A case study of GW 170817: Connection between binary neutron star mergers and short gamma ray bursts revealed through radio observations

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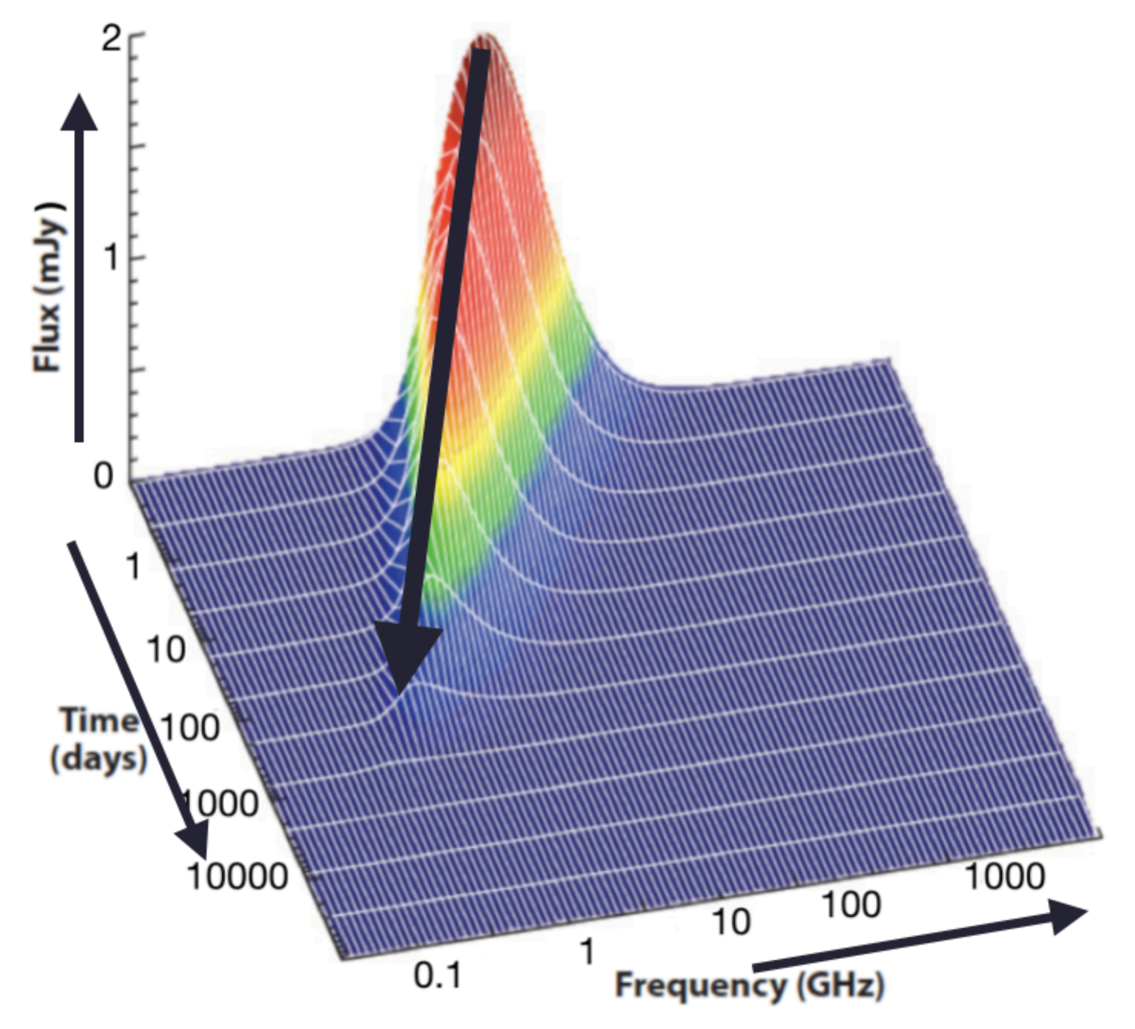
Gravitational waves from compact mergers

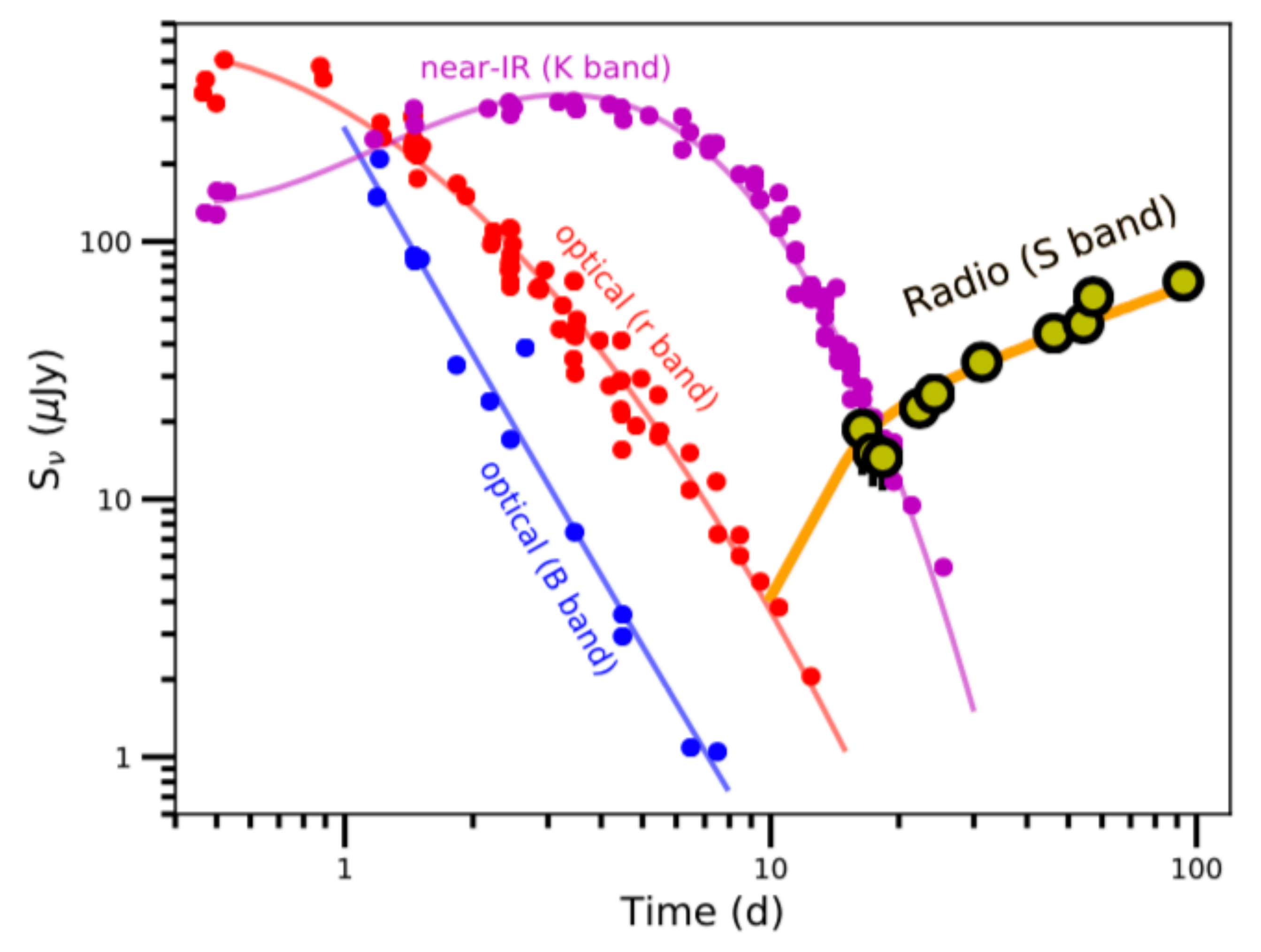
- Binary black hole mergers (BBH) predicted to be source of strong gravitational waves; Adv. LIGO & Adv. Ligo & Adv. Virgo (Abbott+2016, 2017 etc.). But no electromagnetic (EM) radiation expected.

- Mergers involving two neutron stars (BNS) and neutron star black hole (NSBH) expected to give rise to EM radiation (Metzger+2010, 2018, Piran, Nakar, Lazzati etc.)

- From identification of host galaxies of short gamma ray burst (sGRB) - merger involving at least one NS (Paczynski+10, Narayan et al. 2010).

BNS and/or NSBH mergers and radio emission





Slow evolution - catches the complete evolution from very early to very late times.

Parameter space probed by radio emission in BNS and NSBH mergers

- Early Radio Observations:

- Radio scintillations - constraining the size of the EM emitting source *(inhomogeneities in the local interstellar medium cause modulations in the radio flux density of a source whose angular size is less than the characteristic angular size for scintillations)*- Goodman 97; e.g. GRB 970423 (Frail+97), GRB 070125 (PC+08).

- Catching the early radio reverse shock emission (1-2 days) - constraining the Lorentz factor (enhanced peak flux by Γ peak frequency scaled with $1/\Gamma^2$).

- Early-time self-absorbed forward shock emission - only way to constrain the density

- VLBI size constraints and jet motion, e.g. GRB 030329 (Taylor+2004, Philstrom+2007).

Parameter space probed by radio emission in BNS and NSBH mergers

- Late time radio observations:
- Optically thin emission from forward shock, constrain particle energy index

$$N(E) = N_0 E^{-p} dE$$

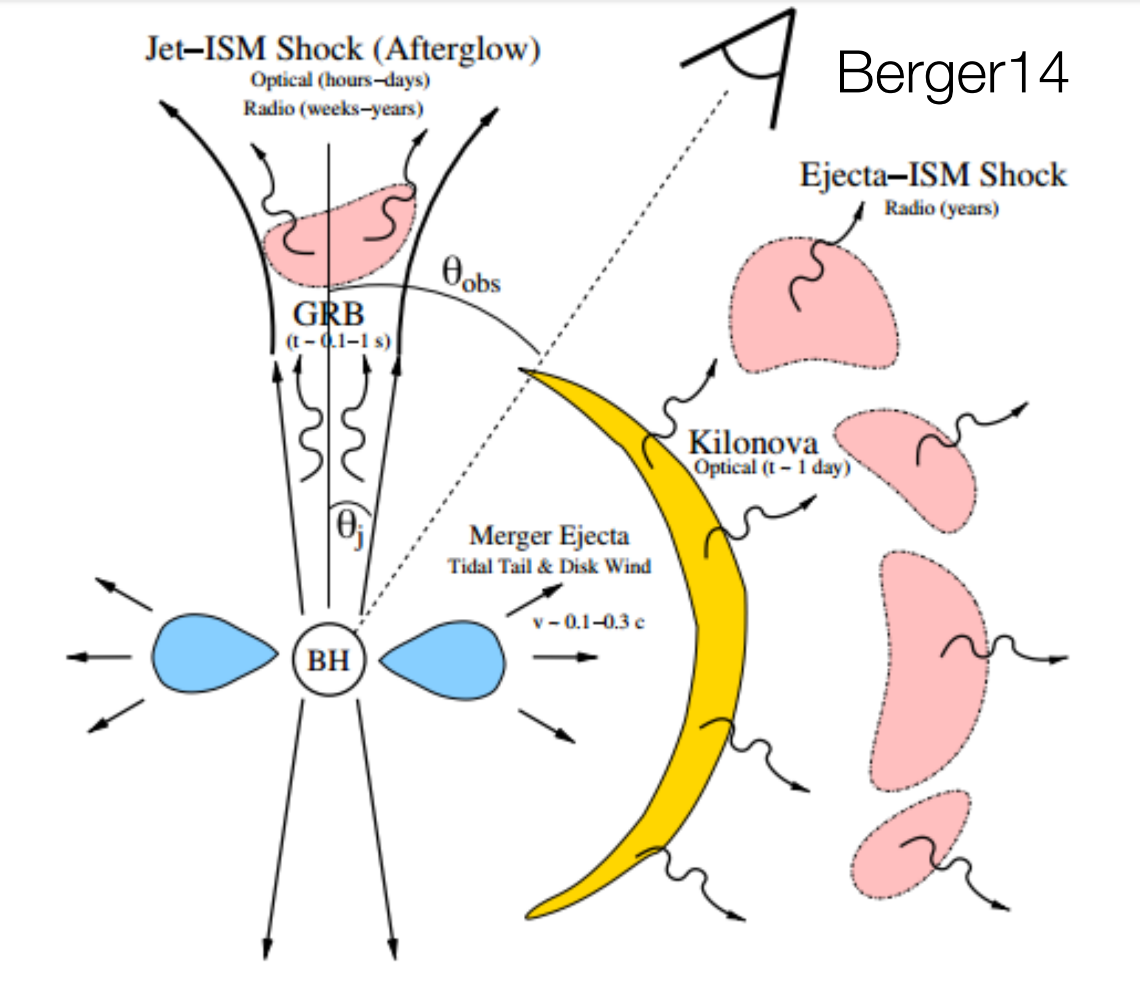
- Late time radio emission
  - Off-axis jet (orphan afterglow) detection
  - Only means to detect EM in cases when high energy signals are missed (off-axis jet, behind the Sun, no jet escaped)
  - Energetics of the EM radiation when observed in non-relativistic phase (Frail+2000)

BNS and/or NSBH mergers and radio emission

Nakar & Piran 2011

- Formation of black hole, powering an ultra relativistic jet (0.9c). Short GRB - jet-medium interaction (weeks to months ~GHz bands)

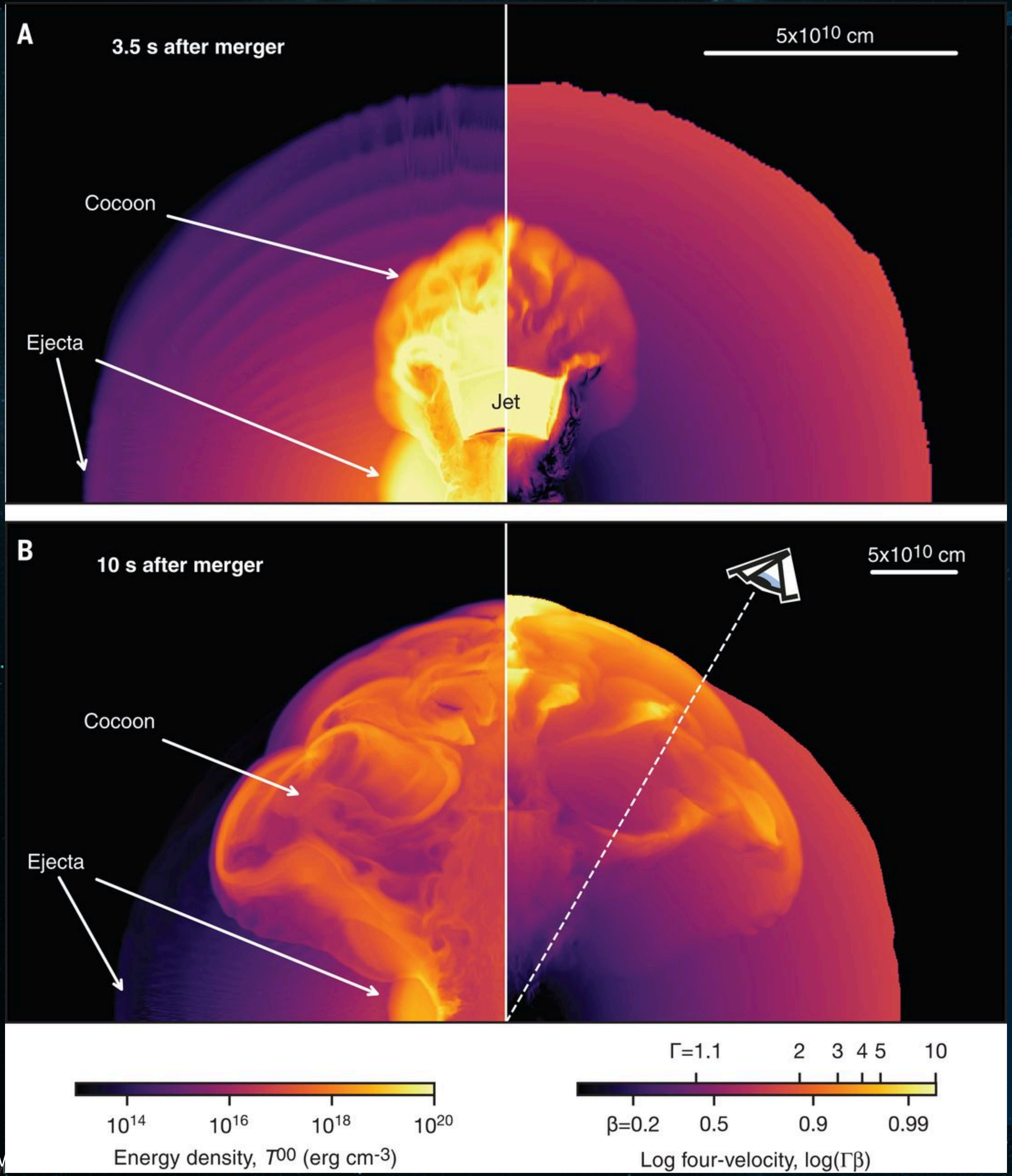
- Isotropic kilonova (radioactive decay of r-process nuclei synthesised in merger ejecta with sub-relativistic speeds ~0.2c). Months to years 0.2-1 GHz .



Berger14

BNS, NSBH mergers - radio counterpart

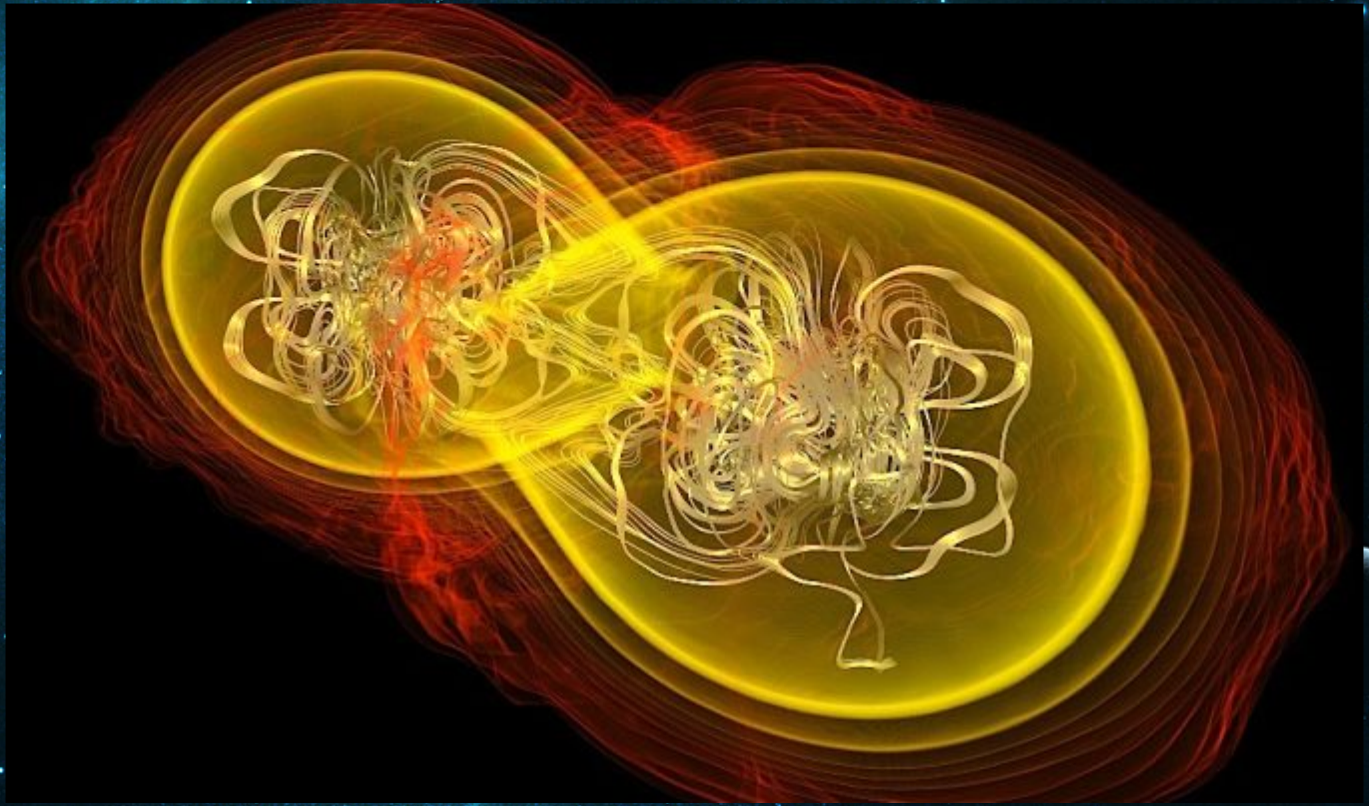
Gottlieb+2017



Another component - mildly relativistic dynamic ejecta from polar regions (low lanthenide, low optical depth). Since in the same direction as jet, it forms a cocoon via jet transferring some energy to it and have another component of radio emission. Not predicted in NSBH.

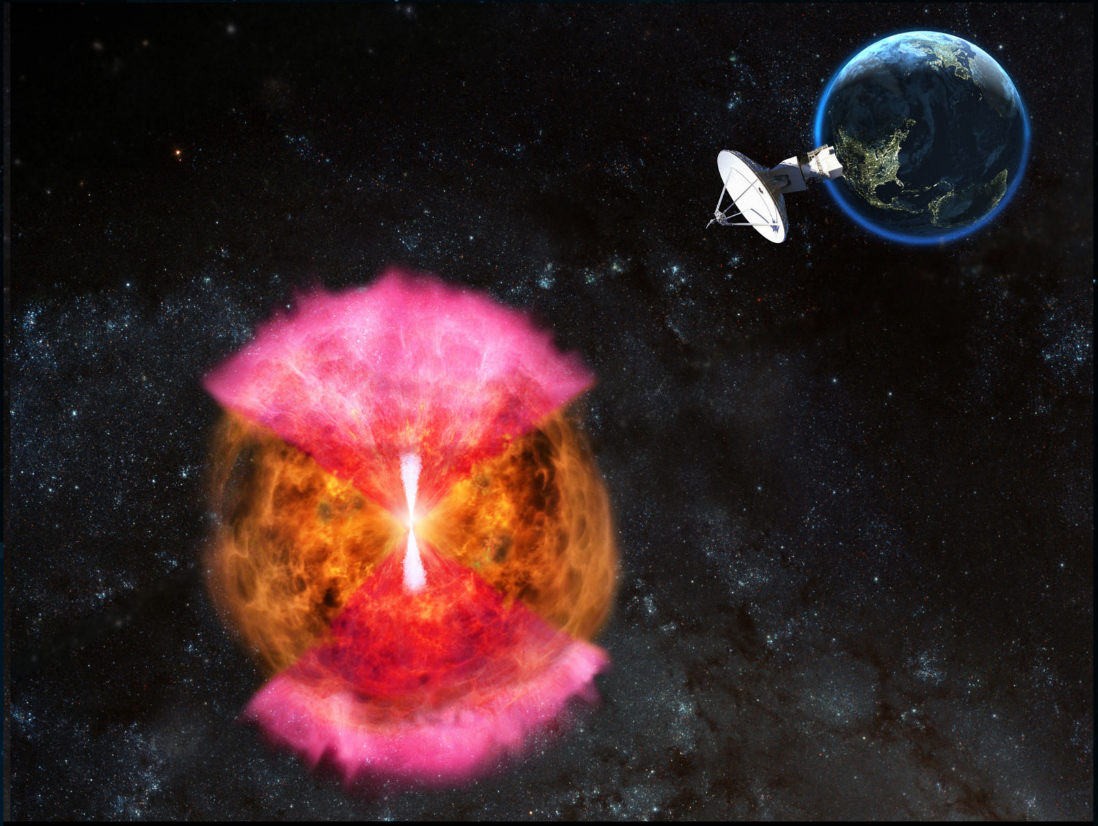
Binary neutron star merger
2017 August 17 - GW 170817

- The gravitational wave event - GW 170817
- Short gamma ray burst - 1.7s; GRB 170817A
- A Kilonova (an optical counterpart) - 11hr; AT2017gfo



Credit: NASA's Goddard Space Flight Center/CI Lab

Lessons learnt from GW 170817 and its Radio counterpart

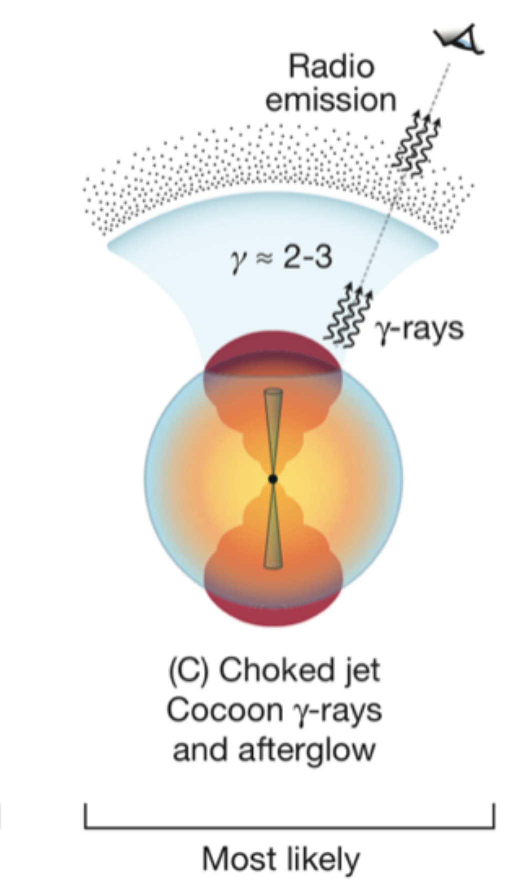

Choked Jet Cocoon

Credit: NRAO

- Detected 16 days after the event (Hallinan..PC..+2017) - Not on-axis
- But also not off-axis
    - From 1.7s delay between GW event and Fermi detection).
    - $t^{0.8}$ rise (suggesting on-axis emission. Off-axis $>t^3$, Nakar, Piran 2018). Emission from sub-relativistic cocoon v<=0.4c (gamma rays shock breakout of the cocoon; Mooley,…,PC..+2018a)
- Energy injection. Structure in jet - cocoon most viable model (~2-7, Mooley, …,PC..+2018a, Nakar, Piran 2018)

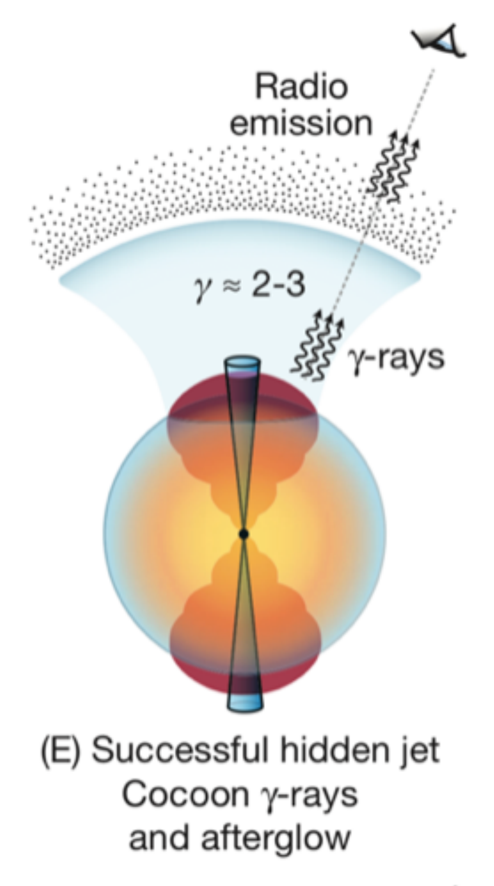
GW 170817 and connection with short GRB

Nakar & Piran 2018



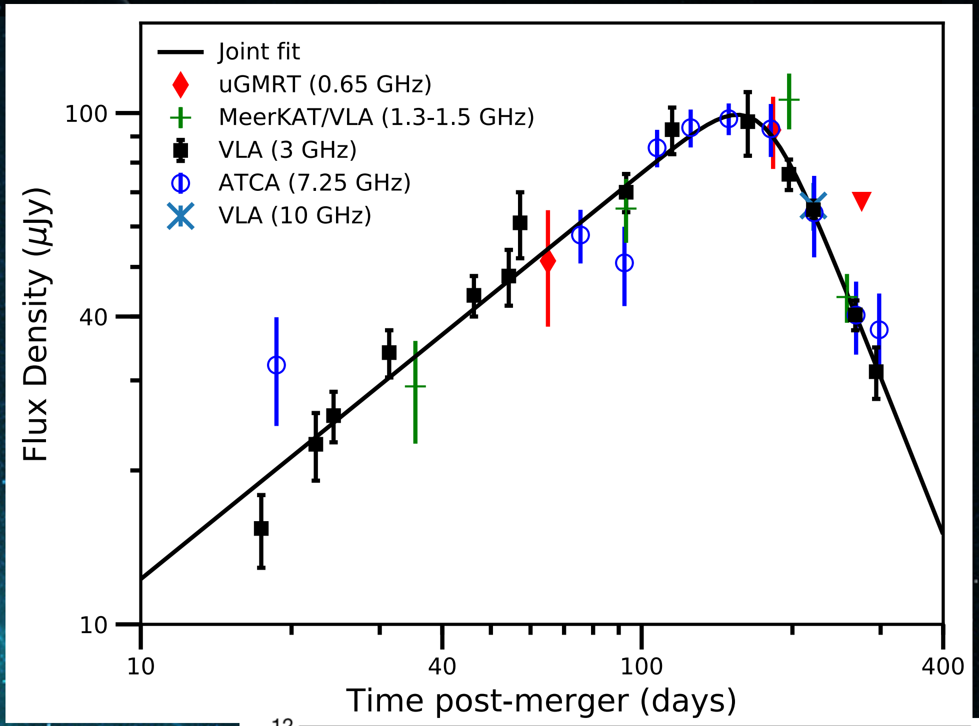
(C) Choked jet
Cocoon γ-rays
and afterglow

Most likely



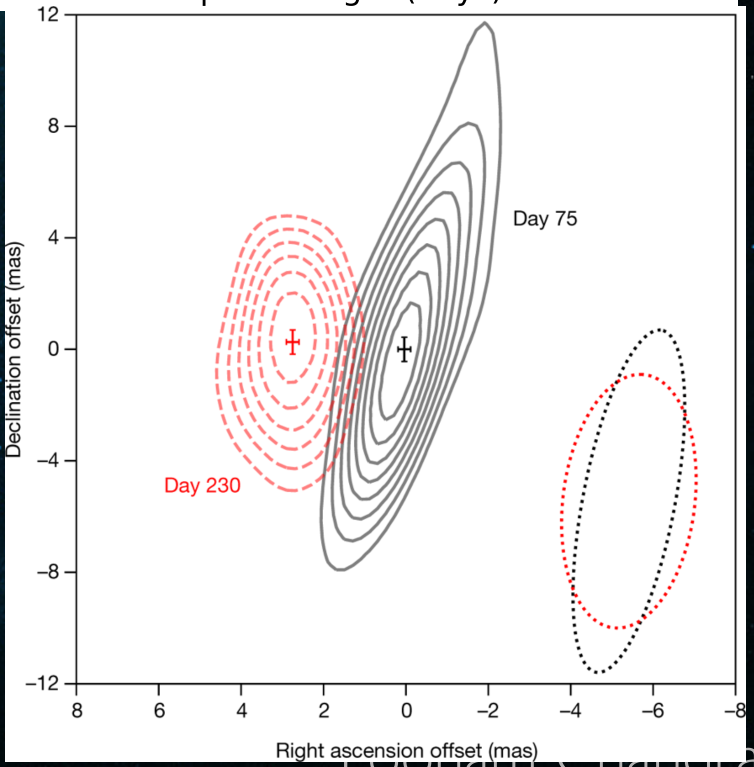
(E) Successful hidden jet
Cocoon γ-rays
and afterglow

Dobbie+2018,
Mooley+2018a,
Mooley… PC..
+2018b,
Ghirlanda+2018



$$N(E)=E_0E^{-p}dE$$

$$F(t)\sim t^{p}\ \text{(jet)},\ F(t)\sim t^{3(p-1)/4}$$



Superluminal motion ~4c
Jet ~5°, 20° off-axis

Questions to be answered

- How many mergers have relativistic jets and how many jets interact with surrounding neutron-rich polar ejecta to produce cocoons?
- How much energy do mergers release?
- What is the nature if NS-BH mergers?
- What are the environments of the mergers?
- How does geometry affect the observed EM radiation?
- **(In many cases, radio observations may provide the only means to detect an EM counterpart, particularly in cases where a bright blue kilonova is absent (NS-BH mergers)**

Preparing for O3

- We have partnered with the PIs of leading EM-GW efforts at the world's major radio facilities in order to use the best capabilities of each of these, and to optimize the use of observing time.
- Proposals with VLA (250 hrs)
- Proposals with ATCA time until 2020 (5 semesters; ~700 hrs)
- MeerKAT team
- uGMRT proposals per semester. Past two cycles.

Preparing for O3

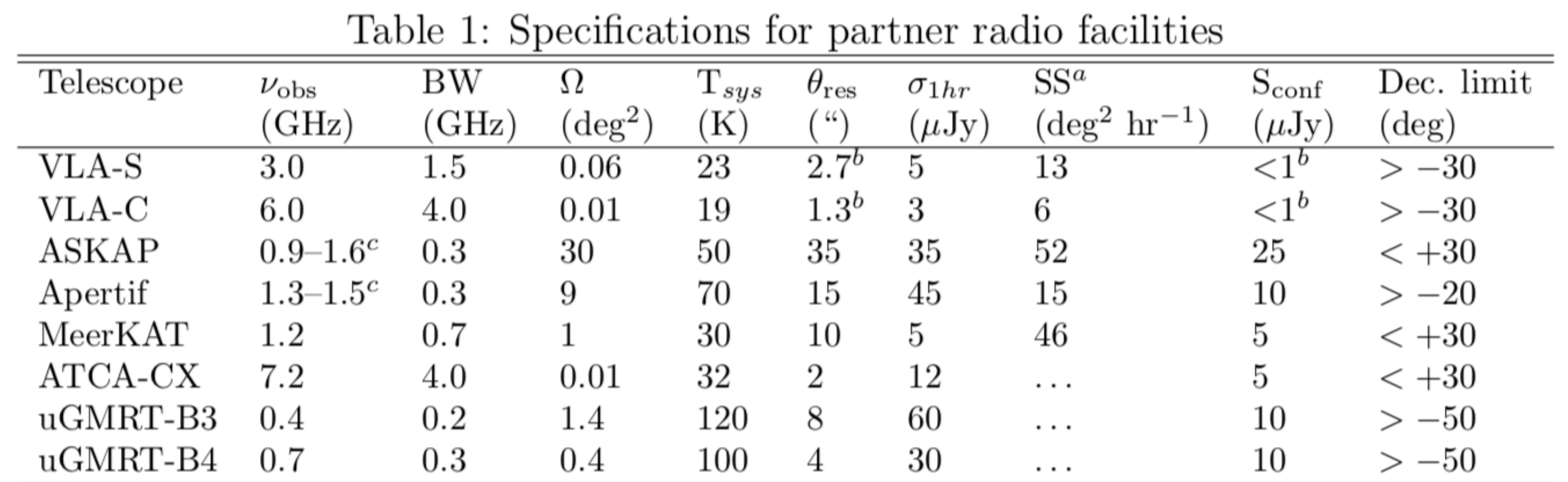
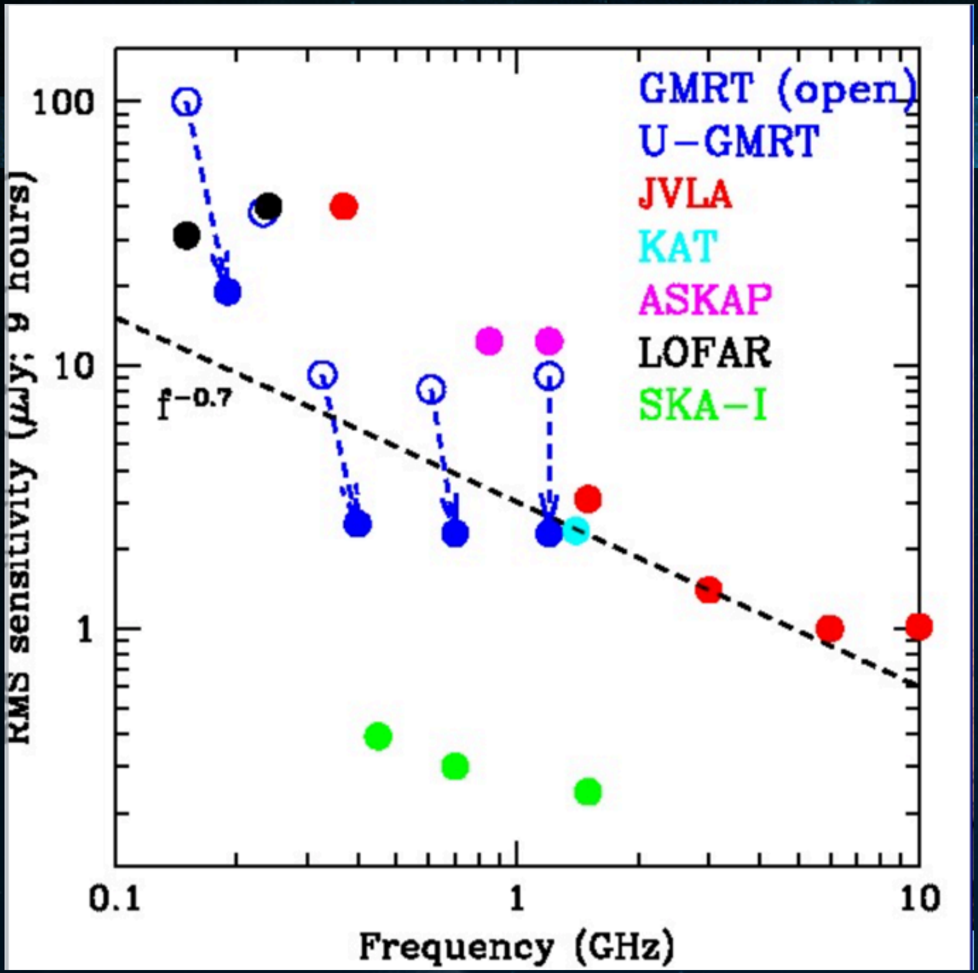


Table 1: Specifications for partner radio facilities

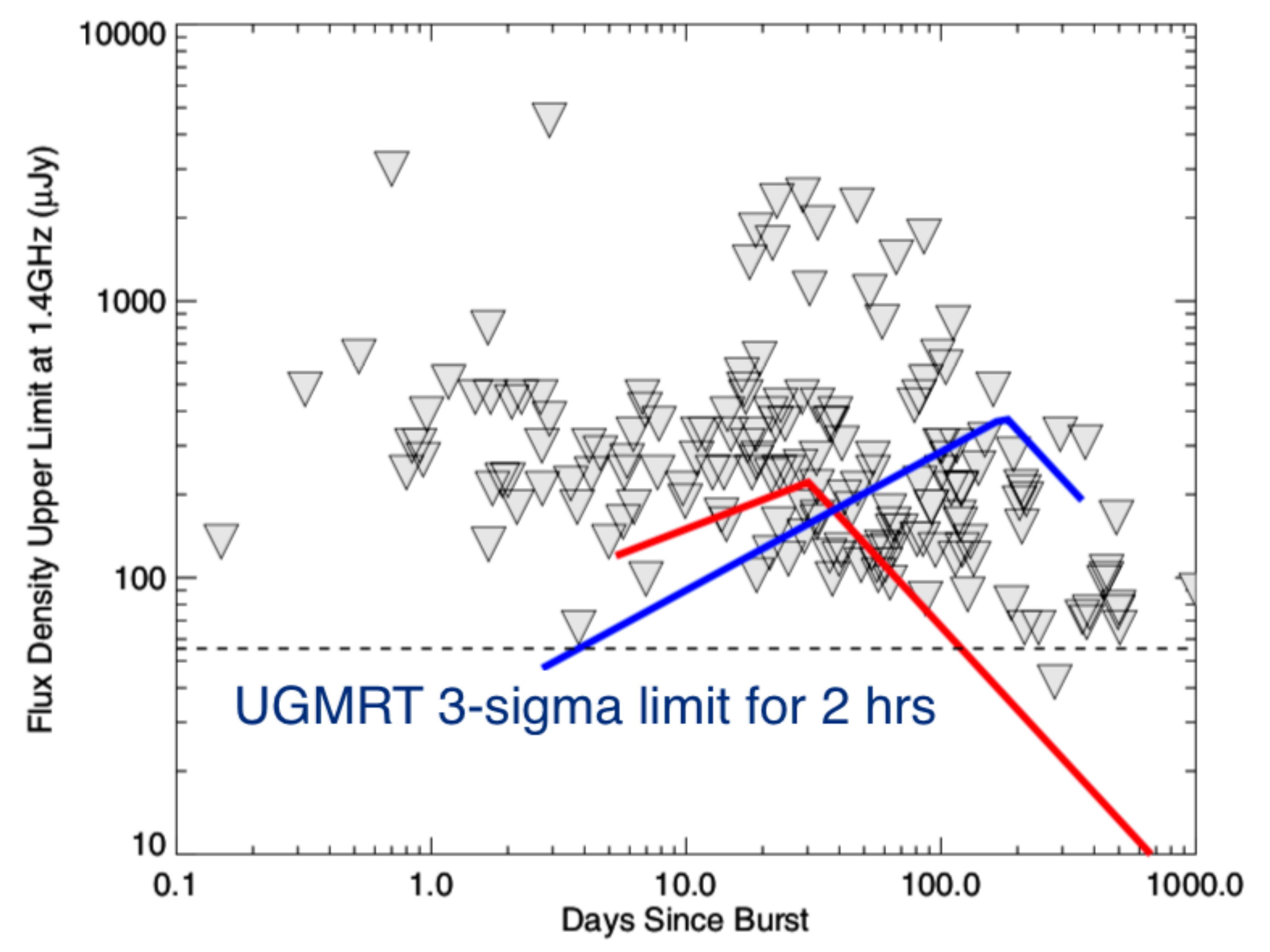
Telescope	$\nu_{\rm obs}$ (GHz)	BW (GHz)	Ω (deg^2)	T_{sys} (K)	$\theta_{\rm res}$ (“)	σ_{1hr} (μJy)	SS^a ($\mathrm{deg}^2\ \mathrm{hr}^{-1}$)	$S_{\rm conf}$ (μJy)	Dec. limit (deg)
VLA-S	3.0	1.5	0.06	23	2.7^b	5	13	$<1^b$	> -30
VLA-C	6.0	4.0	0.01	19	1.3^b	3	6	$<1^b$	> -30
ASKAP	$0.9–1.6^c$	0.3	30	50	35	35	52	25	$< +30$
Apertif	$1.3–1.5^c$	0.3	9	70	15	45	15	10	> -20
MeerKAT	1.2	0.7	1	30	10	5	46	5	$< +30$
ATCA-CX	7.2	4.0	0.01	32	2	12	...	5	$< +30$
uGMRT-B3	0.4	0.2	1.4	120	8	60	...	10	> -50
uGMRT-B4	0.7	0.3	0.4	100	4	30	...	10	> -50

The uGMRT

Credit: Nissim Kanekar



Currently the most sensitive telescope with best resolution (2” at 1420 MHz, 5” (610 MHz), 11” (325 MHz), 22”(150 MHz)) - low confusion noise.



PC+Frail 2012, PC 2016

Goal 1: Constraints on the Environments

- The lowest frequency detection of GW 170817 was at 600 MHz with the GMRT - Crucial for density.

- The event was optically thin, i.e. synchrotron self absorption peak <600 MHz. Caused degeneracy in parameters because of uncertainty in the density (Hallinan+2017).

- SSA is λ^2, so low frequencies like uGMRT has a unique role to play.

- Very different environments for various GRBs (For GRB 090423 (z=8.3), we found n=1 cm^{-3} (PC+2010), for GRB 50904 (z=6.2), GRB 070125 (n~50 cm^{-3}); n=100-600 cm^{-3} (Gou+07) (Very different environments)

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Goal 2: No high frequency EM counterpart

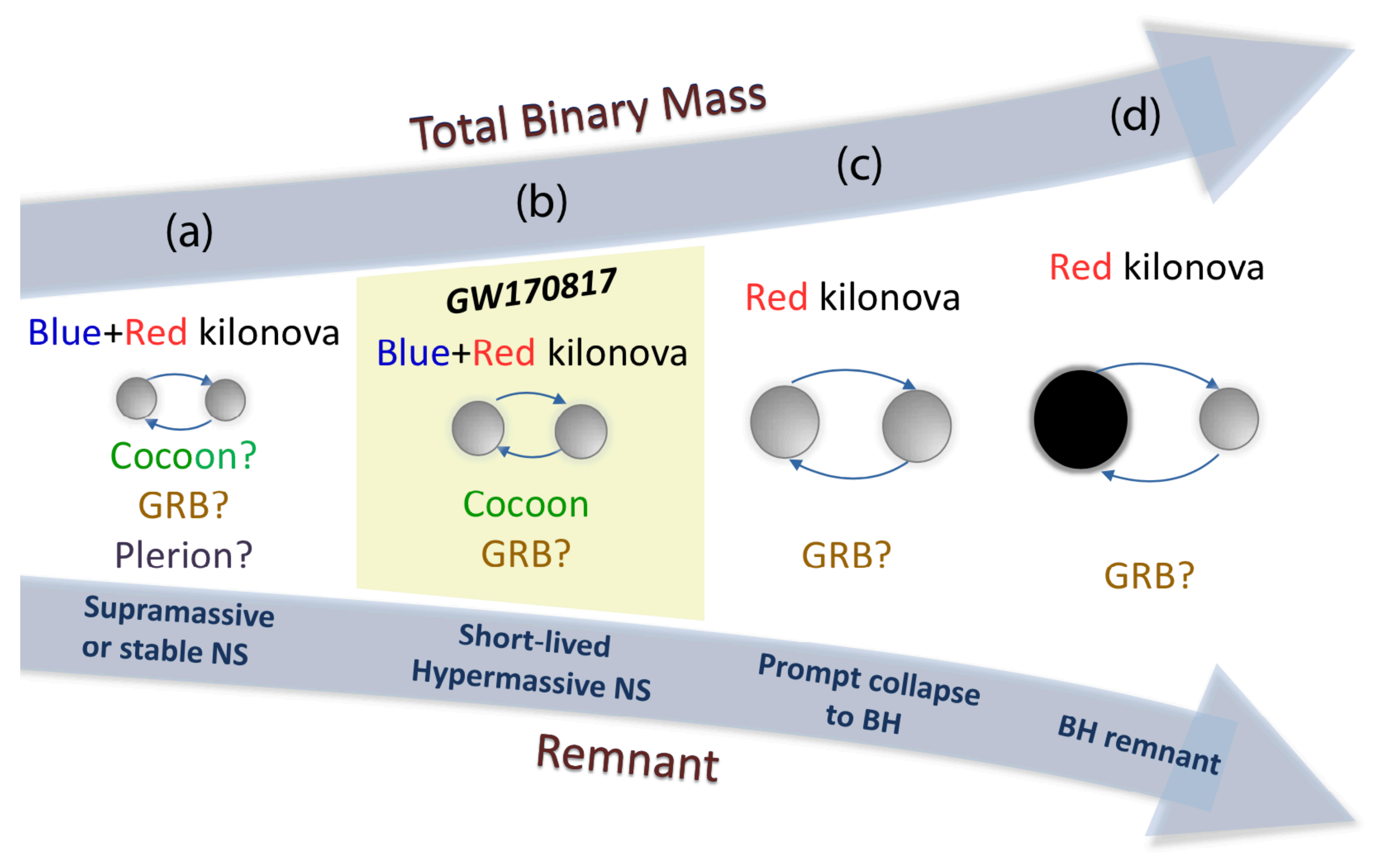
- Low mass BNS - a long-lived supramassive, or stable NS remnant (e.g. Metzger 2017), blue and red kilo nova - wider cocoon - better prospects of detecting wider cocoon.

- Massive NS-NS, NS-BH - prompt collapse to BH (e.g. Kasen et al. 2017). Missing blue kilonova

- Off-axis jet and short lived kilonova hiding behind the Sun.

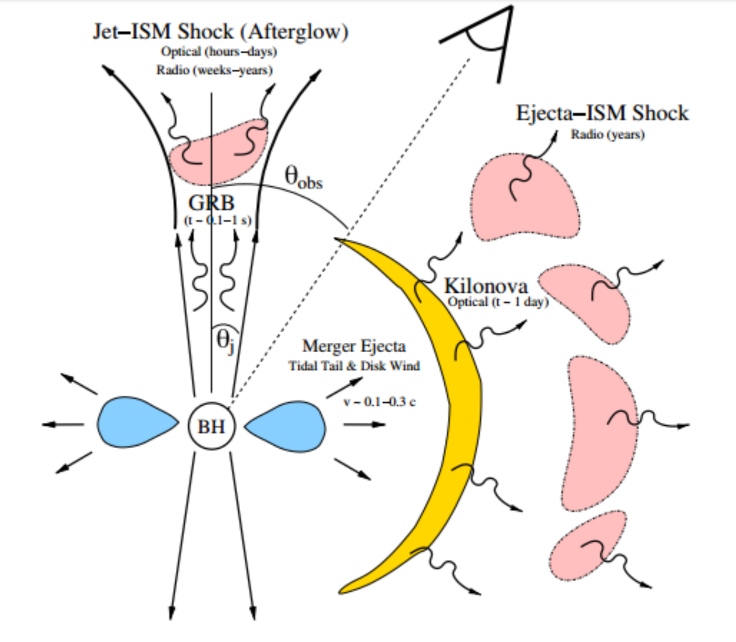
- 1.4 GHz is the ideal band to detect early to late time afterglow.

Expected EM counterparts



Function of mass, spin, magnetic field etc.

Goal 3: Off-axis afterglow & sub-relativistic merger ejecta



- Sub-relativistic merger ejecta (long-lasting radio remnants)
- ultra-relativistic jets (orphan GRB afterglows)
- For observers on or close to the jet axis, observing at higher radio frequencies (e.g., 5 GHz) is preferable for bright synchrotron. On the contrary, for the long-lasting radio remnants and off-axis orphan afterglows, observing at lower radio frequencies is preferable because the characteristic frequency is typically lower than 1 GHz (Hotokezaka+16).

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Strategy

- 1.4 GHz and 150 MHz are ideal bands.

- Ideal 1.4 GHz survey at five epochs separated by logarithmic time intervals: within a day after the detection, at 10 days, at ~ 30 days, at ~100 days, at ~300 days and at 1000 days (Nakar+Piran 2011, Hotokezaka+2016).

- Late time 150 MHz deep survey (to distinguish from other radio transients)

- Hotokezaka et al. (2016) estimated the detectability of the radio counterparts of simulated GW-merger events for advanced LIGO and Virgo- 20-60% resulting in radio counterparts above 10^{50} ergs kinetic energy, n=0.1 cm^{-3}. 15-20% radio afterglows will be detected with KE $3x10^{48}$ ergs orphan AG.

Goal 4: The energetics from non-relativistic phase

- Months to years after the burst, the jet becomes sub-relativistic (i.e., Sedov self- similar evolution) and the outflow is expected to be quasi-spherical.
- The non-relativistic afterglow will peak at <1 GHz (Nakar Piran 2011).
- The sub relativistic ejecta which gave rise to kilo nova will also give radio emission in radio and peak at sub-GHz (Berger 2014).

Concluding remarks

- Truly an era of multi-messenger Astronomy in transients.
- The GW170817 was not what had been predicted, and we still do not know how typical it is. The only way to fully answer this question is by collecting a large, well-monitored sample of GW mergers with broad-band EM follow up.
- Radio counterparts of EM counterparts of GW (with at least one NS) can reveal energy, environment and geometry.