INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

The radio afterglow of GRBs

probing explosive transients at the longest wavelengths

with the (fundamental) help of
A. Colombo, G. Ghirlanda, M. Giroletti, O. S. Salafia, L. Nava, B. Marcote, and many more…

Outline

1. Introduction
2. GRBs in radio
3. GW(s) in radio
4. Prospects
5. Conclusions

My supervisors and me at Effelsberg

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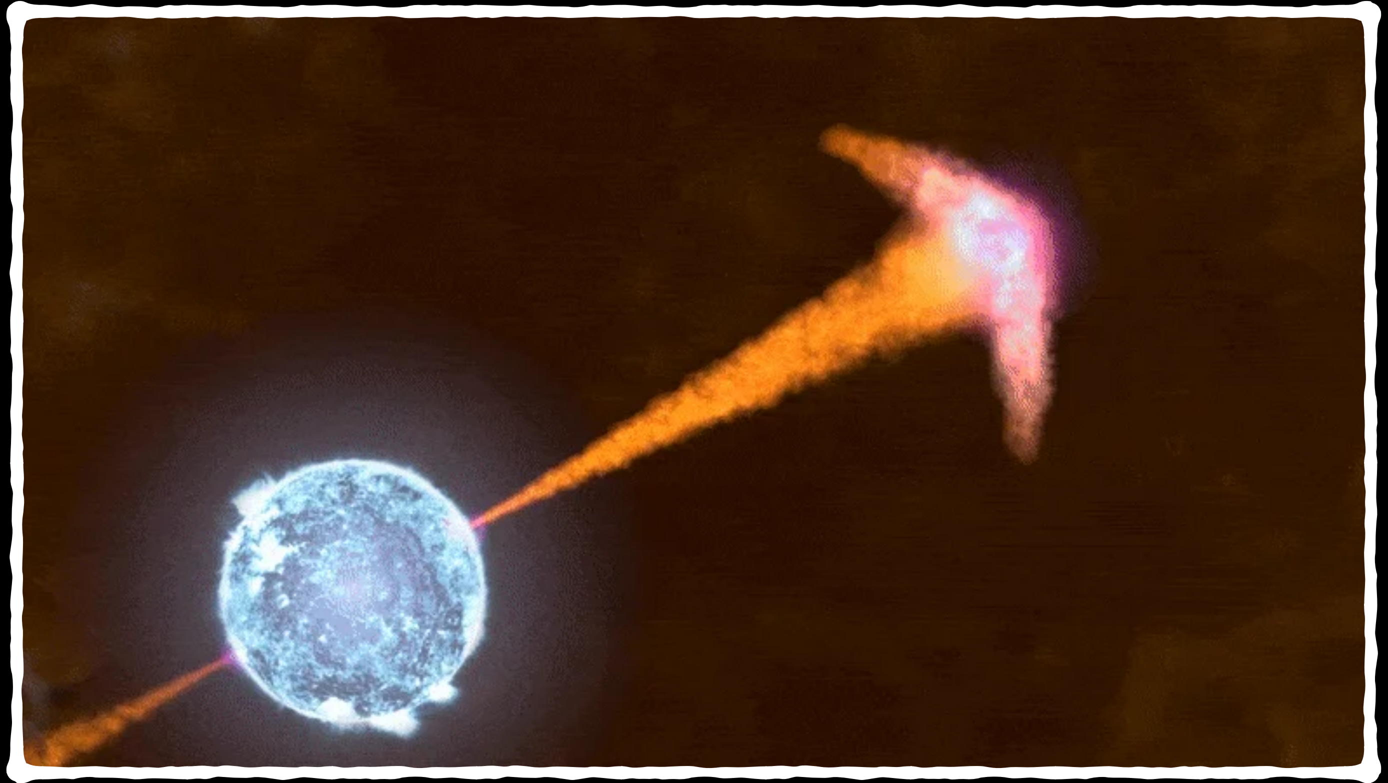
Gamma-Ray Bursts

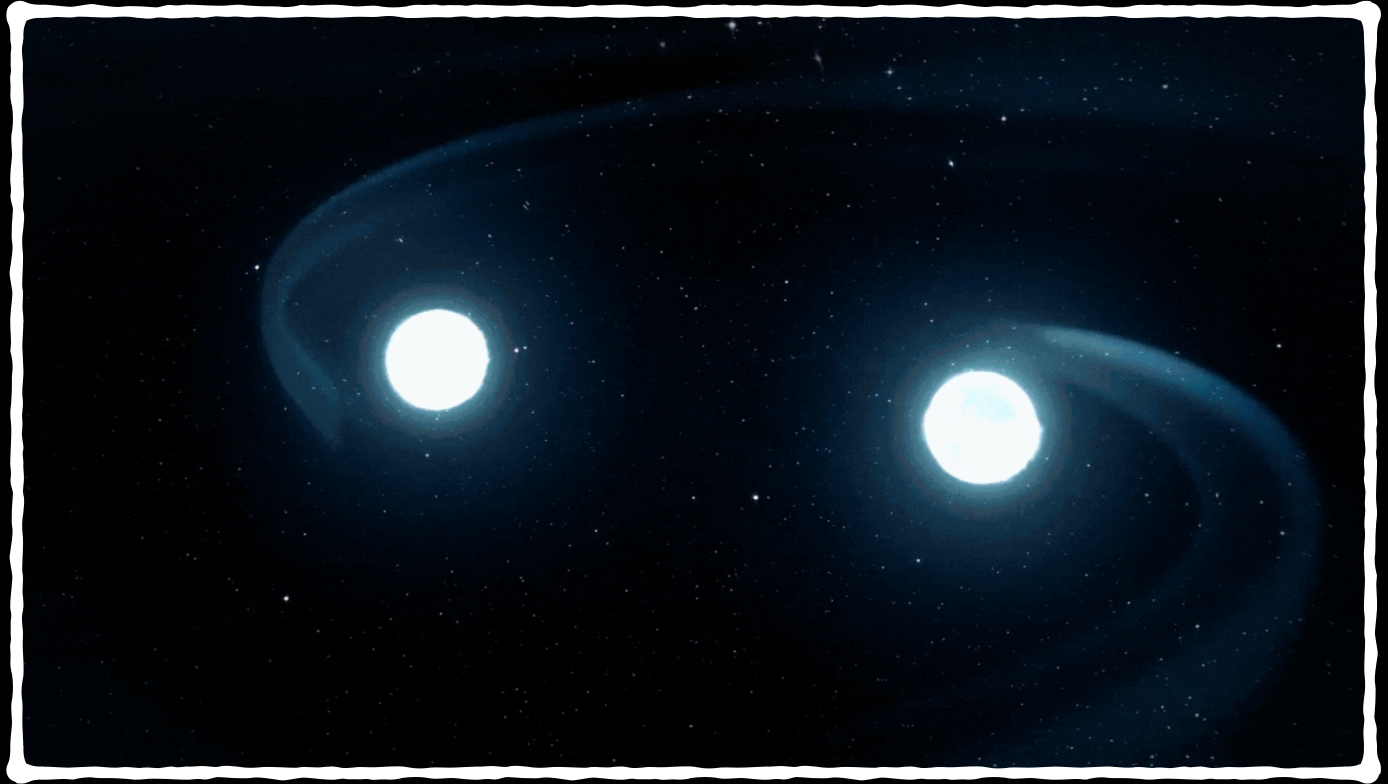
See Maria Grazia's talk!

Long

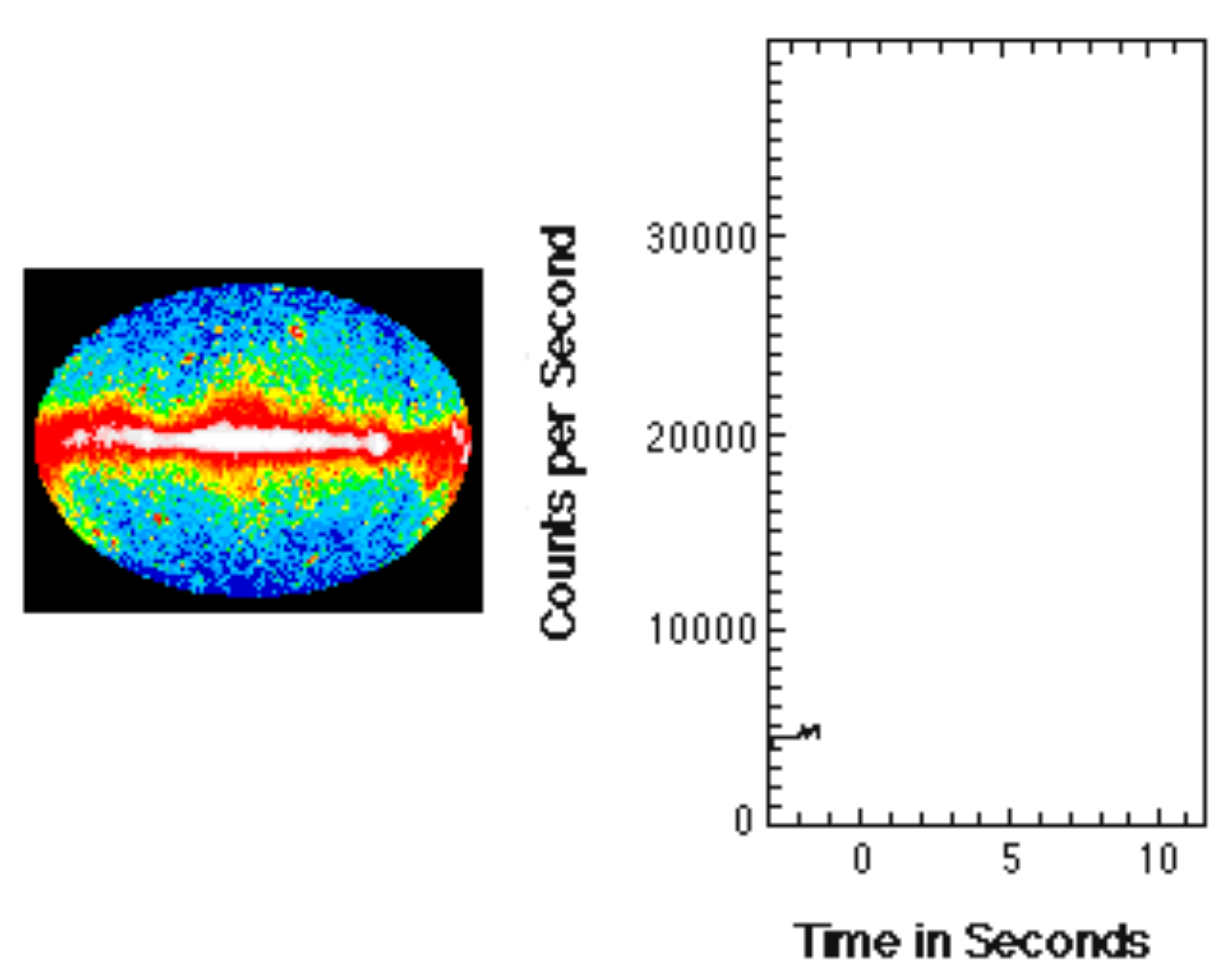


Credits: NASA's Goddard Space Flight Center

Short



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



A GRB detected by *BATSE* on-board the Compton Gamma-Ray Observatory

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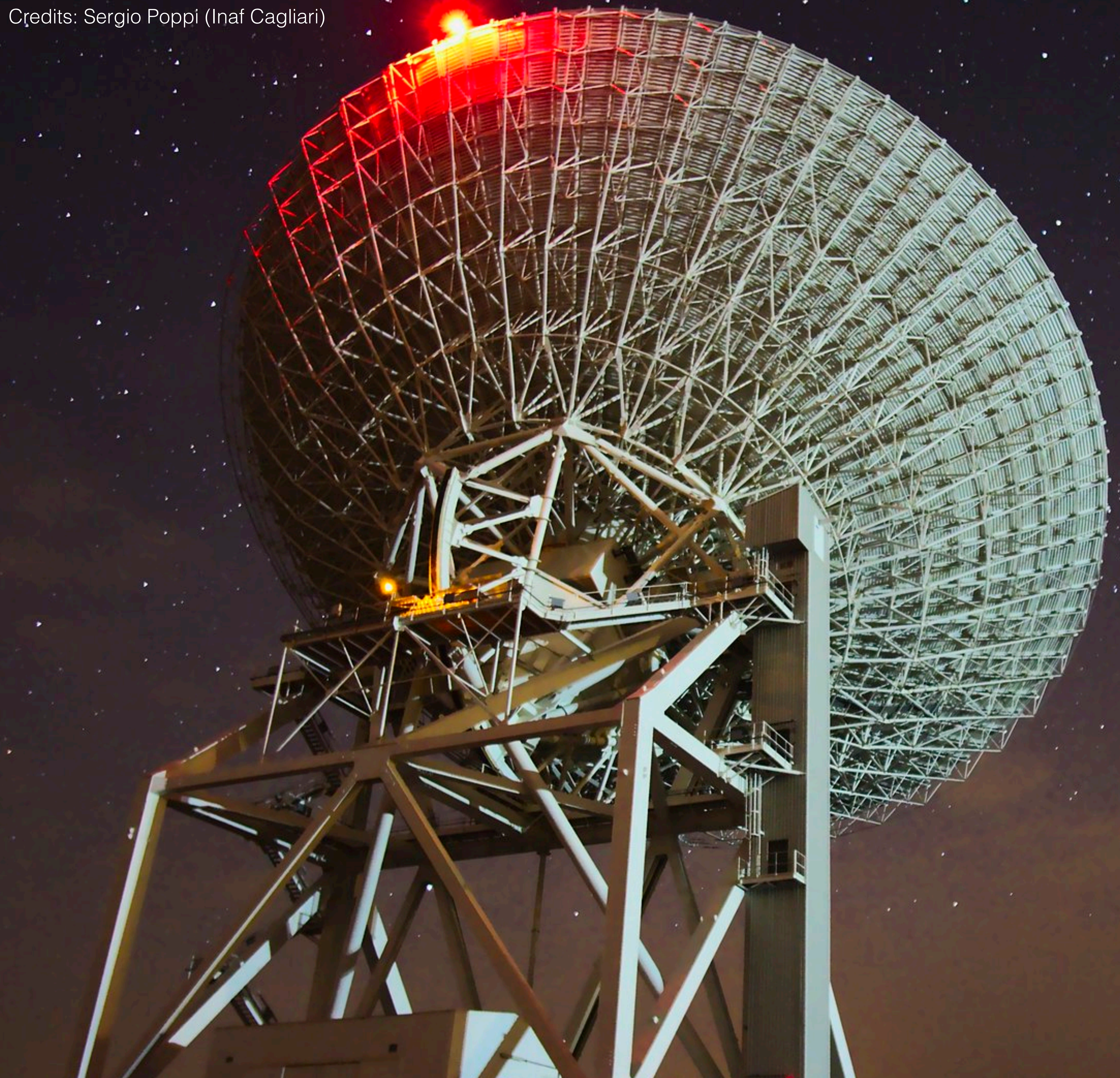
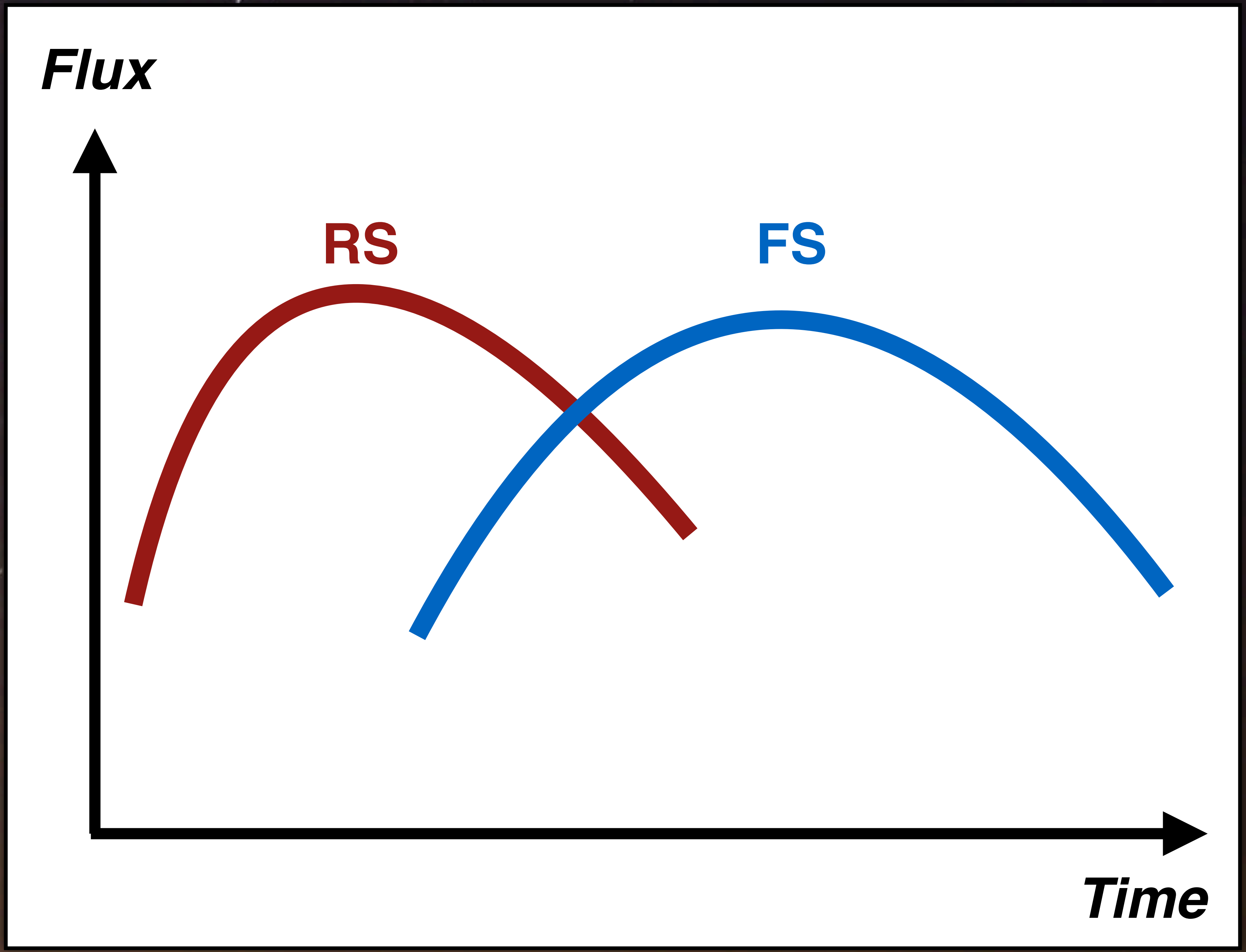
Credits: Sergio Poppi (Inaf Cagliari)



GRBs in Radio

Emission mechanism

Forward vs Reverse shocks



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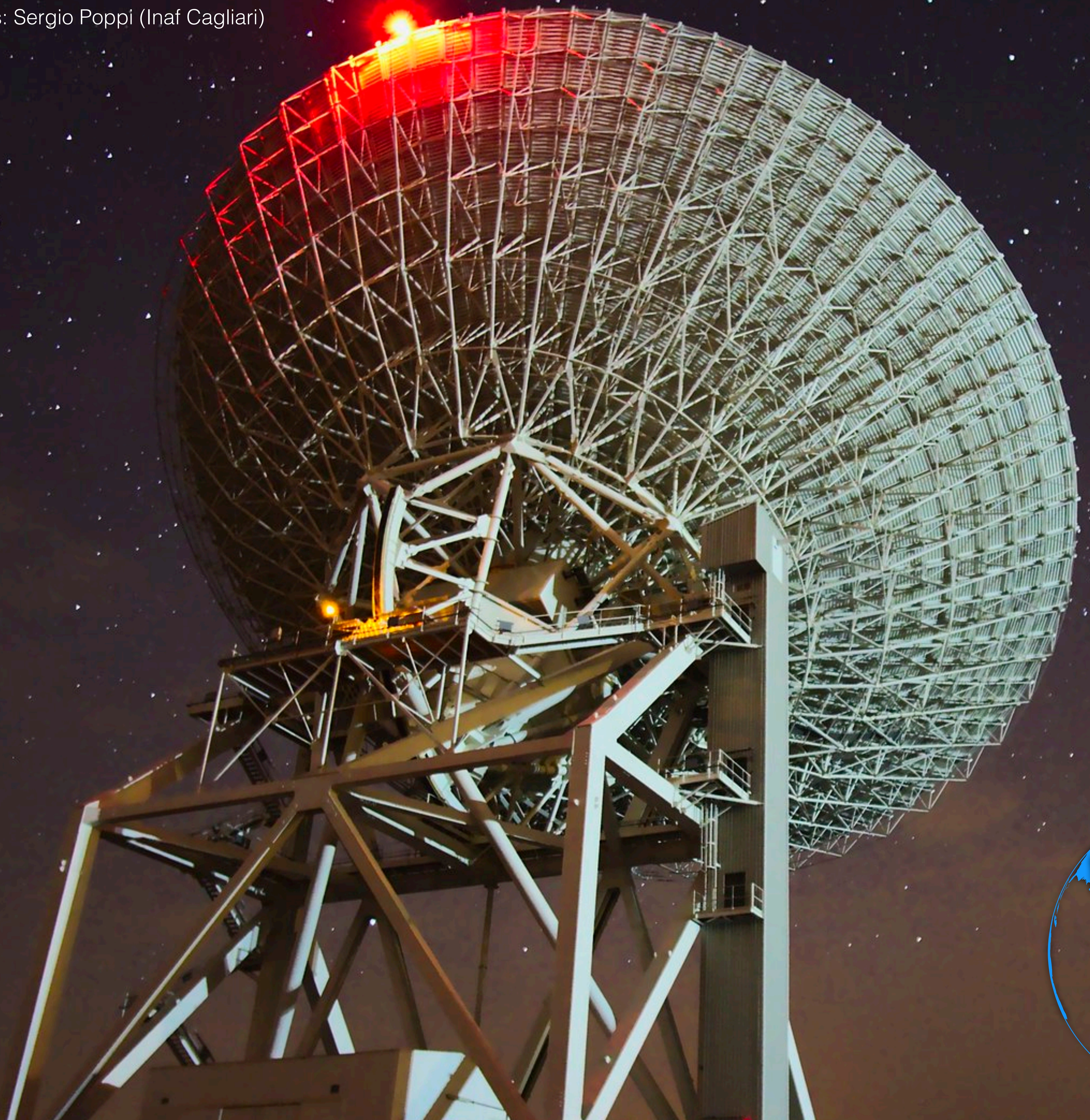


GRBs in Radio

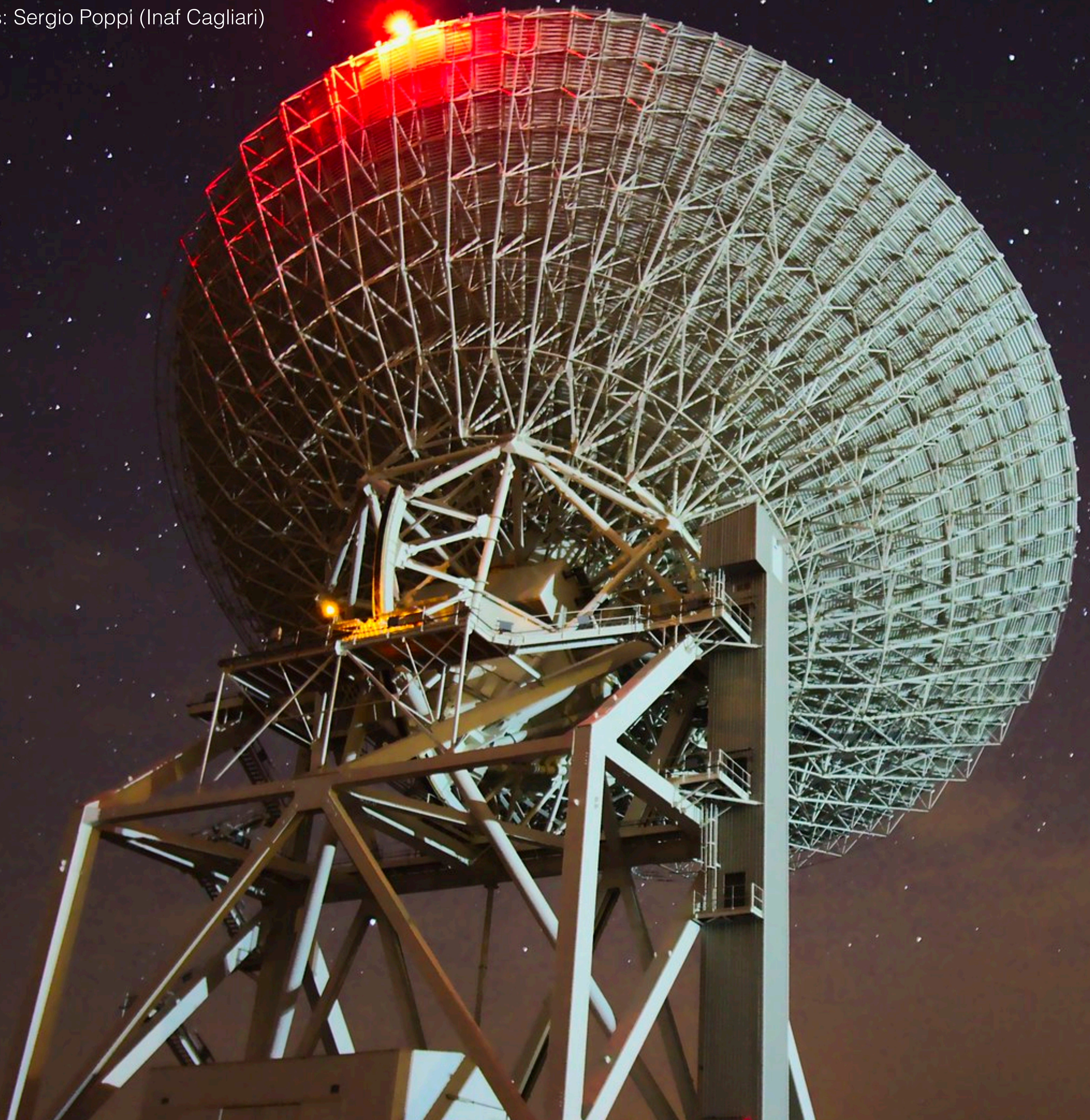
Geometry

Viewing angle

Collimation angle

Size and structure

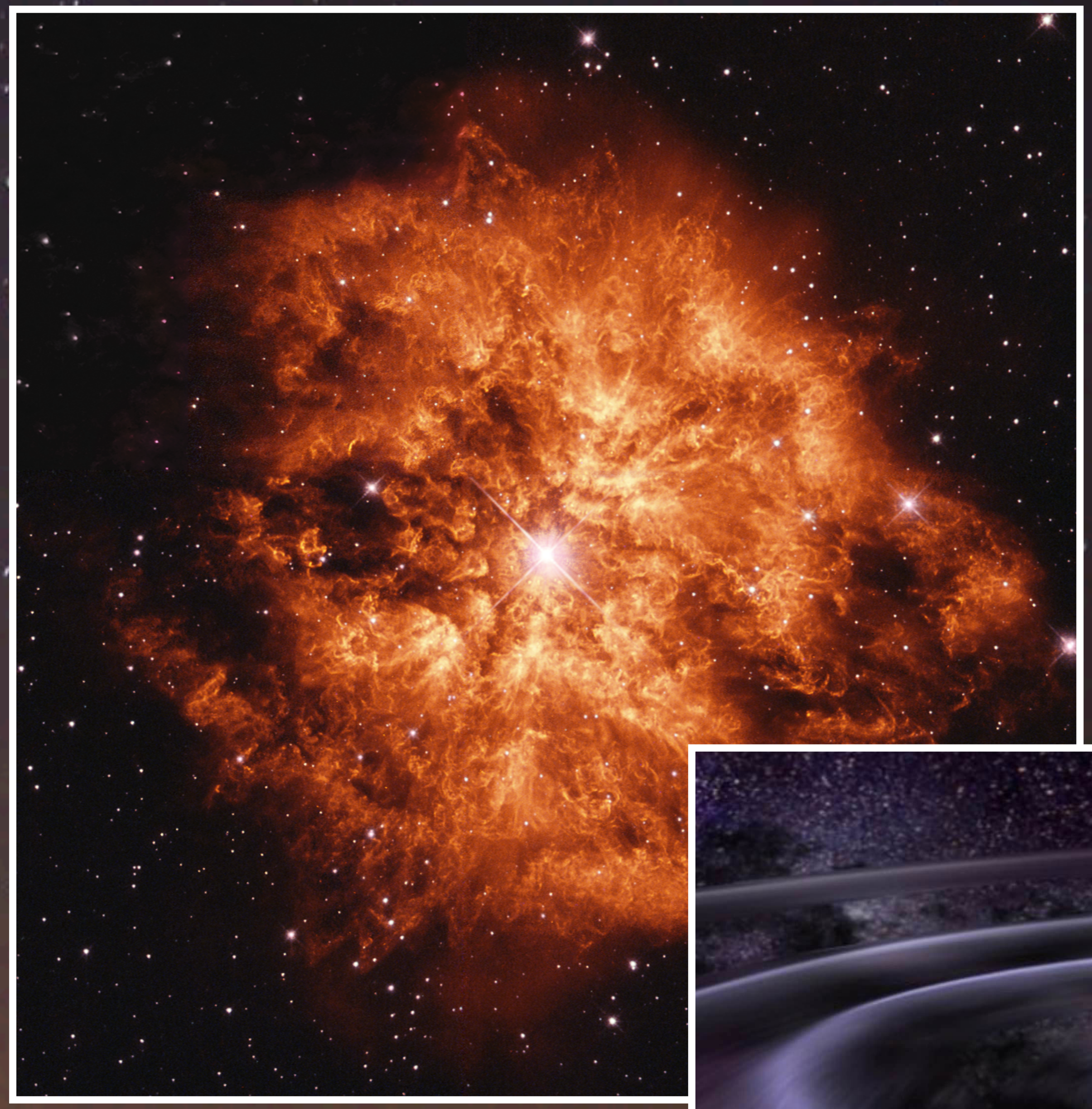
Credits: Sergio Poppi (Inaf Cagliari)

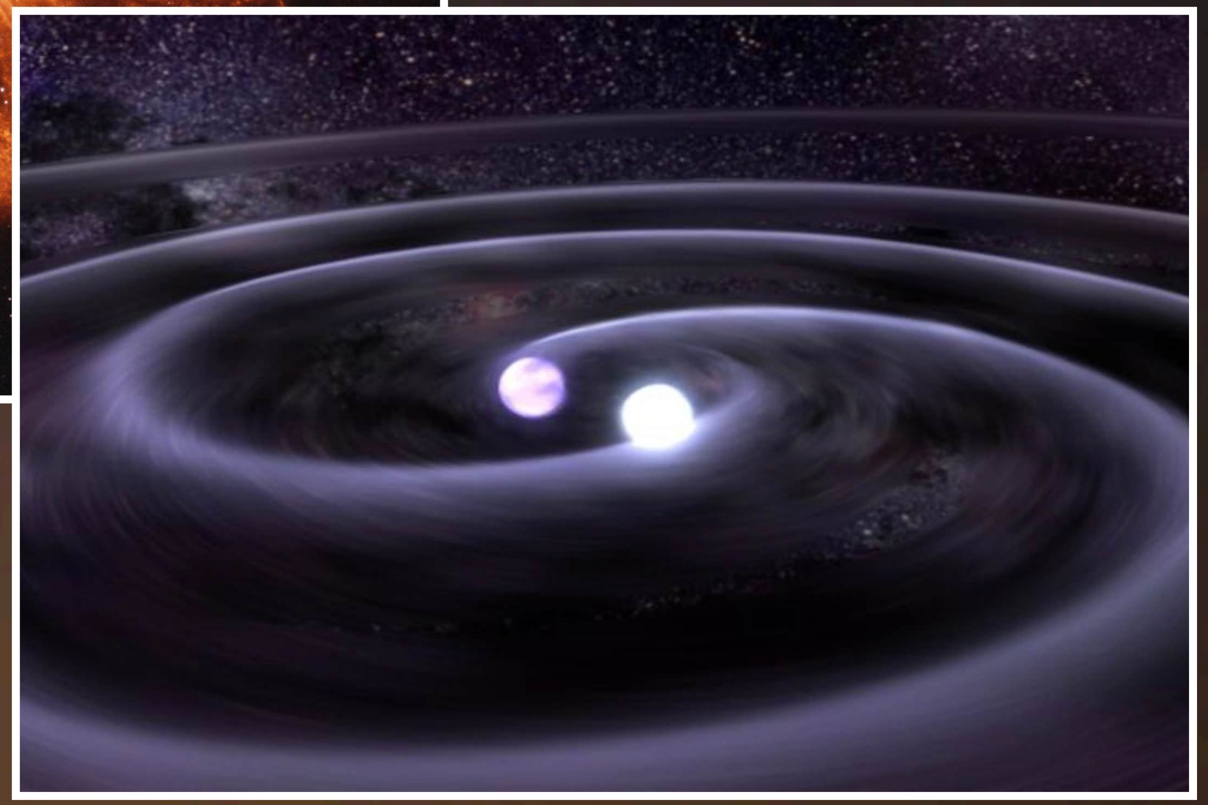


GRBs in Radio

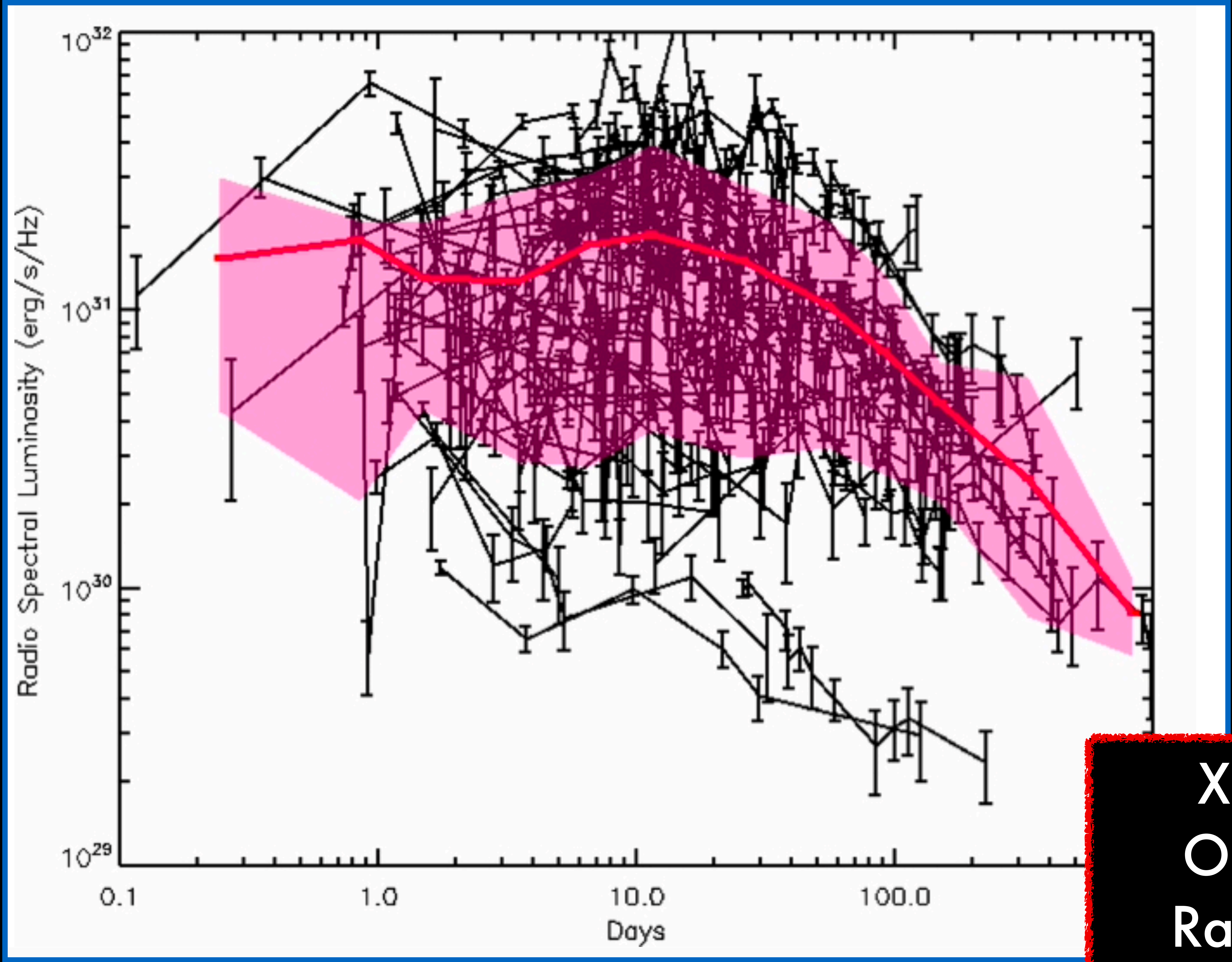
Progenitors

Circum-burst density profile





A general view

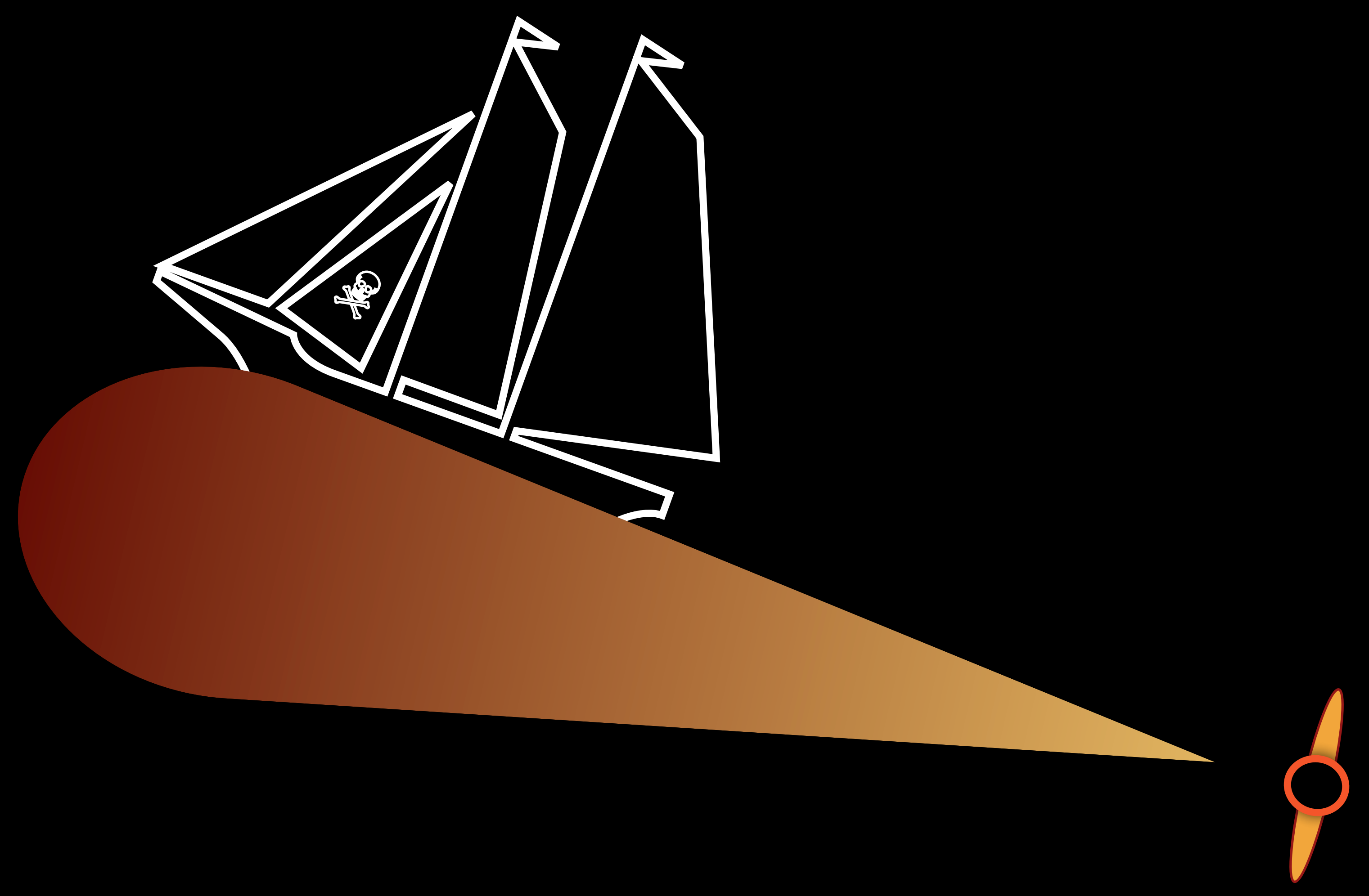


X-rays: 95%
Optical: 70%
Radio: 31% (*)

From *Chandra & Frail (2012)*

GRB 221009A

the Brightest Of All Time

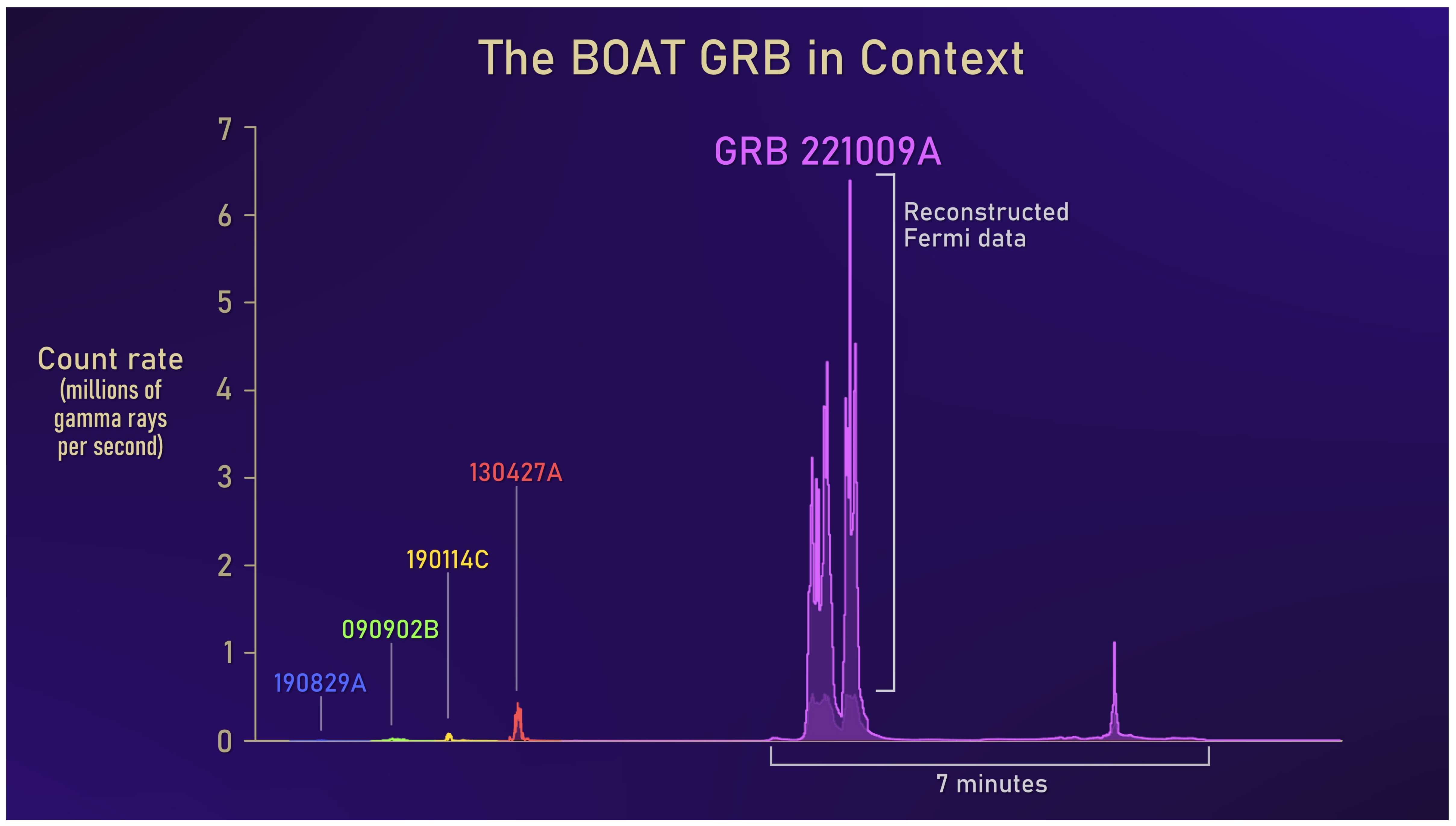


GRB 221009A

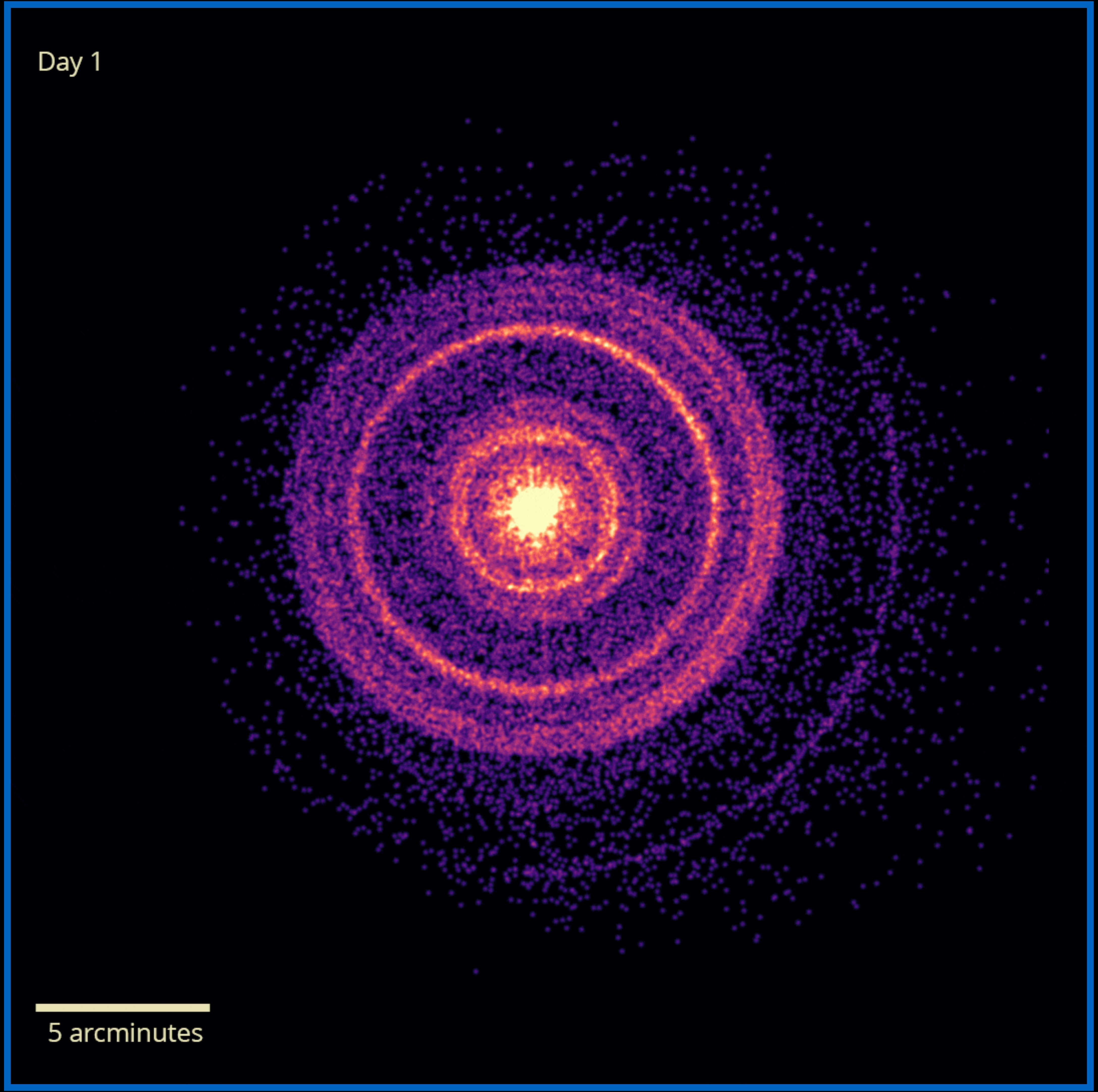
$E_{iso} \simeq 3 \times 10^{54}$ erg

$z = 0.151$

$R = 1/10000\, yr^{-1}$



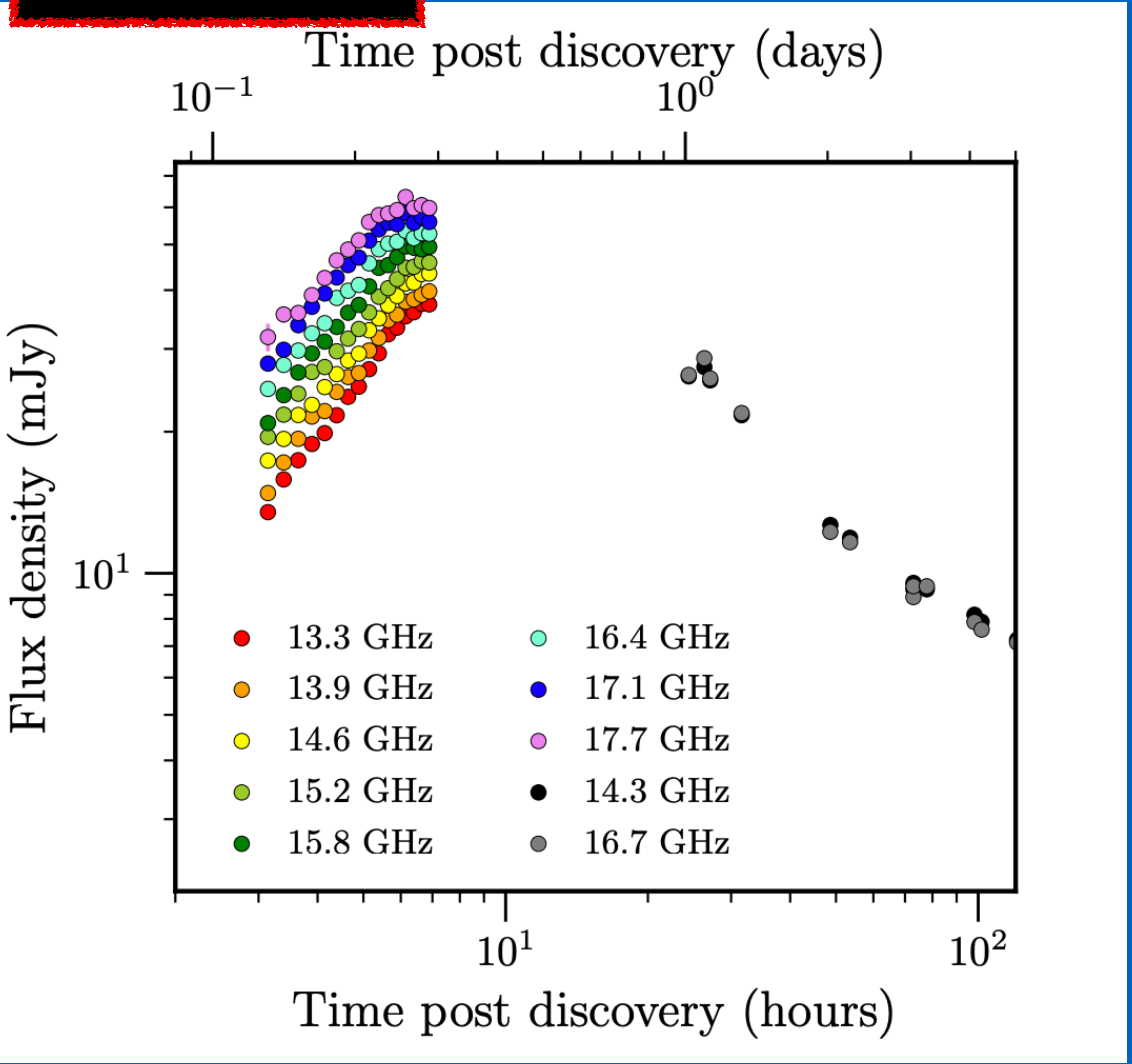
Credit: NASA's Goddard Space Flight Center and Adam Goldstein (USRA)



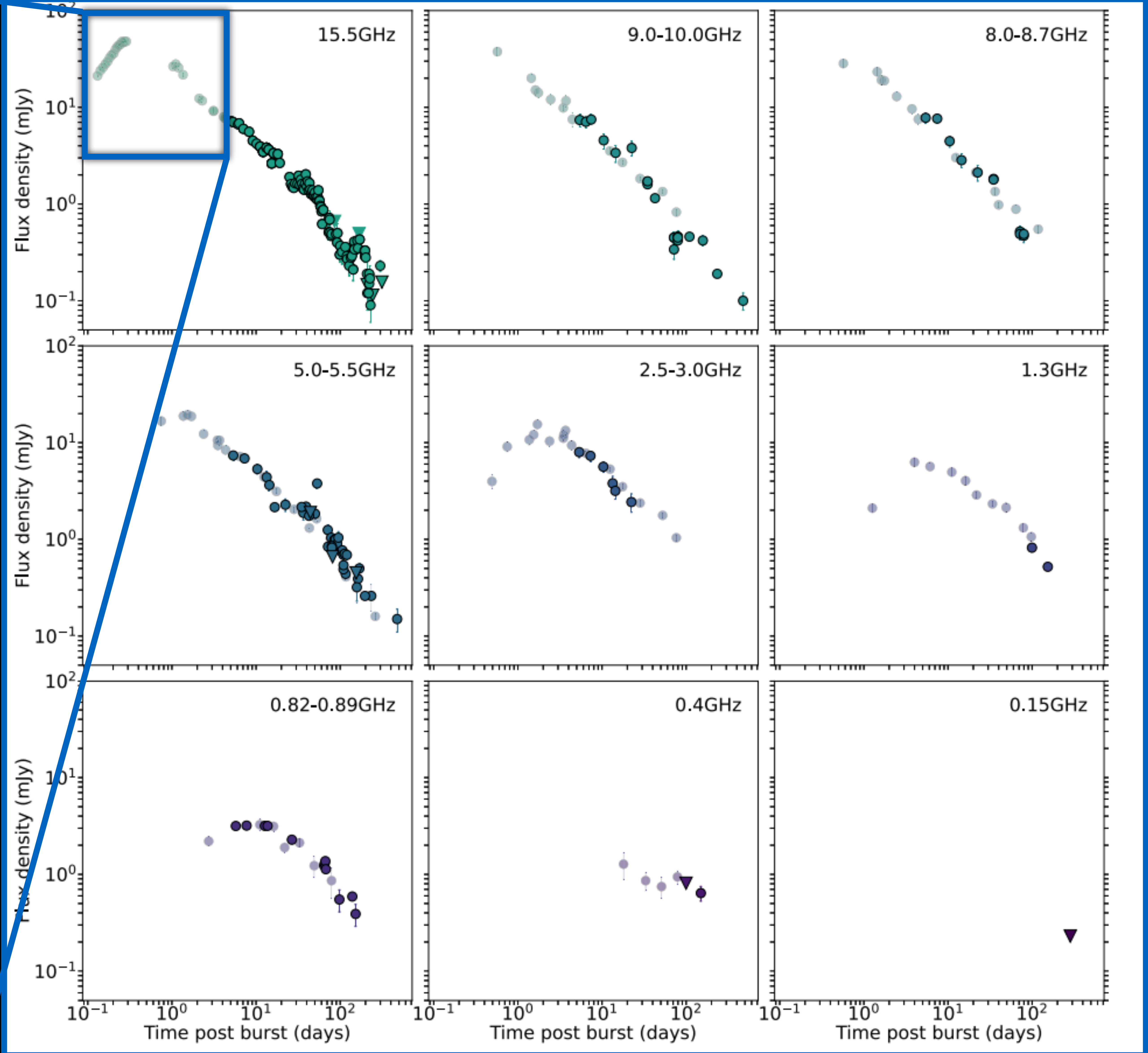
Credit: NASA/Swift/A. Beardmore (Univ of Leicester)

GRB 221009A

Self-absorbed RS emission

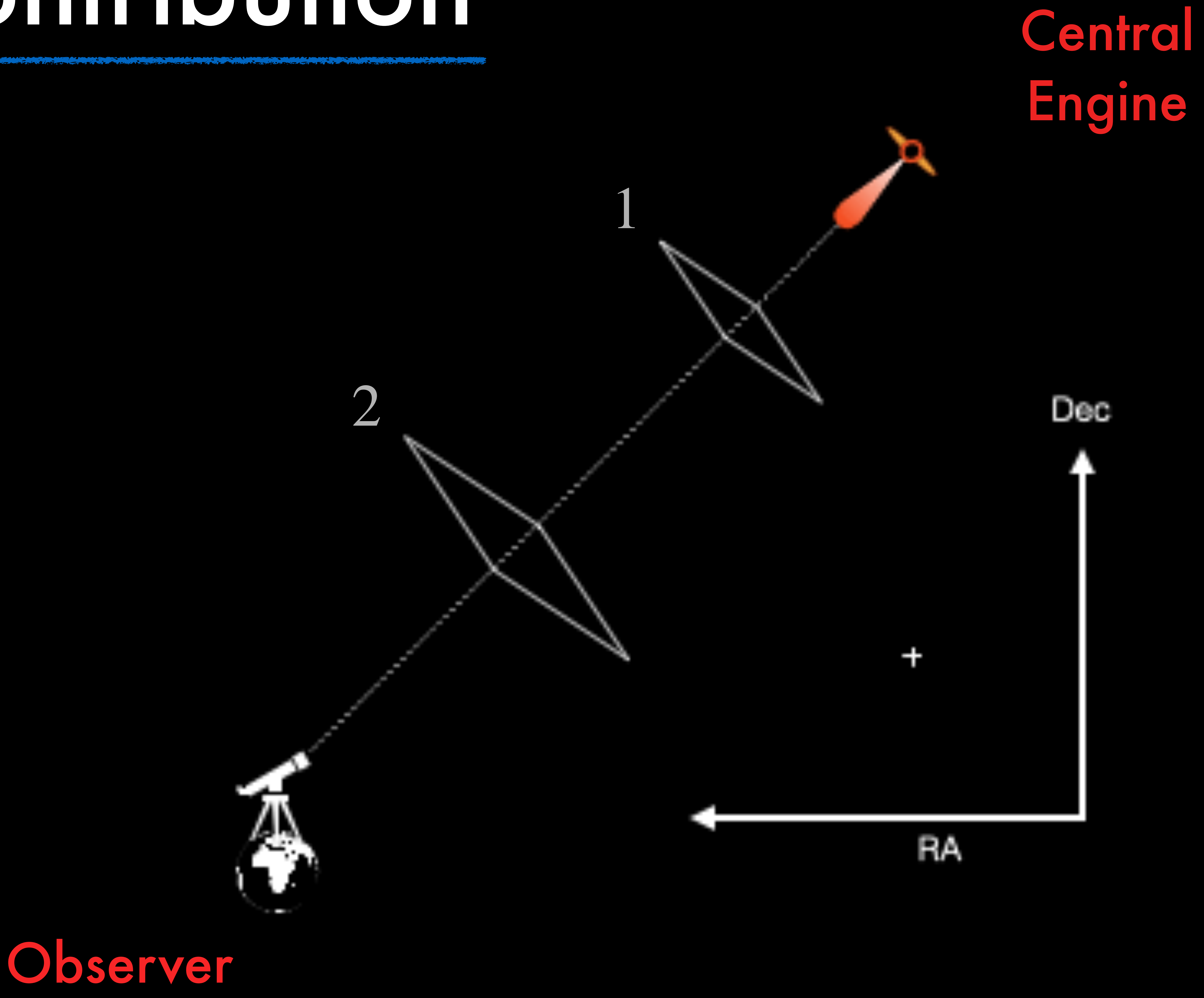


From *Bright, ..., SG et al. (2023)*

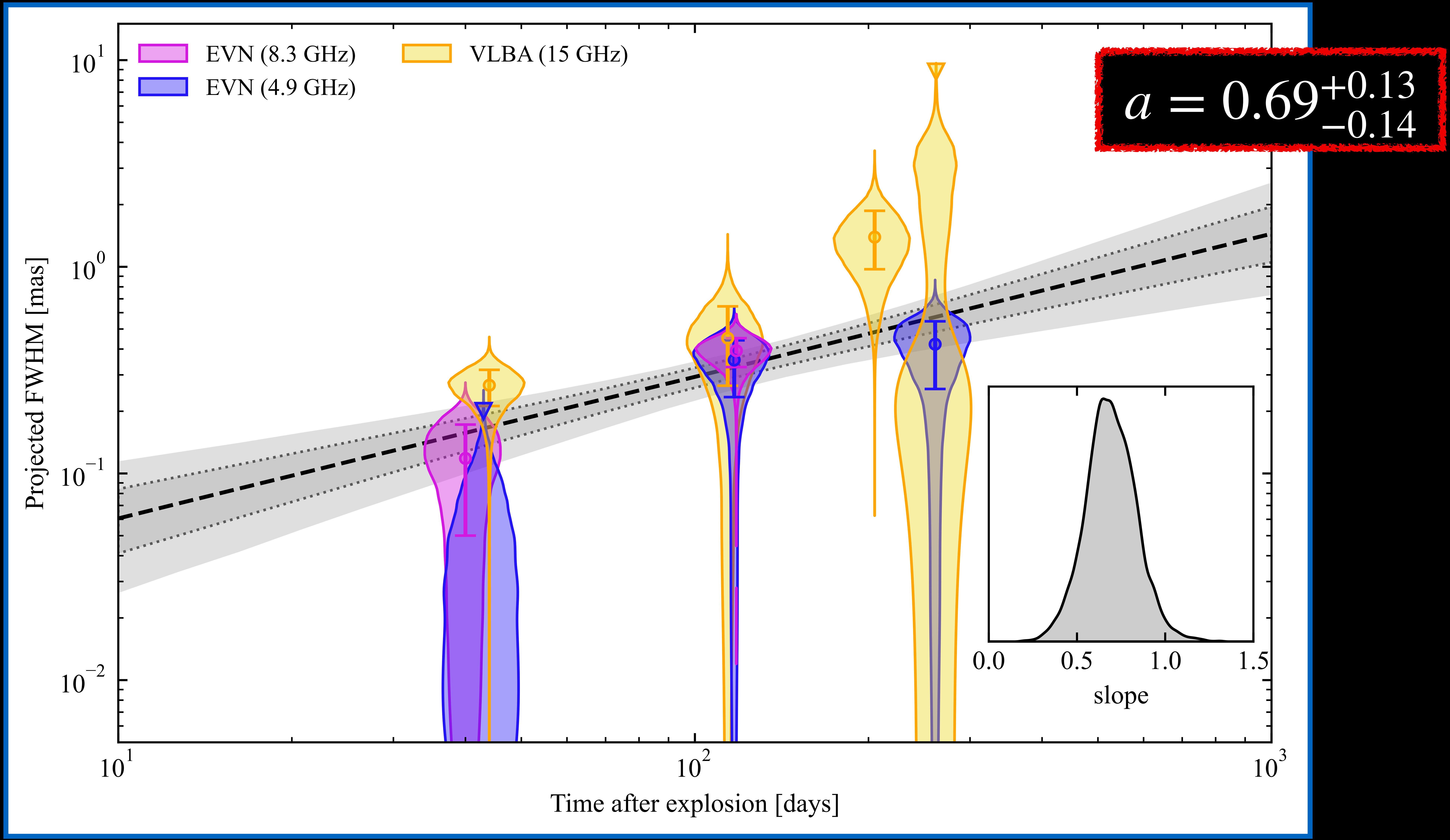


From *Rhodes, ..., SG et al. (2024)*

VLBI contribution



GRB 221009A



Apparent size evolution.
From *Giarratana et al. (2024)*

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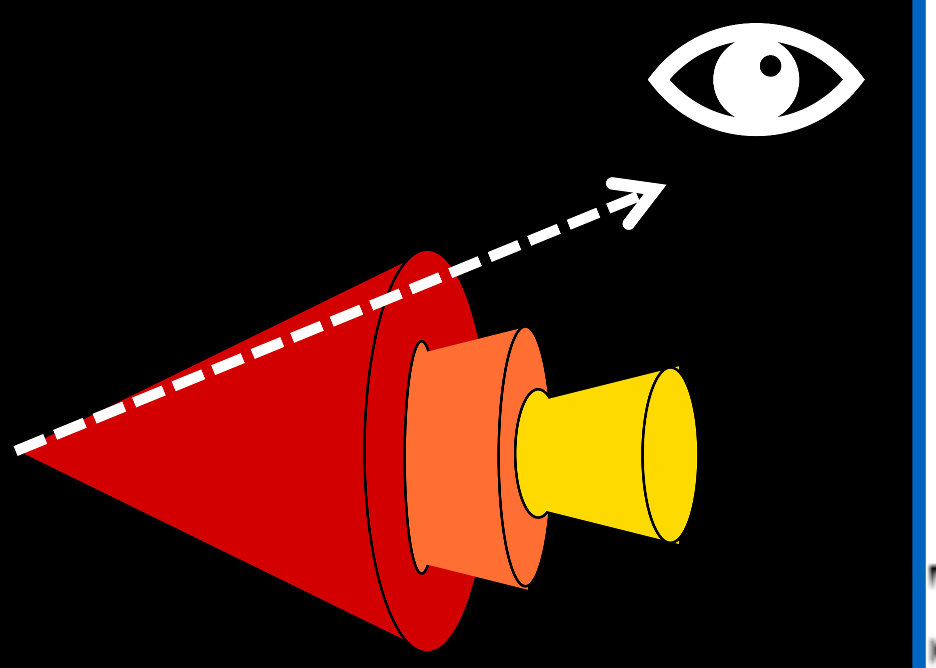
GRB 170817A

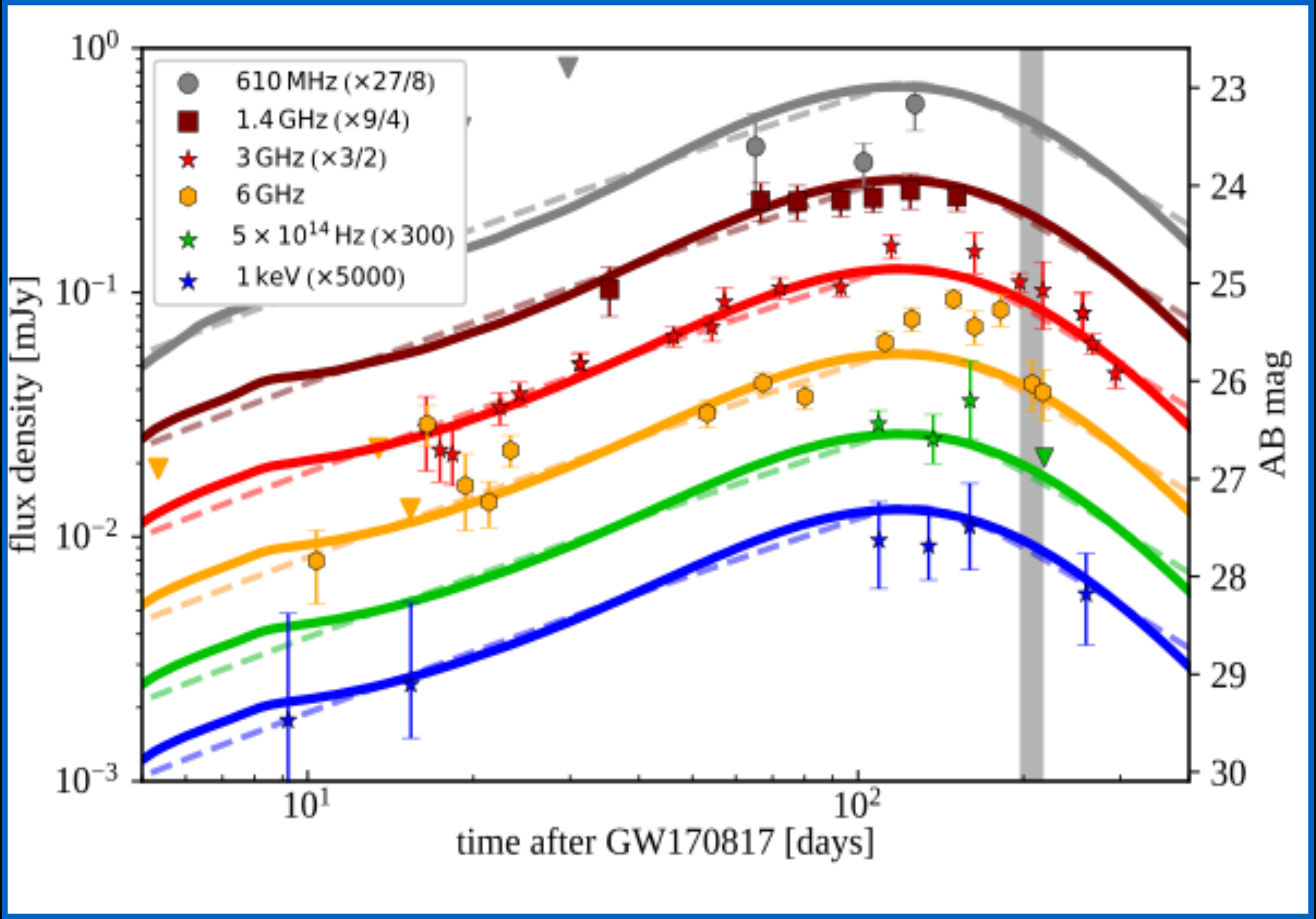
... the only one, so far 🥲

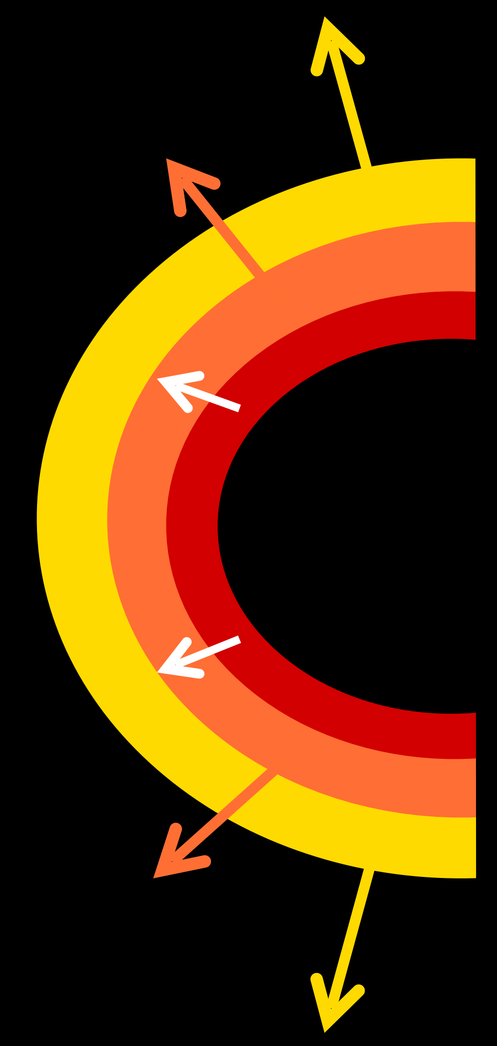
GRB 170817A



$\Gamma_1 < \Gamma_2 < \Gamma_3$

$E_1 < E_2 < E_3$



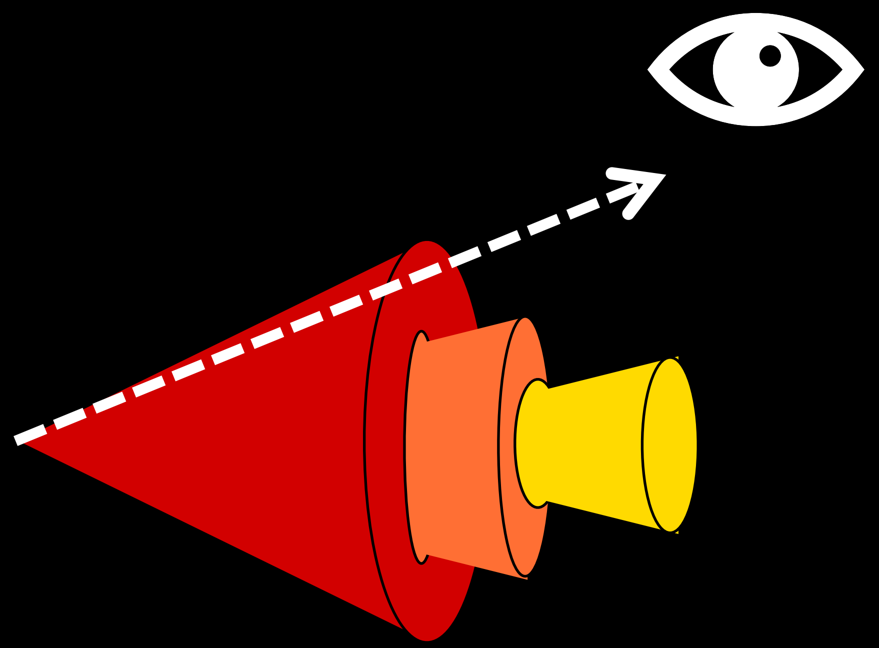


$\Gamma_1 < \Gamma_2 < \Gamma_3$

$E_1 > E_2 > E_3$

From *Ghirlanda et al. (2019)*

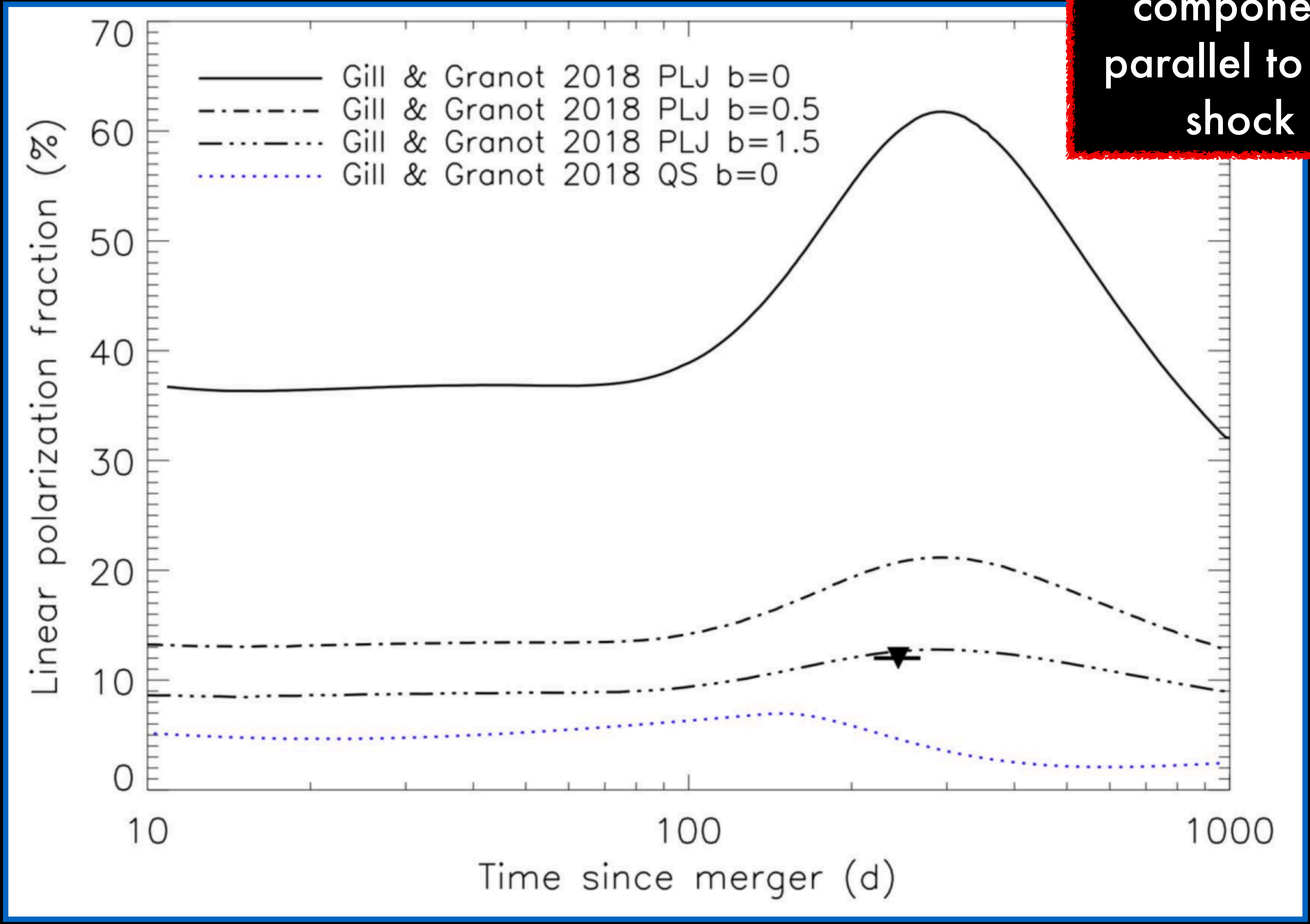
GRB 170817A



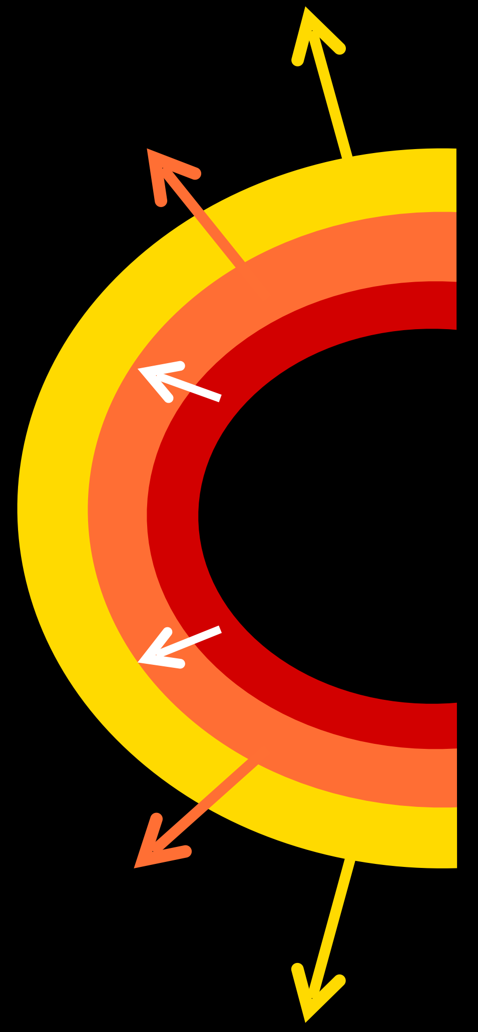
$\Gamma_1 < \Gamma_2 < \Gamma_3$

$E_1 < E_2 < E_3$

PLJ



Low B component parallel to the shock



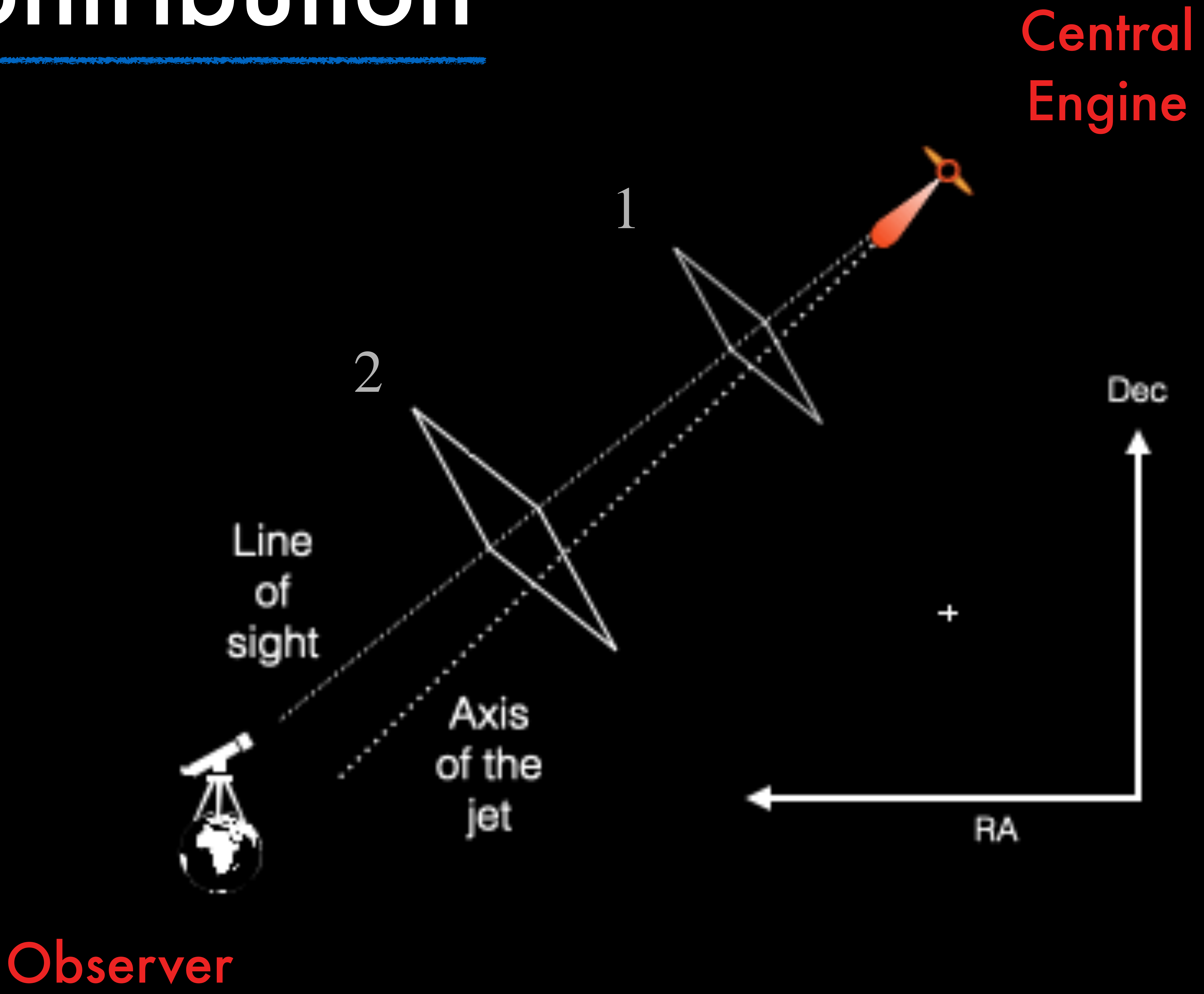
$\Gamma_1 < \Gamma_2 < \Gamma_3$

$E_1 > E_2 > E_3$

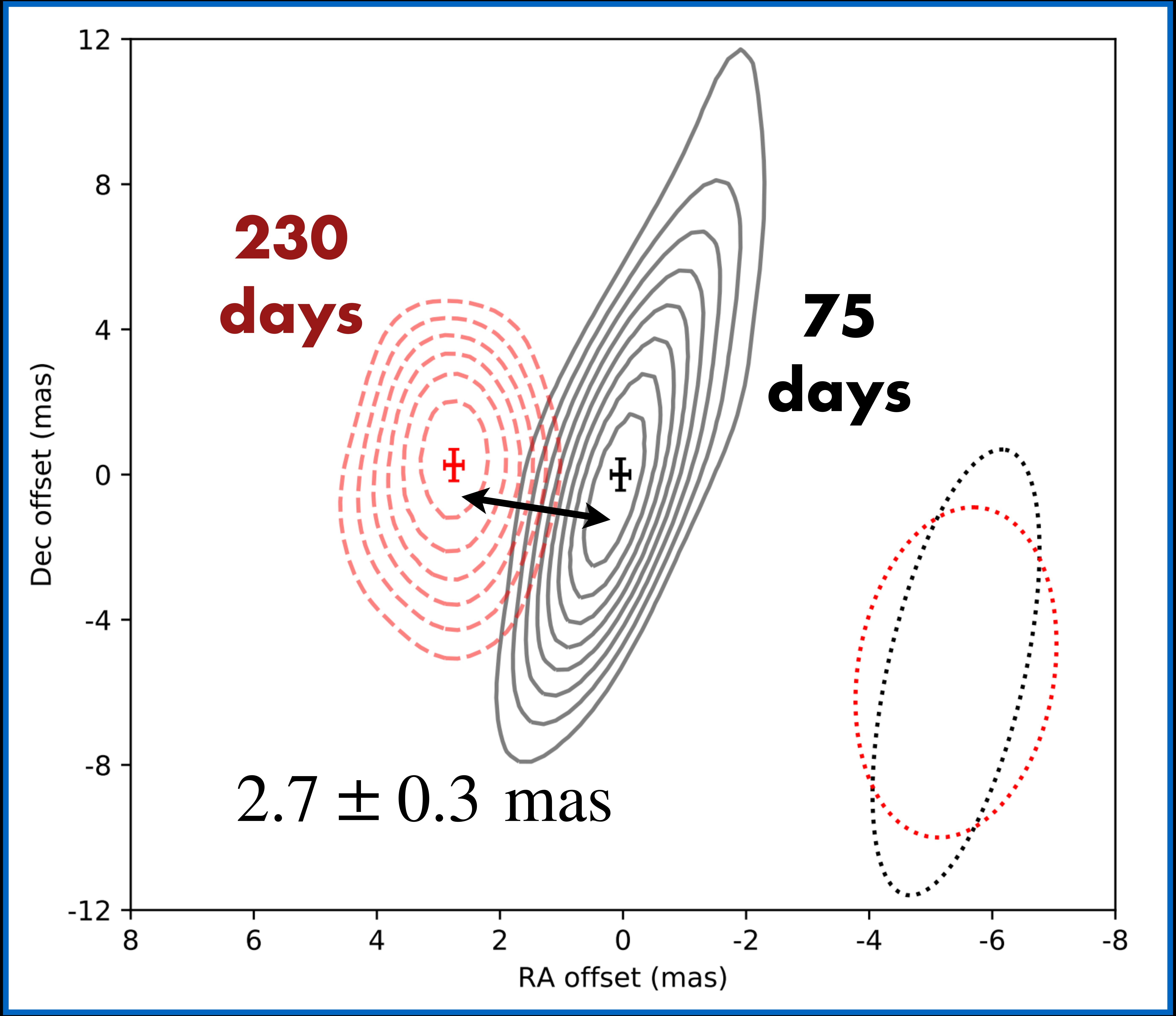
QS

From *Corsi et al. (2018)*

VLBI contribution



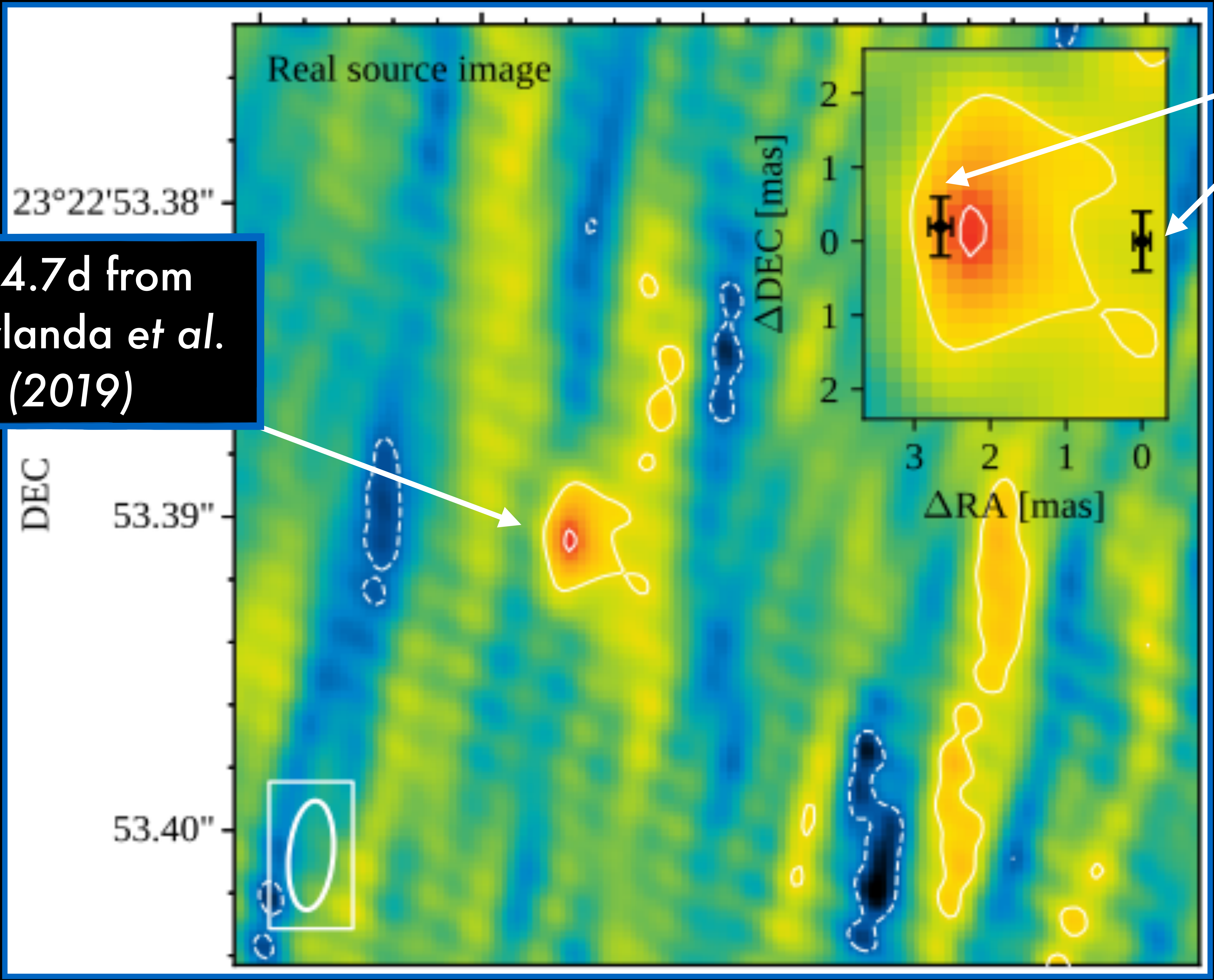
GRB 170817A



From *Mooley et al. (2018)*

A (slightly) off-axis GRB

GRB 170817A



75d & 230d from *Mooley et al.* (2018)

204.7d from Ghirlanda *et al.* (2019)

First proof of successful jet from a BNS merger

From *Ghirlanda et al. (2019)*

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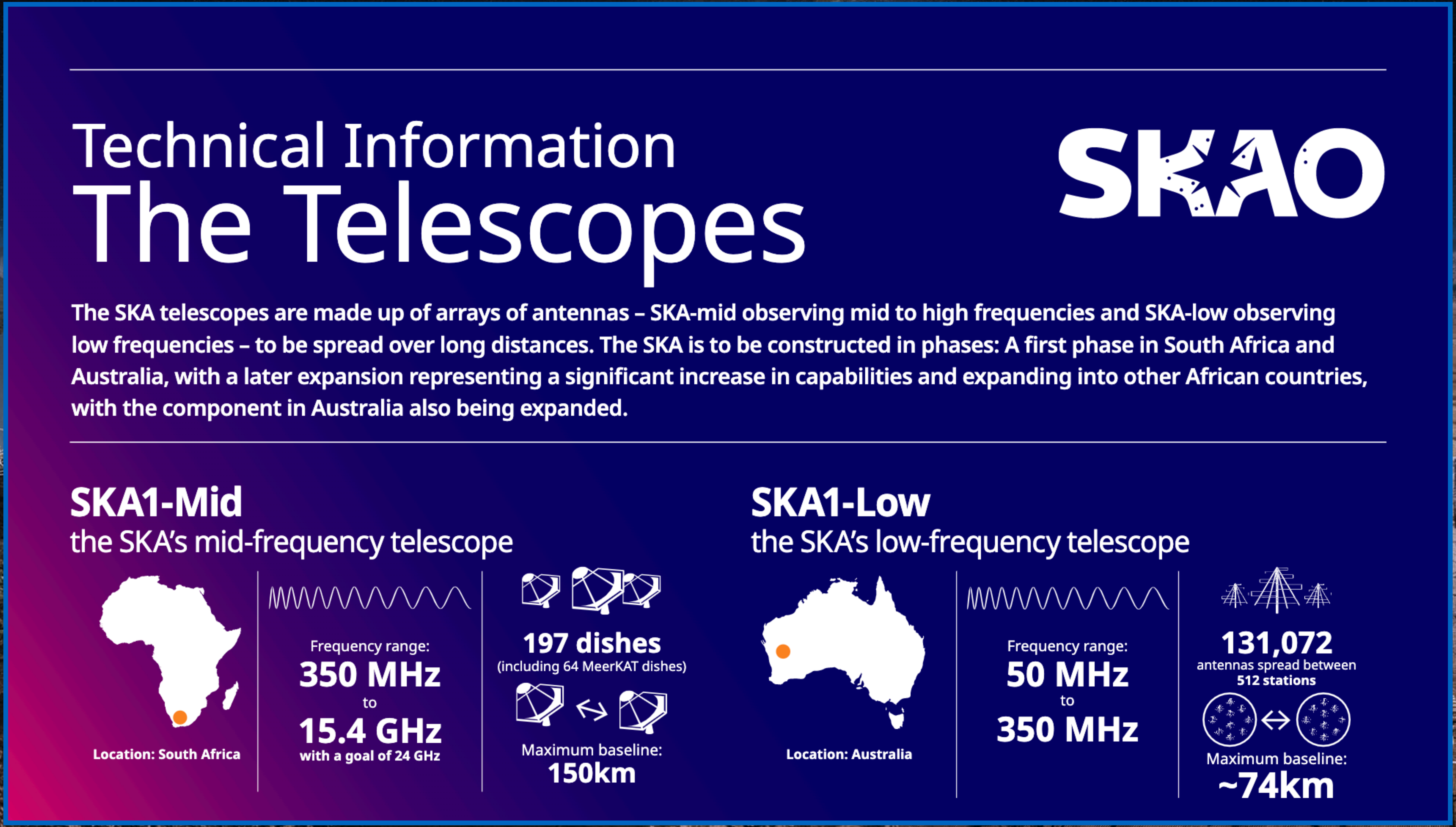
The Square Kilometer Array



Technical Information
The Telescopes

The SKA telescopes are made up of arrays of antennas – SKA-mid observing mid to high frequencies and SKA-low observing low frequencies – to be spread over long distances. The SKA is to be constructed in phases: A first phase in South Africa and Australia, with a later expansion representing a significant increase in capabilities and expanding into other African countries, with the component in Australia also being expanded.

SKA1-Mid
the SKA's mid-frequency telescope

Location: South Africa

Frequency range:
350 MHz
to
15.4 GHz
with a goal of 24 GHz

197 dishes
(including 64 MeerKAT dishes)

Maximum baseline:
150km

SKA1-Low
the SKA's low-frequency telescope

Location: Australia

Frequency range:
50 MHz
to
350 MHz

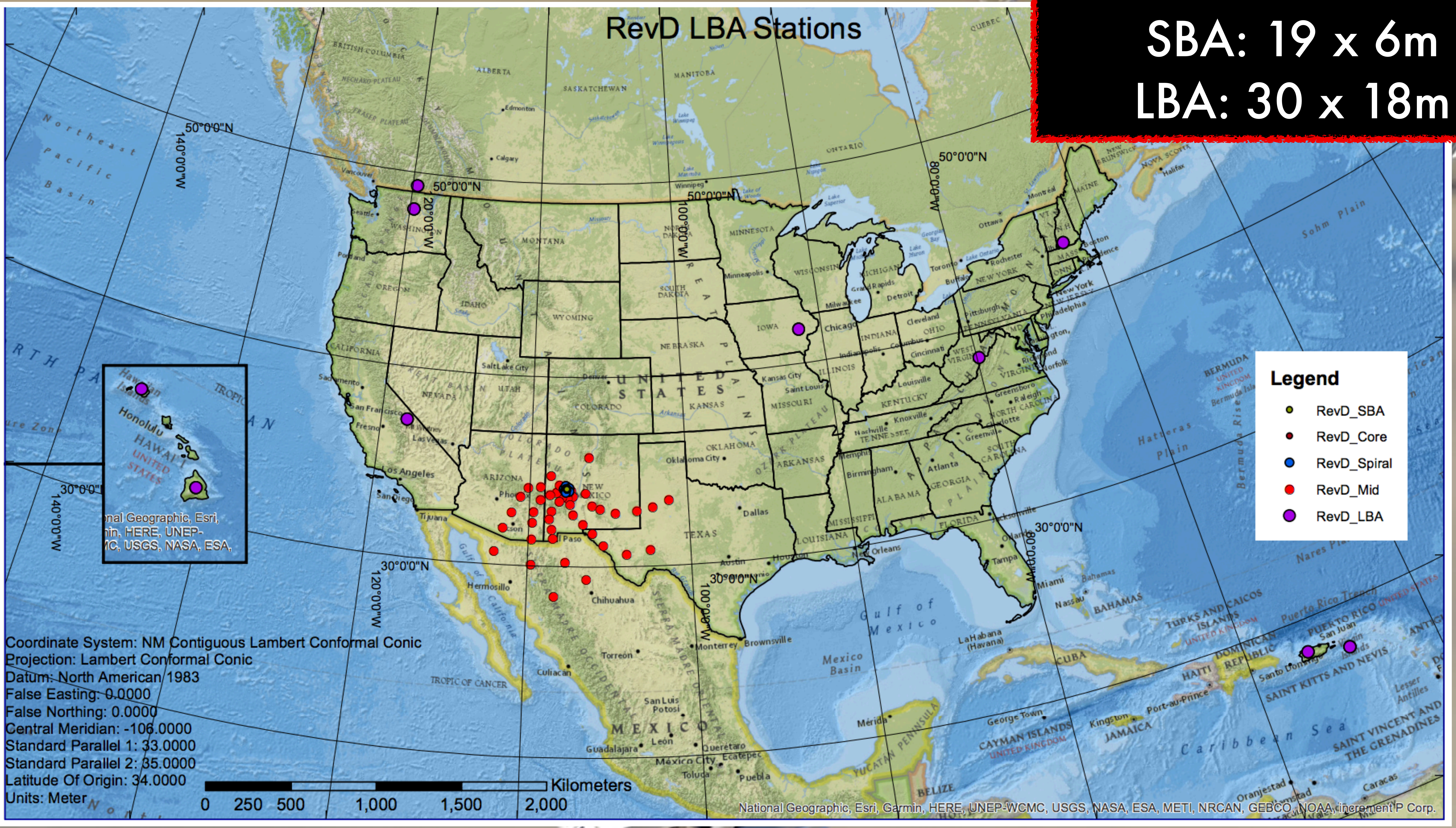
131,072
antennas spread between 512 stations

Maximum baseline:
~74km

SKA info sheet from the public SKAO website

The ngVLA

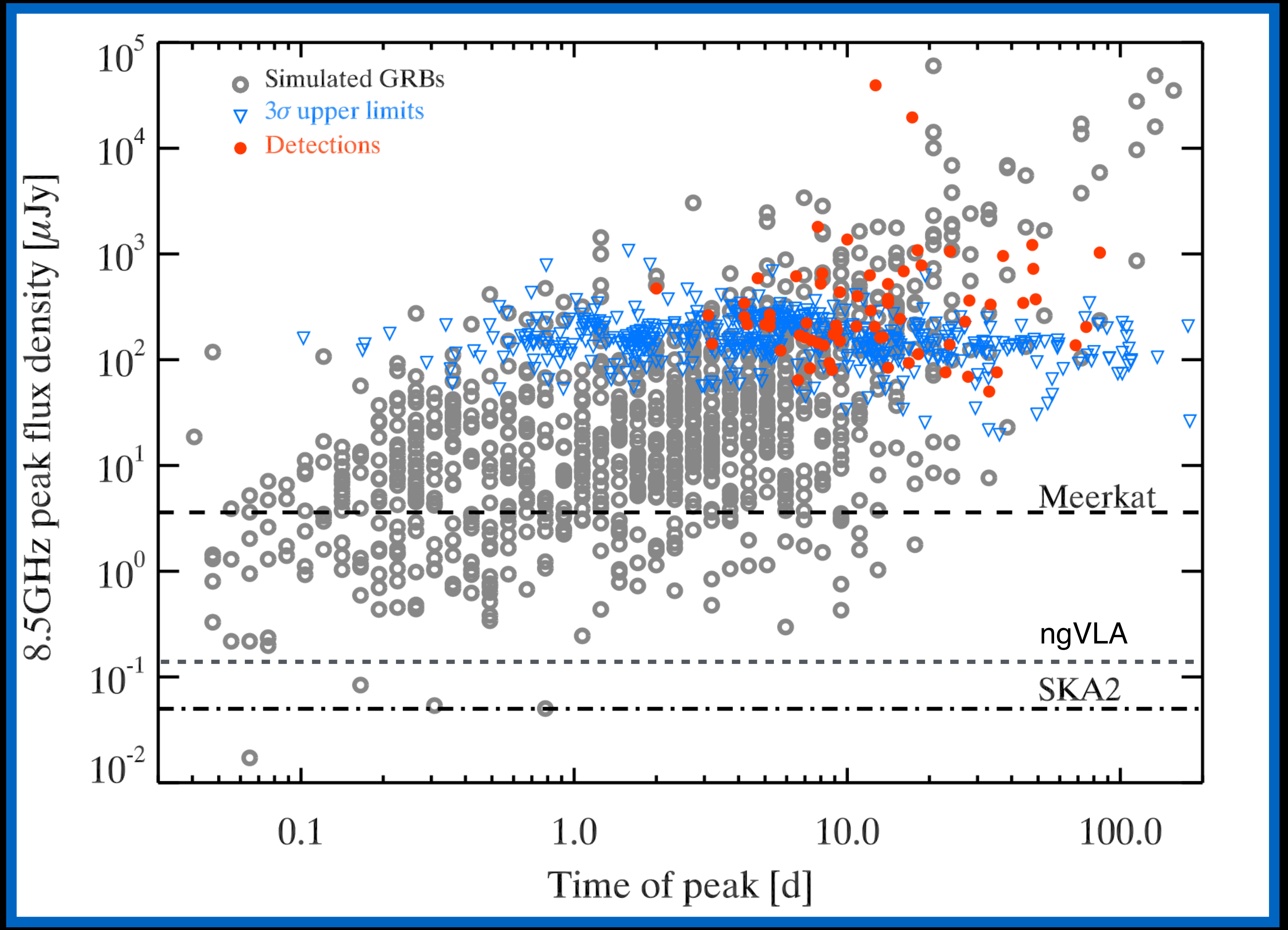
Main: 214 x 18m
SBA: 19 x 6m
LBA: 30 x 18m



From the public ngVLA website

GRBs in the SKA & ngVLA era

To be updated!

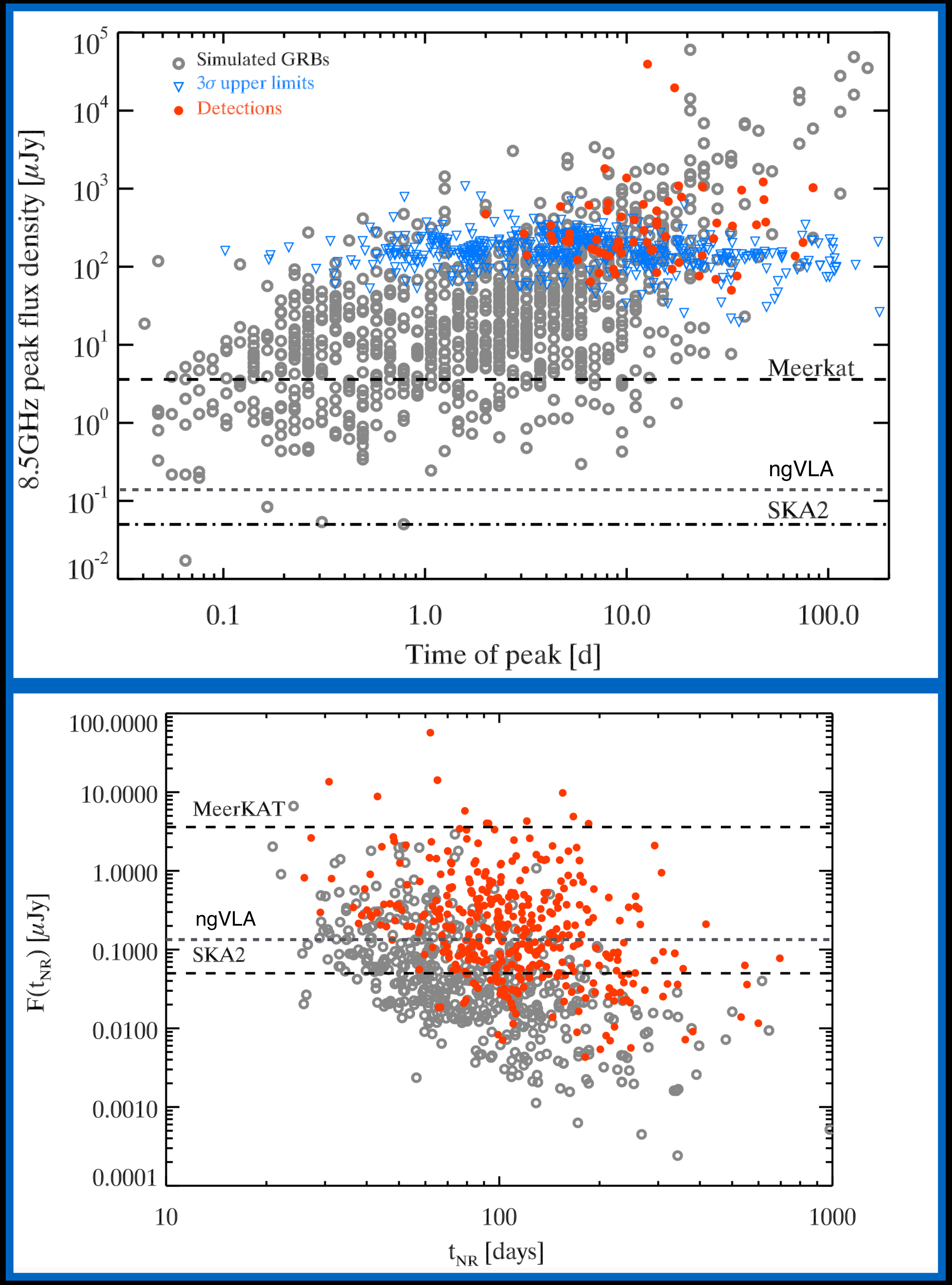


Adapted from *Ghirlanda et al. (2013)*

From 30% to almost 100% of detection rate

GRBs in the SKA & ngVLA era

To be updated!



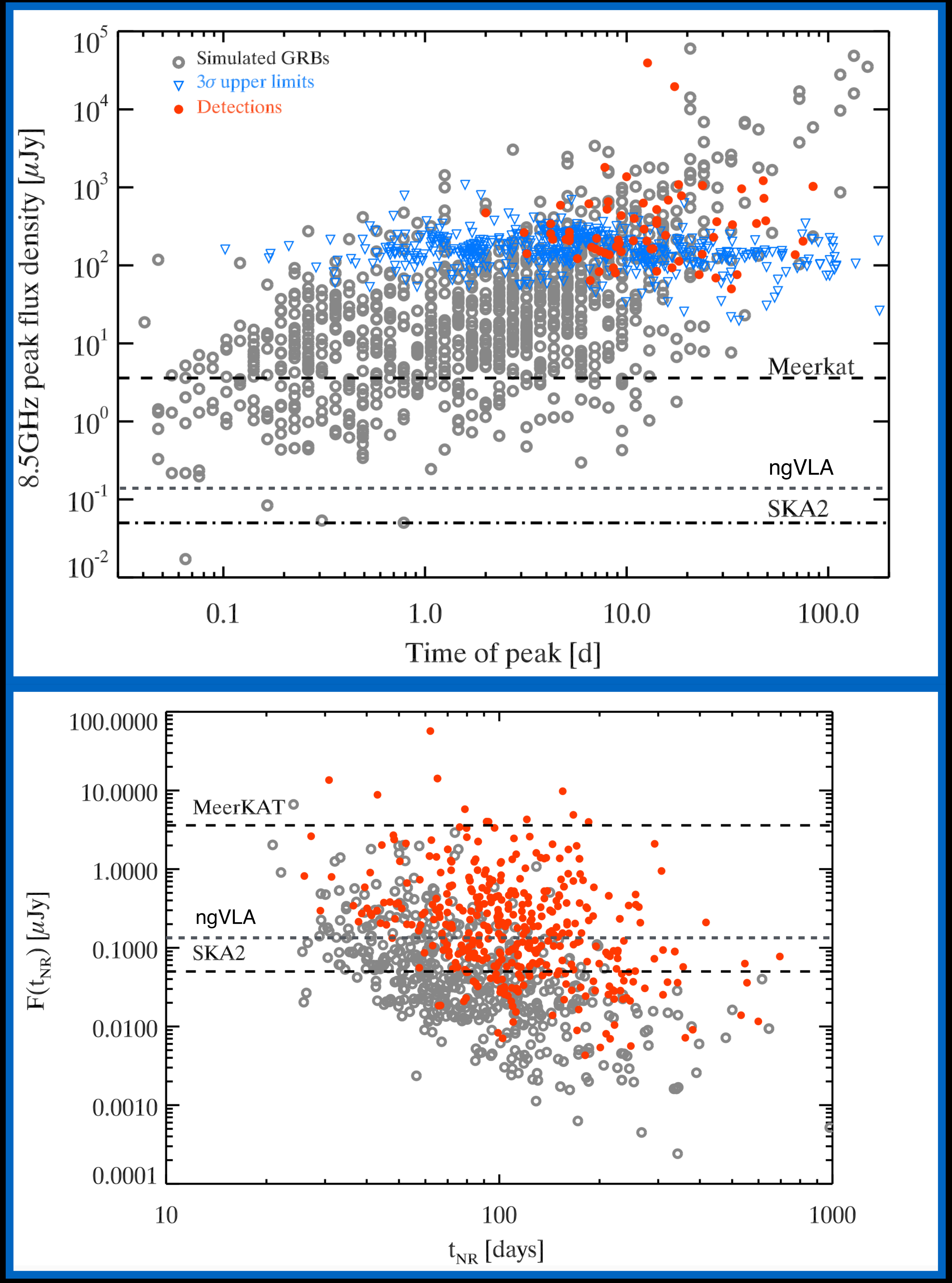
Adapted from *Ghirlanda et al. (2013)*

From 30% to almost 100% of detection rate

From <15% to almost 50% of detections at the transition time

GRBs in the SKA & ngVLA era

To be updated!



Adapted from *Ghirlanda et al. (2013)*

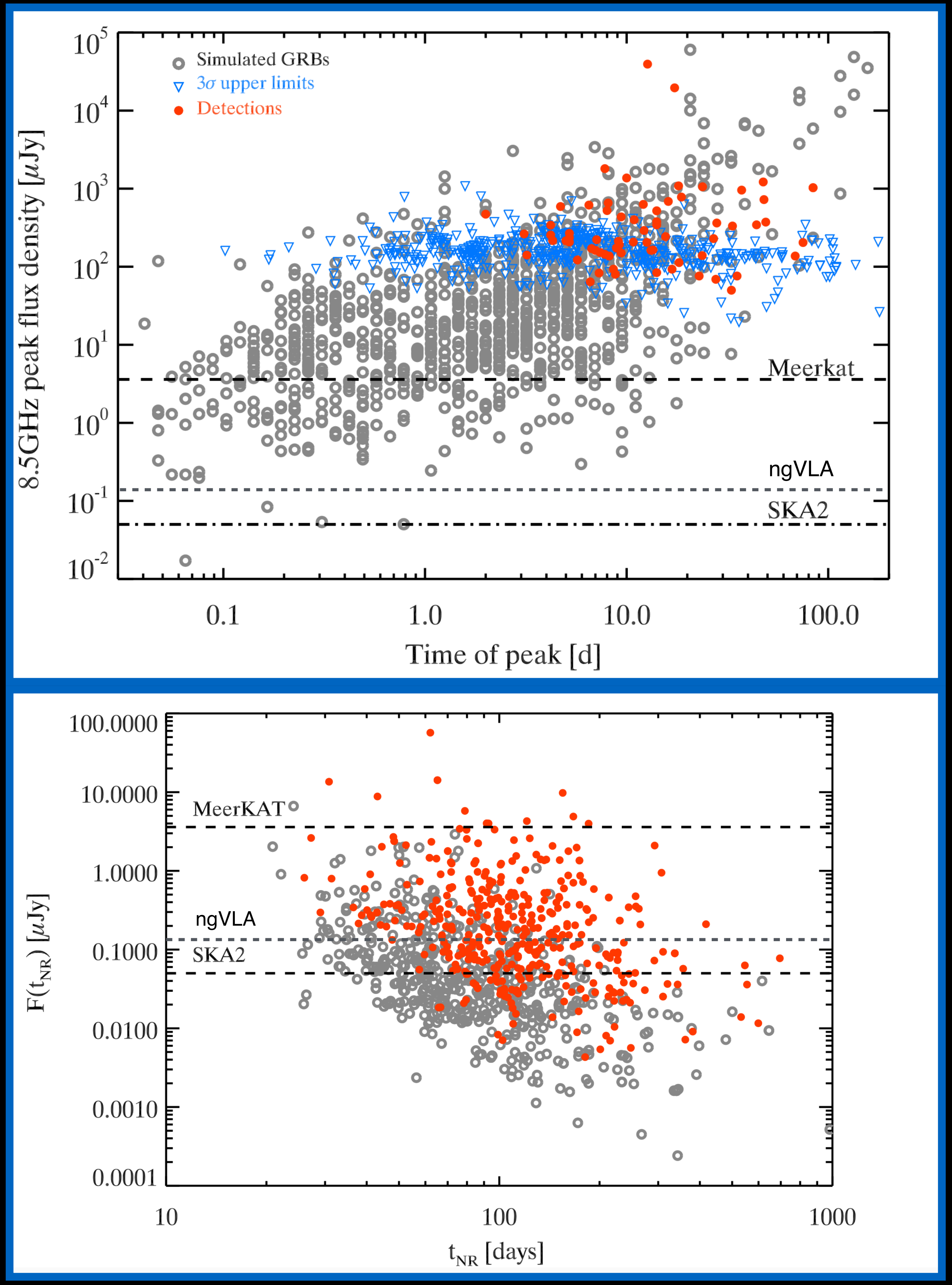
From 30% to almost 100% of detection rate

From <15% to almost 50% of detections at the transition time

+VLBI: structure and geometry

GRBs in the SKA & ngVLA era

To be updated!



Adapted from *Ghirlanda et al. (2013)*

From 30% to almost 100% of detection rate

From <15% to almost 50% of detections at the transition time

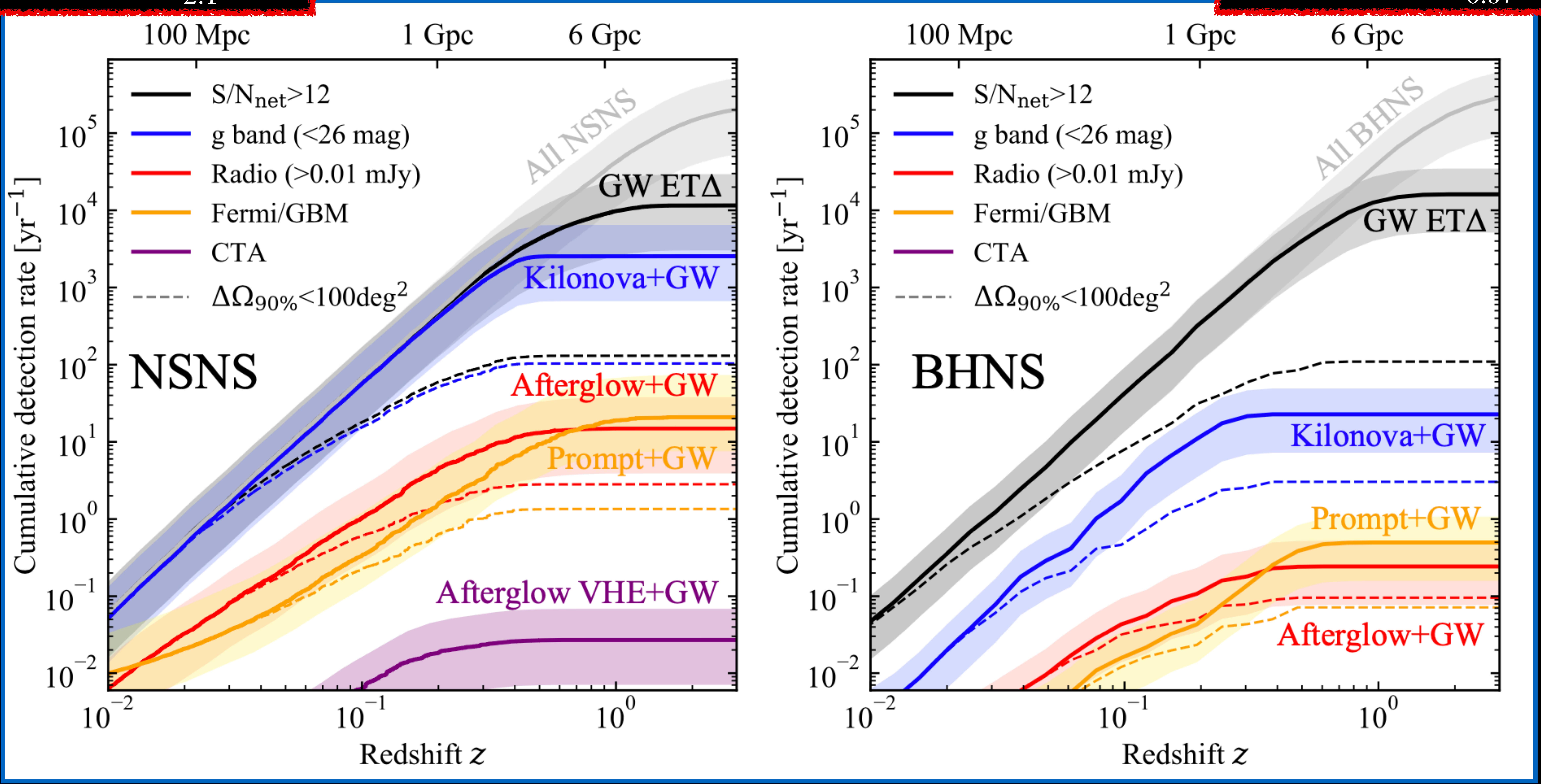
+VLBI: structure and geometry

...Unknown!

GW counterparts in the ET era

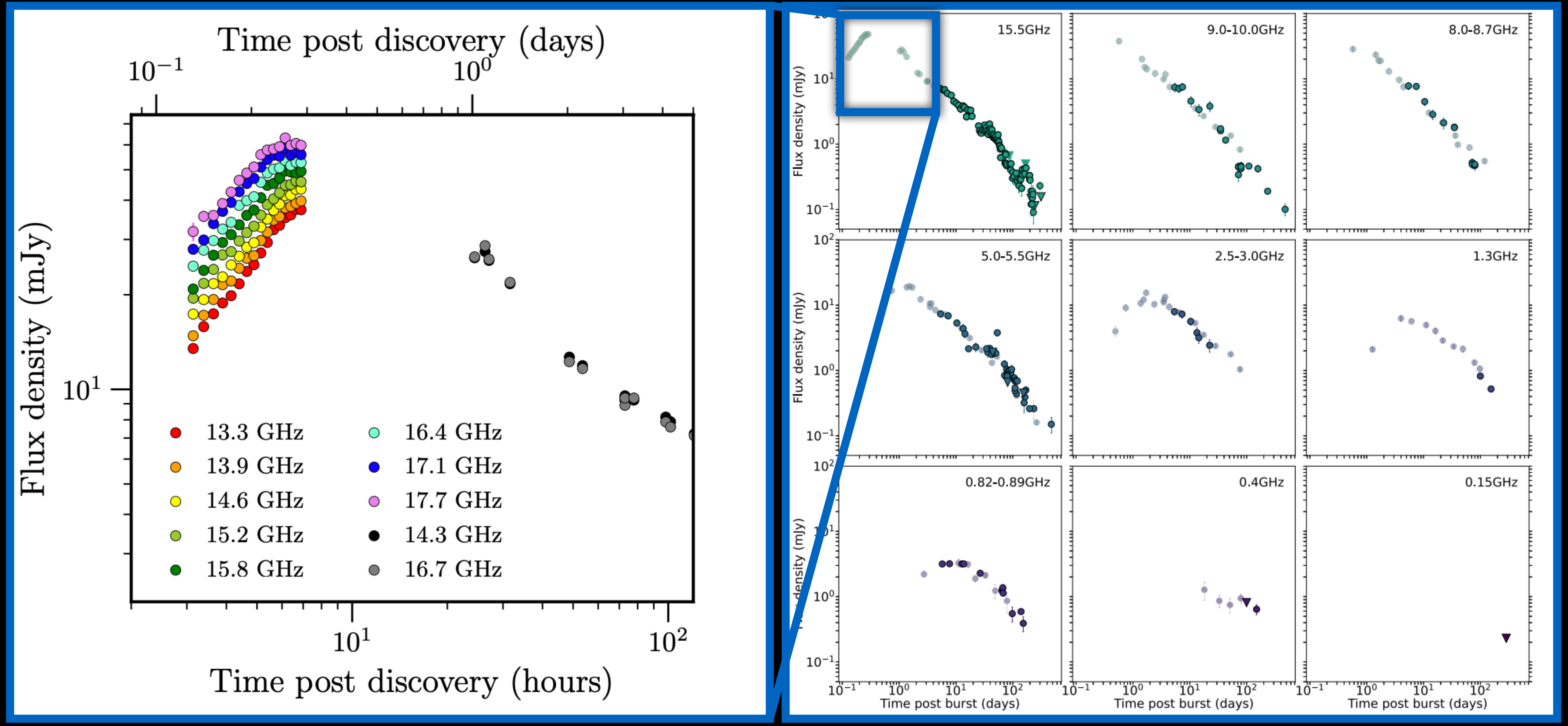
$\mathrm{NSNS} = 2.8^{+4.4}_{-2.1}\,\mathrm{yr}^{-1}$

$\mathrm{BHNS} = 0.11^{+0.10}_{-0.07}\,\mathrm{yr}^{-1}$

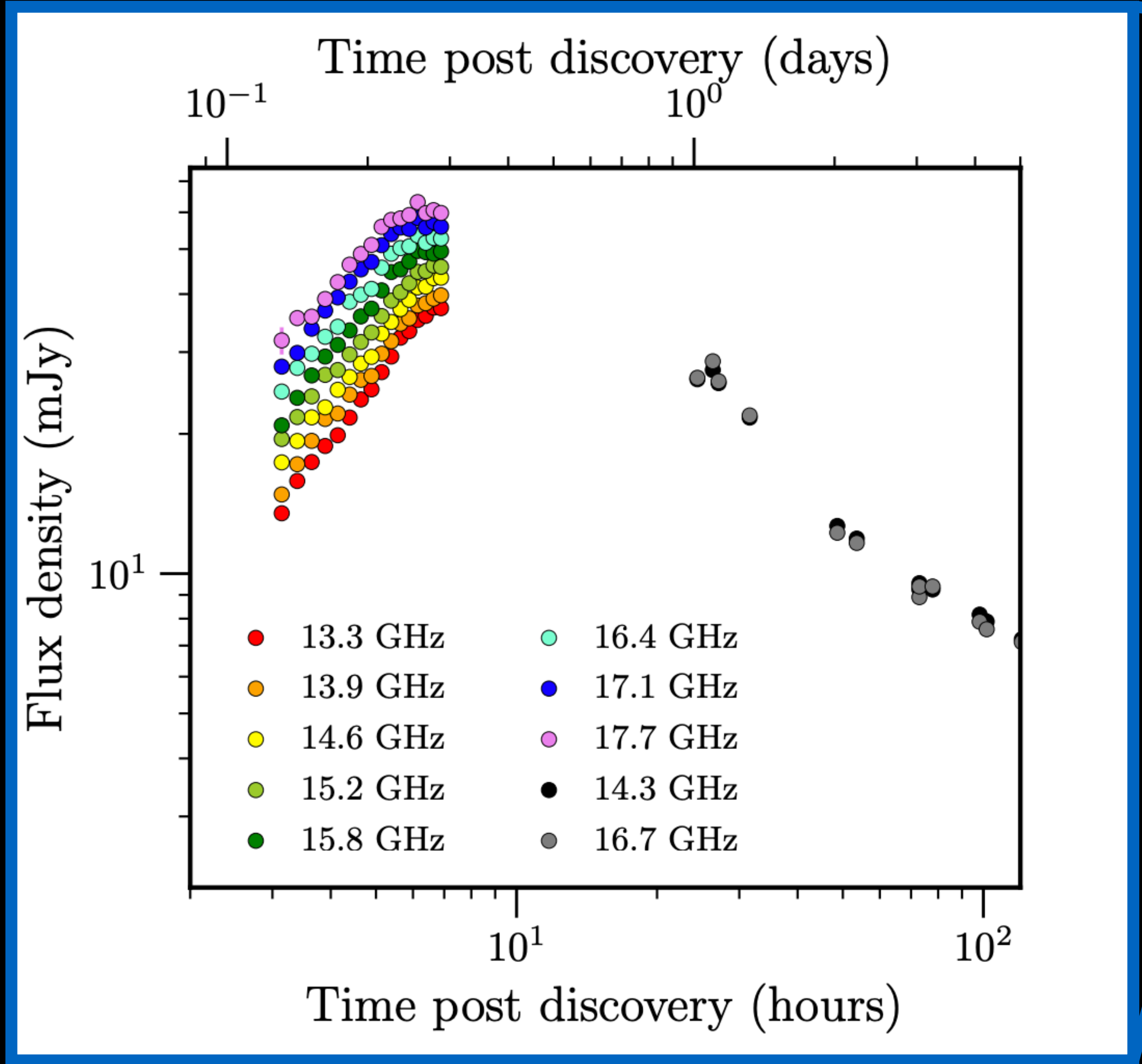


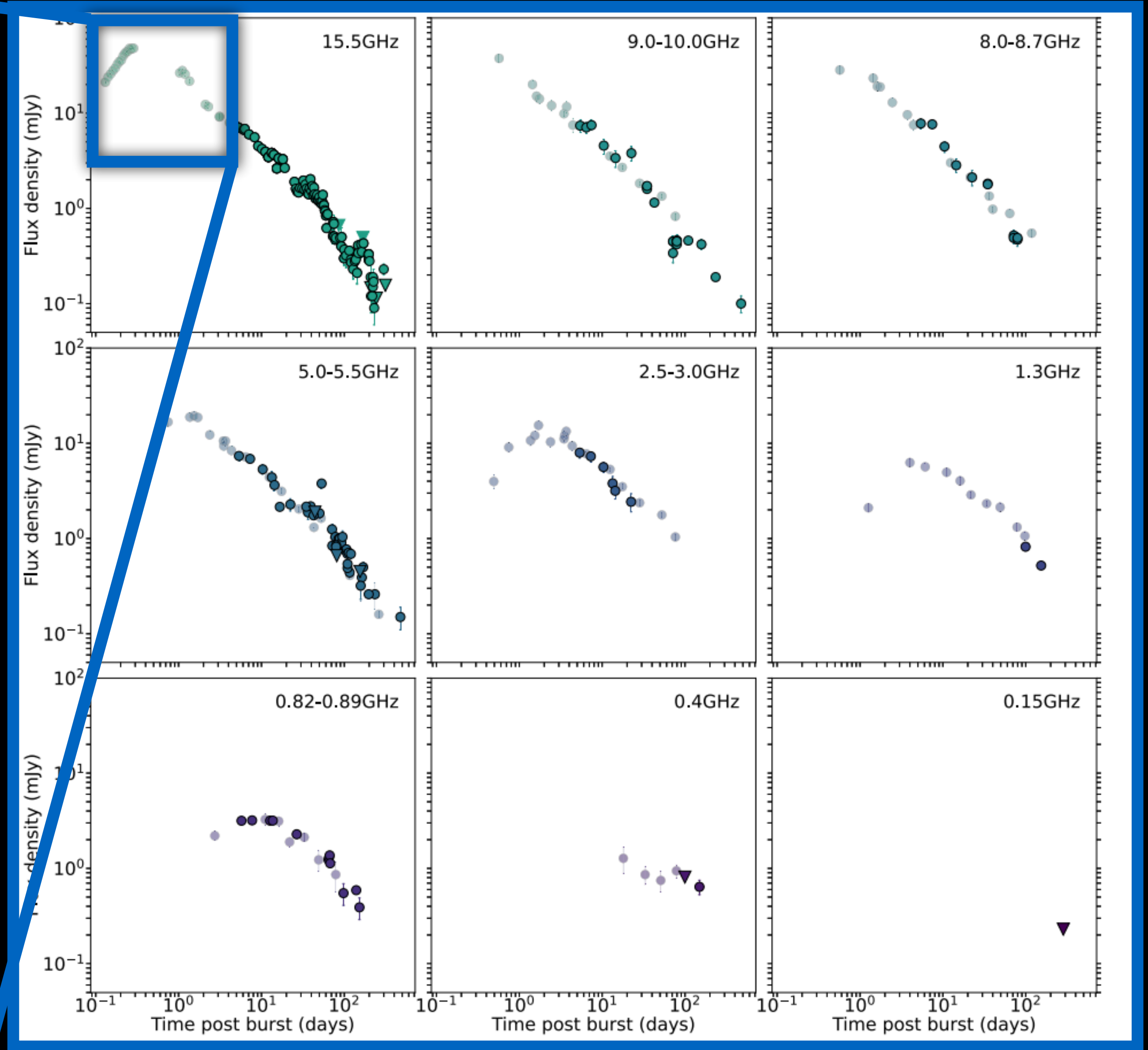
From *Colombo et al. (2025)*

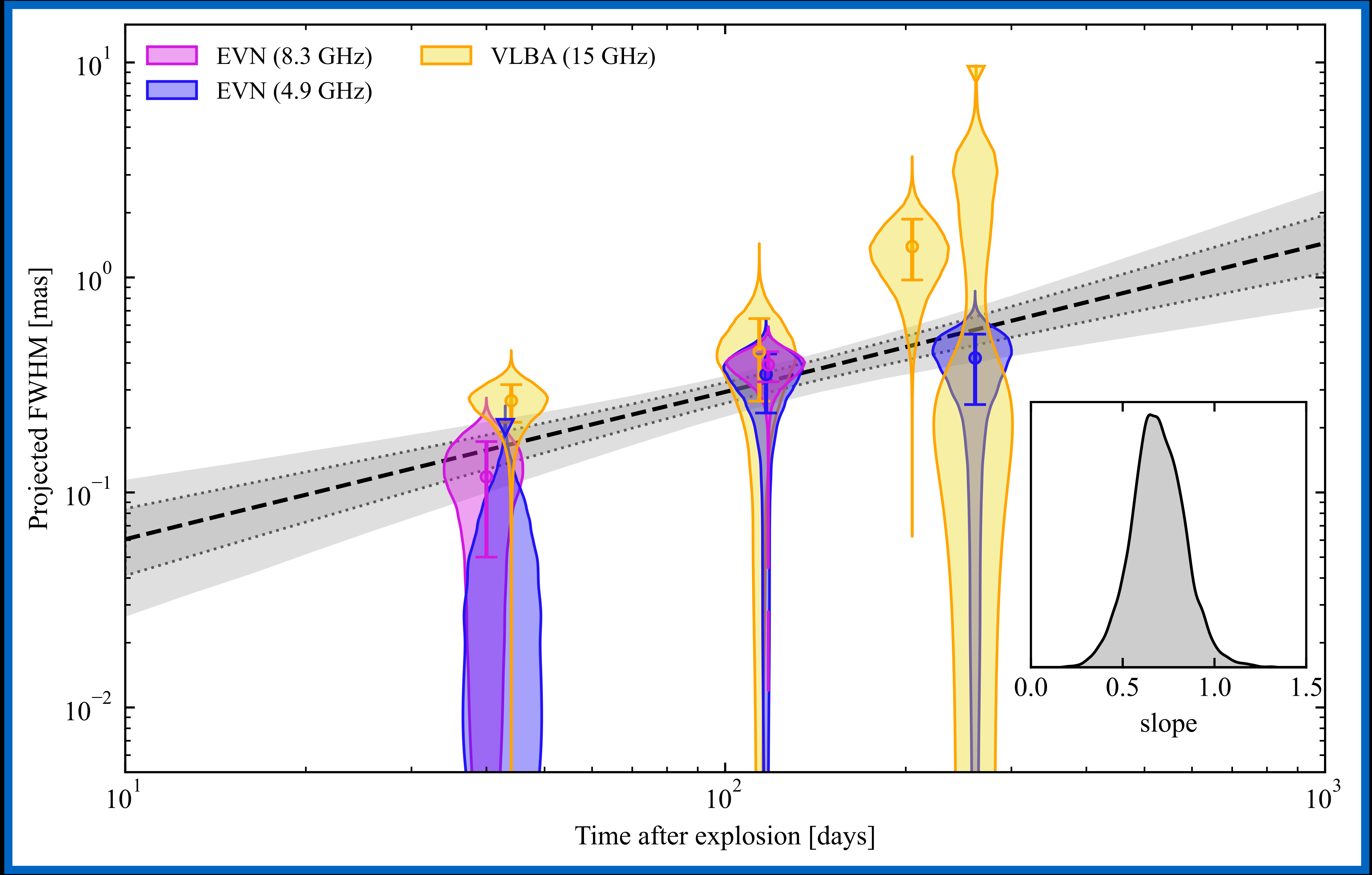
(some) Conclusions



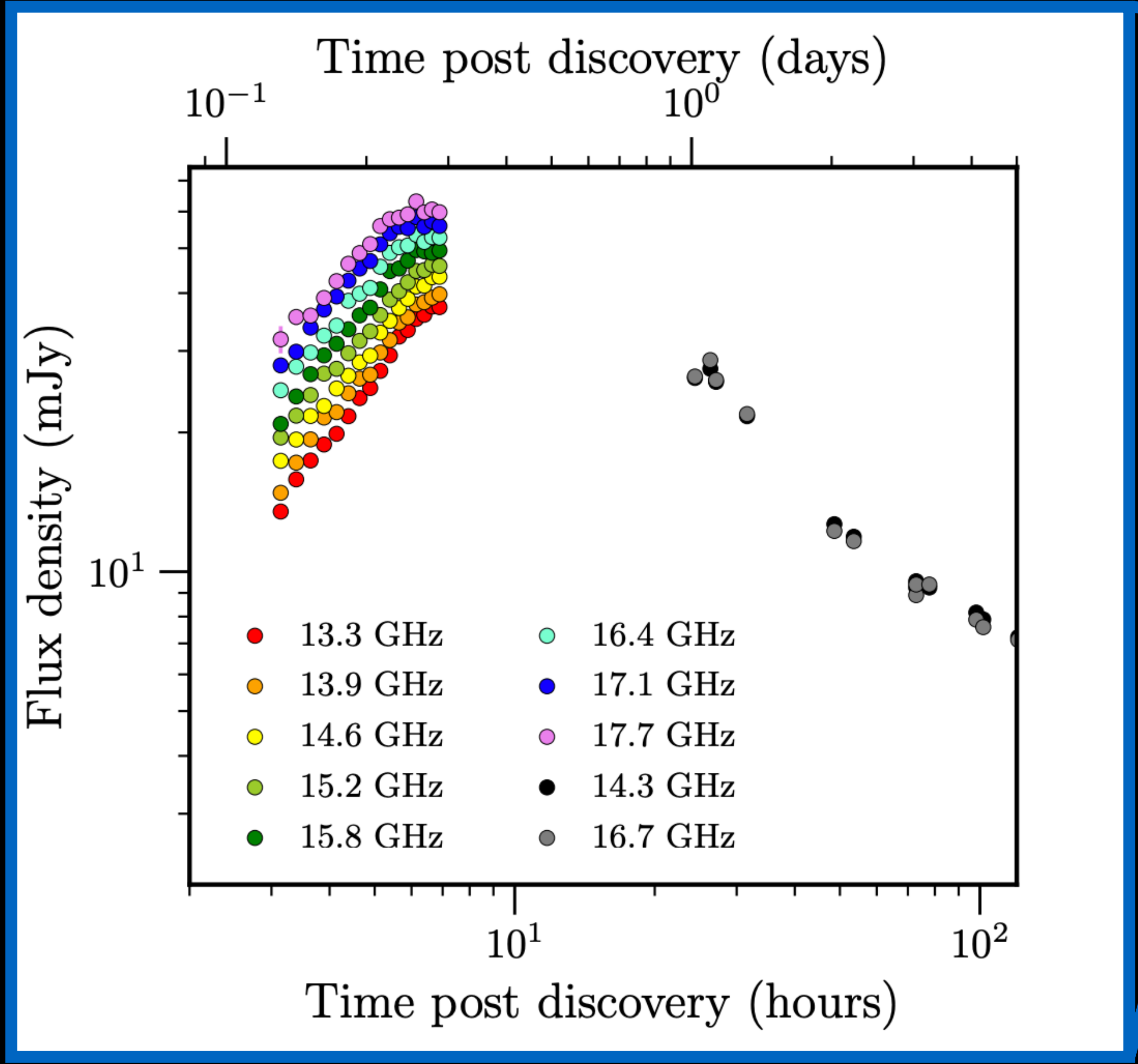
(some) Conclusions

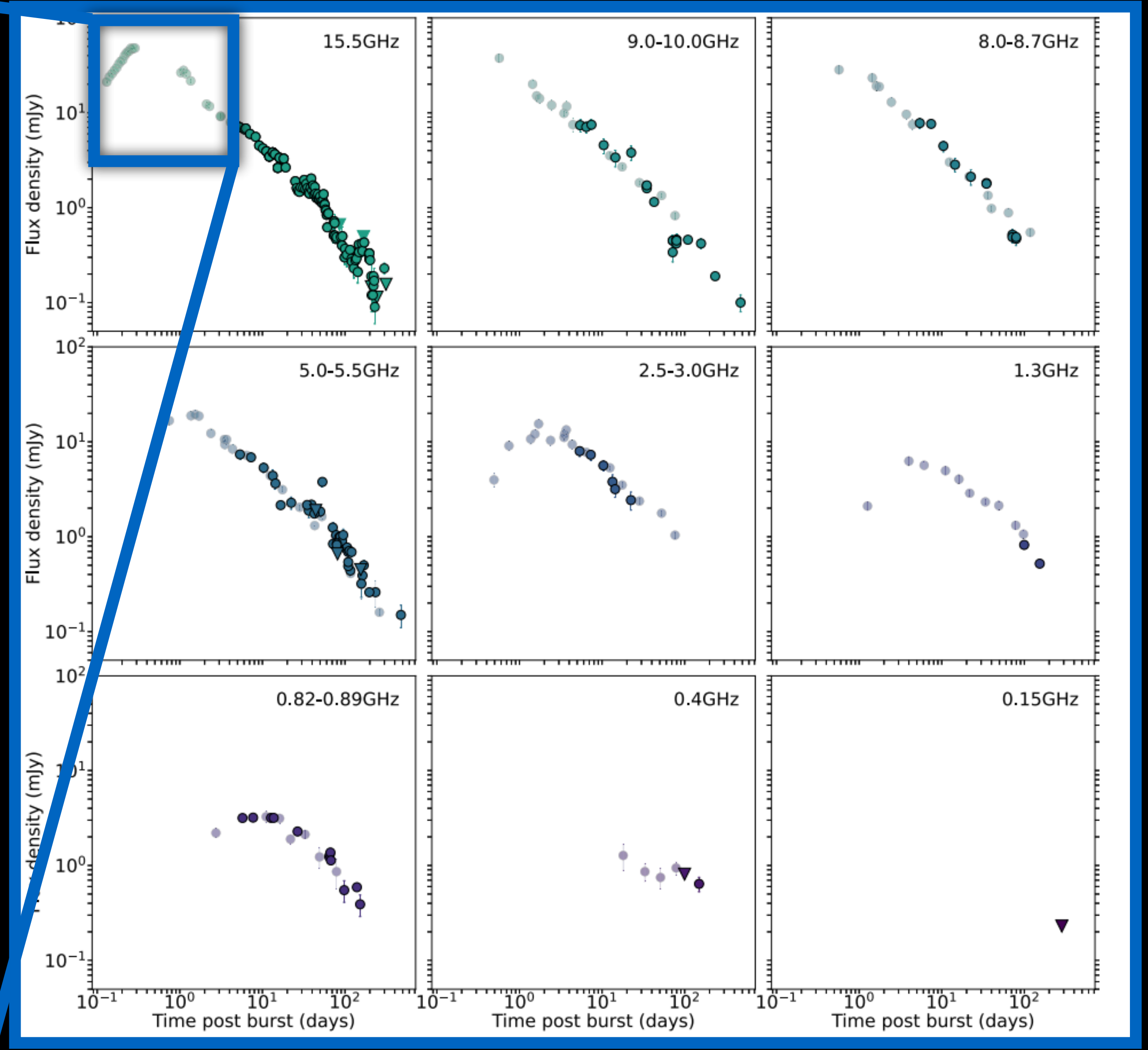


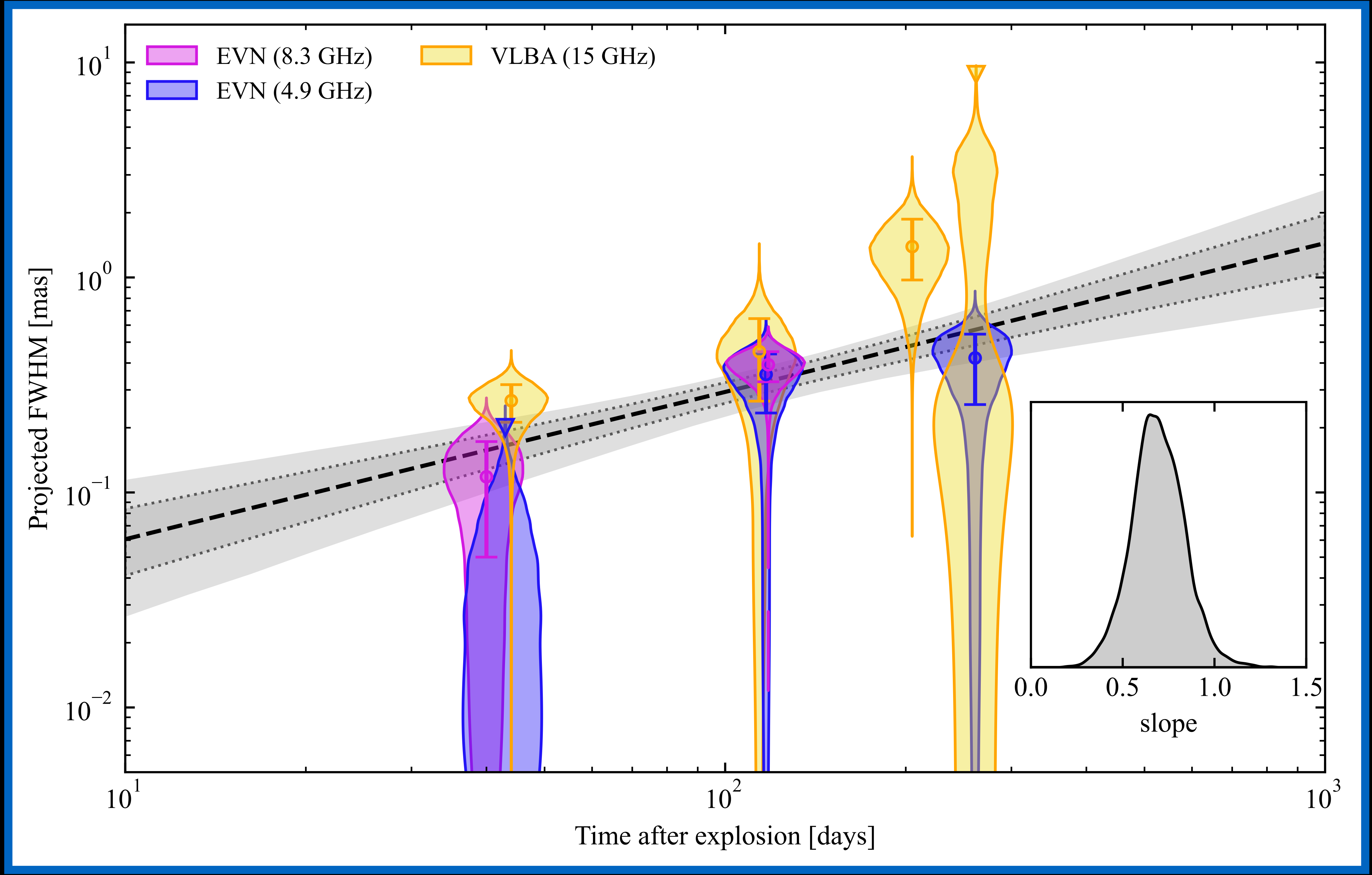


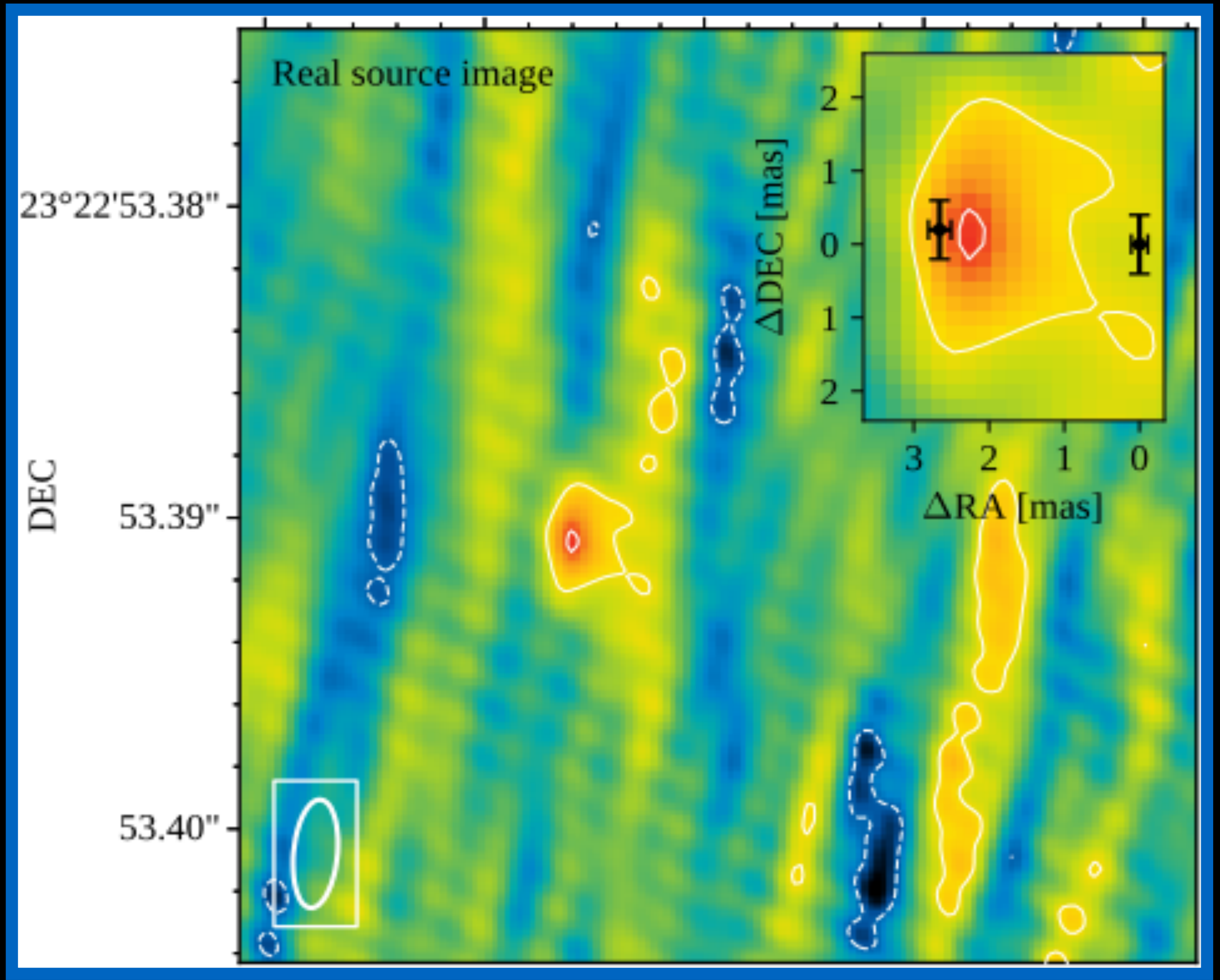


(some) Conclusions









Take home message

Take home message

Radio is

FUNDAMENTAL

to study GRBs

Take home message

Radio is

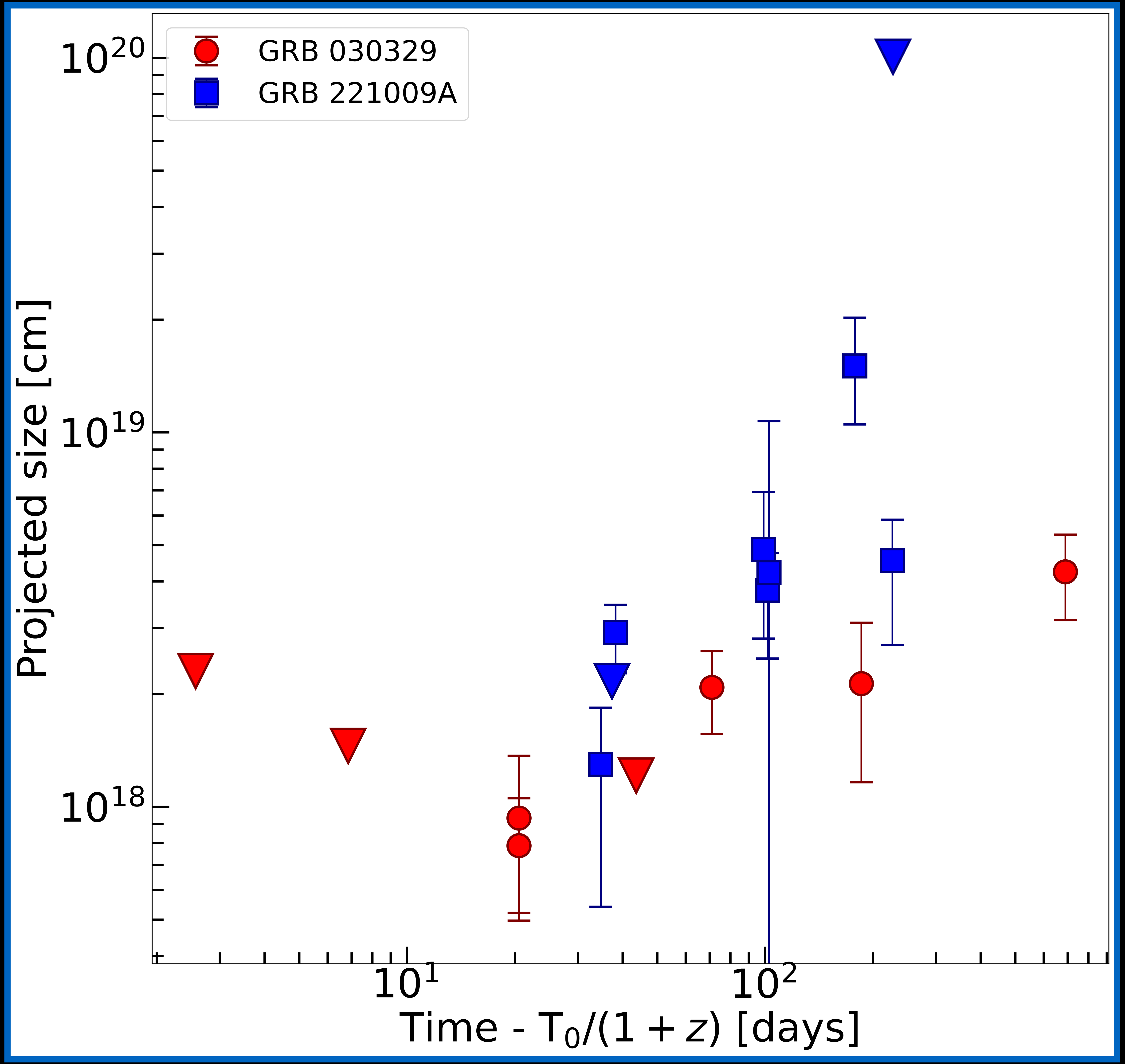
<u>FUNDAMENTAL</u>

to study GRBs

Thank you!

Backup Slides

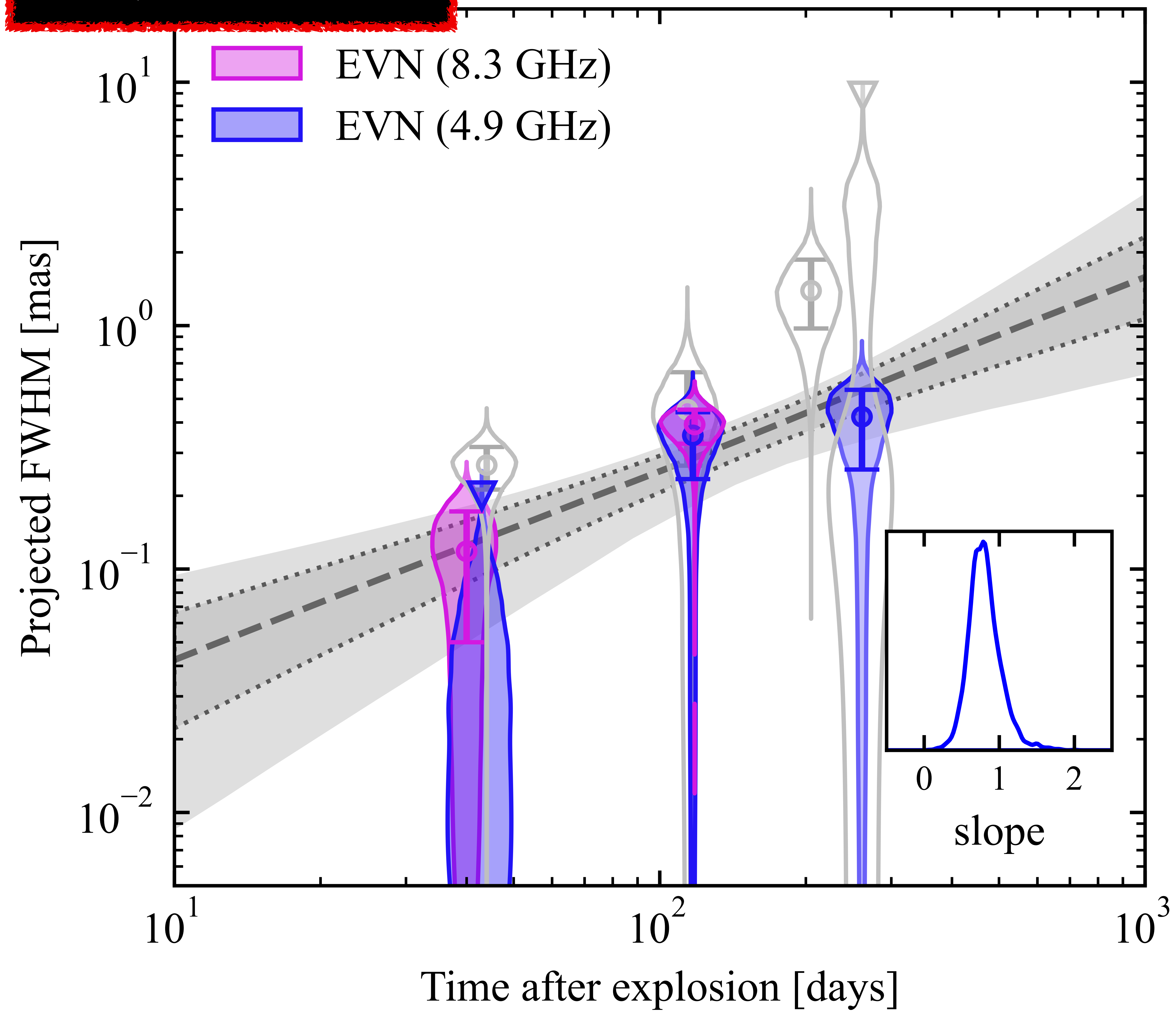
GRB 221009A

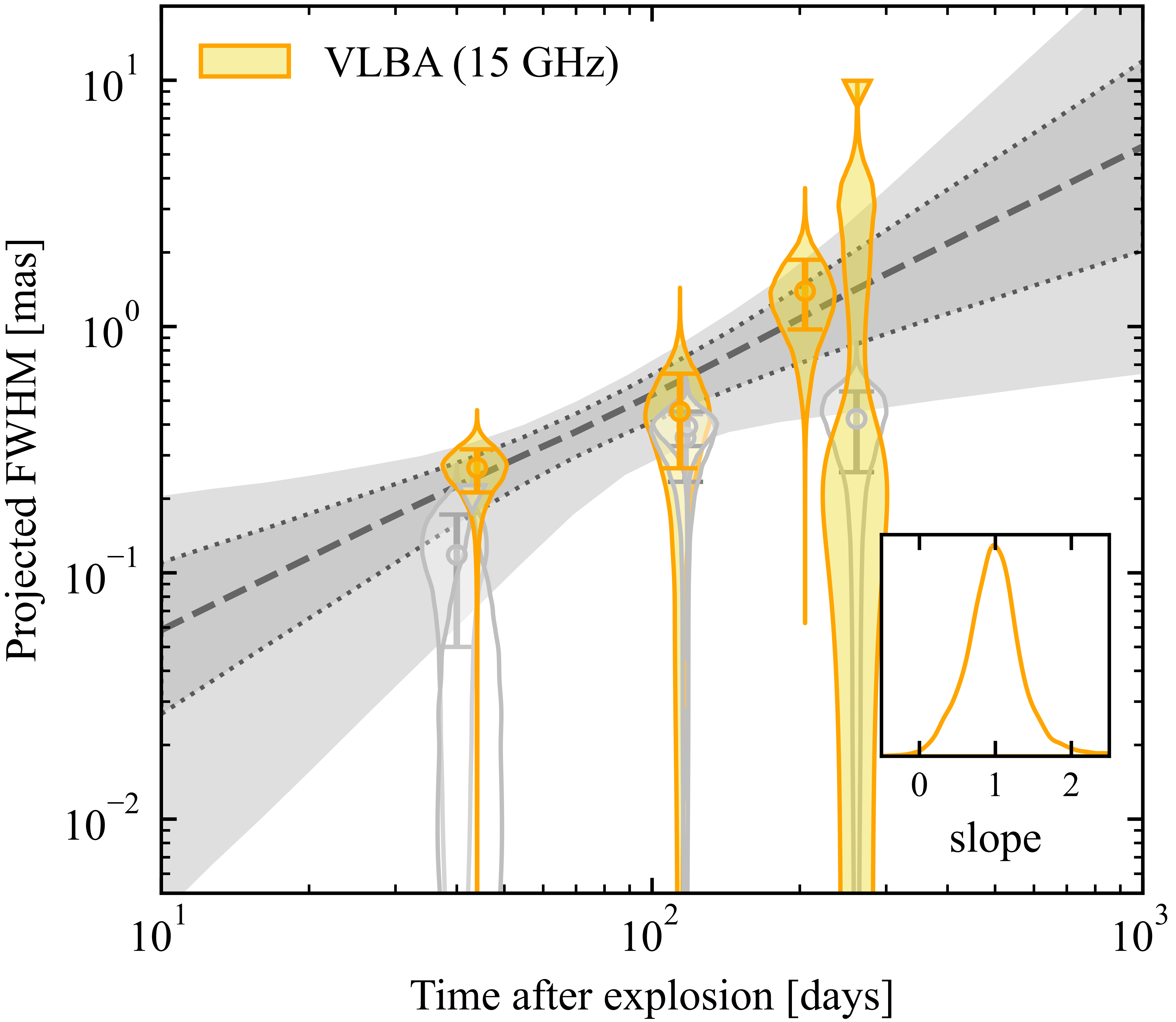


Size evolution of GRB 221009A and GRB 030329.
From *Giarratana et al. (in press)*

Hint for different size evolutions

Forward vs Reverse shocks?





From *Giarratana et al. (2024)*

GRB 221009A

$E/A \simeq 10^{57}$ erg cm^3
$\theta_j \simeq 21°$

Model size evolution in a FS + RS scenario.
From *Giarratana et al. (2024)*

$E/A \simeq 10^{55}$ erg cm^3
$\theta_j \simeq 23°$

The SKA and the ngVLA

SKA1 Telescope Expected Performance – Imaging

Nominal frequency	110 MHz	300 MHz	770 MHz	1.4 GHz	6.7 GHz	12.5 GHz
Range [GHz]	0.05-0.35	0.05-0.35	0.35-1.05	0.95-1.76	4.6-8.5	8.3-15.4
Telescope	Low	Low	Mid	Mid	Mid	Mid
FoV [arcmin]	327	120	109	60	12.5	6.7
Max. resolution [arcsec]	9.7	3.5	0.7	0.3	0.06	0.03
Max. bandwidth [MHz]	300	300	700	810	3900	2 x 2500
Cont. rms, 1hr [μJy/beam] [a]	26	14	4.4	2	1.3	1.2
Line rms, 1hr [μJy/beam] [b]	1850	800	300	140	90	85
Resolution range for cont. & line rms [arcsec] [c]	12-600	6-300	1-145	0.6-78	0.13-17	0.07-9
Channel width (uniform resolution across max. bandwidth) [kHz]	5.4	5.4	13.4	13.4	80.6	80.6
Narrowest bandwidth, zoom mode [MHz]	3.9	3.9	3.1	3.1	3.1	3.1
Finest zoom channel width [Hz]	226	226	210	210	210	210

a. Continuum sensitivity at nominal frequency, assuming fractional bandwidth of $\Delta\nu/\nu = 0.3$

b. Line sensitivity at nominal frequency, assuming fractional bandwidth per channel of $\Delta\nu/\nu = 10^{-4}$ ($>10^{-6}$ will be possible]

c. The sensitivity numbers apply to the range of beam sizes listed

For more details refer to the document "Anticipated SKA1 Science Performance" (SKA-TEL-SKO-0000818 available on astronomers.skatelescope.org and at arxiv.org/abs/1912.12699)

SKA info sheet from the public SKAO website.

ngVLA Key Performance Metrics

Parameter [units]	2.4 GHz	8 GHz	16 GHz	27 GHz	41 GHz	93 GHz
Band Lower Frequency, f_L [GHz]	1.2	3.4	12.3	20.5	30.5	70.0
Band Upper Frequency, f_H [GHz]	3.5	12.3	20.5	34.0	50.5	116.0
Field of View FWHM [arcmin]	24.852	7.440	3.561	2.143	1.442	0.628
Aperture Efficiency [%]	0.828	0.936	0.941	0.920	0.886	0.648
Effective Area, A_{eff} x 10^3 [m^2]	51.41	58.15	58.42	57.10	55.03	40.25
System Temp, T_{sys} [K]	17.07	22.00	24.40	32.42	47.41	65.37
Max Inst. Bandwidth [GHz]	2.3	8.8	8.2	13.5	20.0	20.0
Antenna SEFD [Jy]	232.3	264.8	292.2	397.3	602.8	1136.3
Resolution of Max. Baseline θ_{max} [mas]	2.97	0.89	0.43	0.26	0.17	0.08
Naturally Weighted Sensitivity						
Continuum rms, 1 hr [μJy/beam]	0.24	0.14	0.16	0.17	0.21	0.40

ngVLA expected performance. From the public ngVLA website.

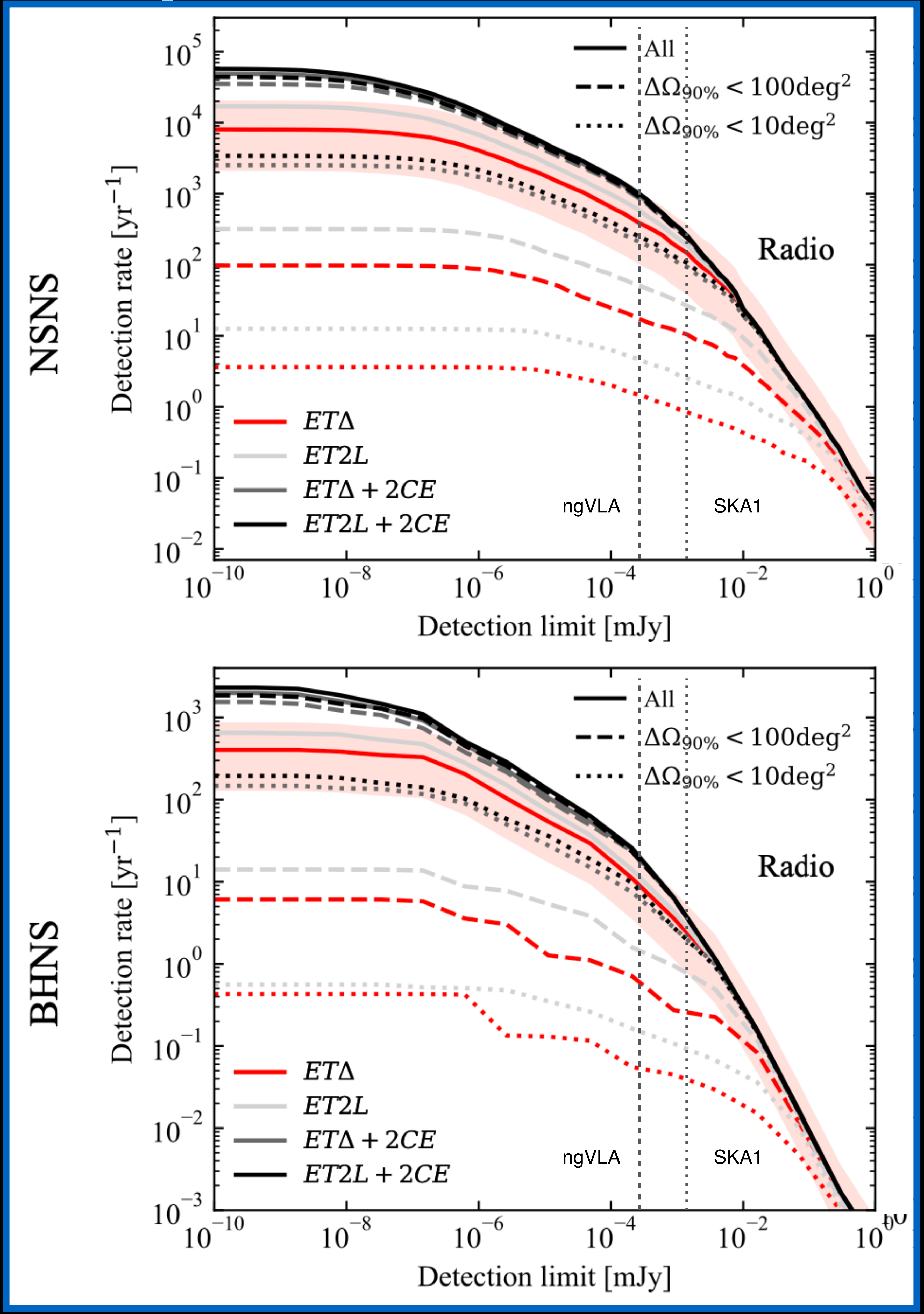
The SKA

Milestones	Mid (end-date)	Low (end-date)
AA0.5 • 4 Mid dishes • 4 Low stations	2026 Jan	2024 Dec
AA1 • 8 Mid dishes • 18 Low stations	2026 Aug	2025 Nov
AA2 • 64 Mid dishes • 64 Low stations	2027 Jul	2026 Oct
AA* (staged delivery plan) • 144 Mid dishes • 307 Low stations	2028 May	2028 Jan
Operations Readiness Review	2028 Aug	2028 Apr
Formal end of construction (including schedule contingency)	2029 Mar	
AA4 (design baseline) • 197 Mid dishes • 512 Low stations	TBD	

Telescope	Maximum baseline length		
	AA2	AA*	AA4
Low	39.0 km	73.4 km	73.4 km
Mid	108.0 km (36.0 km, excluding dish SKA008)	108.0 km (36.0 km, excluding dish SKA008)	159.6 km

Timeline and maximum baseline length.

GW counterparts in the ET and CE era



Adapted from *Colombo et al. (2025)*

GW counterparts in the ET and CE era

Table 2. Detection limits and predicted detection rates for NSNS and BHNS, assuming ET triangle 10 km. We report in parenthesis the detection rates assuming $\Delta\Omega_{90\%} < 100\mathrm{deg}^2$. The GW detection limits refer to the S/N_{net} threshold. Near infrared and optical limiting magnitudes are in the AB system; radio limiting flux densities are in mJy @ 1.4 GHz; X-ray limiting flux densities are in erg $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{keV}^{-1}$ @ 1 keV; gamma-ray limiting fluence is in erg cm^{-2} (*Fermi*/GBM). Detection rates are in yr^{-1}. The reported errors, given at the 90% credible level, stem from the uncertainty on the overall merger rate, while systematic errors are not included.

	GW ET	KN+GW			GRB Afterglow+GW				GRB Prompt+GW
		J	z	g	Radio	Optical	X-rays	VHE	*Fermi*
NSNS									
Limit	12	21	24.4	26	0.01	26	10^{-13}	CTA	3.09×10^{-7}
ETΔ									
Rate	$1.16^{+1.79}_{-0.85} \times 10^4$	$2.4^{+3.8}_{-1.8}$	271^{+419}_{-200}	$2.54^{+3.93}_{-1.88} \times 10^3$	15^{+23}_{-11}	15^{+23}_{-11}	33^{+51}_{-24}	$0.03^{+0.04}_{-0.02}$	21^{+53}_{-13}
($\Delta\Omega_{90\%} < 100\mathrm{deg}^2$)	(130^{+202}_{-96})	$(1.8^{+2.8}_{-1.3})$	(42^{+65}_{-31})	(104^{+160}_{-76})	$(2.8^{+4.4}_{-2.1})$	$(1.2^{+1.8}_{-0.9})$	$(1.7^{+2.7}_{-1.3})$	$(0.01^{+0.02}_{-0.01})$	$(1.3^{+2.1}_{-1.0})$
ET2L									
Rate	$2.40^{+3.70}_{-1.77} \times 10^4$	$2.4^{+3.8}_{-1.8}$	268^{+415}_{-198}	$2.89^{+4.47}_{-2.13} \times 10^3$	15^{+23}_{-11}	20^{+31}_{-15}	45^{+69}_{-33}	$0.03^{+0.04}_{-0.02}$	27^{+68}_{-17}
($\Delta\Omega_{90\%} < 100\mathrm{deg}^2$)	(412^{+636}_{-304})	$(2.0^{+3.2}_{-1.5})$	(125^{+193}_{-92})	(283^{+437}_{-208})	$(6.6^{+10.1}_{-4.8})$	$(4.0^{+6.1}_{-2.9})$	$(5.7^{+8.8}_{-4.2})$	$(0.02^{+0.03}_{-0.01})$	$(3.9^{+6.1}_{-2.9})$
ETΔ + 2CE									
Rate	$6.70^{+10.34}_{-4.93} \times 10^4$	$2.4^{+3.8}_{-1.8}$	278^{+430}_{-205}	$3.29^{+5.09}_{-2.43} \times 10^3$	16^{+25}_{-12}	25^{+38}_{-18}	65^{+100}_{-45}	$0.03^{+0.04}_{-0.02}$	37^{+100}_{-23}
($\Delta\Omega_{90\%} < 100\mathrm{deg}^2$)	$(4.87^{+7.53}_{-3.60} \times 10^4)$	$(2.4^{+3.8}_{-1.8})$	(270^{+417}_{-200})	$(3.10^{+4.78}_{-2.28} \times 10^3)$	(16^{+25}_{-12})	(24^{+38}_{-18})	(63^{+97}_{-46})	$(0.03^{+0.04}_{-0.02})$	(36^{+56}_{-27})
ET2L + 2CE									
Rate	$7.81^{+12.06}_{-5.76} \times 10^4$	$2.4^{+3.8}_{-1.8}$	278^{+430}_{-205}	$3.31^{+5.12}_{-2.44} \times 10^3$	16^{+25}_{-12}	25^{+39}_{-19}	68^{+100}_{-50}	$0.03^{+0.04}_{-0.02}$	38^{+100}_{-23}
($\Delta\Omega_{90\%} < 100\mathrm{deg}^2$)	$(6.04^{+9.32}_{-4.45} \times 10^4)$	$(2.4^{+3.8}_{-1.8})$	(270^{+417}_{-200})	$(3.10^{+4.78}_{-2.28} \times 10^3)$	(16^{+25}_{-12})	(24^{+38}_{-18})	(63^{+97}_{-46})	$(0.03^{+0.04}_{-0.02})$	(36^{+56}_{-27})
BHNS									
Limit	12	21	24.4	26	0.01	26	10^{-13}	CTA	3.09×10^{-7}
ETΔ									
Rate	$1.61^{+1.87}_{-1.10} \times 10^4$	$0.06^{+0.07}_{-0.04}$	$4.9^{+5.6}_{-3.3}$	22^{+26}_{-15}	$0.24^{+0.28}_{-0.17}$	$1.3^{+1.5}_{-0.9}$	$1.6^{+1.9}_{-1.1}$	$< 10^{-3}$	$0.50^{+0.58}_{-0.34}$
($\Delta\Omega_{90\%} < 100\mathrm{deg}^2$)	(109^{+127}_{-75})	$(0.05^{+0.05}_{-0.03})$	$(0.9^{+1.1}_{-0.6})$	$(3.0^{+3.5}_{-2.1})$	$(0.10^{+0.11}_{-0.07})$	$(0.12^{+0.14}_{-0.08})$	$(0.16^{+0.19}_{-0.11})$		$(0.07^{+0.07}_{-0.05})$
ET2L									
Rate	$2.92^{+3.38}_{-1.98} \times 10^4$	$0.06^{+0.07}_{-0.04}$	$4.8^{+5.6}_{-3.3}$	23^{+27}_{-16}	$0.24^{+0.28}_{-0.17}$	$1.9^{+2.2}_{-1.3}$	$2.4^{+2.8}_{-1.7}$	$< 10^{-3}$	$0.54^{+0.63}_{-0.37}$
($\Delta\Omega_{90\%} < 100\mathrm{deg}^2$)	(368^{+426}_{-250})	$(0.05^{+0.06}_{-0.04})$	$(2.2^{+2.6}_{-1.5})$	$(7.1^{+8.3}_{-4.9})$	$(0.17^{+0.20}_{-0.12})$	$(0.28^{+0.33}_{-0.19})$	$(0.33^{+0.38}_{-0.22})$		$(0.17^{+0.19}_{-0.11})$
ETΔ + 2CE									
Rate	$7.28^{+8.45}_{-4.96} \times 10^4$	$0.06^{+0.07}_{-0.04}$	$4.9^{+5.6}_{-3.3}$	24^{+27}_{-16}	$0.25^{+0.29}_{-0.17}$	$3.3^{+3.8}_{-2.2}$	$5.3^{+6.2}_{-3.6}$	$< 10^{-3}$	$0.75^{+0.87}_{-0.51}$
($\Delta\Omega_{90\%} < 100\mathrm{deg}^2$)	$(5.65^{+6.55}_{-3.85} \times 10^4)$	$(0.06^{+0.07}_{-0.04})$	$(4.8^{+5.6}_{-3.2})$	(24^{+27}_{-16})	$(0.25^{+0.29}_{-0.17})$	$(3.3^{+3.8}_{-2.2})$	$(5.3^{+6.2}_{-3.6})$		$(0.74^{+0.86}_{-0.50})$
ET2L + 2CE									
Rate	$8.30^{+9.63}_{-5.65} \times 10^4$	$0.06^{+0.07}_{-0.04}$	$4.9^{+5.6}_{-3.3}$	24^{+28}_{-16}	$0.26^{+0.30}_{-0.18}$	$3.3^{+3.9}_{-2.3}$	$5.3^{+6.2}_{-3.6}$	$< 10^{-3}$	$0.75^{+0.87}_{-0.51}$
($\Delta\Omega_{90\%} < 100\mathrm{deg}^2$)	$(6.76^{+7.84}_{-4.60} \times 10^4)$	$(0.06^{+0.07}_{-0.04})$	$(4.8^{+5.6}_{-3.3})$	(23^{+26}_{-15})	$(0.26^{+0.30}_{-0.18})$	$(3.3^{+3.9}_{-2.3})$	$(5.3^{+6.2}_{-3.6})$		$(0.74^{+0.86}_{-0.50})$

From *Colombo et al. (2025)*