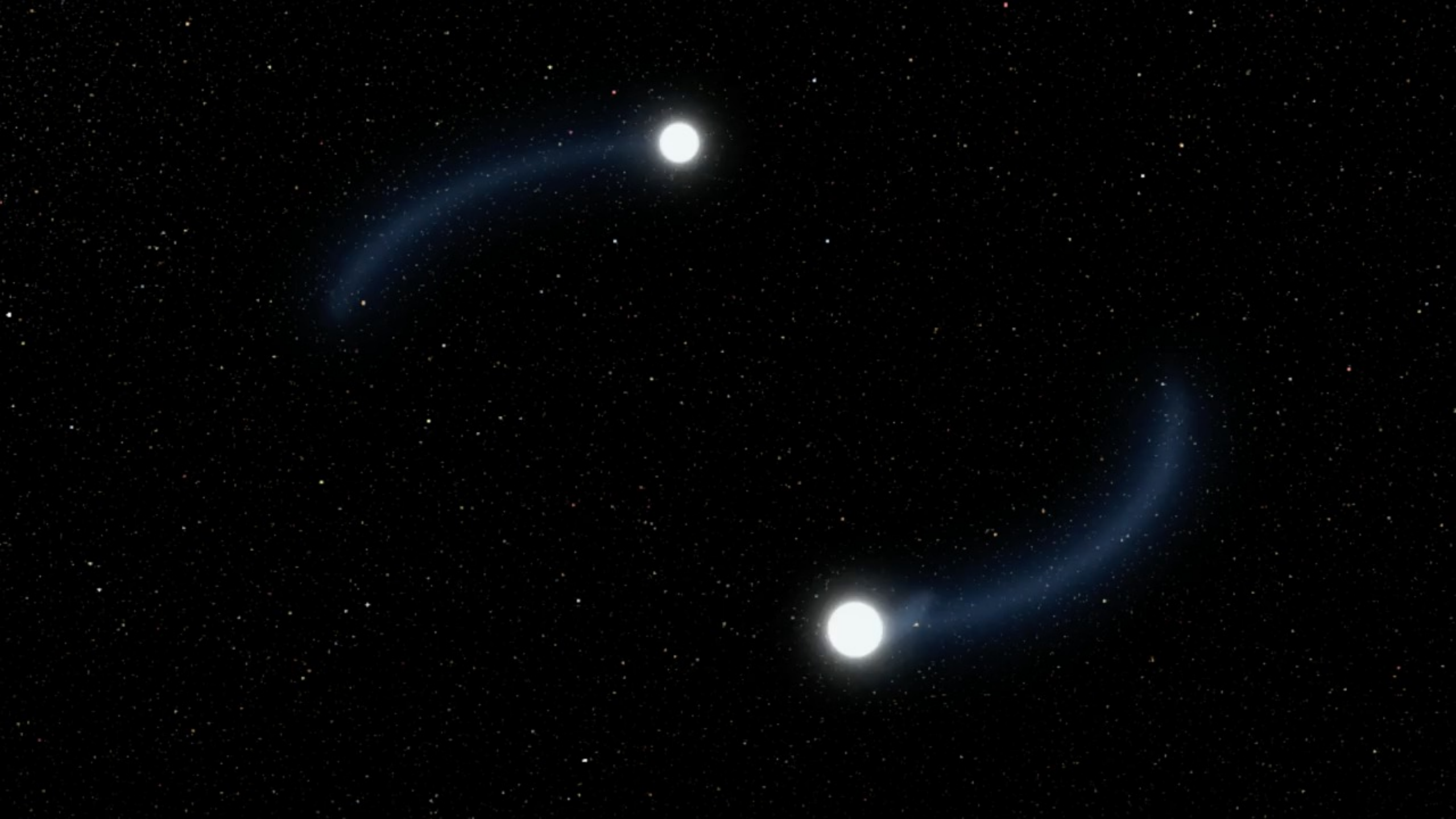
Korean Society of High Energy Physics

Multi-messenger Transients

from gamma-ray bursts to kilonovae

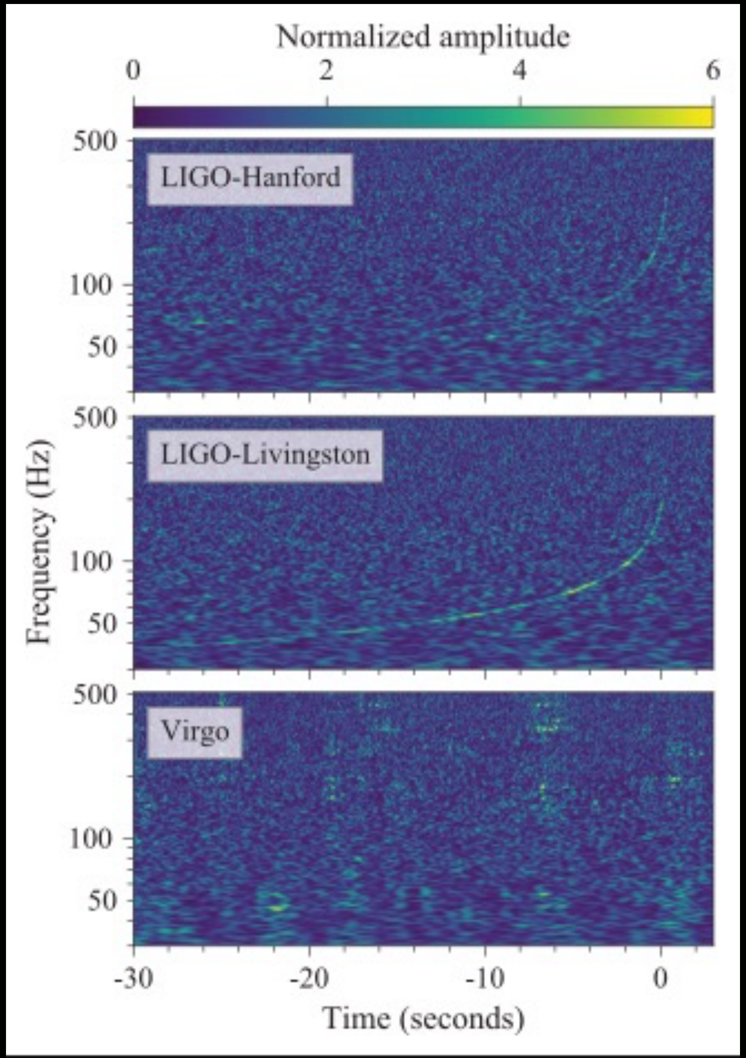
Donggeun Tak

Kyung Hee University



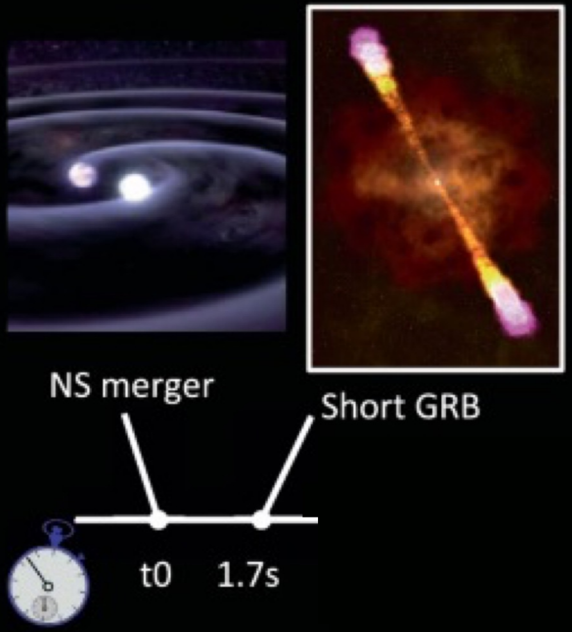
In 2017,

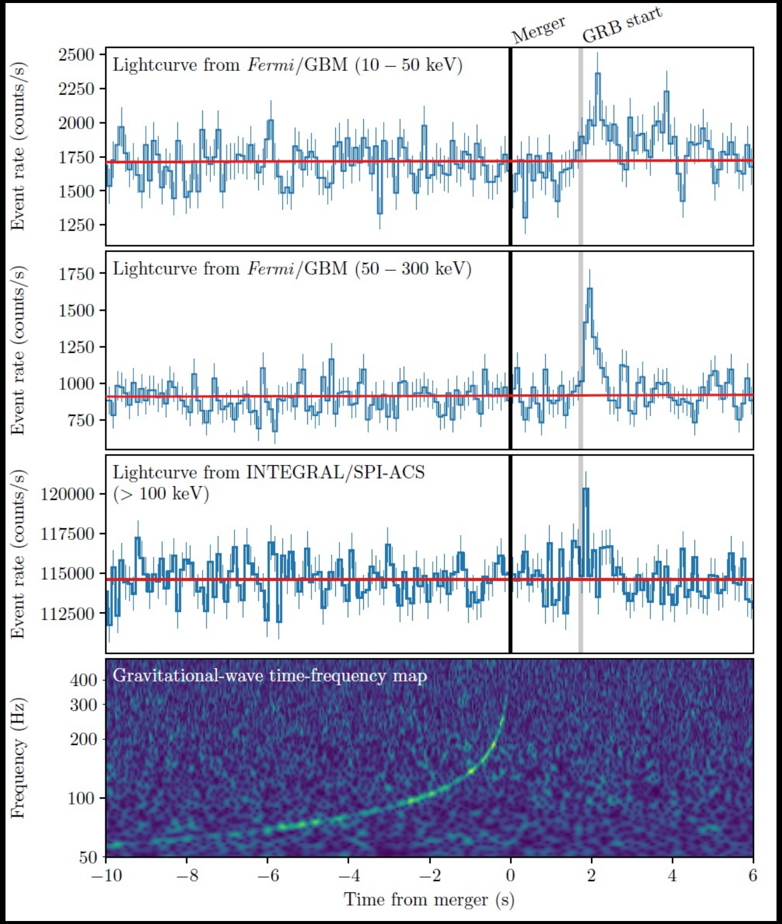
Binary NS merger produces:
GW170817
GRB170817A
AT2017gfo

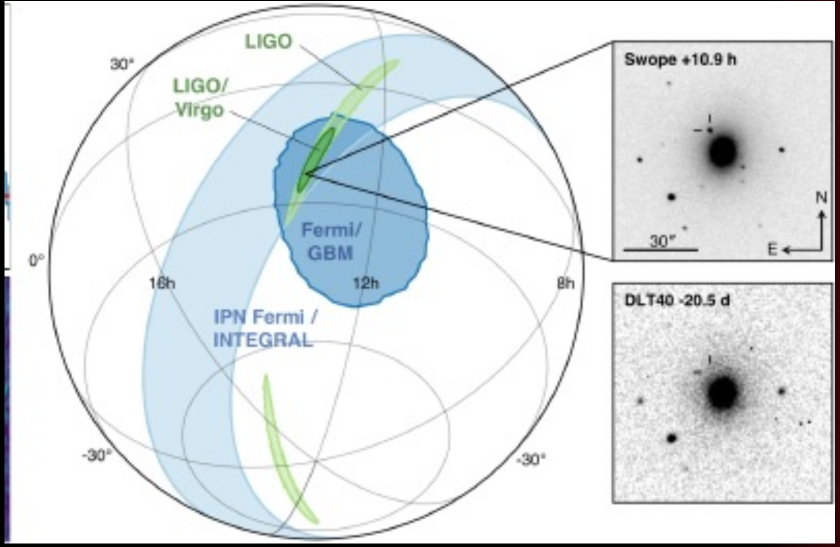


* NS: neutron star

In 2017,







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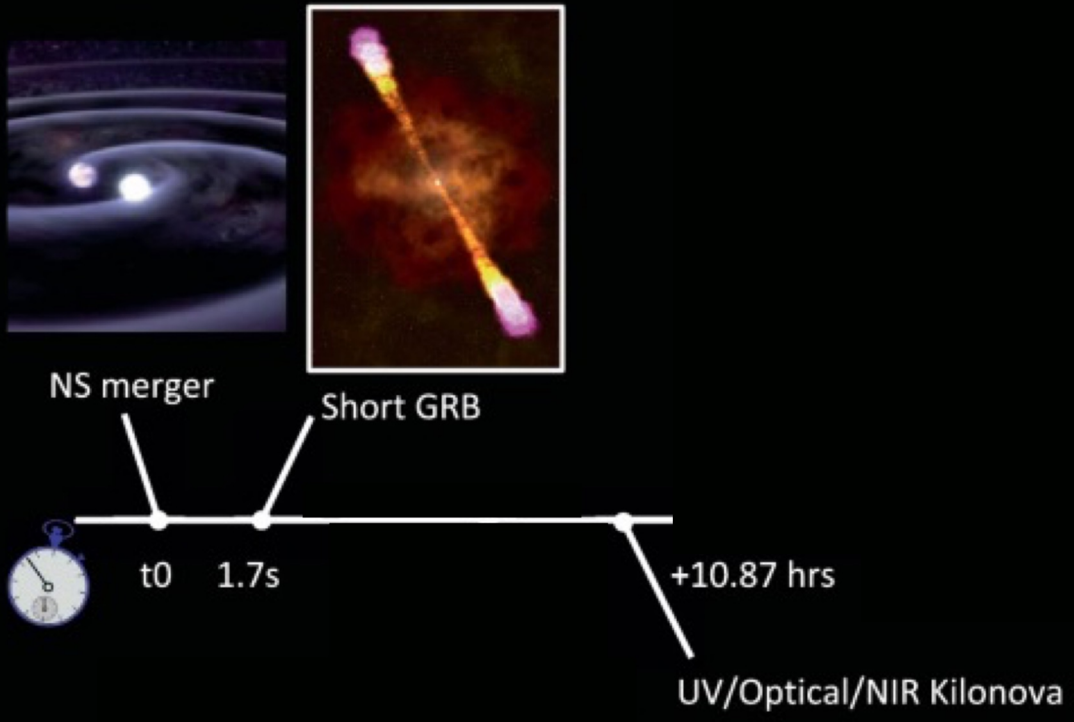

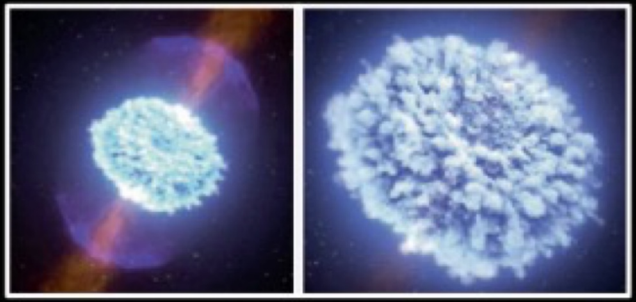

Binary NS merger produces:
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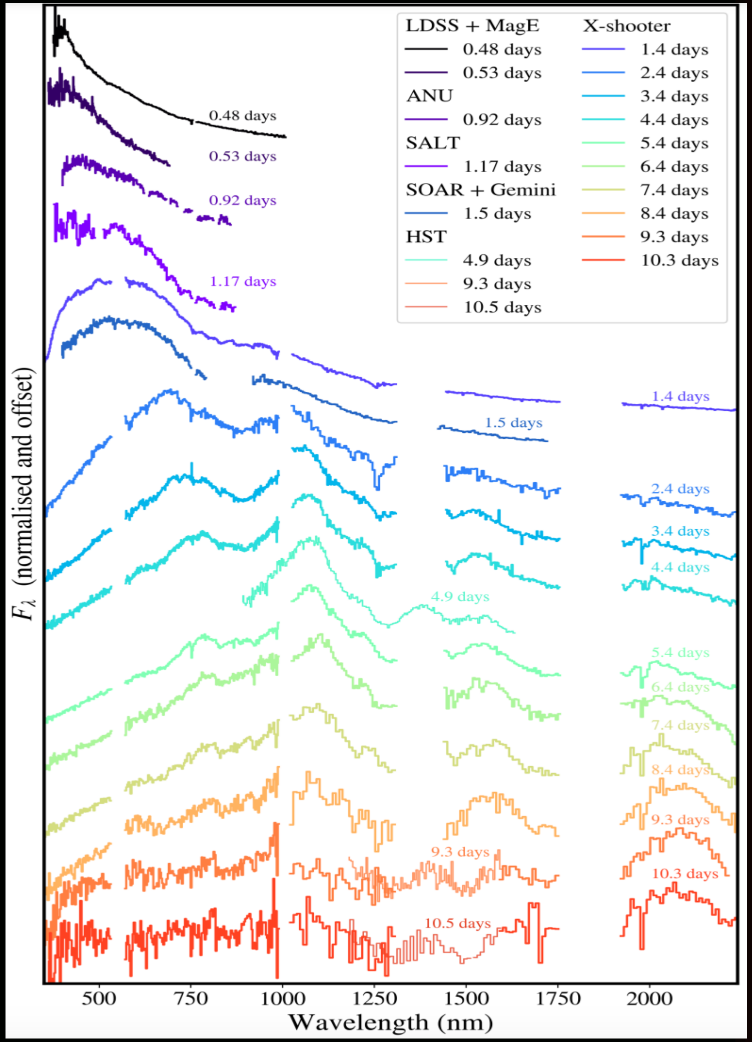
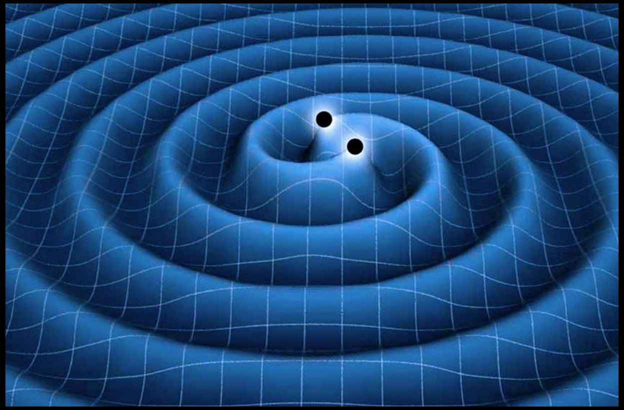
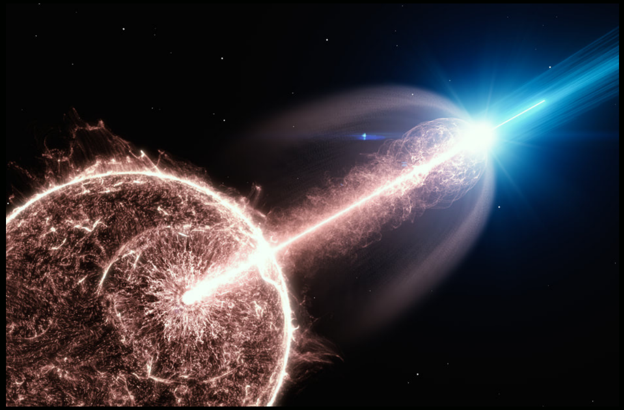


* NS: neutron star

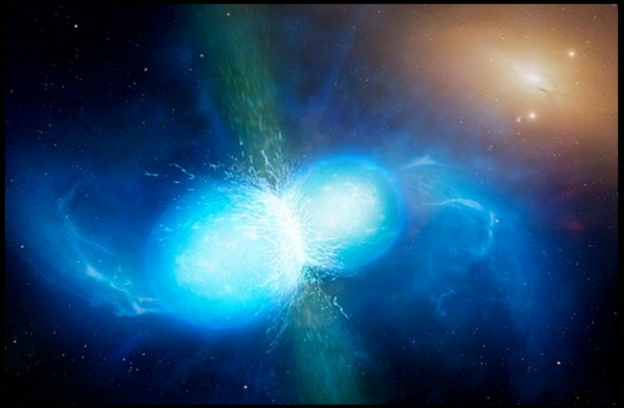
ALL CONNECTED



Gravitational wave



Gamma-ray burst



Kilonova

To build a complete picture, we need to consider

**these multi-messenger events as a whole,
as well as study each of them in detail.**

GAMMA-RAY BURST

GAMMA-RAY BURST

A Unique Laboratory for Modern Astrophysics

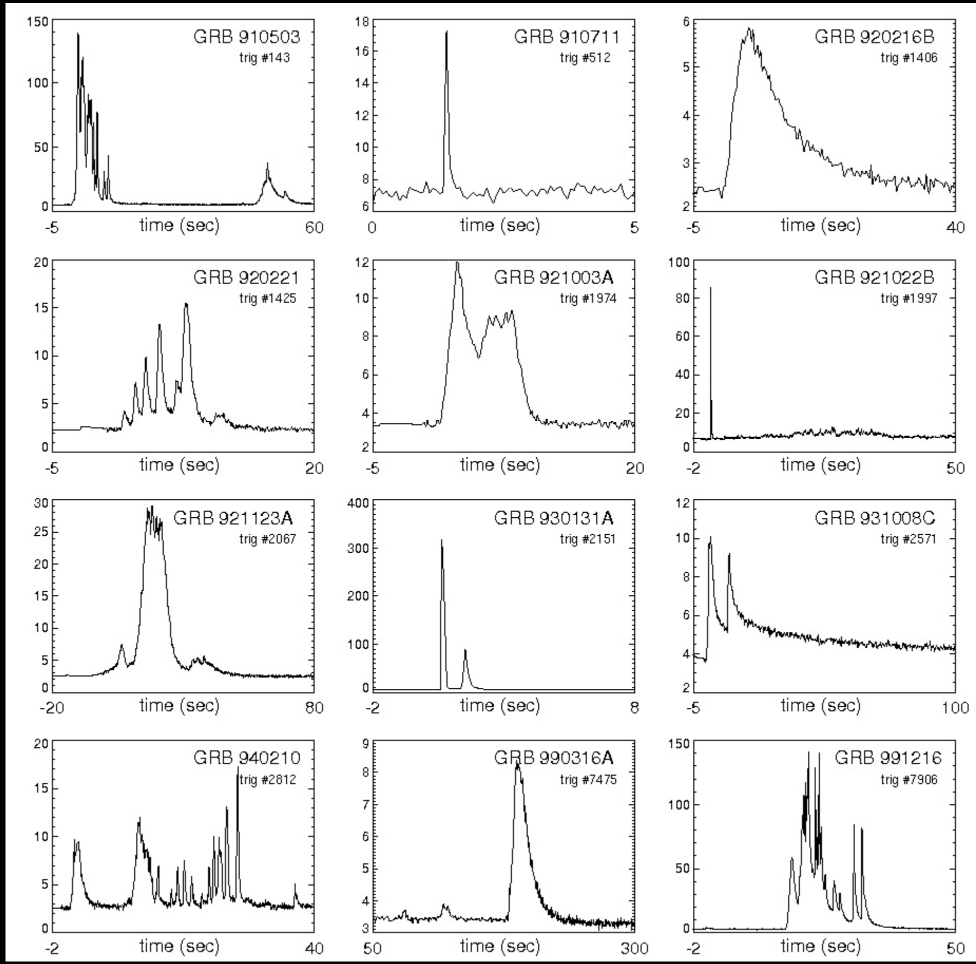
The **most energetic and luminous** electromagnetic events $(10^{50} - 10^{54} erg)$

The **fastest motion** in the universe $(\Gamma > 100)$

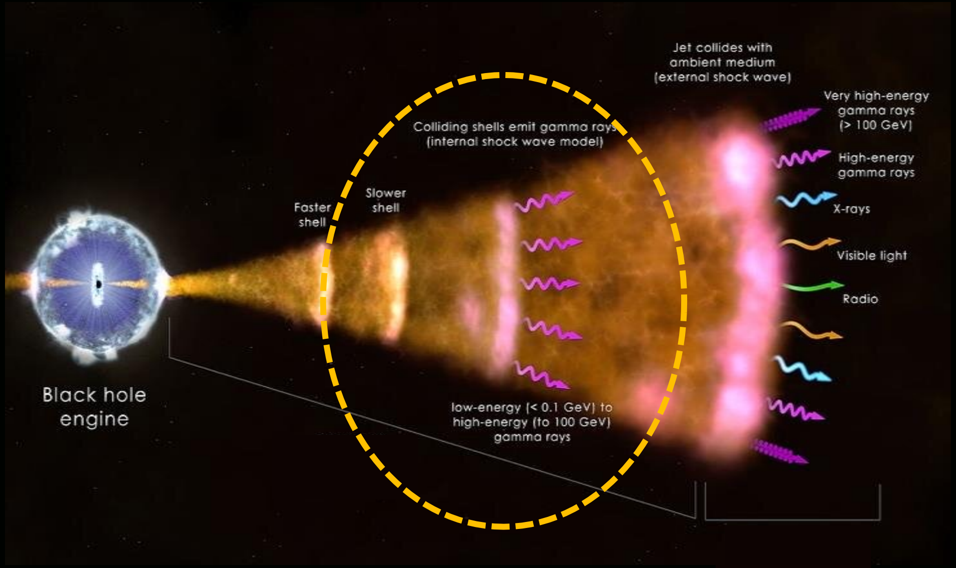
One of the **most distant** events (z > 8)

$* \Gamma = 100 \rightarrow v = 0.99995\, c$

PROMPT EMISSION



Diversity of GRB prompt emission



Short, spiky, and luminous emission in the keV-MeV energy band.

LEADING MODELS

Photosphere model

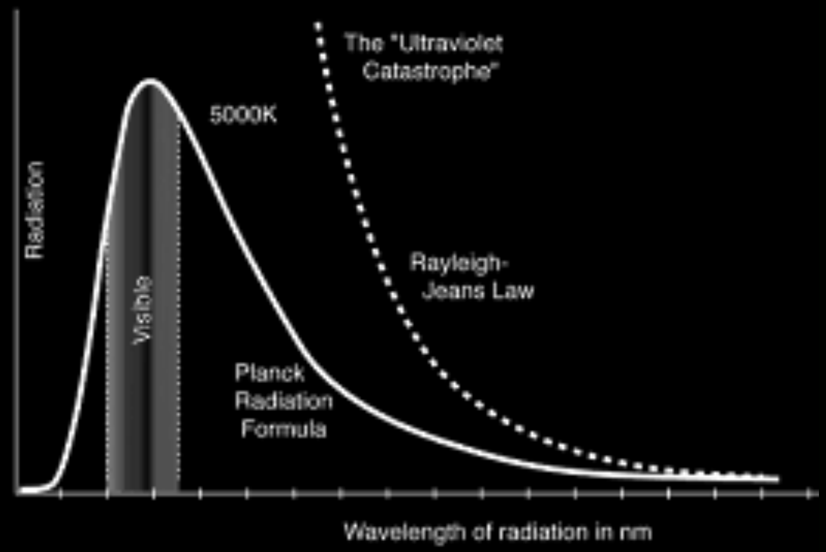
Naturally expected from the explosive event, where $\tau_{\gamma\gamma} \sim 1$.

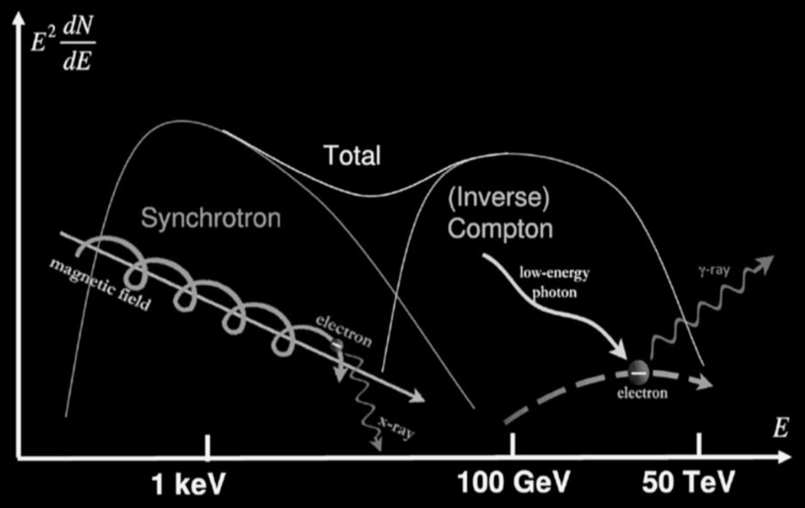
Internal-shock model

In an unsteady outflow, a shock condition can be easily produced, powering the emission.

Magnetic-jet model

In a highly magnetized outflow, the magnetic reconnection can power the emission





DISCREMENATE MODELS

Spectral Features

Photosphere model

Thermal emission (blackbody-like)

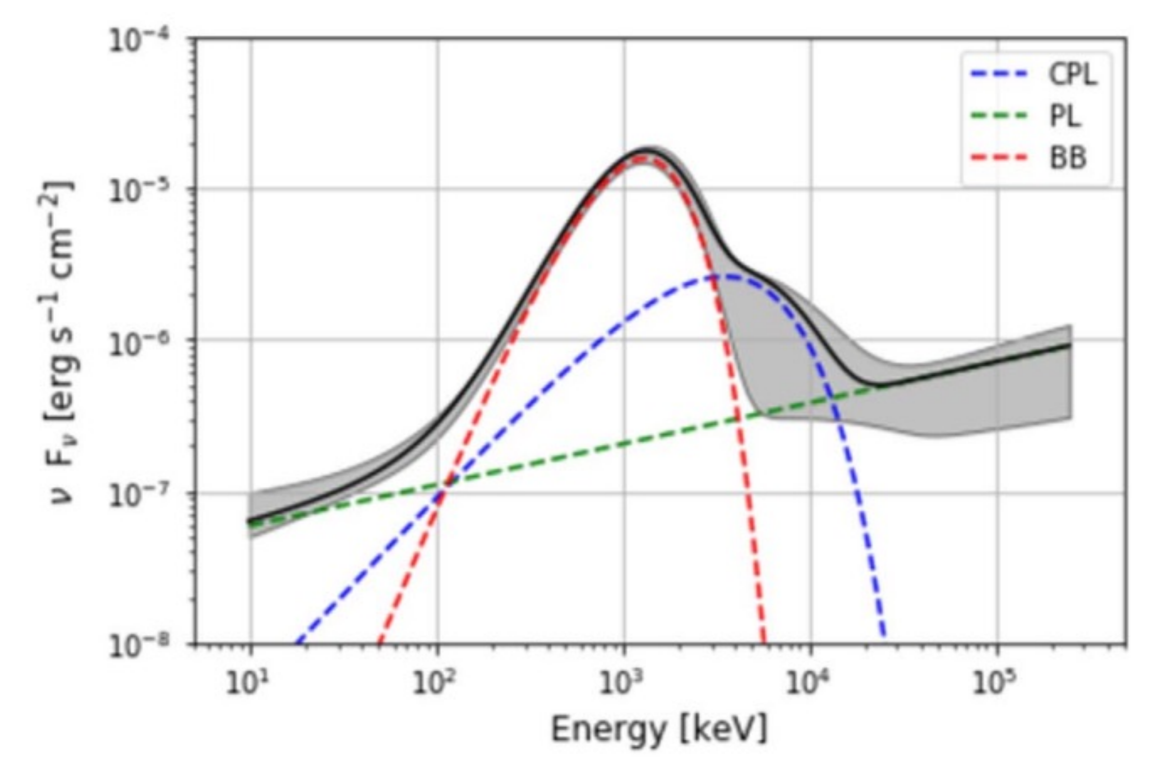
Internal-shock model

Non-thermal emission (synchrotron)

Magnetic-jet model

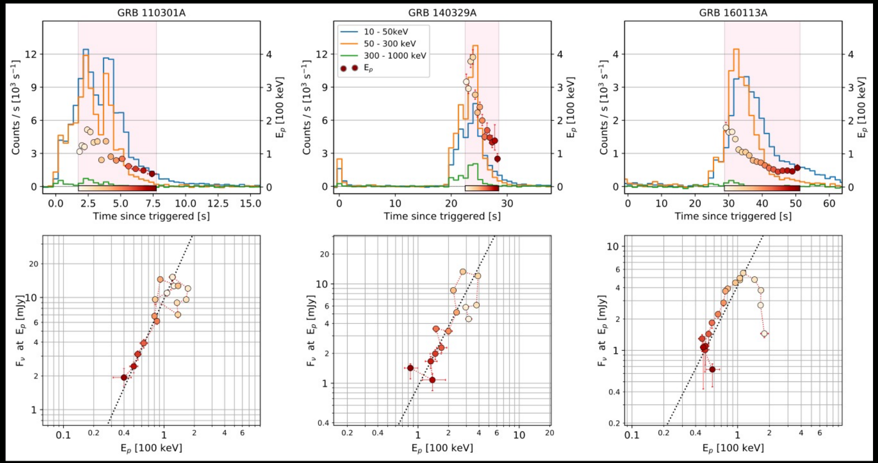
Non-thermal emission (synchrotron)

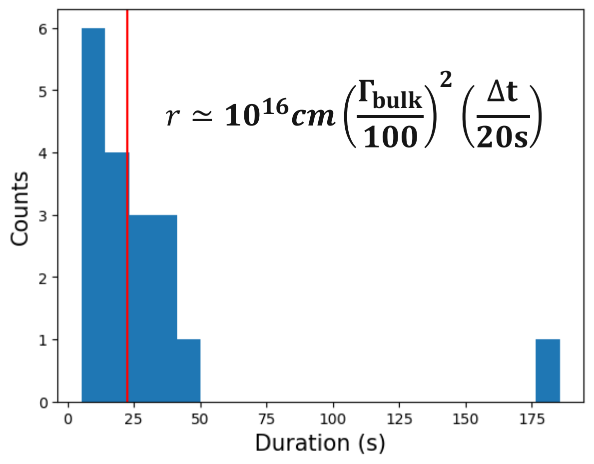
Tak+2019a



Short GRB160709A:
Thermal + Non-thermal emissions

PREFERRED MODEL





When a curvature feature exists,

$$r \simeq 2c\Gamma\Delta t_{pulse}$$

Emitting Radii

Photosphere model

$r \sim 10^{11} - 10^{12}\ cm$

Internal-shock model

$r \sim 10^{13} - 10^{14}\ cm$

Magnetic-jet model

$r \sim 10^{15} - 10^{16}\ cm$

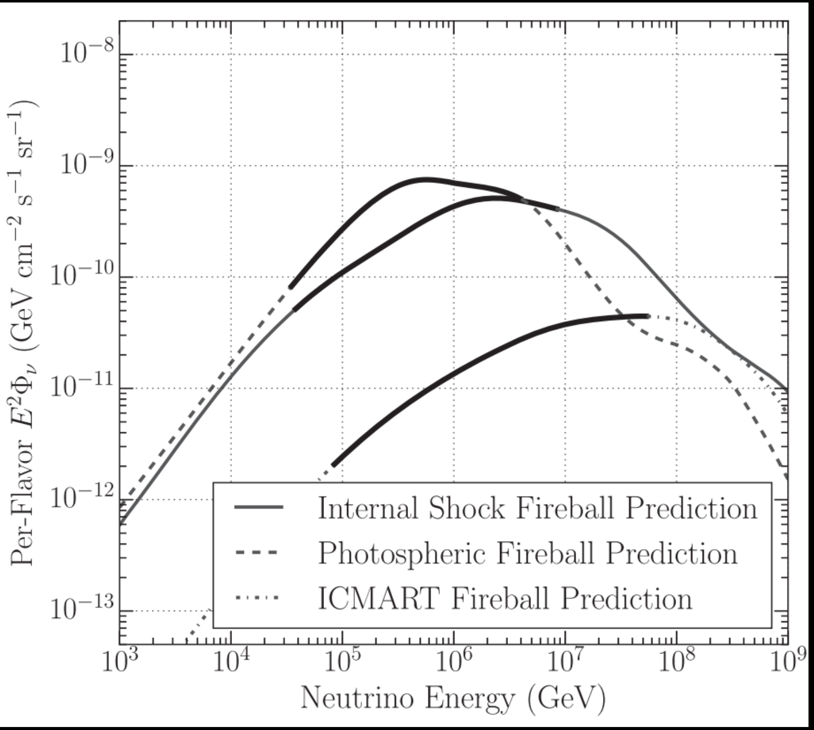
NEED MORE DATA

GRB	Inst	Filter	Mag	$T_{followup}$	Exposure	Ref
GRB041219A	RAPTOR	Rc	18.6	115 s	30 s	Vestrand+2005
GRB050820A	RAPTOR	R	15.4	27 s	30 s (10/20 s)	Vestrand+2006
GRB051109A	ROTSE-III	R	15.0	32 s	5s, 10s, 20s	Yost+2007
GRB051111	ROTSE-III	R	13.0	26.9 s	5s, 10s, 20s	Yost+2007
GRB080319	TORTORA	V	5.3	0 s	0.13s (7.5 frames/s)	Racusin+2008
GRB160625B	MASTER	V	7.9	58 s	5 s	Troja+2017
GRB180325A	TAROT	r	17.8	26.1 s	60 s	Becerra+2020
GRB201223A	GWAC	R	14.5	0 s	10 s	Xin+2023

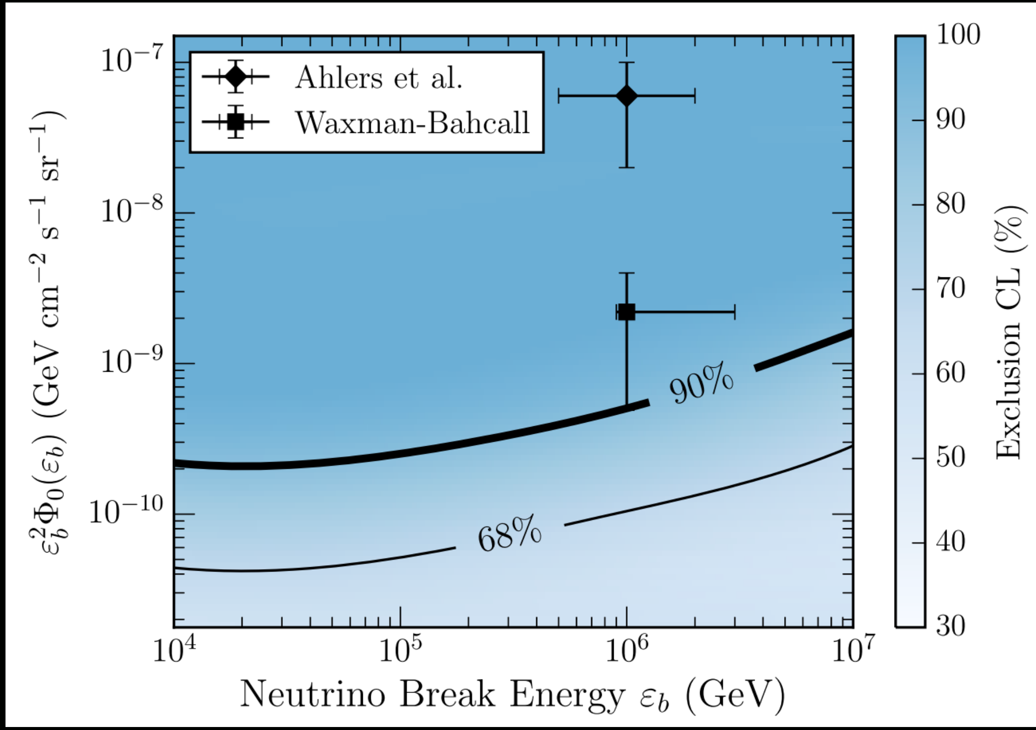
Only few GRBs with a single filter in the optical band.

NEED NEUTRINO

IceCube collaboration 2016



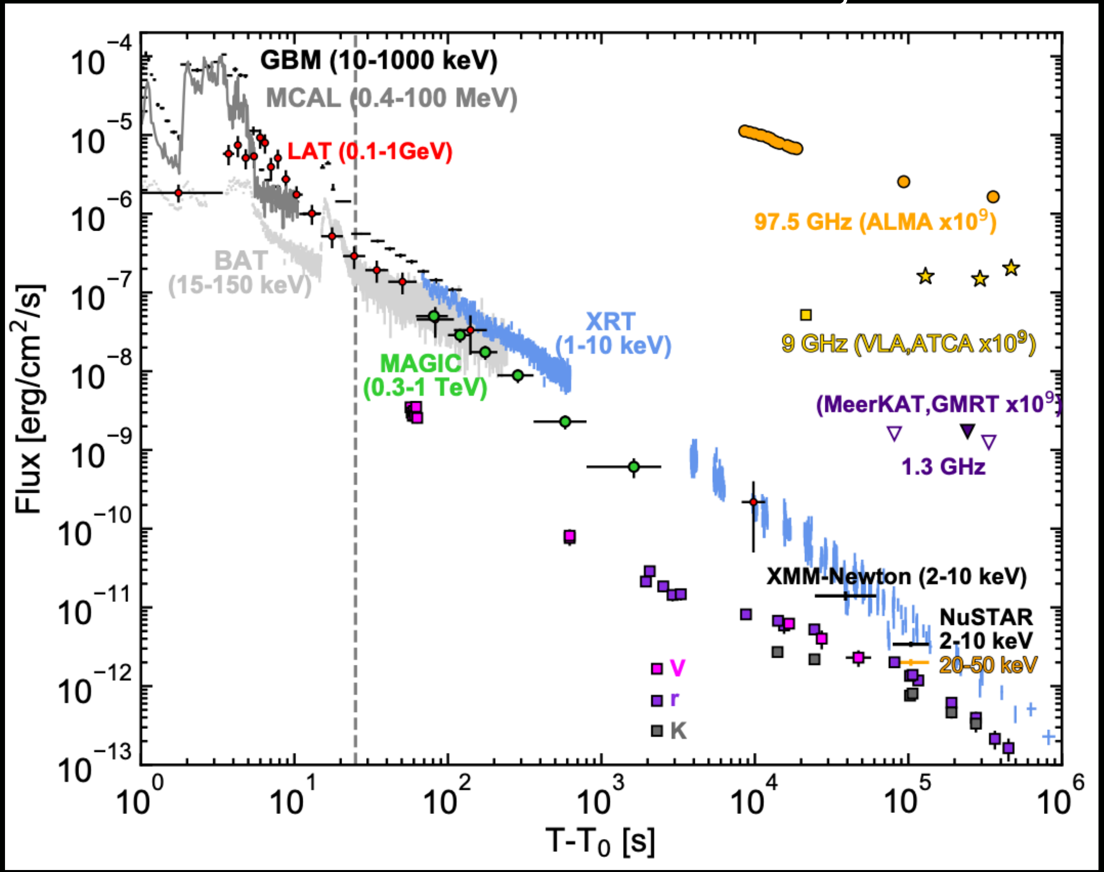
Neutrino flux **prediction** by GRB models



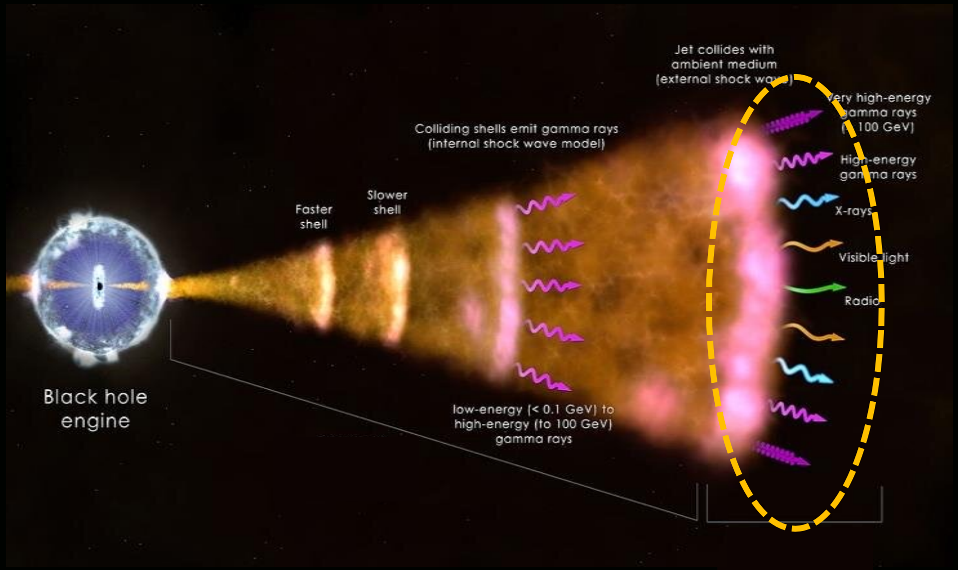
Upper limits from IceCube challenge GRB models as well as UHECR models

AFTERGLOW

Acciari, Tak+2022



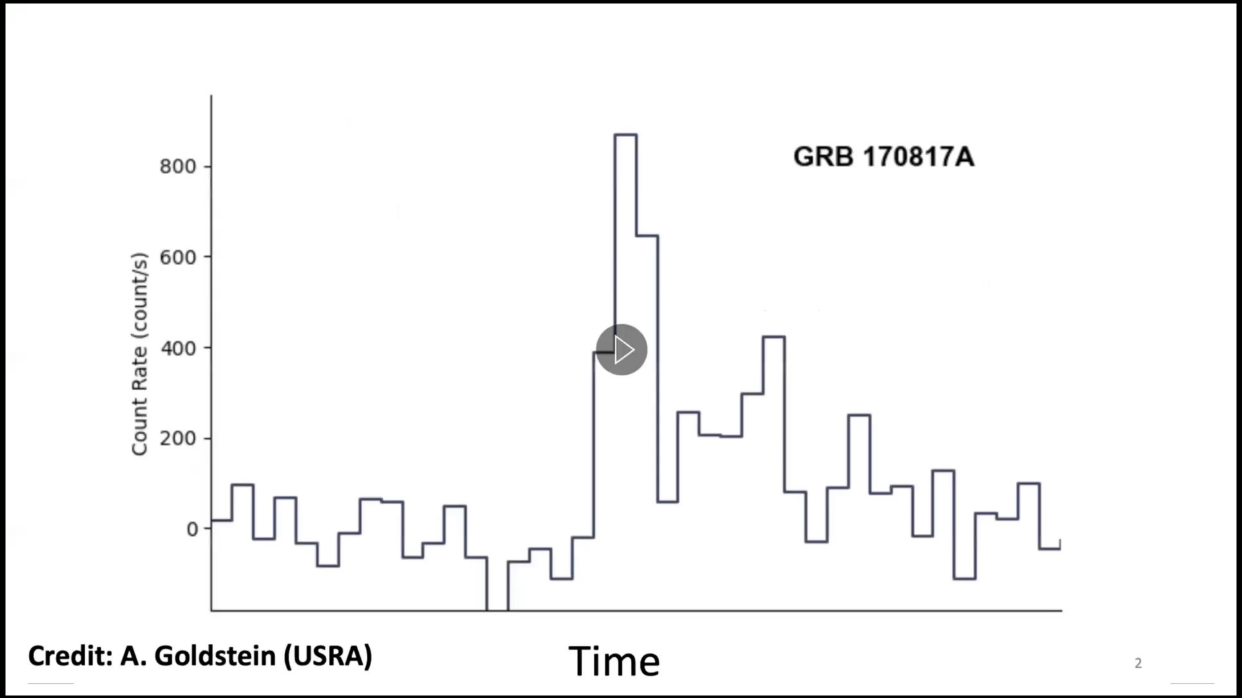
GRB190114C light curve

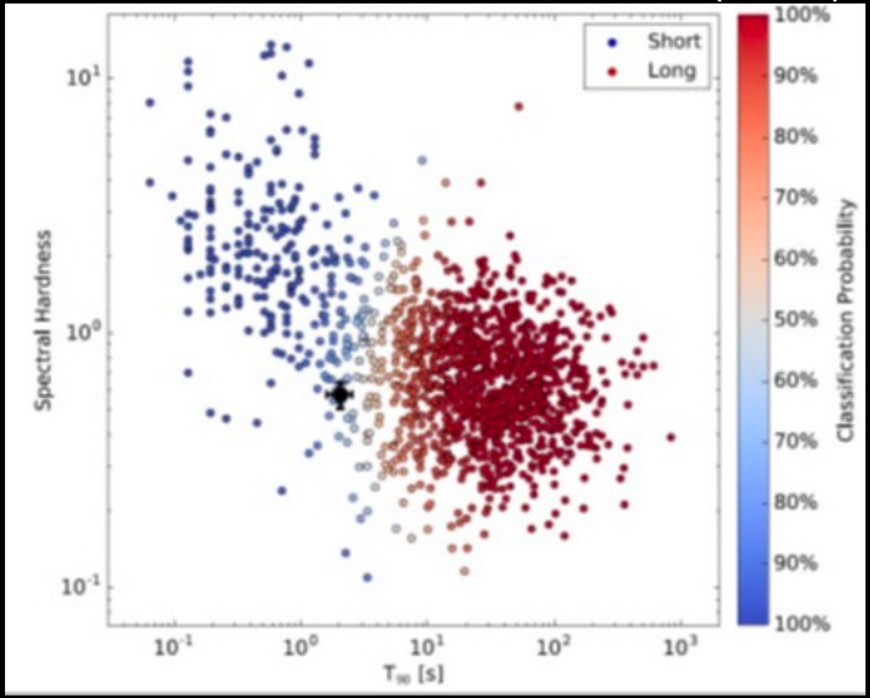


Long-lasting, fading emission observed in the **broad band** from radio to **TeV** energies.

MME GRB170817A

Fermi-GBM collabs. (2017)





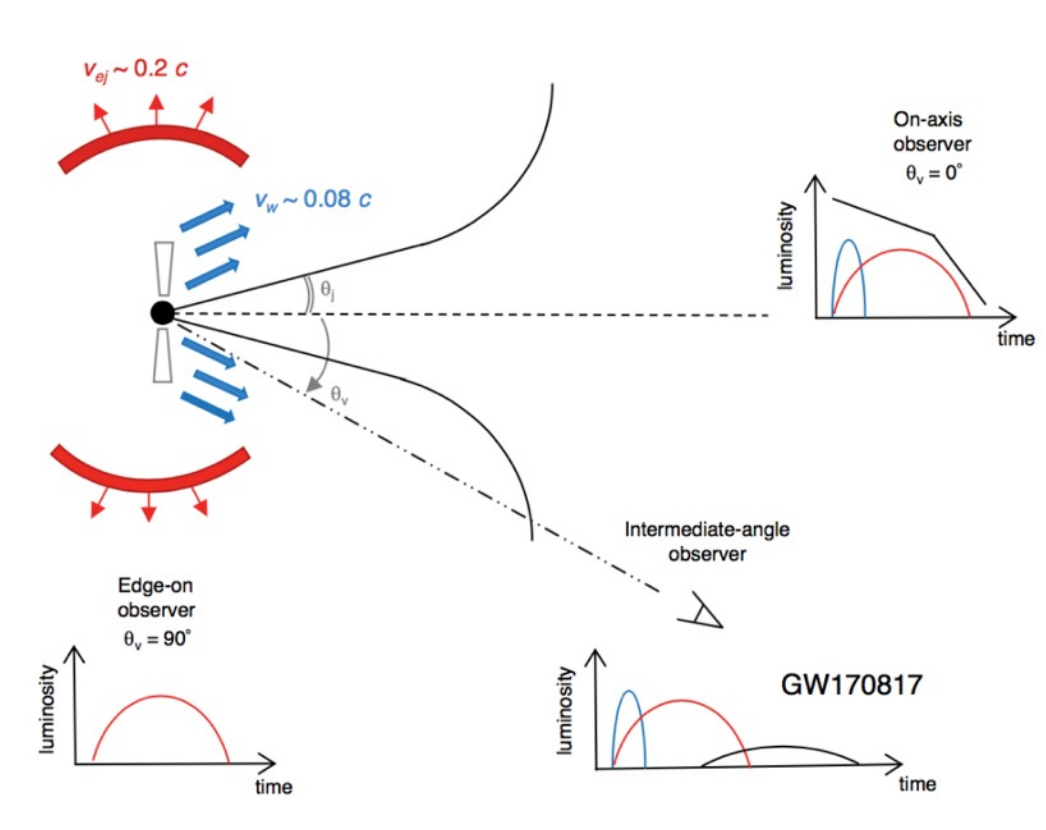
- The prompt emission of this GRB is not interesting.
- With the multi-messeger, its afterglow phase turns out to be **SPECIAL**

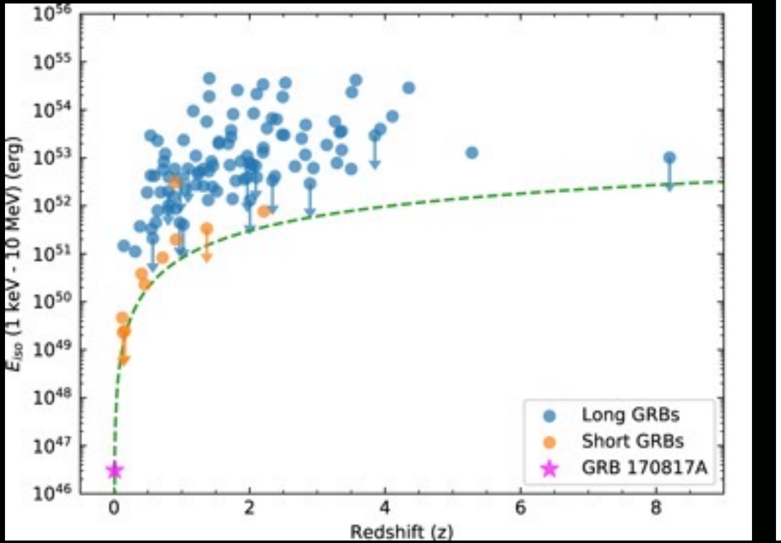
JET STRUCTURE

1. **Off-axis emission**

   This GRB is fainter than a typical GRB considering its proximity, suggesting off-axis emission

E. Troja et al. (2017)



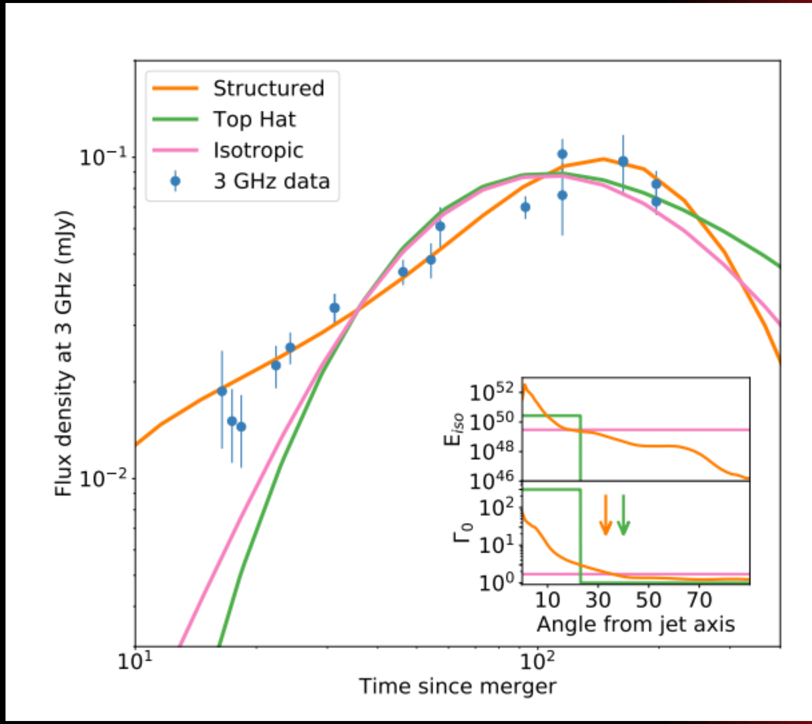


JET STRUCTURE

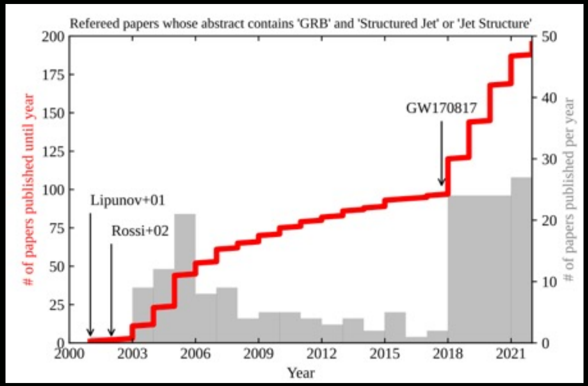
1. **Off-axis emission**

2. **Structured jet**
   The broadband afterglow can be explained when we introduce the structured jet

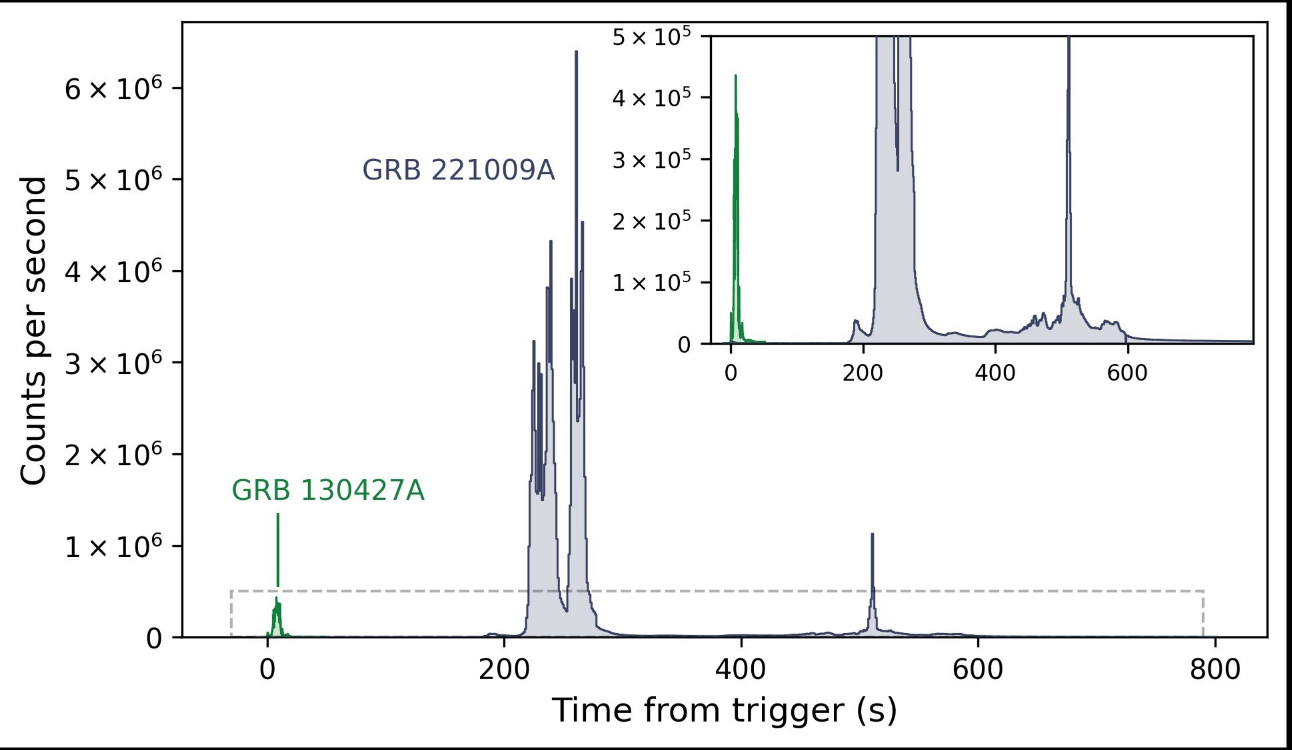
Lazzati et al. (2017)



Salafia & Ghirlanda (2022)



BOAT GRB221009A

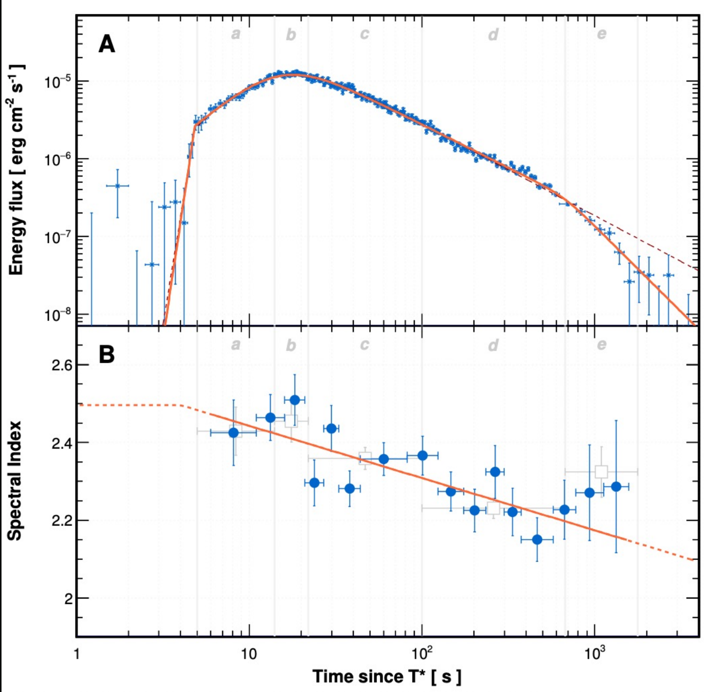


GRB221009A is **the most energetic burst** ever detected with a redshift of 0.151.

LHAASO in China reported the observation of 5,000 very-high-energy (>100 GeV) photons.

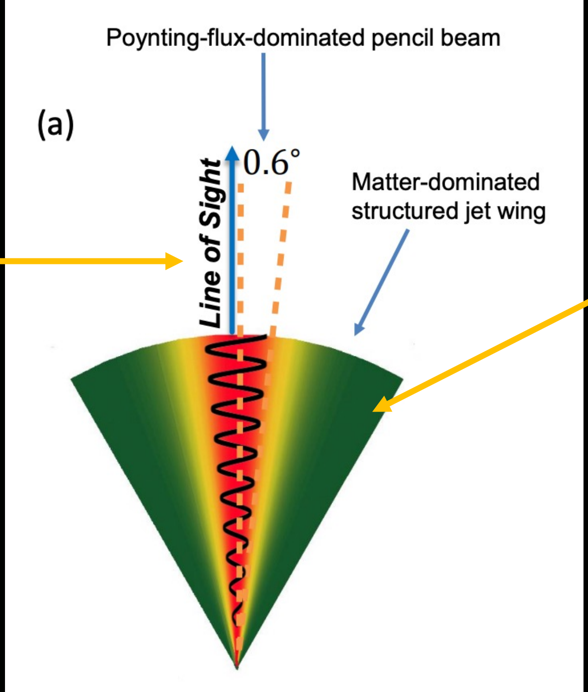
JET STRUCTURE

LHAASO 2023

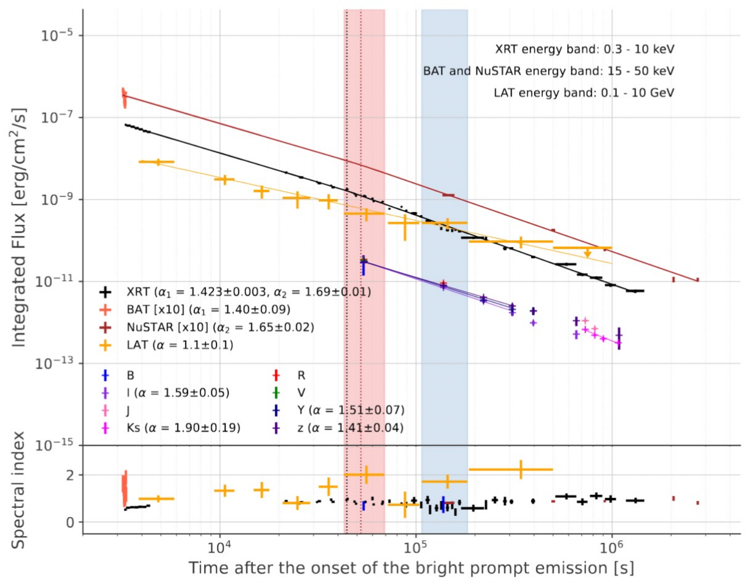


Lightcurve and spectrum of GRB221009A in the TeV regime

Zhang+2023



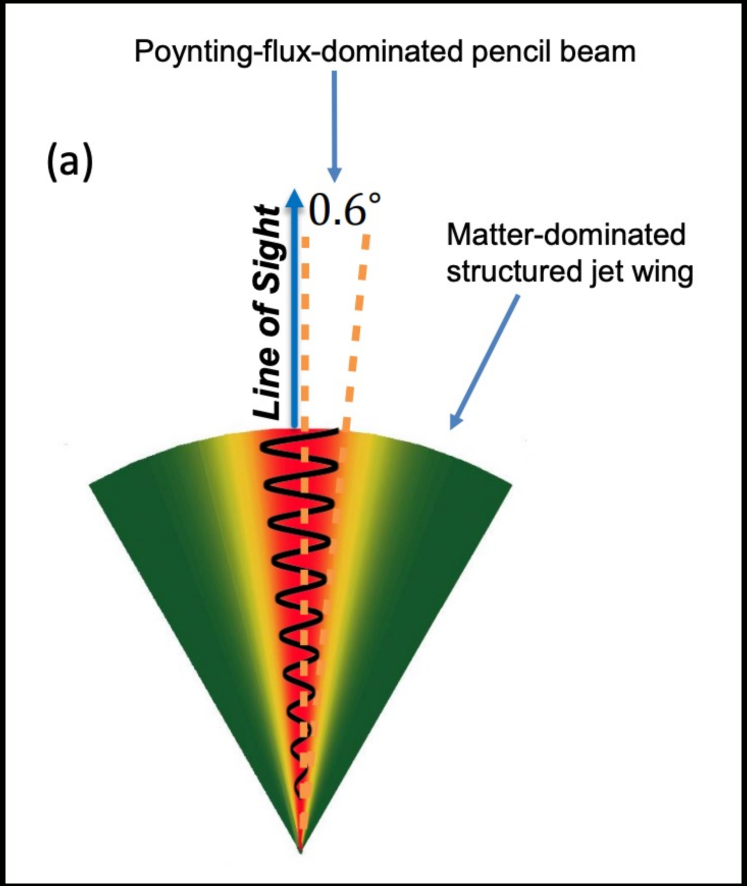
Tak+2025



Multiwavelength lightcurve of GRB221009A

JET STRUCTURE

Zhang+2023



Sato+2025

	θ_v [rad]	θ_0 [rad]	Γ_0	$E_{\mathrm{iso,K}}$ [erg]	n_0 [cm^{-3}]	p	ϵ_e	ϵ_B	f_e	η
GRB 180720B[a]										
narrow jet	0.0	0.015	350	4.0×10^{53}	10	2.4	5.0×10^{-3}	5.0×10^{-4}	0.2	0.6
wide jet		0.1	20	1.0×10^{53}		2.2	9.0×10^{-2}	9.0×10^{-4}	0.4	–[c]
GRB 190114C[a]										
narrow jet	0.0	0.015	350	4.0×10^{53}	3.0	2.8	9.0×10^{-3}	6.0×10^{-5}	0.1	0.4
wide jet		0.1	20	1.0×10^{53}		2.6	8.0×10^{-2}	9.0×10^{-4}	0.2	–[c]
GRB 190829A[a]										
narrow jet	0.031	0.015	350	4.0×10^{53}	0.01	2.44	3.5×10^{-2}	6.0×10^{-5}	0.2	0.4[d]
wide jet		0.1	20	1.0×10^{53}		2.2	0.29	1.0×10^{-5}	0.35	–[c]
GRB 201216C[a]										
narrow jet	0.0	0.015	350	4.0×10^{53}	1.0	2.3	3.5×10^{-2}	6.0×10^{-5}	0.4	0.5
wide jet		0.1	20	1.0×10^{53}		2.8	0.1	5.0×10^{-5}	0.2	–[c]
GRB 221009A[b]										
narrow jet	0.0	0.0018	800	3.0×10^{55}	0.1	2.2	2.0×10^{-2}	1.0×10^{-4}	0.2	0.3
wide jet		0.06	30	3.0×10^{53}		2.2	0.1	1.5×10^{-5}	0.1	–[c]

The two jets may have different properties

KILONOVA

KILONOVA

A Celestial Factory for Heavy Elements

Neutron-rich ejecta allows to produce heavier elements

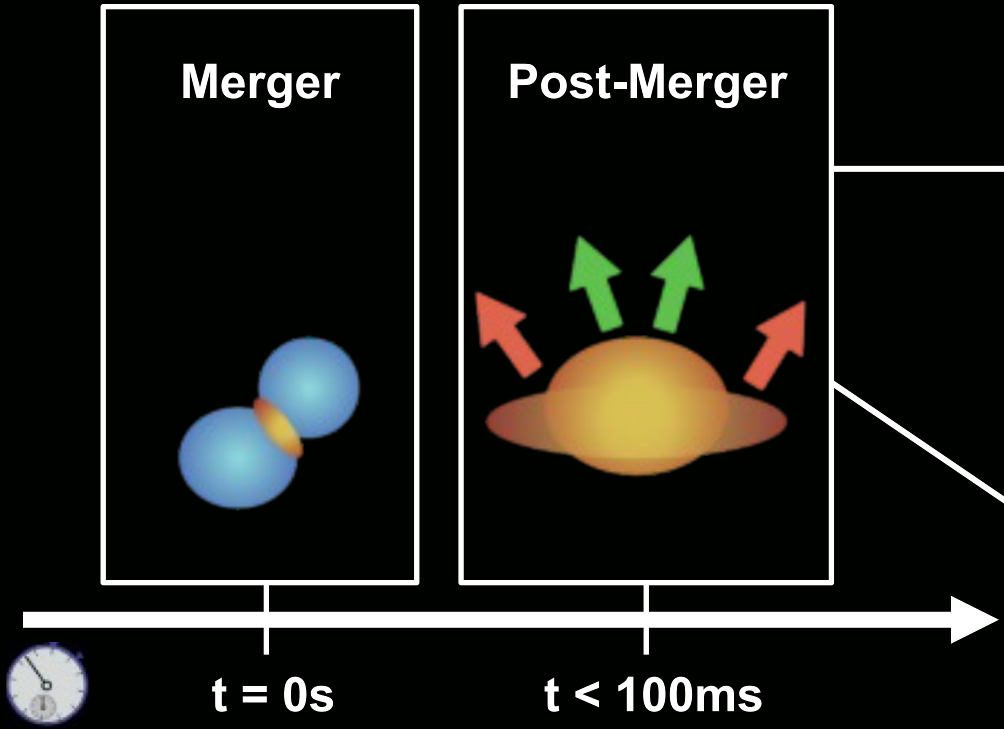
Less luminous (1-10% of supernovae)

Rapid decay (a few weeks)

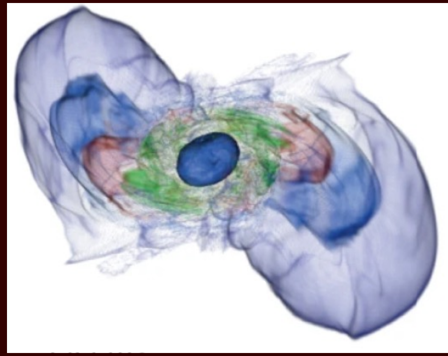
KILONOVA

TIMELINE

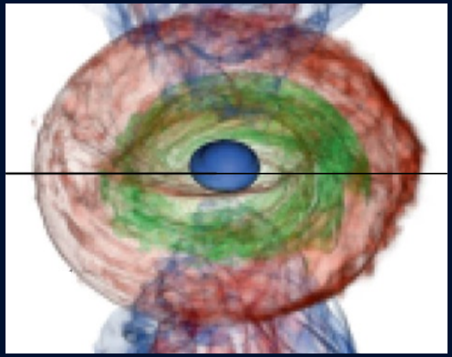
Credit: Hotokezaka



Theoretical View



Dynamical ejecta
Timescale: about ms
Mass: 0.01 $M_\odot$
Velocity: high (>0.1c)
Composition: neutron rich

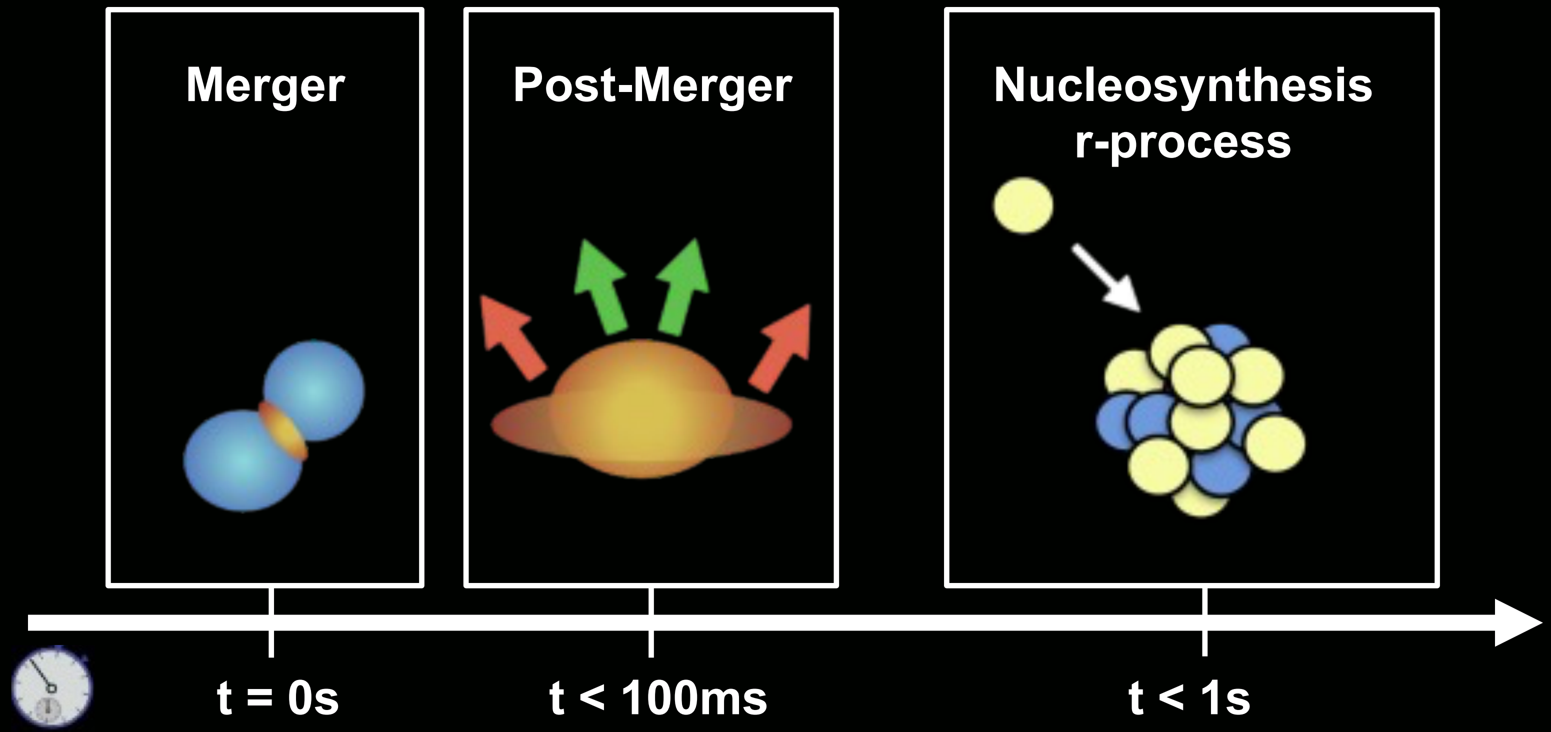


Post-merger ejecta
Timescale: < 1 s
Mass: 0.05 $M_\odot$
Velocity: low (~0.1c)
Composition: less neutrons

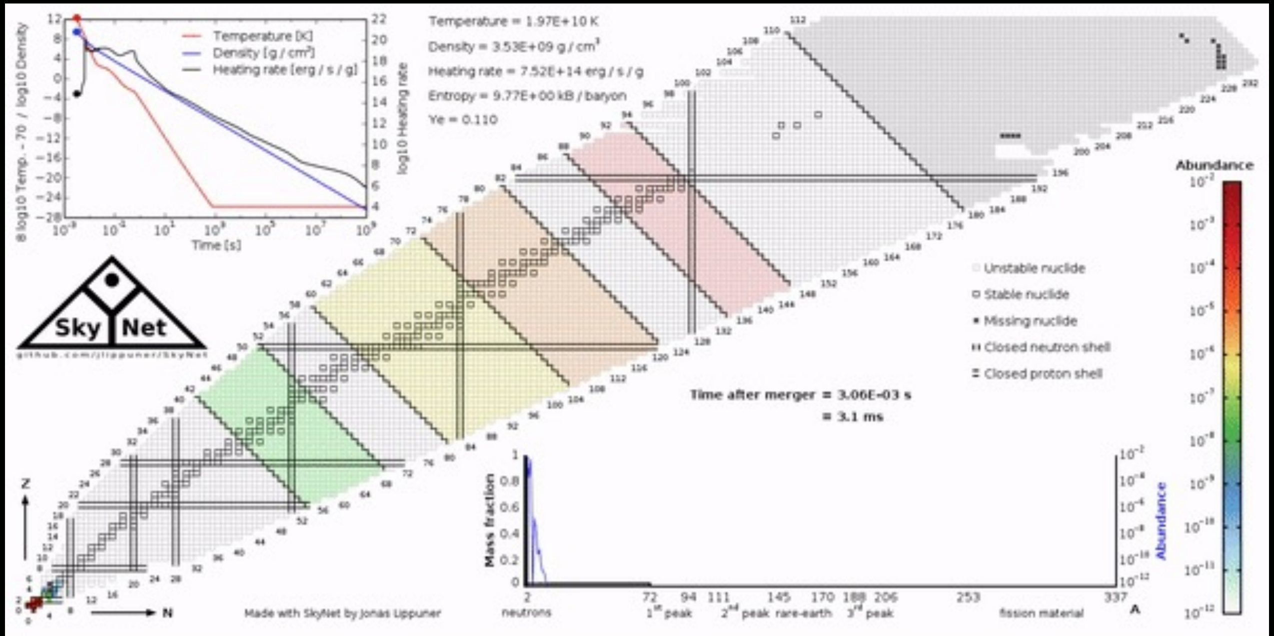
Neutrino capture: $n + \nu_e \rightarrow p + e^-$

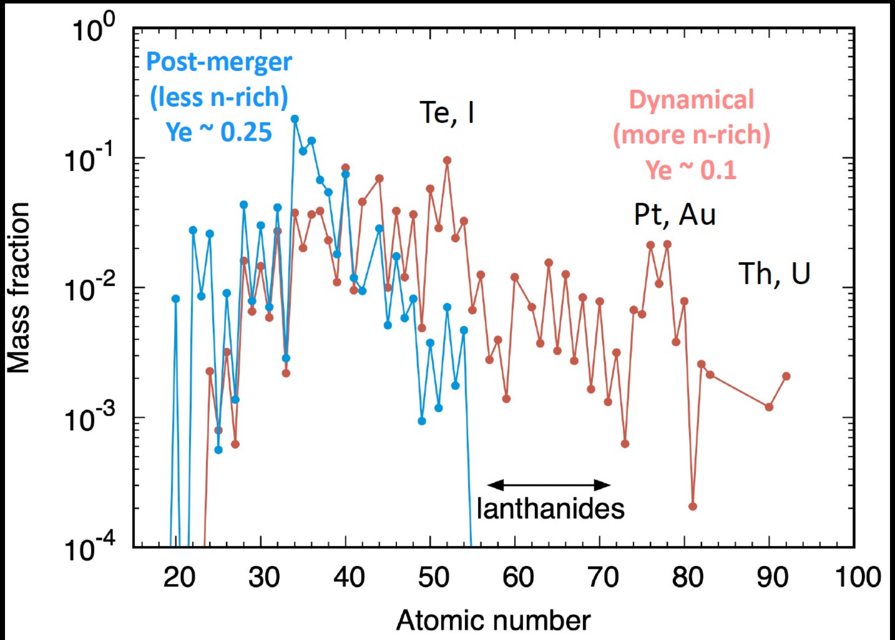
TIMELINE

Credit: Hotokezaka



PRODUCE HEAVY ELEMENTS



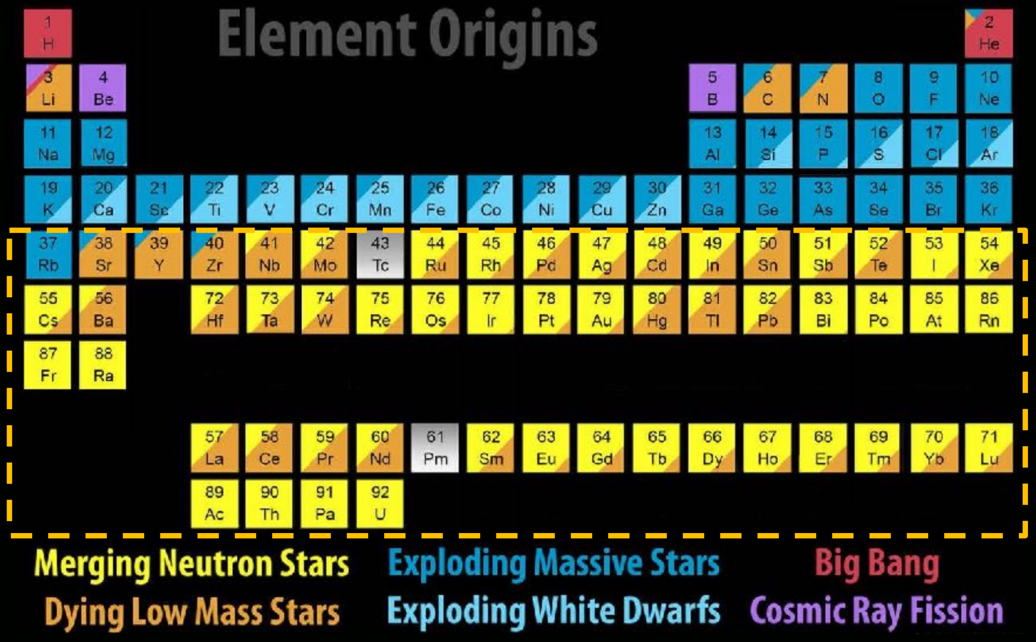


Credit: Lippuner

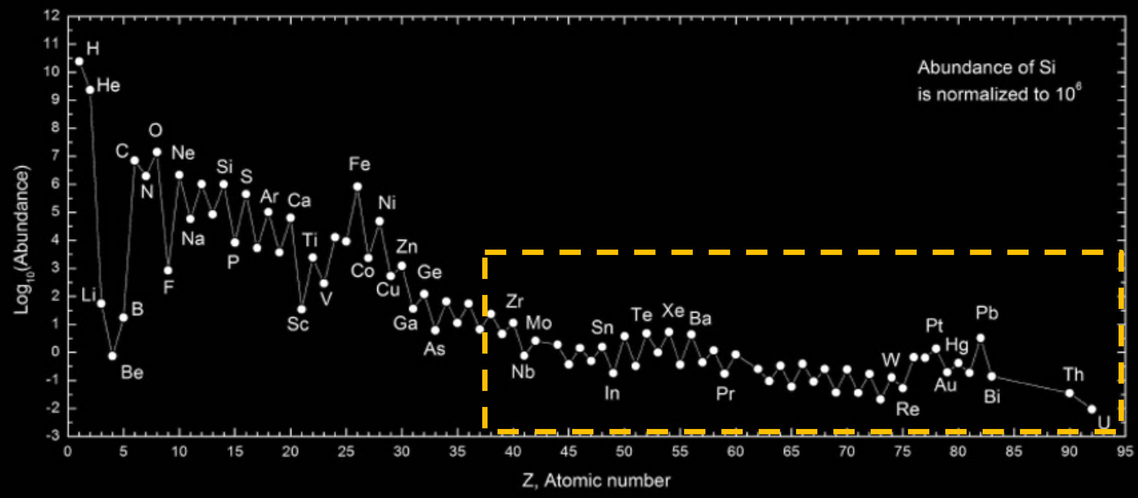
$$Y_e = \frac{N_e}{N_p + N_n} = \frac{N_p}{N_p + N_n}$$

A neutron-rich environment allows rapid neutron captures, preventing nuclei from decaying (e.g., β− decay) before capturing another neutron.

HEAVY ELEMENTS



Periodic table

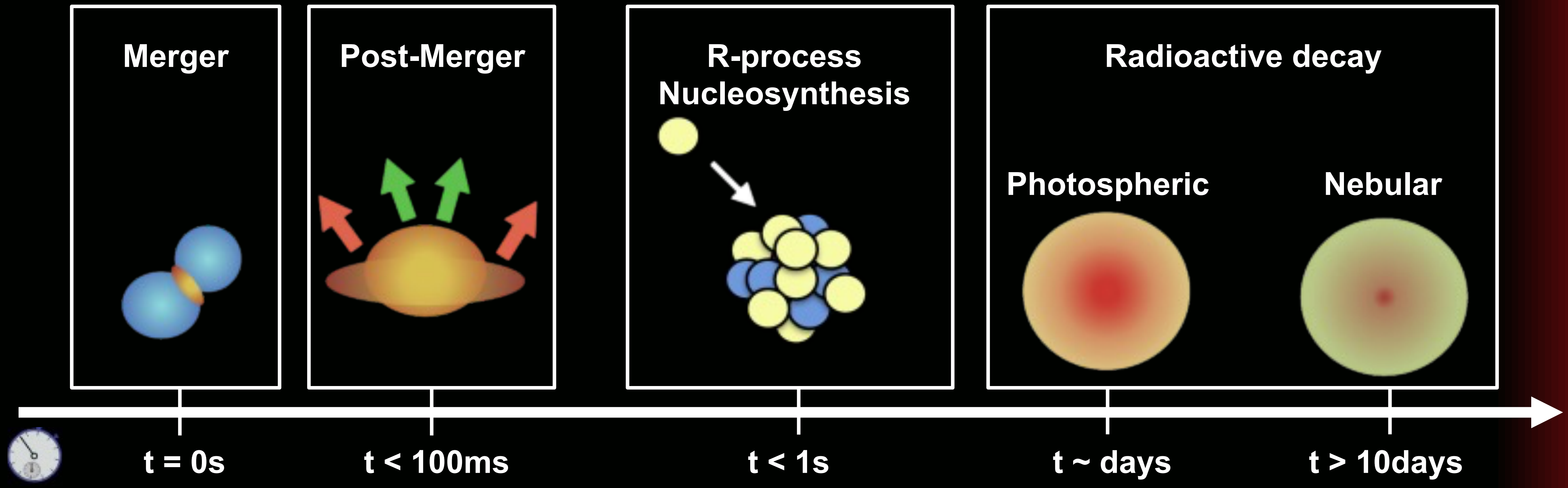


Solar abundance

They are from neutron star mergers

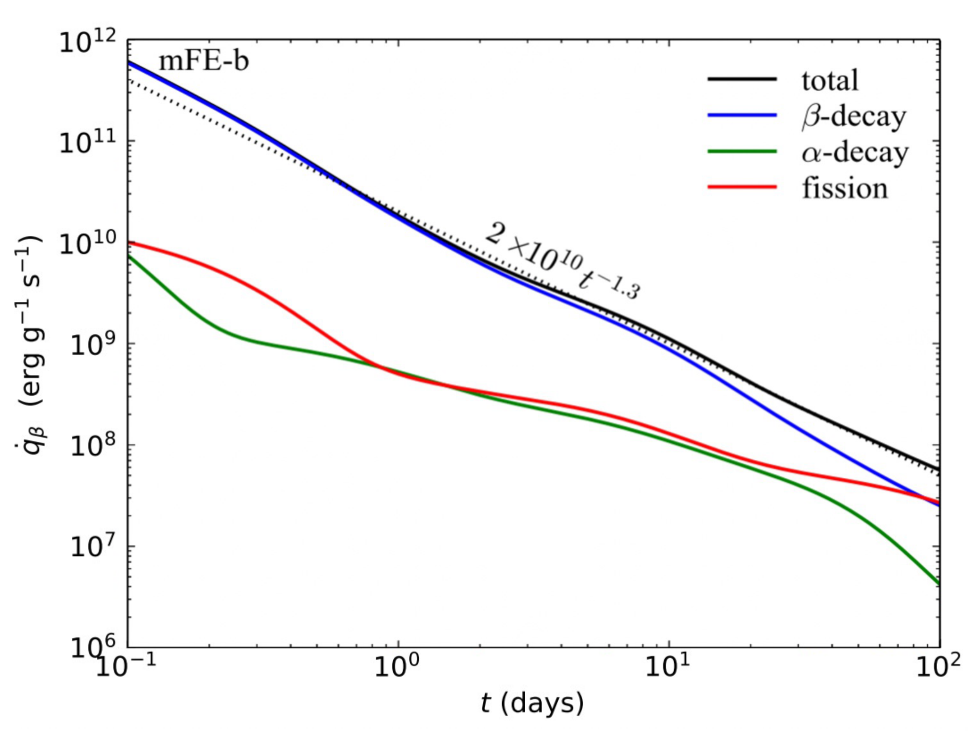
TIMELINE

Credit: Hotokezaka



HEATING SOURCE

Wanajo 2018



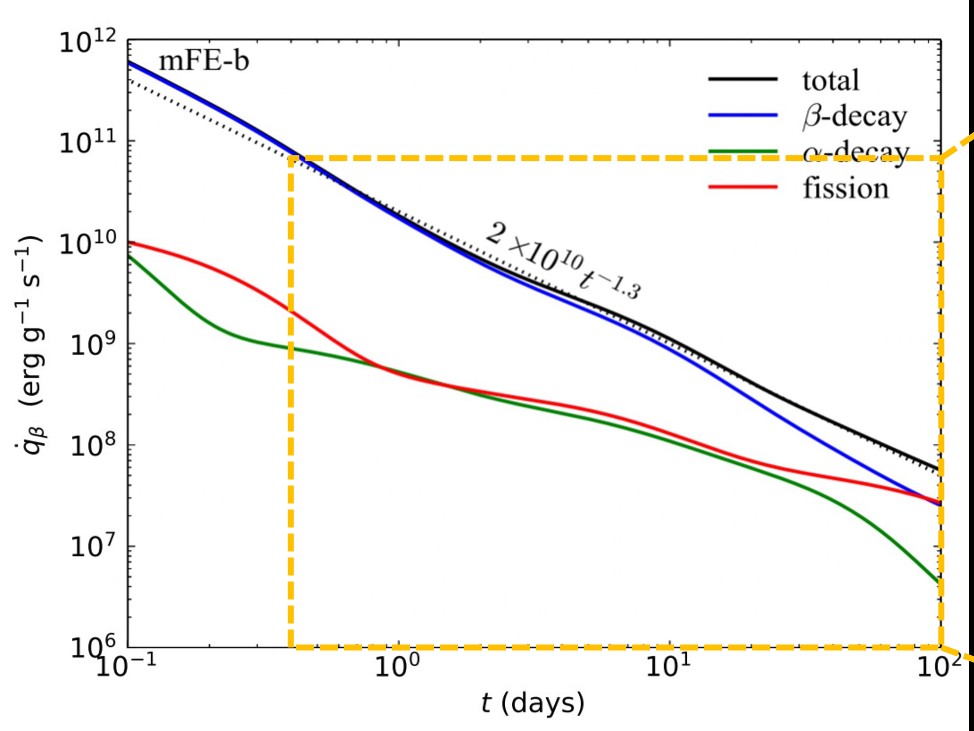
Unstable isotopes undergo the beta decay and release energy.

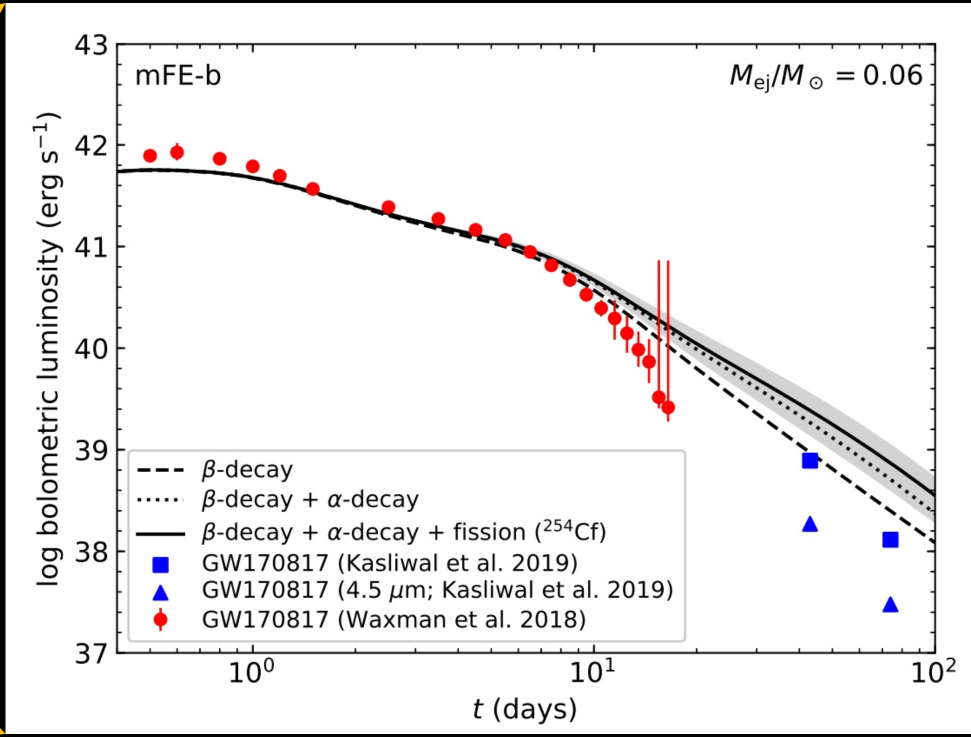
$$n \rightarrow p + \beta^- + \bar{\nu}_e + 0.8\ \mathrm{MeV}$$

Other forms of energy release are not significant in the early phase.

HEATING SOURCE

Wanajo 2018

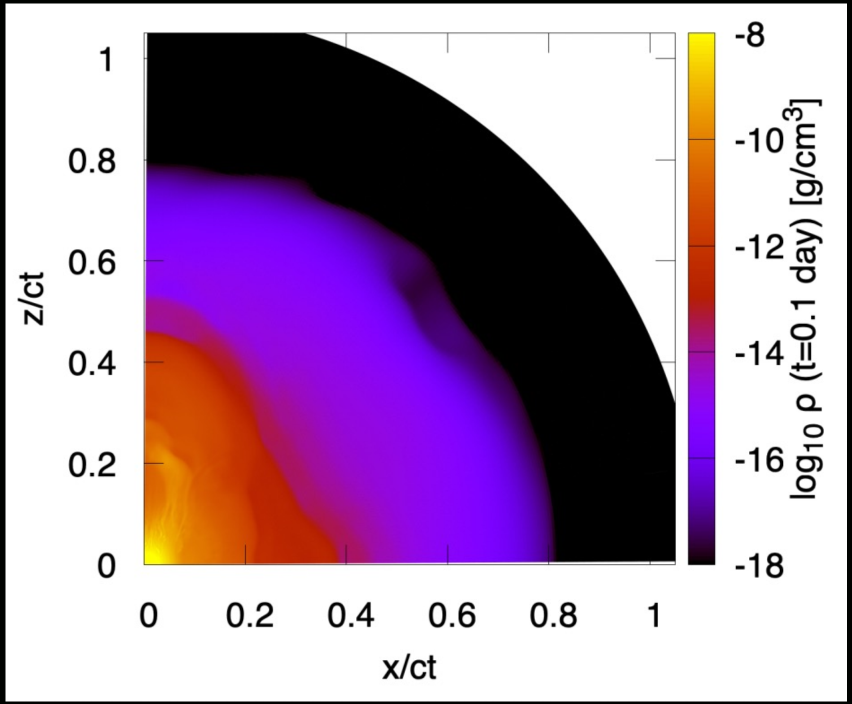


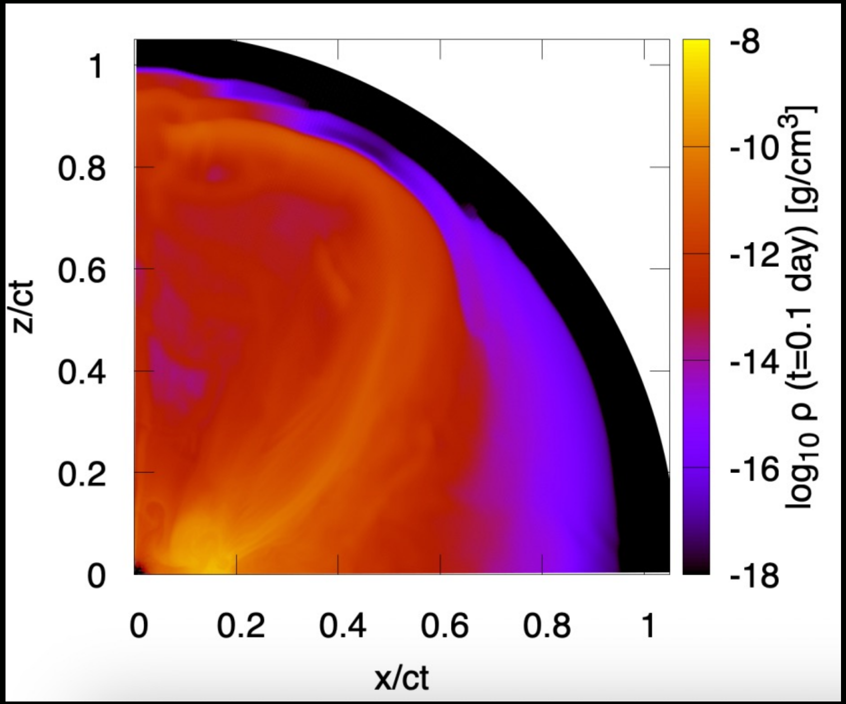


The radioactive decay actually powers kilonovae.

DIVERSE PROFILE

Bernuzzi+2020

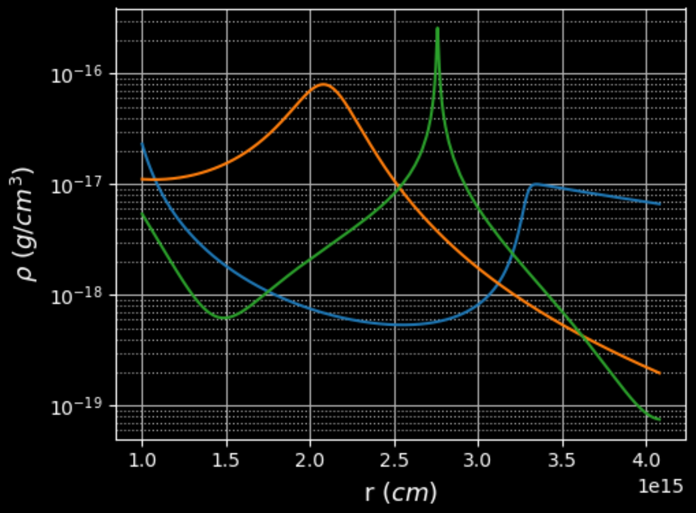


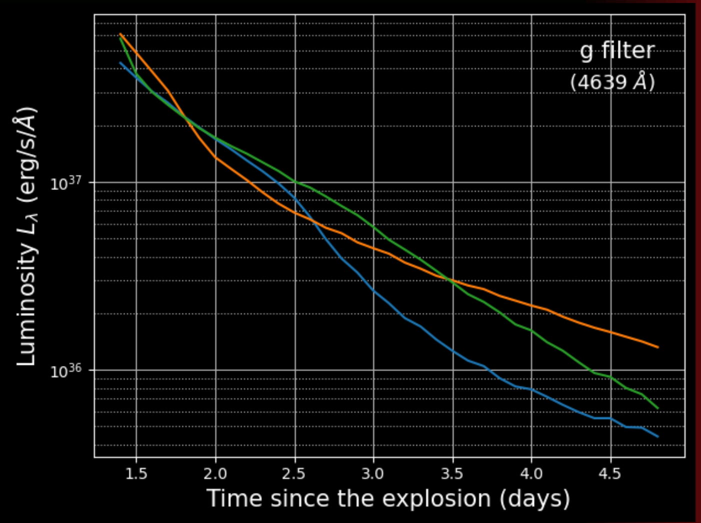


Depending on various initial parameters (ejecta mass, magnetic-field strength, EOS of neutron stars, etc.), the kilonova density can exhibit diverse profiles

EJECTA PROFILE

Tak+2023

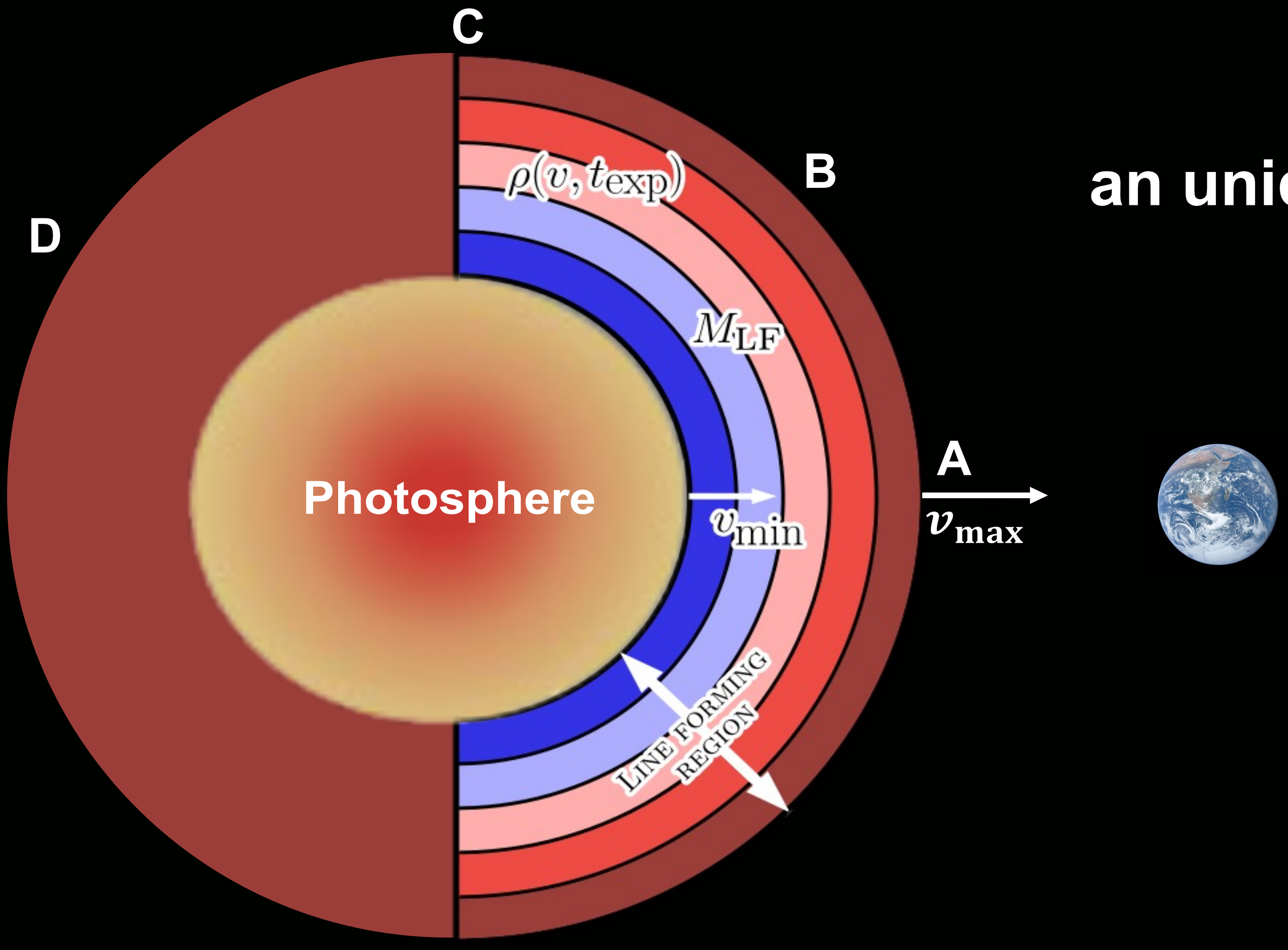




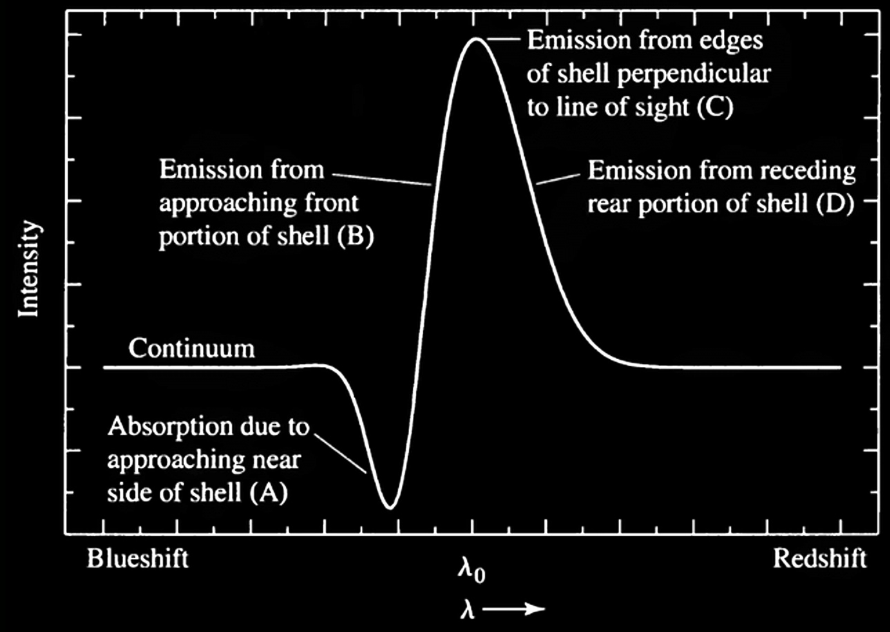
Unsteady ejection **Diverse density profiles** **Imprint on the lightcurve**

All these features are due to the bound-bound transition by heavy elements, allowing us to find such signatures at specific wavelengths.

PHOTON DIFFUSION

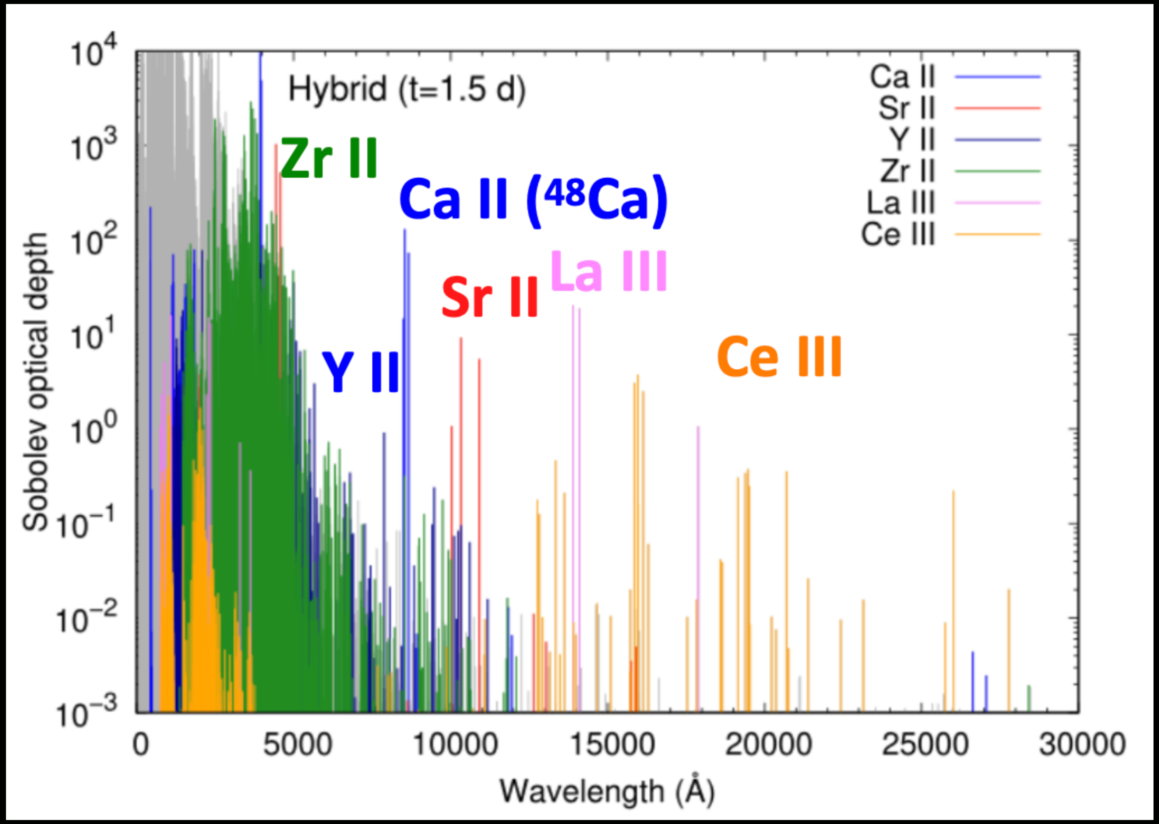


Due to the Doppler effect, an unique profile (P cygni) is observed.



WHICH ELEMENTS?

Domoto+2022

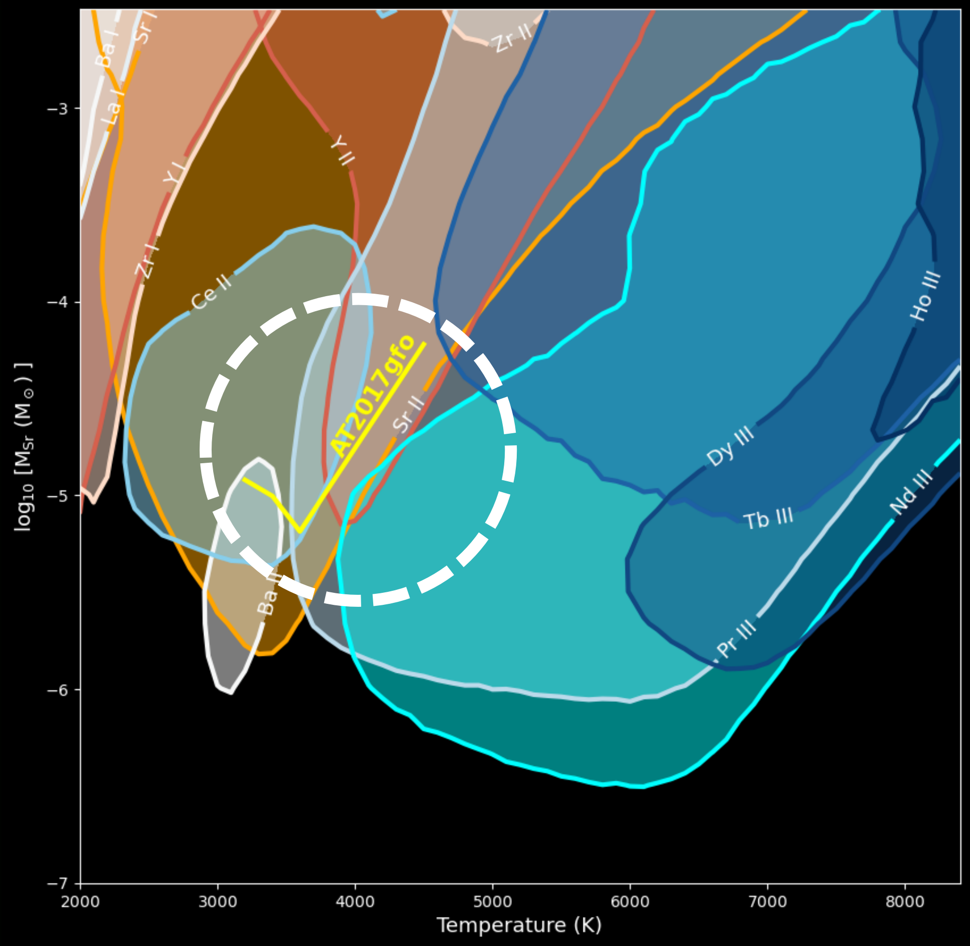


Species with a higher probability of interaction (or optical depth) can leave their signatures in the kilonova spectrum.

Lanthanide: from lanthanum to lutetium (atomic numbers 57–71, including Pr, Nd, Tb, Dy, Ho)

WHICH CONDITIONS?

Tak+2024

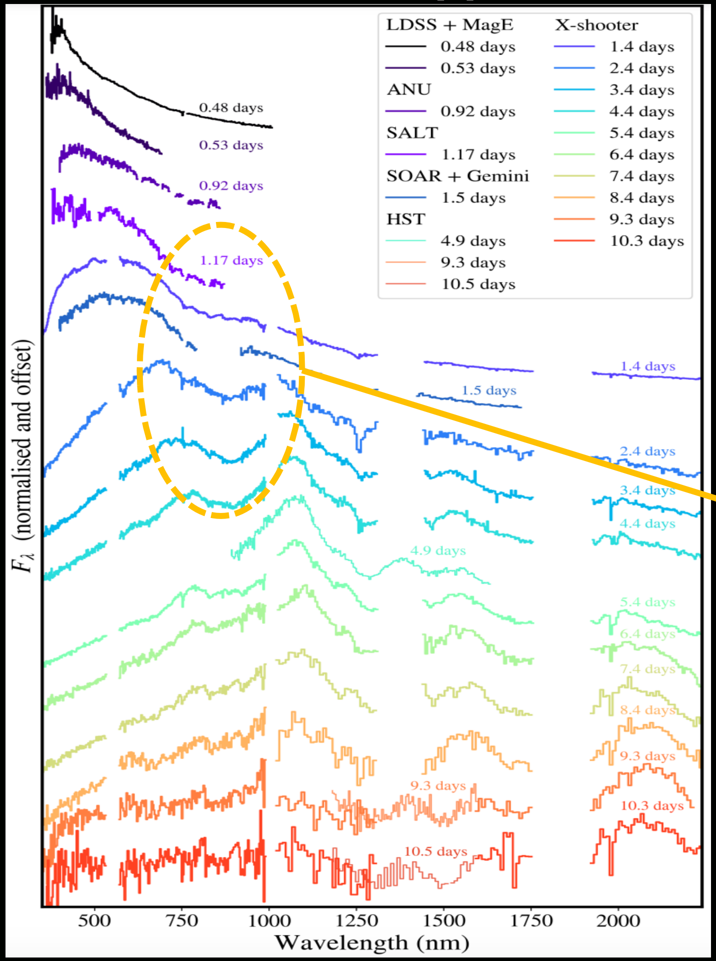


Each species has **its own condition(s)** in which its signature is prominent.

Lanthanide: from lanthanum to lutetium (atomic numbers 57–71, including Pr, Nd, Tb, Dy, Ho)

AT2017gfo

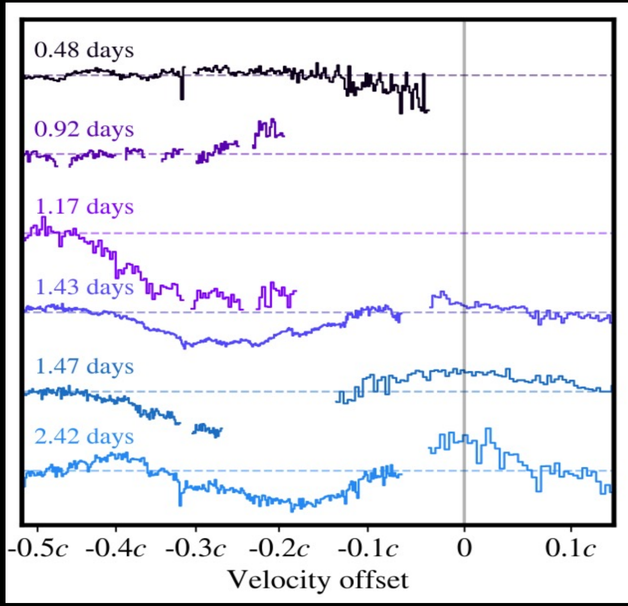
Sneppen+2024



Identified P Cygni lines in AT2017gfo

- **Y II (760nm)**: Sneppen & Watson 2023
- **Sr II (1μm)**: Watson+2019, Gillanders+2022
- **La III (1.4μm)**: Domoto+2022
- **Ce III (1.6μm)**: Domoto+, 2023, Tanaka+2023

Sr II P Cygni feature



CONCLUSION

MULTIMESSENGER TRANSIENTS

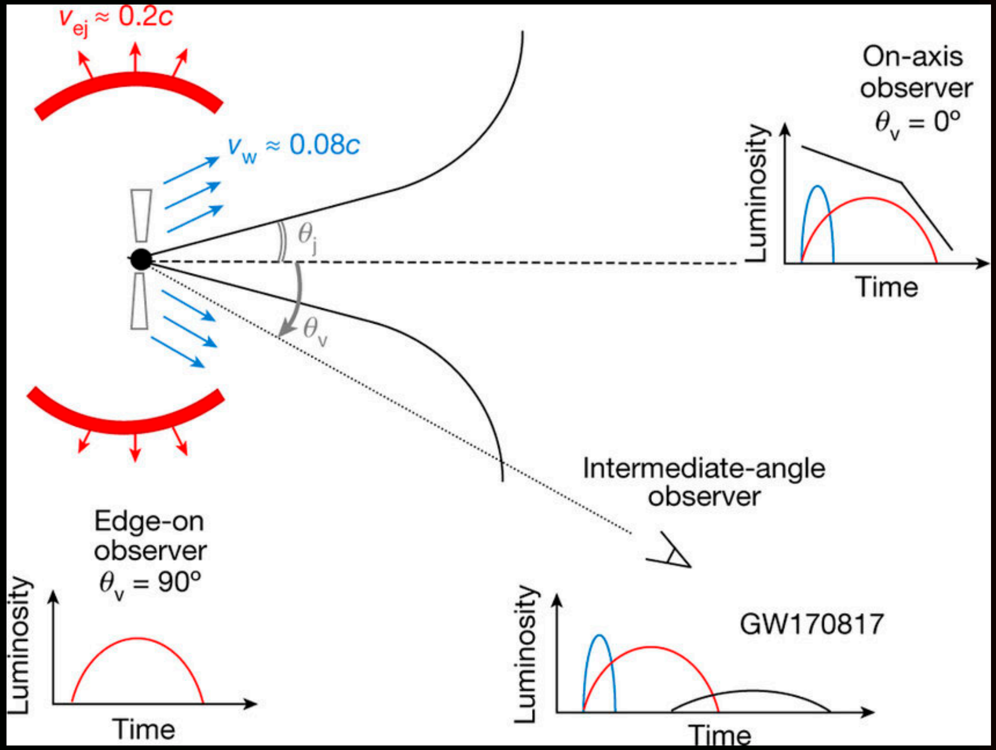
Not only are the details of individual events important, but **combining them yields additional physical constraints**.

Binary merger and its details

- **Progenitor system**
- **Jet geometry**
- **Nucleosynthesis**

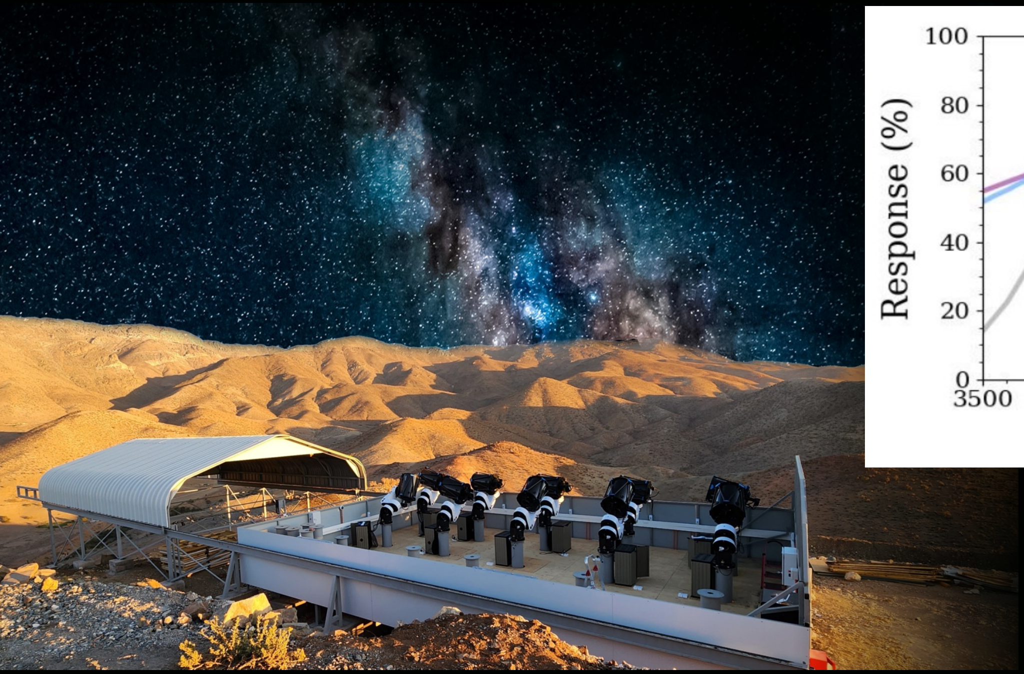
Fundamental physics

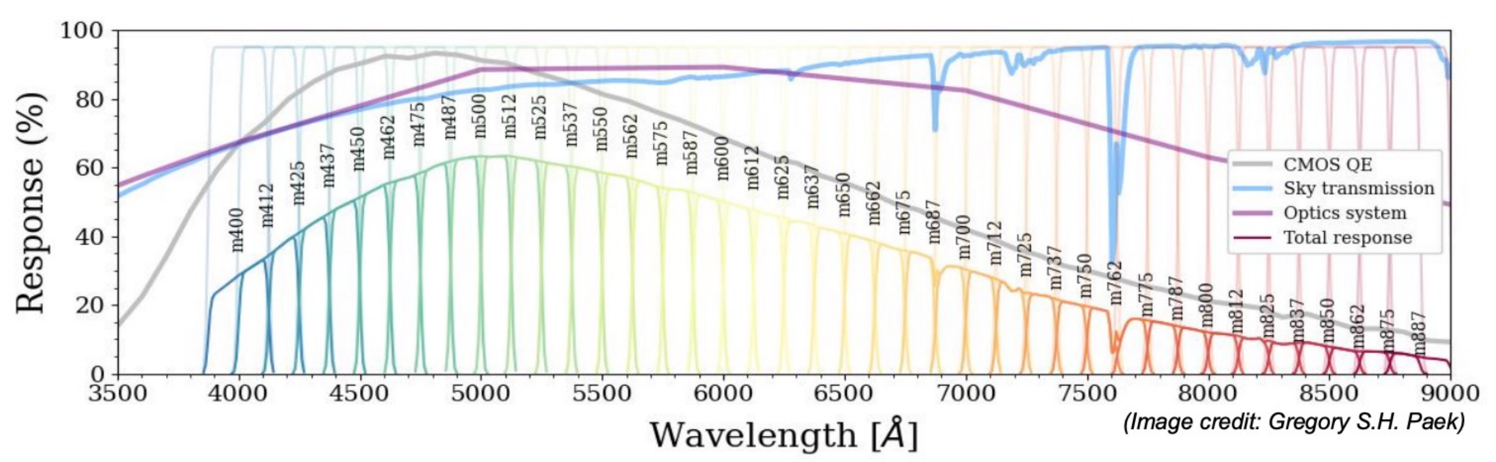
- **Physics in extreme conditions**
- **Speed of gravity**
- **Equivalence principle**



7 DIMENSIONAL TELESCOPE

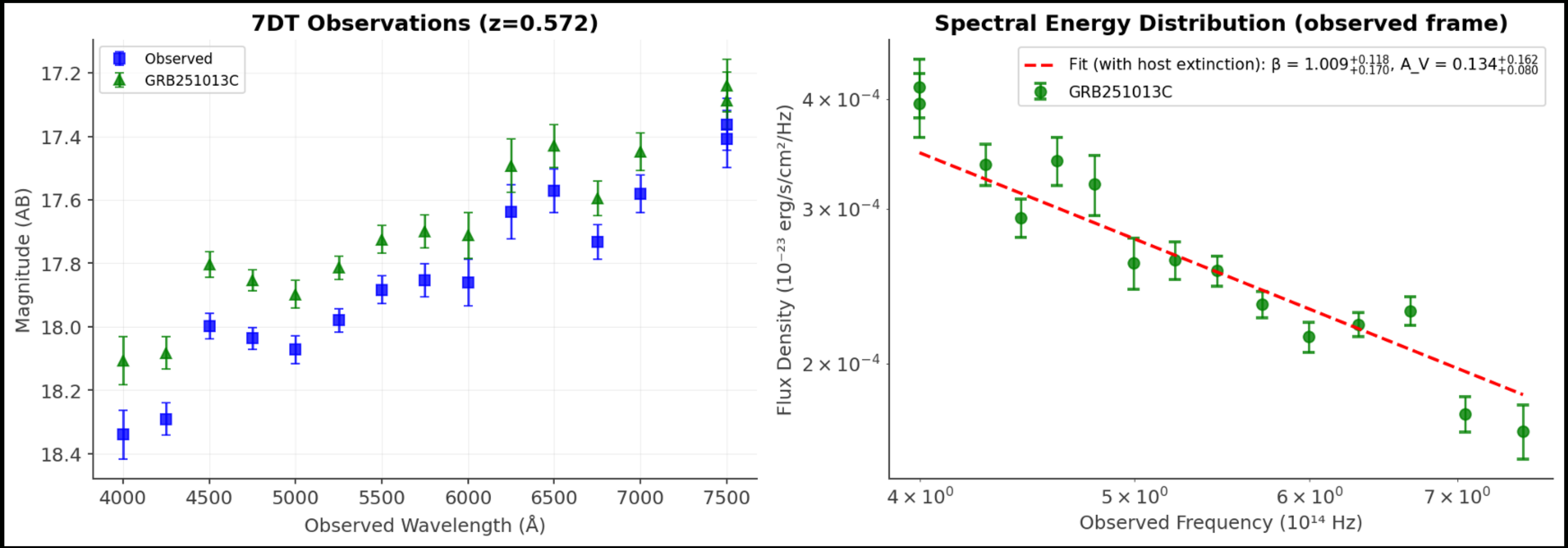
The 7-Dimensional Telescope (7DT), a pioneering multi-telescope system, consists of 16 individual telescopes that cover wavelengths from 4000 to 9000 Å using medium-band filters, located at Chile.





(Image credit: Gregory S.H. Paek)

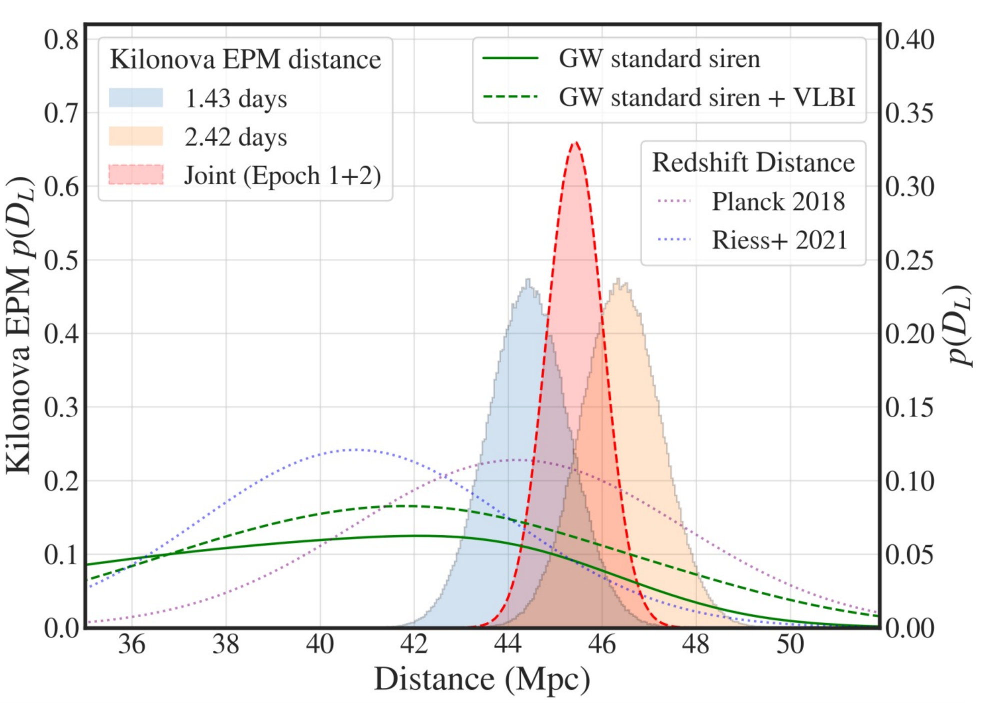
GRB WITH 7DT

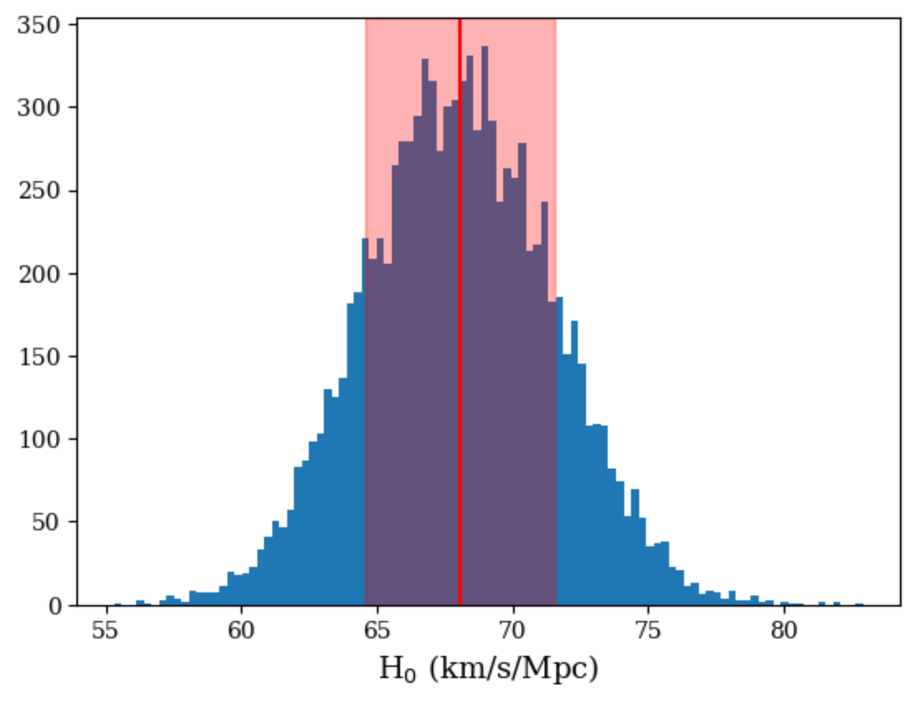


Unlike stars or galaxies, GRB spectrum is **relatively smooth** so that the observation with **medium-band filters** is sufficient for most GRB studies.

KILONOVA WITH 7DT

Sneppen+2023a





With the NIR and optical observations, we can address the Hubble tension

Simulation based on Sneppen+2023b

Thank you

Anyone who are interested in these topics, let me know

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