Dusting off the BOAT

the GRB 221009A afterglow through the reddened eyes of JWST

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IV.INNO

Khang, Grabham, Lamb et al. (in prep)

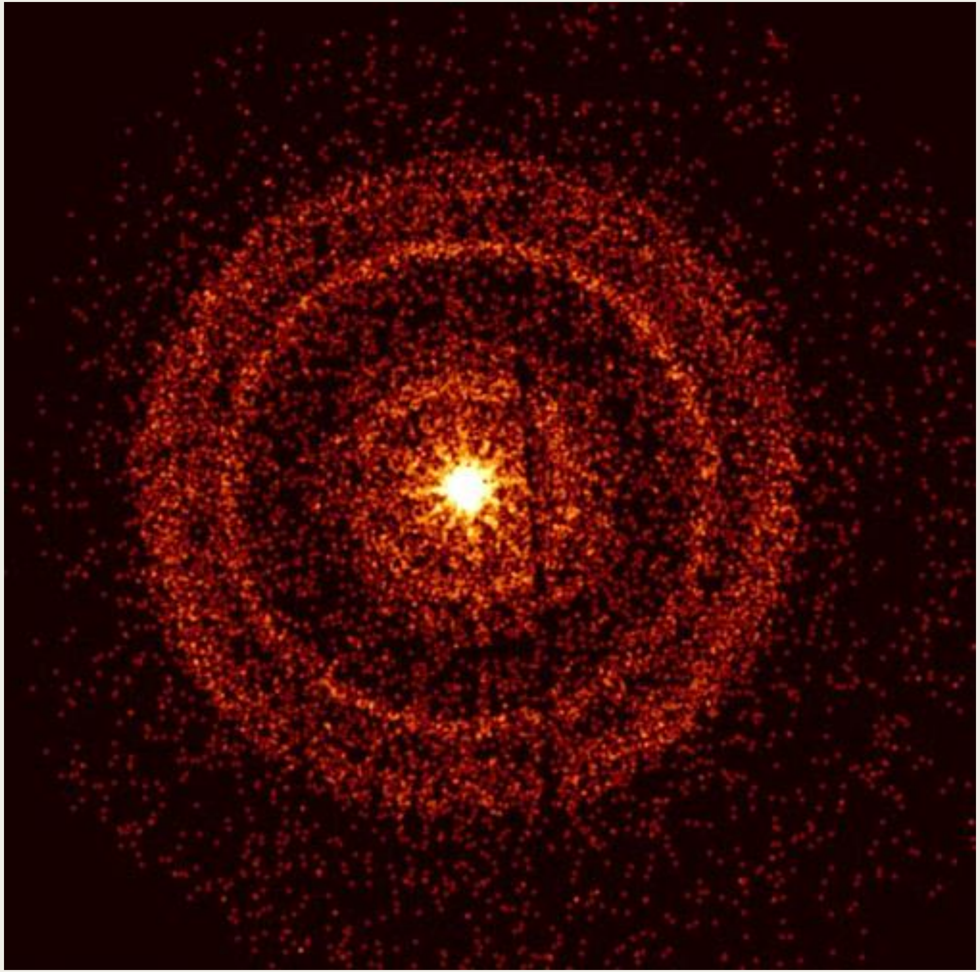
My own evolution

Star Formation Khang - Observer

GRB Khang – Theory (Modelling)

GRB 221009A – the knowns

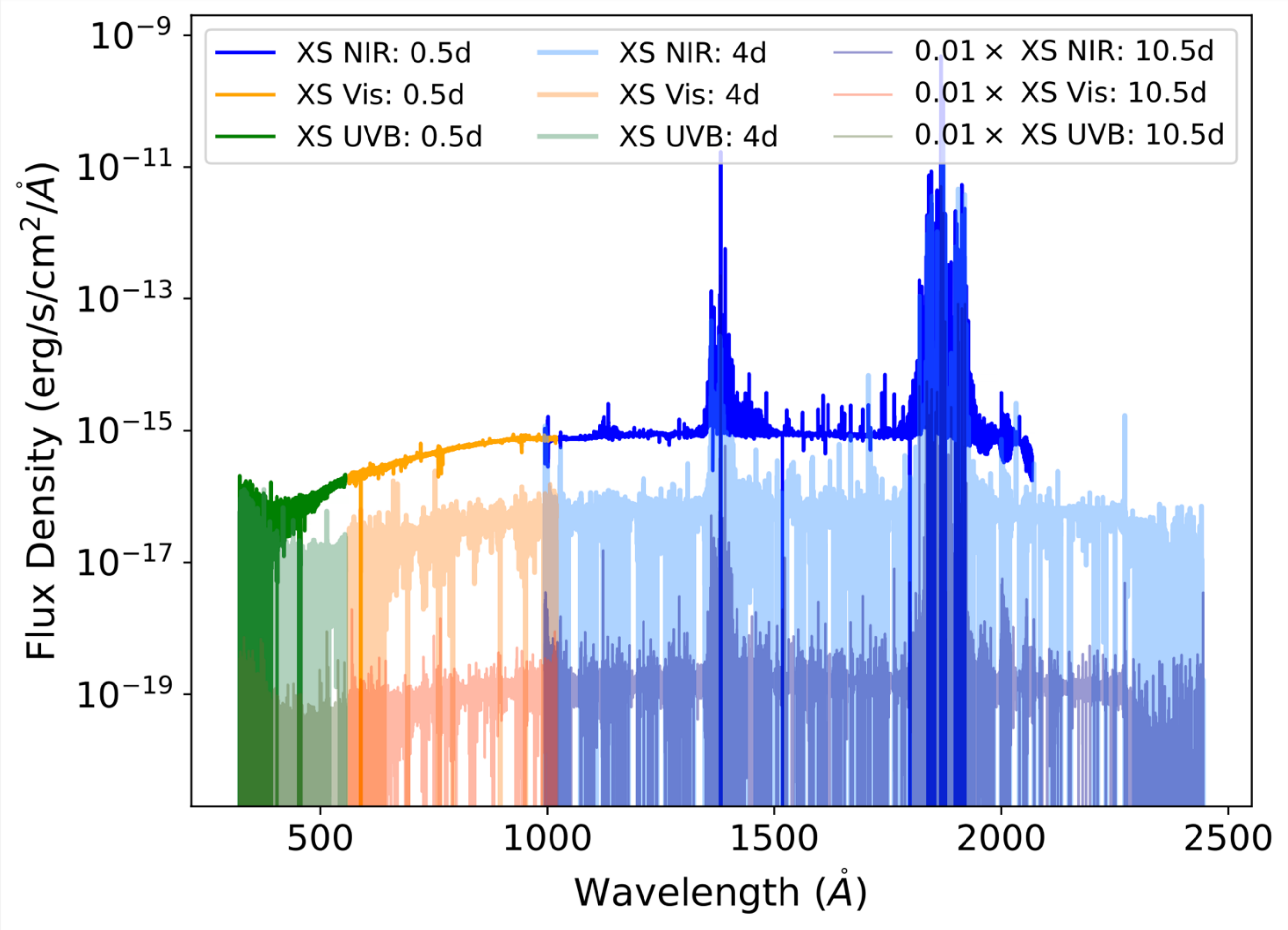
- Brightest of all time (BOAT) LGRB (~600s) - a once in 10,000 years event (Burns+23)
- Isotropic gamma-ray energy output ~ 10^{55} erg (between 20 keV – 10 MeV, Rhodes+24)
- Peak emission produces very-high-energy photons of up to hundreds of TeV (Dzhappuev+22)
- z ~ 0.151 (de Ugarte Postigo+22)
- Affected heavily by foreground extinction – on-sky location is near Galactic plane (Levan+23)



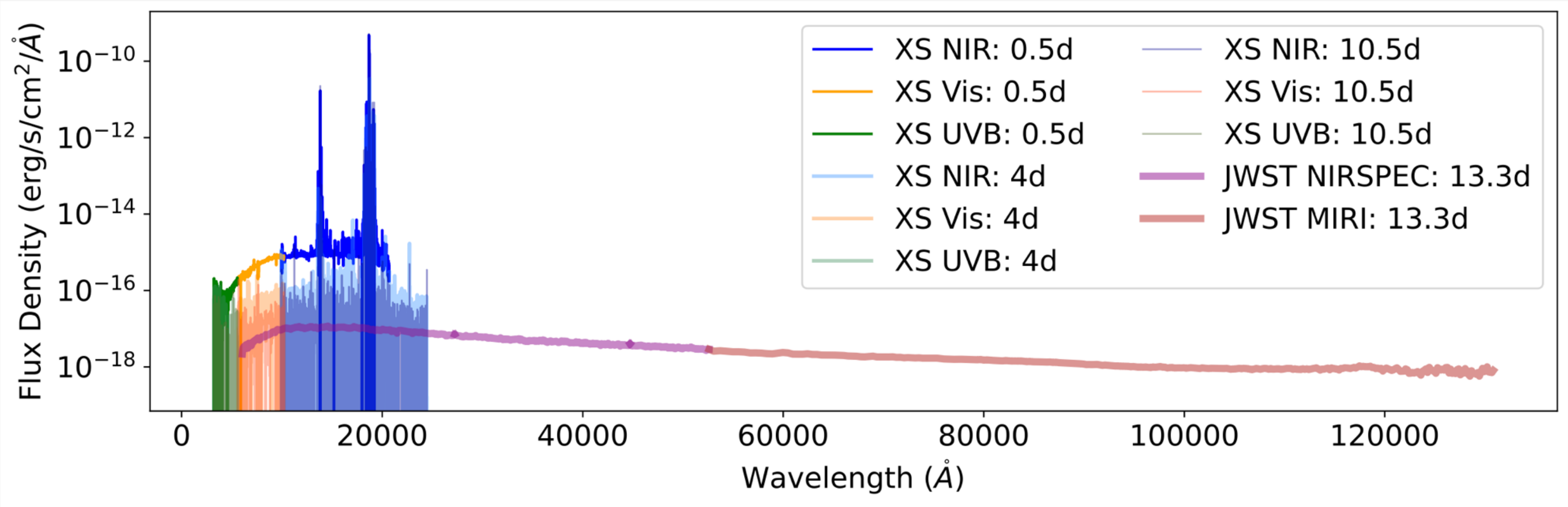
X-ray image from NASA/Swift

X-Shooter & JWST spectra

- **X-Shooter** spectra obtained by Malesani+23.
- Wavelength ranges from 0.3 - 2.0 microns
- **JWST** spectra obtained by Levan+23
- Wavelength ranges from 0.6 – 13.1 microns



X-Shooter & JWST spectra

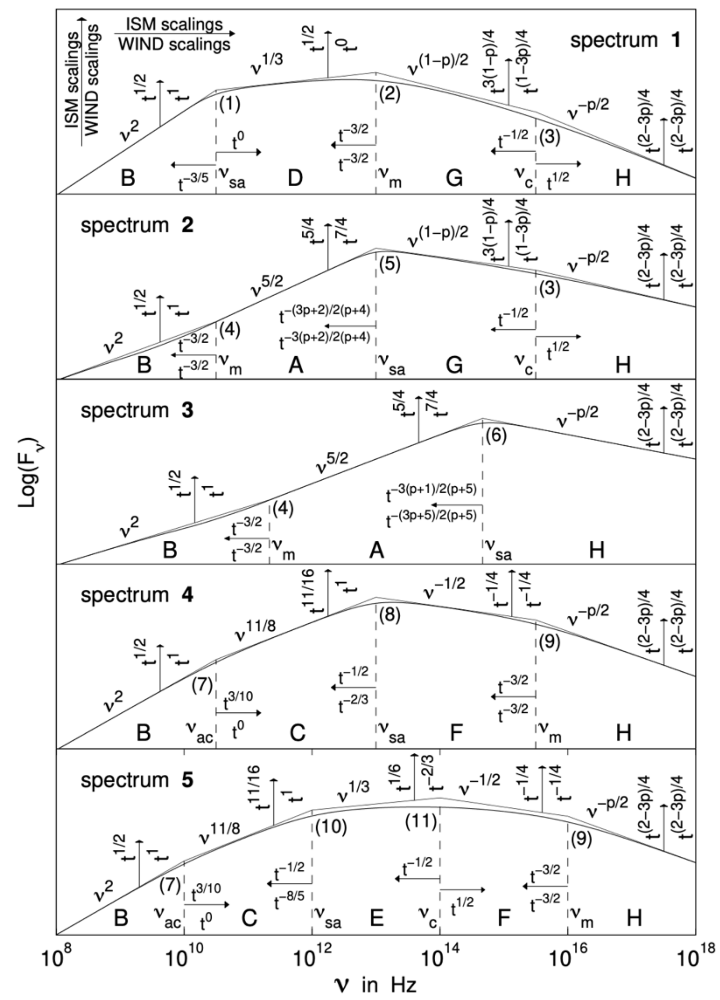


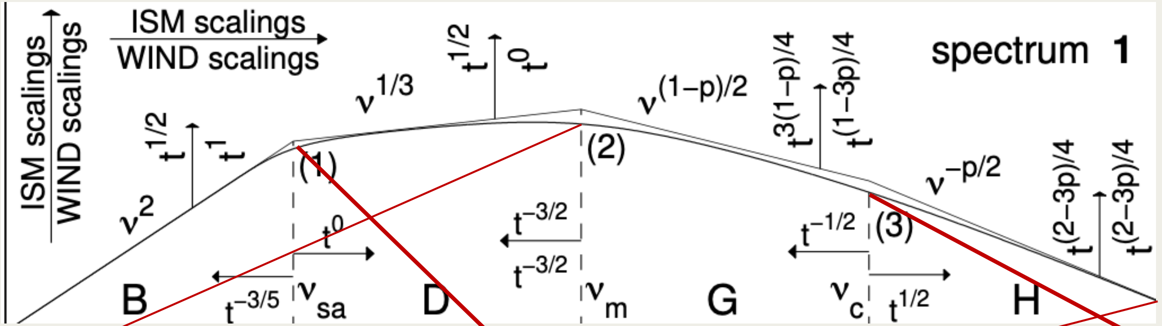
Viable Afterglow Models

(Granot & Sari 02)

TABLE 2
THE BREAK FREQUENCIES AND CORRESPONDING FLUX DENSITIES

b	β_1	β_2	ν_b	$\nu_b(p)$ in Hz	$F_{\nu_b,\mathrm{ext}}(p)$ in mJy	$s(p)$	MRD in %
1	2	$\frac{1}{3}$	ν_{sa}	$1.24\frac{(p-1)^{3/5}}{(3p+2)^{3/5}}10^9(1+z)^{-1}\bar{\epsilon}_e^{-1}\epsilon_B^{1/5}n_0^{3/5}E_{52}^{1/5}$	$0.647\frac{(p-1)^{6/5}}{(3p-1)(3p+2)^{1/5}}(1+z)^{1/2}\bar{\epsilon}_e^{-1}\epsilon_B^{2/5}n_0^{7/10}E_{52}^{9/10}t_{\mathrm{days}}^{1/2}d_{L28}^{-2}$	1.64	6.68
				$8.31\frac{(p-1)^{3/5}}{(3p+2)^{3/5}}10^9(1+z)^{-2/5}\bar{\epsilon}_e^{-1}\epsilon_B^{1/5}A_*^{6/5}E_{52}^{-2/5}t_{\mathrm{days}}^{-3/5}$	$9.19\frac{(p-1)^{6/5}}{(3p-1)(3p+2)^{1/5}}(1+z)^{6/5}\bar{\epsilon}_e^{-1}\epsilon_B^{2/5}A_*^{7/5}E_{52}^{1/5}t_{\mathrm{days}}^{-1/5}d_{L28}^{-2}$	1.06	1.02
2	$\frac{1}{3}$	$\frac{1-p}{2}$	ν_m	$3.73(p-0.67)10^{15}(1+z)^{1/2}E_{52}^{1/2}\bar{\epsilon}_e^2\epsilon_B^{1/2}t_{\mathrm{days}}^{-3/2}$	$9.93(p+0.14)(1+z)\epsilon_B^{1/2}n_0^{1/2}E_{52}d_{L28}^{-2}$	1.84-0.40p	5.9
				$4.02(p-0.69)10^{15}(1+z)^{1/2}E_{52}^{1/2}\bar{\epsilon}_e^2\epsilon_B^{1/2}t_{\mathrm{days}}^{-3/2}$	$76.9(p+0.12)(1+z)^{3/2}\epsilon_B^{1/2}A_*E_{52}^{1/2}t_{\mathrm{days}}^{-1/2}d_{L28}^{-2}$	1.76-0.38p	7.2
3	$\frac{1-p}{2}$	$-\frac{p}{2}$	ν_c	$6.37(p-0.46)10^{13}e^{-1.16p}(1+z)^{-1/2}\epsilon_B^{-3/2}n_0^{-1}E_{52}^{-1/2}t_{\mathrm{days}}^{-1/2}$	$4.68\,e^{4.82(p-2.5)}10^3(1+z)^{\frac{p+1}{2}}\bar{\epsilon}_e^{p-1}\epsilon_B^{p-\frac{1}{2}}n_0^{\frac{p}{2}}E_{52}^{\frac{p+1}{2}}t_{\mathrm{days}}^{\frac{1-p}{2}}d_{L28}^{-2}$	1.15-0.06p	1.9
				$4.40(3.45-p)10^{10}e^{0.45p}(1+z)^{-3/2}\epsilon_B^{-3/2}A_*^{-2}E_{52}^{1/2}t_{\mathrm{days}}^{1/2}$	$8.02\,e^{7.02(p-2.5)}10^5(1+z)^{p+\frac{1}{2}}\bar{\epsilon}_e^{p-1}\epsilon_B^{p-\frac{1}{2}}A_*^pE_{52}^{1/2}t_{\mathrm{days}}^{\frac{1}{2}-p}d_{L28}^{-2}$	0.80-0.03p	4.4
4	2	$\frac{5}{2}$	ν_m	$5.04(p-1.22)10^{16}(1+z)^{1/2}\bar{\epsilon}_e^2\epsilon_B^{1/2}E_{52}^{1/2}t_{\mathrm{days}}^{-3/2}$	$3.72(p-1.79)10^{15}(1+z)^{7/2}\bar{\epsilon}_e^5\epsilon_Bn_0^{-1/2}E_{52}^{3/2}t_{\mathrm{days}}^{-5/2}d_{L28}^{-2}$	$3.44p-1.41^{\dagger}$	$0.7^{\dagger}$
				$8.08(p-1.22)10^{16}(1+z)^{1/2}\bar{\epsilon}_e^2\epsilon_B^{1/2}E_{52}^{1/2}t_{\mathrm{days}}^{-3/2}$	$3.04(p-1.79)10^{15}(1+z)^3\bar{\epsilon}_e^5\epsilon_BA_*^{-1}E_{52}^2t_{\mathrm{days}}^{-2}d_{L28}^{-2}$	$3.63p-1.60^{\dagger}$	$1.8^{\dagger}$
5	$\frac{5}{2}$	$\frac{1-p}{2}$	ν_{sa}	$3.59(4.03-p)10^9e^{2.34p}\left[\frac{\bar{\epsilon}_e^{4(p-1)}\epsilon_B^{p+2}n_0^4E_{52}^{p+2}}{(1+z)^{6-p}t_{\mathrm{days}}^{3p+2}}\right]^{1/2(p+4)}$	$20.8(p-1.53)e^{2.56p}d_{L28}^{-2}\left[\frac{(1+z)^{7p+3}\epsilon_B^{2p+3}E_{52}^{3p+7}}{\bar{\epsilon}_e^{10(1-p)}t_{\mathrm{days}}^{5(p-1)}}\right]^{1/2(p+4)}$	1.47-0.21p	5.9
				$1.58(4.10-p)10^{10}e^{2.16p}\left[\frac{\bar{\epsilon}_e^{4(p-1)}\epsilon_B^{p+2}A_*^8}{(1+z)^{2-p}E_{52}^{2-p}t_{\mathrm{days}}^{3(p+2)}}\right]^{1/2(p+4)}$	$158(p-1.48)e^{2.24p}d_{L28}^{-2}\left[\frac{(1+z)^{6p+9}\epsilon_B^{2p+3}E_{52}^{4p+1}}{\bar{\epsilon}_e^{10(1-p)}A_*^{2(p-6)}t_{\mathrm{days}}^{4p+1}}\right]^{1/2(p+4)}$	1.25-0.18p	7.2
6	$\frac{5}{2}$	$-\frac{p}{2}$	ν_{sa}	$3.23(p-1.76)10^{12}\left[\frac{\bar{\epsilon}_e^{4(p-1)}\epsilon_B^{p-1}n_0^2E_{52}^{p+1}}{(1+z)^{7-p}t_{\mathrm{days}}^{3(p+1)}}\right]^{1/2(p+5)}$	$76.9(p-1.08)e^{2.06p}d_{L28}^{-2}\left[\frac{(1+z)^{7p+5}\epsilon_B^{2p-5}E_{52}^{3p+5}}{\bar{\epsilon}_e^{10(1-p)}n_0^pt_{\mathrm{days}}^{5(p-1)}}\right]^{1/2(p+5)}$	0.94-0.14p	12.4
				$4.51(p-1.73)10^{12}\left[\frac{\bar{\epsilon}_e^{4(p-1)}\epsilon_B^{p-1}A_*^4E_{52}^{p-1}}{(1+z)^{5-p}t_{\mathrm{days}}^{3p+5}}\right]^{1/2(p+5)}$	$78.6(p-1.12)e^{1.89p}d_{L28}^{-2}\left[\frac{(1+z)^{6p+5}\epsilon_B^{2p-5}E_{52}^{4p+5}}{\bar{\epsilon}_e^{10(1-p)}A_*^{2p}t_{\mathrm{days}}^{4p-5}}\right]^{1/2(p+5)}$	1.04-0.16p	11.0
7	2	$\frac{11}{8}$	ν_{ac}	$1.12\frac{(3p-1)^{8/5}}{(3p+2)^{8/5}}10^8(1+z)^{-13/10}\bar{\epsilon}_e^{-8/5}\epsilon_B^{-2/5}n_0^{3/10}E_{52}^{-1/10}t_{\mathrm{days}}^{3/10}$	$5.27\frac{(3p-1)^{11/5}}{(3p+2)^{11/5}}10^{-3}(1+z)^{-1/10}\bar{\epsilon}_e^{-11/5}\epsilon_B^{-4/5}n_0^{1/10}E_{52}^{3/10}t_{\mathrm{days}}^{11/10}d_{L28}^{-2}$	1.99-0.04p	1.9
				$1.68\frac{(3p-1)^{8/5}}{(3p+2)^{8/5}}10^8(1+z)^{-1}\bar{\epsilon}_e^{-8/5}\epsilon_B^{-2/5}A_*^{3/5}E_{52}^{-2/5}$	$3.76\frac{(3p-1)^{11/5}}{(3p+2)^{11/5}}10^{-3}\bar{\epsilon}_e^{-11/5}\epsilon_B^{-4/5}A_*^{1/5}E_{52}^{1/5}t_{\mathrm{days}}d_{L28}^{-2}$	1.97-0.04p	1.9
8	$\frac{11}{8}$	$-\frac{1}{2}$	ν_{sa}	$1.98\cdot10^{11}(1+z)^{-1/2}n_0^{1/6}E_{52}^{1/6}t_{\mathrm{days}}^{-1/2}$	$154(1+z)\epsilon_B^{-1/4}n_0^{-1/12}E_{52}^{2/3}d_{L28}^{-2}$	0.907	1.71
				$3.15\cdot10^{11}(1+z)^{-1/3}A_*^{1/3}t_{\mathrm{days}}^{-2/3}$	$119(1+z)^{11/12}\epsilon_B^{-1/4}A_*^{-1/6}E_{52}^{3/4}t_{\mathrm{days}}^{1/12}d_{L28}^{-2}$	0.893	2.29
9	$-\frac{1}{2}$	$-\frac{p}{2}$	ν_m	$3.94(p-0.74)10^{15}(1+z)^{1/2}\bar{\epsilon}_e^2\epsilon_B^{1/2}E_{52}^{1/2}t_{\mathrm{days}}^{-3/2}$	$0.221(6.27-p)(1+z)^{1/2}\bar{\epsilon}_e^{-1}\epsilon_B^{-1/2}E_{52}^{1/2}t_{\mathrm{days}}^{1/2}d_{L28}^{-2}$	3.34-0.82p	4.5
				$3.52(p-0.31)10^{15}(1+z)^{1/2}\bar{\epsilon}_e^2\epsilon_B^{1/2}E_{52}^{1/2}t_{\mathrm{days}}^{-3/2}$	$0.165(7.14-p)(1+z)^{1/2}\bar{\epsilon}_e^{-1}\epsilon_B^{-1/2}E_{52}^{1/2}t_{\mathrm{days}}^{1/2}d_{L28}^{-2}$	3.68-0.89p	4.2
10	$\frac{11}{8}$	$\frac{1}{3}$	ν_{sa}	$1.32\cdot10^{10}(1+z)^{-1/2}\epsilon_B^{6/5}n_0^{11/10}E_{52}^{7/10}t_{\mathrm{days}}^{-1/2}$	$3.72(1+z)\epsilon_B^{7/5}n_0^{6/5}E_{52}^{7/5}d_{L28}^{-2}$	1.213	5.22
				… ††	… ††	… ††	… ††
11	$\frac{1}{3}$	$-\frac{1}{2}$	ν_c	$5.86\cdot10^{12}(1+z)^{-1/2}\epsilon_B^{-3/2}n_0^{-1}E_{52}^{-1/2}t_{\mathrm{days}}^{-1/2}$	$28.4(1+z)\epsilon_B^{1/2}n_0^{1/2}E_{52}d_{L28}^{-2}$	0.597	0.55
				… ††	… ††	… ††	… ††





$$F = f\left(\frac{\lambda}{\lambda_b}\right)^{\beta_2+1/2}\left[1+\left(\frac{\lambda}{\lambda_b}\right)^{s/2}\right]^{-1/s}$$

$$F = f\left(\frac{\lambda}{\lambda_b}\right)^{\beta_1}\left[1+\left(\frac{\lambda}{\lambda_b}\right)^{s(\beta_1+1/3)}\right]^{-1/s}$$

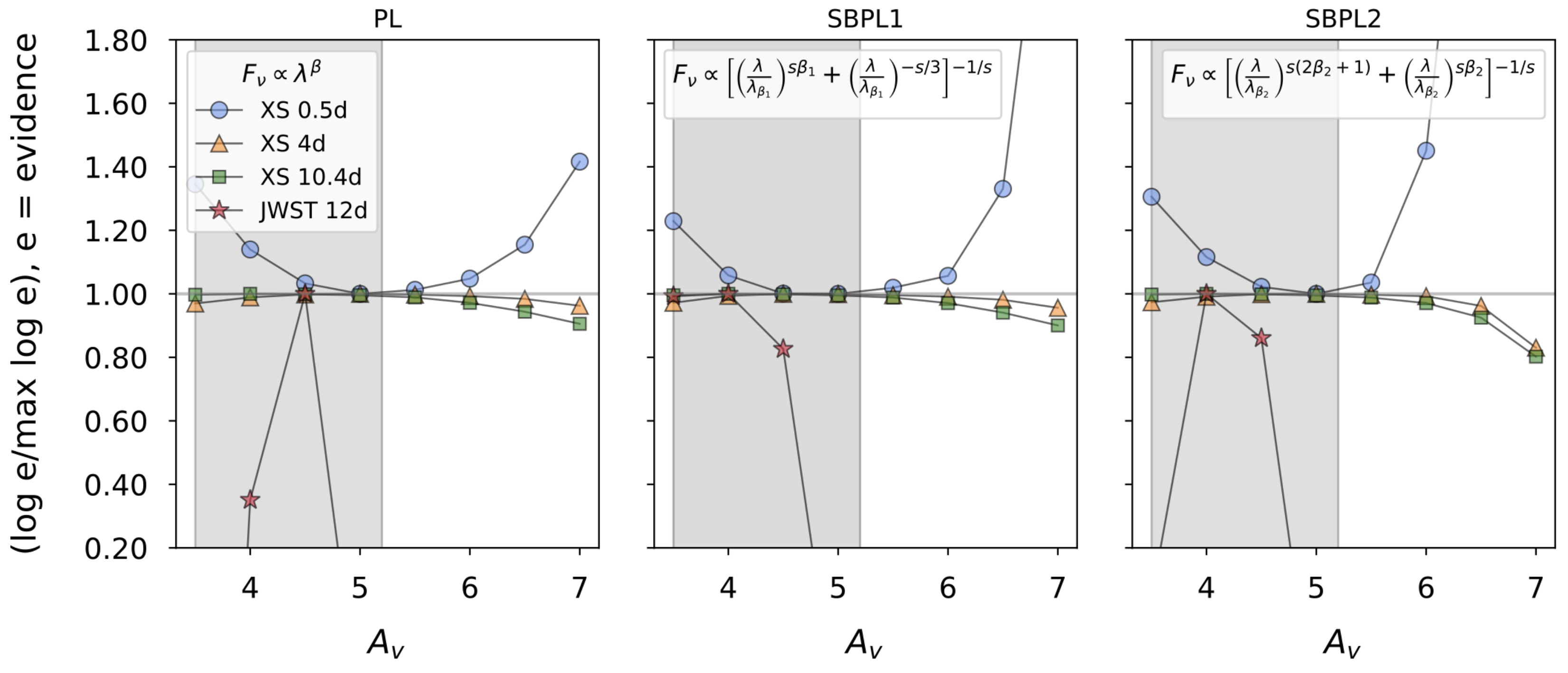
SBPL2 - Smoothly Broken Power Law 2 – Cooling Break, ν_c

SBPL1 – Smoothly Broken Power Law 1 – Synchrotron Peak, ν_m

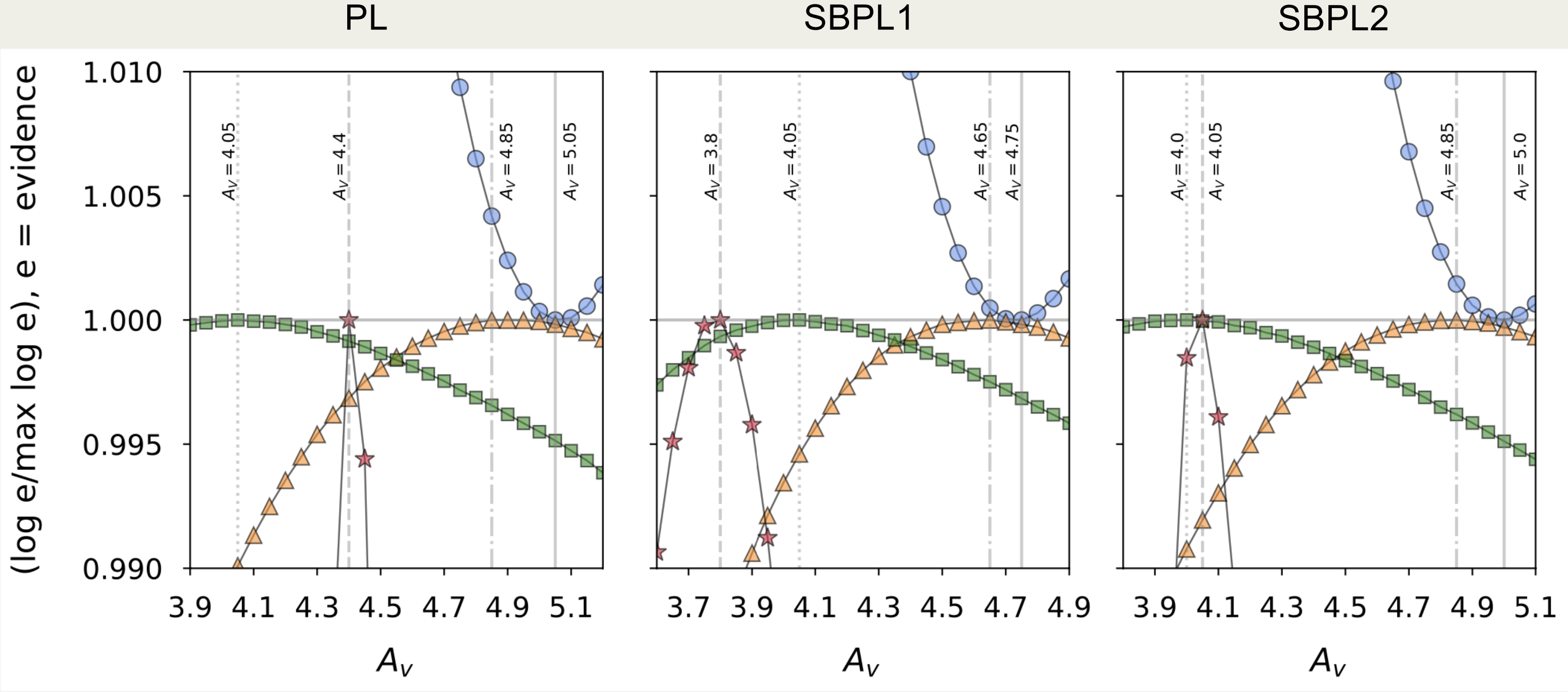
GRB 221009A – the BOAT's extinction kerfuffle

Work	A_V	$E(B-V)$	R_V	β, ($[p-1]/2$)	p, ($2\beta+1$)
Fulton et al. (2023)	$A_r = 4.64$	-	3.1	0.8	-, (2.6)
Kann et al. (2023)	5.202 ± 0.085	1.69 ± 0.03	3.1	-, (0.501, 0.715)	$2.003^{+0.005}_{-0.003}$ [narrow], $2.43^{+0.03}_{-0.02}$ [wide]
Laskar et al. (2023)	4.1034	1.32	3.1	-, (0.765)	2.53 ± 0.01
Levan et al. (2023)	4.935 ± 0.005	1.680 ± 0.003	2.938 ± 0.008	0.362 ± 0.001, (0.3)	~ 1.6, (1.724)
Malesani et al. (2023)	4.177	1.347	3.1	0.8 or 0.4	-, (2.6)
Shrestha et al. (2023)	4.1 and 5.4	1.32 and 1.74	3.1	0.59 ± 0.17	-, (2.18)
Srinivasaragavan et al. (2023)	-	$1.31^{+0.06}_{-0.07}$	-	-	-
Sato et al. (2023)	$A_r = 4.31$	-	-	-, (0.85, 0.7)	2.7 [narrow], 2.4 [wide]
Blanchard et al. (2024)	$4.63^{+0.13}_{-0.64}$	-	$4.24^{+0.74}_{-0.64}$	0.41 ± 0.01	-, (1.82)
Kong et al. (2024)	-	1.36	-	-	-
Ren et al. (2024)	-	1.32	-	-, (0.673, 0.573)	2.345 ± 0.075 [narrow], $2.145^{+0.020}_{-0.037}$ [wide]
Sánchez-Ramírez et al. (2024)	4.03 ± 0.19	1.30 ± 0.06	3.1	0.579 ± 0.022, (0.3)	1.6, (2.158)
Sears et al. (2025)	4.63	-	4.24	0.76	2.52 ± 0.14, (2.52)
Sato et al. (2025)	-	-	-	-, (0.6)	2.2 [narrow and wide]

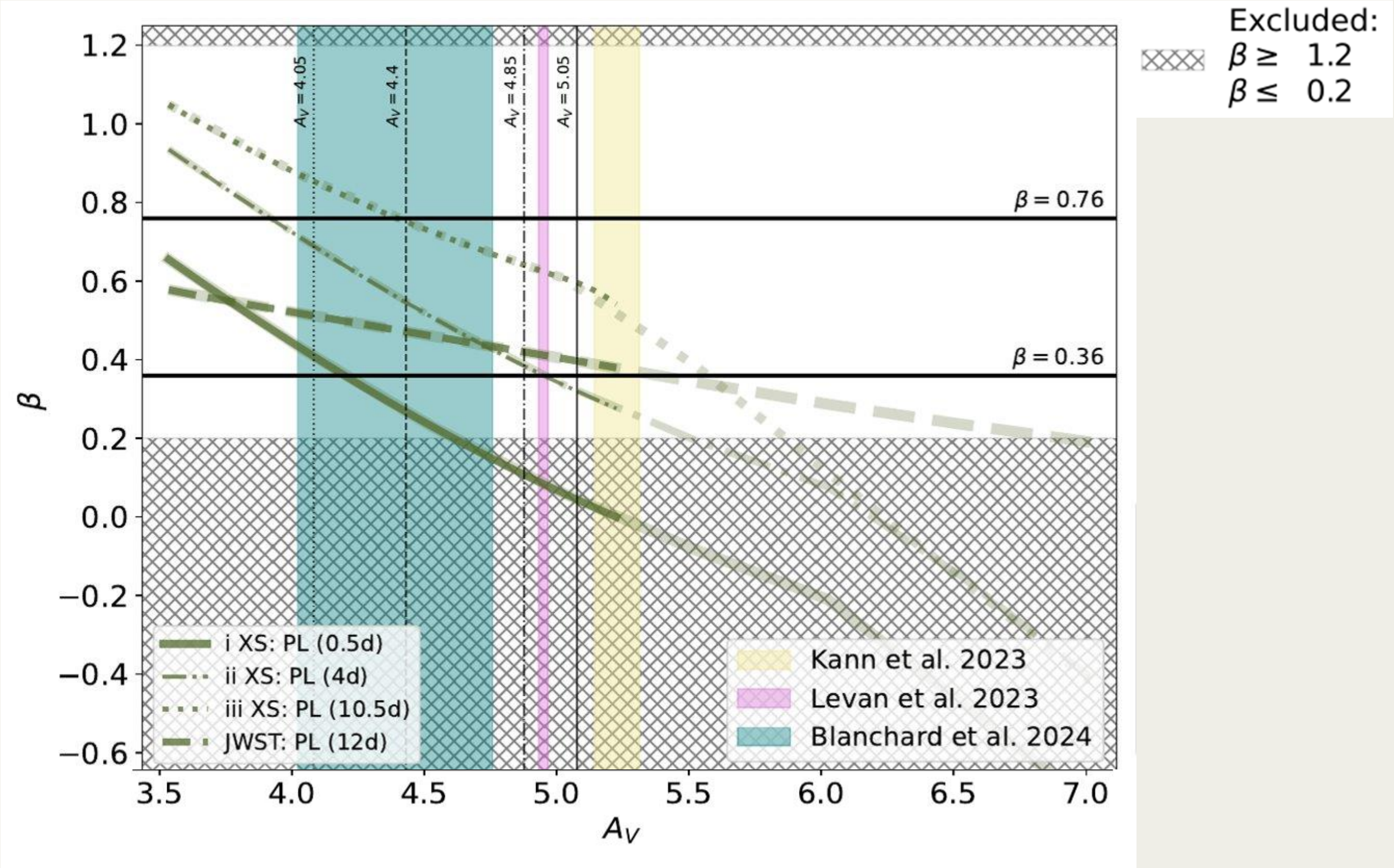
Most favourable extinctions



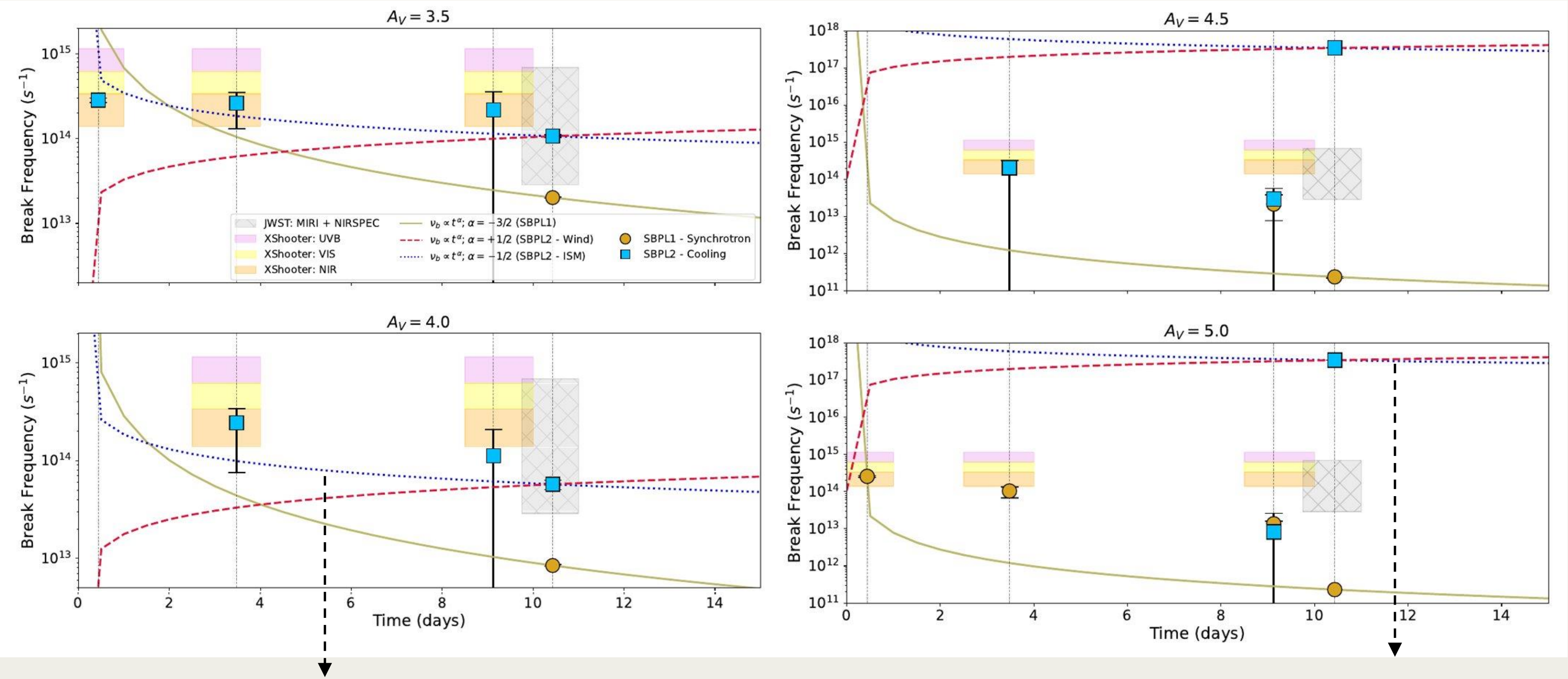
Refined evidences (zoomed-in)



Visual Extinction vs. Spectral Index



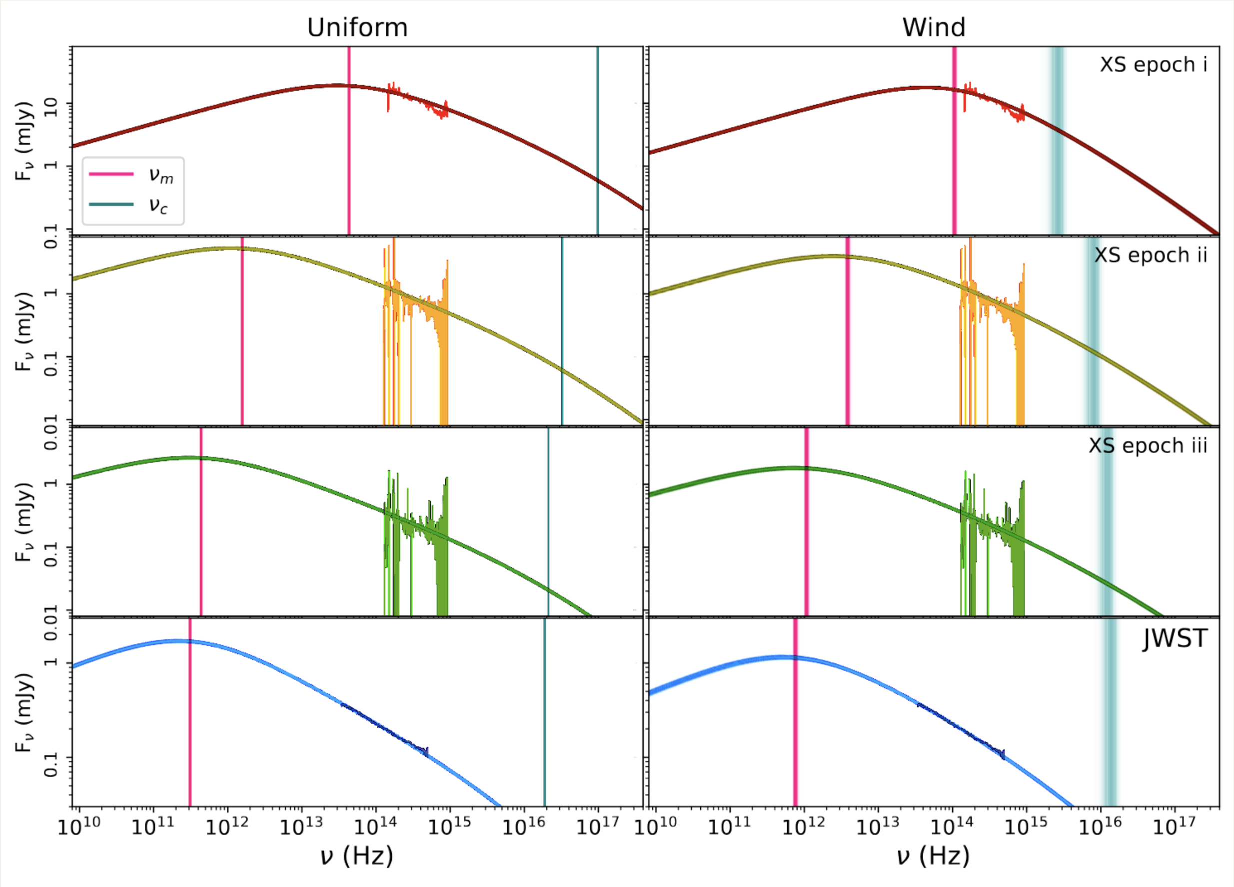
Break frequency time evolution



Consistent with shocks travelling through uniform ISM, not wind medium

These points are fitted on the 'wrong' side of the power-law curve, hence pushing the breaks to the edges

Double Smoothly-Broken Power Law



Parameters do fit...

Parameter	Prior	Uniform	Wind
$\beta = (p-1)/2$	$(0.0,\ 1.0)$	0.447 ± 0.001	0.425 ± 0.003
λ_c (μm)	$10^{(-1.8,\ 0.5)}$	0.016 ± 0.000	0.022 ± 0.003
λ_m (μm)	$10^{(-6.0,\ 6.0)}$	968 ± 13	395 ± 13
A_V (mag)	$(2.5,\ 7.0)$	4.402 ± 0.004	$4.326 \pm \pm 0.007$
$E(B-V)$	$(0.7,\ 2.2)$	1.308 ± 0.004	1.276 ± 0.005
Δ_i	–	3.33	0.0

With the new data, the joint analysis fits the four epochs being considered with **β = 0.447** (wind - 0.425) extinction **AV = 4.402** (wind - 4.326)

The value for the electron index, **p = 1.894** (wind - 1.85) and consistent with $p < 2$

Given a post-jet-break decline, the optical and the x-ray temporal index should be, **α1 = 1.48** (wind - 1.73), and **α2 = 1.73** (wind - 1.48)

Summary

- X-Shooter & JWST data re-analysis for modelling the afterglow (with careful treatment of extinction)

- Double Smoothly Broken Power Law employed to fit a coherent solution for both X-Shooter & JWST

- **β = 0.447** (wind - 0.425)
  p = 1.894 (wind - 1.85)
  Extinction **AV = 4.402** (wind - 4.326)

- Light curve analysis needed of the BOAT, combining optical, X-rays and radio