Formation of double Neutron star systems and implications for heavy element production

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Formation of double Neutron star systems and implications for gold production

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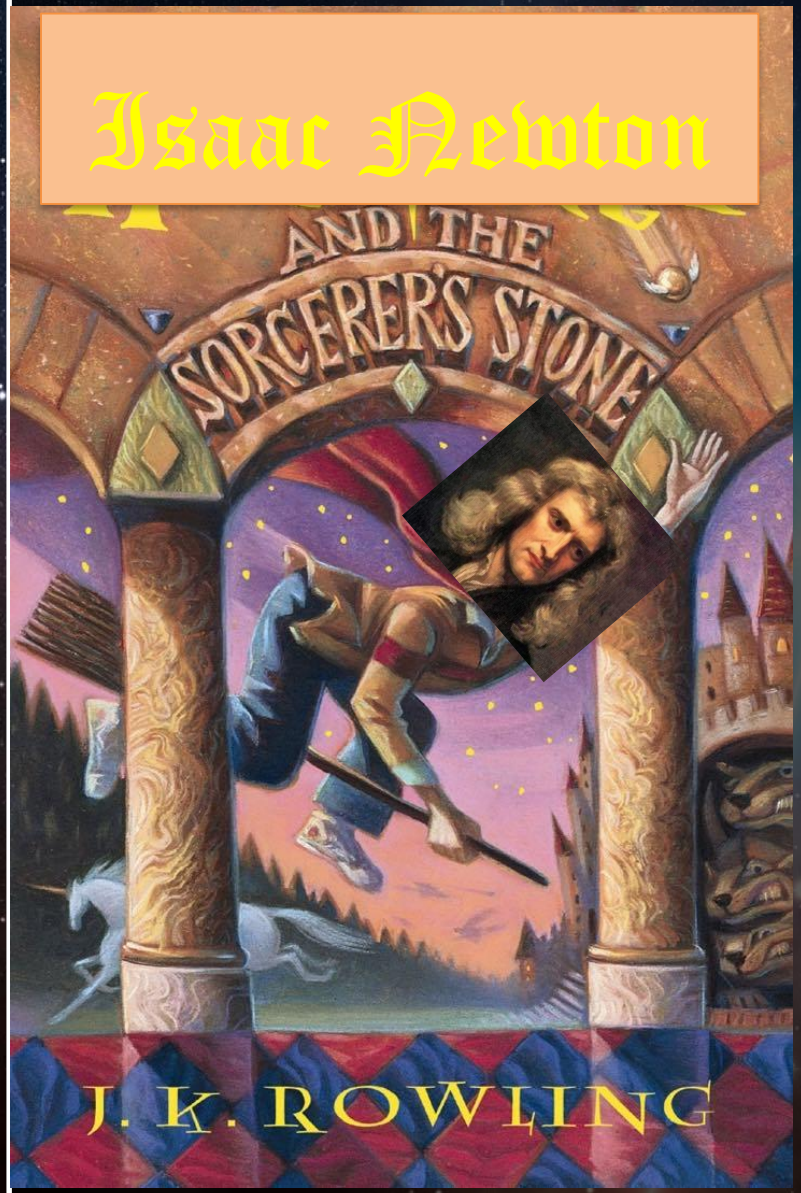
Creation of an r-process element *(a.k.a. gold)* in mythology

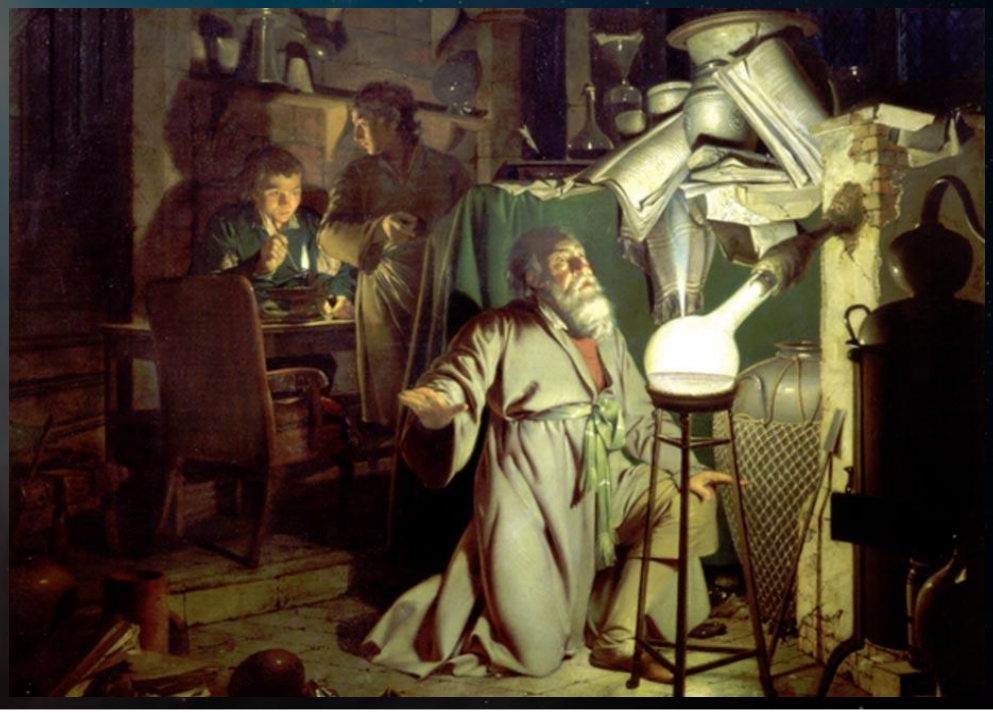
- Inti – Inca sun god who's tears were gold

- Midas – king in Greek mythology 'gifted' with golden touch

Alchemy

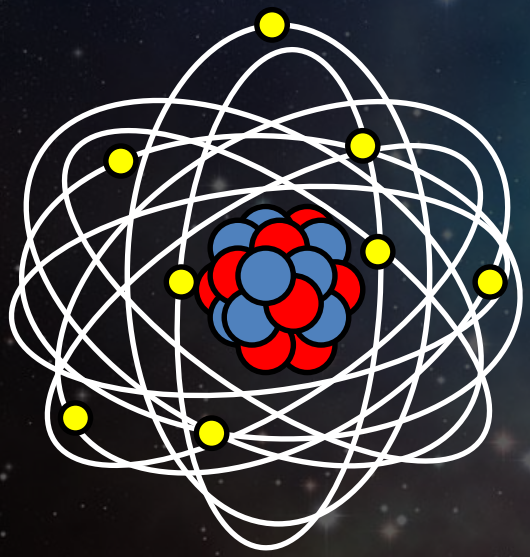


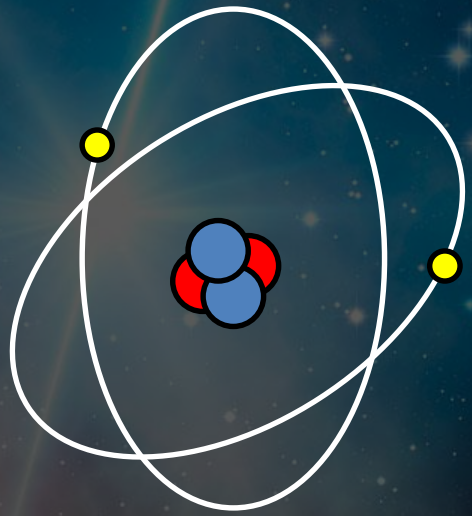
- Isaac Newton, Robert Boyle and Tycho Brahe were obsessed with the sorcerer's stone that would turn base metals into gold and grant immortality

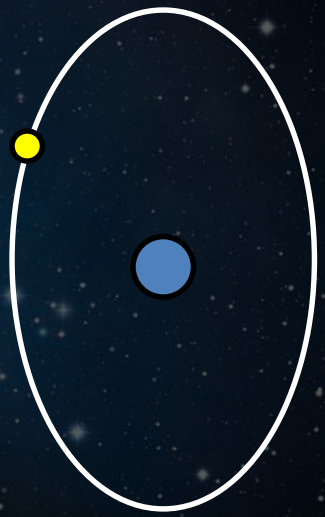


Modern understanding of elements – The structure of matter

- Matter composed of atoms which differ by proton and neutron number in nuclei







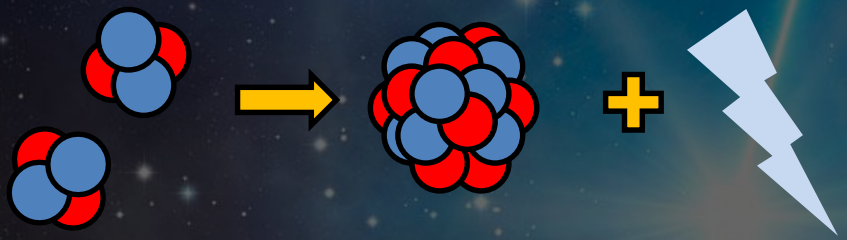
$^{16}_{8}O$ $^{4}_{2}He$ $^{1}_{1}H$

Total number of particles in nucleus

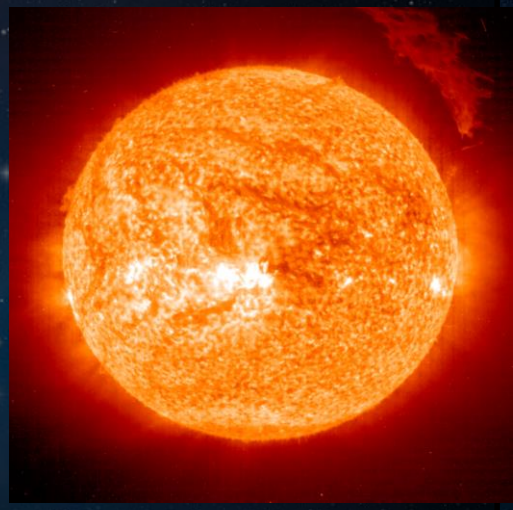
Number of protons in nucleus

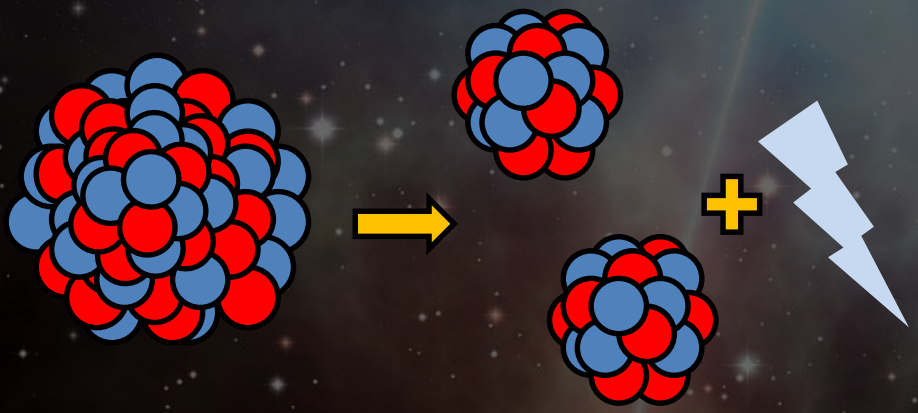
Modern understanding of elements – The structure of matter

- Matter transforms between forms



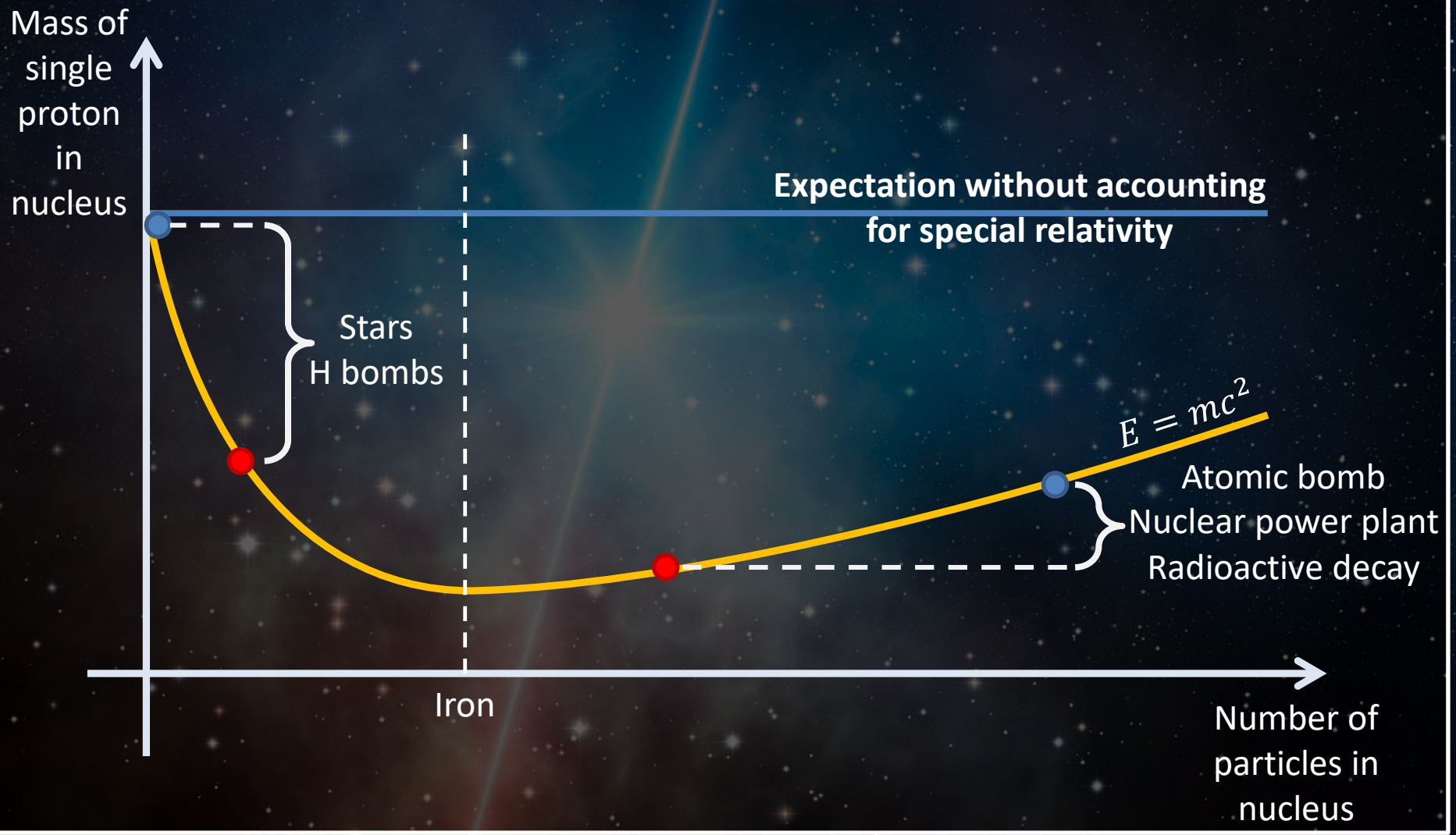
Fusion
(e.g. stars)



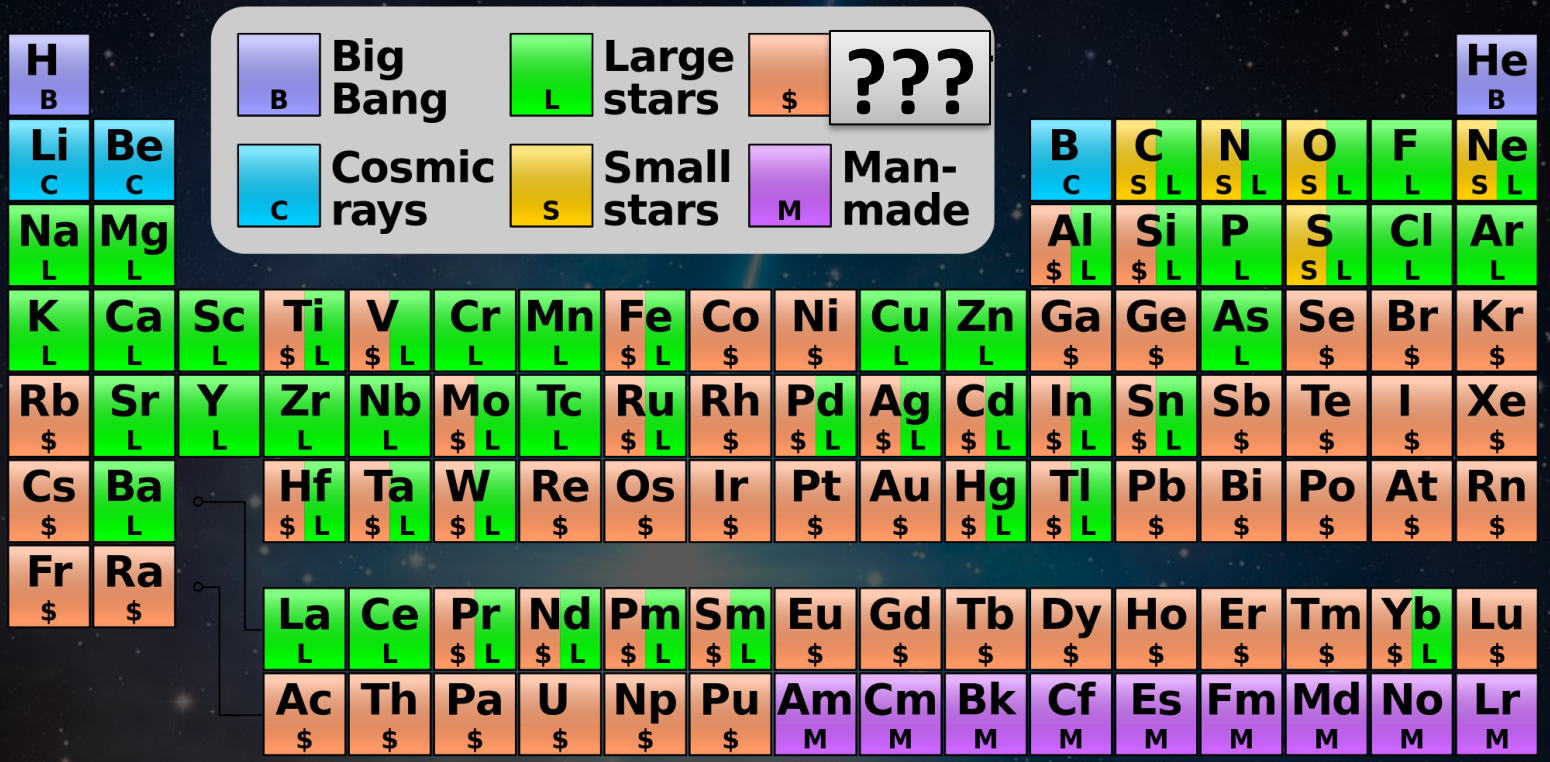


Fission
(e.g. nuclear power plants)

Major difference between fusion in stars and fission in nuclear power plants

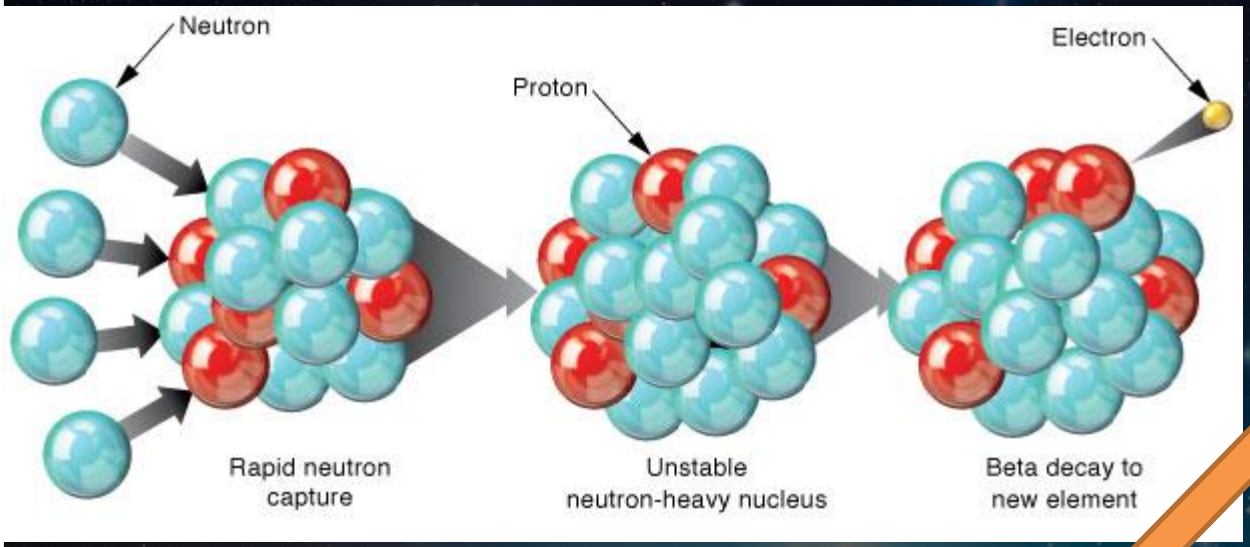


Modern understanding of elements



- Light elements mostly formed in big bang and cosmic rays
  - Heavier elements forged in hearts of stars
- Heavier elements still require external source of energy – Created in extreme temperatures and densities via the **r-process**

The r-process



Silver

Gold

Mercury

WHERE DID THEY COME FROM?

■ Elements that have been made in part by the *r* process

1 H Hydrogen																	2
3 Li Lithium	4 Be Beryllium										5 B Boron		7 N Nitrogen	8 O			10 Ne Neon
11 Na Sodium	12 Mg Magnesium											14 Si Silicon	15	16 S Sulfur	17 Cl Chlorine	18 Ar Argon	
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper		31 Ga		33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Caesium	56 Ba Barium	57-71	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81	82 Lead	83 Bismuth	84 Polonium	85 Astatine	86 Radon
87 Fr Francium	88 Ra 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 Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U 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

- Traditionally r-process thought as linked to **supernovae**
  Explosions of dying massive stars

Hubble space telescope mosaic image

r-process – astrophysical evidence

- **Total mass of r-process material in the Milky Way**

Total mass of r-process material - ***measured***

$$M_{tot} = t\ R\ m$$

Time of active formation - ***known***

Rate of events - ***unknown***

r-process mass created per event- ***unknown***

Events either ‘common’ (every ~ 50 years) and produce small amounts of mass per event (0.005% of sun’s mass)

Or

Events rare (every ~ 50,000 years) and produce large amounts of mass per event (5% of sun’s mass)

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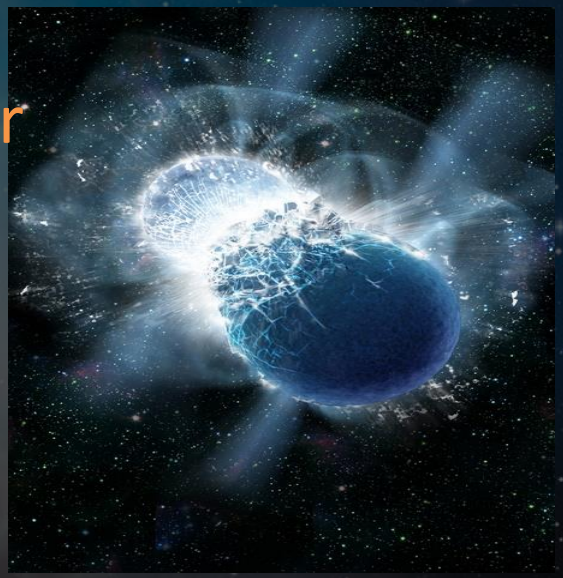
Supernovae

Or



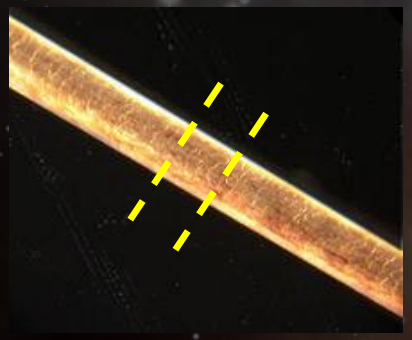
Double Neutron star mergers

Events rare (every ~ 50,000 years) and produce large amounts of mass per event (5% of sun’s mass)

What are neutron stars?

- Extremely dense remnants of once massive stars that exploded in supernovae and lost their envelopes
- A Neutron star with the mass of the sun is only **10 km in radius!**

- Like condensing a jumbo jet to a size of a single hair as long as it is wide



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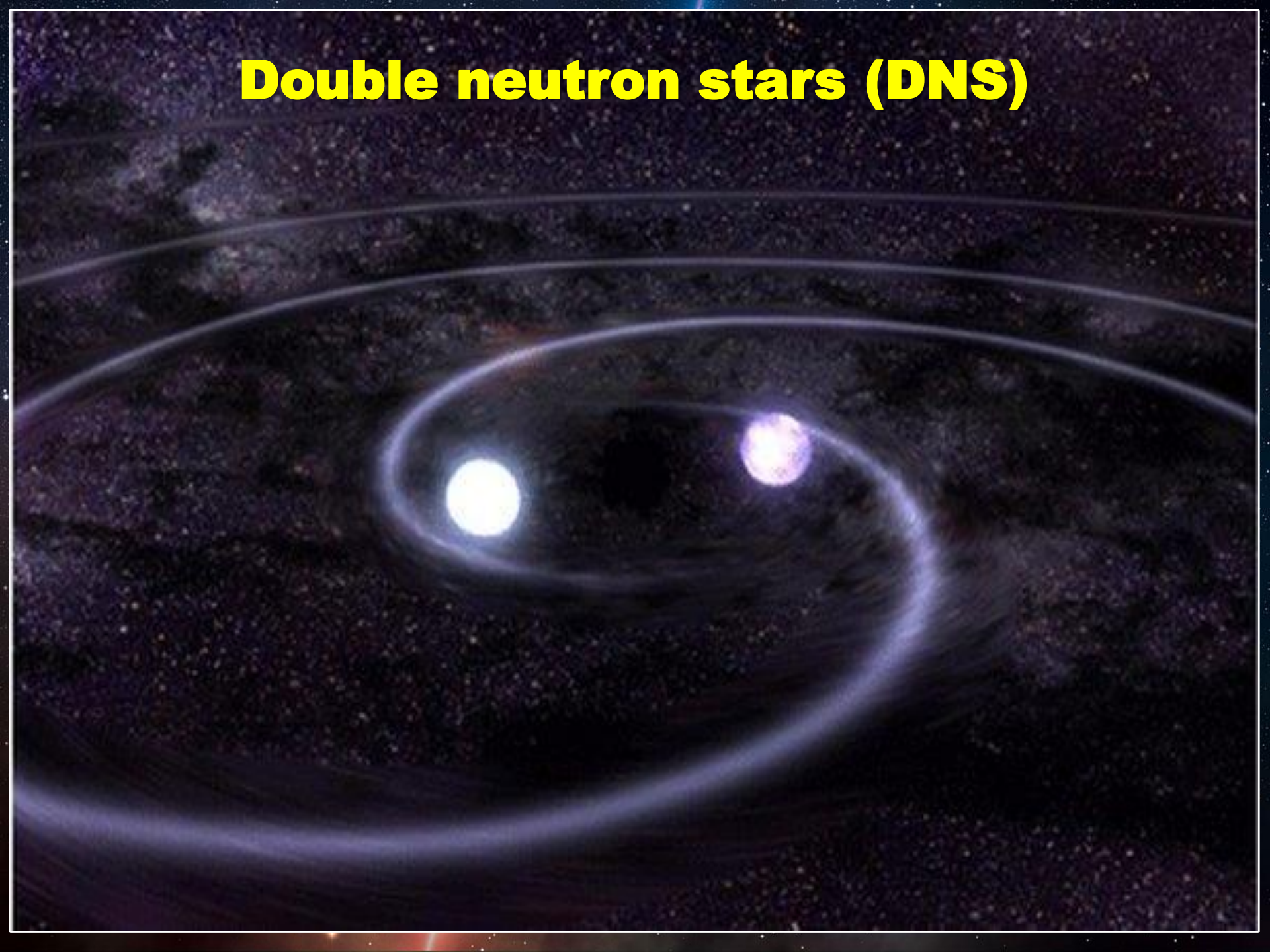
Double neutron stars (DNS)



Merger due to gravitational waves

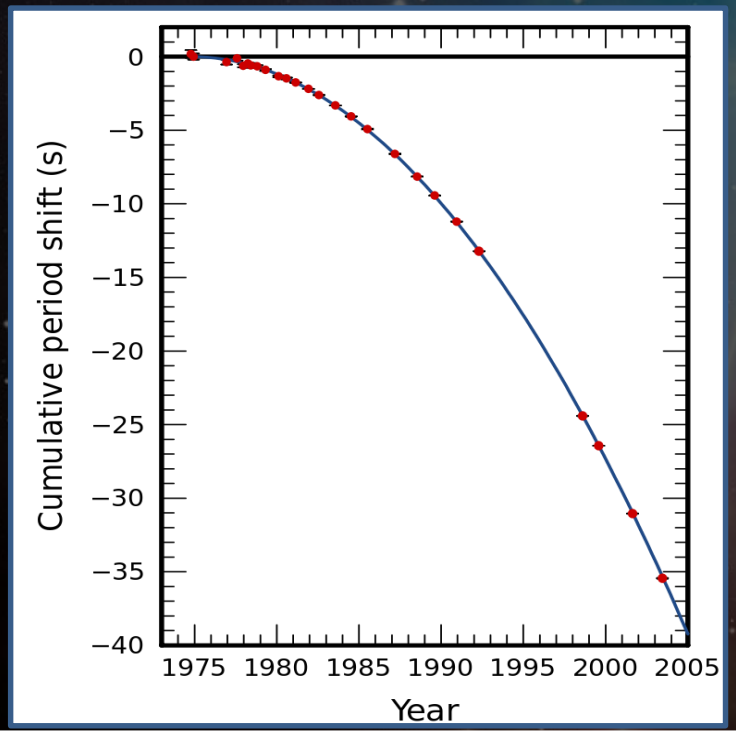
- Masses orbiting each other lose energy due to gravitational waves
- The separation between the objects decreases over time, until their eventual merger

- Merger results in a gamma-ray burst, and also in a weaker explosion known as the kilonova, that is powered by radioactive decay of r-process elements

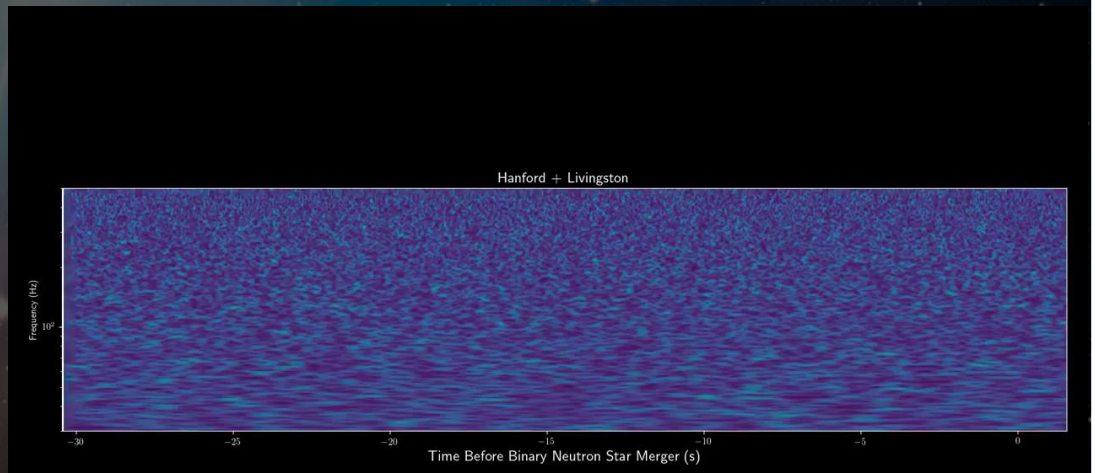
Merger due to gravitational waves

- Gravitational radiation is a general relativistic effect that was predicted by Einstein and observationally confirmed using a DNS system in the seventies. The radiation itself was directly observed for the first time in 2015 from black holes and in 2017 from neutron stars.

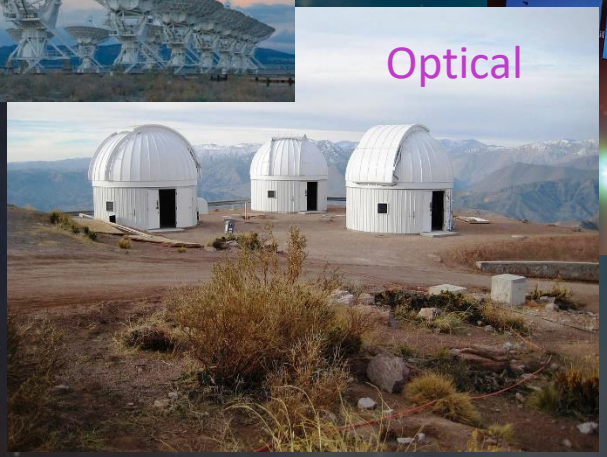
Hulse & Taylor 74
(Nobel prize 93)

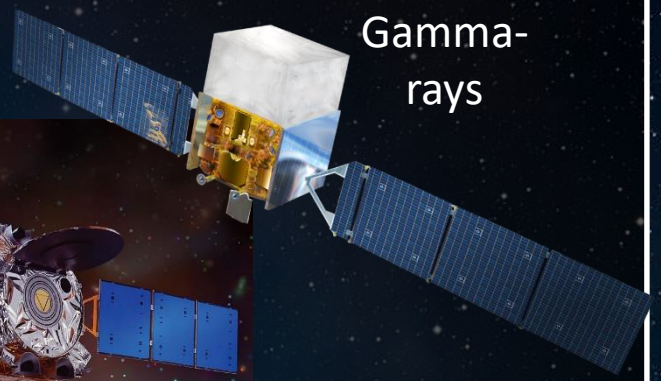


LIGO's first detection of gravitational waves from a merging DNS (Nobel prize 2017)



GW 170817

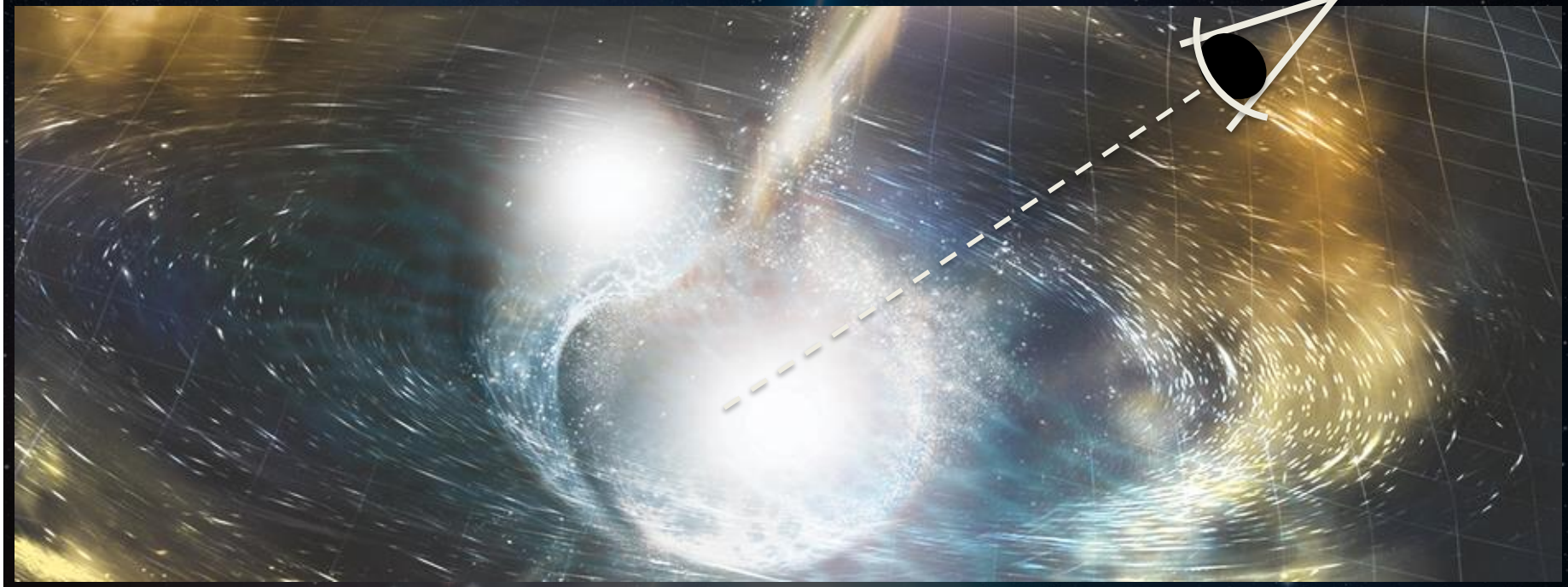




After the discovery an alert was sent to telescopes across the planet

This lead to discovery of a gamma-ray burst and other electromagnetic counterparts that accompanied the gravitational waves

Discovery by gravitational waves allows us to detect gamma-ray bursts at a closer distance and from a different viewing angle

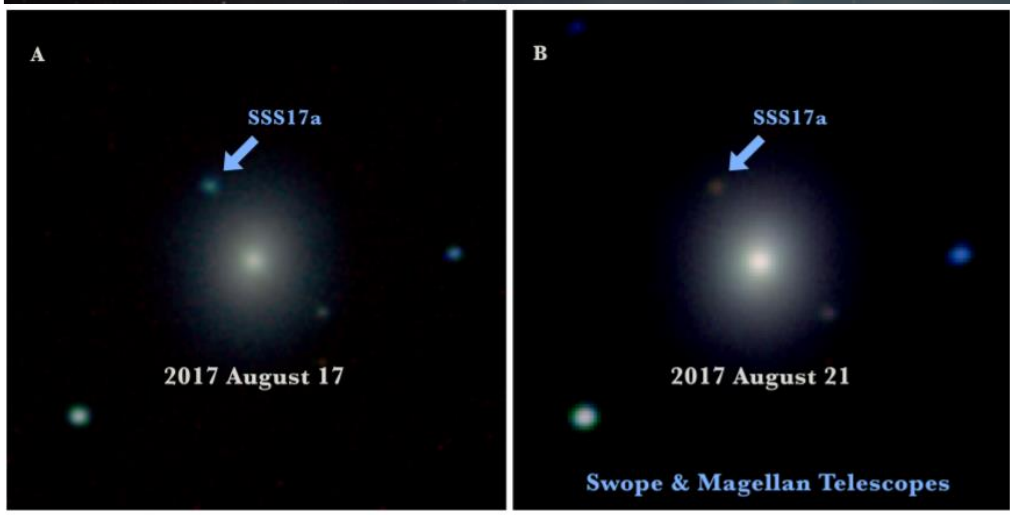


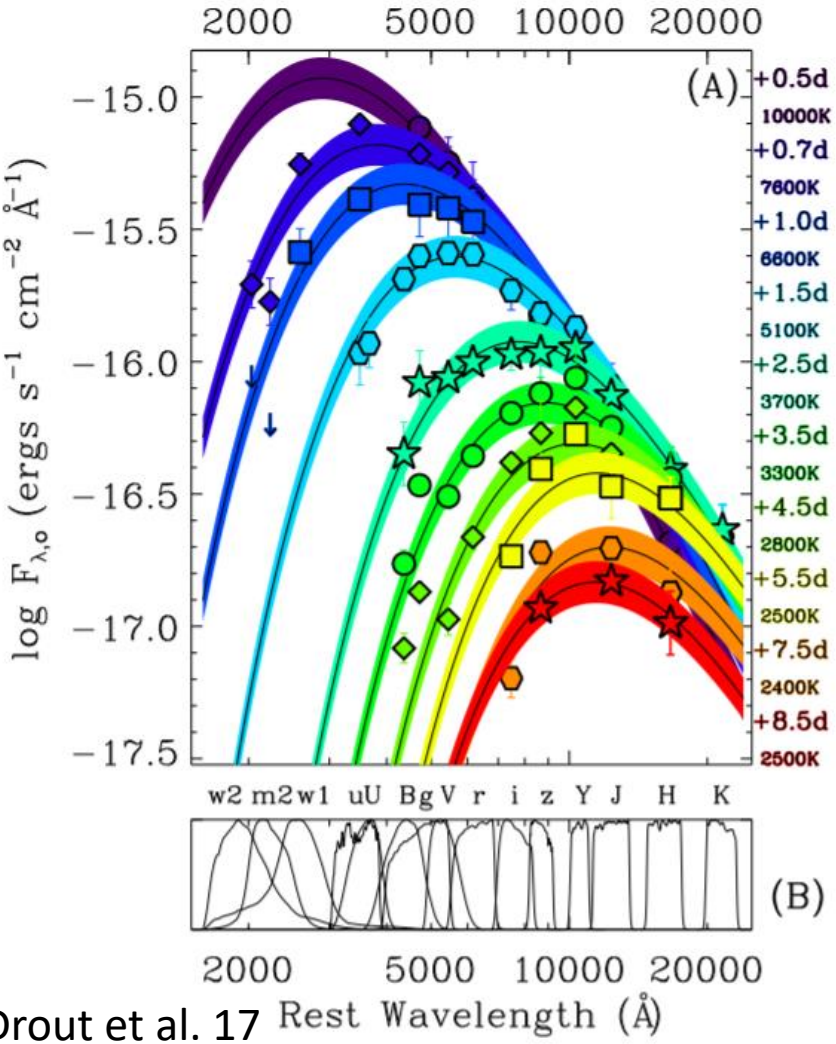
This allows us to detect different kinds of electromagnetic signals that were previously hidden from view

Kilonova

- Kilonova observed by optical telescopes days after merger
- Wavelength, brightness and duration of signal allow us to calculate total mass of r-process elements formed in explosion
- So how much r-process formed?

The expected kilonova signal was first detected in 2017





Drout et al. 17

Kilonova

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We'll get back to this…

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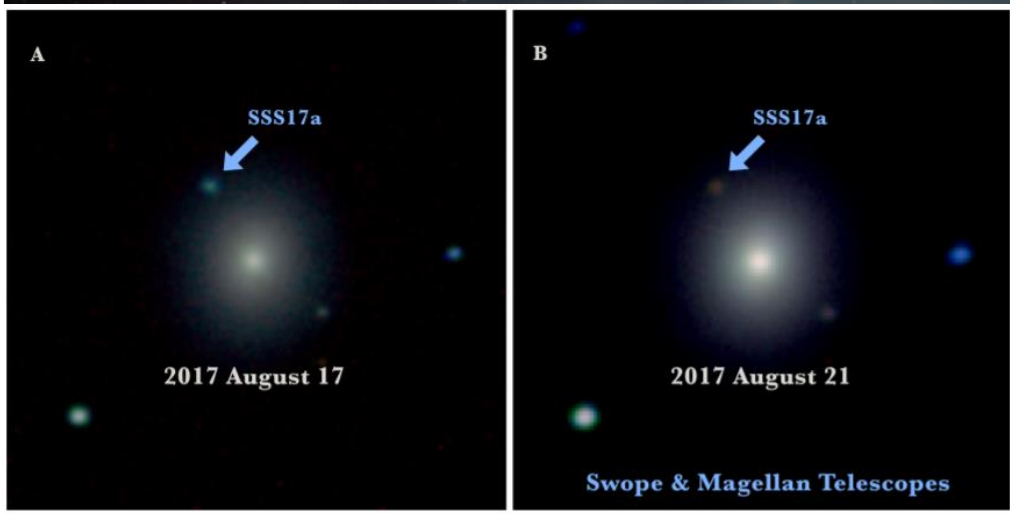
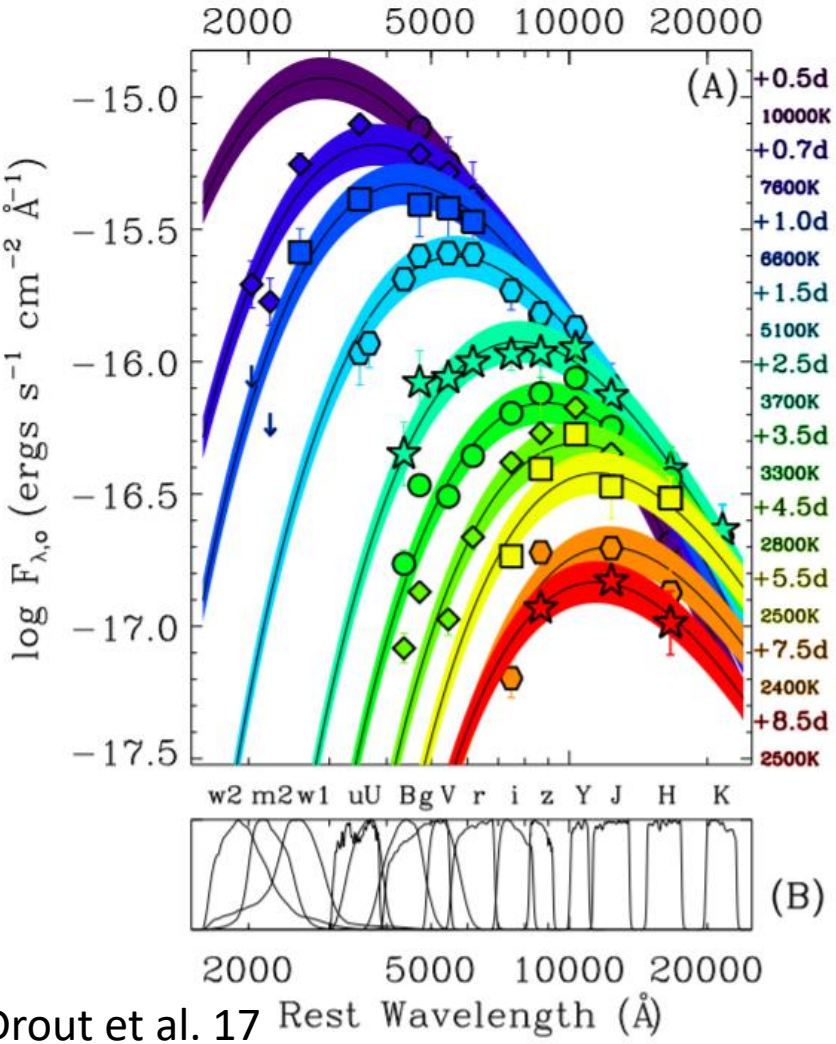
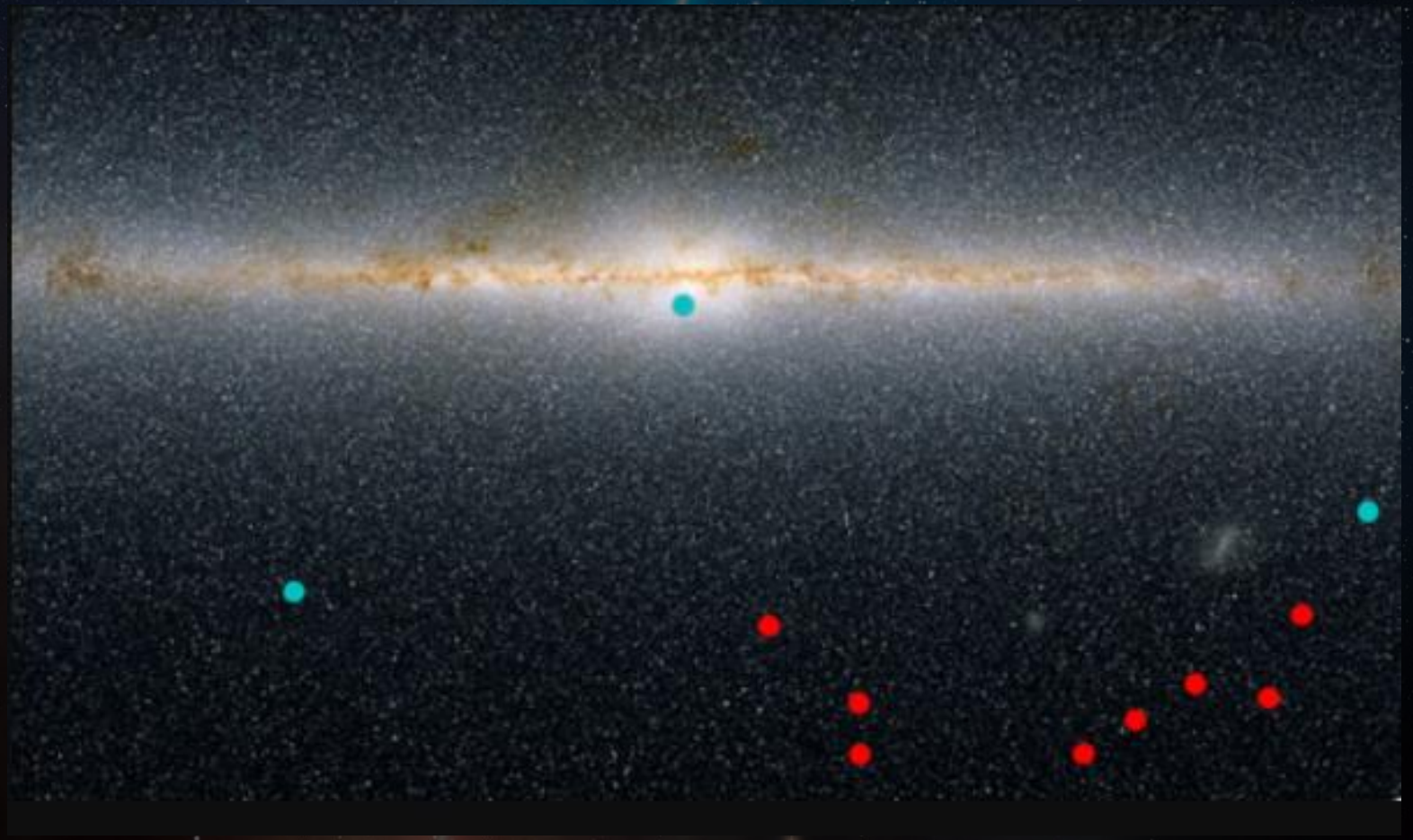




Drout et al. 17

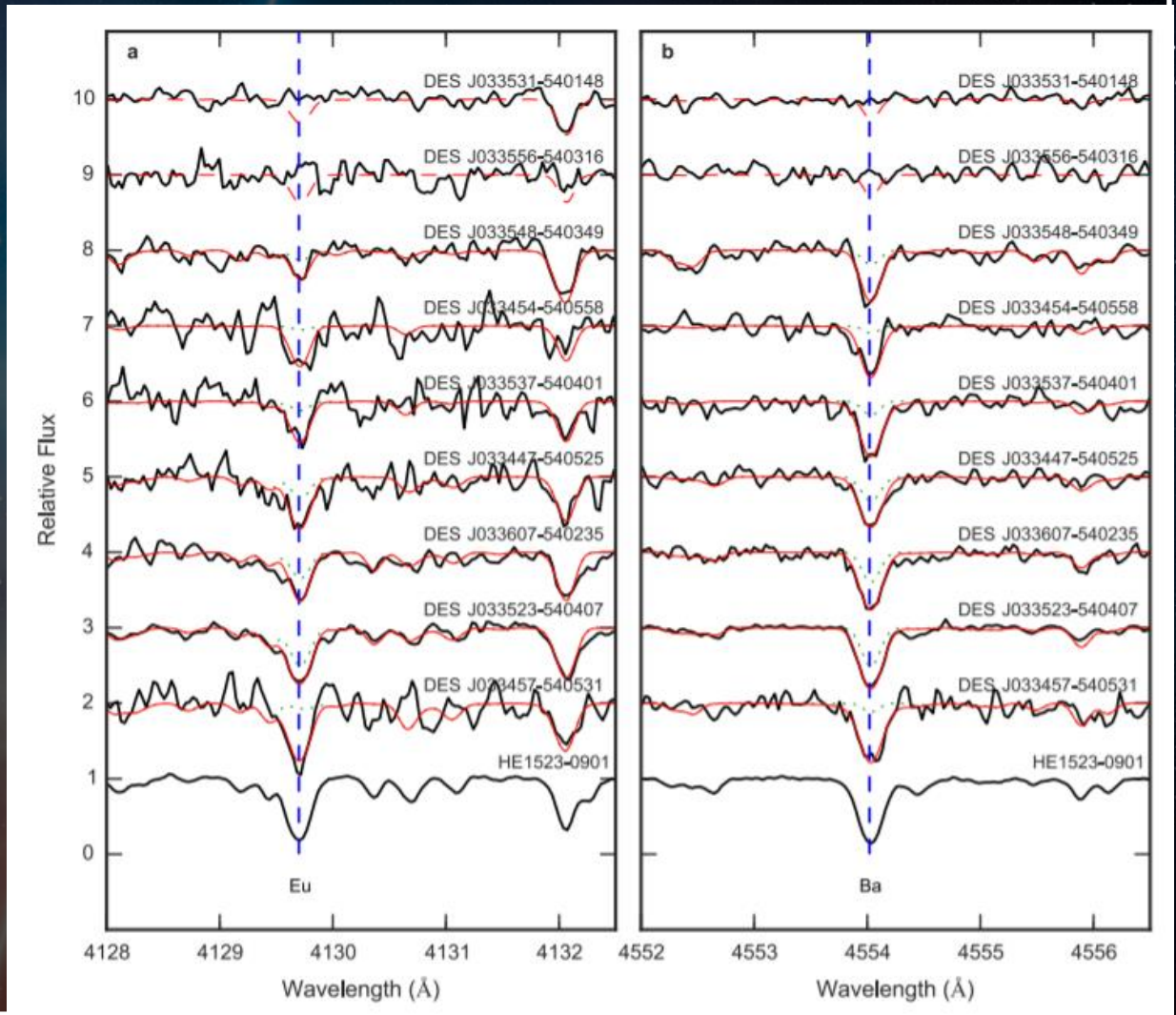
Ultra faint dwarf galaxies

- Extremely small and old galaxies, satellites of the Milky Way
- Mainly composed of dark matter: halo mass $\sim 10^5 M_\odot$ with only $\sim 10^3$ stars



DNS mergers and r-process elements in dwarf galaxies

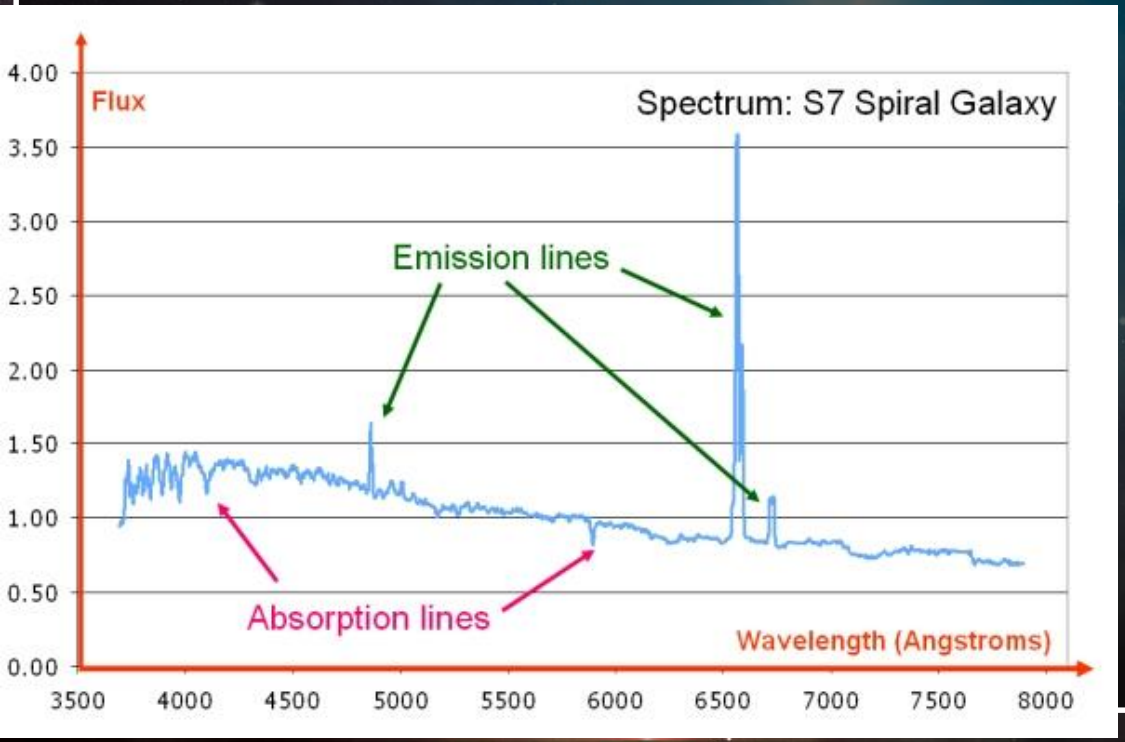
- r-process elements recently detected in one Ultra Faint Dwarf galaxy and some other "classical" dwarves (Ji et al. 2015, Roederer et al. 2016)

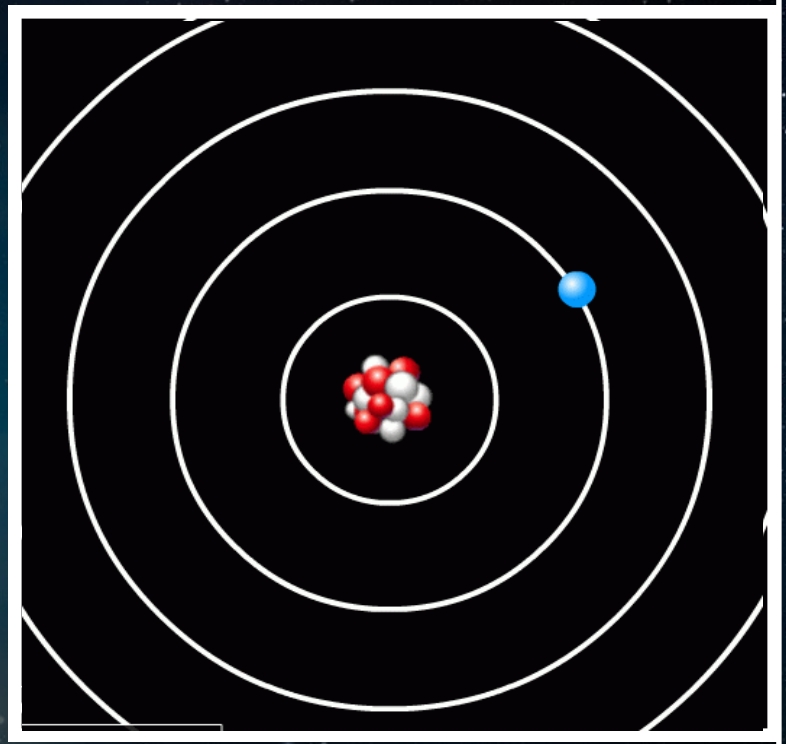


How do we measure r-process material?

- Different atoms have different energy levels
  different emission and absorption lines

- Measuring these lines is like taking
  a unique fingerprint of the matter

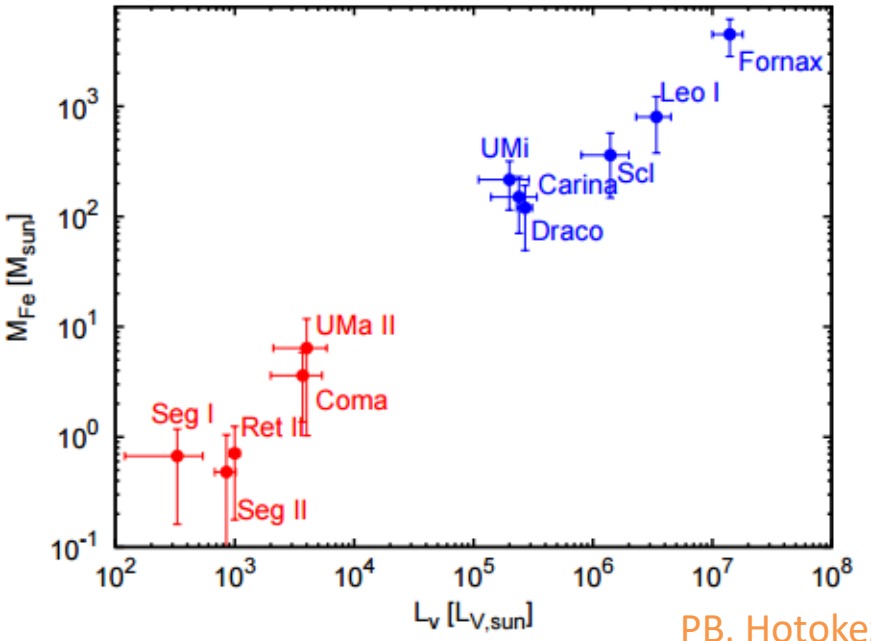




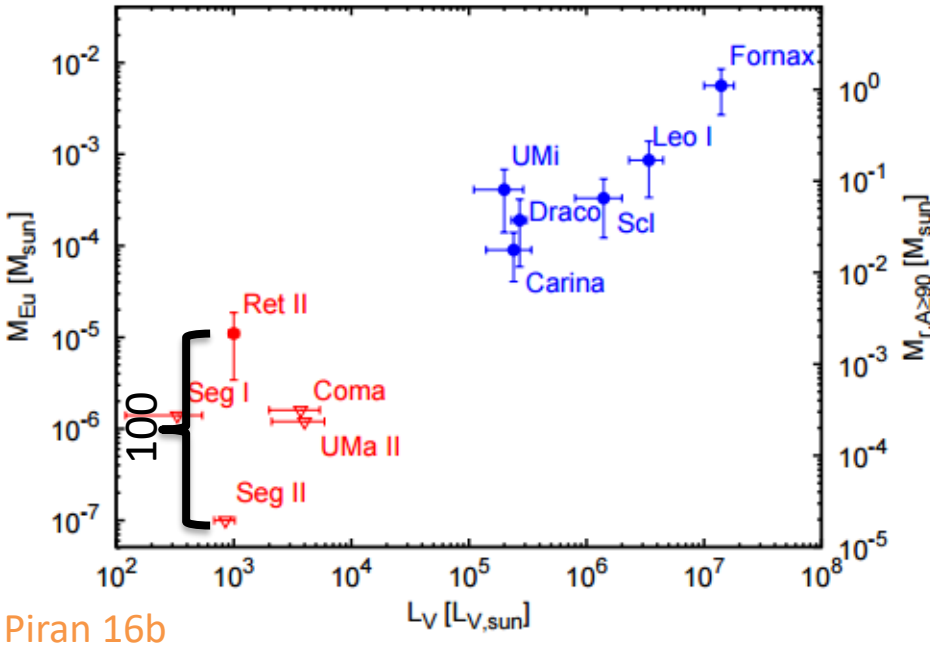
Fe and Eu in dwarf galaxies

- Fe mass ∝ Luminosity -> number of supernovae producing Fe ∝ number of stars
- For Eu similar trend observed but with much larger scatter
- Upper limit of $M_{Eu} = 10^{-7} M_{\odot}$ in one galaxy along with a measurement of $10^{-5} M_{\odot}$ in a galaxy of similar luminosity suggests Eu in the latter dominated by a single event

Iron mass in dwarf galaxies



Eu mass in dwarf galaxies



PB, Hotokezaka & Piran 16b

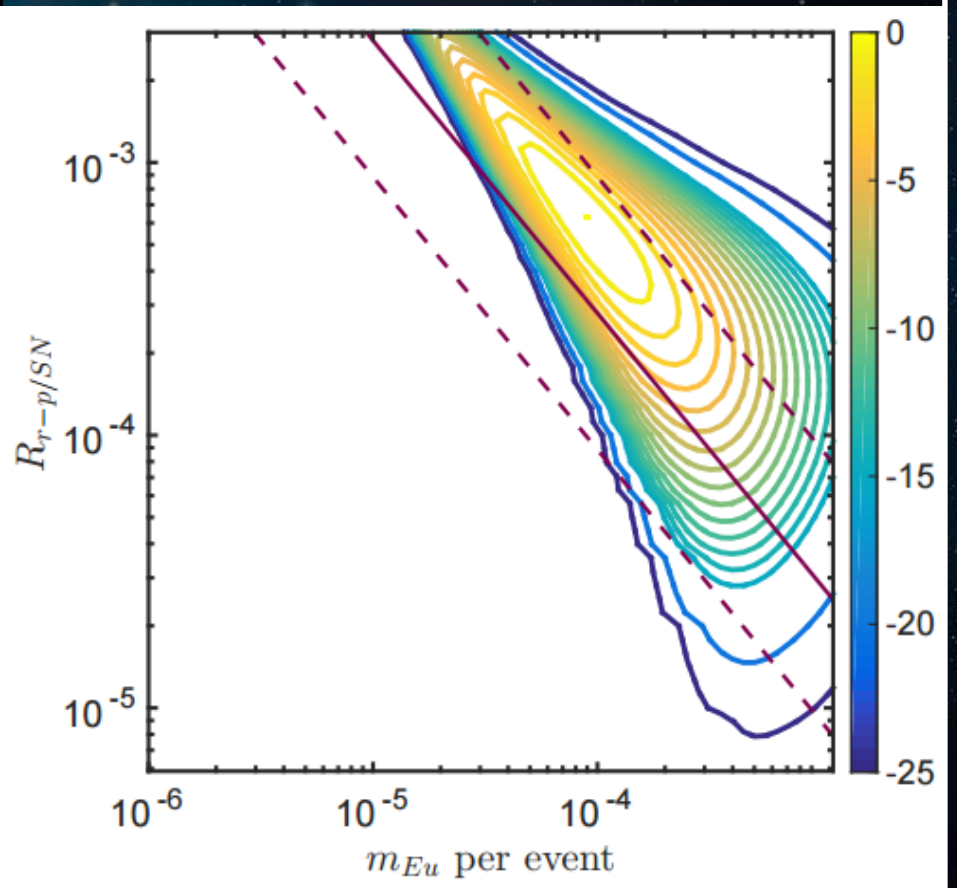
Fe and Eu in dwarf galaxies

PB, Hotokezaka & Piran 16b

- R-process rate and mass per event estimated *independently* from each other:

Rate (per SNe)$\approx 10^{-3}$<<1 &

$m_{Eu} \approx 10^{-4} M_{\odot}$

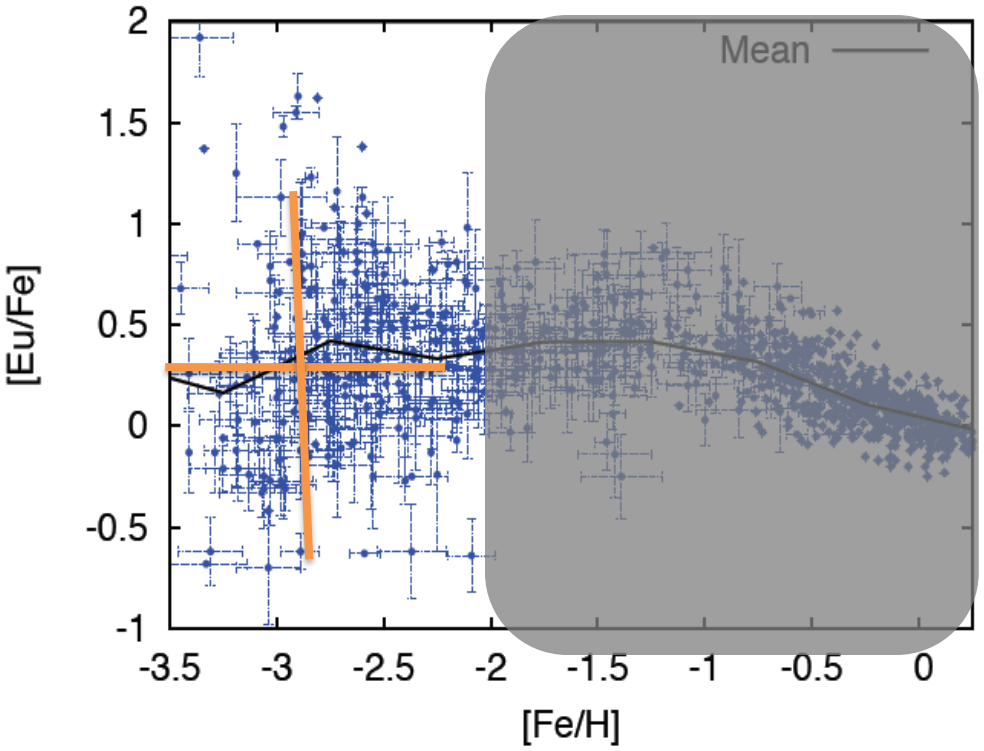


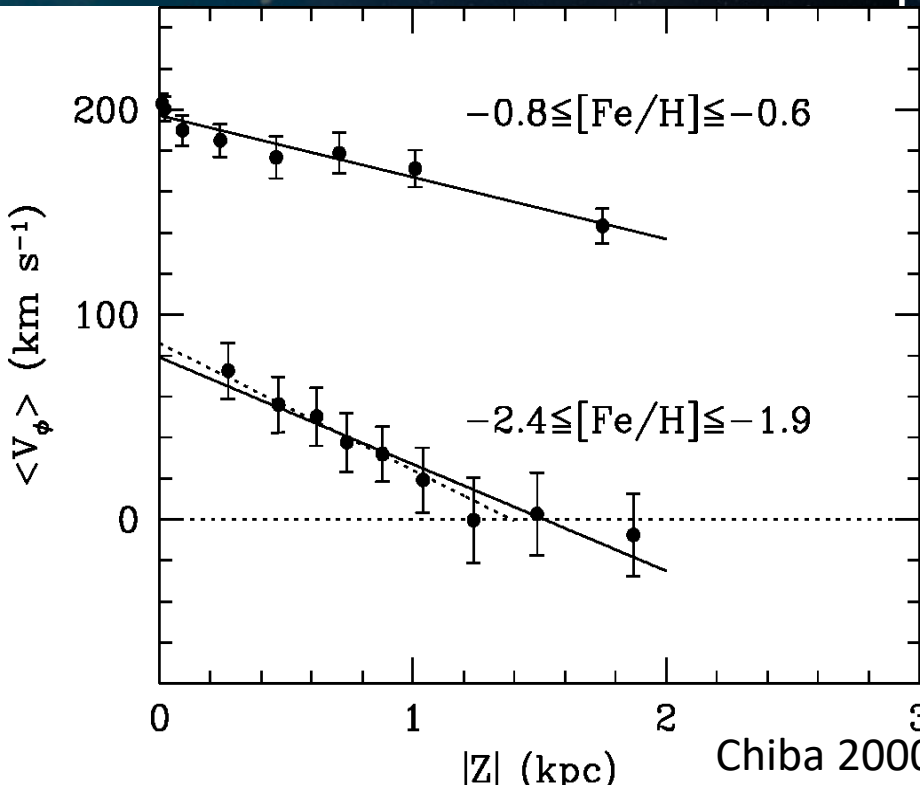
UFDs as building blocks of galactic halo metal poor stars

- Galactic halo stars were suggested to originate from dwarf precursors
  (Frebel et al. 10, Van de Voort et al. 15, Ishimaru et al. 15, Griffen et al. 16, Macias & Ramirez Ruiz 16)

If ~7% of dwarf precursors have an event leading to n_{Eu}/n_{Fe} ~30 larger than solar, then <[Eu/Fe]>~0.3 with spatial variations of up to ± 2

- Ranges of Fe/H and Eu/Fe from dwarf precursors, consistent with galactic halo stars



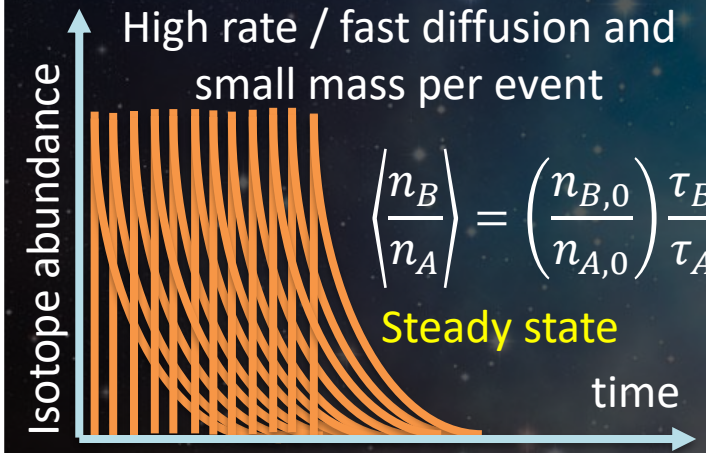


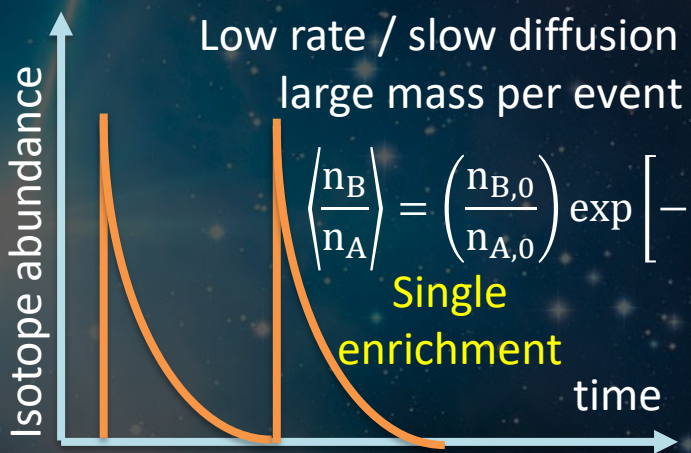
Chiba 2000

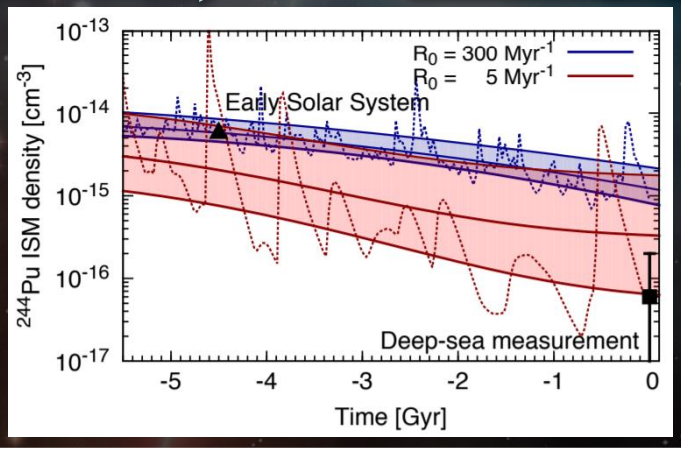
Mixing of elements in the interstellar medium

Radioactively unstable isotopes

At the time of formation of the solar system the abundance of isotopes such as ^{244}Pu, ^{247}Cm was significantly higher than measured today







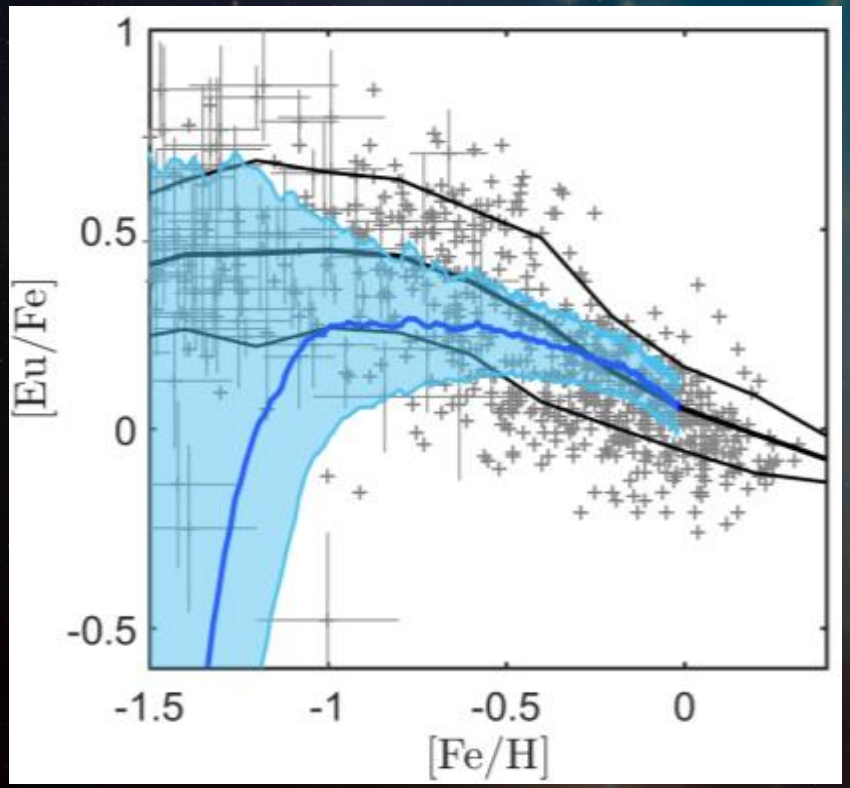
Hotokezaka et al. 2015, PB & Hotokezaka 2020

Mixing of elements in the interstellar medium

Radioactively stable elements

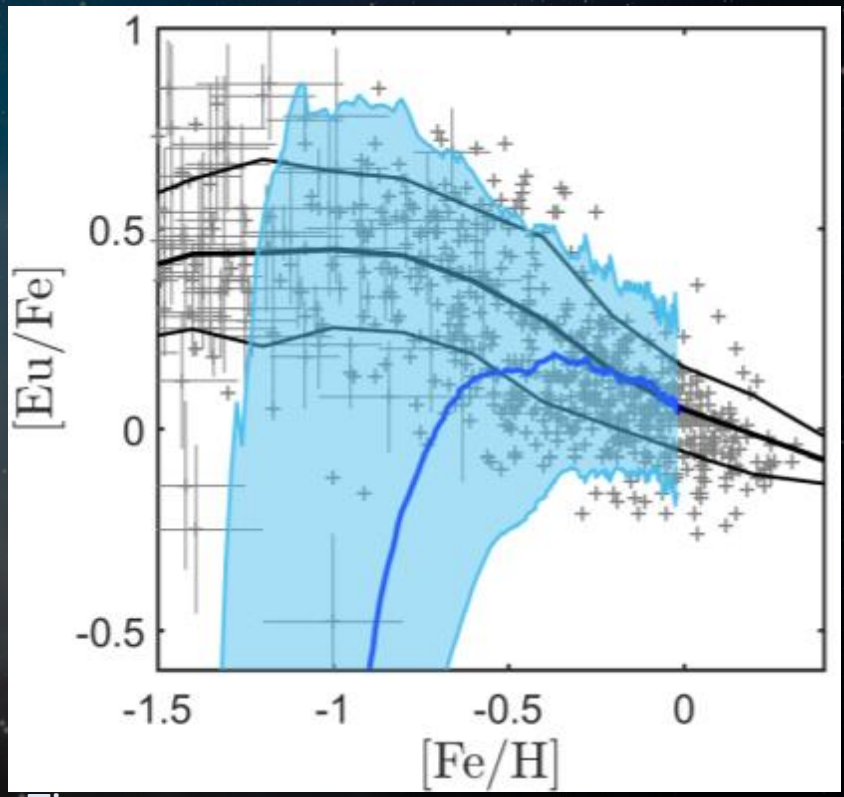
The scatter in abundances of stable elements is larger than observed if rate is low or diffusion slow (even with a constant mass per event)

High rate / fast diffusion



Time →

Low rate / slow diffusion

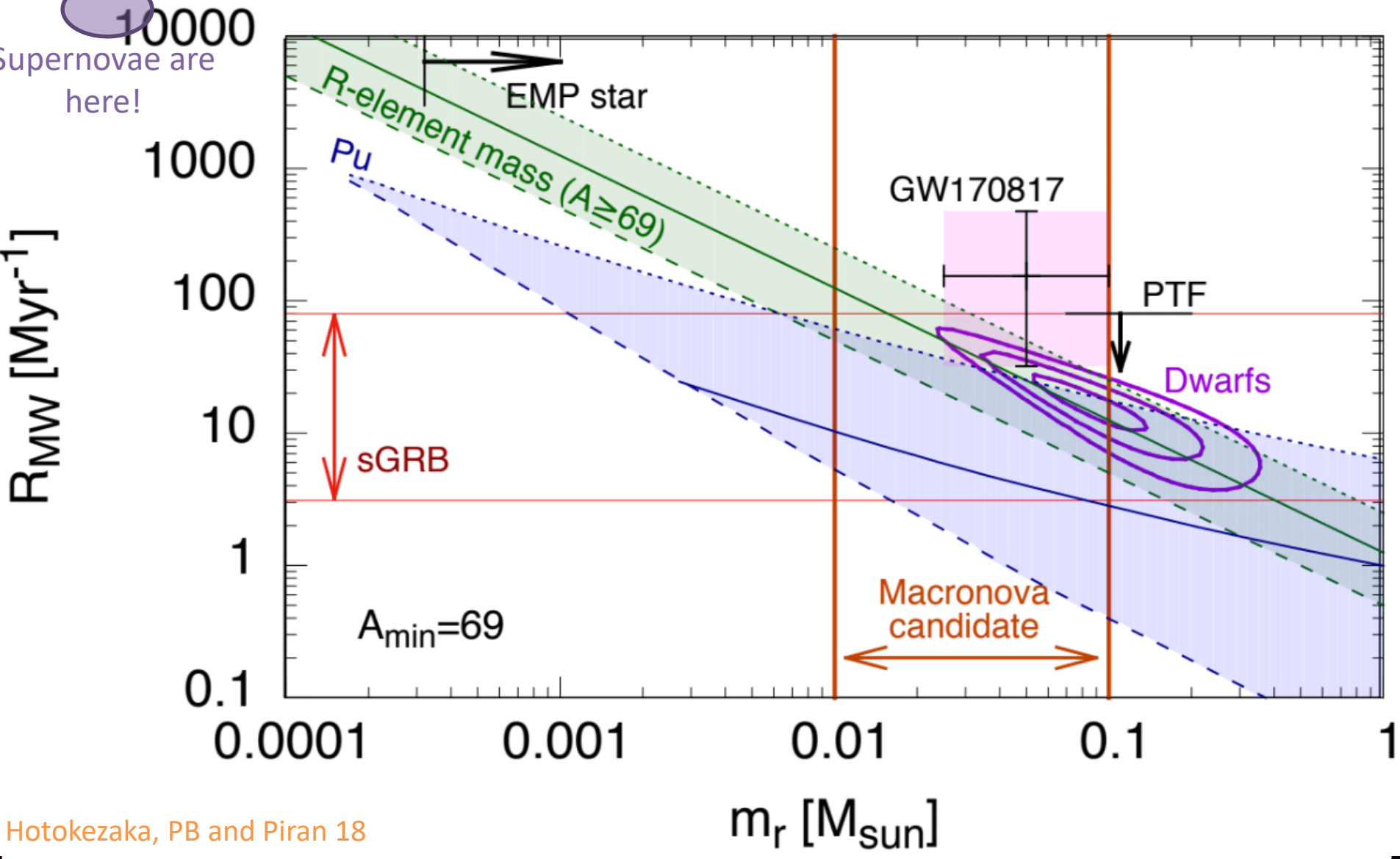


Time →

PB & Hotokezaka 2020

Combining everything together

Supernovae are here!



Hotokezaka, PB and Piran 18

Summary

- Many independent lines of evidence constrain rate of r-process events and amount of mass created per event.

- The observations suggest that double neutron star systems formed most of the r-process elements in the Universe.


Thank You!