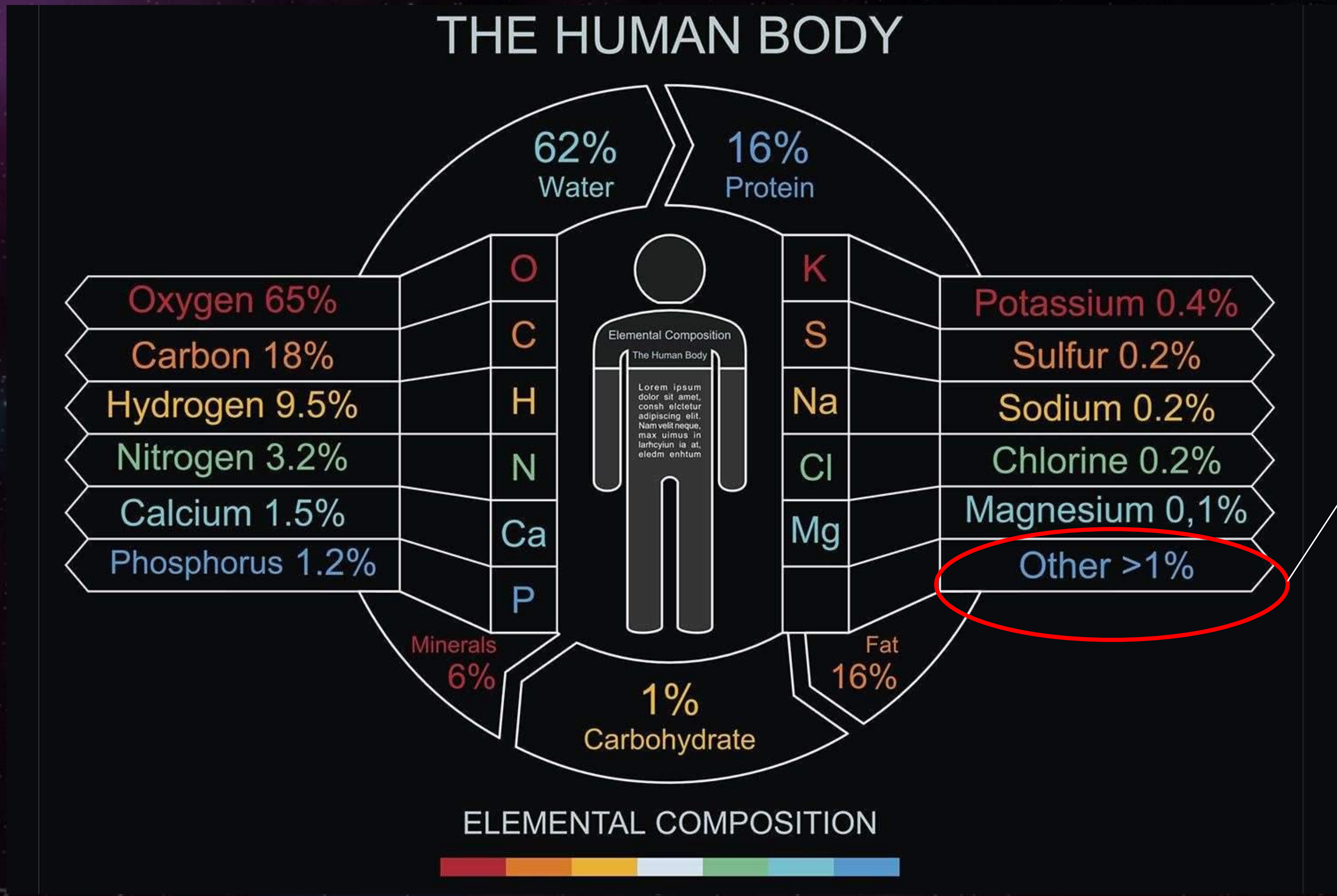
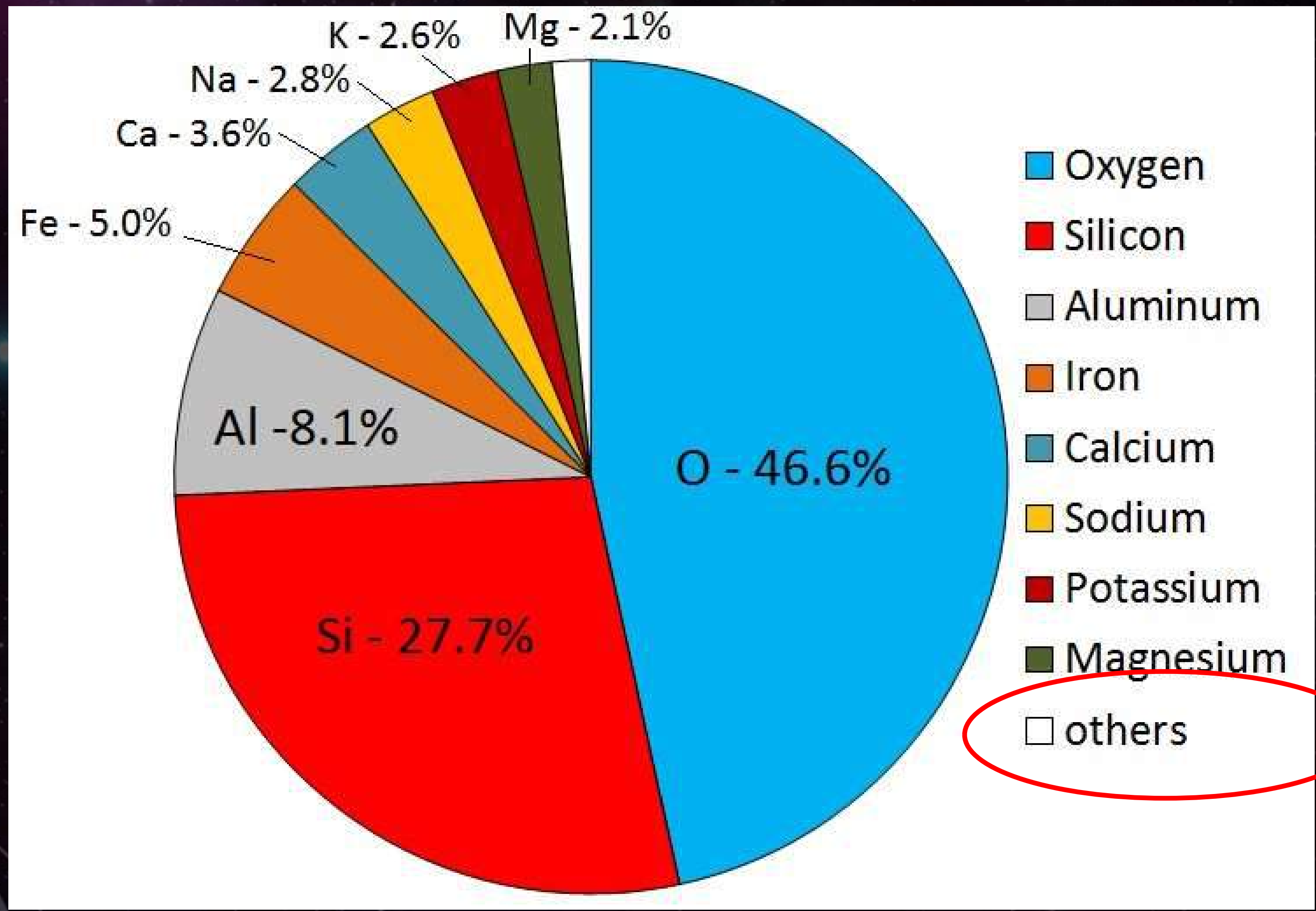


- Gold
- Silver
- Lanthanum
- Strontium
- More…

Image Credit:
Youst/Getty Images

What about the Earth?



- Gold
- Silver
- Lanthanum
- Strontium
- Thorium
- More + Radioactive Elements

Note: Radioactive elements (U,Th,K) = Core and Interior heating!

Image Credit:
University of Saskatchewan

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Where did these elements come from?

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Broad channels of formation…

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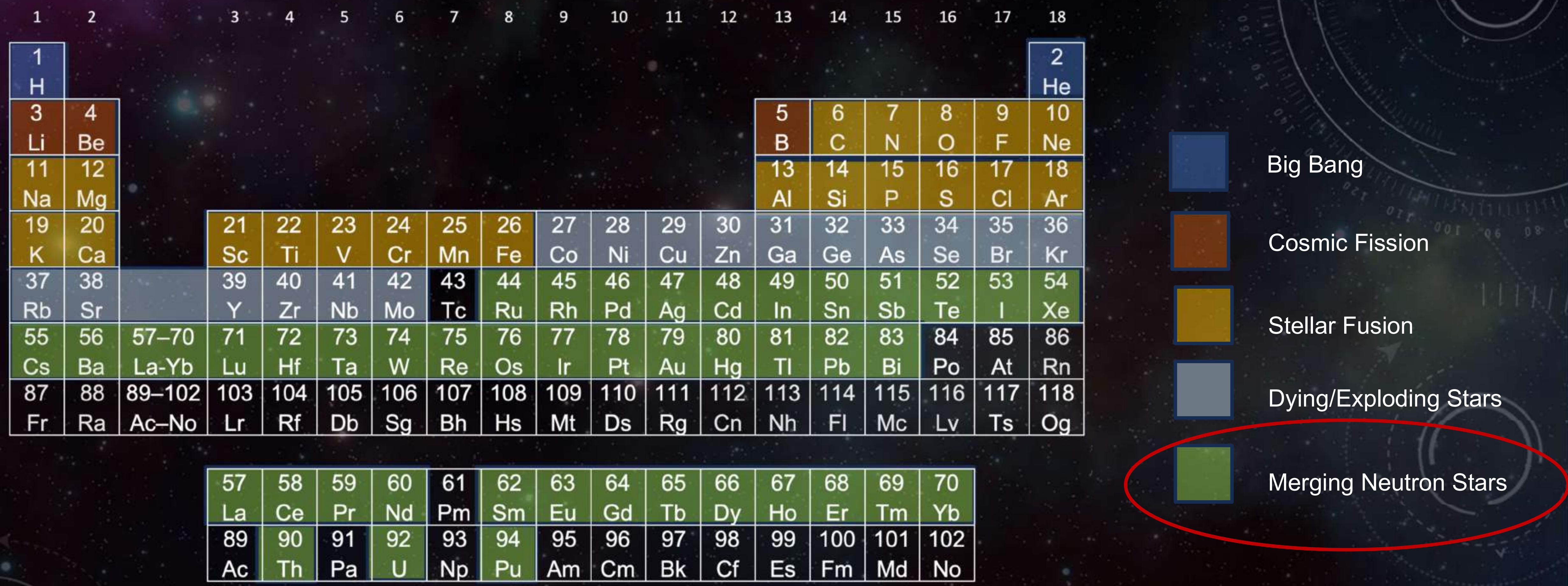
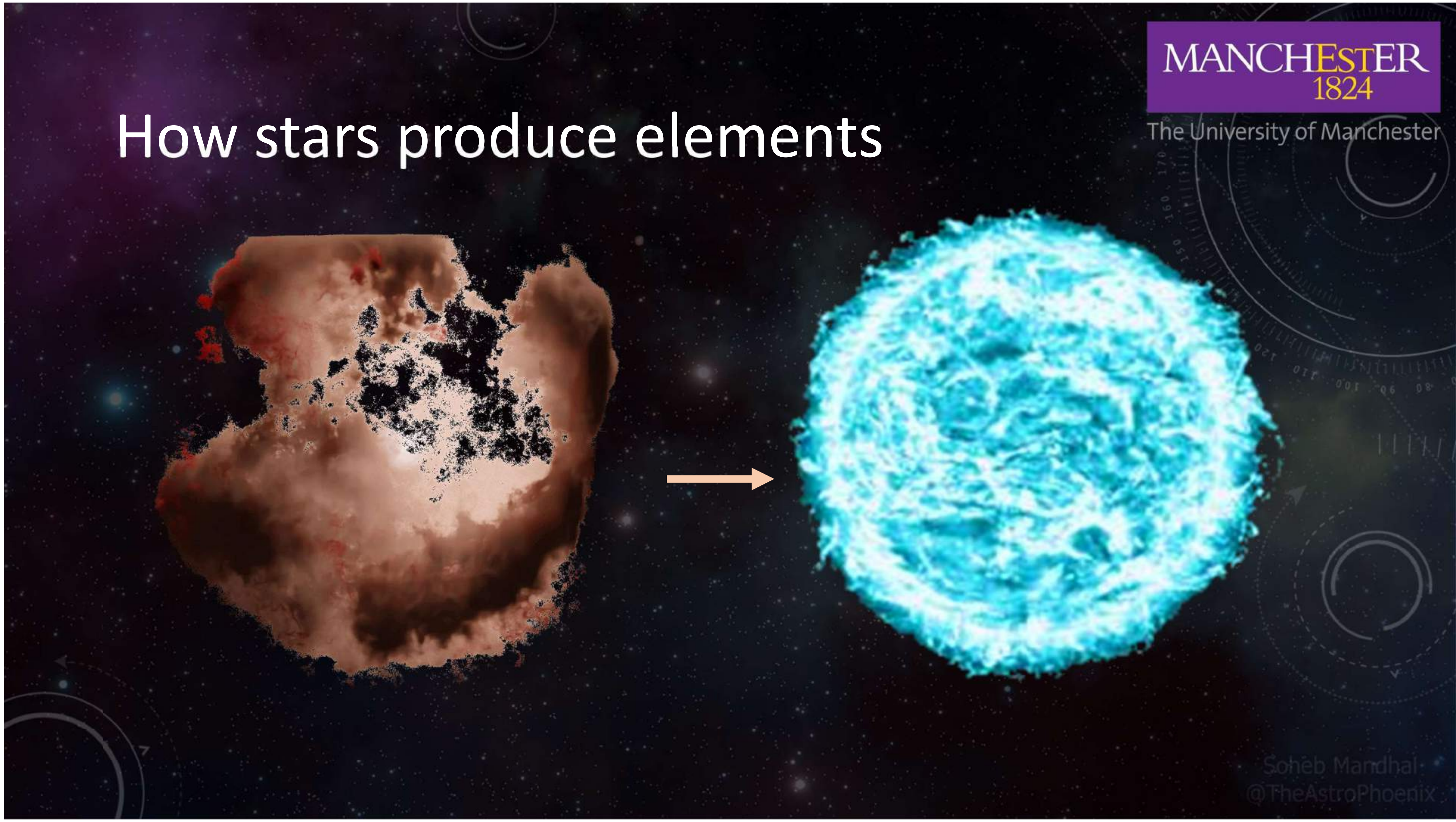


Image Credit (Original):
Sandbh/Wikipedia


How stars produce elements
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Role of fusion in stars

- Tug of war: Gravity vs Thermal Pressure
- Fusing elements releases energy
- Elements heavier than Iron (Fe) are inefficient to produce
- H/He easiest to fuse

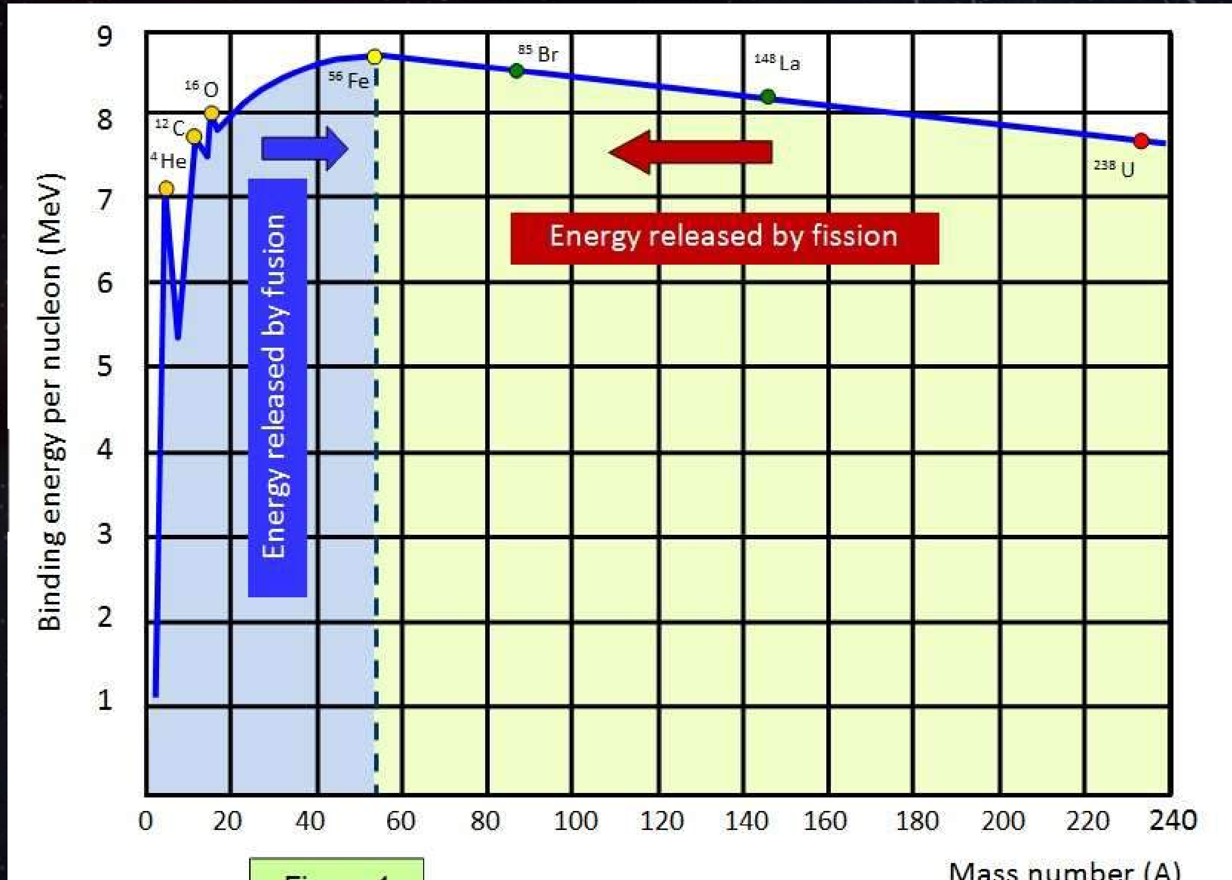

Figure 1

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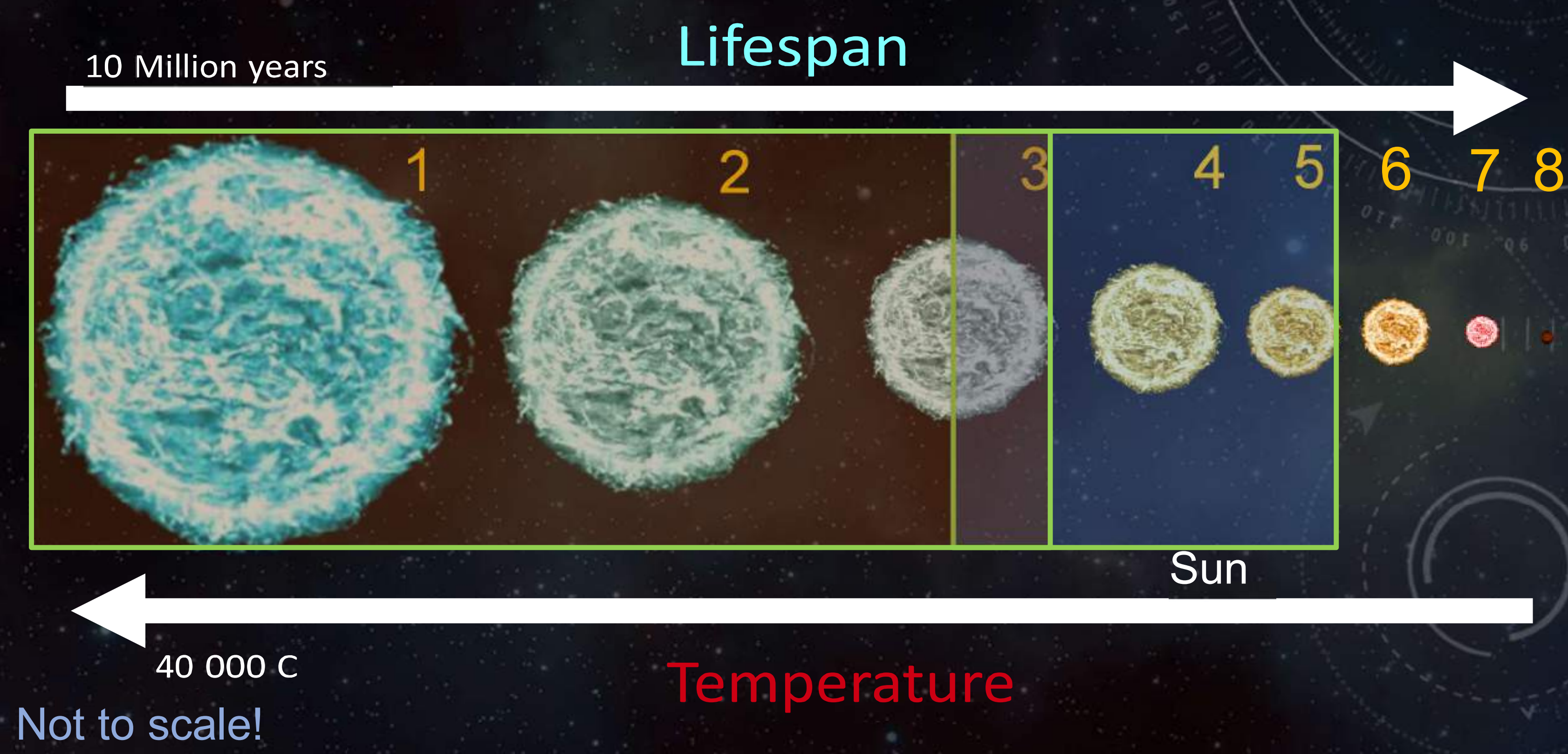
Note on the evolution of stars

- All stars will produce elements up to Iron
- Can slowly produce some elements > Fe
- Supernova produce heavy elements up to Tc



What are we missing?

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Supernovae

- Mark the death of a star
- Can produce heavy elements
- Enrich the galaxy
- Can briefly outshine their galaxy

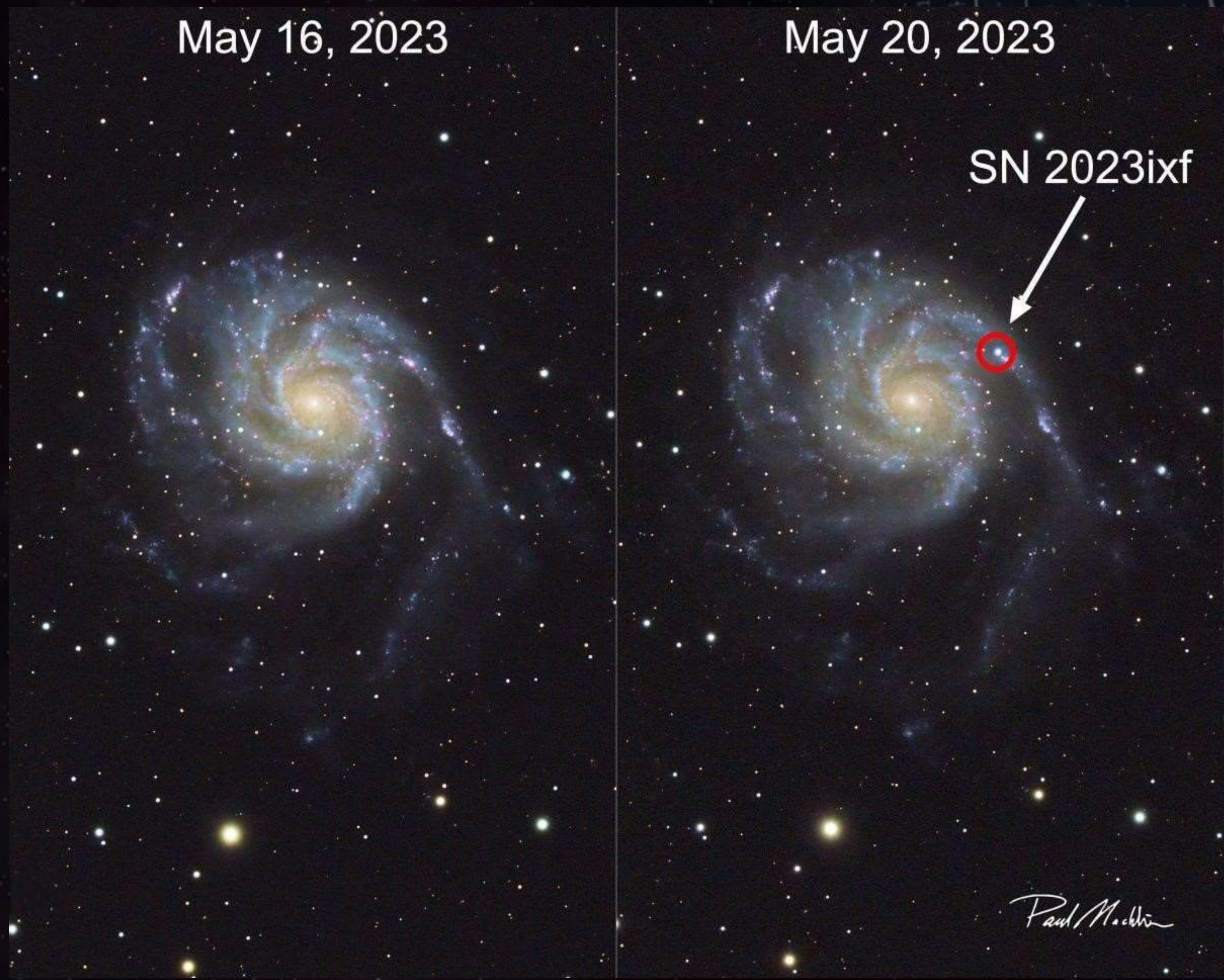

Image Credit (Original):
Sandbh/Wikipedia

Remnants of stars…

- In addition to nebulae, dense compact objects may form. Such as:
  - White Dwarf
  - Neutron Star
  - Black Hole
- These objects push the limits of physics.
- Despite their size, they have high masses comparable to the Sun.
- Can these objects be responsible for the majority of heavy elements?

Not to scale!

Alone – No. But what about in a binary system?

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YES!

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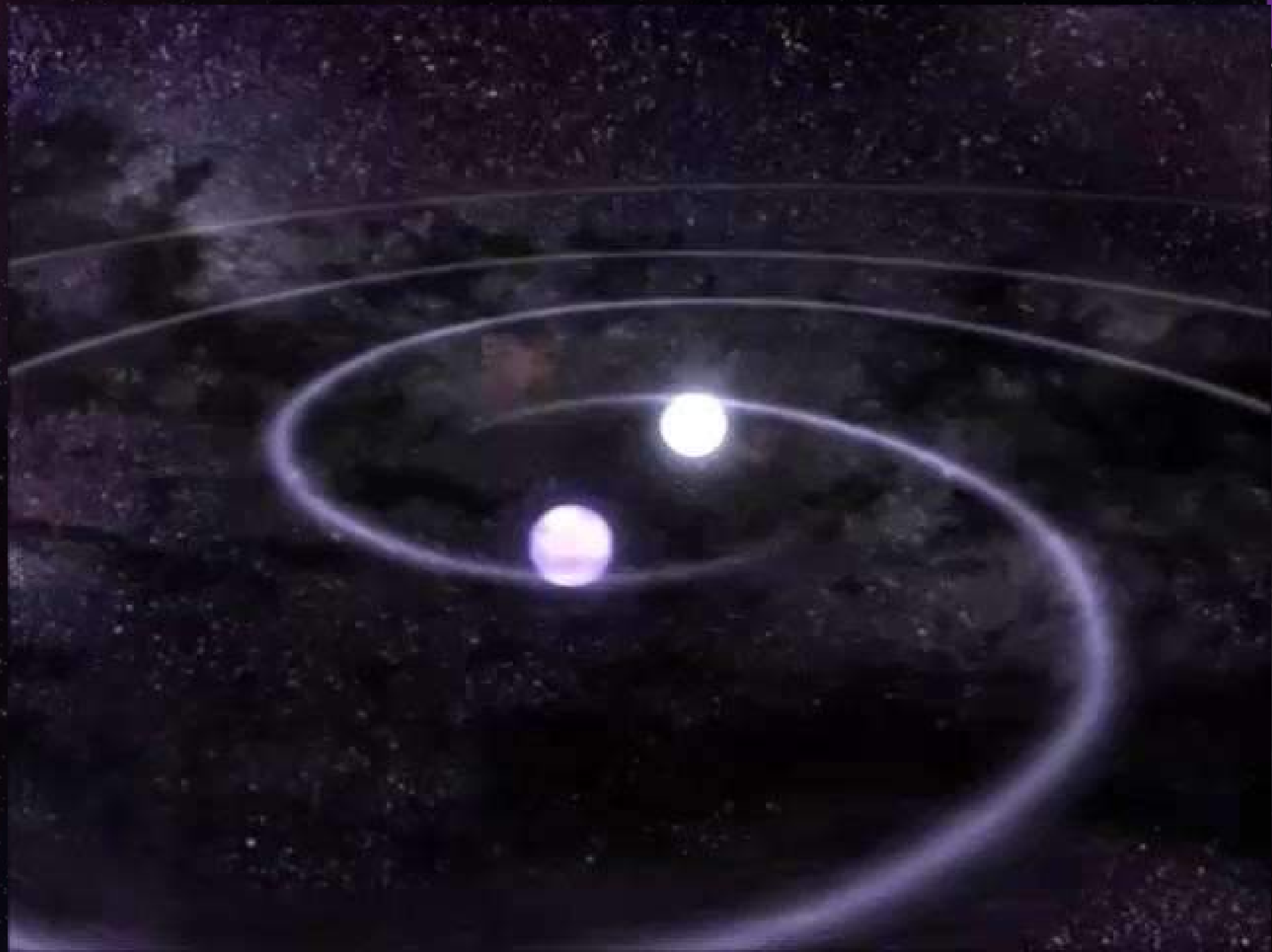
In a binary system, these objects can…

- Produce detectable gravitational waves
- Generate highly energetic radiation
- Eject matter into a high temperature environment

Video Source: (2x) NASA/Goddard Space Flight Center



How can we find these systems?

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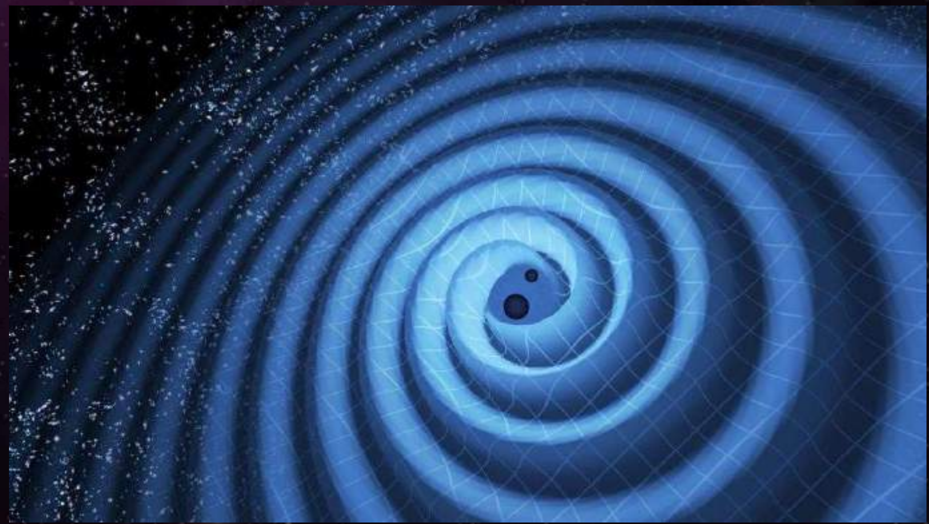
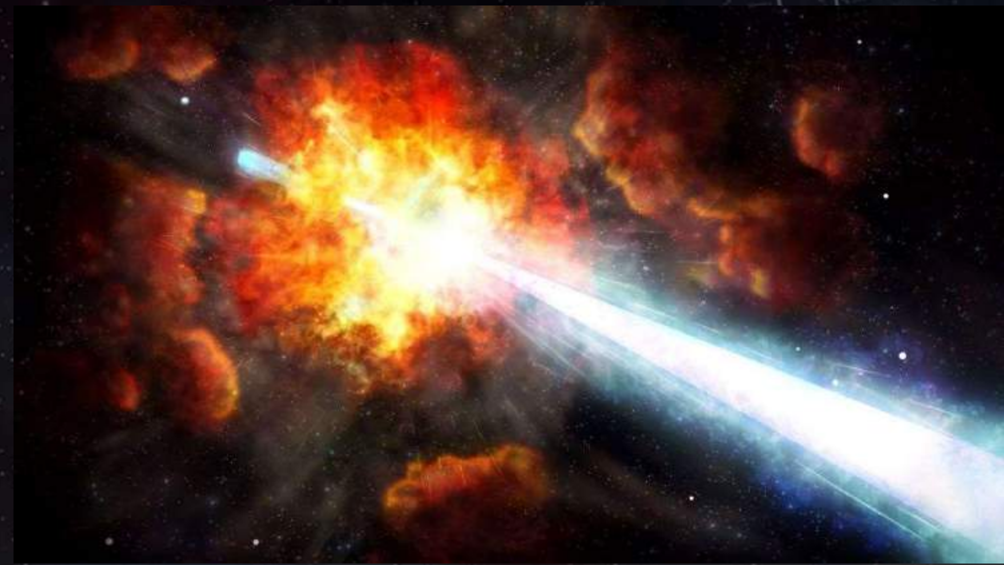


Gravitational Waves

Image Credit: LIGO\T Pyle



Electromagnetic Radiation

Neutrinos?

Image Credit: Siarhei

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Gravitational Wave Instruments

Image Credit (Original):
LIGO

Image Credit (Original):
Virgo Collaboration

+ KAGRA,
LIGO-India,
NEMO… and
more to come

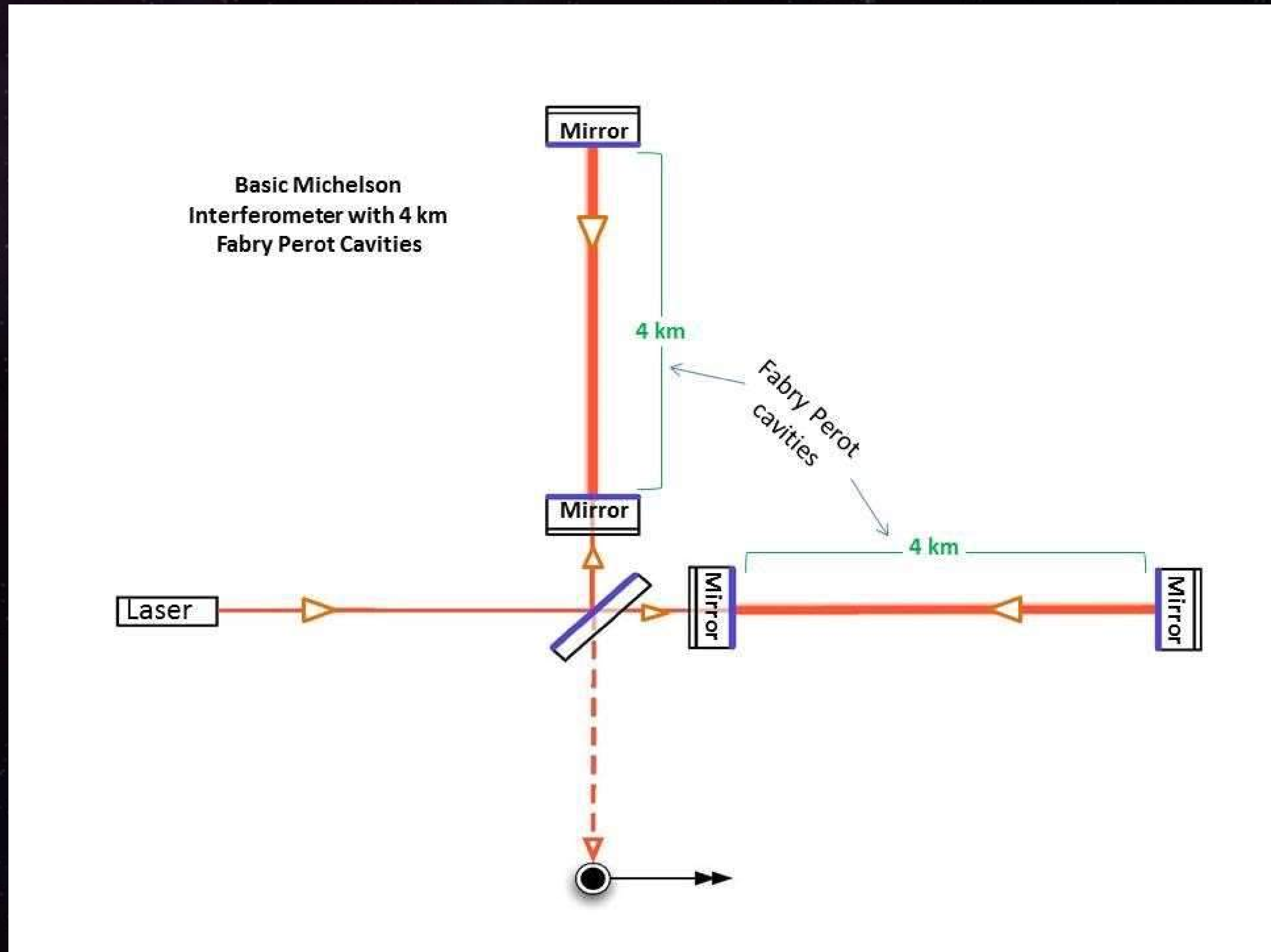


Image Credit: LIGO

First detection in 2015…

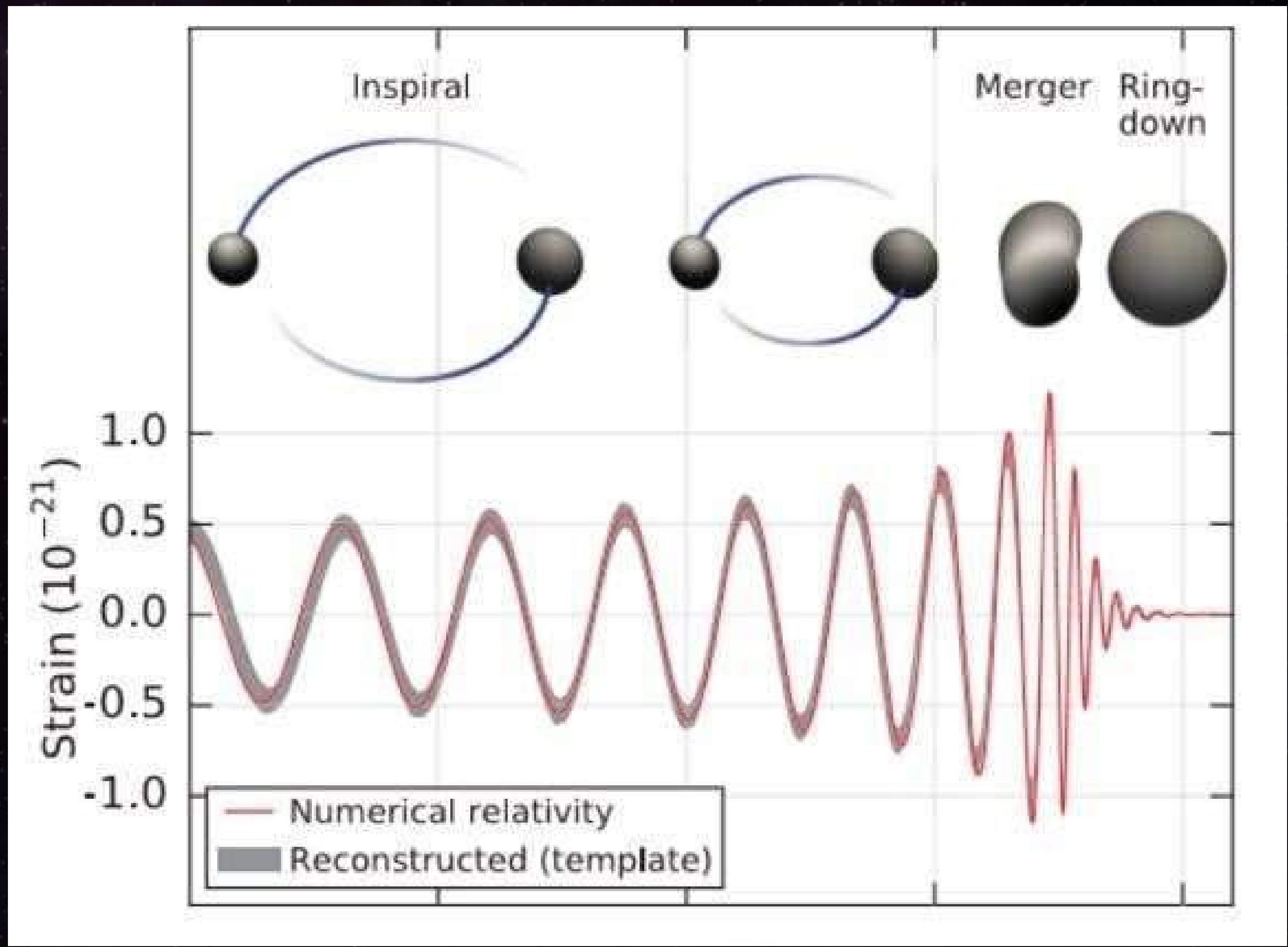
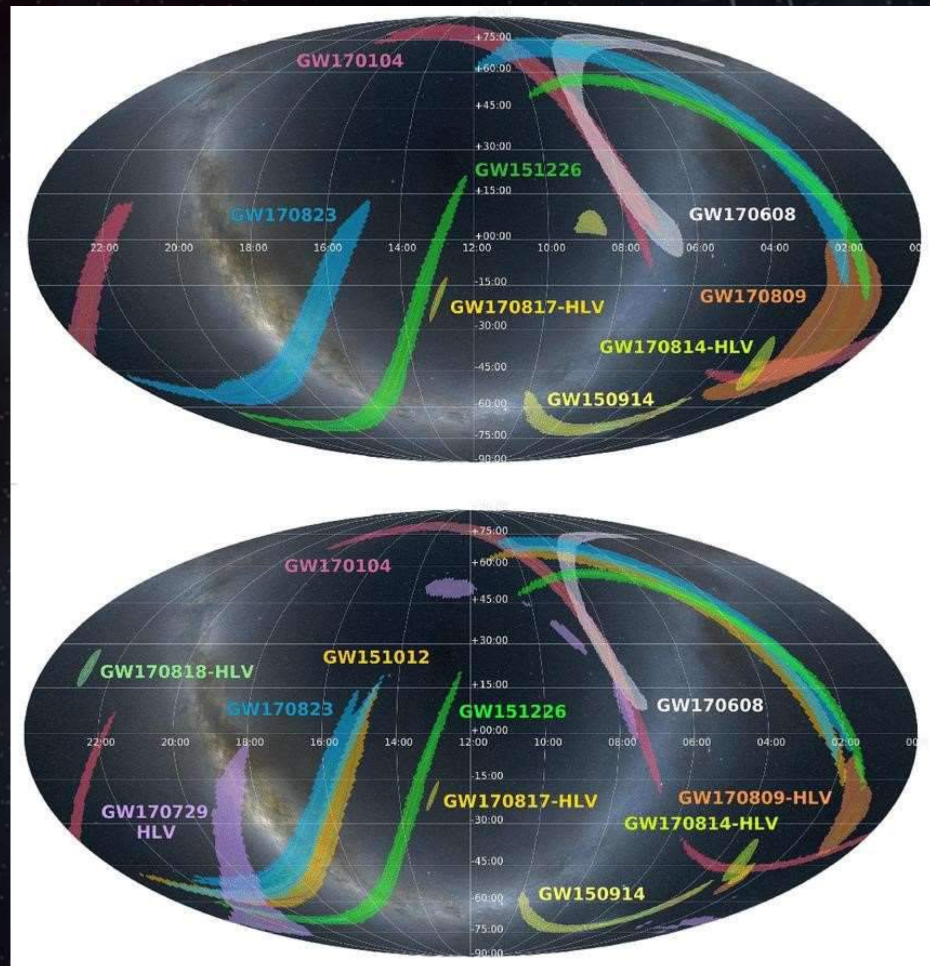


Image Credit (Original):
LIGO + Virgo
Collaborations, 2016

General Localisations:

- Large volumes – contain many galaxies that could host the binary merger
- Sensitivity varies across the sky
- Improves with the number of detectors



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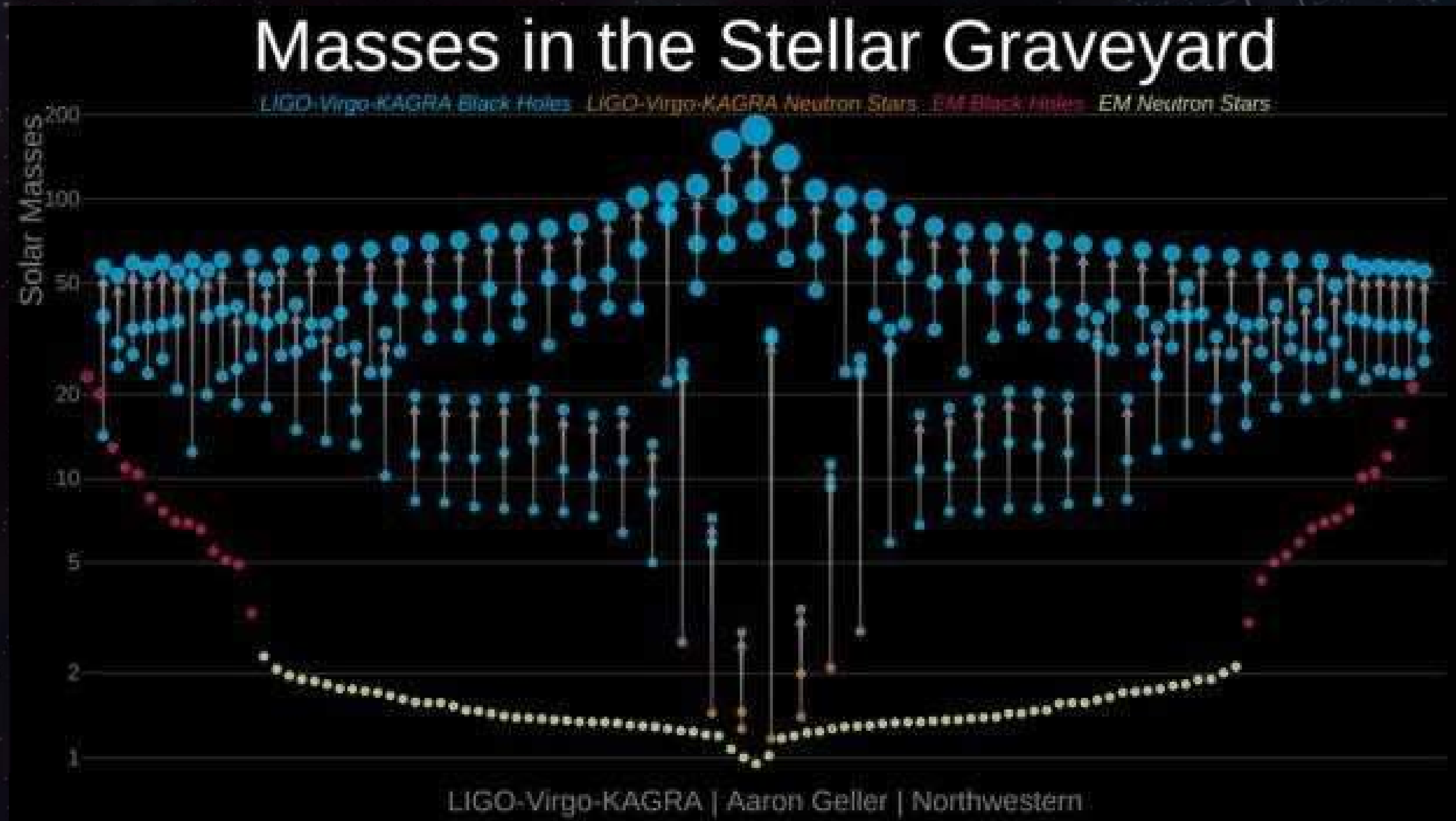
Sensitivity

- Detect fluctuations 1/1000 – 1/10000 th an atomic nucleus!

How many Gravitational Wave detections?

- Up to the last run (2015-2020)

Note: 4th Run underway with 10s of events already detected!



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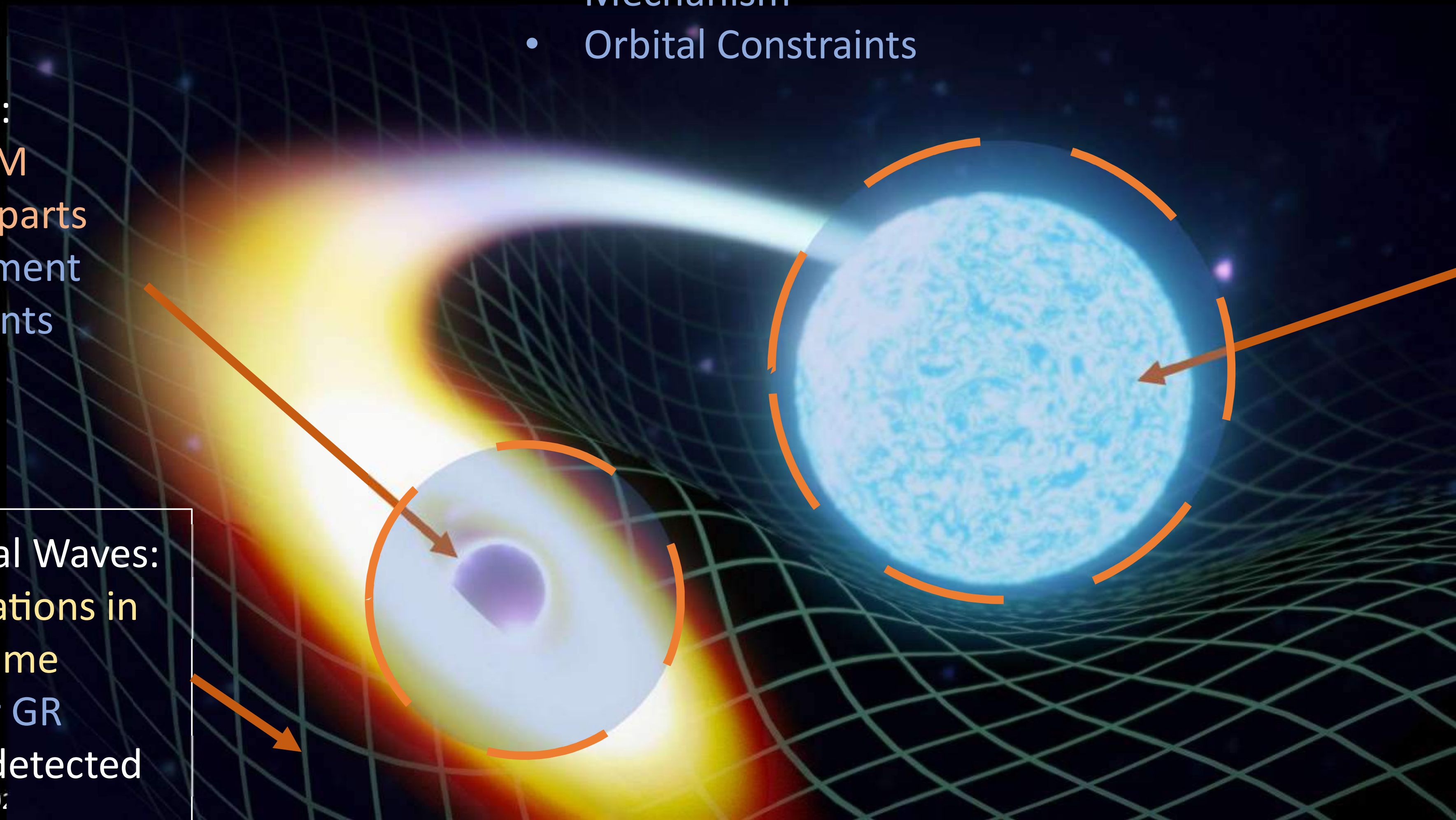
Breakdown:

General:
- Insight into Formation Mechanism
- Orbital Constraints

Black-Holes:
- Stifles EM Counterparts
- Environment Constraints



Neutron Star:
- Responsible for EM Counterparts
- Equation of State
- Constraints on Mass Limits

Gravitational Waves:
- Perturbations in Space-Time
- Tests for GR
- Can be detected

Key:
Progenitor
Astrophysics
Definition

In the absence of Gravitational Waves…

What are the “EM counterparts”?

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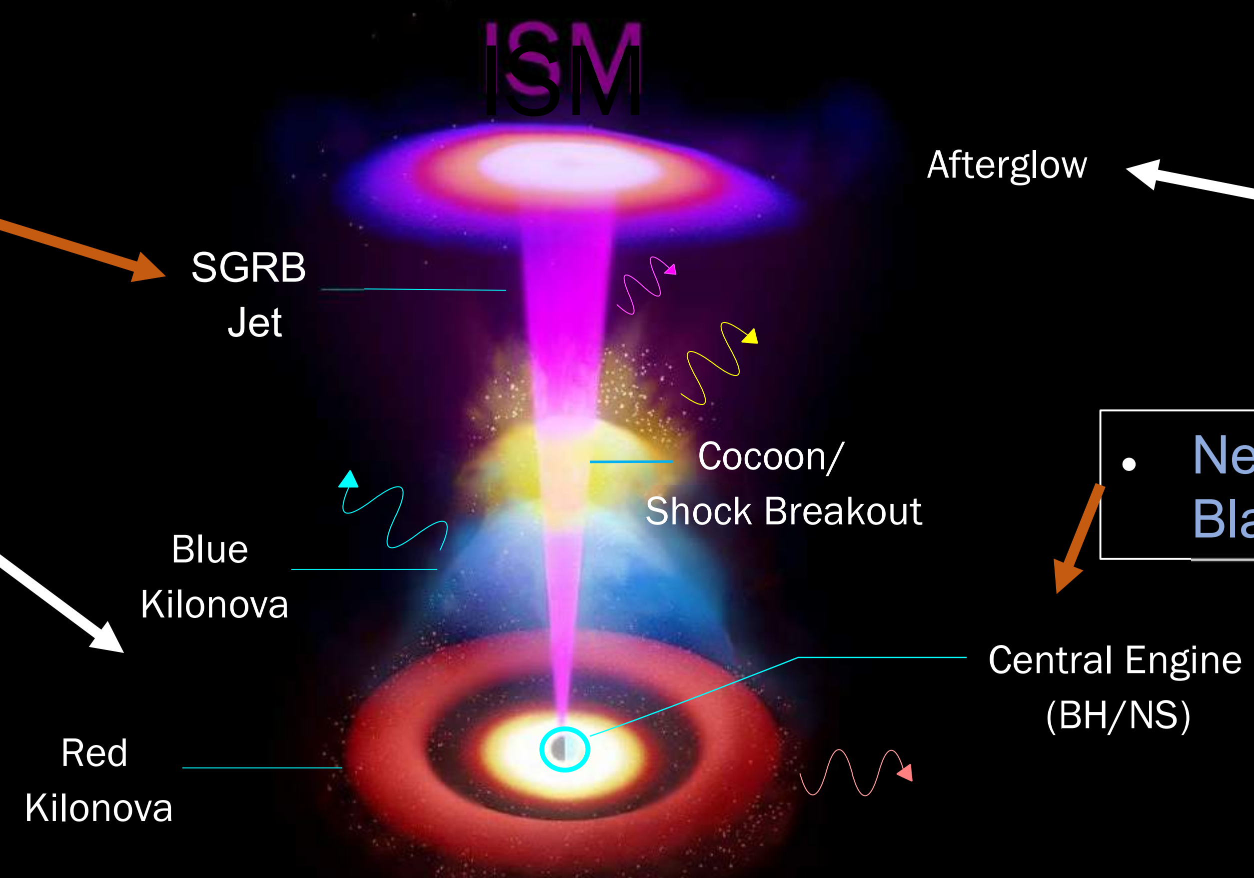
- Beamed Gamma Rays
- Caused by Rapid Accretion on Central Engine

- R-process nucleosynthesis

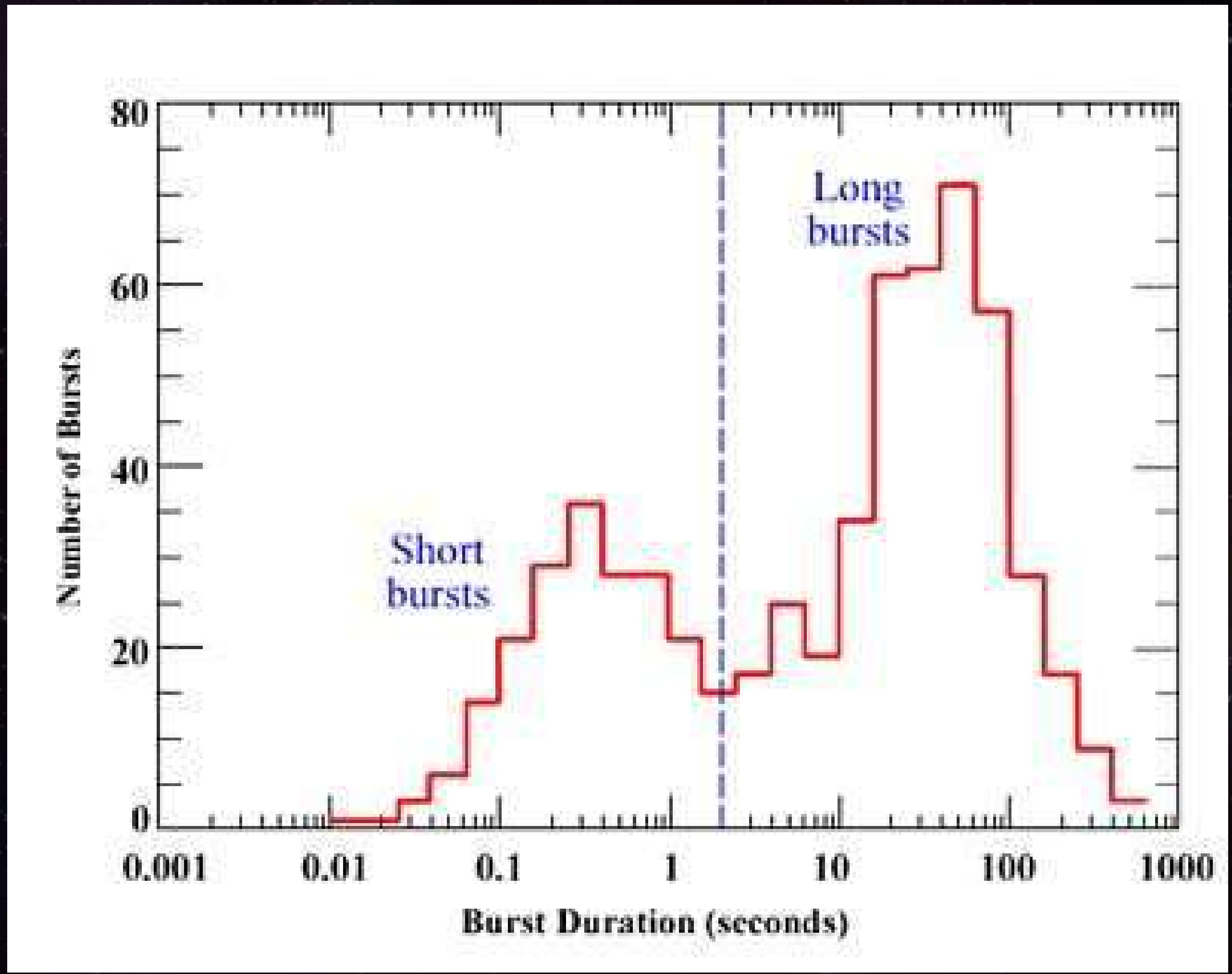


- Caused by synchrotron radiation

- Neutron Star Or Black Hole

Key:
Progenitor
Astrophysics
Definition

A bit more on Gamma-Ray Bursts



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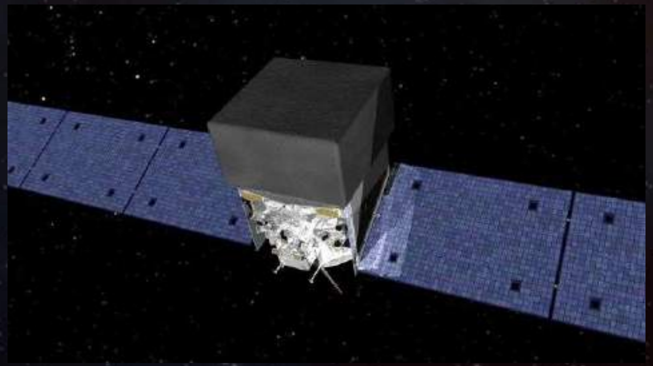
Importance of SGRBs

- More detections than Gravitational Waves
- Allow localisation of neutron star binary mergers
- Insight into energetics
- Interaction with surroundings

Image Credit: Gizmodo

CGRO

Integral



Fermi

Swift

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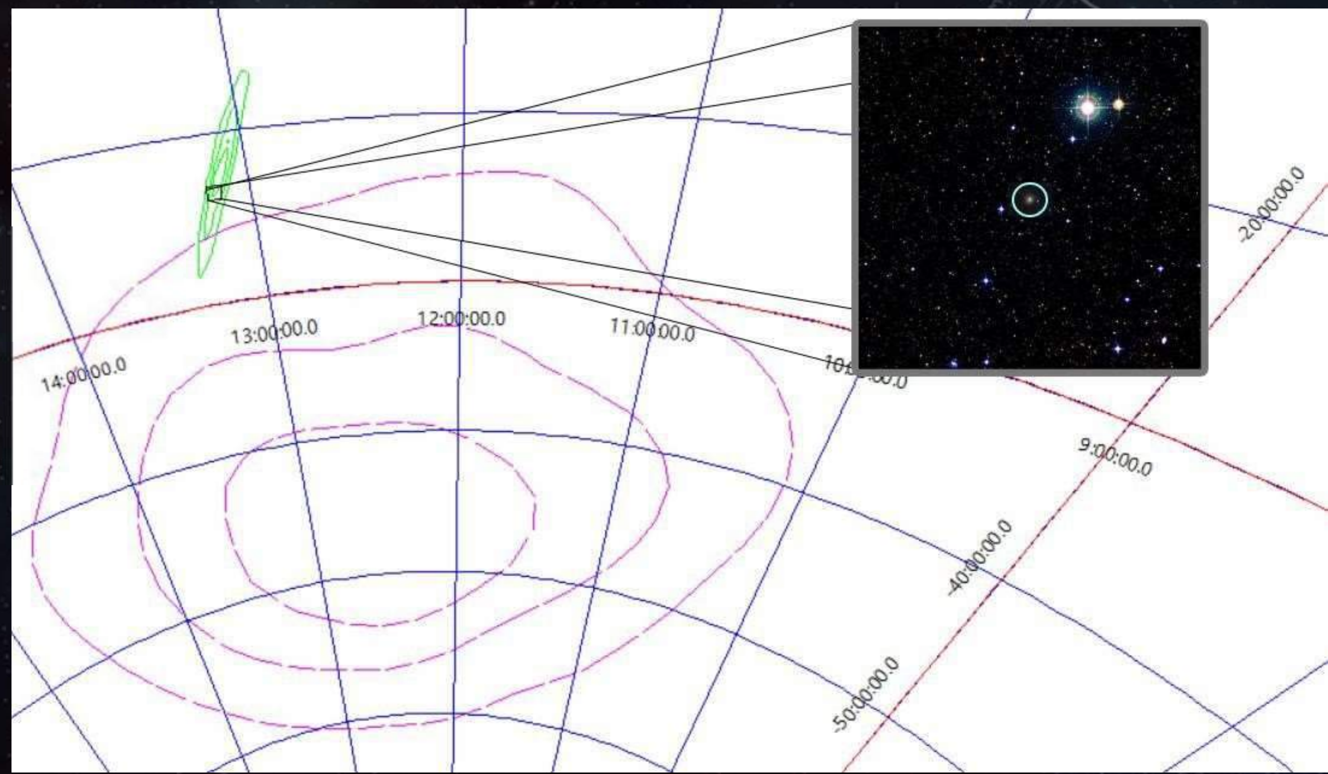
Caveats

- Gamma-Rays must be pointed towards us
- Telescopes must be pointed at the right part of the sky
- Needle in the haystack…

Only Swift is precise enough to give us sub-arcsecond locations!



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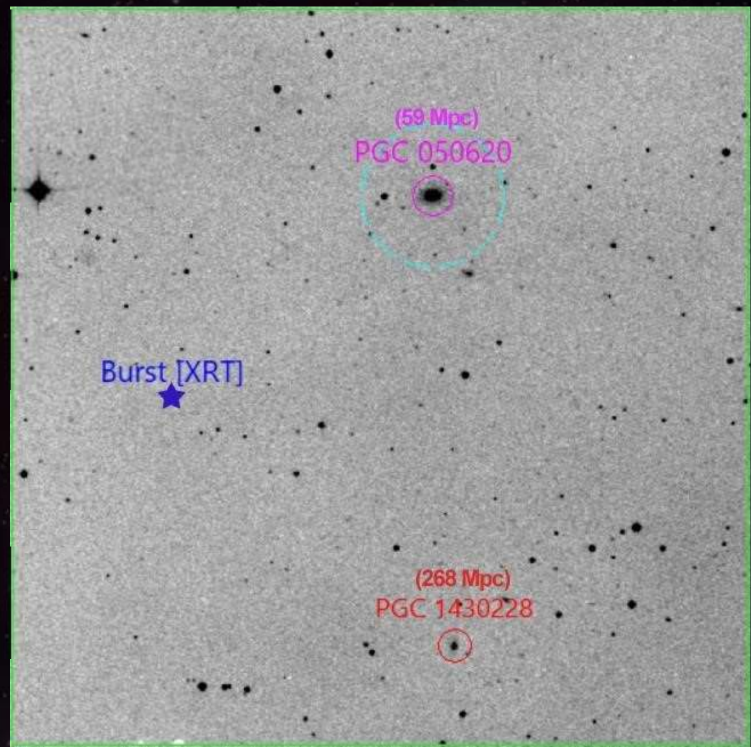
Extragalactic: Possible Ejected Cases

- Gravitational Waves give distance estimates
- EM counterparts provide a chance at better localisation
- Binaries can travel beyond their galaxy



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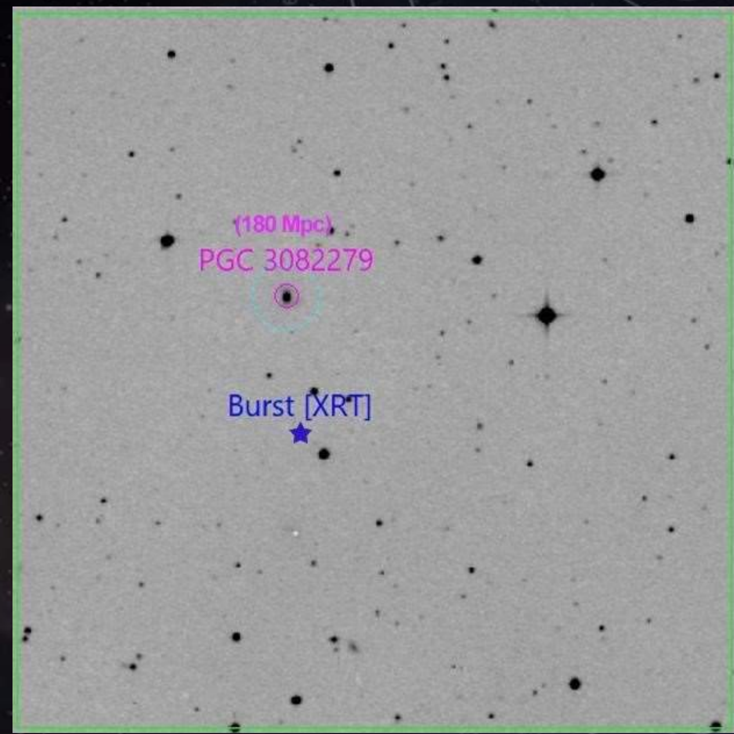

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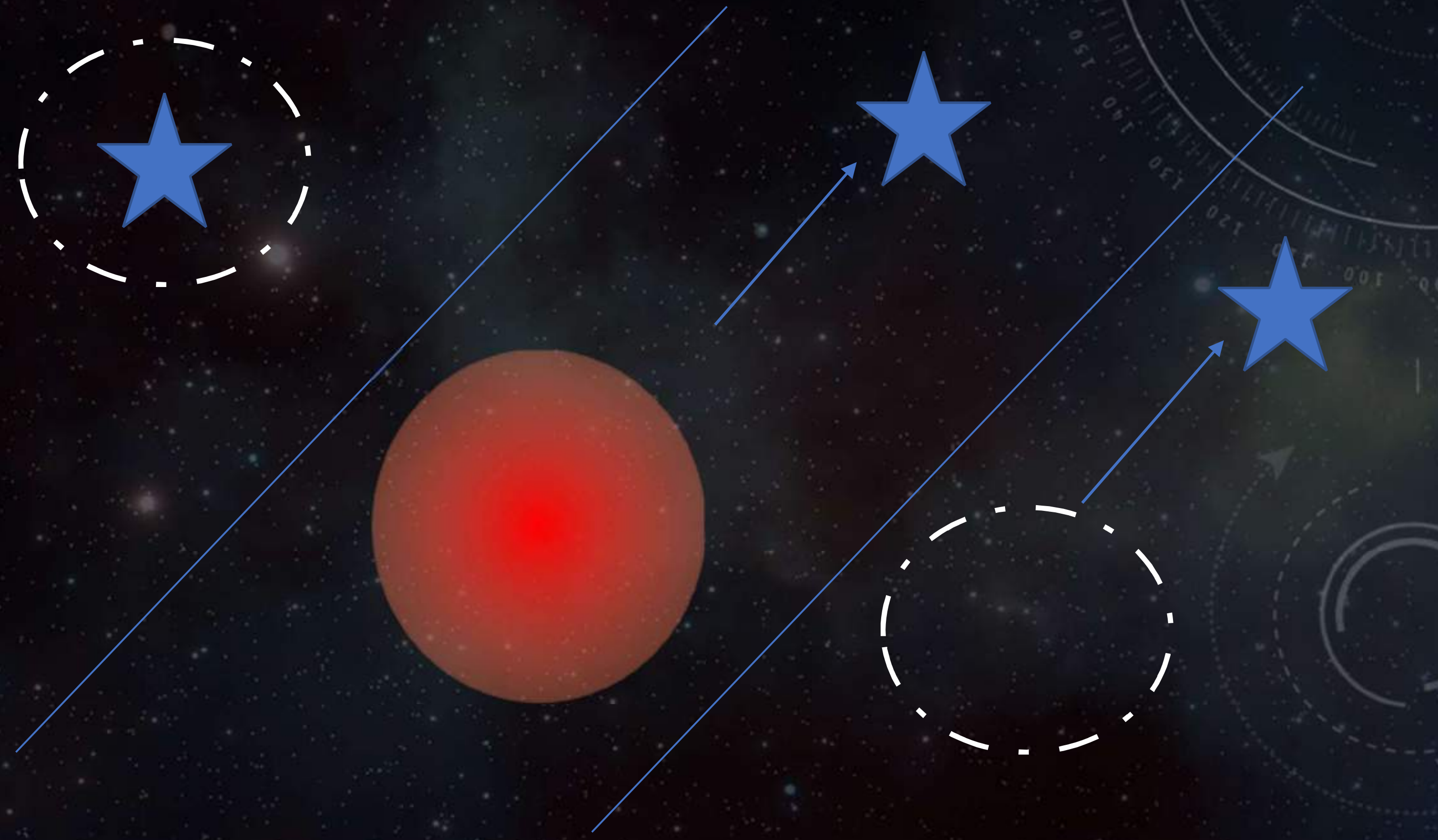
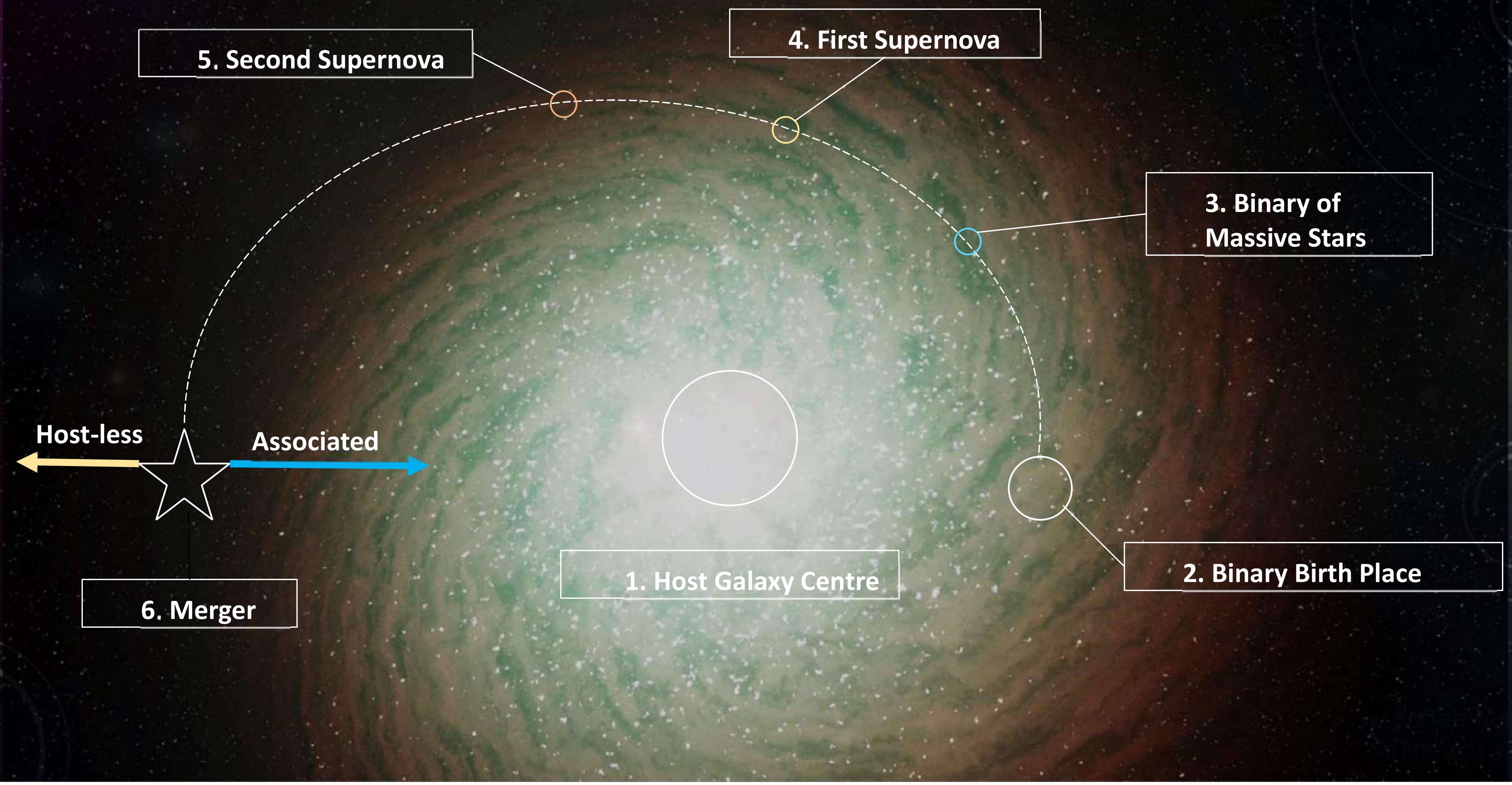
What are the challenges?

- Galaxy identification is important – Isolates distance to binary
- Galaxies can be faint
- Binaries can get ejected from their galaxies



Schematic:


5. Second Supernova
4. First Supernova
3. Binary of Massive Stars
Host-less
Associated
2. Binary Birth Place
1. Host Galaxy Centre
6. Merger

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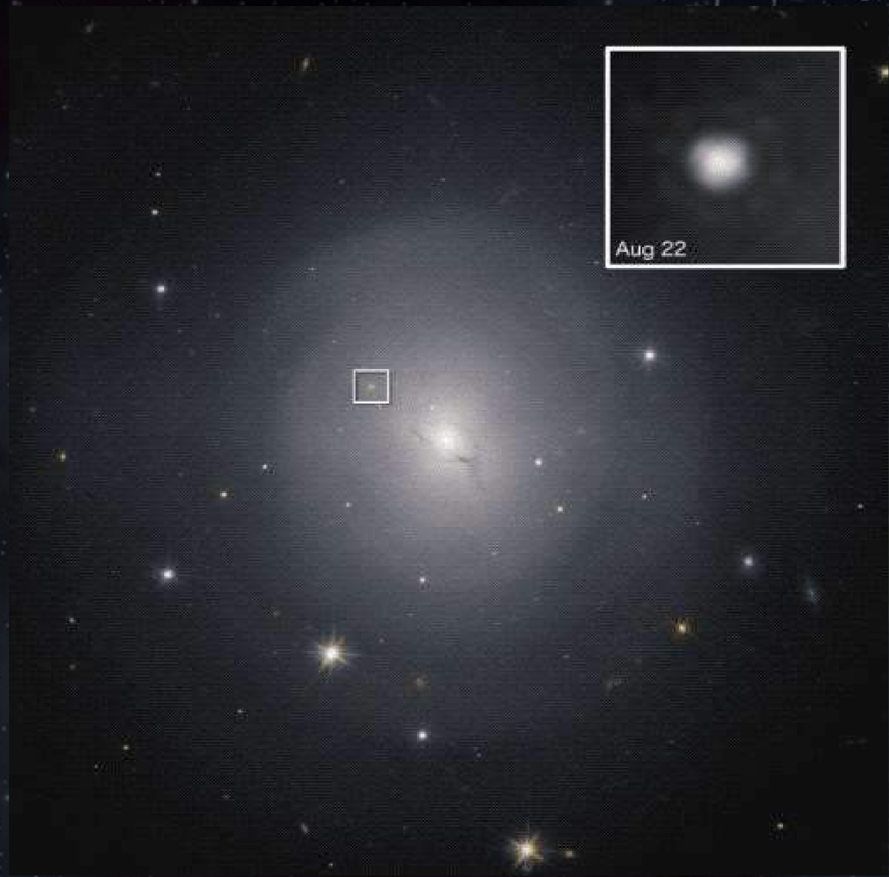
There is hope!

- Gravitational waves
- Short Duration Gamma-Ray Bursts (SGRBs)
- Afterglow
- Kilonovae
- All four together! GW170817
  - Merger of two neutron stars
  - Host Galaxy: NGC 4993



NGC 4993 – EM Counterpart to GW170817
Image Source: NASA and ESA

Kilonova Observations!

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- Observations of the kilonova revealed:
  - The presence of heavy elements beyond Tc
- With kilonovae observations, we can identify the abundances of more elements!

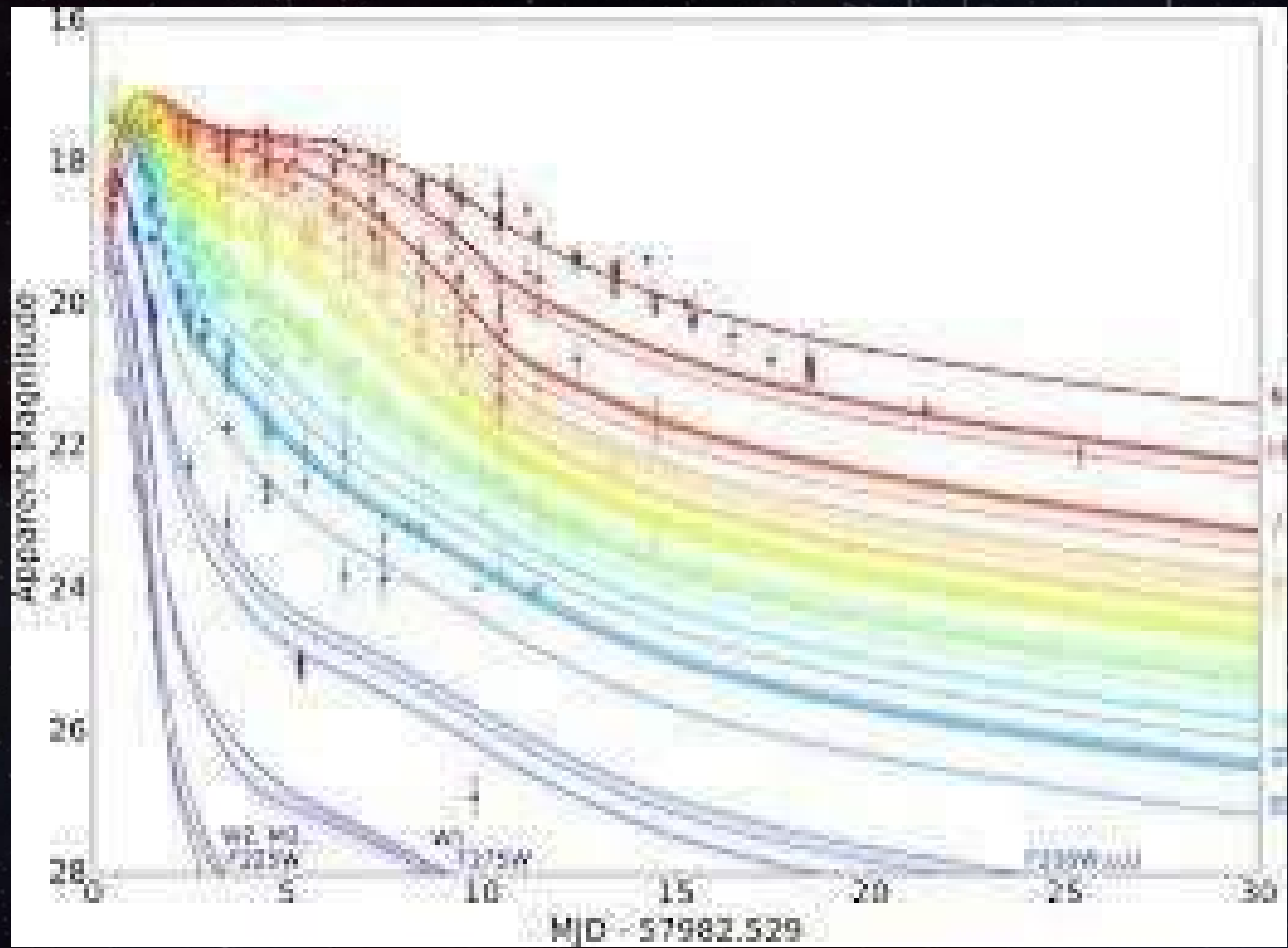
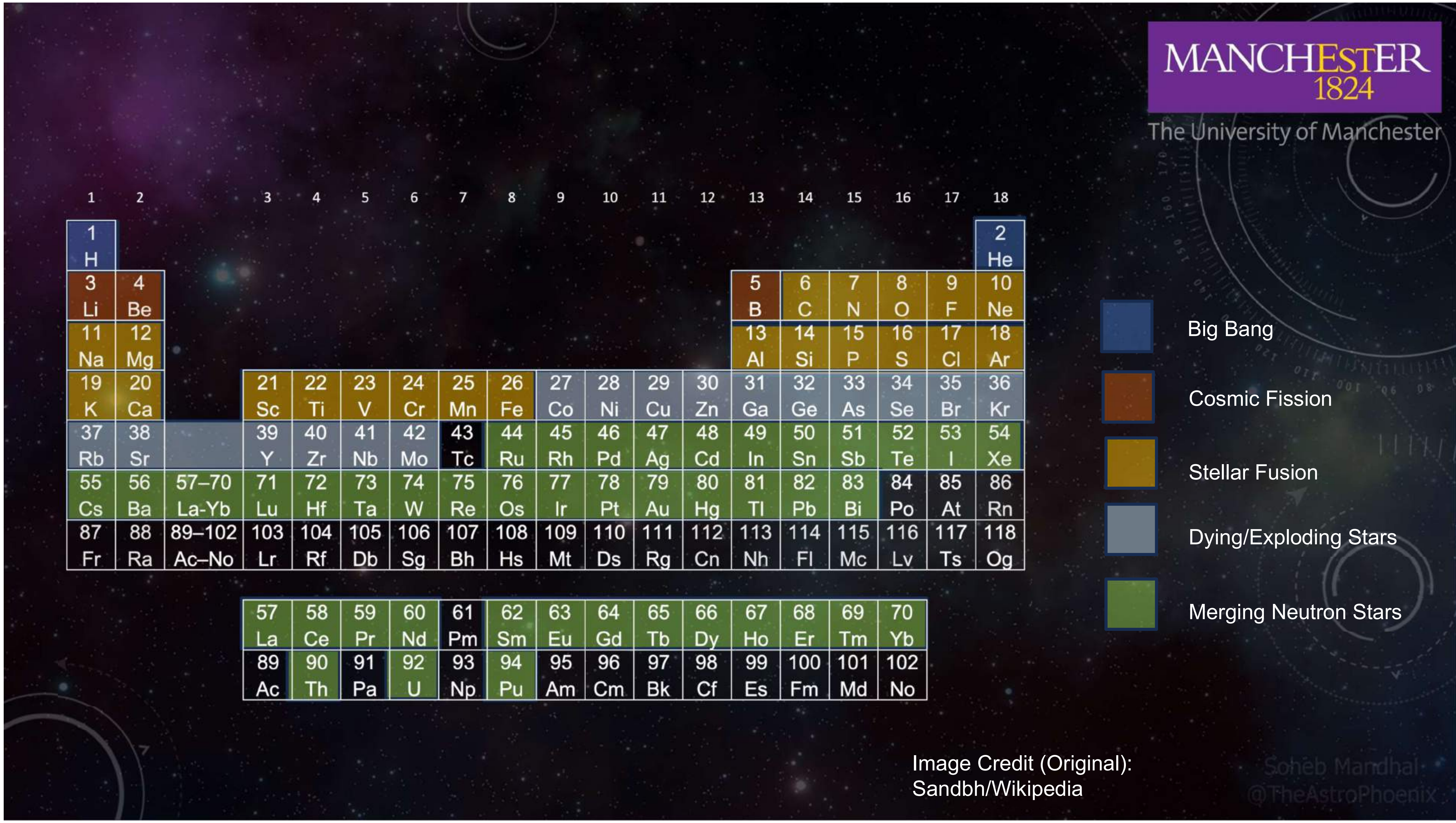


Image Credit: Villar et al., 2017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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
1 H
2 He
3 Li 4 Be
5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg
13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba 57–70 La-Yb 71 Lu 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Ra 89–102 Ac–No 103 Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 Ds 111 Rg 112 Cn 113 Nh 114 Fl 115 Mc 116 Lv 117 Ts 118 Og
57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb
89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No
Big Bang
Cosmic Fission
Stellar Fusion
Dying/Exploding Stars
Merging Neutron Stars
Image Credit (Original):
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Can we find more of these binaries?

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Gravitational-Wave Optical Transient Observer (GOTO)

- Array of 8, 40 cm diameter astrographs – encased in a clamshell enclosure (x2 per site).
  - Sites in La Palma, Spain and in Australia
- Synoptic Survey – Aims to map the sky frequently
- Get involved! Citizen Science Projects Science Projects:
  - GOTO Zoo
  - Kilonova Seekers


Get involved with GOTO science
kilonova-seekers.org
Kilonova Seekers: Citizen Science for Gravitational Wave Follow-up with GOTO
GOTO
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER
Join us on the
Zooniverse!

Vera Rubin Observatory/LSST

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- Currently under construction
  - First Light Expected January 2025
- Based in Chile (El Peñón, Cerro Pachón, Coquimbo)
- Synoptic Survey that will:
  - Image the entire sky every few nights
- Houses a reflecting telescope with an 8.4 m primary mirror.

Image Credit: Rubin Obs/NSF/AURA

Ground Based Gravitational Wave Detectors

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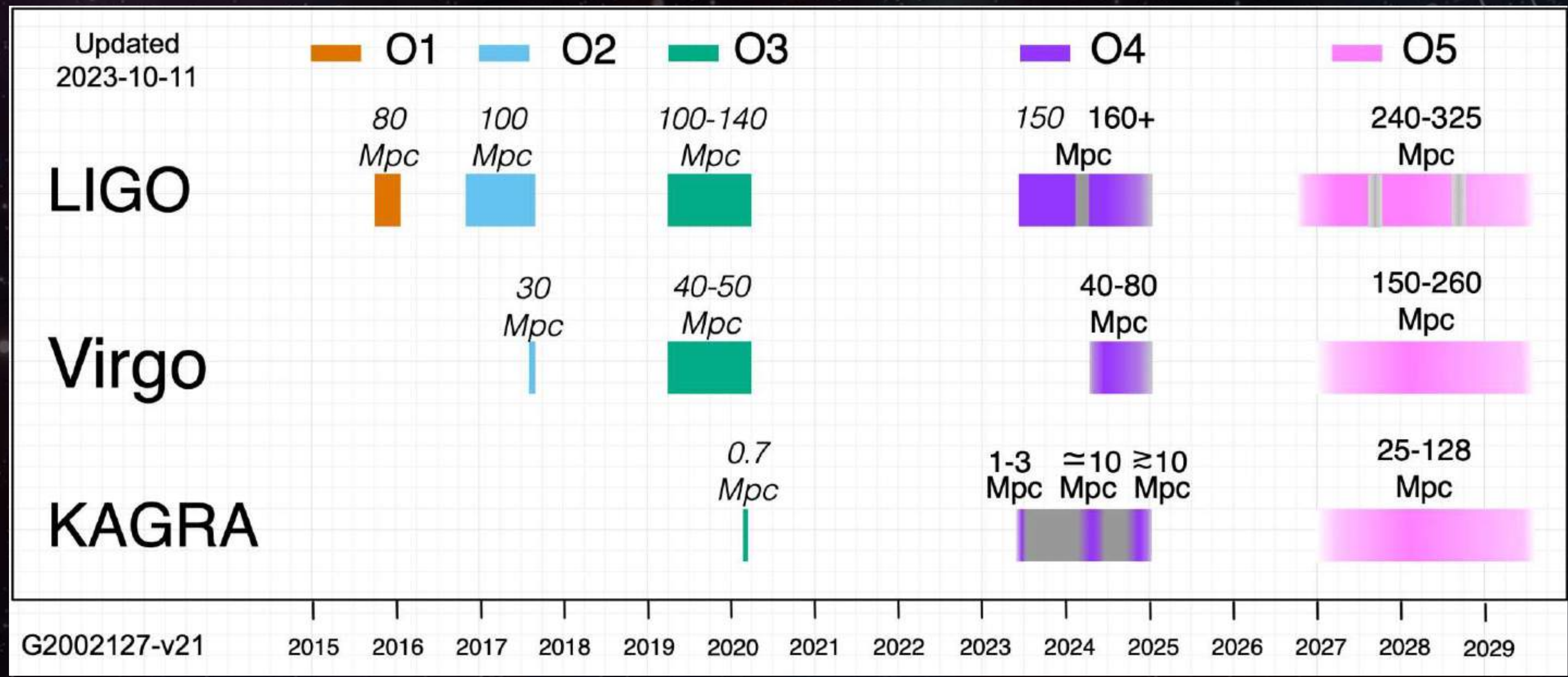

Image Credit: LVK+ Collaboration

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Space Based Gravitational Wave Detectors

LISA - Laser Interferometer Space Antenna

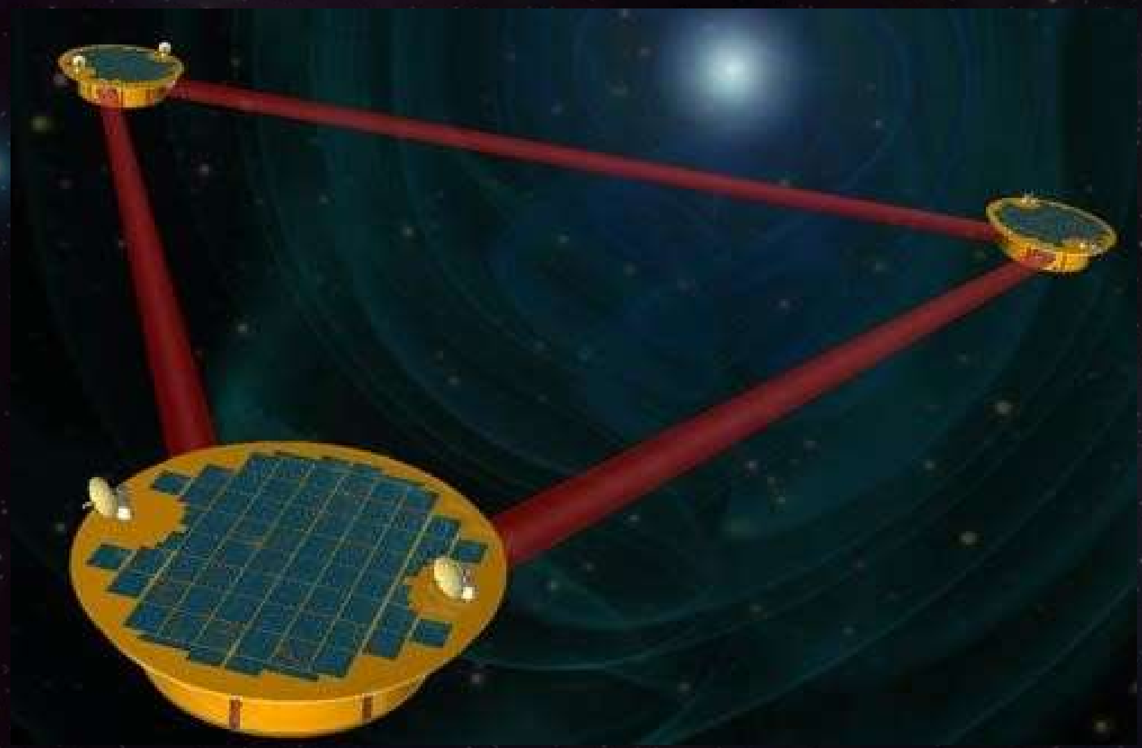

Image Credit: NASA

DECIGO - Deci-hertz Interferometer Gravitational wave Observatory

Image Credit: University of Tokyo

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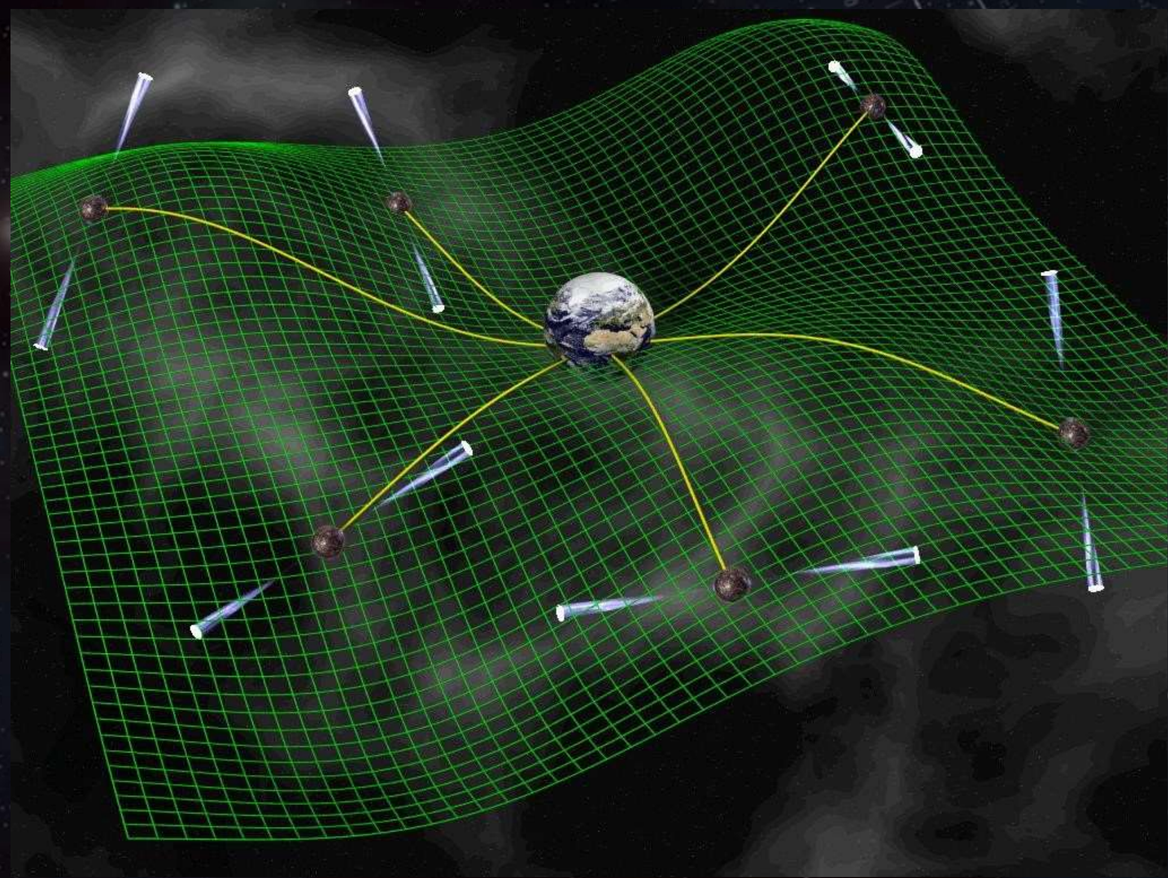
These will look at:

1. Coalescing Massive Black-Holes
2. Binaries within the Milky Way
3. Inspiralling Binaries

Pulsar Timing Array

- Pulsars are rapidly spinning neutron stars
  - Release Radio Emission
- Well timed
- 6+ decades of pulsar observations
- Small discrepancies in timing could indicate the presence of gravitational waves



Summary

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- The merger of neutron stars lead to the production of heavy elements
  - You are more than just star dust. You are special on a cosmological scale.
- Within the last decade, we have gained the ability to feel the cosmos, not just observe it
- You can leave your mark with projects such as GOTO Zoo/Kilonova Seekers
- Have questions? Email – Soheb.Mandhai@manchester.ac.uk