Multimessenger astronomy with compact binary mergers in light of O4

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Plan of the talk

1. Current status of gravitational-wave observations
2. r-process nucleosynthesis and kilonova
3. Future direction: black-hole formation
4. Summary

1. Current status of gravitational-wave observations

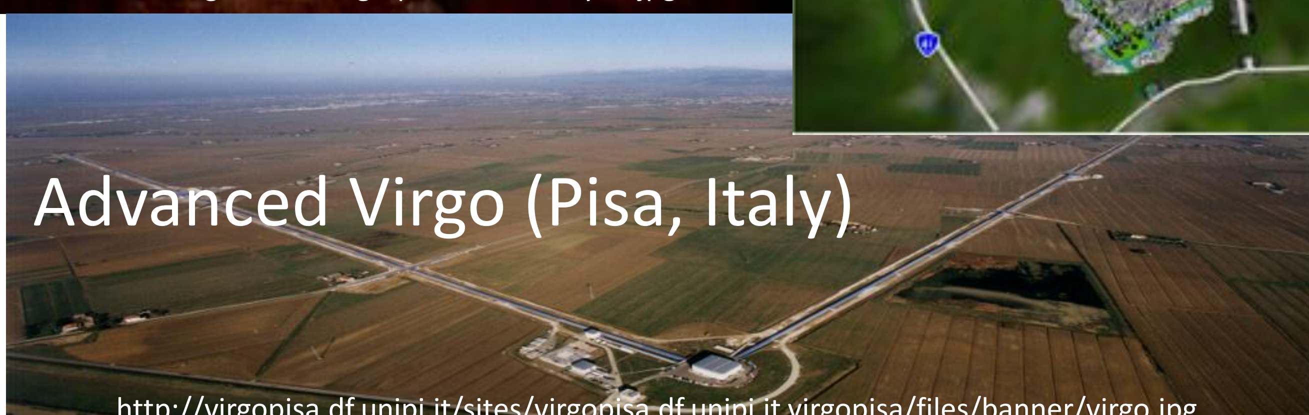
Gravitational-wave detectors

Advanced LIGO
(Hanford/Livingston, USA)

https://www.advancedligo.mit.edu/graphics/summary01.jpg

http://gwcenter.icrr.u-tokyo.ac.jp/wp-content/themes/lcgt/images/img_abt_lcgt.jpg

KAGRA (Kamioka, Japan)

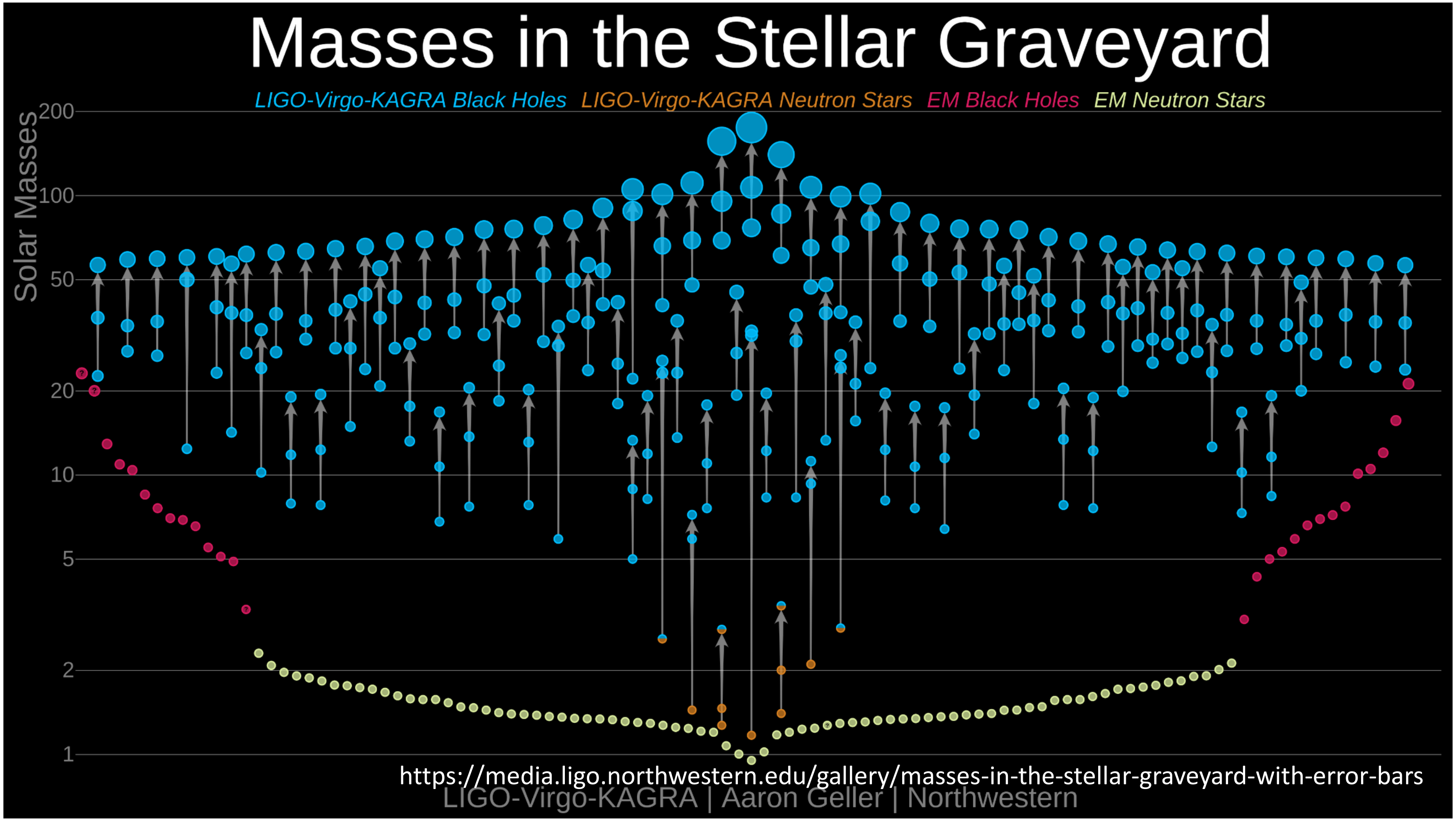


Advanced Virgo (Pisa, Italy)

http://virgopisa.df.unipi.it/sites/virgopisa.df.unipi.it.virgopisa/files/banner/virgo.jpg

Observed event by the end of O3

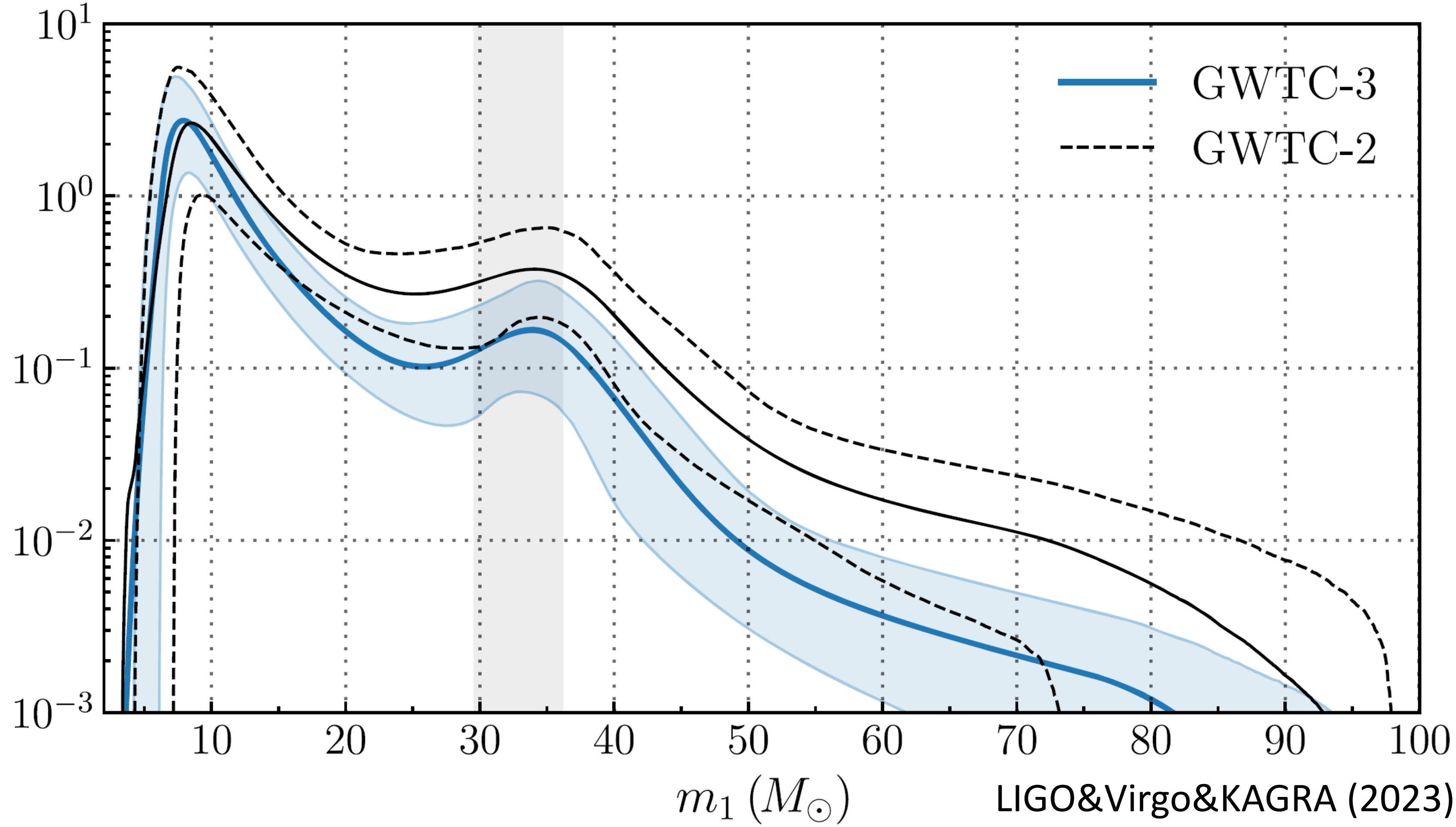
~90 binary black holes vs. 2 binary neutron stars



https://media.ligo.northwestern.edu/gallery/masses-in-the-stellar-graveyard-with-error-bars

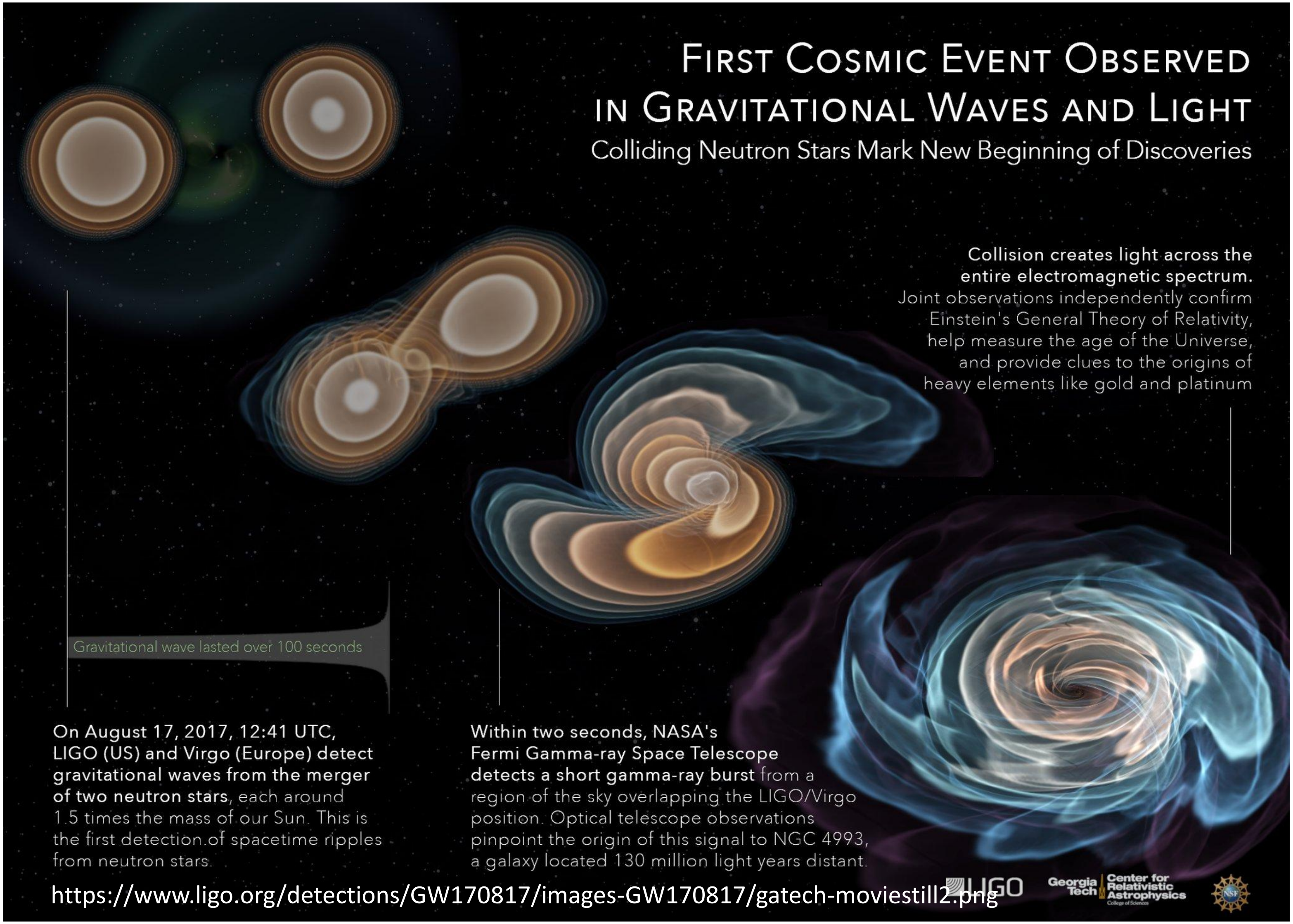
Mass distribution of black holes

Note: this is the distribution of primary black holes



LIGO&Virgo&KAGRA (2023)

Binary neutron star: GW170817

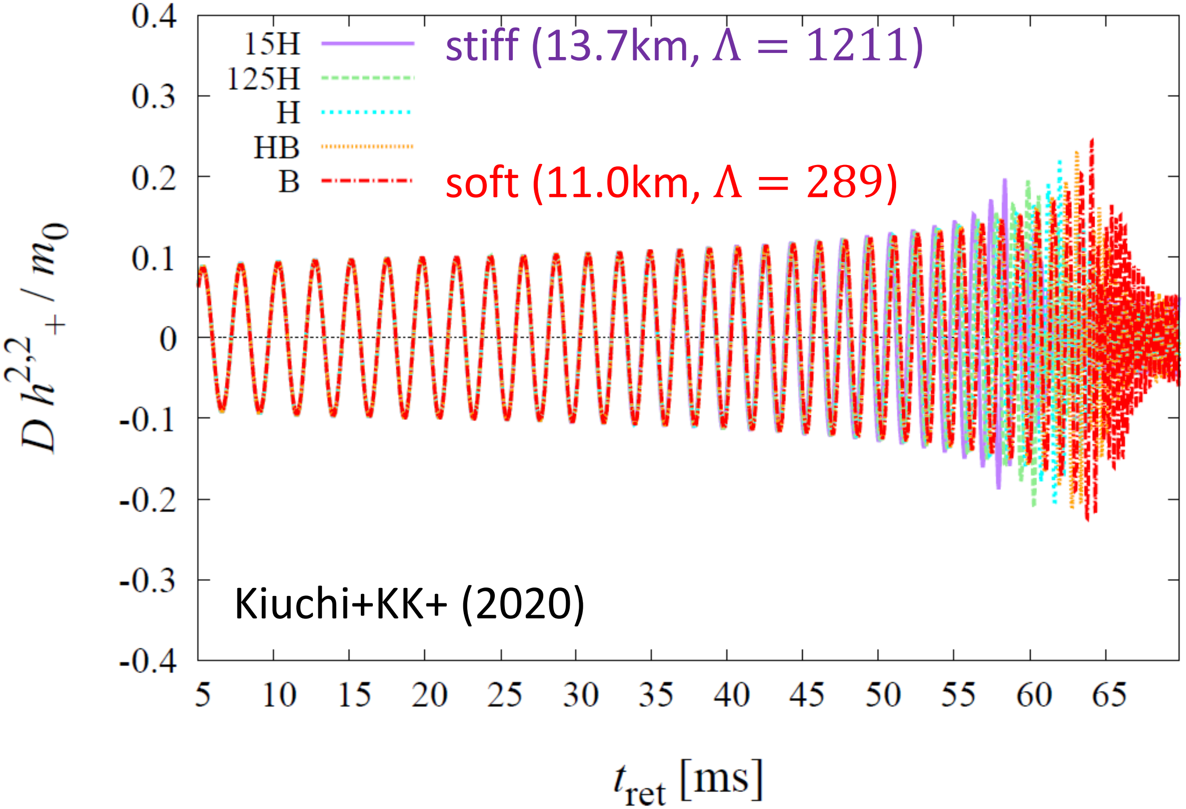


https://www.ligo.org/detections/GW170817/images-GW170817/gatech-moviestill2.png

Gravitational waveform

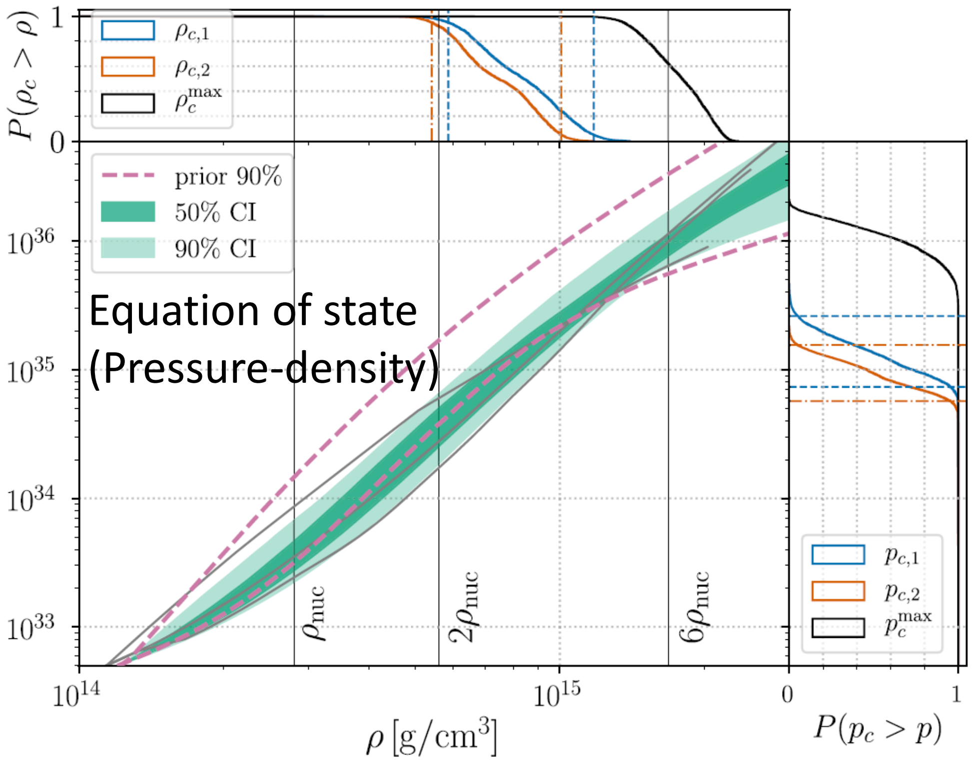
Binaries merge earlier for stiffer equations of state

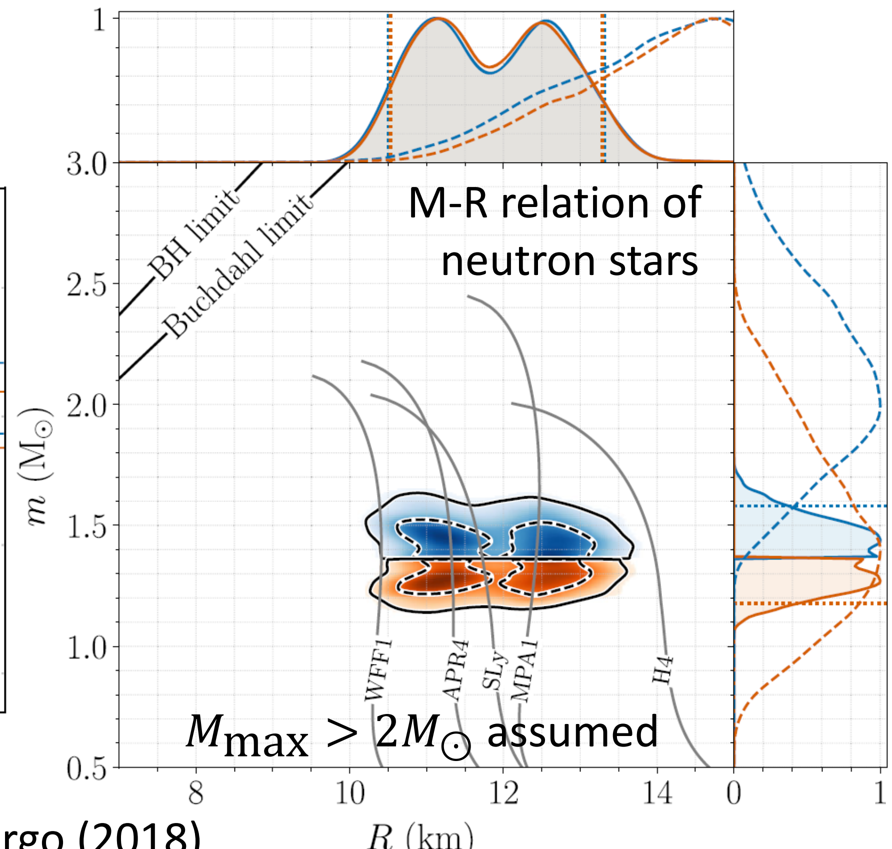
This allows us to measure the tidal deformablity



Current status of understanding

The equation of state has already been constrained and will be constrained more severely in the near future

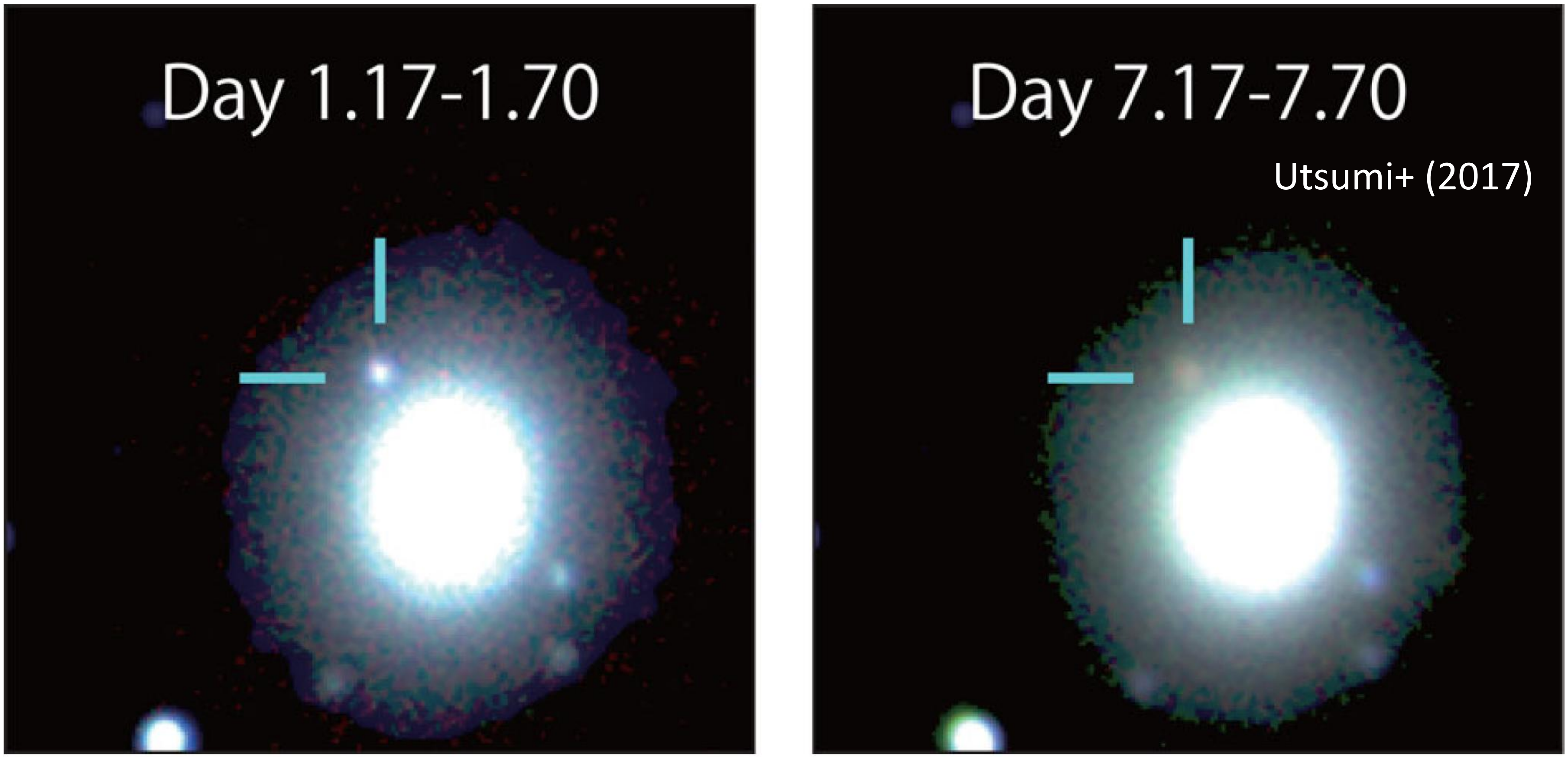




LIGO&Virgo (2018)

AT 2017gfo and the host galaxy

The redshift is determined and H_0 is measured



Did GW170817 form a black hole?

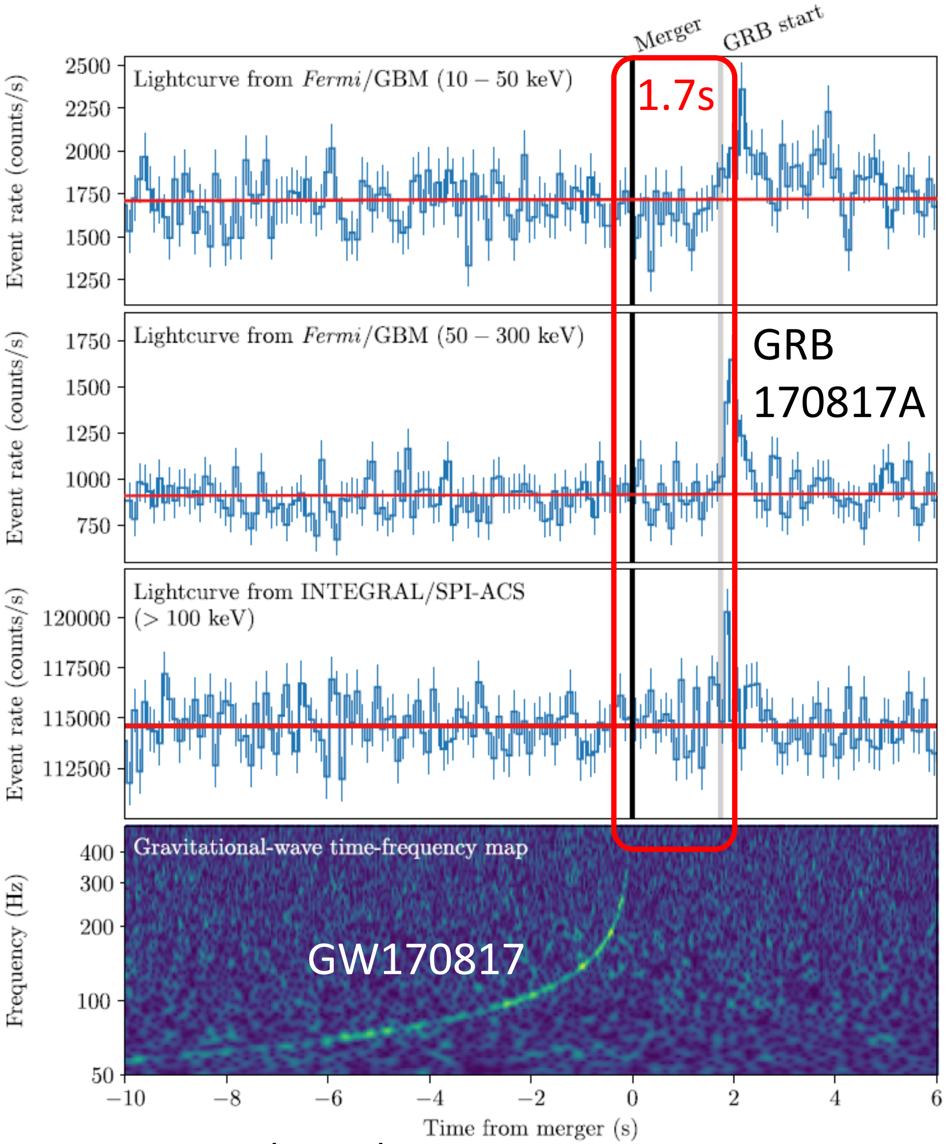
Nobody knows the answer

Important for

- QCD phase structure
- gamma-ray burst
- r-process and kilonova

Gravitational waves are emitted for 10-100ms at ~kHz and will be the key

[neutrinos? Kyutoku-Kashiyama 2018]

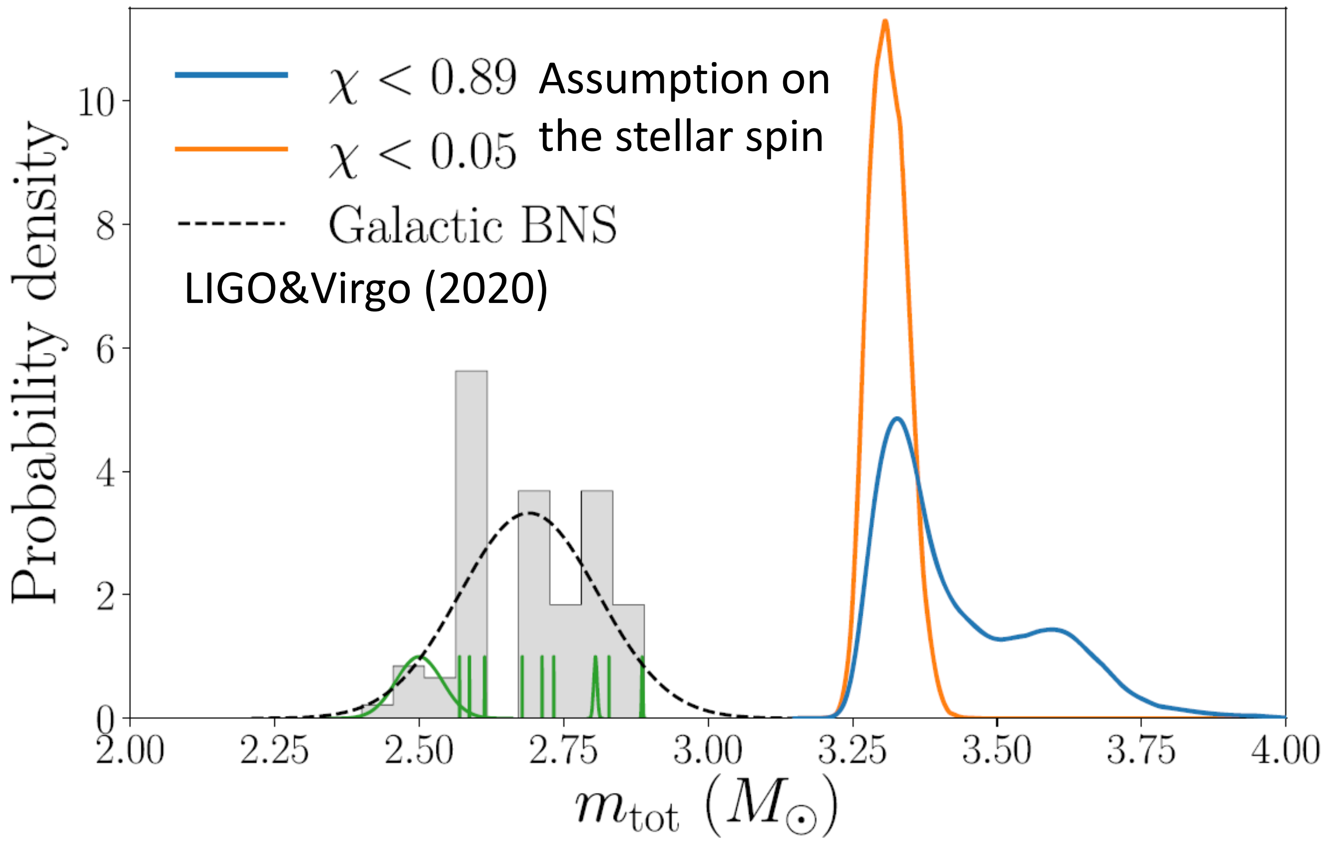


LIGO&Virgo&Fermi&INTEGRAL (2017)

Second event: GW190425

Total mass $m_{\rm tot} = 3.4^{+0.3}_{-0.1} M_\odot$, no EM counterpart

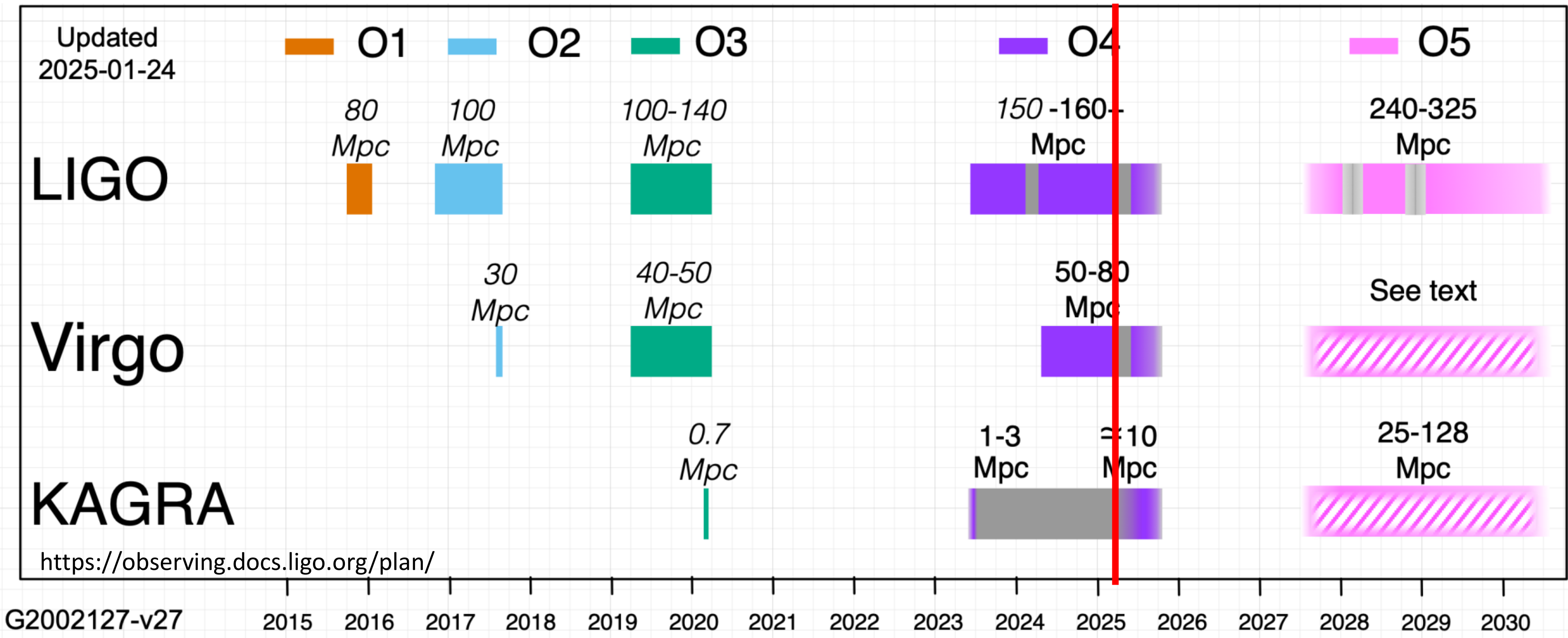
Heavier by >5sigma than Galactic binary neutron stars



Observation plan and the status

O4b will continue until early October with break

O5 will be 2027-2030, and then detectors are upgraded



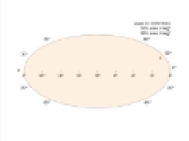
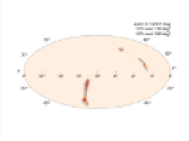
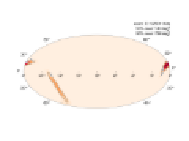
Candidate from O4

~190 binary black holes vs. **0 binary neutron stars**

(with a few black hole-neutron star merger candidates)

GraceDB Public Alerts Latest Search Documentation Login https://gracedb.ligo.org/superevents/public/O4/#

Please log in to view full database contents.

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S250119cv	BBH (>99%)	Yes	Jan. 19, 2025 19:02:38 UTC	GCN Circular Query Notices | VOE		1 per 7.9146e+11 years	
S250119ag	BBH (>99%)	Yes	Jan. 19, 2025 02:51:38 UTC	GCN Circular Query Notices | VOE		1 per 94621 years	
S250118dp	BBH (>99%)	Yes	Jan. 18, 2025 17:05:23 UTC	GCN Circular Query Notices | VOE		1 per 5.7028e+16 years	

Thought and concern

Binary-neutron-star mergers are

“less frequent than binary-black-hole mergers”

This is not particularly surprising at least for me

(and probably most gravitational-wave astronomers)

“in fact, two-orders-of-magnitude less frequent”

Unexpected at least for me, unlikely to be a fluke

- consistent with short-hard gamma-ray bursts?
- consistent with r-process elements in the universe?

Back-of-the-envelope estimation

Rate at the end of O3 [LIGO&Virgo&KAGRA 2023]

Model	BNS $m_1 \in [1, 2.5]M_\odot$ $m_2 \in [1, 2.5]M_\odot$
PDB (pair)	170^{+270}_{-120}
PDB (ind)	44^{+96}_{-34}
MS	660^{+1040}_{-530}
BGP	$98.0^{+260.0}_{-85.0}$
MERGED	10–1700
	$\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Now this might be lowered by ~3 (from #binary black holes)… 100?

Milky-way equivalent galaxy has the density of $\sim 0.01\ \mathrm{Mpc}^{-3}$

-> once in $\sim 10^5$ yr in our Galaxy?

Galactic r-process production rate $\sim 10^{-6} M_\odot\ \mathrm{yr}^{-1}$

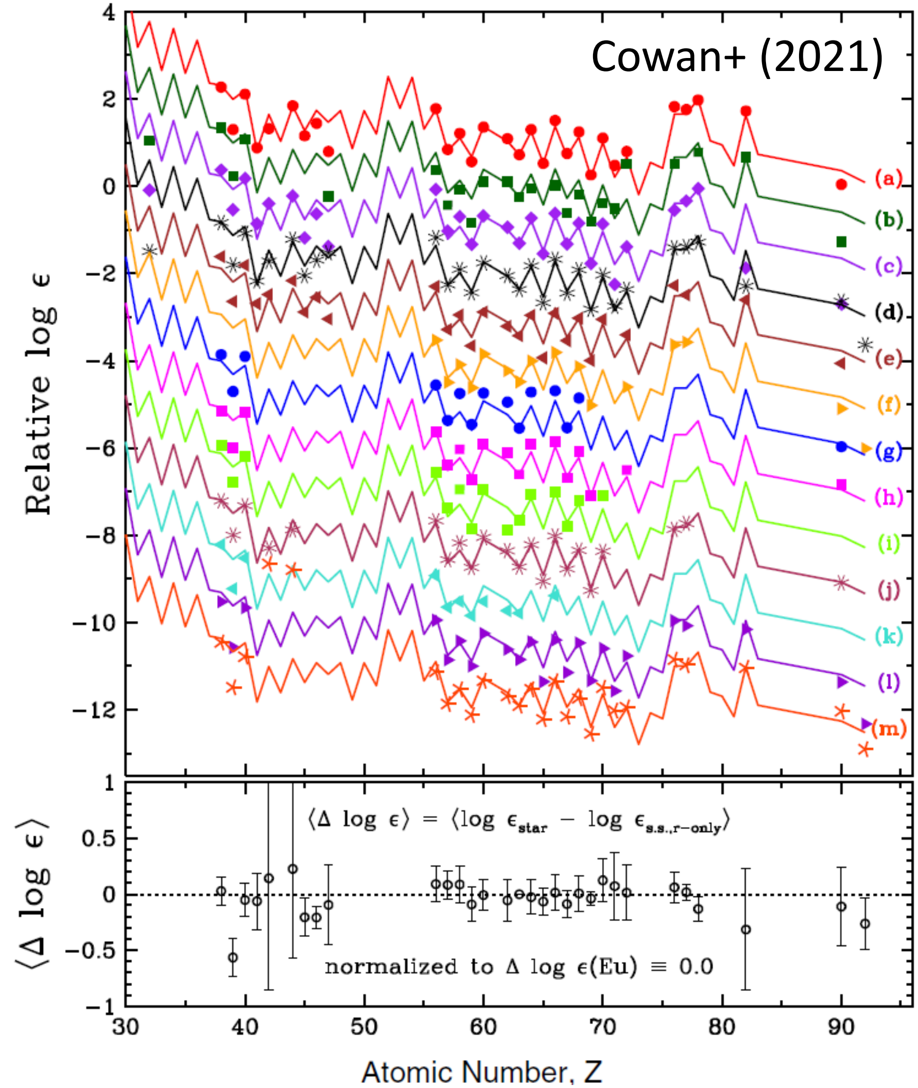
One merger produces $\sim 0.1 M_\odot$ r-process element ???

2. r-process nucleosynthesis and kilonova

Universality of r-process elements

Most metal-poor stars that
are likely experienced only
a few r-process events
show similar patterns
to the solar abundance

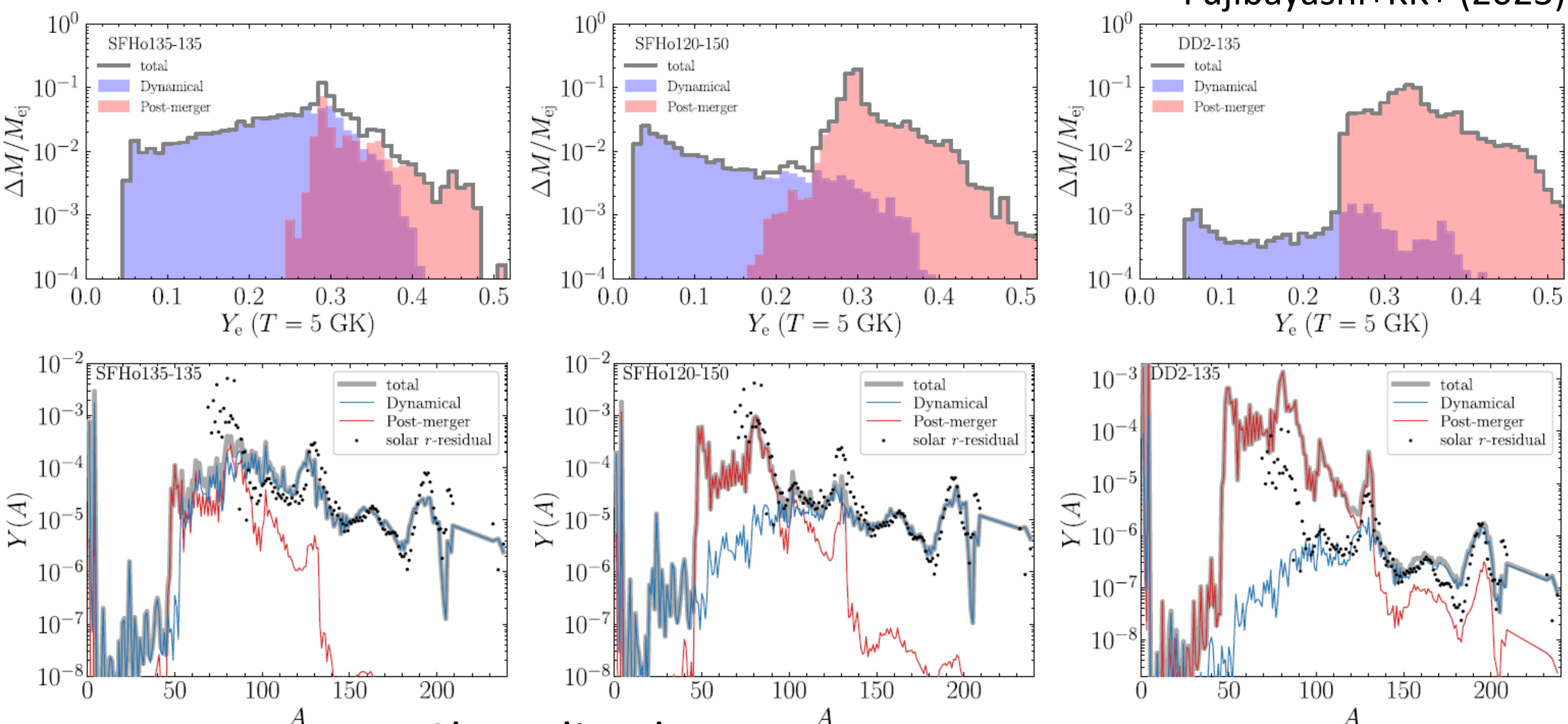
Individual r-process events
must reproduce this pattern
(with possible exceptions)



Condition for the solar pattern

The solar pattern tends to be reproduced if the merger results in short-lived remnant formation

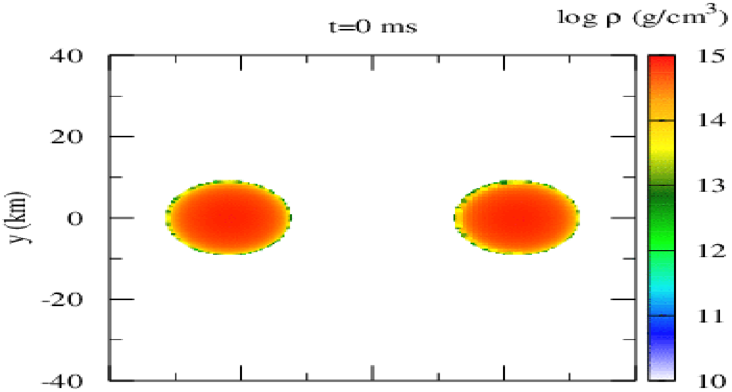
Fujibayashi+KK+ (2023)



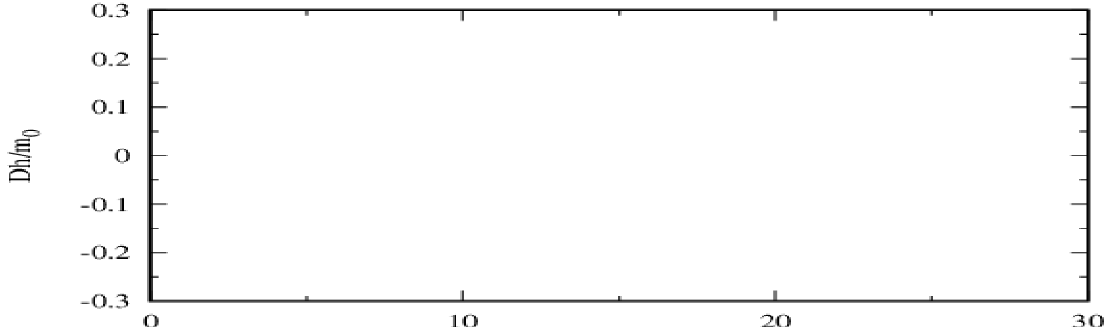
Short-lived

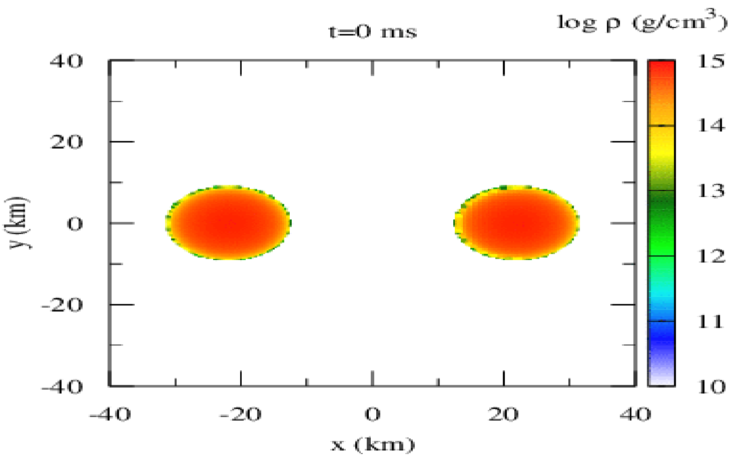
Long-lived

Merger and gravitational waves

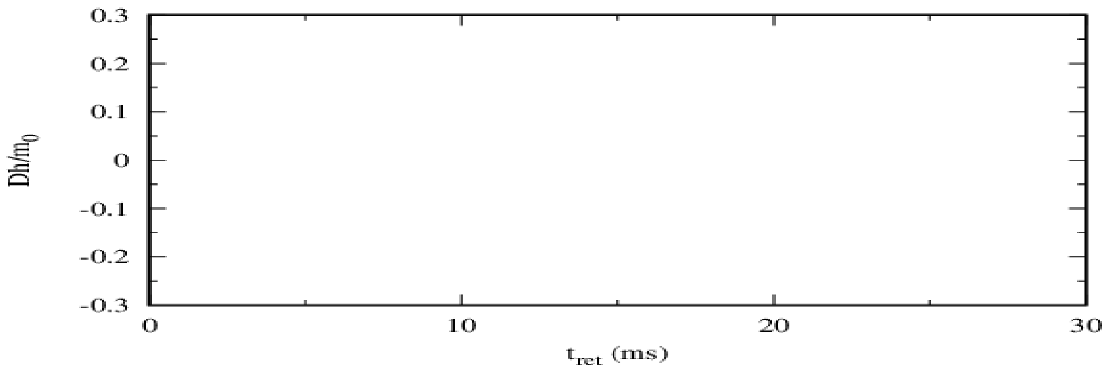


Short-lived





Long-lived



Mass ejection mechanism

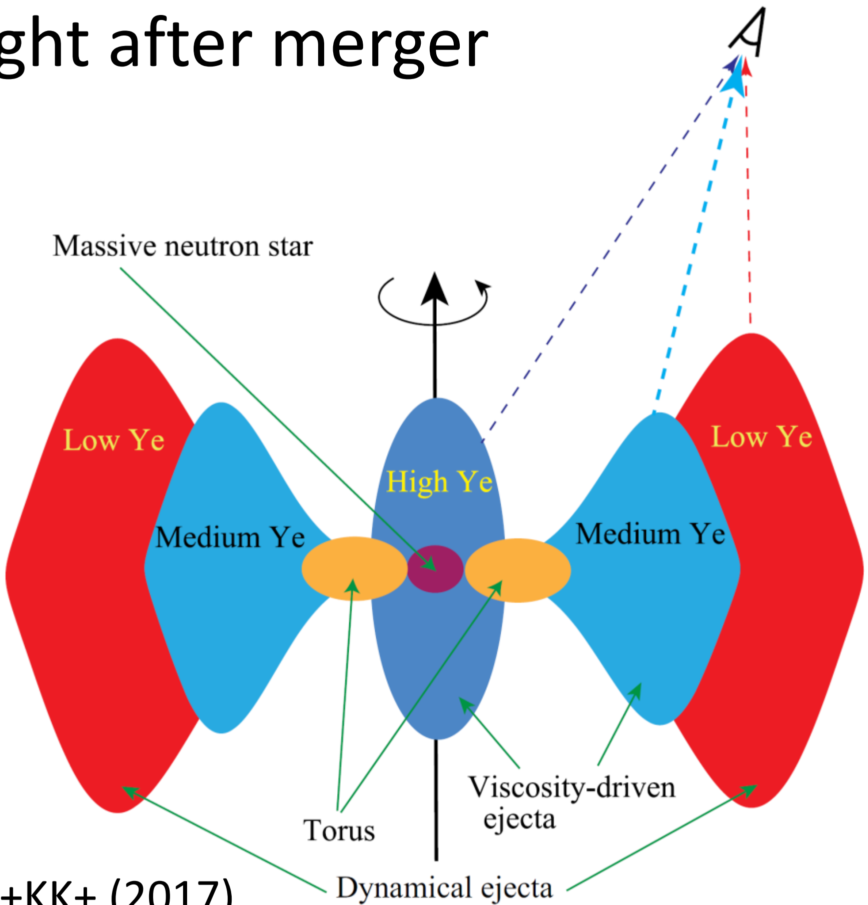
Dynamical mass ejection

Fast and neutron-rich ejecta right after merger

Postmerger wind/outflow

Slow and moderately neutron-rich ejecta generated on ~1s time scale

Long-lived remnants can eject a large amount of mass



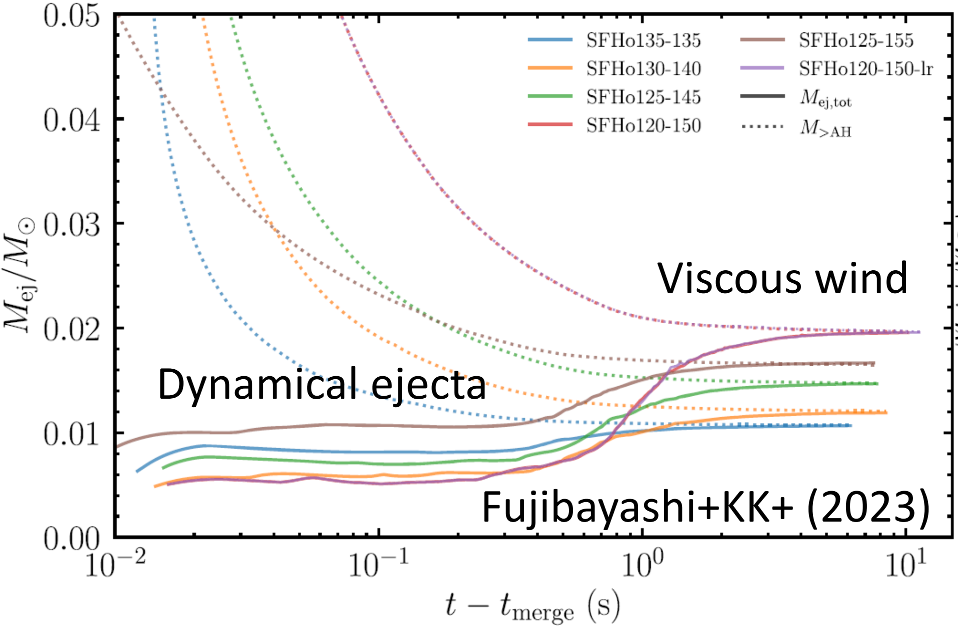
Shibata+KK+ (2017)

Comparison: ejecta mass

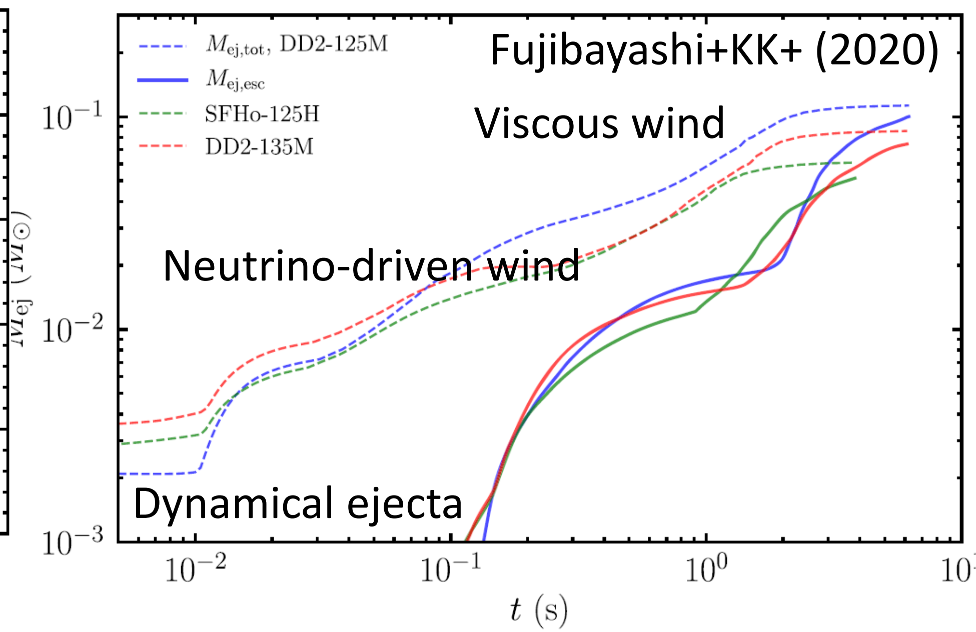
$\sim 0.01 M_{\odot}$ may be ejected from short-lived remnants (<~20ms), and the upper limit appears to be $\sim 0.03 M_{\odot}$

$\sim 0.1 M_{\odot}$ may be ejected from long-lived remnants

Short-lived



Long-lived



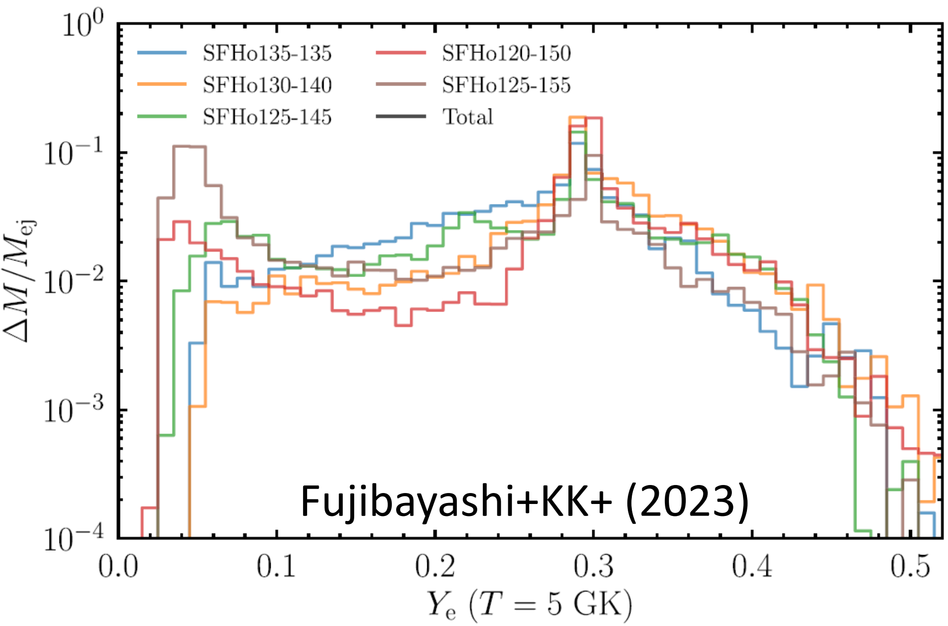
Comparison: electron fraction

$$Y_e = \#\text{proton}/\#\text{nucleon} = n_p/(n_p + n_n)$$

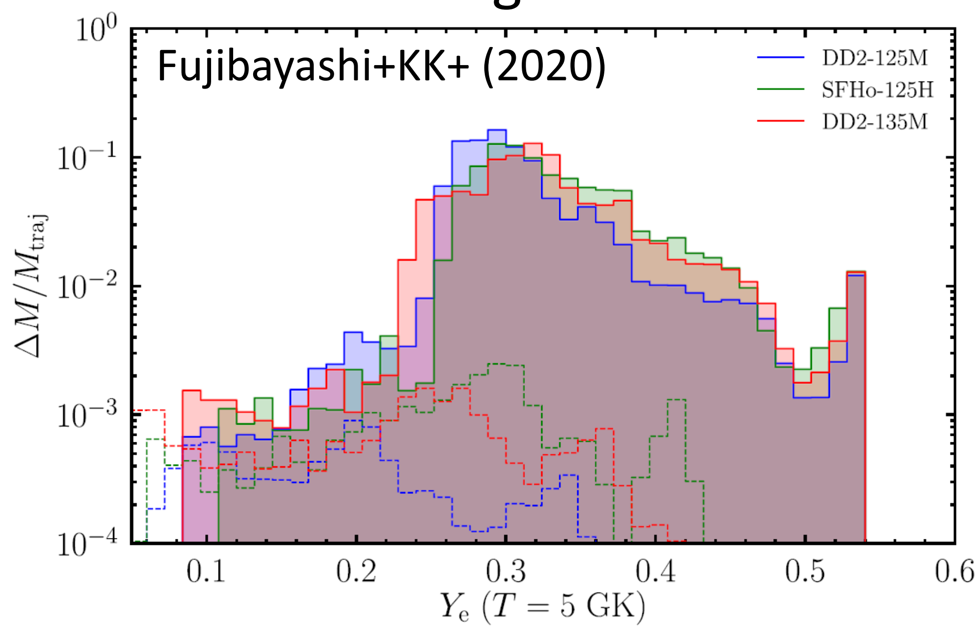
Abundant low-Y_e for short-lived from dynamical ejecta

$Y_e > 0.25$ is dominant for long-lived due to the wind

Short-lived



Long-lived

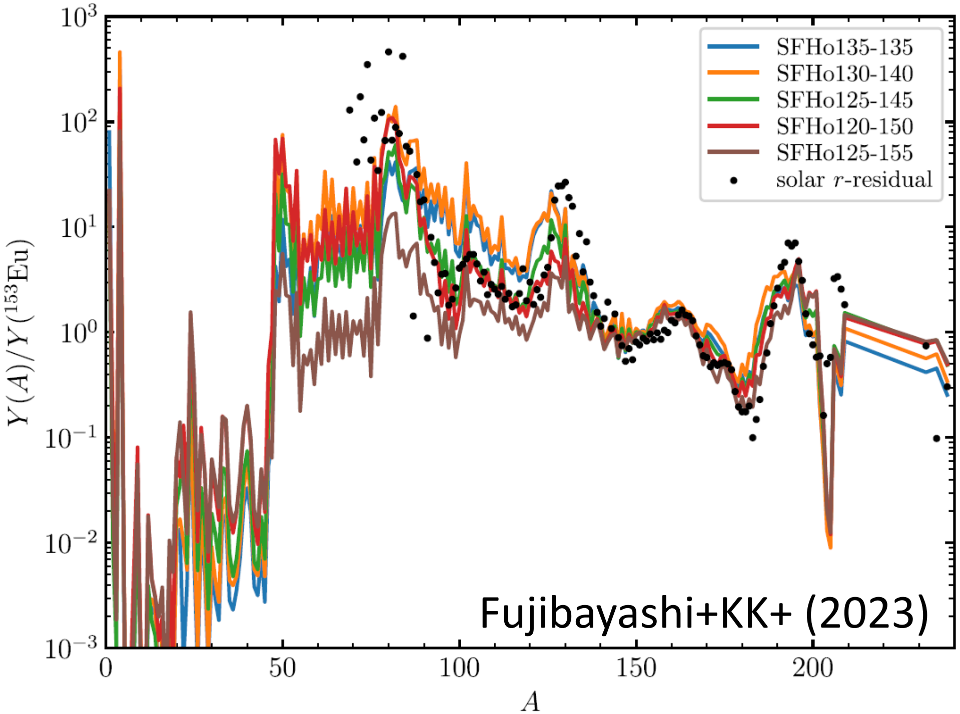


Comparison: r-process pattern

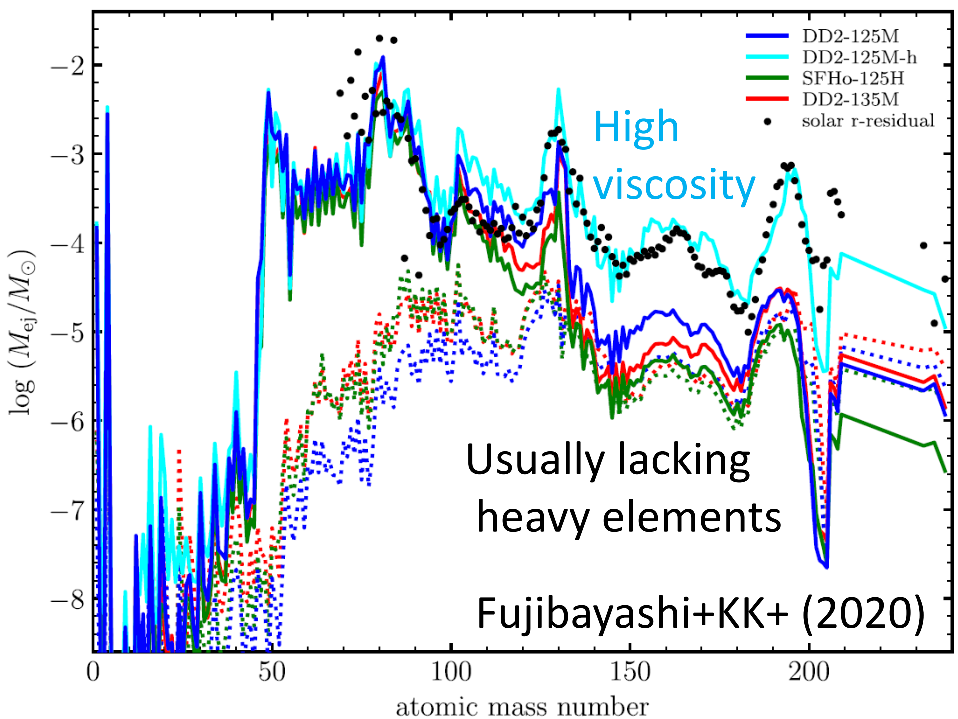
Short-lived better reproduce the solar r-process pattern

Long-lived may also be allowed if the viscosity is strong

Short-lived

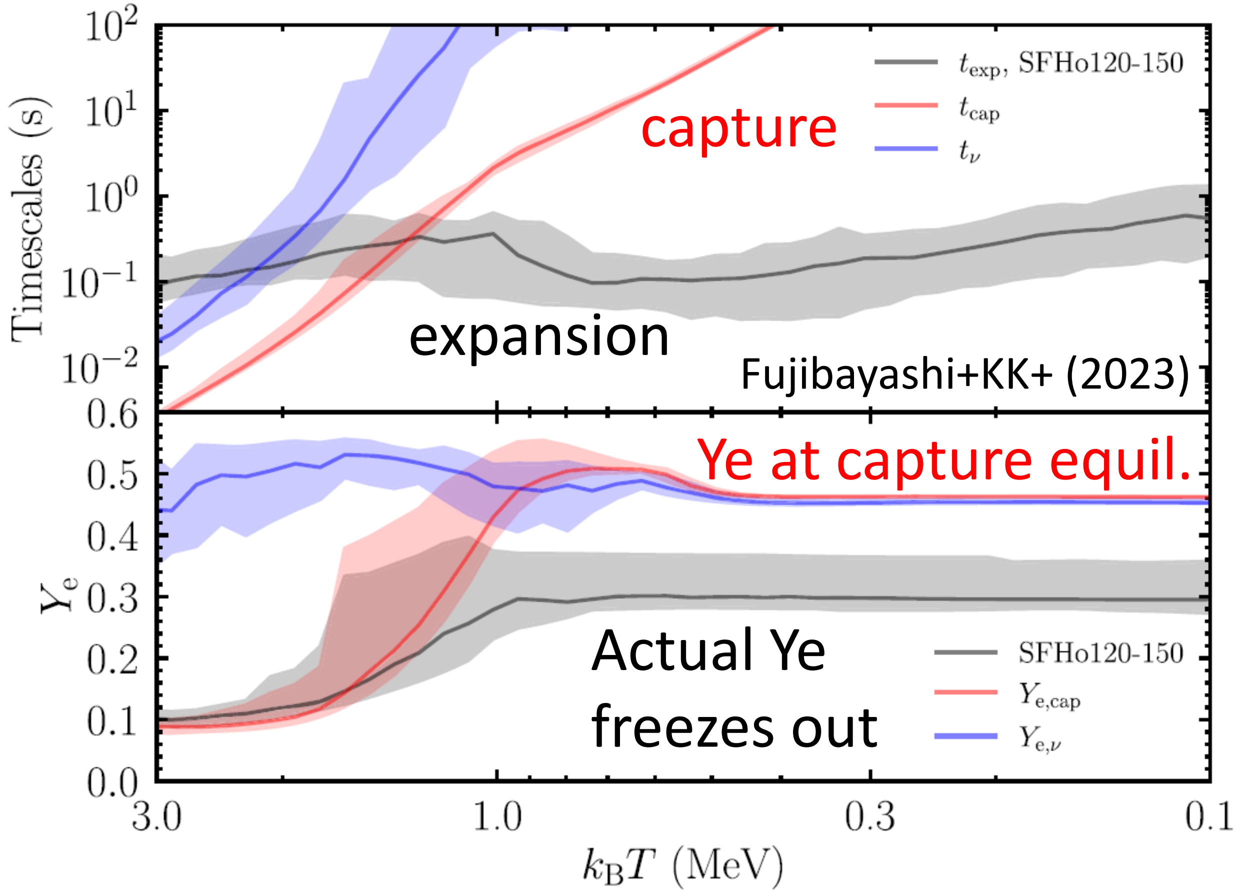


Long-lived



How the electron fraction is given

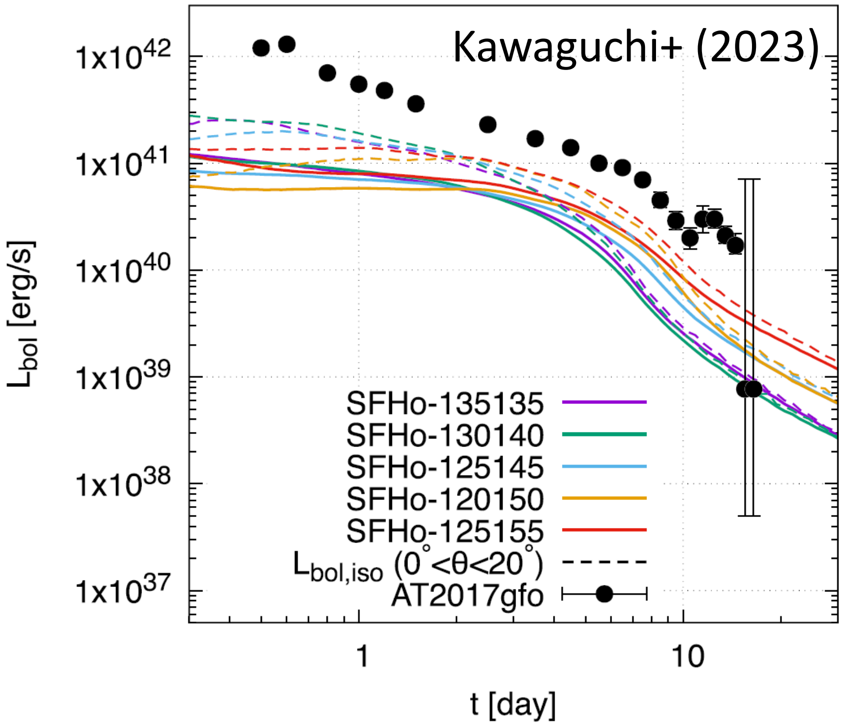
When the $e^{-}e^{+}$ capture becomes slower than the expansion of the ejecta, Y_e freezes out



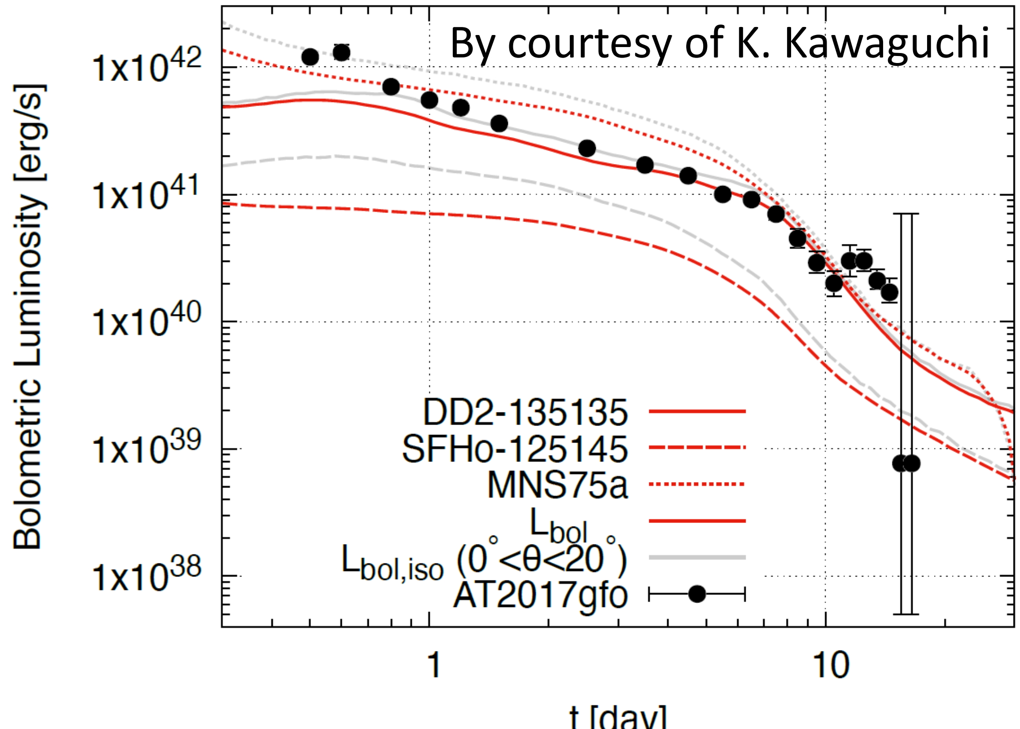
Comparison: kilonova

$\sim 0.05 M_\odot$ of AT 2017gfo may be possible only with long-lived remnants… the "norm" with high viscosity?

Short-lived



Long-lived

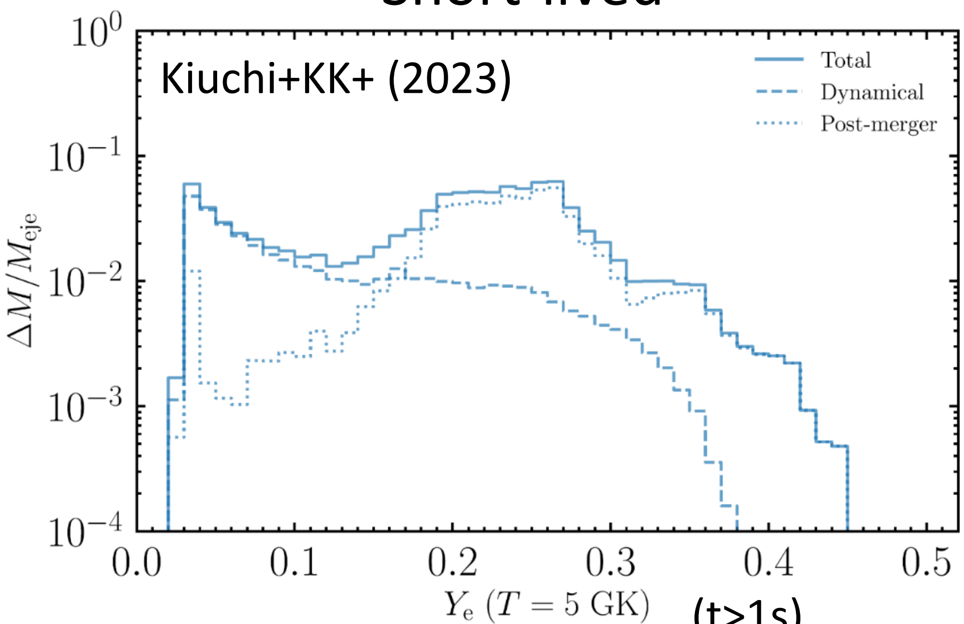


Magnetohydrodynamics (MHD)

Realistically, viscosity is caused by magnetic turbulence

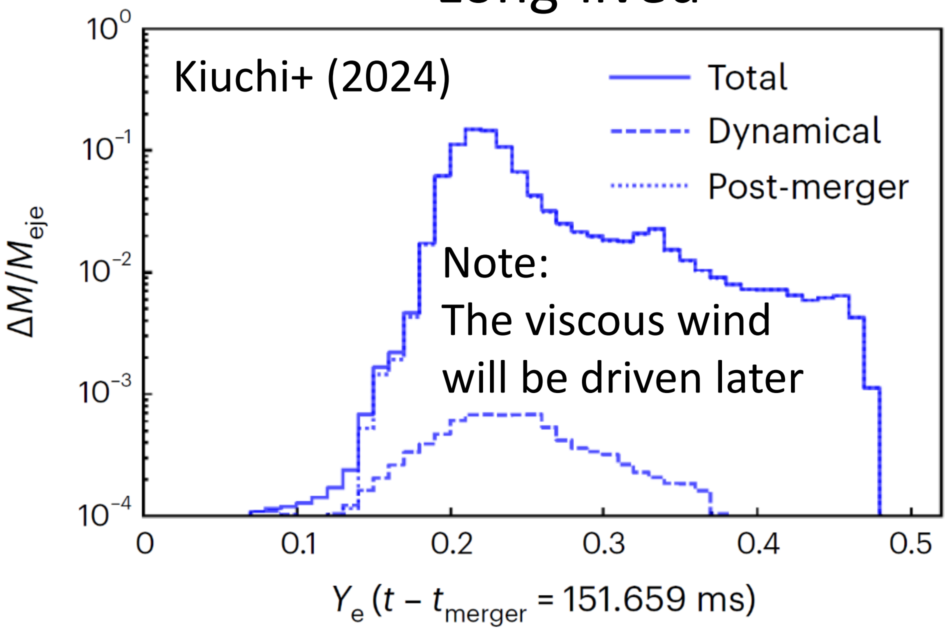
MHD simulations tend to produce lower-Ye ejecta than viscous hydrodynamics… room for long-lived remnants?

Short-lived



(t>1s)

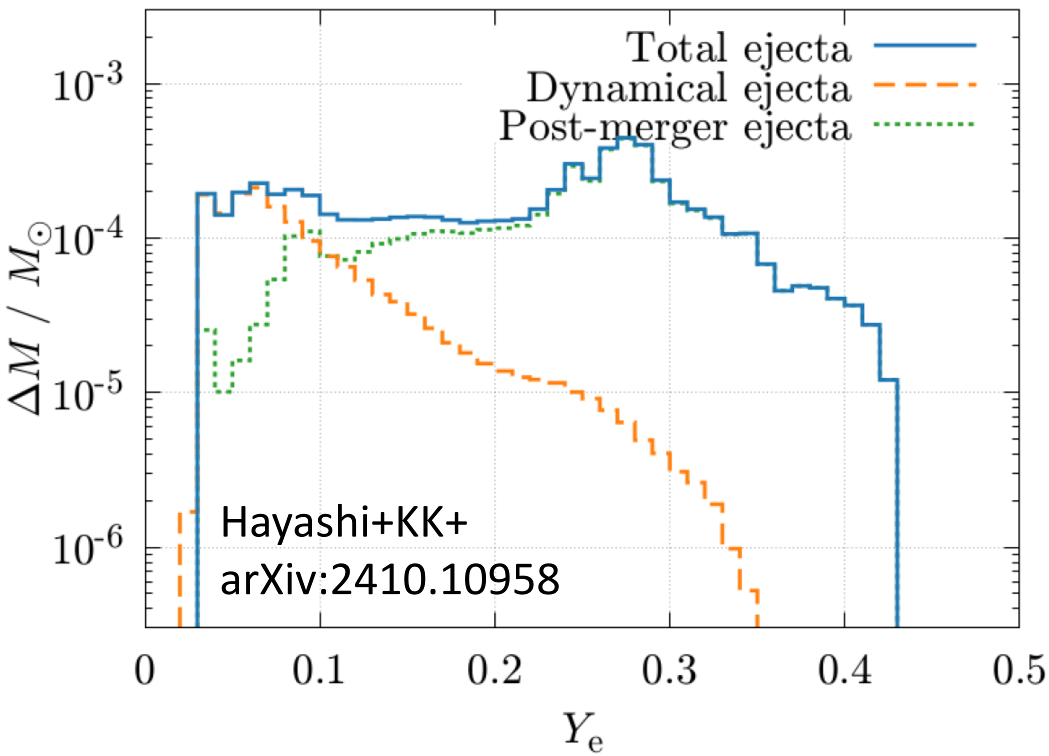
Long-lived



Prompt black-hole formation

Asymmetric binaries eject material even if the remnant collapses immediately, but only $< 0.01 M_\odot$

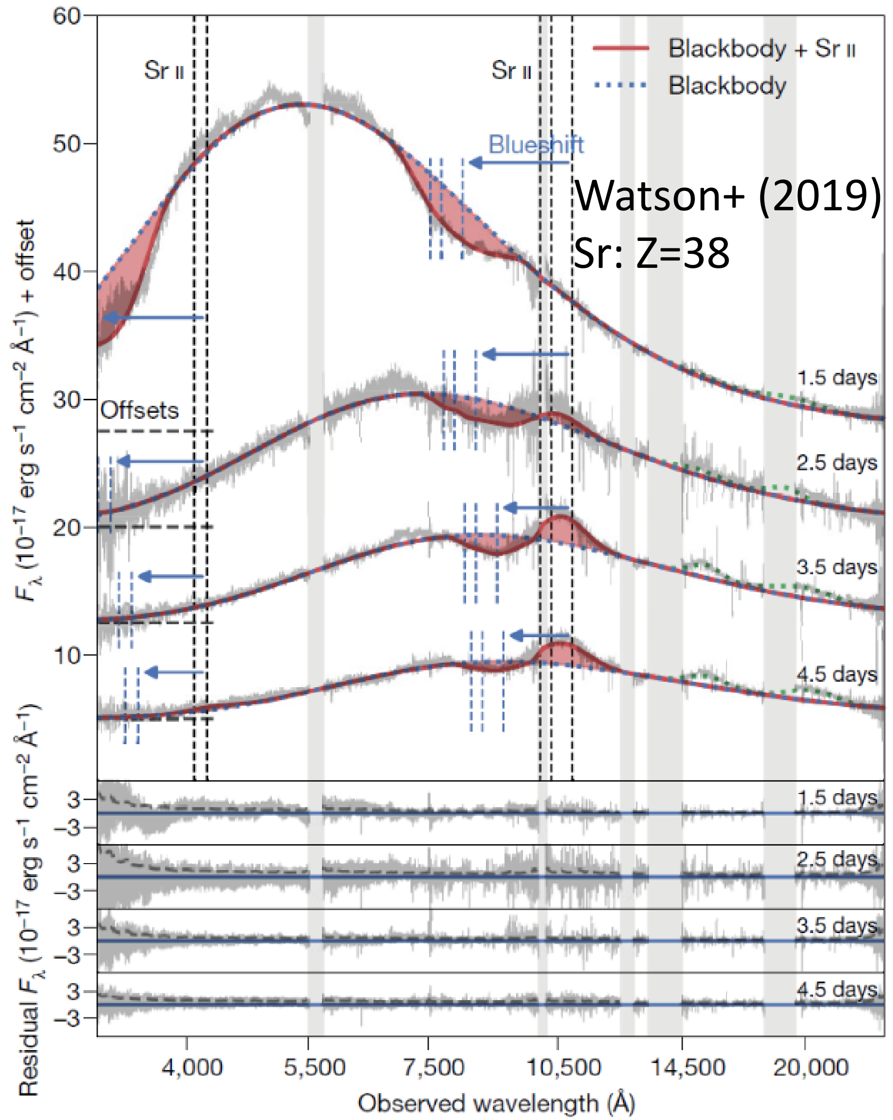
GW190425-like systems are unlikely to be the norm



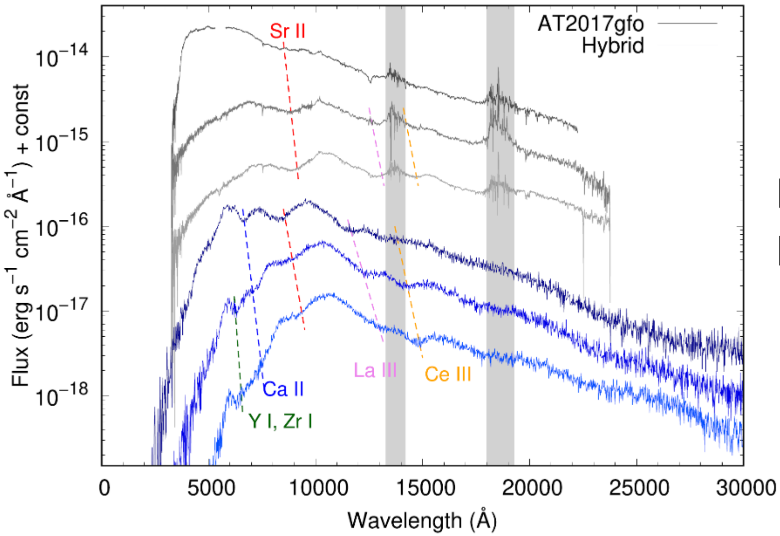
Absorption line of strontium

Identification of elements requires the spectrum and careful decomposition of absorption/emission lines

Although it is difficult for the kilonova because of fast motion/many elements, effort are ongoing

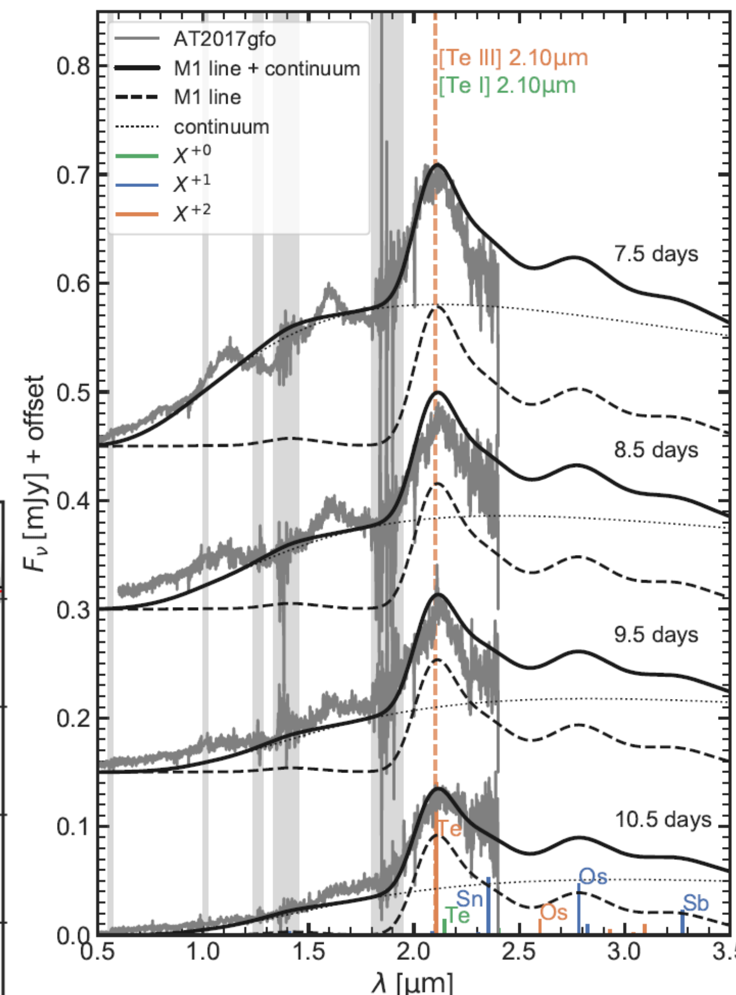


And further heavy elements?

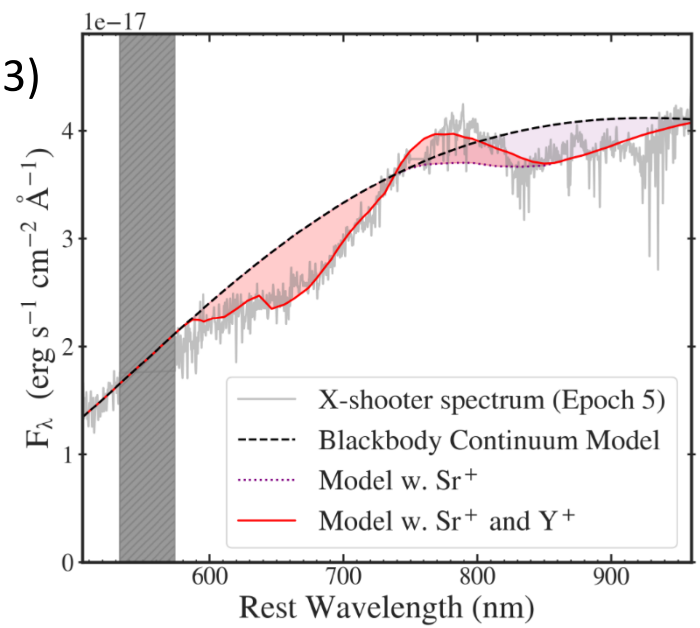


Domoto+ (2022)
La: Z=57, Ce: Z=58

Hotokezaka+ (2023), Te: Z=52



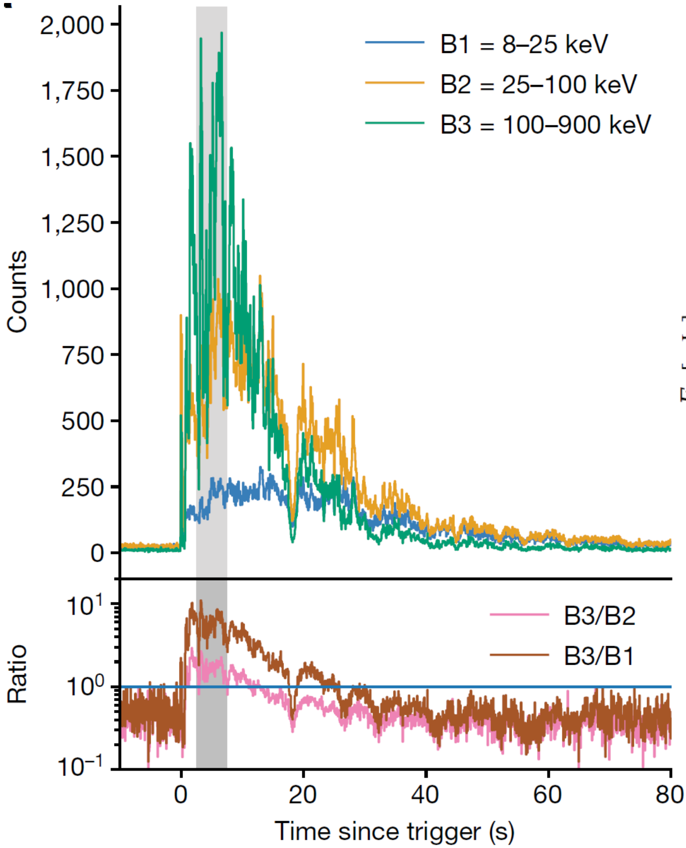
Sneppen-Watson (2023)
Sr: Z=38, Y: Z=39

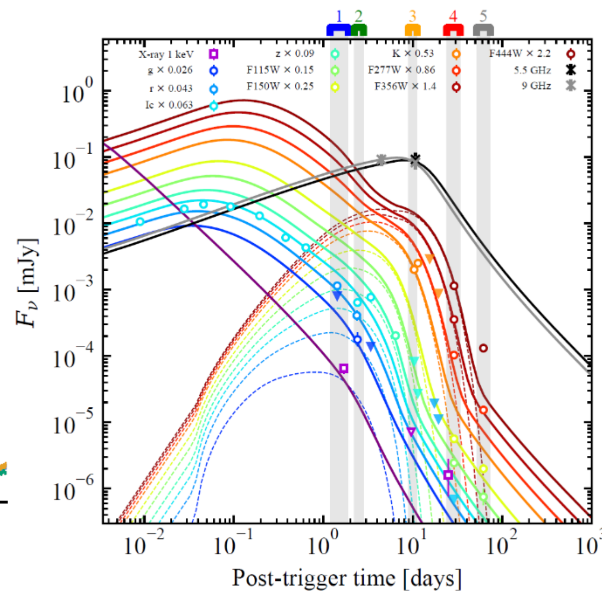


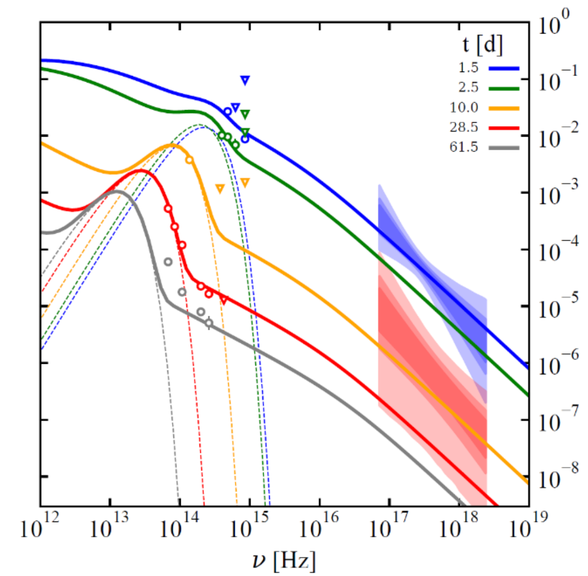
Kilonova from GRB 230307A?

Some reports of kilonovae from long gamma-ray bursts

GRB 230307A: very bright 35s burst from z~0.065





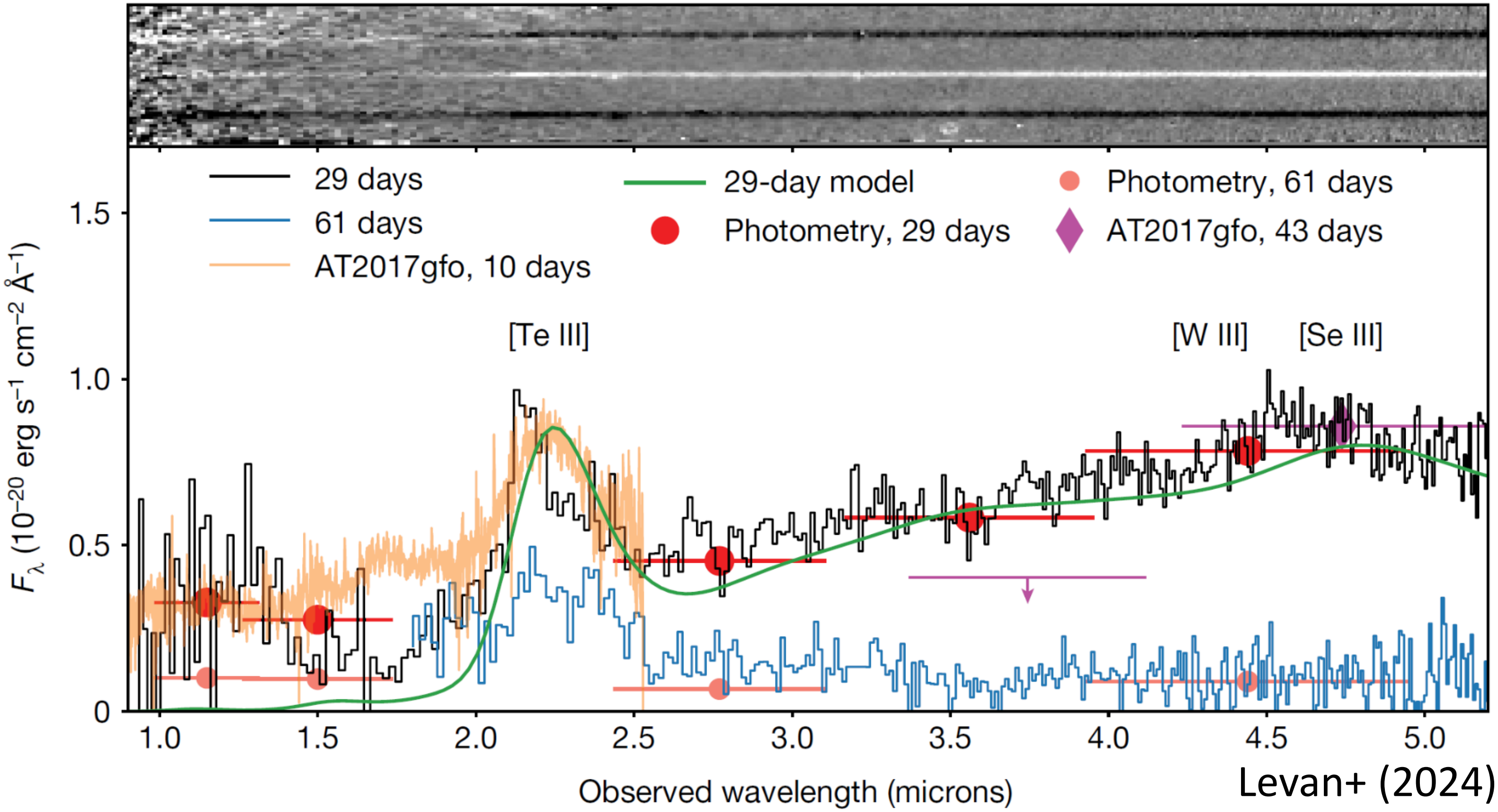


Levan+ (2024)

Emission line of Te?

r-process nucleosynthesis from long gamma-ray burst?

Binary-merger-driven long GRB, or collapsar r-process?



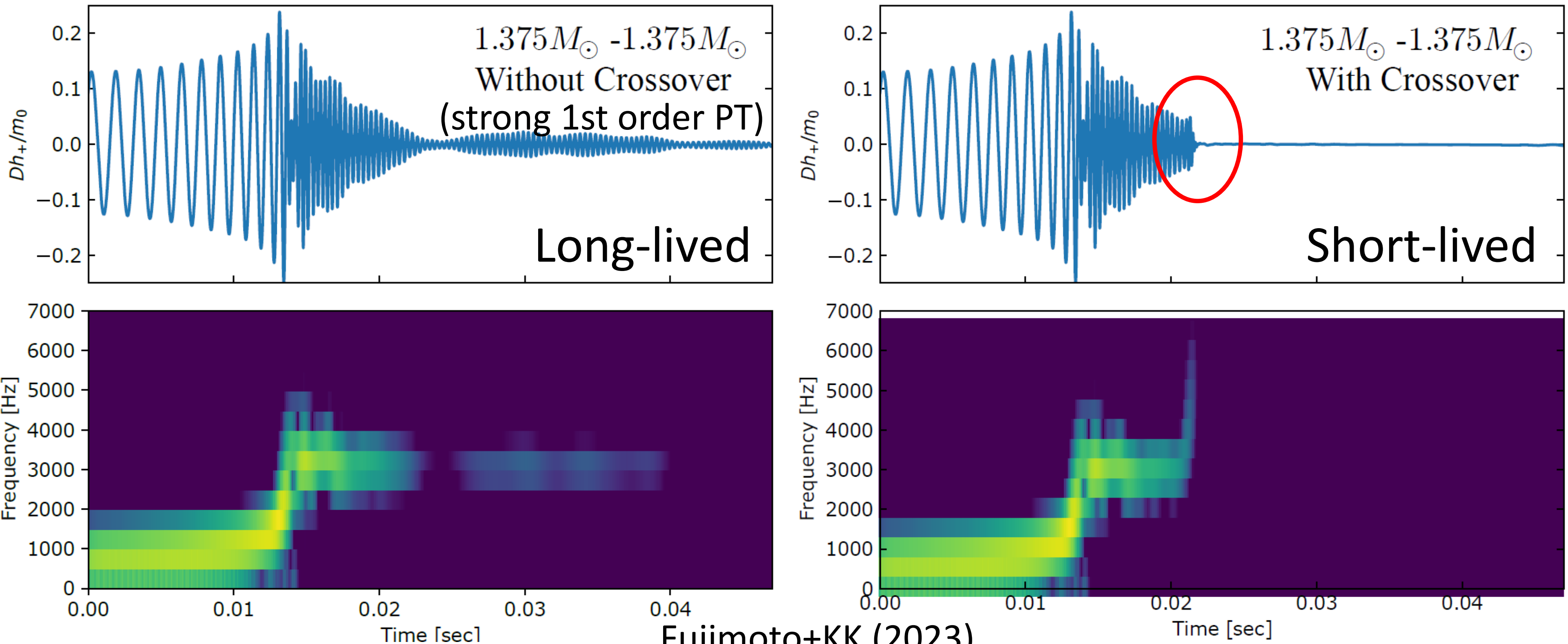
Levan+ (2024)

3. Future direction: black-hole formation

Black-hole formation as a key

Sudden shutdown indicates the gravitational collapse

Information for gravitational, nuclear, and astrophysics



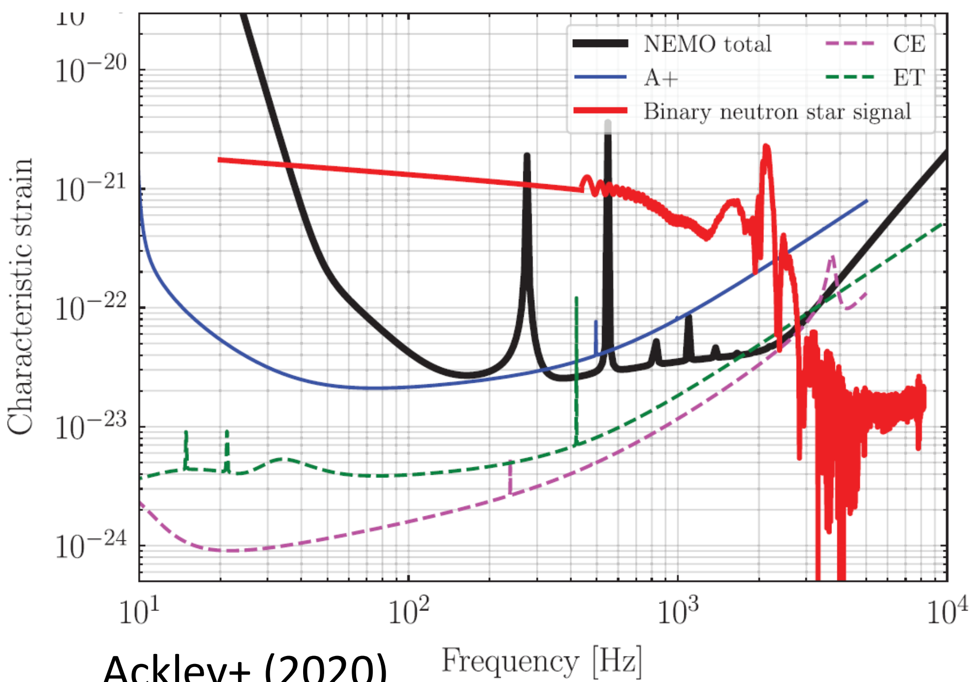
Fujimoto+KK (2023)

Future high-frequency observation

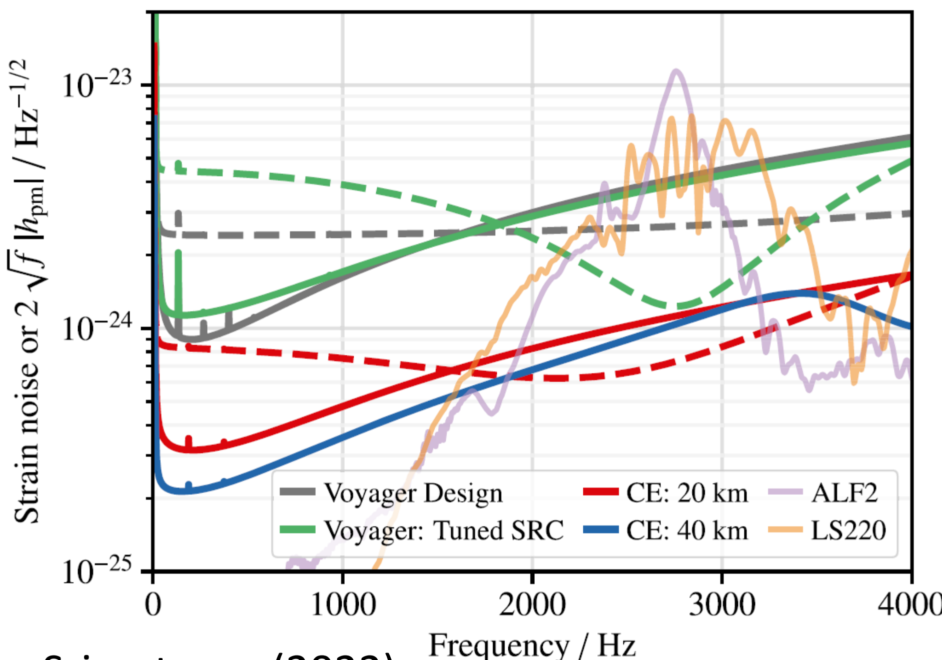
The high density requires high-frequency observations

$$f \sim \sqrt{G\rho}$$

Some proposals are made for postmerger signals



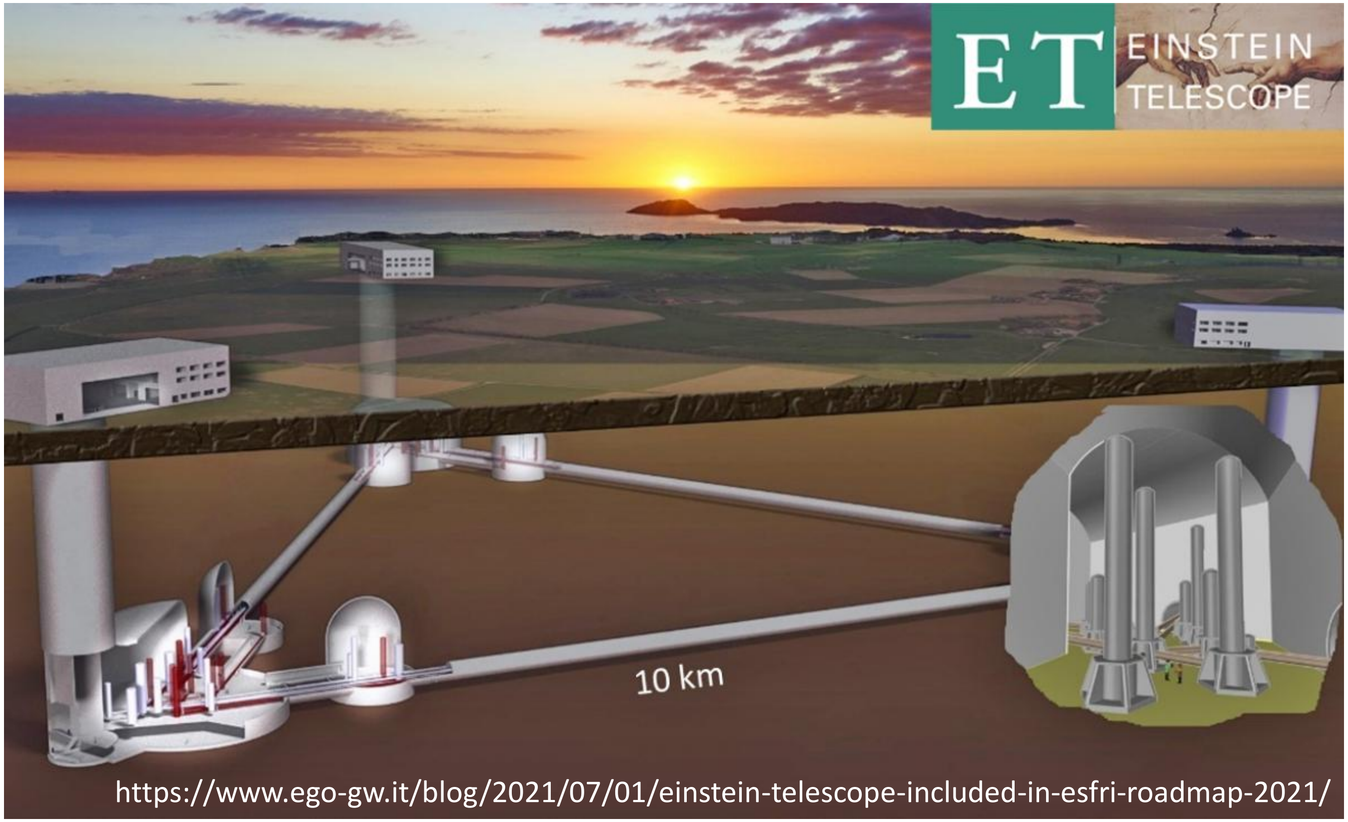
Ackley+ (2020)



Srivastava+ (2022)

Third-generation detector

Einstein Telescope, Cosmic Explorer … aiming at more precise understanding of already-detected binaries



Distinguishable in reality?

Bayesian hypothesis testing with simulated real signals

$$B = \frac{Z_{\mathrm{co}}}{Z_{\mathrm{pt}}} \sim \frac{L(\mathrm{data}|\mathrm{crossover})}{L(\mathrm{data}|\mathrm{phase\ transition})}$$

Compare the consistency of the residual with the noise

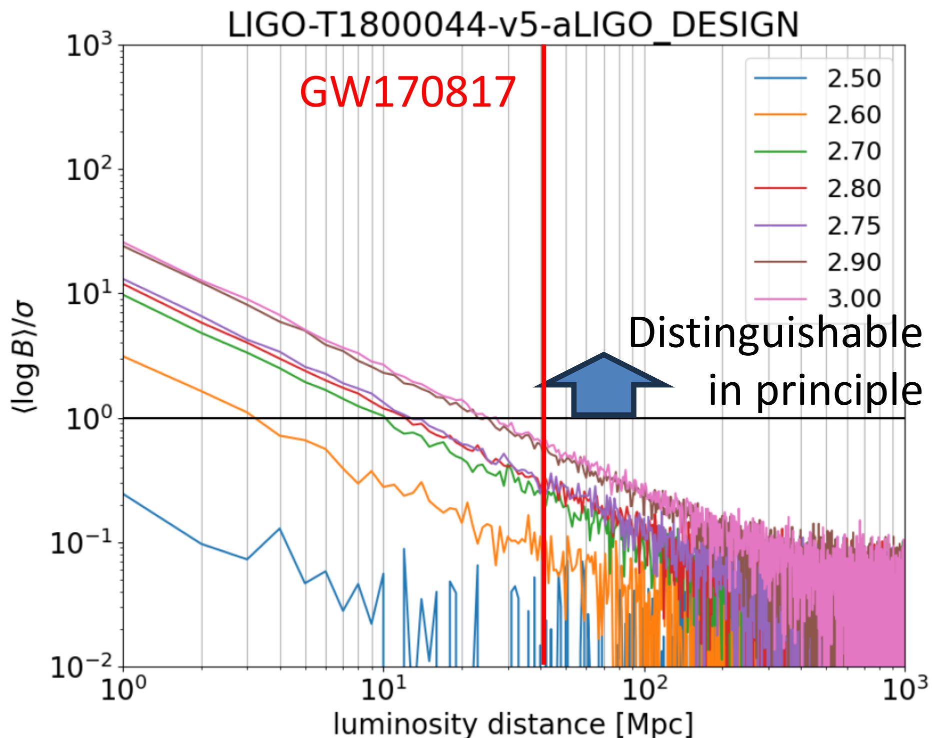
$$L \propto \exp\left(-\frac{1}{2}|\mathrm{data} - \mathrm{waveform\ model}|^2\right)$$

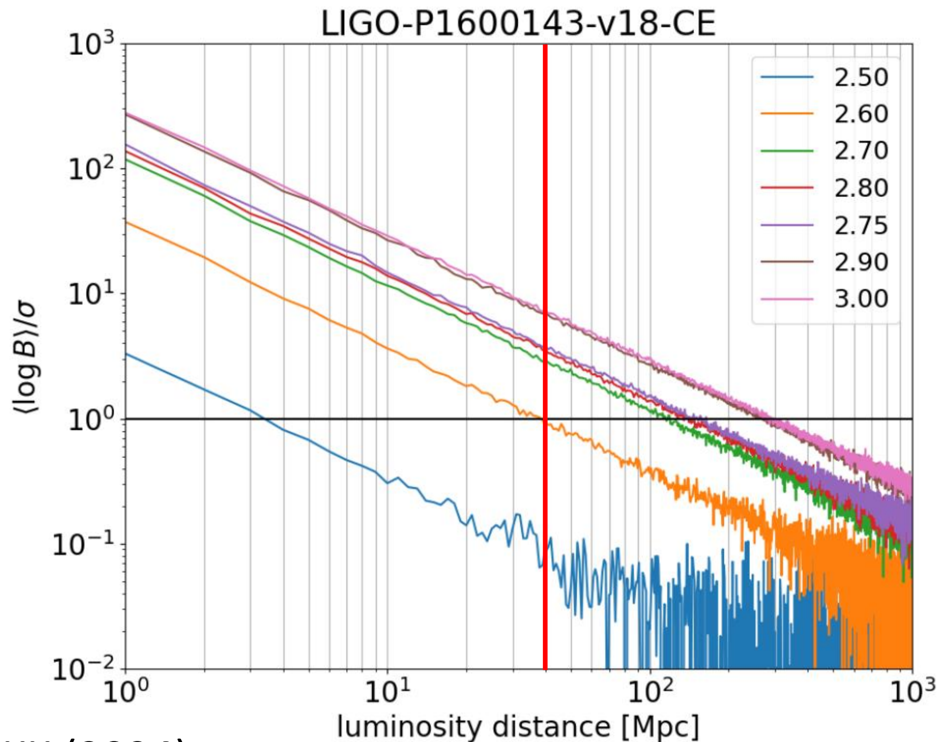
Transition scenarios should easily be distinguishable with sensitive detectors and/or nearby events

Distinguishability in data analysis

AdLIGO is insufficient even at design sensitivity (left)

Third-generation detectors may do at >100Mpc (right)



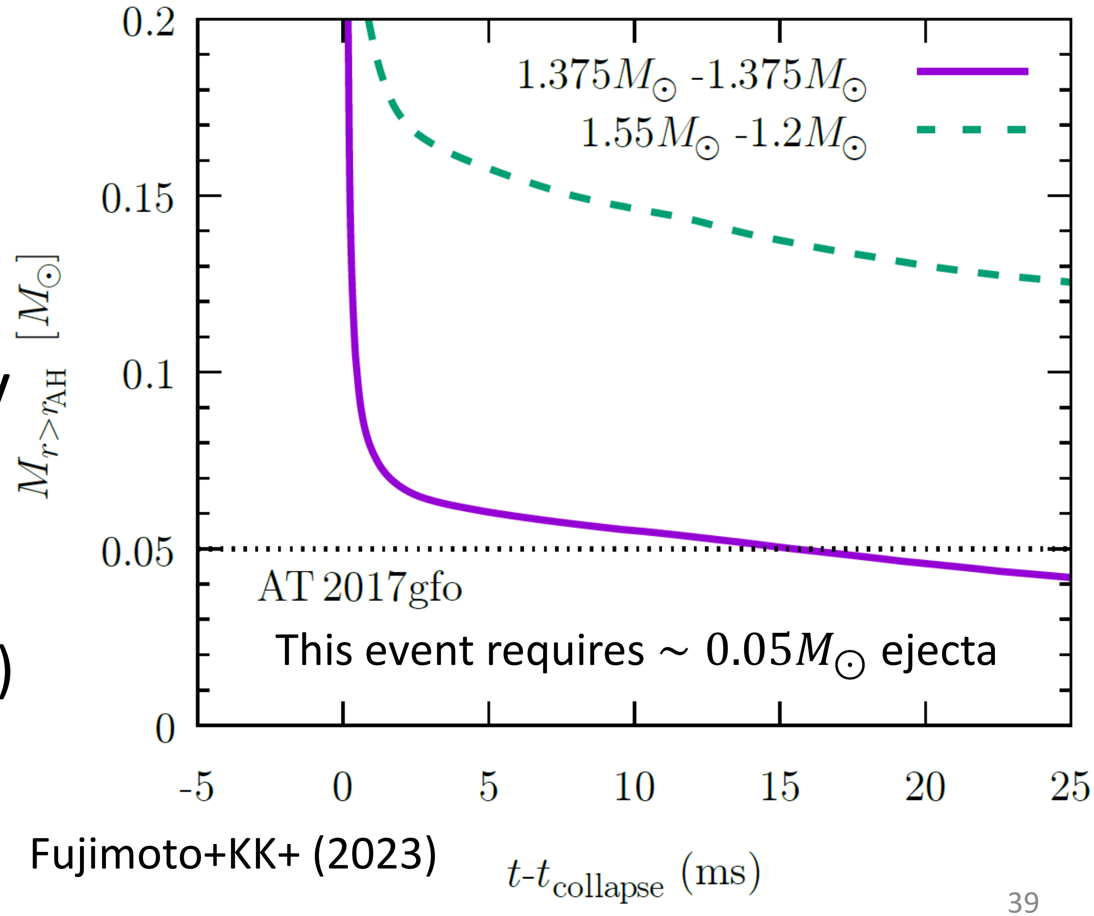


Harada+KK (2024)

Multimessenger observation

If the collapse is too early, no material is left outside and the kilonova cannot be as bright as AT 2017gfo

Our crossover model may be pass this test with mass asymmetry
(1s-order PT trivially
passes this test because
no gravitational collapse)



Fujimoto+KK+ (2023)

4. Summary

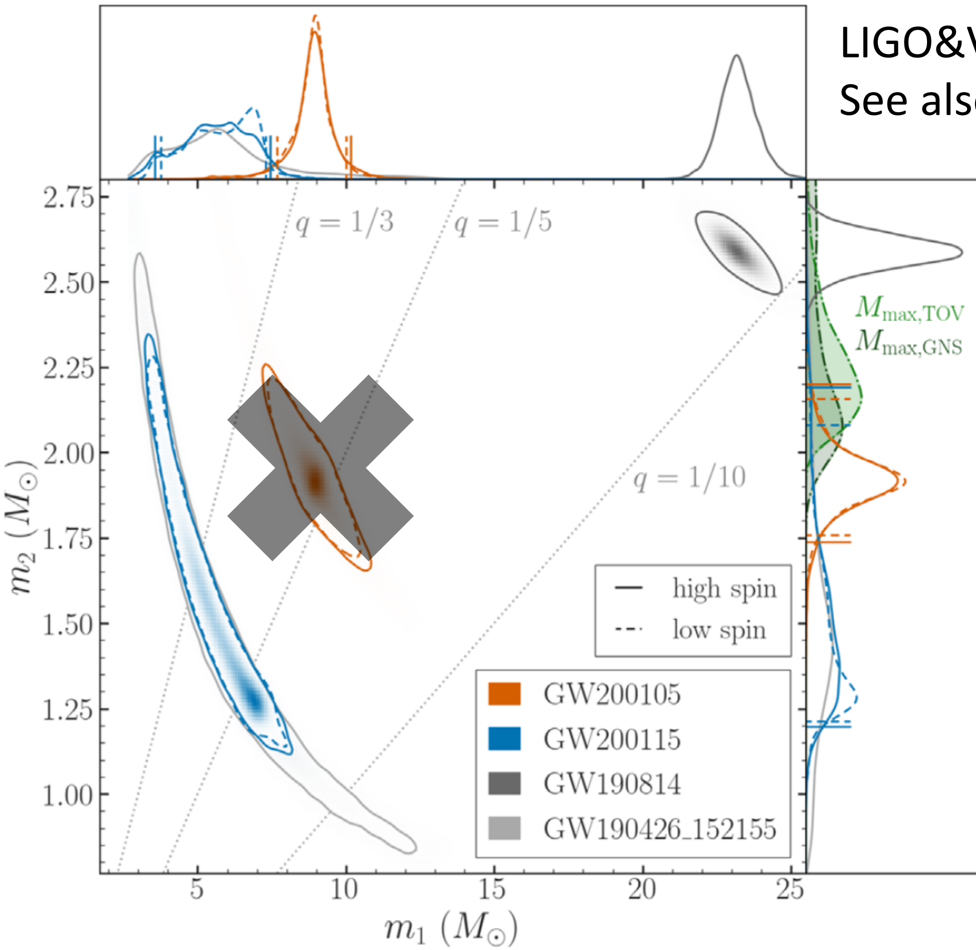
Summary

- Taking the result of O4 observation, the rate of binary-neutron-star mergers may not be very high, and it is becoming unclear whether they can explain the amount of all the Galactic r-process elements.
- If the merger remnant is long-lived, a large amount of mass is ejected with an associated bright kilonova, but the r-process pattern may be lighter-than-solar.
- A short-lived remnant is advantageous in terms of the r-process pattern, but the mass is not sufficient.
- Identifying black-hole formation will be important.

Appendix

Black hole-neutron star binaries

GW200115 remains but GW200105 went subthreshold



LIGO&Virgo&KAGRA (2021)
See also GWTC-3 catalog

Neutron star binary coalescence

Gravitational waves

high-density matter signature: equation of state, QCD…

test of the theory of gravitation in a non-vacuum

Formation of a hot massive remnant (star/disk)

central engine of short gamma-ray bursts

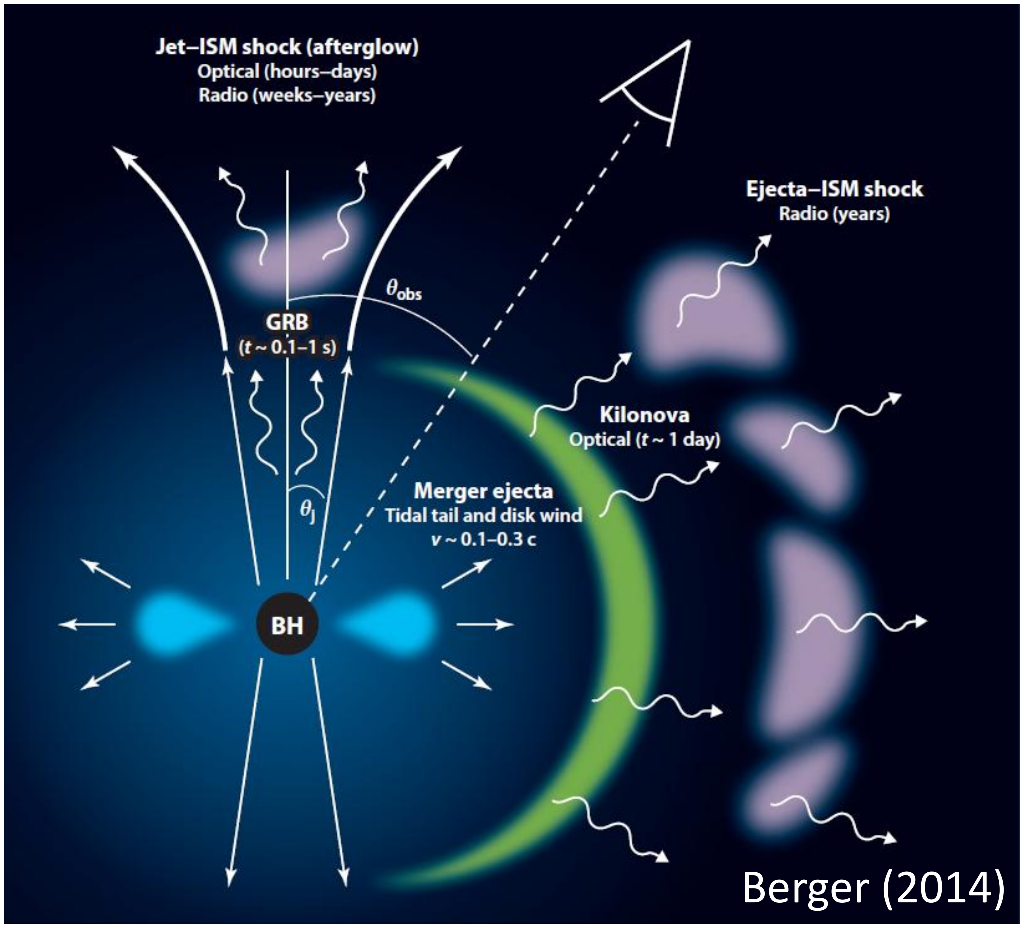
Mass ejection of neutron-rich material

r-process nucleosynthesis

radioactively-driven “kilonova/macronova”

Electromagnetic counterpart

EM radiation will accompany neutron star mergers



localization

host identification

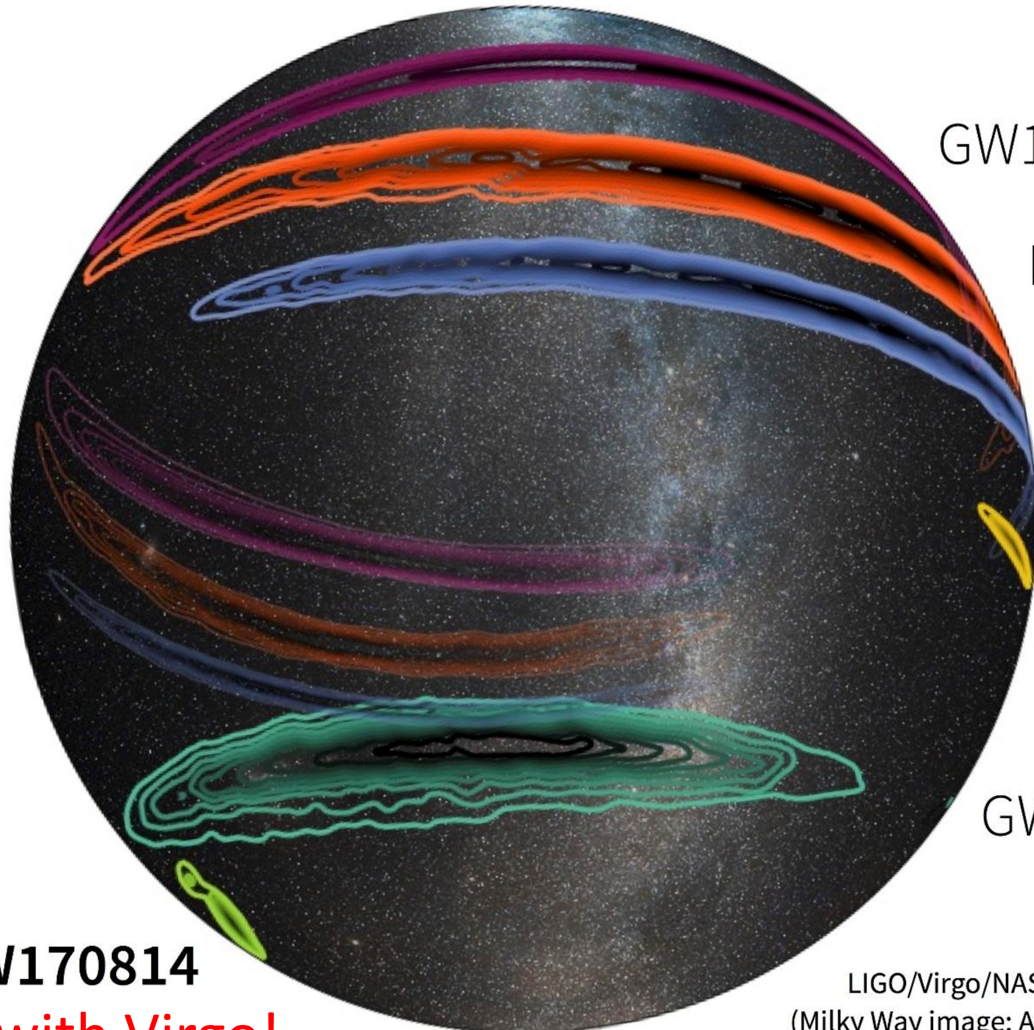
cosmological redshift

ejecta properties

ejection mechanism

r-process element

Sky map and localization accuracy

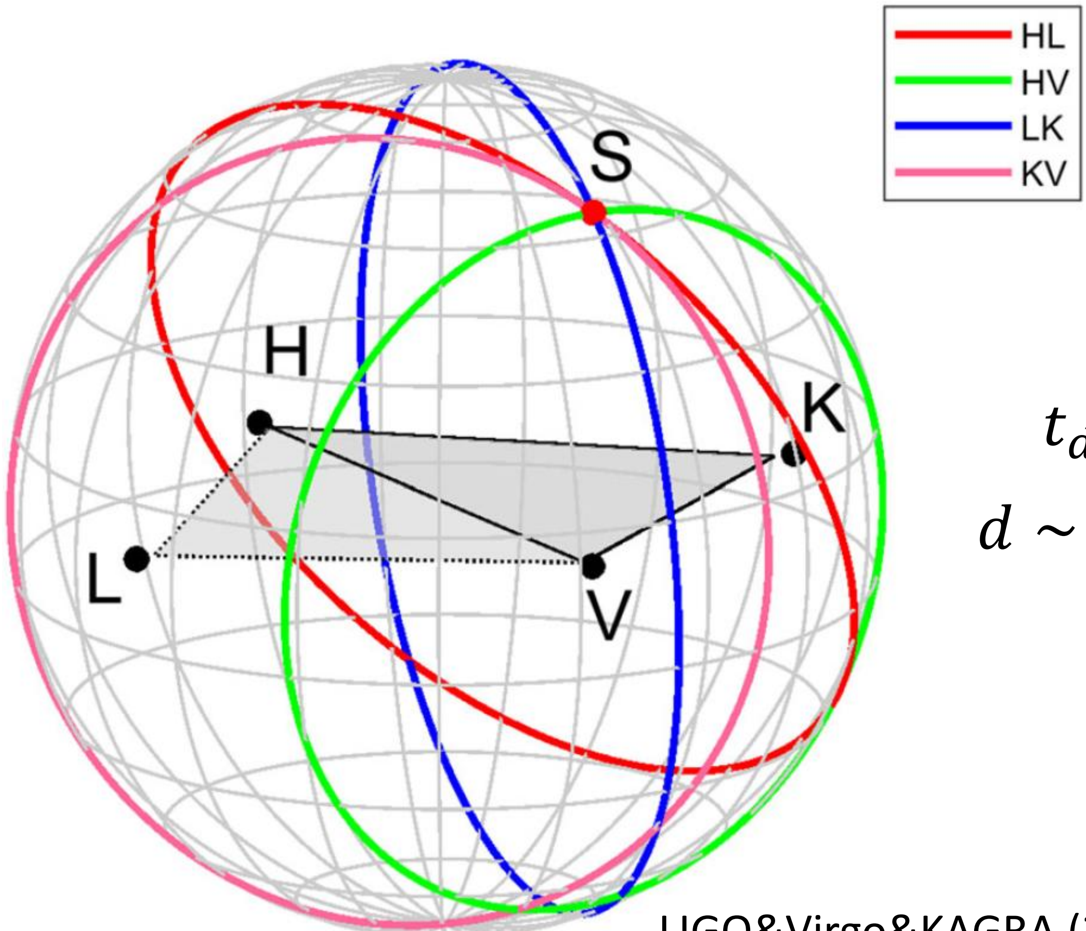


LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

http://www.ligo.org/detections/GW170817/images-GW170817/O1-O2-skymaps-white.jpg

Triangulation by detectors

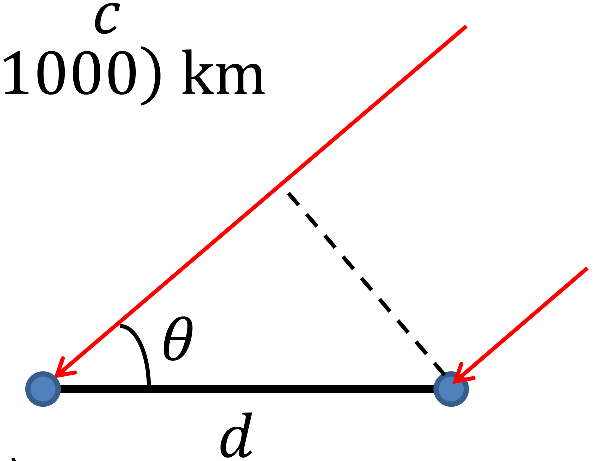
Sky position is determined via the timing difference



Multiple detectors are indispensable

$$t_d = \frac{d\cos\theta}{c}$$

$$d \sim O(1000)\ \mathrm{km}$$



LIGO&Virgo&KAGRA (2020)

Short gamma-ray burst

About 10^{51}erg/s explosions

- the sun is $\sim 4 \times 10^{33}$erg/s

Long-soft GRB: ≥ 2s

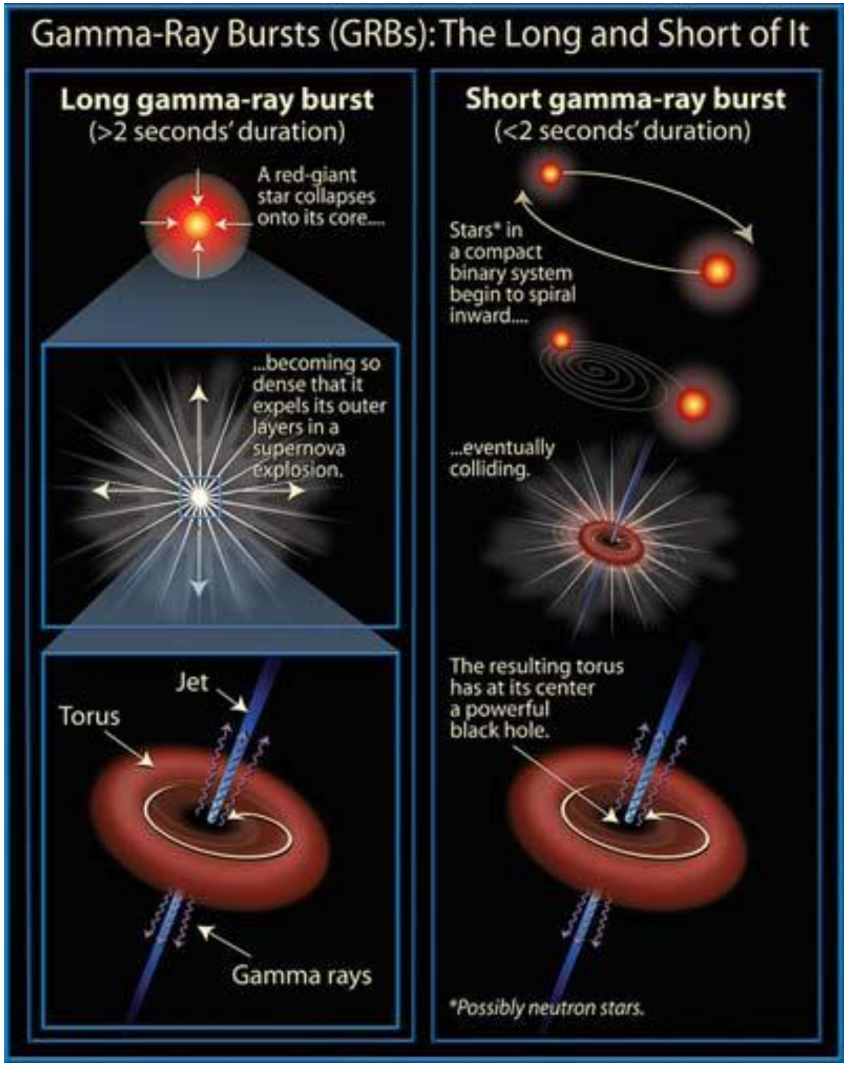
deaths of massive stars

Short-hard: ≤ 2s

neutron star binary merger?

rigorous confirmation needs

gravitational waves

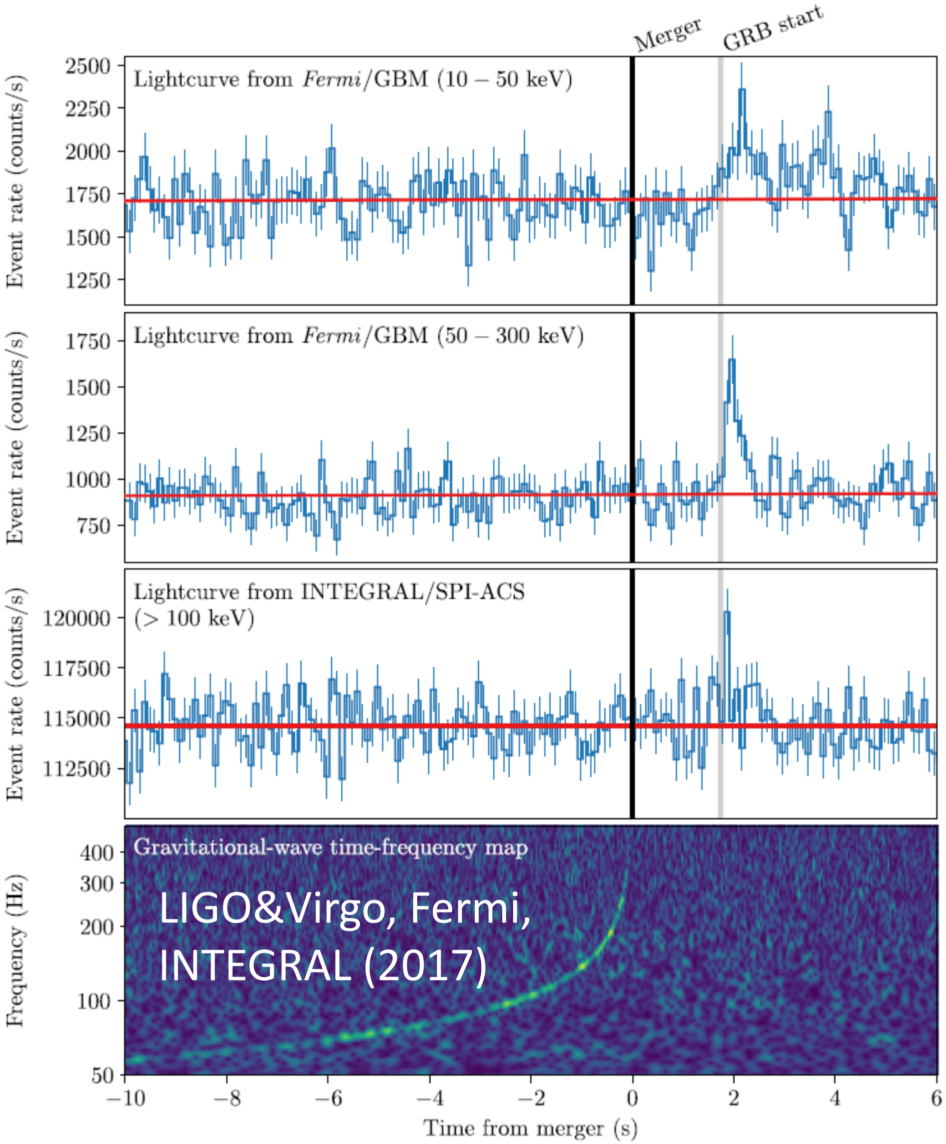


http://www.daviddarling.info/images/gamma-ray_bursts.jpg

GRB 170817A

Fermi and INTEGRAL
agree each other
though relatively weak

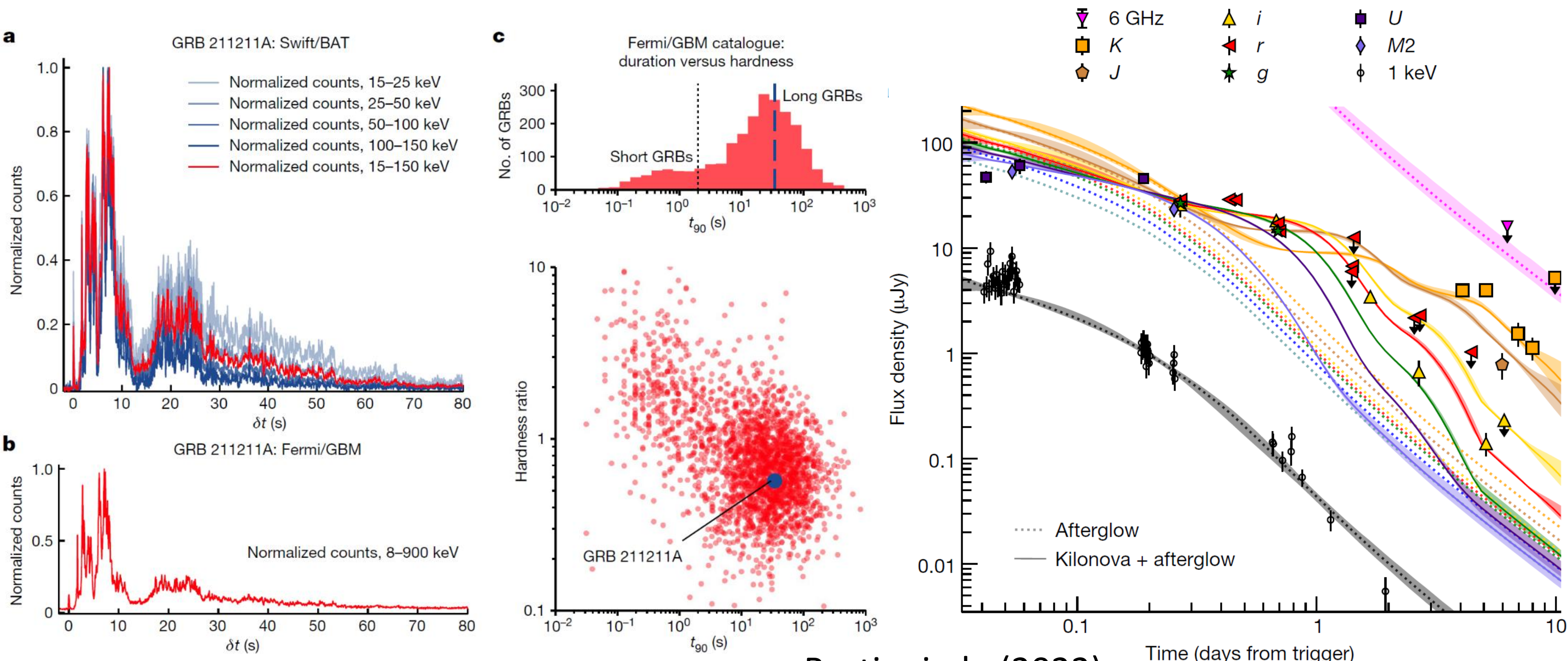
The 1.7s delay from GWs
- jet launch
- jet propagation in
the ejected material
- onset of transparency



Kilonova from GRB 211211A?

R-process nucleosynthesis in long gamma-ray bursts?

Binary-merger-driven long gamma-ray bursts?



Rastinejad+ (2022)

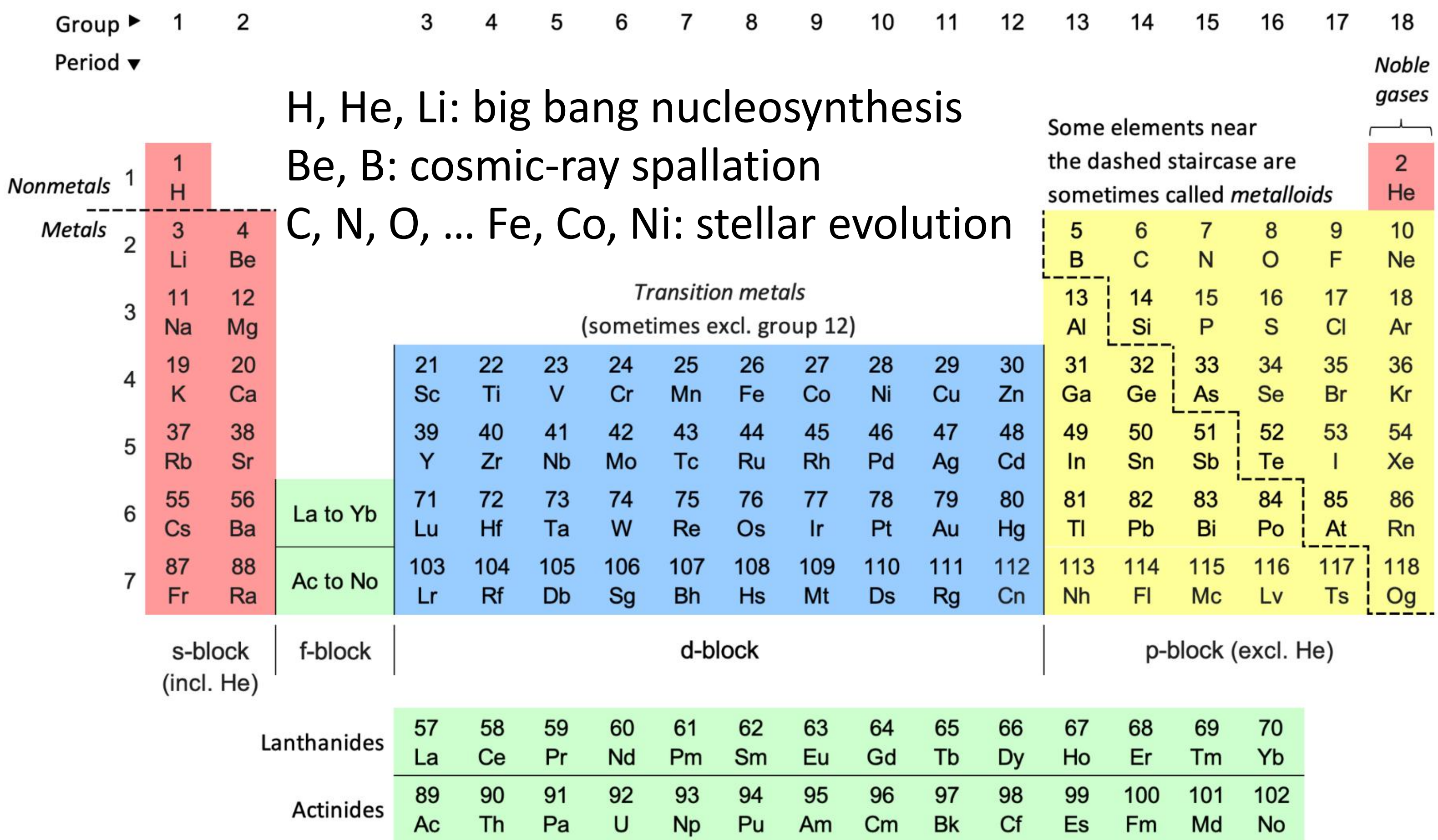
Bigger picture

Where are the elements produced in the universe?

H, He, Li: big bang nucleosynthesis

Be, B: cosmic-ray spallation

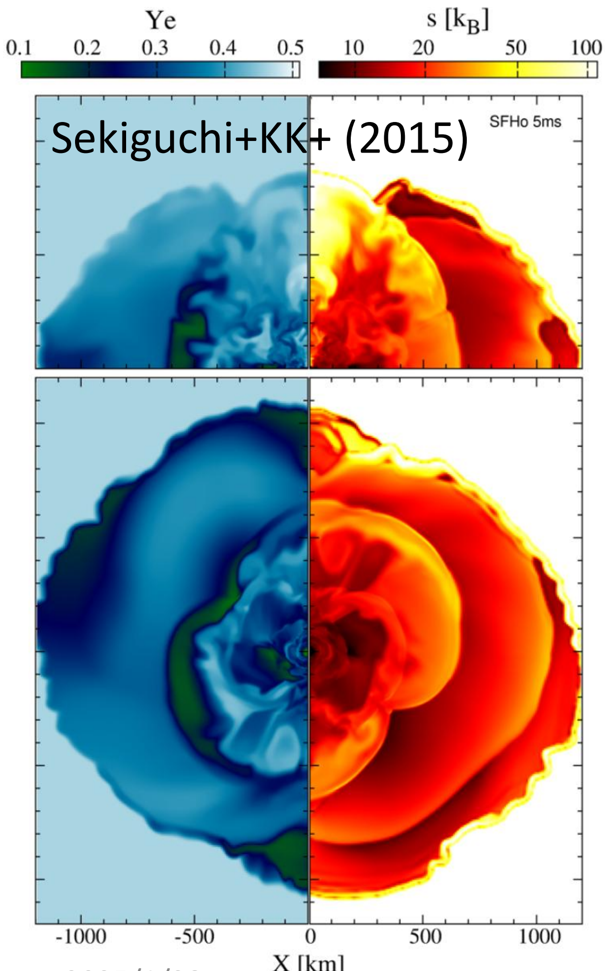
C, N, O, … Fe, Co, Ni: stellar evolution

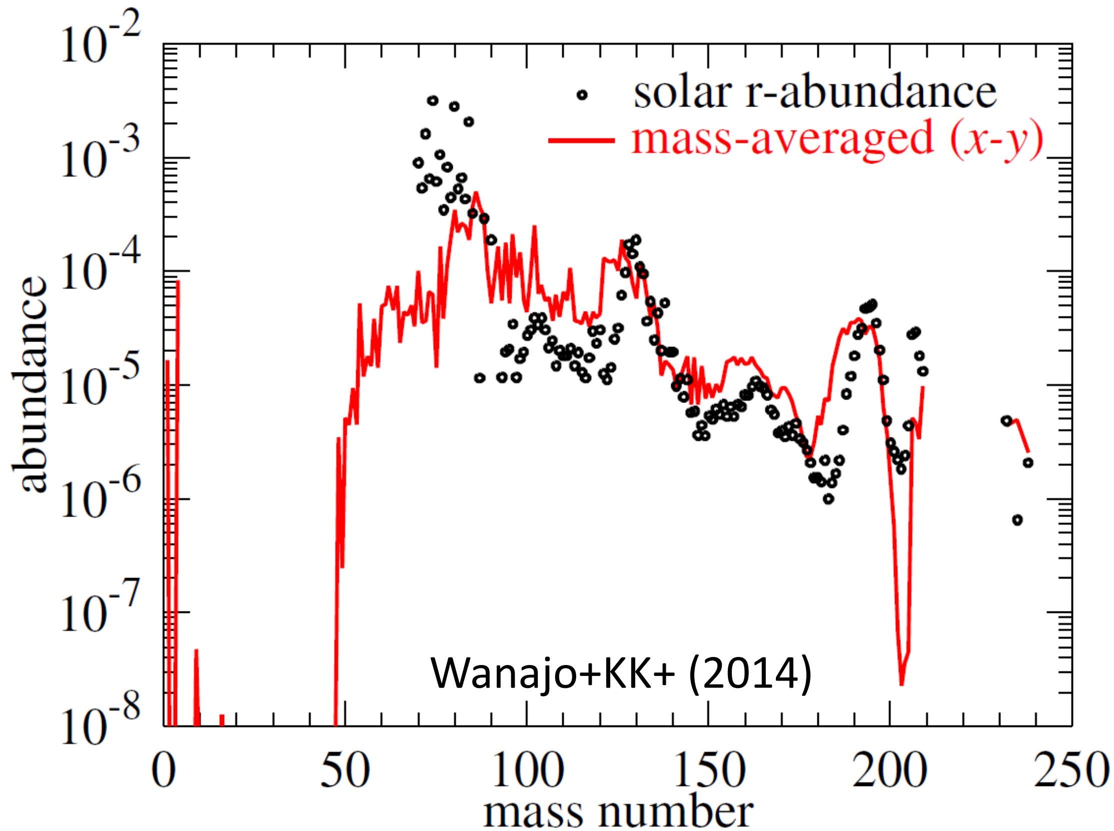


Merger and r-process nucleosynthesis

Likely successful for typical binary merger models

How can we confirm this idea?





Kilonova/macronova

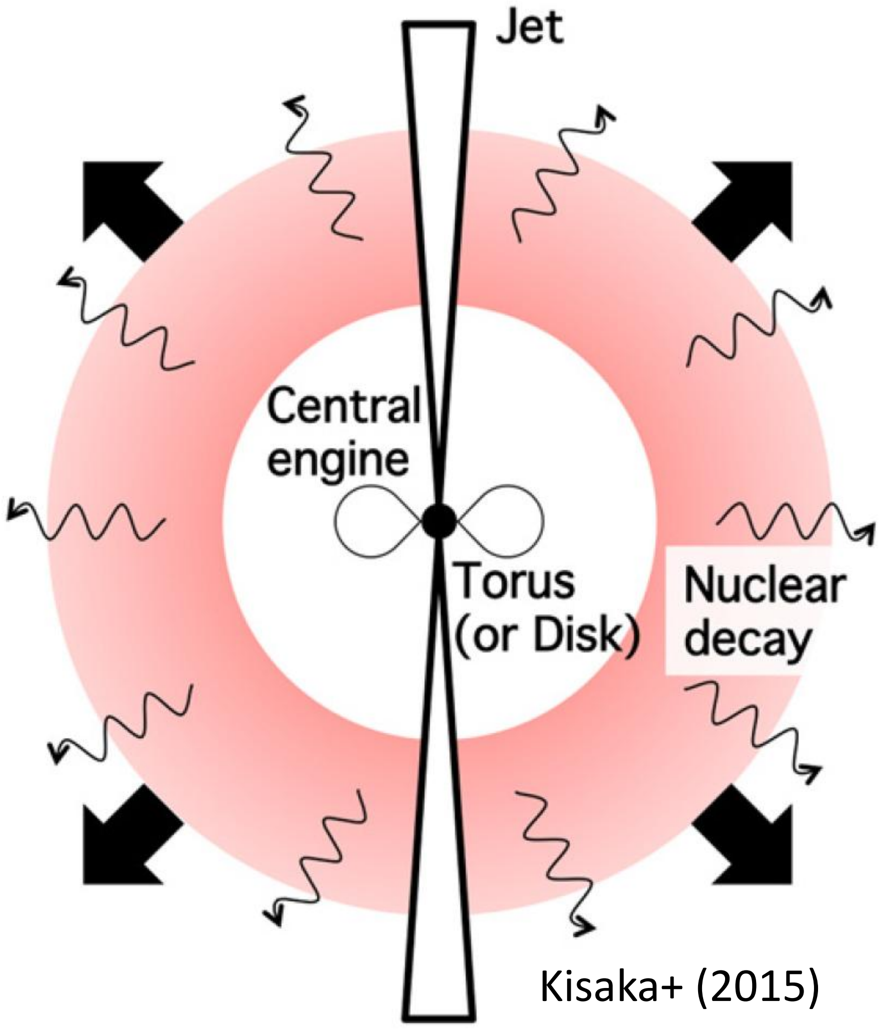
Ejected material contain radioactive r-elements

Their decay heat the ejecta

Thermal photons try to diffuse from the ejecta

But r-elements efficiently traps the photon inside

Characteristic "kilonova"!



Kisaka+ (2015)

Kilonova/macronova characteristics

For spherical ejecta (Li-Paczynski 1998, also Arnett 1982)

The peak luminosity: $L_{\text{peak}} \propto f\kappa^{-1/2}M^{1/2}v^{1/2}$

The peak time : $t_{\text{peak}} \propto \kappa^{1/2}M^{1/2}v^{-1/2}$

Heating efficiency f and opacity κ – microphysics

particularly, r-process elements have high opacity

Ejecta mass M and ejecta velocity v – macrophysics

small mass and high velocity (vs supernovae)

High opacity of the lanthanides

The fraction of synthesized lanthanides is the key

The opacity changes by a few orders by magnitude

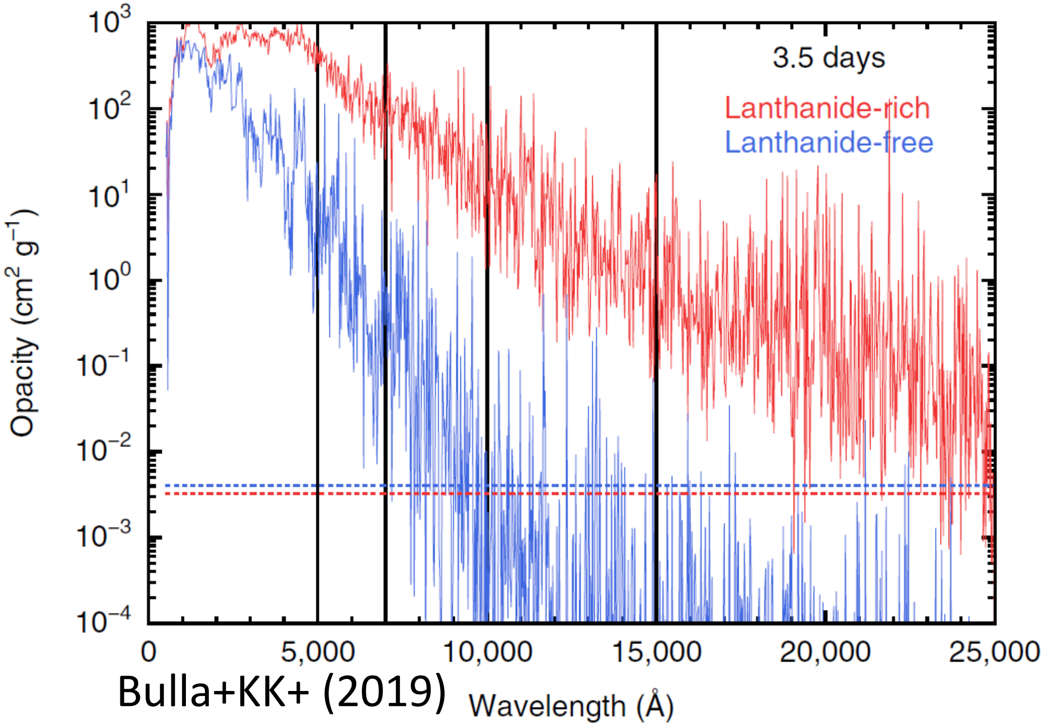
- interaction cross section with photons per mass

Formed if Ye<~0.25

lanthanide rich

Not if Ye>~0.25

lanthanide free



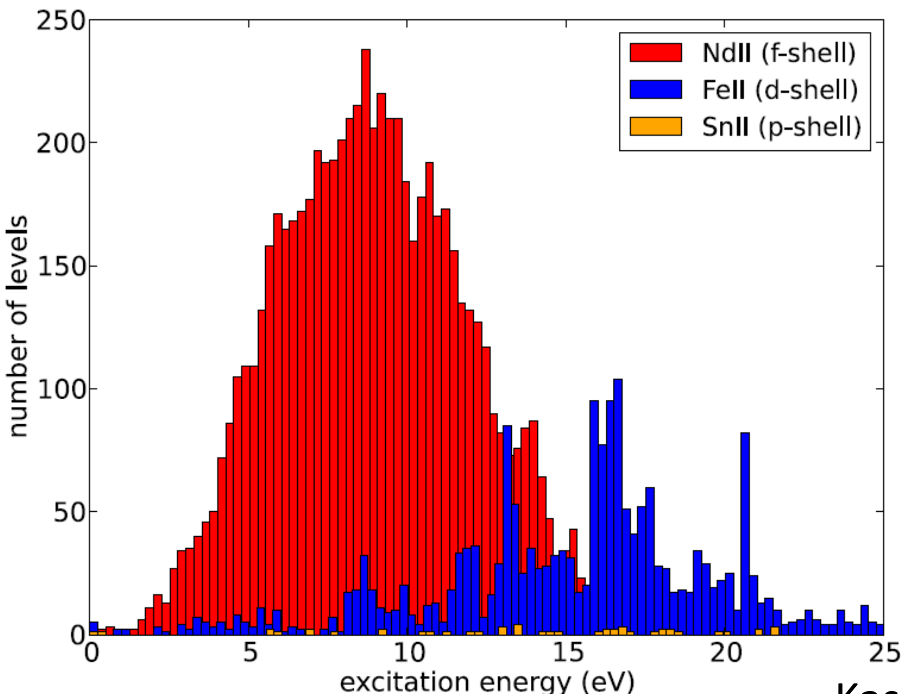
Bulla+KK+ (2019)

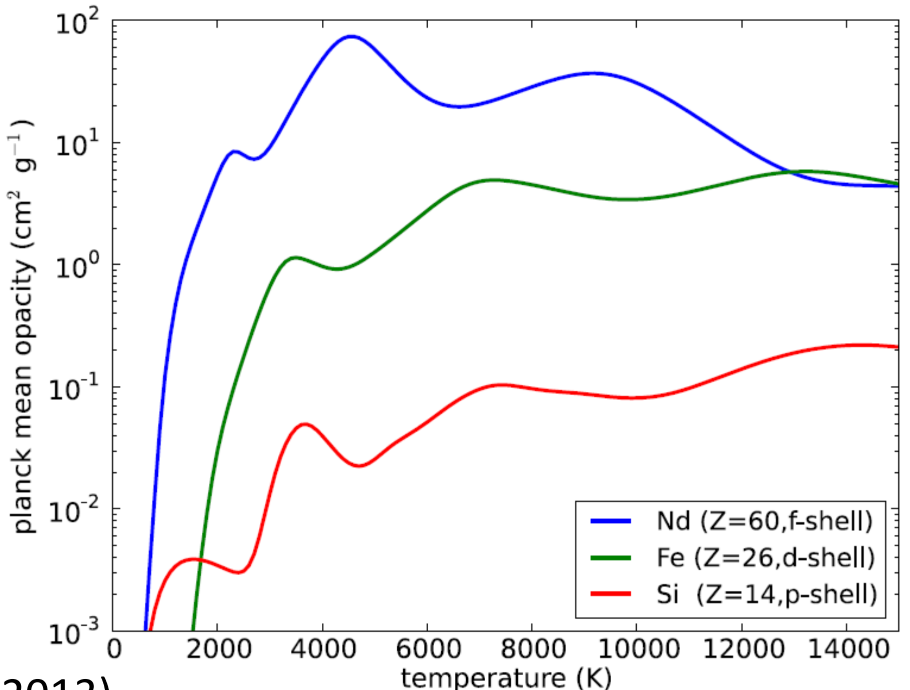
Too many lines of lanthanides

A bunch of energy levels -> complex line structures

-> very frequent interaction -> very high opacity

But modeling is incomplete (quantum many-body)



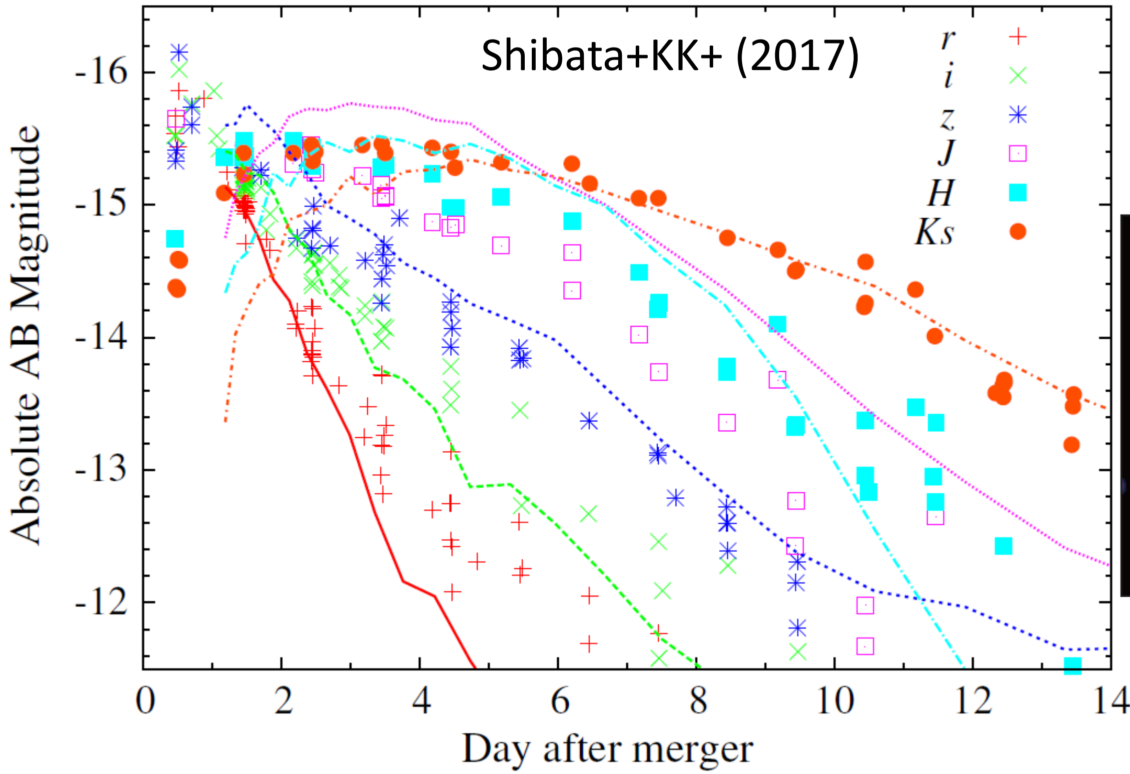


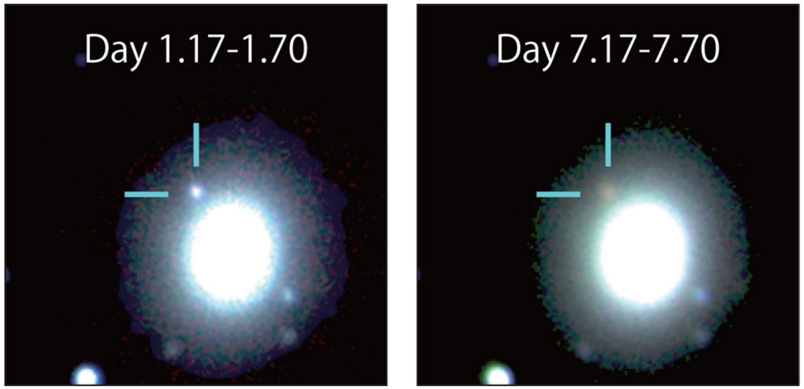
Kasen+ (2013)

AT 2017gfo

Largely consistent w/ theoretical prediction

In particular, ~10day time scales in infrared bands:
unique to kilonovae



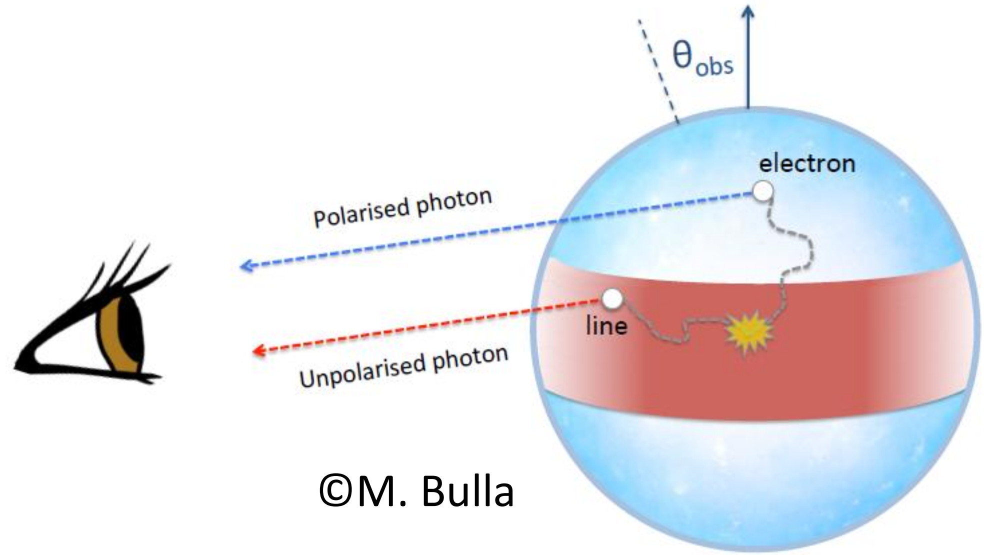


Utsumi+ (2017)

Polarization

Ejecta geometry and atomic distribution could be inferred from polarization due to electron scattering

This is possible only if both light and heavy r-process elements exist in the ejecta

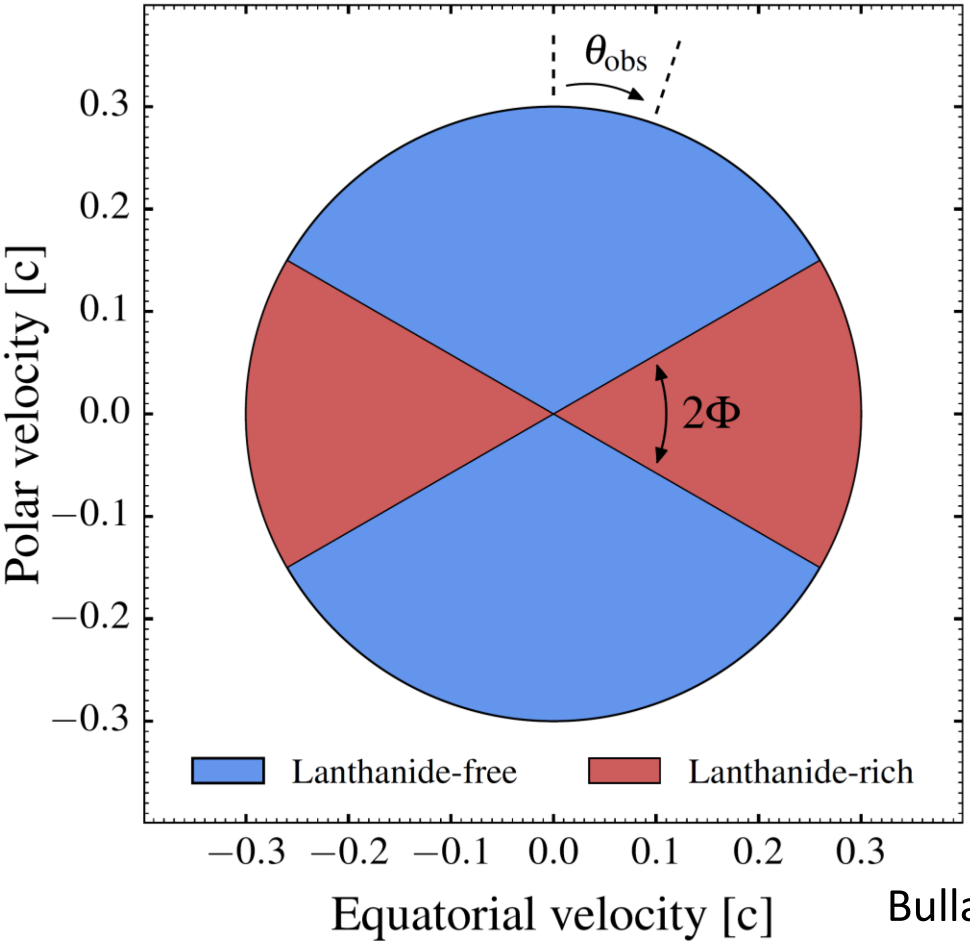


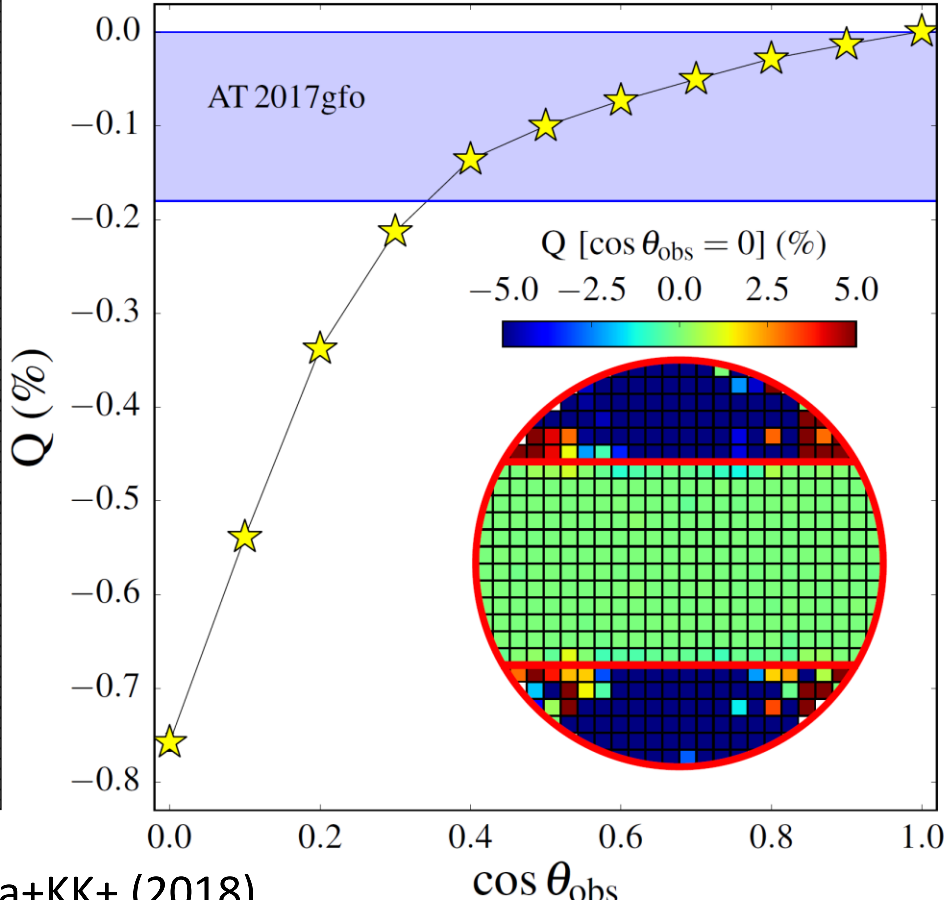
©M. Bulla

No polarization for AT 2017gfo [Covino et al. 2017]

Probe into the atomic distribution

~1% polarization is possible for binary neutron stars





Bulla+KK+ (2018)

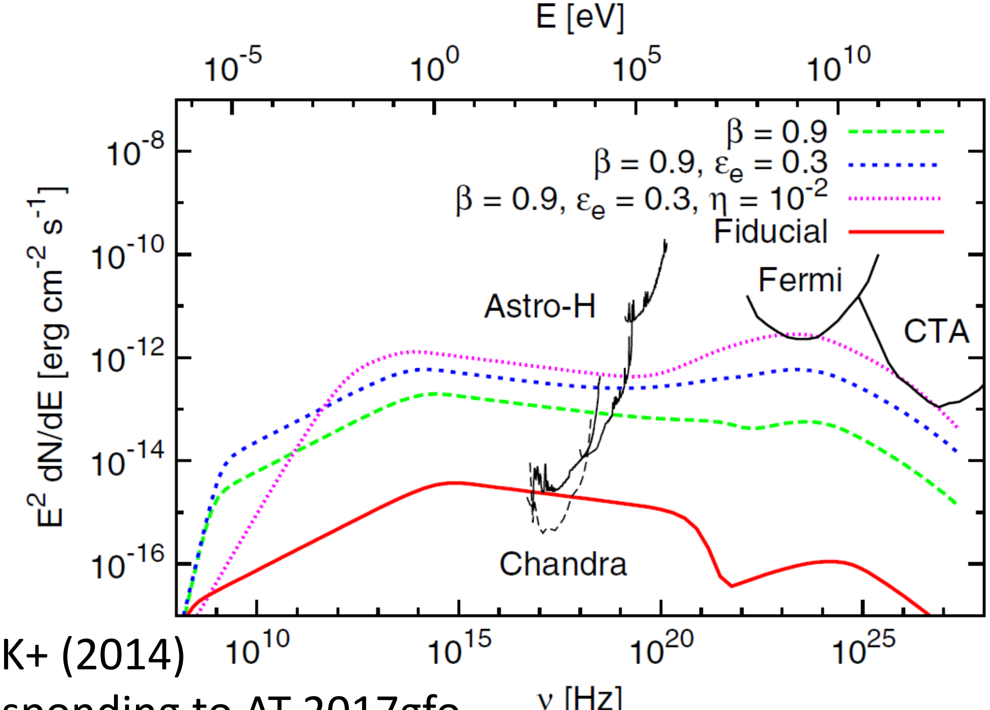
Future of the kilonova ejecta

The ejecta with $0.03 - 0.05 M_{\odot}$ and $0.1 - 0.2c$ will eventually collide with the interstellar medium

-> a system very similar to supernova remnants

Broadband emission is expected (mainly radio)

Gamma-rays are possible for (very) extreme cases e.g., with magnetars



Takami, KK+ (2014)
Not corresponding to AT 2017gfo

Cosmic-ray acceleration?

The velocity of the r-process-enriched merger ejecta is larger by an order of magnitude than supernova’s

If all the r-process elements are produced in mergers, they must be born with two order-of-magnitude larger kinetic energy (per mass) than elements from the supernova explosion, e.g., iron

Then: r-process cosmic rays could be highly abundant as far as the reverse-shock acceleration is efficient

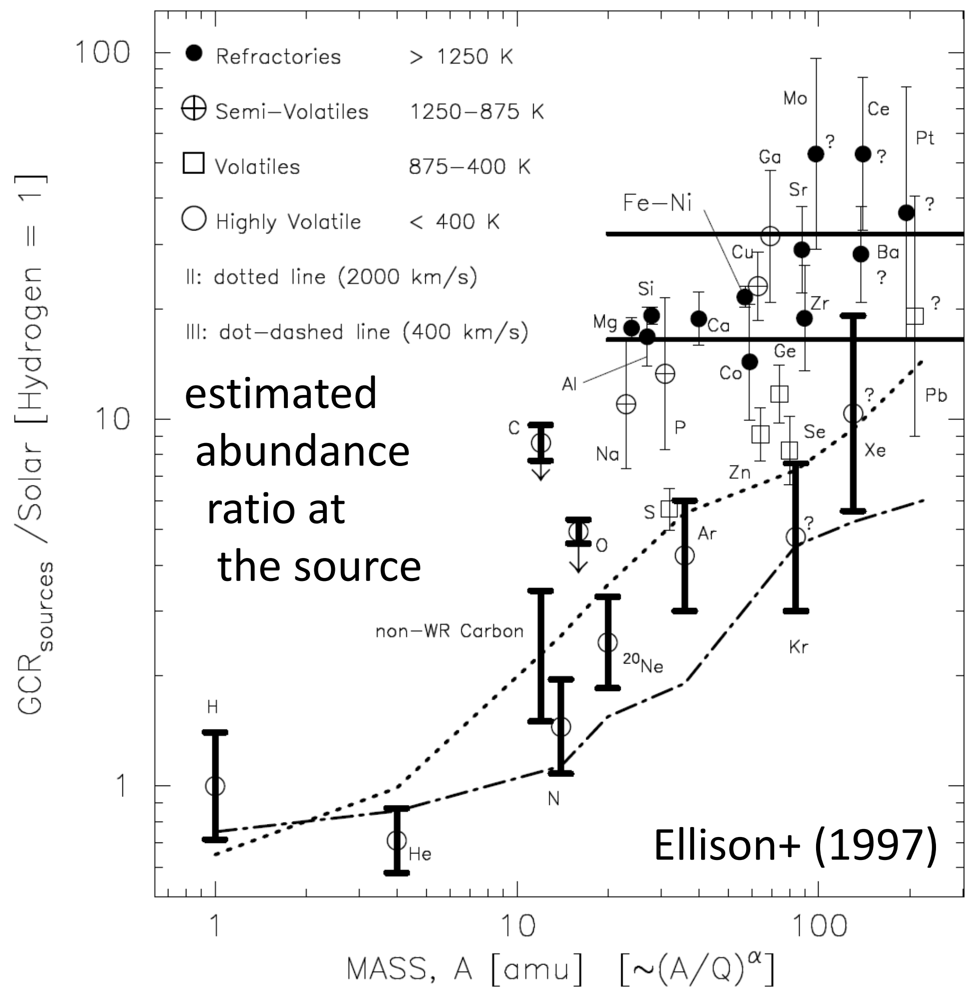
Observed cosmic-ray composition

No selective r-process enhancement is observed

"solar composition"

Enhancement for

- refractory elements that tend to form dusts
- all the heavy elements (or for large A/Q ?)



Limit on acceleration efficiency

Particle acceleration and emission may be inefficient in the reverse shock of the kilonova ejecta