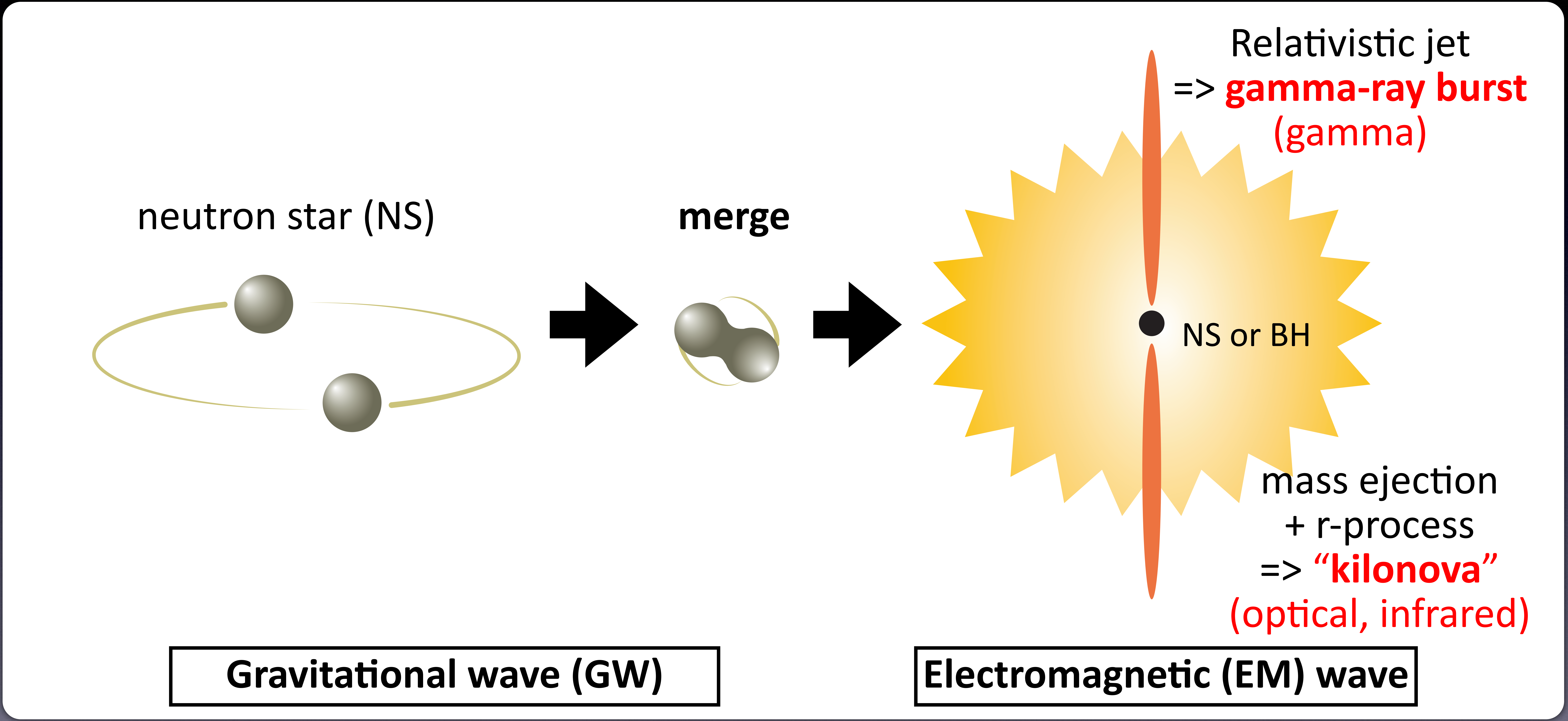
Optical and infrared observations of kilonovae

Masaomi Tanaka (Tohoku University)

Optical and infrared observations of kilonovae

- Neutron star merger and kilonova
- Toward optical-infrared observations
  - Localization
  - Alert latency

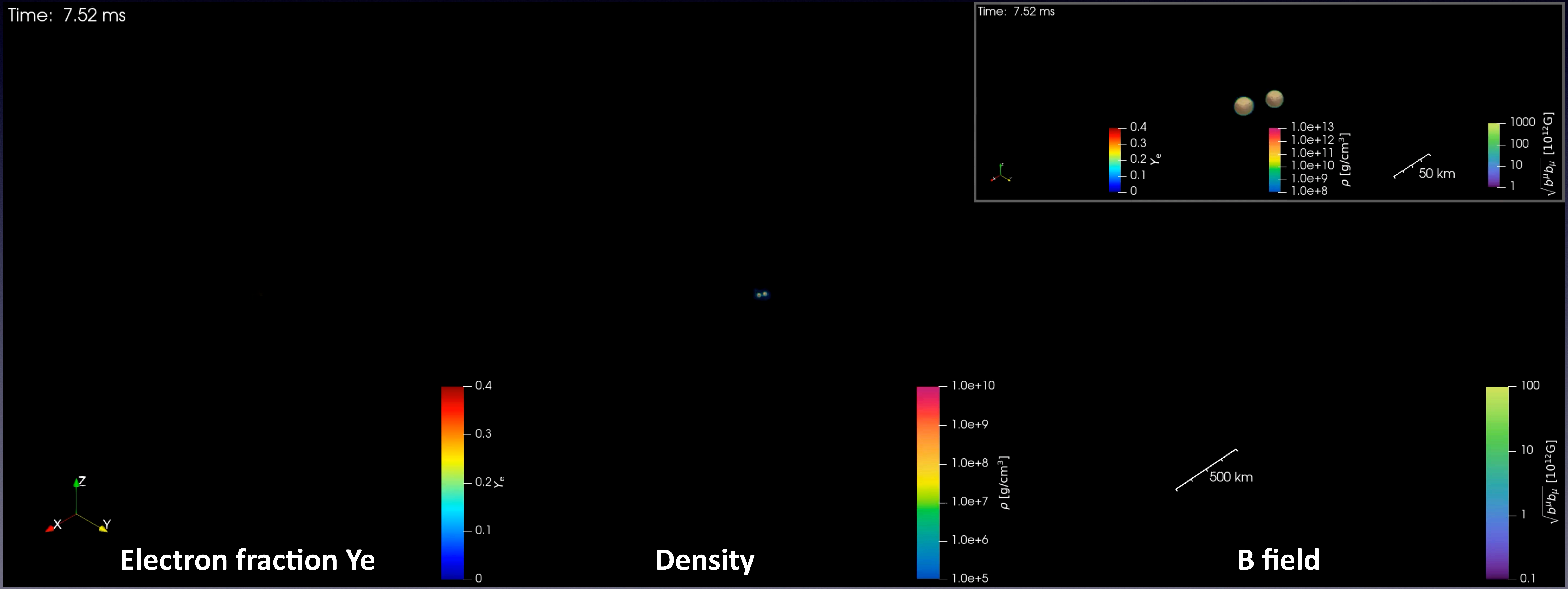
Multi-messenger from neutron star merger



NS merger => dynamical mass ejection (< 0.1 sec)

=> “wind” from disk (~ 1 sec)

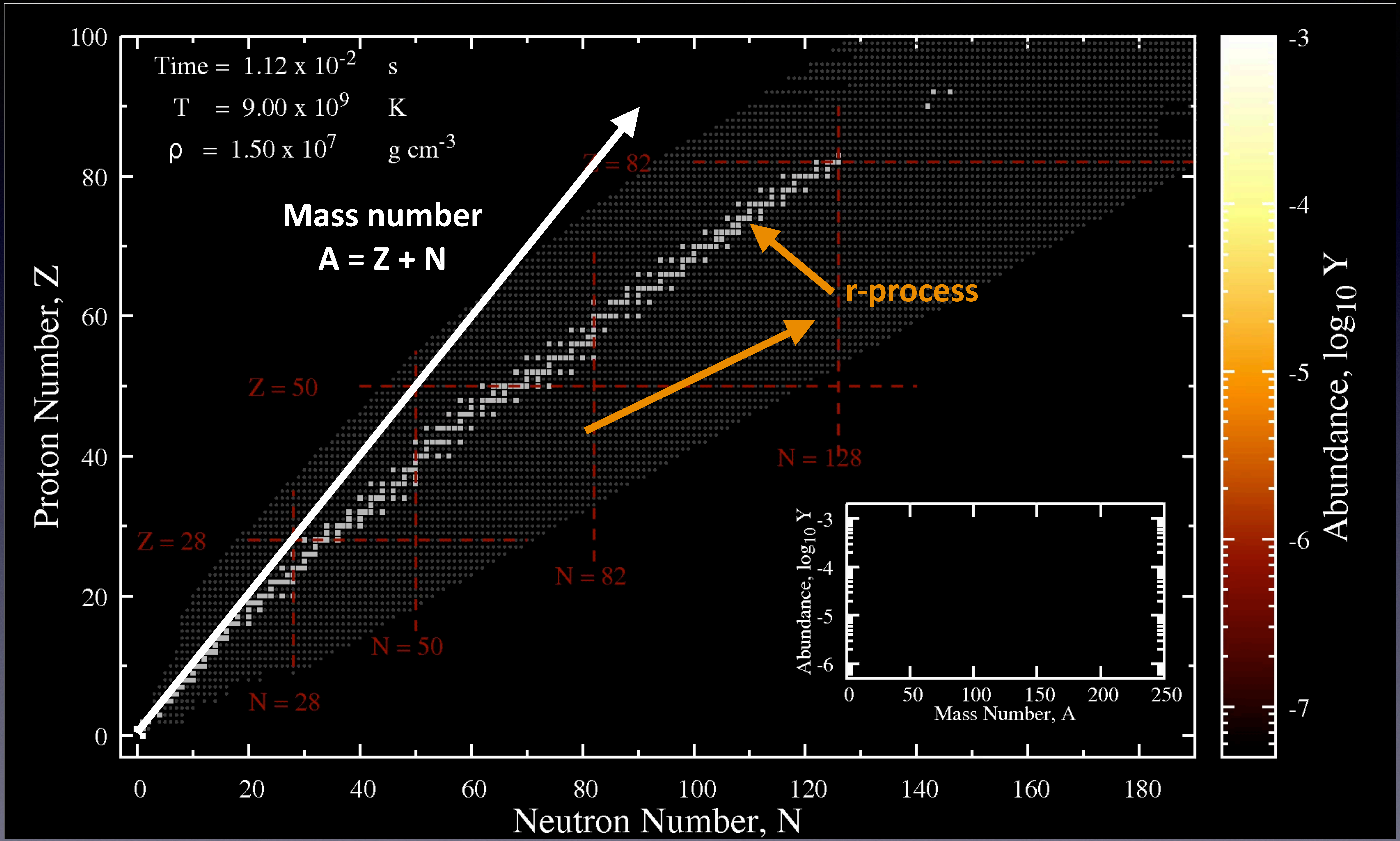
+ relativistic jets (=> gamma-ray burst)



Kiuchi+23

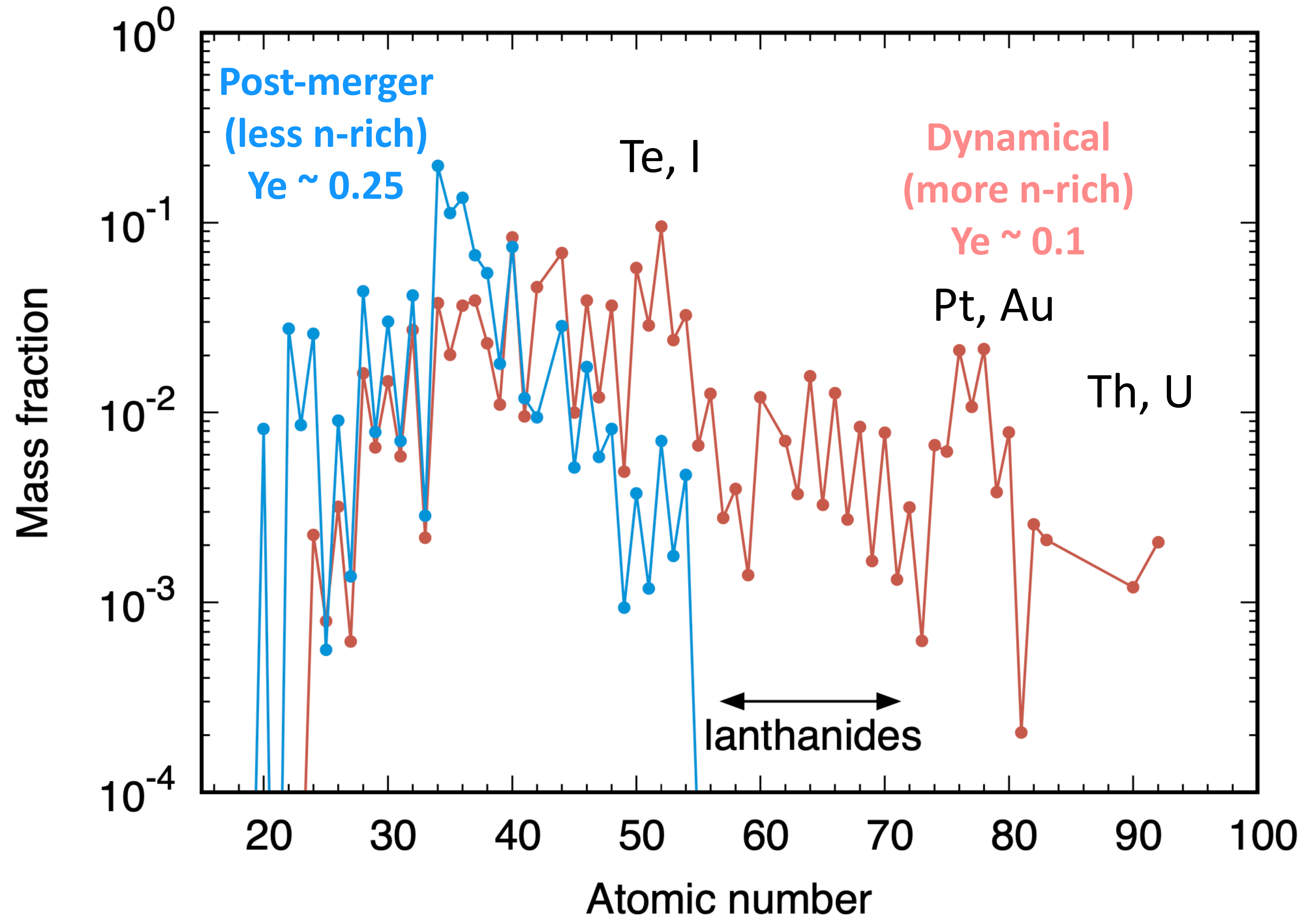
Rapid neutron capture nucleosynthesis (r-process)

(C) Nobuya Nishimura

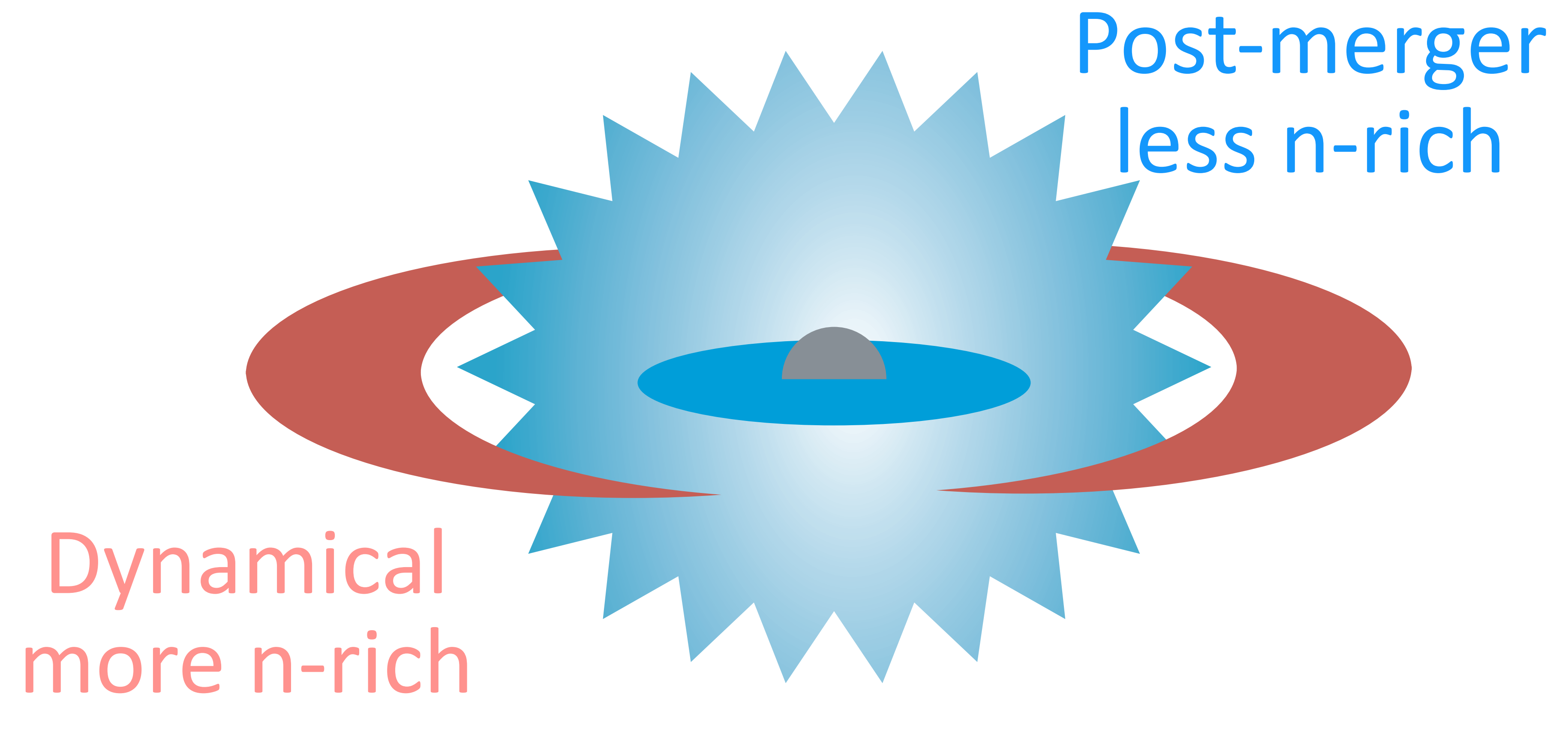


Heavy element production in NS mergers

Lattimer & Schramm 1974, Eichler et al. 1989,
Goriely et al. 2011, Korobkin et al. 2012,
Bauswein et al. 2013, Wanajo et al. 2014, …



$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

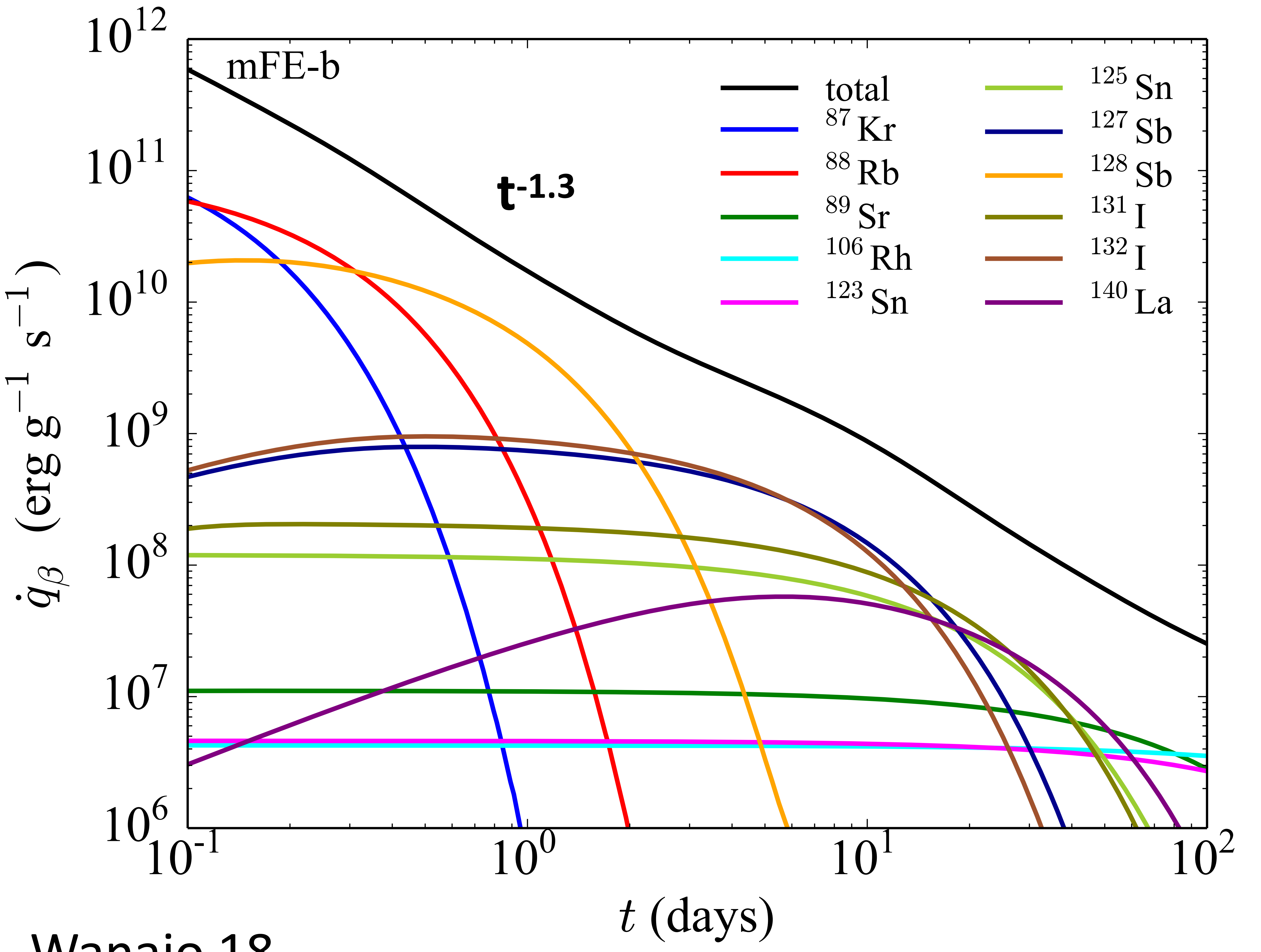


* mass fraction is
normalized for
each component

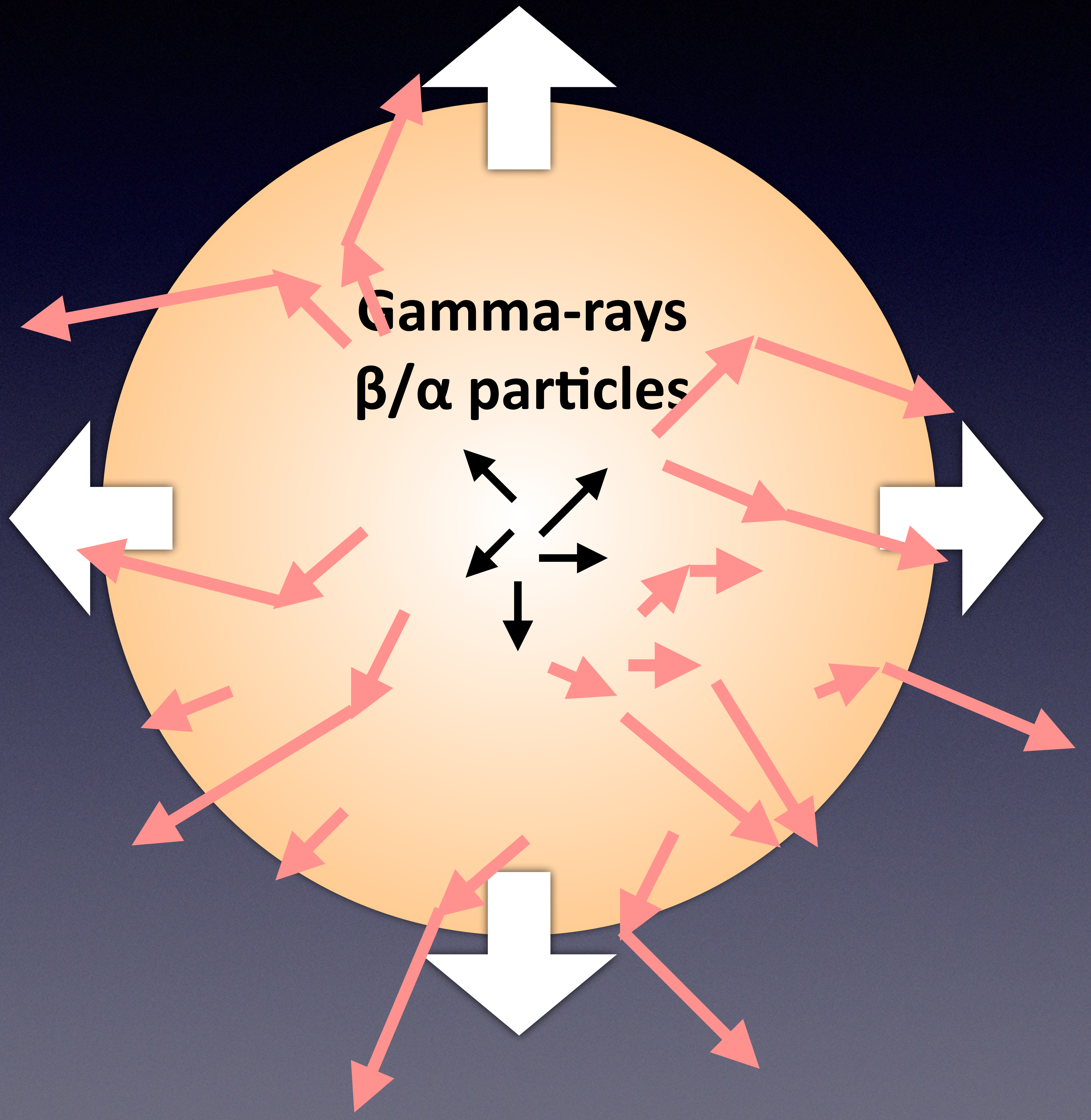
Fujibayashi+23

Radioactive decays => Kilonova (EM signal)

Metgzer+10, Lippuner+15, Wanajo18, …



Wanajo 18



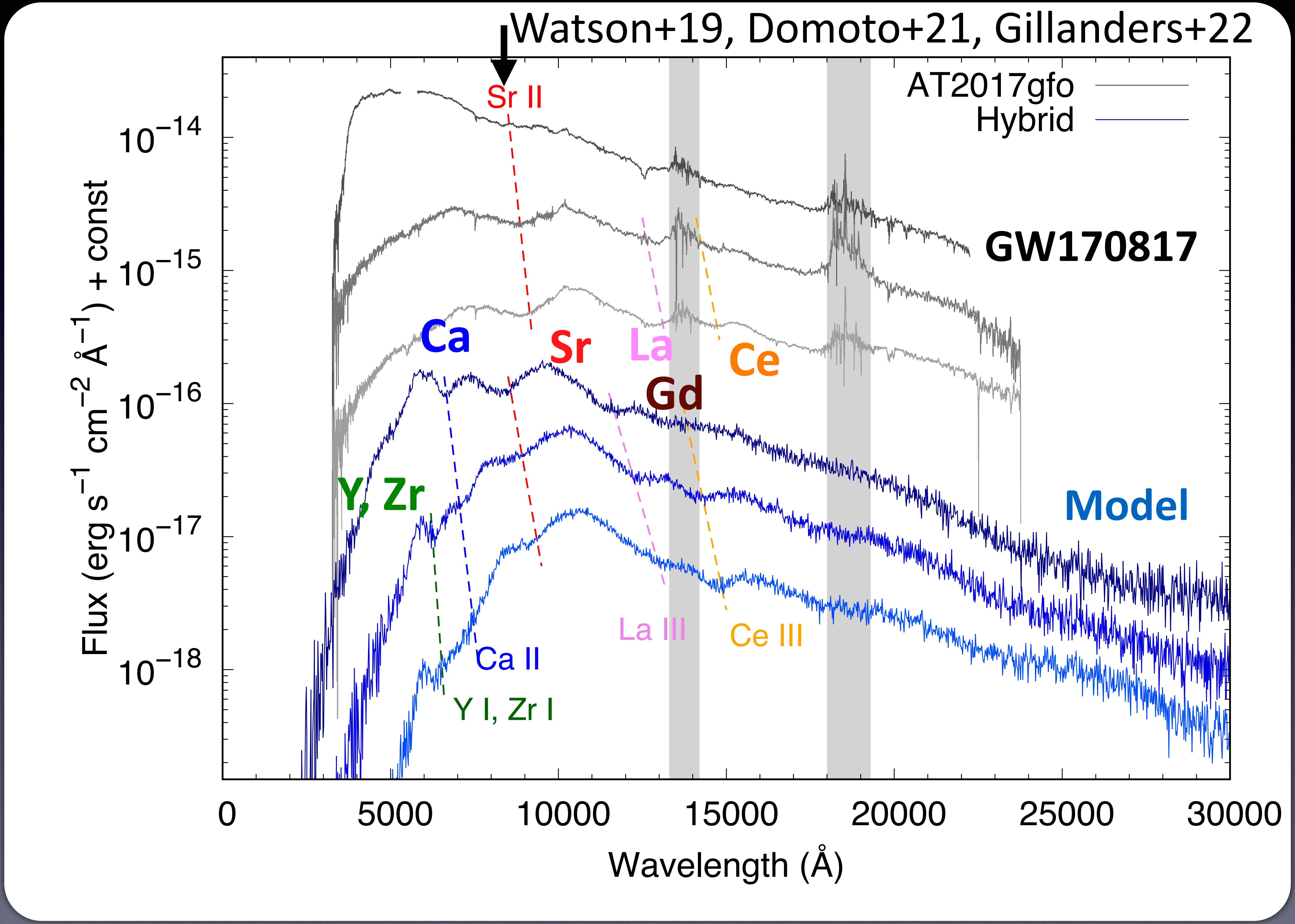
Search for EM (optical) counterpart

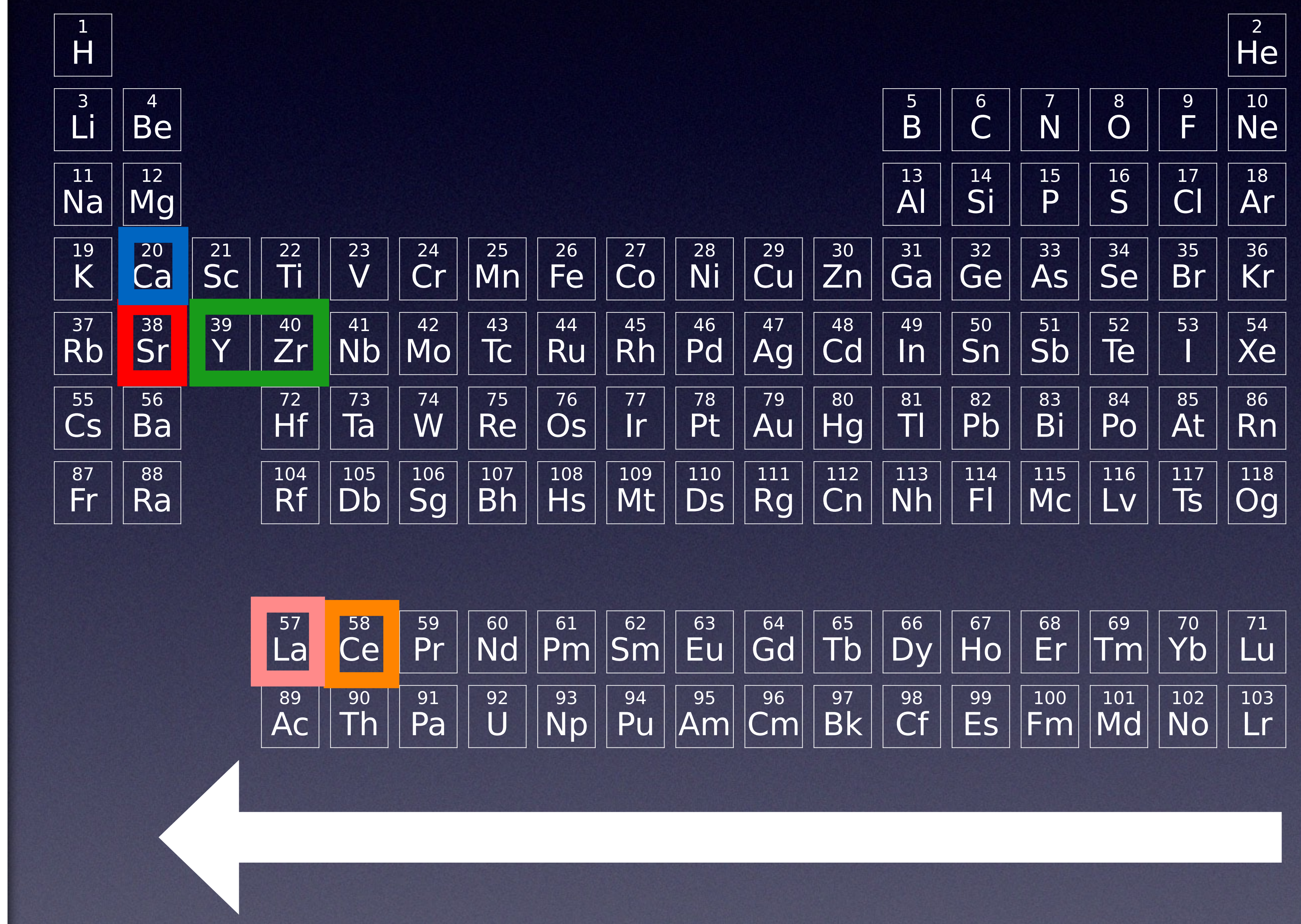
Neutron star merger => r-process nucleosynthesis

Movie: Utsumi, MT+17, Tominaga, MT+18

Direct evidence of heavy element production

Domoto, MT+22
MT+23, Domoto+23
Rahmouni+25





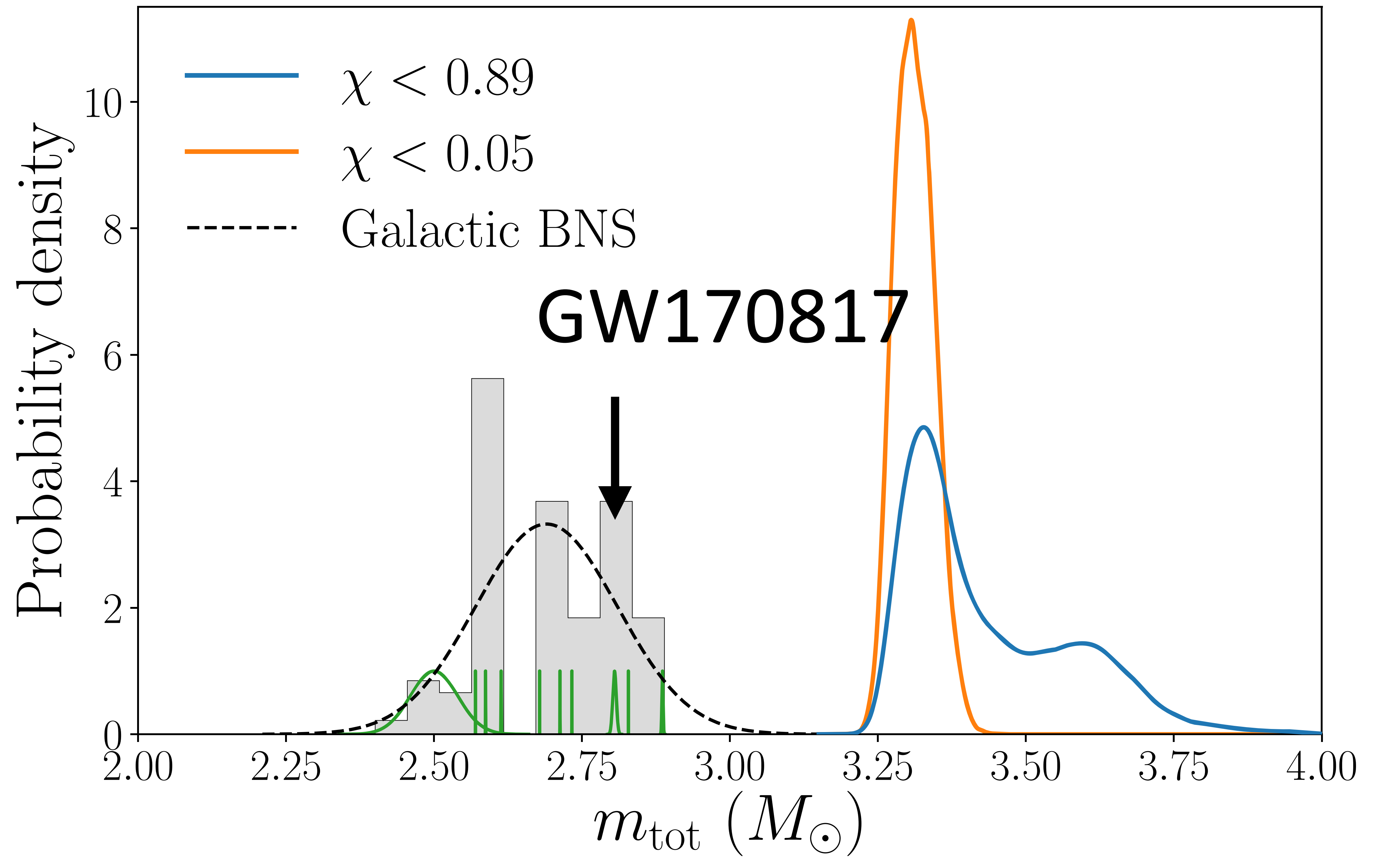
Power of multi-messenger astronomy

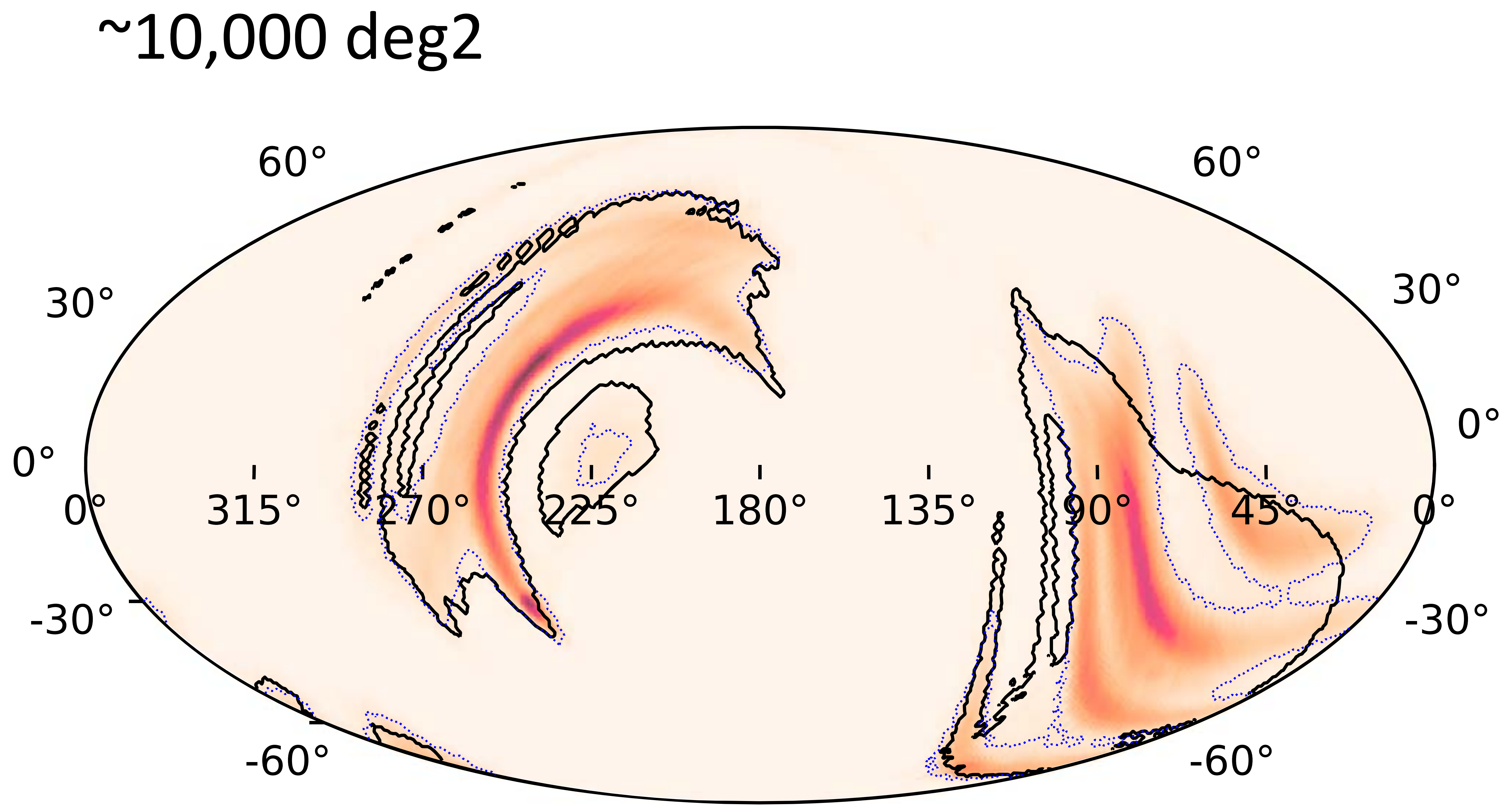
	GW	EM
Origin of GRBs	Nature of merging objects	Gamma-ray burst
Origin of elements	Nature of merging objects	Kilonova
Cosmology	Luminosity distance	Redshift
Fundamental physics	Speed of GW	Speed of light

(C) Tohoku University

GW190425: 2nd NS merger event

Total NS mass ~ 3.4 Msun





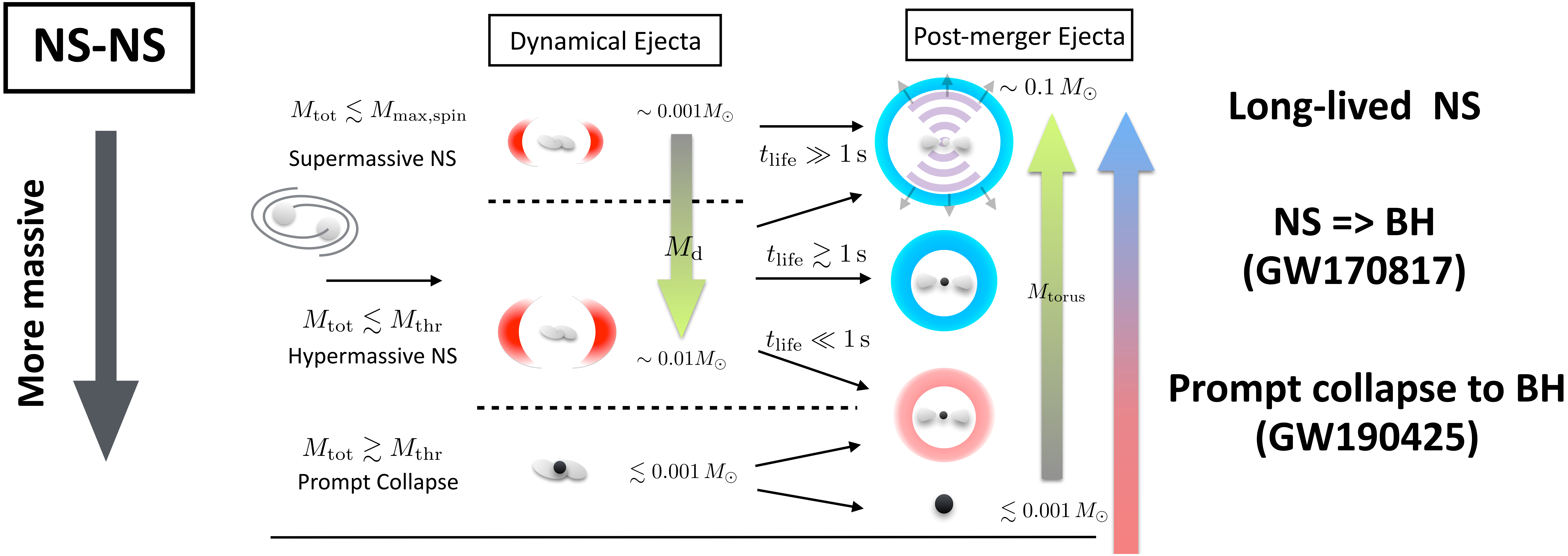
Diversity in neutron star masses

=> diversity in mass ejection, r-process, and kilonova

Abbott+2020

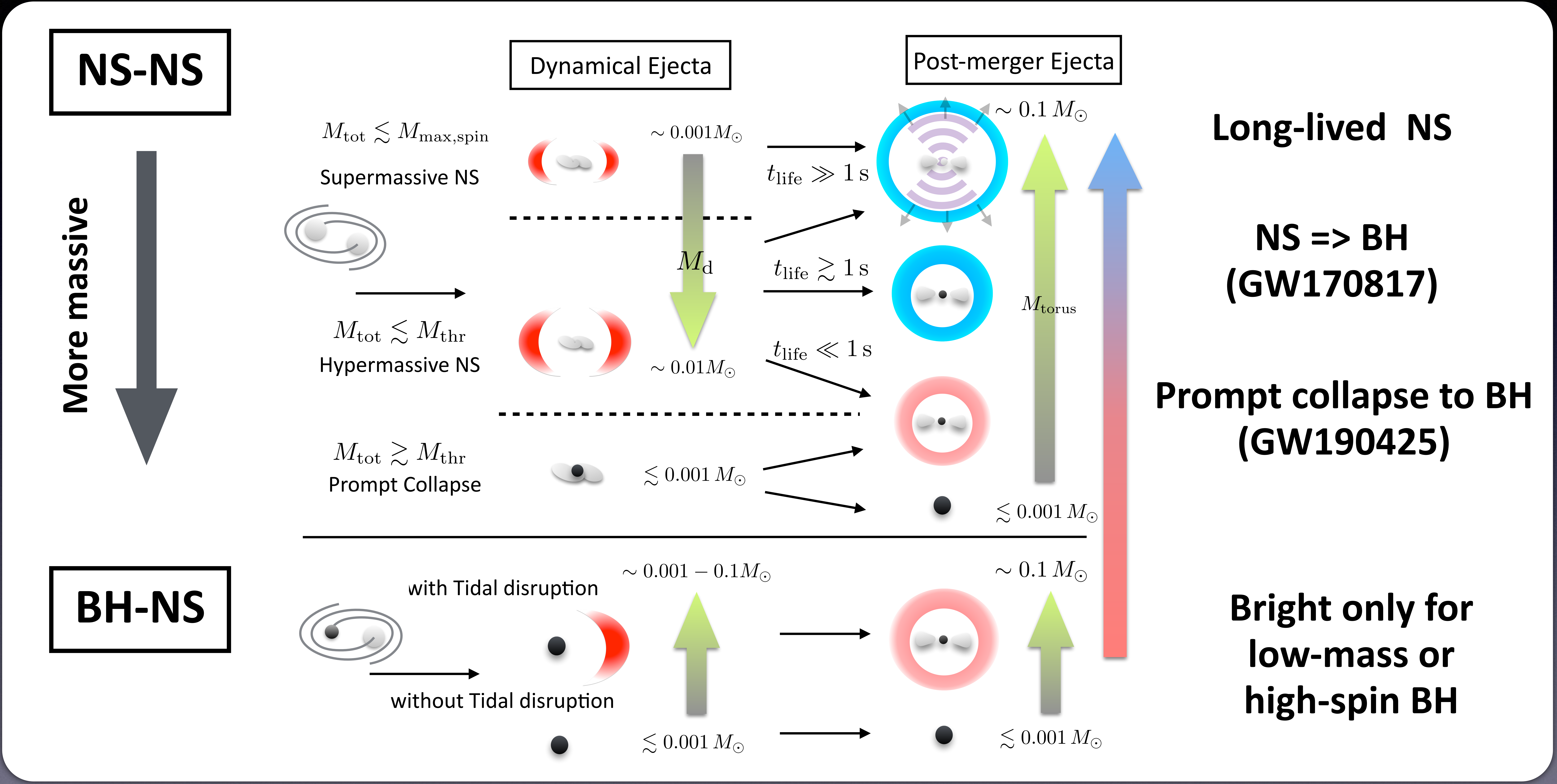
Diversity in NS merger and kilonova

Kawaguchi, Shibata, MT 2020



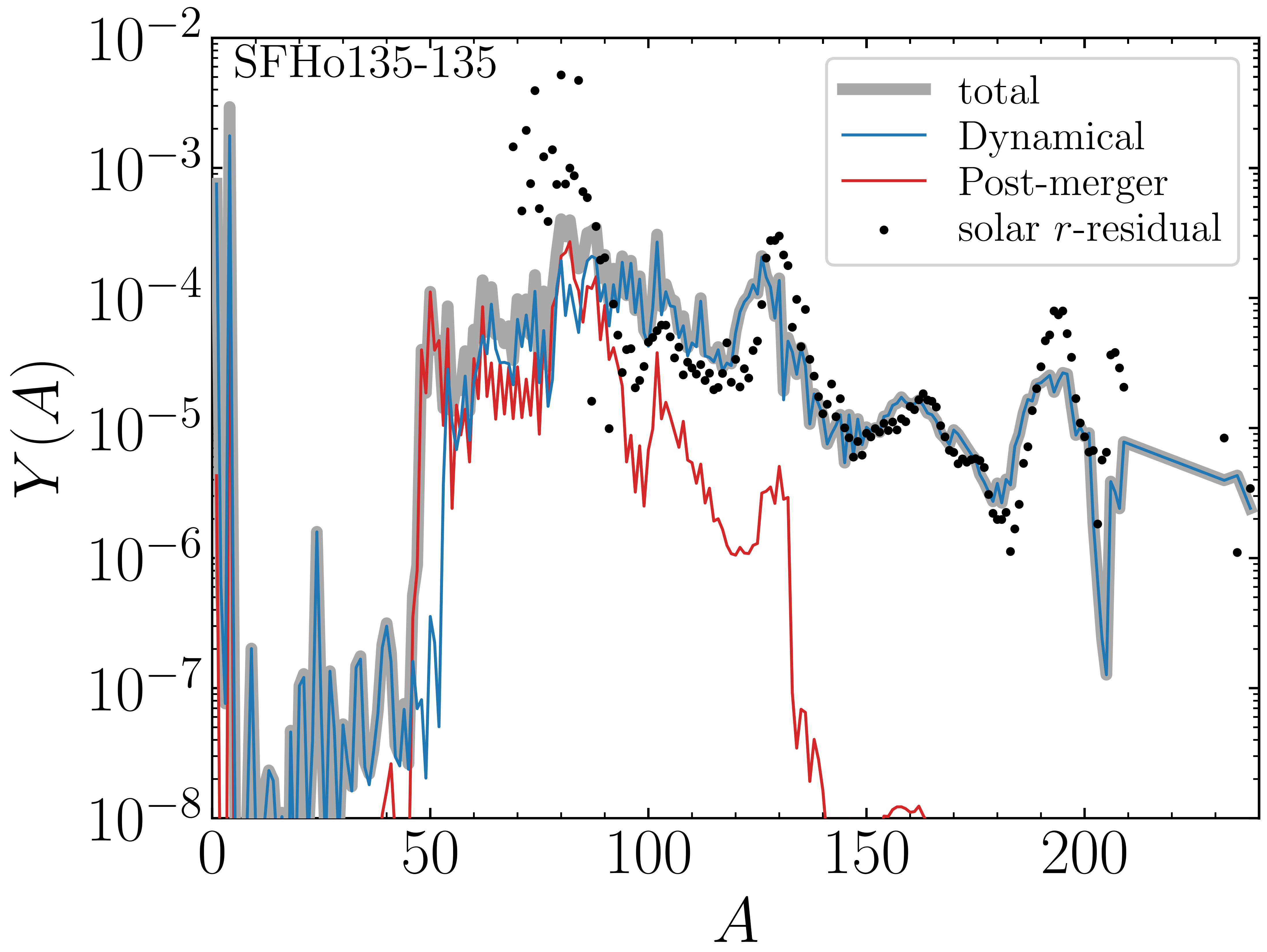
Diversity in NS merger and kilonova

Kawaguchi, Shibata, MT 2020

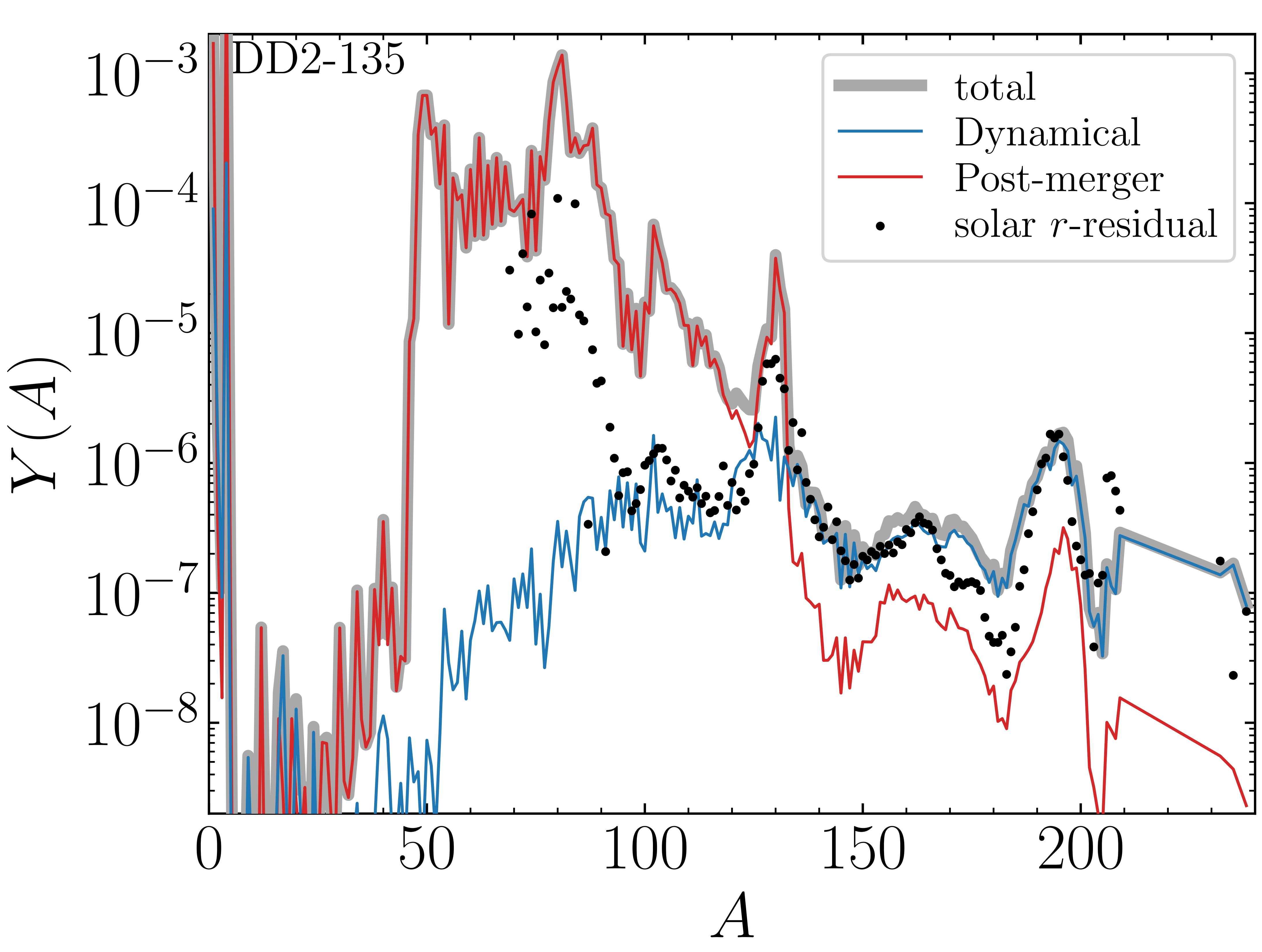


Impact to the nucleosynthesis

Hypermassive NS τ ~ 10 msec

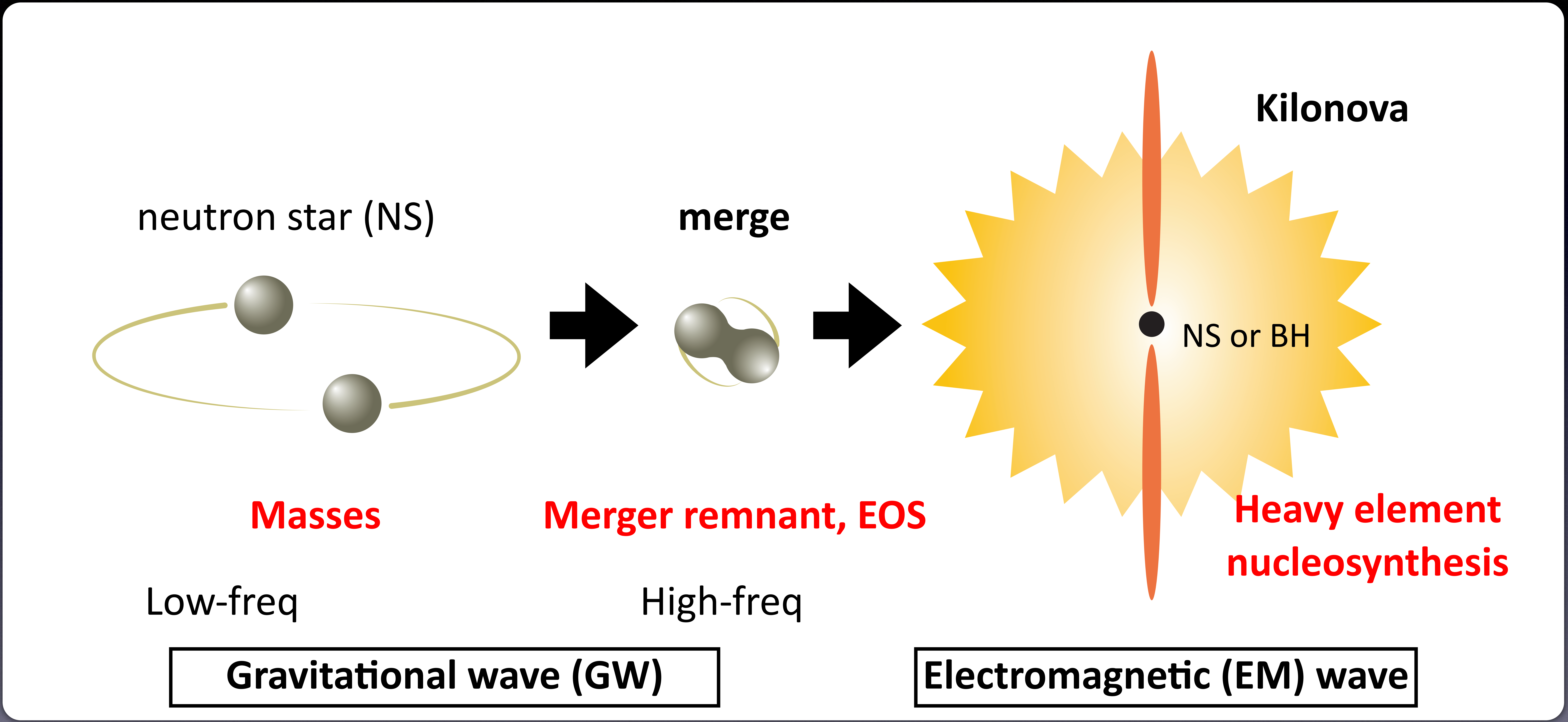


Long-lived NS (> 10 sec)



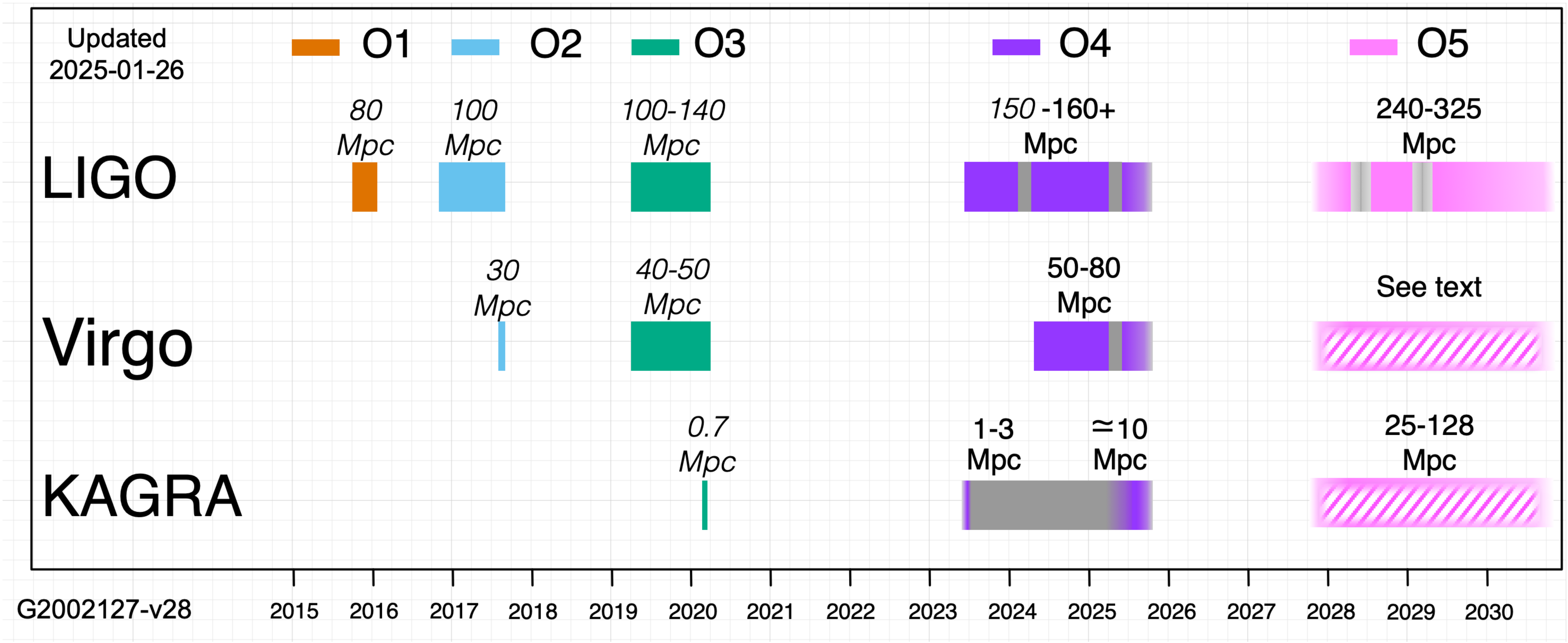
Fujibayashi+23

Multi-messenger from neutron star merger



Optical and infrared observations of kilonovae

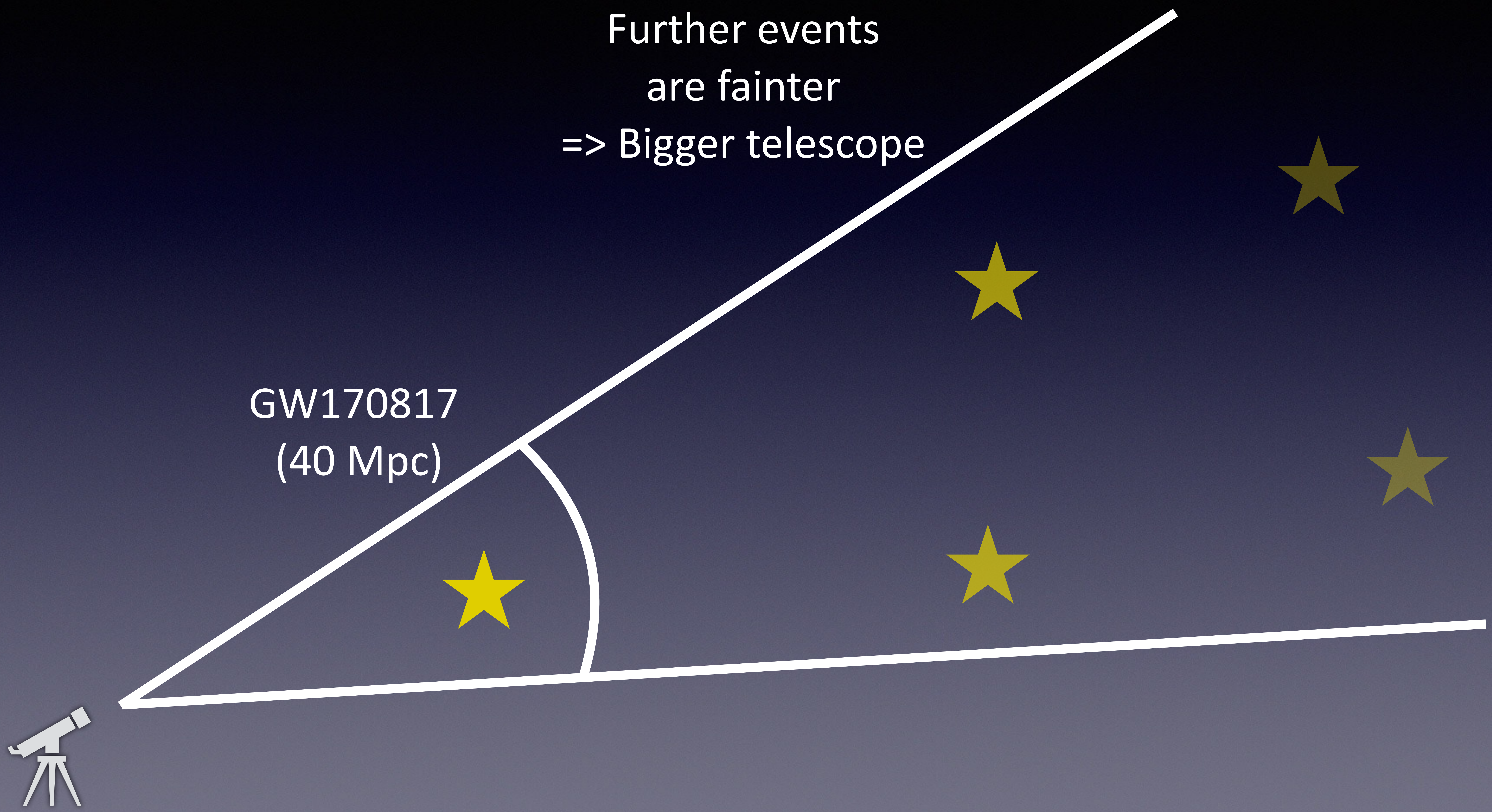
- **Neutron star merger and kilonova**
- **Toward optical-infrared observations**
    - Localization
    - Alert latency



https://observing.docs.ligo.org/plan/

Better sensitivity = more events!

Challenges in optical+infrared observations of NS mergers



Wide-field optical telescopes

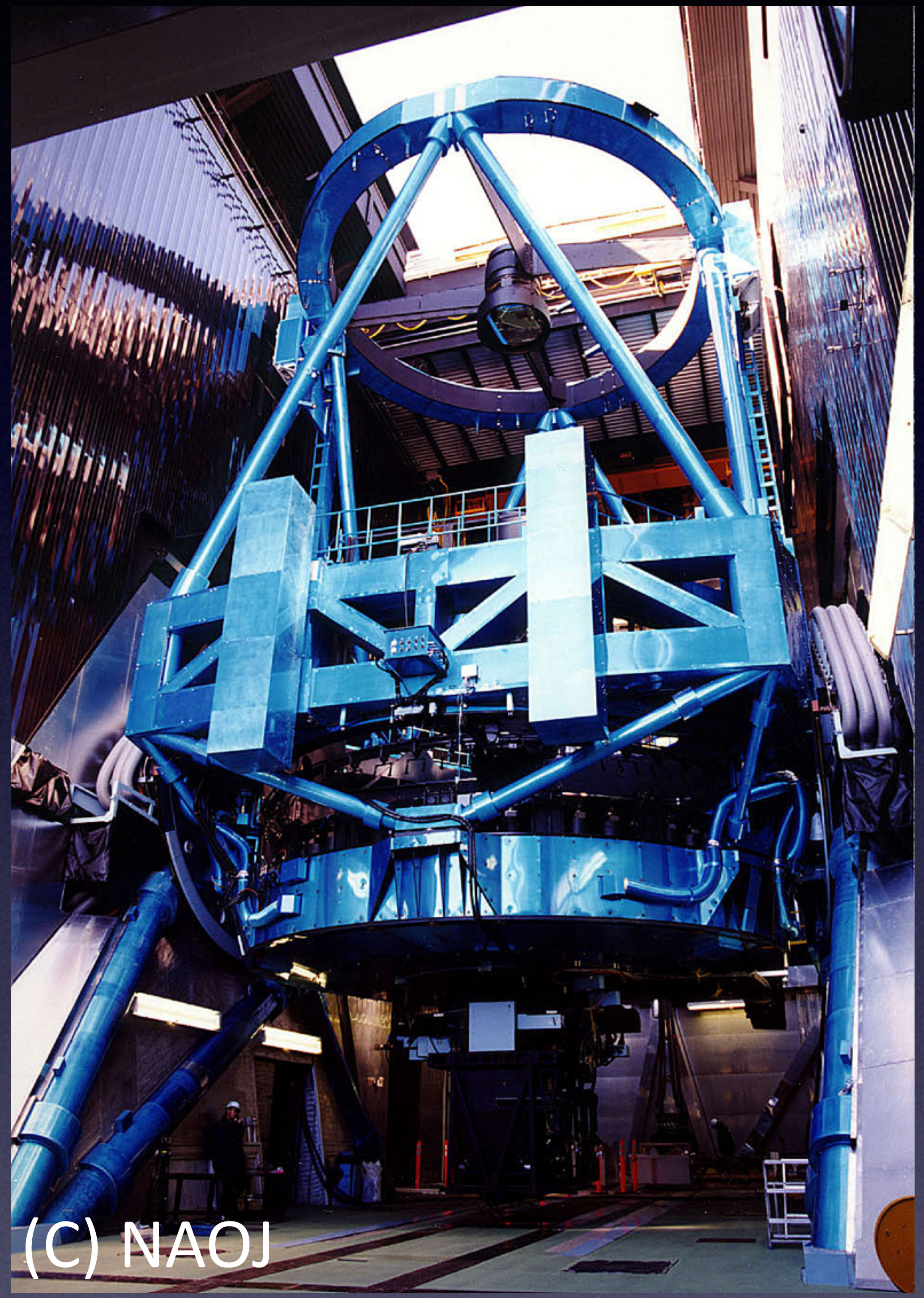
see Niino-san's talk

1m telescope

4m telescope

(C) DOE/FNAL/DECam/R. Hahn/
CTIO/NOIRLab/NSF/AURA

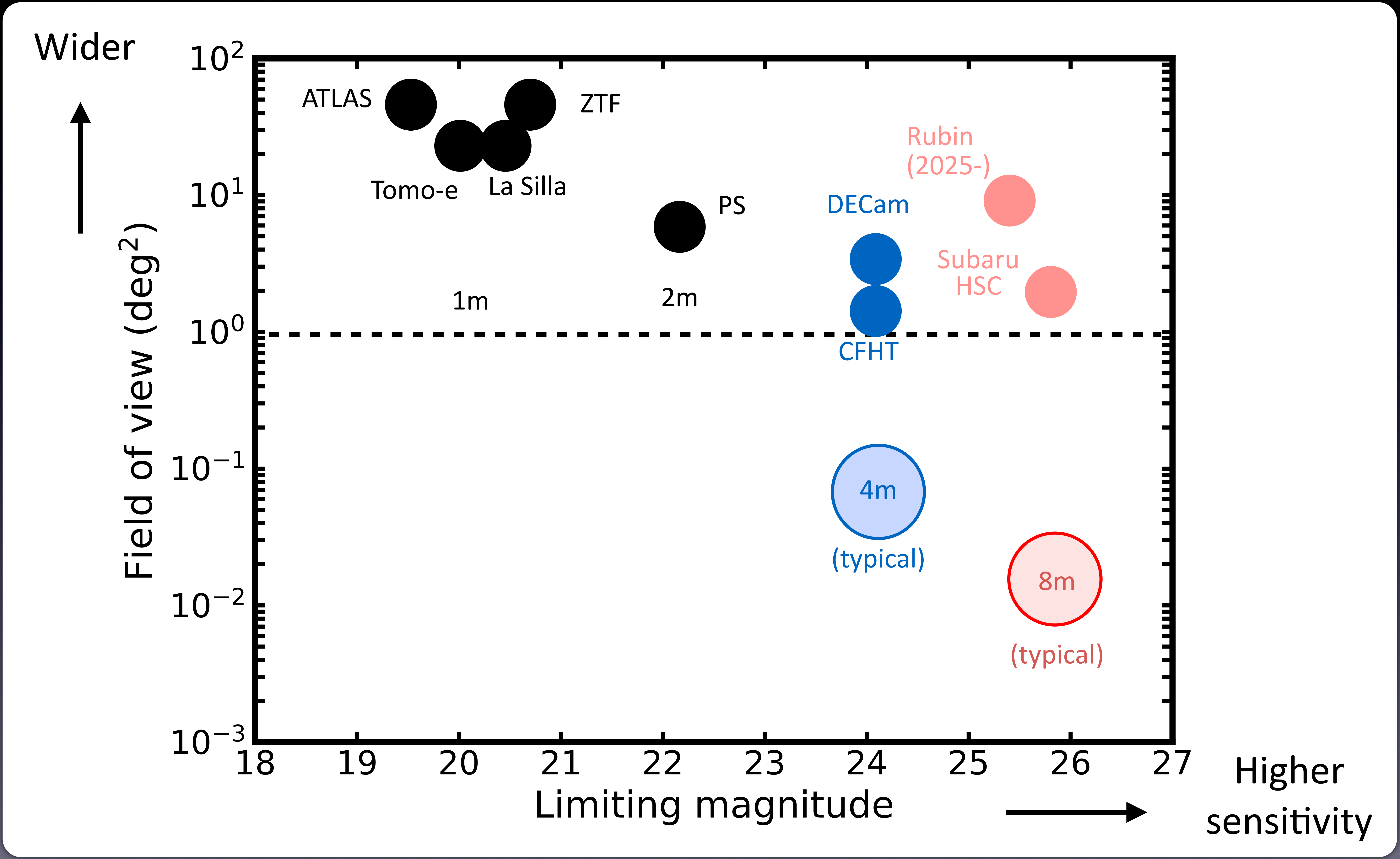
8m telescope



→ **Better sensitivity**

Wider field of view
More telescopes ←

Sensitivity vs field of view



Larger optical telescopes tend to have a smaller field of view

Expected brightness

40 Mpc (GW170817)

Spectroscopy

1m

4m

8m

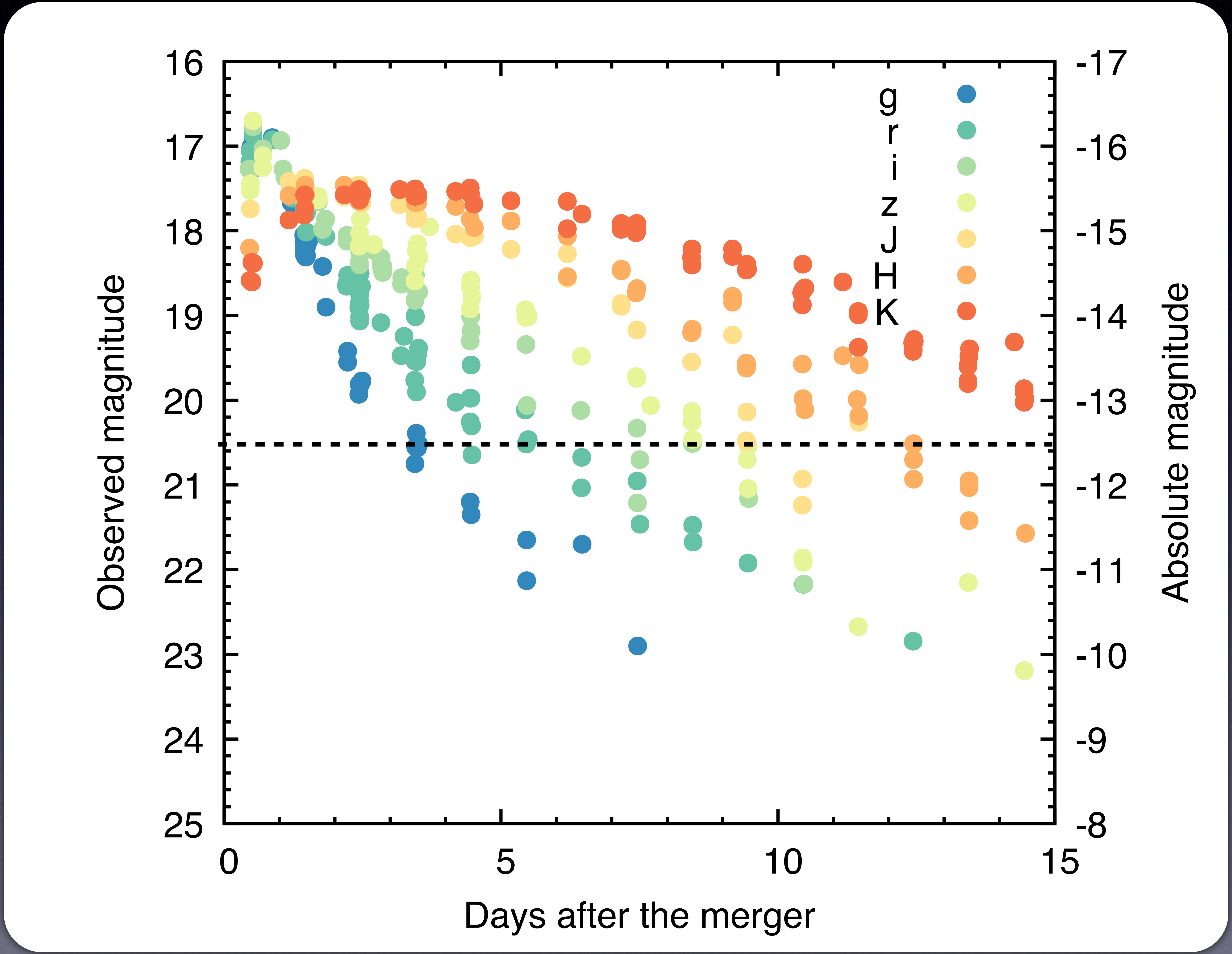
30m
space

Imaging

1m telescope →

4m telescope →

8m telescope →



Expected brightness

100 Mpc

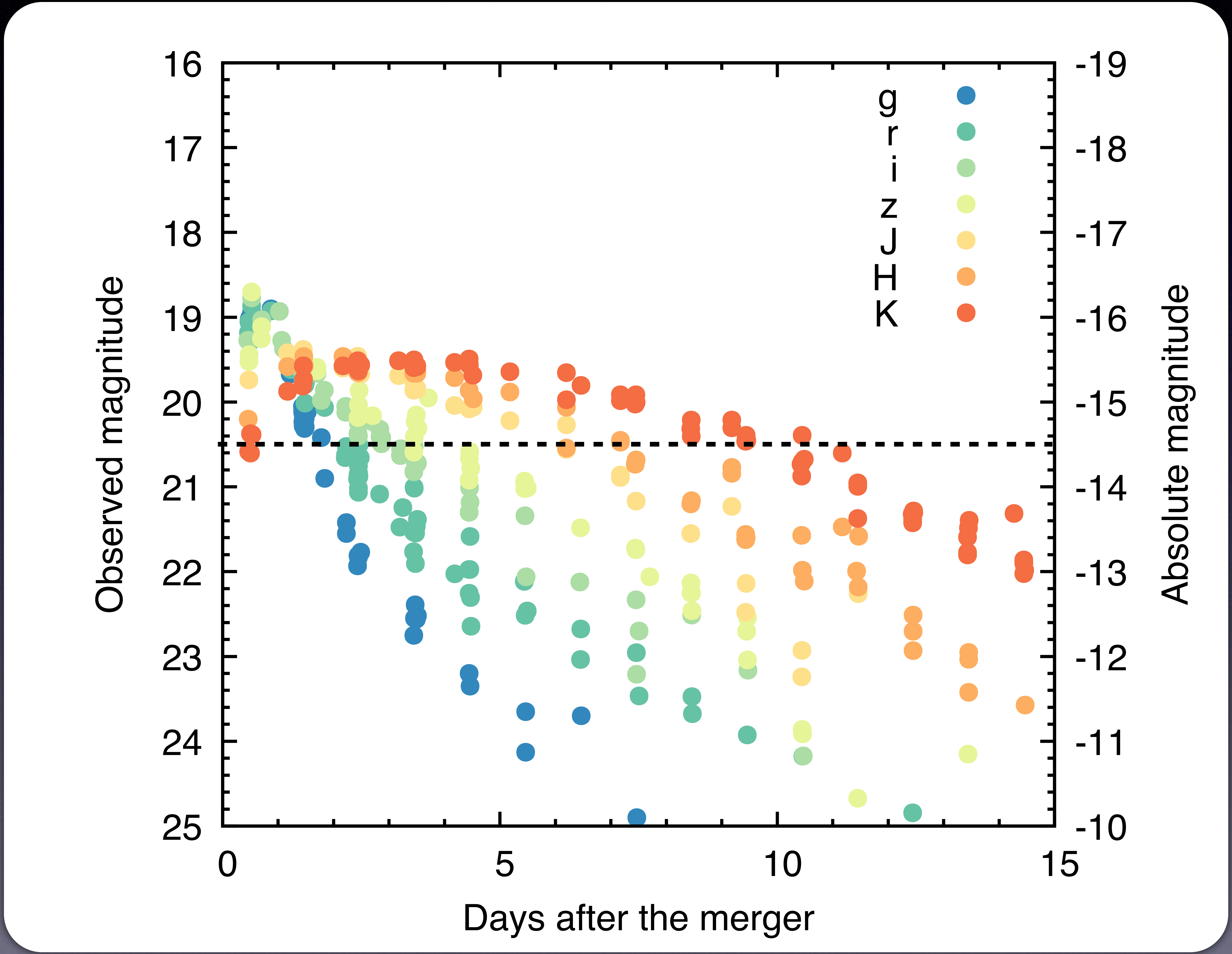
2 mag fainter than GW170817
(x 1/6)

Imaging

1m telescope →

4m telescope →

8m telescope →



Expected brightness

150 Mpc

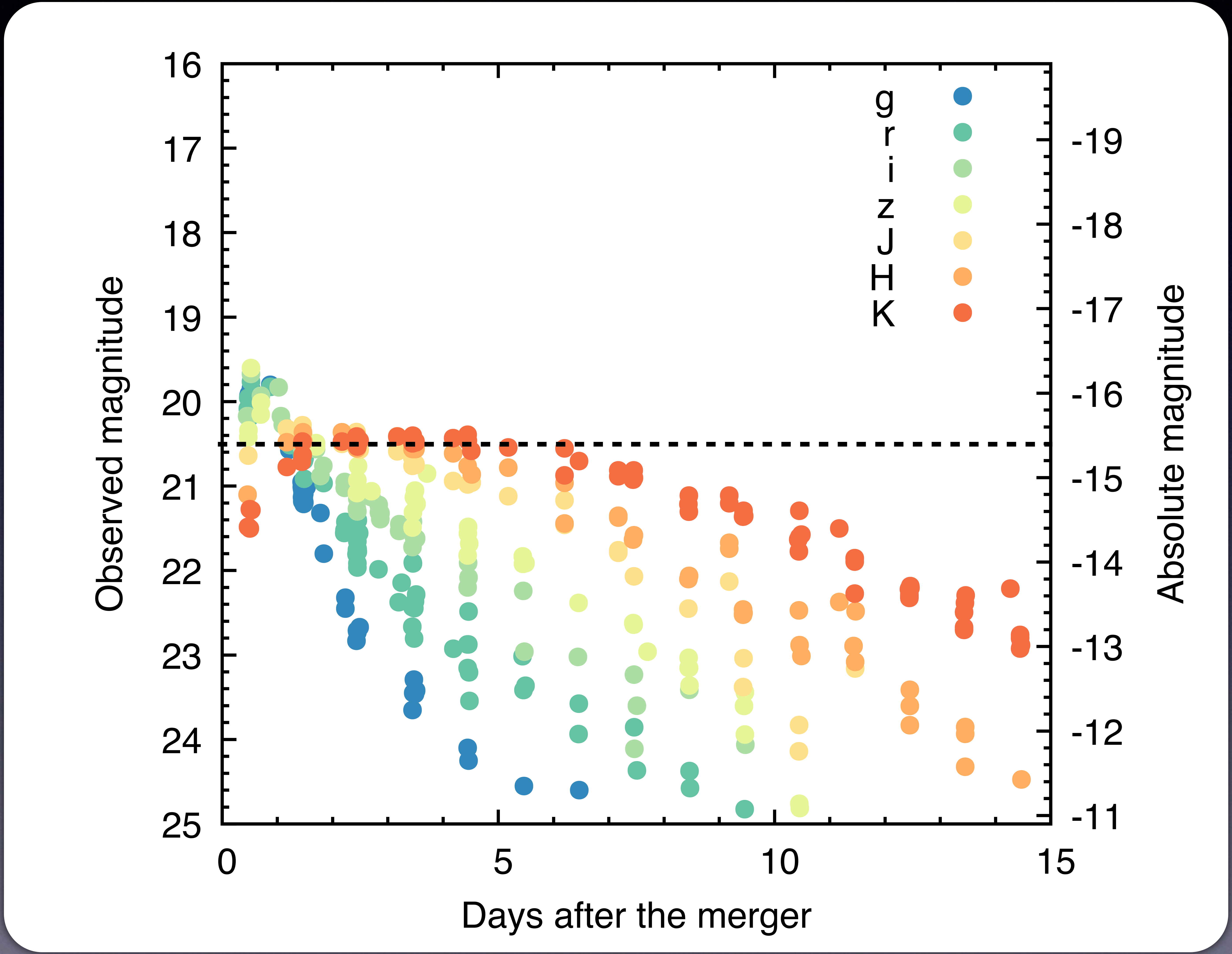
3 mag fainter than GW170817
(x 1/15)

Imaging

1m telescope →

4m telescope →

8m telescope →



Expected brightness

200 Mpc

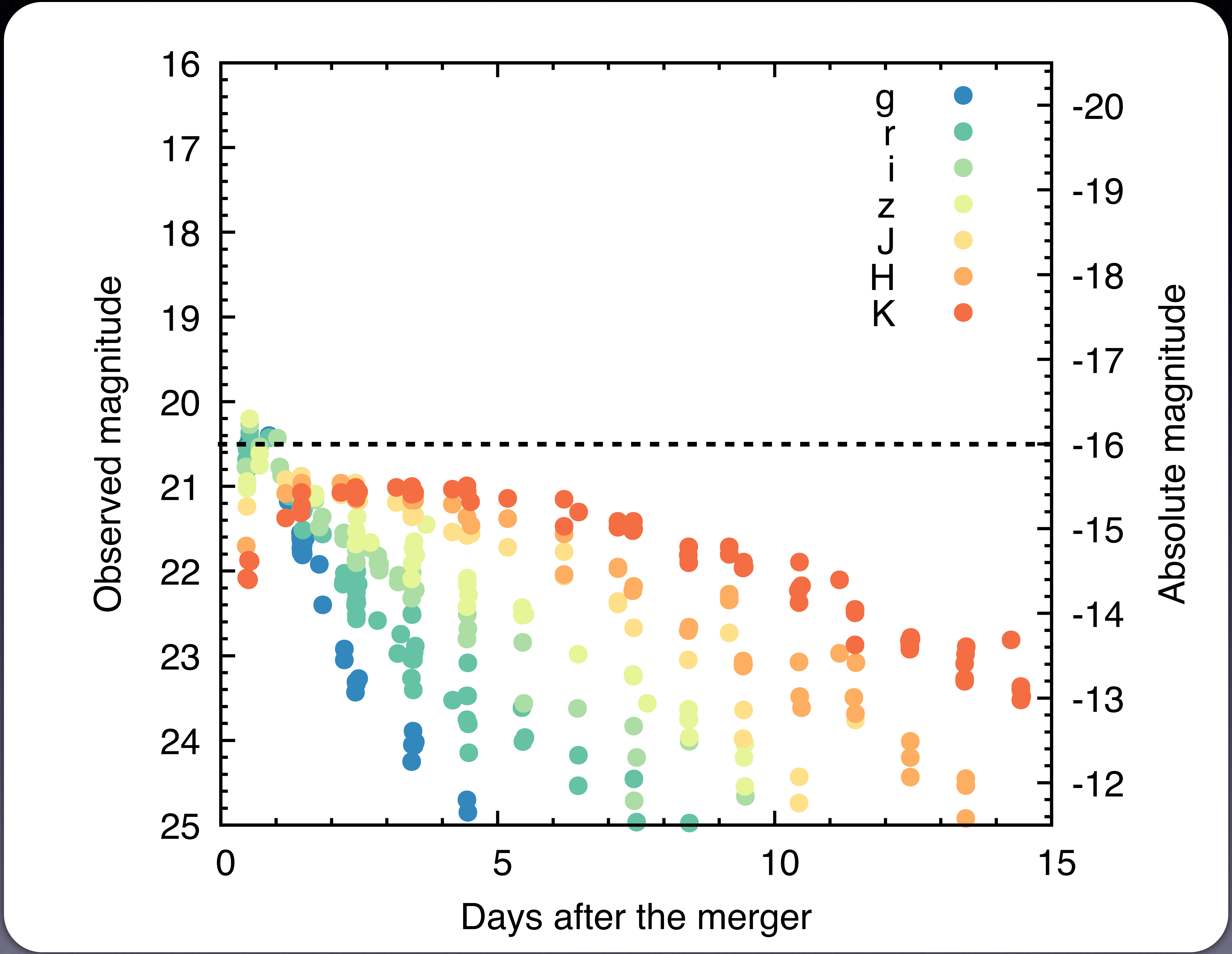
3.5 mag fainter than GW170817
(x 1/25)

Imaging

1m telescope →

4m telescope →

8m telescope →



Expected brightness

400 Mpc

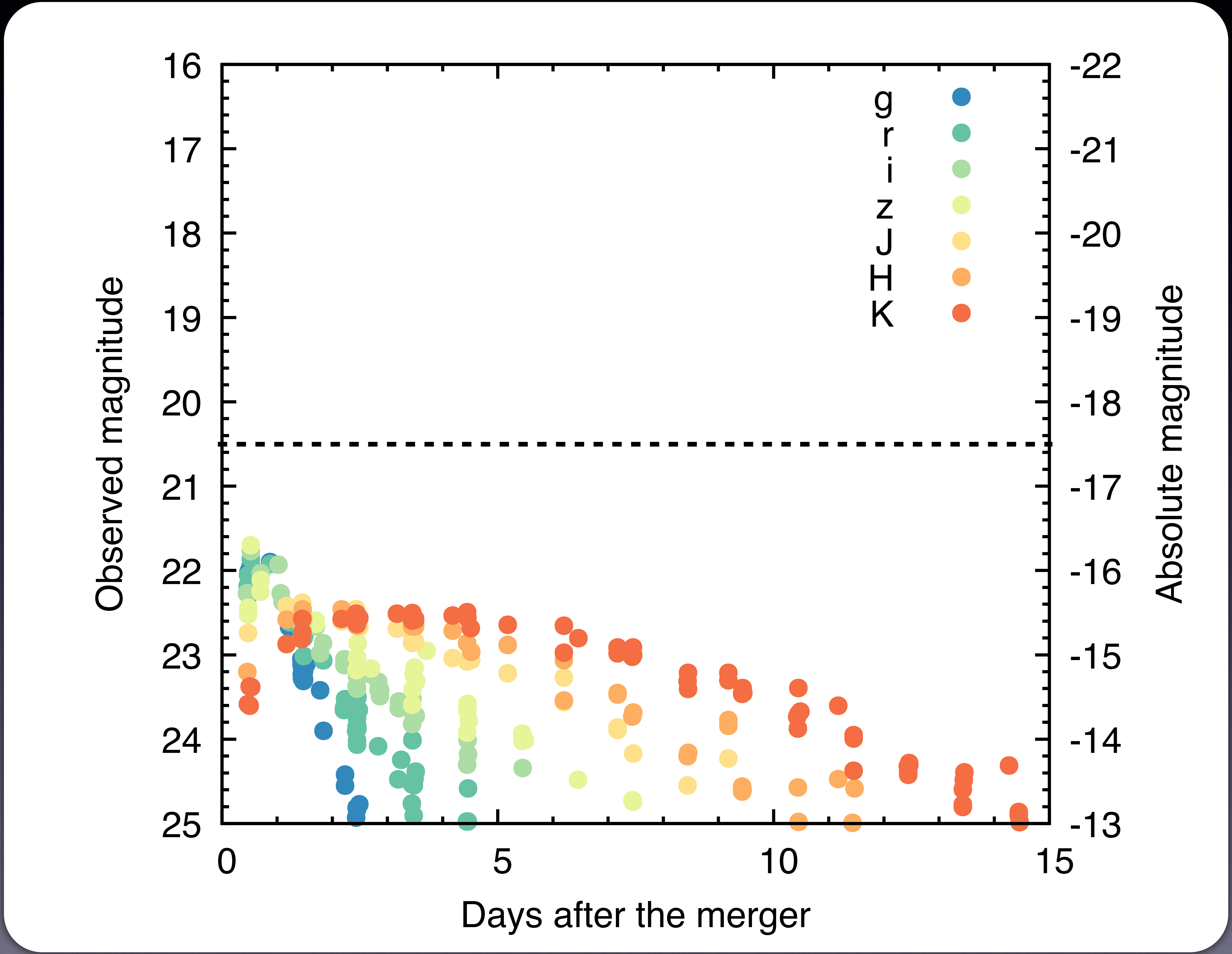
5 mag fainter than GW170817
(x 1/100)

Imaging

1m telescope →

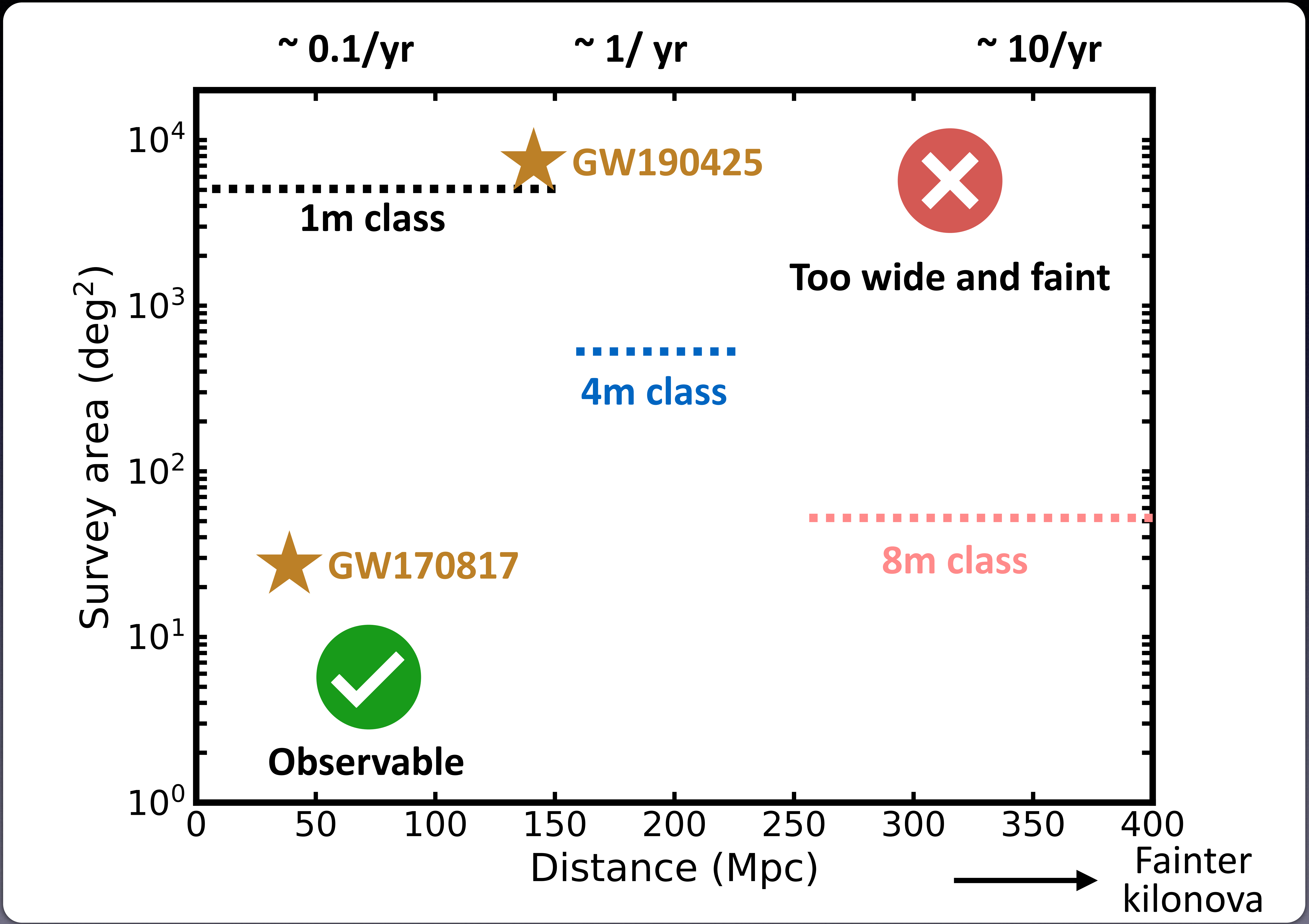
4m telescope →

8m telescope →



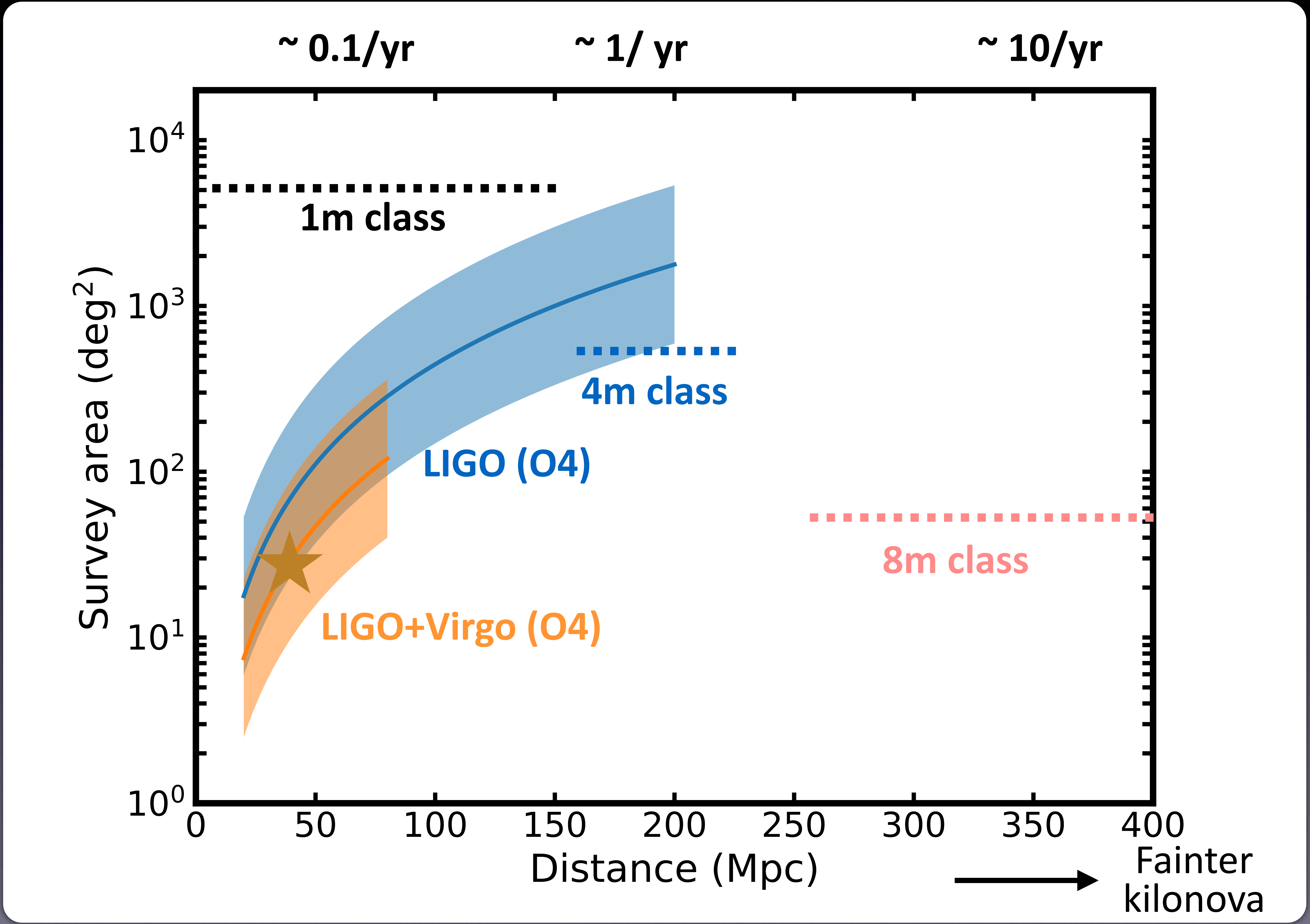
Survey area vs distance

Assumption
Survey area = 100 x FOV
Distance: GW170817 is detectable at 2 day



Survey area vs distance

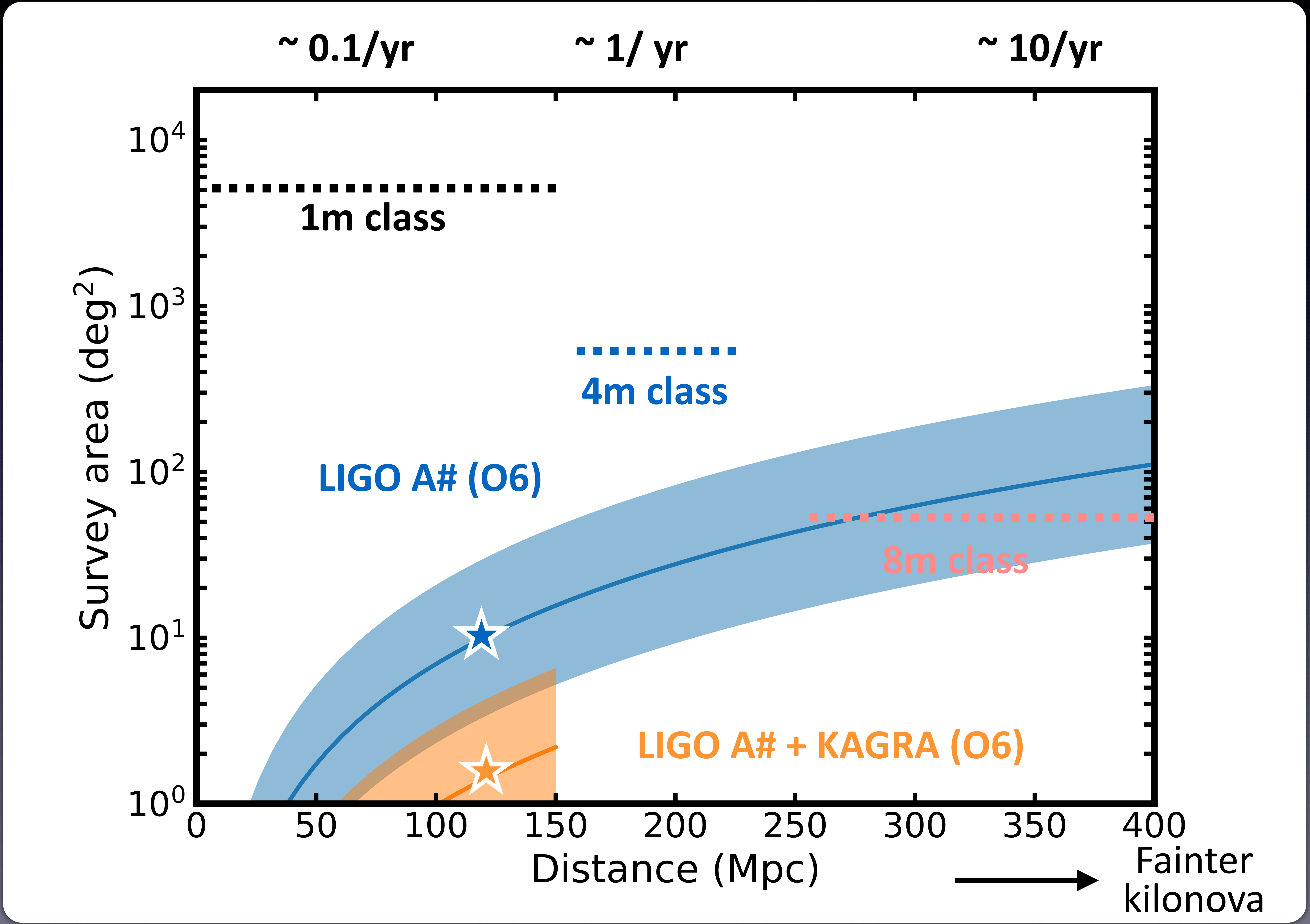
Assumption: $\Delta\Omega \sim (S/N)^{-2} \sim d^2$
LIGO: 1000 deg2 at 150 Mpc
LIGO+Virgo: 30 deg2 at 40 Mp (GW170817)



Survey area vs distance

Assumption: $\Delta\Omega \sim (S/N)^{-2} \sim d^2$
LIGO: 10 deg2 at 120 Mpc
LIGO+KAGRA: 1.2 deg2 at 120 Mpc

Thanks to Michimura-san



IF we are targeting the event at < 150 Mpc

- Current optical survey with 1m class telescopes can detect EM counterpart (ex. GW170817)
- Joint localization with LIGO, Virgo, KAGRA:
  1-10 deg^2 < FOV of the optical telescopes!
  One-pointing will find EM counterpart (no more "search")
- Low event rate…

Table courtesy of Michimura-san

		KAGRA	A# (LIGO O6 upgrade)	LF2019	LF2024	BB2019	BB2024	HF2019	HF2024	HF3k
BBH / BNS ranges (SNR>8)	$100M_\odot$ - $100M_\odot$	353 Mpc	4927 Mpc	2019 Mpc	3787 Mpc	306 Mpc	2154 Mpc	112 Mpc	200 Mpc	277 Mpc
	$30M_\odot$- - $30M_\odot$	1095 Mpc	6144 Mpc	1088 Mpc	2382 Mpc	842 Mpc	4229 Mpc	270 Mpc	407 Mpc	552 Mpc
	$1.4M_\odot$ - $1.4M_\odot$	153 Mpc	670 Mpc	85 Mpc	196 Mpc	178 Mpc	537 Mpc	155 Mpc	133 Mpc	104 Mpc
BNS sky localization ※		10.64 deg^2 (HL-only) → 1.40 deg^2 (with K)		10.28 deg^2	2.65 deg^2	0.77 deg^2	0.42 deg^2	0.57 deg^2	0.61 deg^2	0.93 deg^2

120 Mpc

IF the majority of BNS events are at > 150 Mpc...

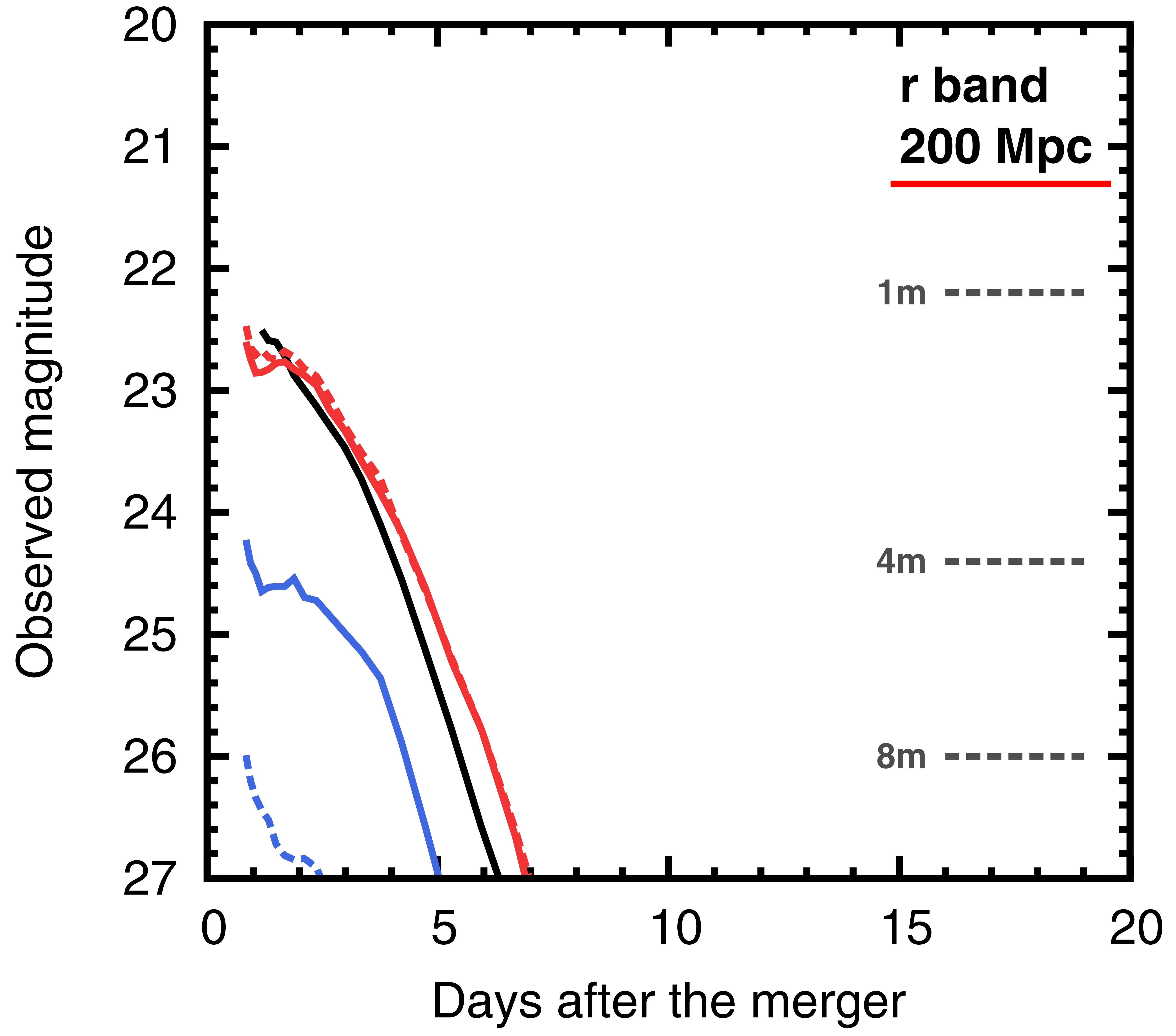
- Optical follow-up requires a relatively deep observations (deep survey for > a few 1000 deg^2 is challenging)
- Follow-up will be feasible with upcoming GW observing run (O5-O6)
- Further improvement in the localization (w/ Virgo, KAGRA) enhances the chance of multi-messenger observations
- Sensitivity is the most important (contributing to the event at > 150 Mpc)

“Common sense” before 2017…

6.1. Follow-up Observations of EM Counterparts

In this section, we discuss the detectability of UVOIR emission from NS merger ejecta. Figure 8 shows the expected observed light curves for an NS merger event at 200 Mpc. The model NSM-all (black) and four realistic models (red and blue) are shown. Note that all the magnitudes in Figure 8 are given in the AB system for ease of comparison with different survey projects. The horizontal lines show 5σ limiting magnitudes for different sizes of telescopes assuming 10 minute exposure times.

MT & Hotokezaka 13



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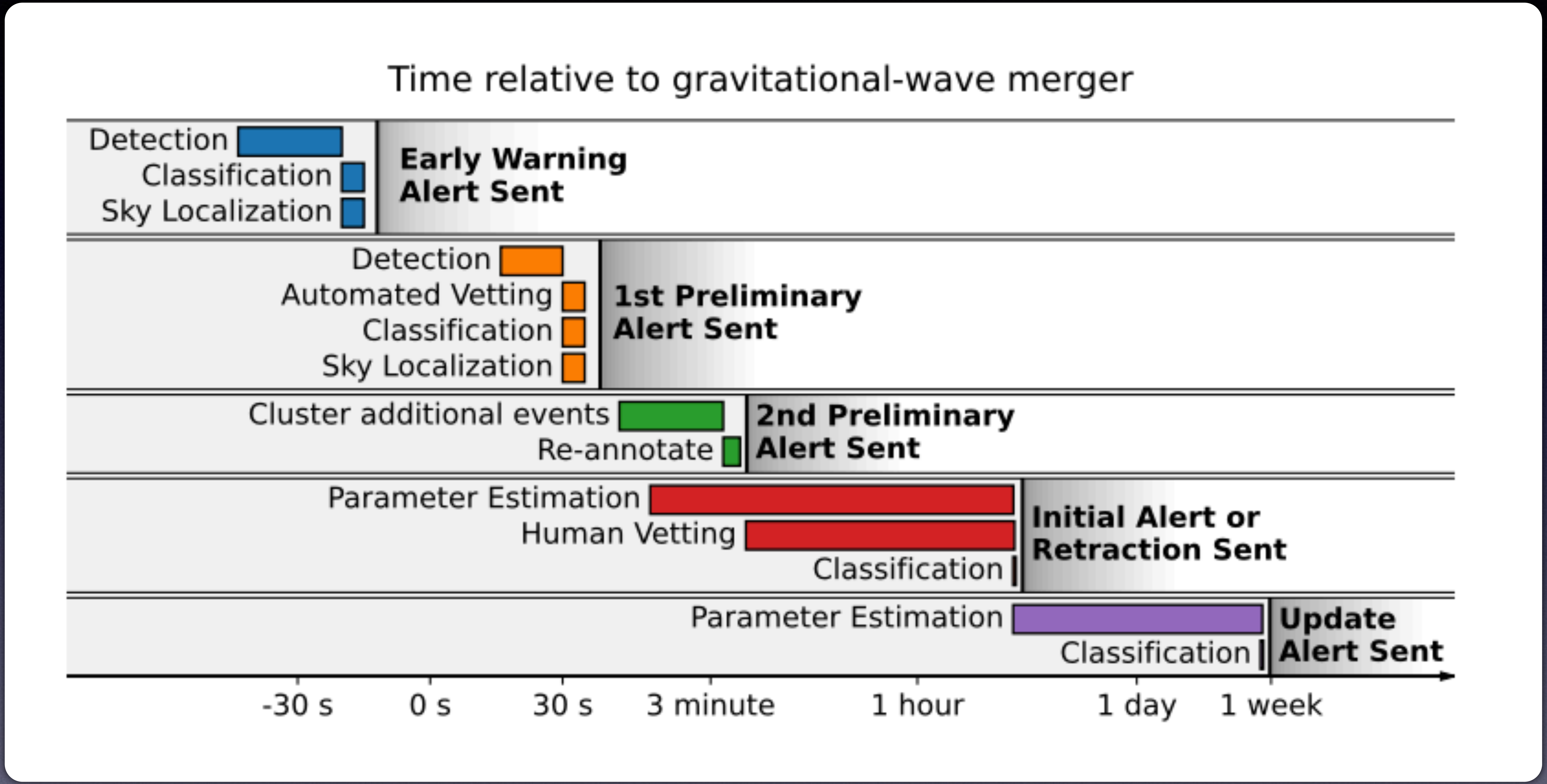
Timeline



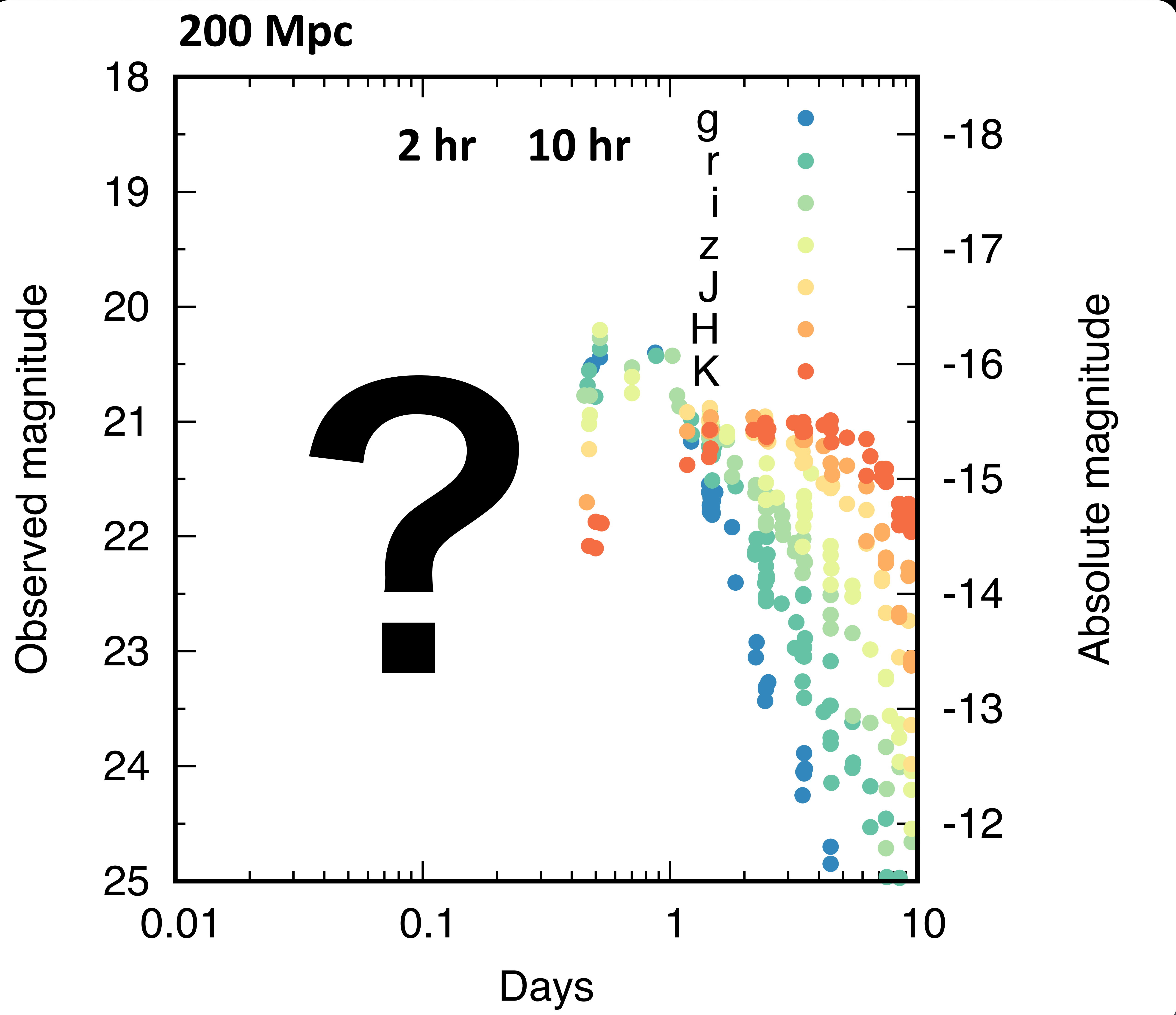
GRB

see Serino-san's talk

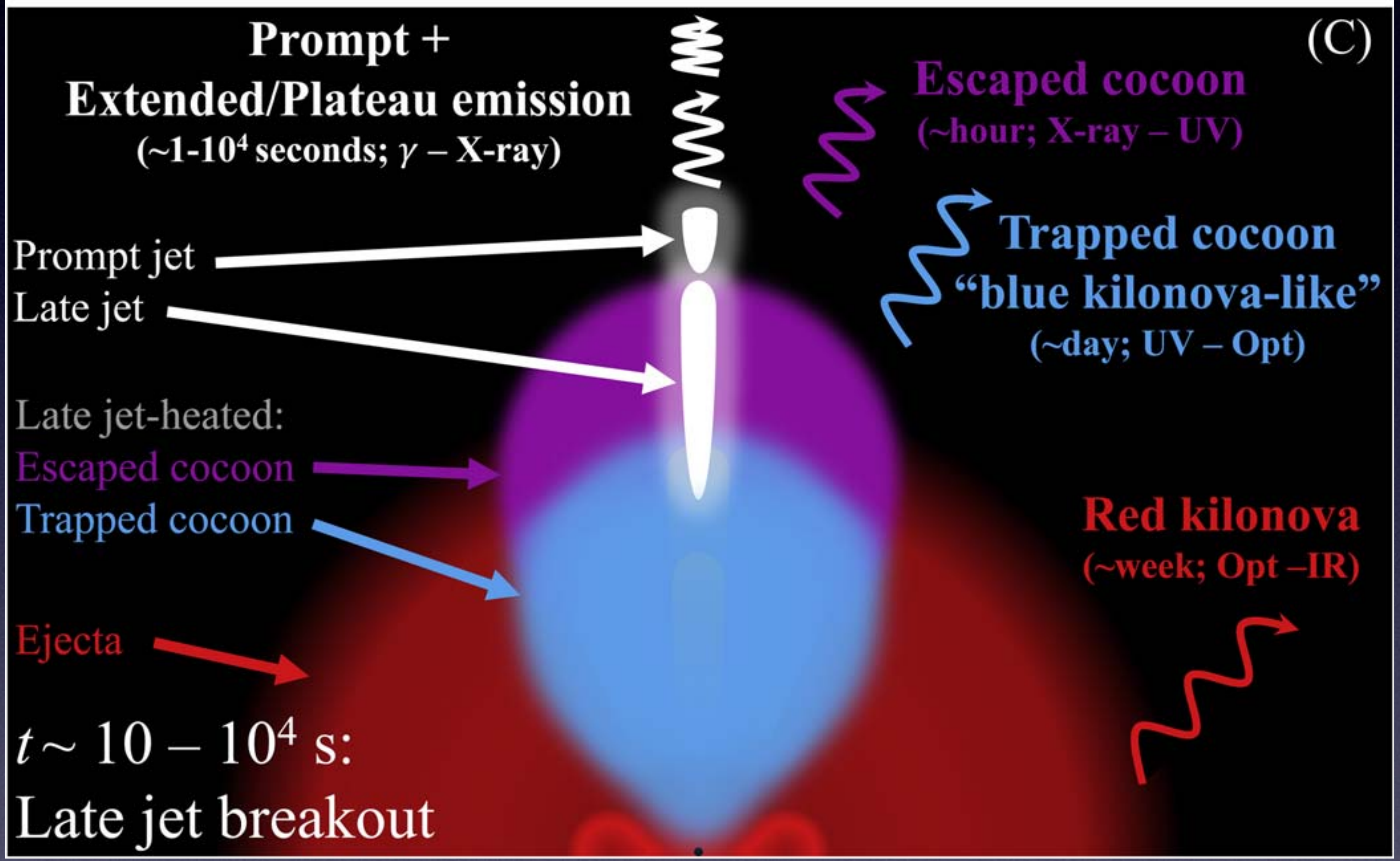
Kilonova

https://emfollow.docs.ligo.org/userguide/analysis/index.html#alert-timeline

Early kilonova emission

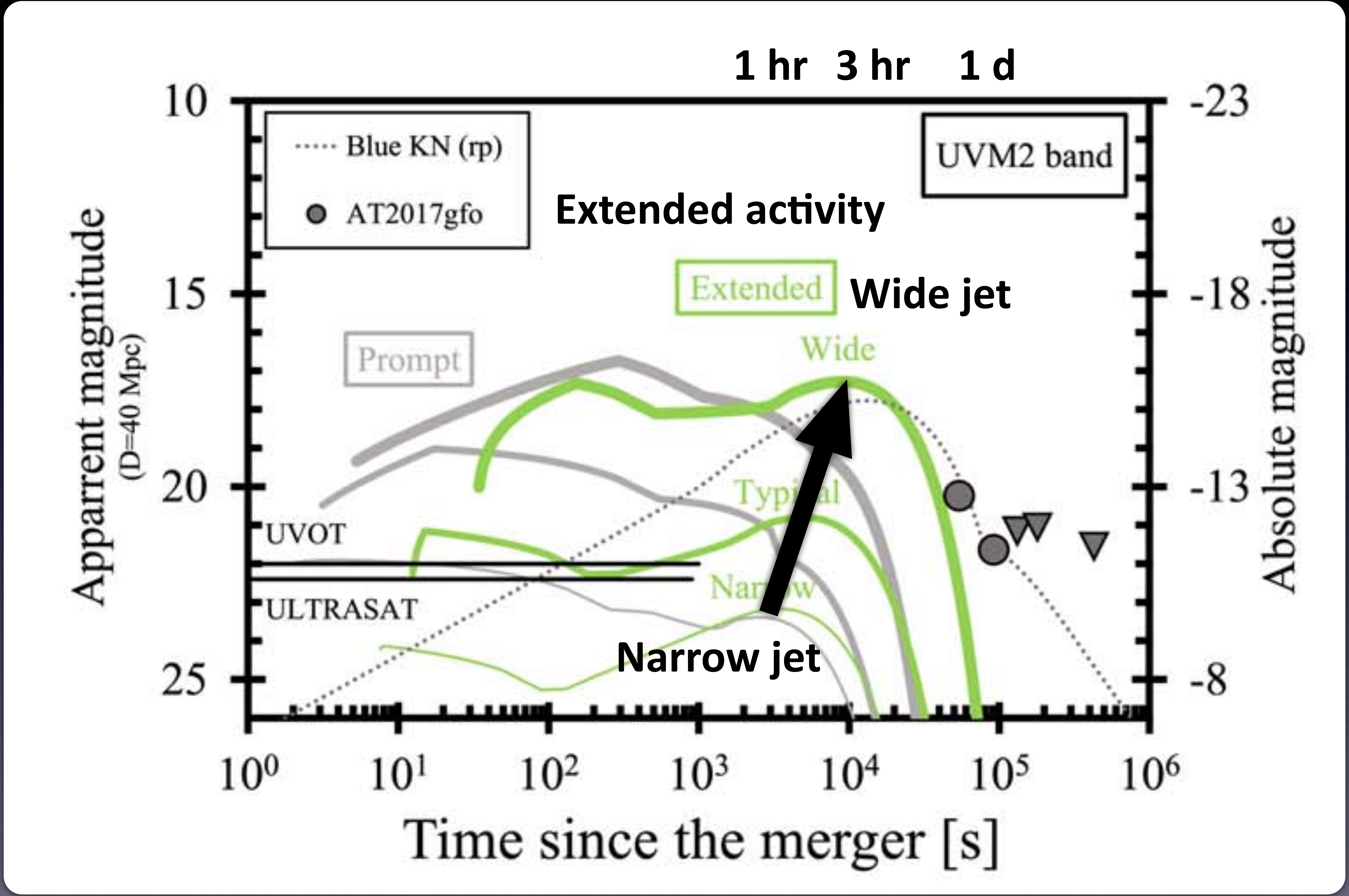


Additional emission from jet-cocoon (mainly in UV)



Hamidani+23,24

Probe of the central engine



Future wide-field UV satellites (PETREL, ULTRASAT, UVEX, …)

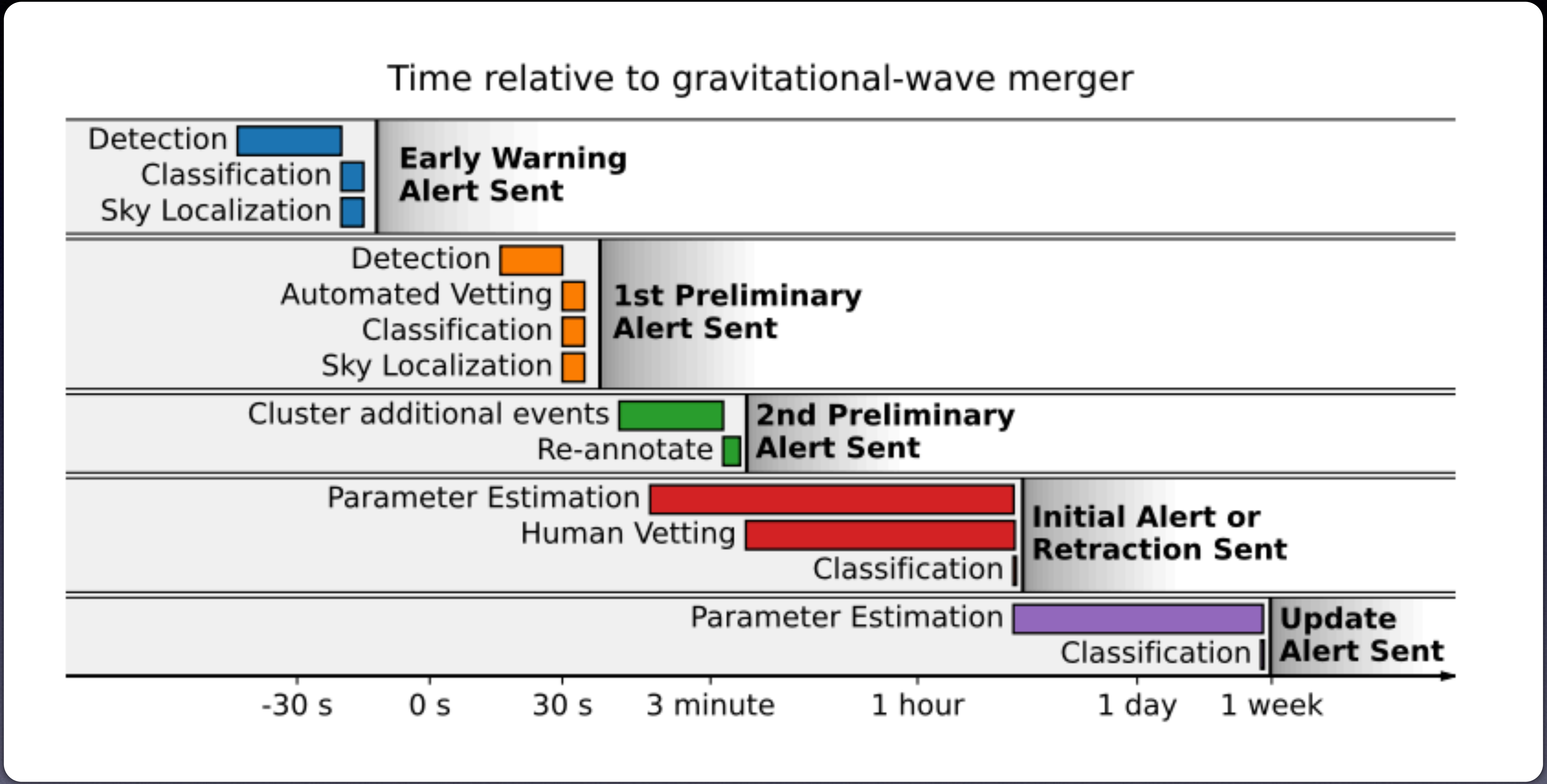
Hamidani+24

Important timescale = 1 hr

(~ practical observational timescale: communication, pointing, exposure, …)

Important information for follow-up observations

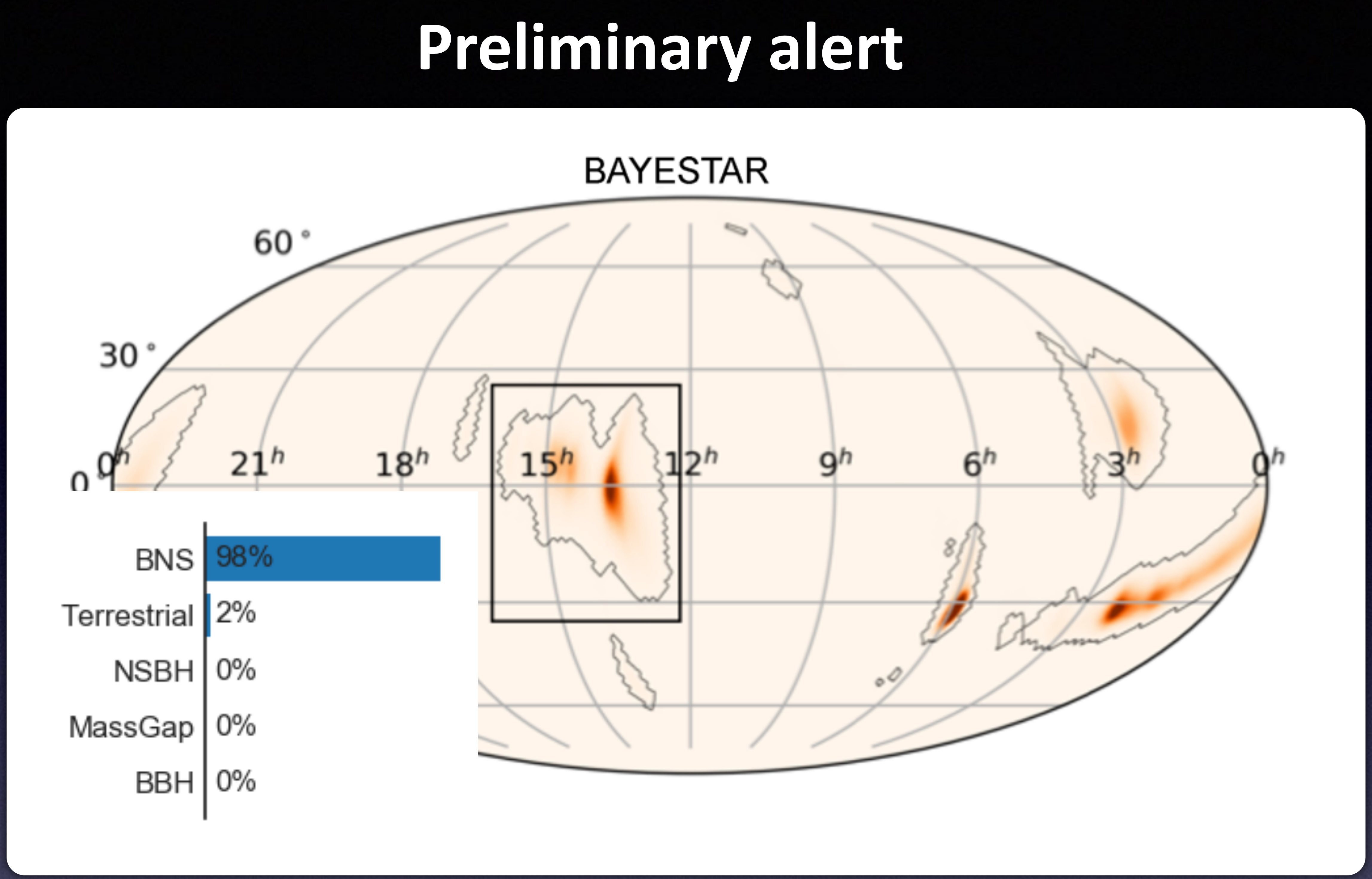
Retraction: as early as possible… (< 1 hr)

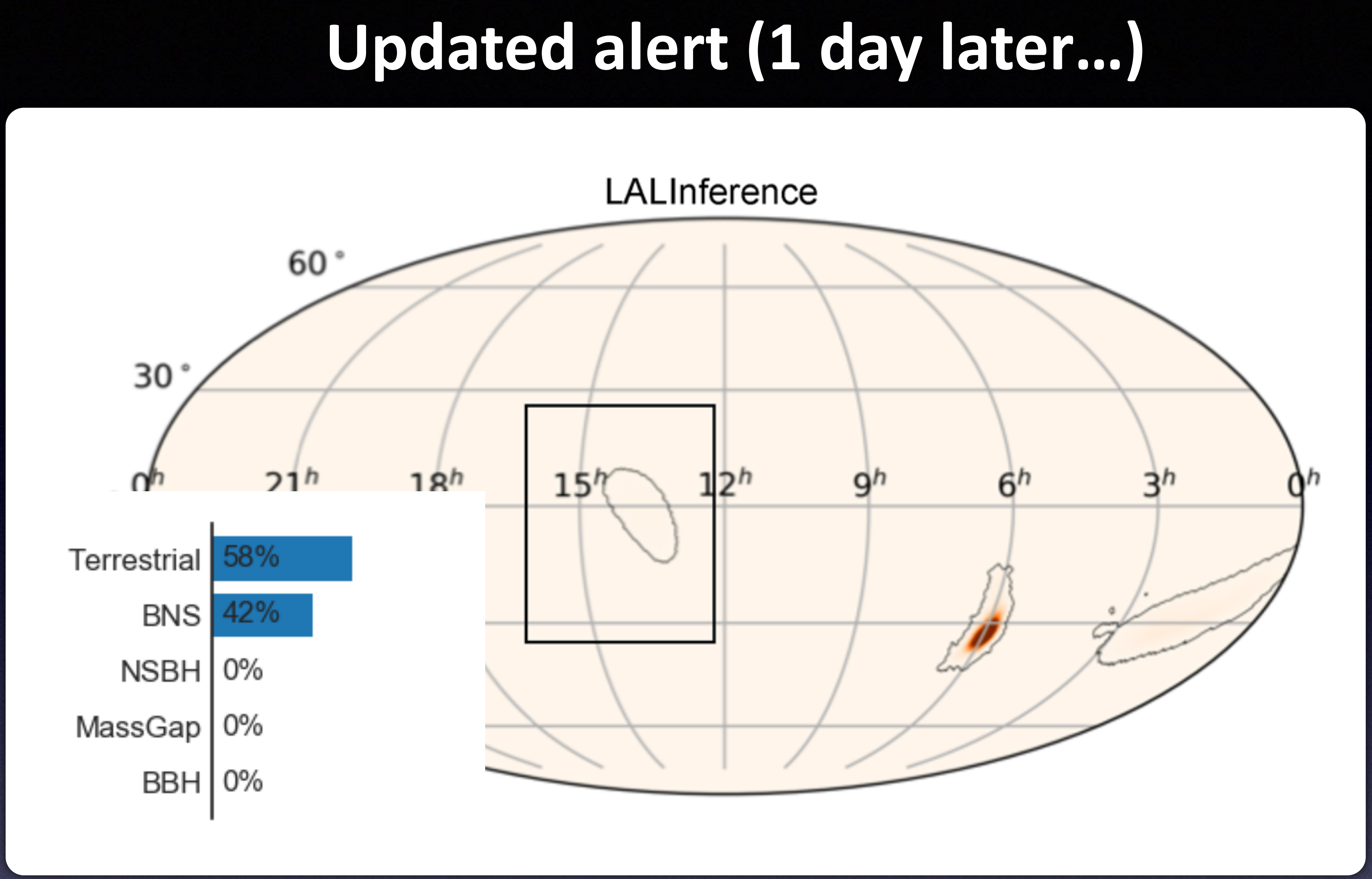


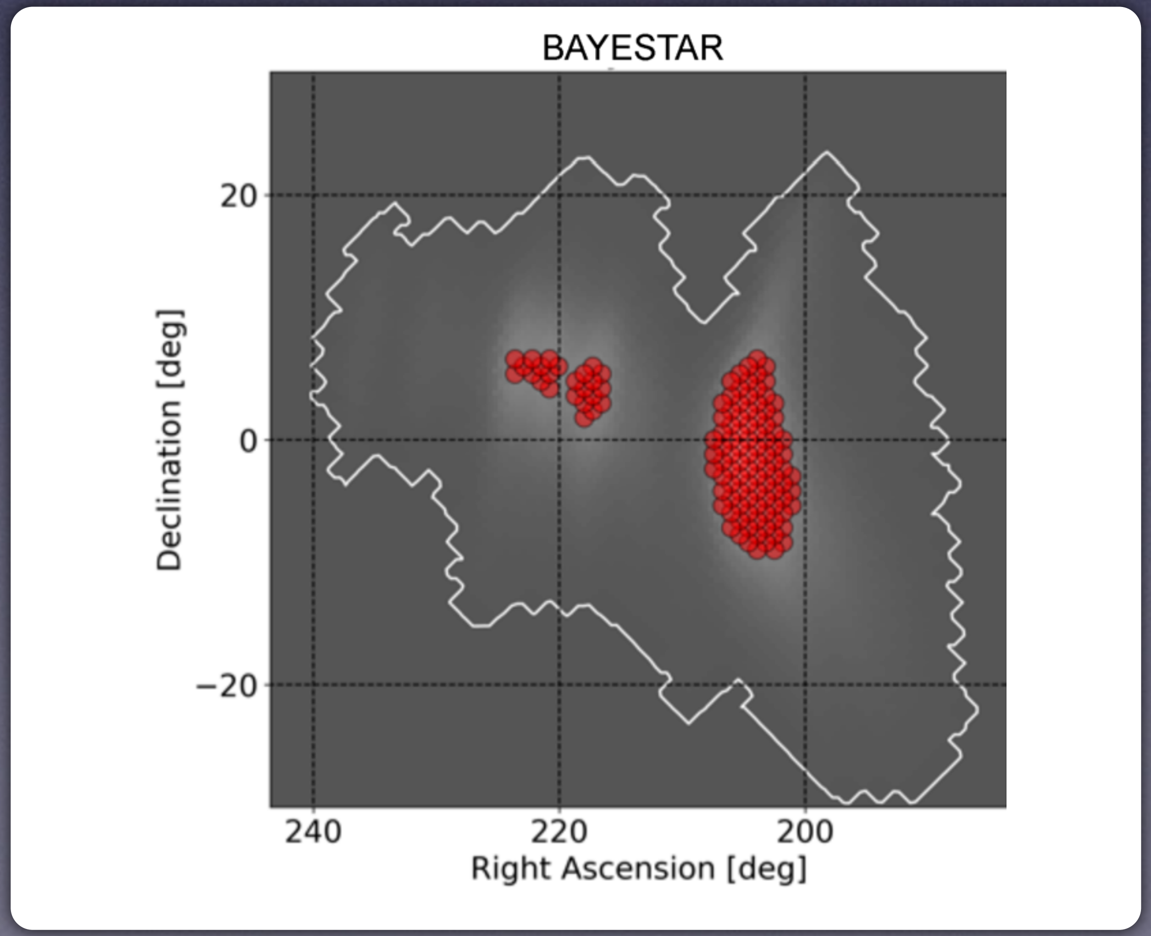
Updated sky map: as early as possible… (< 1hr)

https://emfollow.docs.ligo.org/userguide/analysis/index.html#alert-timeline

Importance of rapid source classification/localization







118 deg^2 (!) observations
with Subaru/HSC
1.7 hours after the alert
(S190510g, Ohgami+21)

Conservative classification/localization including systematics would be appreciated

Summary

- **Neutron star mergers and kilonova**
  - Production site of heavy elements
  - Diversity in nucleosynthesis depending on merging system
- **Localization**
  - BNS events at < 150 Mpc are already feasible (but event rate is not high)
  - BNS events at > 150 Mpc require relatively deep observations
    - < a few x 100 deg^2 localization at > 150 Mpc (O5-O6)
- **Alert latency**
  - Hour timescale emission can be a probe of central engine
  - Accurate (and conservative) classification and sky map within 1 hr are appreciated