eas Leiden 2020 Virtual

European Astronomical Society Annual Meeting

EWASS

SS16

Registering the Universe at the highest spatial accuracy

(Re)solving the riddle about the size of GRB170817A through global VLBI observations

by

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Intro: gravitational waves (GW)

[“Gravitational Waves”, artwork by Penelope Cowley]

Perturbations of space-time metric (a.k.a. gravity) $\rightarrow$ cause dilation/contraction (“strain”) perpendicular to propagation

Produced by mass-energy distributions whose quadrupole moment accelerates

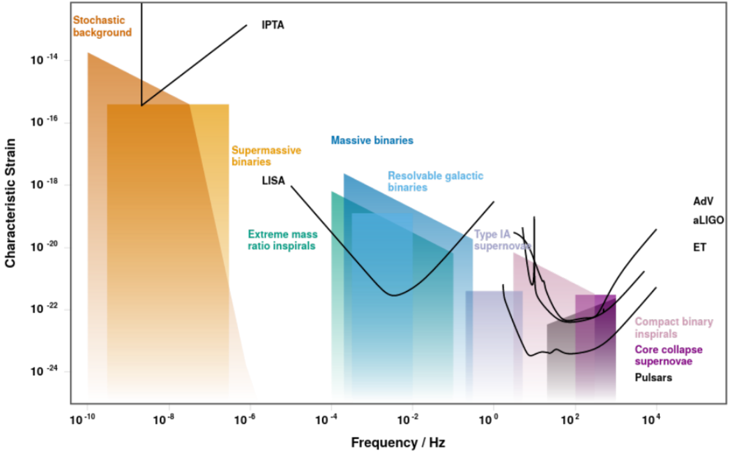
Quadrupole moment:

$$Q_{jk} = \int \rho x^j x^k dx$$

Strain: $h_{jk} = \frac{2}{r}\frac{d^2 Q_{jk}}{dt^2}$

Propagate at c (experimentally!)

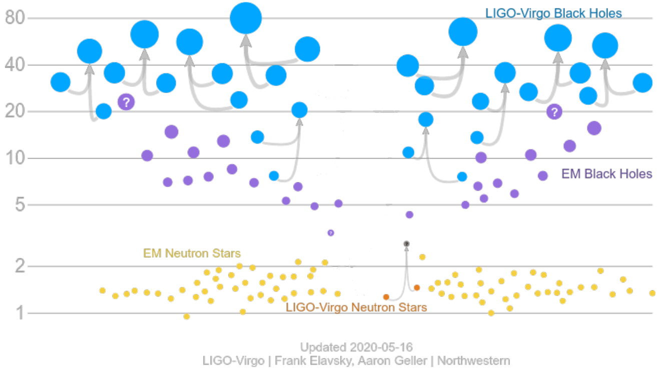
GW sources & detectors



[Moore et al. 2015]

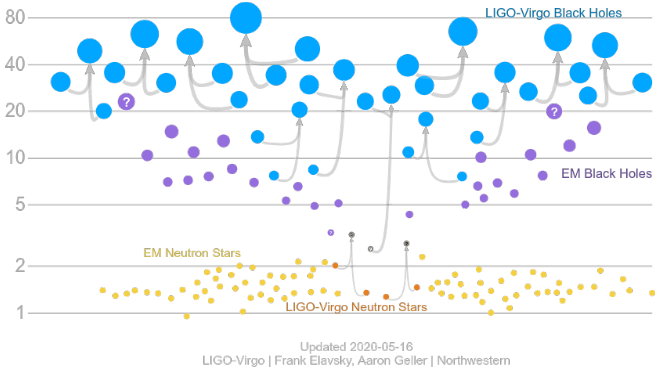
- Continuous (e.g. rotating, asymmetric star)
- Transient
  - Compact binary mergers
  - Supernovae
  - Other unknown "bursts"
- Stochastic background

LIGO-Virgo GW detections to date



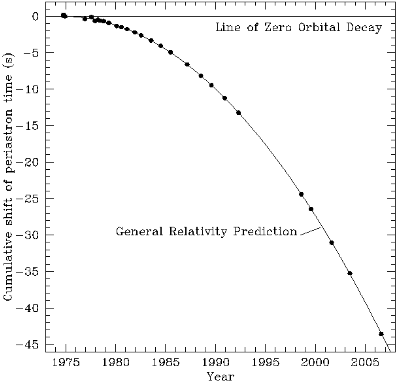
- O1 & O2 (2015 – 2017)
  - 10 BBH
  - 1 BNS (multi-messenger)

LIGO-Virgo GW detections to date



- O1 & O2 (2015 – 2017)
  - 10 BBH
  - 1 BNS (multi-messenger)
- O3 (2019 – 2020)
  - 3 published events (all with far-reaching implications)
  - 56 public alerts issued
  - interrupted due to Covid-19

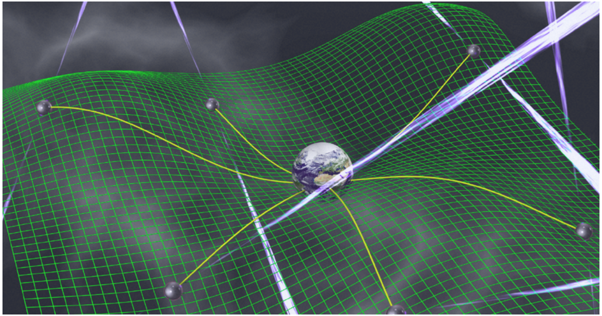
The GW – Radio connection: an old liaison



[Weisberg et al. 1981]

- first observational support of GW: Hulse-Taylor pulsar (Taylor et al. 1975, 1979)

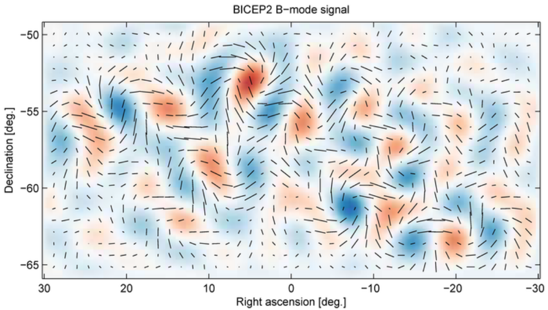
The GW – Radio connection: an old liaison



[Artwork: David J. Champion]

- first observational support of GW: Hulse-Taylor pulsar (Taylor et al. 1975, 1979)
- pulsar timing arrays (Detweller 1979)

The GW – Radio connection: an old liaison

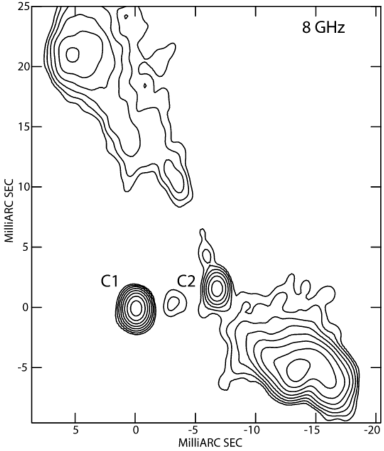


[BICEP2 Collaboration 2014]

- first observational support of GW: Hulse-Taylor pulsar (Taylor et al. 1975, 1979)
- pulsar timing arrays (Detweller 1979)
- CMB polarization → imprint of primordial GW

The GW – Radio connection: supermassive BH binaries

0402-379

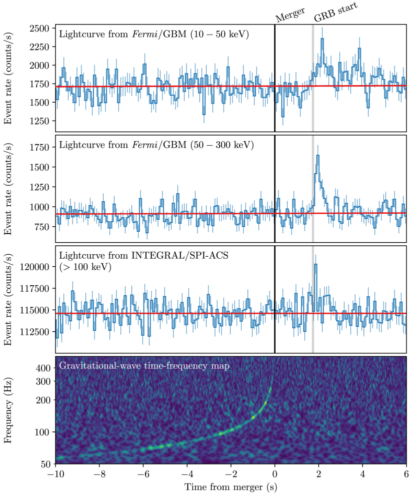


[Rodriguez et al. 2006]

VLBI observations
best view on supermassive BH binary candidates & dual AGNs

→ ultimate answer from LISA & SKA pulsar timing

GW170817 + GRB 170817A discovery



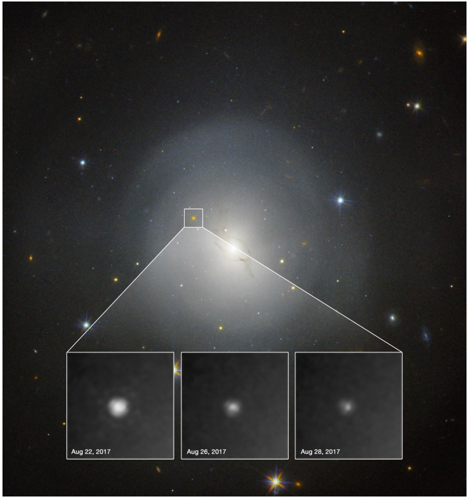
[Abbott et al. 2017]

First ever GW+EM multimessenger event

Close temporal + spatial association

Weak short GRB

Kilonova & host galaxy



[HST image - NASA/ESA/A.J.Levan/N.R.Tanvir/A.Fruchter/O. Fox]

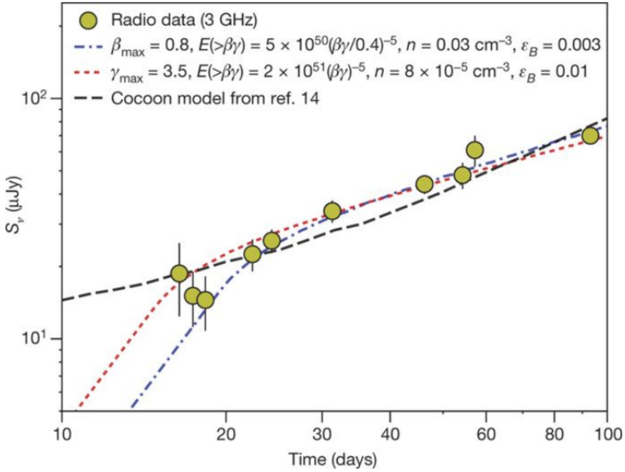
First-ever kilonova identified $\lesssim$ 12 h post-merger (Coulter et al. 2017)

Precise position $\rightarrow$ host galaxy $\rightarrow$ redshift

$\rightarrow$ multi-wavelength monitoring

Radio afterglow

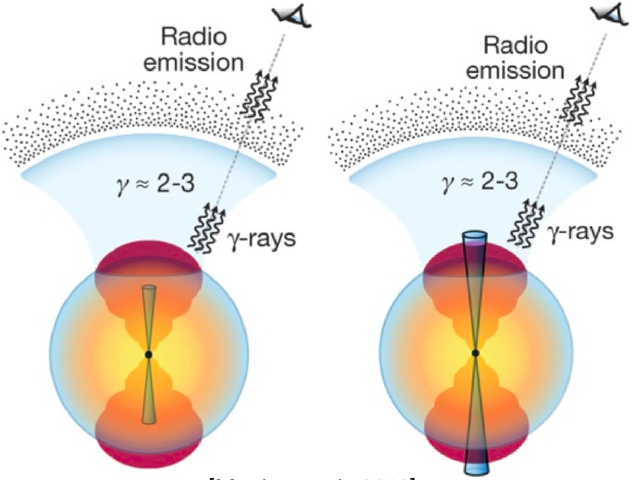
Figure 4: Quasi-spherical ejecta models.



Slowly brightening radio counterpart identified ~ 16 days post-merger in 3 GHz VLA obs (seen also in X-rays and later in Optical)

The successful jet/choked jet dichotomy

choked jet

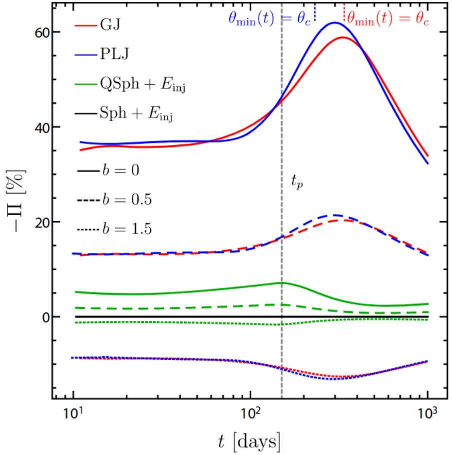


successful jet

[Mooley et al. 2018]

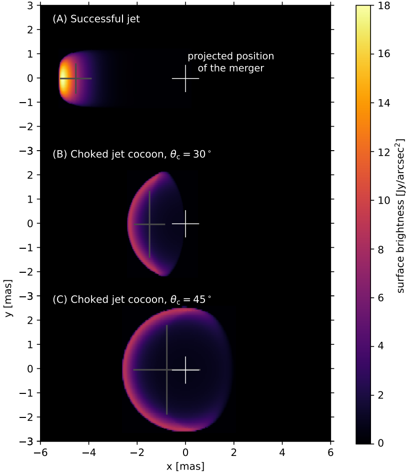
Breaking the degeneracy

Polarization



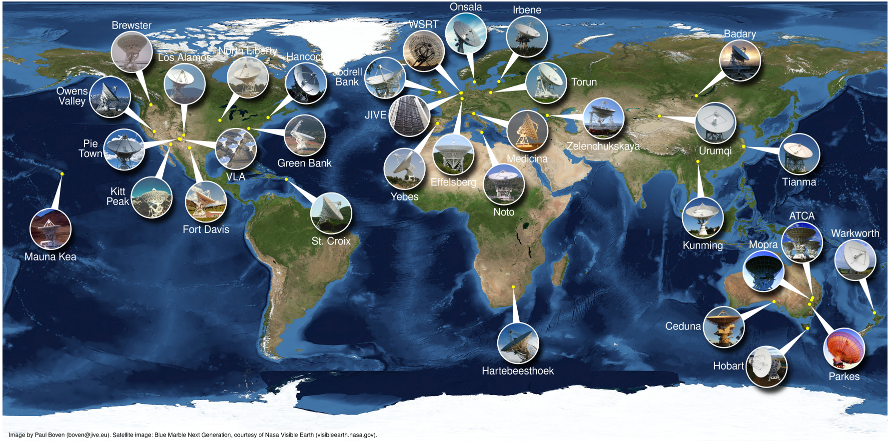
[Gill & Granot 2018]

Size & Motion



[Ghirlanda, **Salafia** et al. 2019]

Our global VLBI array (P.I. G. Ghirlanda)



[Paul Boven (JIVE) / NASA Visible Earth]

JIVE Support

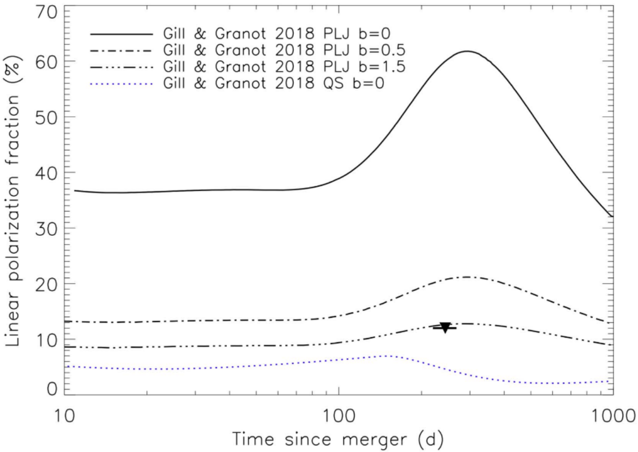
[G. Ghirlanda, M. Leeuwinga & myself at JIVE]

Support in

- data access
- data reduction
- data analysis

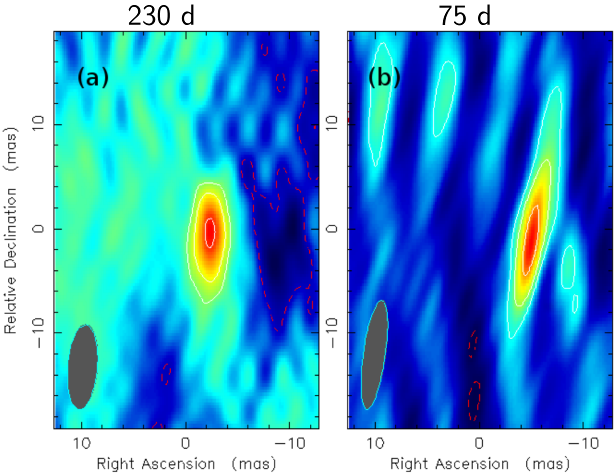
plus: accommodation at the Astron guest house

Meanwhile: polarization inconclusive



[Corsi et al. 2018]

Meanwhile: apparent superluminal motion



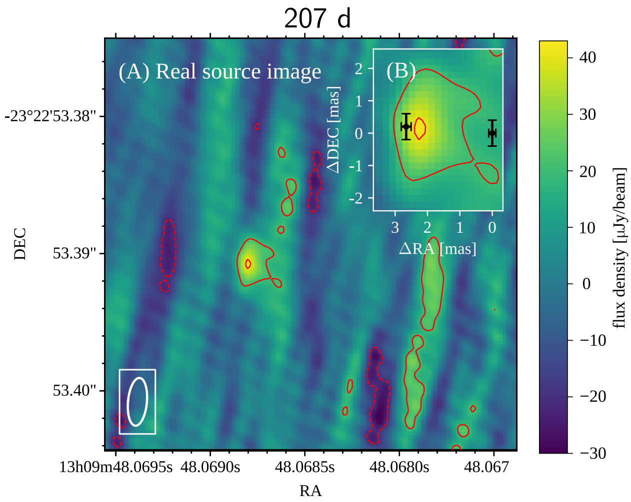
[Mooley et al. 2018b]

$\Delta\theta \sim 2.7\,\mathrm{mas}$
$\Delta t_{\mathrm{obs}} \sim 155\,\mathrm{d}$
$d_{\mathrm{L}} \sim 40\,\mathrm{Mpc}$

$\rightarrow \beta_{\mathrm{app}} \sim 4$

(yes, we've been scooped!)

Our result: unresolved source



Observed size

$\theta_{\rm obs} < 2.5\,{\rm mas}$

Predicted size

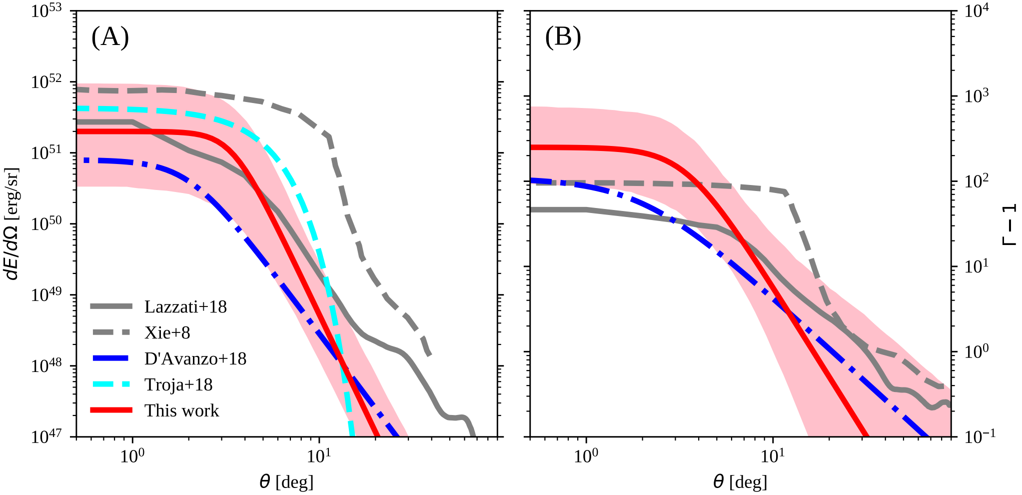
$\theta_{\rm choked} \gtrsim 3\,{\rm mas}$

$\theta_{\rm success} \lesssim 2\,{\rm mas}$

$\rightarrow$ Jet!

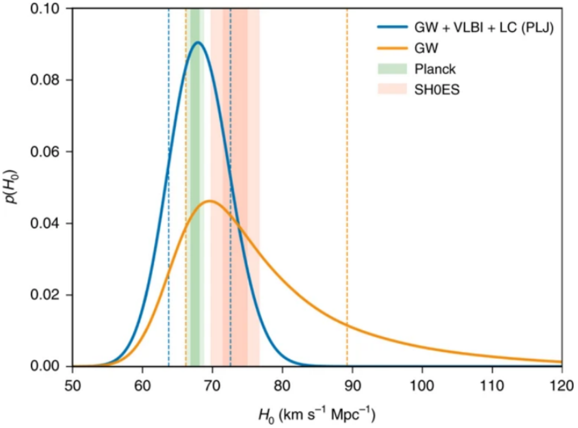
[Ghirlanda, **Salafia** et al. 2019, Science]

Lightcurve+VLBI: information on jet structure & viewing angle



→ constraint on Hubble constant

Fig. 2: Posterior distributions for H_0.



[Hotokezaka et al. 2019]

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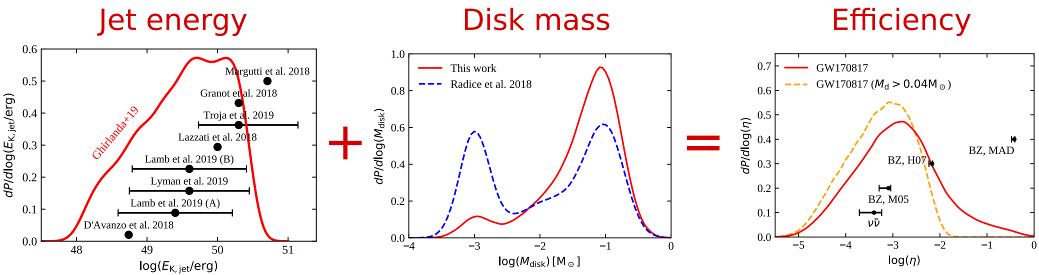
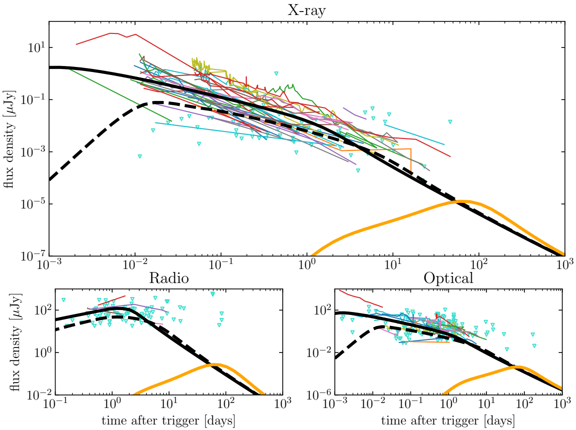
Jet energy + Disk mass = Efficiency

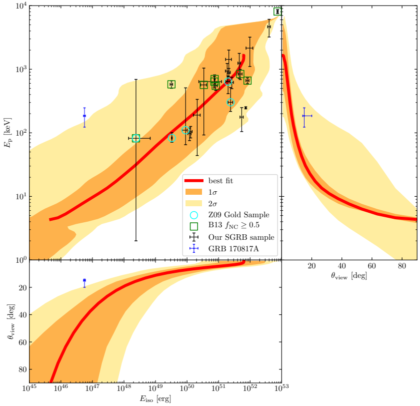


[**Salafia** & Giacomazzo 2020, arXiv:2006.07376]

Afterglow



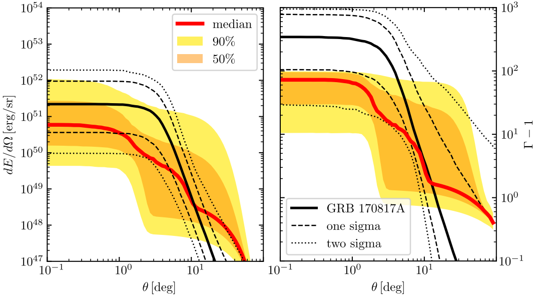
Prompt emission



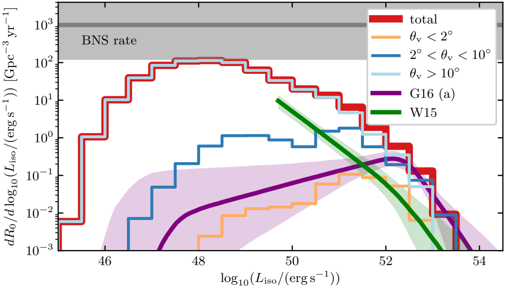
[**Salafia** et al. 2019, A&A 628, A18]

→ universal SGRB jet structure? (2)

Quasi-universal jet structure model

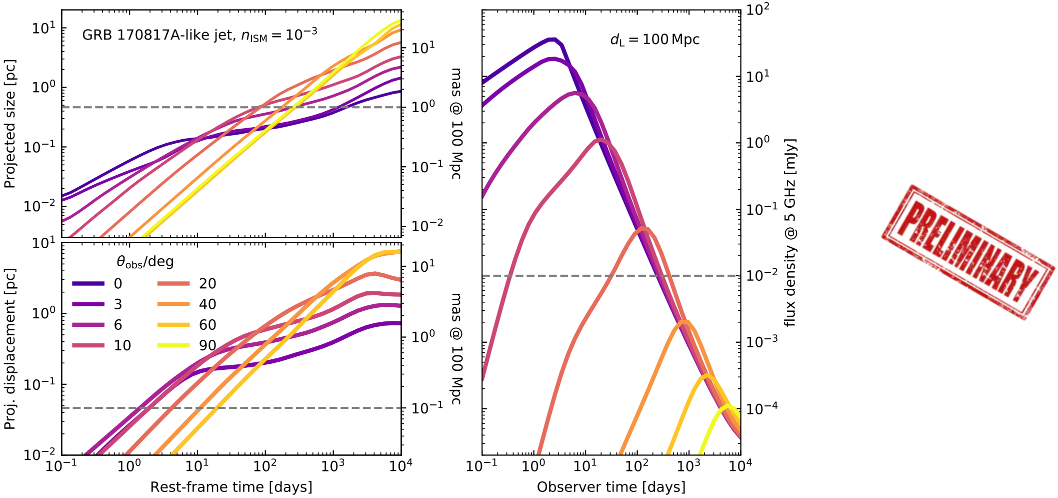


Reproduces SGRB luminosity function



[**Salafia** et al. 2020, A&A 636, A105]

Will we able to do it again?



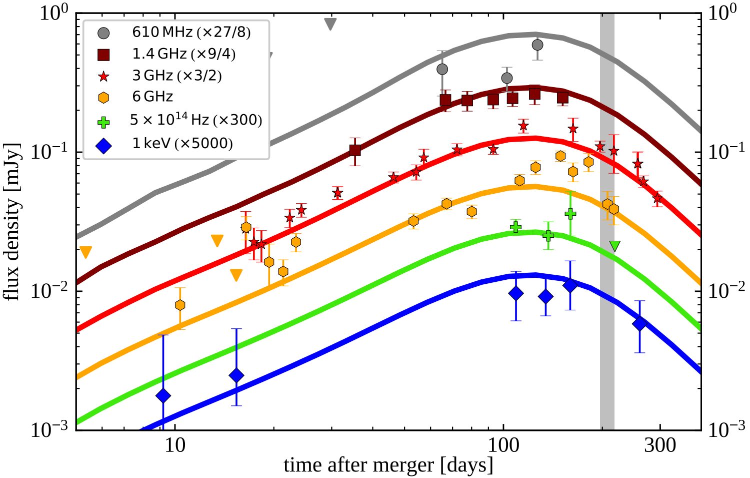
Final remarks

- GW – Radio Astronomy connection keeps producing great science (just a tiny part shown here)
- VLBI will have a leading role
- future "golden" events can unveil GRB and compact binary physics (see deluge of papers following GW/GRB 170817), and enhance standard-siren cosmology
- next sources may be even fainter! Looking forward to MeerKAT joining VLBI

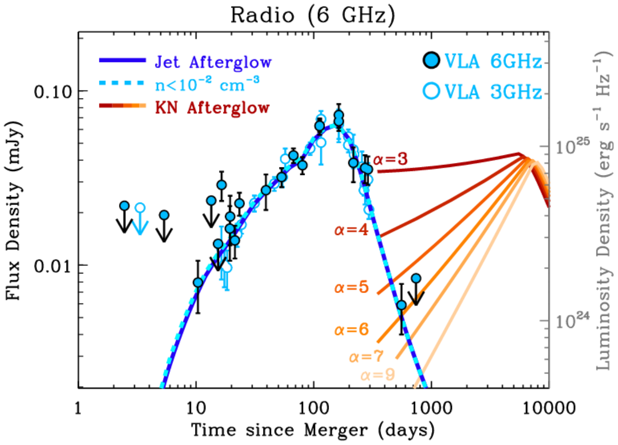
Thank you!

Backup slides

Multi-wavelength lightcurve of the GRB 170817A afterglow



Constraints on the KN velocity distribution



[Hajela et al. 2020]

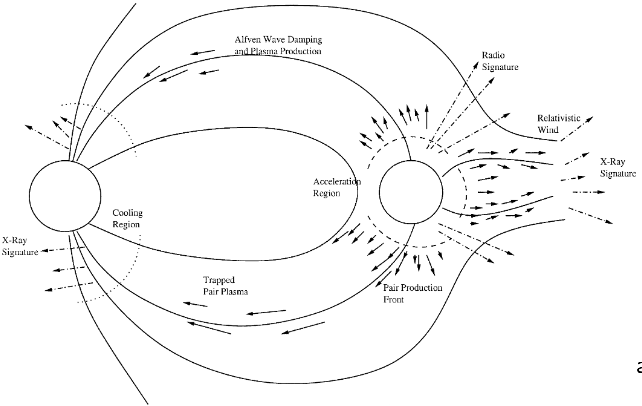
Current, late-time monitoring disfavours very fast KN ejecta (but see Margalit & Piran 2020)

Expected detection rates (Abbott et al. 2018, LRR 21:3)

Table 3 Summary of a plausible observing schedule, expected sensitivities, and source localization with the Advanced LIGO, Advanced Virgo and KAGRA detectors, which will be strongly dependent on the detectors' commissioning progress

Epoch		2015–2016	2016–2017	2018–2019	2020+	2024+
Planned run duration		4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc	LIGO	40–60	60–75	75–90	105	105
	Virgo	–	20–40	40–50	40–70	80
	KAGRA	–	–	–	–	100
Expected BNS range/Mpc	LIGO	40–80	80–120	120–170	190	190
	Virgo	–	20–65	65–85	65–115	125
	KAGRA	–	–	–	–	140
Achieved BNS range/Mpc	LIGO	60–80	60–100	–	–	–
	Virgo	–	25–30	–	–	–
	KAGRA	–	–	–	–	–
Estimated BNS detections		0.05–1	0.2–4.5	1–50	4–80	11–180

The GW – Radio connection: stellar compact binary mergers (1)



[Hansen & Lyutikov 2001]

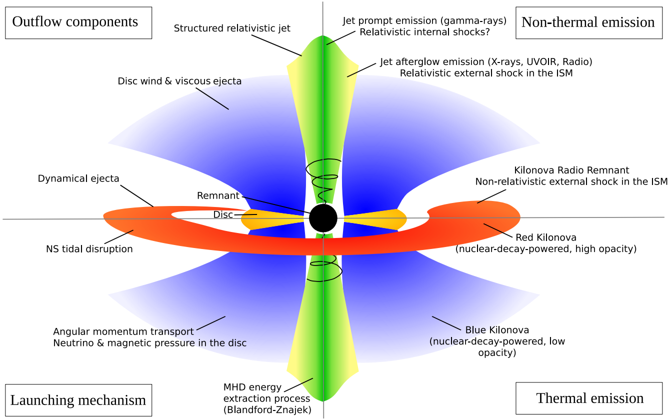
Pre-merger

Interaction of magnetospheres

→ dissipation of orbital (& possibly rotational) energy

→ possible coherent emission & reconnection events (FRB?)

(see also Lai 2012; Piro 2012; Palenzuela et al. 2013; Paschalidis et al. 2013; Ponce et al. 2014; Mezger & Zivancev 2016; Wang et al. 2016; Carrasco & Shibata 2020; Most & Philippov 2020)



[Barbieri, **Salafia** et al. 2019]

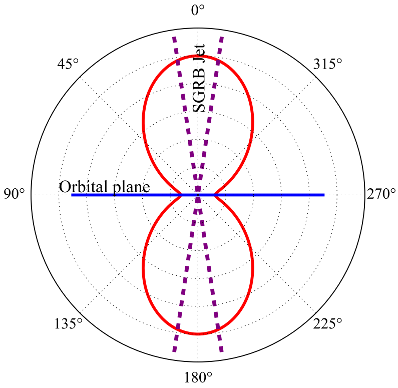
Post-merger

Fast ejecta produced in BNS and BHNS mergers: jet and dynamical ejecta

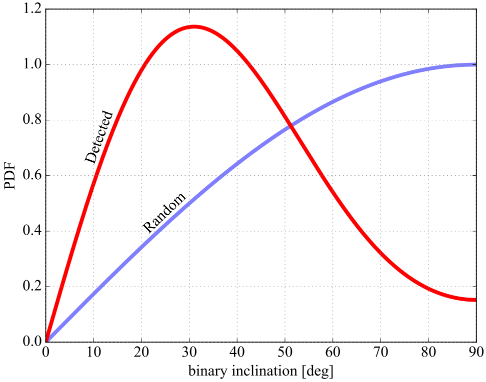
→ shock in ISM

→ synchrotron emission

GW radiation pattern

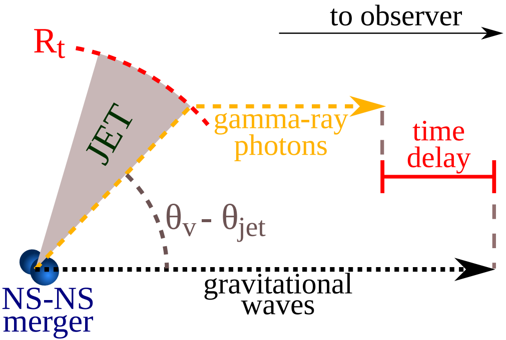


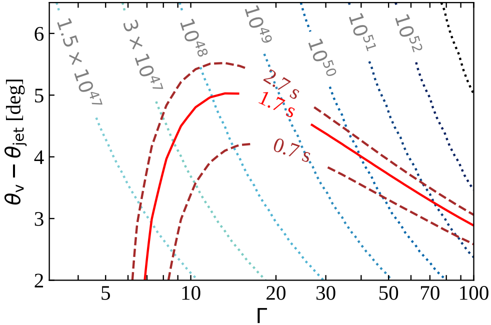
Inclination probability



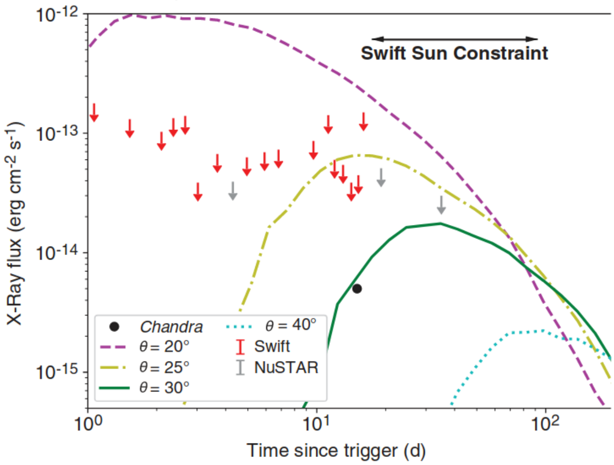
[Schutz 2011]

GW – GRB delay





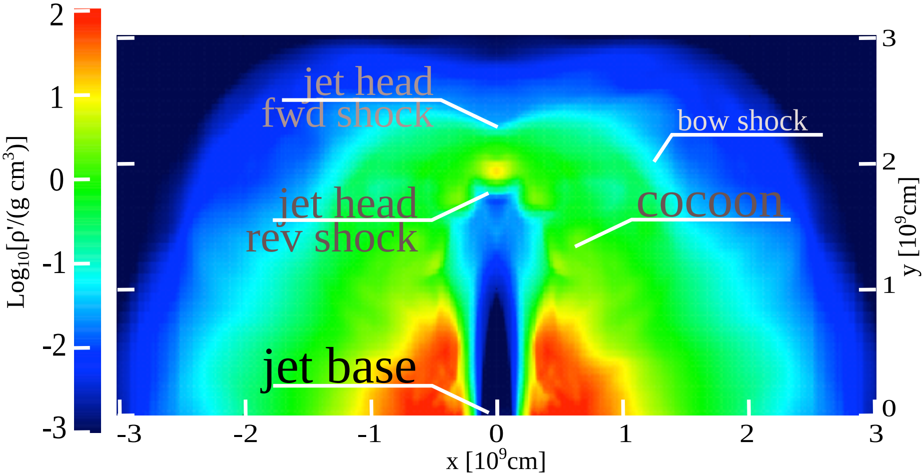
[Salafia et al. 2018]



[Evans et al. 2017]

No X-ray afterglow identified during the first ~ 10 days
$\rightarrow$ on-axis jet & slightly off-axis uniform jet excluded

What the heck is the “cocoon”?



[Lazzati et al. 2016]

Low SNR, non-Gaussian noise: how to constrain the size?

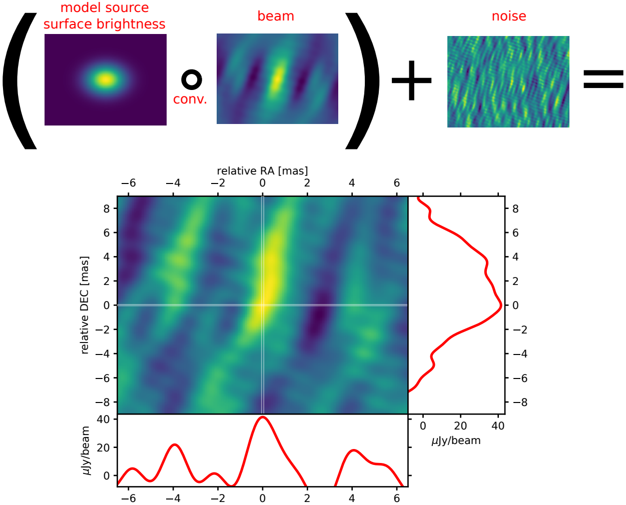
Bayesian approach

Posterior on size $(s_\mathrm{x}, s_\mathrm{y})$ & total flux F exploiting:

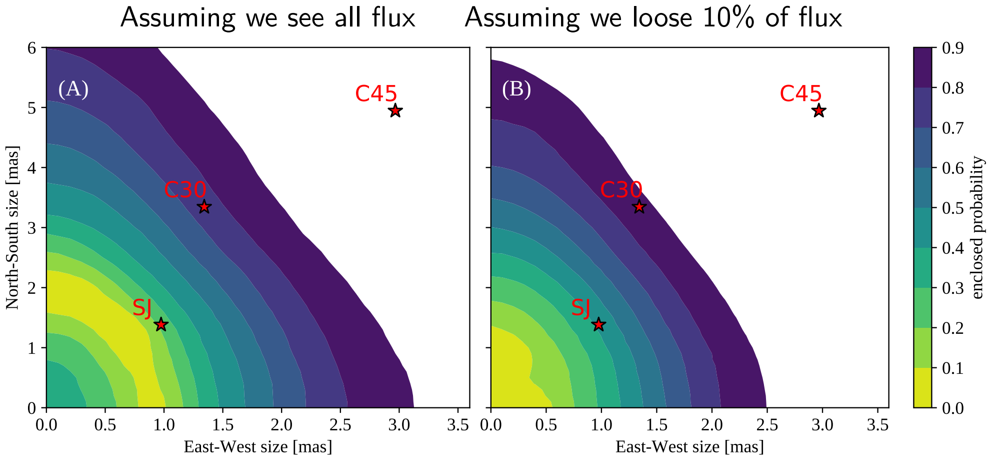
- our peak flux measurement $F_\mathrm{p} = 42\,\mu\mathrm{Jy/beam}$
- the prior $F = 47 \pm 9\,\mu\mathrm{Jy}$ based on VLA high-sens. measurements
- knowledge of the noise

$$P(s_\mathrm{x}, s_\mathrm{y}, F \,|\, F_\mathrm{p}, \mathrm{noise}) = \frac{P(F_\mathrm{p} \,|\, s_\mathrm{x}, s_\mathrm{y}, F, \mathrm{noise}) P(F) P(s_\mathrm{x}, s_\mathrm{y})}{P(F_\mathrm{p})}$$

How to compute $P(F_{\rm p}\,|\,s_{\rm x}, s_{\rm y}, F, {\rm noise})$



Result


Assuming we see all flux
Assuming we loose 10% of flux
(A)
(B)
C45
C30
SJ
North-South size [mas]
East-West size [mas]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
1
2
3
4
5
6
enclosed probability
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9