

Electromagnetic counterparts of GW sources

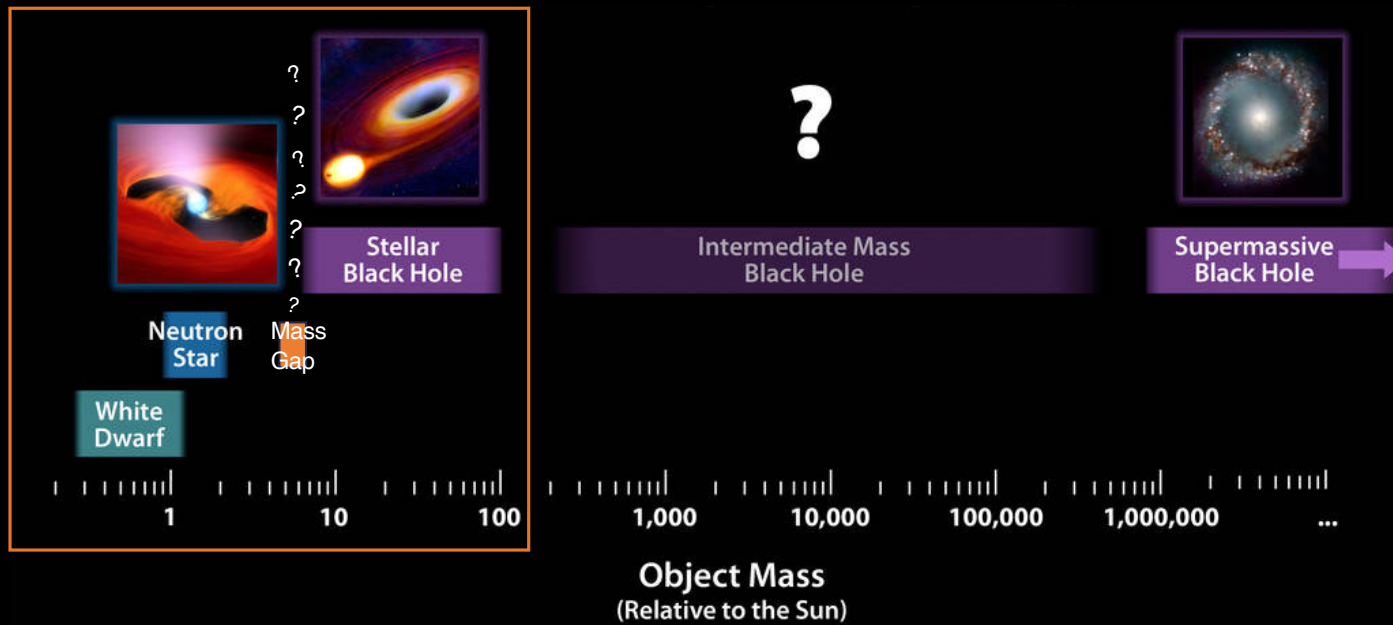
Eleonora Troja

University of Tor Vergata



Observed Mass Ranges of Compact Objects

This talk



GW170817



NGC 4993

130 Mly

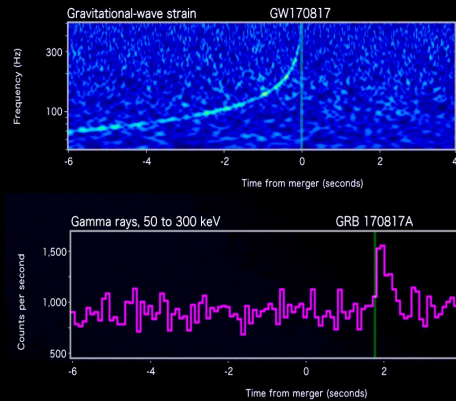


The Washington Post
Democracy Dies in Darkness

Scientists detect gravitational waves from a new kind of nova, sparking a new era in astronomy

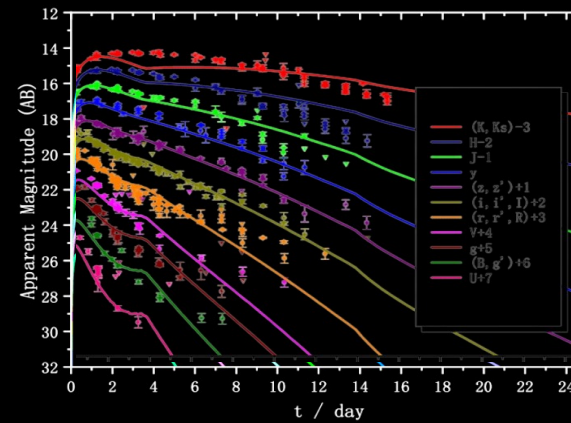


A GRB followed by a kilonova



GRB170817A

Abbott et al. 2017
Goldstein et al. 2017
Savchenko et al. 2017
Zhang et al. 2018



The kilonova AT2017gfo

Coulter et al. 2017, Valenti et al. 2017, Drout et al. 2017, Arcavi et al. 2017, Lipunov et al. 2017, Soares-Santos et al. 2017, Tanvir et al. 2017, Andreoni et al. 2017, Smartt et al. 2017, Chornock et al. 2017, Kasliwal et al. 2017, Pian et al. 2017, Troja et al. 2017, Cowperthwaite et al. 2017,...

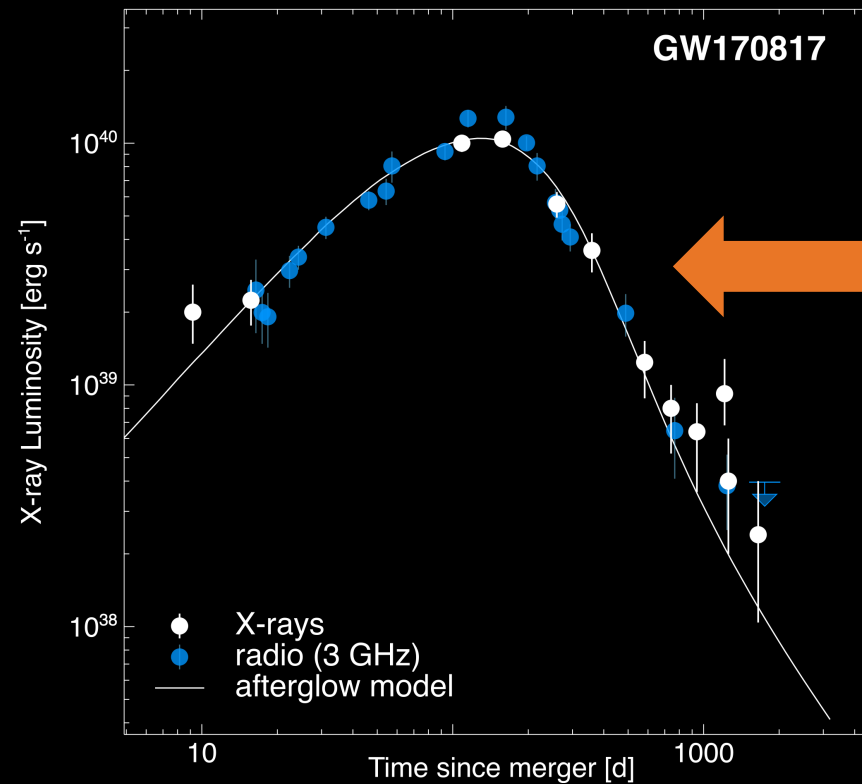
Cauldron of heavy elements

Legend																	
□	Non-metal	□	Metal	□	Noble gas												
□	Alkali metal	□	Metalloid	□	Actinide												
□	Alkaline earth metal	□	Halogen	□	Lanthanide												
□	Transition metal																
1 H HYDROGEN 1.0079										2 He HELIUM 4.0026							
3 Li LITHIUM 6.941	4 Be BERYLLIUM 9.0122										5 B BORON 10.811	6 C CARBON 12.011	7 N NITROGEN 14.007	8 O OXYGEN 15.999	9 F FLUORINE 18.998	10 Ne NEON 20.1797	
11 Na SODIUM 22.989	12 Mg MAGNESIUM 24.305										13 Al ALUMINIUM 26.981	14 Si SILICON 28.085	15 P PHOSPHORUS 30.974	16 S SULFUR 32.064	17 Cl CHLORINE 35.453	18 Ar ARGON 39.948	
19 K POTASSIUM 39.098	20 Ca CALCIUM 40.078	21 Sc SCANDIUM 44.955	22 Ti TITANIUM 47.867	23 V VANADIUM 50.9415	24 Cr CHROMIUM 51.9961	25 Mn MANGANESE 54.938	26 Fe IRON 55.845	27 Co COBALT 58.933	28 Ni NICKEL 58.6934	29 Cu COPPER 63.546	30 Zn ZINC 65.38	31 Ga GALLIUM 69.723	32 Ge GERMANIUM 72.63	33 As ARSENIC 74.921	34 Se SELENIUM 78.971	35 Br BROMINE 79.904	36 Kr KRYPTON 83.798
37 Rb RUBIDIUM 85.467	38 Sr STRONTIUM 87.62	39 Y YTTRIUM 88.9058	40 Zr ZIRCONIUM 91.224	41 Nb NIOBIUM 92.9063	42 Mo MOLYBDENUM 95.95	43 Tc TECHNETIUM (98)	44 Ru RUTHENIUM 101.07	45 Rh RHODIUM 102.90	46 Pd PALLADIUM 106.42	47 Ag SILVER 107.8682	48 Cd CADMIUM 112.414	49 In INDIUM 114.818	50 Sn TIN 118.710	51 Sb ANTIMONY 121.760	52 Te TELLURIUM 127.60	53 I IODINE 126.90	54 Xe XENON 131.293
55 Cs CAESIUM 132.905	56 Ba BARIUM 137.327	57-71 Lanthanide	72 Hf HAFNIUM 178.49	73 Ta TANTALUM 180.94	74 W TUNGSTEN 183.84	75 Re RHENIUM 186.207	76 Os OSMIUM 190.23	77 Ir IRIDIUM 192.222	78 Pt PLATINUM 195.084	79 Au GOLD 196.9665	80 Hg MERCURY 200.59	81 Tl THALLIUM 204.38	82 Pb LEAD 207.2	83 Bi BISMUTH 208.98	84 Po POLONIUM (209)	85 At ASTATINE (210)	86 Rn RADON (222)
87 Fr FRANCIUM (223)	88 Ra RADIUM (226)	89-103 Actinide	104 Rf RUTHERFORDIUM (261)	105 Db DUBNIUM (268)	106 Sg SEABORGIUM (271)	107 Bh BOHRIUM (272)	108 Hs HASSIUM (276)	109 Mt MEITNERIUM (278)	110 Ds DAIRMSTADTIUM (281)	111 Rg ROENTGENIUM (285)	112 Cn COPECNICIUM (289)	113 Uut UNUNTRIUM (294)	114 Fl FLEROVIUM (289)	115 Uup UNUNPENTIUM (288)	116 Lv LIVERMORIUM (293)	117 Uus UNUNSEPTIUM (294)	118 Uuo UNUNOCTIUM (294)
		57 La LANTHANUM 138.90	58 Ce CERIUM 140.116	59 Pr PRASEODYMIUM 140.90	60 Nd NEODYMIUM 144.242	61 Pm PROMETHIUM (145)	62 Sm SAMARIUM 150.36	63 Eu EUROPIUM 151.964	64 Gd GADOLINIUM 157.25	65 Tb TERBIUM 158.92	66 Dy DYSPROSIUM 162.500	67 Ho HOLMIUM 164.93	68 Er ERBIUM 167.259	69 Tm THULIUM 168.93	70 Yb YTTERIUM 173.054	71 Lu LUTETIUM 174.968	
		89 Ac ACTINIUM (227)	90 Th THORIUM 232.0377	91 Pa PROTACTINIUM 231.03	92 U URANIUM 238.02	93 Np NEPTUNIUM (237)	94 Pu PLUTONIUM (244)	95 Am AMERICIUM (243)	96 Cm CURIUM (247)	97 Bk BERKELIUM (247)	98 Cf CALIFORNIUM (251)	99 Es EINSTEINIUM (252)	100 Fm FERMIUM (257)	101 Md MENDELEVIUM (258)	102 No NOBELIUM (259)	103 Lr LAWRENCIUM (262)	

Last but not least, the broadband afterglow

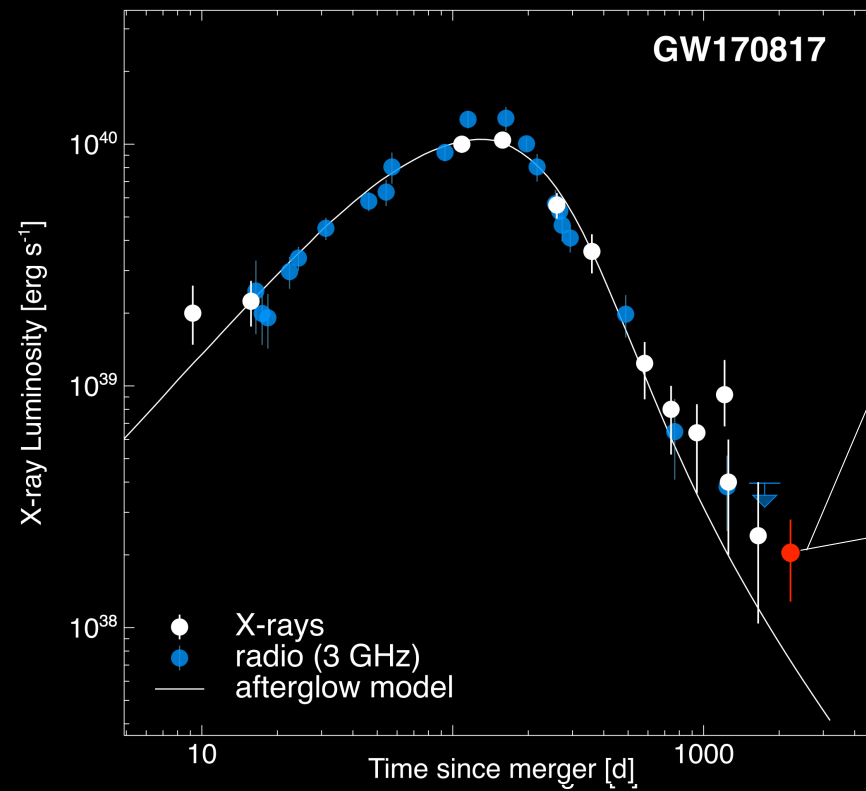
Troja et al. 2017
Troja et al. 2018
Troja et al. 2019
Piro, Troja et al. 2019
Ryan et al. 2020
Troja et al. 2020
Troja et al. 2022
Ryan et al. 2024

Hallinan et al. 2017
Lazzati et al. 2017
Mooley et al. 2017
Mooley et al. 2018
Balasubramanian et al. 2021

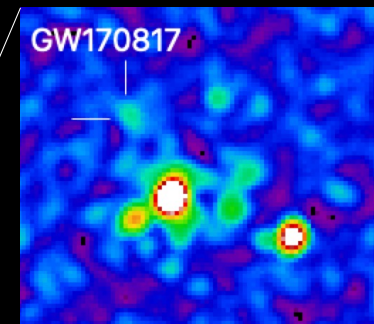


A relativistic structured jet seen off-axis

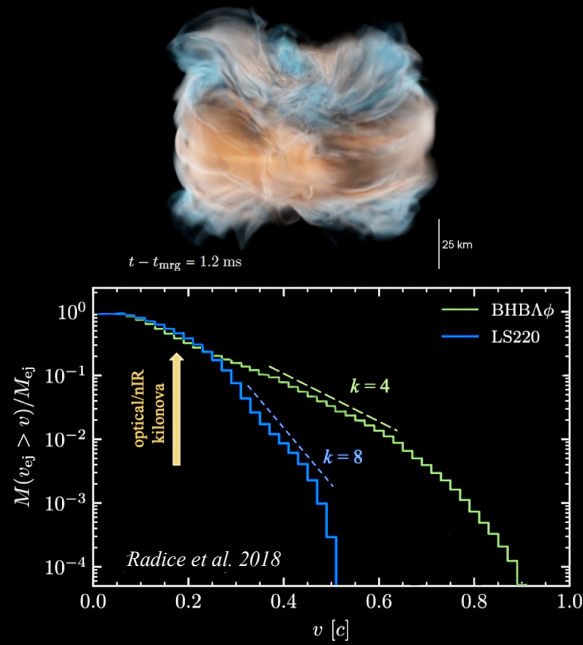
GW170817, lately



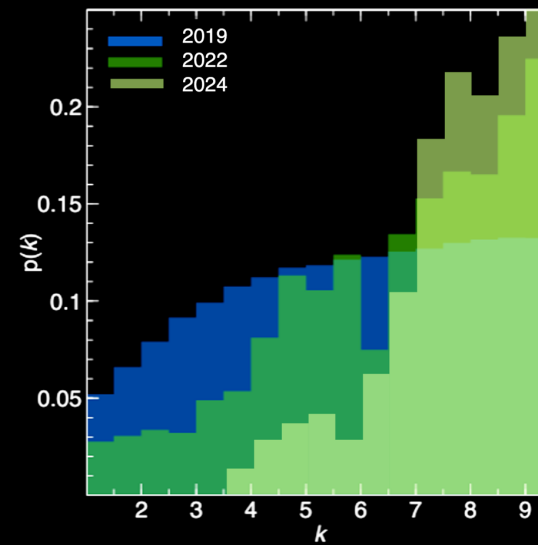
PI: E. Troja



Beyond the GRB jet: novel constraints on the ejecta



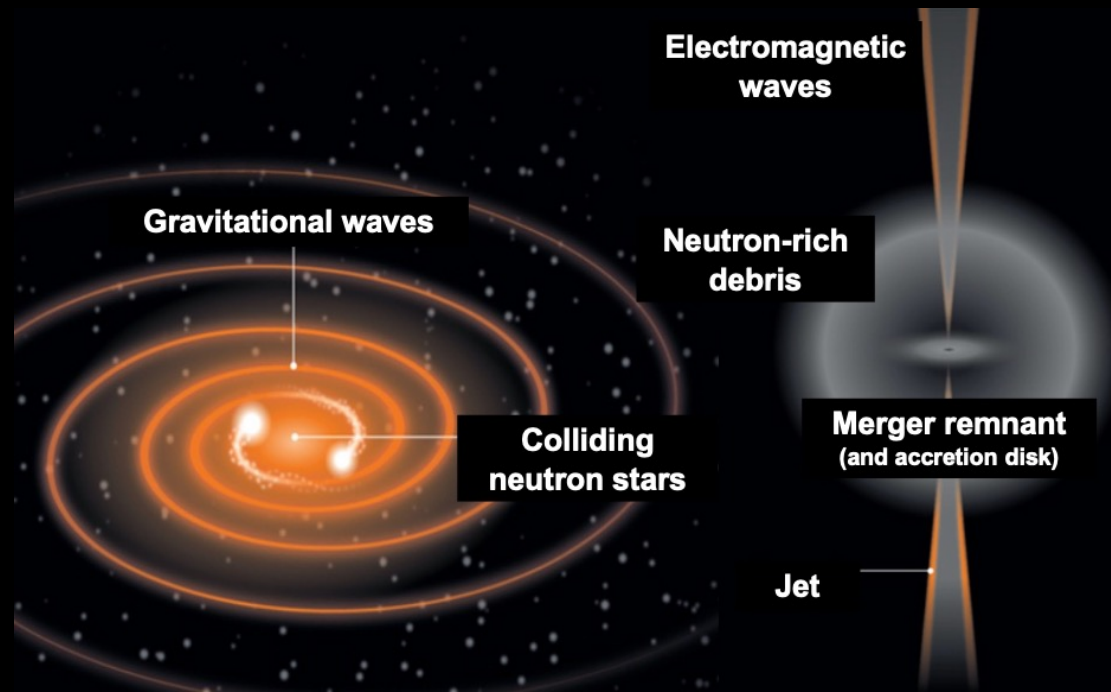
Troja et al. 2024 (PRELIMINARY)



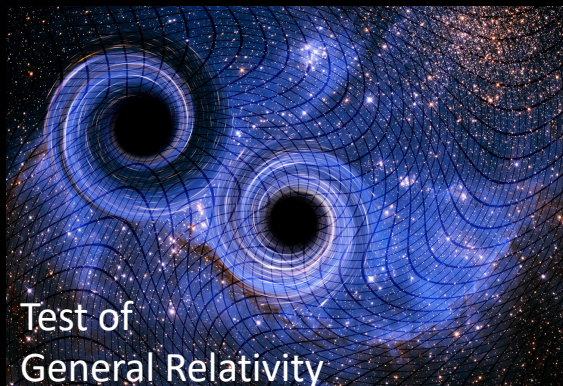
Exploring a phase of dense matter otherwise not accessible

Why multi-messenger astronomy?

All messengers are needed to complete the big picture of cosmic explosions



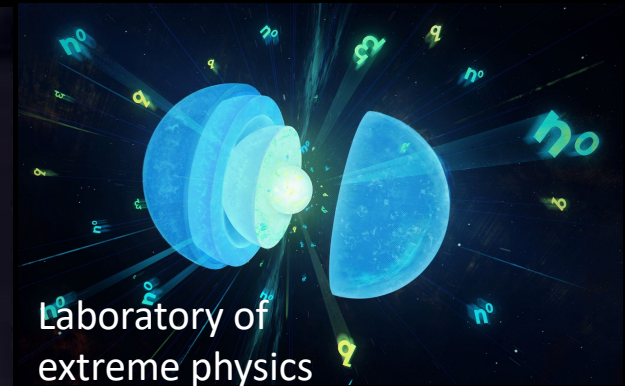
Key questions of modern astrophysics



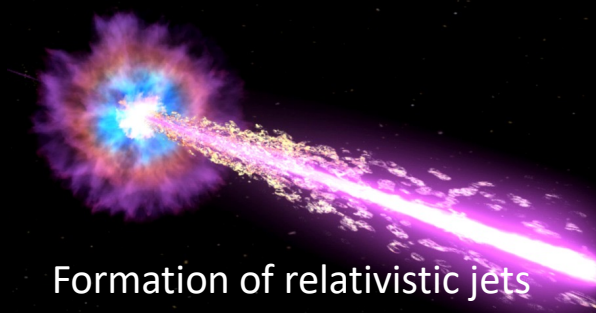
Test of
General Relativity



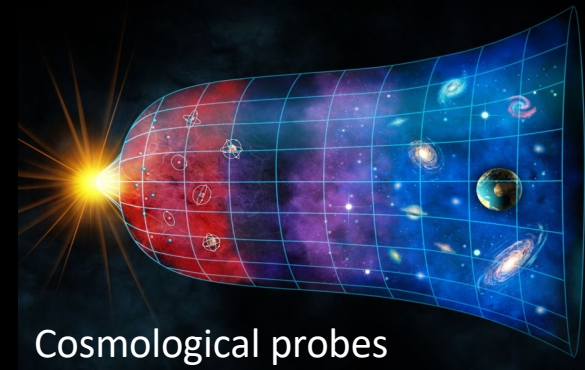
Origin of the heavy
r-process elements



Laboratory of
extreme physics



Formation of relativistic jets



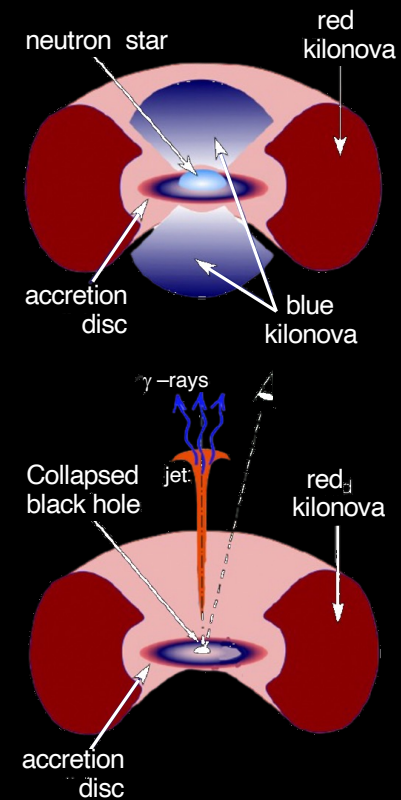
Cosmological probes

Expanding our
discovery
space

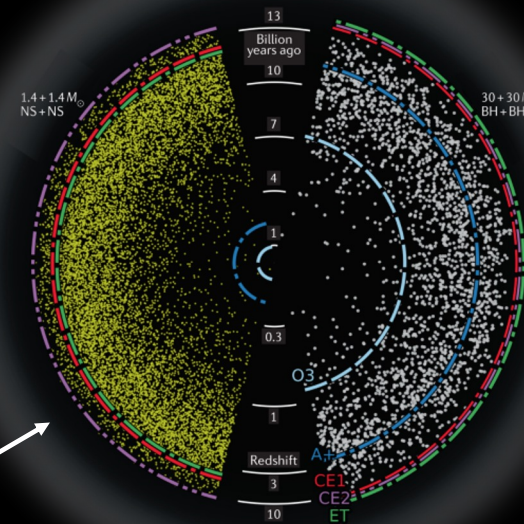
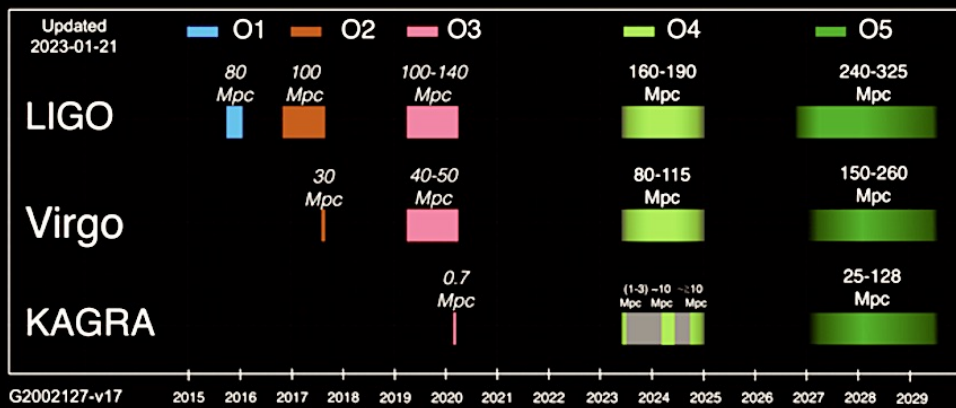
Outstanding questions

- ❖ Do all NS mergers produce relativistic jets and GRBs like GRB170817A?
- ❖ Do all NS mergers forge large amounts of heavy elements? How robust is the r-process production?
- ❖ What is the remnant of a NS merger, a massive NS or a prompt BH? Does it produce FRBs?
- ❖ How do NS-BH mergers look like?
- ❖ In which conditions binary BHs emit light?

We need **MORE EVENTS** to map and understand the diversity of initial conditions and outcomes.

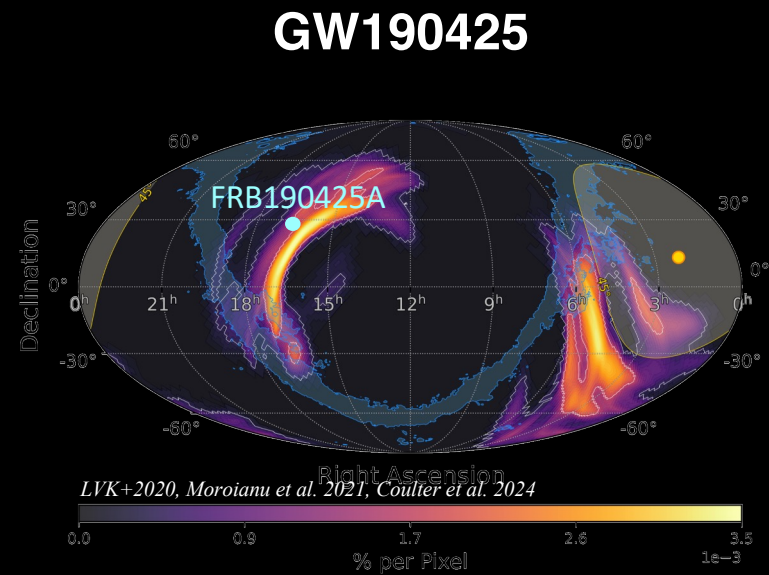
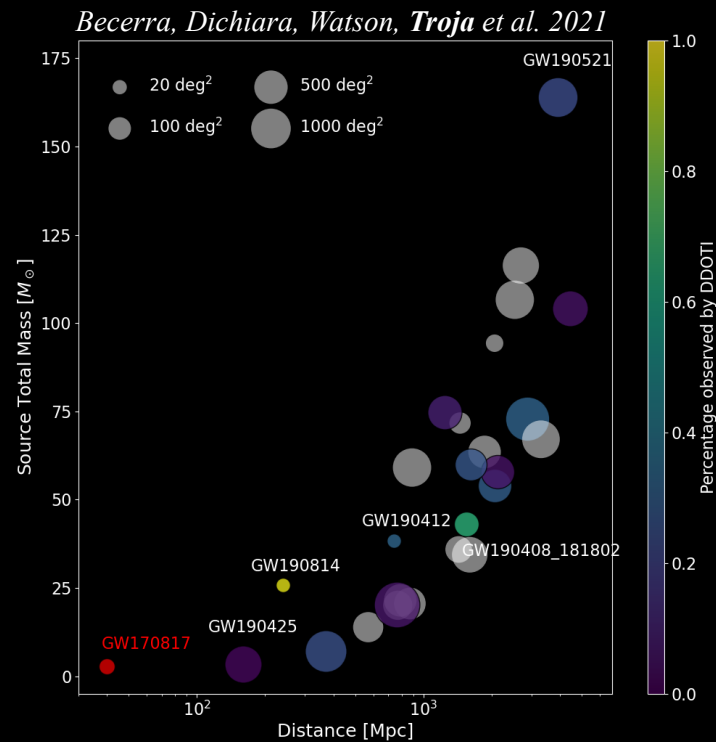


Finding new GW sources

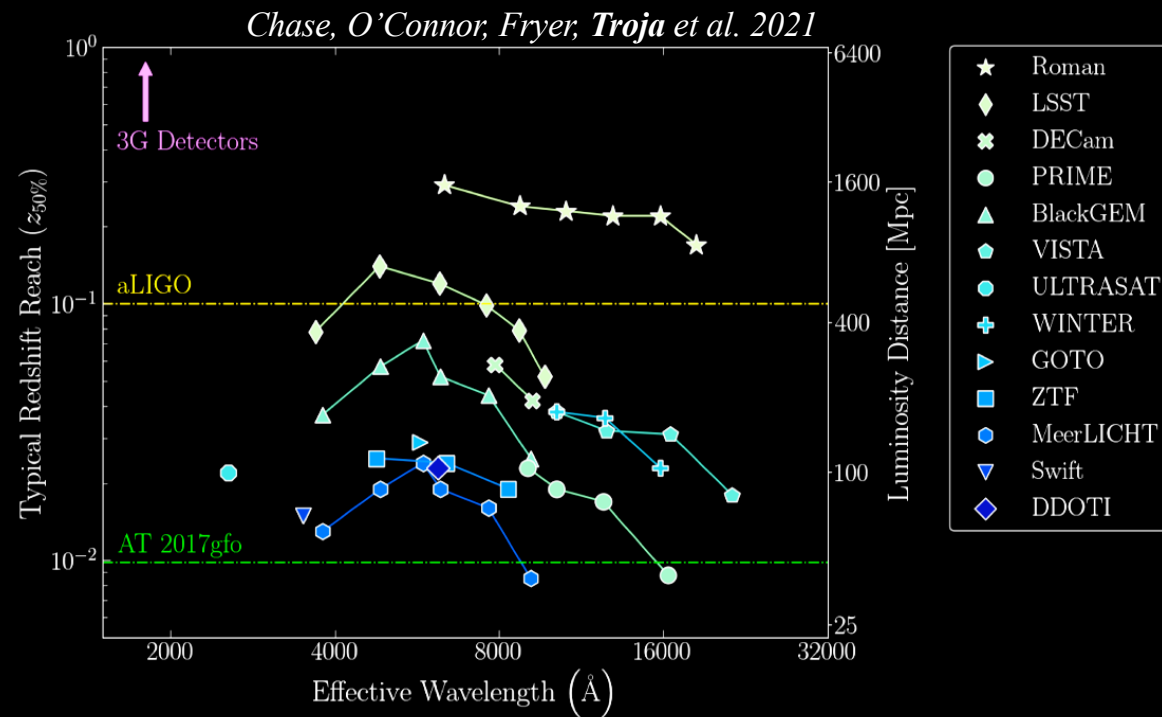


From a trickle ... to a flood

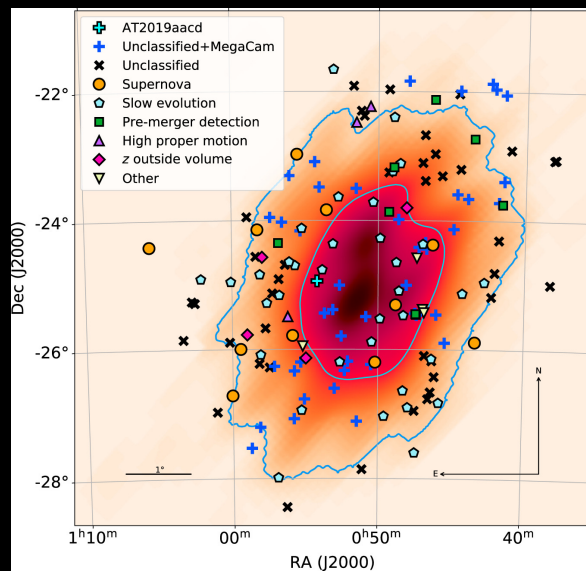
Localizations, localizations, localizations



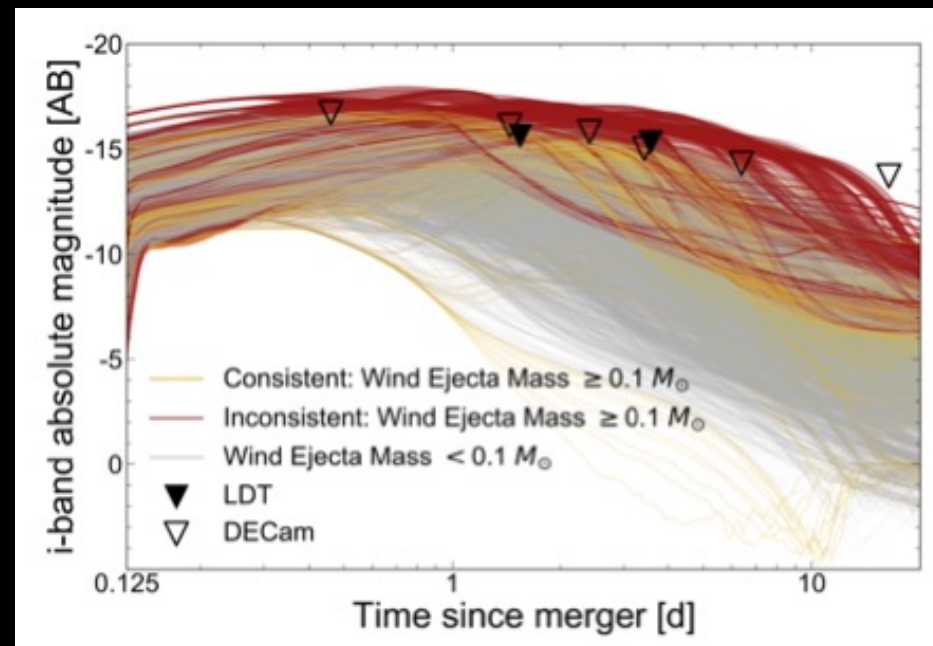
Kilonova detectability



Constraints from GW follow-up: GW190814

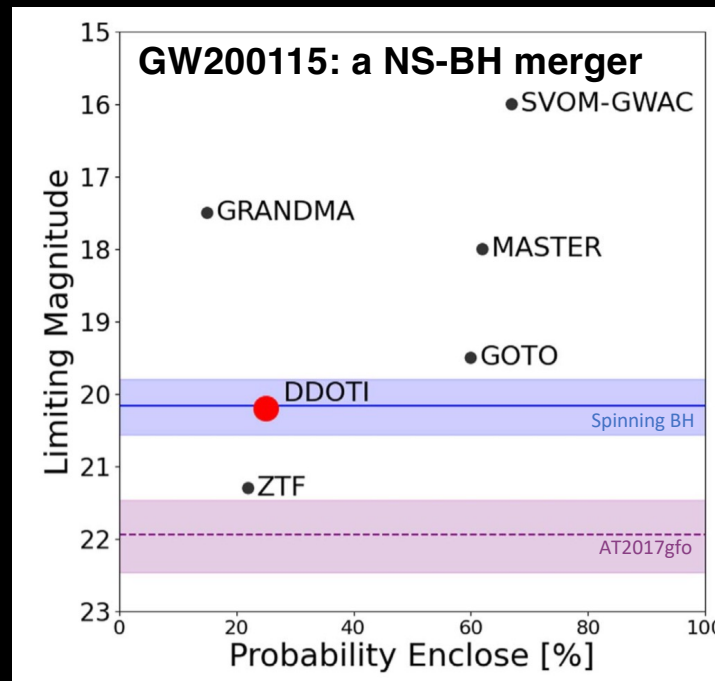


Vieira et al. 2020



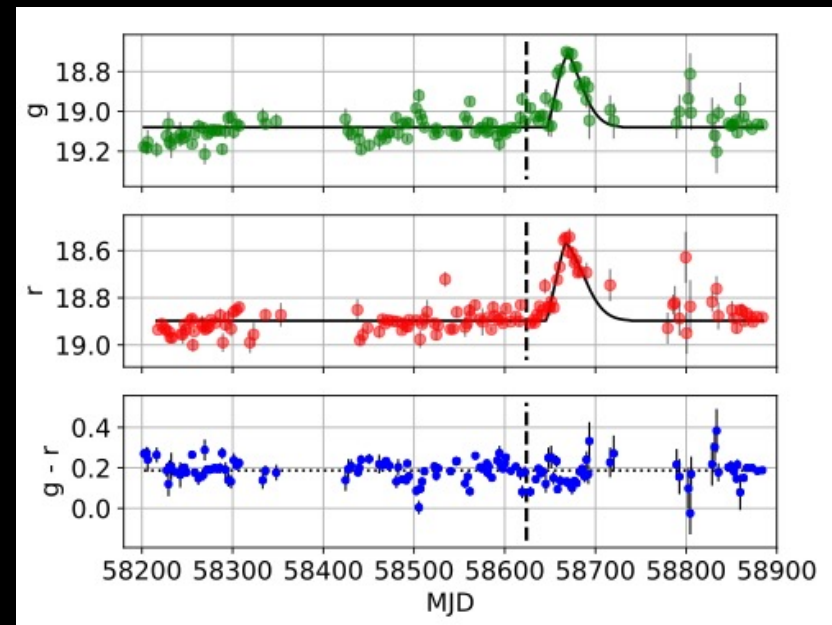
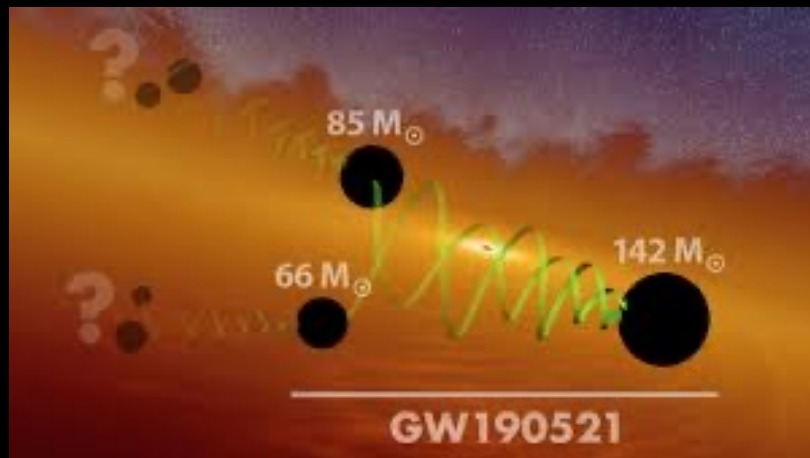
Thakur, Dichiara, Troja, et al. 2020

Constraints from GW follow-up: GW200115



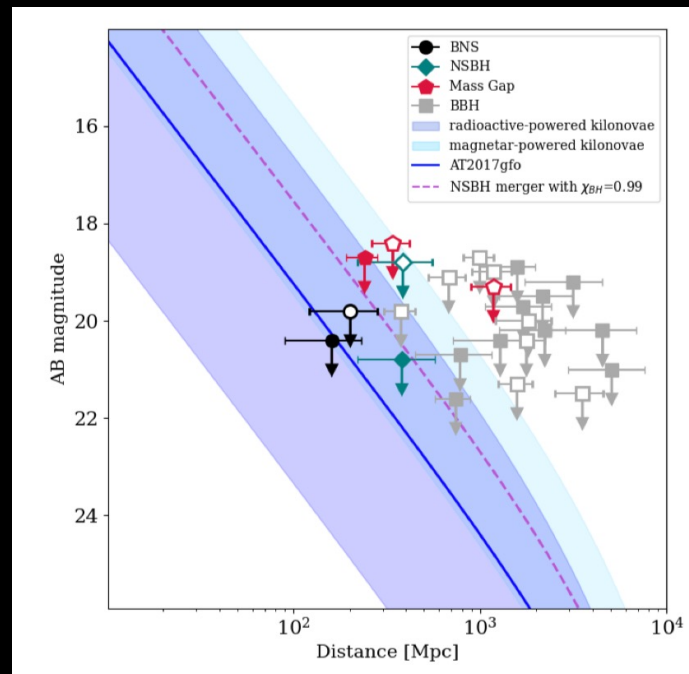
Dichiara, Becerra, Chase, Troja, et al. 2021

Constraints from GW follow-up: GW190521



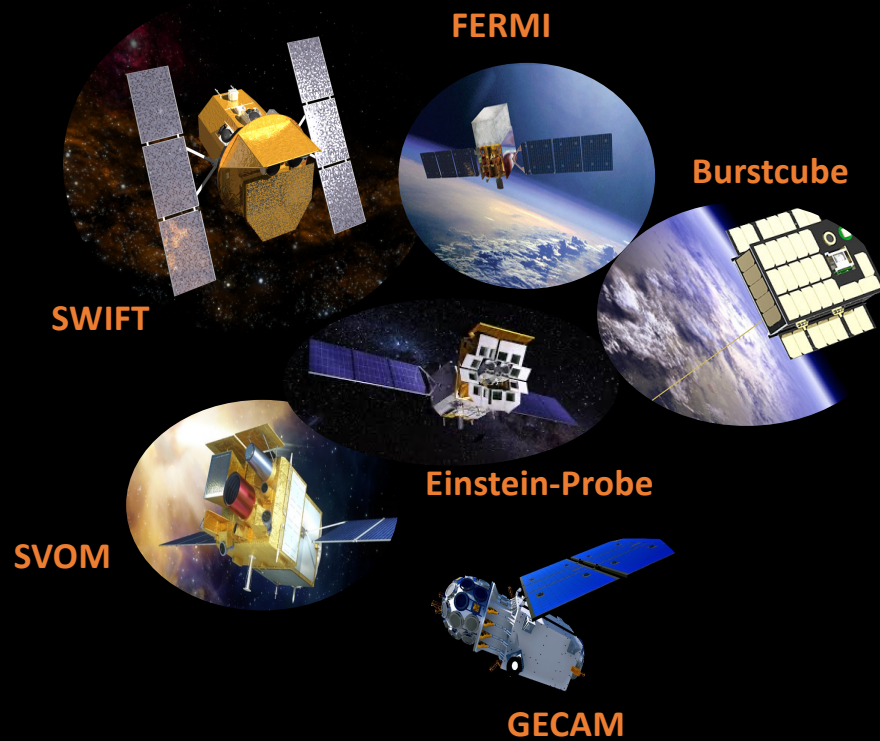
Graham et al. 2021

Constraints from GW follow-up: summary

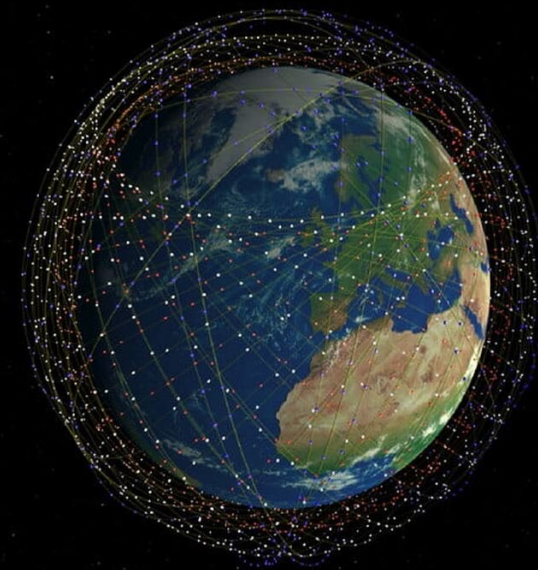


Becerra, Dichiara, Watson, Troja, et al. 2021

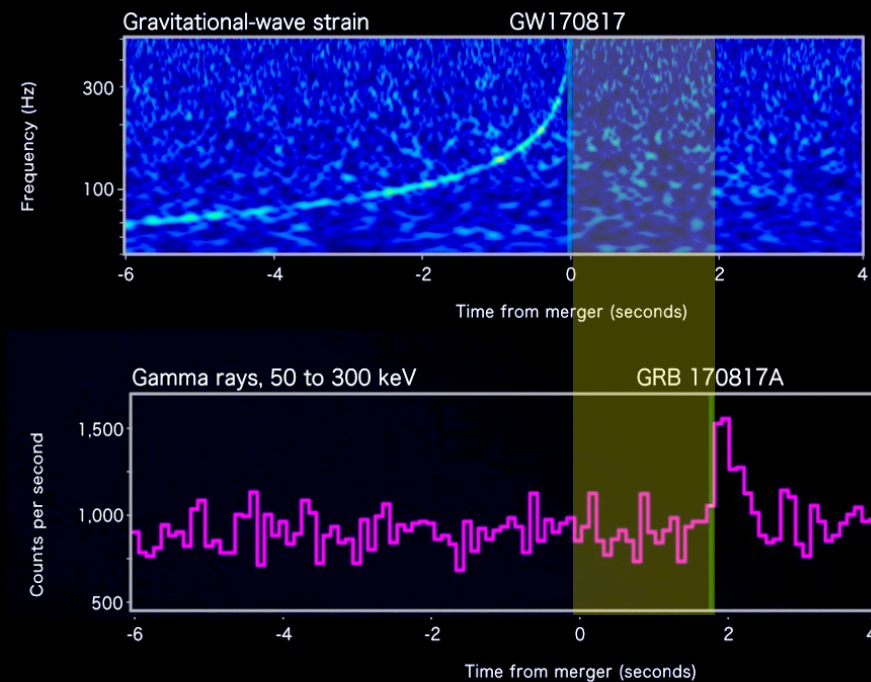
GW sources at high-energies



Full view of the sky at any time



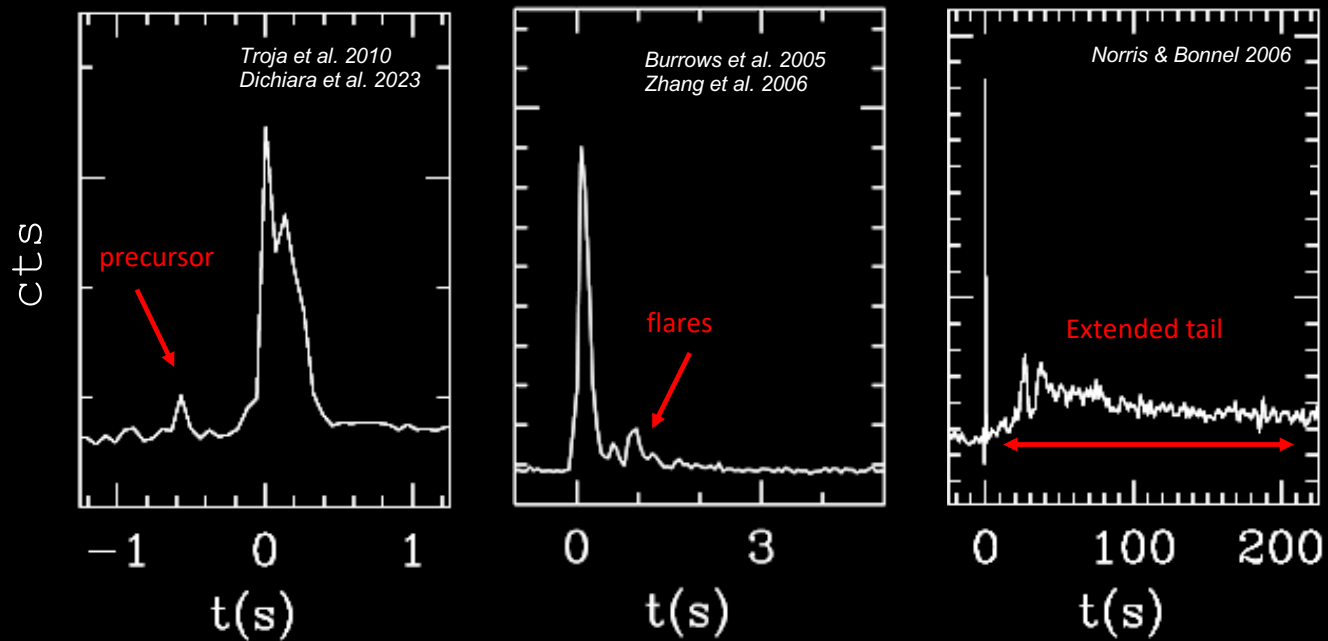
The GRB/GW connection



Why a
1.7 s delay?

- Viewing angle?
- Jet-launching?
- NS collapse?
- Modified gravity?

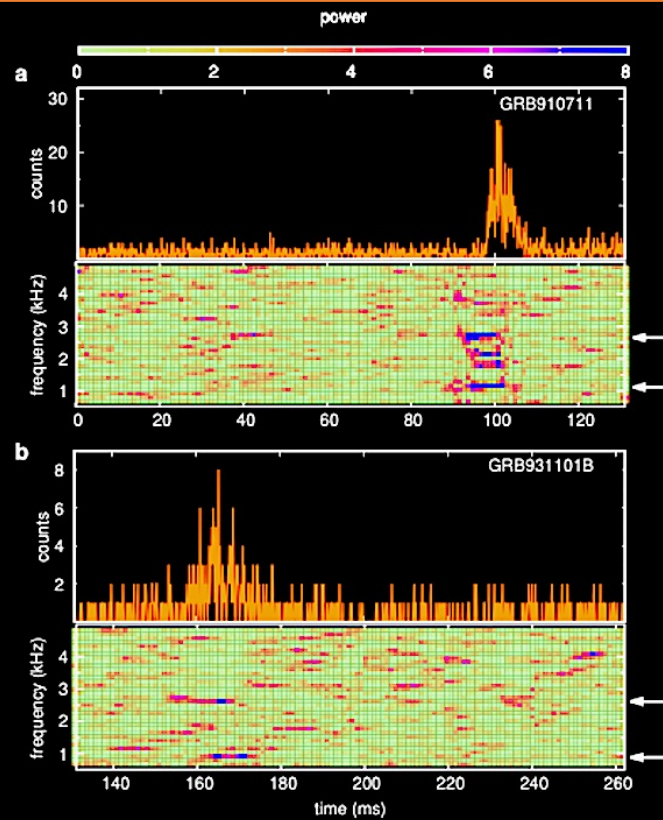
A new look at the gamma-ray emission



A new look at the gamma-ray emission

*Possible
Quasi-Periodic Oscillations*

*Chirenti et al. 2023
Chirenti et al. 2024*

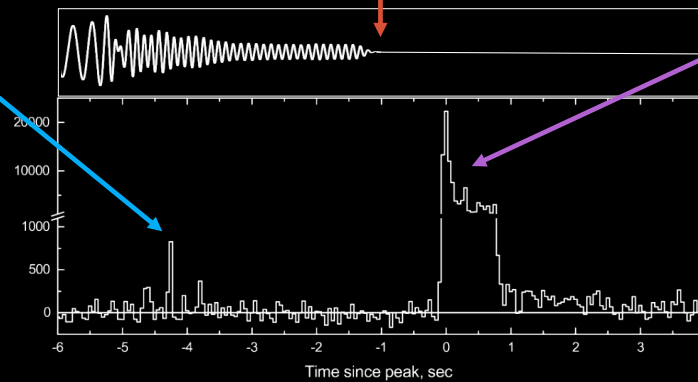


Stellar forensics: a multi-messenger approach

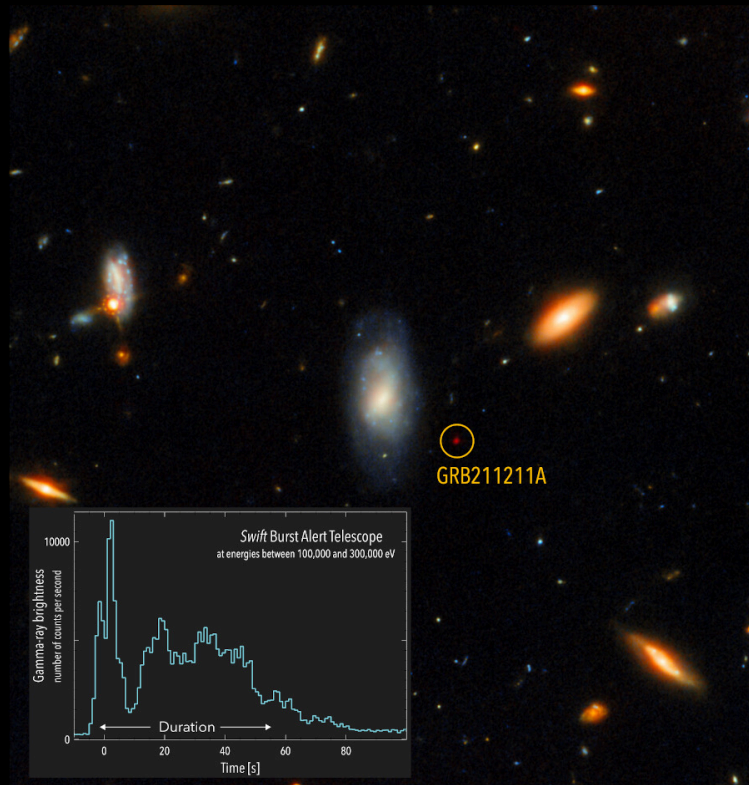
Formation of a
hypermassive NS

Birth of a
Black Hole

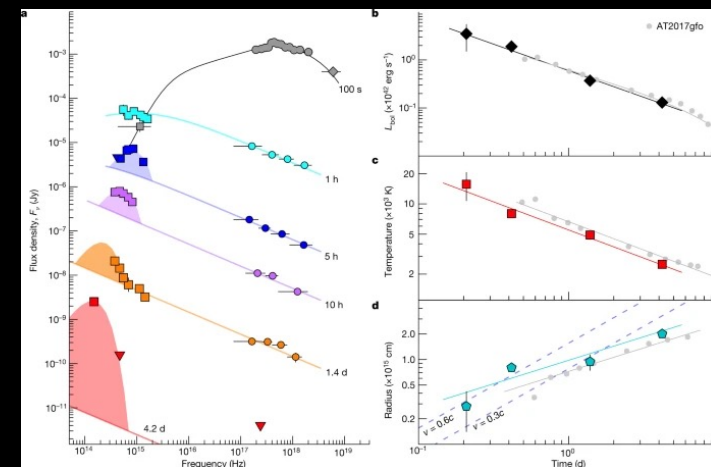
Launch of an
ultrafast outflow



New Enigma: Long GRBs from NS mergers



Troja et al., Nature, 2022



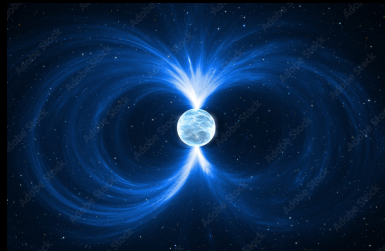
See also Yang et al. 2022, Rastinejad et al. 2022, Yang et al. 2024, Levan et al. 2024

Who will solve the enigma?

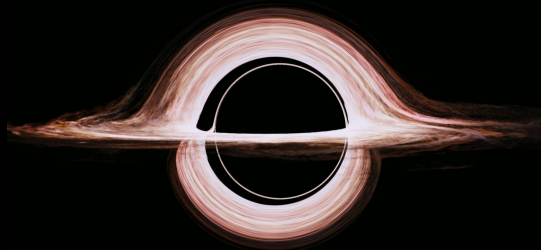
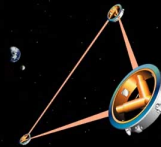
LIGO and Virgo



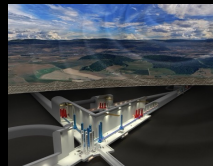
A long lived Magnetar?



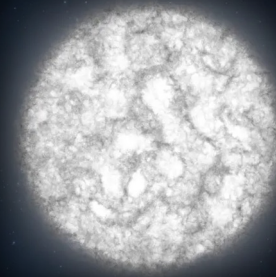
LISA



Neutron Star - Black Hole merger?



Einstein Telescope



White Dwarf – Neutron Star merger?

Summary and final thoughts

The combination of multiple messengers is the **most powerful tool** to explore our Universe. EM observations can break the degeneracy of some GW parameters (distance, inclination, merger remnant).

To fully realize the promise of multi-messenger astronomy, electromagnetic facilities must keep up with the advancement of GW detectors

Our knowledge will be built upon a few key events in the next few years, but the **rate of events** might dramatically increase in the next decade

Expect the unexpected: GW170817 was one NS-NS merger, a wide range of diverse outcomes is likely



Thanks!