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Multimessenger Astronomy- Low energy EM observations of GW events

Poonam Chandra
Tata Institute of Fundamental Research
National Centre for Radio Astrophysics

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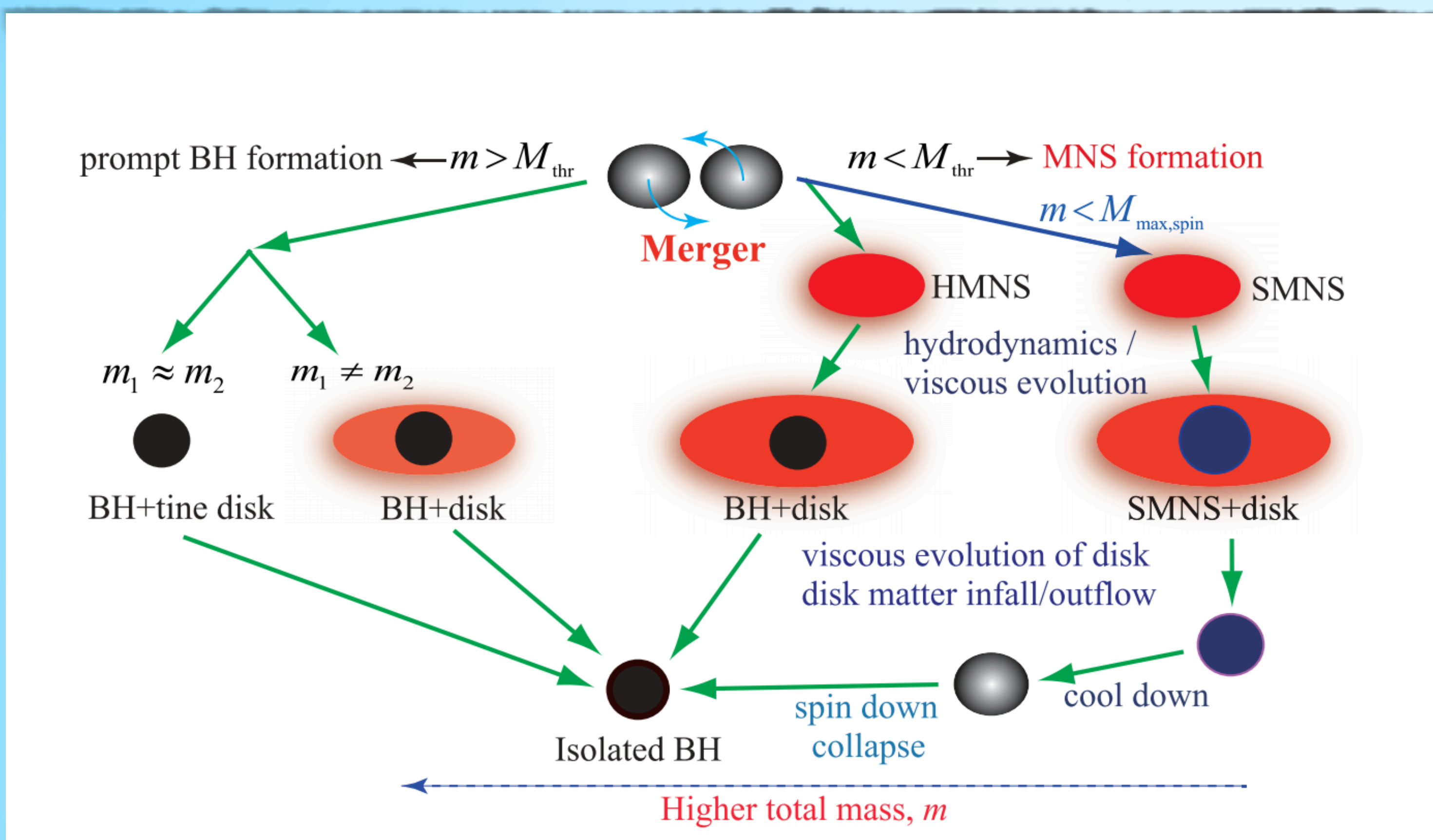
EM from GW events

- One and only event so far - GW 170817
- The merger process,
- Subsequent mass ejection
- EM emission arising from the ejected mass
- Binary neutron star (BNS) mergers, neutron star- black hole (NS-BH) mergers

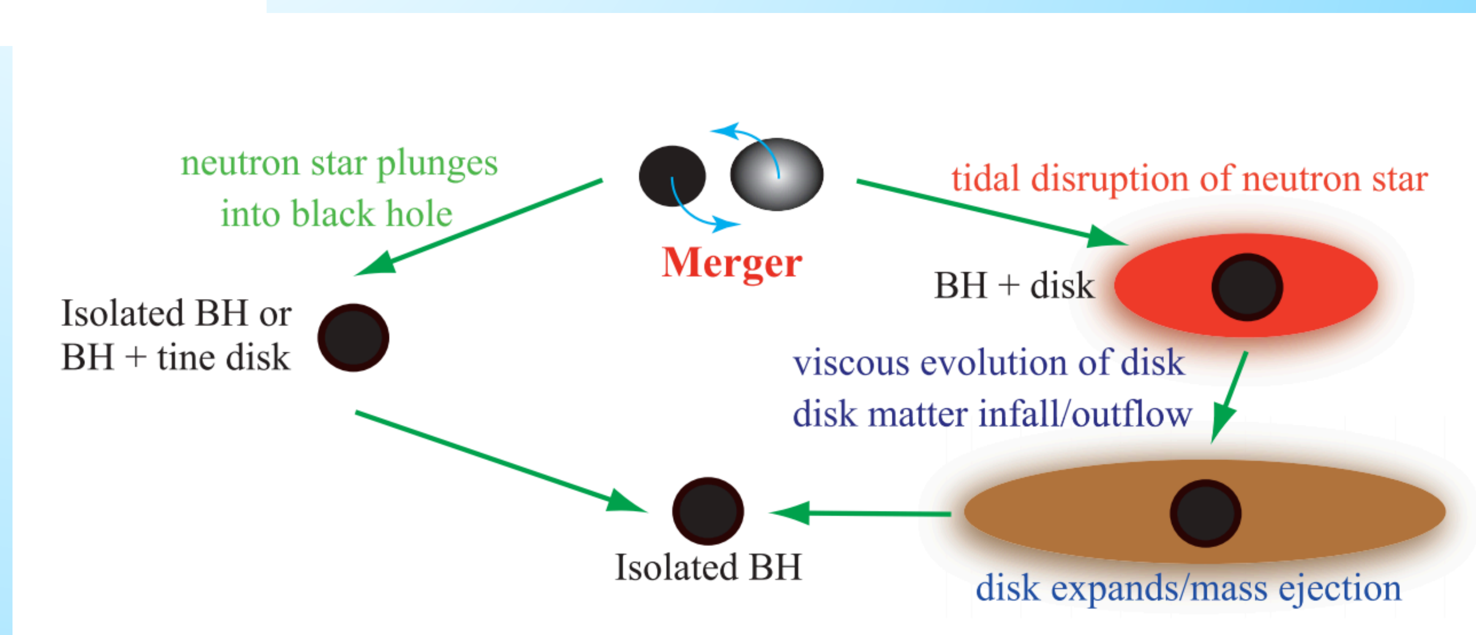
BNS merger ejecta

Shibata & Hotokezaka 2019

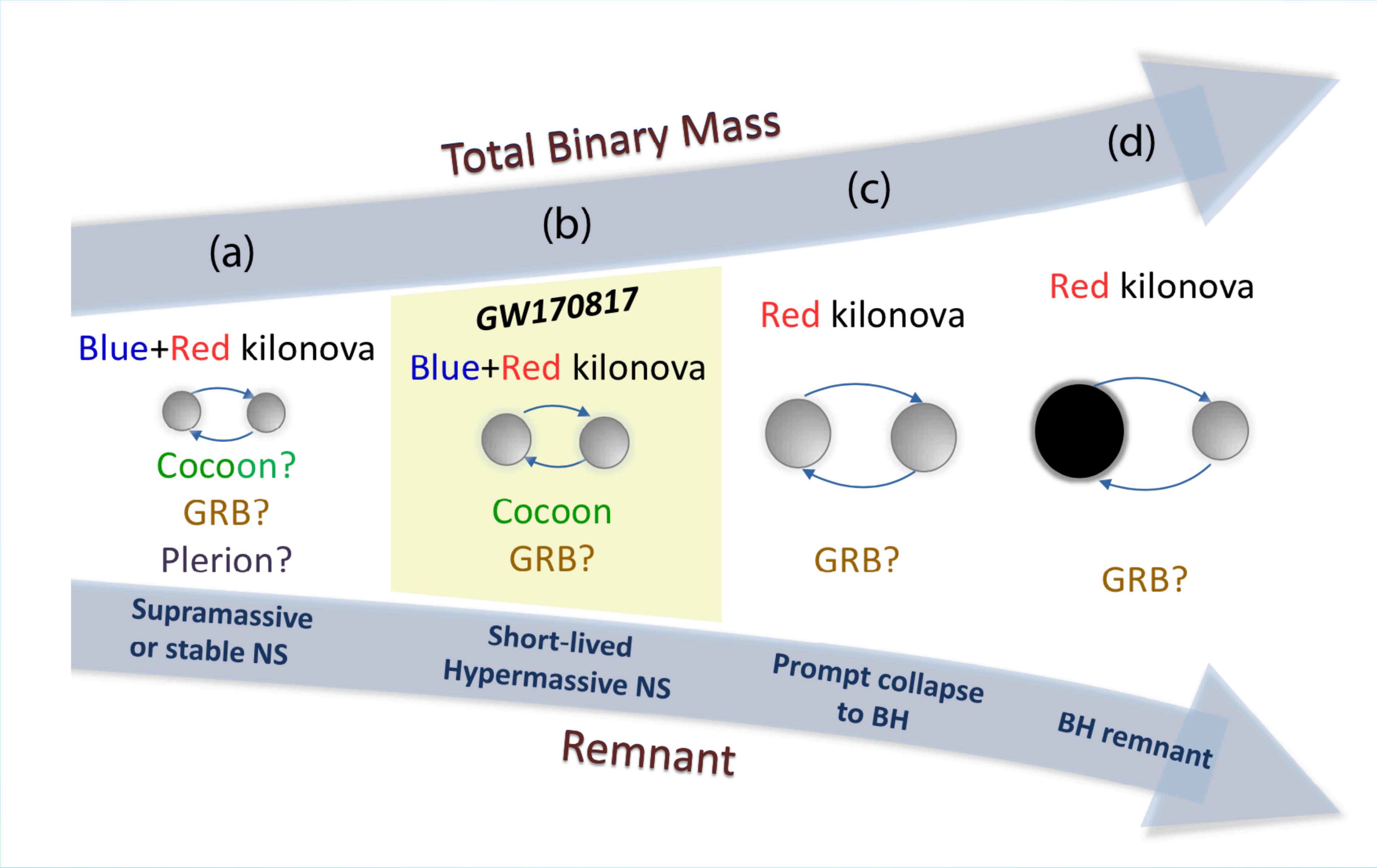


- The fate of neutron star mergers depends on the mass (m_1, m_2), mass ratio ($q = m_2/m_1$) spin of binary components, and on the neutron star EOS.

NS-BH has two possible fates; the neutron star is tidally disrupted or not by the companion BH. For the case of tidal disruption, the remnant is a spinning BH surrounded by a disk.



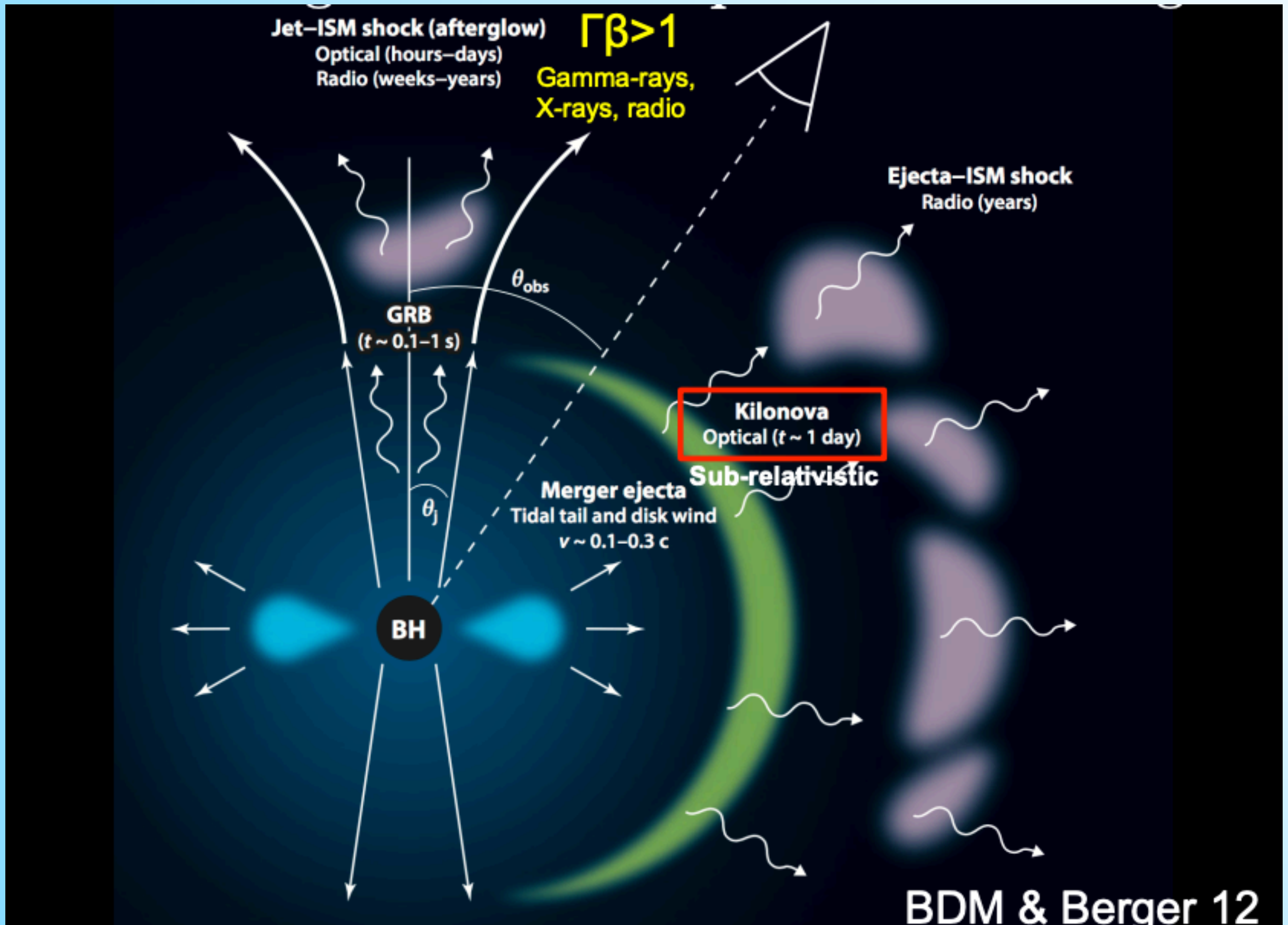
BNS and NS-BH events

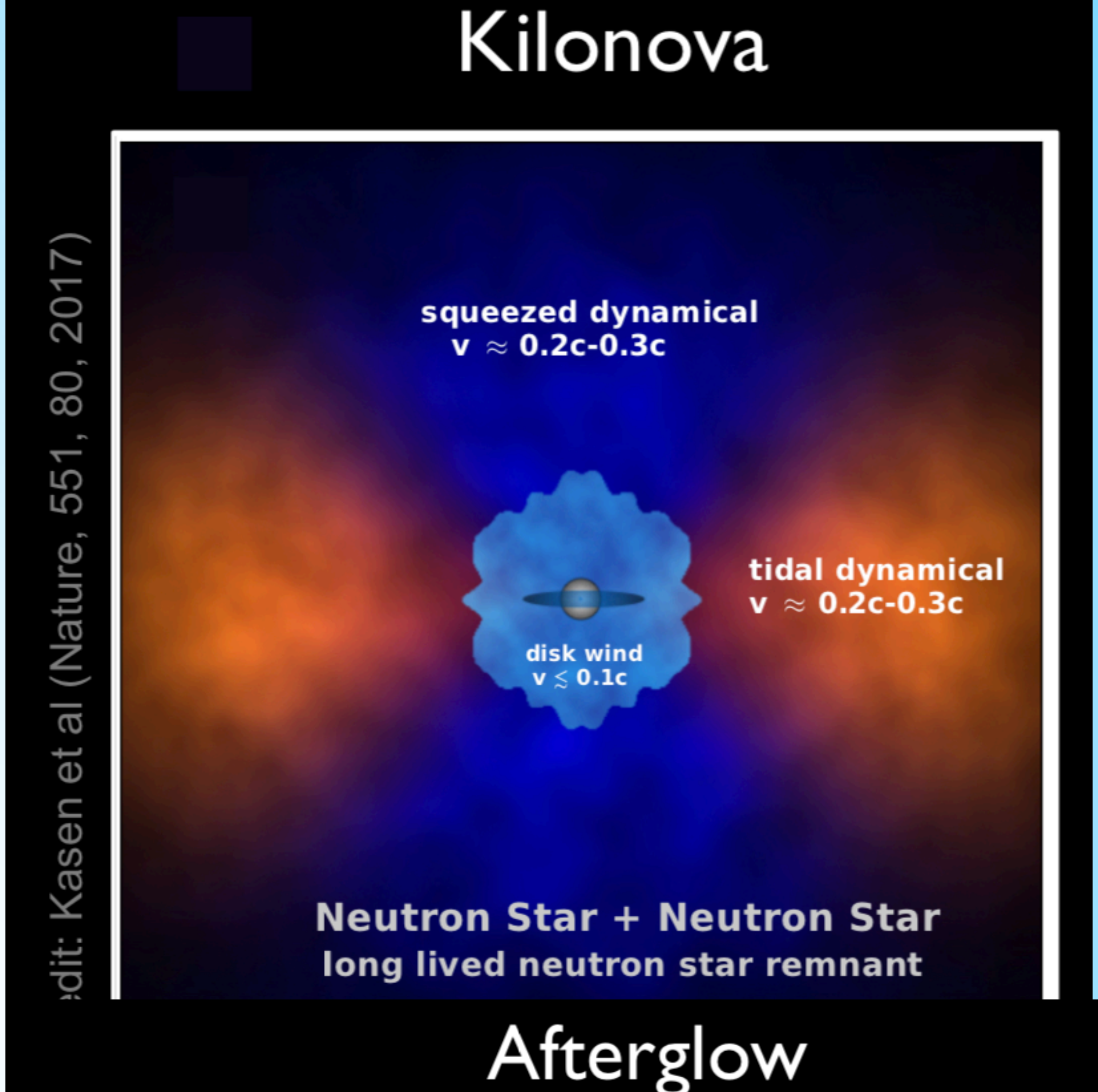


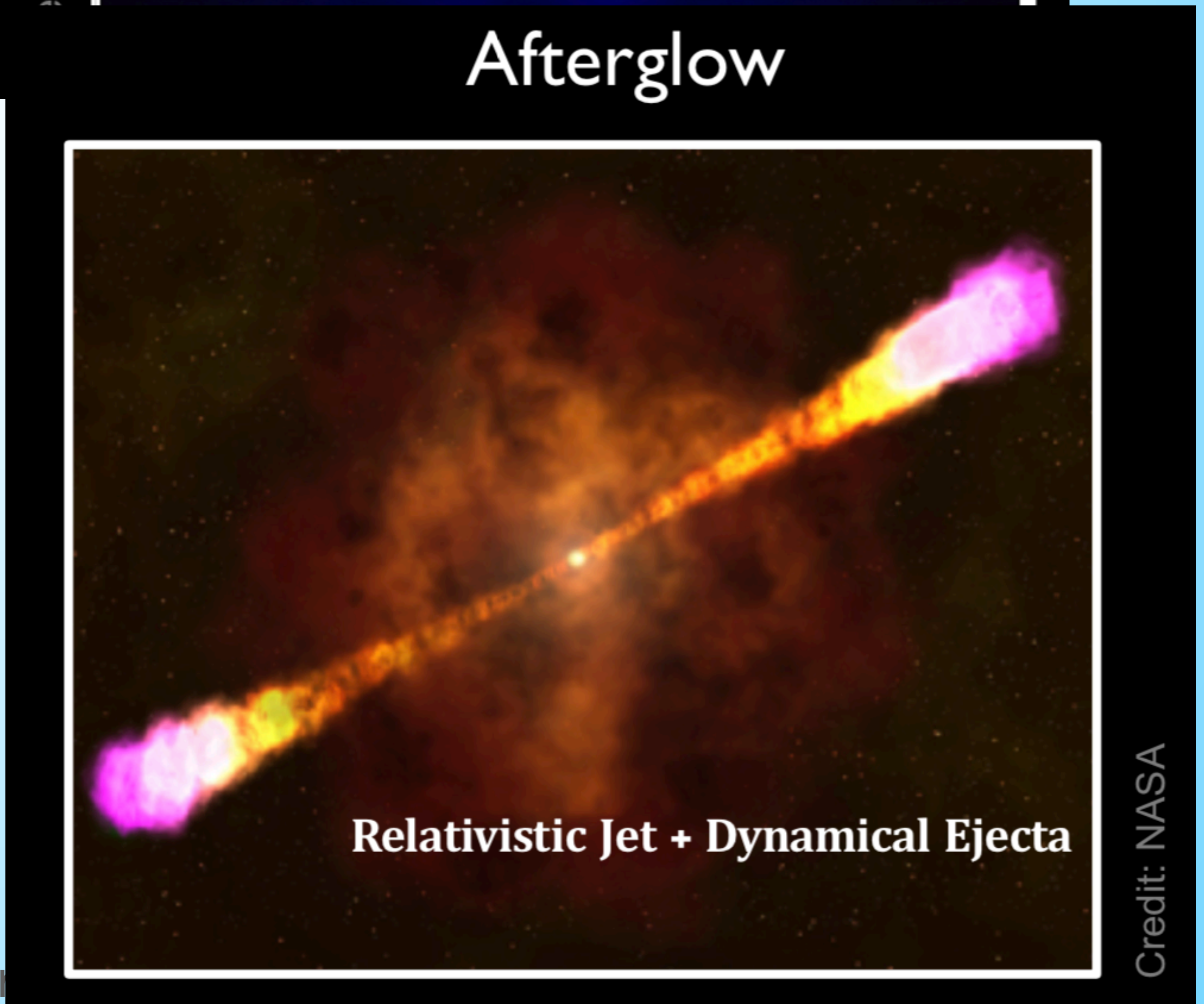
EM from BNS, NS-BH

- A coherent prompt radio pulse from a magnetically driven, relativistic plasma outflow prior to the DNS merger have also been proposed (Hansen & Lyutikov 2001; Pshirkov & Postnov 2010; Palenzuela et al. 2013; Totani 2013).
- sGRBs and their afterglows (Eichler et al. 1989; Paczynski 1991; Narayan et al. 1992) - ultra-relativistic afterglow.
- Optical–near-IR counterparts called macronovae or kilonovae (e.g., Li & Paczyński 1998; Kulkarni 2005; Metzger et al. 2010; Roberts et al. 2011; Metzger & Berger 2012; Barnes & Kasen 2013; Berger et al. 2013; Tanaka & Hotokezaka 2013; Tanvir et al. 2013; Yang et al. 2015; Jin et al. 2016) - cocoon
- Long-lasting radio merger remnants (Nakar & Piran 2011; Piran et al. 2013; Hotokezaka & Piran 2015).

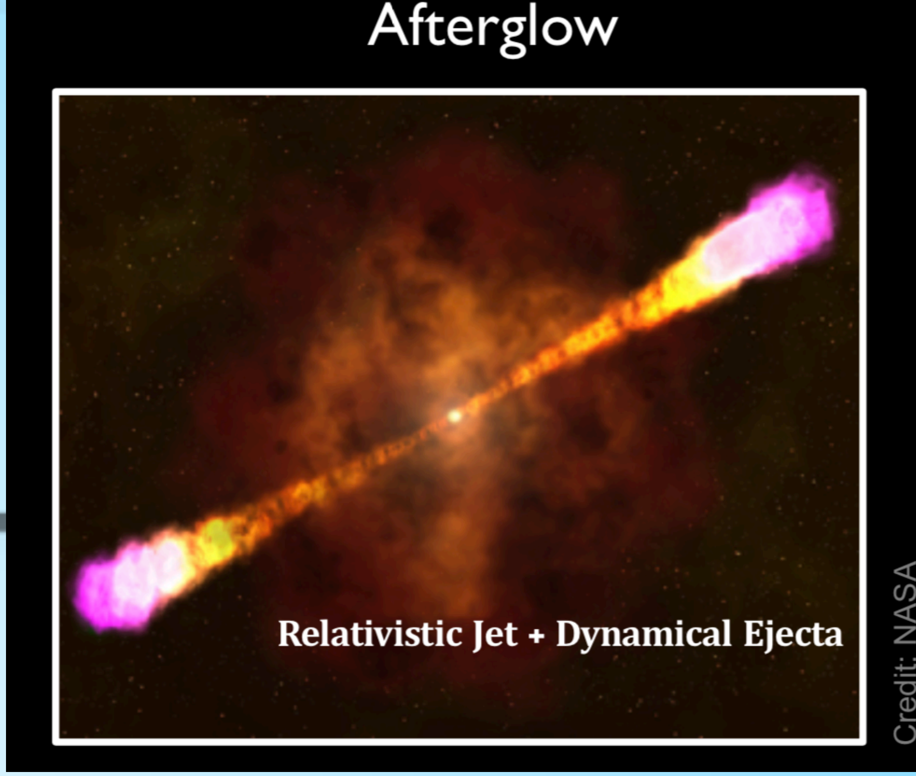
Afterglow emission in BNS merger







Jet production



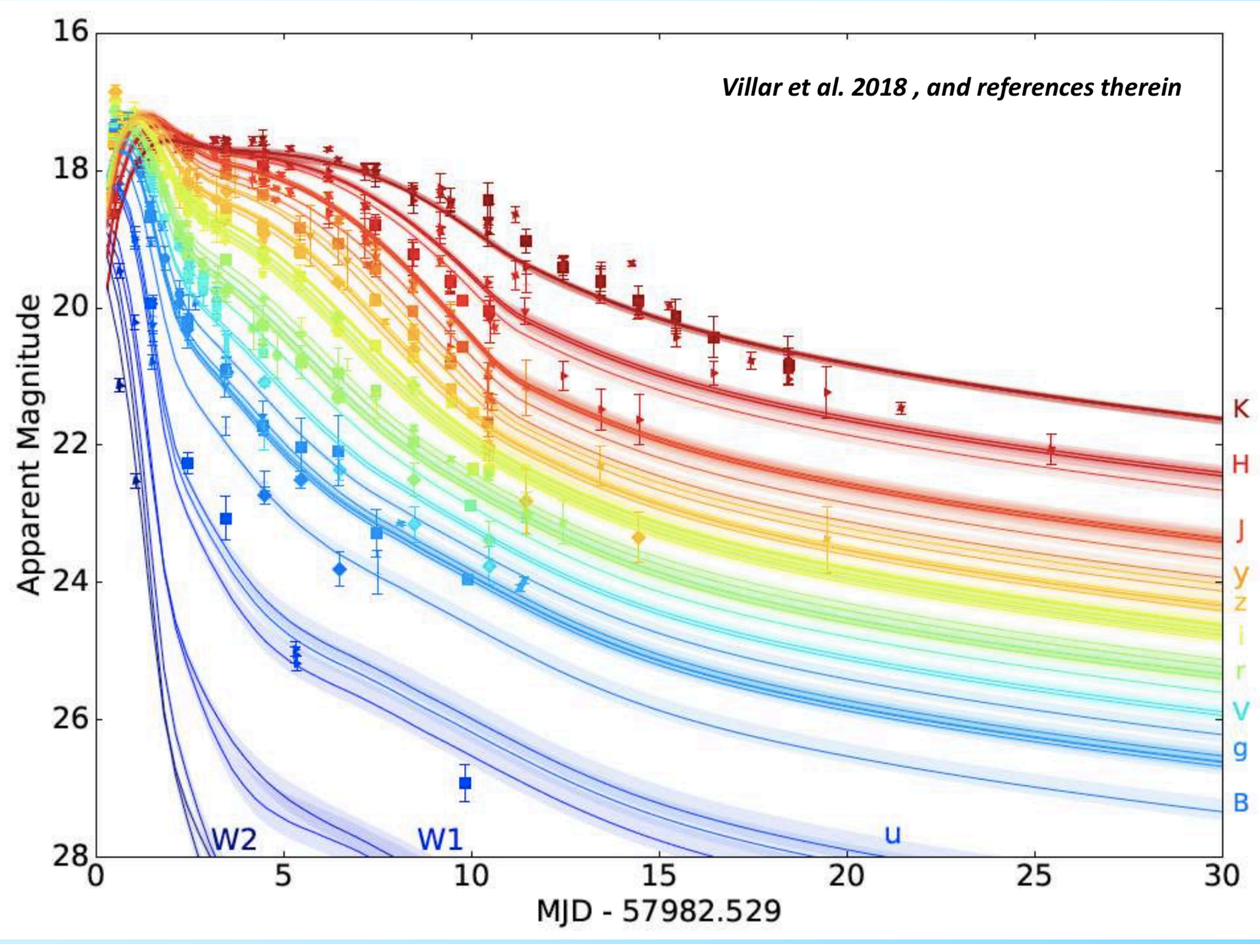
- Following a neutron-star merger, a jet, launched due to the rapid accretion of ejected matter onto a compact remnant, will propagate through the merger ejecta medium.

- The interaction of the jet with the ejecta will result in a structured outflow where the wider components are the product of a cocoon of accelerated ejecta material (e.g. Nagakura et al. 2014; Murguia-Berthier et al. 2017).

GW 170817 - merger ejecta

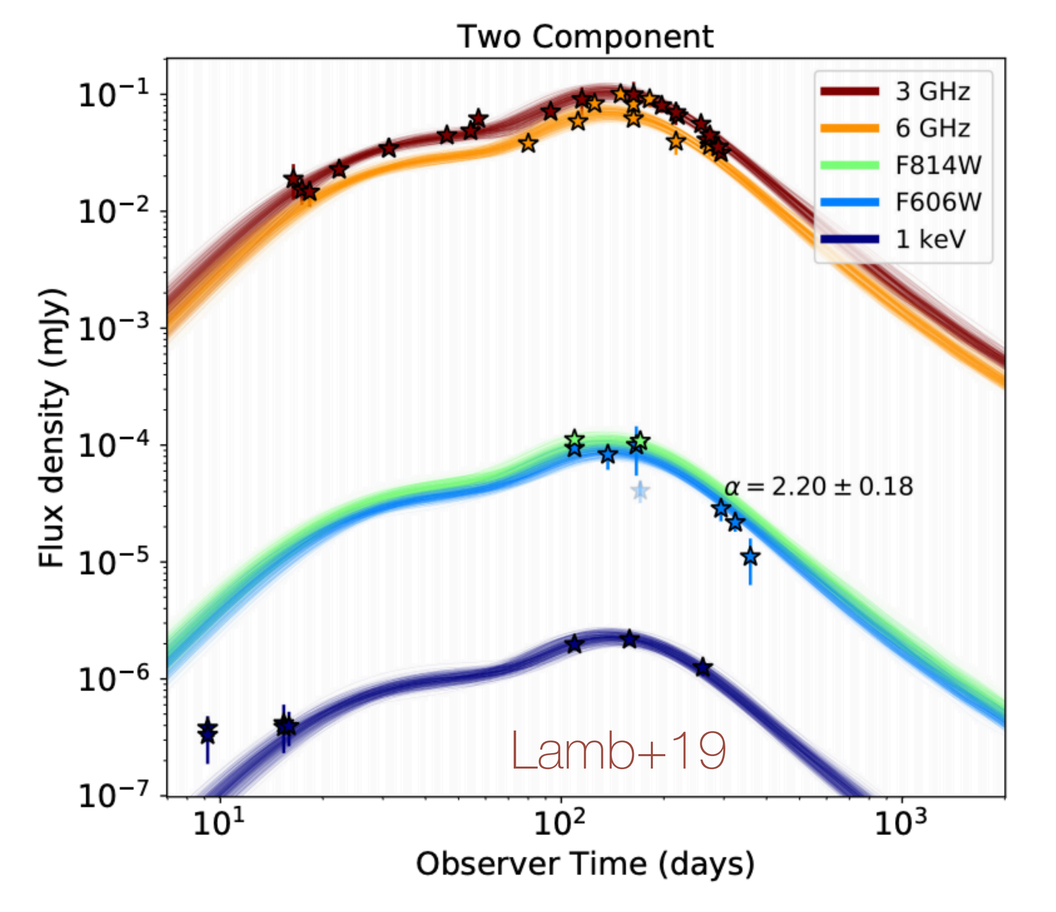
- Neutron star mergers eject a substantial amount of neutron-rich material, in which r-process nucleosynthesis robustly occurs. Subsequently, synthesized radioactive elements shine, in particular, as a kilonova (macronova).

- In addition, the ejecta have large kinetic energy with mildly-relativistic velocities, leading to a long-lasting synchrotron remnant.



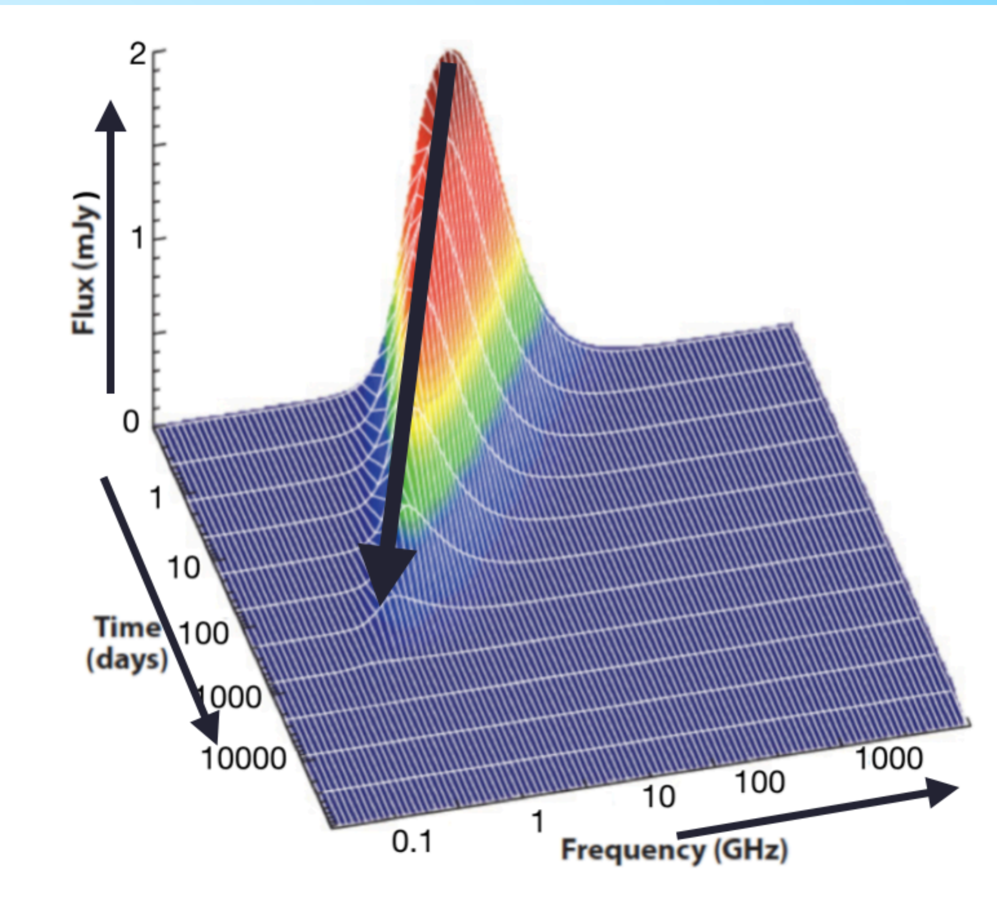
Synchrotron emission

- Various types of merger ejecta,
  - sGRB jets
  - Cocoons
  - Dynamical ejecta
  - Post-merger ejecta,



- The interaction of merger ejecta with the surrounding ISM produces a long-lasting synchrotron emission observable in multi-wavelength bands from radio to X-rays.

Radio emission



- The EM signatures from energetic matter outflows at different timescales.
- Ultra-relativistic jets
- Cocoon
- Sub-relativistic merger ejecta
- Non-relativistic slowed down jet

Days to weeks.
Depends on environments.

Months to years.
Peaks at sub-GHz

Why radio emission?

- The longer duration radio remnants that may last from months to years (Nakar & Piran 2011; Piran et al. 2013; Hotokezaka & Piran 2015; Margalit & Piran 2015). Uniquely probe their **energetics and environments and geometry.**
- Radio transient sky is far quieter compared to the optical one, so we expect far fewer false positives by a factor of a hundred or more depending on the sky location than in the optical–IR (e.g., Frail et al. 2012; Mooley et al. 2013, 2016).
-

Parameter space probed by 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, Frail+97, Chandra+08
- VLBI size constraints and jet motion, e.g. GRB 030329 (Taylor+2004, Philstrom+2007), GW 170817 (Mooley+18)
- Catching the early radio reverse shock emission (1-3 days) - constraining the Lorentz factor (enhanced peak flux by Γ, peak frequency scaled with $1/\Gamma^2$) - Ramirez-Ruiz+04, Kobayashi+2000,2002, Laskar+2013,2018.
- Early-time self-absorbed forward shock emission - only way to constrain the density (Chandra+08, Chandra+10, Chandra2016, Berger+04,06)

Break frequencies of afterglow emission

$$\nu_c \approx 10^{14}\,\mathrm{Hz}\left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-3/2}\left(\frac{\epsilon_B}{0.1}\right)^{-3/2}\left(\frac{t}{30\,\mathrm{d}}\right)^{-2}\beta^{-3},$$

$$\nu_m \approx 1\,\mathrm{GHz}\left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{1/2}\left(\frac{\epsilon_B}{0.1}\right)^{1/2}\left(\frac{\epsilon_e}{0.1}\right)^{2}\beta^{5},$$

$$\nu_{a,\mathrm{dec}} \approx 1\,\mathrm{GHz}\left(\frac{E}{10^{49}\,\mathrm{erg}}\right)^{\frac{2}{3(p+4)}}\left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{\frac{3p+14}{6(p+4)}}\left(\frac{\epsilon_B}{0.1}\right)^{\frac{p+2}{2(p+4)}}\left(\frac{\epsilon_e}{0.1}\right)^{\frac{2(p-1)}{p+4}}\beta_0^{\frac{15p-10}{3(p+4)}}.$$

Environmental Constraints

- 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 GMRT has a unique role to play.
- (For GRB 090423 (z=8.3), we found n=1 cm^{-3} (Chandra+10), for GRB 50904 (z=6.2), n=100-600 cm^{-3} (Gou+07) (Very different environments)

Parameter space probed by late radio observations

- Optically thin emission from forward shock, constrain particle energy index $N(E)dE \sim E^{-p}dE$, $F_\nu \sim \nu^{-\alpha}$, $\alpha=(p-1)/2$
- Late time radio emission
  - Off-axis jet (orphan afterglow) detection
  - Only means to detect EM in cases when kilonova and sGRB are missed (off-axis jet, behind the Sun, no jet escaped)
  - Energetics of the EM radiation when observed in non-relativistic phase (Frail+2000).
- The lack of radio detections usually associated with short γ-ray bursts does not constrain the radio transients from mildly relativistic and subrelativistic outflows (Nakar & Piran 2011)

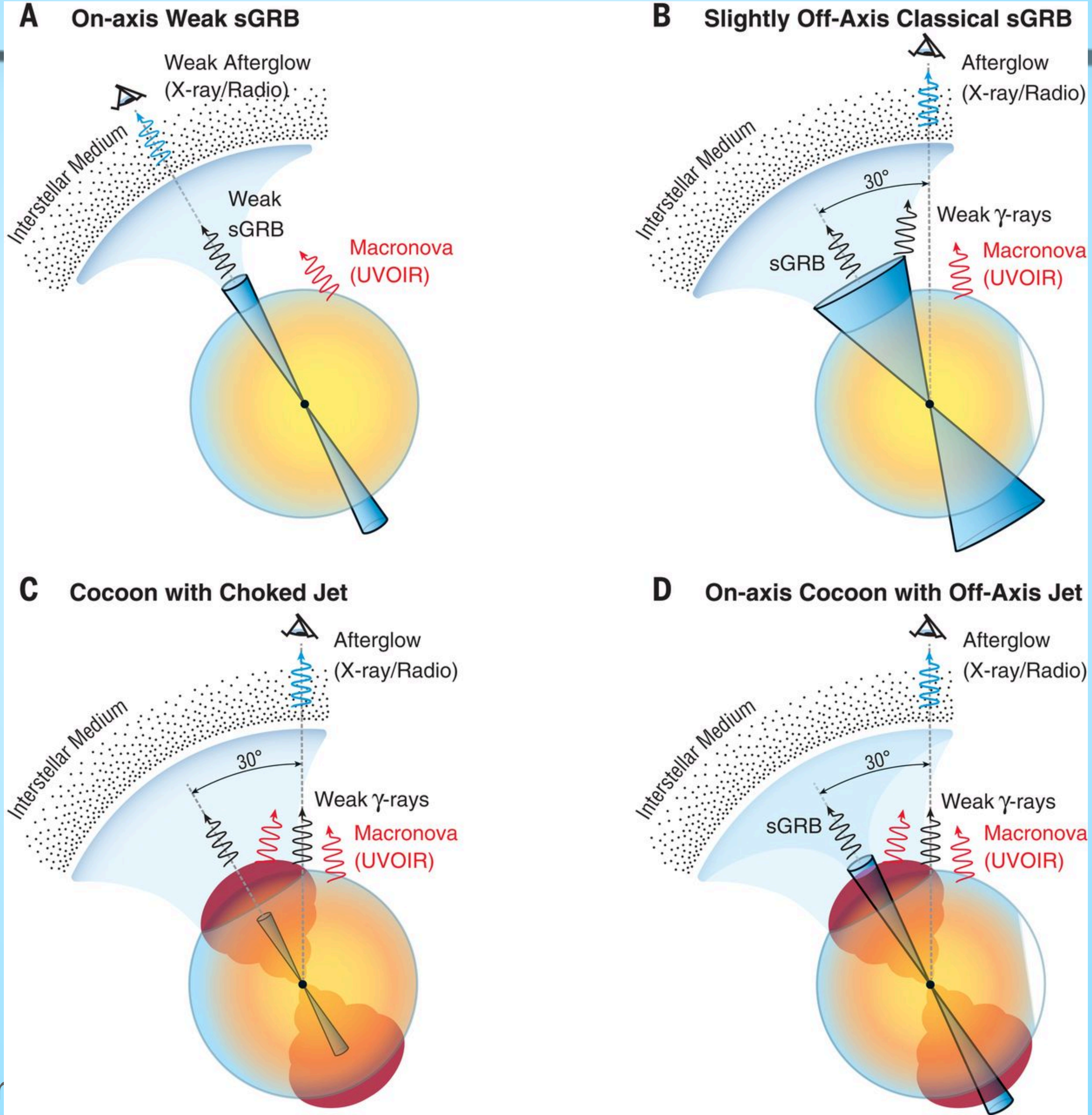
Off-axis afterglow

- Simulations by Perna, Lazzati, Farr (2019) - detection probability ~ 6-7% by Fermi/Swift.
- (i) sub-relativistic merger ejecta (long-lasting radio remnants) (ii) ultra-relativistic jets (orphan GRB afterglows)
- The lack of radio detections usually associated with short γ-ray bursts does not constrain the radio transients from mildly relativistic and subrelativistic outflows (Nakar & Piran 2011)

The energetics from non-relativistic phase

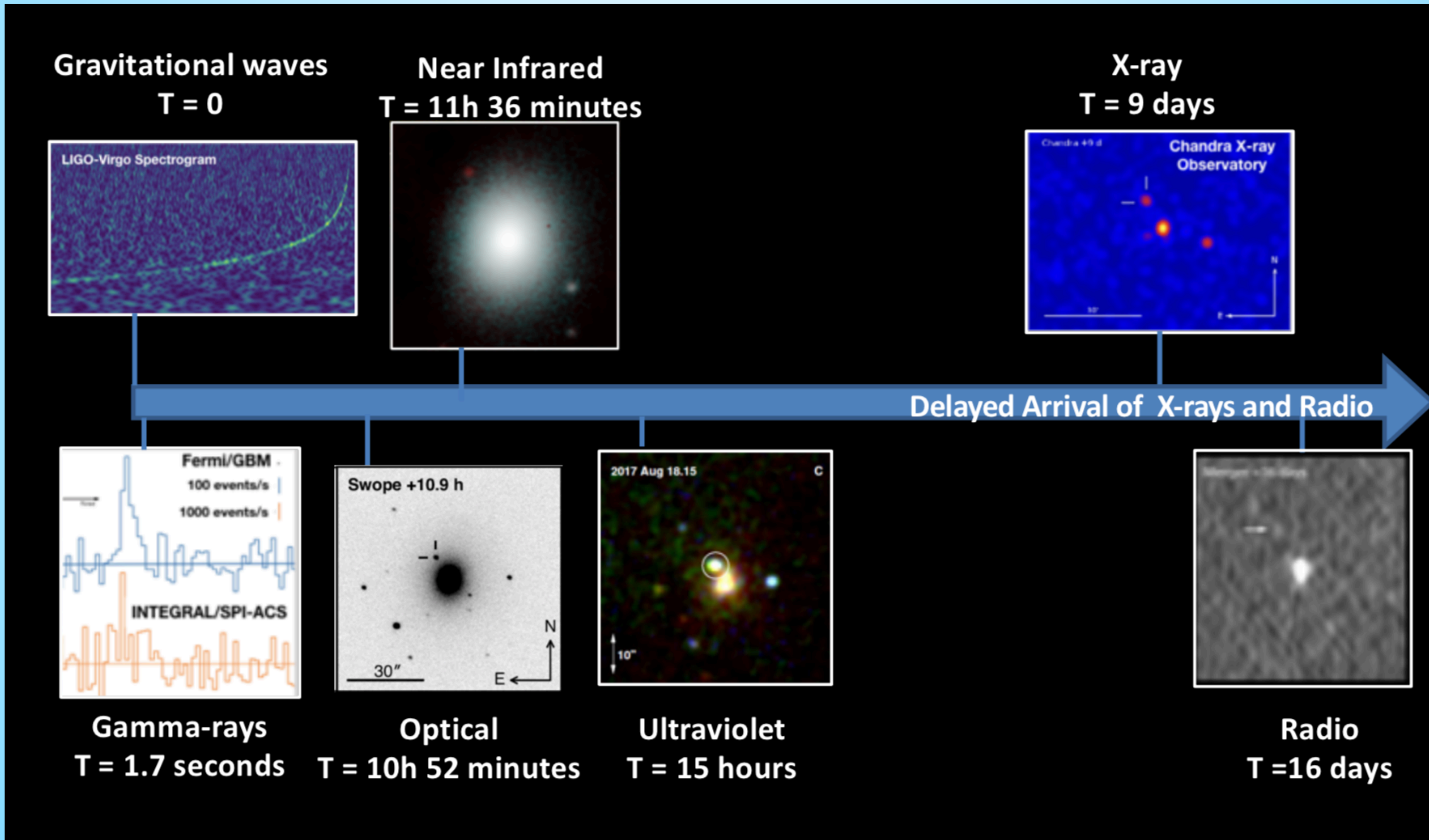
- Months to years after the burst, the jet becomes sub-relativistic (i.e., Sedov self- similar evolution) and the outflow is expected to be quasi-spherical.
- The non-relativistic afterglow will peak at <1 GHz (Nakar Piran 2011).
- The sub relativistic ejecta which gave rise to kilo nova will also give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

GW 170817

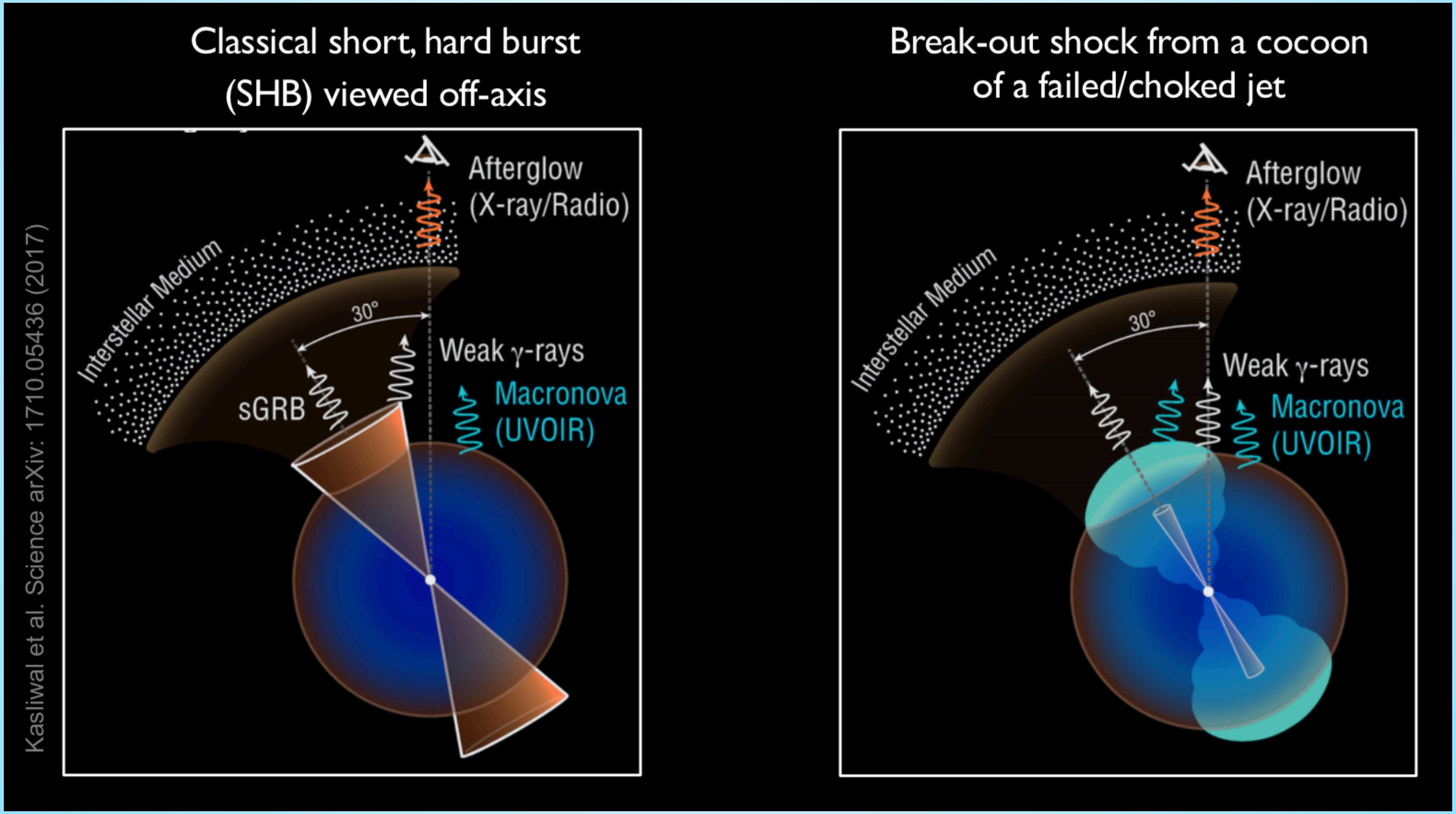


A
On-axis Weak sGRB
Weak Afterglow
(X-ray/Radio)
Interstellar Medium
Weak
sGRB
Macronova
(UVOIR)
B
Slightly Off-Axis Classical sGRB
Afterglow
(X-ray/Radio)
Interstellar Medium
30°
Weak γ-rays
sGRB
Macronova
(UVOIR)
C
Cocoon with Choked Jet
Afterglow
(X-ray/Radio)
Interstellar Medium
30°
Weak γ-rays
Macronova
(UVOIR)
D
On-axis Cocoon with Off-Axis Jet
Afterglow
(X-ray/Radio)
Interstellar Medium
30°
Weak γ-rays
sGRB
Macronova
(UVOIR)

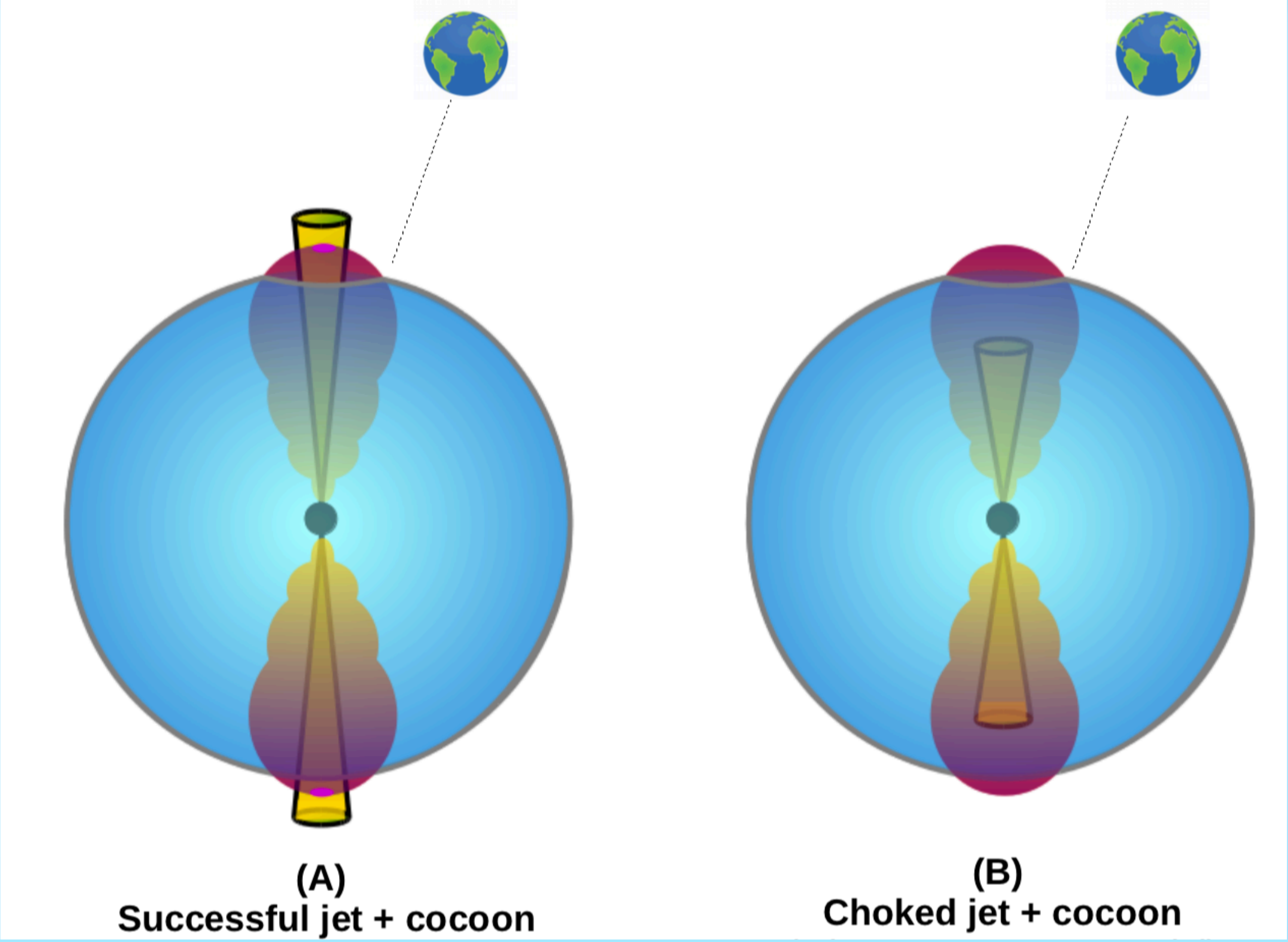
Multiwavelength emission from GW 170817



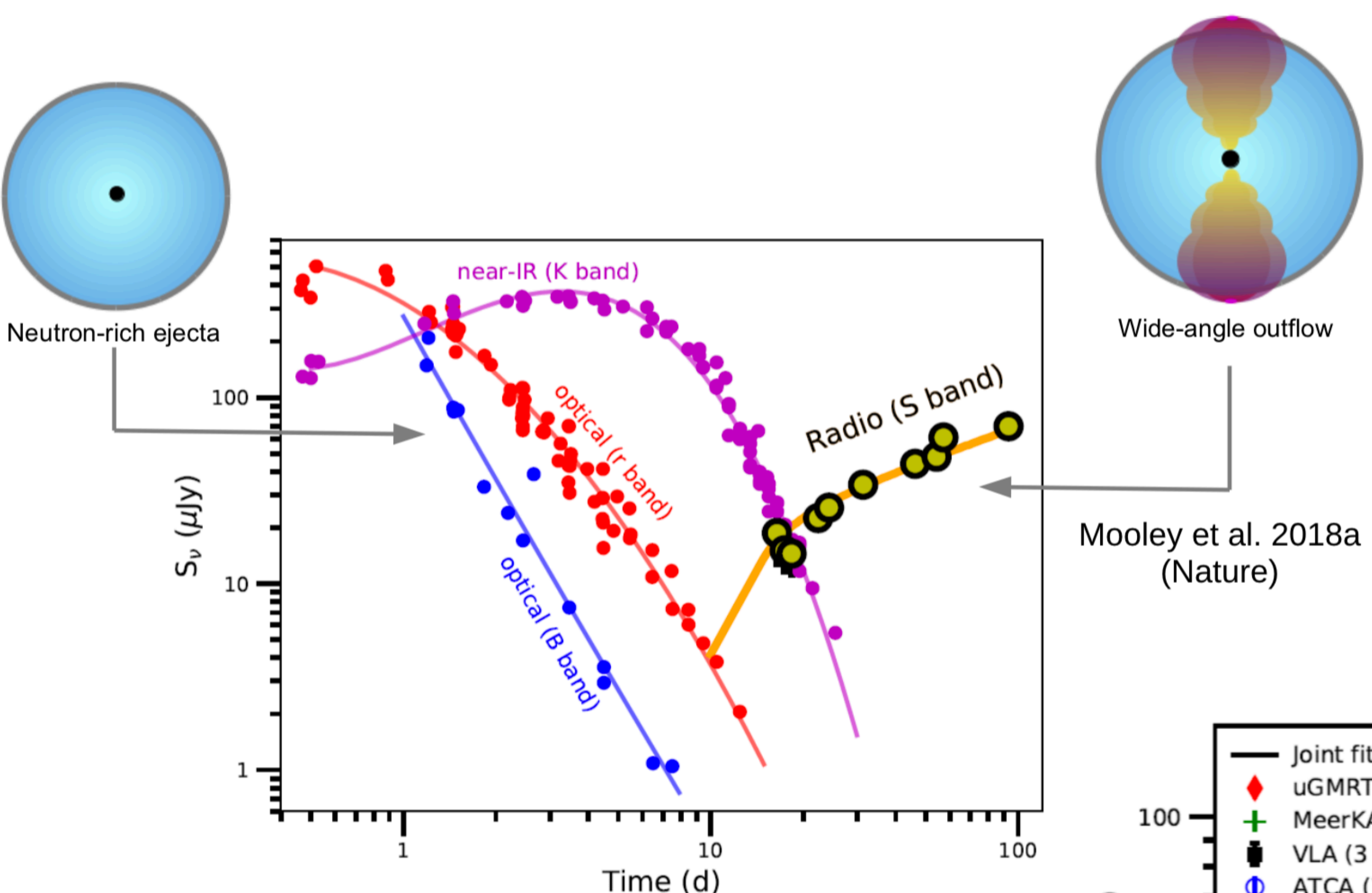
Models for prompt & afterglow emission

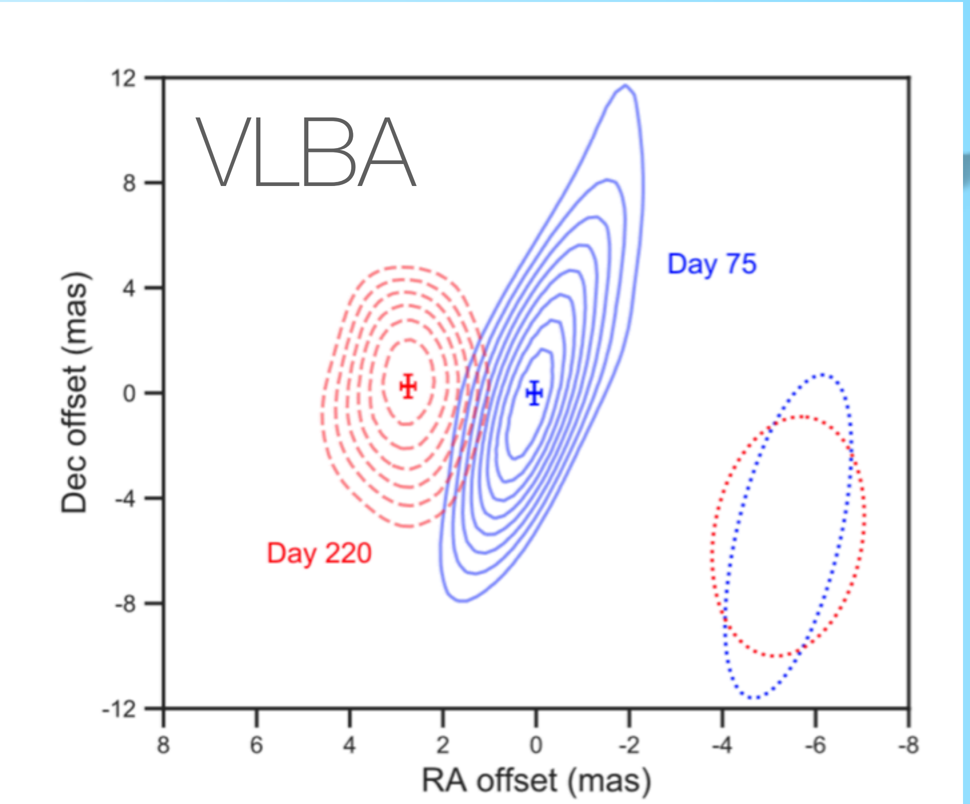


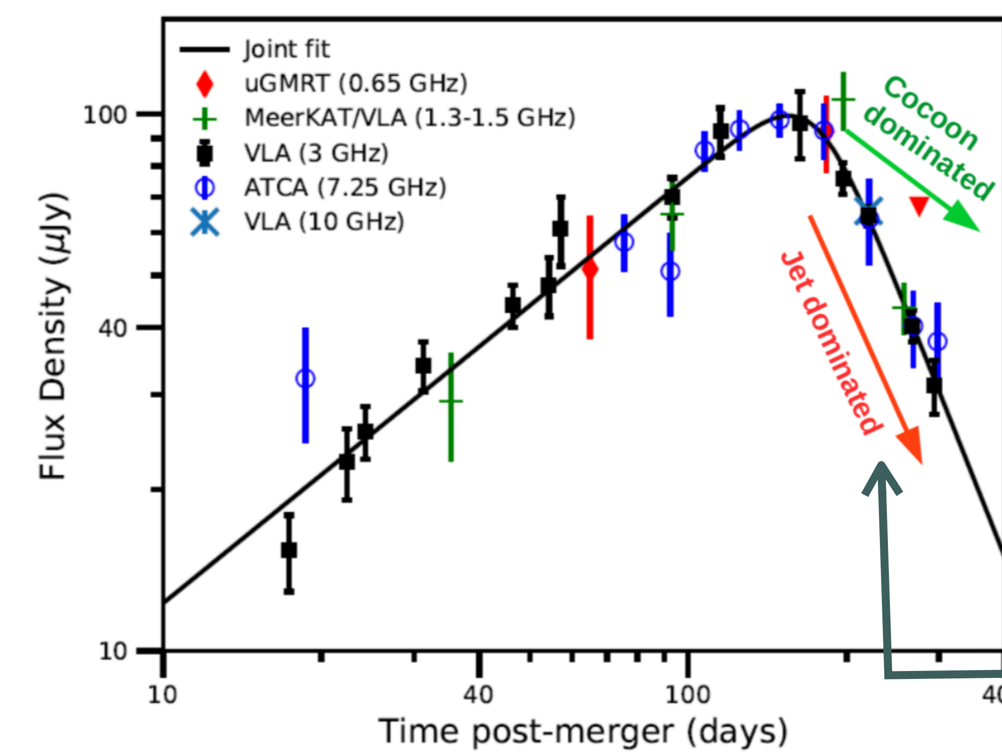
Radio emission in GW 170817

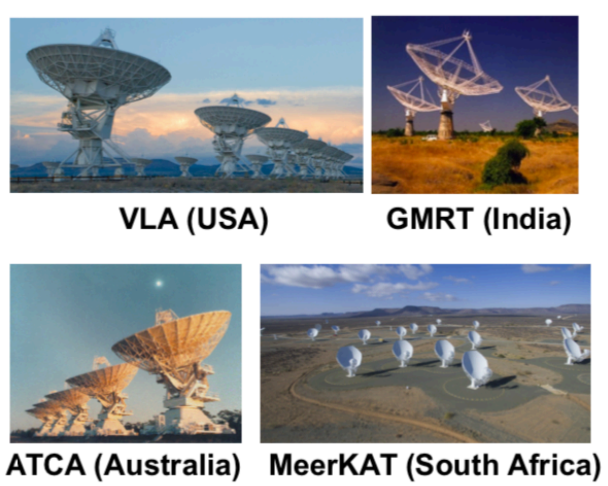


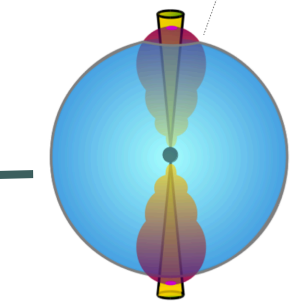
Radio emission from GW 170817









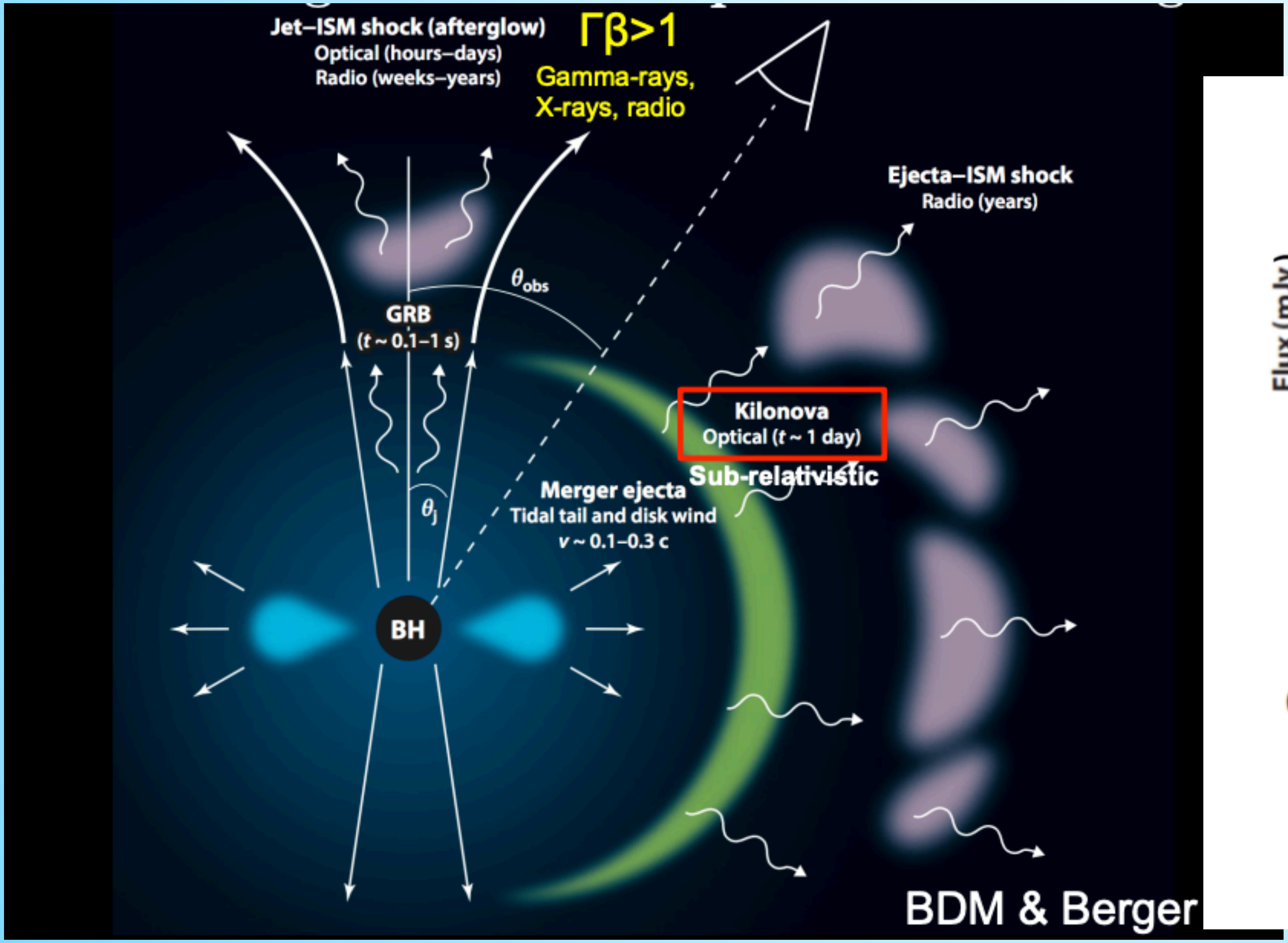


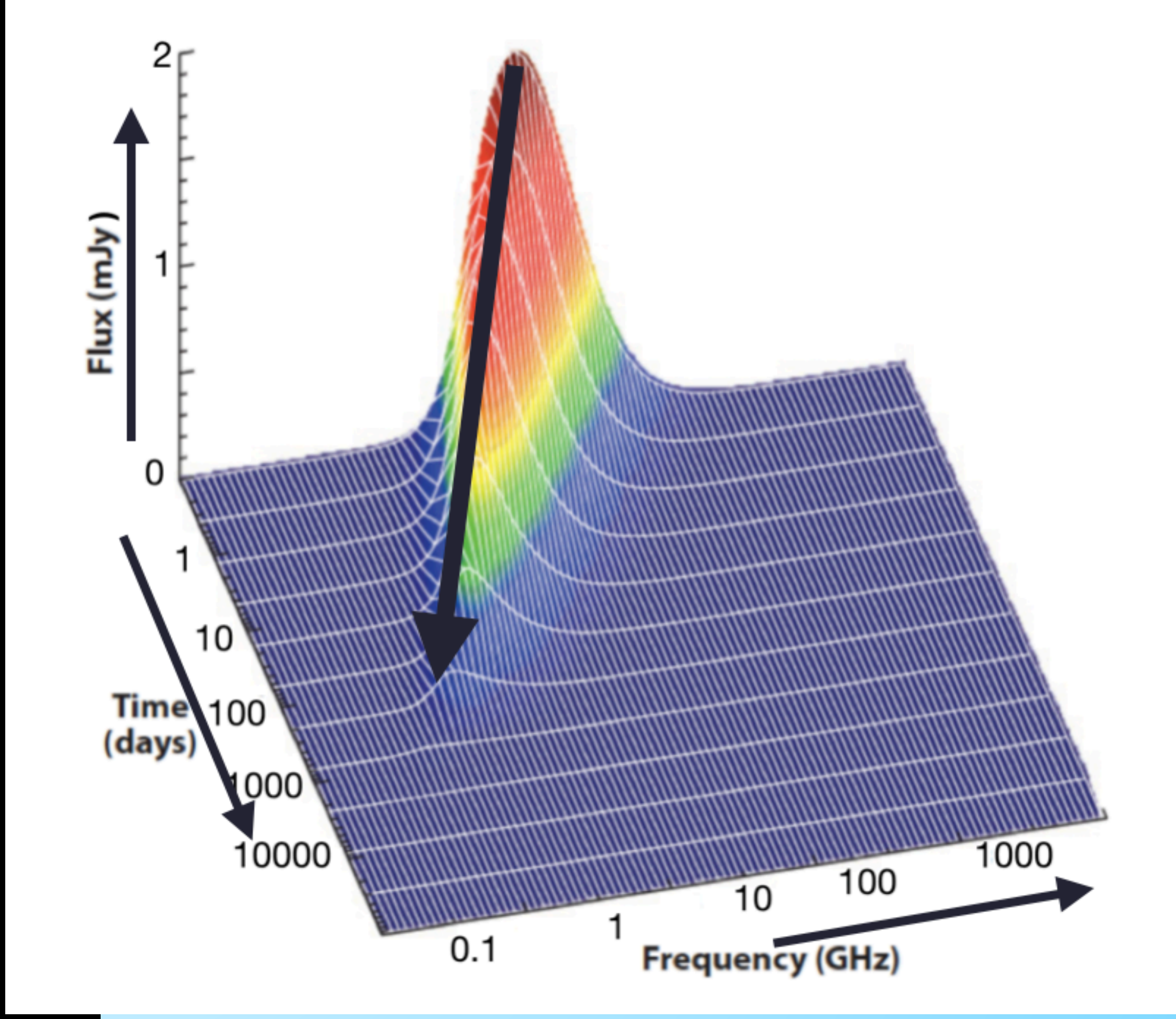
Off-axis vs cocoon

- After years of circumstantial evidence, we now have direct proof that SHBs are generated by NS mergers
- Rate of SHB ~ NS/NS rate
- Viewing angle constrains orbital inclination. Breaks H_0 degeneracy.

- There is a diversity of central engine outcomes. Some launch jets while others fail.
- Rate of SHB ≤ NS/NS rate
- Expect a larger number of EM counterparts than off-axis jet
- Wide-angle ejecta are visible over a wider solid angle
- Cocoon boosts early UV/blue kilonova brightness

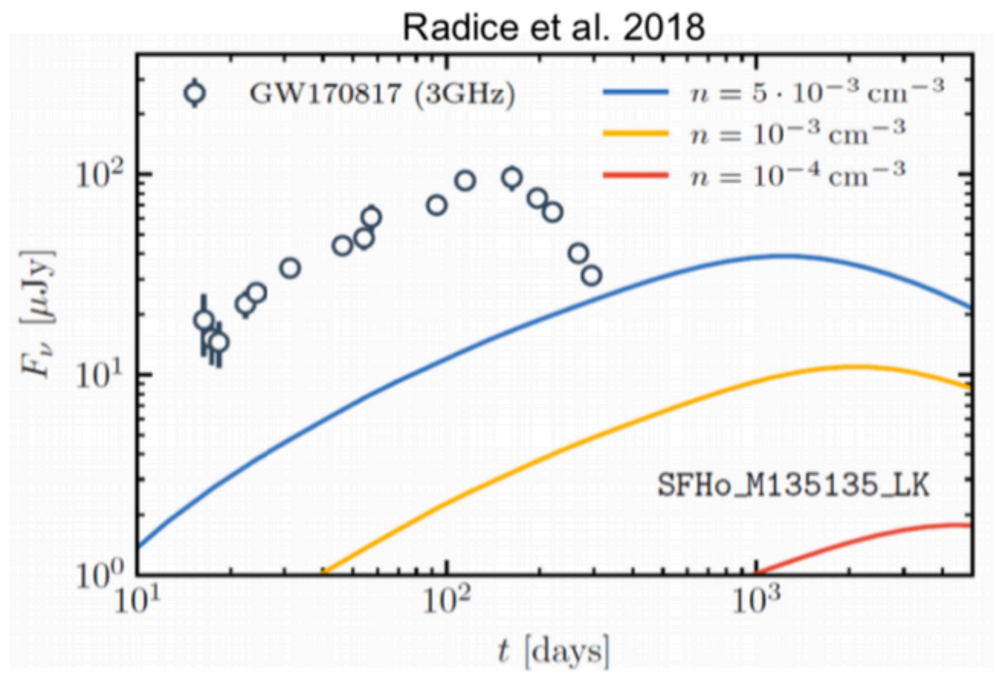
What's next for GW 170817?

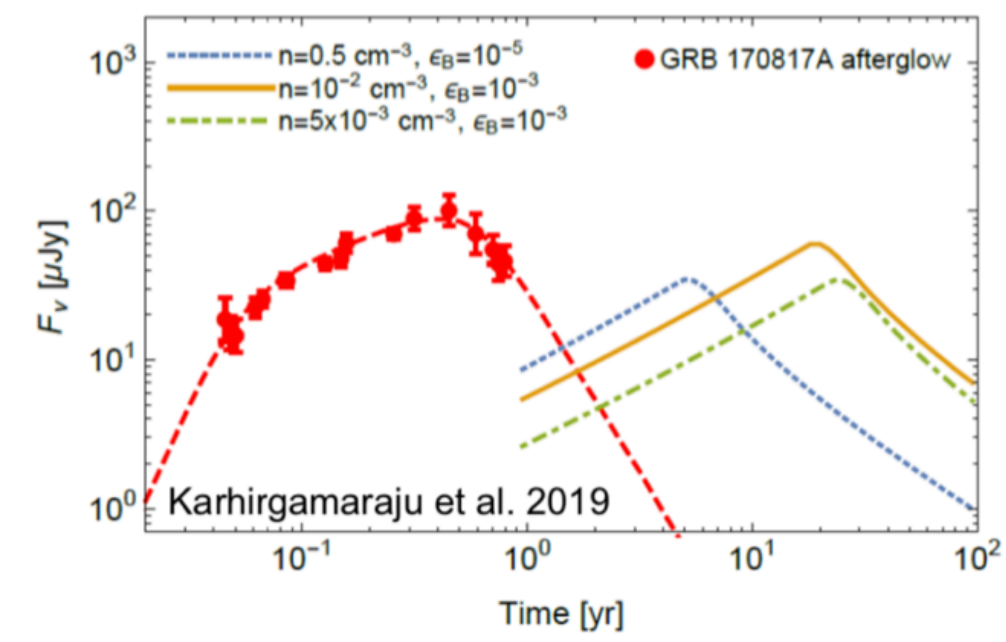




What next for GW 170817

- The relativistic jet-cocoon interaction nearly faded.
- Kilonova/dynamical ejecta has KE with ~0.05M$_\odot$ at ~0.1c.
- Synchrotron emission years after merger
- Search for rising radio component.





Worldwide Radio Facilities

Table 1: Specifications for partner radio facilities

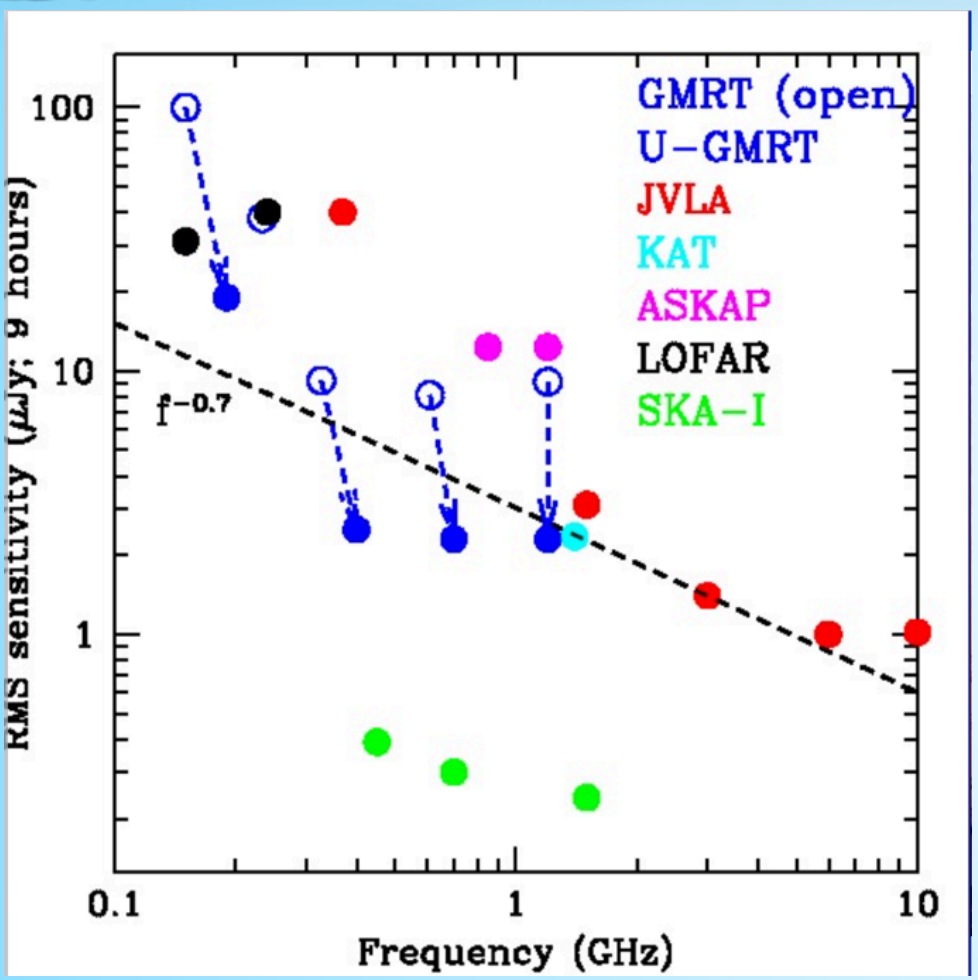
Telescope	ν_{obs} (GHz)	BW (GHz)	Ω (deg^2)	T_{sys} (K)	θ_{res} (")	σ_{1hr} (μJy)	SS[a] ($deg^2\ hr^{-1}$)	S_{conf} (μJy)	Dec. limit (deg)
VLA-S	3.0	1.5	0.06	23	2.7[b]	5	13	<1[b]	> −30
VLA-C	6.0	4.0	0.01	19	1.3[b]	3	6	<1[b]	> −30
ASKAP	0.9–1.6[c]	0.3	30	50	35	35	52	25	< +30
Apertif	1.3–1.5[c]	0.3	9	70	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

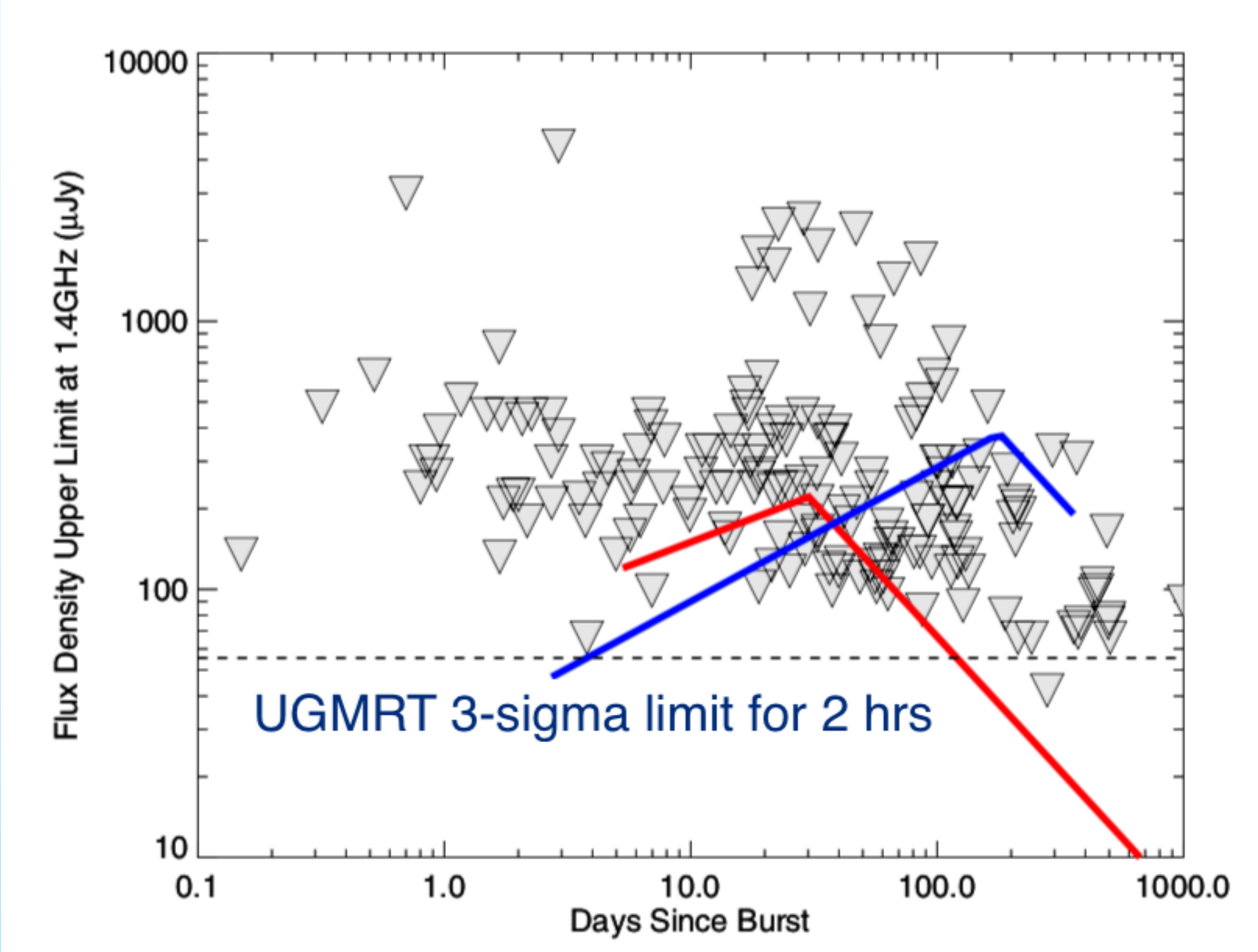
Notes: ν_{obs} is the center observing frequency, BW is bandwidth, Ω is the field of view (FWHM), T_{sys} is the system temperature, θ_{res} is the angular resolution, σ_{1hr} is the continuum sensitivity (thermal/confusion noise) reached with 1hr on-source time, SS is the survey speed, S_{conf} is the confusion noise, and the last column gives the declination limit for observing.
[a]assumes 100 μJy RMS noise, [b]assumes B config, [c]tunable

Radio detectability & uGMRT

- Will peak at low frequencies < 1 GHz.
- LOFAR confusion noise 600 uJy
- uGMRT confusion noise 34 uJy

Why uGMRT?





PC+12, PC+16, Kanekar

Unique role of SKA

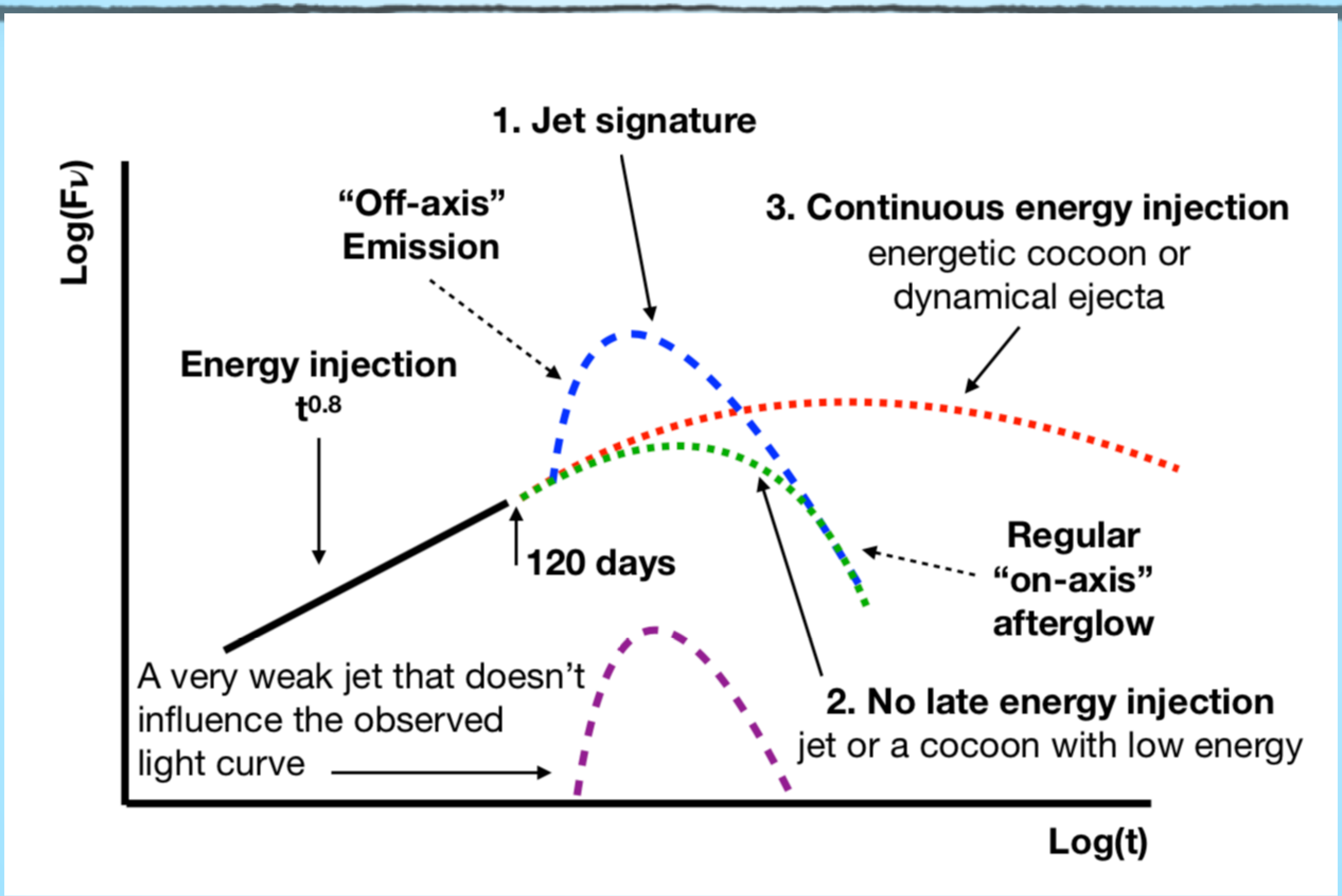
- Wide range of radio frequencies
- Extremely high resolution (e.g. GW 170817 host galaxy)
- SKA VLABI - jet Lorentz factor etc.
- High sensitivity - GW 170817
- Late time prediction ~10 uJy (SKA 1 uJy)
- India partner of SKA-India
- Energetics, Environments and Geometry

Questions to be answered.

- How much energy do mergers release?
- How many mergers have relativistic jets and how many jets interact with surrounding neutron-rich polar ejecta to produce cocoons?
- What is the nature if NS-BH mergers?
- What is the underlying relation between NS-NS mergers and SGRBs?
- 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)

Extra Slides

Jet and cocoon



Nakar & Piran 2018

Radio Observations

- A comprehensive census of radio counterparts from LIGO/Virgo's third observing run O3 will provide the best insight into the local environments of NS mergers (Fong et al. 2107)
- Radio observations could establish the fraction of mergers that launch jets, the fraction of those jets that interact with dynamical ejecta to form cocoons, as well as the fraction of jets that escape to produce a SGRB.
- 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 and searches for a red kilonova have been unsuccessful.

Unique role of uGMRT

- The uGMRT provides the sensitivity and resolution at the critical low frequencies < 1.5 GHz, where the VLA and other telescopes are not well suited to do. This is crucial. Early-time measurements at low radio frequencies, accessible to the uGMRT, give very important constraints on the synchrotron self-absorption frequency, and hence on the nature of the outflow and density of the ambient medium

- Low frequency observations are also crucial once the jet becomes sub-relativistic, on timescales of weeks to months. This allows us to constrain the true energetics of the short GRB associated with the GW event, independent of the jet geometry

- The equatorial sub-relativistic ejecta interacting with the circum-burst medium (Fig 1) peaks on timescales between 1–3 years and is ideally observed at ~1 GHz or sub-GHz frequencies [28], making uGMRT an ideal instrument to follow it up at late times as well.

EM emission from BBH

- EM from BBH (no accretion material resulting from tidal disruption at merger) - Some source of pre-existing material
  - Related to the progenitor star (Loeb 2016; Woosley 2016; Janiuk et al. 2017), e.g. mini-disk resulting from its supernova explosion (Perna et al. 2016; Murase et al. 2016; Martin et al. 2018).
  - Environment of the merger, such as an AGN disk (Bartos et al. 2017).
  - EM energy source if BH is charged (Liebling & Palenzuela 2016; Zhang 2016; Liu et al. 2016; Fraschetti 2018).
  - GRMHD simulations - the jets are produced from merging BHs if there is some matter around the BHs at the time of merger (Khan et al. 2018).

Post merger ejecta

- Viscous heating - magnetohydrodynamic turbulence
- Neutrino heating
- Nuclear recombination
- Dynamic ejecta - N -rich (low Ye)
- Post merger - less N-rich (due to neutrino absorption)

Dynamical Ejecta

- The mass of the dynamically ejected matter during merger depends strongly on the EOS, total mass and mass ratio of the system, and BH spin (for BH-NS binaries).

- Dynamical mass ejection: shock heating (larger Y_e) and tidal torque (not much weak interactions). Hence, a broad range of electron fraction between $Y_e \approx 0.05$ and $Y_e \approx 0.5$ irrespective of the EOS.This broad Y_e distribution is well suited for explaining the abundance patterns of r-process elements with mass numbers larger than A ~ 90 observed in the Solar System and metal-poor stars.

- For BH-NS binaries, the electron fraction of the dynamical ejecta is always low (Ye ~ < 0.1) as weak interactions do not play a role, and hence, heavy r-process elements (A ~ > 130) are dominantly synthesized.

Post merger ejecta

- After a binary neutron star merger, a BH or massive neutron star (MNS) surrounded by a dense massive disk (or torus) is formed.

- A large fraction of mass of compact disks surrounding the central compact objects is ejected from the system by a viscous, nuclear recombination, and/or MHD effect.

- The mass of this ejecta can be of order $10^{-2} M_\odot$; thus, it can dominate over the mass of dynamical ejecta, implying that this ejecta is as important as or even more important than dynamical ejecta to power EM emission.

- The typical velocity of this ejecta component is smaller than that for dynamical ejecta