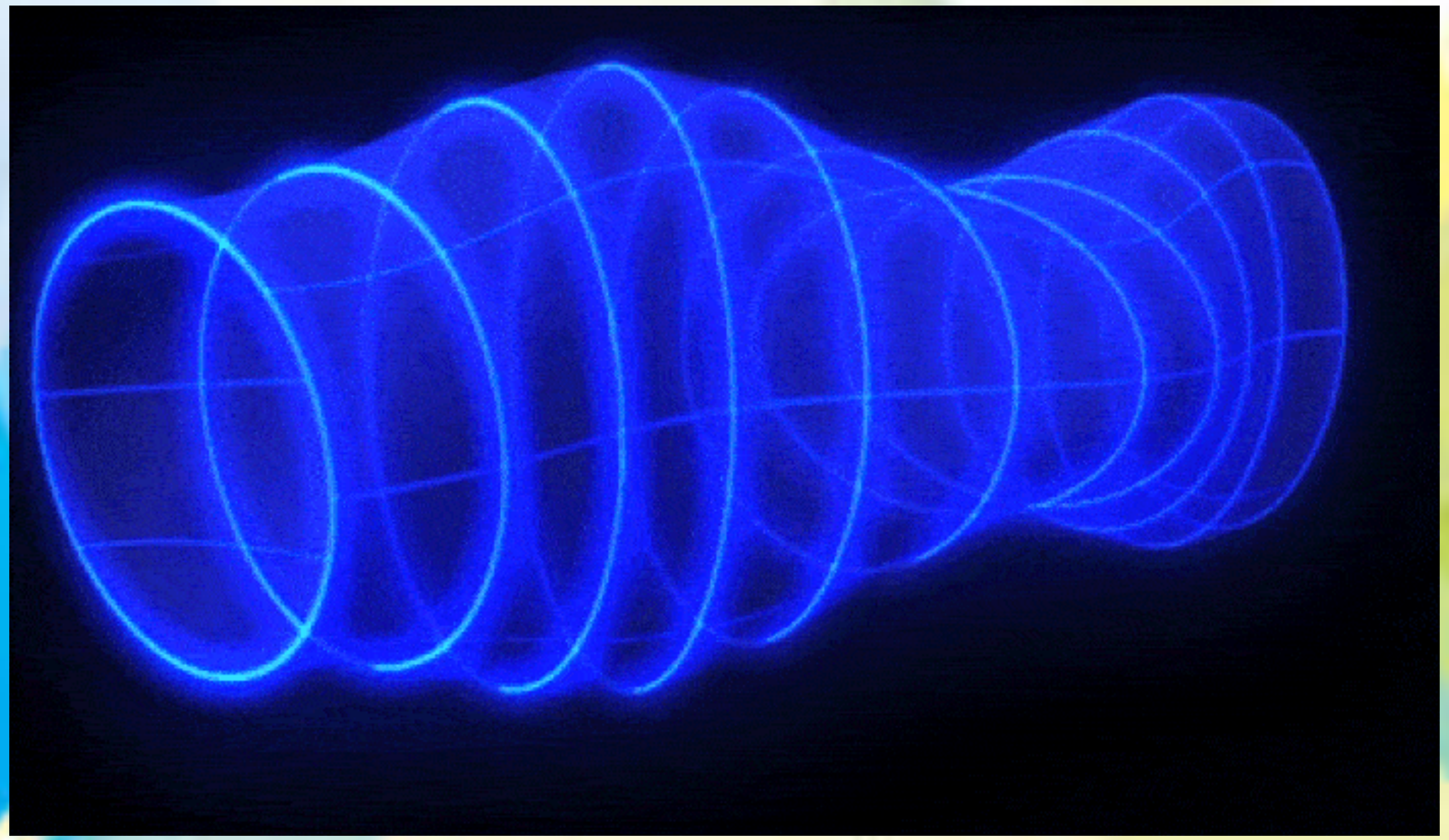
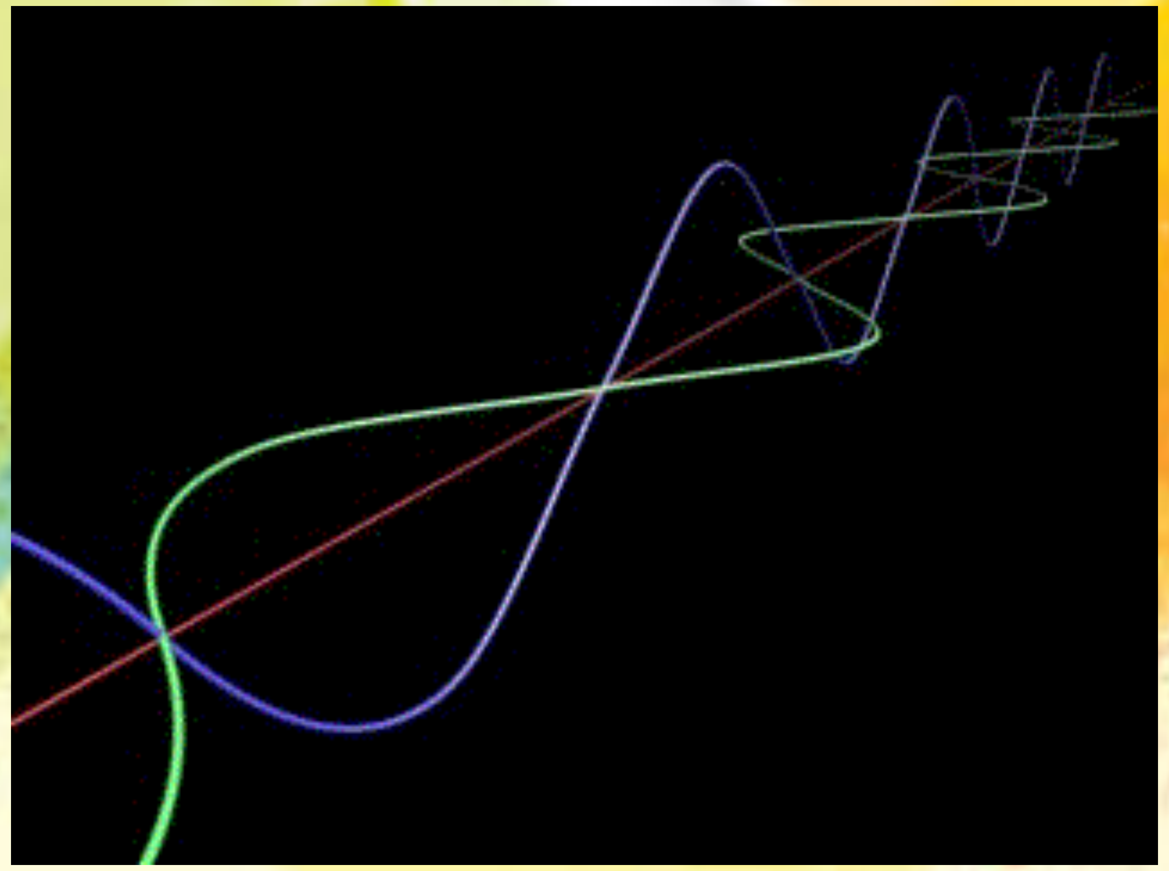
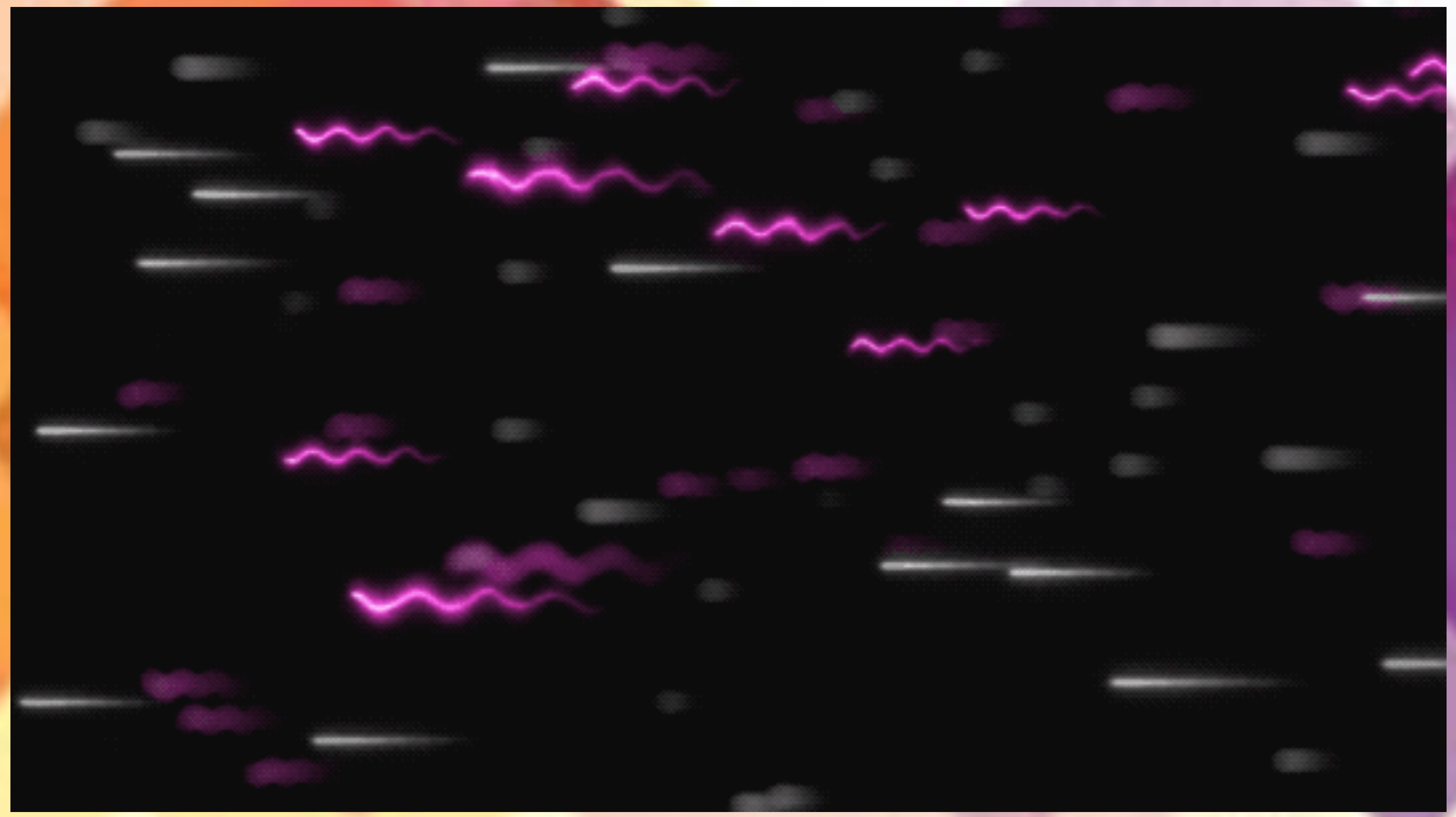
Multi-messenger Astronomy (MMA) in the 3G era



Gravitational Waves - Listening to the Universe



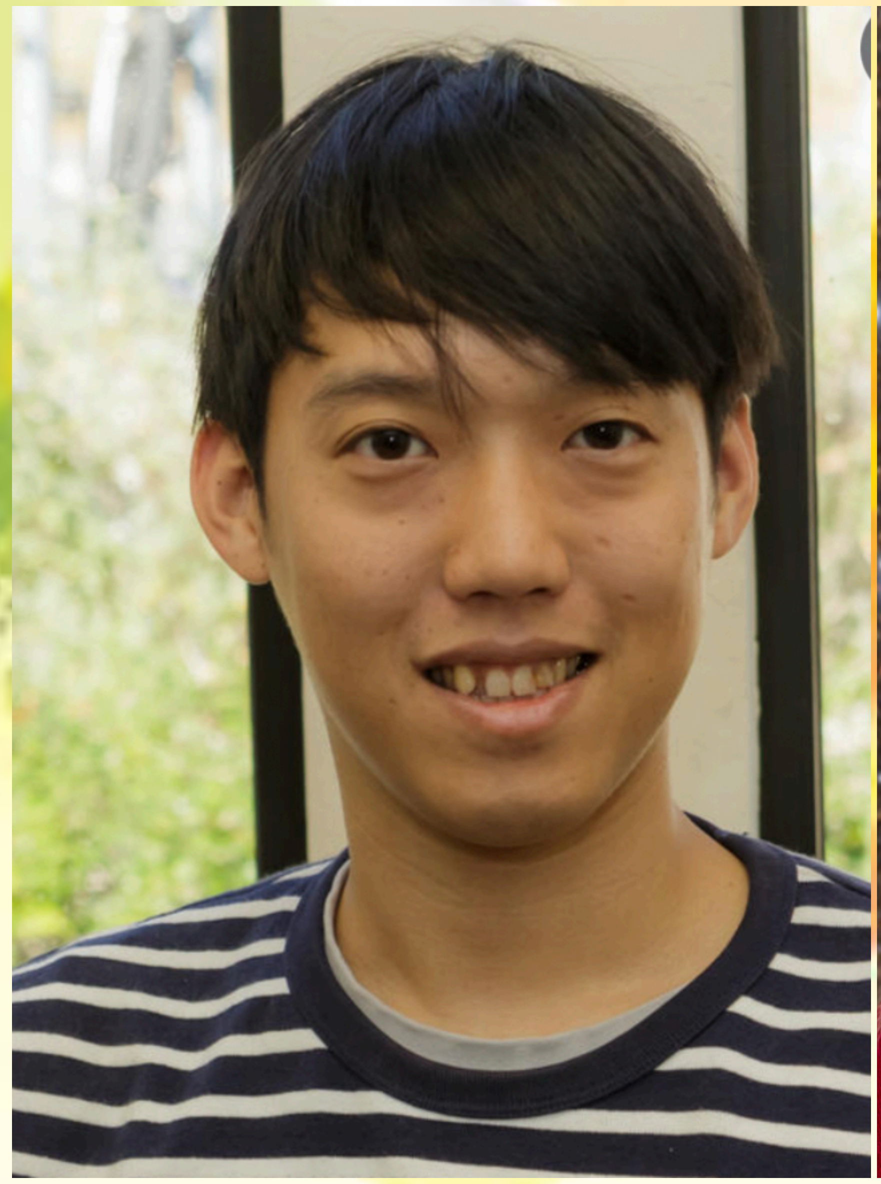
Electromagnetic - Eyes of the Universe



neutrino- Flavor of the Universe

Multi-messenger Astronomy (MMA) in the 3G era


Chairs: **Ashley Villar** (Penn State) & **Poonam Chandra** (NRAO)



Kenta Hotikezaka

(U Tokyo)

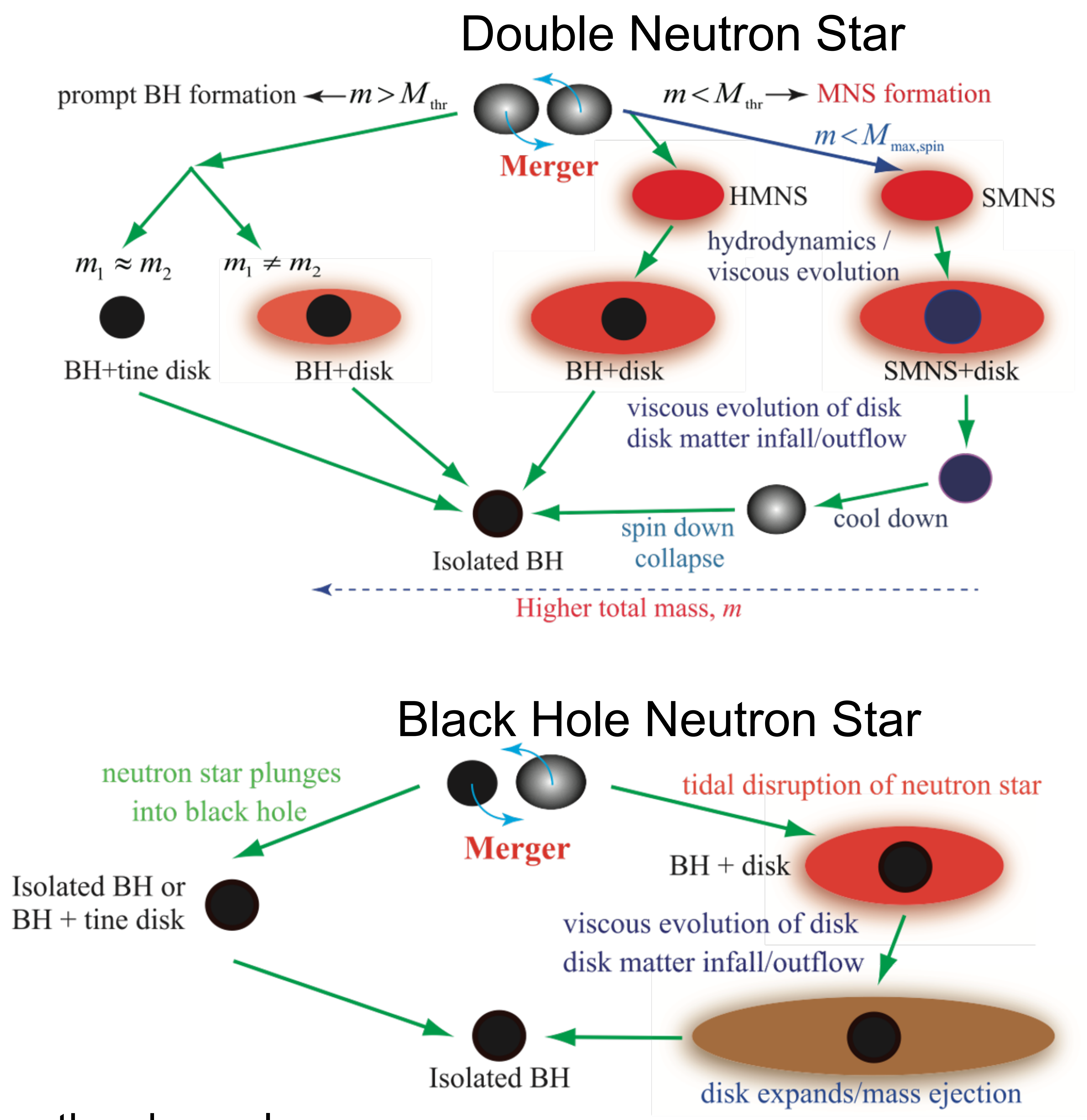
Alessandra Corsi

(Texas Tech)

Charlie Kilpatrick

(Northwestern)

Diversity in neutron star mergers



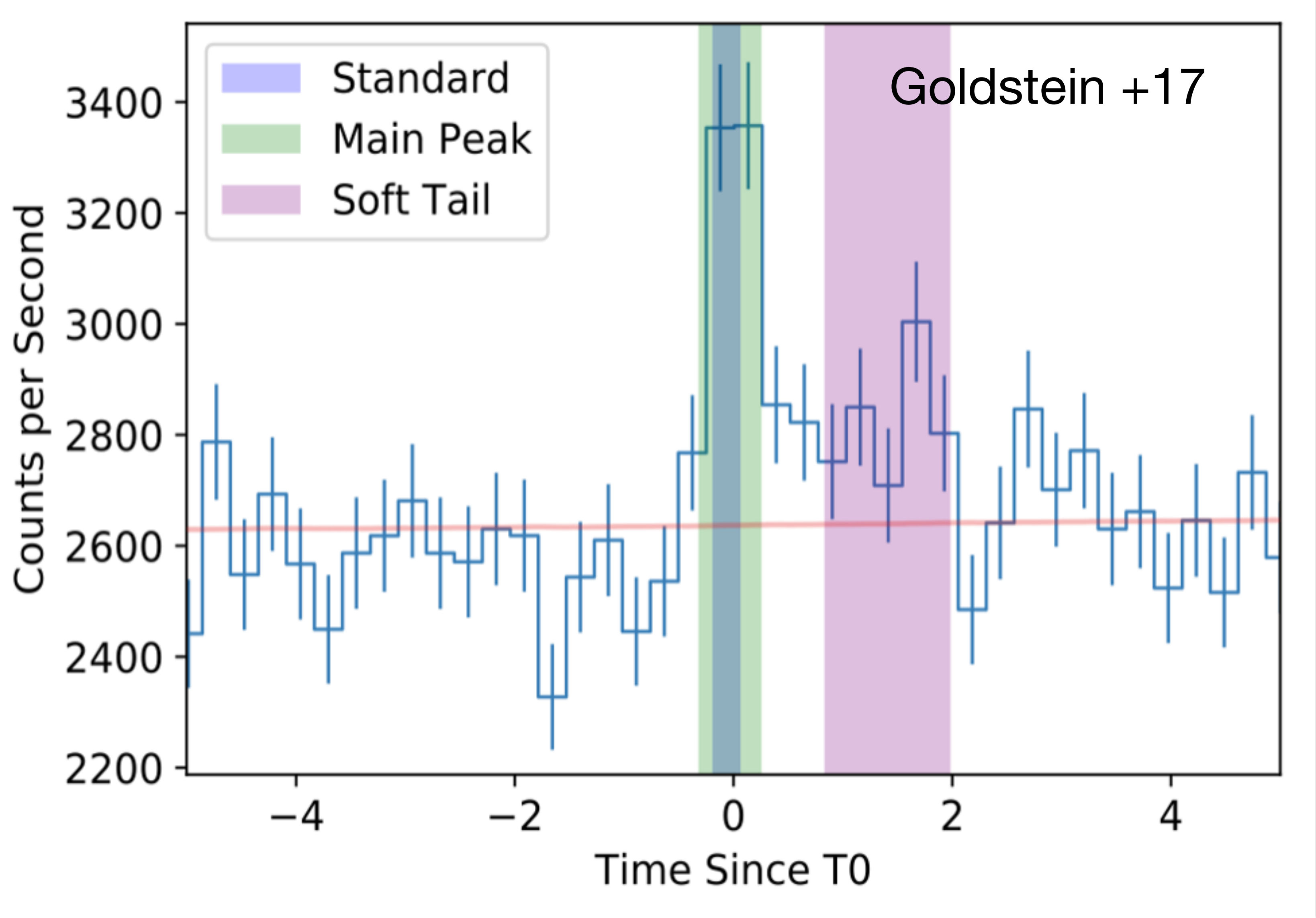
Shibata & KH 19

3G detectors can see this phase for nearby events.

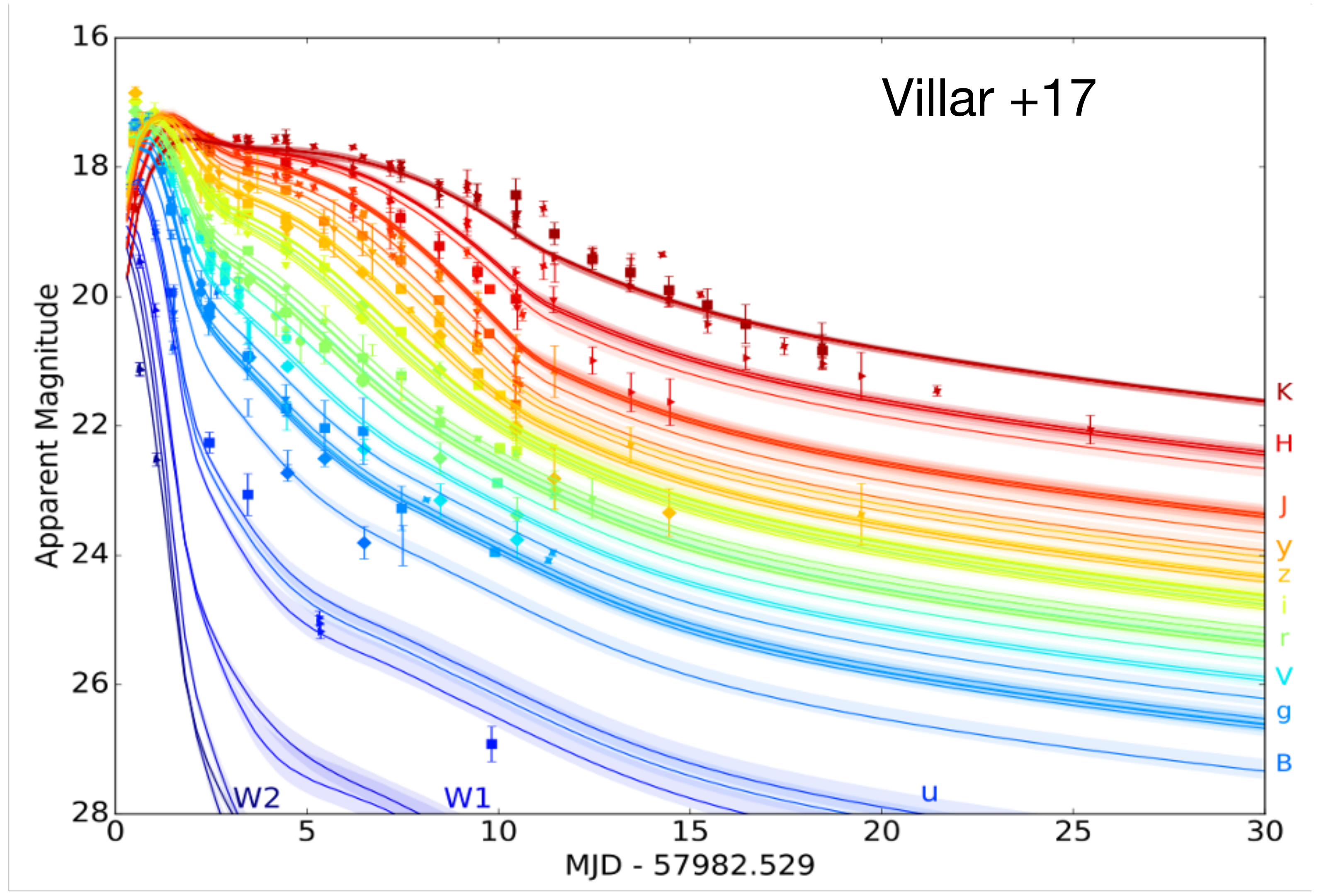
- EM signals depend on the channel.
- The unknown EOS determines the threshold masses.

What we learned from GW170817

γ-ray spike (~sec)

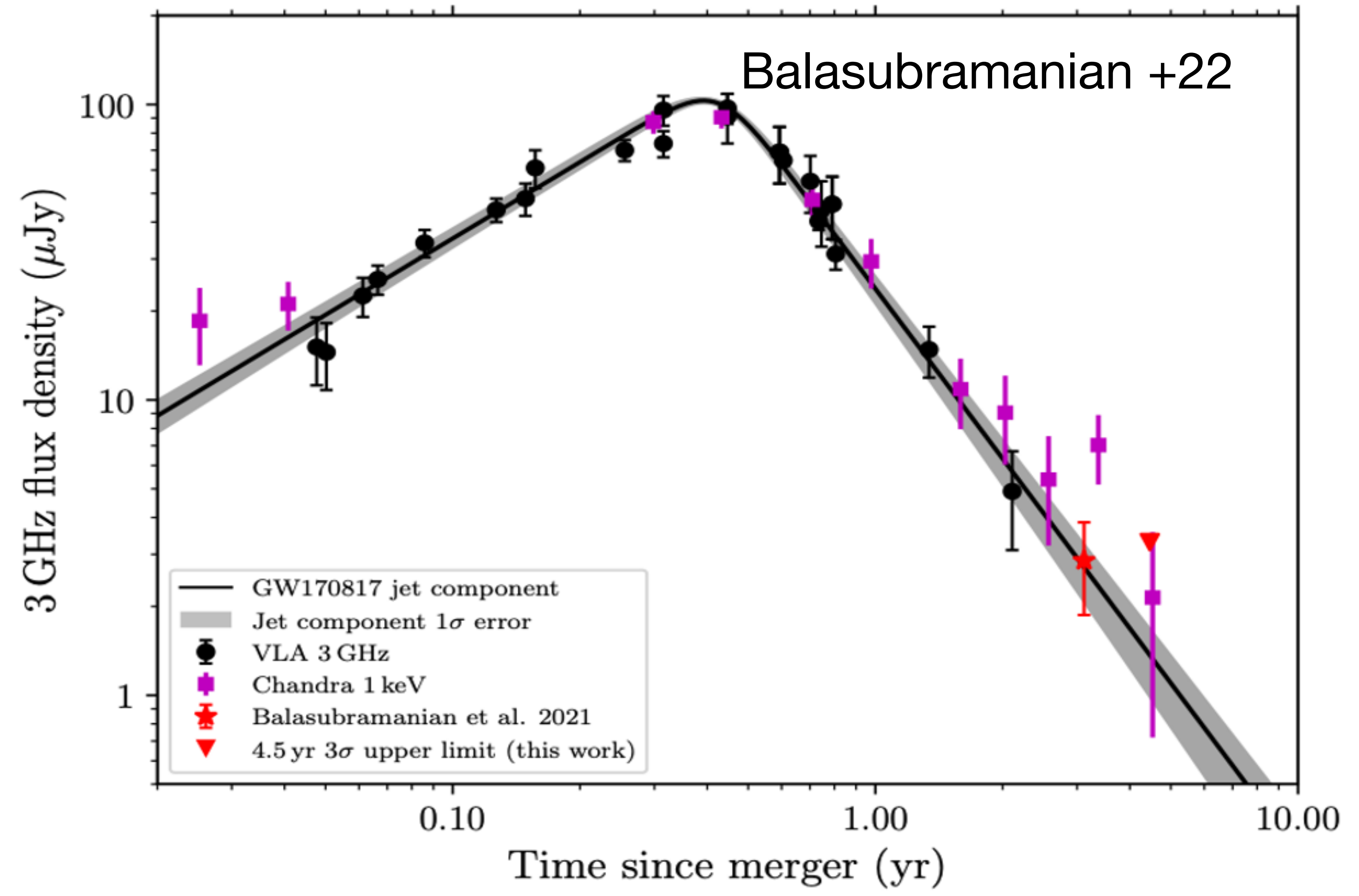


- Delay & Duration ~ O(1sec).
- E_{rad}~10^{47} erg << short GRBs by 3 orders magnitude.



- Evolving fast (~days).
- E_{rad}~10^{47} erg << supernovae by a few orders magnitude.
- Quasi-thermal, Blue -> Red with time.

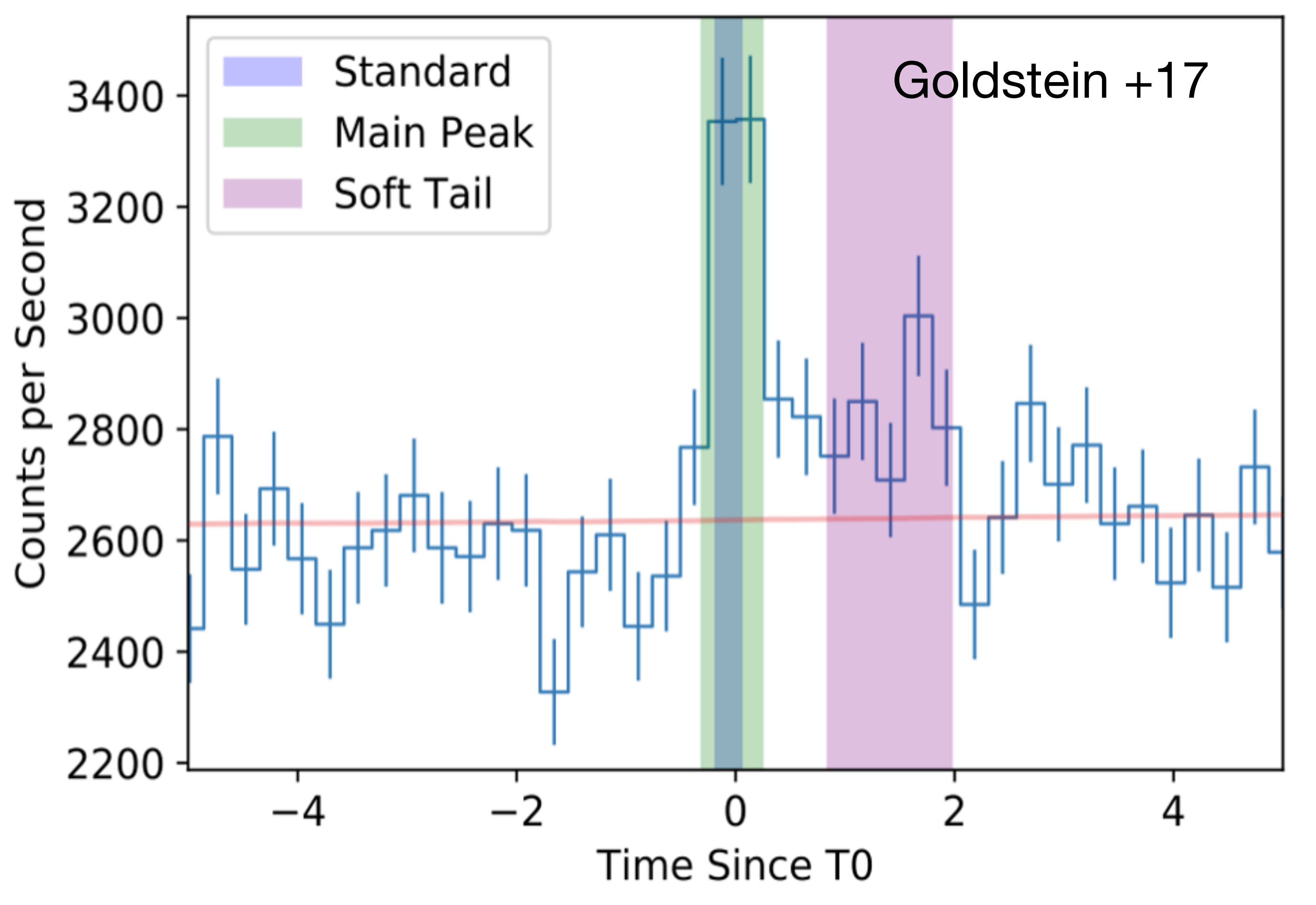
X-radio Afterglow (~yr)



- Peak ~ 150 day.
- E_{rad}~10^{47} erg << cosmological GRB afterglows by 3 orders.
- A single power-law spectrum from radio to X-ray.

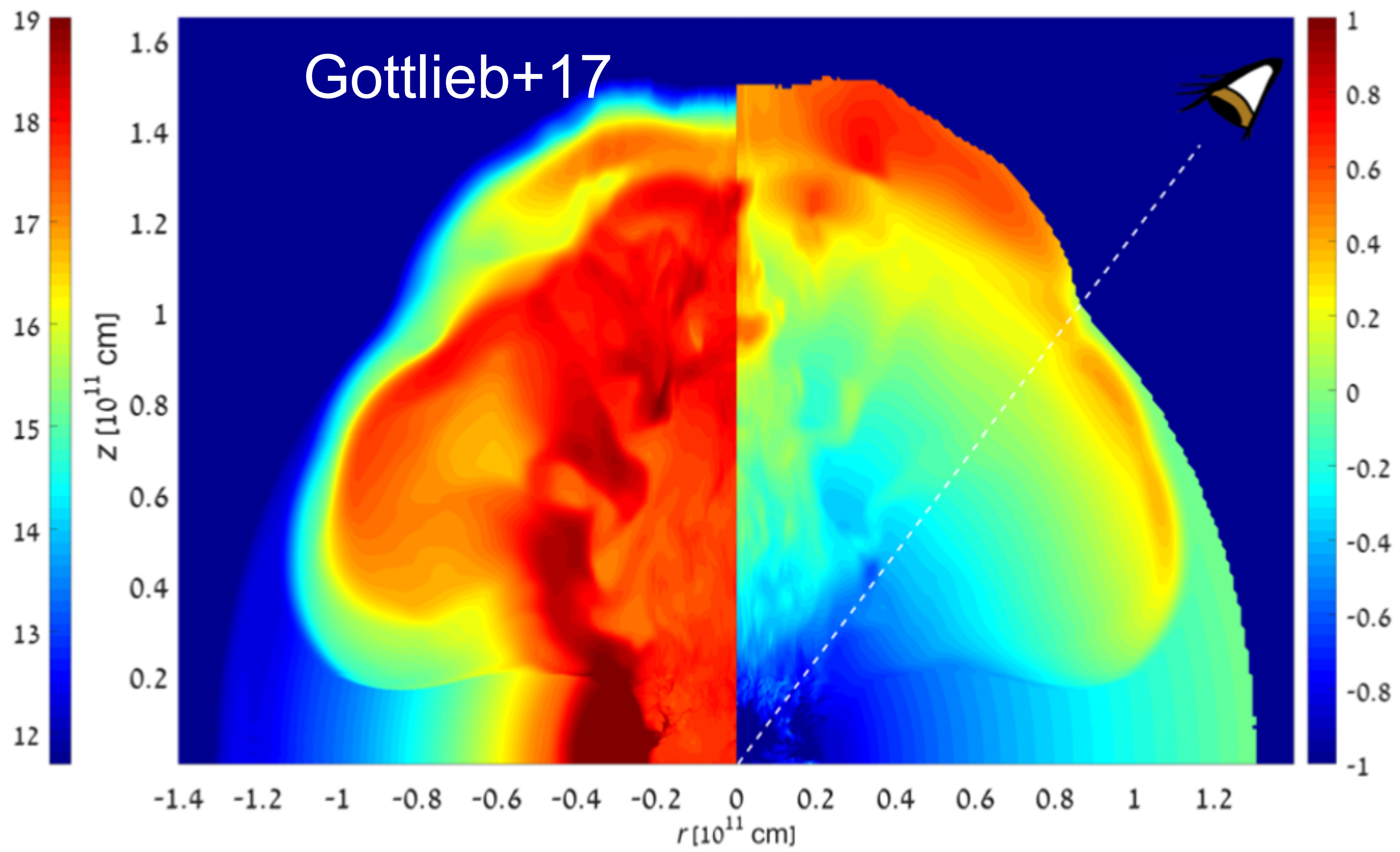
GW170817: GRB

γ-ray spike (~sec)



- Delay & Duration ~ O(1sec).
- E_{rad}~10^{47} erg << short GRBs by 3 orders magnitude.

Cocoon shock breakout

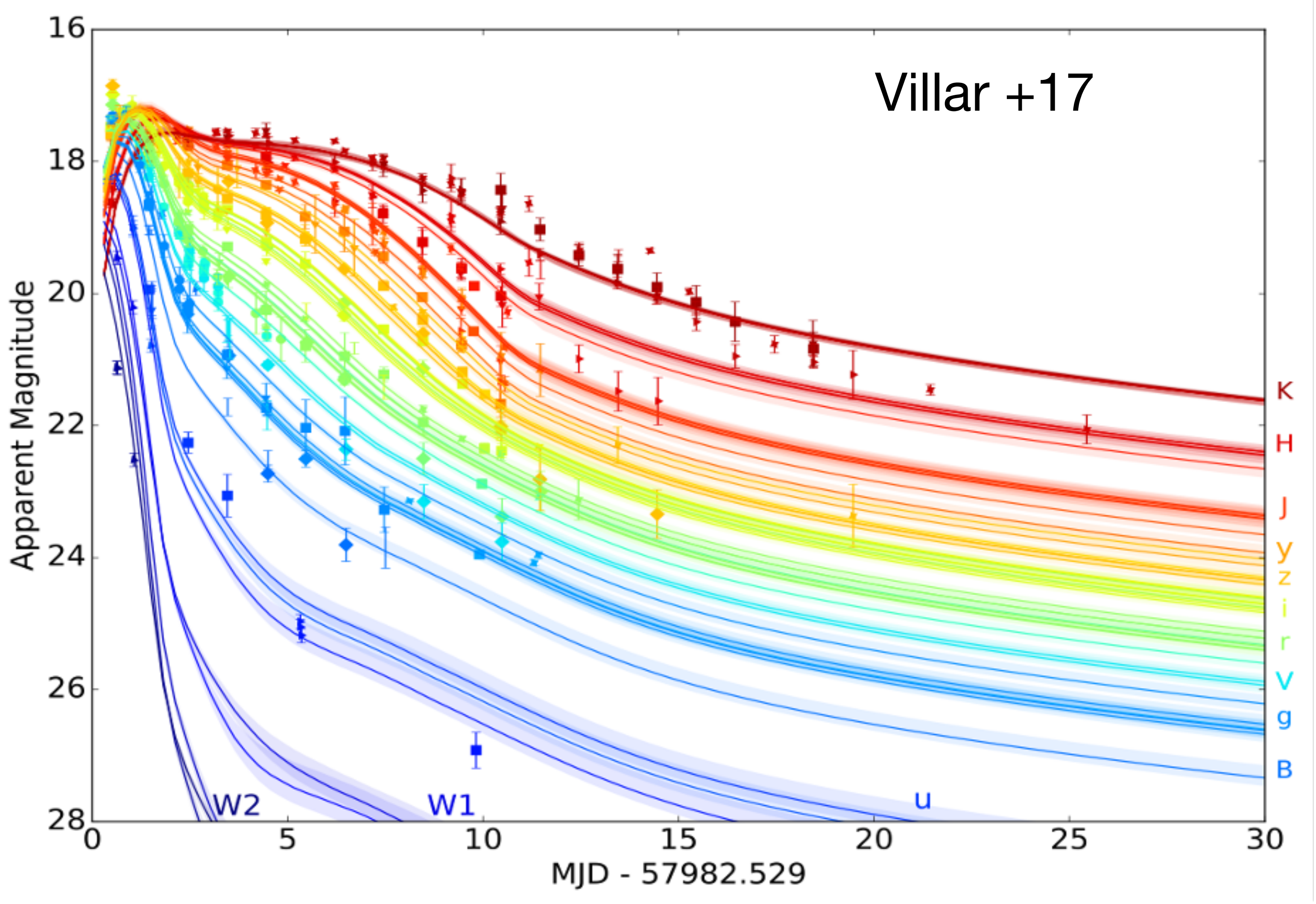


The γ-ray pulse is likely produced by mildly relativistic shock: a cocoon breaks out from fast material (~0.8c) or jet's structure which is unrelated the cocoon-jet interaction.

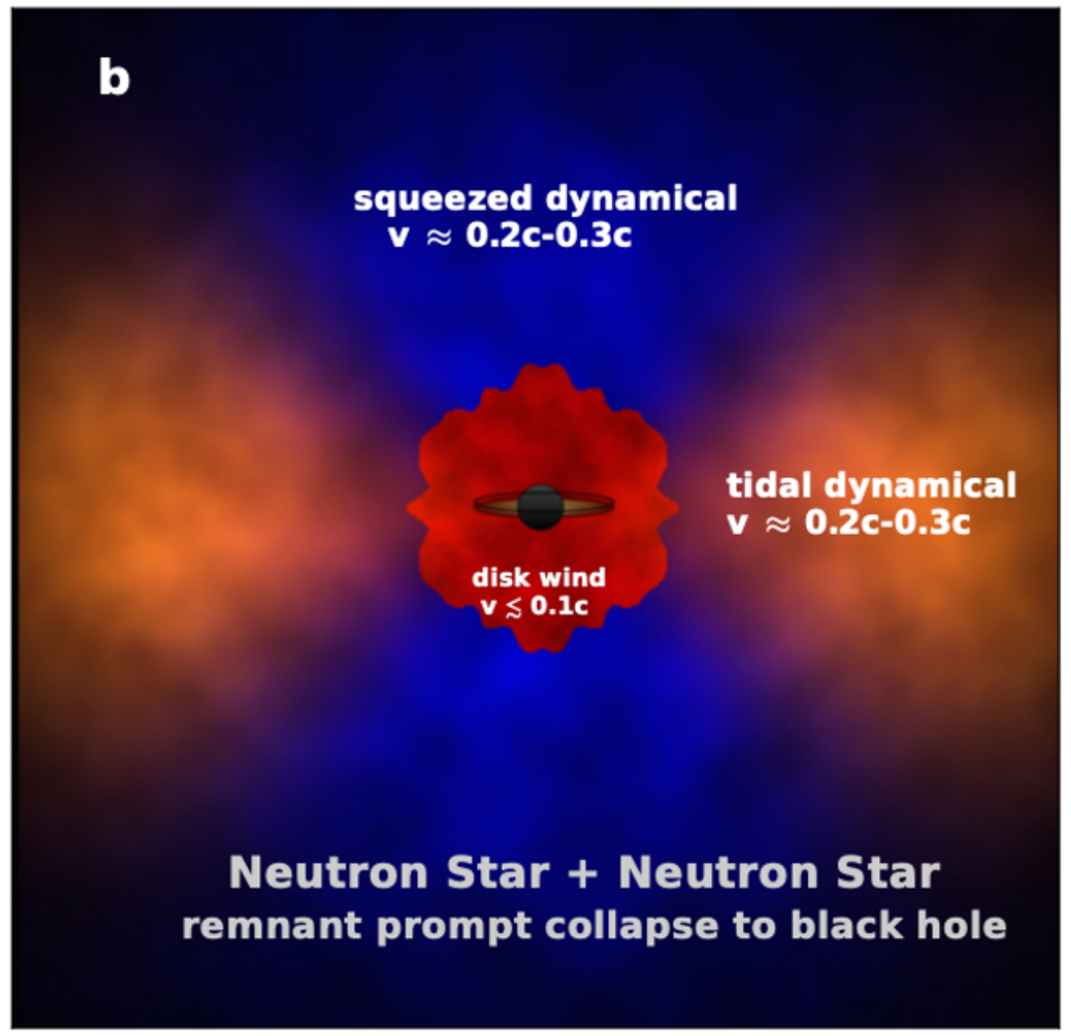
- What is the origin of the γ-rays?
- What determines the delay of jet launch?
- Are there any prompt emission in other wavelengths?
- Does really the fast component exist?

GW170817: Kilonova

uv-opt-IR Kilonova (~ days)



Kasen+2017



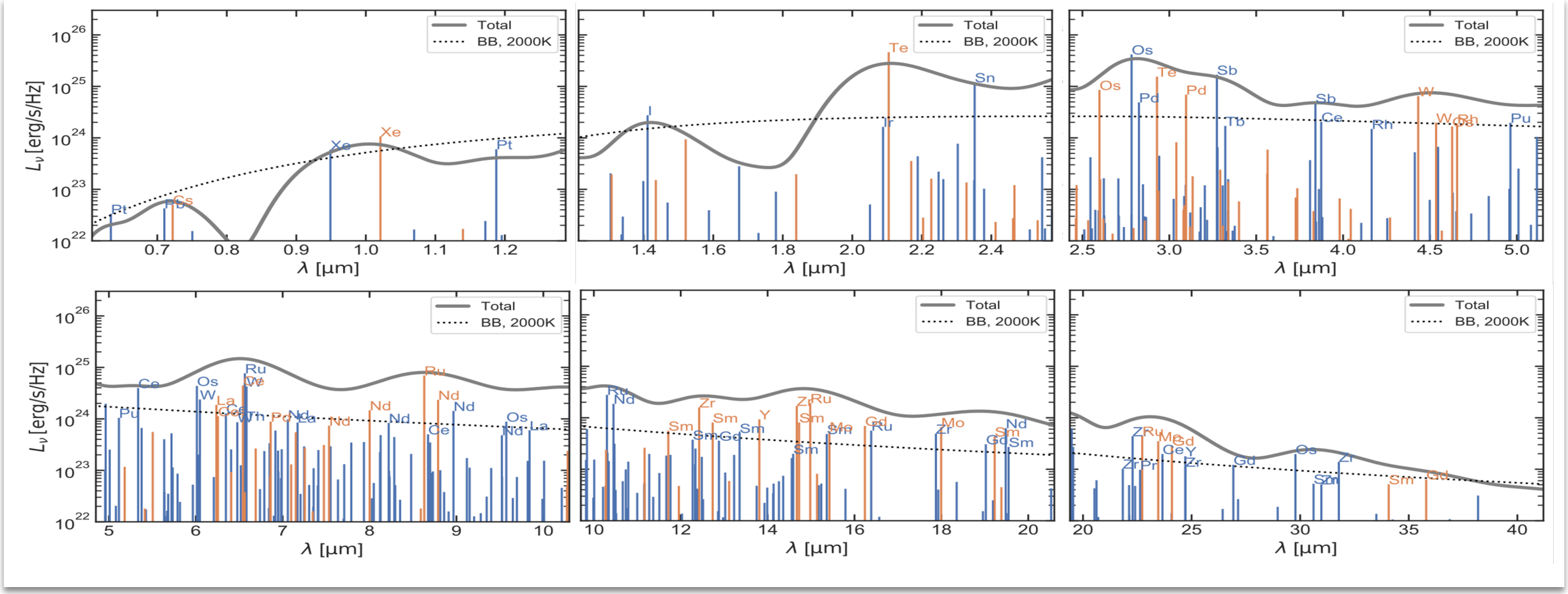
A kilonova is produced by non-relativistic ejecta through radioactivity of r-process nuclei.

- Evolving fast (~days).
- E_{rad}~10^{47} erg << supernovae by a few orders magnitude.
- Quasi-thermal, Blue -> Red with time.

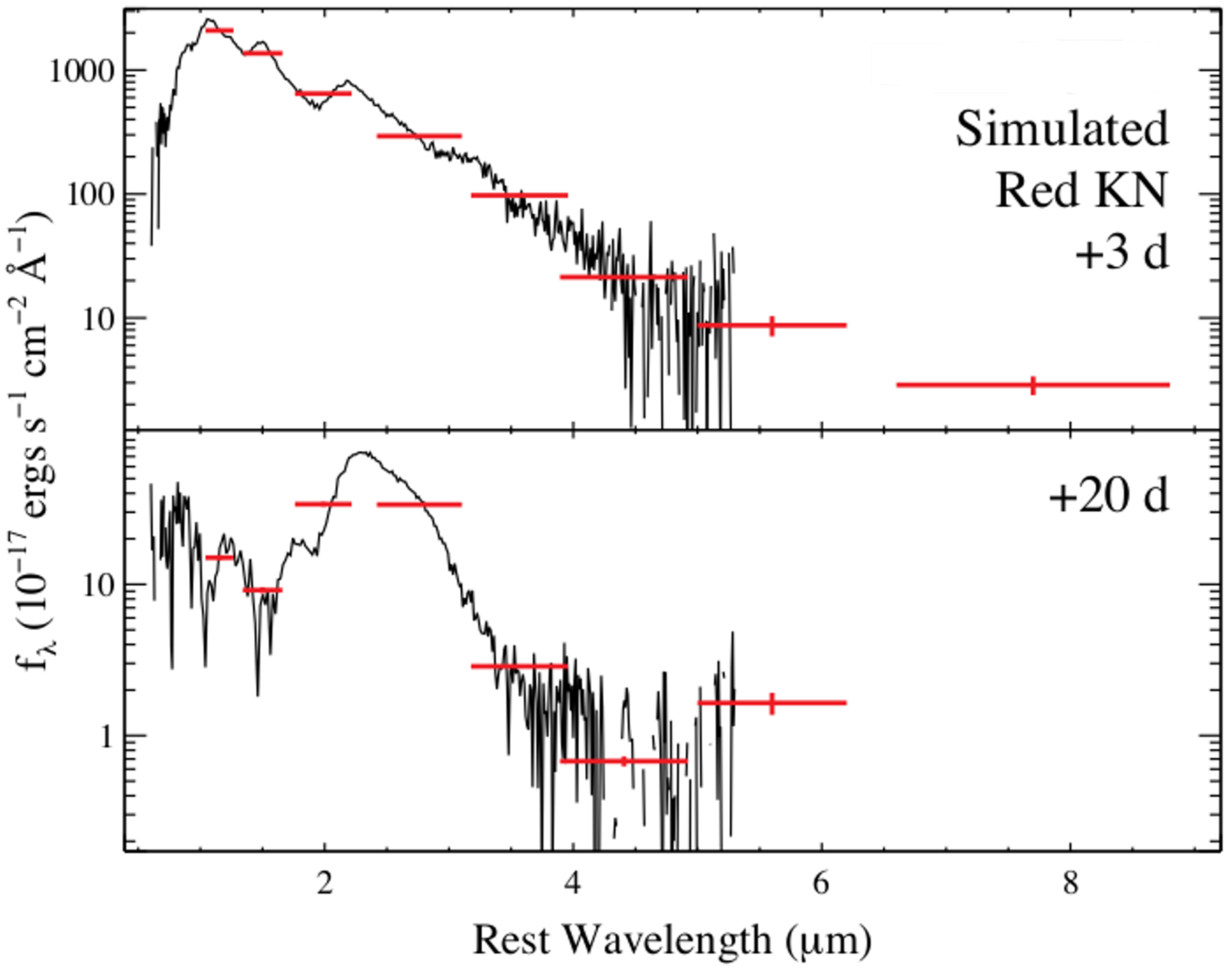
- What is the origin of “blue” & “red”? (alternatively, the increase of opacity in time)
- What is the viewing angle dependence?
- Can we spectroscopically identify atoms? JWST?
- What is the energy source? α, β, γ, fission.
- We are (will be) facing atomic data problems.

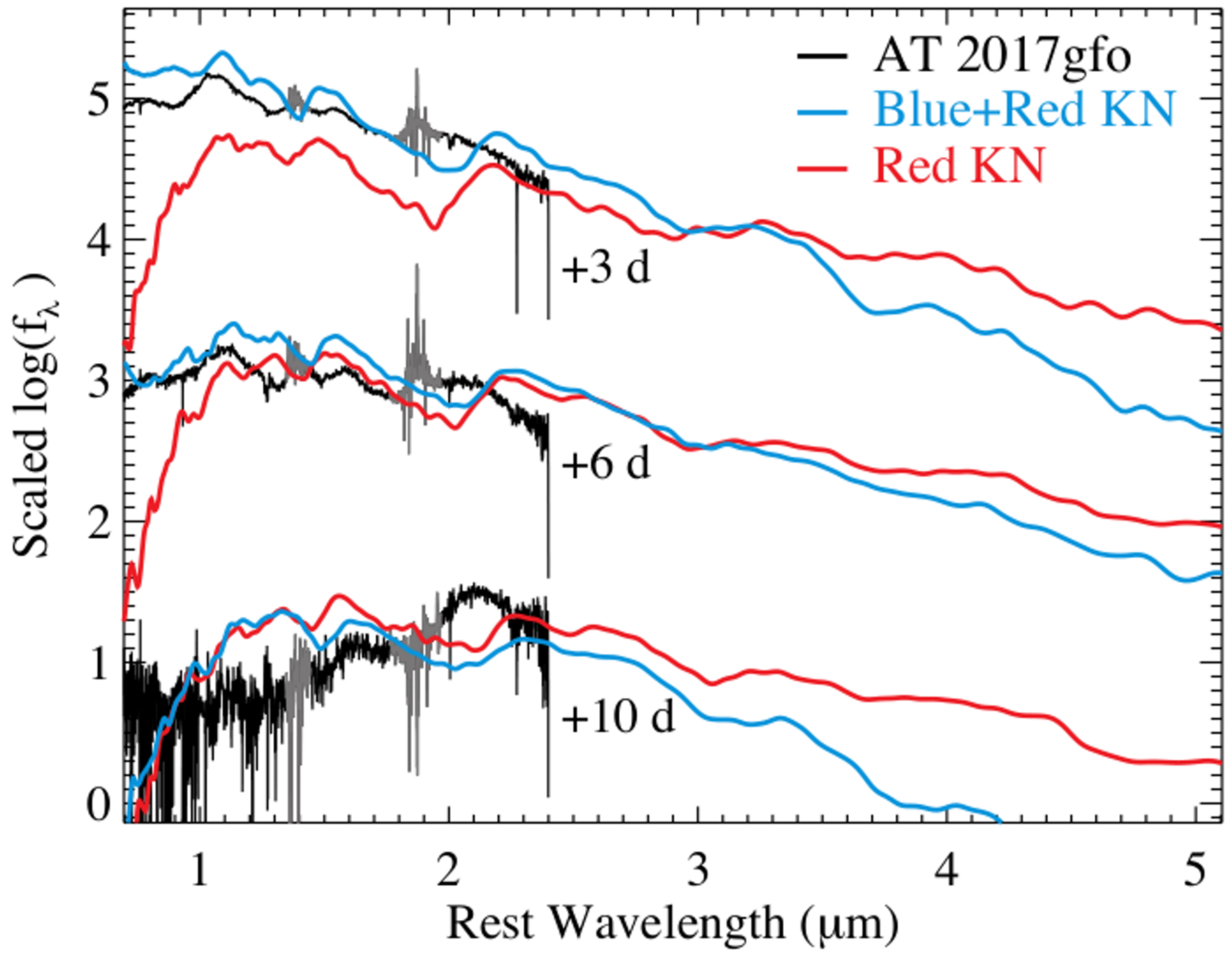
Looking forward to JWST

KH + in prep.



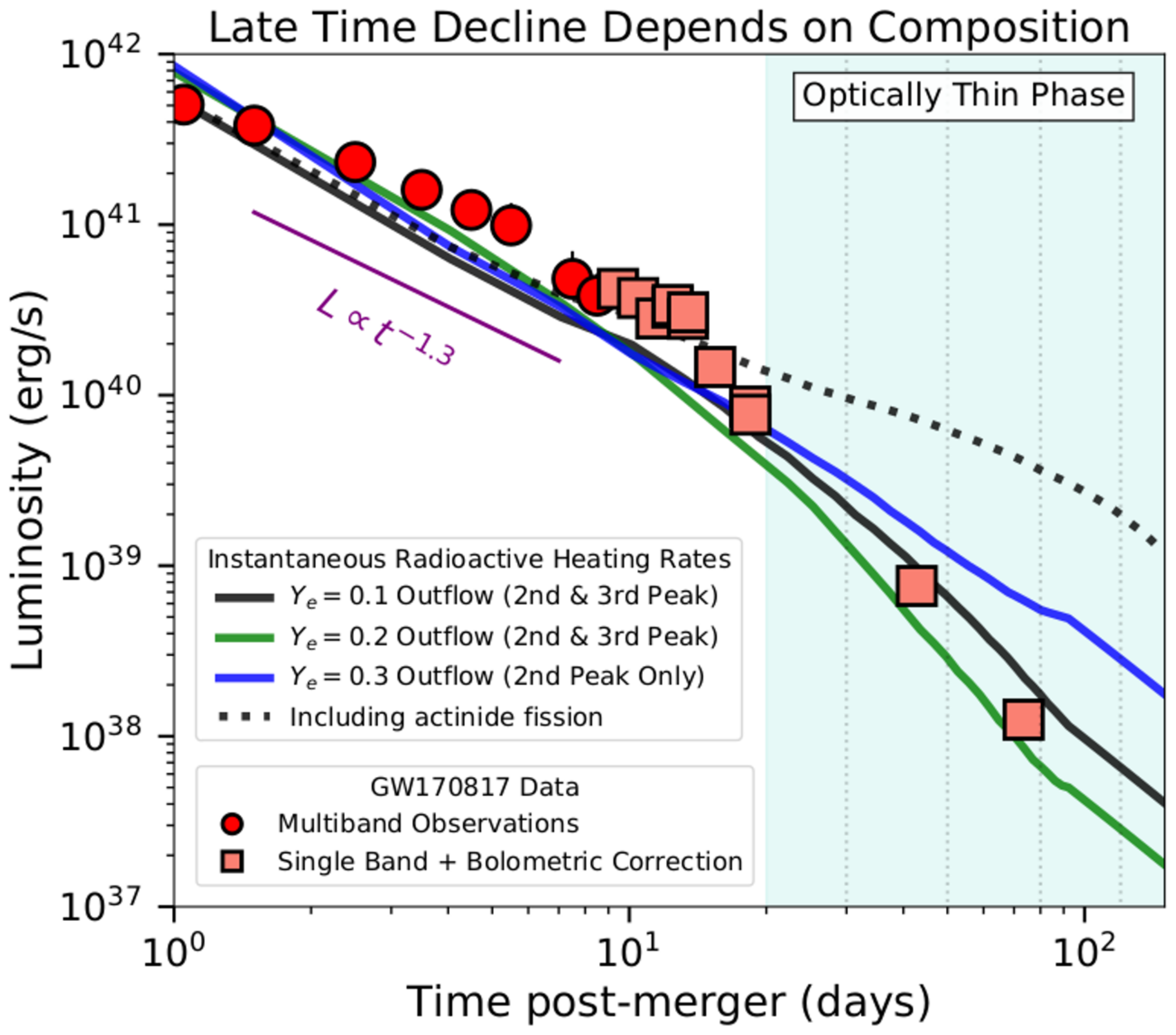
JWST Follow up of kilonovae

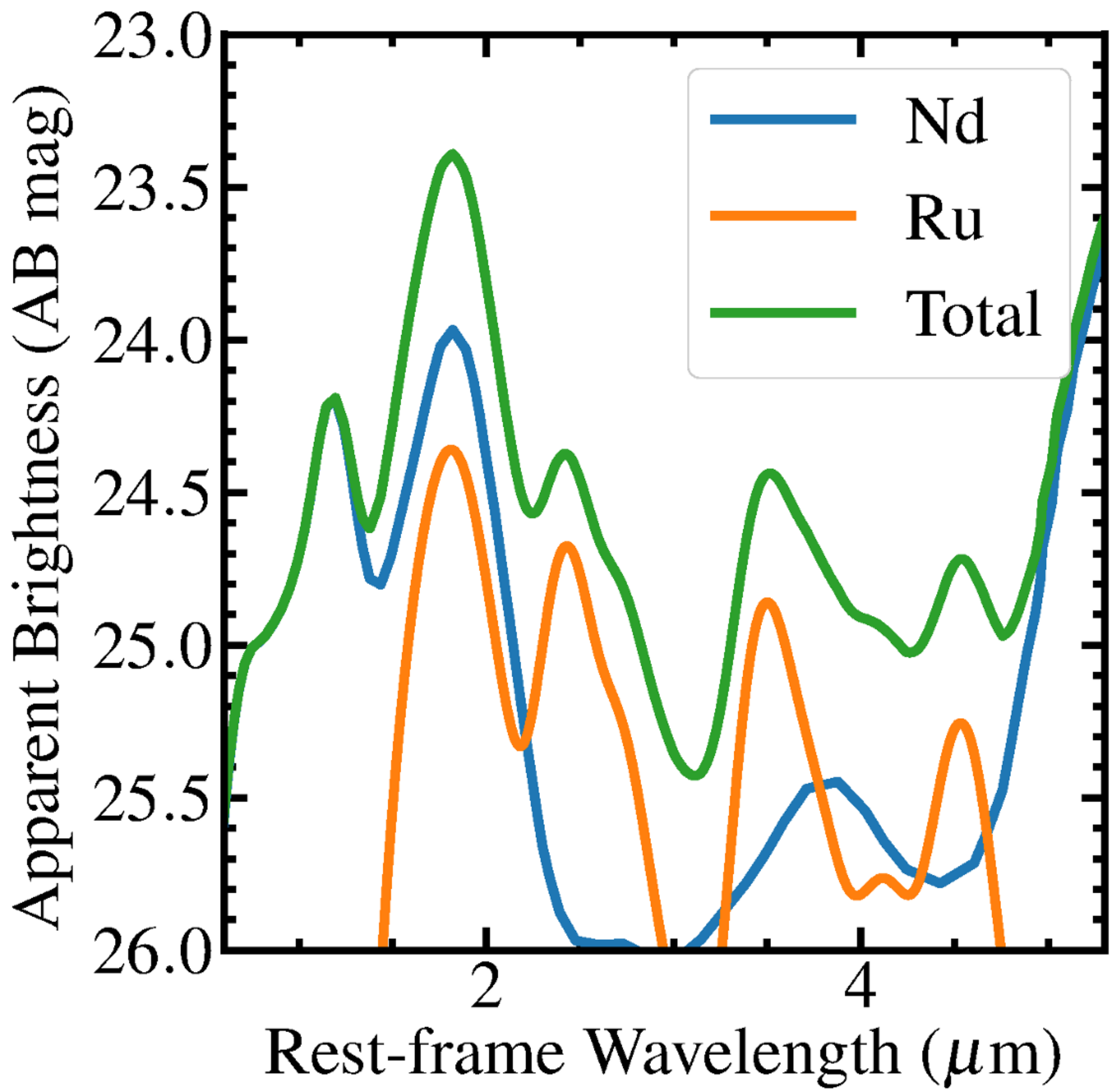




There is no detailed information about the spectral energy distributions of kilonovae beyond ~2 microns. Are we even seeing most of the emission?

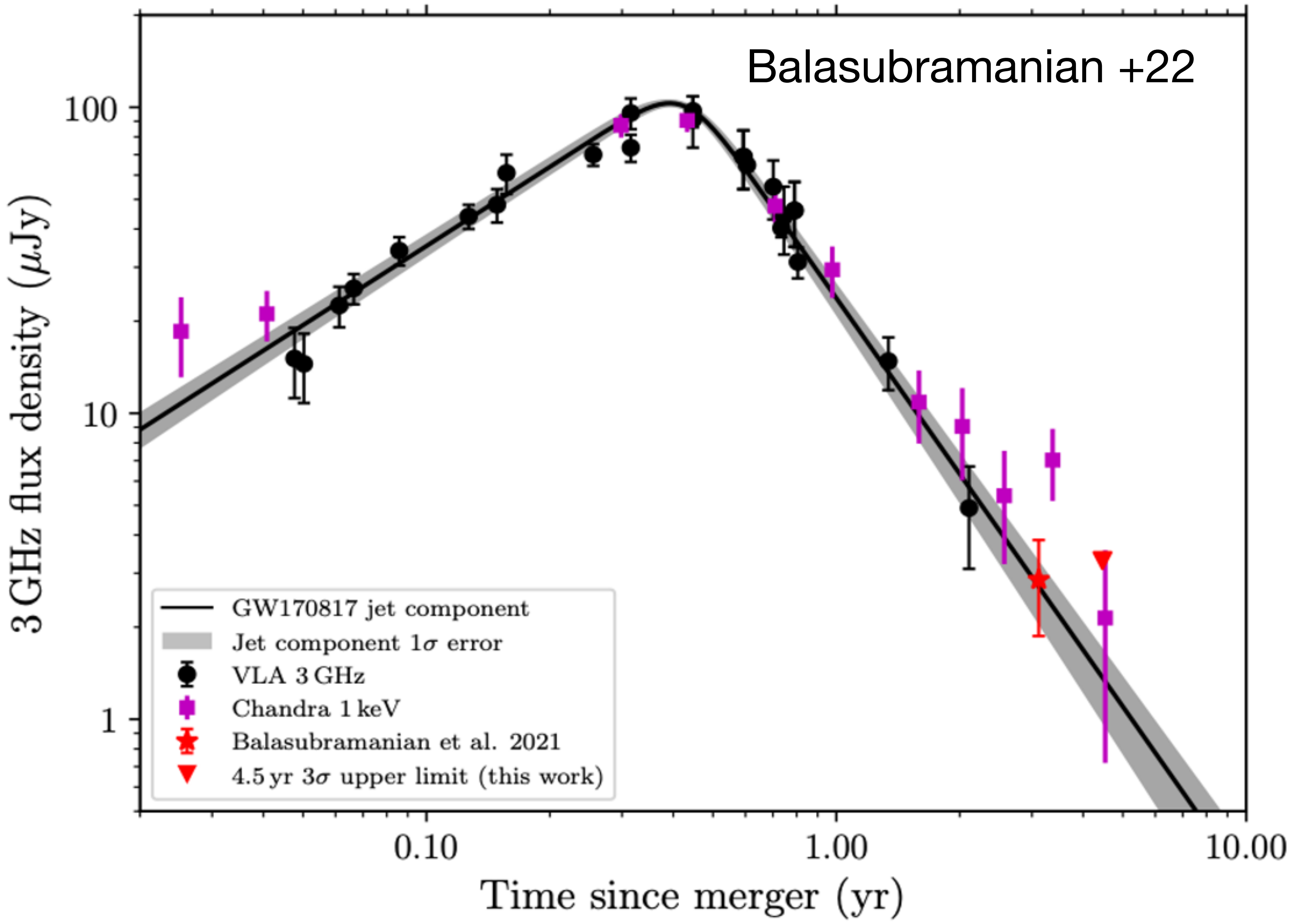
JWST - r-process abundances



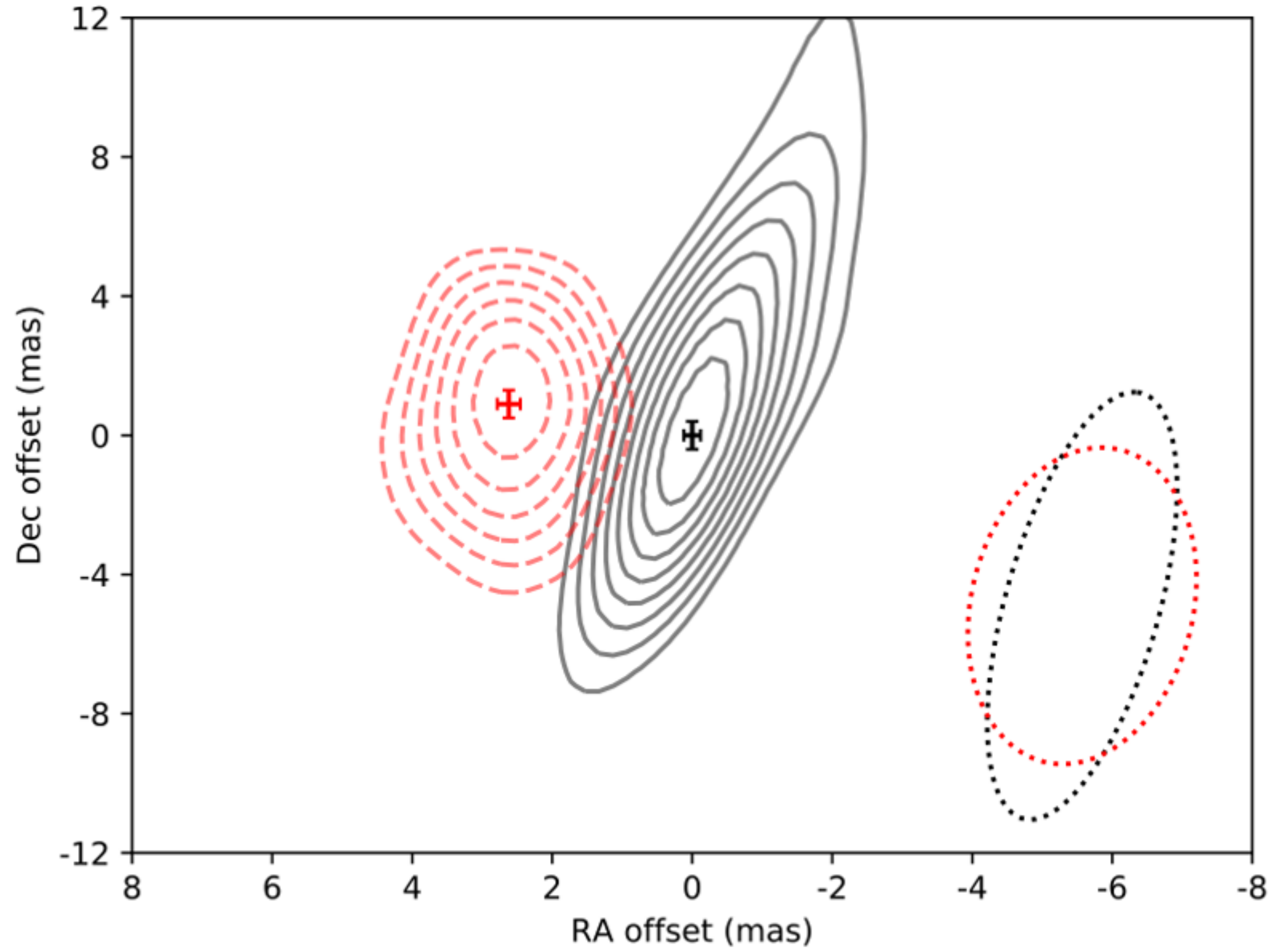


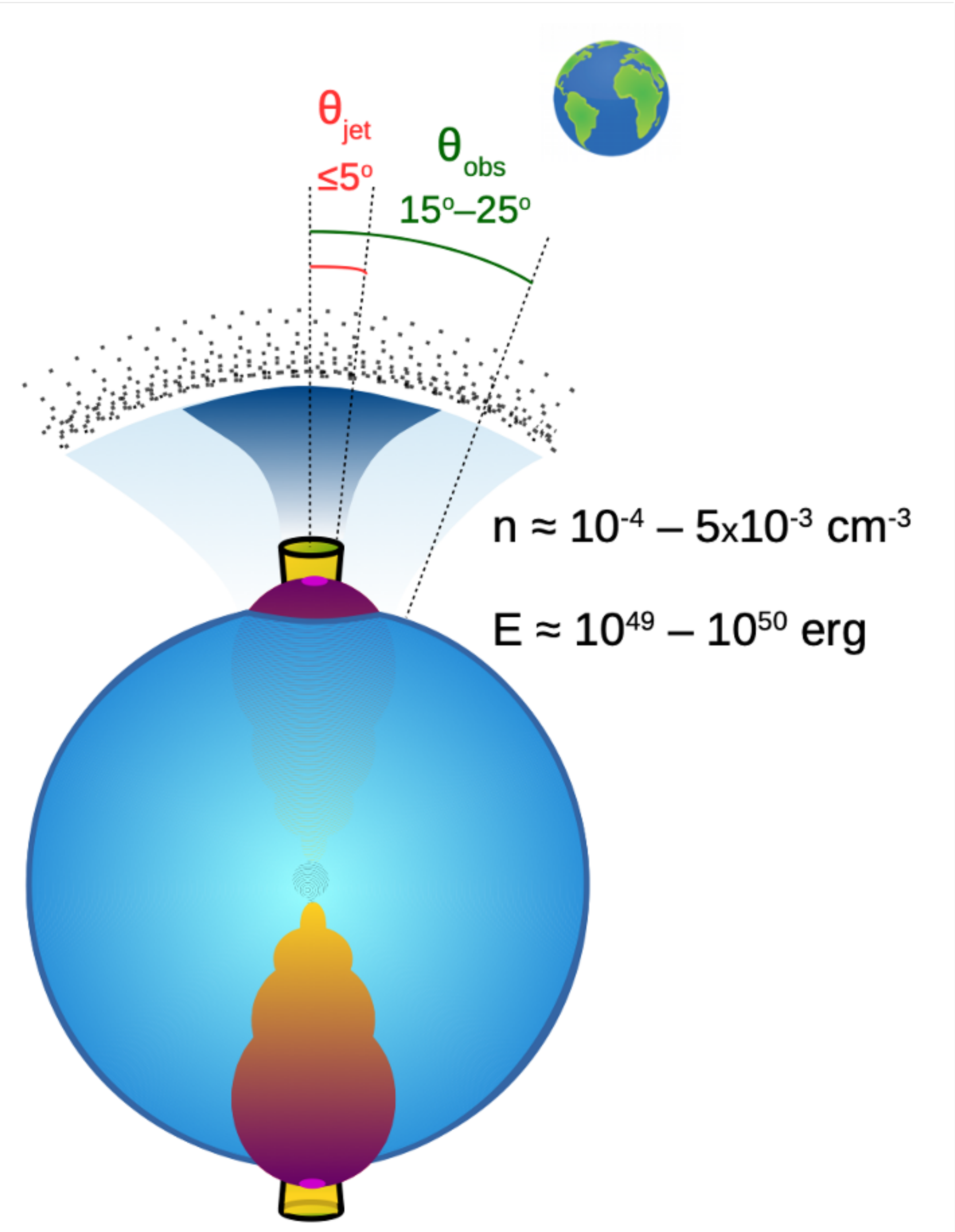
Abundances can be constrained through constraints on late-time heating and through direct detection of species in IR spectra

GW170817: Afterglow



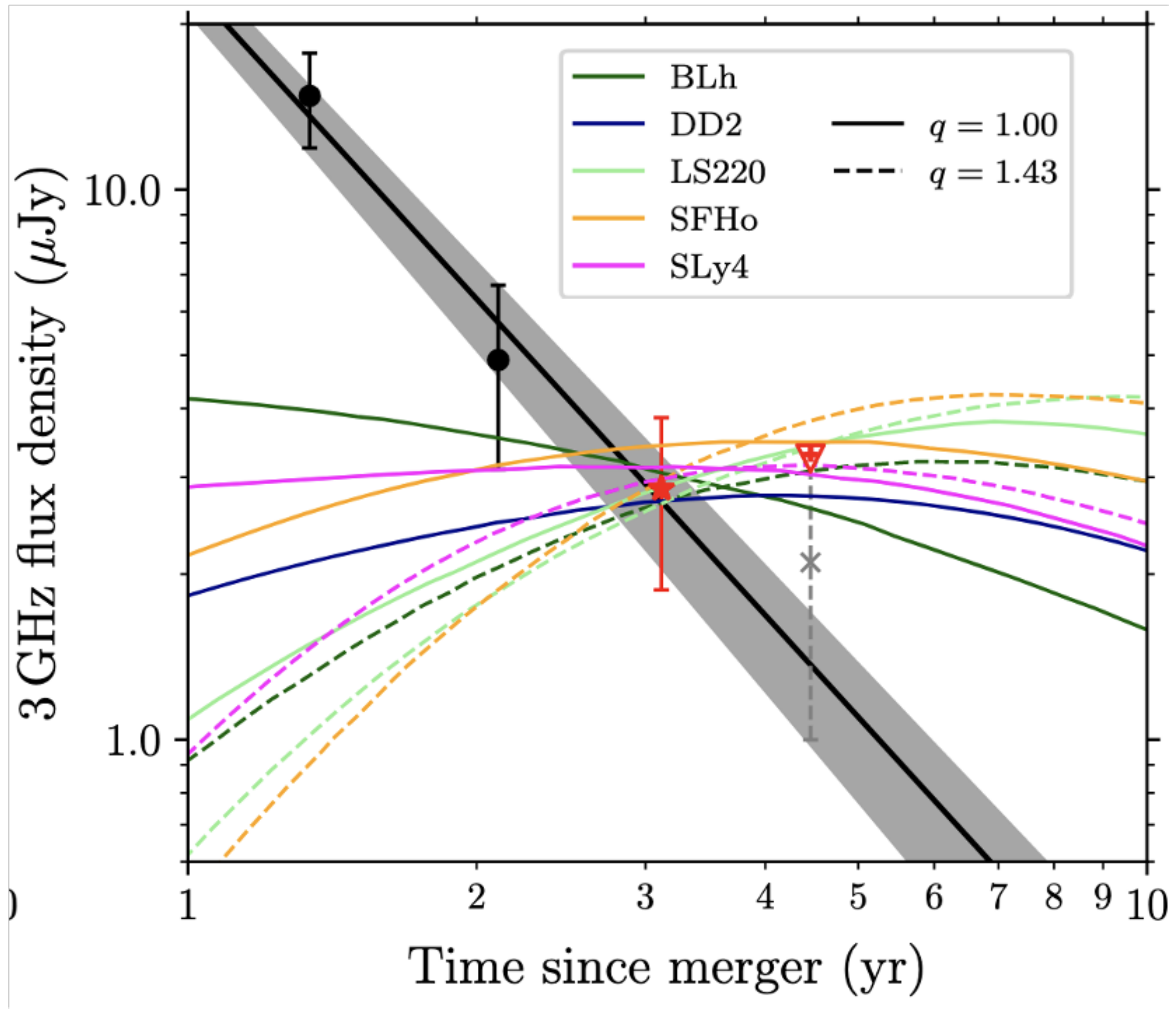
VLBI observation (Mooley+18)





The light curves in radio to X-ray with a superluminal motion resolved by VLBI revealed a relativistic jet.

- Peak ~ 150 day.
- E_{rad}~10^{47} erg << cosmological GRB afterglows by 3 orders.
- A single power-law spectrum from radio to X-ray.

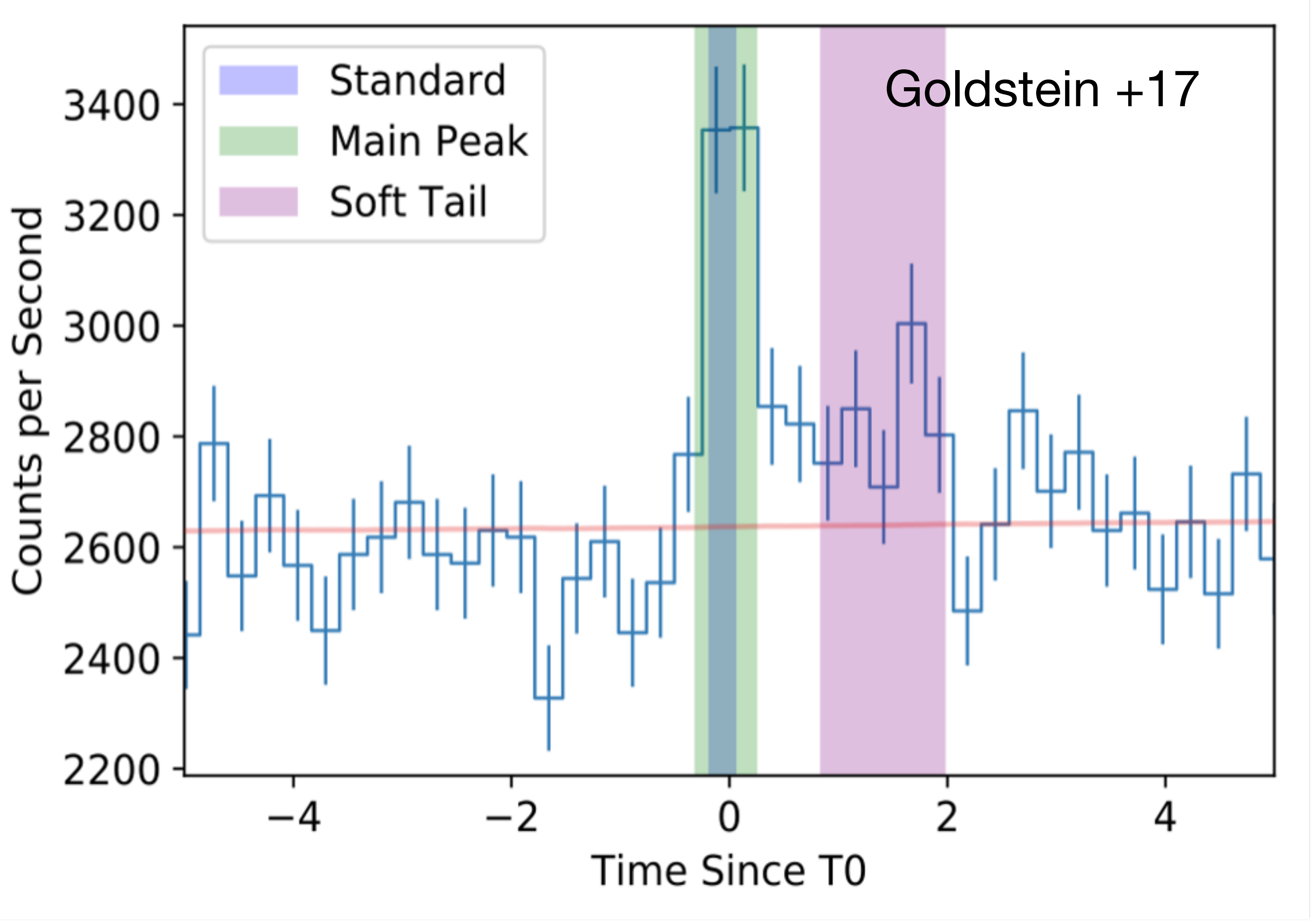


Kilonova afterglow??

- **What determines the jet energy (huge) and opening angle (narrow)?**
- **Can we see fast component of kilonova ejecta?**
- **What happens if a merger occurs in a dense environment?**
- **Extreme events from stable remnant (magnetar)?**

GW170817 in different θ_v and environment

γ-ray spike (~sec)



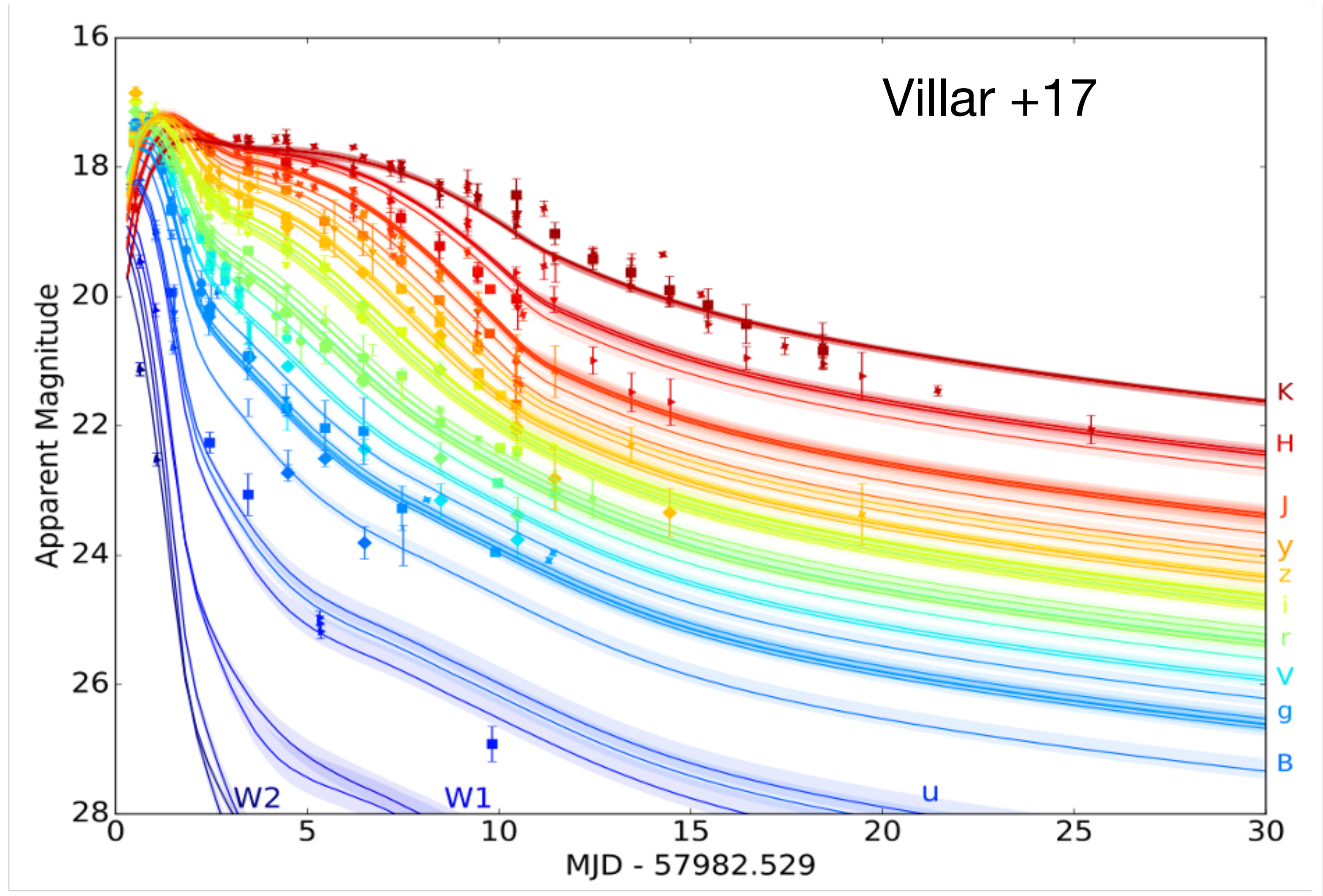
- Delay & Duration ~ O(1sec).
- E_{rad}~10^{47} erg << short GRBs by 3 orders magnitude.

Much brighter if on-axis.

⇩

Cosmological events

uv-opt-IR Kilonova (~ days)



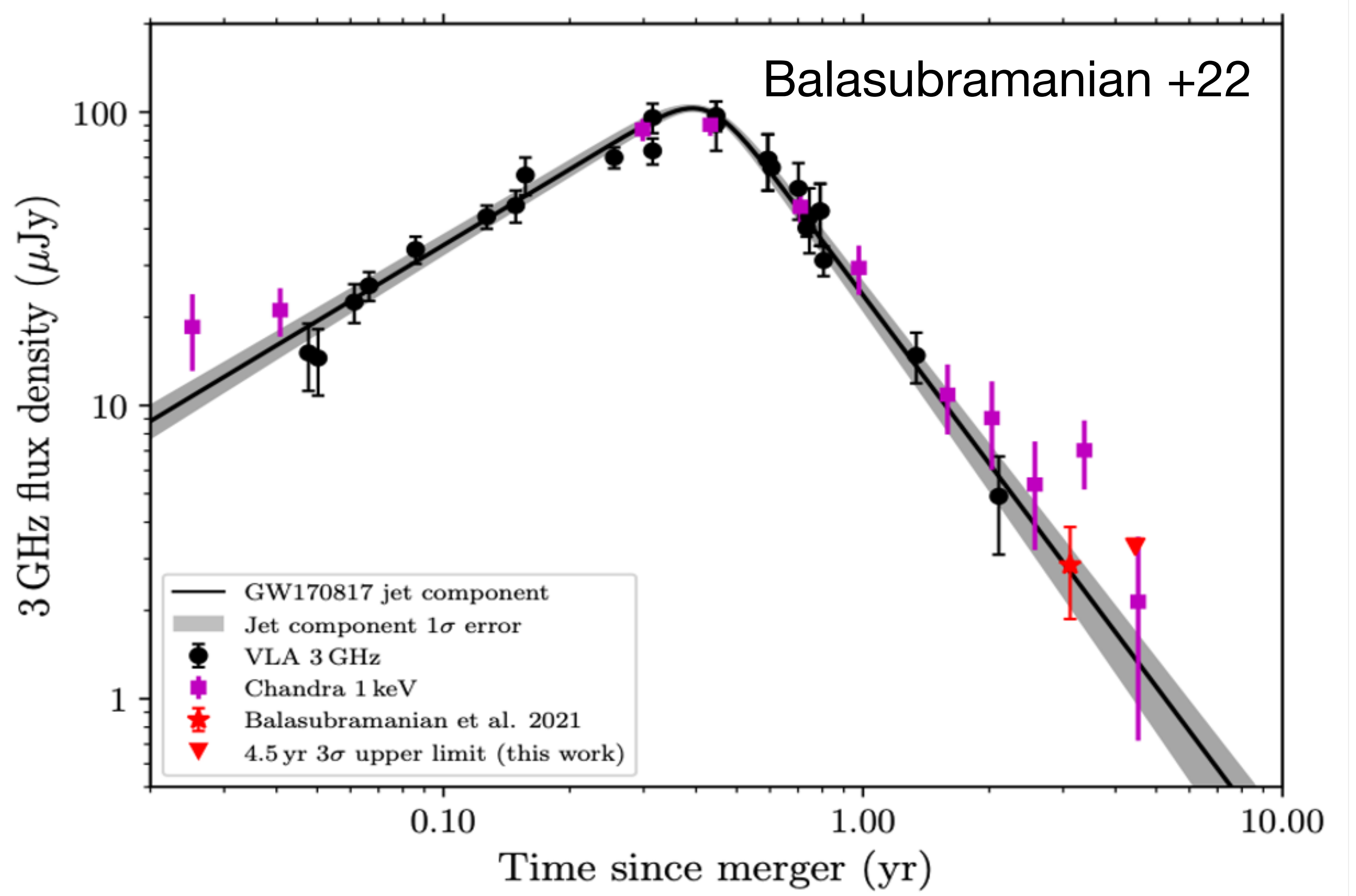
- Evolving fast (~days).
- E_{rad}~10^{47} erg << supernovae by a few orders magnitude.

Cannot be very different.

⇩

Nearby events

X-radio Afterglow (~yr)



- Peak ~ 150 day.
- E_{rad}~10^{47} erg << cosmological GRB afterglows by 3 orders.

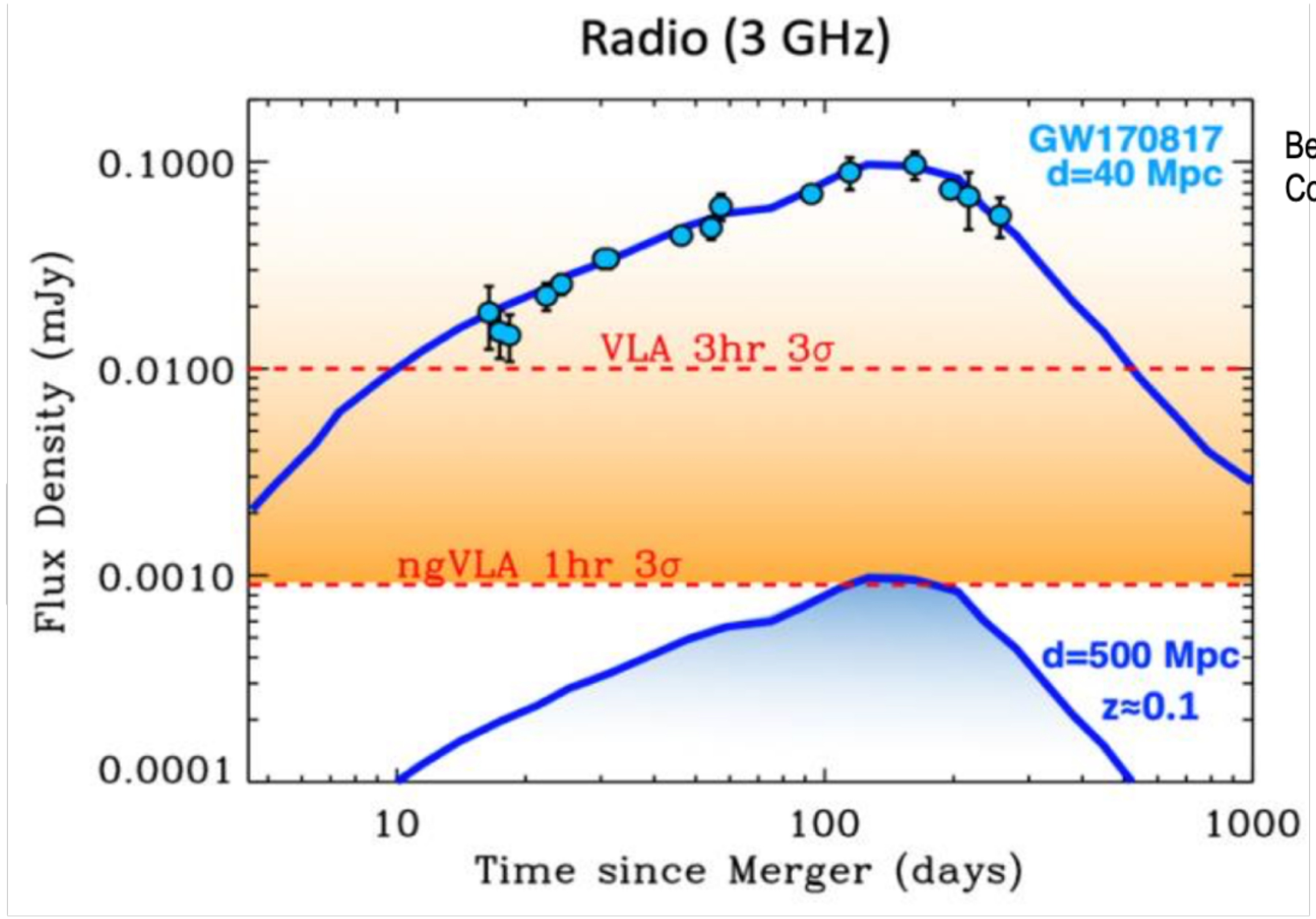
Much brighter if on-axis and dense ISM.

⇩

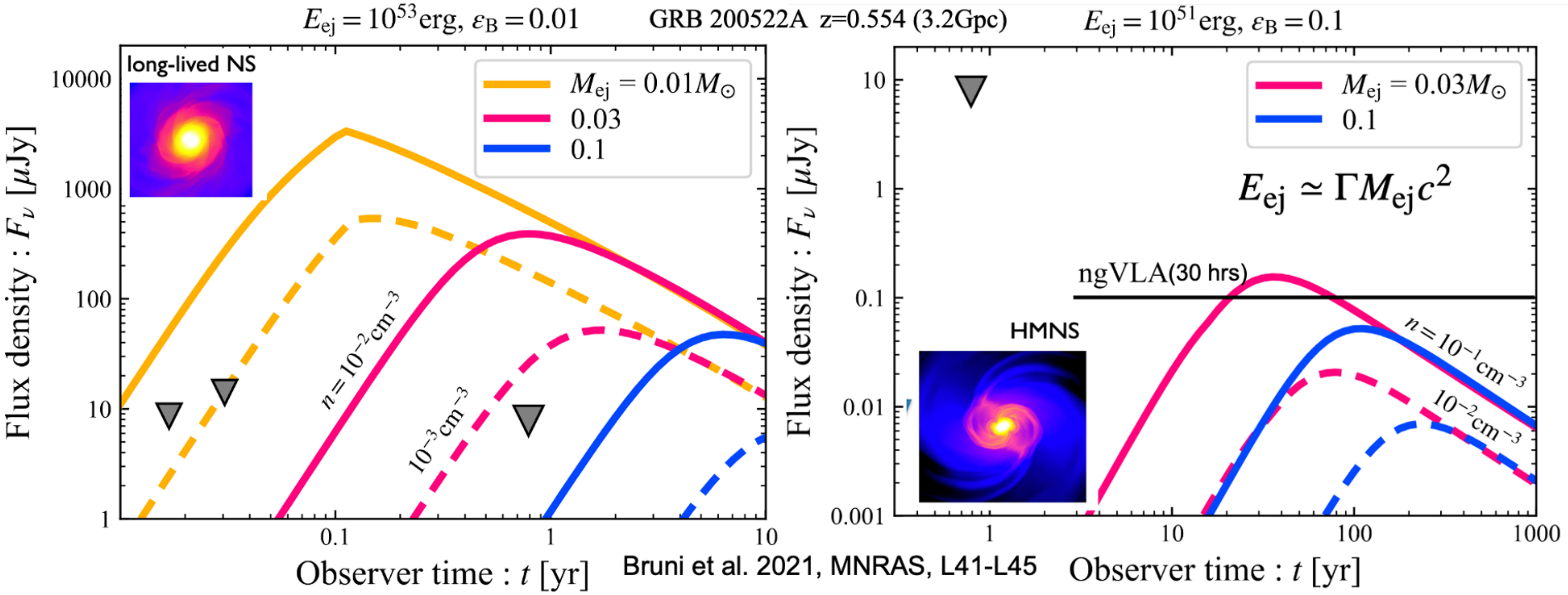
Cosmological events

Next 5-10 years - Afterglows (assuming kilonovae allow for localization)

Run	BNS	NSBH	BBH
	Median 90% credible area (deg^2)		
O5	1250^{+120}_{-120}	1076^{+65}_{-75}	$230.3^{+7.8}_{-6.4}$
	Median luminosity distance (Mpc)		
O5	620^{+16}_{-17}	1132^{+19}_{-23}	2748^{+30}_{-34}
	Annual number of detections		
O5	190^{+410}_{-130}	360^{+360}_{-180}	480^{+280}_{-180}



Beasley et al. Astro2020 White Paper;
Corsi et al. Astro2020 White Paper

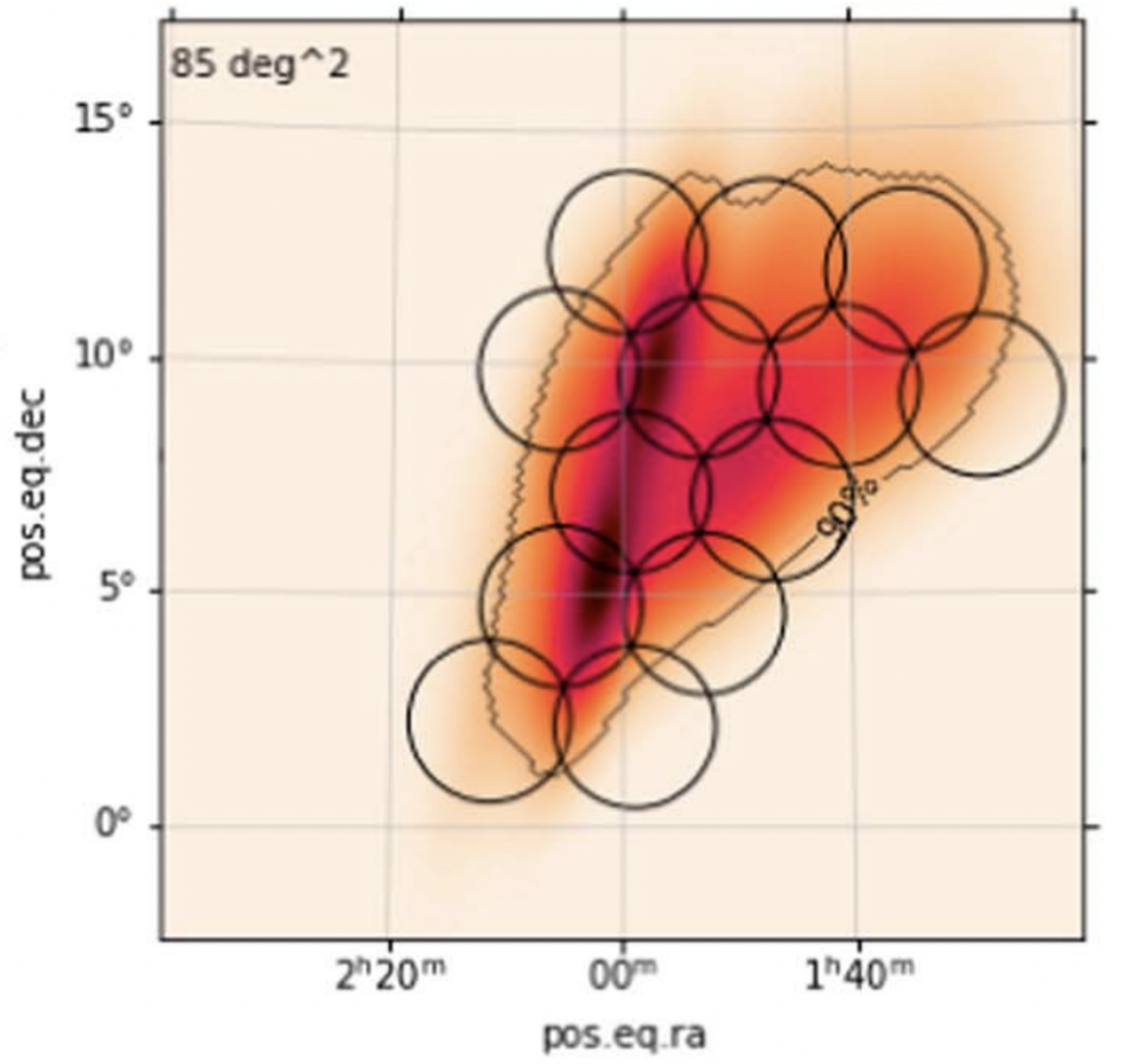


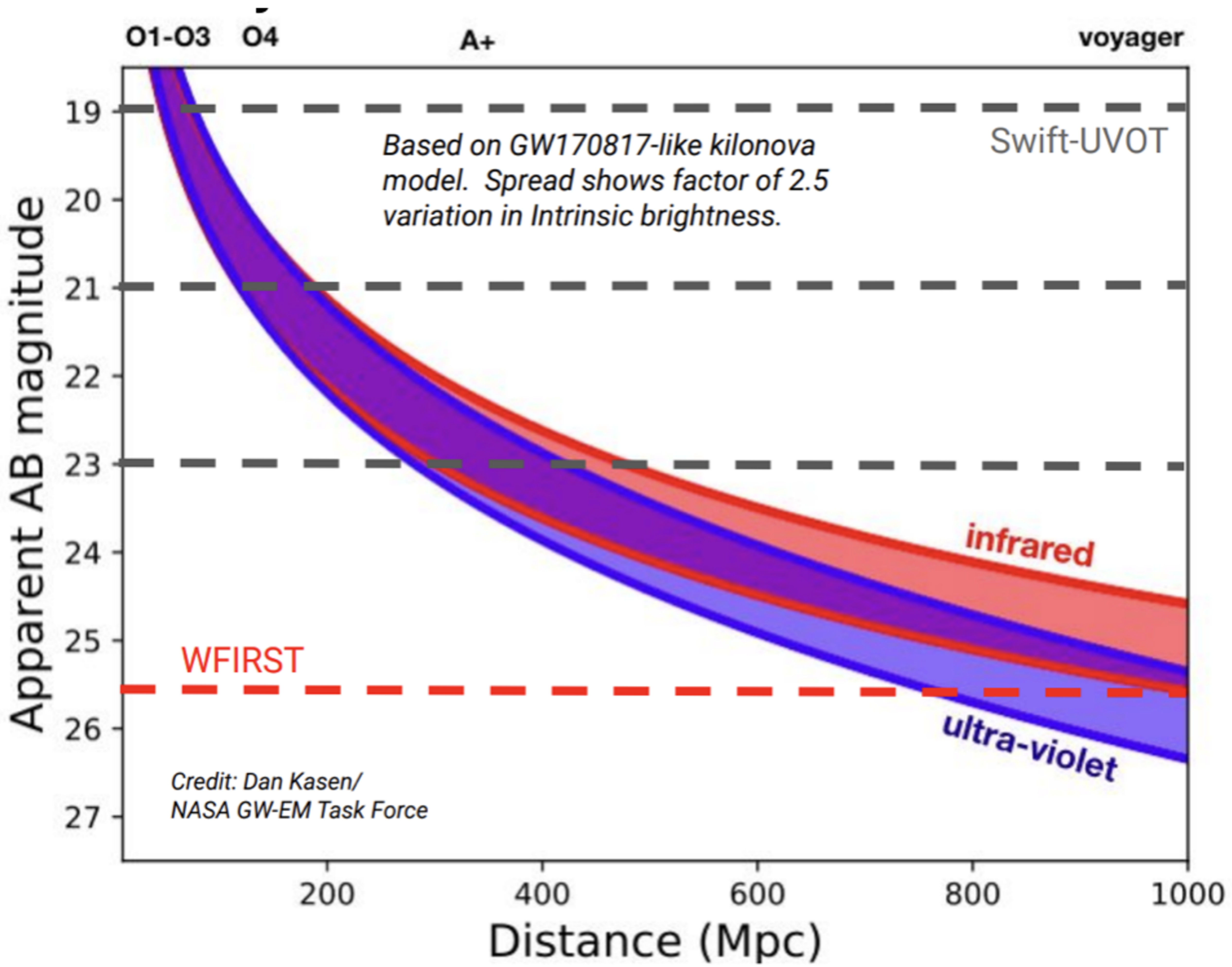
Bruni et al. 2021, MNRAS, L41-L45

Fully probing the diversity of non-thermal afterglows of GW mergers (independently of kilonovae) requires the combination of the exquisite localization capabilities of 3G detectors (for nearby off-axis jets) and arcmin-localization capabilities in gamma-rays (for small viewing-angle events up to SF peak).

Next 5-10 years - kilonovae (finding the needle in a haystack)

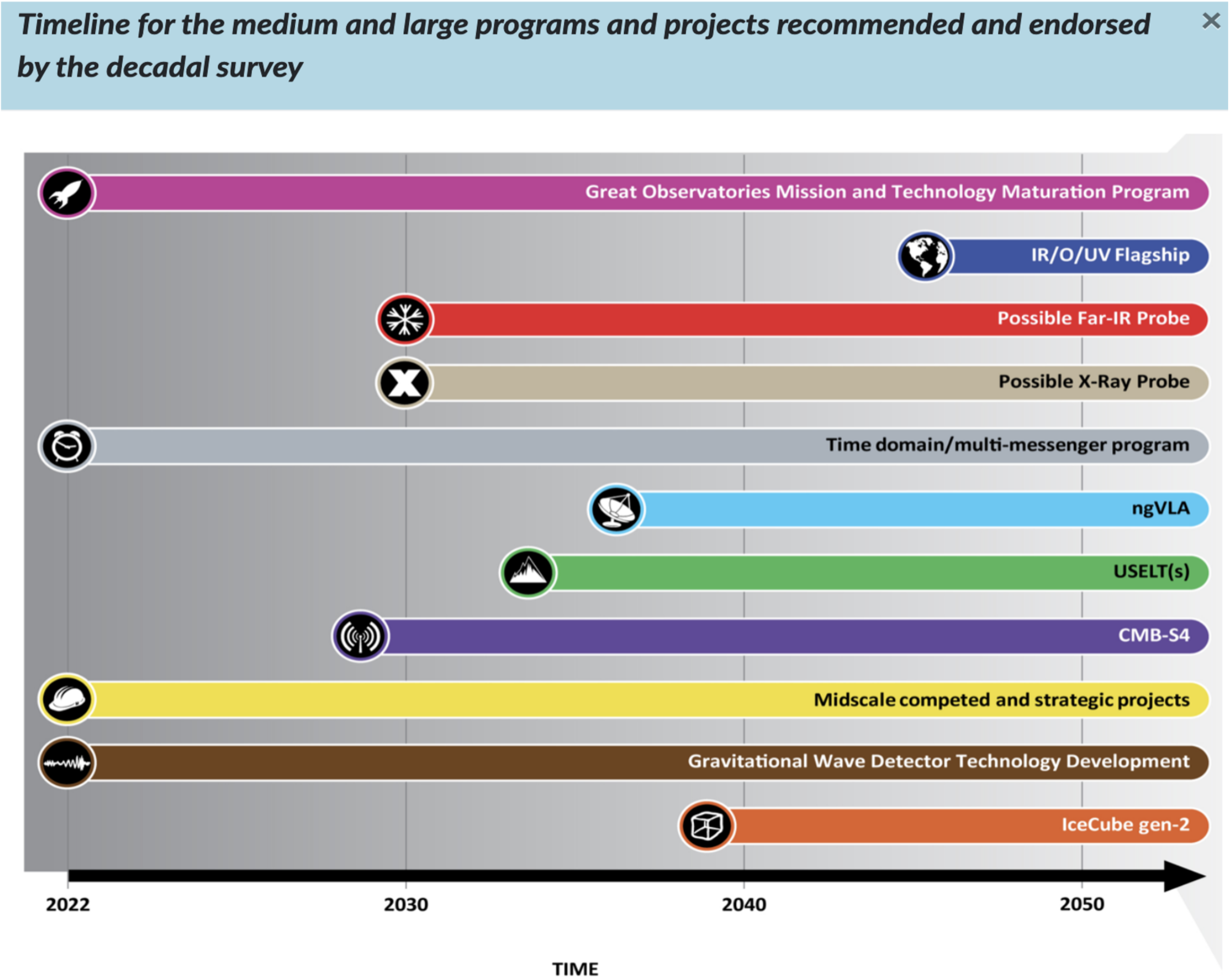
Margutti Astro2020 white paper





Rubin and Roman provide the best deep, wide-field search capabilities for kilonovae in the optical and infrared - we still need rapid vetting, follow up (ELT spectroscopy). Good localization is still key!

MMA over the next decade and beyond



Given these capabilities, how can GW and EM facilities better coordinate to maximize science being done as part of multi-messenger astronomy?

3G era

MMA science absolutely CANNOT be done without NG detectors?

- GW-EM x cosmology
  - What precision can MMA achieve? Worry about systematic errors?
  - Beyond H0?
  - New tests of general relativity with MMA?

- GW-EM x cosmological transients
  - Will MMA solve the diversity in GRBs? Short vs long, extended emission, flare etc.
  - Cosmic star formation history?
  - A new type of extreme transient?
  - What EM facilities are needed to match the capabilities of NG detectors at high redshift?

- GW-EM for nearby objects
  - Precursors and post-merger GW signals
  - More nearby events → searches for kilonova afterglows (EoS)
  - Core collapse supernovae, magnetar flares, pulsars, X-ray binaries, accretion induced collapse
  - What observations are needed to improve models for waveforms observed in NG detectors?

3G era

Multi-messenger: GW x EM x ν

- IceCube gen-2 is very interesting. But we probably need a nearby on-axis jet given the fact that we haven't seen high energy neutrinos from any GRBs.

- If high energy neutrinos from a merger are detected, what information from EM will be the most useful?

- High energy ν and space GW from TDEs?