Multi-messenger astrophysics of neutron star binary mergers

Kyohei Kawaguchi (U. Tokyo, ICRR)

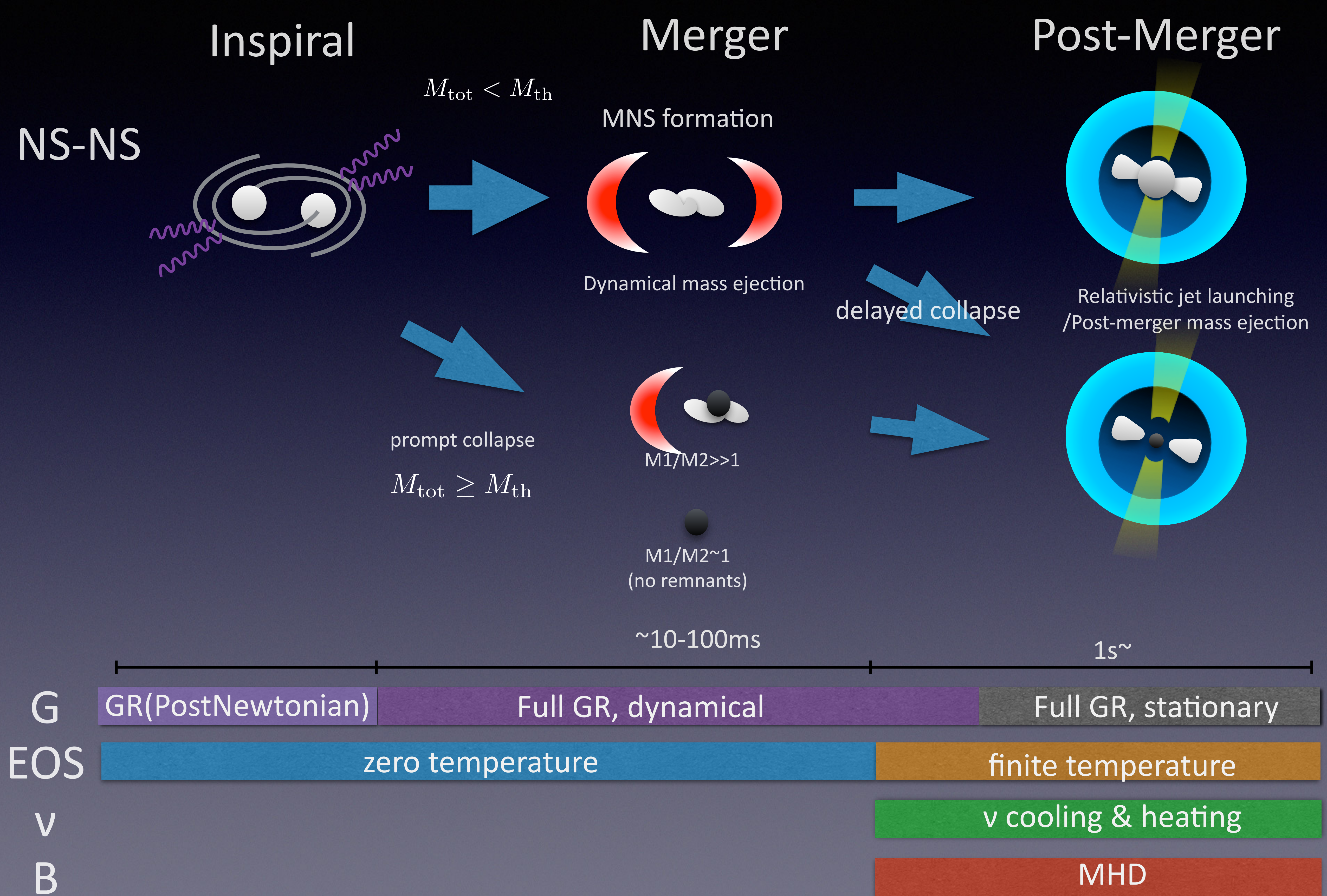
Collaborators:
S. Fujibayashi (AEI), K. Hotokezaka (U. Tokyo),
M. Shibata (AEI, Kyoto. U.), M. Tanaka (Tohoku U.), and S. Wanajo (AEI)

The extreme Universe viewed in very-high-energy gamma rays 2021

Outline

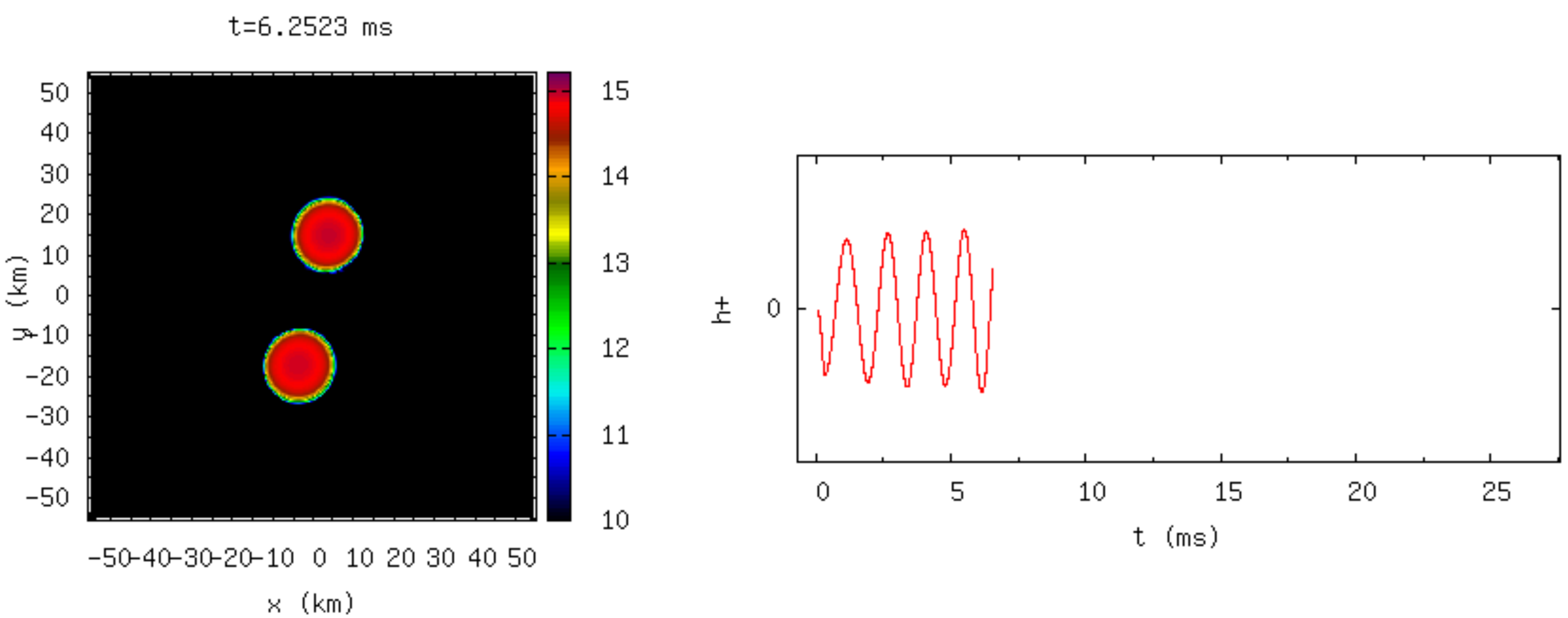
- Brief overview: neutron star binary mergers
- Previous Observations and Multi-messenger astrophysics
- Expectation of Future Observations
- (Our recent study)

Brief picture



Inspiral Gravitational waves from NS-mergers

Ref: K. Hotokezaka et al. 2013



Evolution of the GW phase (frequency)

$$\frac{dx}{dt} = \frac{64\eta}{5} x^5 \left(1 + a_1 x + a_{1.5} x^{1.5} + a_2 x^2 + \cdots\right)$$

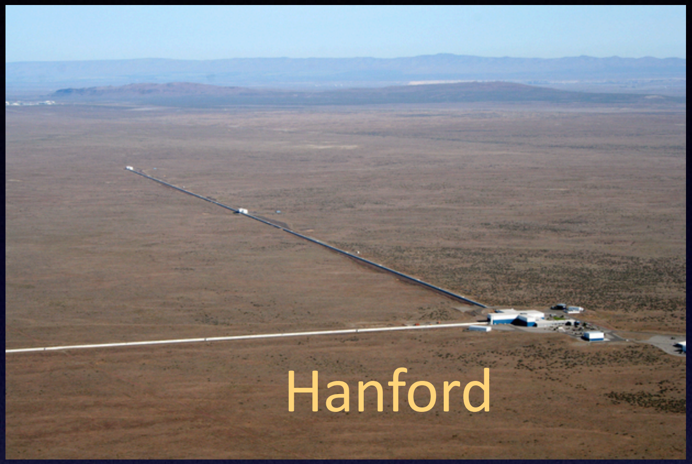
PostNewtonian Parameter (relativistic correction):

$$x := (\pi m f_{\rm GW})^{2/3} \approx \left(\frac{m}{a}\right) \approx v^2$$

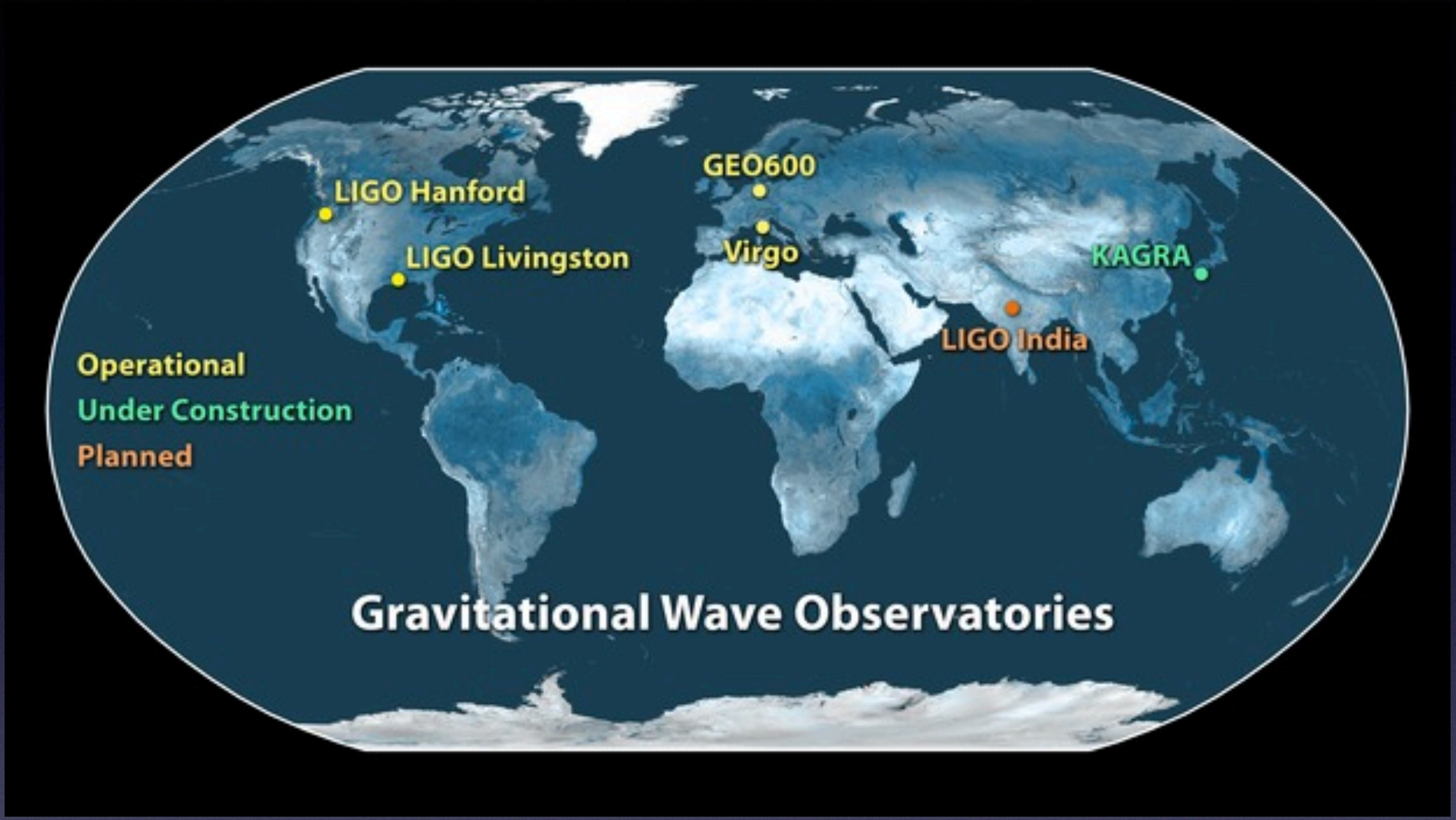
- 0PN: chirp mass: $\mathcal{M}_{\rm chirp} = m\eta^{3/5}$
- 1PN: symmetric mass: $\eta = \frac{m_1 m_2}{(m_1 + m_2)^2}$
- 1.5PN: spin (spin-orbit): $\chi_i = \frac{S_i}{m_i^2}$
- 5PN: tidal deformability: Λ_i
- amplitude: (distance, inclination): $(D_{\rm L}, \iota)$

Gravitational wave detectors

Advanced LIGO



https://www.ligo.caltech.edu/

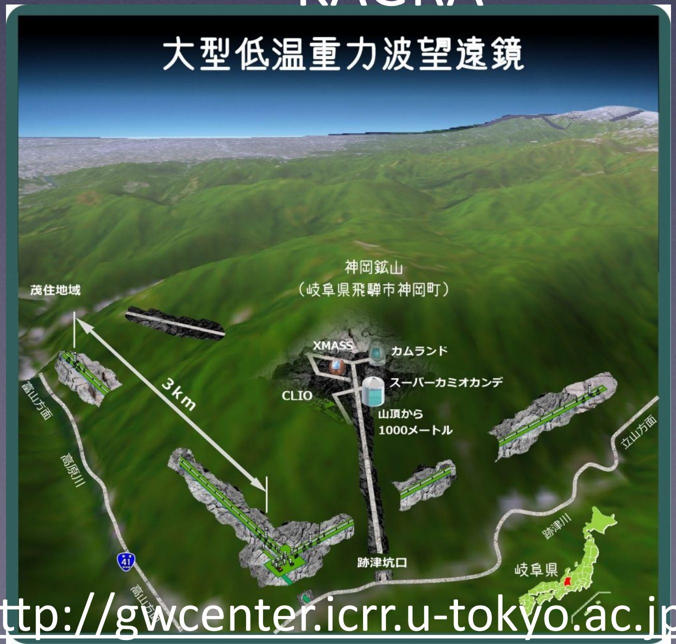


- GW sources for ground-based GW detectors
  - **Compact binary mergers**
  - Core collapse Super Novae
  - Rotating Neutron stars
  - Primordial GW (Inflation)
  - Cosmic Strings

Advanced Virgo

http://www.virgo-gw.eu/

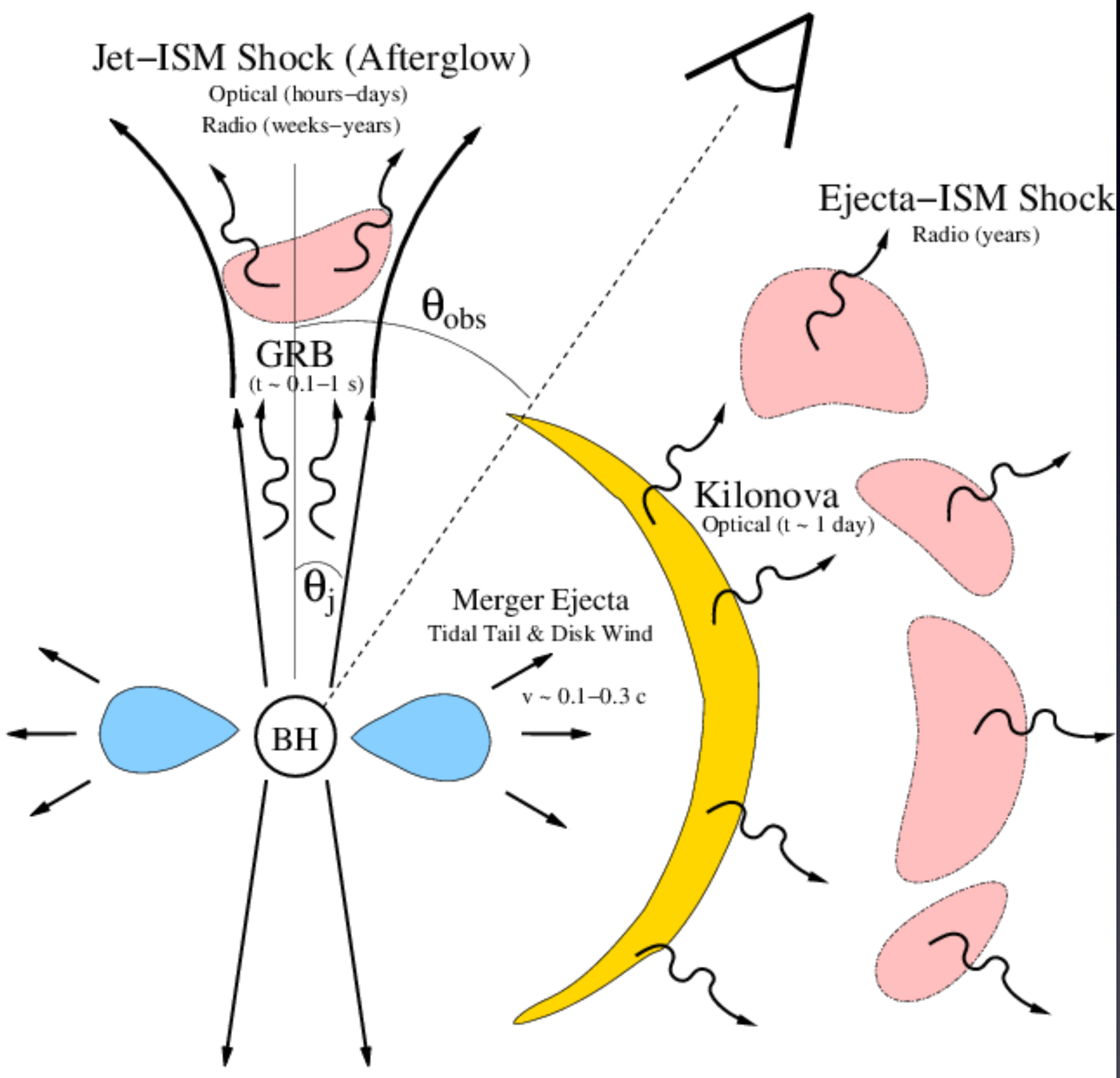
KAGRA



http://gwcenter.icrr.u-tokyo.ac.jp/

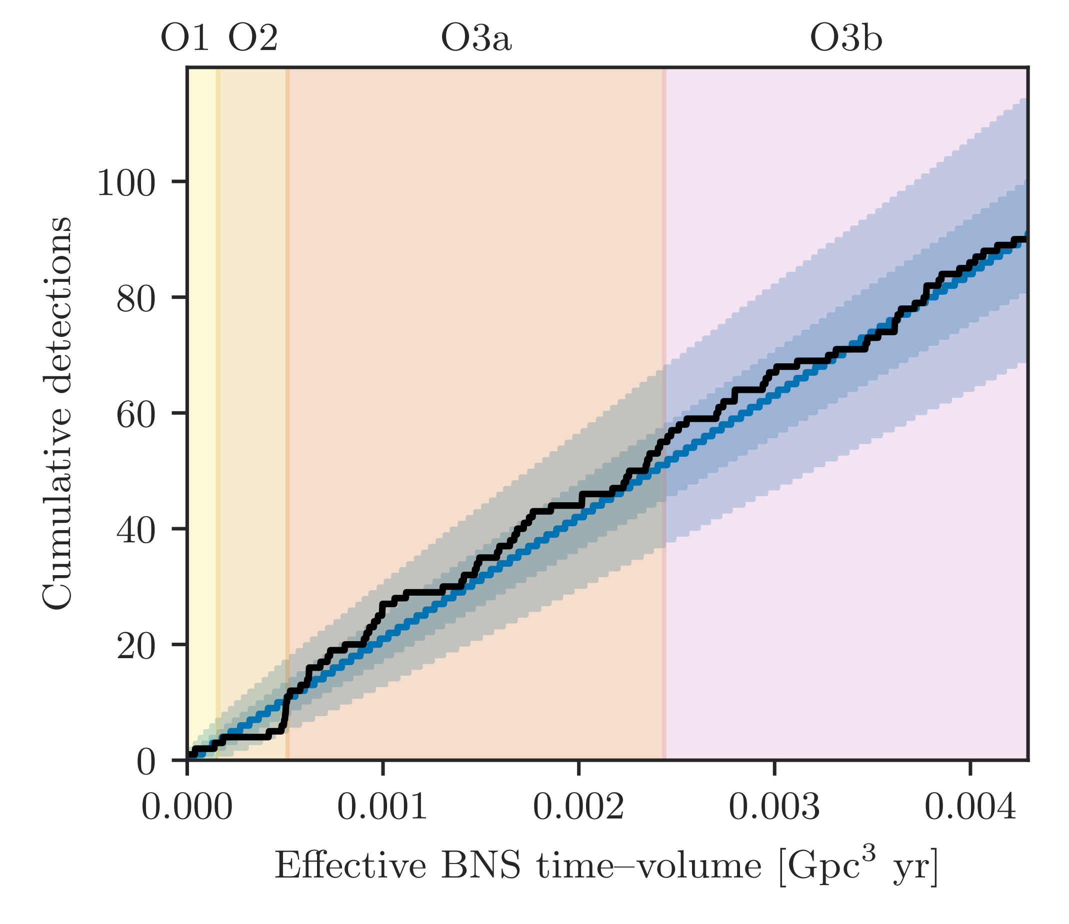
Electromagnetic Counterparts to NS binary mergers

- Various transient EM counterparts that asscociate NS binary mergers:
  - short-hard gamma-ray-burst
  - Afterglow
  - cocoon emission
  - kilonovae/macronovae
  - radio flare, etc.
- Host galaxy identification, remnant properties, environment
- Possible main synthesis site of r-process nuclei in the universe



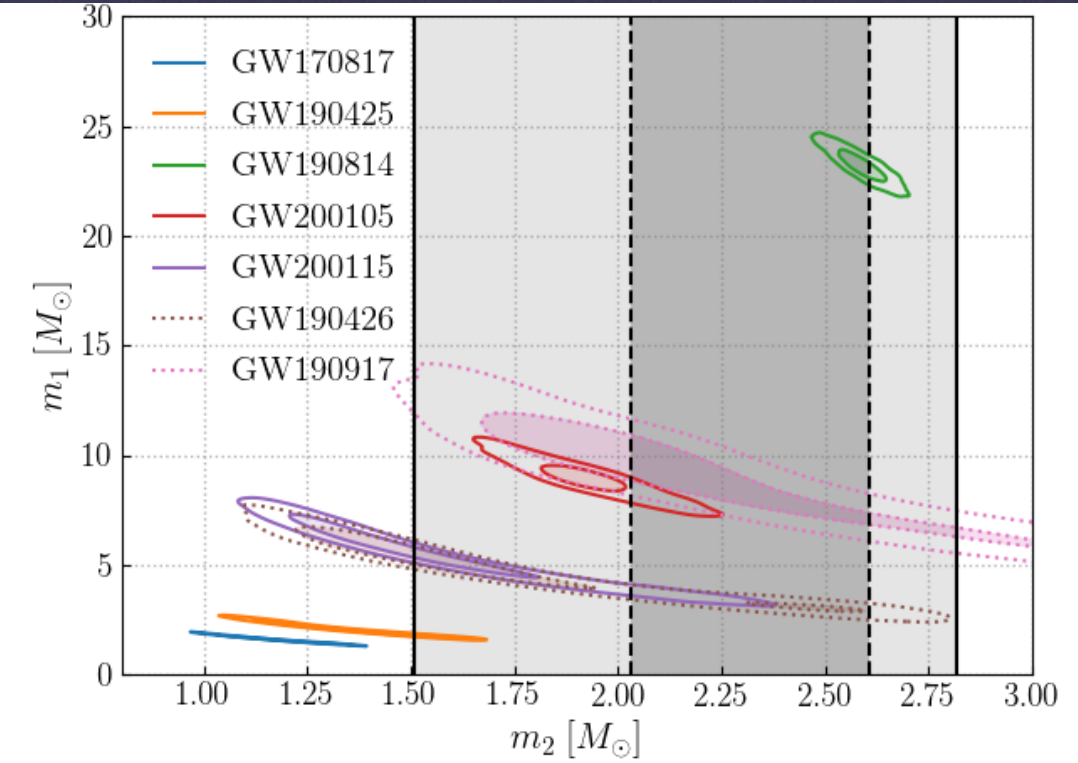
Ref: B. Metzger and E. Berger 2012

Observed GW events



- **LIGO-Virgo: observation (FAR<0.25 yr^{-1}):**

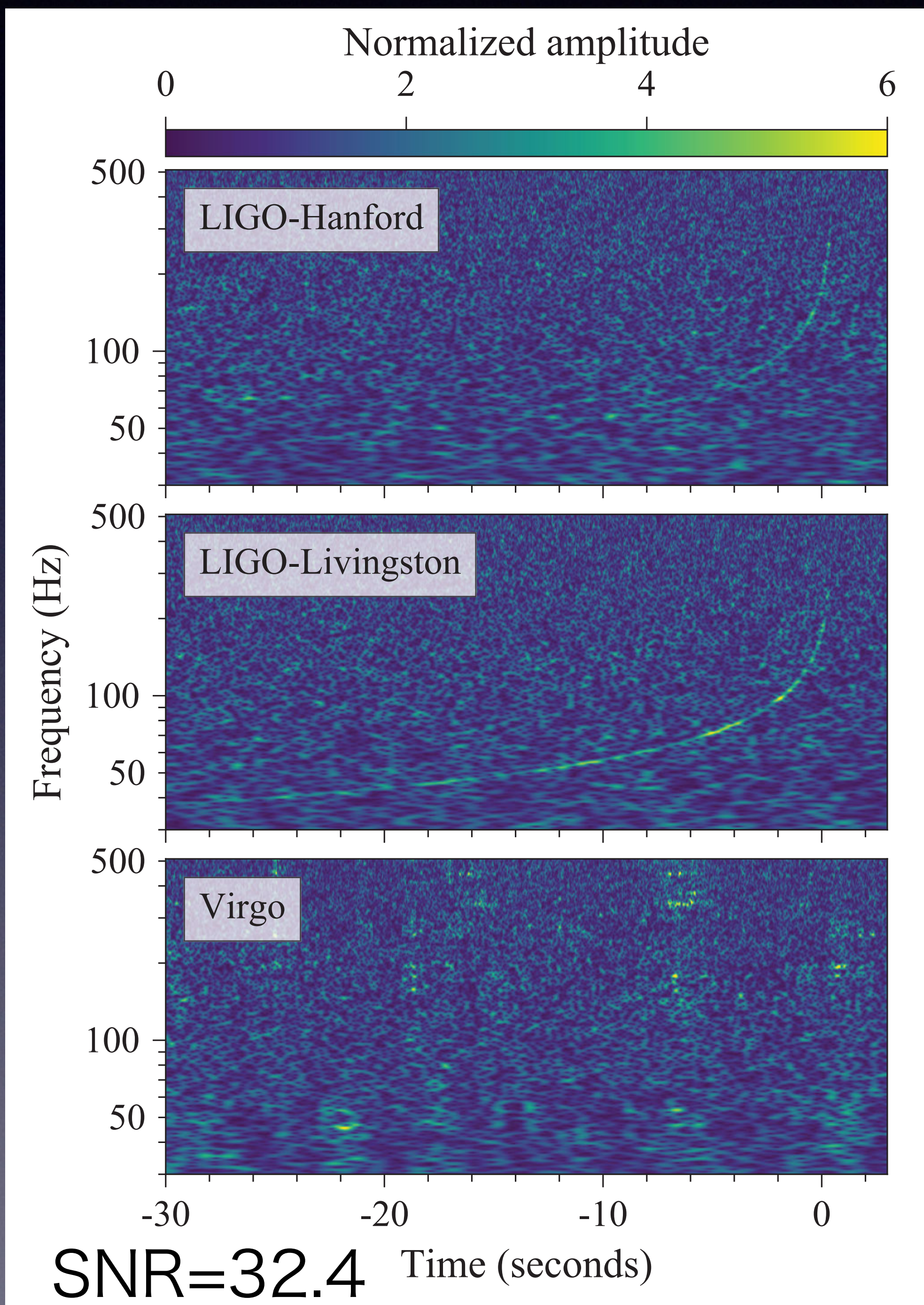
- BBH (BH-BH): 63
- BNS (NS-NS): 2
  - **GW170817, GW190425**
- NSBH: 1 (3)
  - **(GW200105), GW200115 (GW190814 →BBH?)**



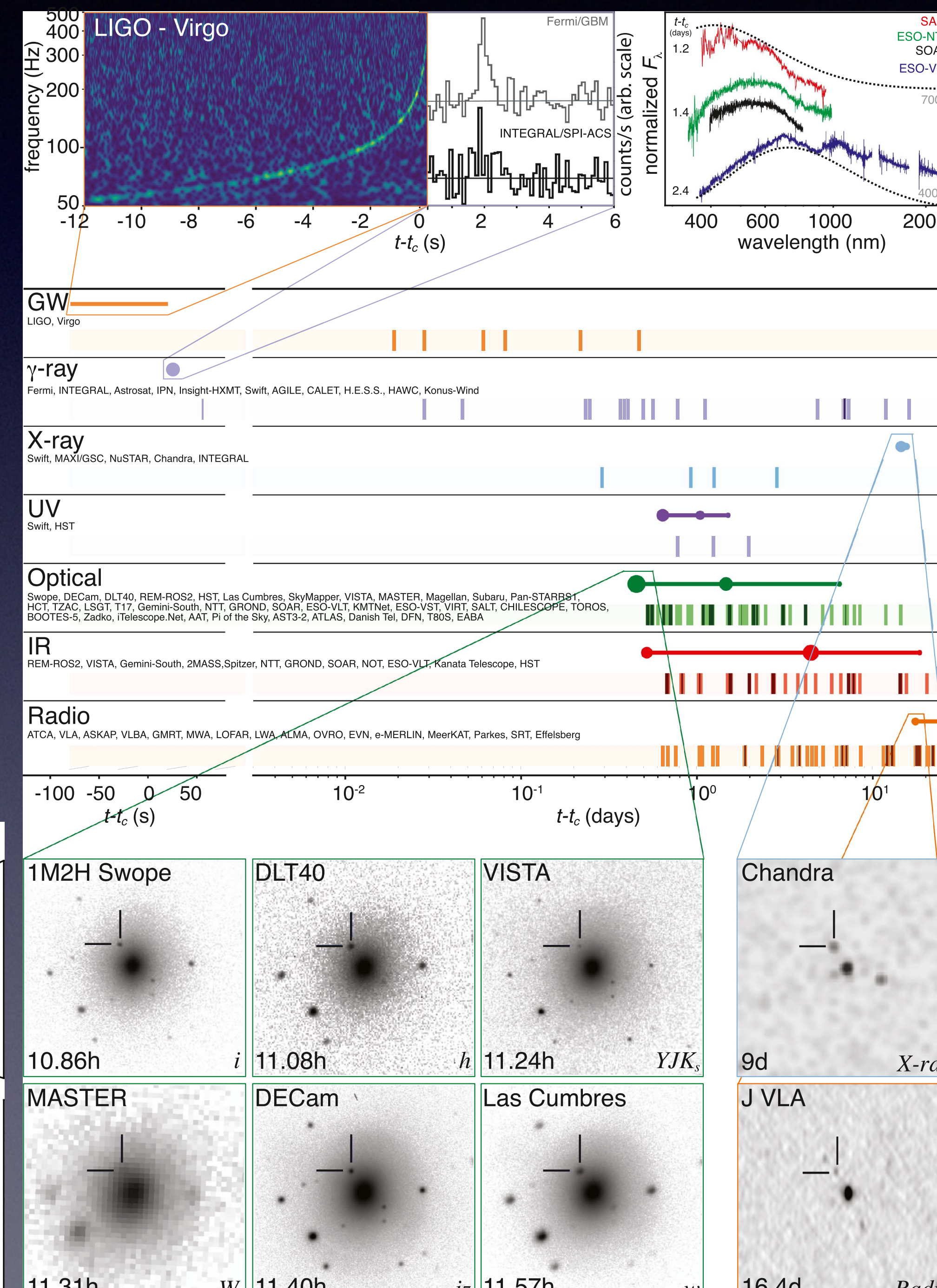
ref) GTWC-3: Abbott et al. 2021

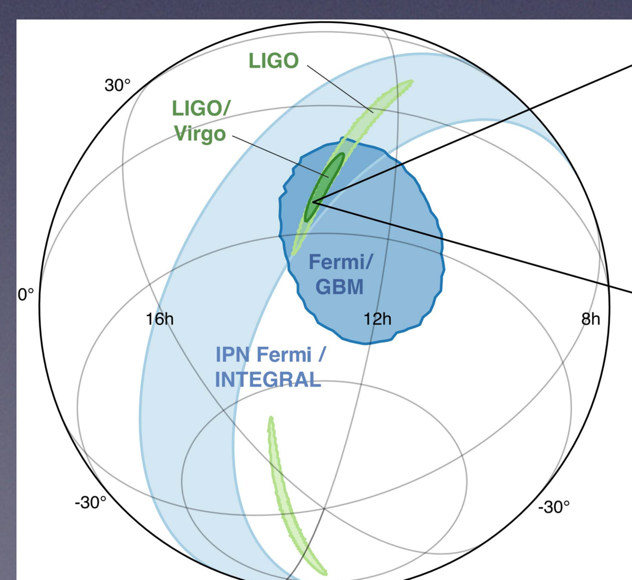
GW170817: GW+EM detection from a NS-NS (BNS) merger

Gravitational waves



EM counterparts

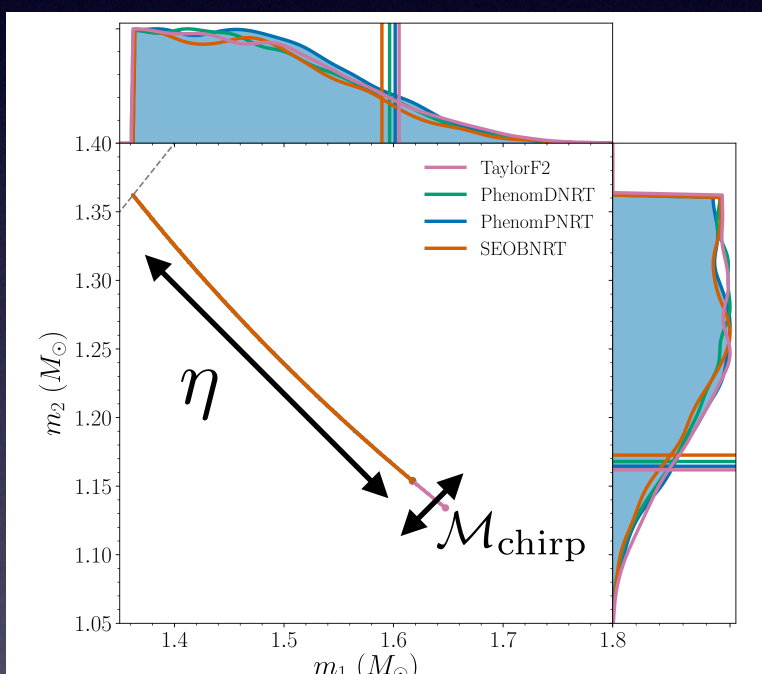




Ref: LIGO/Virgo 2017

GW170817:Constraints on binary parameters

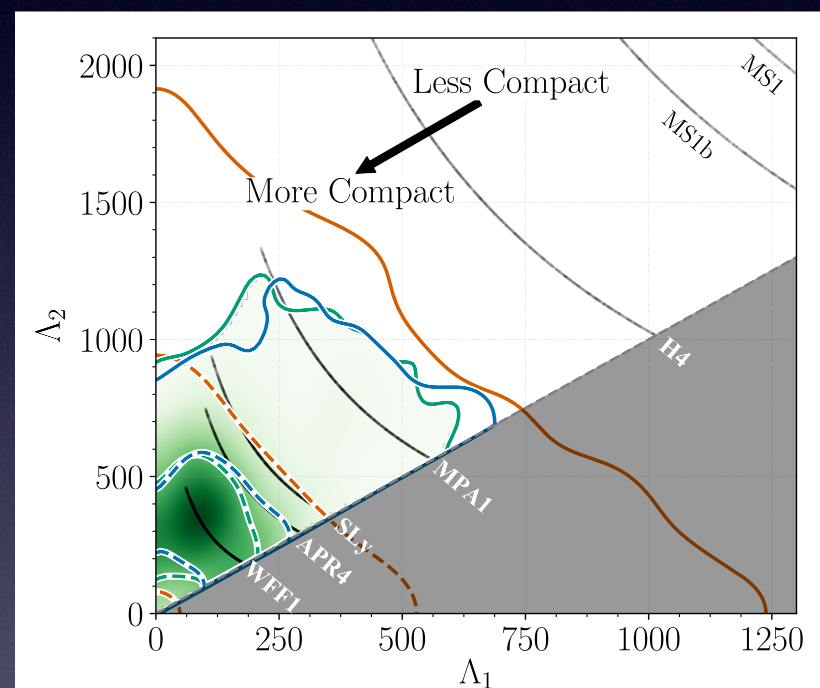
Masses of the binary components



Tidal deformability

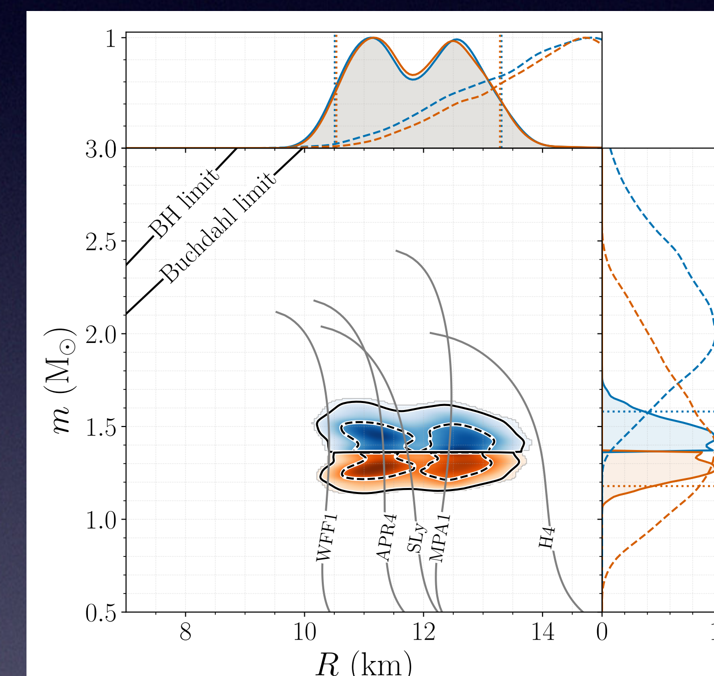
$$\Lambda = G\lambda\left(\frac{c^2}{GM_{\rm NS}}\right)^5 \qquad Q_{\rm ij} = \lambda E_{\rm ij}$$

induced quadrupole tidal field



NS mass - radius relation

$$\Lambda \sim\propto \left(\frac{R_{\rm NS}}{M_{rmNS}}\right)^5$$



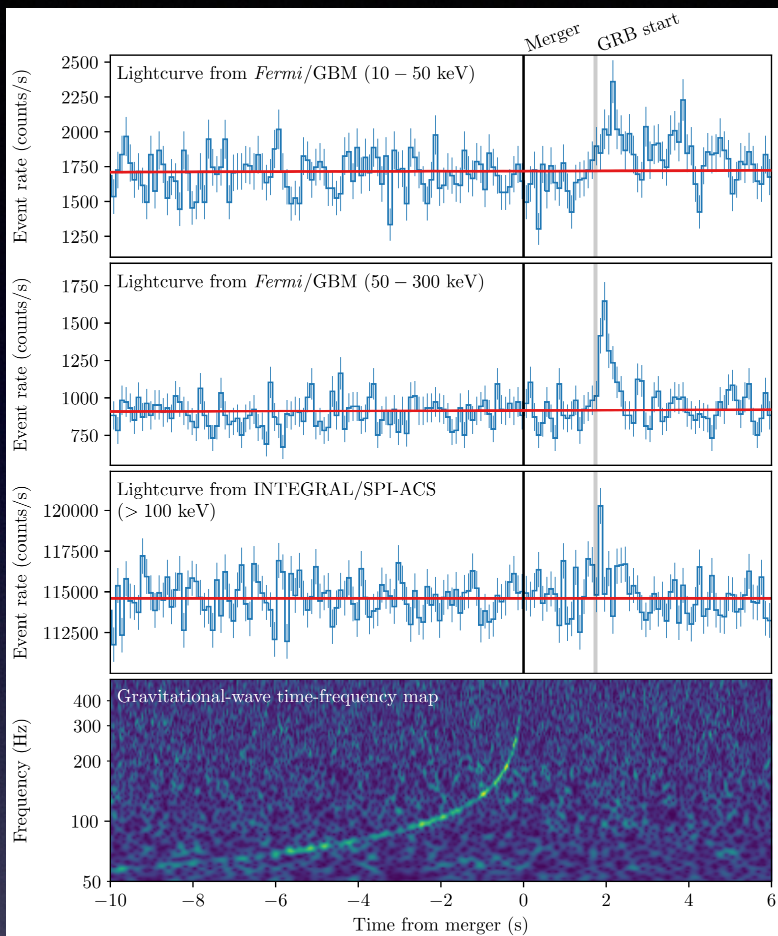
Ref: LIGO/Virgo 2017,2018

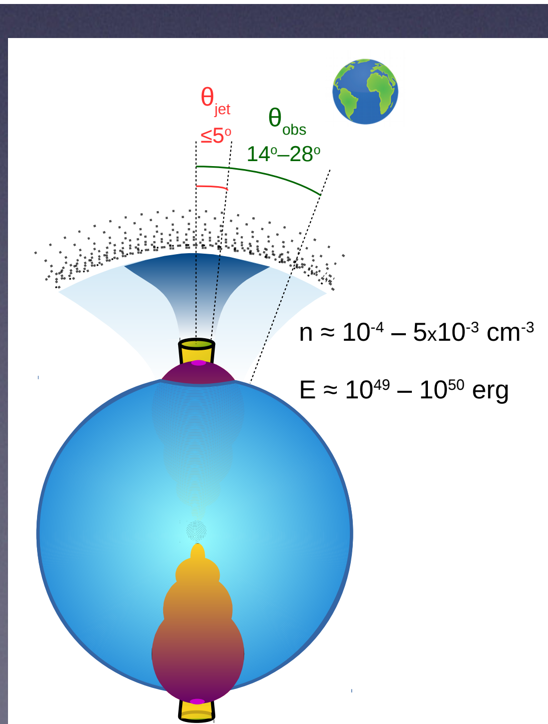
$$M_{\rm tot} = \eta^{-3/5}\mathcal{M}_{\rm chirp}$$
$$\geq 2.3\mathcal{M}_{\rm chirp} \approx 2.72\, M_\odot$$
$$(0 \leq \eta \leq 1/4)$$

	Low-spin prior ($\chi \leq 0.05$)	High-spin prior ($\chi \leq 0.89$)
Binary inclination $\theta_{\rm JN}$	146^{+25}_{-27} deg	152^{+21}_{-27} deg
Binary inclination $\theta_{\rm JN}$ using EM distance constraint [104]	151^{+15}_{-11} deg	153^{+15}_{-11} deg
Detector frame chirp mass $\mathcal{M}^{\rm det}$	$1.1975^{+0.0001}_{-0.0001} M_\odot$	$1.1976^{+0.0004}_{-0.0002} M_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001} M_\odot$	$1.186^{+0.001}_{-0.001} M_\odot$
Primary mass m_1	(1.36, 1.60) $M_\odot$	(1.36, 1.89) $M_\odot$
Secondary mass m_2	(1.16, 1.36) $M_\odot$	(1.00, 1.36) $M_\odot$
Total mass m	$2.73^{+0.04}_{-0.01} M_\odot$	$2.77^{+0.22}_{-0.05} M_\odot$
Mass ratio q	(0.73, 1.00)	(0.53, 1.00)
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$	$0.02^{+0.08}_{-0.02}$
Primary dimensionless spin χ_1	(0.00, 0.04)	(0.00, 0.50)
Secondary dimensionless spin χ_2	(0.00, 0.04)	(0.00, 0.61)
Tidal deformability $\tilde{\Lambda}$ with flat prior	300^{+500}_{-190}(symmetric)/ 300^{+420}_{-230}(HPD)	(0, 630)

Off-axis GRB+Afterglow observation

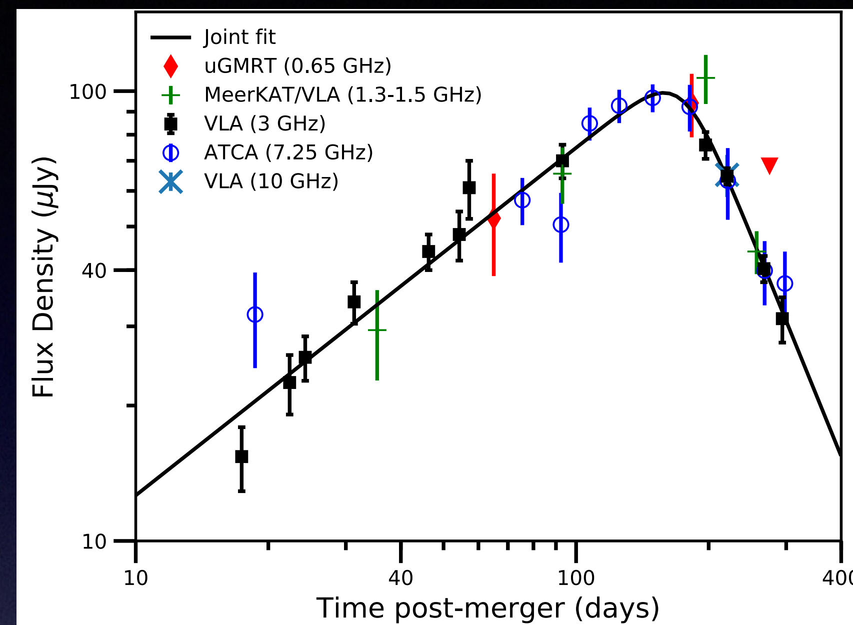
Prompt Emission
LIGO/Virgo/Fermi/INTEGRAL 2017





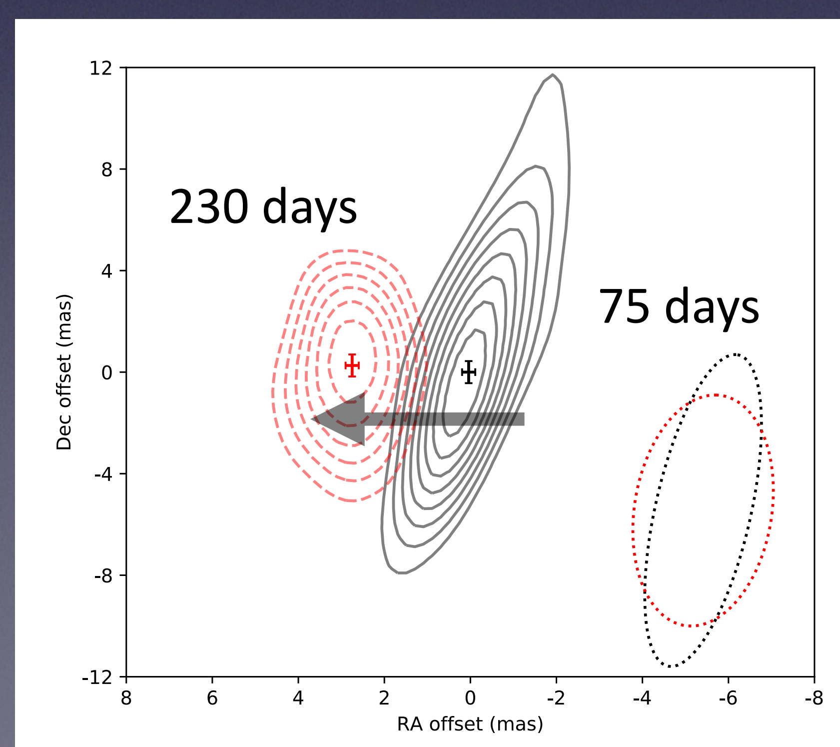
Mooley et al. 2018

Radio afterglow



Mooley et al. 2018

Radio observation (VLBI)



Simultaneous detection of Gamma ray burst:

Prompt emission:
~1.7 s after the GW trigger

Duration ~2 s
E_{peak} ~200 keV

E_{iso} ~ 10^{47} erg

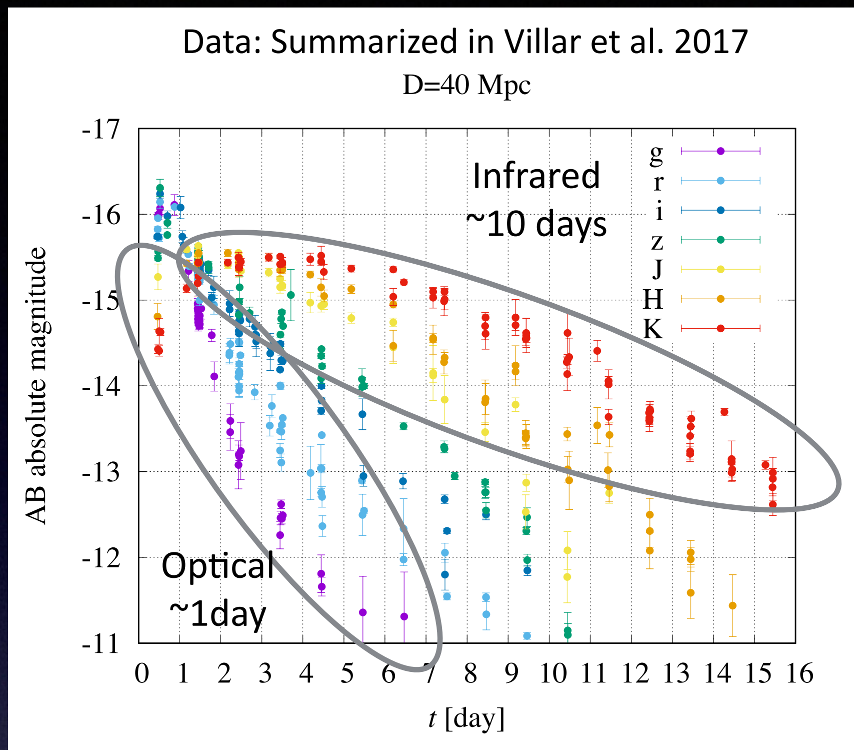
Afterglow emission in radio - optical - X ray bands:

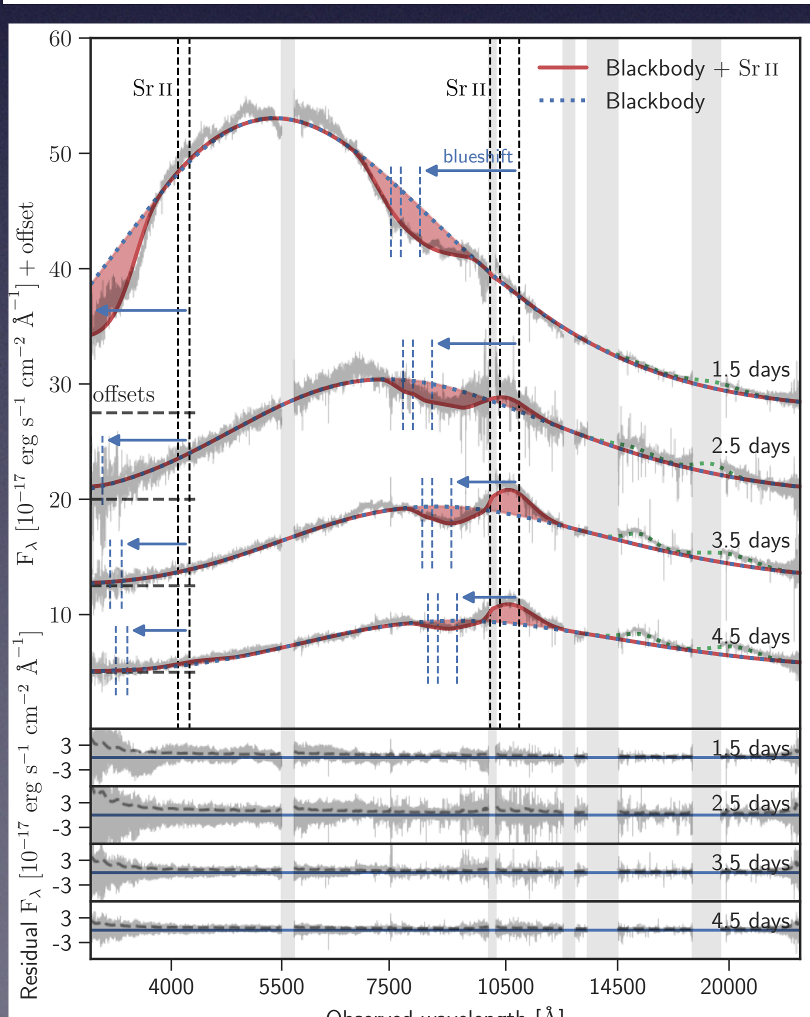
consistent with an off-axis jet model

Radio observation with VLBI:

Superluminal motion of the spot
β_{app}~4.1±0.4
→ existence of relativistic components

AT2017gfo: Kilonova





Watson et al. 2019

Optical & Near Infrared transient:

Consistent with a Kilonova emission with multiple ejecta components

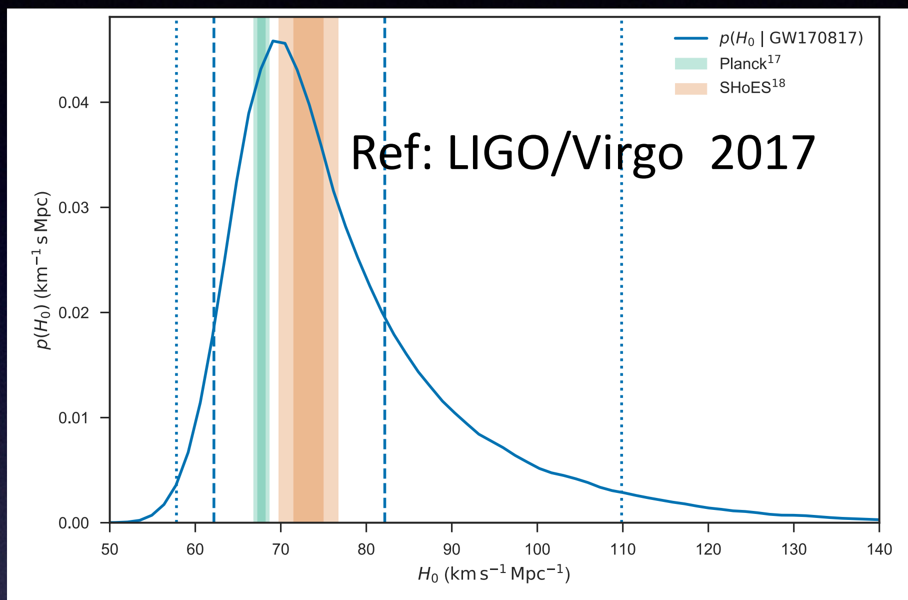
(see e.g., Kasliwal et al. 2017, Cowperthwaite et al. 2017, Kasen et al. 2017, Villar et al. 2017, KK et al. 2018, 2019)

Identification of Host Galaxy: (NGC4993: ~40 Mpc)

Probable identification of SrII line: (Watson et al. 2019, Domoto et al. 2021)

Physics with GW+EM MMA

Hubble parameter constraint



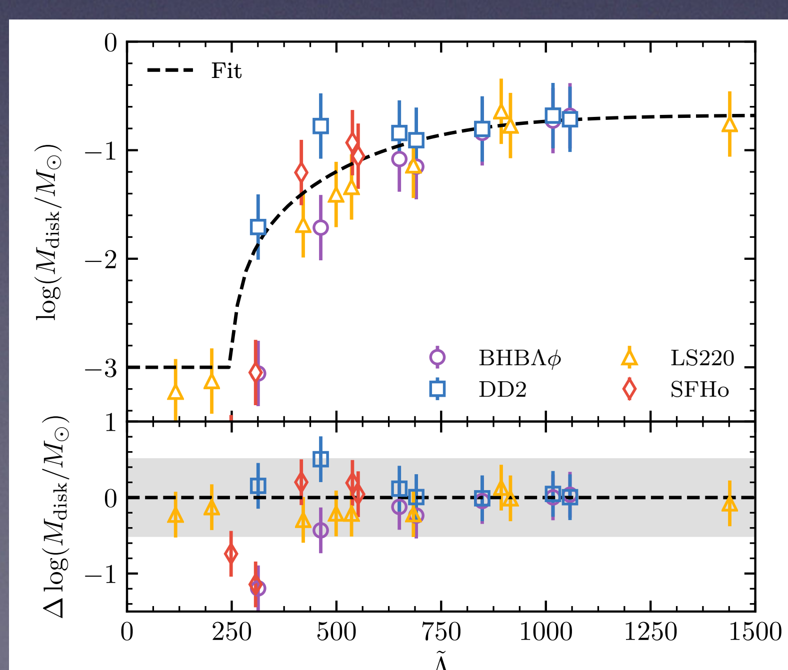
Constraint on GW propagation speed

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\mathrm{EM}}} \leq +7 \times 10^{-16}$$

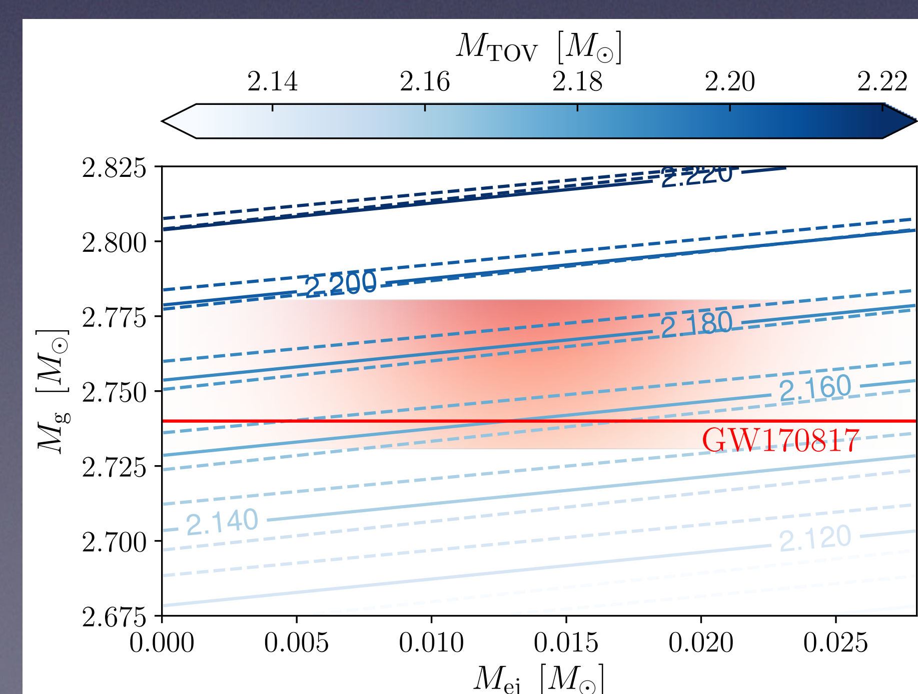
$$\Delta v = v_{\mathrm{GW}} - v_{\mathrm{EM}}$$

Ref: LIGO/Virgo/Fermi/INTEGRAL 2017

Lower limit for the NS tidal deformability
(e.g., Radice & Dai 2018, Kiuchi et al. 2019)

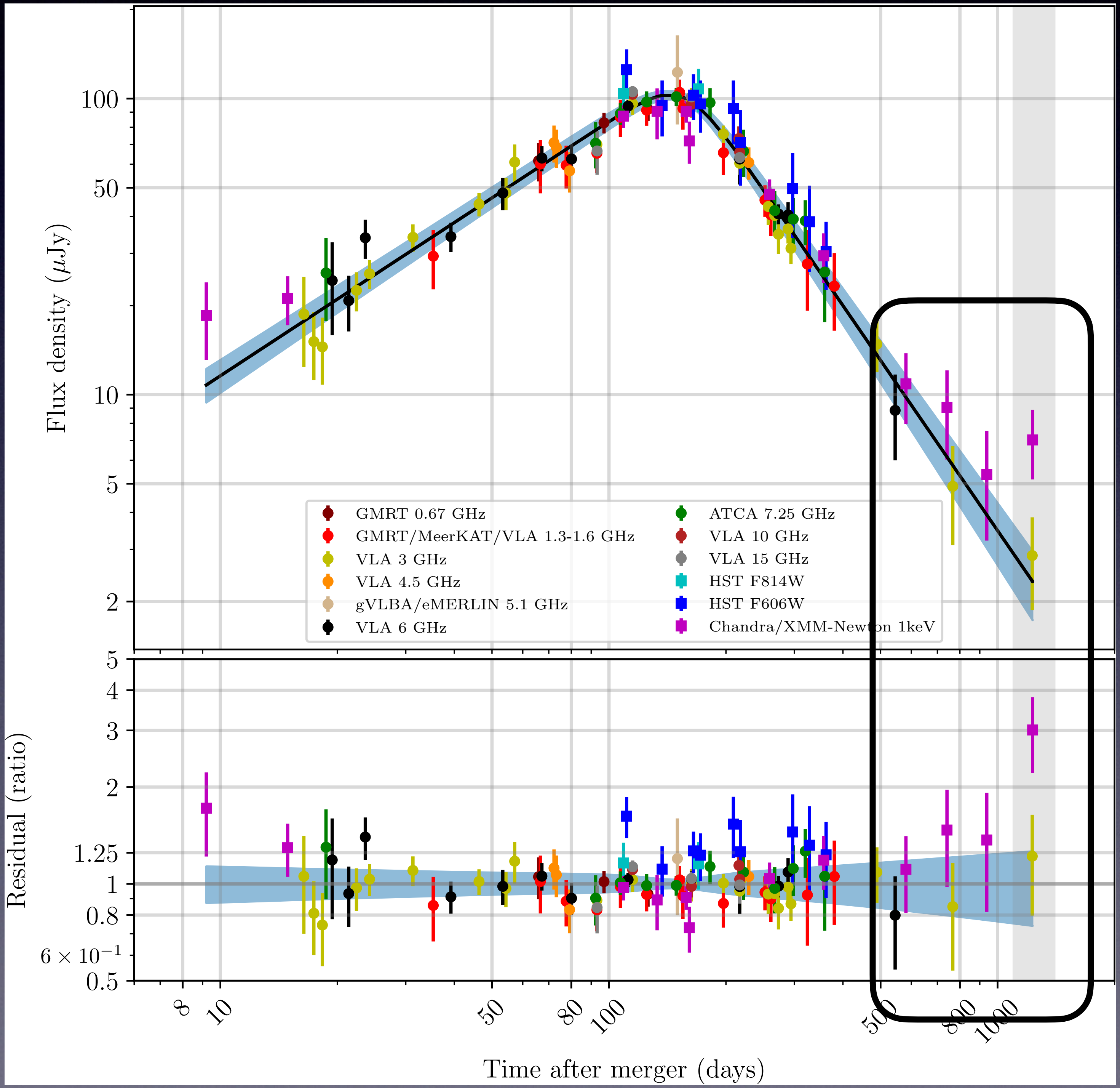


Upper limit on the NS maximum mass
(e.g., Margalit & Metzger 2017,
Rezzolla et al. 2018 , Shibata et al. 2019)



3.5 years from the merger: X-ray Excess

Balasubramanian et al. 2021, Troja et al. 2021, Hajela et al 2021



X-ray excess from the off-axis jet afterglow model:

Chandra: ~1234 days after the merger

No excess in found radio band:

VLA: 3 GHz (non detection in 15 GHz)

Possible scenarios:

・Arise of the synchrotron emission due to the interaction of (sub~mildly-relativistic) kilonova ejecta and ISM (Hotokezaka et al. 2018)

・X-ray emission due to fall-back disk (Ishizaki et al. 2021, Metzger & Fernandez 2021)

O3: no GW+EM detections

NS mergers during O3

1 NS-NS: GW190425

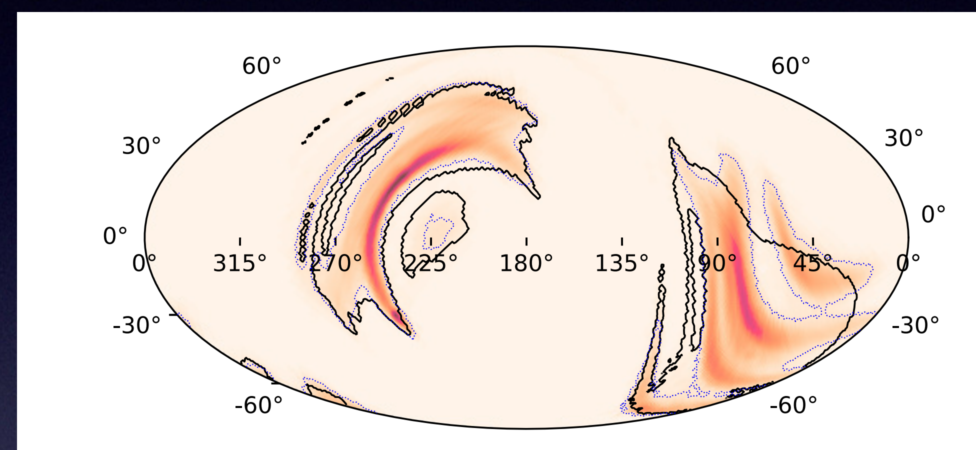
1 (2) BH-NS:
GW200115, (GW200105)

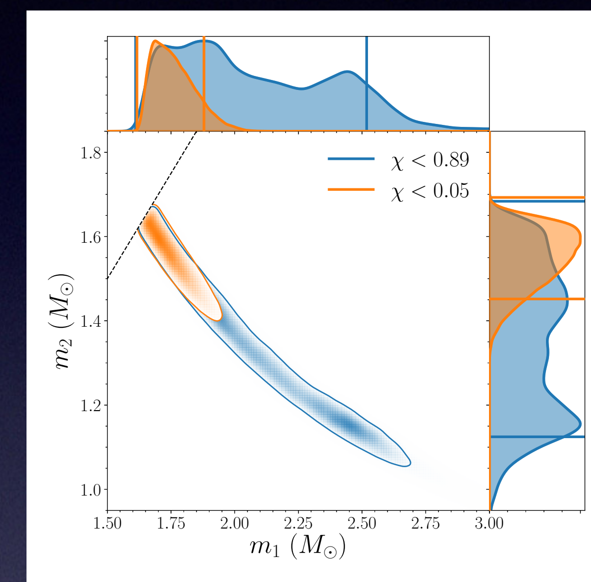
BH-BH? BH-NS:
GW190814

no EM counterparts were found

Implication from EM follow-up
(e.g., Andreoni et al. 2019, KK et al. 2020
Gomez et al 2020, Ackley et al. 2020
M.Coughlin 2019, 2020, …)

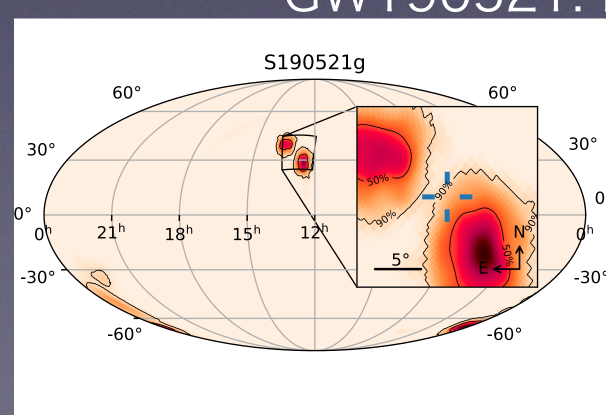
GW190425: the second NS-NS GW event
(Abbot et al. 2020)



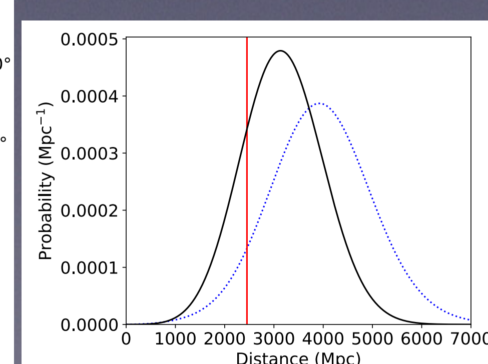


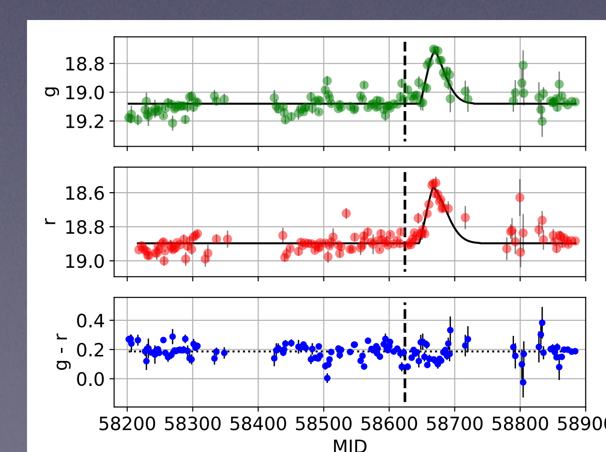
D~160 Mpc, $\Omega_{90\%}$~10,000 deg^2

GW190521: BH-BH with potential EM counterparts?



Graham et al. 2020



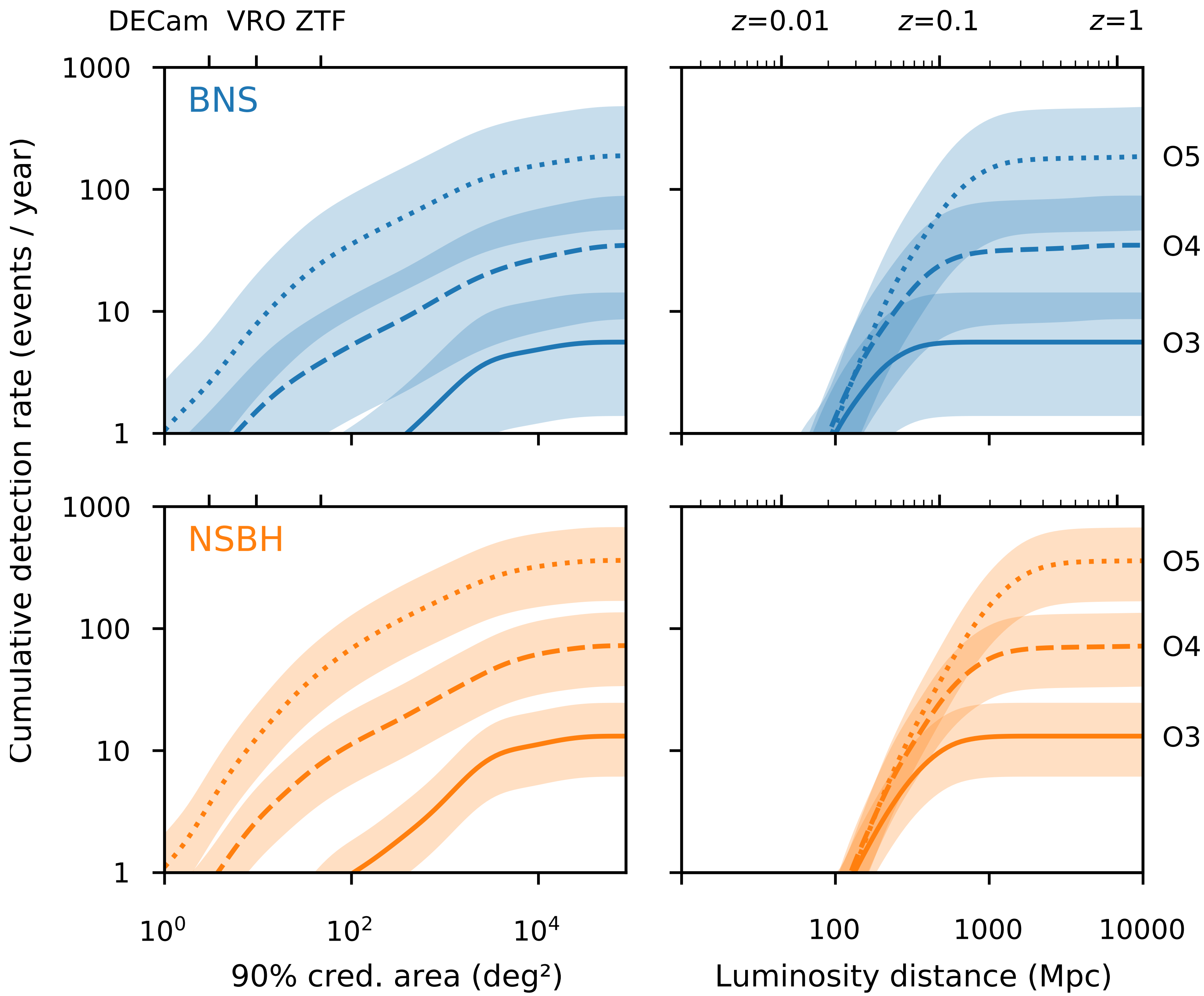


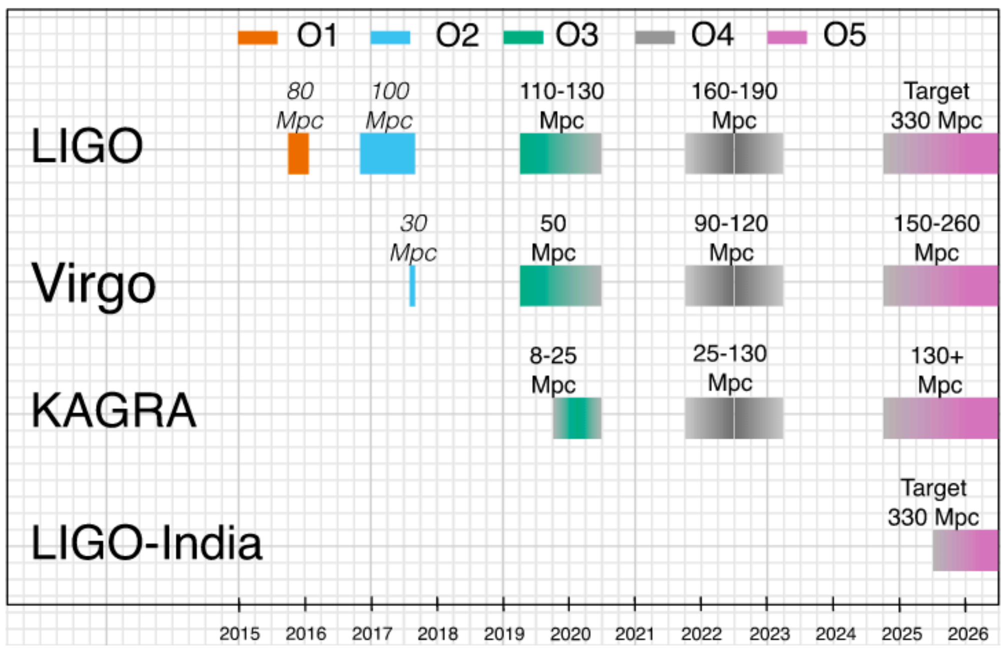
Future observation

Expected Detection rate, Localization, & Distance @ O4,O5

	O4			O5		
	Total	$20 < \Omega_{90\%} \leq 100$	$\Omega_{90\%} \leq 20$	Total	$20 < \Omega_{90\%} \leq 100$	$\Omega_{90\%} \leq 20$
NS–NS	34^{+78}_{-25}	$2.5^{+5.7}_{-1.8}$	$2.4^{+5.6}_{-1.8}$	190^{+410}_{-130}	22^{+49}_{-15}	$13^{+29}_{-9.1}$
NS–BH	72^{+75}_{-38}	$6.8^{+7.1}_{-4.0}$	$4.3^{+4.5}_{-2.5}$	360^{+360}_{-180}	45^{+45}_{-23}	23^{+23}_{-12}
BH–BH	106^{+65}_{-42}	$19^{+12}_{-7.7}$	$15^{+9.3}_{-6.0}$	480^{+280}_{-180}	104^{+61}_{-39}	70^{+41}_{-26}

I. Andreoni et al. 2021





https://emfollow.docs.ligo.org/userguide/capabilities.html

P.Petrov et al. 2021

GW-GRB Joint events

Saleem et al. 2020, Howell et al. 2019

	Case	Any ι	$\iota \leq 20°$	$\iota > 20°$
	LHV			
O3	Untriggered BNS	$5.7^{+13.7}_{-4.8}$	$1.1^{+2.6}_{-0.9}$	$4.6^{+11.1}_{-3.9}$
	Total BNS	$6.5^{+15.9}_{-5.6}$	$1.7^{+4.1}_{-1.5}$	$4.8^{+11.8}_{-4.1}$
	Joint BNS-SGRB	$2.2^{+5.5}_{-1.9}$	$1.3^{+3.2}_{-1.1}$	$0.9^{+2.3}_{-0.8}$
	LHVK			
~O4 -O5	Untriggered BNS	$23.5^{+57.3}_{-20.1}$	$4.3^{+10.5}_{-3.7}$	$19.2^{+46.7}_{-16.4}$
	Total BNS	$26.7^{+64.8}_{-22.8}$	$6.8^{+16.4}_{-5.8}$	$19.9^{+48.4}_{-17.0}$
	Joint BNS-SGRB	$8.1^{+19.6}_{-6.9}$	$5.1^{+12.3}_{-4.3}$	$3.0^{+7.3}_{-2.6}$
	LHVKI			
Design ~O5-	Untriggered BNS	$164.8^{+400.6}_{-140.7}$	$31.0^{+75.4}_{-26.5}$	$133.8^{+325.3}_{-114.2}$
	Total BNS	$178.4^{+433.4}_{-152.2}$	$44.1^{+107.1}_{-37.6}$	$134.3^{+326.3}_{-114.6}$
	Joint BNS-SGRB	$34.6^{+84.3}_{-29.6}$	$30.3^{+73.7}_{-25.9}$	$4.3^{+10.6}_{-3.7}$

Untriggered:
Events detectable only by GW

Total BNS:
Events with both GW and GRB triggered

Joint BNS-GRB:
BNS Event which both GW & GRB is detectable

f_{GBM}> 2 x 10^{-7} erg /cm^{-2}
(including off-axis events)

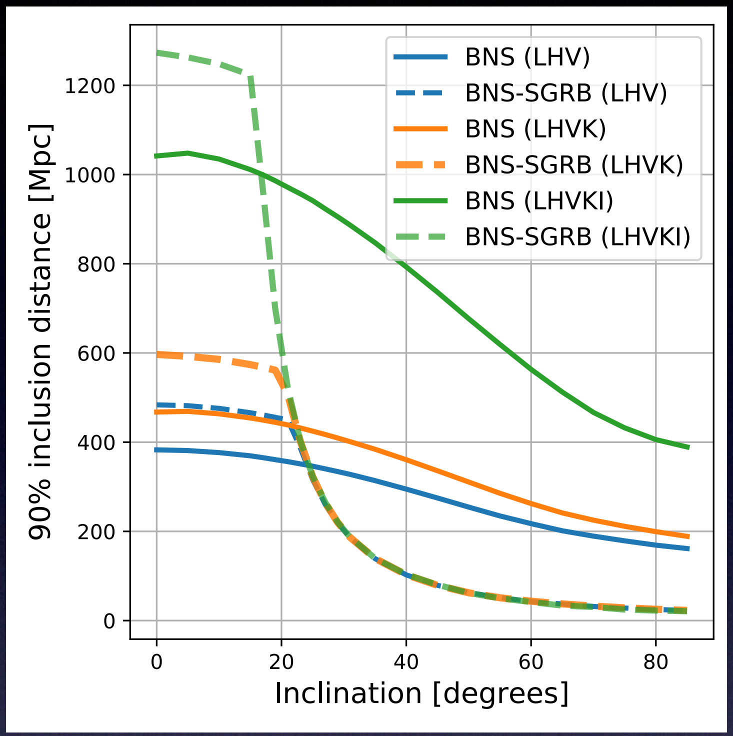
LVK collaboration
Fermi GRB-triggered GW search
Abbot et al. 2021, arXiv: 2111.03608

$$R^{O4}_{GW-GRB} = 1.04^{+0.26}_{-0.27}\ \mathrm{yr}^{-1}$$

(Expected rate for O3 was
0.07-1.8 Event/yr @ O2 era)

VHE photon from BNS mergers

Saleem et al. 2020



VHE (GeV-TeV) photons from GRB

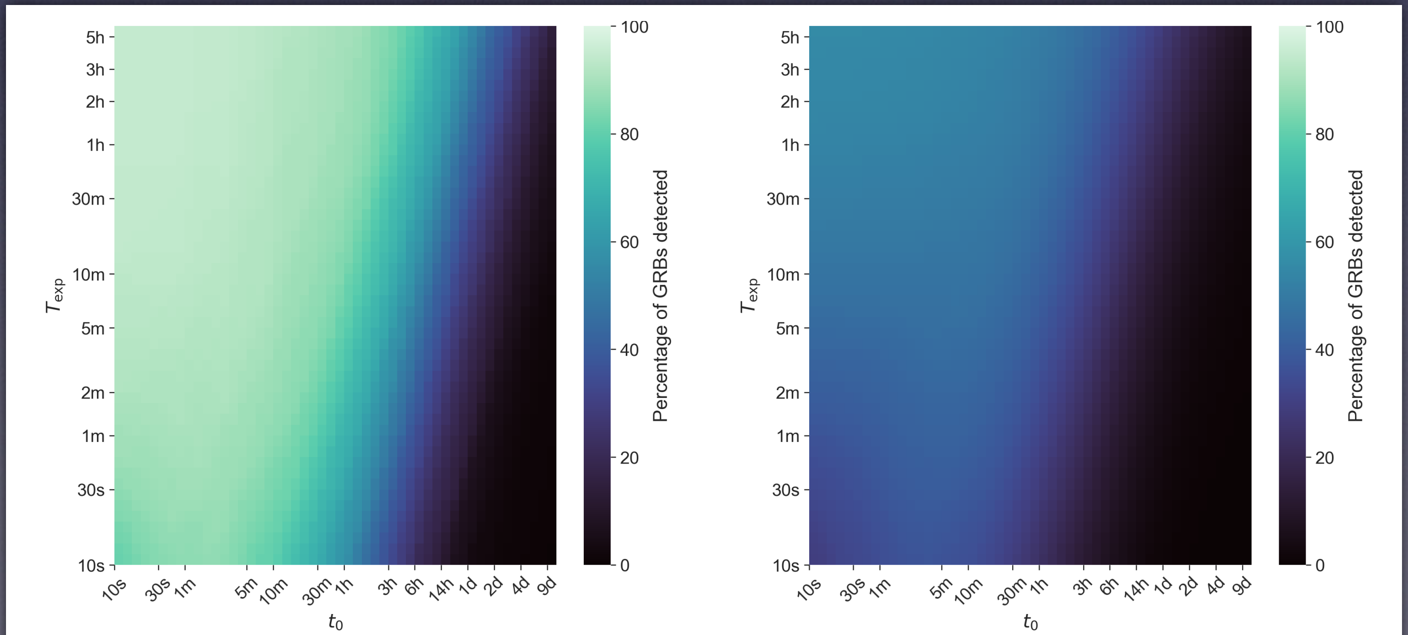
VHE (GeV-TeV) photons are detected for long GRBs
(MAGIC: Acciari et al. 2019,
H.E.S.S.: Abdalla et al. 2019, 2020)

Evidence of VHE (GeV-TeV) photons from a short GRB

GRB160821B (MAGIC: Acciari et al. 2021)

VHE follow-up of GW event by CTA

Patricelli et al., CTA Consortium ICRC2021
(see e.g., Veres & Mezaros et al. 2014, Murase et al. 2018, Kimura et al. 2019 for the mechanisms)



(c) CTA North, z20°, (θ_{view} < 10°) **(d)** CTA North, z20°, (θ_{view} < 45°)

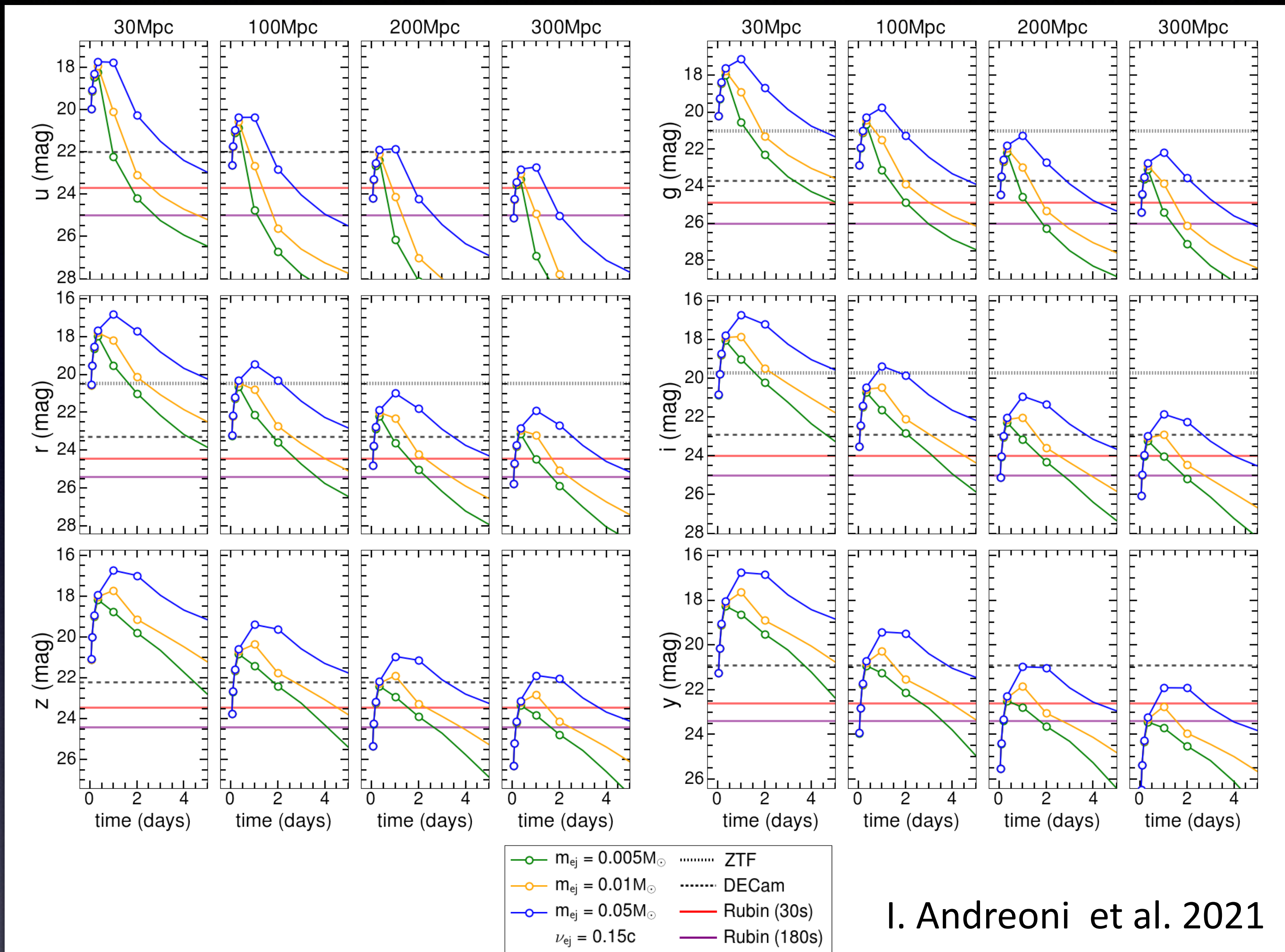
Distance: up to 500 Mpc.
Delay time : 10 min.
$L_X \sim L_{VHE}$

On axis (<10 deg.)
~92% by a few hours of exporsure

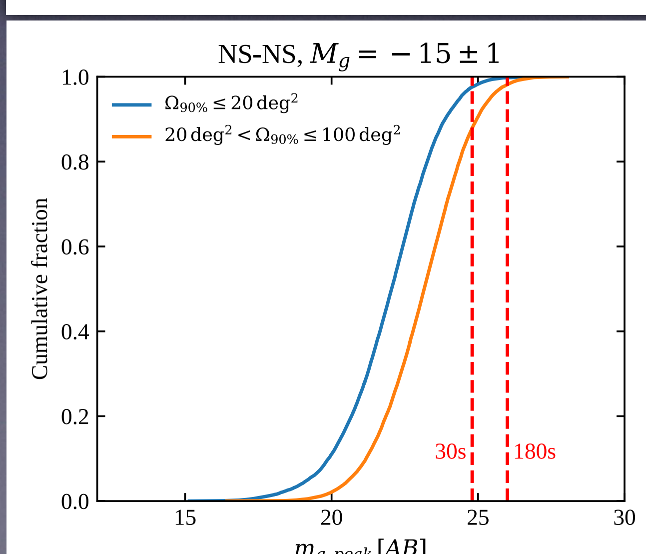
Off axis (<45 deg.)
~54% by a few hours of exporsure

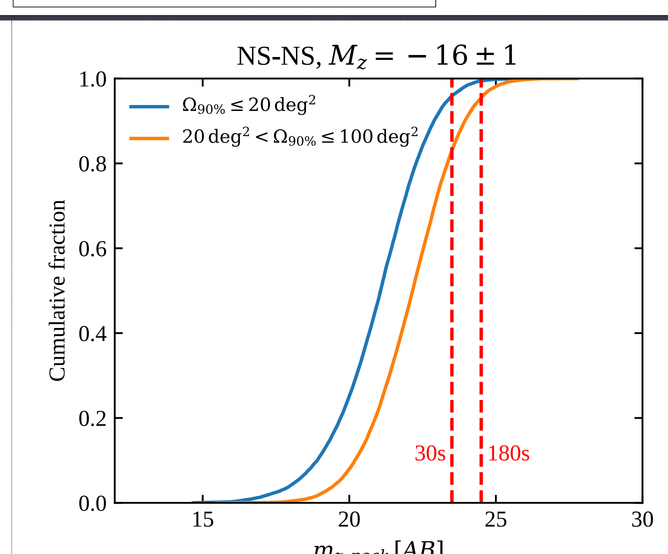
Size of the localization area will be the key point for the follow-up

Kilonova follow-up



I. Andreoni et al. 2021



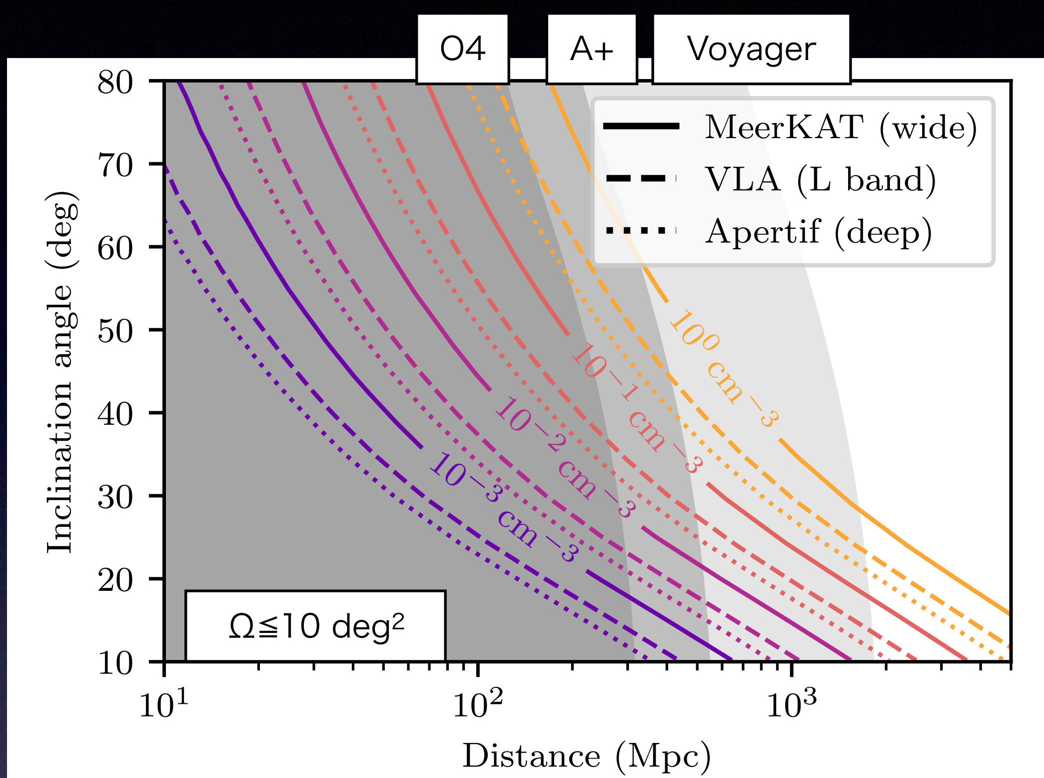


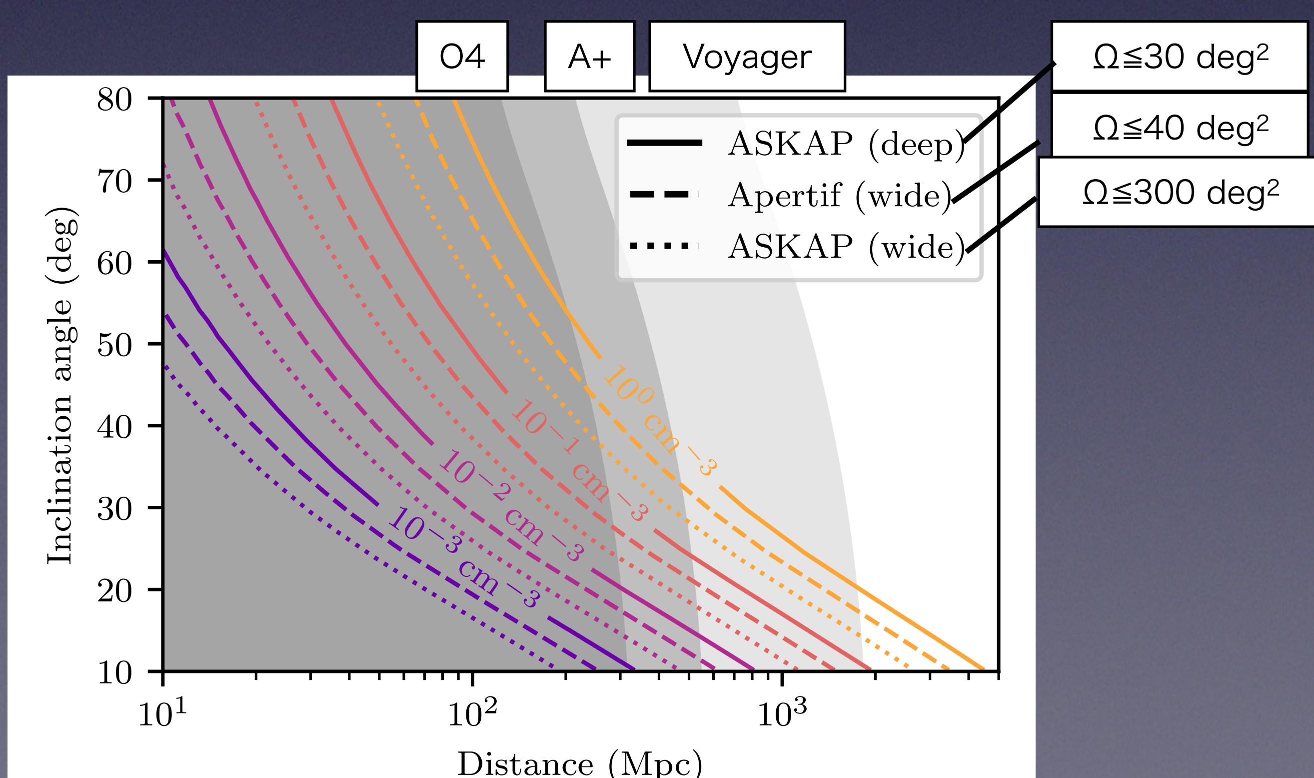
Target of Opportunity follow-up by Vera Rubin (2024+) during O5:

10 BNS:
- ~7 ($\Omega_{90\%}$<20 [deg^2])
- ~3 (20<$\Omega_{90\%}$<100 [deg^2])

15 BHNS:
- ~12 ($\Omega_{90\%}$<20 [deg^2])
- ~3 (20<$\Omega_{90\%}$<100 [deg^2])

Radio jet afterglow follow-up





GW detectors

Epoch	Facilities	Timeline	Range[a] (Mpc)	Localisation[b] (deg^2)	Rate[c] (yr^{-1})
O4	HLVK	2022–23	190[d]	35	10
O5	H$_+$L$_+$V$_+$K	2025–26	330[d]	35	50
2G	H$_+$L$_+$V$_+$KI$_+$	2026	330	35	50
Voy.	H$_V$L$_V$V$_V$	2030	1100	70	1800
3G	ET, CE, Voy	2040	5×10^4	10	10^8
	ET, 2CE		5×10^4	1	10^8

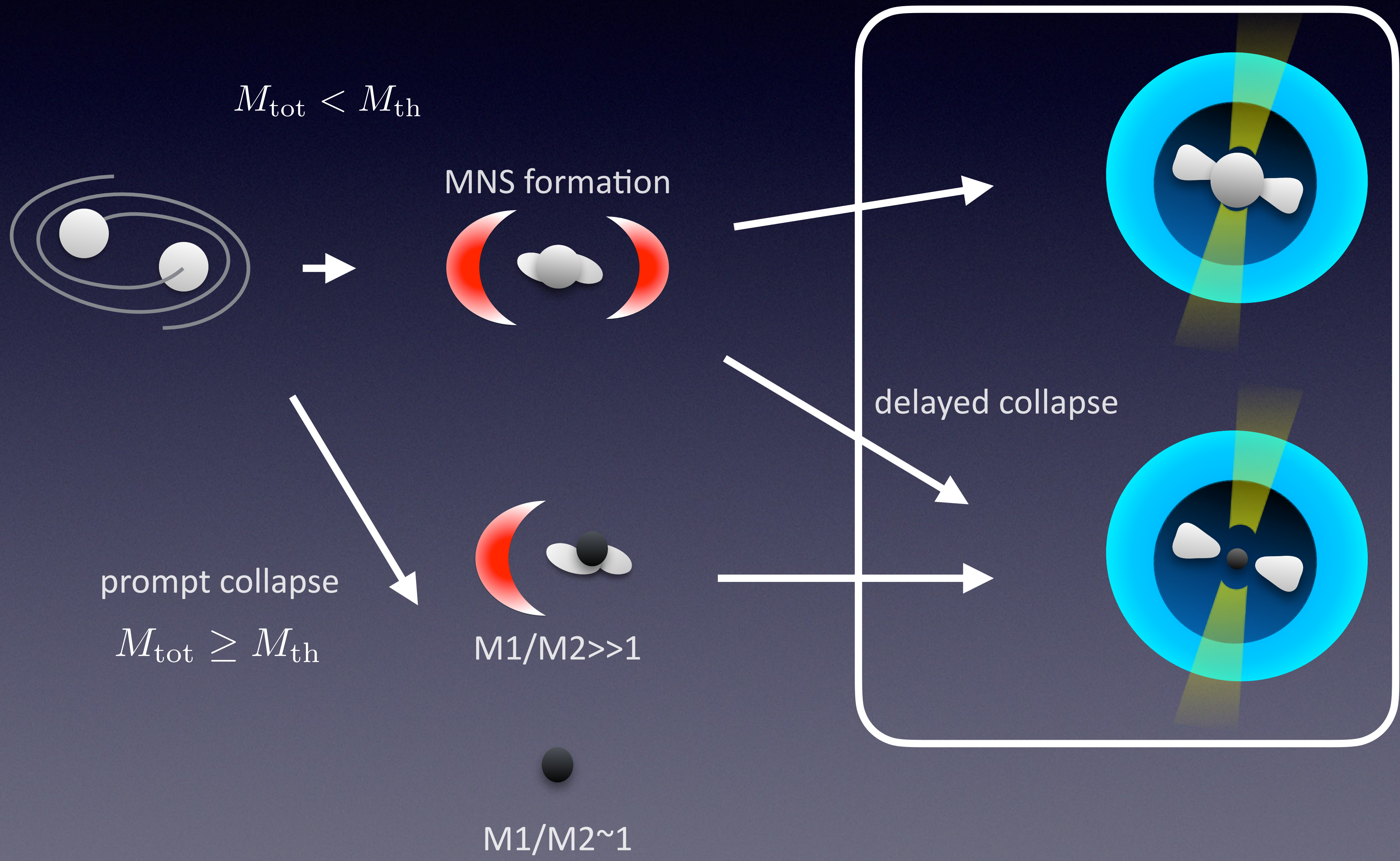
Radio observation

Table 3. Capabilities of unbiased searches for radio afterglows for a range of telescopes and observing strategies, including observing frequency (ν), bandwidth ($\Delta\nu$), total areal coverage ($\Omega_{\rm total}$) and required observing time ($T_{\rm total}$)

Telescope	ν	Strategy (GHz)	$\Omega_{\rm total}$ (deg^2)	$S_{\rm detect}$ (μJy)	$T_{\rm total}$ (hr)
Apertif	1.4	deep	10	125	12
		wide	40	250	12
ASKAP	0.9	deep	30	175	10
		wide	300	550	10
DSA	1.35	deep	10	5	1
		wide	100	5	2.5
MeerKAT	1.4	wide	10	35	12
ngVLA	2.4	wide	10	5	10
		ultra-wide	100	25	10
SKA-1	1.43	wide	10	10	10
		ultra-wide	100	40	10
SKA-2	1.43	wide	10	1	10
		ultra-wide	100	4	10
VLA	1.5	wide	5	75	12

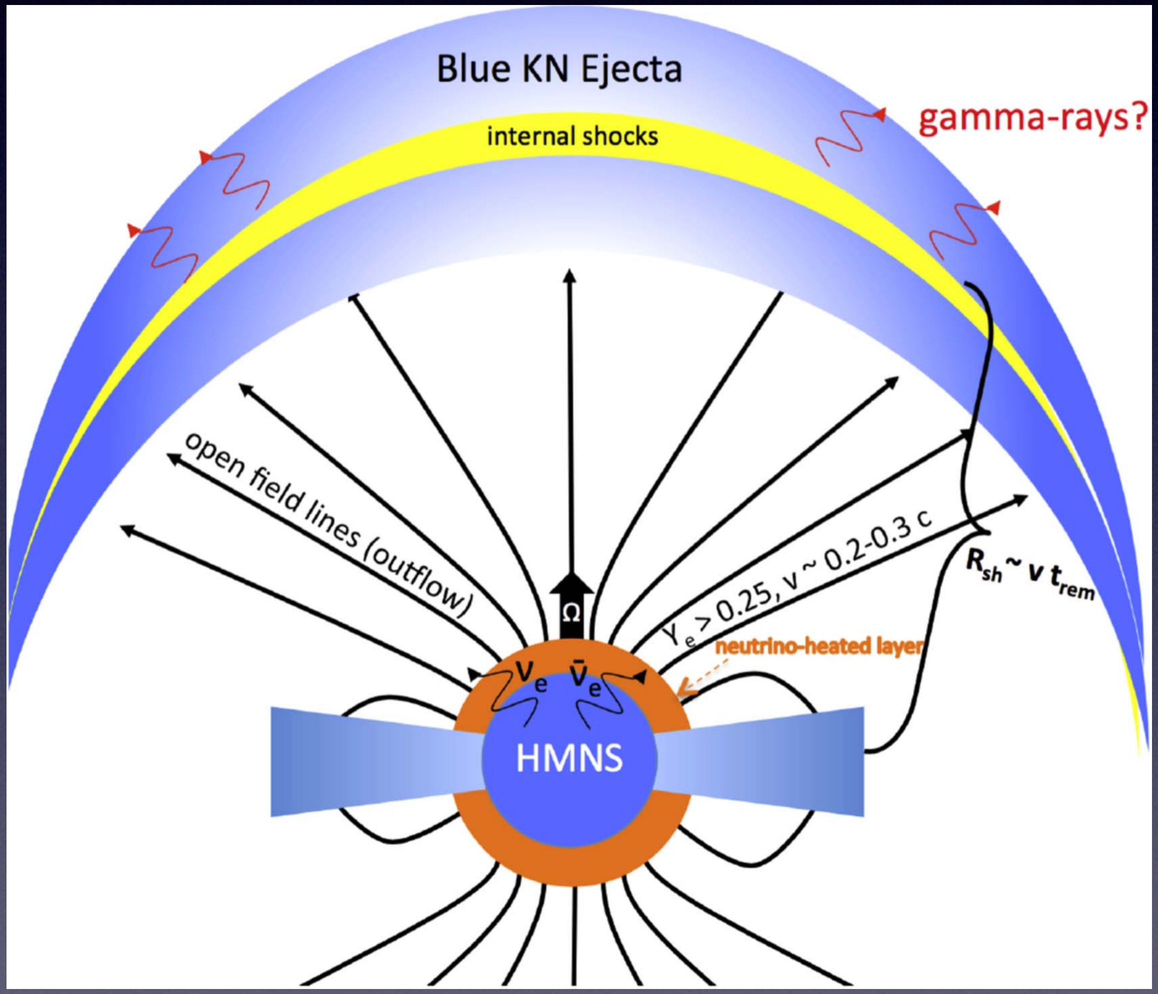
Dobie et al. 2021

Question: Can we tell about the fate of the merger remnant from the observation?



Long-lived strongly magnetized remnant MNS

e.g. Shibata et al. 2017, Metzger et al. 2018

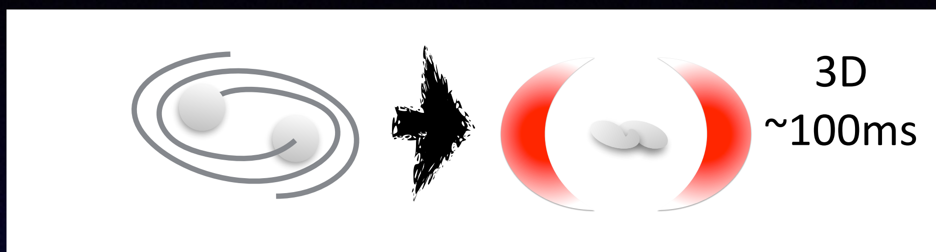


Rotational kinetic energy of MNS: $E_{\rm rot} \sim 10^{52}\,{\rm erg}$

Our recent study: Long-term simulation for a NS merger with a strongly magnetized long-lived MNS

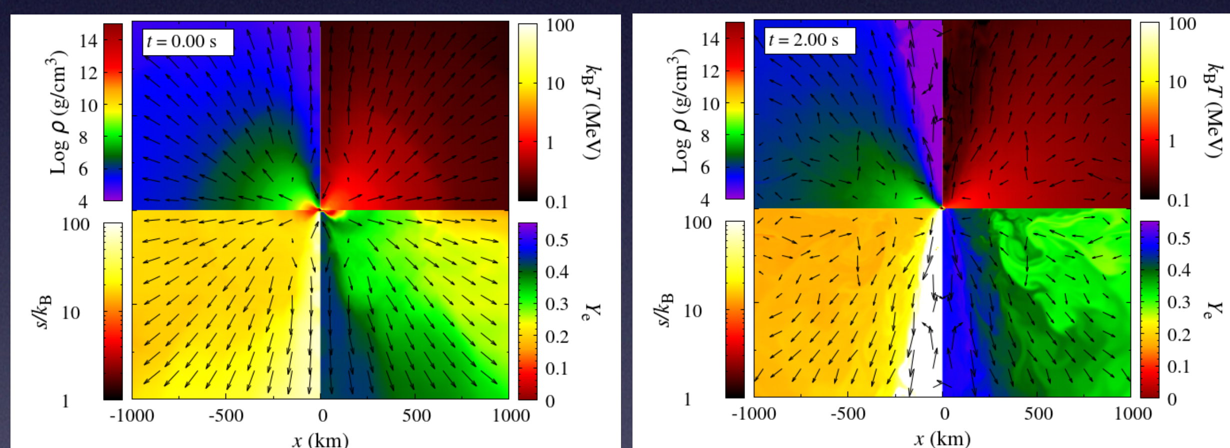
Model : 1.35 M_{sun} + 1.35 M_{sun} (DD2 EOS)
3D GRRHD BNS merger simulation

Shibata et al. 2021, KK et al. in prep.

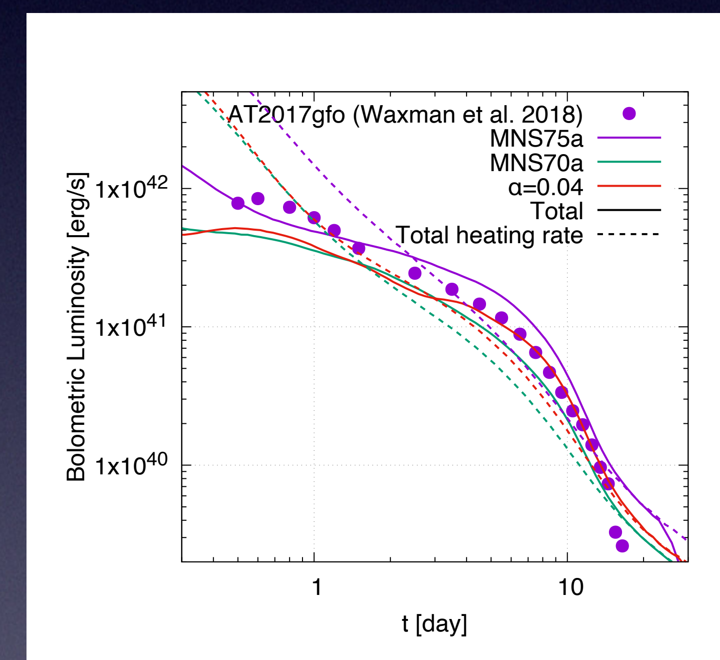


Axisymmetrize

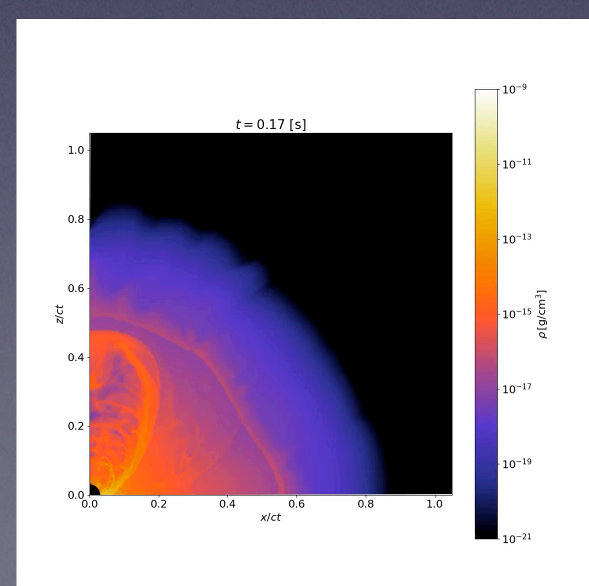
Long-term GR-R-MHD simulation (~3 s)
with mean field dynamo term



Radiative transfer simulation
synchrotron emission calculation



Extract ejecta component

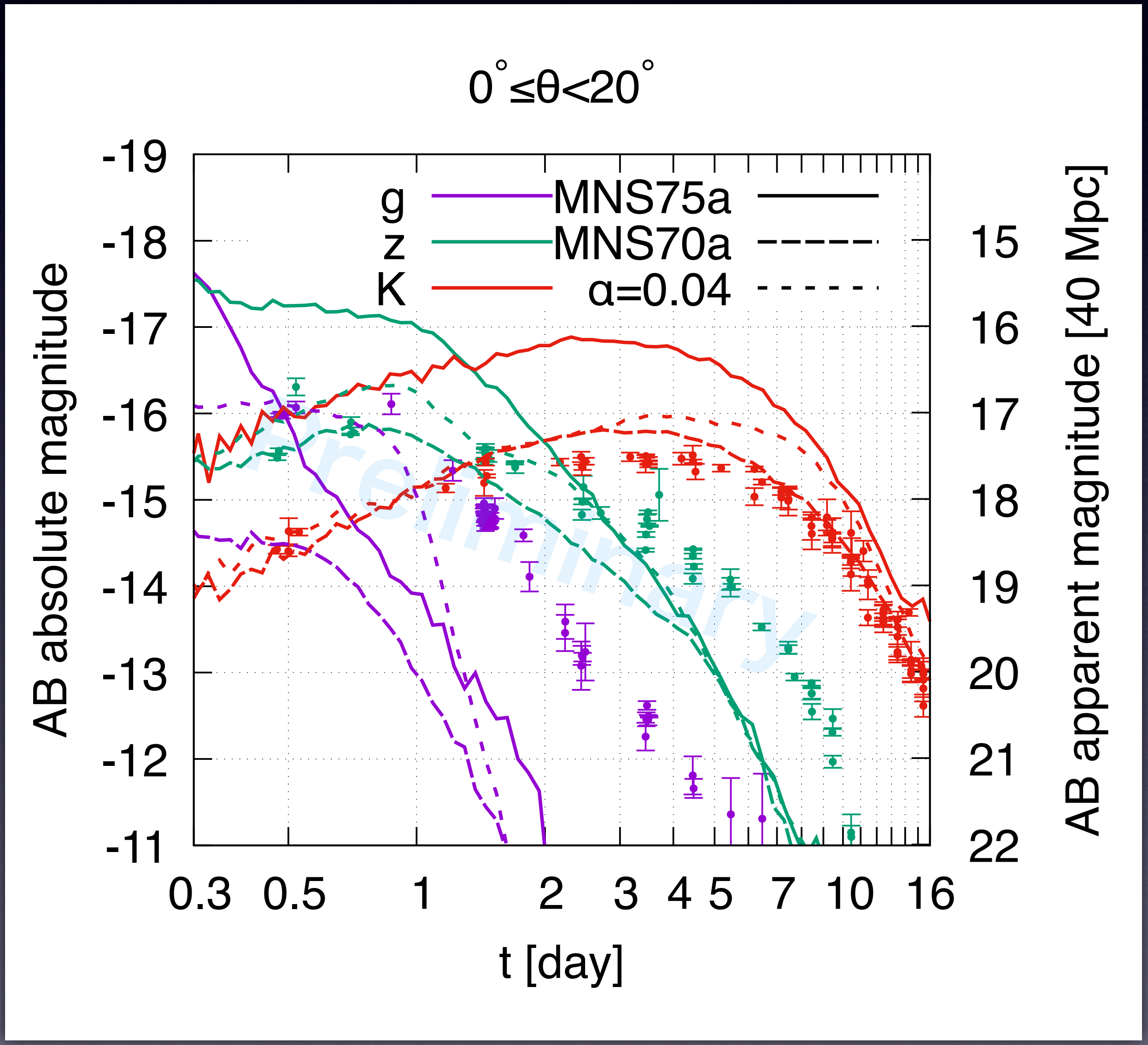


EM counterpart prediction

GR-HD simulation for the longterm ejecta evolution (~0.1 d)

Kilonova emission

Kilonova Lightcurves
(polar view. data: AT2017gfo)



Model : 1.35 M_{sun} + 1.35 M_{sun} (DD2 EOS)

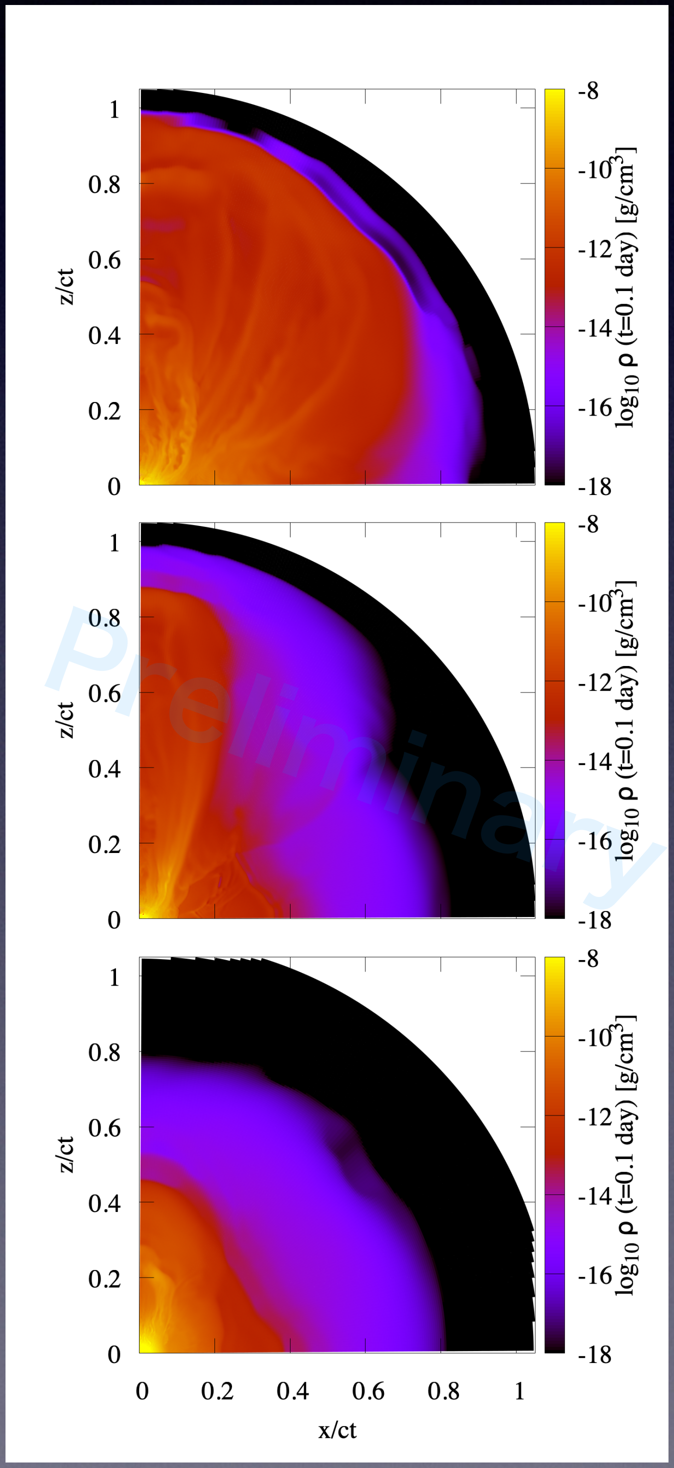
KK et al. in prep.

Density profile @ t = 0.1 d

MNS75a

MNS70a

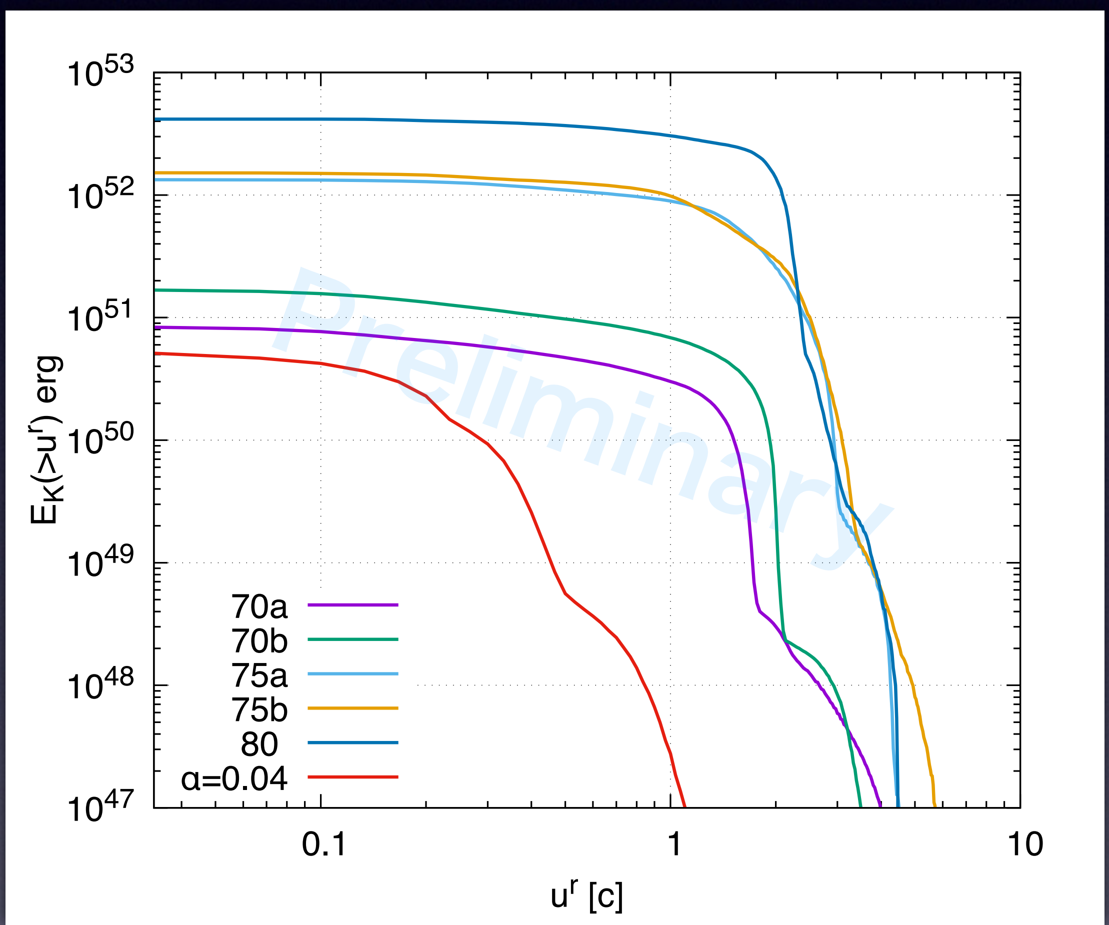
α=0.04
(viscous)



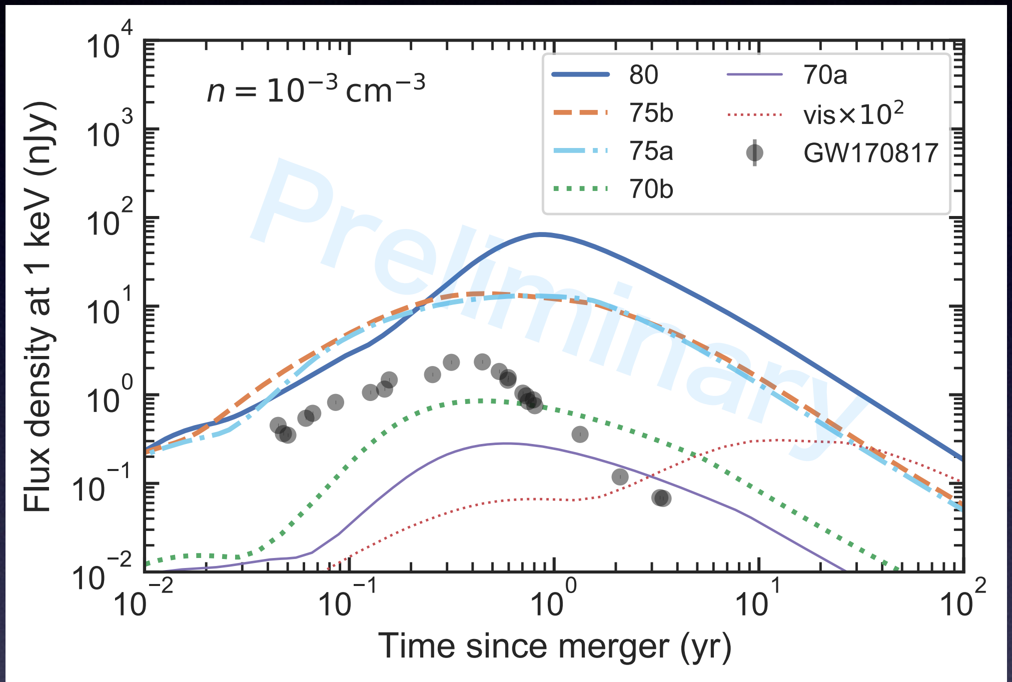
Significant MHD (large dynamo) effect

Synchrotron flare from the ejecta fast tail

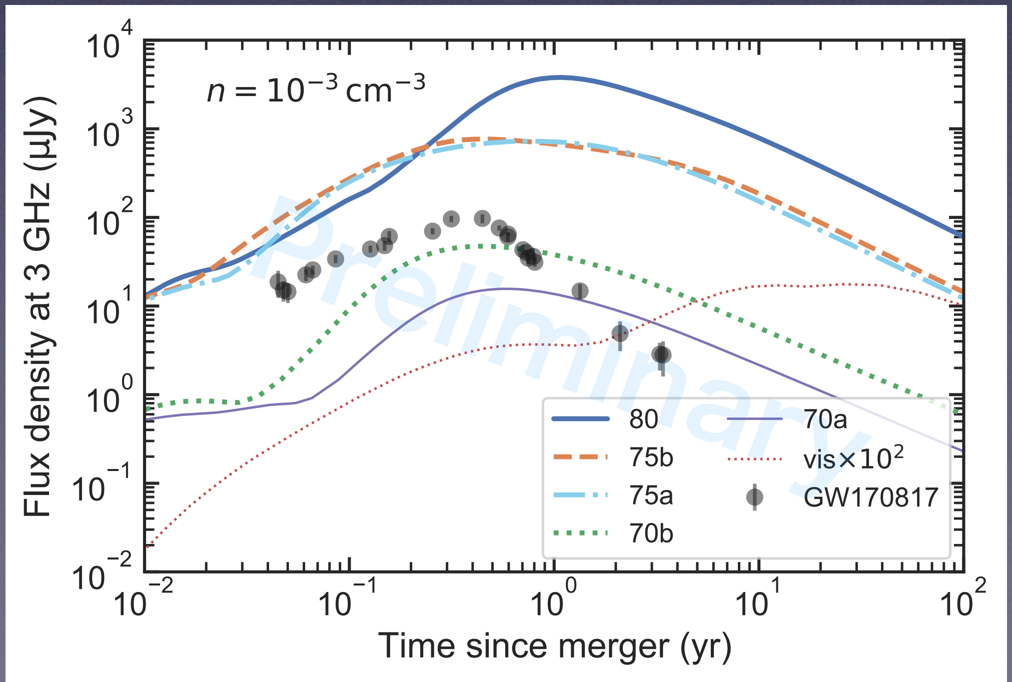
Kinetic energy distribution



X-ray band (1 keV, 200 Mpc)



Radio band (3 GHz, 200 Mpc)



KK et al. in prep.
(see also Hotokezaka & Piran et al. 2015)

70a,b < 75a,b < 80
Significant MHD (large dynamo) effect

Summary

- GW170817 have been providing very interesting astrophysical information even 3.5 years after the onset of the merger.
- Though it was not found in O3, GW+EM detections of NS mergers are promising at least in O5 era.
- Multiple GRB-GW joint observations are expected to be achieved particularly in O5 era. VHE photons might be observed from such events even after ~10^4 s after the GW/GRB trigger.
- A long-lived remnant with strong global magnetic field would be a source of bright EM counterparts. The Xray/radio-band follow-up observation will be an important tools for such an observation in the future.