JCHE - Tuesday, May 4, 2021 (prepared by F. Daigne)

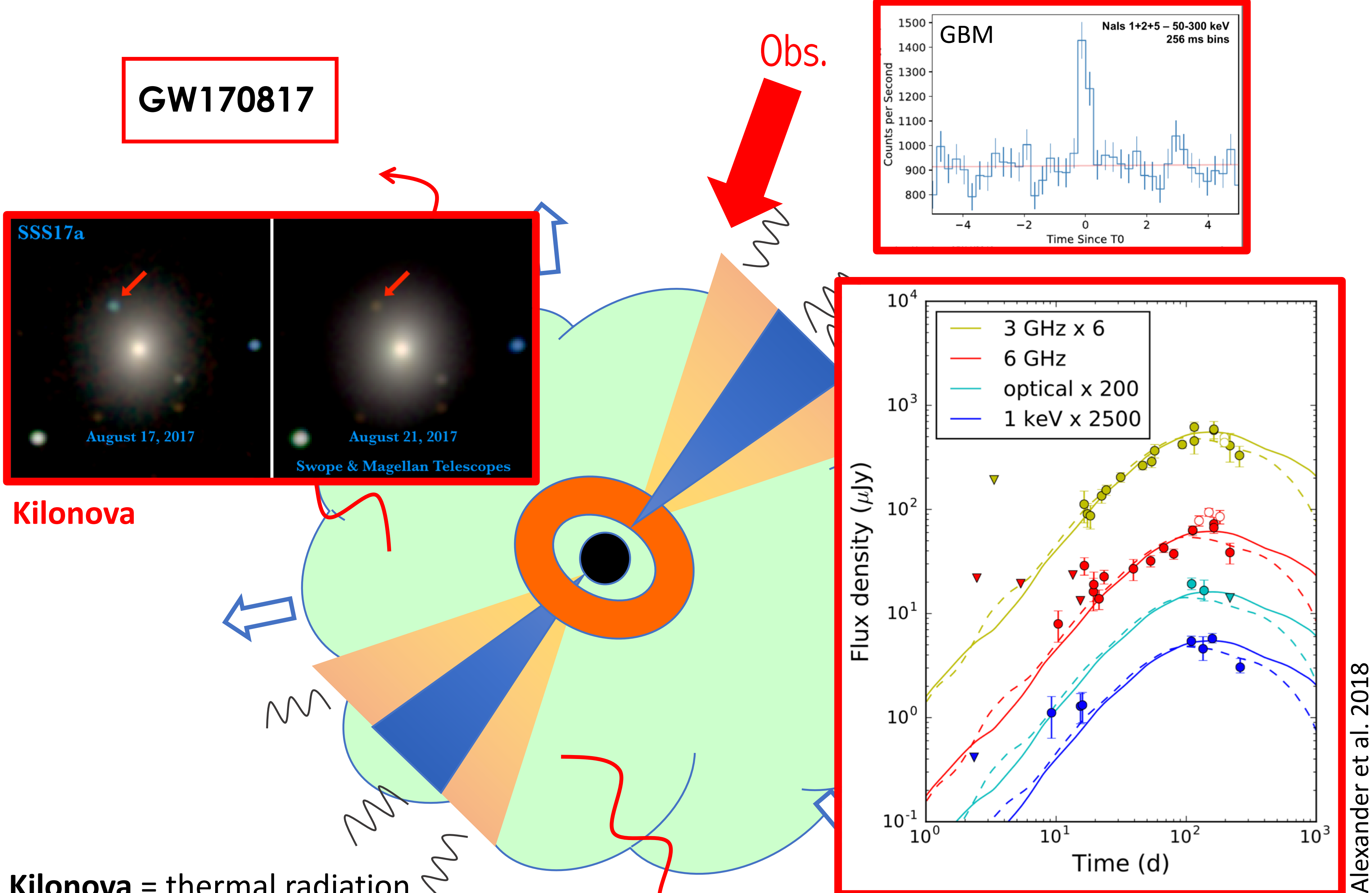
Late X-ray and radio observations of 170817
A new component?
Kilonova afterglow?

- **The emergence of a new source of X-rays from the binary neutron star merger GW170817 ; Hajela et al. 2021 ; arXiv:2104.02070**

- **Continued radio observations of GW170817 3.5 years post-merger Balasubramanian et al. 2021 ; arXiv:2103.04821**
- **Dynamical ejecta synchrotron emission as a possible contributor to the rebrightening of GRB170817A ; Nedora et al. 2021 ; arXiv:2104.04537**

- **Accurate flux calibration of GW170817: is the X-ray counterpart on the rise? Troja et al. 201 ; arXiv:2104.13378**

- **Determining the viewing angle of neutron star merger jets with VLBI radio images Fernandez, Kobayashi & Lamb, 2021 ; arXiv:2101.05138**



Kilonova = thermal radiation
(quasi-isotropic ejecta, heated by the radioactivity of r-process elements)
Afterglow = non-thermal radiation
(deceleration of a relativistic jet with lateral structure: forward shock)

3. Predictions for the late afterglow of the structured relativistic jet

Determining the viewing angle of neutron star merger jets with VLBI radio images

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
Very long base interferometry (VLBI) radio images recently proved to be essential in breaking the degeneracy in the ejecta model for the neutron star merger event GW170817. We discuss the properties of synthetic radio images of merger jet afterglow by using semi-analytic models of laterally spreading or non-spreading jets. The image centroid initially moves away from the explosion point in the sky with an apparent superlumianal velocity. After reaching a maximum displacement its motion is reversed. This behavior is in line with that found in full hydrodynamics simulations. Since the evolution of the centroid shift and jet image size are significantly different in the two jet models, observations of these characteristics for very bright events might be able to confirm or constrain the lateral expansion law of merger jets. We explicitly demonstrate how $\theta_{\rm obs}$ is obtained by the centroid shift of radio images or its apparent velocity provided the ratio of the jet core size θ_c and the viewing angle $\theta_{\rm obs}$ is determined by afterglow light curves. We show that a simple method based on a point-source approximation provides reasonable angular estimates ($10-20\%$ errors at most). By taking a sample of structured Gaussian jet results, we find that the model with $\theta_{\rm obs} \sim 0.32$ rad can explain the main features of the GW170817 afterglow light curves and the radio images.

Key words: Transients: gamma-ray bursts - Transients: neutron star mergers - Physical data and processes: gravitational waves - methods: numerical.

arXiv:2101.05138 : includes a discussion of the importance of the lateral expansion for the late evolution (including VLBI diagnostic) and of the current uncertainties in modeling this expansion.

4. New X-ray detection at ~3.4 years

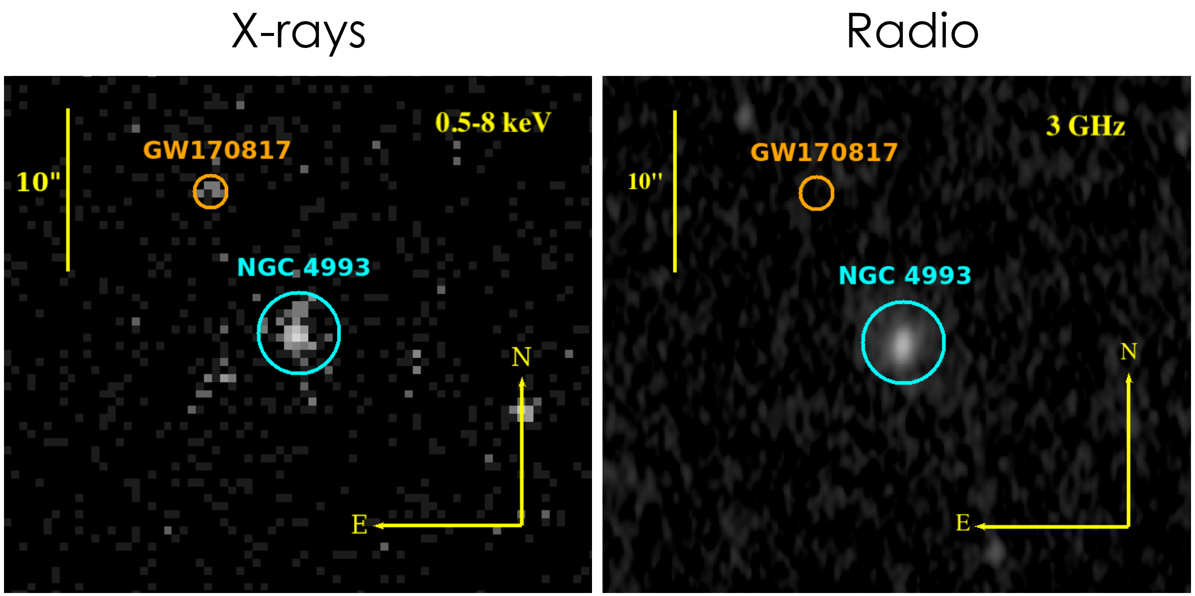


Figure 1 | Combined images of GW170817 at δt ~ 3.4 years: *Left Panel*: Combined X-ray image consisting of *CXO* observations spanning $\delta t \sim 1209 - 1258$ days in the 0.5 – 8 keV energy range. An X-ray source is clearly detected at the location of GW170817 with statistical significance of $7.2\,\sigma$ (Extended Data Table 1). *Right Panel*: Combined radio image comprising VLA 3 GHz observations acquired in the time range $\delta t \sim 1216 - 1265$ days. No radio emission is detected at the location of GW170817. The RMS noise around the location of the BNS merger is $\sim 1.7\,\mu$Jy (§2). In both panels the orange and light-blue regions have a $1''$ and $2.5''$ radius, respectively, and mark the location of the BNS merger and its host galaxy.

4. New X-ray detection at ~3.4 years

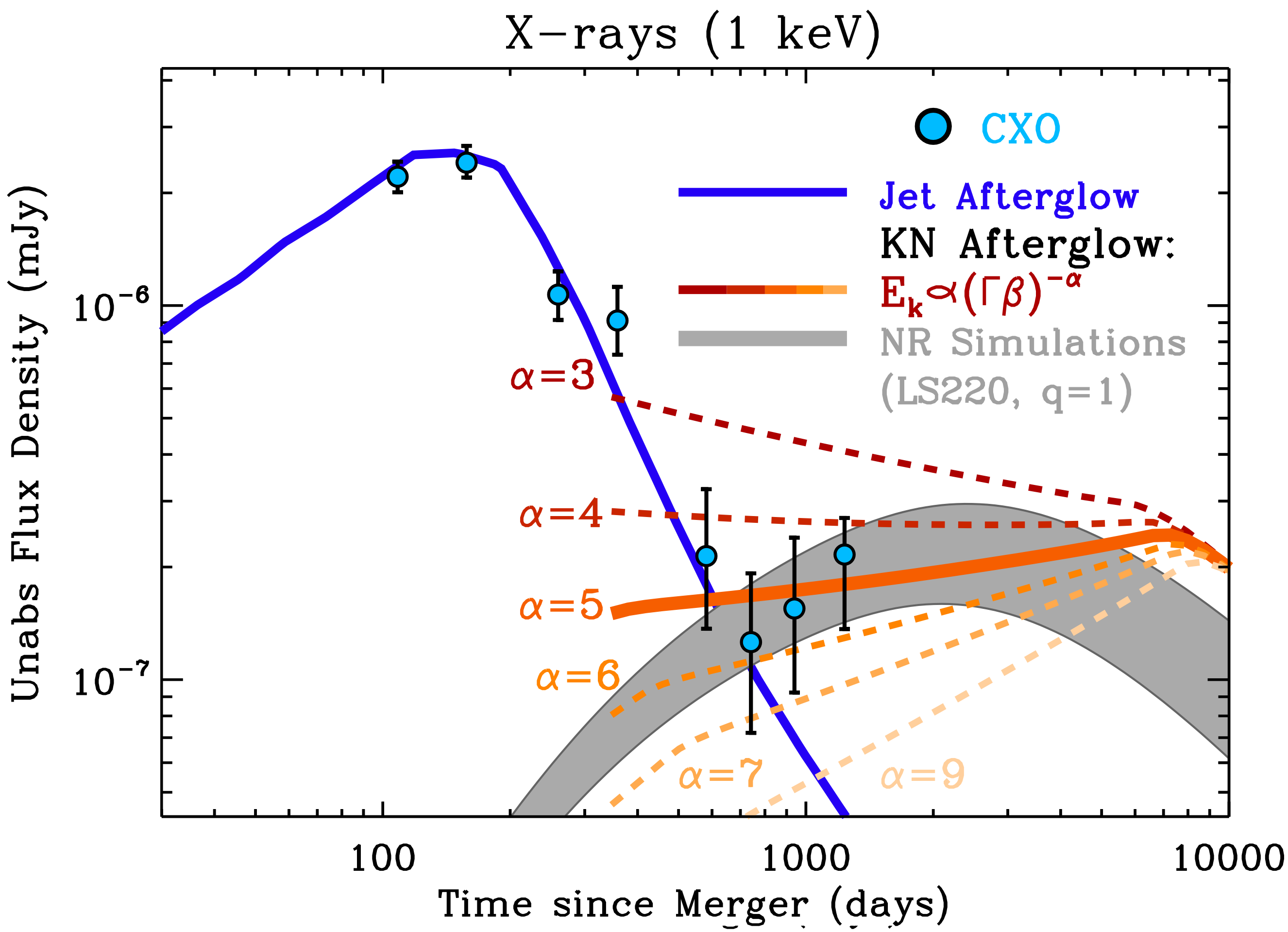
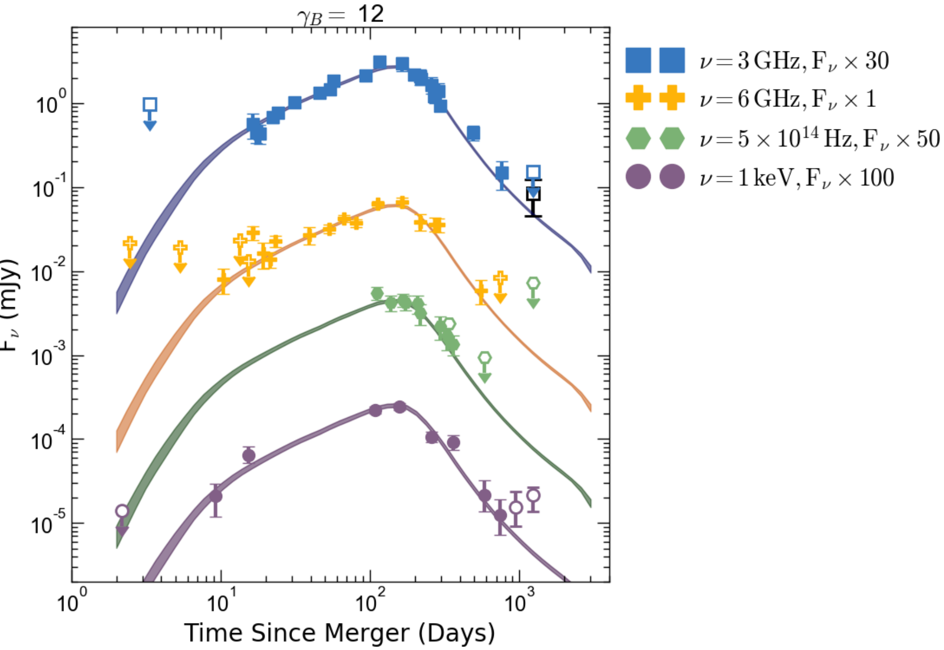


Figure 2 | X-ray and radio light-curves of GW170817 X-ray (*upper panel*) evolution of the emission from GW170817 as detected by the *CXO* At $\delta t > 900$ days the X-ray emission shows an excess compared to the off-axis jet afterglow model (solid blue line, §4 and §6) that indicates the emergence of a new emission component.

4. X-ray excess



Extended Data Figure 2 | Broadband afterglow modeled by `JetFit` with $\gamma_B = 12$: *Top Panel:* Non-thermal emission from GW170817 across the electromagnetic spectrum and best fitting jet-afterglow model computed with `JetFit` for $n = 0.01\,cm^{-3}$, $\epsilon_e = 0.1$, and $\gamma_B = 12$. Empty symbols have not been included in the fitting procedure. Colored bands identify the 68% flux confidence interval. Black empty square symbol is the peak pixel value within one synthesized beam at the location of GW170817 at 3 GHz from Balasubramanian et al.[26]. *Bottom Panel:* One- and two-dimensional projections of the posterior distributions of the model's free parameters. Vertical dashed lines mark the 16^{th}, 50^{th}, and 84^{th} percentiles of the marginalized distributions (i.e. the median and 1-σ range). The contours are drawn at 68%, 95%, and 99% credible levels.

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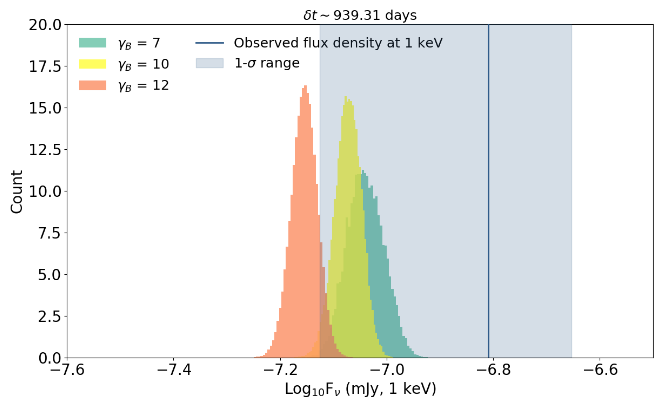
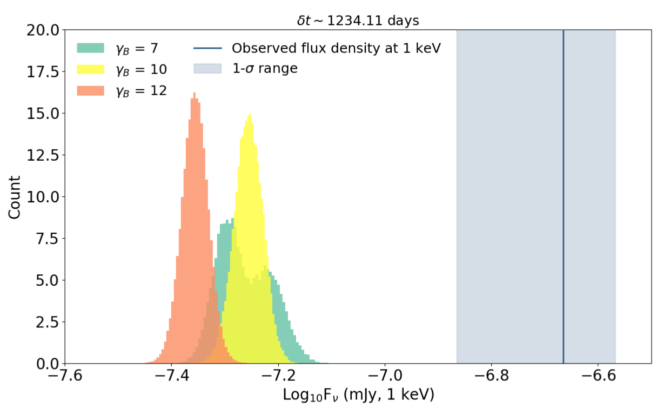
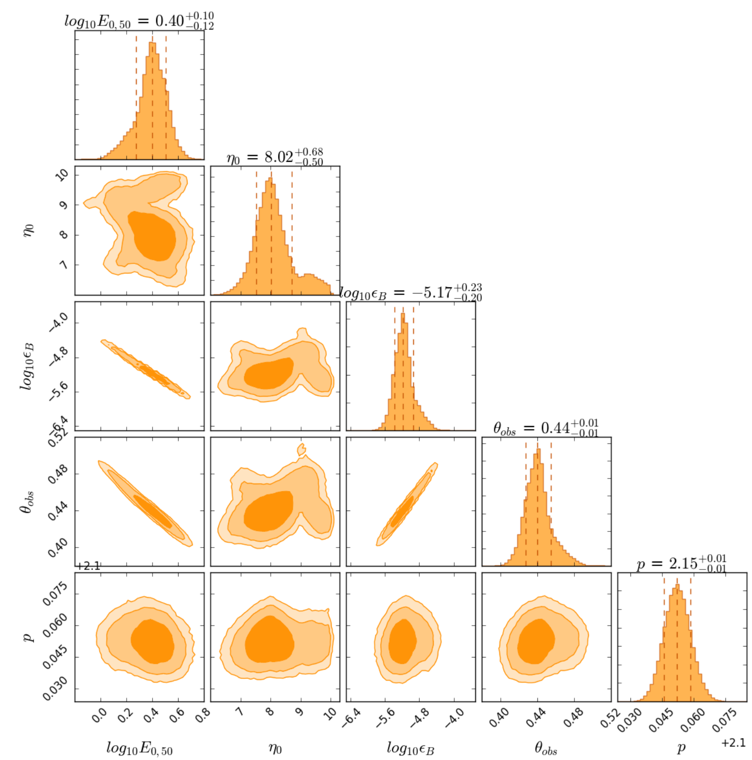




Extended Data Figure 3 | `JetFit` model flux distributions: *Top Panel:* Expected 1-keV flux density distributions at 939.31 days (histograms in color) derived from the fitting of the multi-wavelength afterglow of GW170817 in the time range $2 < \delta t < 900$ days using the code `JetFit`(using different values of γ_B). Vertical blue thick line and shaded area: observed X-ray flux density at this epoch and $\pm 1\sigma$ confidence range. *Bottom Panel:* Same as the top panel for 1234.11 days since merger.



4. X-ray excess

Accurate flux calibration of GW170817: is the X-ray counterpart on the rise?

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
X-ray emission from the gravitational wave transient GW170817 is well described as non-thermal afterglow radiation produced by a structured relativistic jet viewed off-axis. We show that the X-ray counterpart continues to be detected at 3.3 years after the merger. Such long-lasting signal is not a prediction of the earlier jet models characterized by a narrow jet core and a viewing angle ≈20 deg, and is spurring a renewed interest in the origin of the X-ray emission. We present a comprehensive analysis of the X-ray dataset aimed at clarifying existing discrepancies in the literature, and in particular the presence of an X-ray rebrightening at late times. Our analysis does not find evidence for an increase in the X-ray flux, but confirms a growing tension between the observations and the jet model. Further observations at radio and X-ray wavelengths would be critical to break the degeneracy between models.

Key words: stars: neutron – gravitational waves – gamma-ray burst

arXiv:2104.13378

4. X-ray excess

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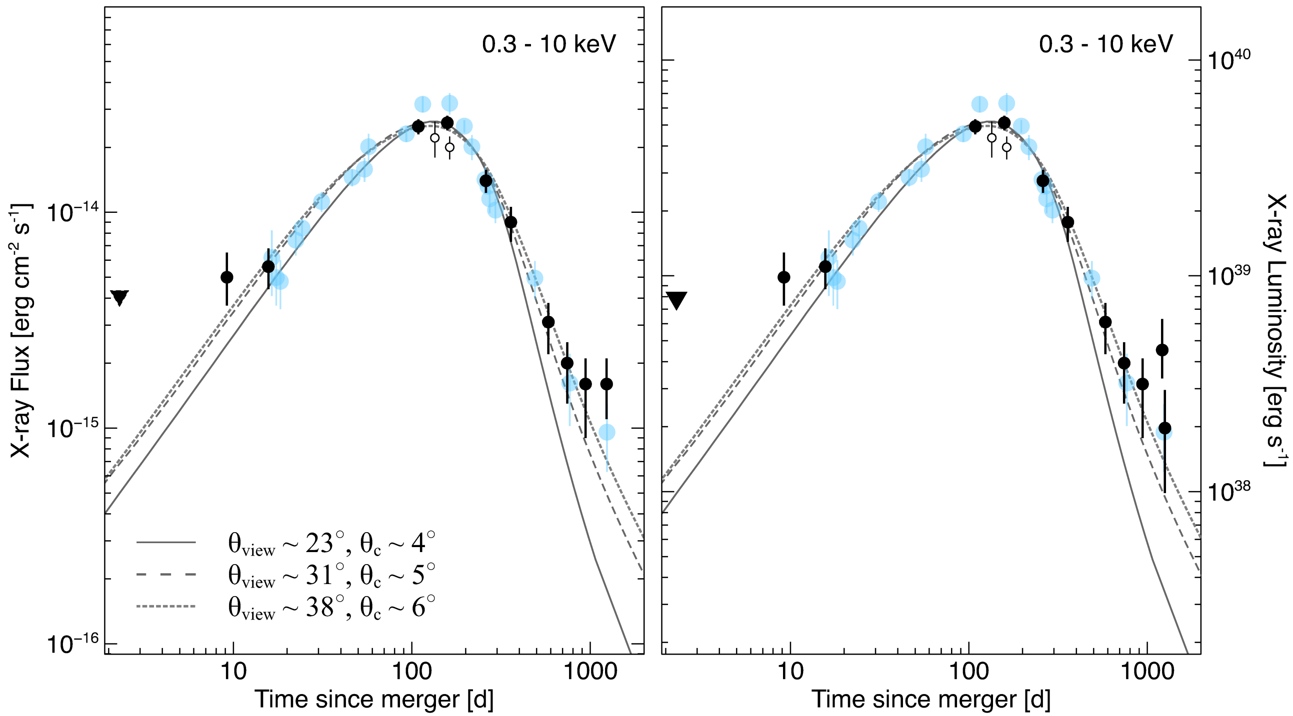

Figure 5. X-ray (black circles: *Chandra*; open circles: XMM-Newton) light curves compared with the jet model of Ryan et al. (2020) (solid line), Troja et al. (2020) (dashed line), and this work (dotted line). Radio data (blue; Makhathini et al. 2020; Balasubramanian et al. 2021) at 3 GHz were rescaled using a spectral slope of 0.585. At late times a deviation from the jet model is visible. By rebinning the last two *Chandra* observations (left panel), the X-ray emission seems to flatten. This effect is mostly driven by the detection of soft (<2 keV) X-ray emission at 1211 d, visible in the unbinned light curve (right panel).

5. Upper limits in radio + recent detection ?

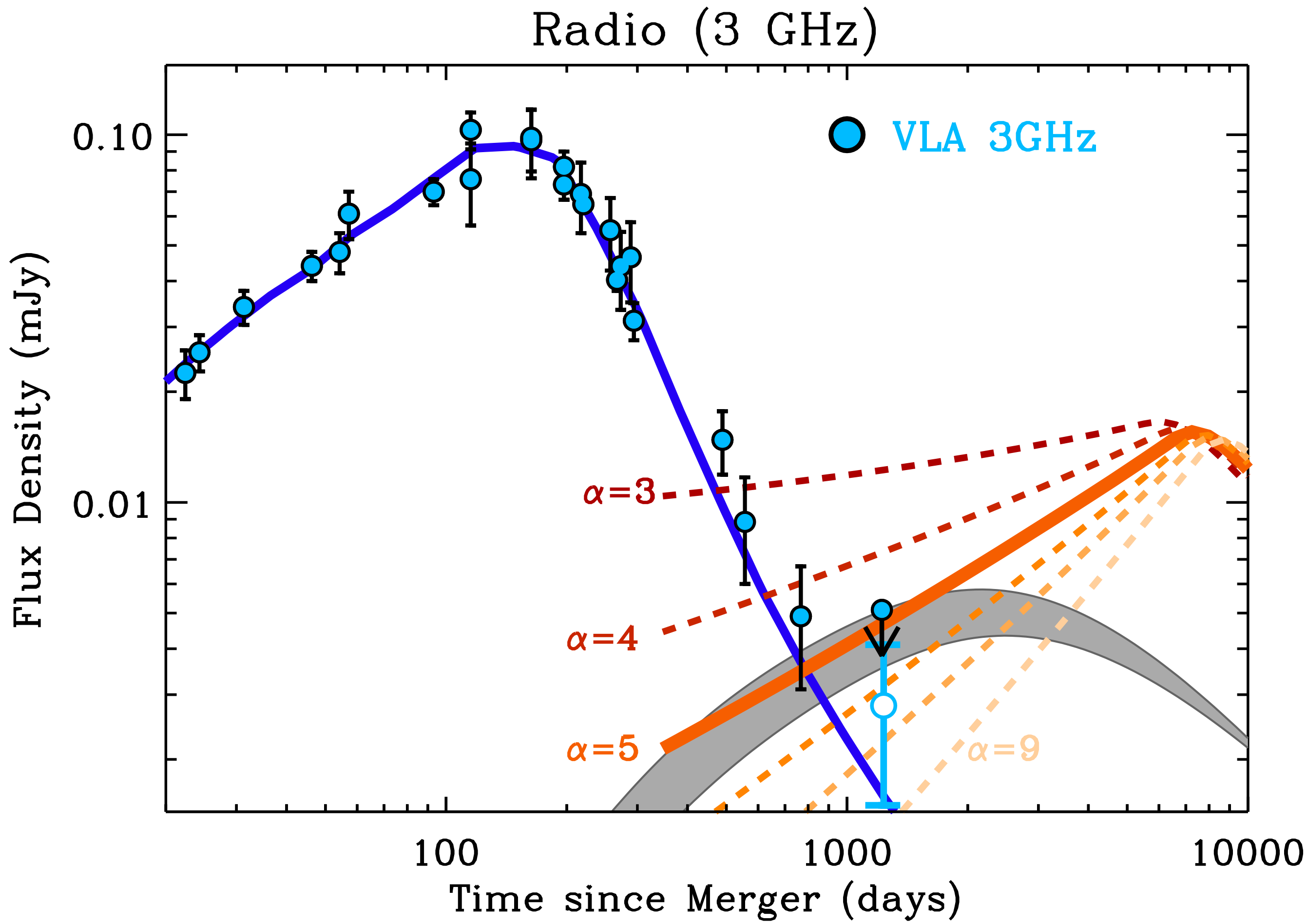

Figure 2 | X-ray and radio light-curves of GW170817 radio (3 GHz, *lower panel*) evolution of the emission from GW170817 as detected by the VLA (light-blue circles). Open circle: peak pixel flux value within one synthesized beam at the location of GW170817 from Balasubramanian et al.[26]

5. Upper limits in radio + recent detection ?

CONTINUED RADIO OBSERVATIONS OF GW170817 3.5 YEARS POST-MERGER

Arvind Balasubramanian[1], Alessandra Corsi[1], Kunal P. Mooley[2], Murray Brightman[2], Gregg Hallinan[2], Kenta Hotokezaka[3], David L. Kaplan[4], Davide Lazzati[5], and Eric J. Murphy[6]

Draft version March 18, 2021

ABSTRACT

We present new radio observations of the binary neutron star merger GW170817 carried out with the Karl G. Jansky Very large Array (VLA) more than 3 yrs after the merger. Our combined dataset is derived by co-adding more than ≈ 32 hours of VLA time on-source, and as such provides the deepest combined observation (RMS sensitivity $\approx 0.99\,\mu$Jy) of the GW170817 field obtained to date at 3 GHz. We find no evidence for a late-time radio re-brightening at a mean epoch of $t \approx 1200$ d since merger, in contrast to a 2-3 σ excess observed at X-ray wavelengths at the same mean epoch. Our measurements agree with expectations from the post-peak decay of the radio afterglow of the GW170817 structured jet. Using these results, we constrain the parameter space of models that predict a late-time radio re-brightening possibly arising from the high-velocity tail of the GW170817 kilonova ejecta, which would dominate the radio and X-ray emission years after the merger (once the structured jet afterglow fades below detection level). Our results point to a steep energy-speed distribution of the kilonova ejecta (with energy-velocity power law index $\alpha \gtrsim 5$). We suggest possible implications of our radio analysis, when combined with the recent tentative evidence for a late-time re-brightening in the X-rays, and highlight the need for continued radio-to-X-ray monitoring to test different scenarios.

Subject headings: GW170817, Kilonova afterglow: general — radio continuum: general

arXiv:2103.04821

5. Upper limits in radio + recent detection ?

CONTINUED RADIO OBSERVATIONS OF GW170817 3.5 YEARS POST-MERGER

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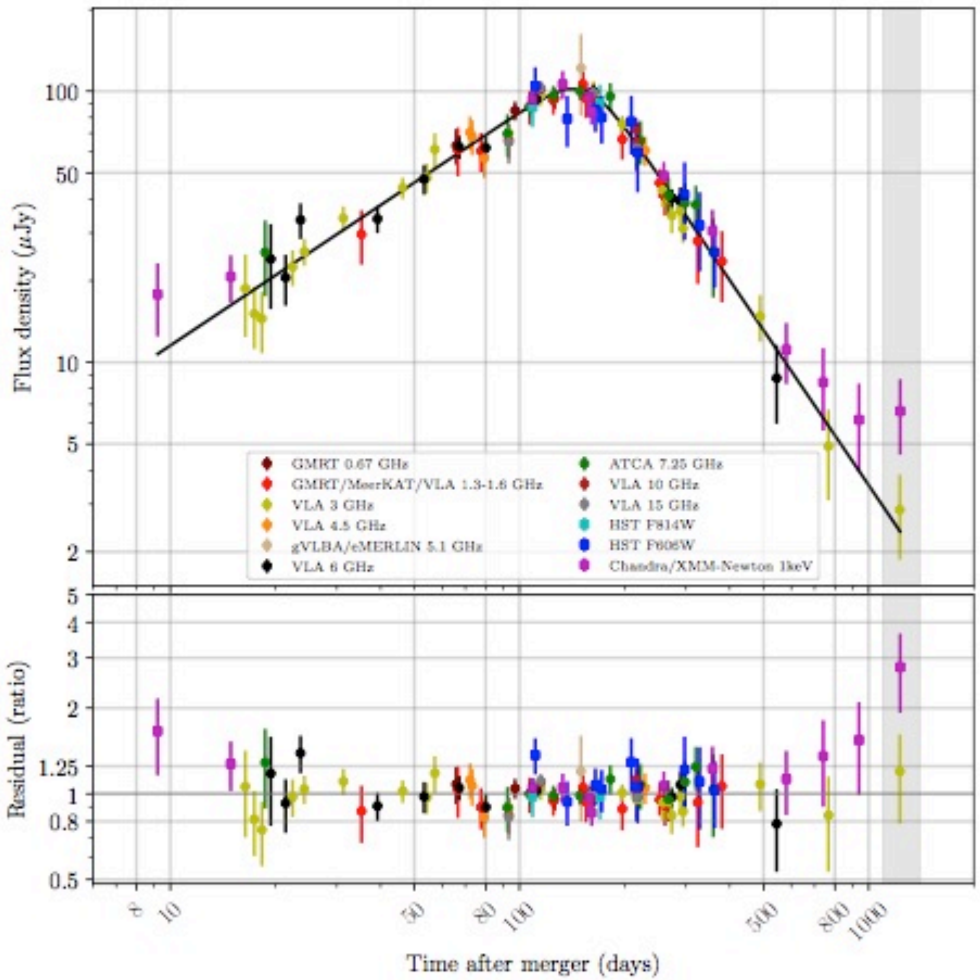
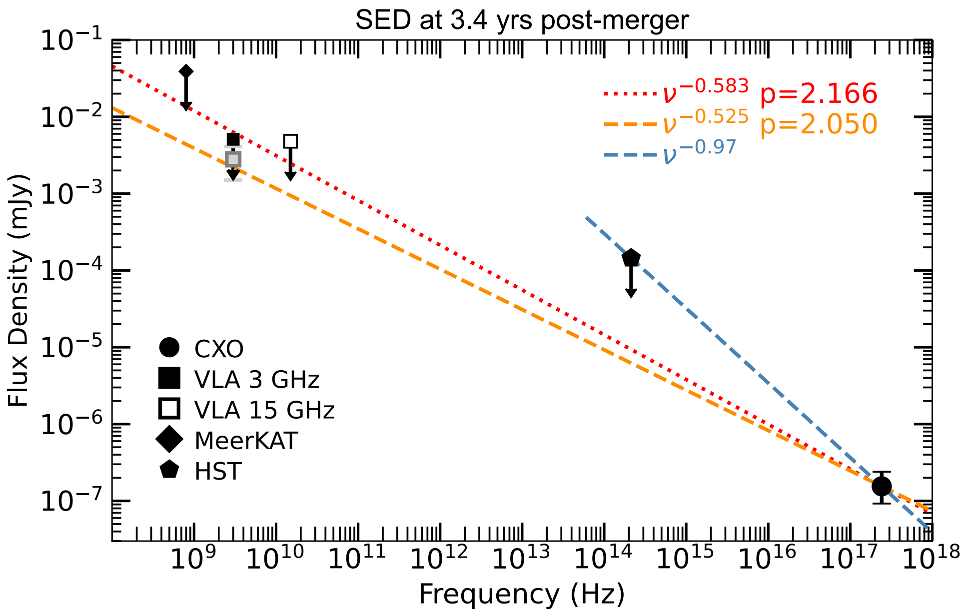


FIG. 1.— Comprehensive 3 GHz light curve of GW170817 as presented in our recent work Makhathini et al. (2020), which includes data from Fong et al. (2019); Ghirlanda et al. (2019); Nynka et al. (2018), together with our latest measurement in the radio (3 GHz, latest yellow data point in the grey, shaded region) and X-rays (latest purple data point in the grey, shaded region) extrapolated to 3 GHz using the spectral index derived in Makhathini et al. (2020). The best fit structured jet model for GW170817 is also plotted (top panel, black line). As evident from the lower panel, our radio measurement is compatible with the tail of the GW170817 jet within the large errors. On the other hand, the X-rays seem to show a more significant discrepancy and suggest that a kilonova flare may be taking over the emission (Hajela et al. 2020a, 2021; Troja et al. 2020).

5. Spectral evolution



Extended Data Figure 4 | Broadband SED at 1234 days: Broad-band spectral energy distribution acquired around δt ≈3.4 years post-merger, including CXO X-ray data (filled circle), VLA upper limits at 3 and 15 GHz (filled and open square, respectively), MeerKAT flux limit (filled diamond) and HST/F140W flux limit (filled hexagon). Grey filled square: 3 GHz peak flux pixel value of 2.8 μJy (with RMS of 1.3 μJy) within one synthesized beam at the location of GW170817 from Balasubramanian et al.[26]. Red dotted line: $F_\nu \propto \nu^{-(p-1)/2}$ spectrum with $p = 2.166$ that best fitted the jet-afterglow data.[22] The VLA 3 GHz limit suggests a shallower spectrum (§5). Orange dashed line: $F_\nu \propto \nu^{-(p-1)/2}$ with $p = 2.05$. HST observations imply a NIR-to-X-ray spectral slope steeper than ≈ 1.

6. Discussion

(i) « same-shock » scenarios

In the supplementary material, the authors discuss (section 6):

- over-density:
requires too steep gradient of density (x3 10^8 at 1pc)

- late energy injection:
needs to inject same Ekinetic at late time, no source?

- time-varying microphysics parameters:
requires non physically motivated ad hoc variations of ε_B and ε_e

- transition to NR evolution:
expected to be achromatic

- emergence of counter-jet:
expected at later time with a flat LC

6. Discussion

(ii) New component

- The kilonova afterglow is the preferred model of the authors: discussed in the main text

- alternatives (accretion on to the new compact object) are discussed in the supplementary material (section 8)

There are also new papers on arXiv to explore this scenario:
- Fallback accretion model for the years-to-decades X-ray counterpart to GW170817
Ishizaki et al. 2021 ; arXiv:2104.04433
- Fallback accretion halted by r-process heating in neutron star mergers and GRBs
Ishizaki et al. 2021 ; arXiv:2104.04708

In this scenario we see the very beginning of the accretion on a new compact object (most probably a BH).

7. Kilonova afterglow model

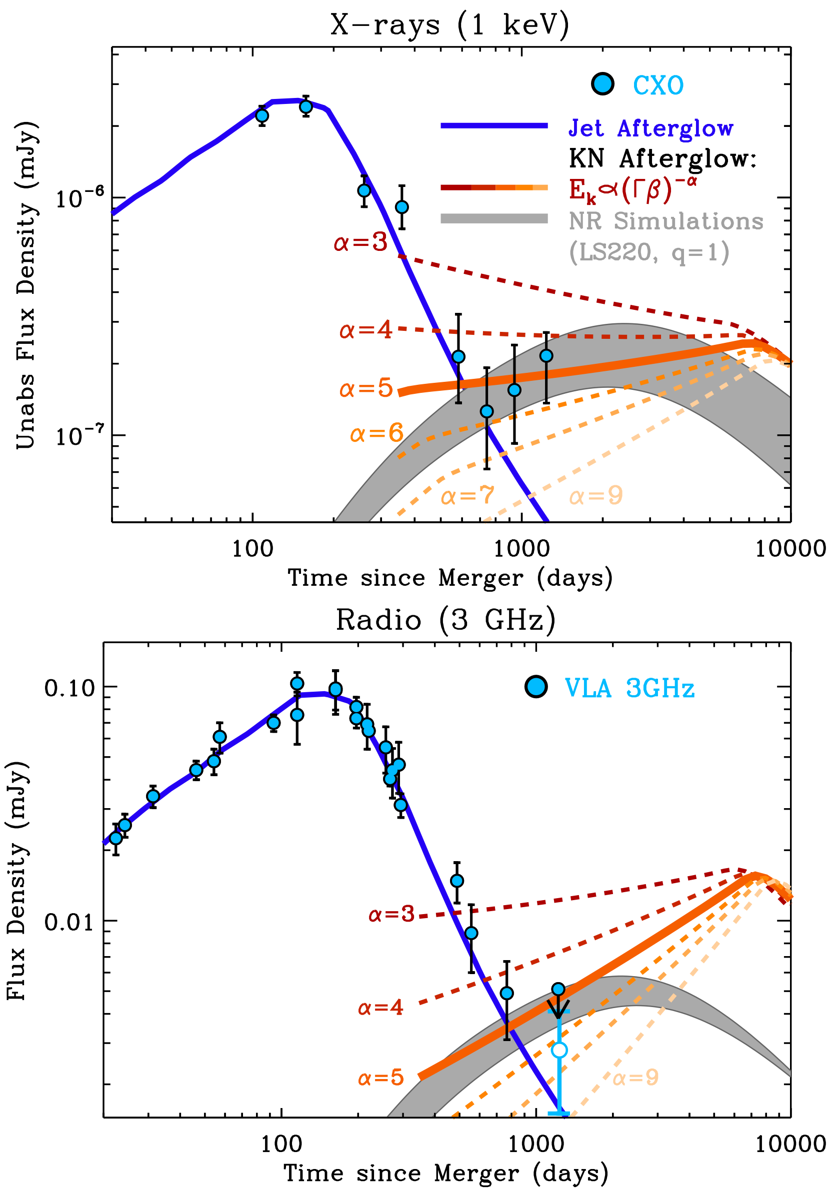


Figure 2 | X-ray and radio light-curves of GW170817 X-ray (*upper panel*) and radio (3 GHz, *lower panel*) evolution of the emission from GW170817 as detected by the *CXO* and the VLA (light-blue circles). Open circle: peak pixel flux value within one synthesized beam at the location of GW170817 from Balasubramanian et al.[26] At $\delta t > 900$ days the X-ray emission shows an excess compared to the off-axis jet afterglow model (solid blue line, §4 and §6) that indicates the emergence of a new emission component. Red-to-orange dashed lines: synchrotron radiation from the kilonova afterglow calculated using semi-analytical models[32] where we parametrized the kilonova kinetic energy distribution as $E_{\rm k} \propto (\Gamma\beta)^{-\alpha}$ for $\beta \geq 0.35$ and we used a total kilonova kinetic energy of 10^{51} erg. These models require $p < 2.15$ to avoid violating our radio upper limit. Here we use $p = 2.05$ and we emphasize with a solid thick line the $\alpha = 5$ model. Other kilonova afterglow parameters assumed: $\epsilon_B = 0.001$, $\epsilon_e = 0.1$, $n = 0.001\,{\rm cm}^{-3}$. Grey shaded area: synchrotron emission calculated from kilonova kinetic ejecta profiles derived from ab-initio numerical relativity simulations using a neutron-star mass-ratio $q = 1$ and the LS220 equation of state (§7). These simulations emphasize the contribution from the merger's dynamical ejecta. The shaded area corresponds to values $p_{KN} = 2.05 - 2.15$, $n = 6 \times 10^{-3}\,{\rm cm}^{-3}$, $\epsilon_e = 0.1$ and $\epsilon_B = 0.01$.

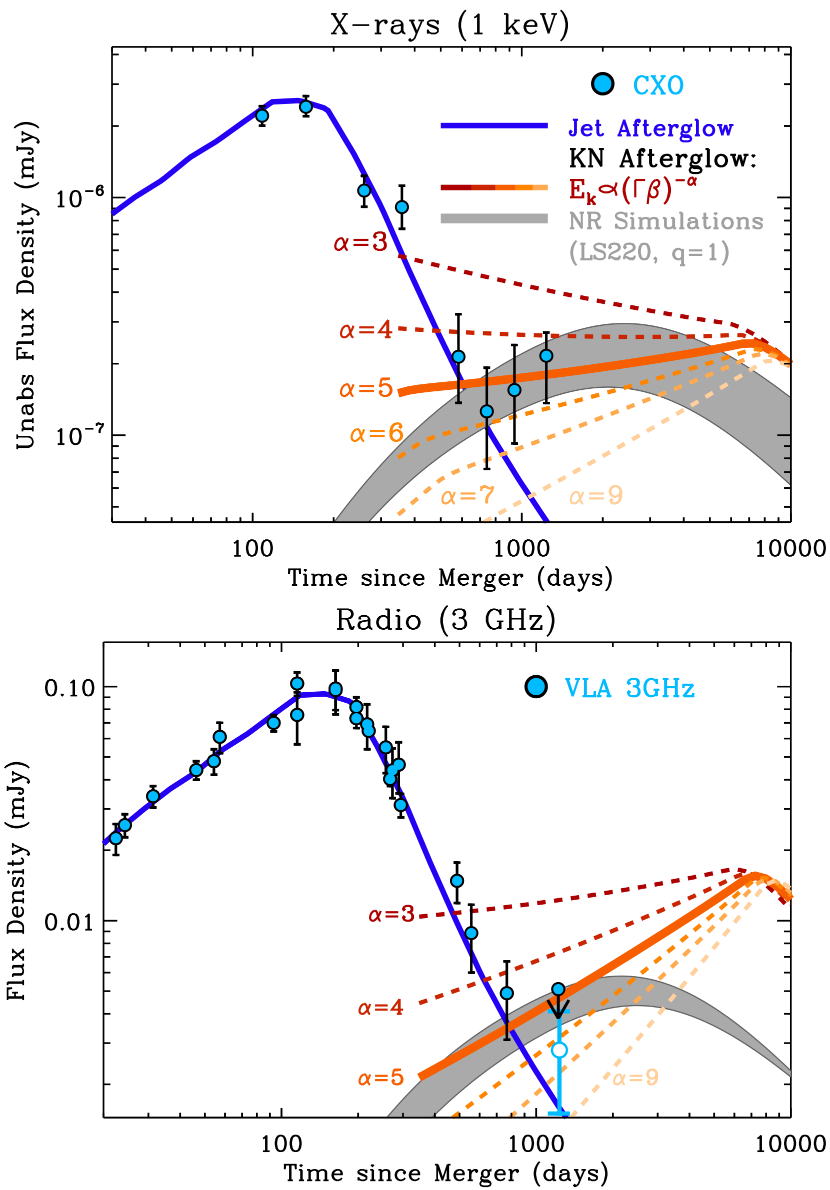
α = radial structure of the KN ejecta
(fast part: β > 0.35)

Favors steep α > 4-5 ?

Other parameters:

- total kinetic energy 10^{51} erg
  (~ 0.01 Msun at 0.3 c)
- p = 2.05 (constraint: p < 2.15 ; AG: 2.17)
- $\varepsilon_B = 0.001$; $\varepsilon_e = 0.1$
- n = 0.001 cm^{-3}

8. More realistic Kilonova afterglow model



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Gray shaded area = models of Nedora et al.

- $p = 2.05$-2.15
- $\varepsilon_B = 0.01$; $\varepsilon_e = 0.1$
- $n = 0.006\ \mathrm{cm}^{-3}$

Note the difference in peak time !
Simple model ~ 6000 days ~ 16 years
Realistic model ~ 2000 days ~ 5.5 years

8. More realistic Kilonova afterglow model

Dynamical ejecta synchrotron emission as a possible contributor to the rebrightening of GRB170817A

Vsevolod Nedora[1], David Radice[2,3,4], Sebastiano Bernuzzi[1], Albino Perego[5,6],
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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
Over the past three years, the fading non-thermal emission from the GW170817 remained generally consistent with the synchrotron afterglow from the forward shock of a relativistic structured jet. Recent observations by Hajela et al. (2021) indicate the emergence of a new component in the X-ray band. We show that the new observations are compatible with a rebrightening due to non-thermal emission from the fast tail of the dynamical ejecta of ab-initio binary neutron star (BNS) merger simulations. This provides a new avenue to constrain binary parameters. Specifically, we find that equal mass models with soft equation of state (EOS) and high mass ratio models with stiff EOS are disfavored as they typically predict afterglows that peak too early to explain observations. Moderate stiffness and mass ratio models, instead, tend to be in good overall agreement with the data.

Key words: neutron star mergers – stars: neutron – equation of state – gravitational waves

arXiv:2104.04537

Initial state (kilonova ejecta) taken from num-GR simulations (various EOS, mass ratio)
Afterglow : standard model with each shell evolving adibatically (not full SR hydro)

8. More realistic Kilonova afterglow model

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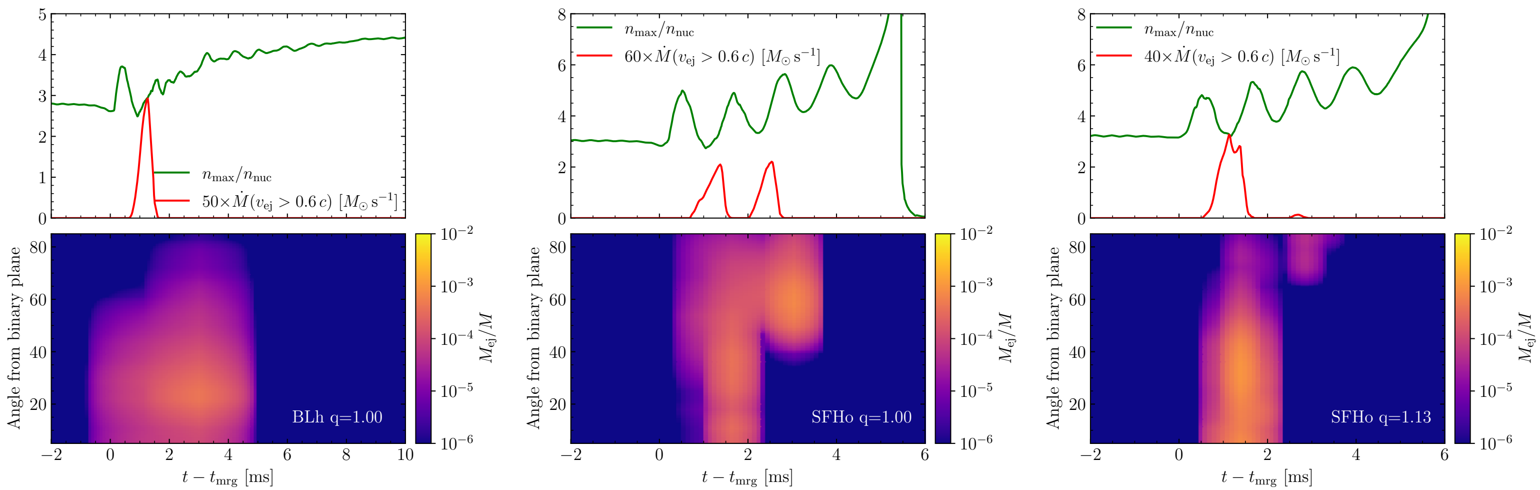

Figure 1. Ejection mechanism and properties of the fast tail of the ejecta shown for three simulations, with two EOSs: BLh and SFHo and two mass ratios: $q = 1.00$ and $q = 1.22$. The upper panel in each plot shows the time evolution of the maximum density in the simulation (green curves) and the mass flux of the ejecta with asymptotic velocities exceeding $0.6c$ (red curve). The bottom panel shows the mass histogram of the fast ejecta tail as a function of time. In both panels the outflow rate and histograms are computed at a radius of $R = 443$ km and shifted in time by $R\langle v_{\rm fast}\rangle^{-1}$, $\langle v_{\rm fast}\rangle$ being the mass averaged velocity of the fast tail at the radius R. The plot shows that most of the fast ejecta are generally produced at first core bounce with a contribution from the second in models with soft EOSs.

8. More realistic Kilonova afterglow model

Dynamical ejecta sy **ribution to the**
rebrightening of GR

Vsevolod Nedora[1], David Ra
Boris Daszuta[1], Andrea End

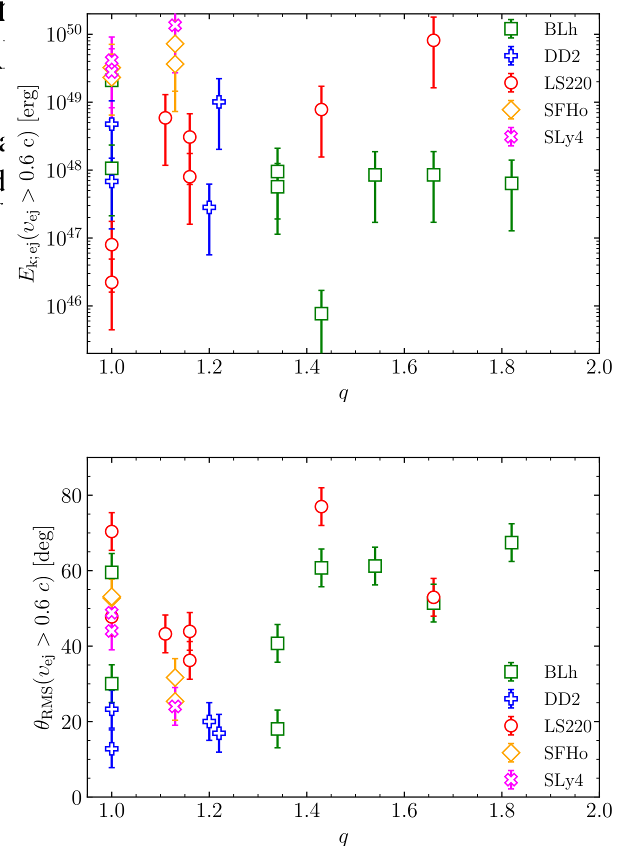

Figure 2. Properties of the fast tail of the dynamical ejecta: total kinetic energy (*top panel*) and half-RMS angle around the binary plane (*bottom panel*) from a selected set of simulations where this tail is present (see text). We assume conservative uncertainties for the angle, 0.5 deg, and half of the value for the kinetic energy. The top panel shows that only for some EOSs the total kinetic energy appear to depend on mass ration. Specifically, LS220m SFho and SLy4 EOSs. The half-RMS angle appears to depend more on EOS, and to be overall larger for high-q models.

8. More realistic Kilonova afterglow model

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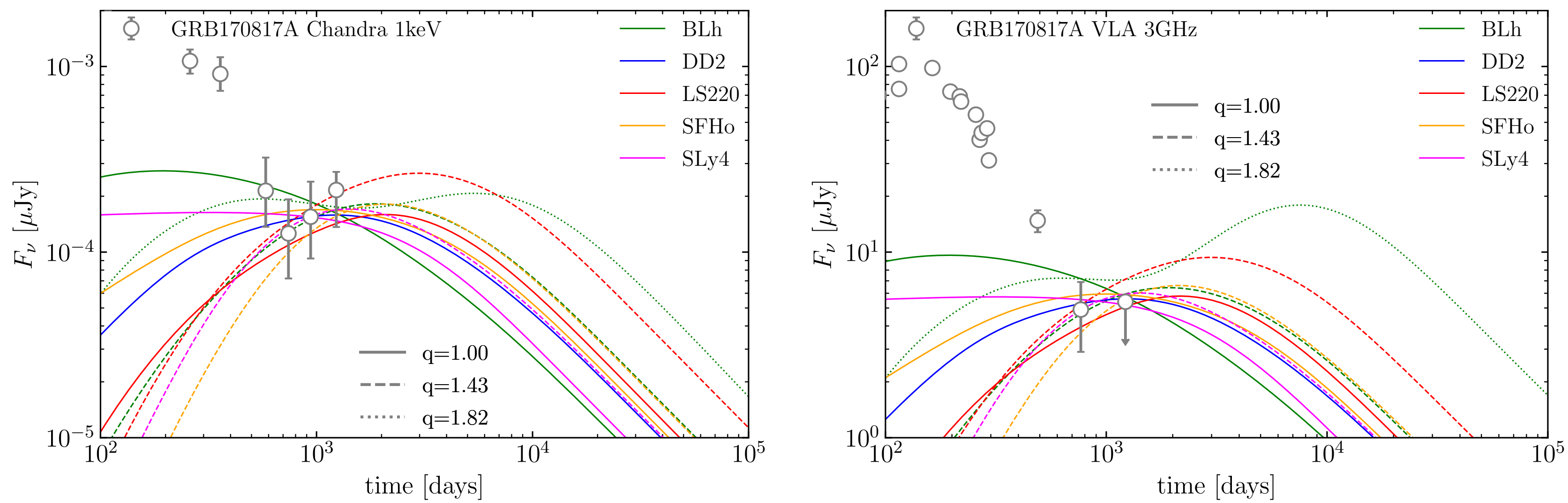

Figure 4. Representative kilonova afterglow LCs for NR models, in X-ray (*left panel*) and in radio (*right panel*), where the gray circles are the observational data (Hajela et al. 2021). The synthetic LCs are computed with varying micrphysical parameters and ISM density within the range of credibility to achieve a better fit to observational data (see Tab. 3 for details). The plots show that, within allowed parameter ranges, the LCs from all models are in agreement with observations. Models with moderately stiff EOS and $q < 1 < 1.8$ are tentatively preferred, as their flux is rising at $t \geq 10^3$ days, in agreement with observations.

9. Some consequences: neutron free fast ejecta / shock breakout and SGRB

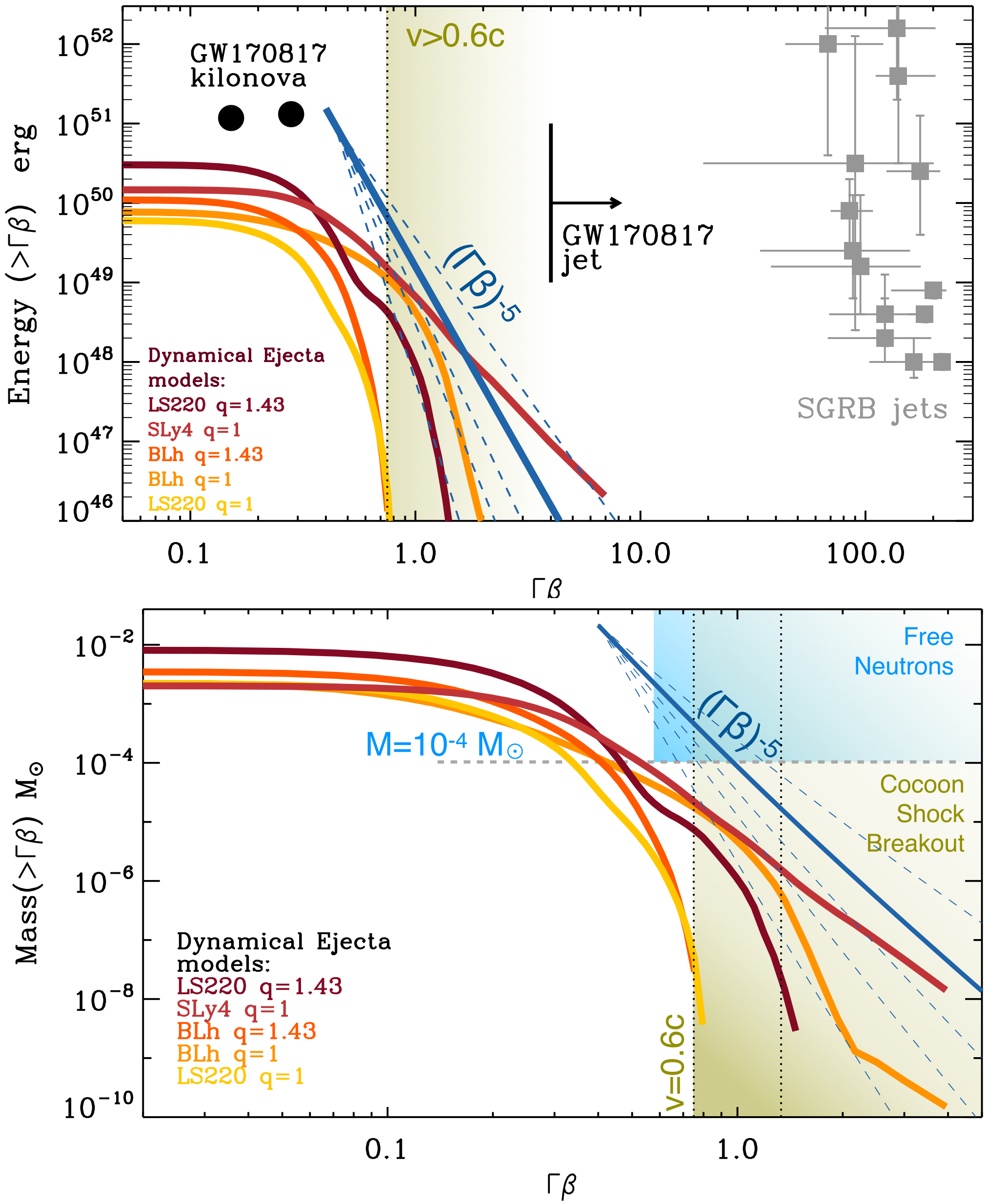

Figure 3 | **Kilonova kinetic energy and mass profiles** *Upper Panel:* Colored lines: kinetic energy profile of the fastest kilonova ejecta as a function of specific momentum $\Gamma\beta$. Dark-red to orange shade: dynamical ejecta profiles as inferred from ab-initio numerical-relativity simulations described in §7 for different EoS and NS mass ratios q. Blue lines: $E_{\rm KN}(>\Gamma\beta) \propto (\Gamma\beta)^{-\alpha}$ analytical profiles that include the contributions from all types of kilonova ejecta for $\alpha = 4, 5, 6, 7, 9$. Black filled circles: kinetic energy inferred from the modeling of the UV/optical/NIR kilonova emission.[11] Grey squares: SGRB jets.[55] *Lower Panel:* kilonova ejecta profiles in the mass phase-space. Colored area: region of the parameter space consistent with a cocoon shock breakout origin of GRB 170817A.[43]

Note: shock breakout and SGRB, condition on ejection time?