GW170817 afterglow:
a more natural electron distribution leads to a new solution

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MNRAS in press

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Afterglow from GW170817, the 1st BNS merger

- We have observed afterglow from GW170817, the first binary neutron star (BNS) merger for > 1 year
- Modeled by 20+ papers using *Standard afterglow theory* (~ 1990s)
- However, there are several limitations of this theory:
  - For simplicity, it assumes an unrealistically large nonthermal population: *ALL* electrons in the shock are accelerated
  - Lowest energy of electrons is not determined by electron-ion equipartition
  - Ultra-relativistic limit may not be applicable to BNS mergers
- So…is standard afterglow theory reliable for BNS mergers?

Image: D. Berry, SkyWorks Digital, Inc.

Content

- Standard afterglow theory:
  - Limitations, and our improvements
- Re-examine GW170817 afterglow modeling:
  - A new solution to the afterglow spectrum

Limitations of standard theory and our improvements

Standard afterglow theory

A shock (Lorentz factor Γ_s) sweeps up external medium matter (number density n)

Swept-up mass $$M = \frac{4}{3}\pi R^3 n m_p$$

1. Power-law distribution of accelerated electrons in the shock

$$N_{\gamma_e} \propto \gamma_e^{-p} \quad (\gamma_e > \gamma_m)$$

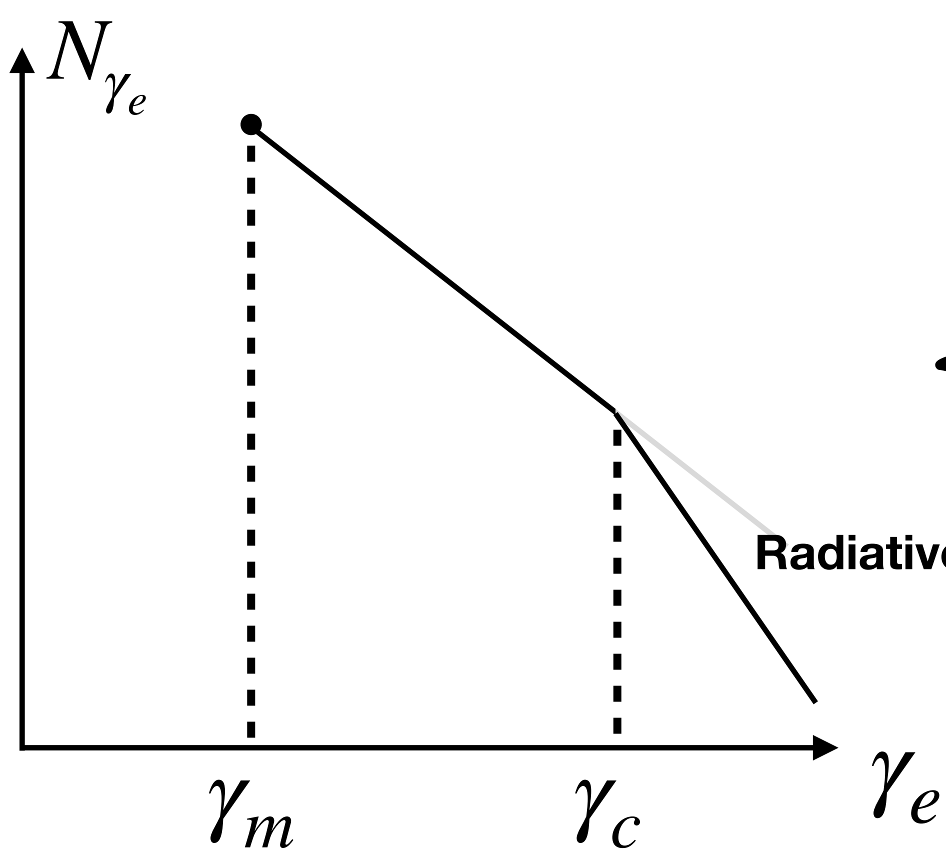
2. ϵ_e (ϵ_B) of shock energy goes to accelerated electrons (magnetic field)

3. ***ALL electrons in the shock are accelerated*** $$N_e = \int_{\gamma_m}^{\infty} d\gamma_e N_{\gamma_e} = \frac{M}{m_p}$$

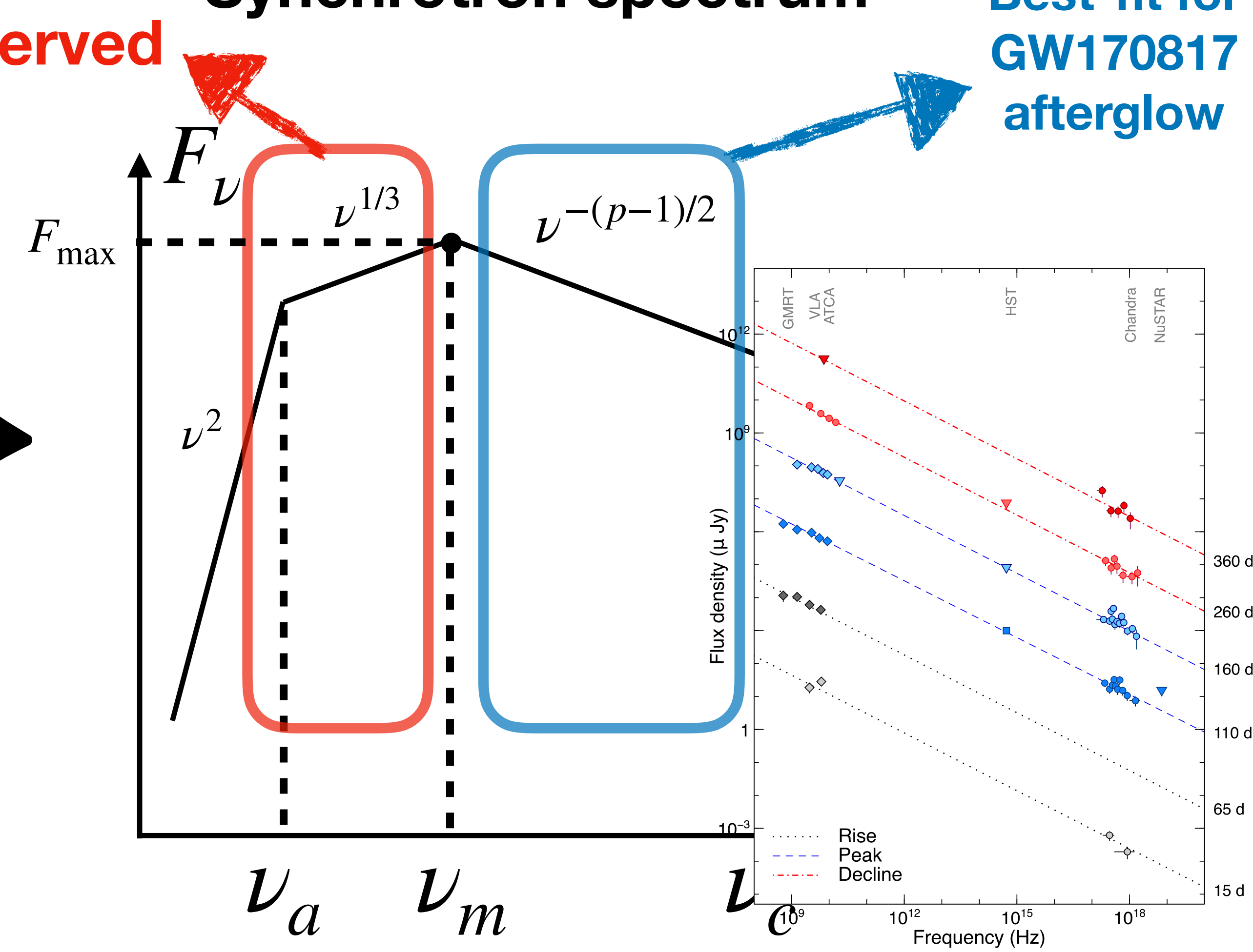
Minimum electron energy $$\gamma_m = \epsilon_e \frac{p-2}{p-1} \frac{m_p}{m_e} \Gamma_s$$

Standard afterglow theory

Electron energy distribution



Synchrotron spectrum



Troja+18

(I) 100% acceleration?

Standard theory assumes the number fraction f of accelerated electrons is **100%**, for simplicity.

However, $f \ll 1$ is normally observed in supernova remnants (e.g. Cas A ~ 4%, SN 1006 ~ 0.1%) and in PIC simulation of relativistic shock (e.g. ~ 2%, *Sironi & Spitkovsky 2011*).

For a variable f

$$\gamma_m = \frac{\epsilon_e}{f}\frac{p-2}{p-1}\frac{m_p}{m_e}\Gamma_s$$

$$N_e = f\frac{M}{m_p}$$

→

$$\nu_m = \frac{1}{2\pi}\frac{eB'}{m_e c}\gamma_m^2\Gamma_s \propto f^{-2}$$

$$F_{\max} \simeq \frac{e^3B'}{m_e c^2}N_e\Gamma_s^3 \propto f$$

f greatly affects estimate of the peak frequency!

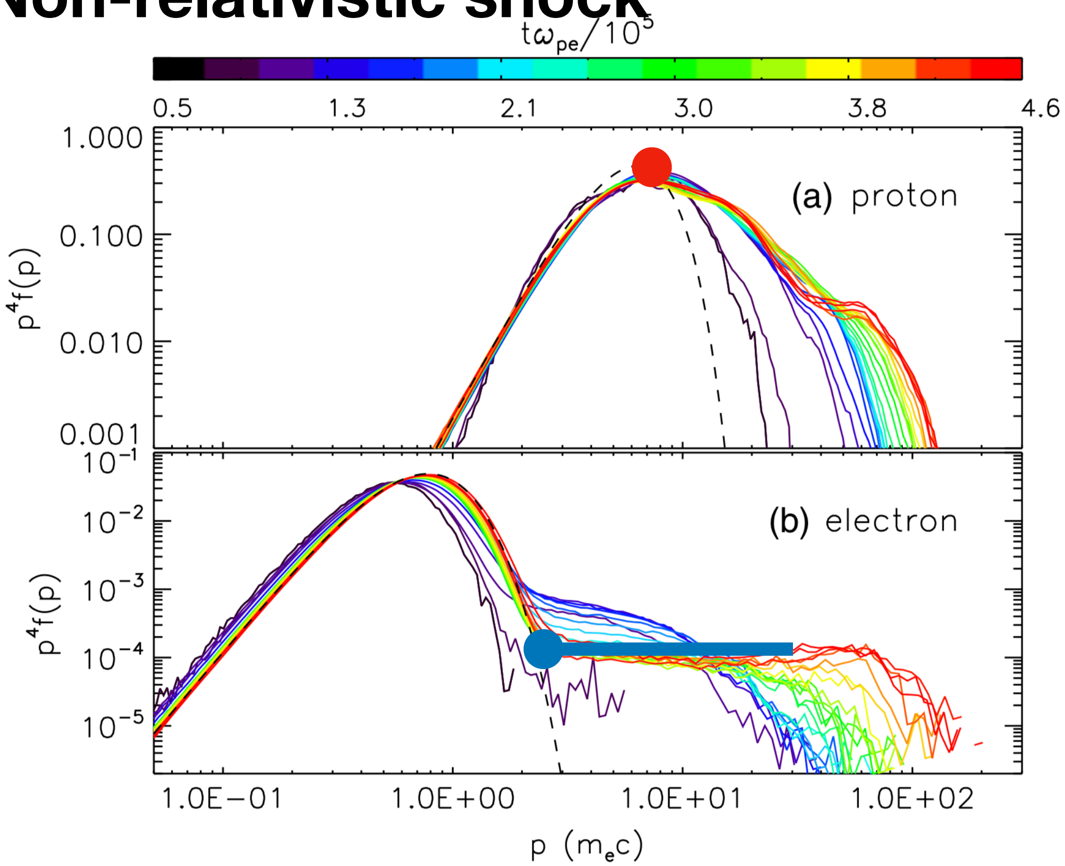
(II) Minimum electron energy

$$\gamma_m = \epsilon_e \frac{p-2}{p-1} \frac{m_p}{m_e} \Gamma_s$$

Standard model controls γ_m with the total energy and slope, just for simple math

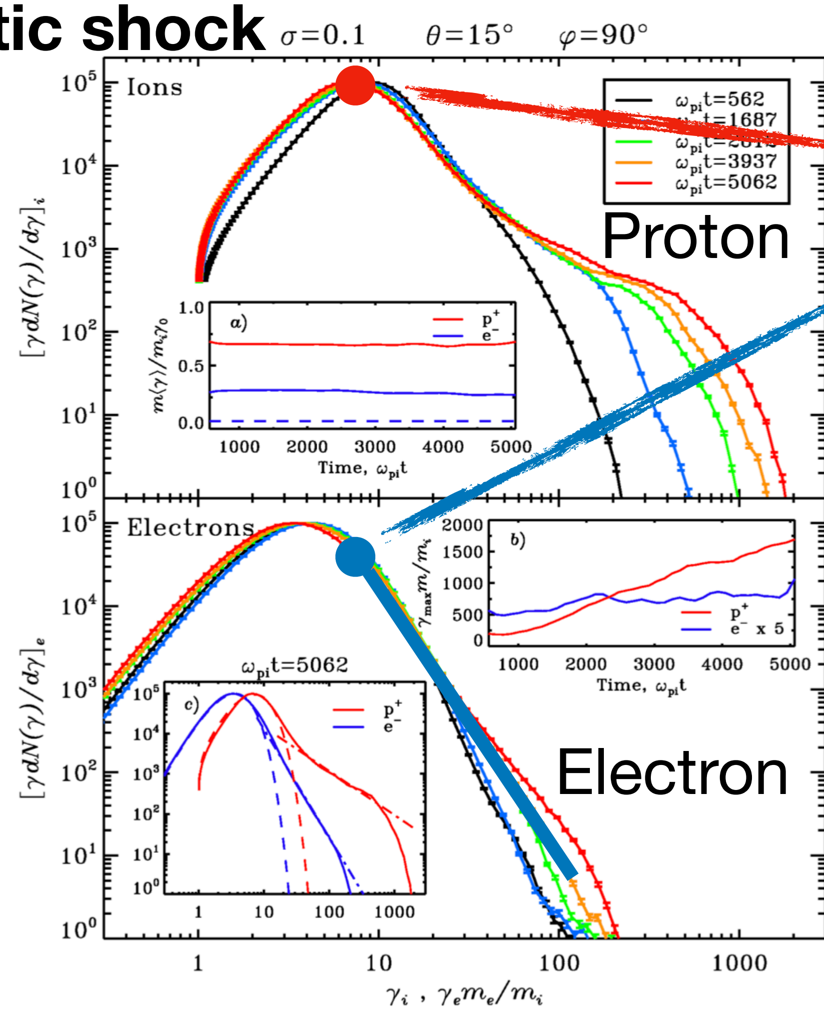
But γ_m should be determined by interactions between downstream electrons and protons:

Non-relativistic shock



Park et al. 2015

Relativistic shock



Sironi & Spitkovsky 2011

By latest PIC simulations

$$m_e\gamma_m \sim m_p\Gamma_s$$

close to equipartition

A natural way to determine γ_m!

$$\eta_e \equiv \frac{m_e\gamma_m}{m_p\Gamma_s} \qquad \eta_e \sim 1$$

(II) Minimum injection energy

η_e: electron-ion coupling efficiency

$$\gamma_m m_e c^2 = \eta_e m_p c^2 (\Gamma_s - 1)$$

$\eta_e \sim 1$: equipartition

$\eta_e \sim m_e/m_p \sim 10^{-3}$: no energy transfer

4 parameters to model electron distribution: ϵ_e, p, f, η_e

Total d.o.f = 3:

$$f = \frac{\epsilon_e}{\eta_e} \frac{p-2}{p-1}$$

100% acceleration & electron-ion equipartition is impossible!

e.g. fix $f = \eta_e = 1$, $p = 2.2$, then $\epsilon_e = 6$…Clearly unphysical

-> we should expect much smaller f

(III) non-relativistic theory

$$\gamma_m = \epsilon_e \frac{p-2}{p-1} \frac{m_p}{m_e} \Gamma_s \propto \Gamma_s \qquad B' = (32\pi\epsilon_B n m_p)^{1/2} \Gamma_s c \propto \Gamma_s$$

These scalings become incorrect when Γ_s ~ 1…

BNS merger ejecta ~ 0.3c → Γ_s ~ 1.05

$$P_\nu / P_{\max} = \begin{cases} \left(\nu_c/\nu_m\right)^{-(p-1)/2} \left(\nu/\nu_c\right)^{-p/2} & (\nu_c < \nu) \\ \left(\nu/\nu_m\right)^{-(p-1)/2} & (\nu_m < \nu < \nu_c) \\ \left(\nu/\nu_m\right)^{1/3} & (\nu < \nu_m) \end{cases}$$

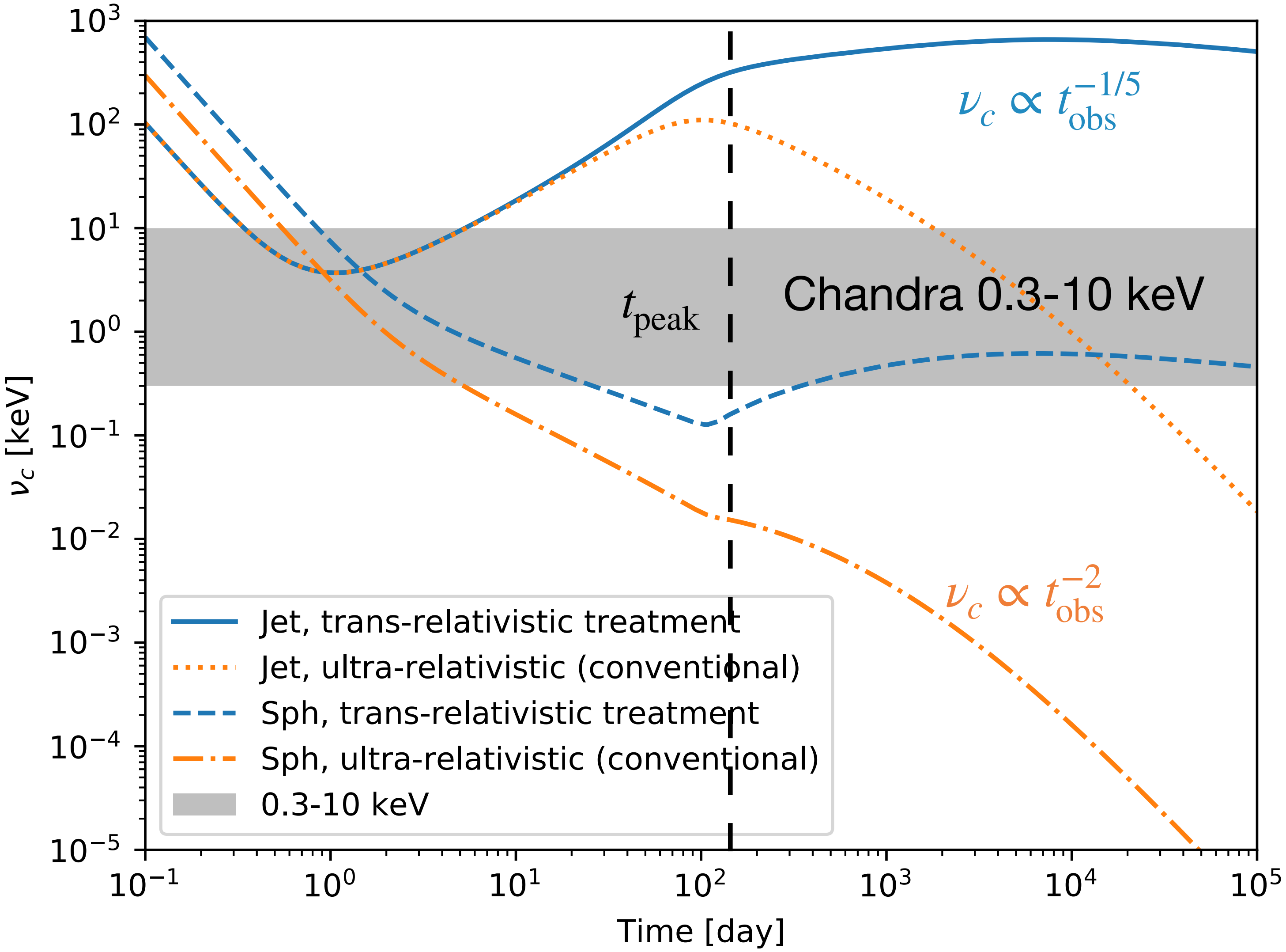
Power-law synchrotron is invalid when γ_m ~ 1, where most electrons emits cyclotron emission line

(III) non-relativistic theory

A criterion e.g. $\gamma_e > 2$ for synchrotron-emitting electrons

$$\gamma_m = \max\left\{\eta_e \frac{m_p}{m_e}(\Gamma_s - 1),\ 2\right\} \qquad N_e = f\frac{M}{m_p} \times \min\left\{1,\ \gamma_m^{p-1}/2^{p-1}\right\}$$

Not relevant in this event since $\Gamma_s - 1 \gtrsim 3$ (**superluminal**) $\gg (\frac{m_p}{m_e})^{-1} \sim \mathcal{O}(10^{-3})$



Trans-relativistic shock jump condition

$$B' = (32\pi\epsilon_B n m_p)^{1/2}\Gamma_s c$$

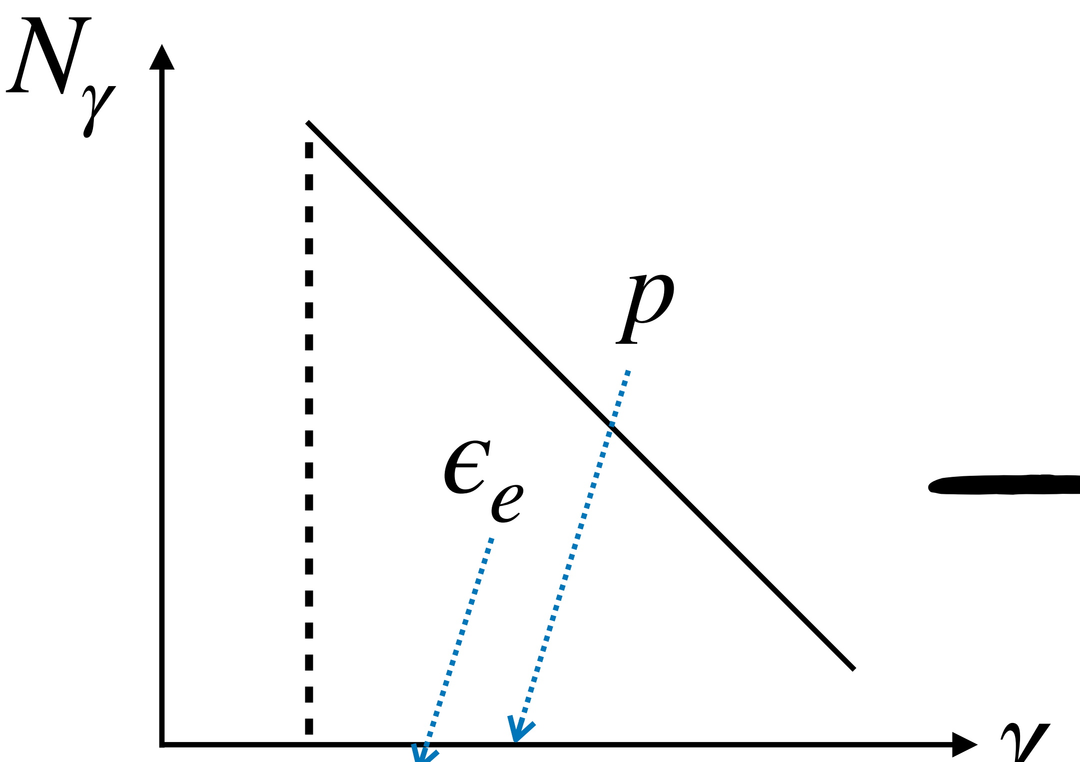
$$\longrightarrow \quad B' = \left[8\pi\epsilon_B \frac{\hat{\gamma}\Gamma_s + 1}{\hat{\gamma} - 1} n m_p c^2 (\Gamma_s - 1)\right]^{1/2}$$

$$\nu_c \propto \begin{cases} t_{\rm obs}^{-1/2} & \textbf{Blandford-Mckee (ultra-rel)} \\ t_{\rm obs}^{-1/5}\ (t_{\rm obs}^{-2}) & \textbf{Sedov-Taylor (non-rel)} \end{cases}$$

Temporal evolution of the spectrum break ν_c is different!

Summary of the new model

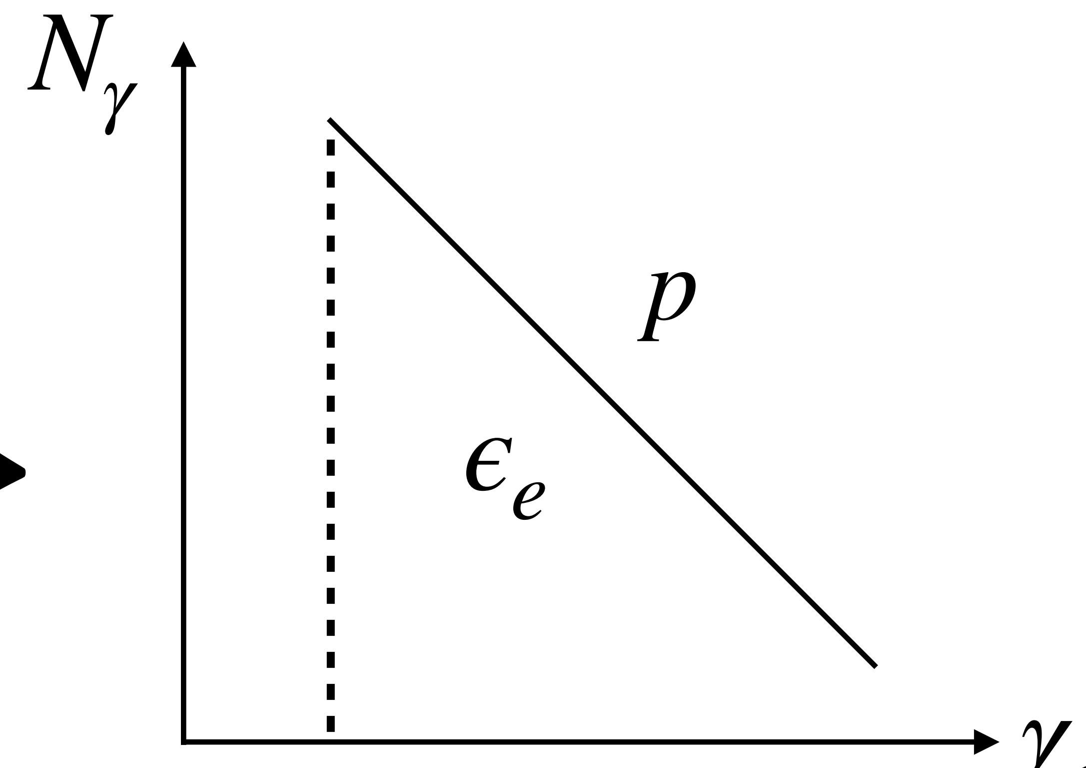
Standard model



$$\gamma_m = \epsilon_e \frac{p-2}{p-1} \frac{m_p}{m_e} \Gamma_s$$

f is fixed as 1

Variable f model



$$m_e \gamma_m = \eta_e m_p (\Gamma_s - 1)$$

$$\eta_e \sim 1$$

Suggested by PIC

$$f = \frac{\epsilon_e}{\eta_e} \frac{p-2}{p-1}$$

f is variable and proportional to energy

Re-examine afterglow modeling of GW170817

Outflow models

Using the two fiducial outflow models from previous studies:

1. Gaussian jet

Viewing angle θ_v

$$E_{k,\,\mathrm{iso}}(\theta) = E_{c,\,\mathrm{iso}} \exp\left(-\frac{\theta^2}{2\theta_c^2}\right)$$

Parameters:

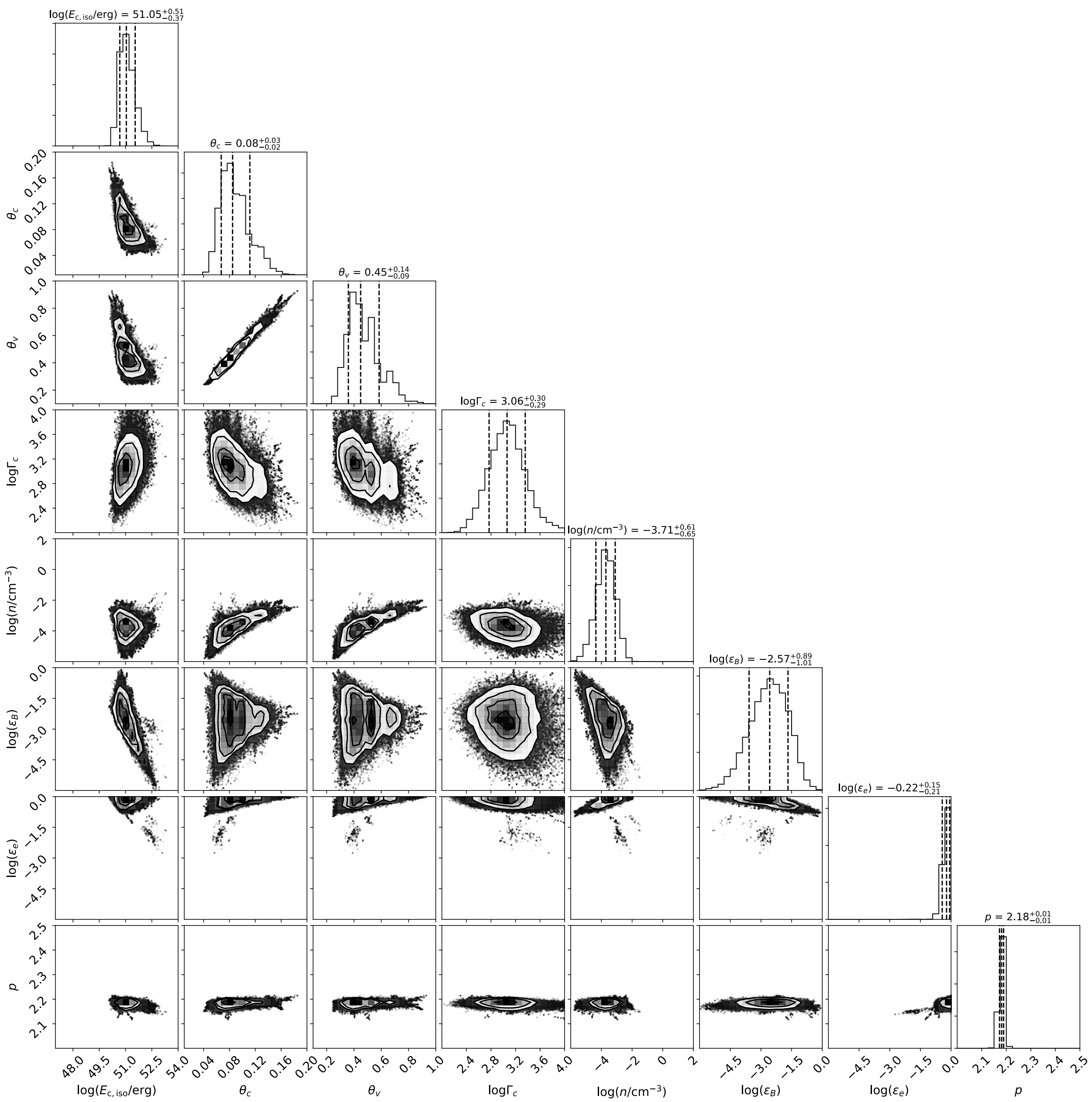
$E_{\mathrm{c,iso}}, \Gamma_c, \theta_c, \theta_v$

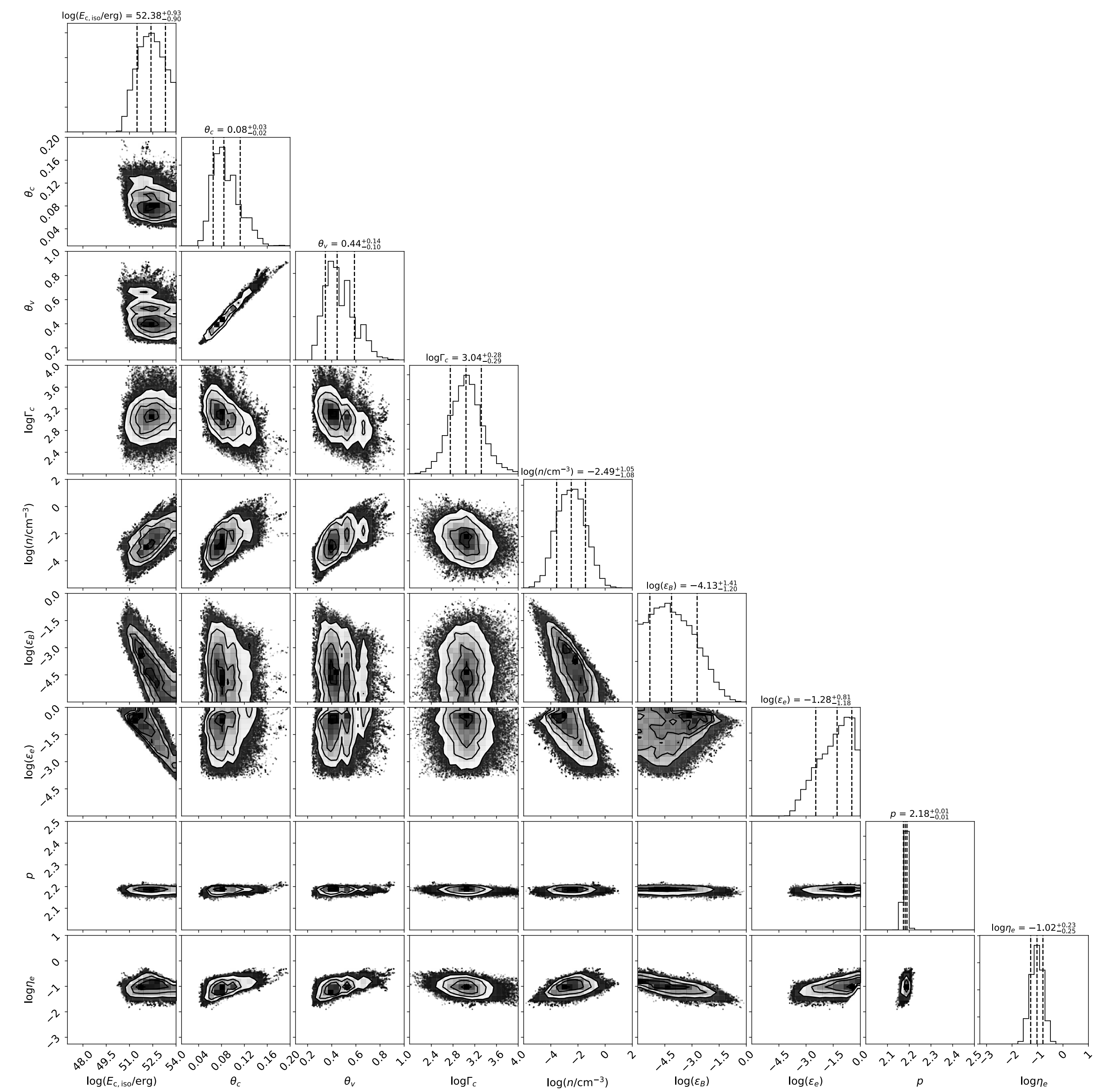
2. Radially-stratified spherical ejecta

$$E(>u) \propto E_{\mathrm{k,iso}}\, u^{-k} \quad (u_{\mathrm{min}} < u < u_{\mathrm{max}})$$

Parameters: $E_{\mathrm{k,iso}}, k, u_{\mathrm{min}}, u_{\mathrm{max}}$

Monte-Carlo Markov-Chain





Monte-Carlo Markov-Chain

Jet (Standard / variable *f*)

Parameter	Jet $f = 1$ 1D dist.[a]	best-fit[b]	1D dist.[a] ($\nu_{obs} > \nu_m$)	best-fit[b] ($\nu_{obs} > \nu_m$)	Jet f free 1D dist.[a]	best-fit[b]
$\log_{10}(E_{c,\,iso}/\mathrm{erg})$	$51.05^{+0.51}_{-0.37}$	51.19	$52.67^{+0.55}_{-0.62}$	52.33	$52.38^{+0.93}_{-0.90}$	52.25
θ_c	$0.08^{+0.03}_{-0.02}$	0.09	$0.07^{+0.02}_{-0.01}$	0.08	$0.08^{+0.03}_{-0.02}$	0.10
θ_v	$0.45^{+0.14}_{-0.09}$	0.47	$0.42^{+0.10}_{-0.06}$	0.50	$0.44^{+0.14}_{-0.10}$	0.50
$\log_{10}\Gamma_c$	$3.06^{+0.30}_{-0.29}$	2.93	$3.58^{+0.31}_{-0.45}$	3.86	$3.04^{+0.28}_{-0.29}$	2.97
$\log_{10}(n/\mathrm{cm}^{-3})$	$-3.71^{+0.61}_{-0.65}$	−3.57	$-2.36^{+0.71}_{-0.75}$	−2.18	$-2.49^{+1.05}_{-1.08}$	−2.28
$\log_{10}\epsilon_B$	$-2.57^{+0.89}_{-1.01}$	−3.12	$-4.30^{+1.38}_{-1.14}$	−4.60	$-4.13^{+1.41}_{-1.20}$	−4.76
$\log_{10}\epsilon_e$	$-0.22^{+0.15}_{-0.21}$	−0.10	$-1.36^{+0.46}_{-0.57}$	−0.83	$-1.28^{+0.81}_{-1.18}$	−0.80
p	$2.18^{+0.01}_{-0.01}$	2.19	$2.16^{+0.01}_{-0.01}$	2.16	$2.18^{+0.01}_{-0.01}$	2.18
$\log_{10}\eta_e$	—	—	—	—	$-1.02^{+0.23}_{-0.25}$	−0.80
$\log_{10} f$	0	0	0	0	$-1.09^{+0.75}_{-1.08}$	−0.83
χ^2		114		140		114

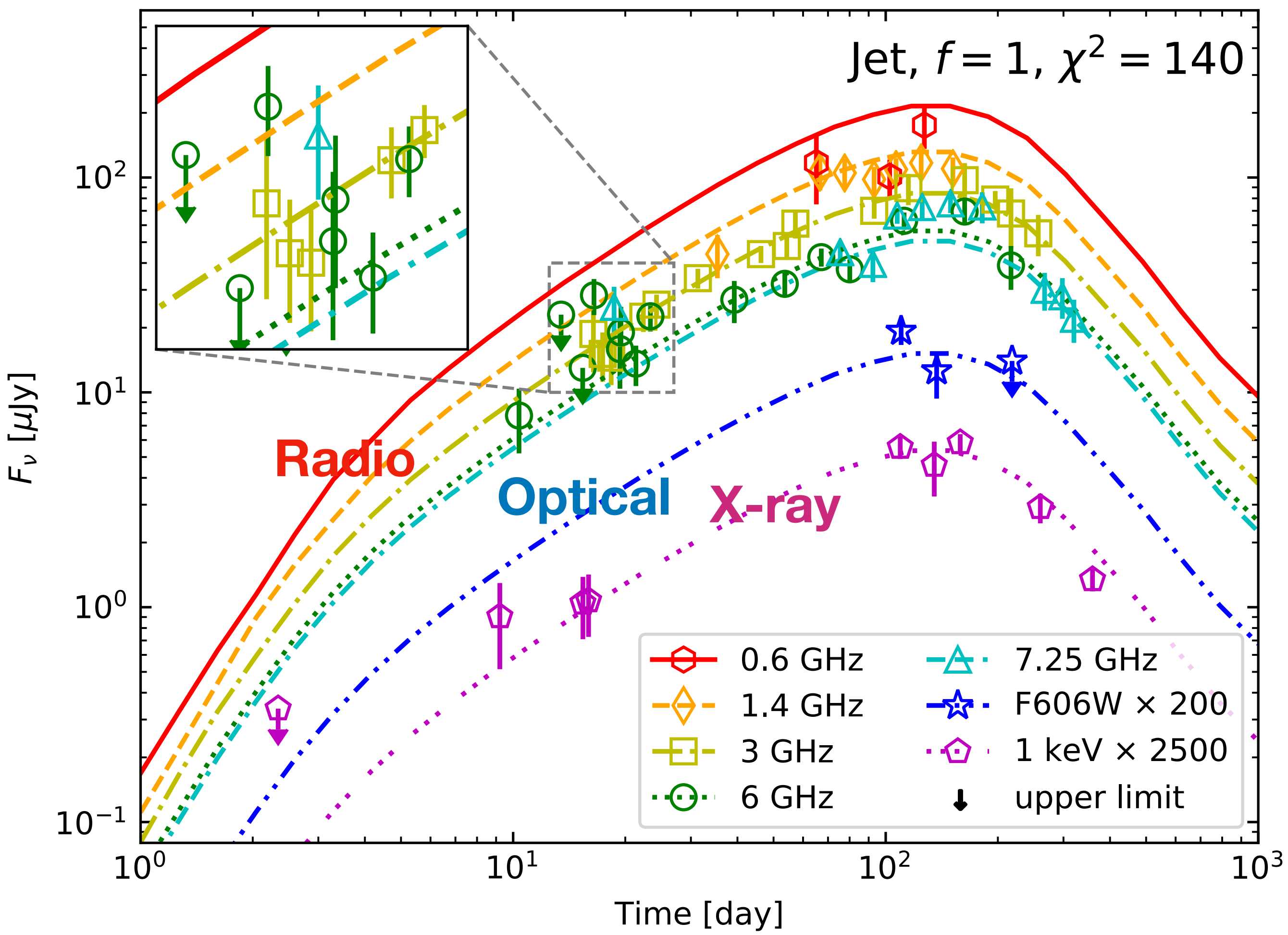
Spherical (Standard / variable *f*)

Parameter	Sph $f = 1$ 1D dist.	best-fit	Sph f free 1D dist.	best-fit
$\log_{10}(E_{k,\,iso}/\mathrm{erg})$	$50.15^{+1.27}_{-0.63}$	50.58	$51.60^{+1.65}_{-1.70}$	50.18
$\log_{10} u_{max}$	$1.20^{+0.53}_{-0.45}$	0.55	$1.31^{+0.46}_{-0.46}$	0.59
$\log_{10} u_{min}$	$0.40^{+0.02}_{-0.08}$	0.24	$0.34^{+0.07}_{-0.02}$	0.24
k	$5.66^{+0.55}_{-0.32}$	6.21	$5.69^{+0.45}_{-0.40}$	5.79
$\log_{10}(n/\mathrm{cm}^{-3})$	$-3.68^{+1.21}_{-0.67}$	−2.25	$-2.05^{+1.66}_{-1.71}$	−2.69
$\log_{10}\epsilon_B$	$-0.94^{+0.61}_{-1.21}$	−1.94	$-2.57^{+1.71}_{-1.66}$	−1.62
$\log_{10}\epsilon_e$	$-1.74^{+0.57}_{-1.22}$	−2.14	$-3.36^{+1.70}_{-1.65}$	−1.93
p	$2.15^{+0.01}_{-0.01}$	2.15	$2.16^{+0.01}_{-0.01}$	2.17
$\log_{10}\eta_e$	—	—	$-1.04^{+0.08}_{-0.12}$	−0.87
$\log_{10} f$	0	0	$-3.17^{+1.71}_{-1.64}$	−1.90
χ^2		148		125

[a]Medians with symmetric 68% uncertainties; [b]Maximum of the posterior probability density function

Standard model ($\nu_{obs} > \nu_m$)

Fit to GW170817 afterglow

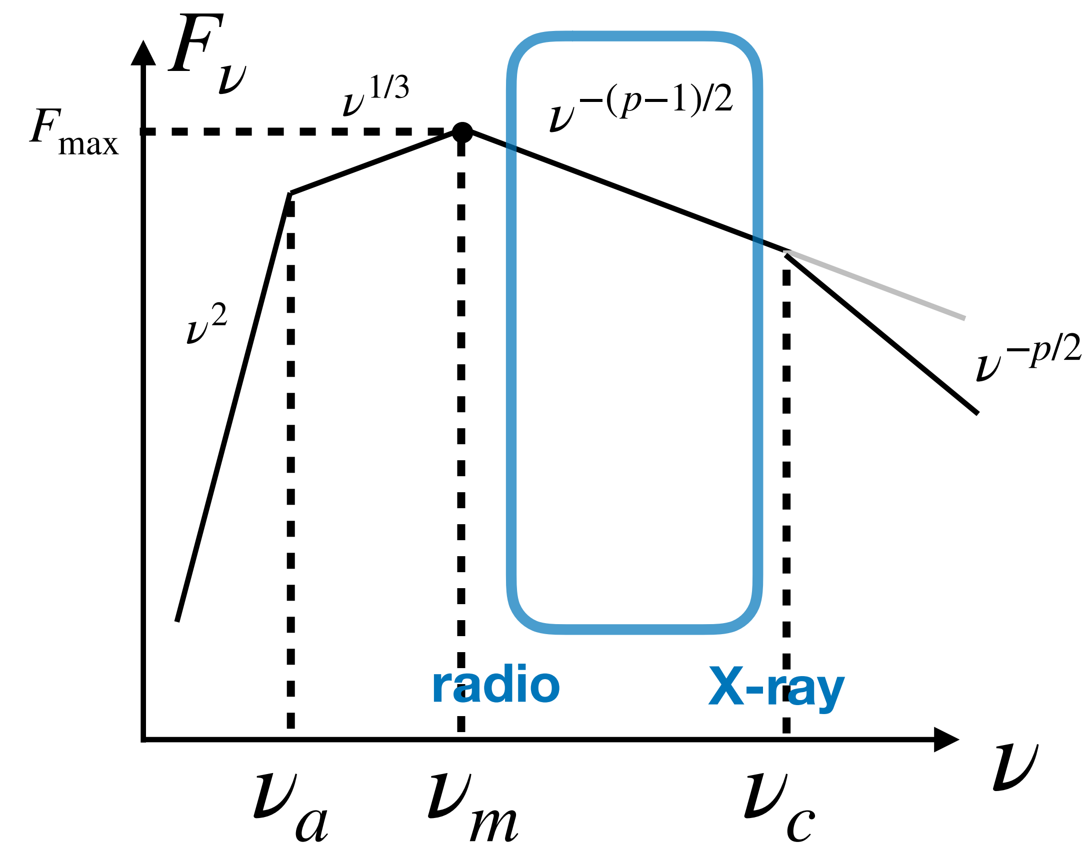


$$\log E_{\rm c,iso} = 52.33, \theta_c = 0.08, \theta_{\rm obs} = 0.50, \log \Gamma_c = 3.86$$

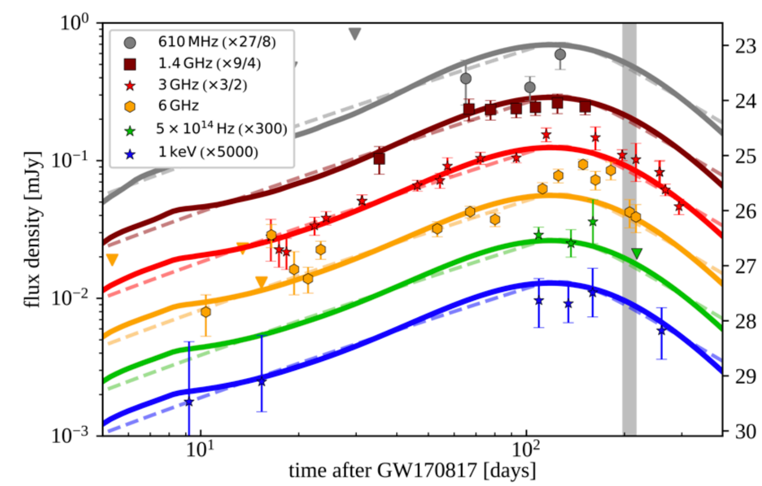
$$\log n = -2.18, \log \epsilon_B = -4.60, \log \epsilon_e = -0.83, p = 2.16$$

$$\chi^2_{\rm min} = \mathbf{140}$$

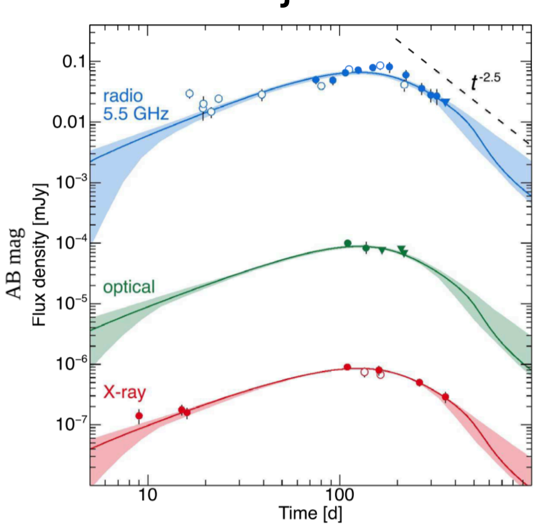
Commonly found by previous work



Ghirlanda+18

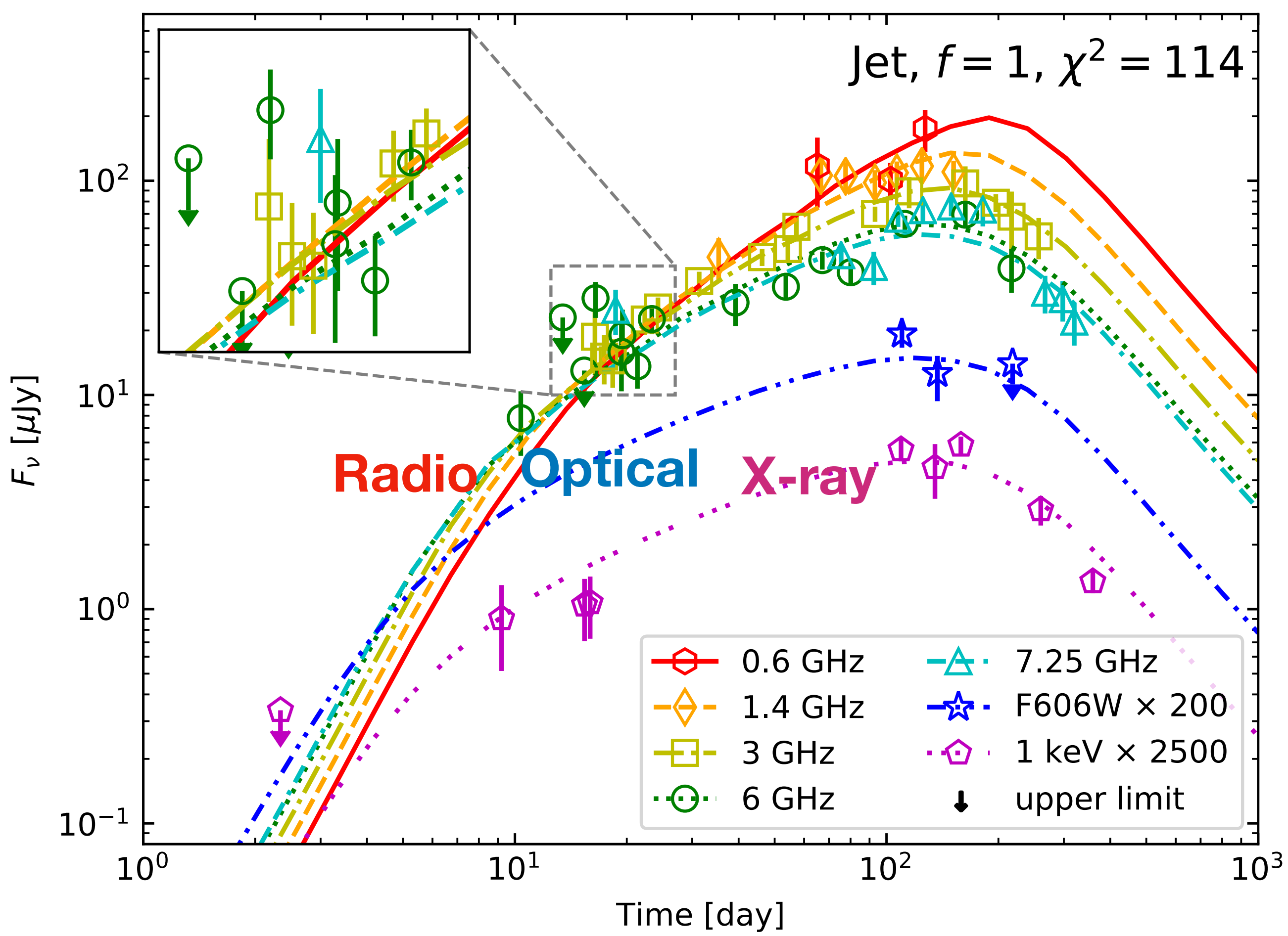


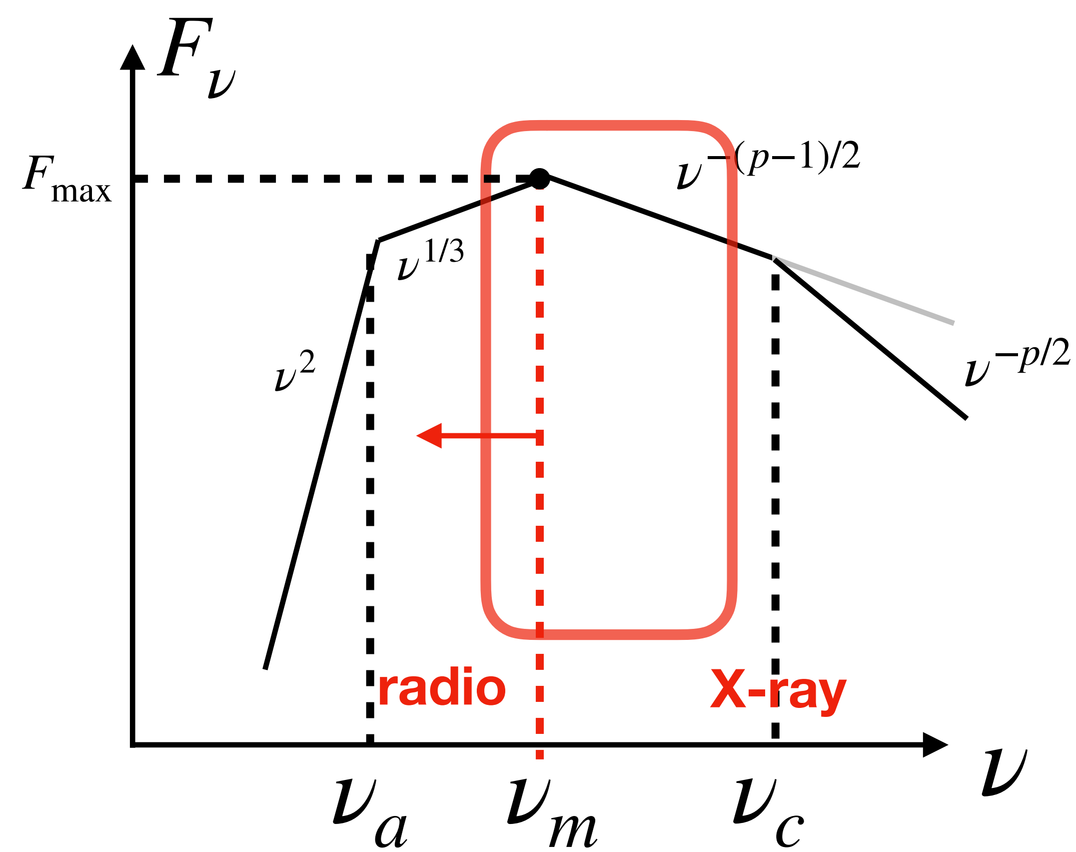
Troja+18



Standard model (no constraint)

Fit to GW170817 afterglow



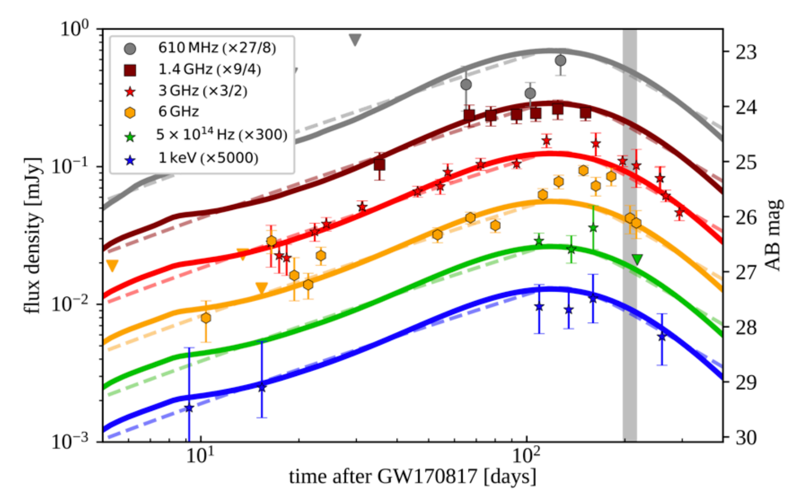


$$\log E_{\rm c,iso} = 51.19, \theta_c = 0.09, \theta_{\rm obs} = 0.47, \log \Gamma_c = 2.93$$

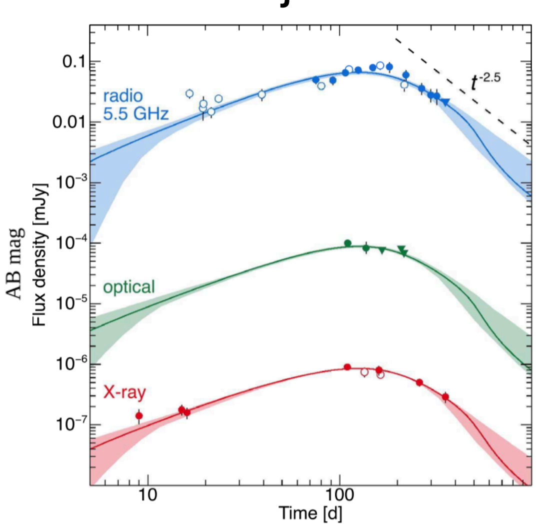
$$\log n = -3.57, \log \epsilon_B = -3.12, \log \epsilon_e = -0.10, p = 2.19$$

$\Delta\chi^2_{\rm min} = -26$ (Data # = 62)

Ghirlanda+18

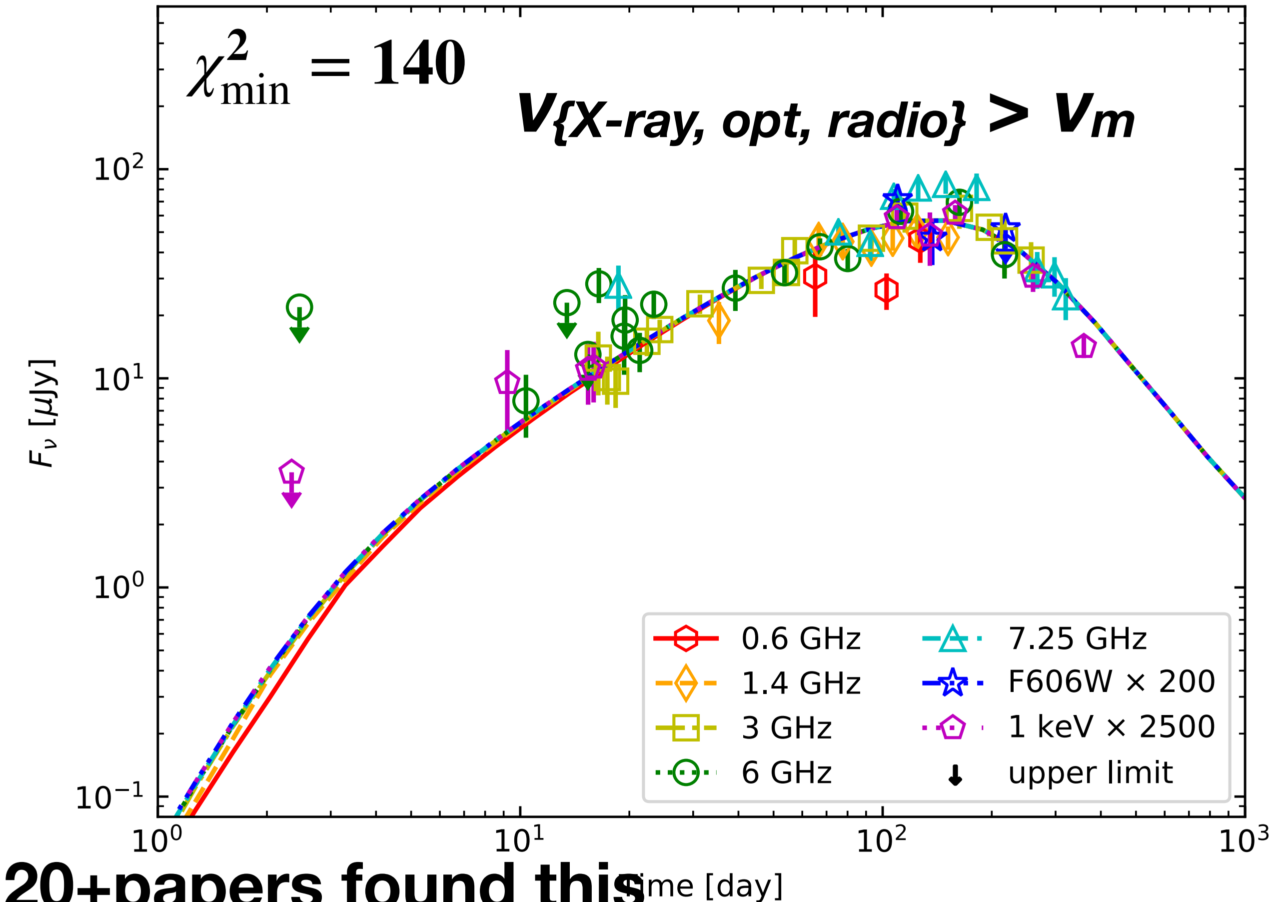


Troja+18

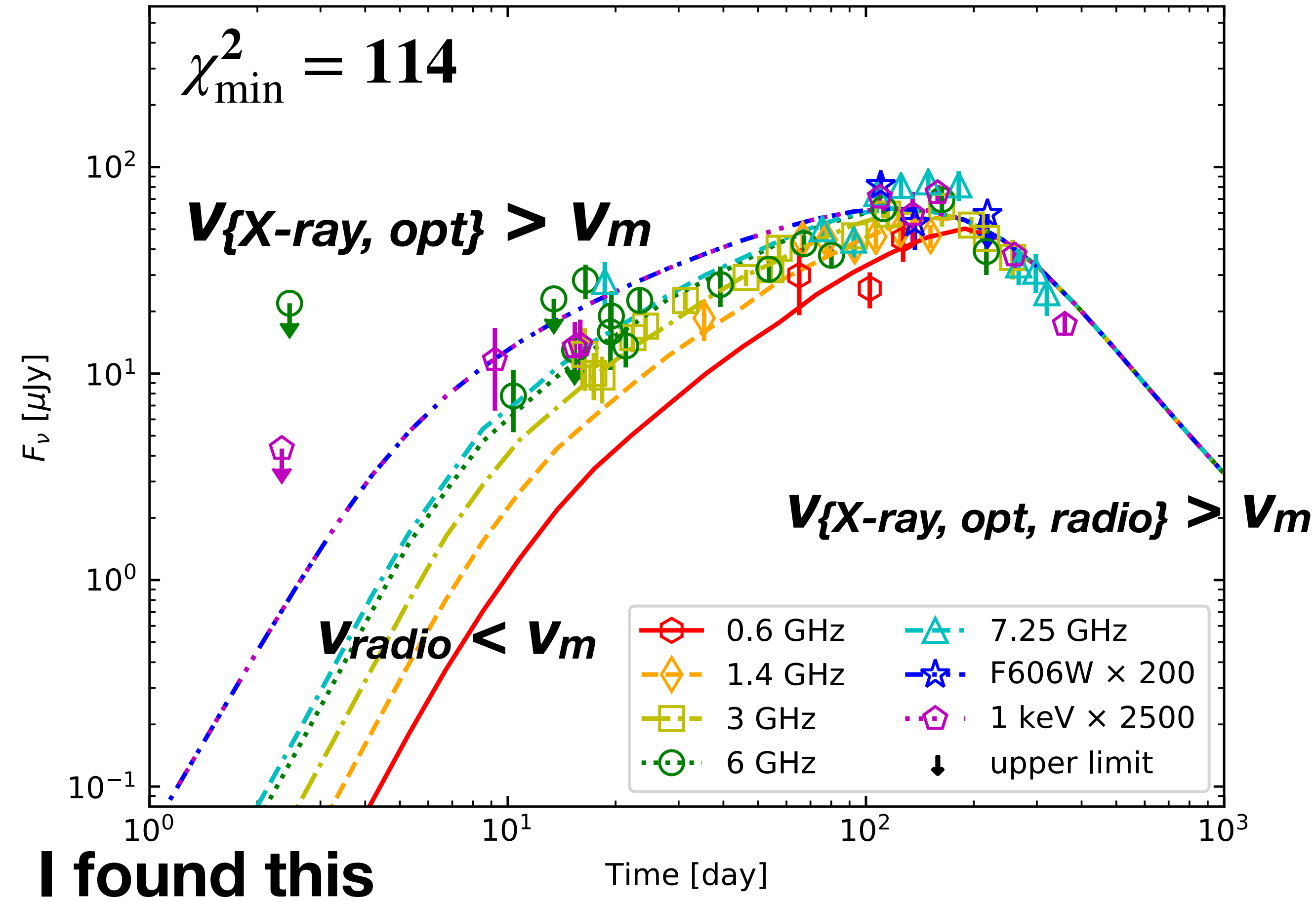


Judge with your eyes!

Light curves normalized to 1 frequency

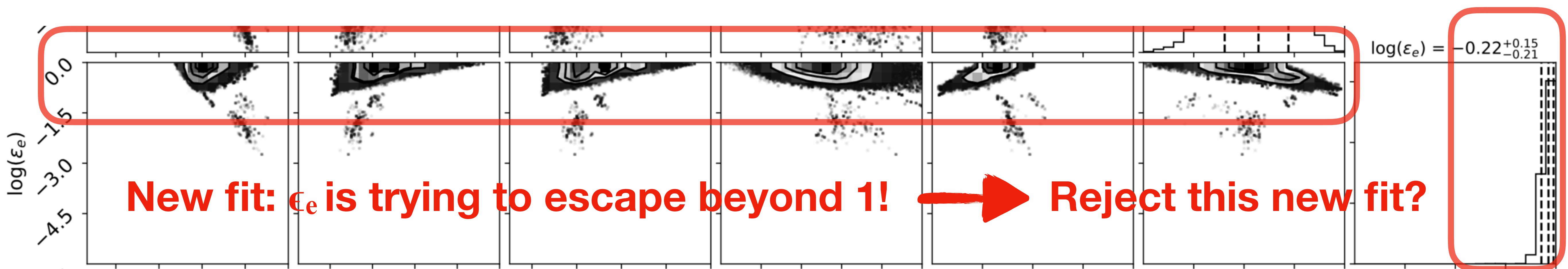


20+papers found this



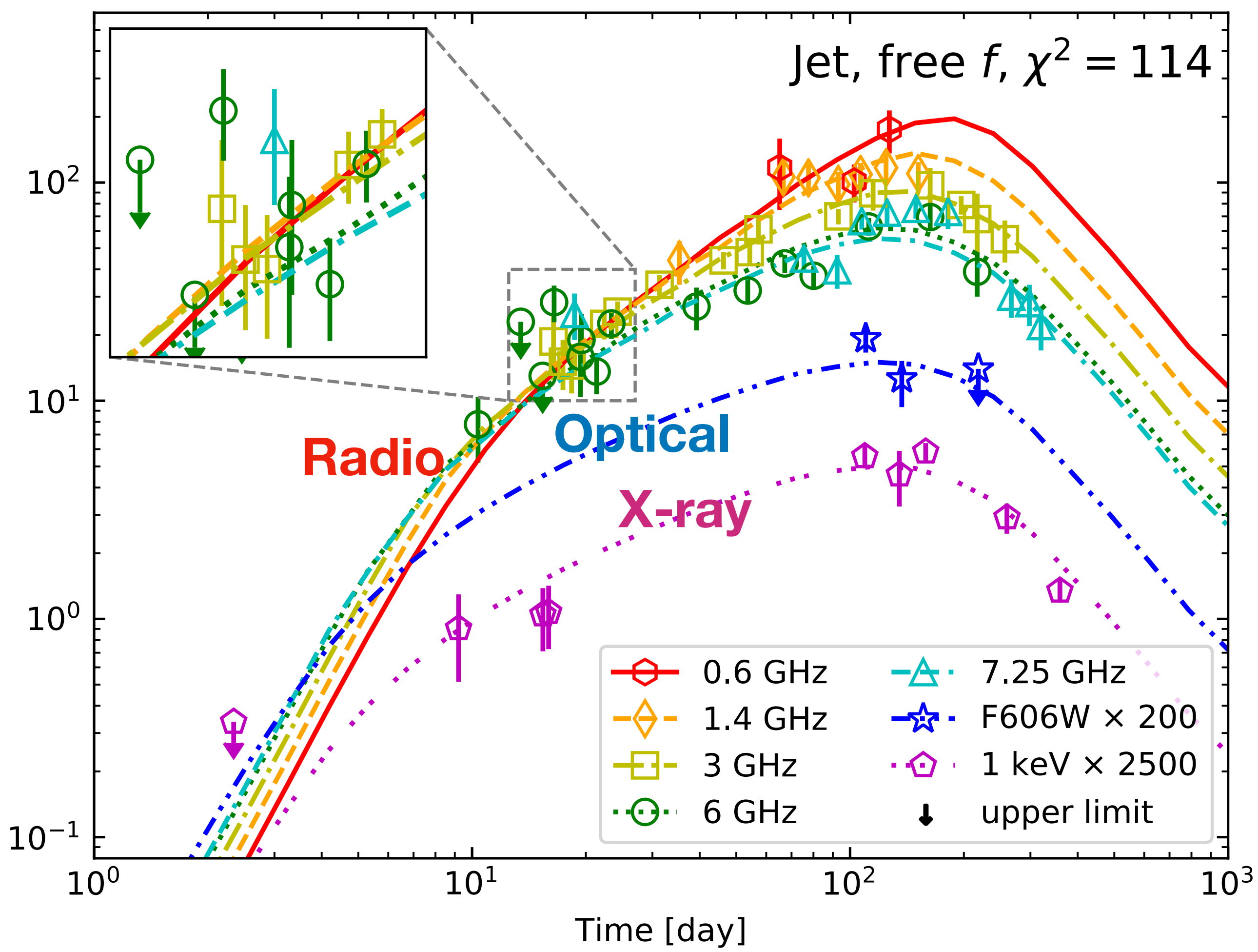
I found this

Synchrotron profile (exact/power-law) does not affect this conclusion



Variable f model

Fit to GW170817 afterglow

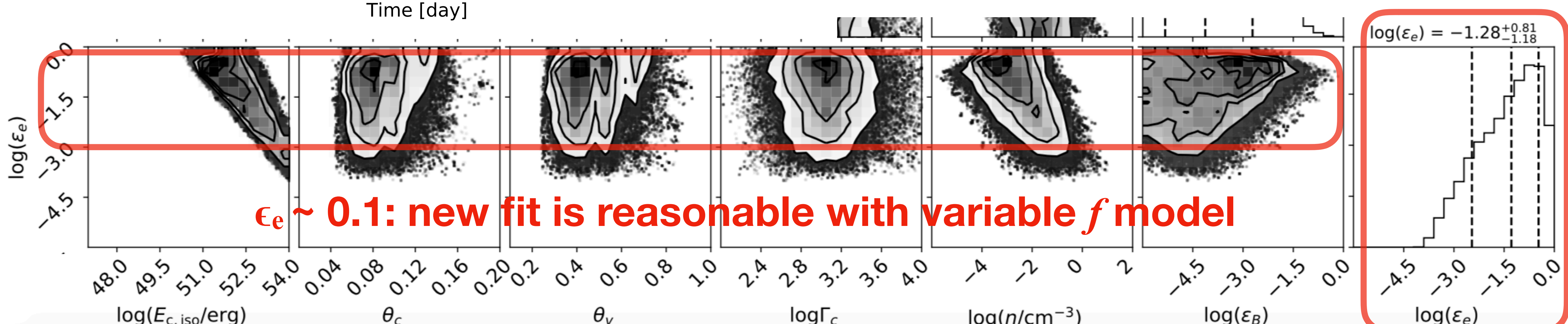


Let f be free… $m_e \gamma_m = \eta_e m_p (\Gamma_s - 1)$

$\log E_{\rm c,iso} = 52.25, \theta_c = 0.10, \theta_{\rm obs} = 0.50, \log \Gamma_c = 2.97$

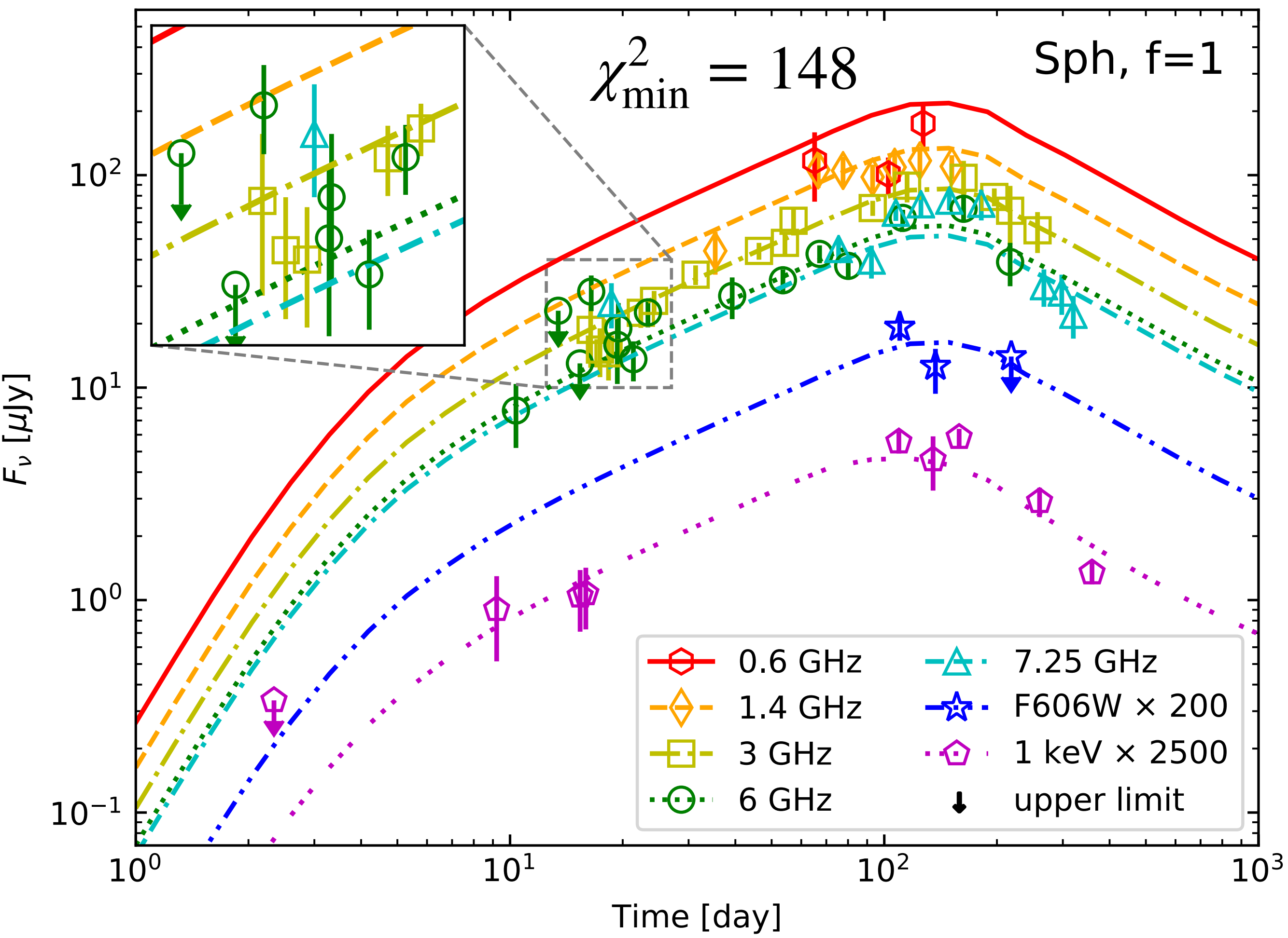
$\log n = -2.28, \log \epsilon_B = -4.76, \log \epsilon_e = -0.80, p = 2.18$

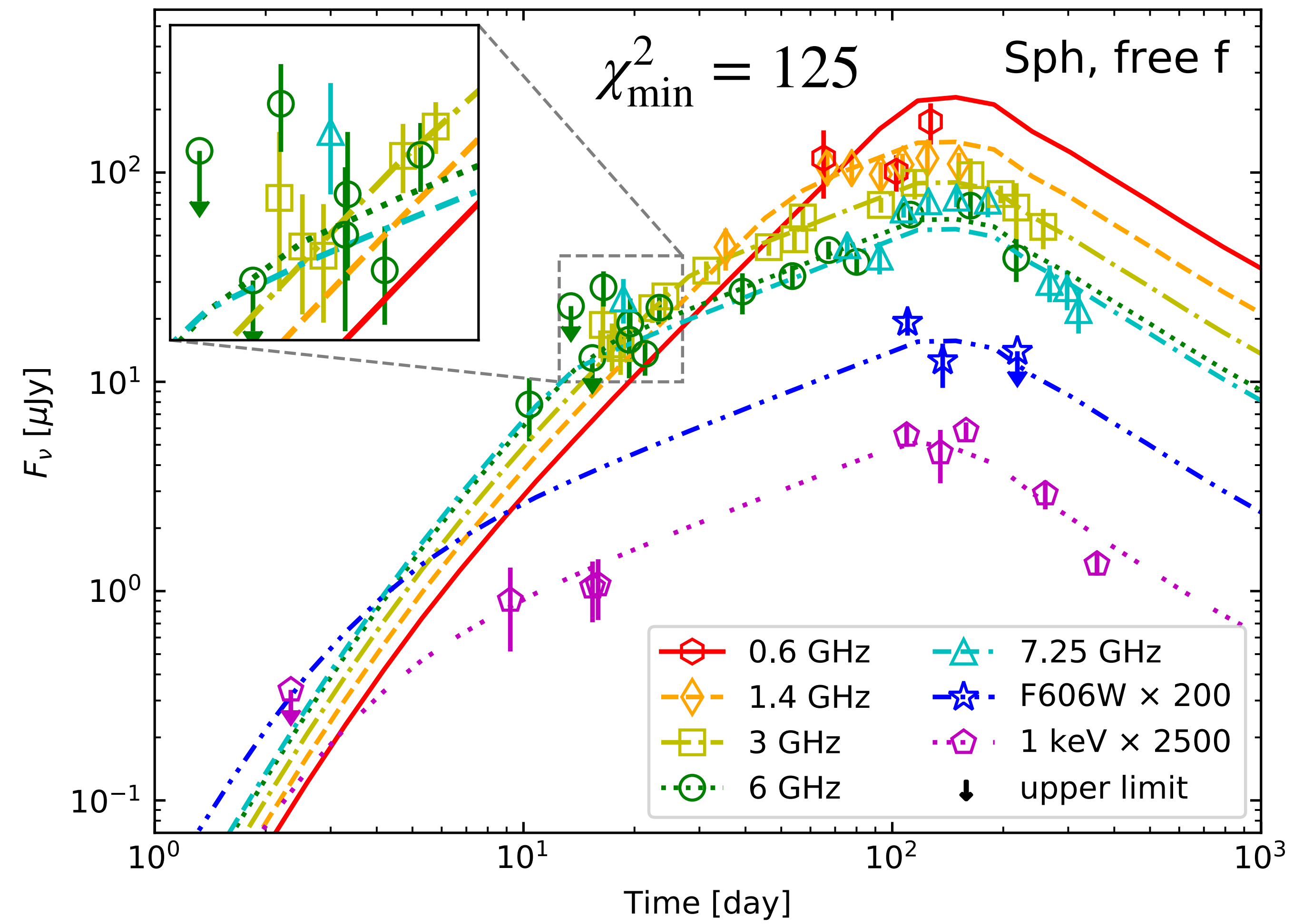
$\log \eta_e = -0.80$



$\epsilon_e \sim 0.1$: new fit is reasonable with variable f model

Modeled with spherical ejecta





$\log E_{\rm k,iso} = 50.58, \log u_{\rm max} = 0.55, \log u_{\rm min} = 0.24, k = 6.21$

$\log n = -2.25, \log \epsilon_B = -1.94, \log \epsilon_e = -0.14, p = 2.15$

$\log E_{\rm k,iso} = 50.18, \log u_{\rm max} = 0.59, \log u_{\rm min} = 0.24, k = 5.79$

$\log n = -2.69, \log \epsilon_B = -1.62, \log \epsilon_e = -1.93, p = 2.17$

$\log \eta_e = -0.80$

$\boldsymbol{\Delta\chi^2_{\rm min} = -23}$! Data num. = 62

Highlights of MCMC

Parameter	Jet f free: 1D dist.[a]	Jet f free: best-fit[b]	Sph f free: 1D dist.	Sph f free: best-fit
$\log_{10}\eta_e$	$-1.02^{+0.23}_{-0.25}$	-0.80	$-1.04^{+0.08}_{-0.12}$	-0.87
$\log_{10} f$	$-1.09^{+0.75}_{-1.08}$	-0.83	$-3.17^{+1.71}_{-1.64}$	-1.90

New fit $\rightarrow m_e\gamma_m \sim 0.1 m_p\Gamma_s$

$$\nu_m \simeq 11.6\,\mathrm{GHz}\,\eta_e^2\epsilon_{B,-2}^{1/2}n_{-3}^{1/2}\Gamma_s^4$$

Only ~10% electrons were accelerated

Parameter	Jet $f=1$: 1D dist.[a]	best-fit[b]	1D dist.[a] ($\nu_{\rm obs} > \nu_m$)	best-fit[b] ($\nu_{\rm obs} > \nu_m$)
$\log_{10}(n/\mathrm{cm}^{-3})$	$-3.71^{+0.61}_{-0.65}$	-3.57	$-2.36^{+0.71}_{-0.75}$	-2.18
$\log_{10}\epsilon_B$	$-2.57^{+0.89}_{-1.01}$	-3.12	$-4.30^{+1.38}_{-1.14}$	-4.60
$\log_{10}\epsilon_e$	$-0.22^{+0.15}_{-0.21}$	-0.10	$-1.36^{+0.46}_{-0.57}$	-0.83
p	$2.18^{+0.01}_{-0.01}$	2.19	$2.16^{+0.01}_{-0.01}$	2.16

For the old fit previously found by standard model:

$$m_e\gamma_m = \epsilon_e \frac{p-2}{p-1} m_p\Gamma_s \sim 0.006 m_p\Gamma_s$$

$$\nu_m \simeq 2.2\,\mathrm{MHz}\,\epsilon_{e,-1}^2\epsilon_{B,-2}^{1/2}n_{-3}^{1/2}\Gamma_s^4$$

Highlights of MCMC

Higher isotropic energy by 1–2 orders of magnitude

Still consistent with previous short GRBs observations (1e50–53 erg)

	Sph f = 1		Sph f free	
Parameter	1D dist.	best-fit	1D dist.	best-fit
$\log_{10}(n/\mathrm{cm}^{-3})$	$-3.68^{+1.21}_{-0.67}$	-2.25	$-2.05^{+1.66}_{-1.71}$	-2.69
$\log_{10}(E_{\mathrm{k,\,iso}}/\mathrm{erg})$	$50.15^{+1.27}_{-0.63}$	50.58	$51.60^{+1.65}_{-1.70}$	50.18

	Jet f = 1				Jet f free	
Parameter	1D dist.[a]	best-fit[b]	1D dist.[a] ($\nu_{\mathrm{obs}} > \nu_m$)	best-fit[b] ($\nu_{\mathrm{obs}} > \nu_m$)	1D dist.[a]	best-fit[b]
$\log_{10}(n/\mathrm{cm}^{-3})$	$-3.71^{+0.61}_{-0.65}$	-3.57	$-2.36^{+0.71}_{-0.75}$	-2.18	$-2.49^{+1.05}_{-1.08}$	-2.28
$\log_{10}(E_{c,\,\mathrm{iso}}/\mathrm{erg})$	$51.05^{+0.51}_{-0.37}$	51.19	$52.67^{+0.55}_{-0.62}$	52.33	$52.38^{+0.93}_{-0.90}$	52.25

Higher ambient density by 1–2 order of magnitude

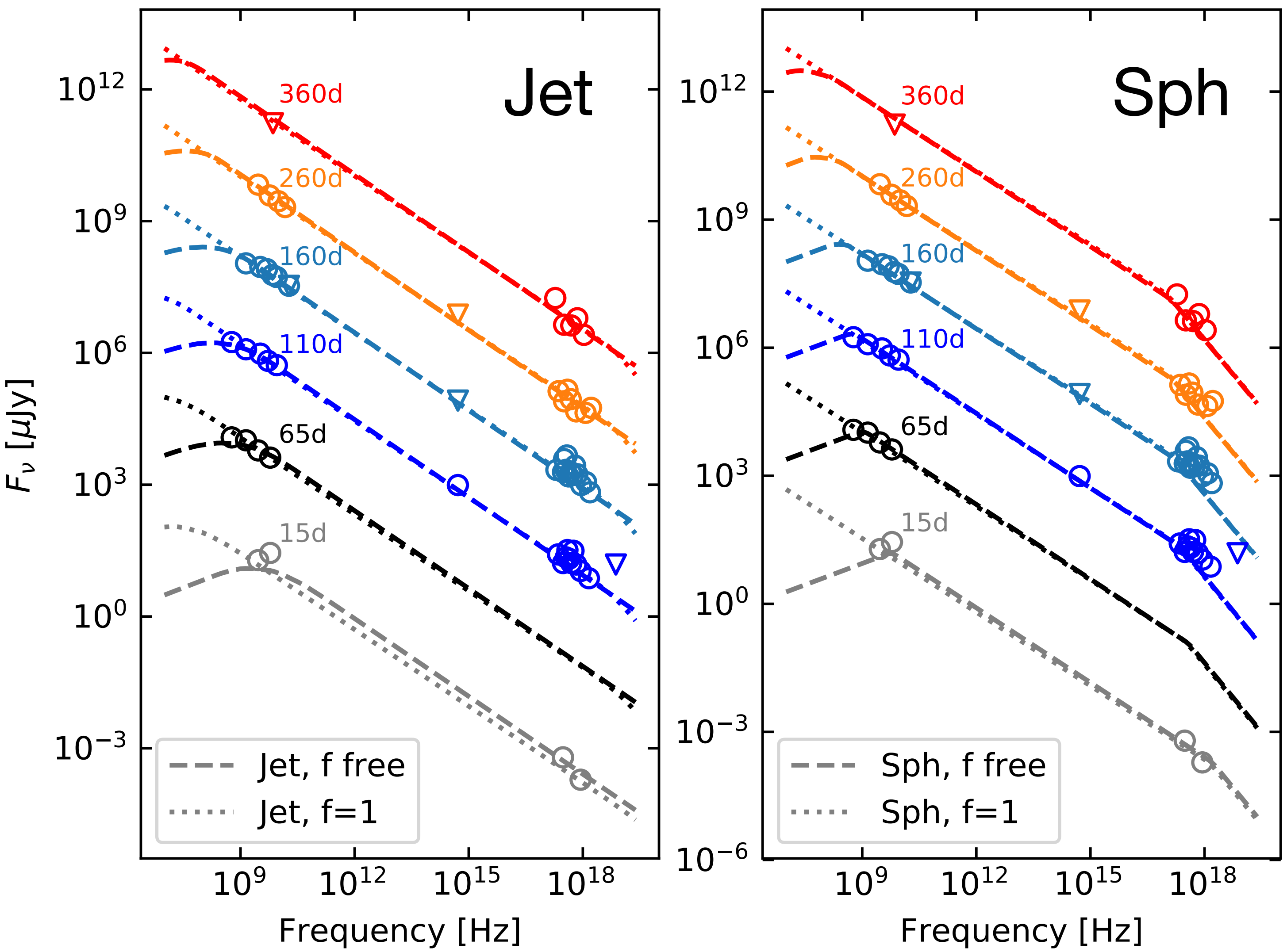
in slight tension with HI obs. (< 0.04 cm^{-3})

Make sense if **hot gas** is taken into account.

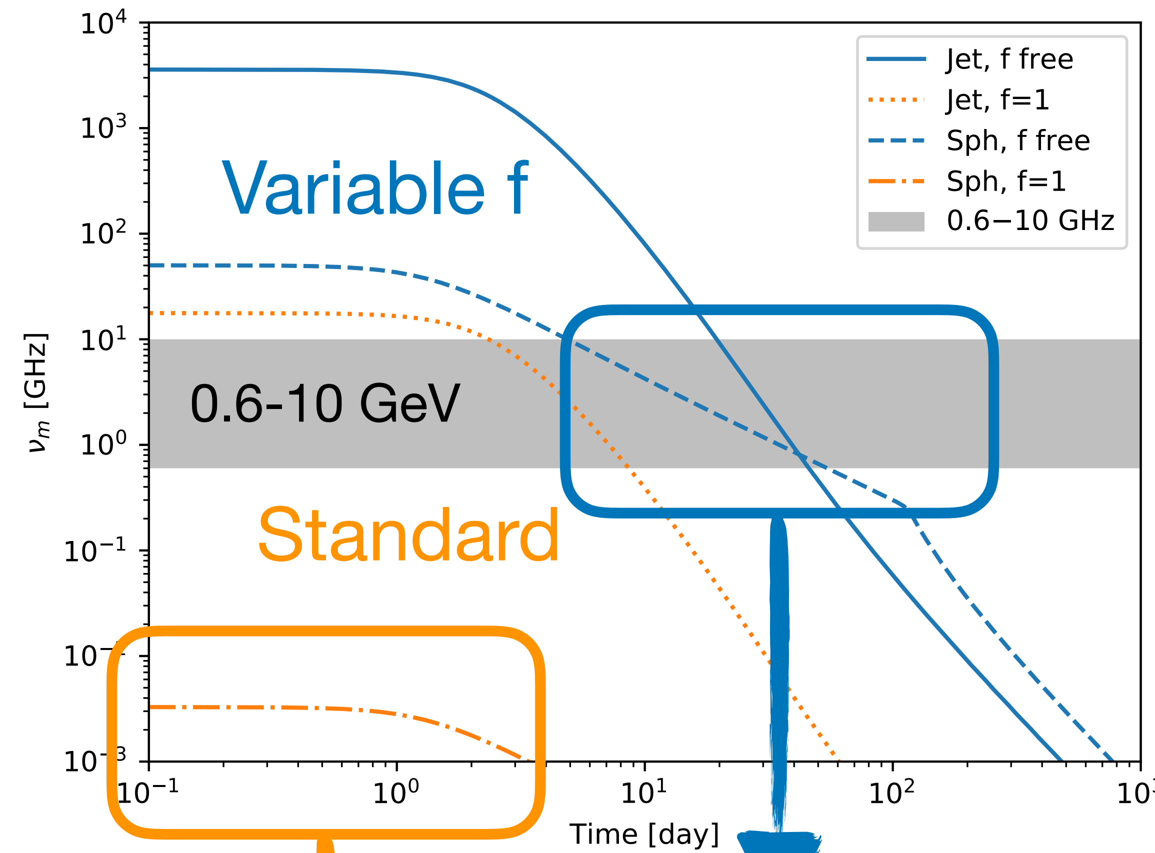
For GW170817, offset = 0.64*(half light radius) n **= 0.01—0.1 cm^{-3}**
in typical giant elliptical galaxies like NGC 4993.

Temporal Evolution of ν_m

SED fit



Temporal Evolution of ν_m



ν_m is usually detectable!

ν_m not detectable for mildly-relativistic ejecta

Summary

Variable-f electron distribution -> **new fit** to GW170817 afterglow

- χ^2 significantly reduced by matching early(10-100d) radio data
- Electrons & protons are close to equipartition
- Only a small fraction (<10%) of electrons is accelerated

Low-frequency, densely-sampled early radio observations in similar future BNS events may clearly detect ν_m passage -> constraining particle acceleration efficiency