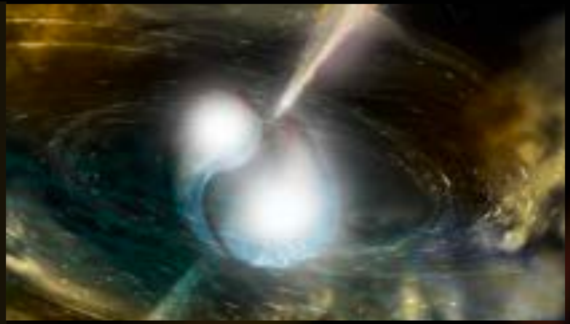
ICRAR

International Centre for Radio Astronomy Research

Rapid-response observations of GRBs with Australian radio telescopes



Gemma Anderson

ICRAR-Curtin University

Kerastari Workshop, 16 June 2023

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Curtin University

THE UNIVERSITY OF WESTERN AUSTRALIA

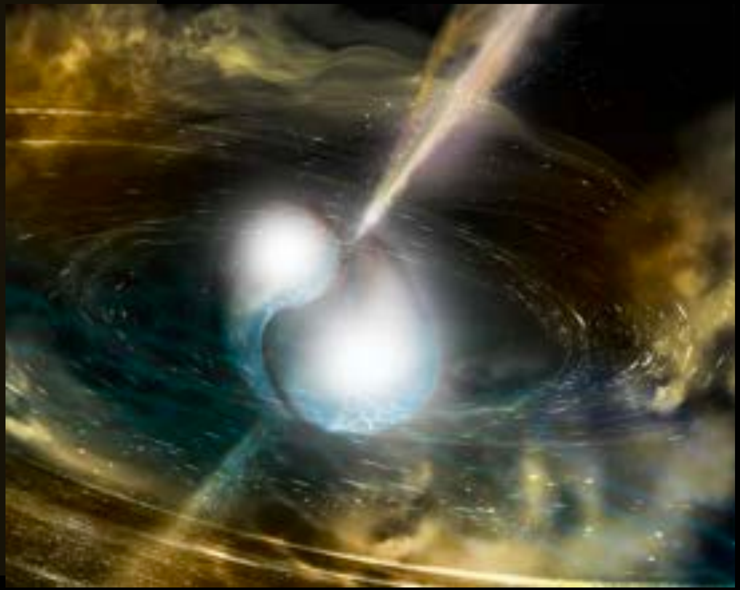
Government of Western Australia
Department of the Premier and Cabinet
Office of Science

GRBs, GWs and FRBs

Long Gamma-ray Bursts

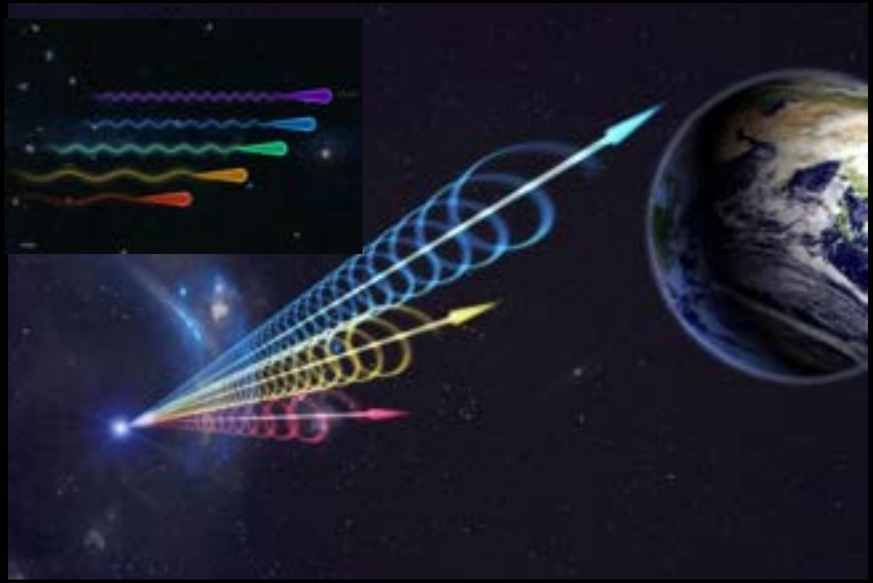
Credit: ESA/Hubble, M. Kornmesser

BNS mergers (GWs and Short Gamma-ray Bursts)



Credit: NSF/LIGO/Sonoma State Uni/ A. Simonnet

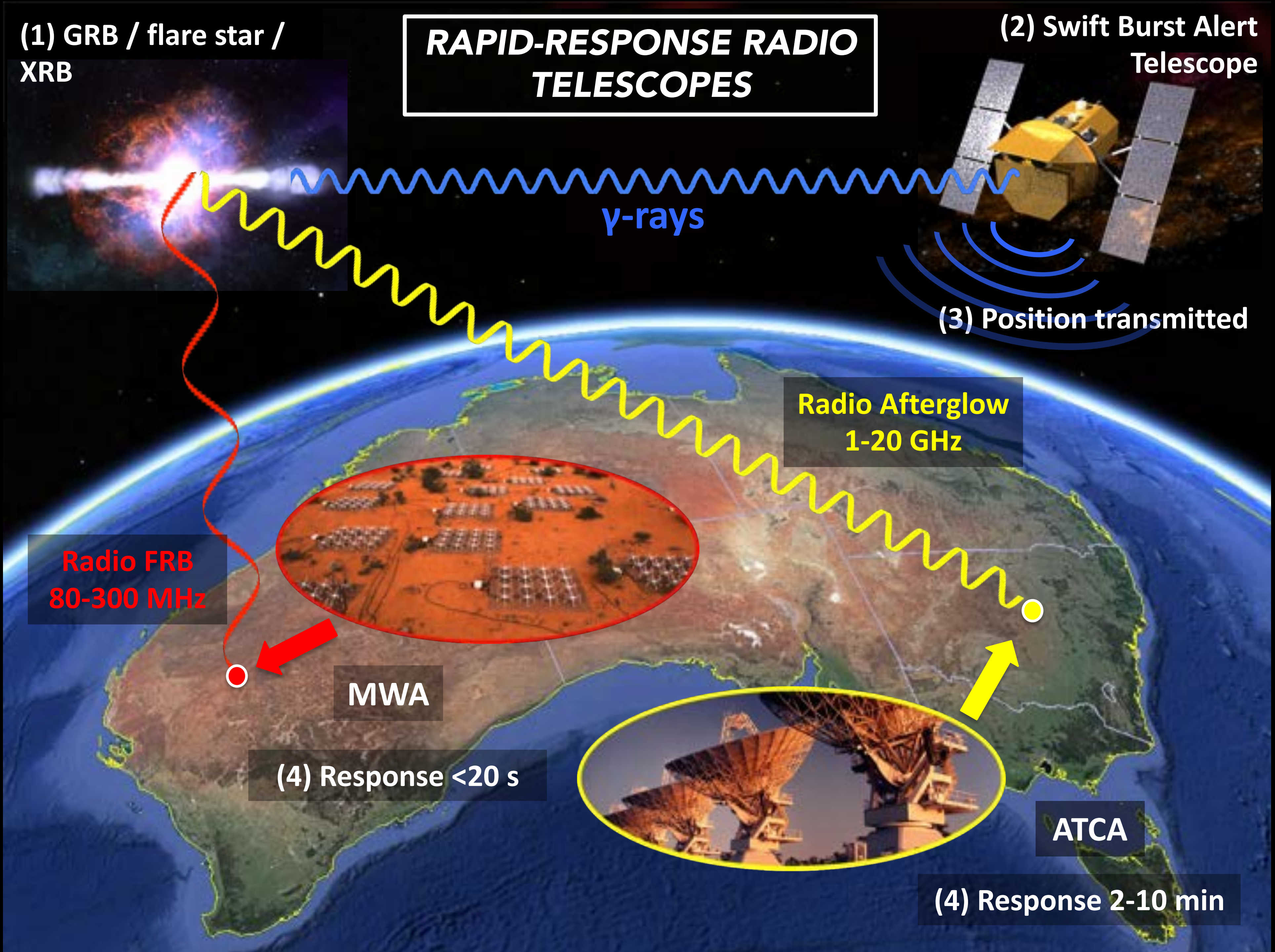
Fast Radio Bursts

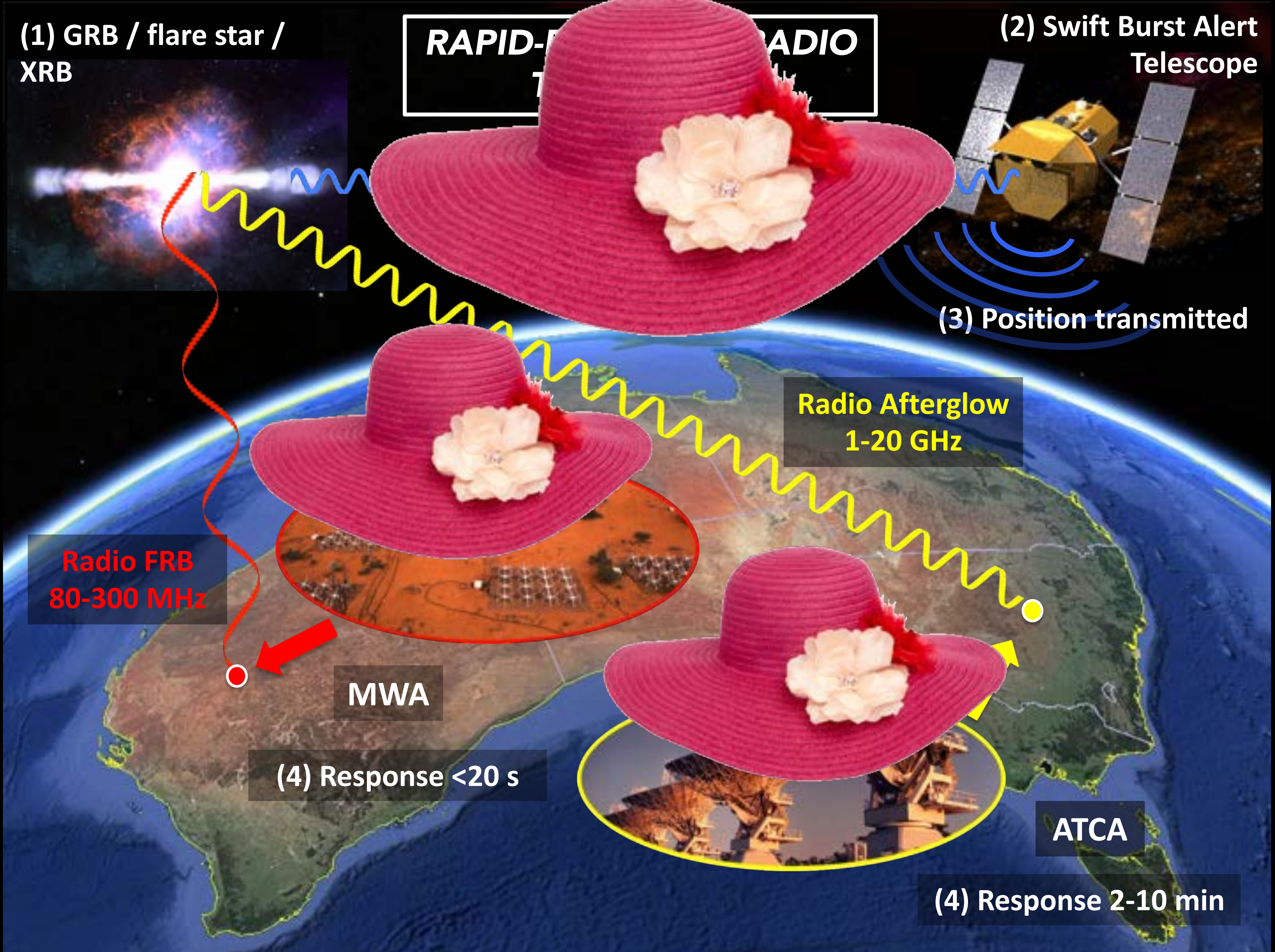


Credit: JINGCHUAN YU, BEIJING PLANETARIUM / NRAO
Credit: CSIRO/ICRAR/OzGrav/Swinburne

- Kelly Gourdji and Iris de Ruiter discussed FRB predictions and radio afterglow from BNS mergers
- Radio probes coherent emission mechanisms and traces relativistic shocks and particle acceleration.
- Most interesting physics at moment of the explosion/outburst

All require rapid and automatic radio triggering!


RAPID-RESPONSE RADIO TELESCOPES
(1) GRB / flare star / XRB
(2) Swift Burst Alert Telescope
γ-rays
(3) Position transmitted
Radio Afterglow 1-20 GHz
Radio FRB 80-300 MHz
MWA
(4) Response <20 s
ATCA
(4) Response 2-10 min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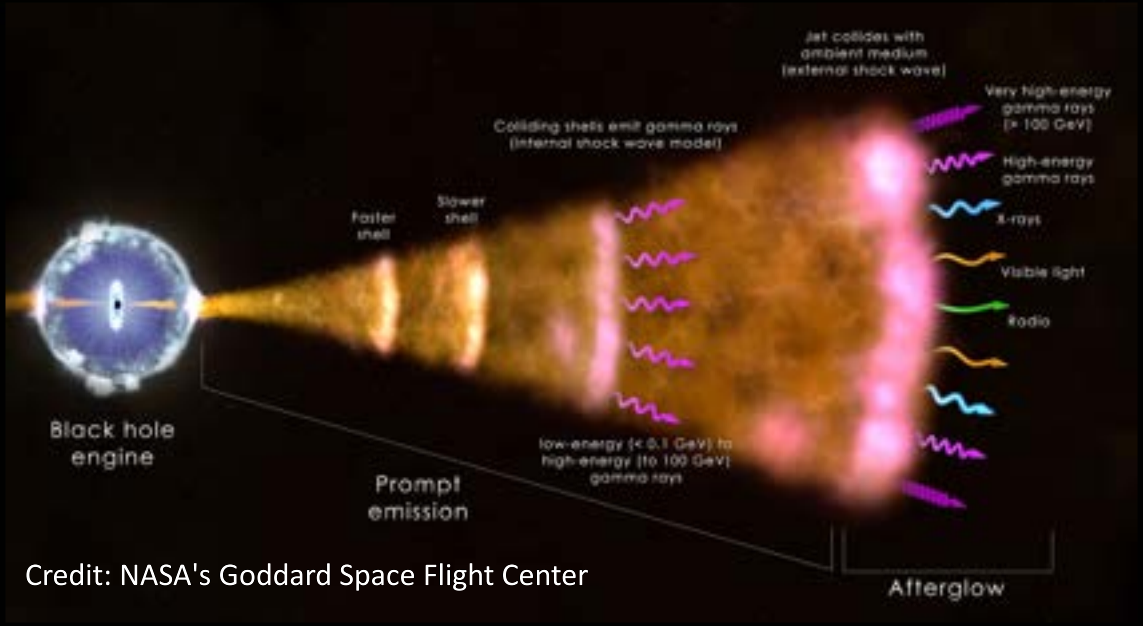
Gamma-ray Bursts

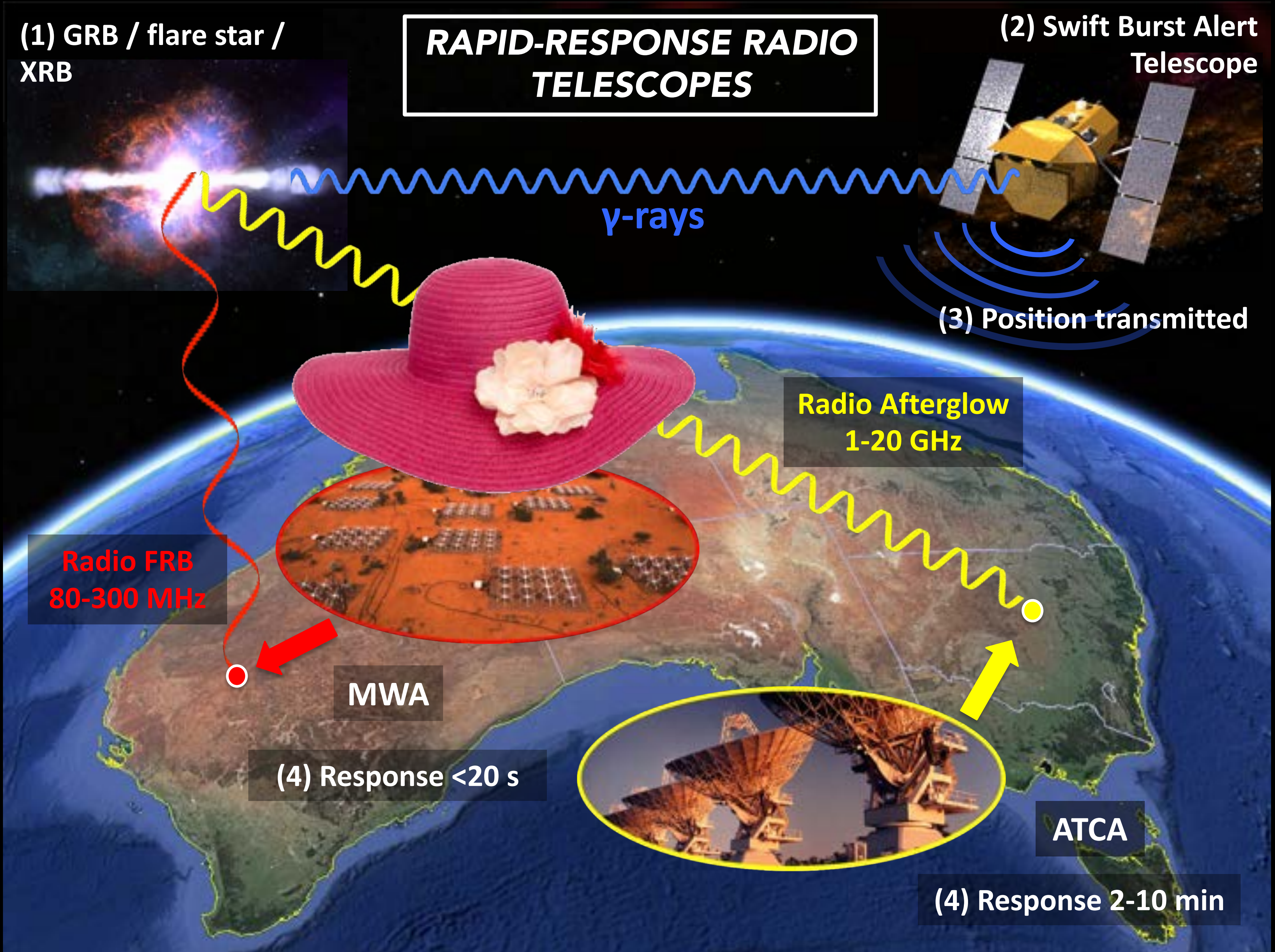
- The most energetic events in our Universe
- The most distant objects ever observed: GRB 090429B z~9.4
- 2 populations
  - Long GRBs: massive stellar collapse (prompt γ-rays >2s)
  - Short GRBs: Merging neutron stars or NS-BH merger (γ -rays <2s) – also GWs!
- Powered by black hole or magnetar engine



Credit: NASA's Goddard Space Flight Center

Fireball model:

- Internal-External shock scenario
  - Internal: prompt emission phase (the gamma-ray burst)
  - External: Afterglow phase (forward and reverse shock) – blast wave physics same for long and short



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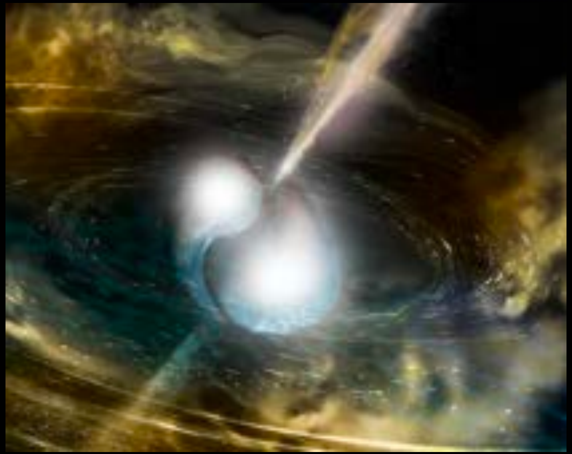
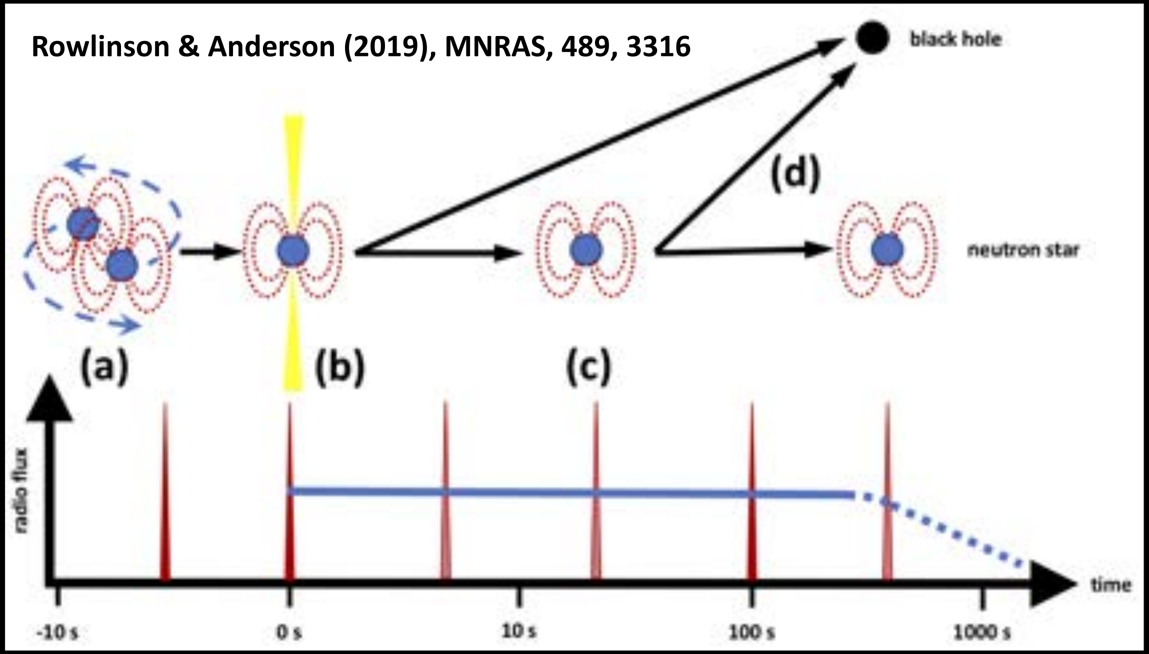
GRB triggering at low (MHz) radio frequencies

Links between GRBs, BNS mergers and FRB-like signals

- Dispersion delay at low frequencies (MWA <200 MHz)
- BNS mergers and long GRBs may have a (short lived) magnetar remnant
- Models predict coherent radio signals
- Models (EoS of nuclear matter)
  - Prompt (FRB-like)
  - Persistent (dipole radiation) from magnetar remnant





a) B field interactions
b) GRB jet-ISM interactions
c) Remnant dipole radiation
d) Collapse to BH

Murchison Widefield Array (MWA)

GW/GRB triggering at low (MHz) radio frequencies

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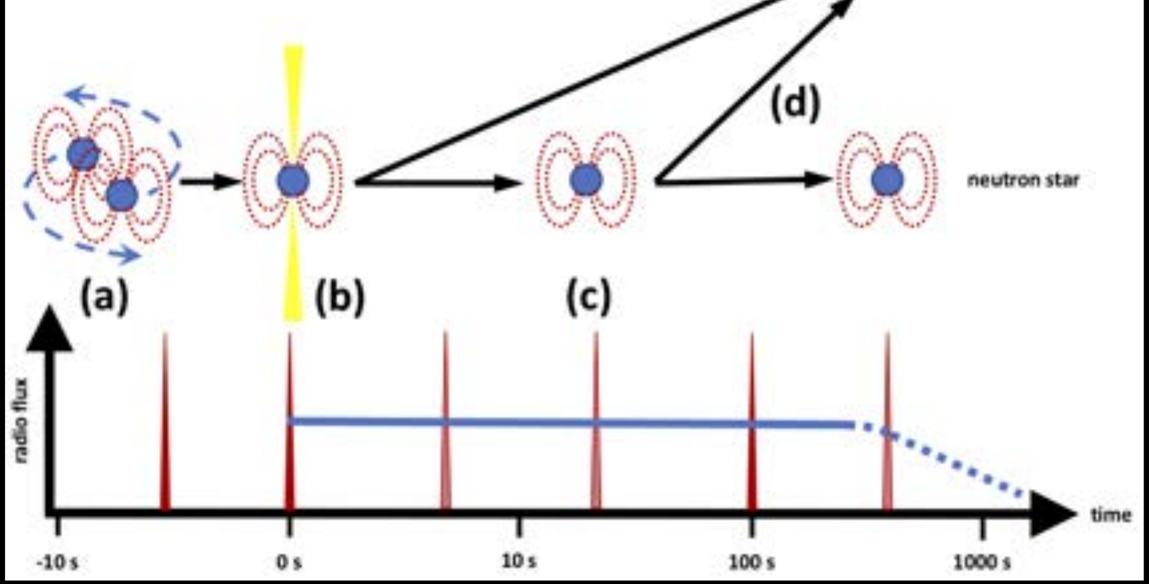
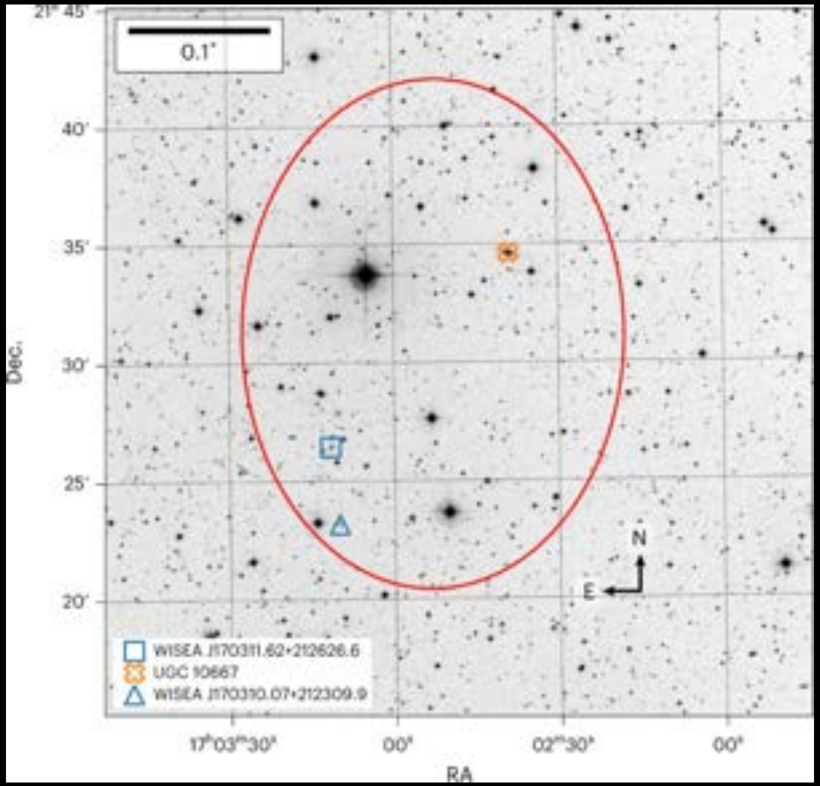


Rowlinson & Anderson (2019), MNRAS, 489, 3316



Potential host association for CHIME FRB 20190425A–GW 190425 (2.8σ) at 2.5 hrs – magnetar collapse into BH
Moroianu et al. (2023), Nature Astronomy

GW/GRB triggering at low (MHz) radio frequencies

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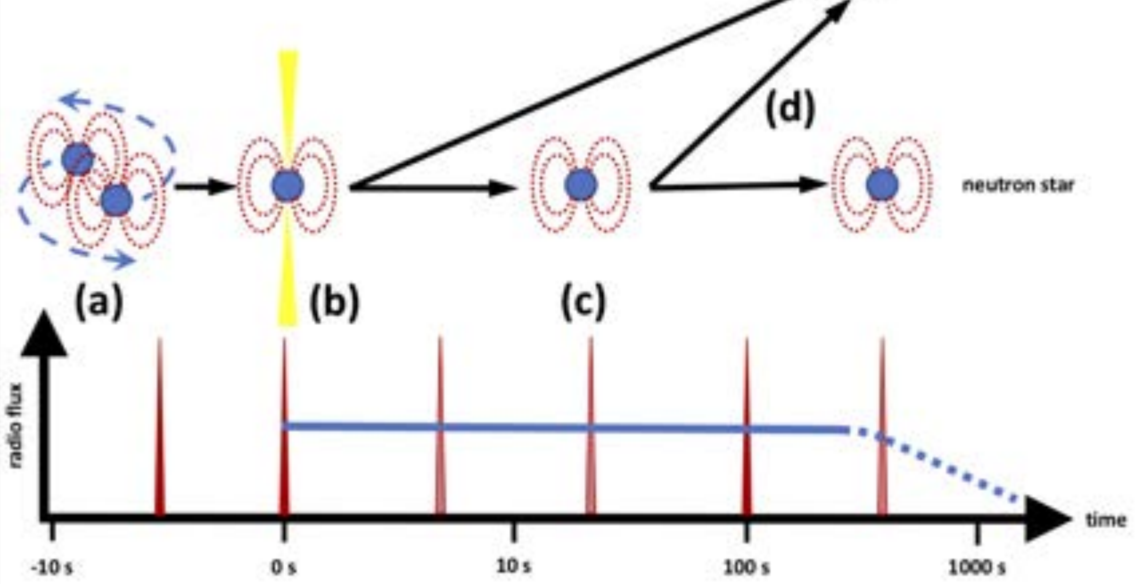
Rowlinson & Anderson (2019), MNRAS, 489, 3316



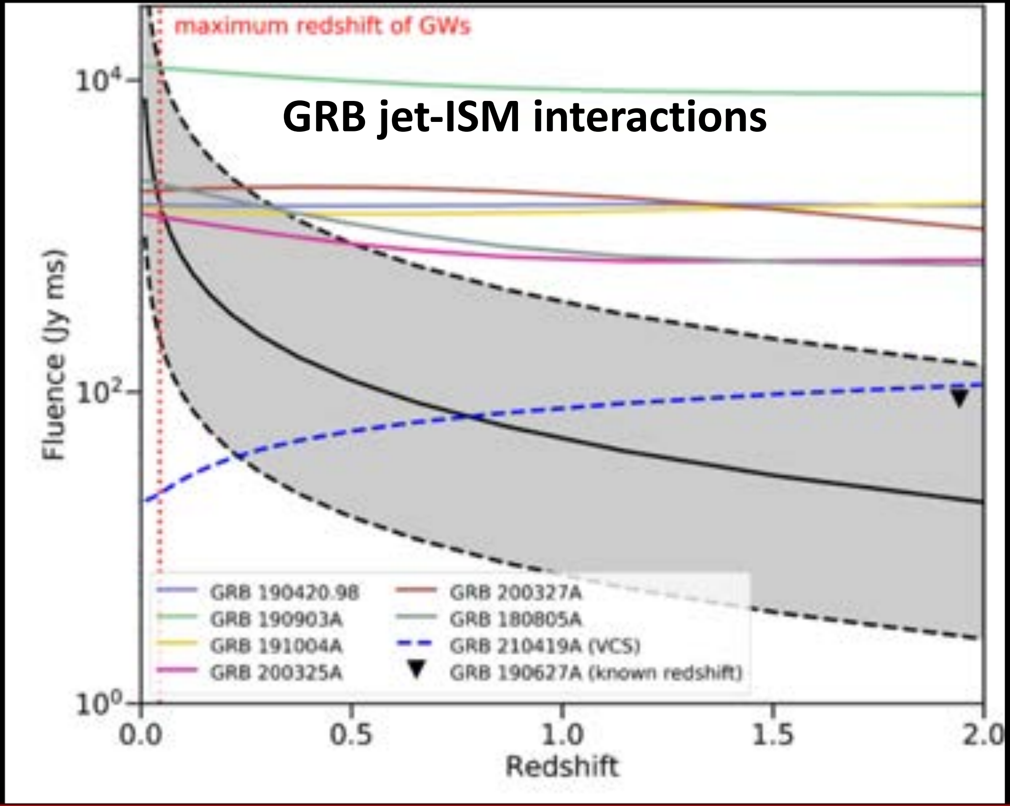
Also Iris de Ruiter's talk on the Birth of a Magnetar!

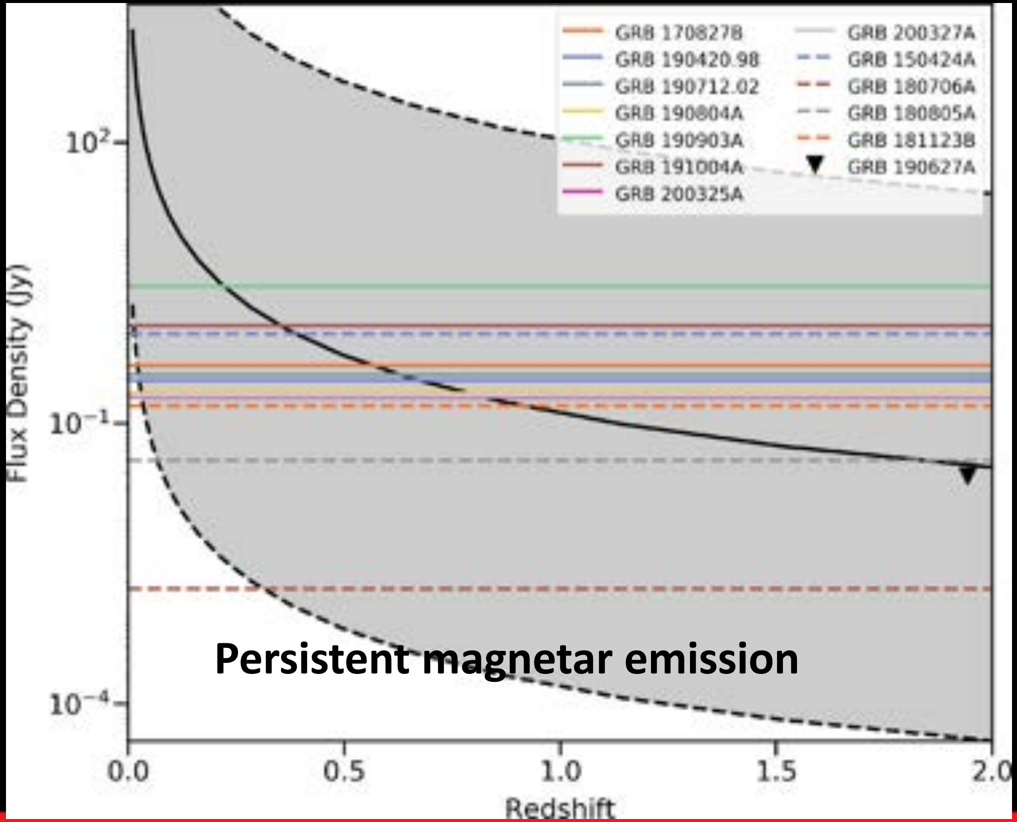
MWA triggering on GRBs

MWA GRBs triggering program:

- MWA on target <20s following GRB alert, integrate 15-30 mins
- Low frequencies – dispersion delay
- 10 short GRBs (3 Swift and 7 Fermi) in the imaging mode (0.5s/1.28MHz)
- 1 long GRB using Voltage Capture System (100µs/10kHz)
- Model constraints: Jet-ISM interactions and persistent (dipole) emission

Anderson et al. (2021), PASA, 38, 26
Tian, Anderson et al. (2022), PASA, 39, 3
Tian, Anderson et al. (2022), MNRAS, 514, 2756





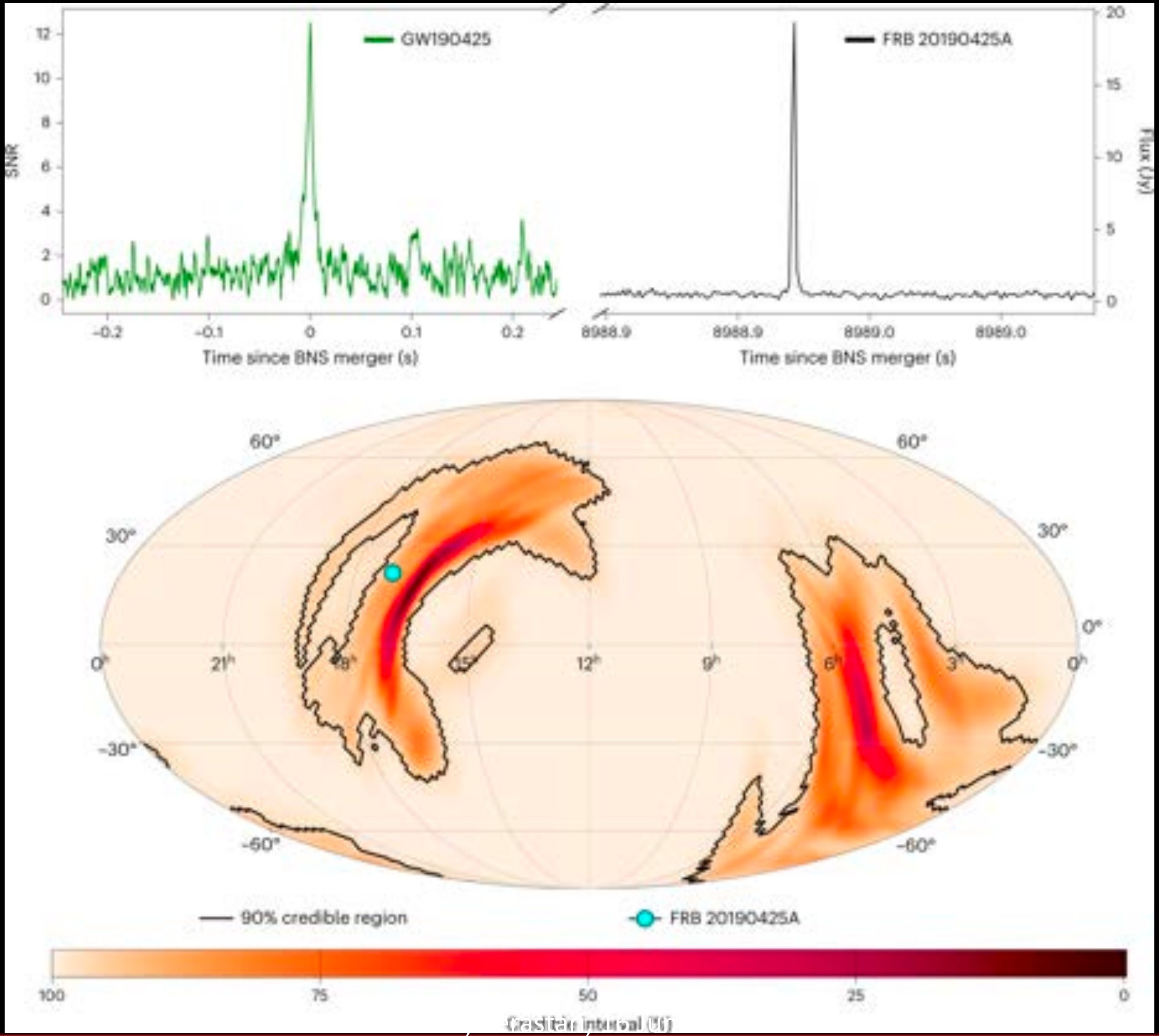
What about GWs (BNS mergers)?

- Targeting FRB-like signals emitted just prior, during or shortly following merger – We now have repointing <10s but is this fast enough?

(Hancock, Anderson, et al., 2019, PASA, 36, 46)

What about GWs (BNS mergers)?

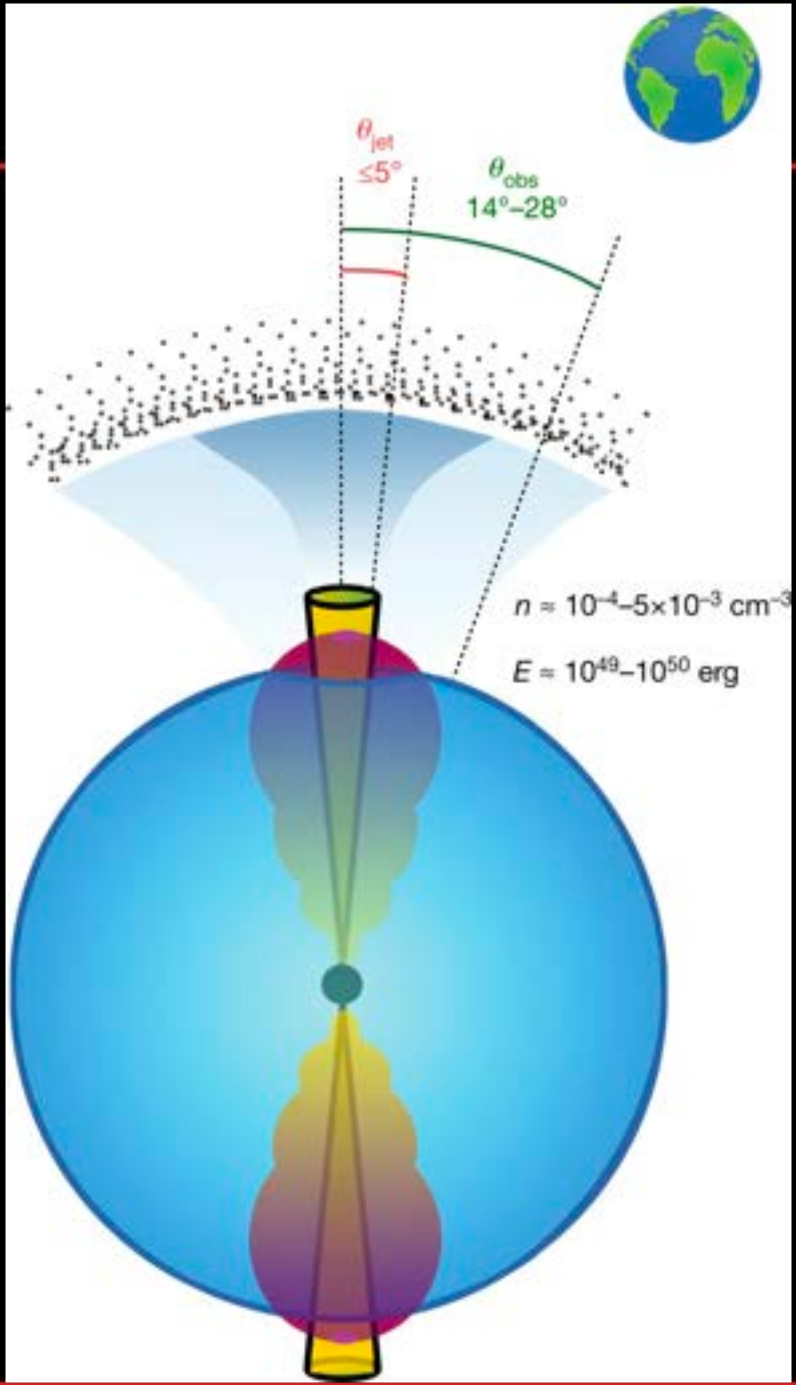
- What about the GW positional accuracy?



BNS merger GW 190425
Moroianu et al. (2023), Nat Astronomy

What about GWs?

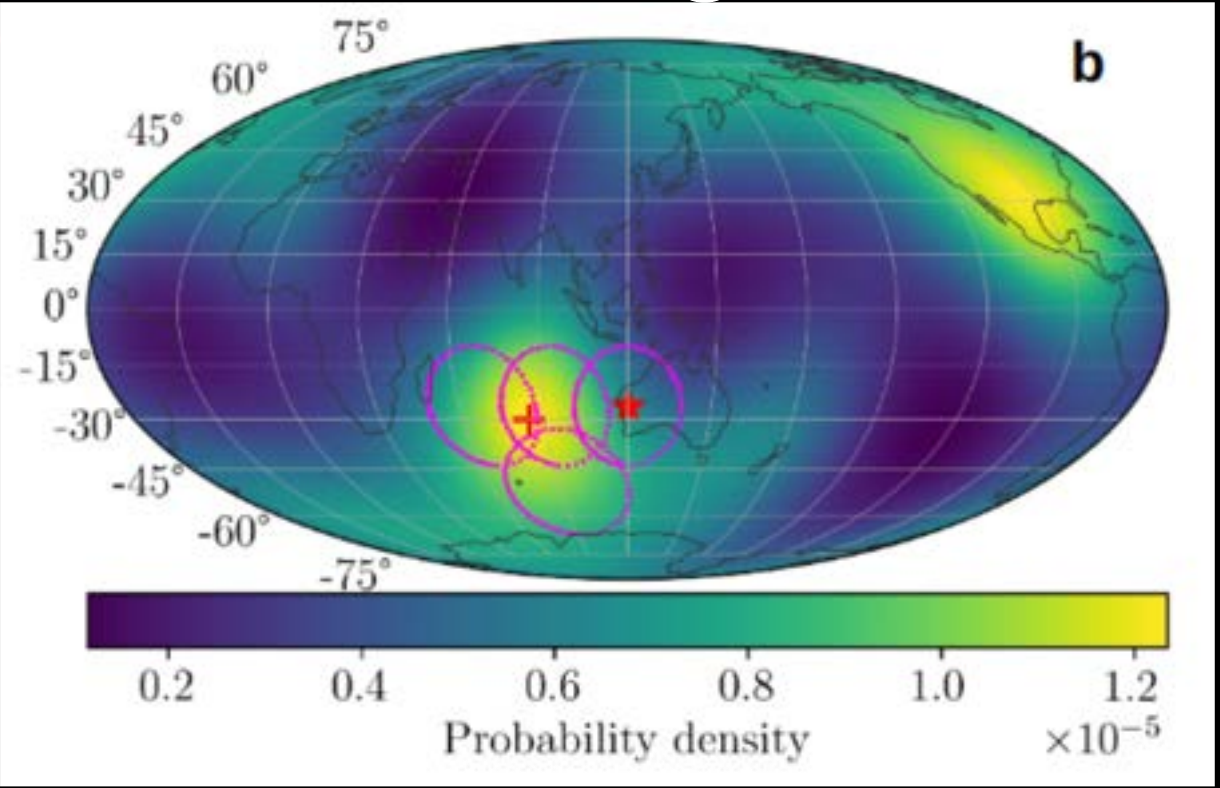
- What about off-axis mergers?



BNS merger GW 170817
Mooley et al. (2018), Nature, 561, 335

MWA triggering on GW BNS during O4

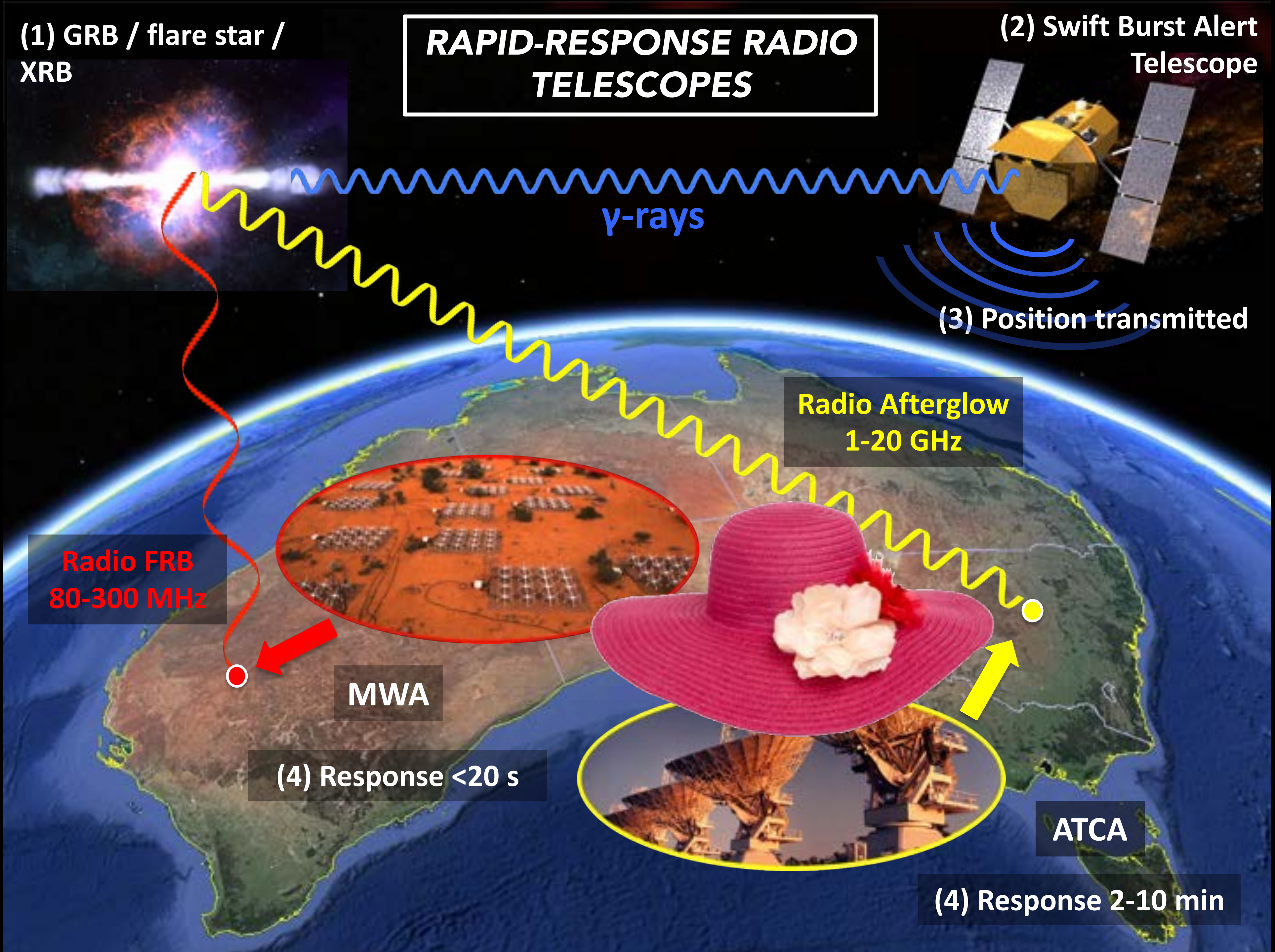
- MWA triggers on EarlyWarning (inspiral) and Preliminary alerts:
  None or poor localisation information!
- Optimise MWA sky cover with good sensitivity with the LOWEST latency possible
- 4 sub-arrays with overlapping pointings
- Shadow LVK GW high sensitivity region over Indian Ocean and trigger buffers (2-3 mins)
- Repoint MWA with better positions
- Voltage capture (μs) and incoherent beam forming.
- Table: Probability of detecting FRB for each model with MWA accounting for off-axis viewing angles



Tian, Anderson et al. in preparation

Model / Mode	NS interaction	Jet-ISM interaction	Pulsar emission	Magnetar collapse
Full array	2.6%	1.2%	4.4%	1.1%
Single dipole per tile	2.2%	0.2%	11.2%	0.1%
Sub-arrays a	4.6%	1.2%	11.4%	0.5%
Sub-arrays b	4.6%	1.2%	11.8%	0.5%

MWA may detect an FRB from 1 merger during O4!



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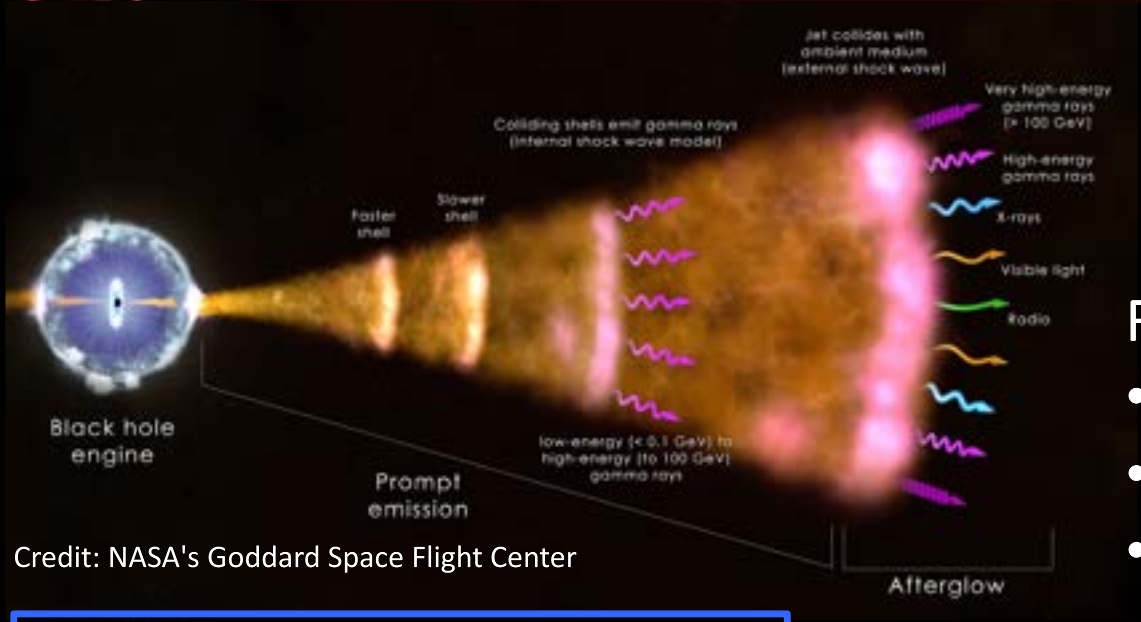
GRB rapid-response GHz radio triggering

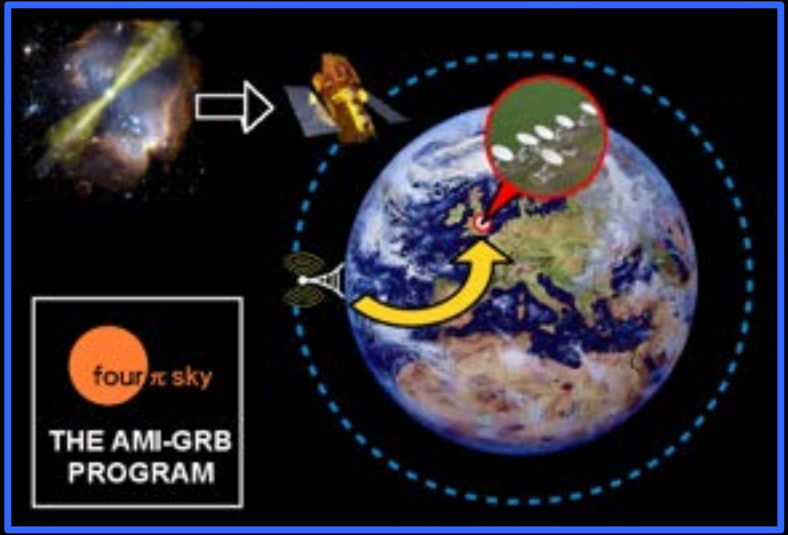


Credit: NASA's Goddard Space Flight Center

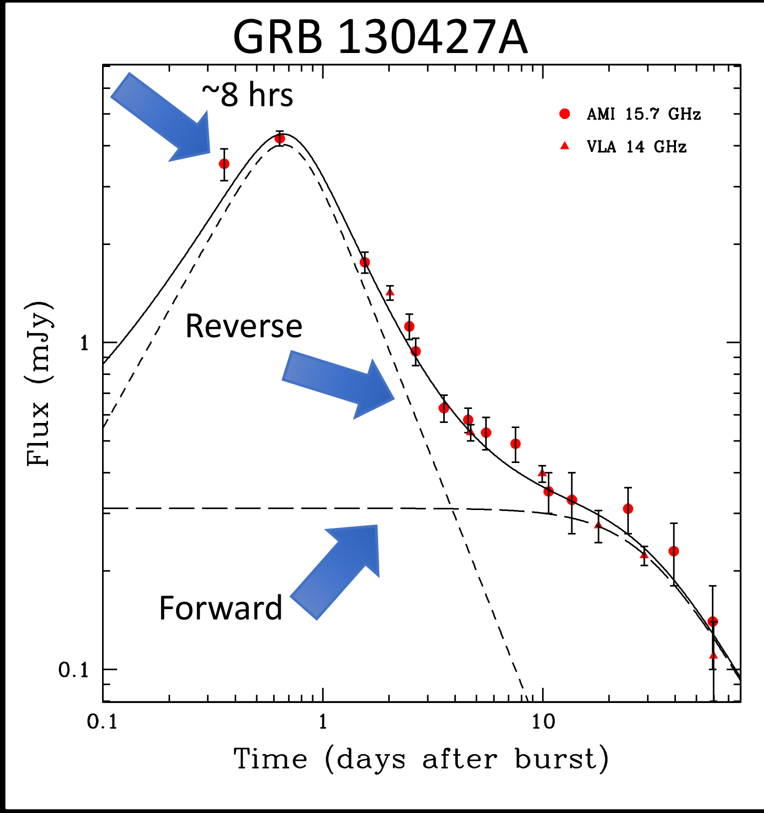
Fireball model:
- Internal-External shock scenario
- External forward and reverse shock

Forward shock:
- Afterglow
- Peaks 10-100s days
- Geometry, circumburst density, energetics

Reverse shock:
- Peaks ~1 day (need rapid-response)
- Jet content (Baryonic vs Poynting flux), magnetic field, initial Lorentz factor

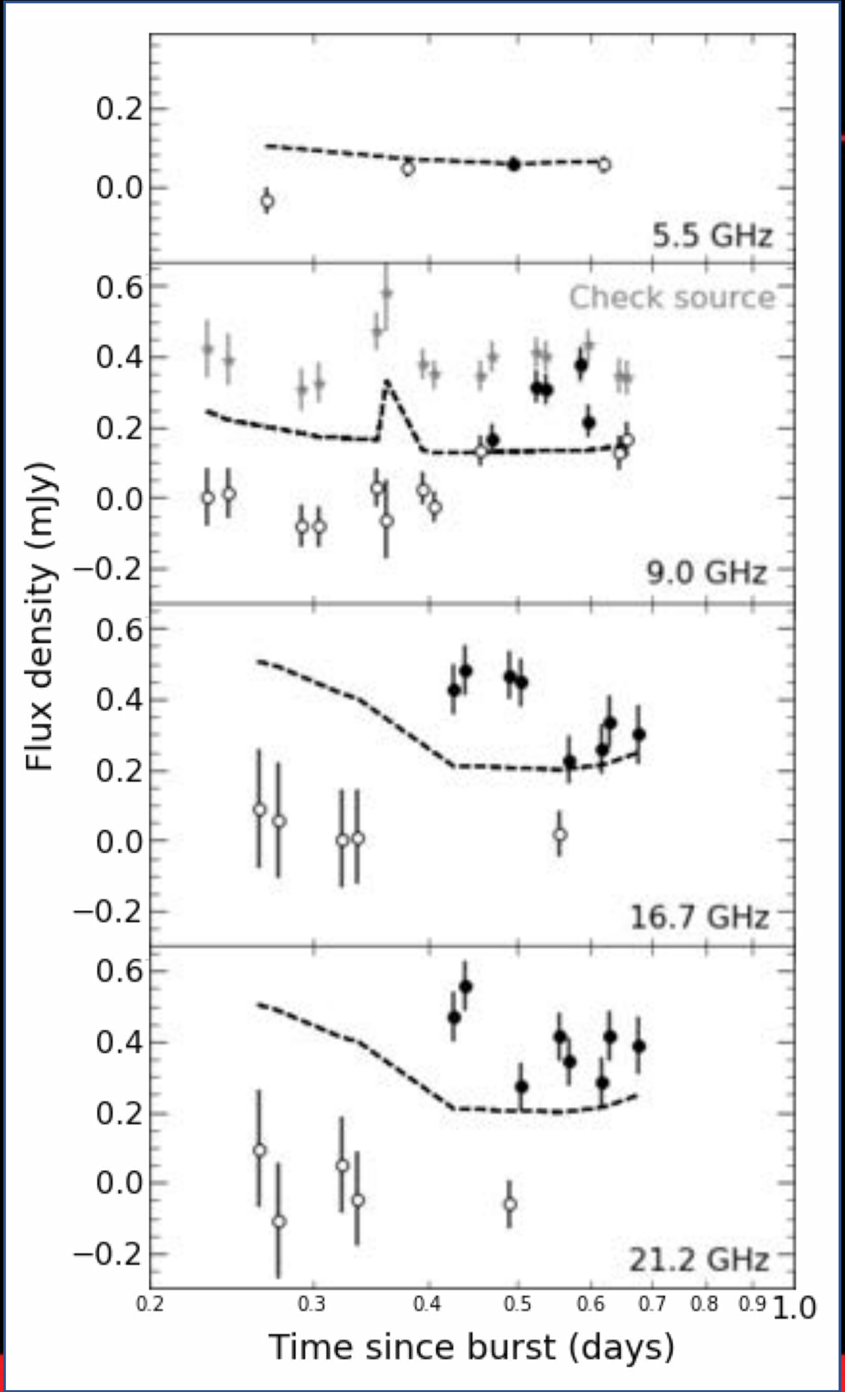


Arcminute Microkelvin Imager (AMI)



Anderson et al. (2014), MNRAS, 440, 2059

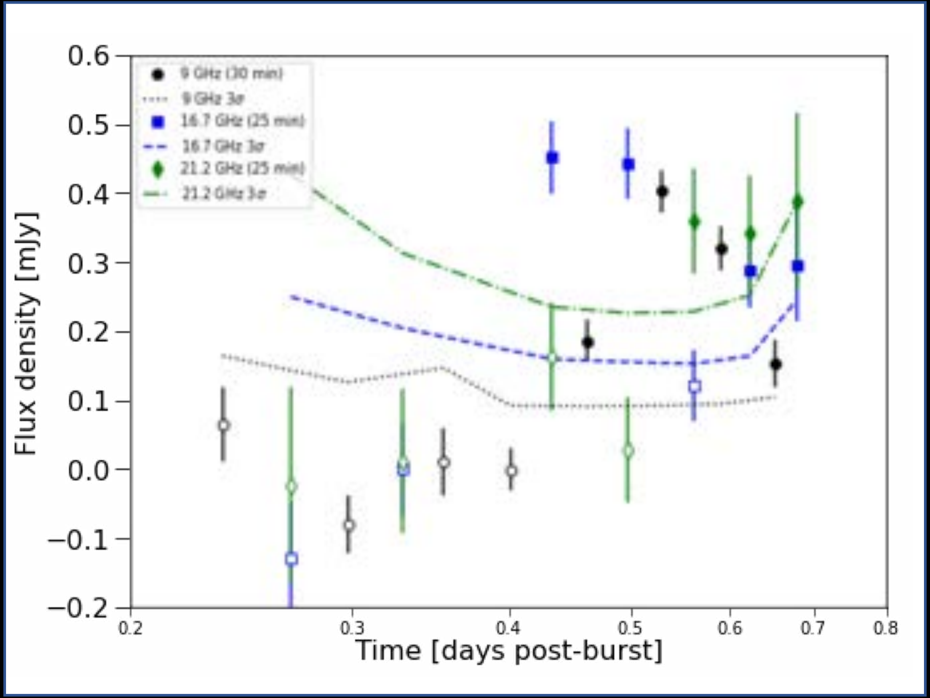
Rapid radio brightening of GRB 210702A

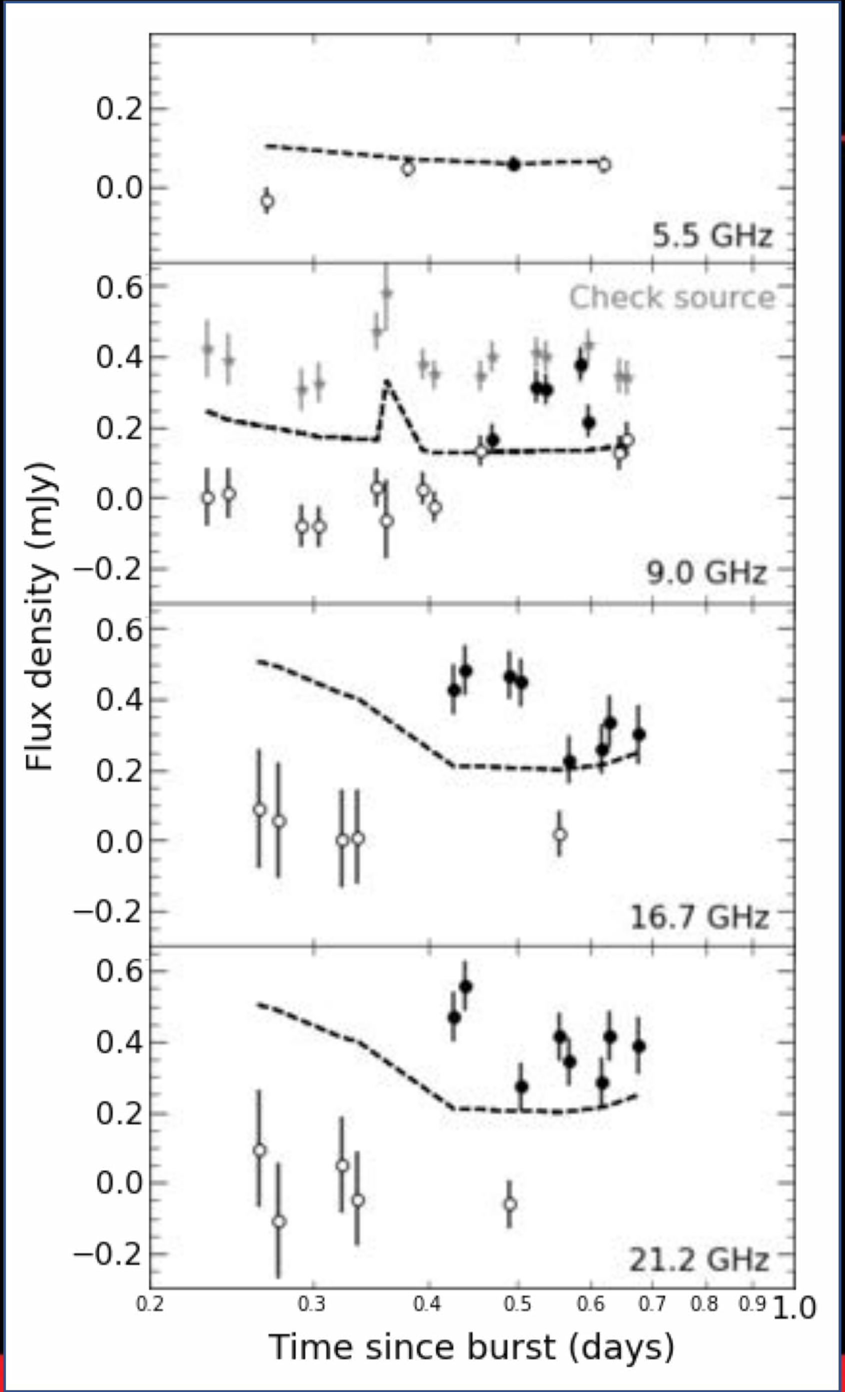


ATCA on target 5.4 hrs post-burst when GRB 210702A above the Horizon 11 hr integration

- Fitting for a point source in the visibility plane (no imaging)
- 5.5 (60 min), 9 GHz (15 min), 16.7/21.2 GHz (12.5 min)
- 9 GHz flare 9-14 hrs - peaks at 13 hrs
- Transient source also detected at 5.5, 16.7 and 21.2 GHz

Anderson, et al. MNRAS, accepted





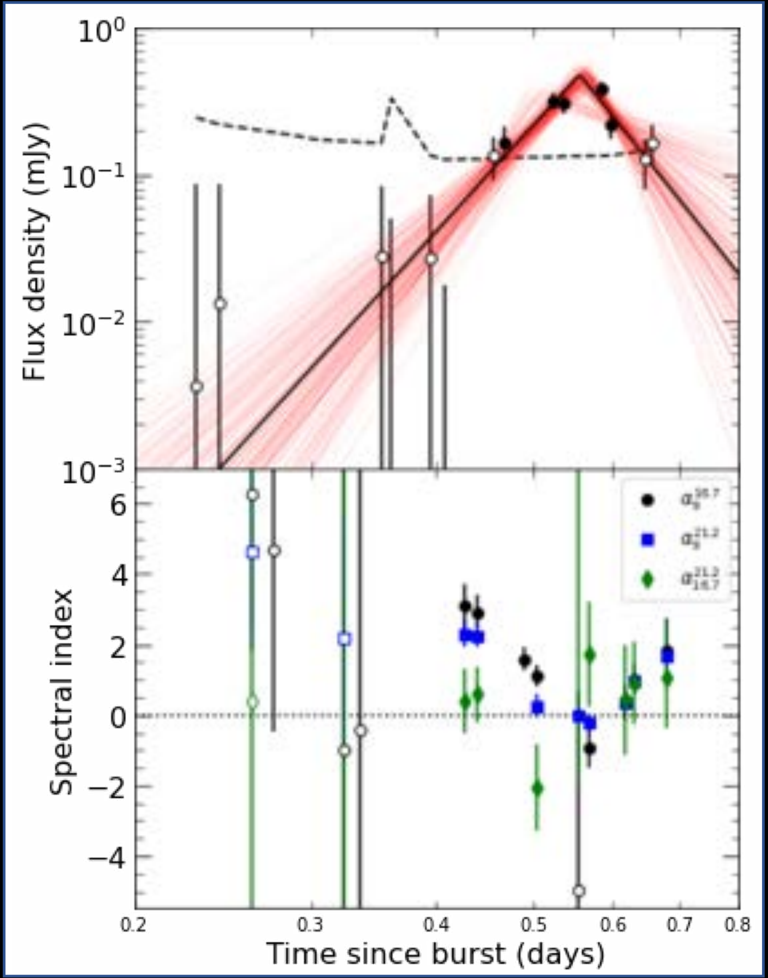
Rapid radio brightening of GRB 210702A

- X-ray-optical afterglow classic forward shock
- Broken PL fit to 9 GHz light curve (MCMC pymc3)
  - Rise α ~+7 decay α ~-8, break 0.56 days
- Positive spectral index
- Not typical radio reverse or forward shock behavior!

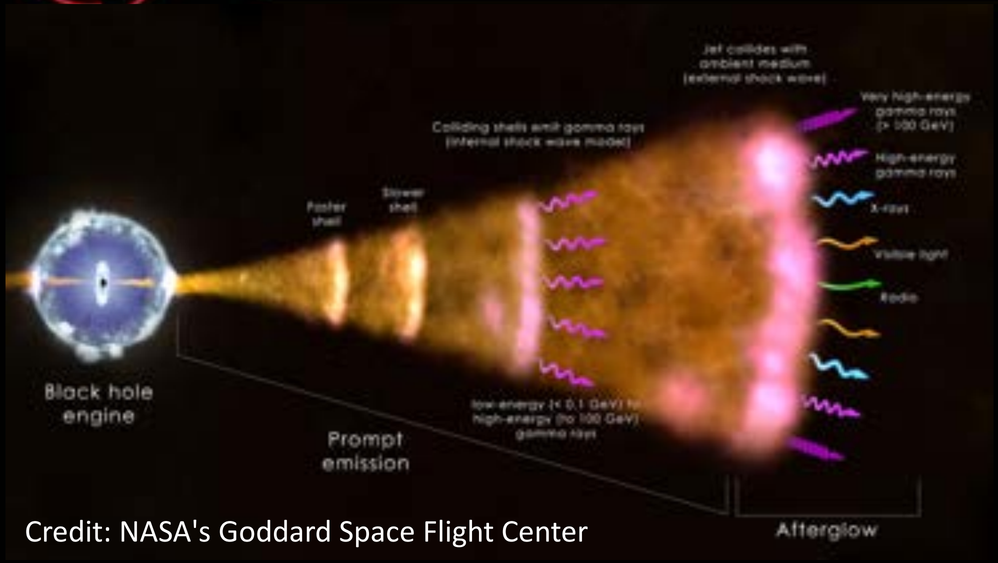
Possible explanation:
Interstellar scintillation (ISS)

- Place earliest GRB source size estimate using ISS: <6 x 10^{16} cm
- Size estimate consistent with model predictions: 8 x 10^{16} cm

Anderson, et al. MNRAS, accepted



PanRadio GRB: ATCA Large Program



Credit: NASA's Goddard Space Flight Center

ATCA triggering experiment:

- 560 hrs of ATCA long GRB follow-up over 12 months
- Rapid triggering: Track reverse shock rise over 12 hrs (start 4-16 hrs post-burst)
- 5.5, 9, 16.7, 21.1 GHz trigger
- 5.5, 9, 16.7, 21.1, 33, 35, 45, 47 GHz monitoring

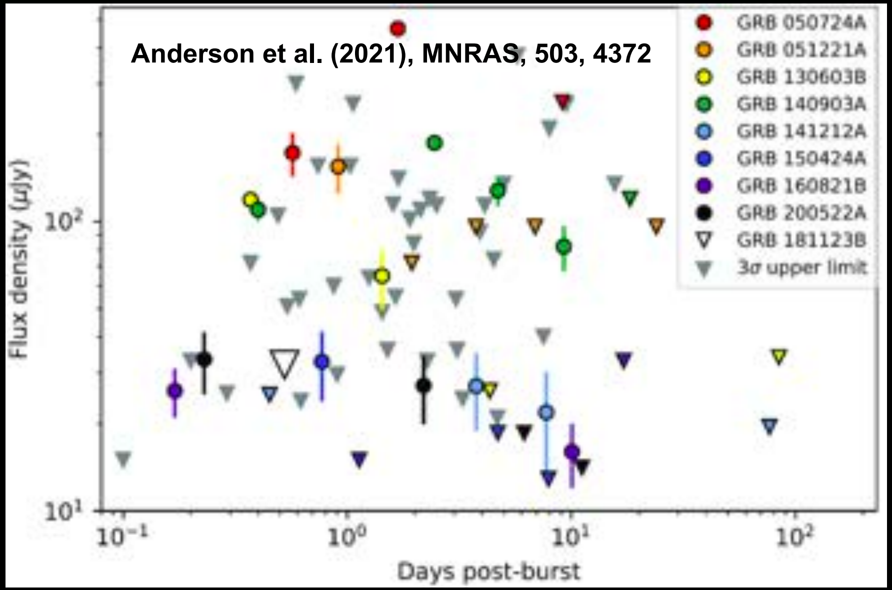
Science Cases for program – **unbiased** radio sampling of Swift Long GRBs

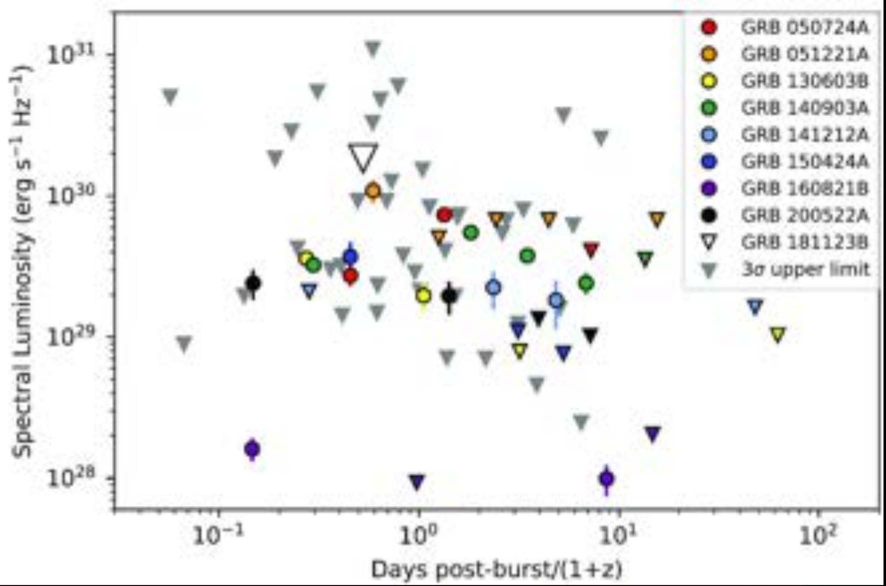
- Comprehensive, high cadence radio coverage of more GRBs (only ~6 GRBs are well sampled)
- Source of early-time radio variability (motivated by GRB 210702A)
- Disentangle early-time reverse shock (RS) radio emission from forward shock (FS)
- Is there a universality to GRB shock wave physics or do these properties evolve with time?
- Late-time radio follow-up in the non-relativistic phase: key to understanding energy budget and environmental properties

ATCA Triggering on short GRBs

Motivation: Gravitational wave links

- BNS merger GW 170817/GRB 170817A
- Only around 11 radio-detected SGRBs
    - Most switch on <1 day post-burst, >50% fade <2 days
- MUST observe <24 hrs post-burst
- Rapid response triggering: Track reverse shock rise over 12 hrs (start 4-16 hrs post-burst)
- 5.5, 9 GHz trigger
- 5.5, 9, 16.7, 21.1 GHz monitoring
- Short GRBs are RARE!
    - First GRB 181123B (Figure right)
    - ~4/7 short GRBs with rapid-response obs
    - First rapid-response radio detection in 2023! GRB 230217A





Conclusions

- Rapid-response systems on MWA and ATCA are targeting GRB science
- MWA is searching for coherent prompt (FRB-like) signals from GRBs
- MWA triggering strategy for gravitational wave events during O4
- Long GRB 210702A: ATCA rapid-response follow-up detects radio flare
  - ISS likely explanation
  - Earliest ISS radio afterglow size constraint at 0.5 days
  - Motivated PanRadio GRB: Large ATCA long GRB follow-up program
- Short GRB 230217A: ATCA rapid-response detection
  - Likely detected reverse shock
  - Earliest GRB radio afterglow detection to date!

Rapid-response observing systems are revealing exciting science!

SKA anyone??