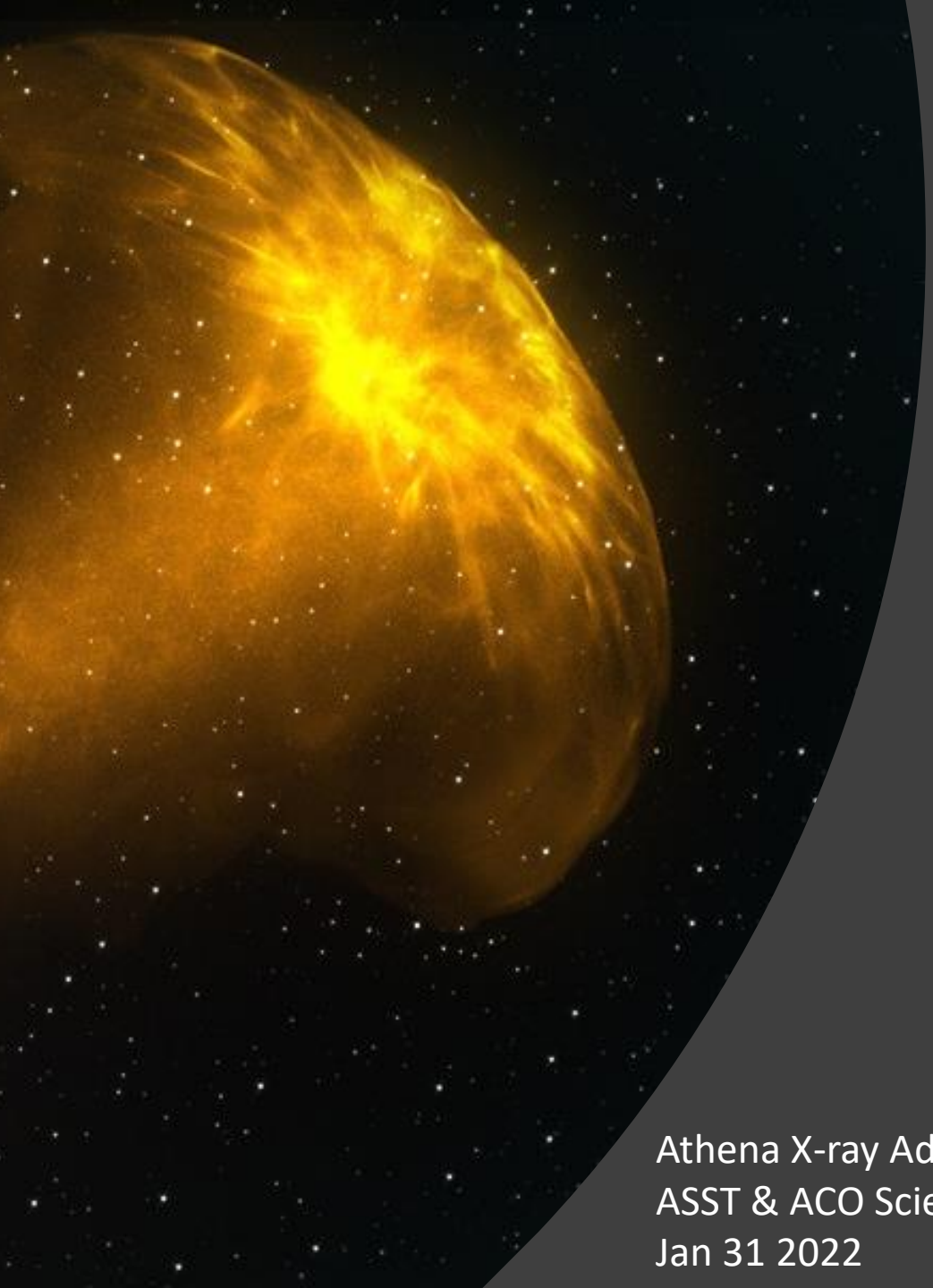


Revealing the physics of multi-messenger events using X-rays

Hendrik van Eerten

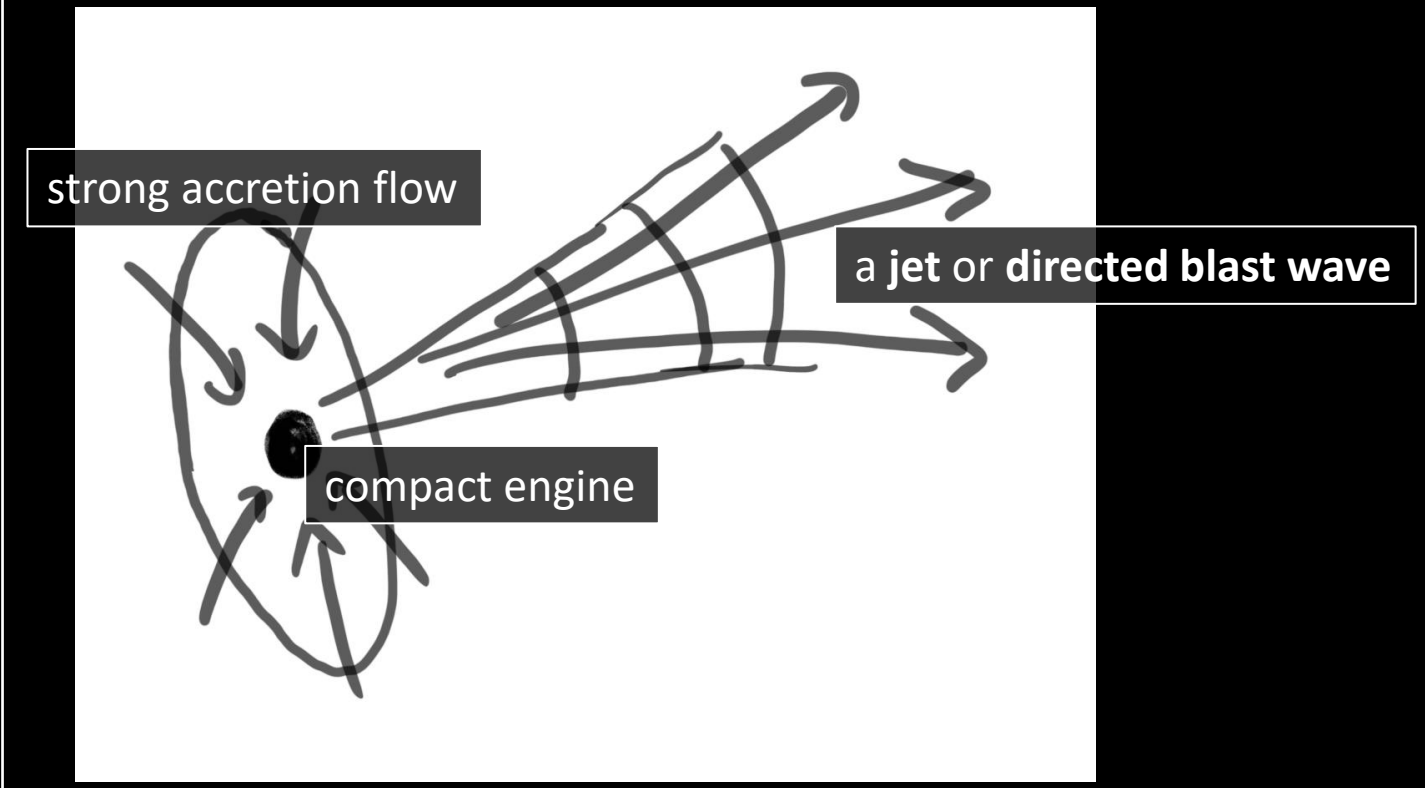
University of Bath (UK)

AHEAD 2020

Athena X-ray Advances:
ASST & ACO Science Webinars
Jan 31 2022

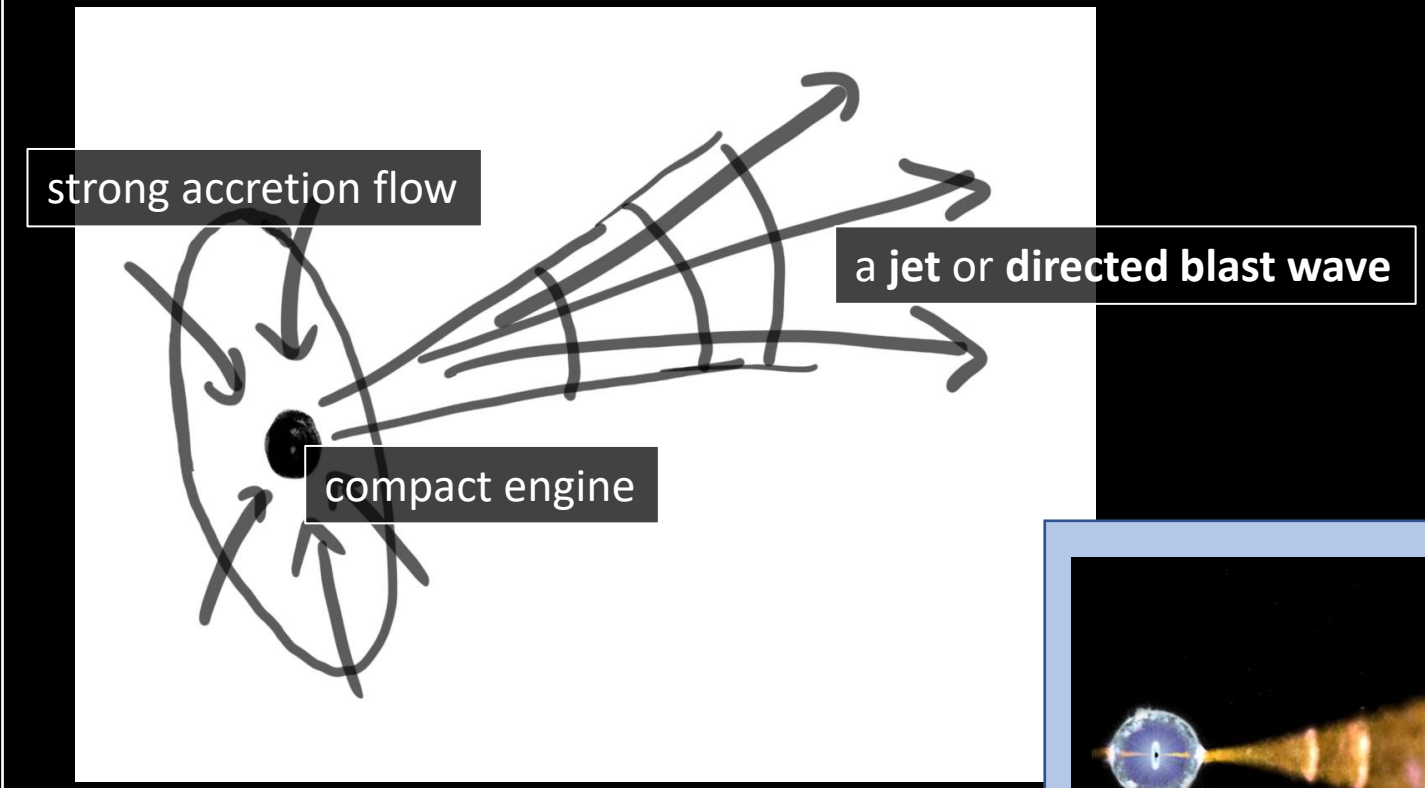
Funded by the Horizon 2020 Framework Program of the European Union Grant Agreement No. 871158

extreme transients ubiquitous in high-energy astrophysics

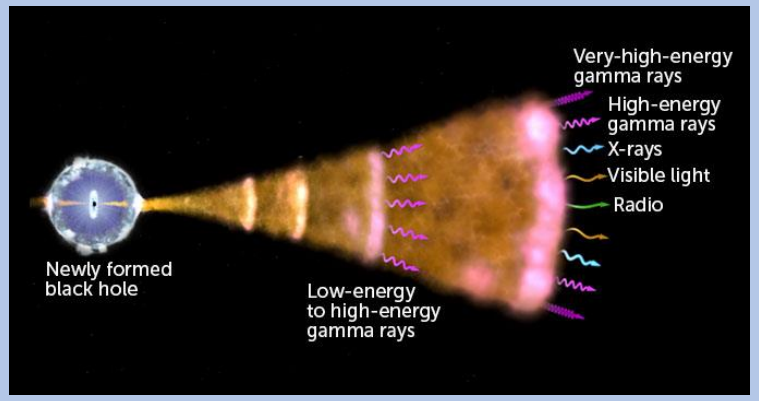


"The biggest explosions in the universe"

extreme transients ubiquitous in high-energy astrophysics

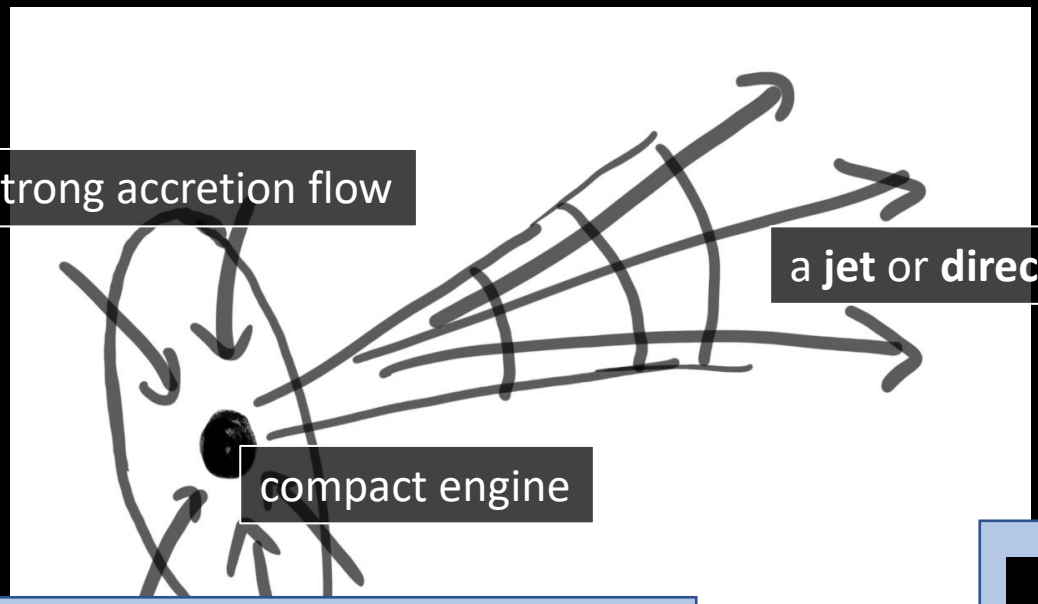


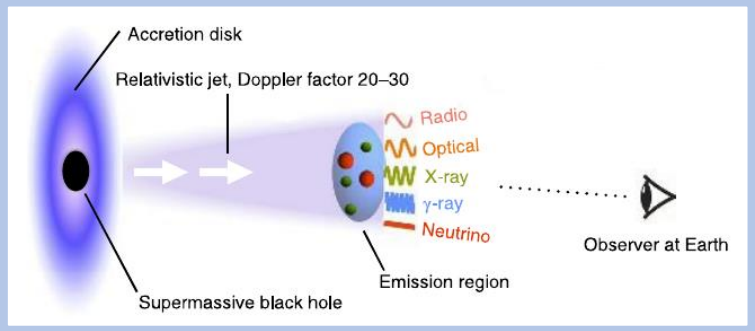
"The biggest explosions in the universe"



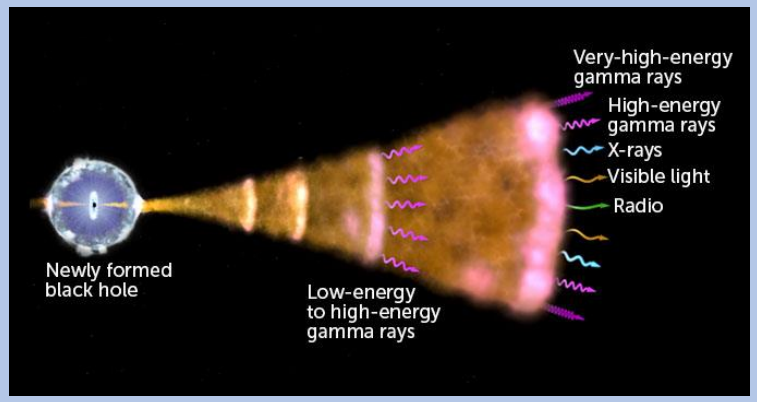
- long gamma-ray bursts (lGRBs)
- short gamma-ray bursts (sGRBs)

extreme transients ubiquitous in high-energy astrophysics



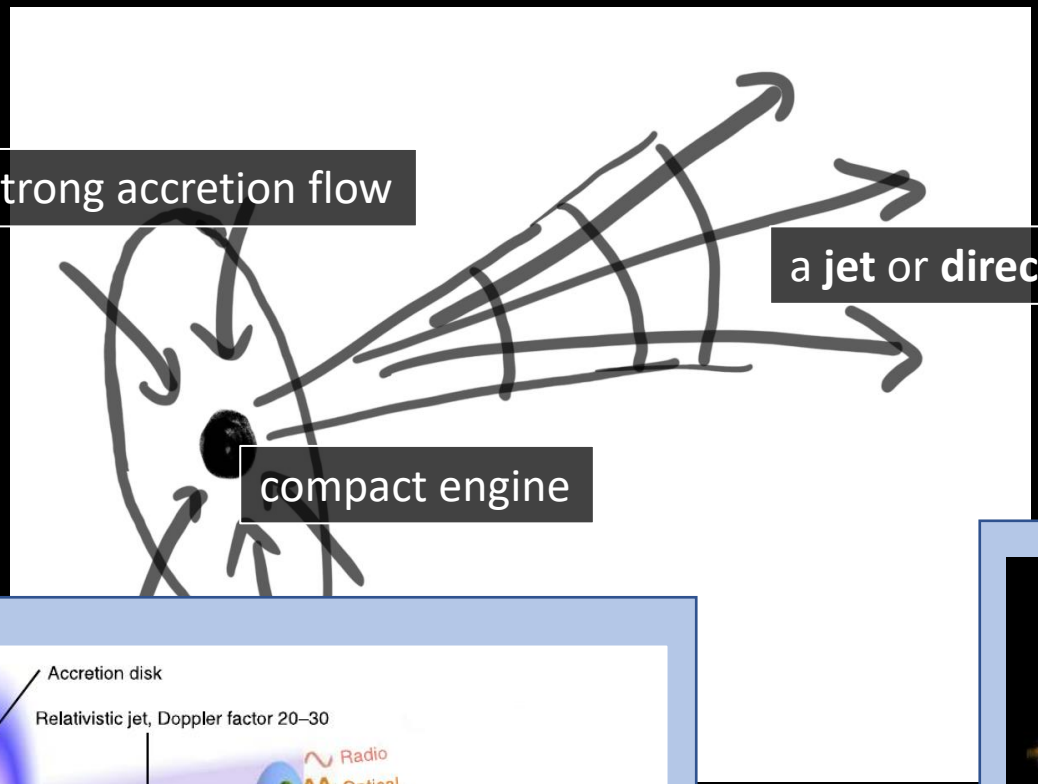


- (flaring) blazars

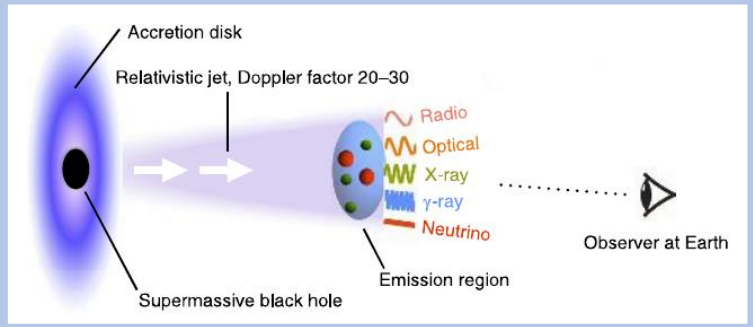


- long gamma-ray bursts (lGRBs)
- short gamma-ray bursts (sGRBs)

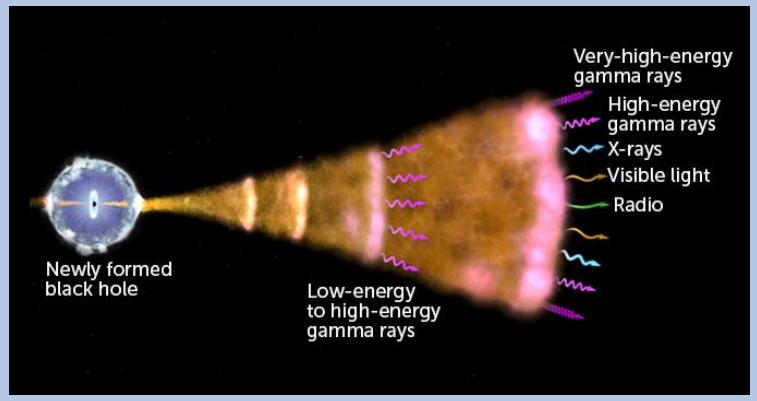
extreme transients ubiquitous in high-energy astrophysics



- Tidal disruption events

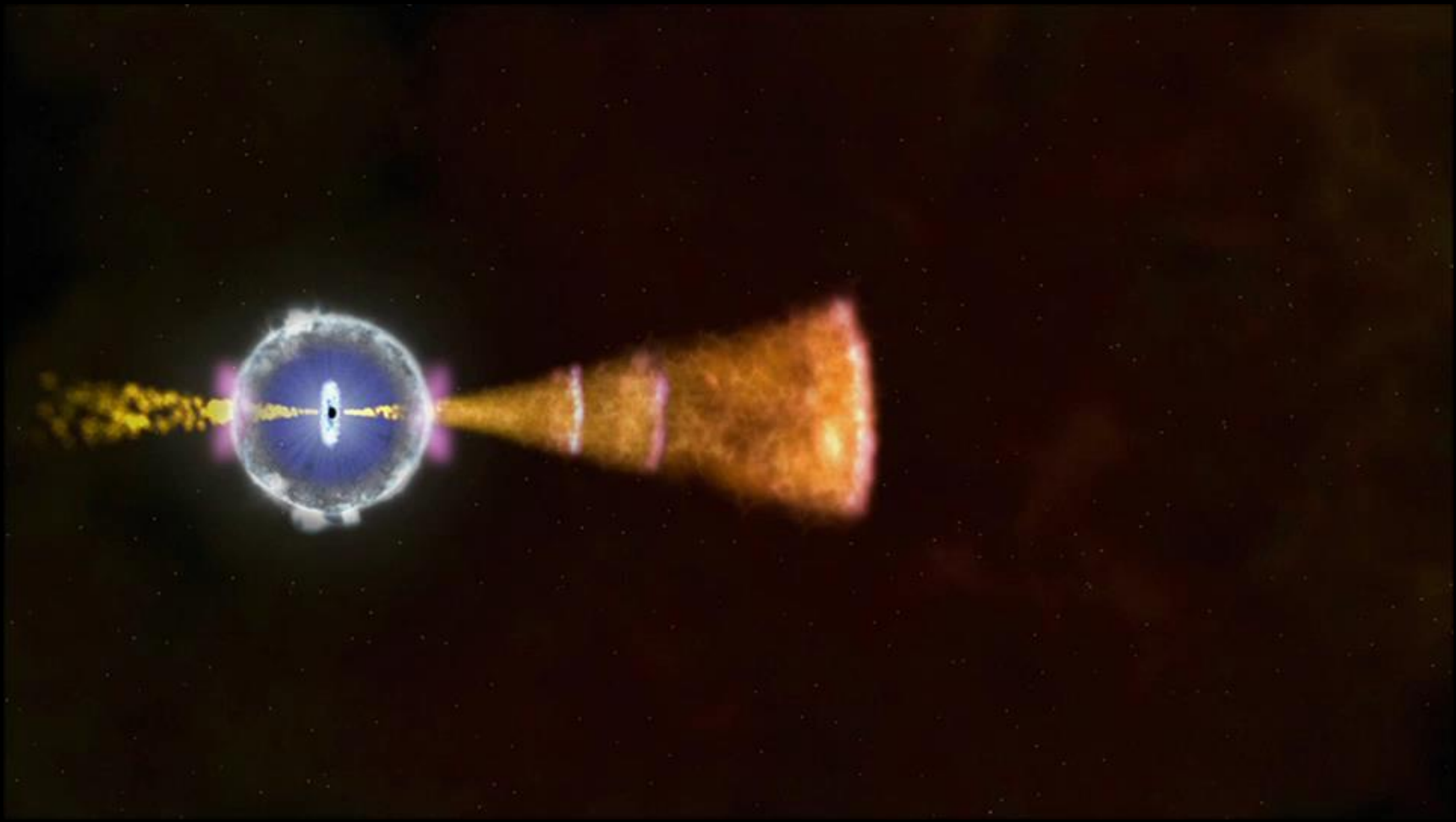


- (flaring) blazars

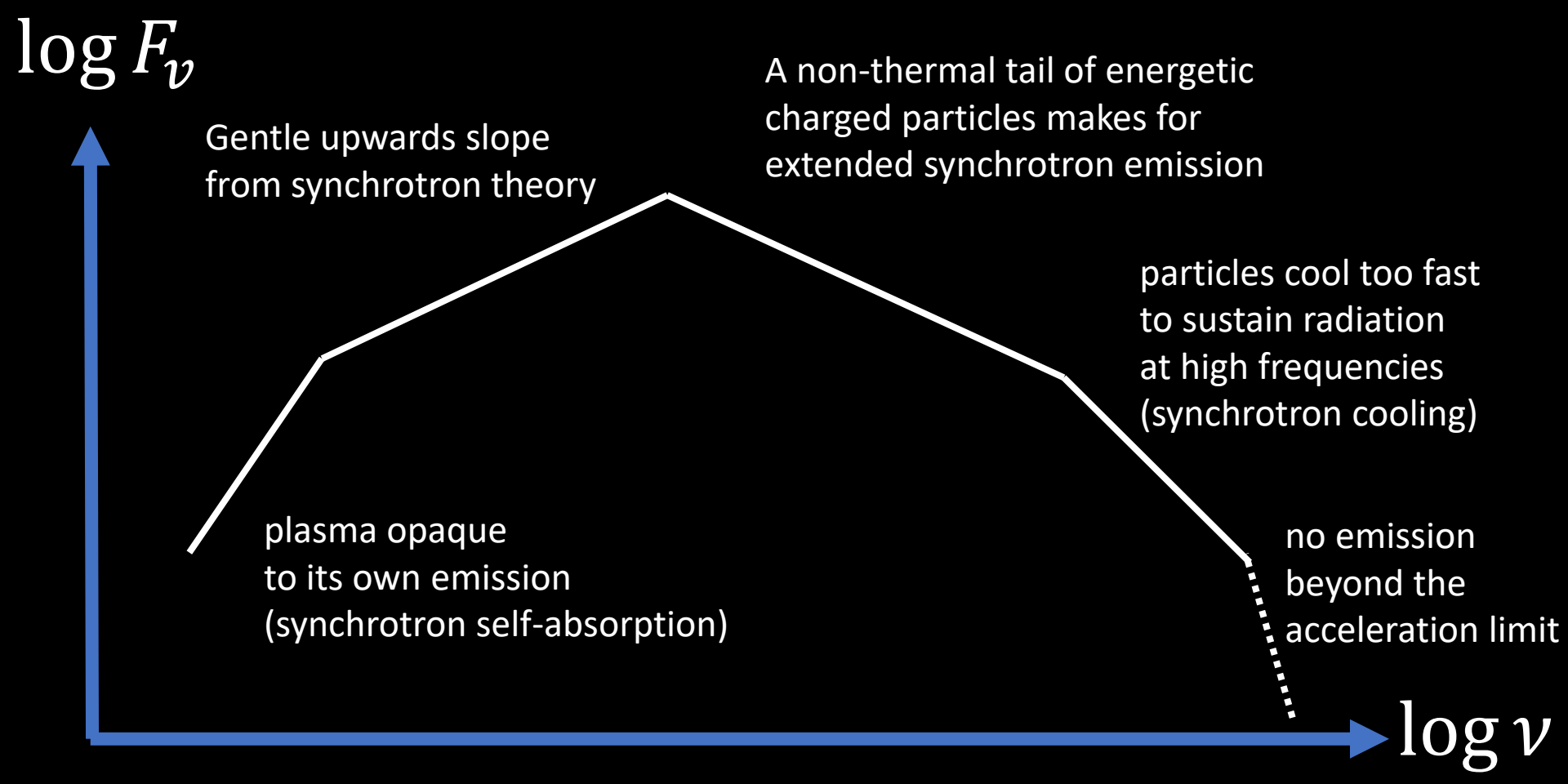


- long gamma-ray bursts (lGRBs)
- short gamma-ray bursts (sGRBs)

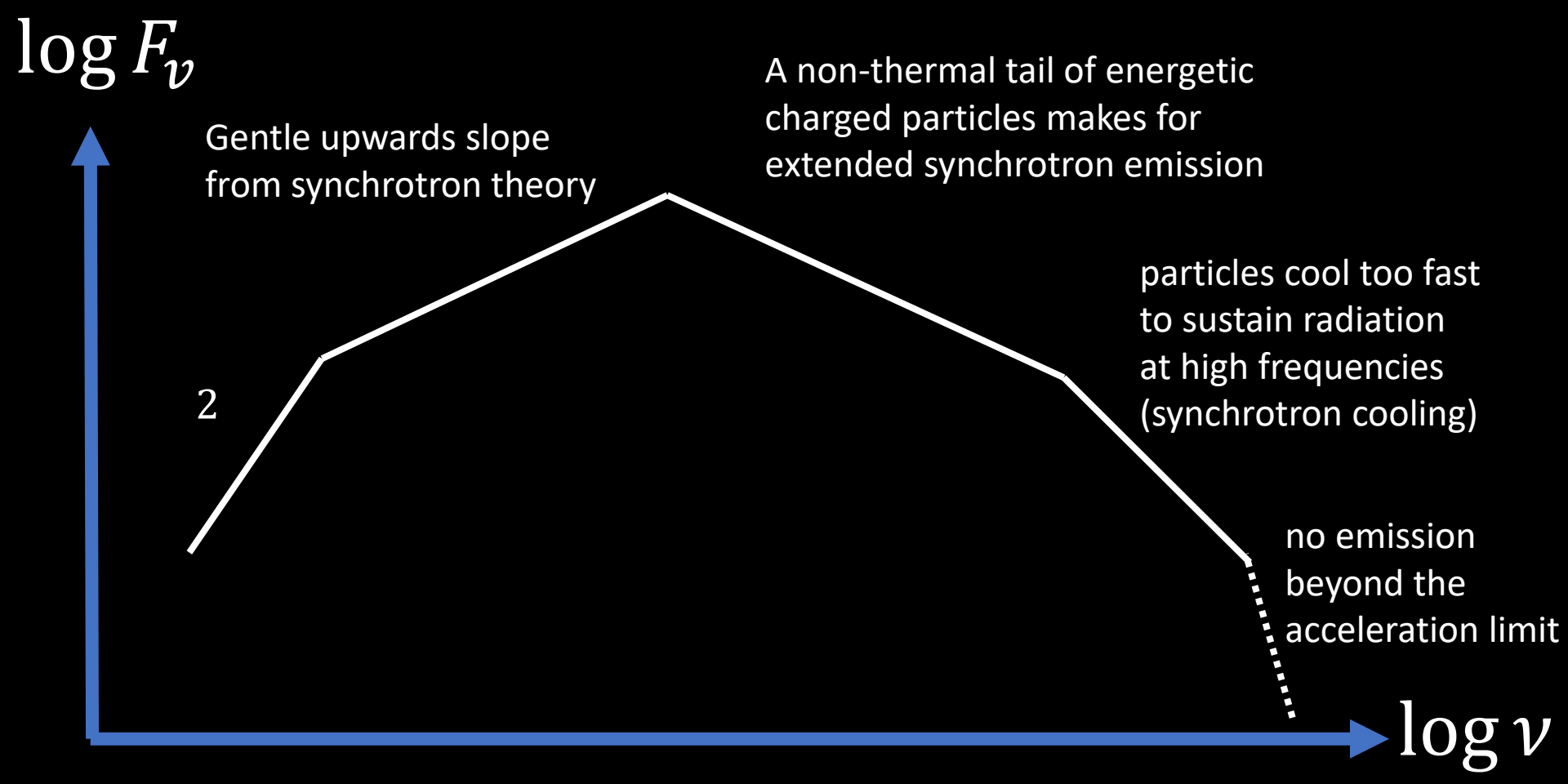
Gamma-ray bursts



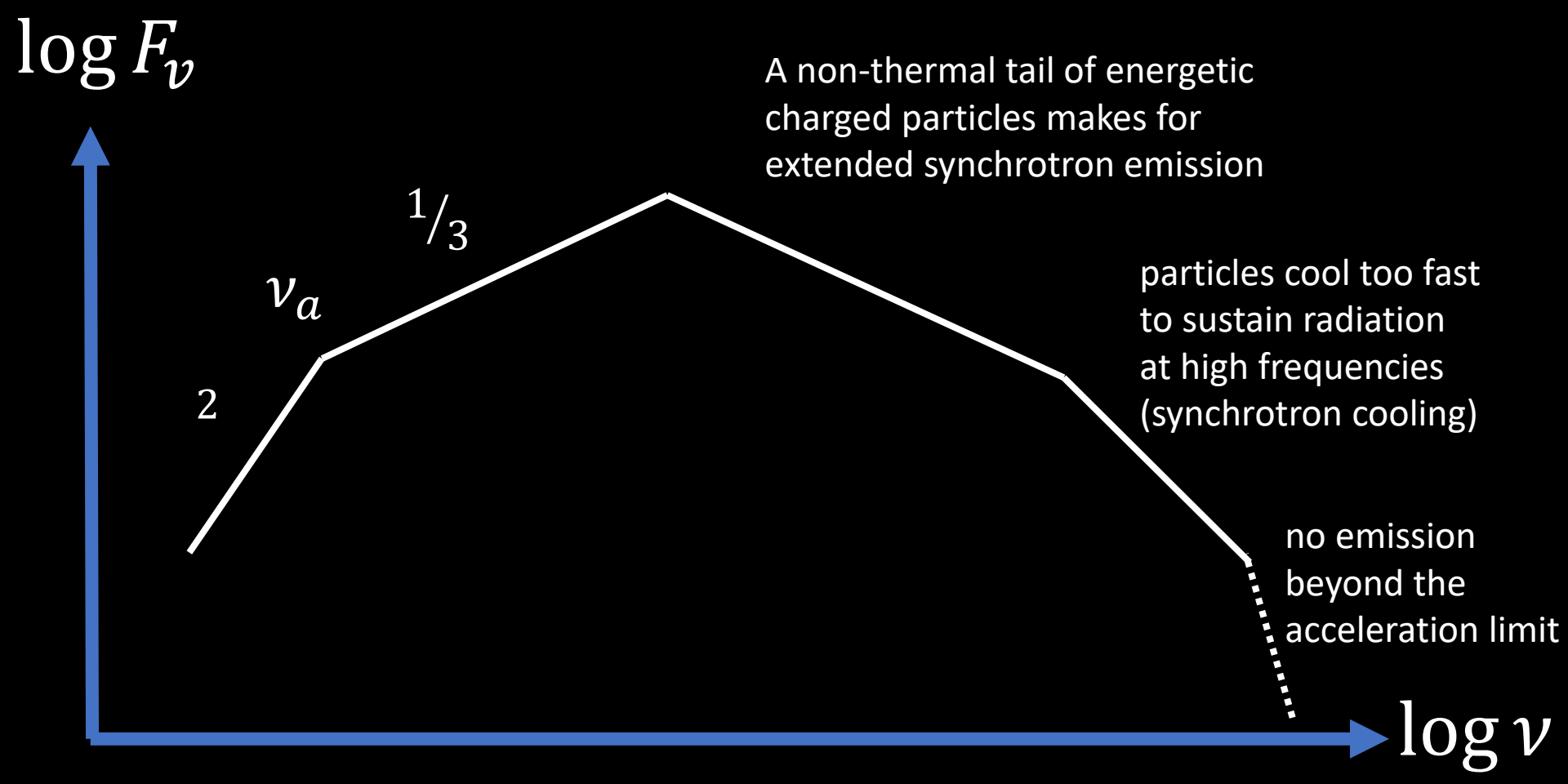
The synchrotron spectrum



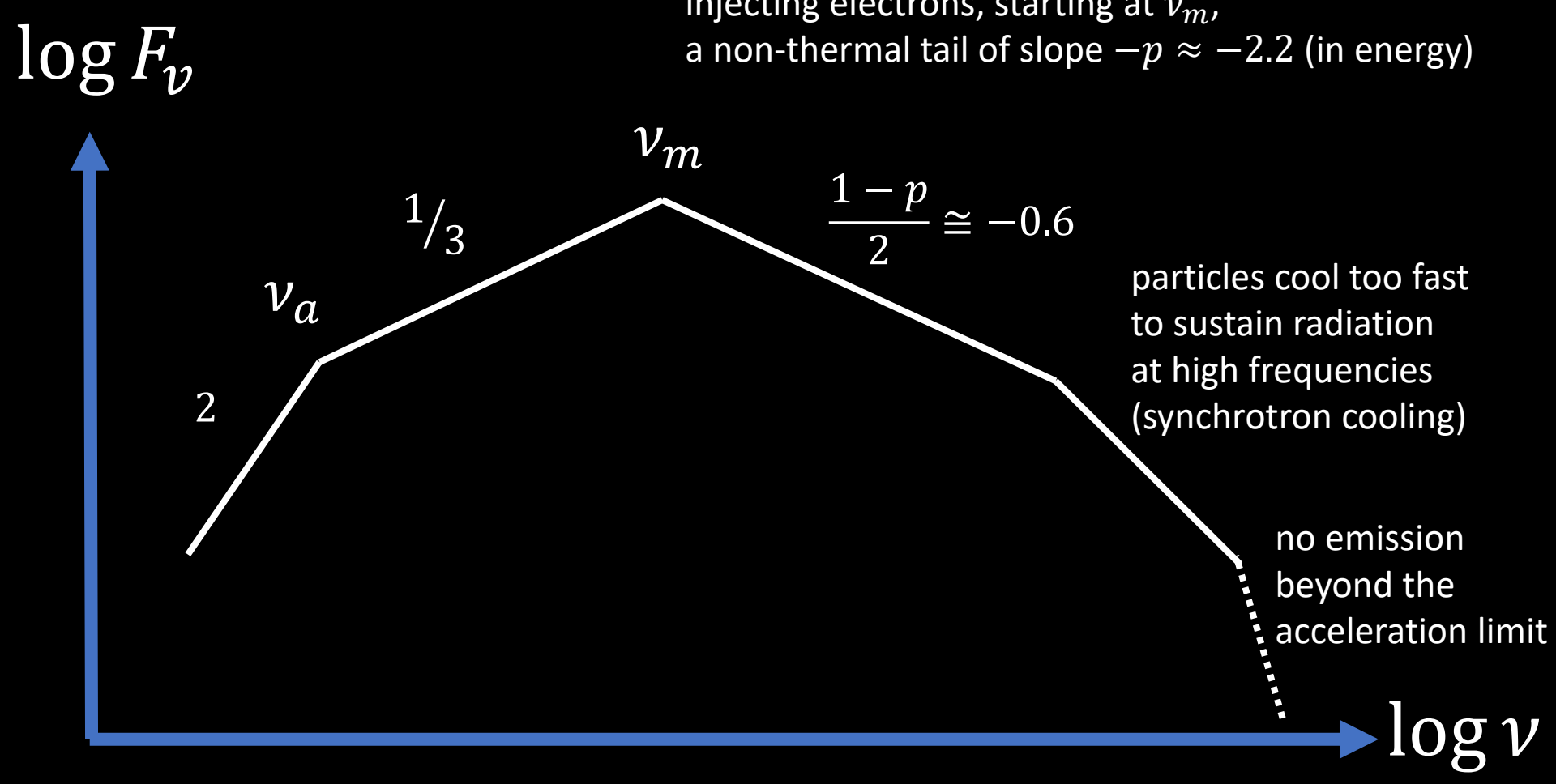
The synchrotron spectrum



The synchrotron spectrum

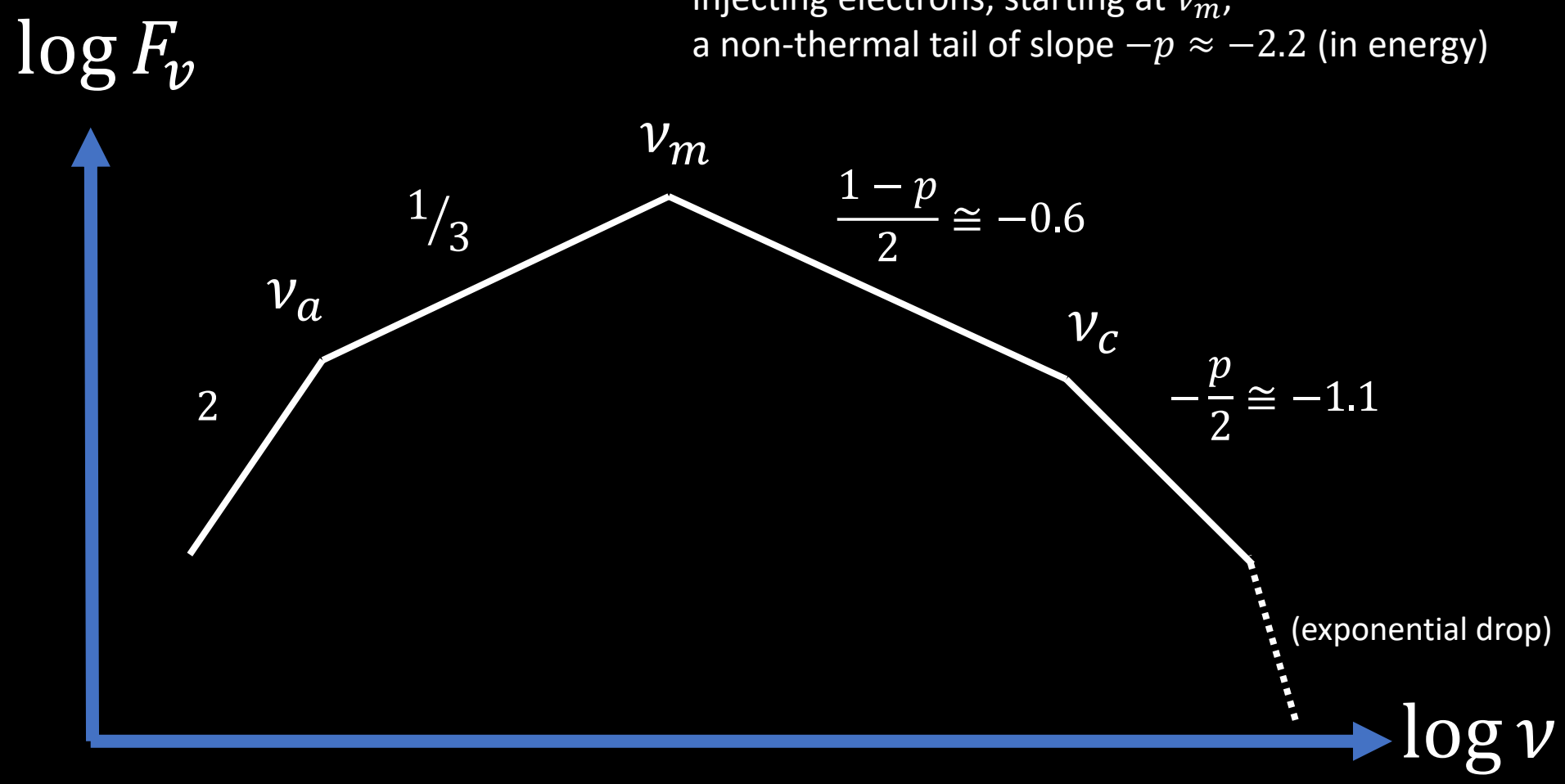


The synchrotron spectrum



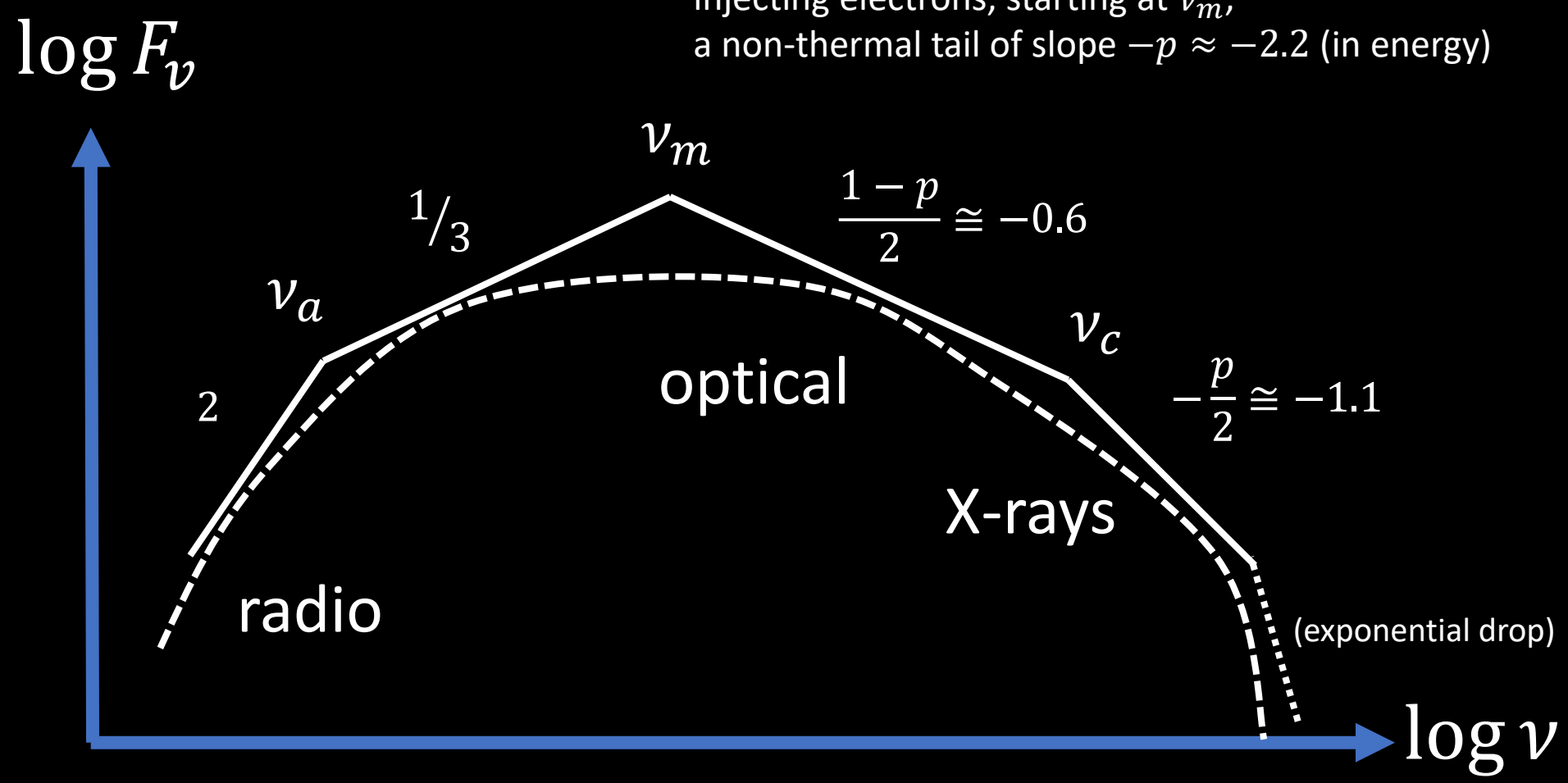
The synchrotron spectrum

injecting electrons, starting at ν_m,
a non-thermal tail of slope $-p \approx -2.2$ (in energy)



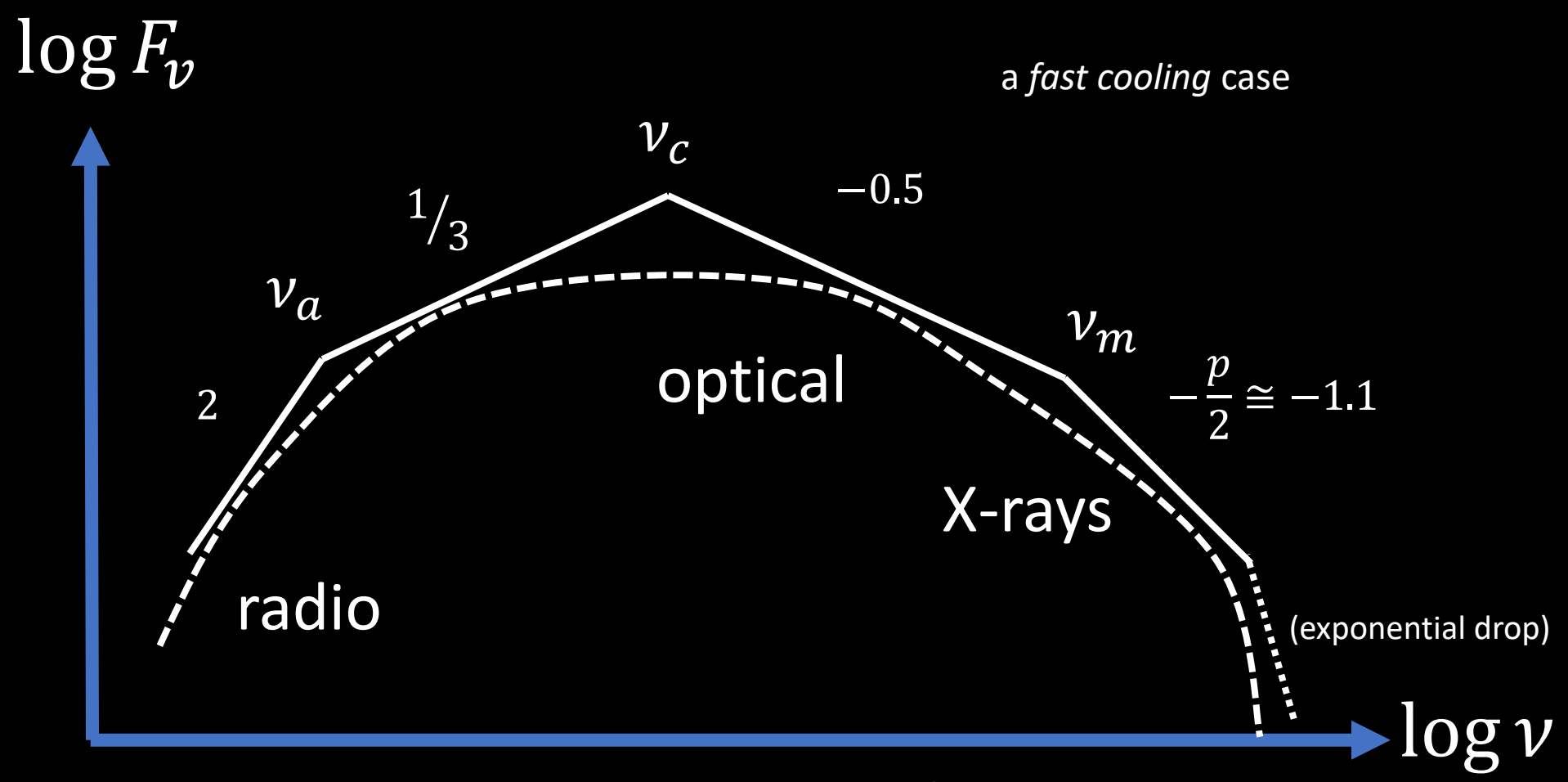
The synchrotron spectrum

injecting electrons, starting at ν_m,
a non-thermal tail of slope $-p \approx -2.2$ (in energy)



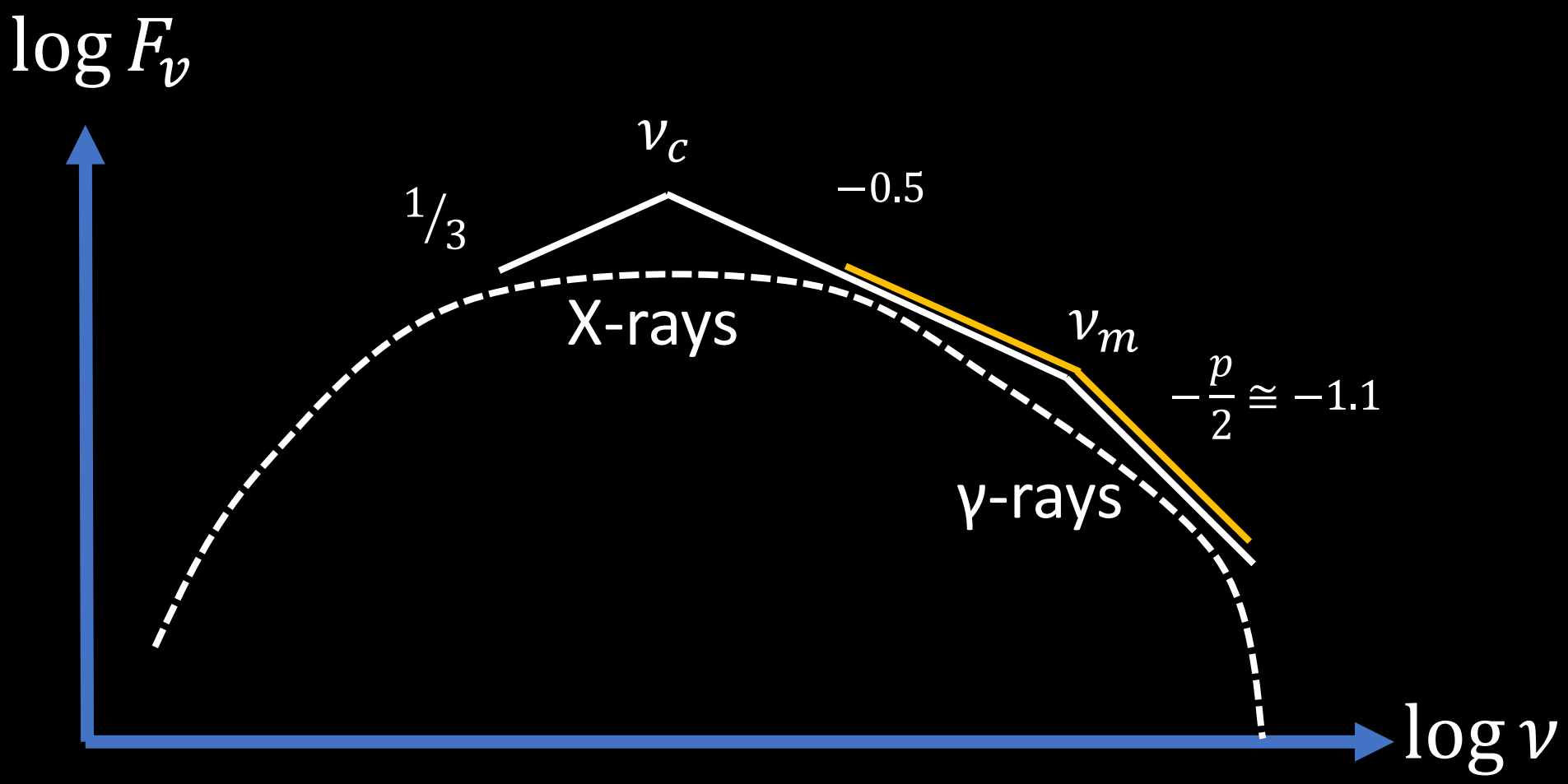
Gamma-ray burst afterglows

The synchrotron spectrum



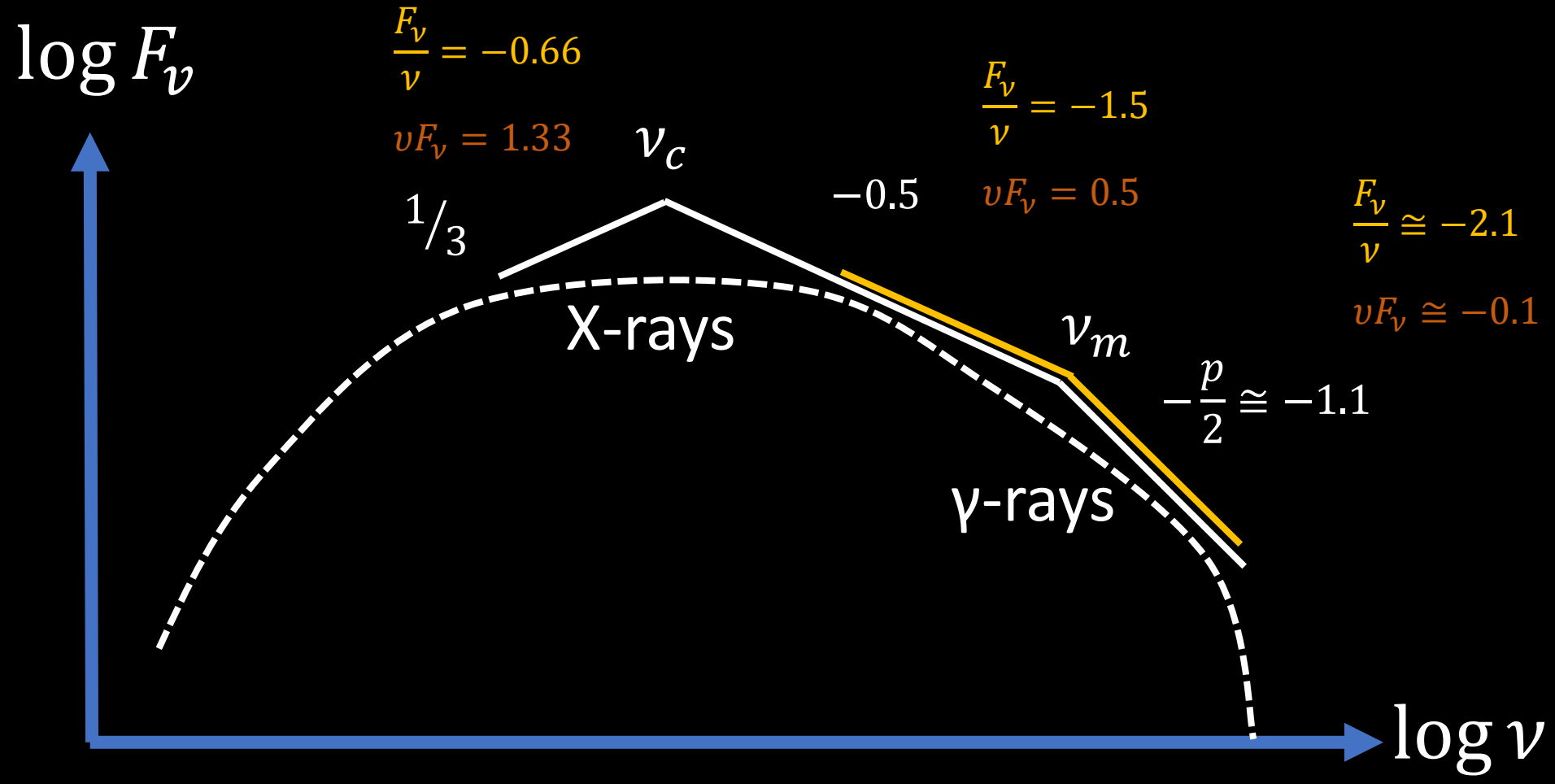
Gamma-ray burst afterglows

The synchrotron spectrum



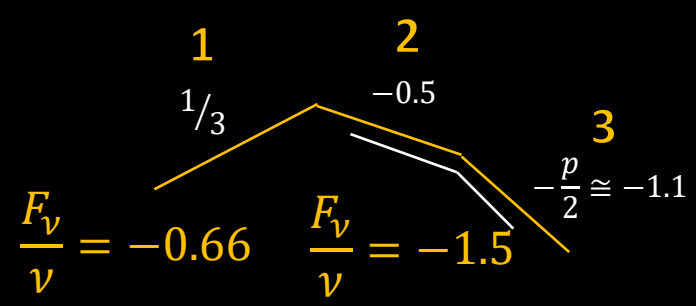
Gamma-ray prompt emission

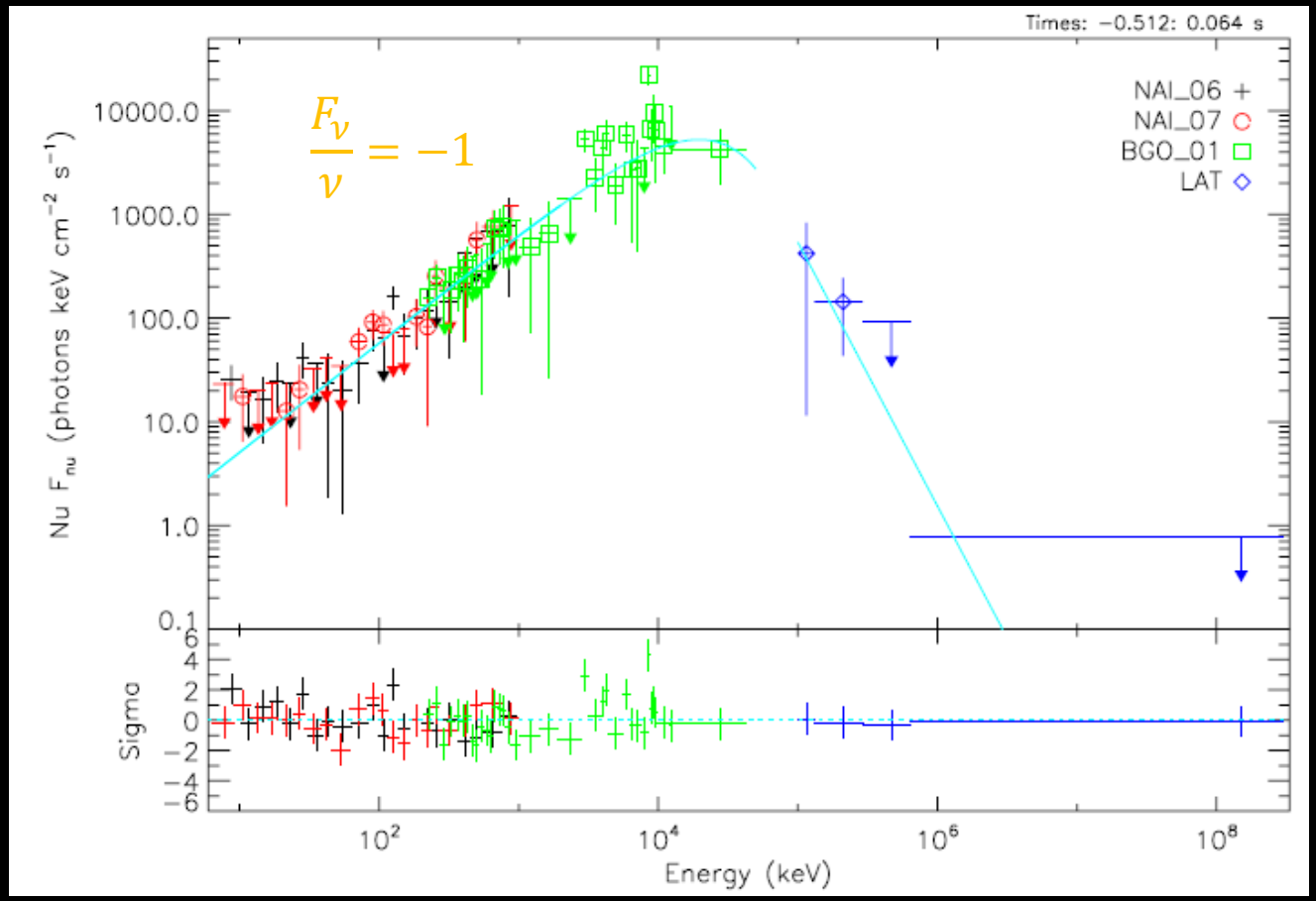
The synchrotron spectrum



Gamma-ray prompt emission

GRB prompt emission remains a persistent puzzle



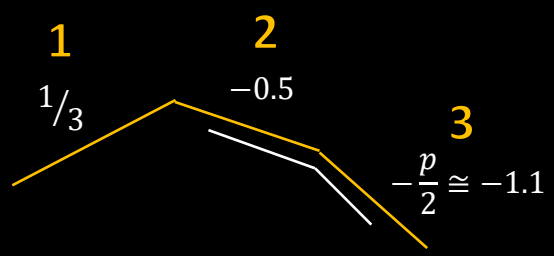


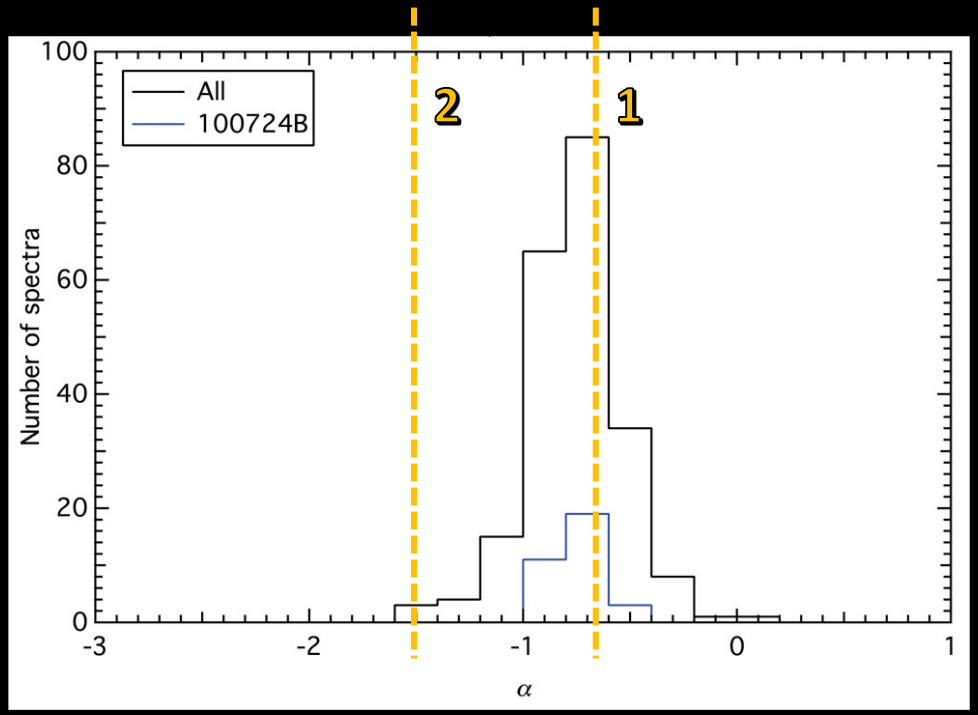
Zhang+ 2012

GRB prompt emission remains a persistent puzzle

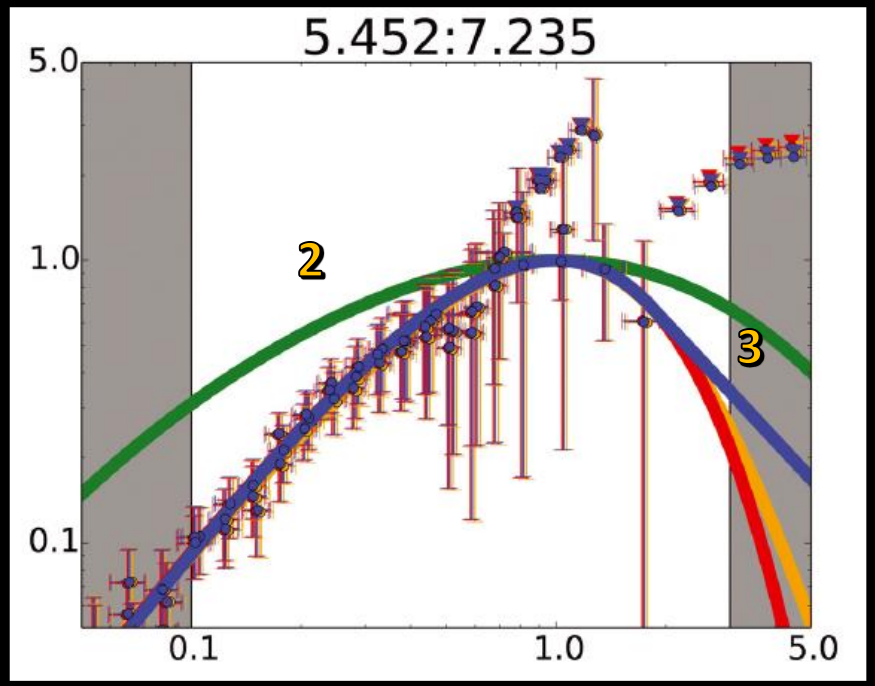
$$\frac{F_\nu}{\nu} = -1.5 \quad \frac{F_\nu}{\nu} = -0.66$$

$$\nu F_\nu = 0.5 \quad \nu F_\nu = 1.33$$





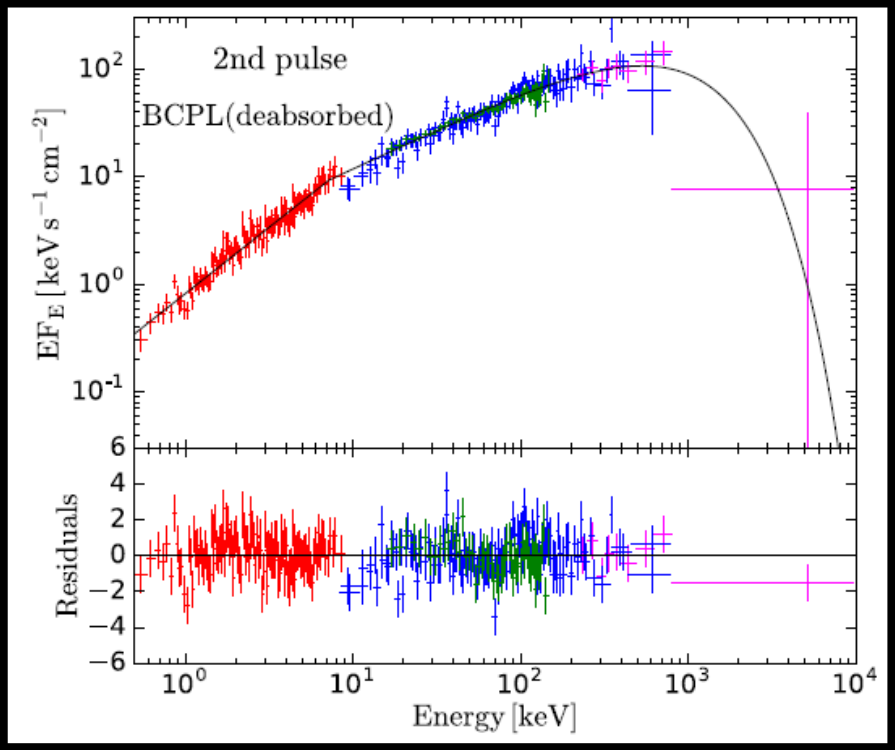
Yu+ 2015 A&A 573, A81

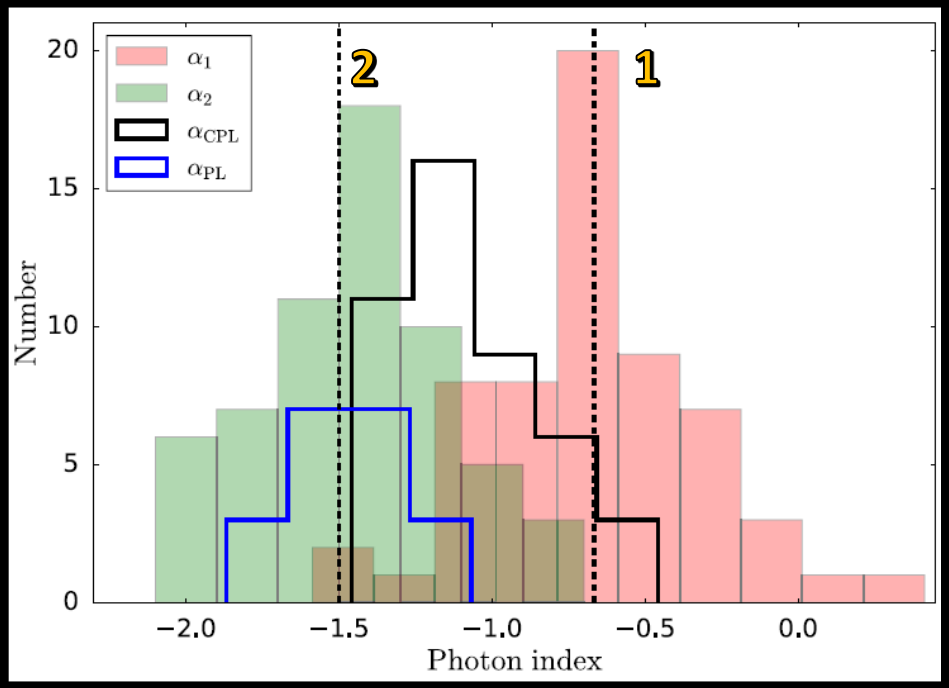


Yu, van Eerten+ 2015 A&A 583, A129

- Prompt spectrum rise too **flat** for synchrotron?
- Prompt spectrum turnover too **abrupt** for synchrotron?

A bigger lever arm thanks to X-rays

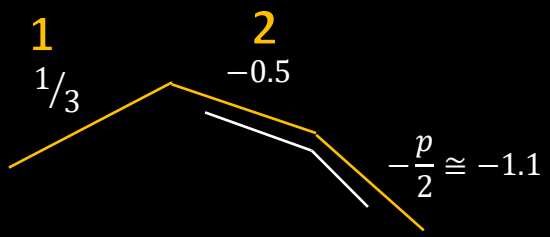




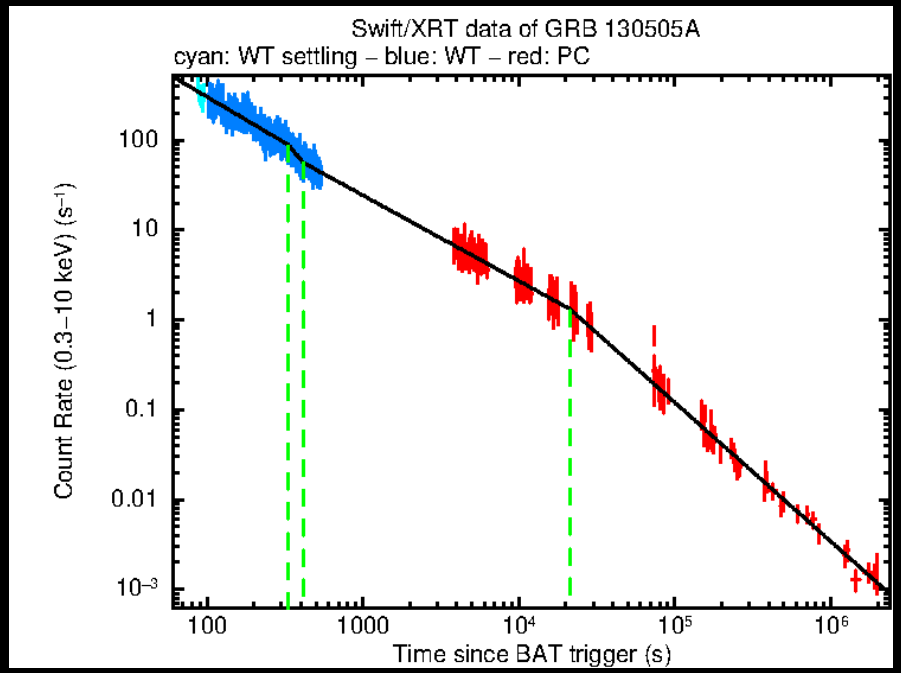
Oganesyan+ 2018, A&A, 616, A138
Oganesyan+ 2017, ApJ, 846, 137

$$\frac{F_\nu}{\nu} = -1.5 \qquad \frac{F_\nu}{\nu} = -0.66$$

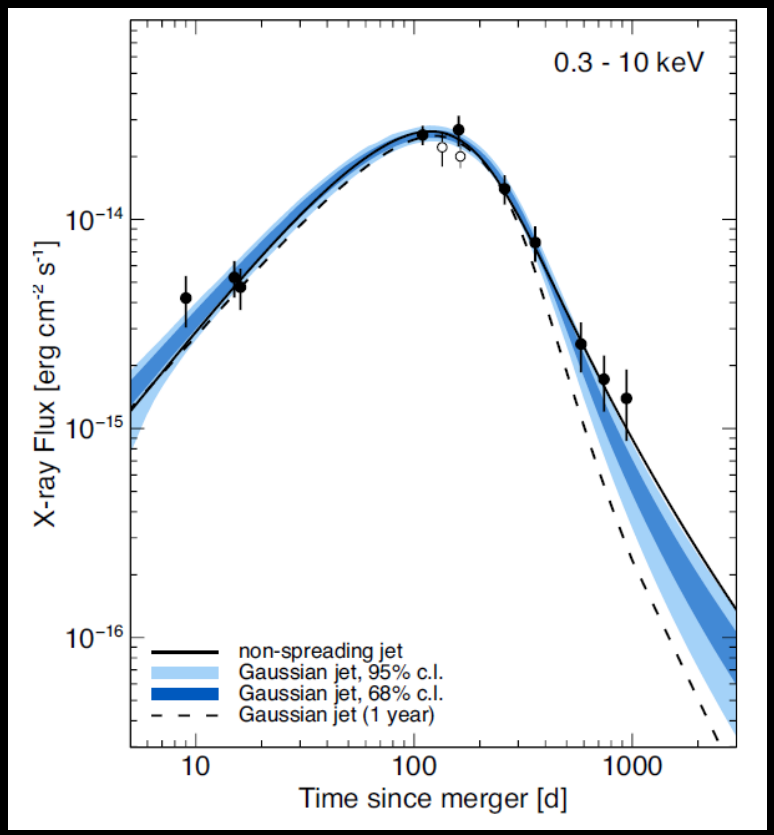
$$\upsilon F_\nu = 0.5 \qquad \upsilon F_\nu = 1.33$$



multi-messenger era dynamics of gamma-ray bursts

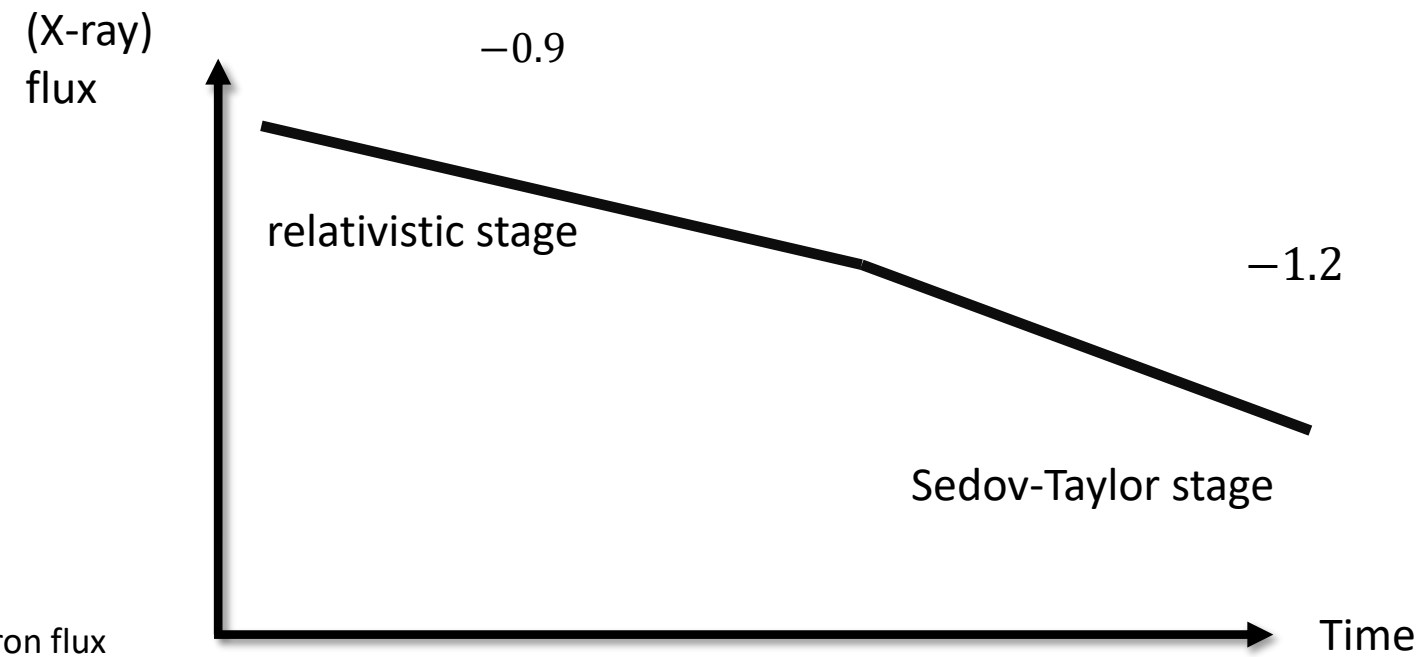


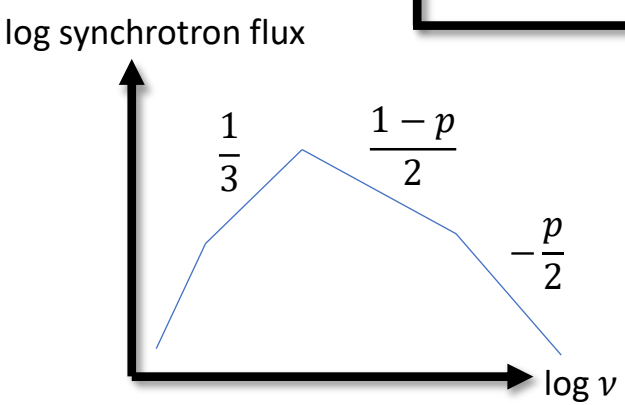
Old style

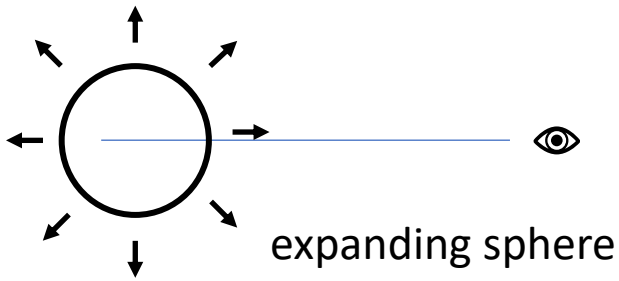


New style

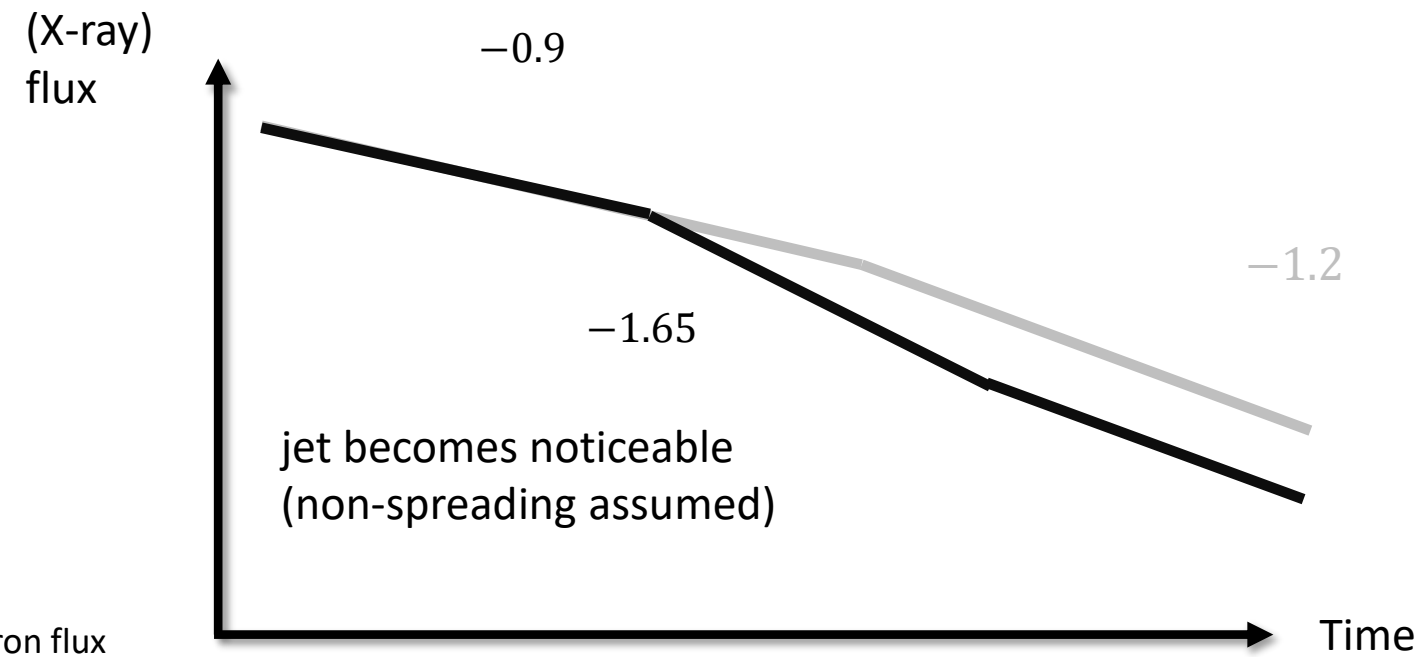
Observing & modeling gamma-ray burst afterglows

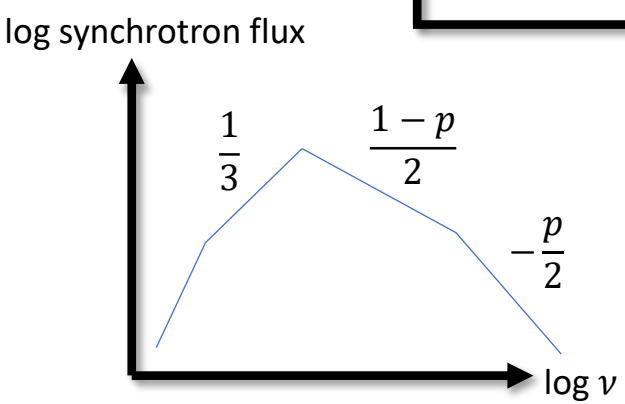


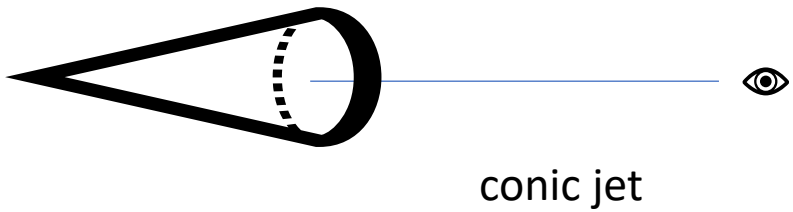




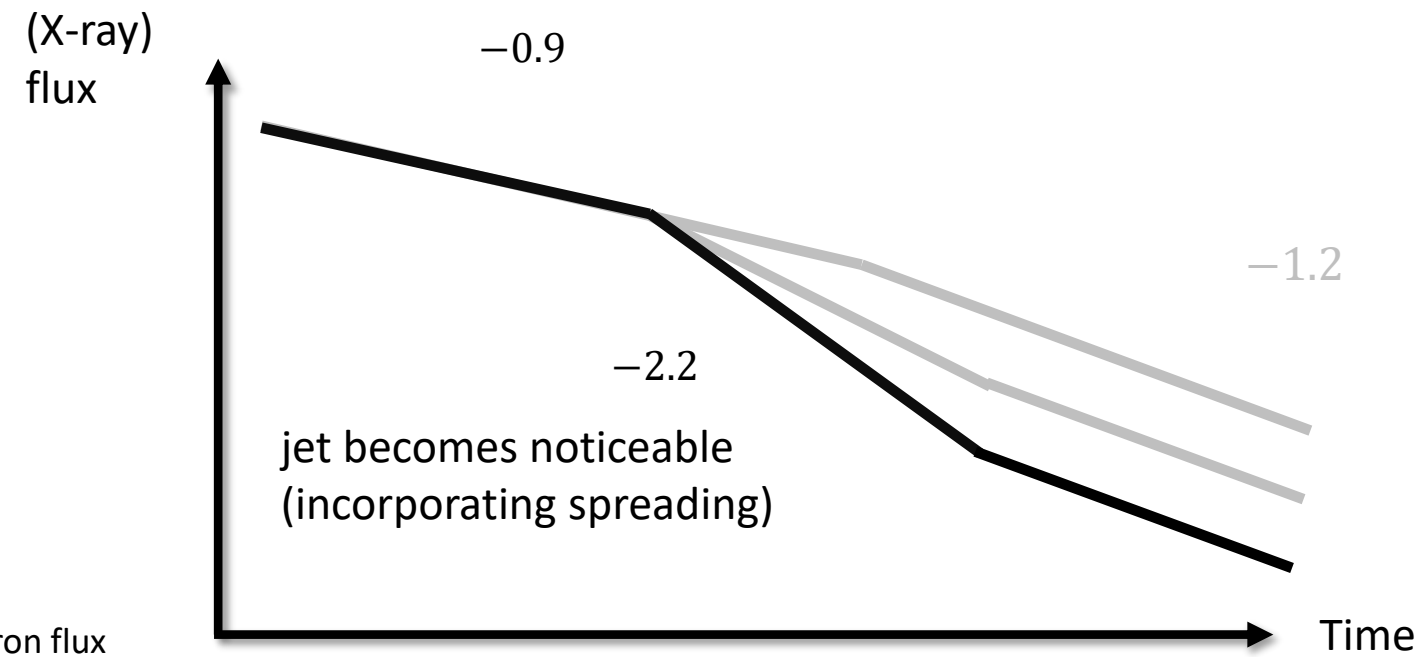
Observing & modeling gamma-ray burst afterglows

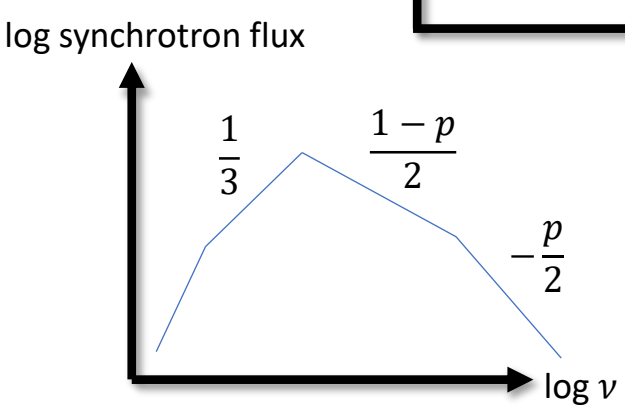


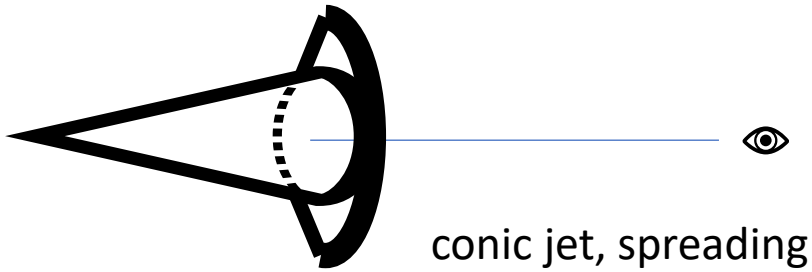




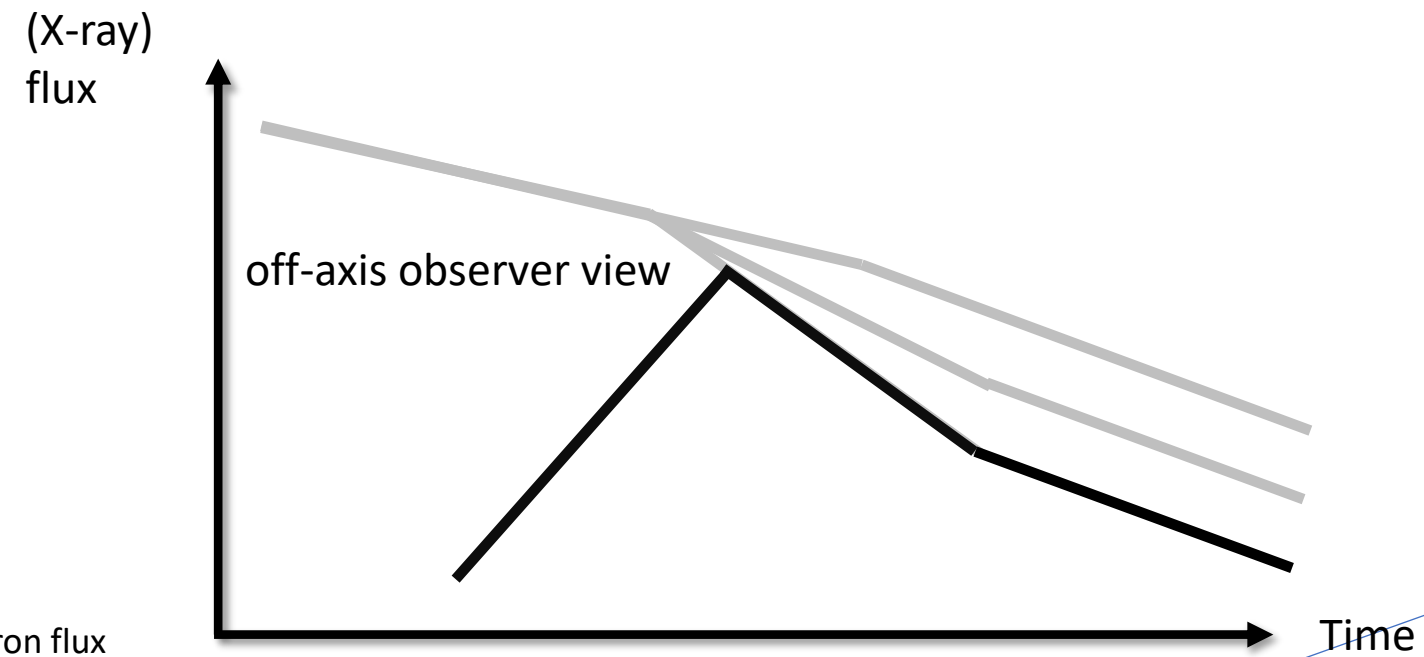
Observing & modeling gamma-ray burst afterglows

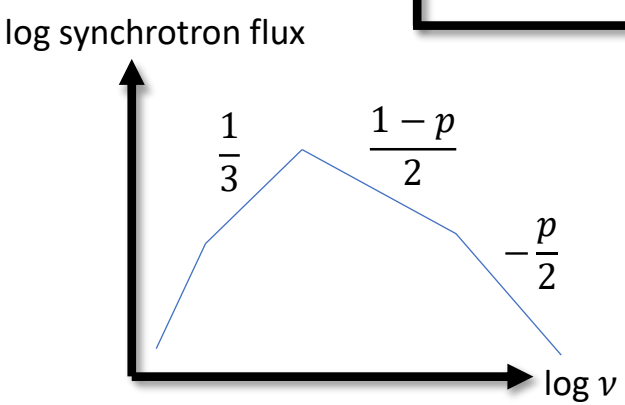


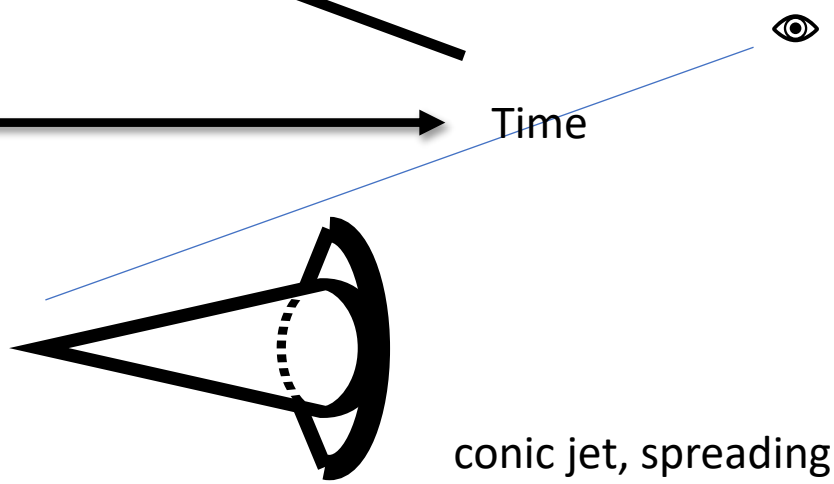




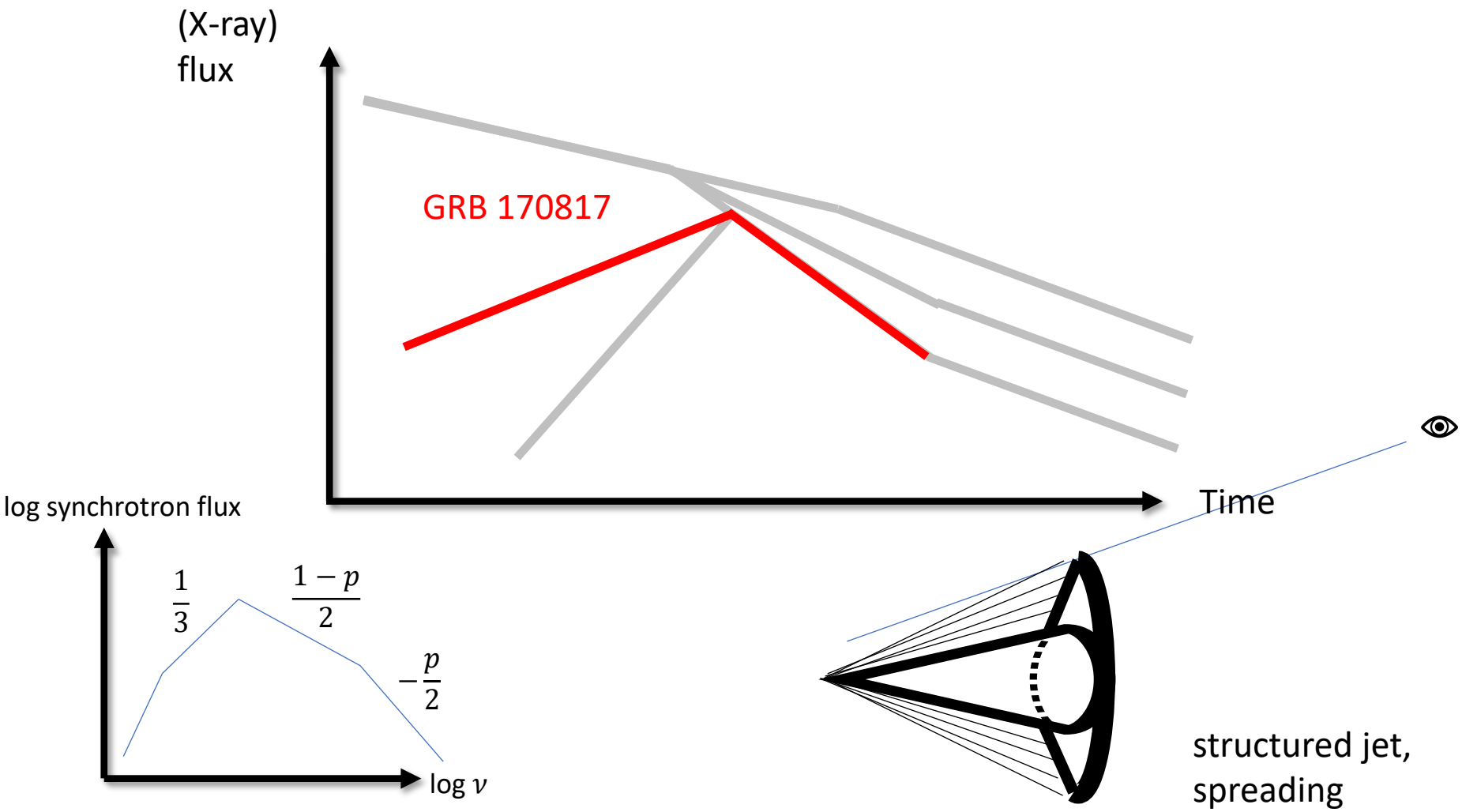
Observing & modeling gamma-ray burst afterglows



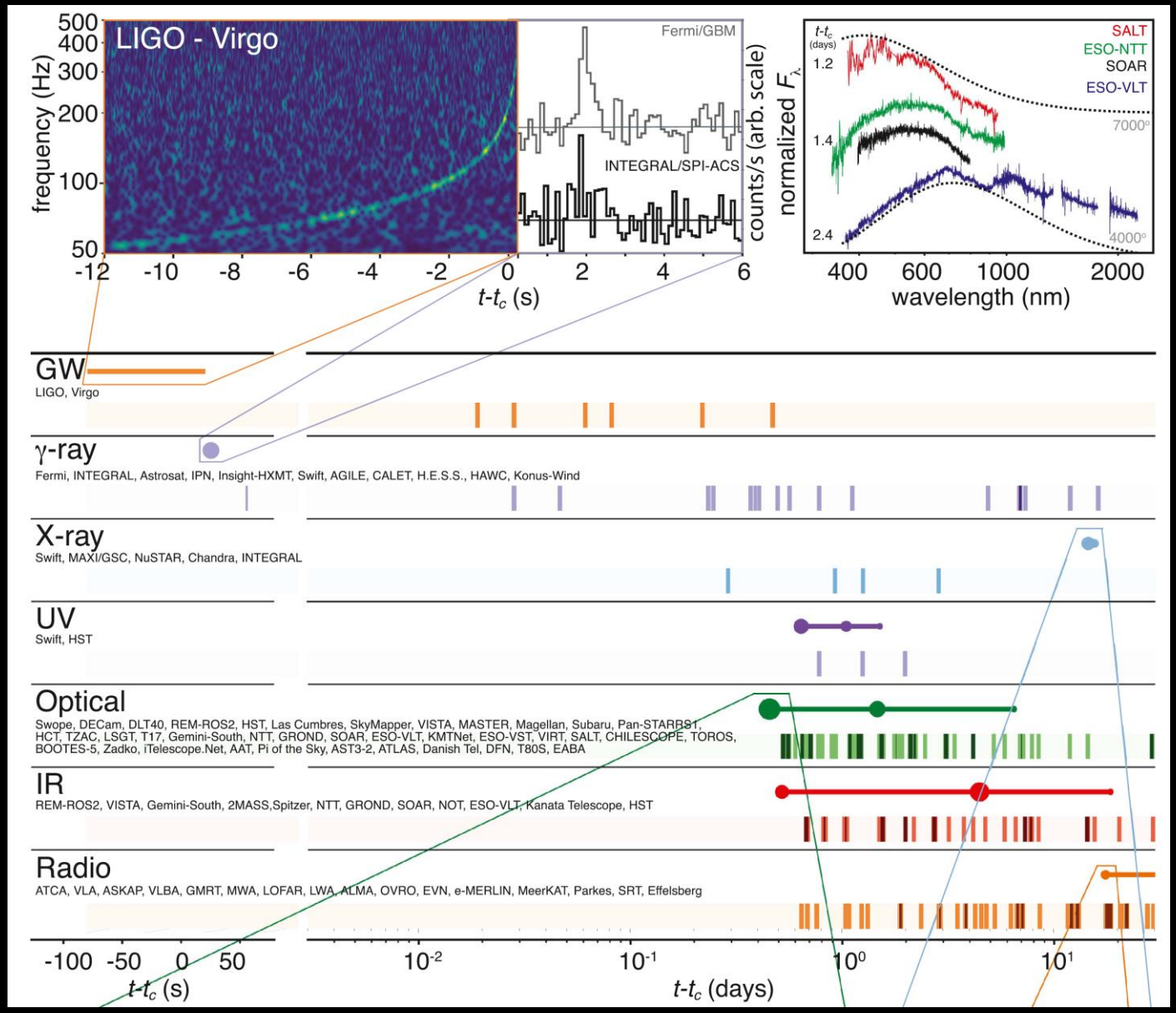




Observing & modeling gamma-ray burst afterglows

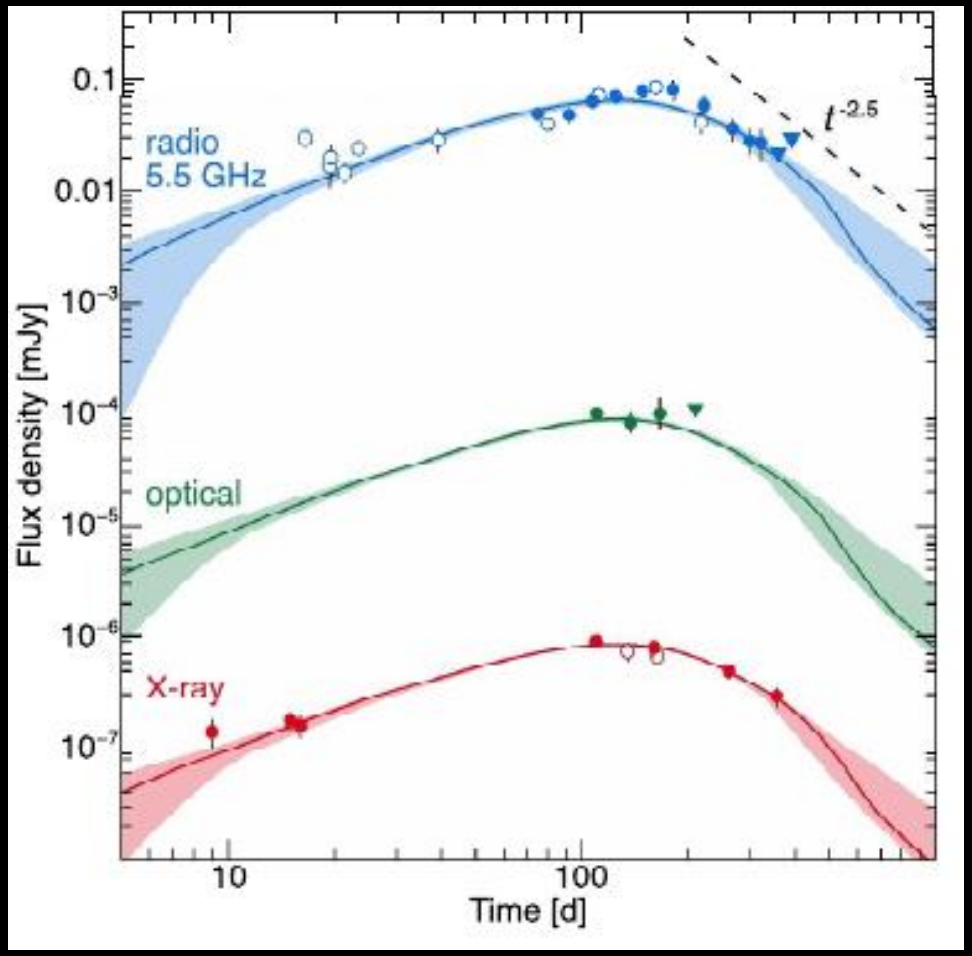


GW170817 and GRB 170817A



Abbott+ 2017, ApJL 848, L12

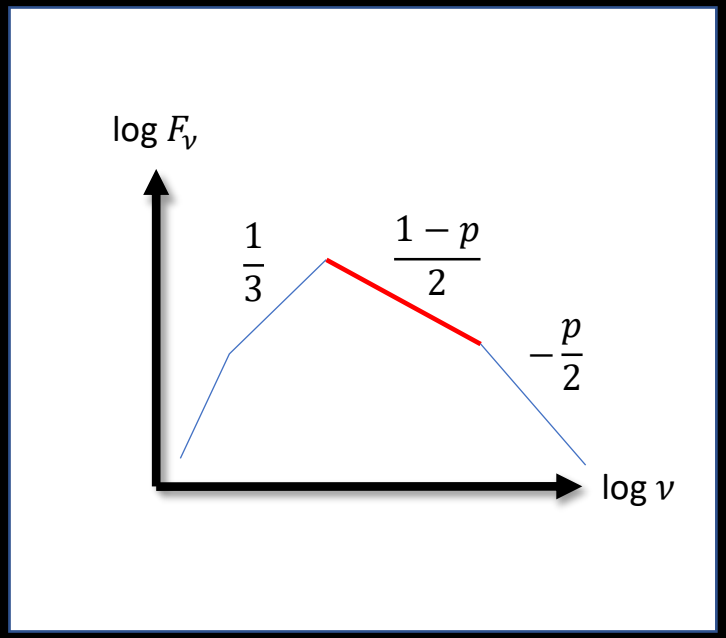
GRB 170817A broadband afterglow observable for long time



Troja, van Eerten+ 2019, MNRAS 489, 1919

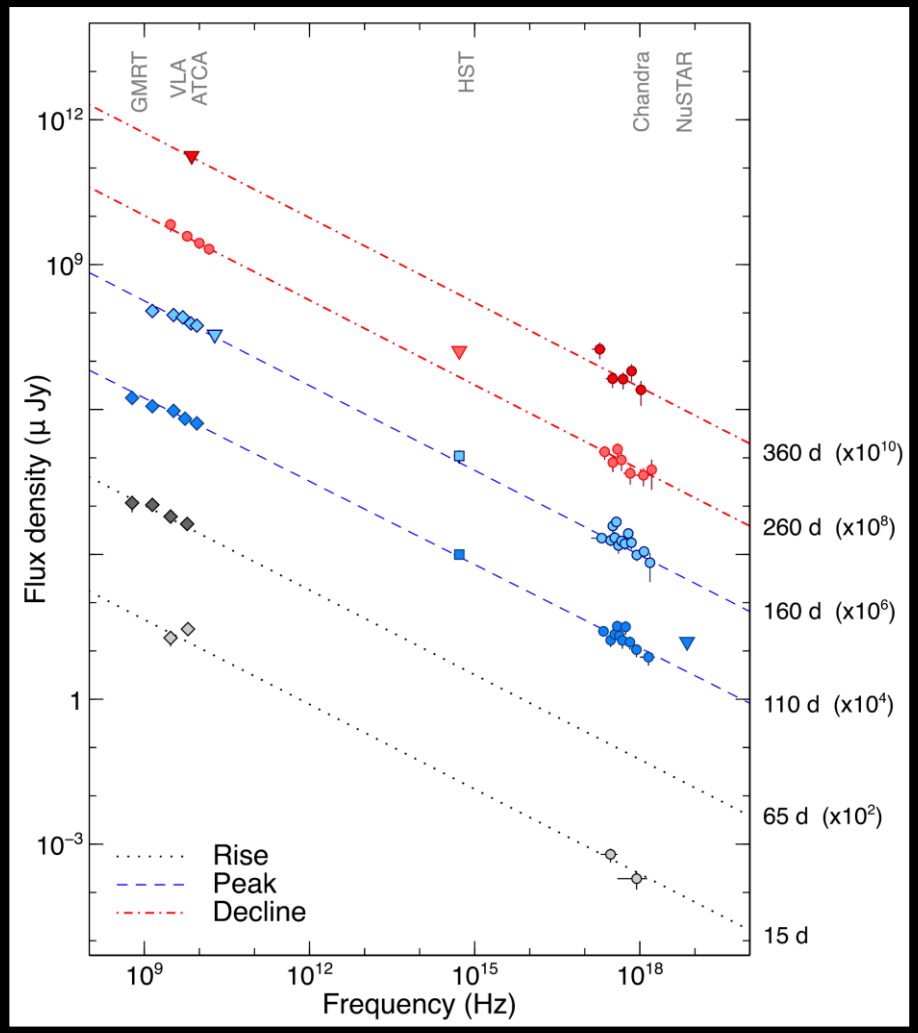
Note how all three light curves look basically the same

The synchrotron spectrum & 170817



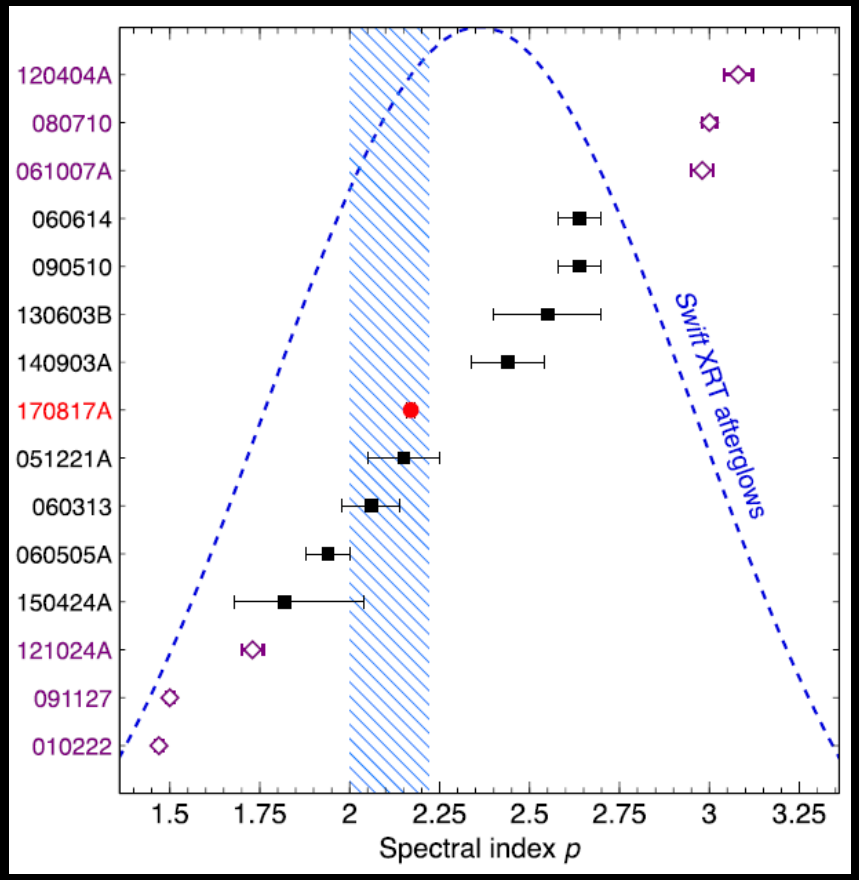
$$p = 2.15^{+0.02}_{-0.02}$$

(reflecting a range of jet models)

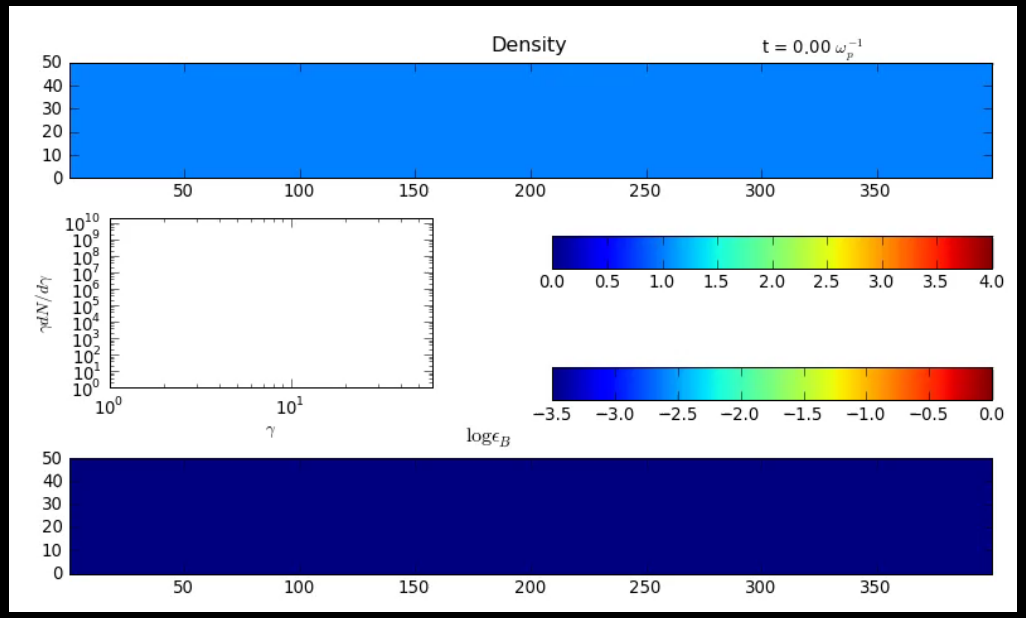


Troja, van Eerten+ 2019, Haggard+ 2017, Hallinan+ 2017, Mooley+ 2018, D'Avanzo+ 2018, Lyman+ 2018, Dobie+ 2018, Margutti+ 2018, Troja+ 2017, 2018, Lamb+ 2019, ...

170817 tightly constrains the energy distribution of shock-accelerated electrons



Troja, van Eerten+ 2019, MNRAS 489, 1919



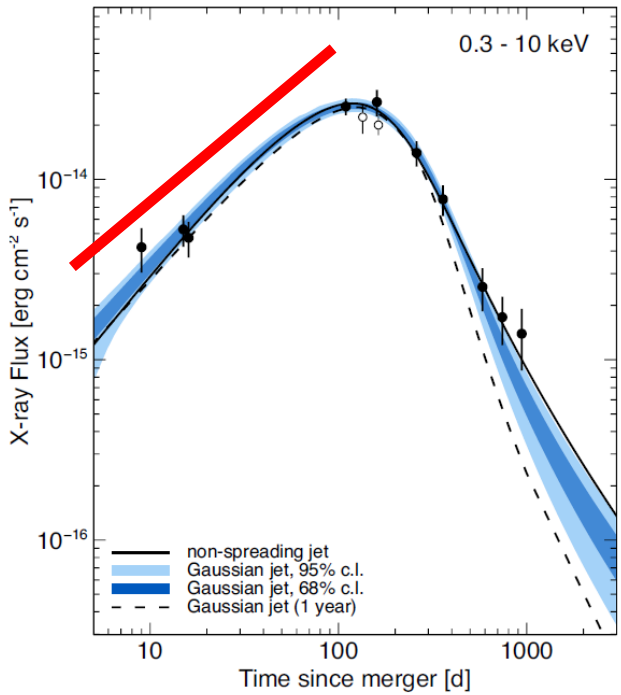
Spitkovsky+ 2008, ApJL 682, L5

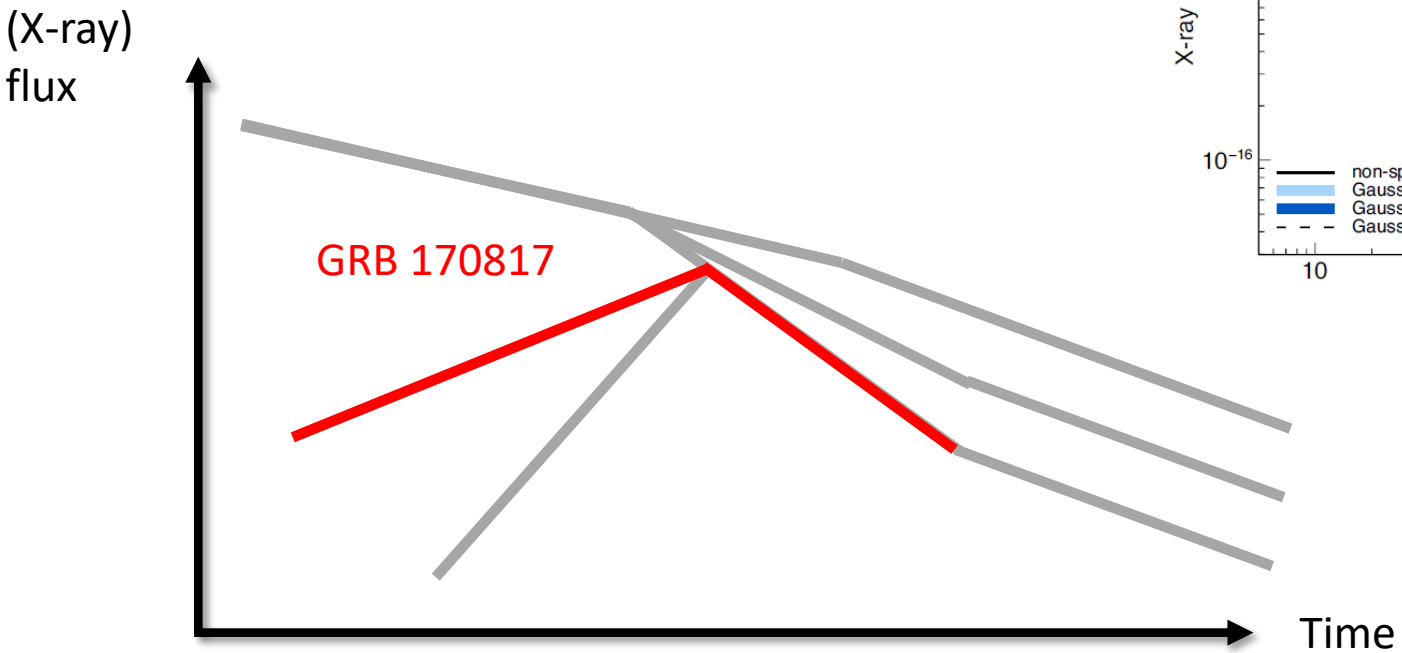
Back to 170817's light curve:

170817 and its shallow rising slope:

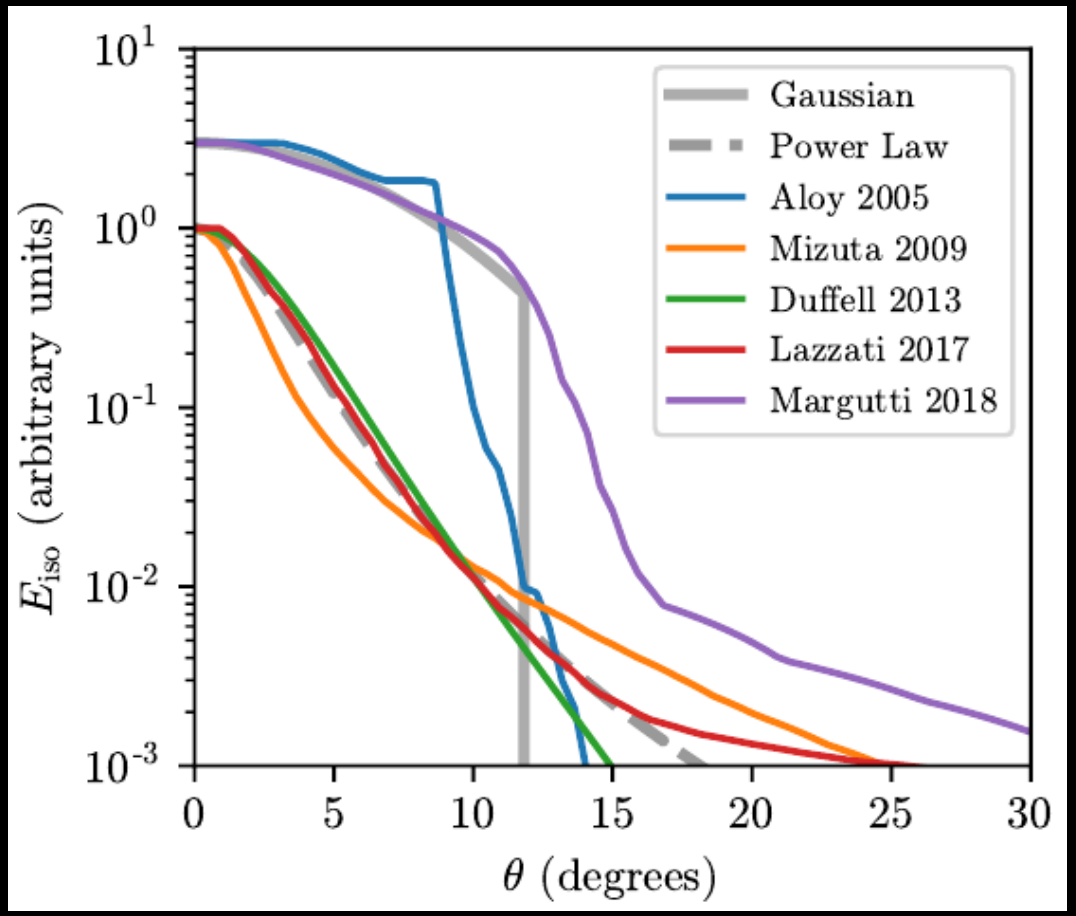
- must be off-axis (ie rising, not falling)
- rise not steep enough for beamed emission seen sideways

✓ Needs a jet with energy *structure*

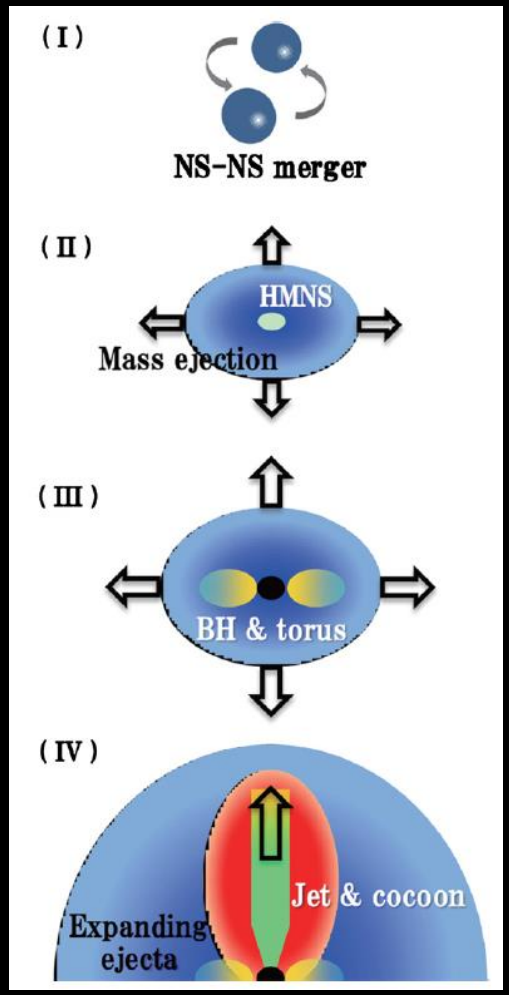




Afterglows and jet lateral structure



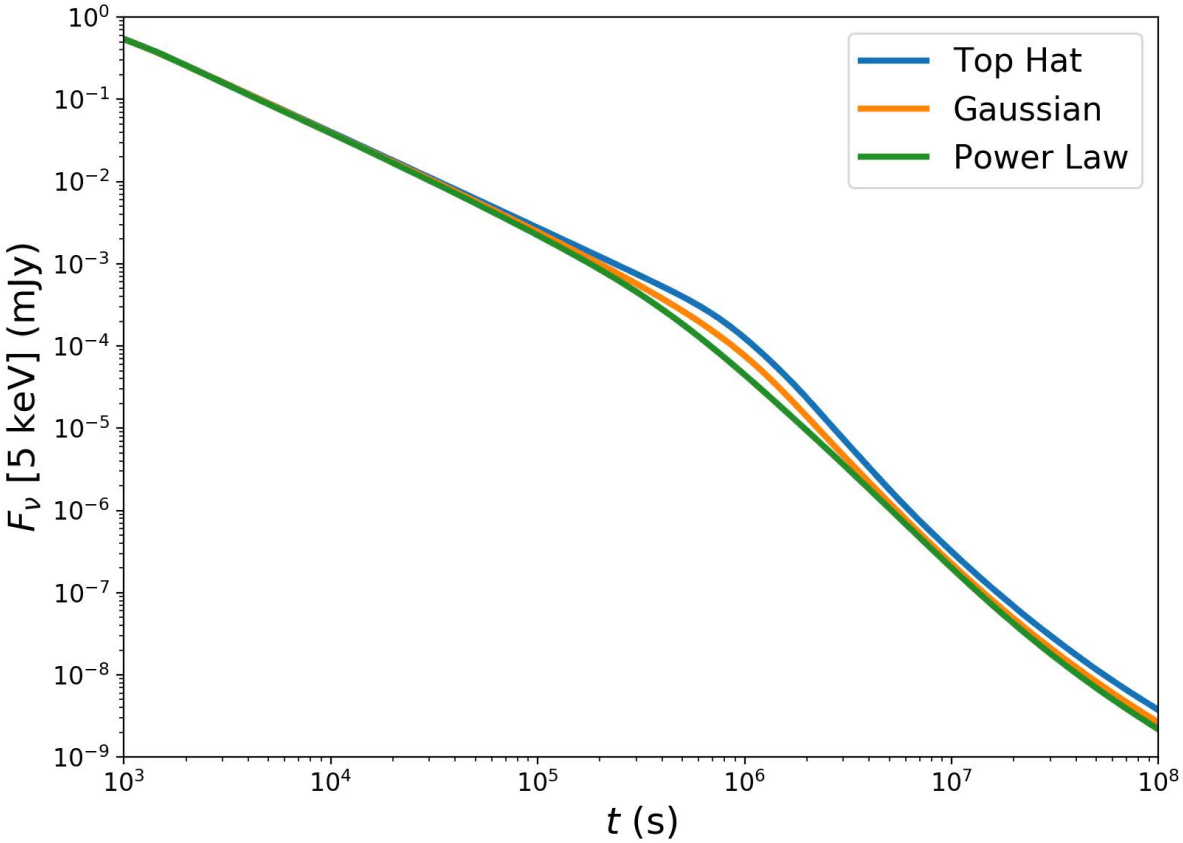
Ryan, van Eerten+ 2019

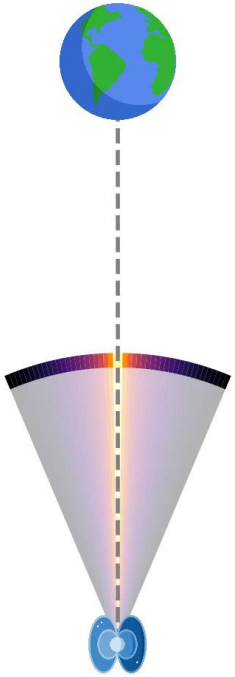


Nagakura+ 2014

- *All* GRB jet launching scenarios give rise to a measure of structure in the outflow geometry. NS merger debris might well further add to this
- Structure can often be modeled straightforwardly with a simplified power-law/Gaussian

initial structure was always there, but only key feature for off-axis observers

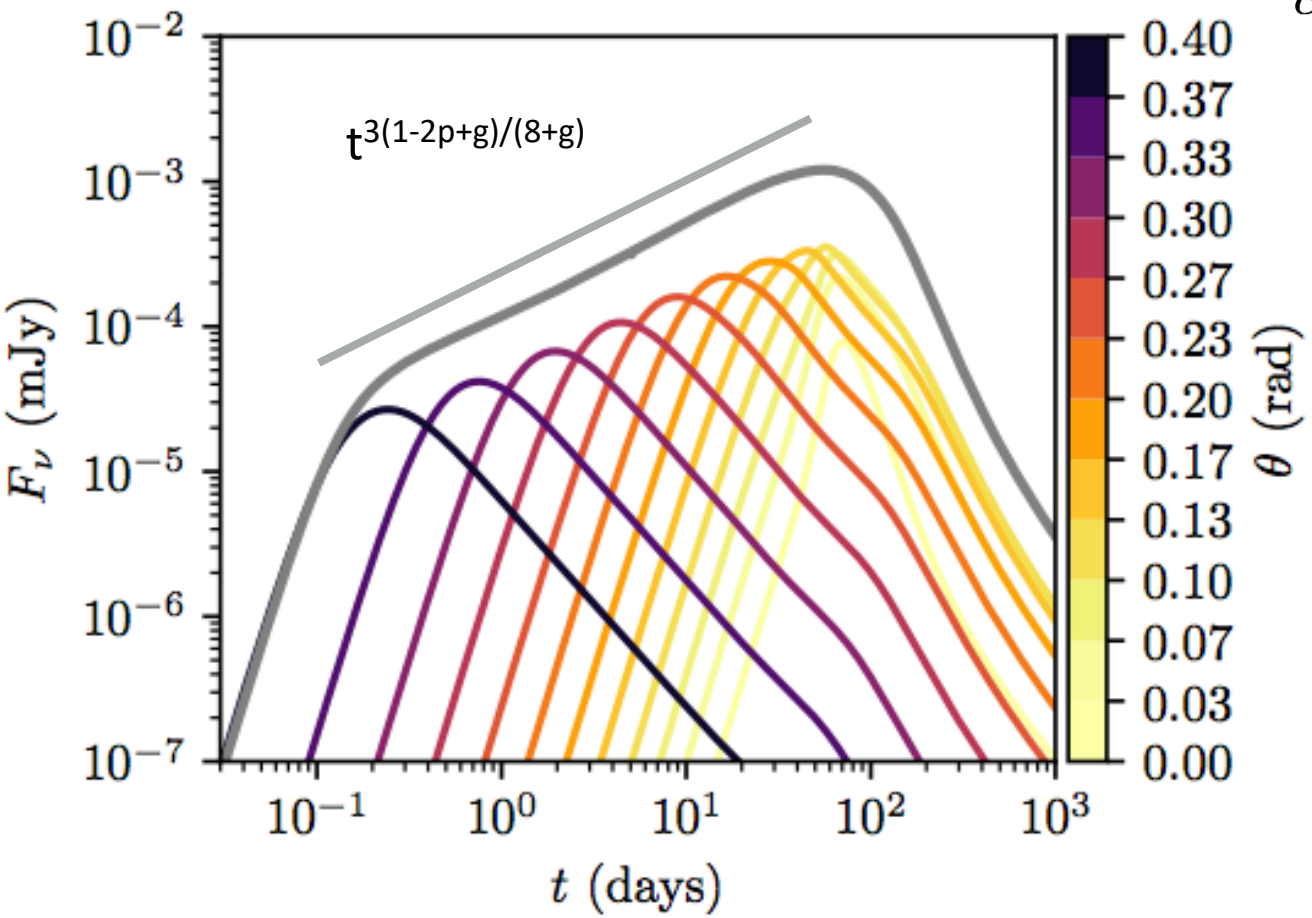


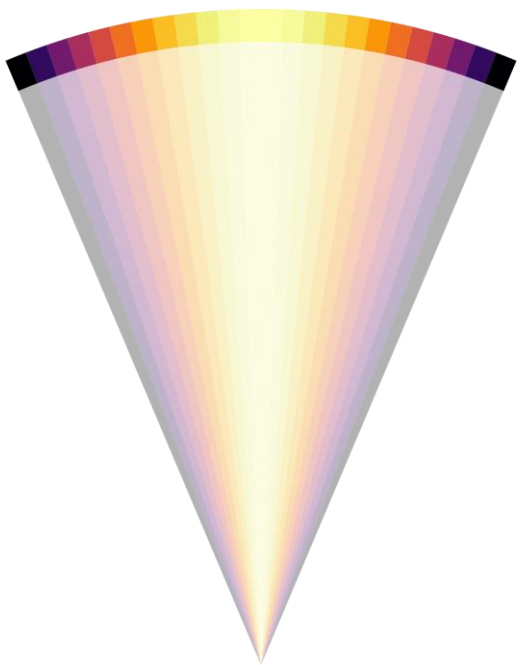


Ryan, van Eerten+ 2020, ApJ 896, 166

Anatomy of a structured jet

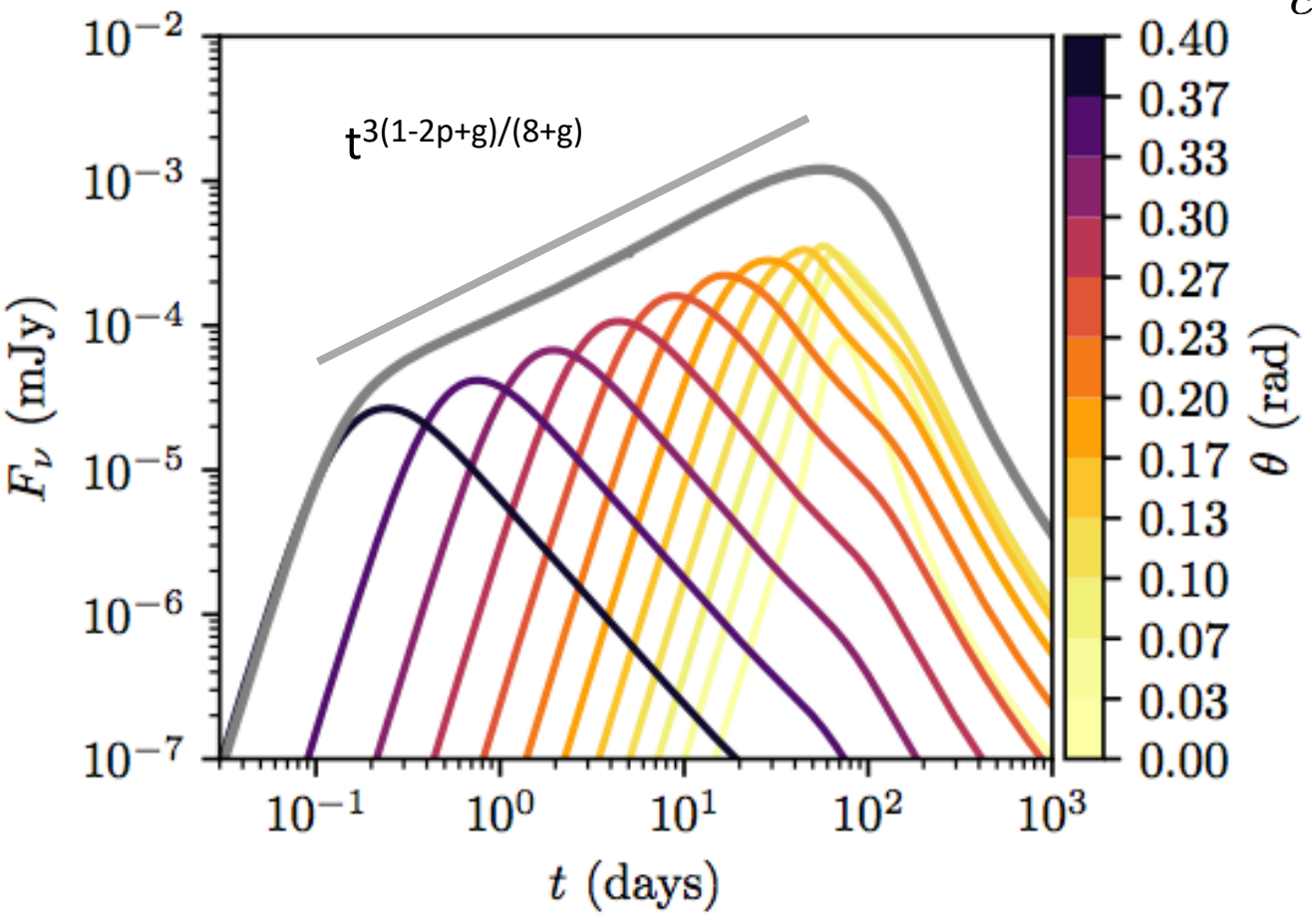
$$g = (\theta_{\rm obs} - \theta)\frac{d\log E}{d\theta} \approx \frac{\theta_{\rm obs}^2}{4\theta_c^2}$$ (for a Gaussian)





Anatomy of a structured jet

$$g = (\theta_{\rm obs} - \theta)\frac{d\log E}{d\theta} \approx \frac{\theta_{\rm obs}^2}{4\theta_c^2}$$ (for a Gaussian)



GW 170817A

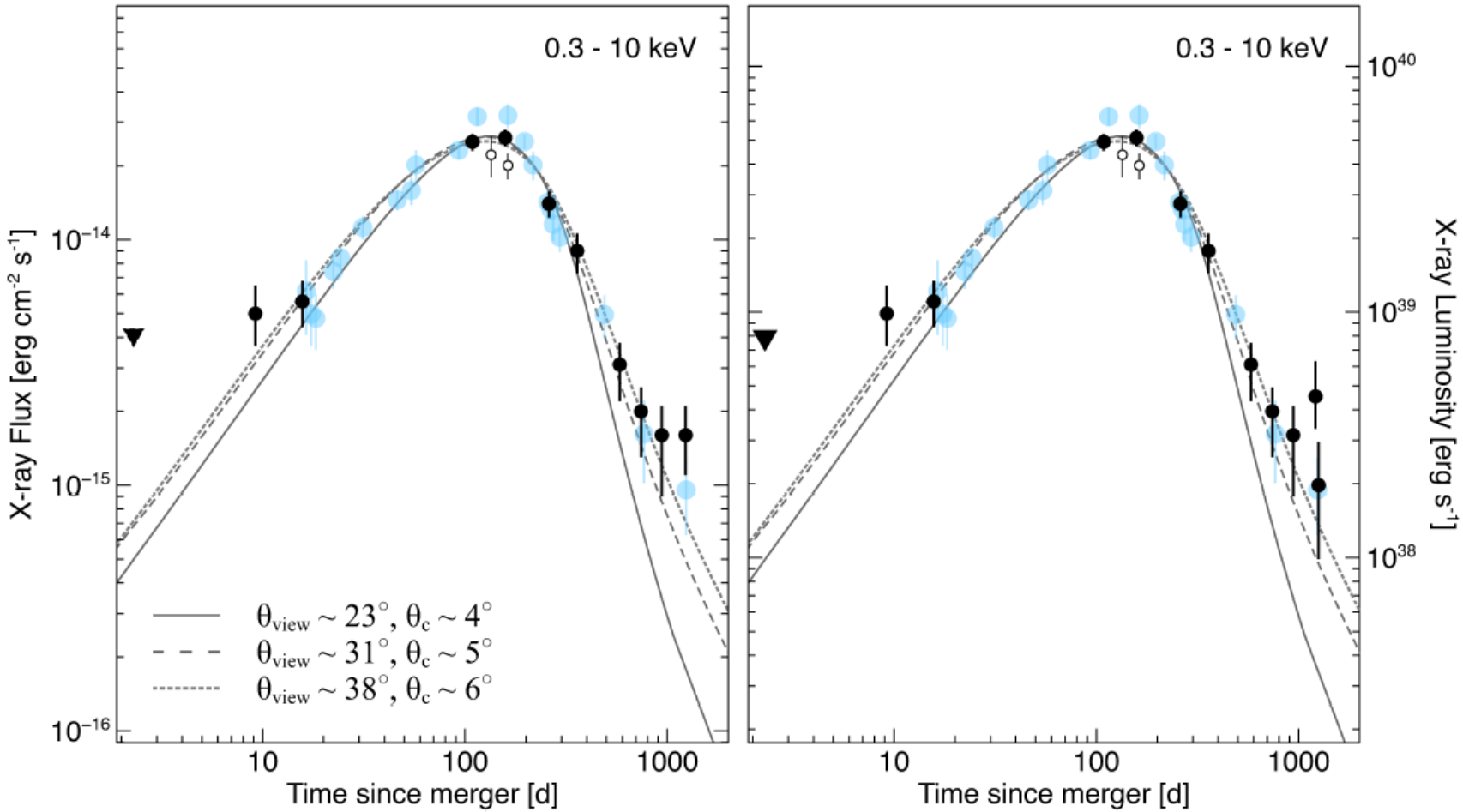
$\alpha = 0.90 \pm 0.06$

$\Longrightarrow g = 8.2$

$\Longrightarrow \theta_{\rm obs} = 5.7\theta_c$

Ryan, van Eerten+ 2019

Follow-up, latest (radio & X-rays)



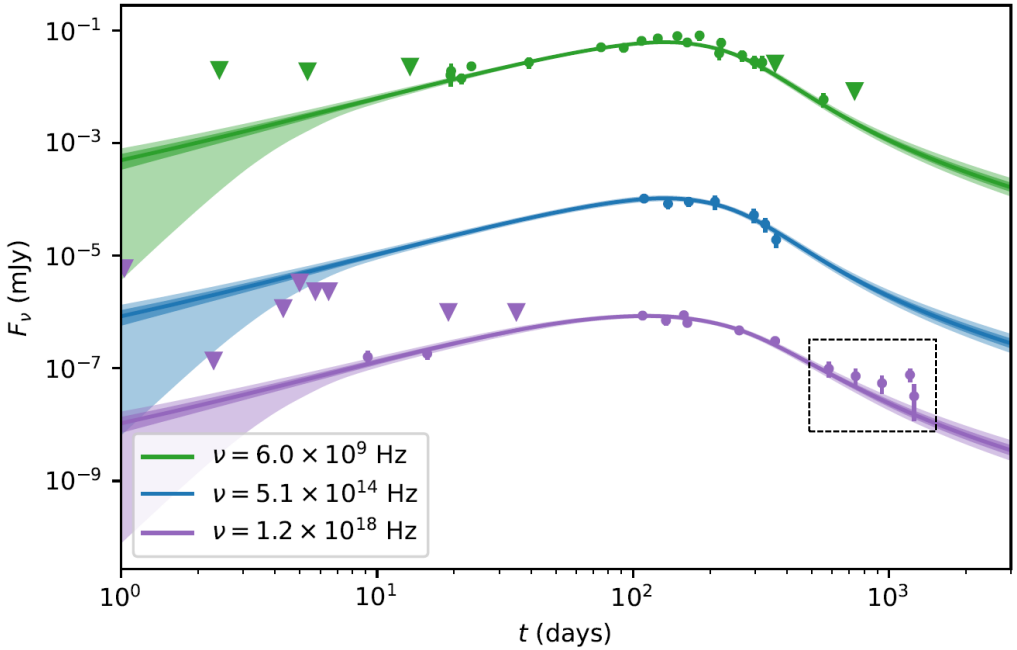
Troja+ 2022 MNRAS 510, 1902

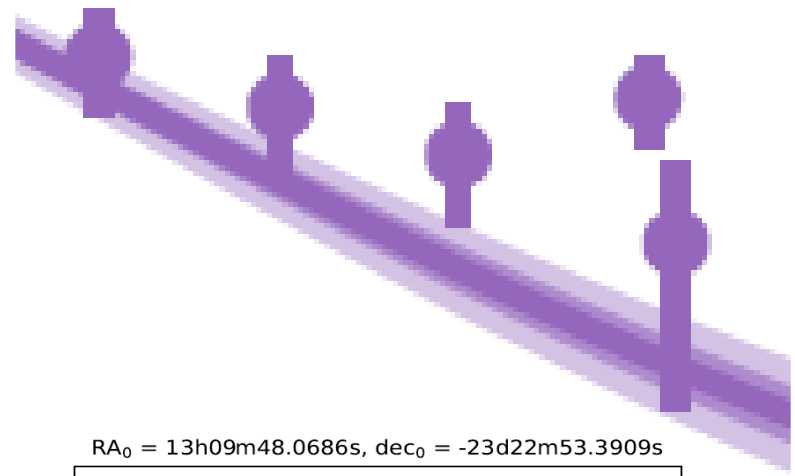
- Blue data points: shifted radio
- Black data points: X-rays
- left figure had X-ray data rebinned

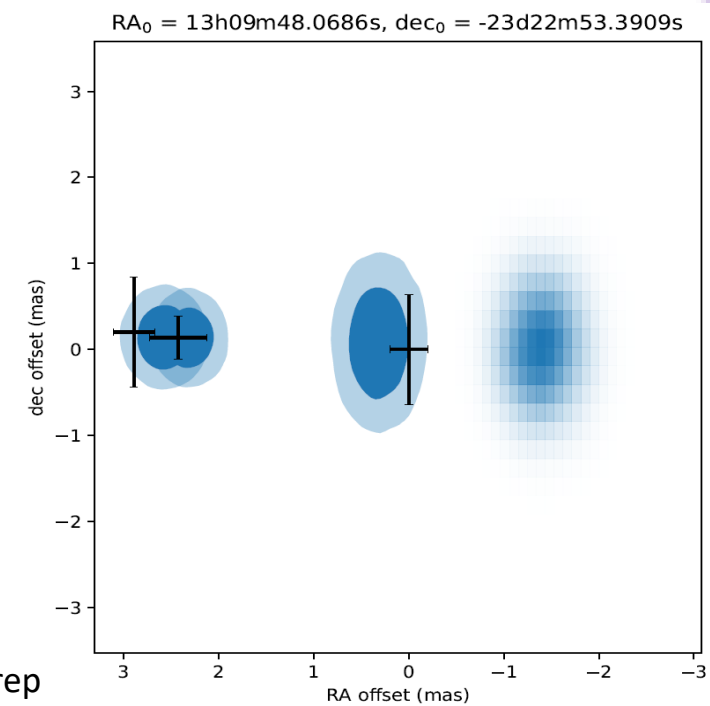
tension as shown above stands at 3.5σ,
(changes with model tweaks)

see also Hajela+ 2021, Balasubramanian+ 2021, ...

Light curve result, no extra luminosity





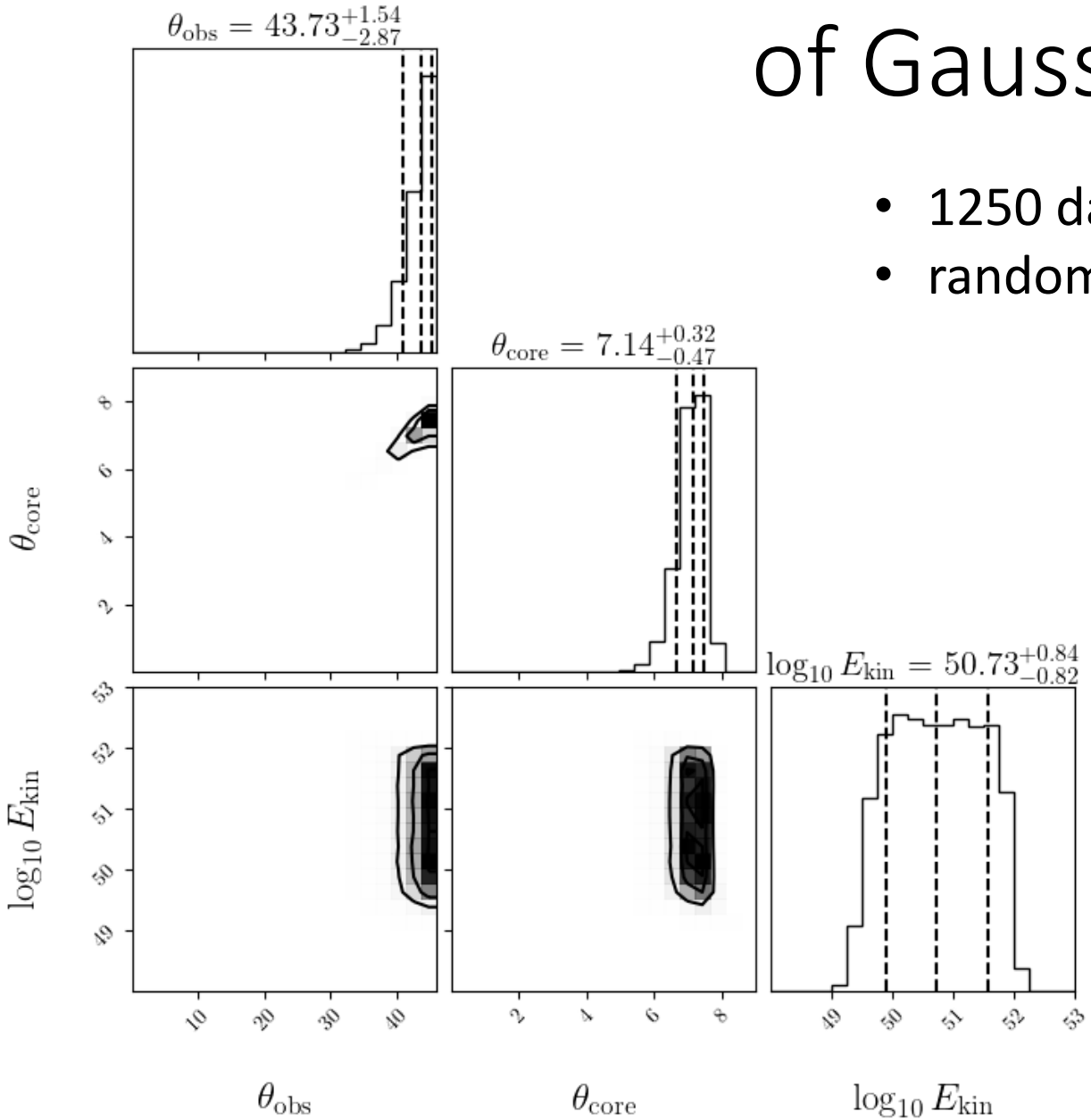


- Fits use Gaussian structured jet (PL fits show similar results)
- Direct co-fit for VLBI observations
- gravitational wave-based prior for orientation
- avoid unphysical electron distribution at late times ('Deep Newtonian regime')

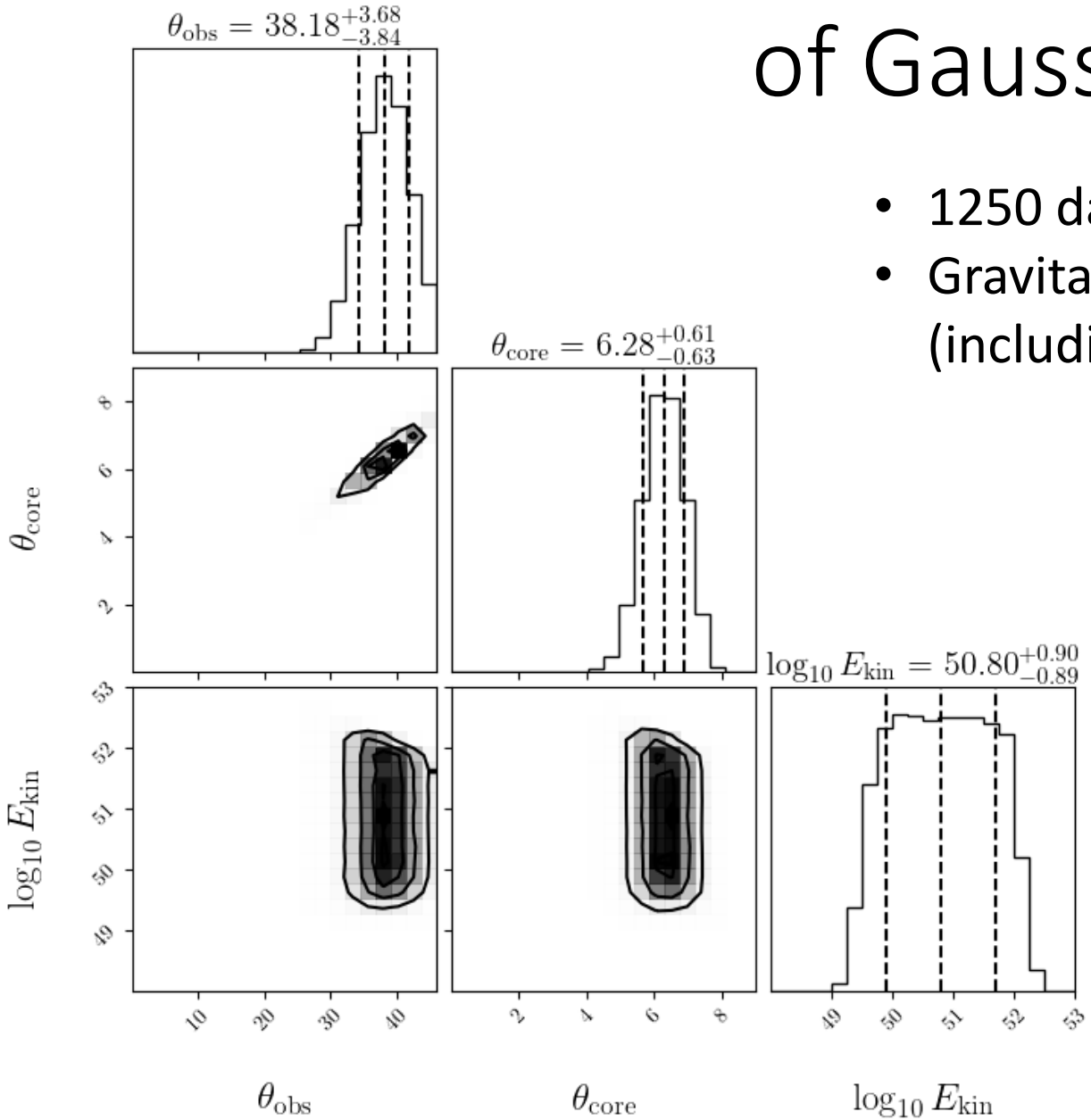
Ryan, Van Eerten+, in prep

Evolution of the posterior of Gaussian jet model

- 1250 days
- random sky orientation prior

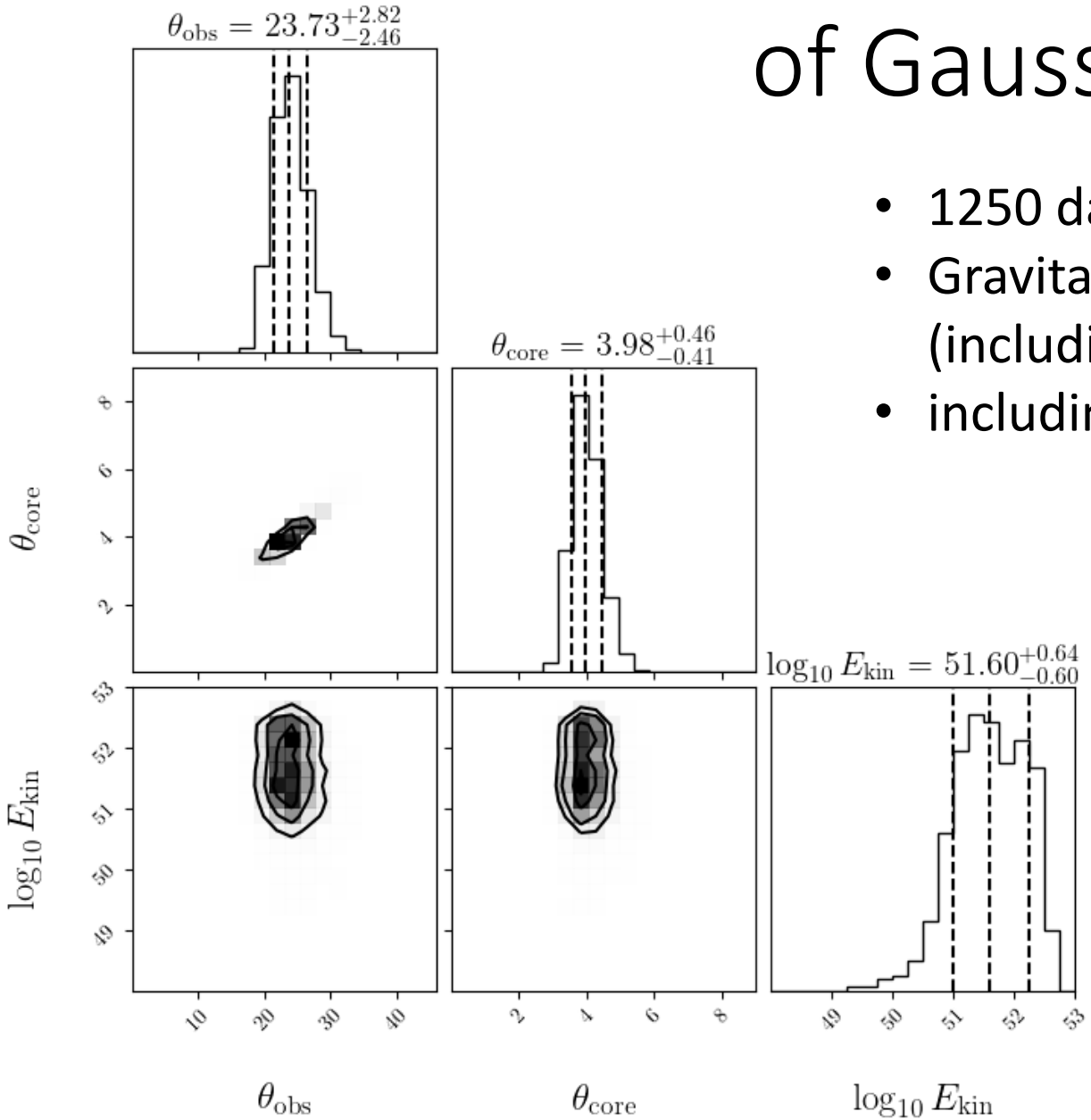


Evolution of the posterior of Gaussian jet model



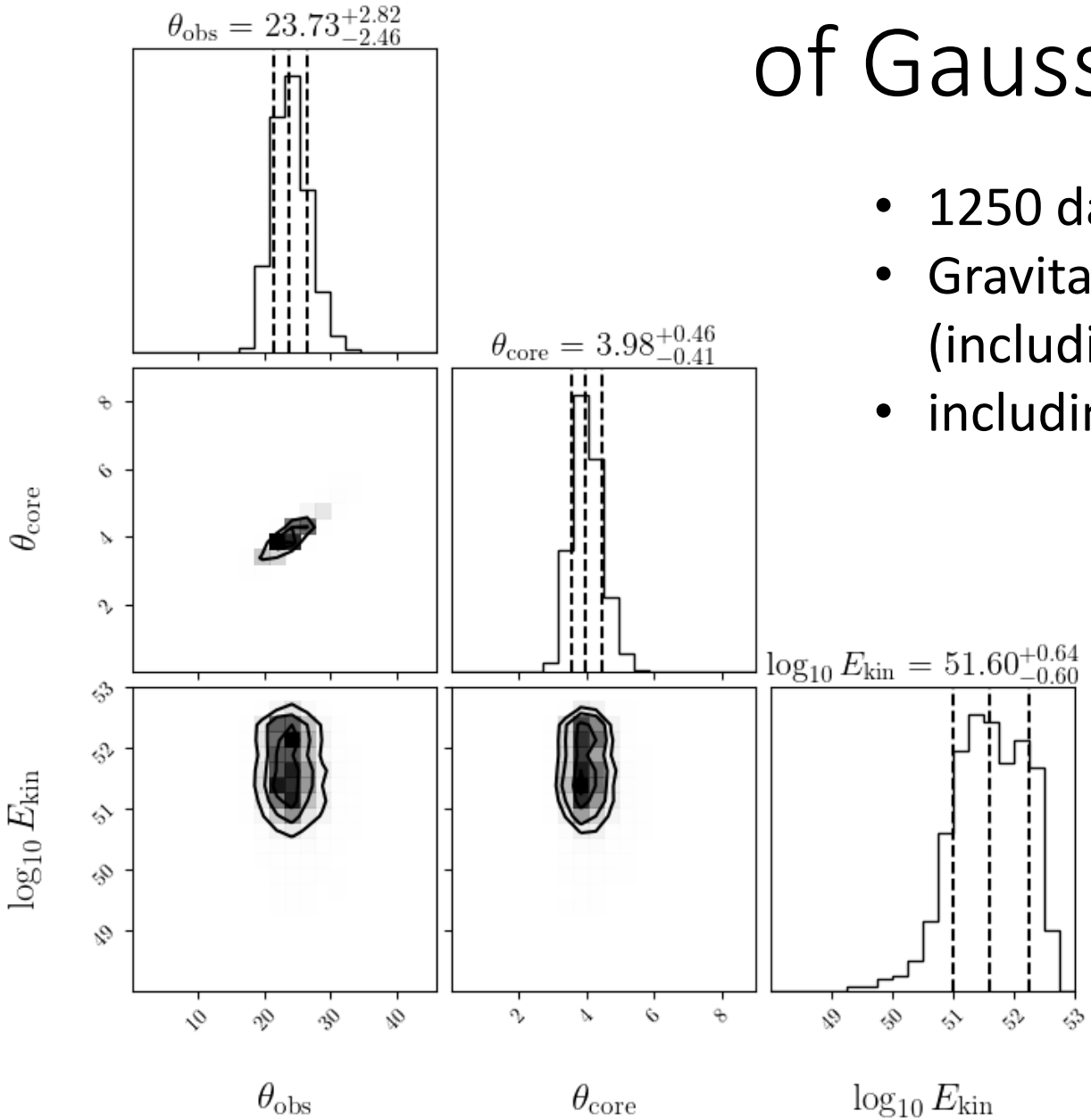
- 1250 days
- Gravitational wave prior (including H_0 assumption)

Evolution of the posterior of Gaussian jet model



- 1250 days
- Gravitational wave prior (including H_0 assumption)
- including centroid motion in fit

Evolution of the posterior of Gaussian jet model

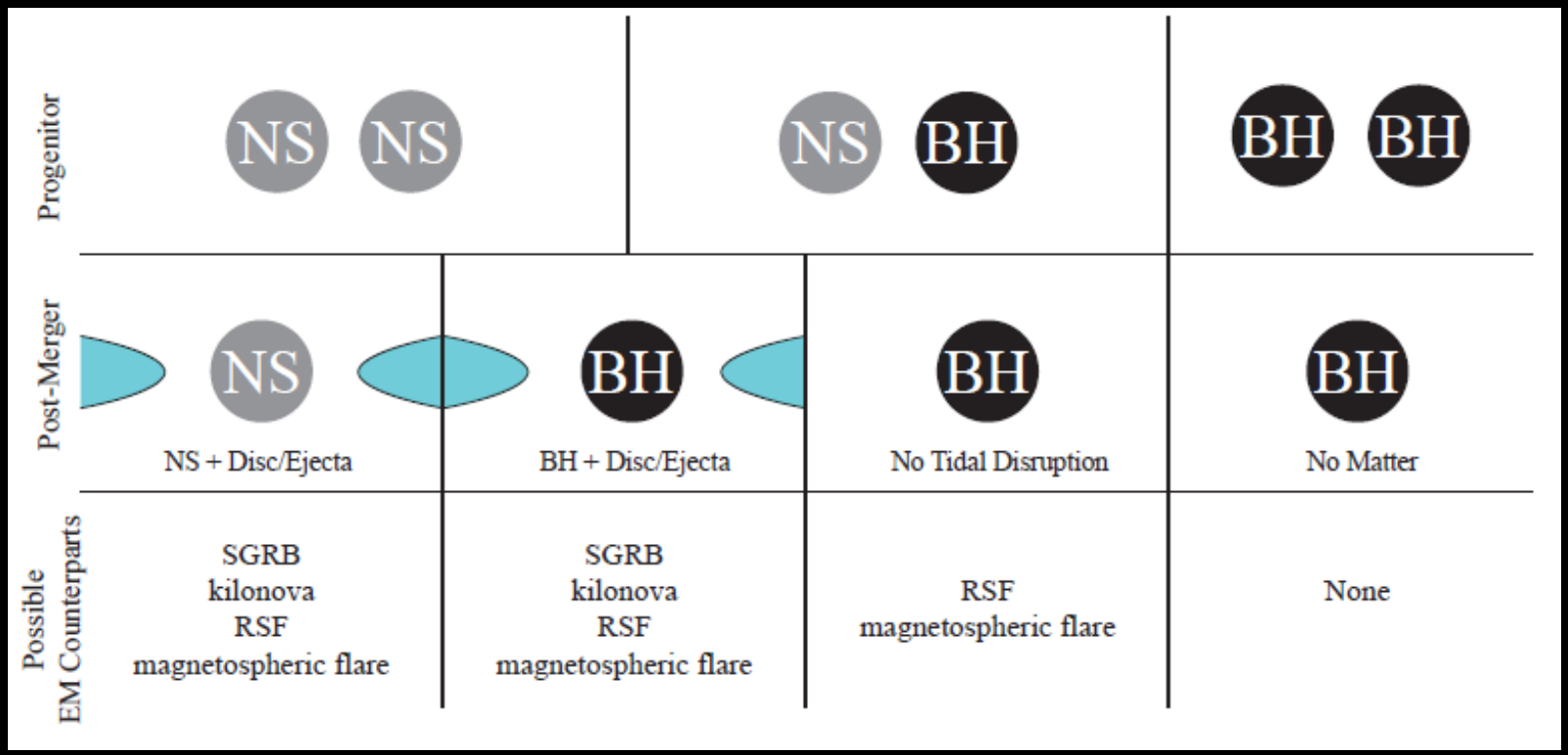


- 1250 days
- Gravitational wave prior (including H_0 assumption)
- including centroid motion in fit

X-rays in the multi-messenger era

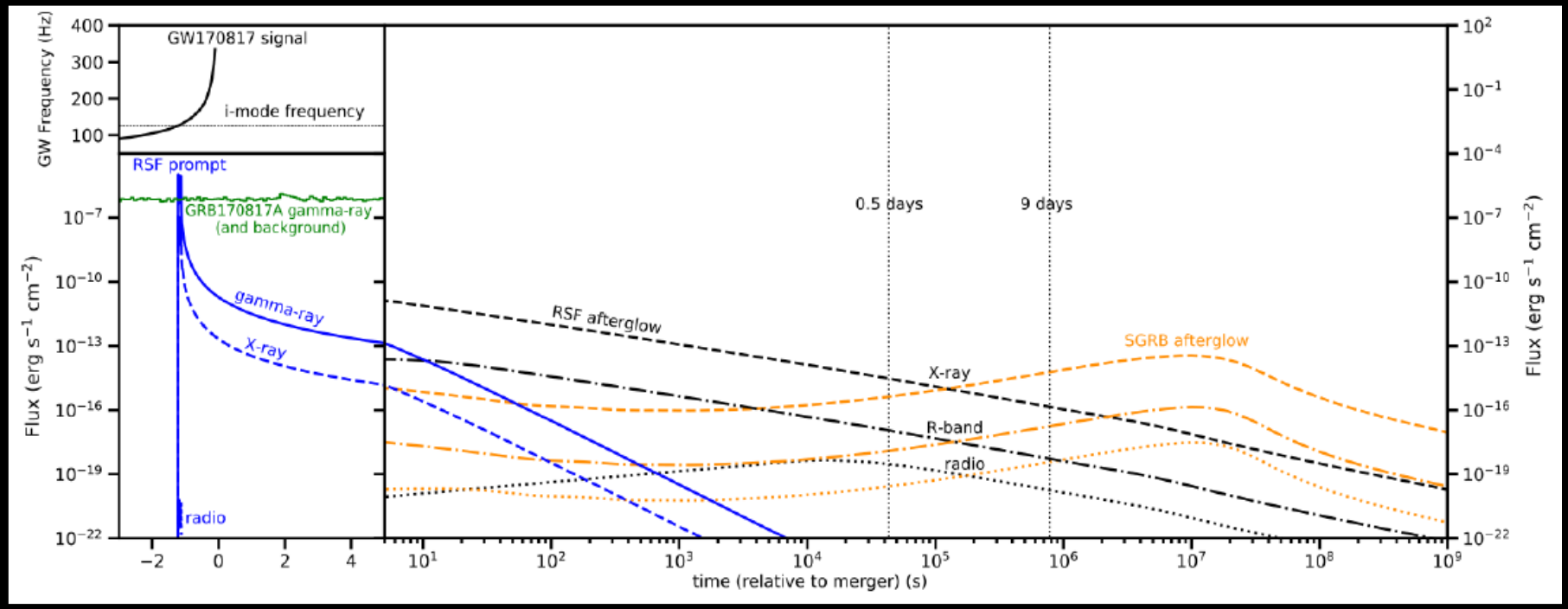
Resonance shattering flares in the X-rays

Systems that can provide shattering flares



Neill+ 2021 Submitted, ArXiv: 2111.03686

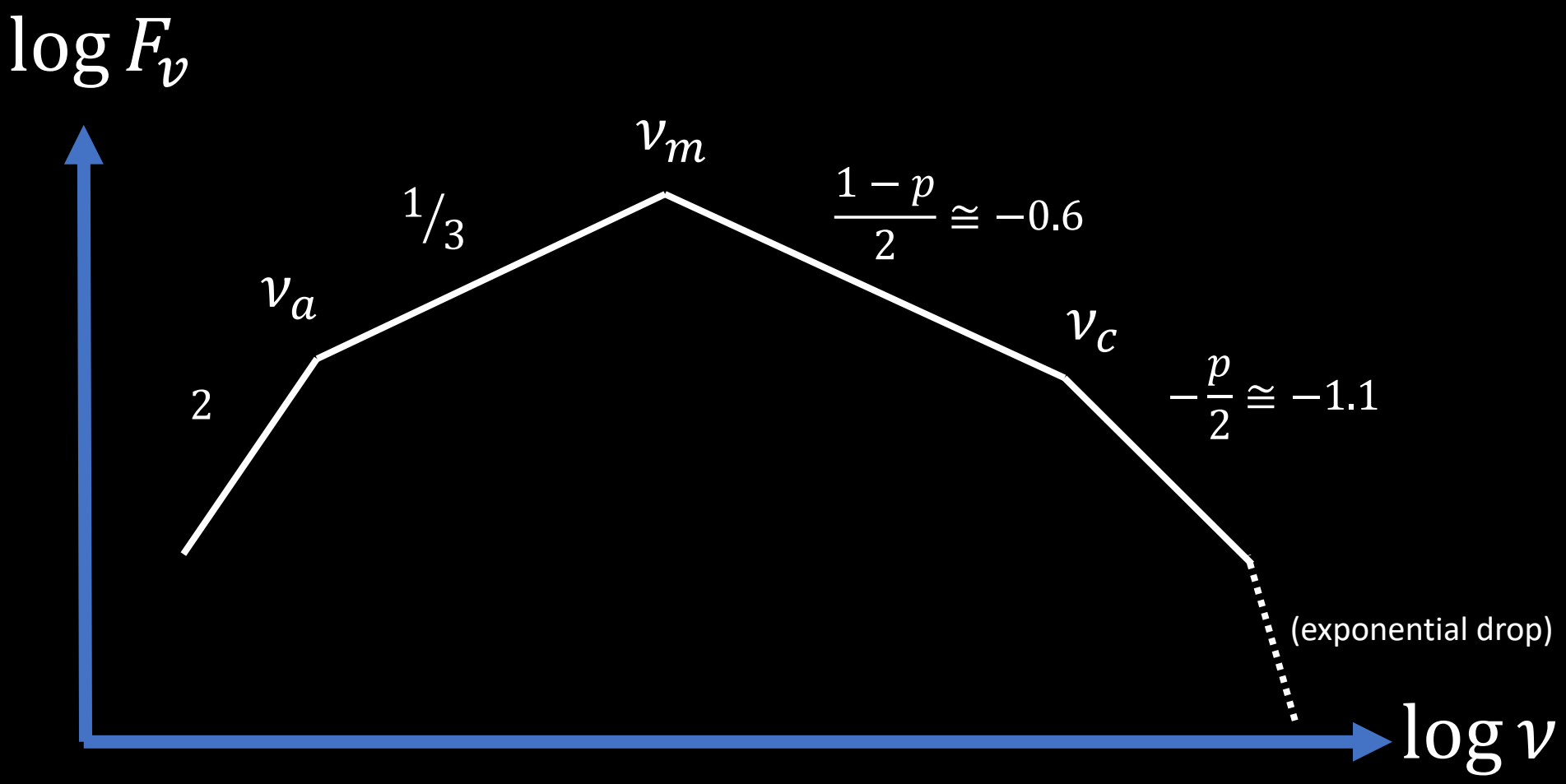
Resonance shattering flares in the X-rays



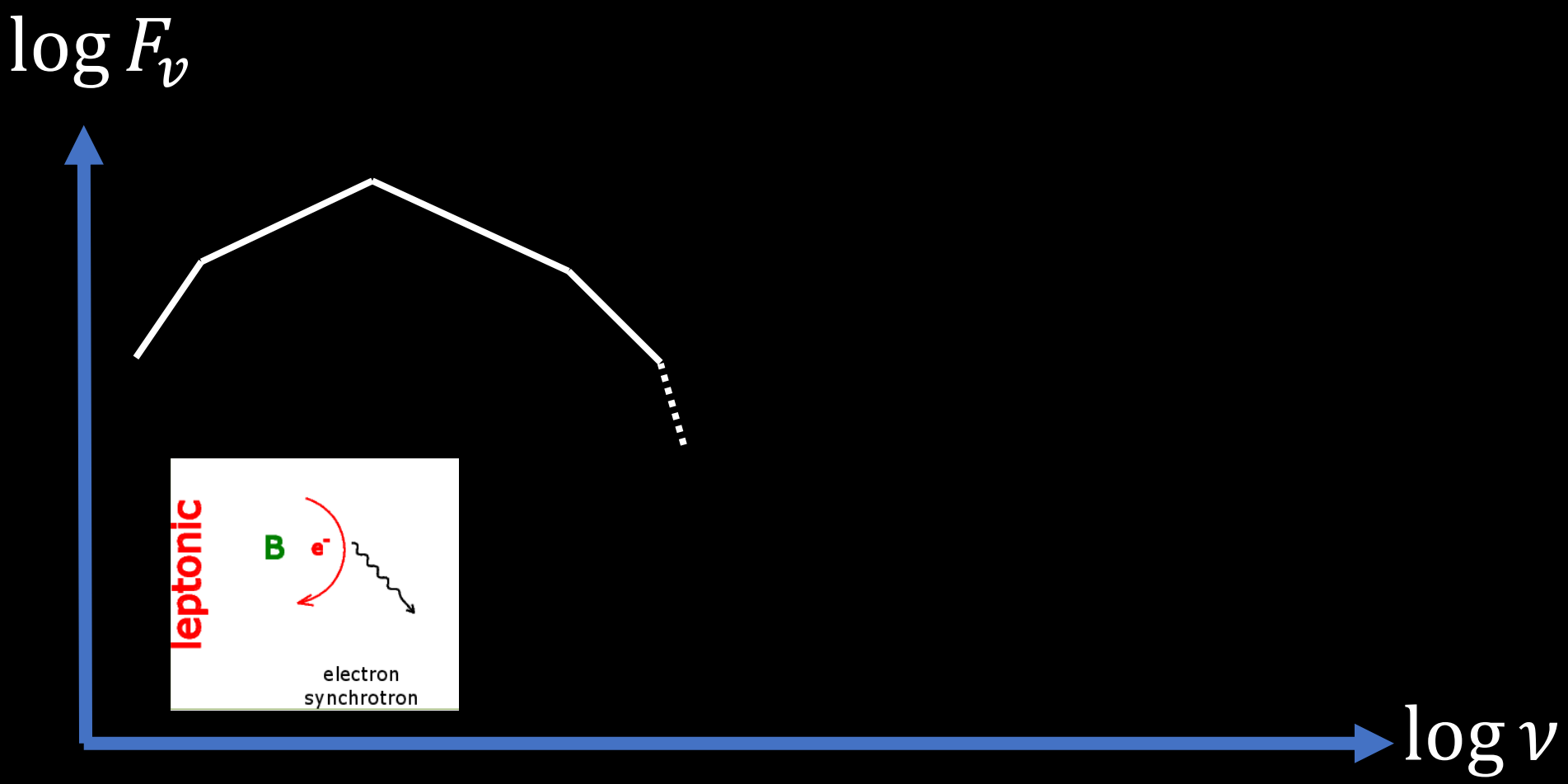
Neill+ 2021 Submitted, ArXiv: 2111.03686

The point being…
the regular afterglow curve (yellow) will be fainter for observers further off-axis, while the RSF afterglow is quasi-spherical

revisiting the non-thermal spectrum

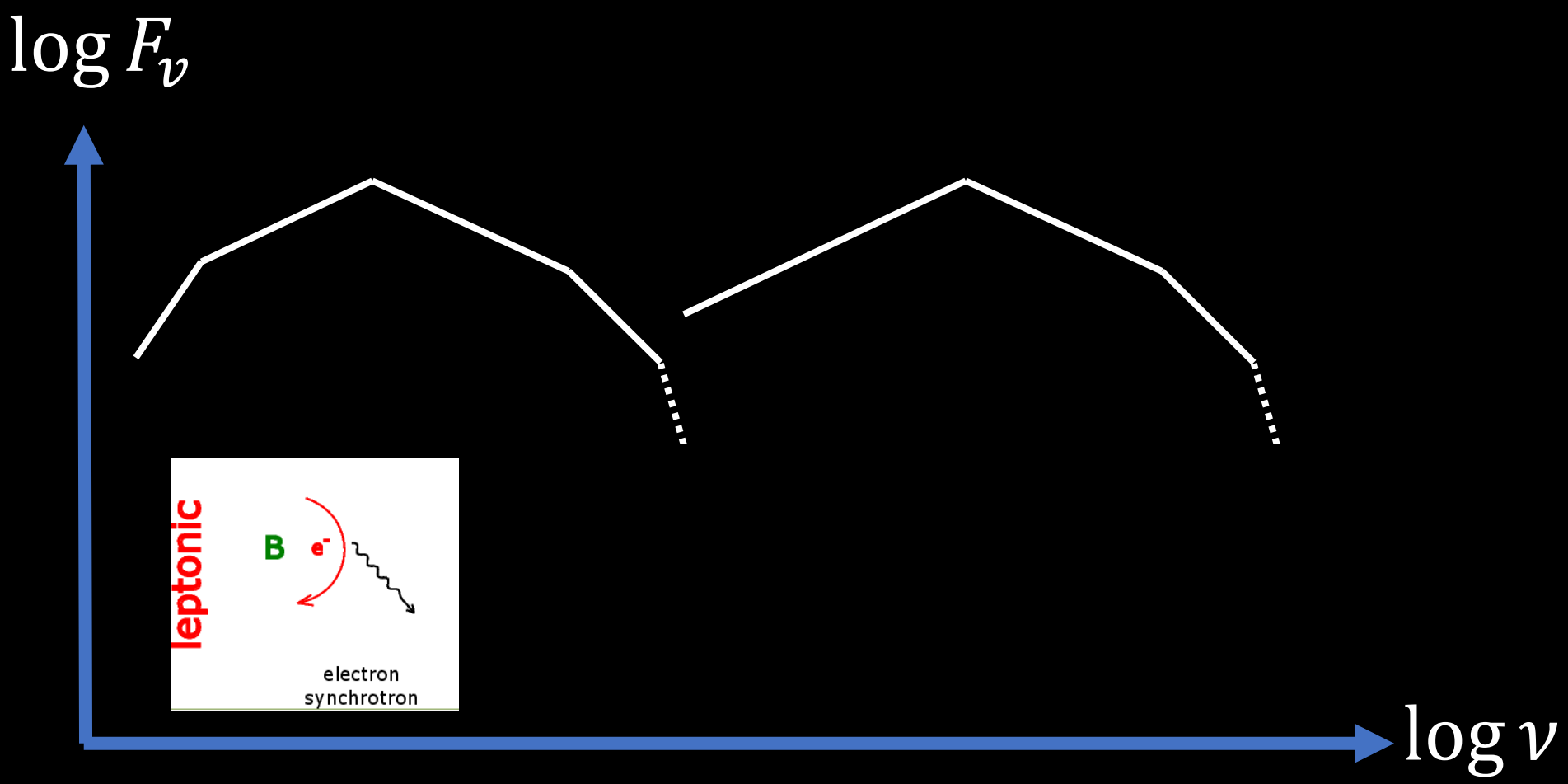


revisiting the non-thermal spectrum



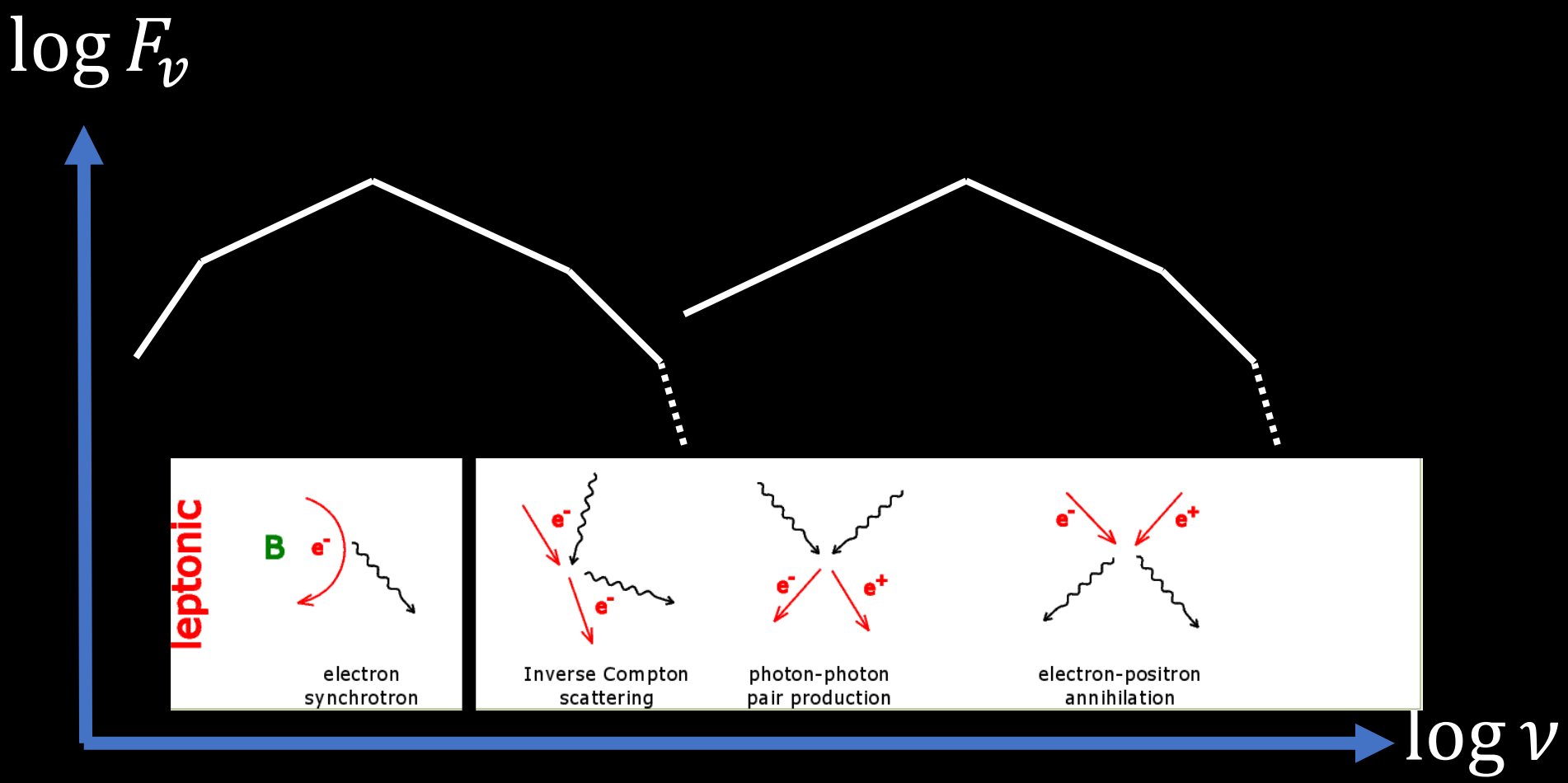
synchrotron emission

revisiting the non-thermal spectrum



synchrotron emission

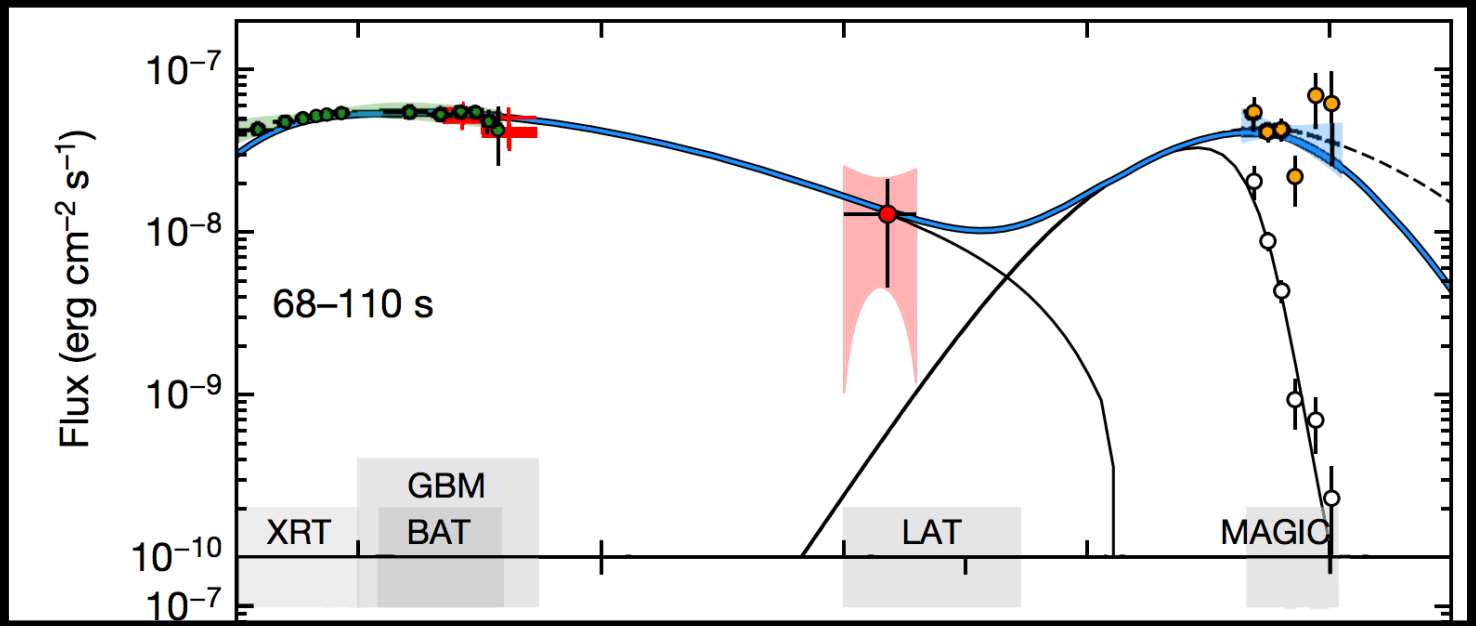
revisiting the non-thermal spectrum



synchrotron emission + scattering processes

revisiting the non-thermal spectrum

$\log F$



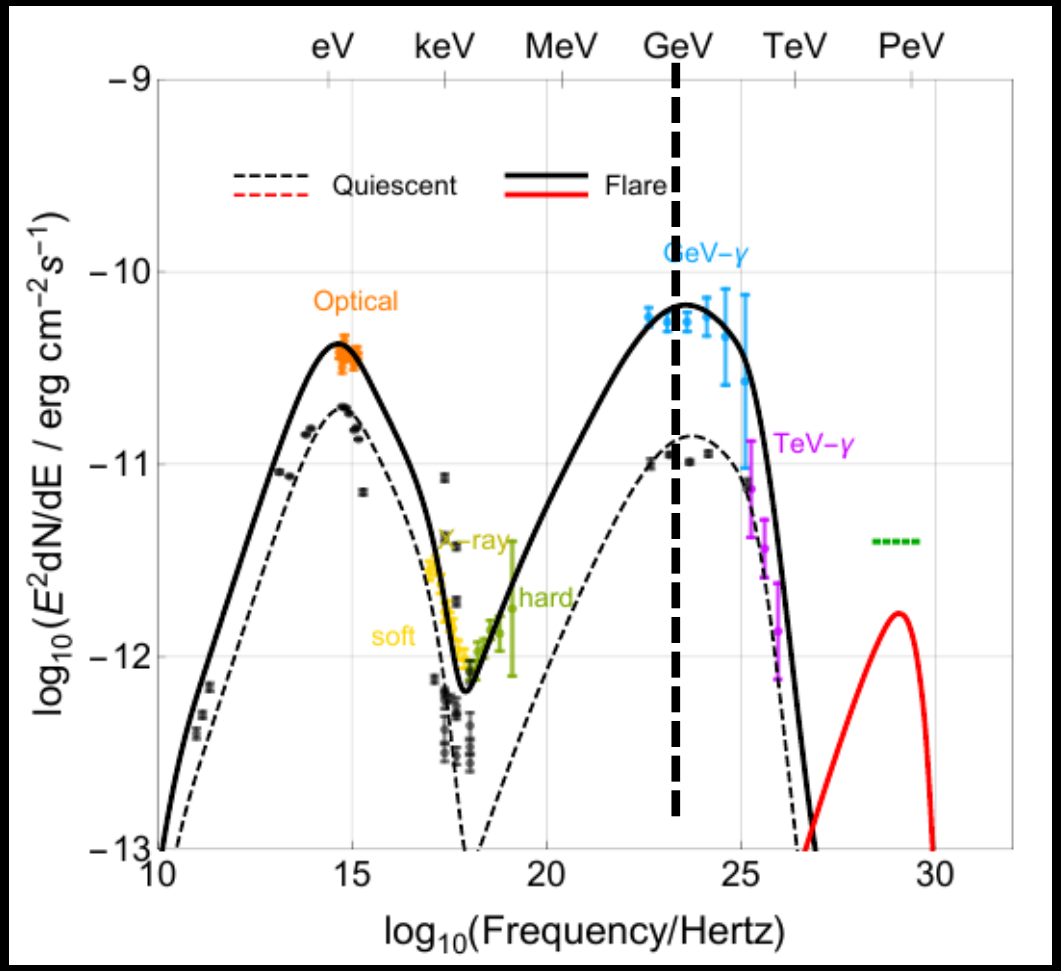
$\log \nu$

afterglow GRB 190114C

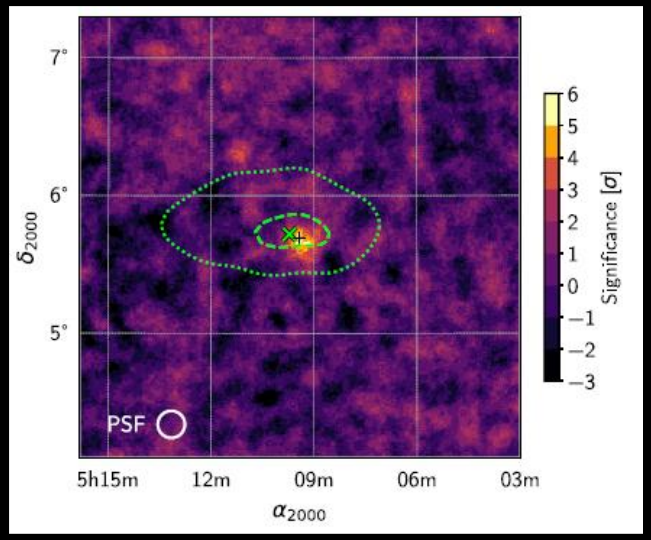
MAGIC+ 2019, Nature

Blazars: non-thermal emission from fast-moving plasma

...plus neutrino(s)?



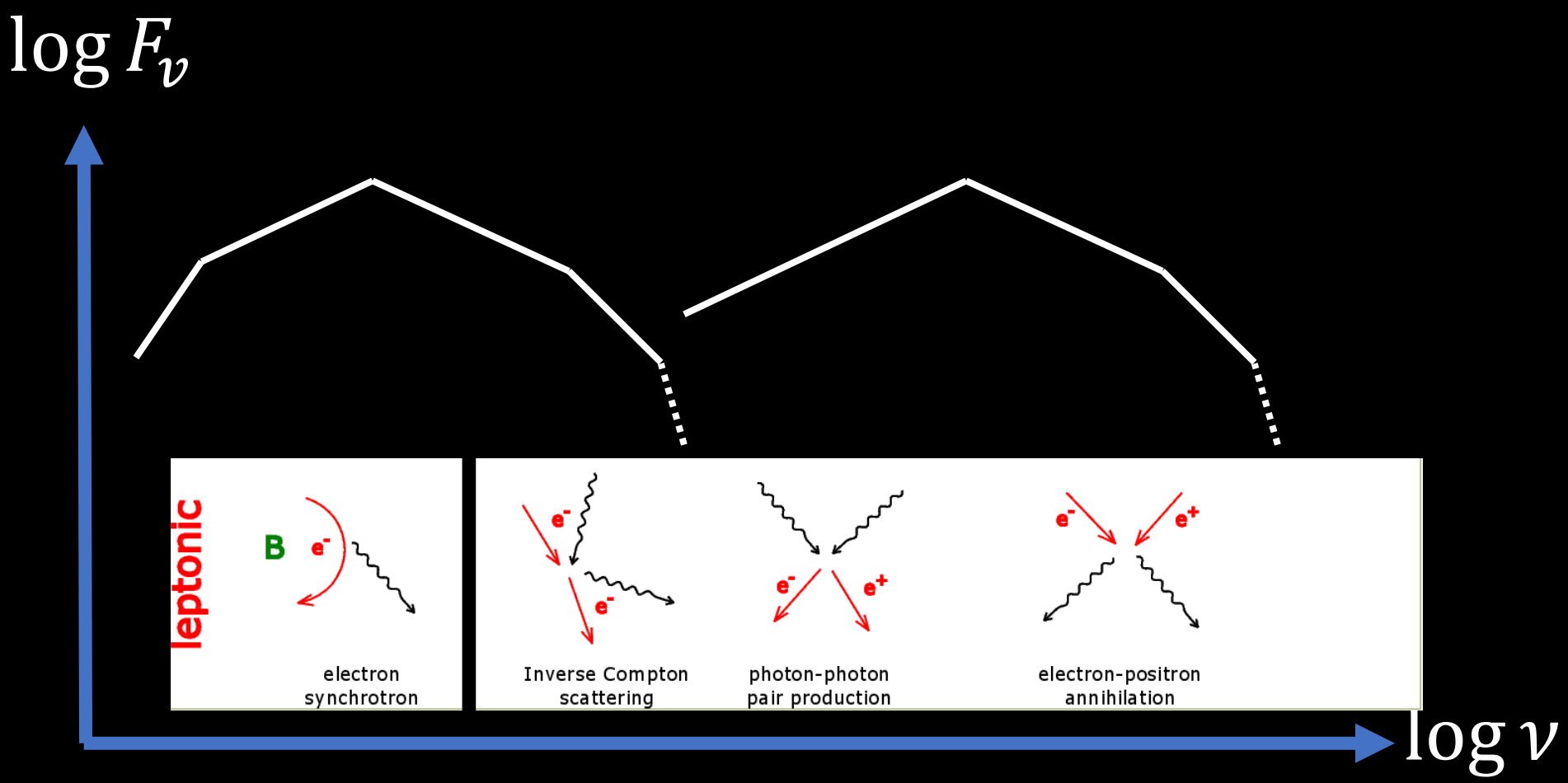
TXS 0506+056, a flaring (90 days) BL Lac blazar coincident with an Icecube neutrino detection



img: VERITAS
Abeysekara+ 2018

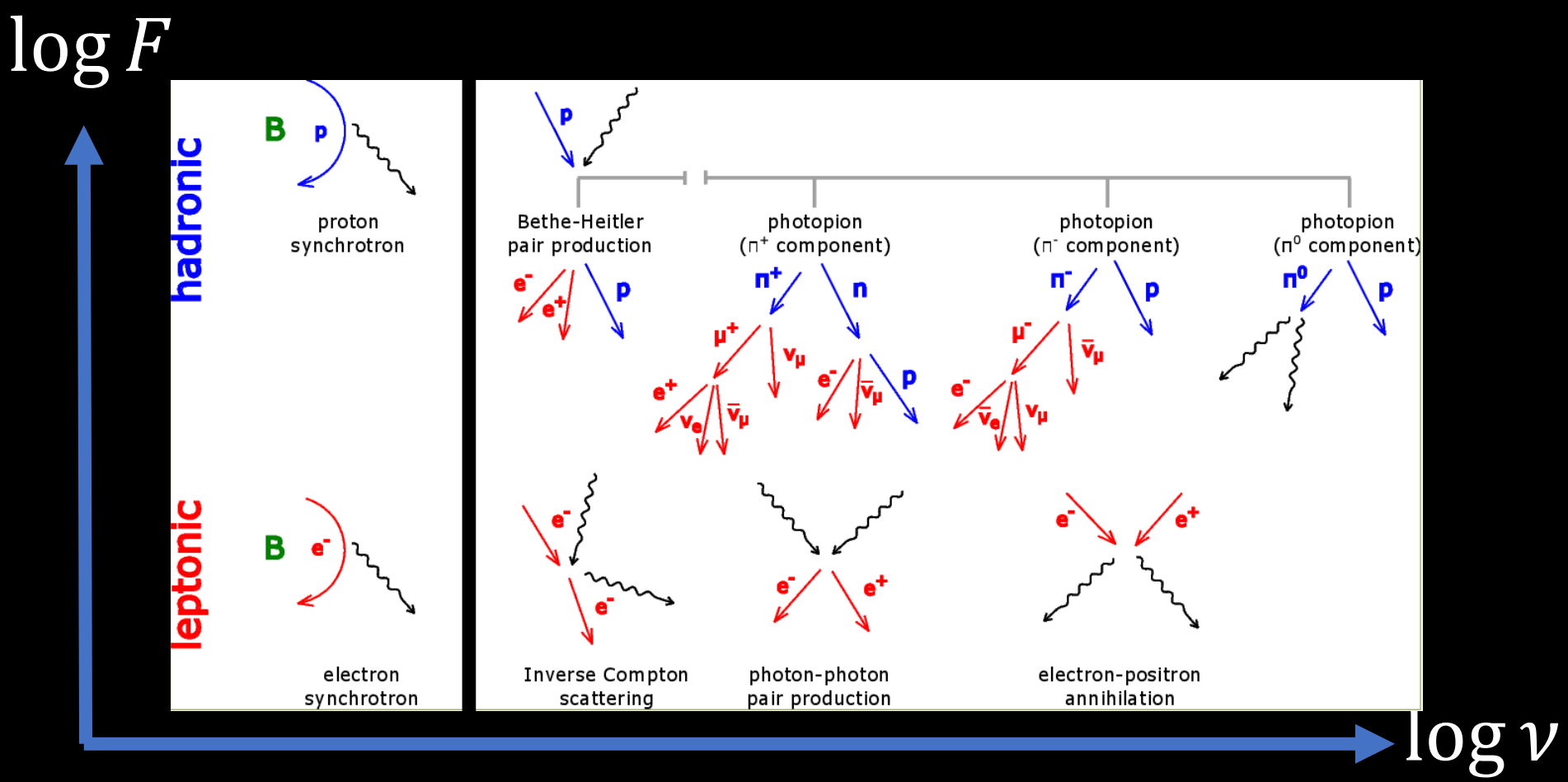
image from Gao+, 2019

revisiting the non-thermal spectrum



synchrotron emission + scattering processes

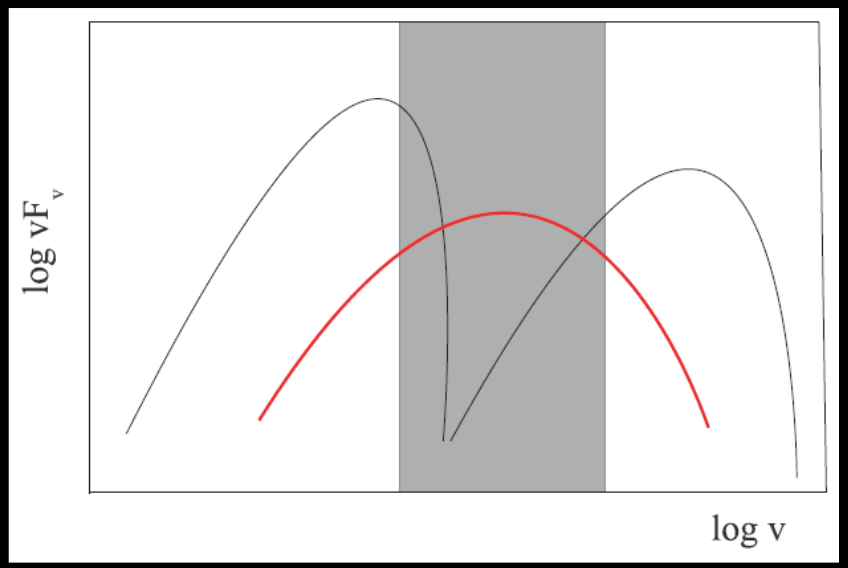
revisiting the non-thermal spectrum



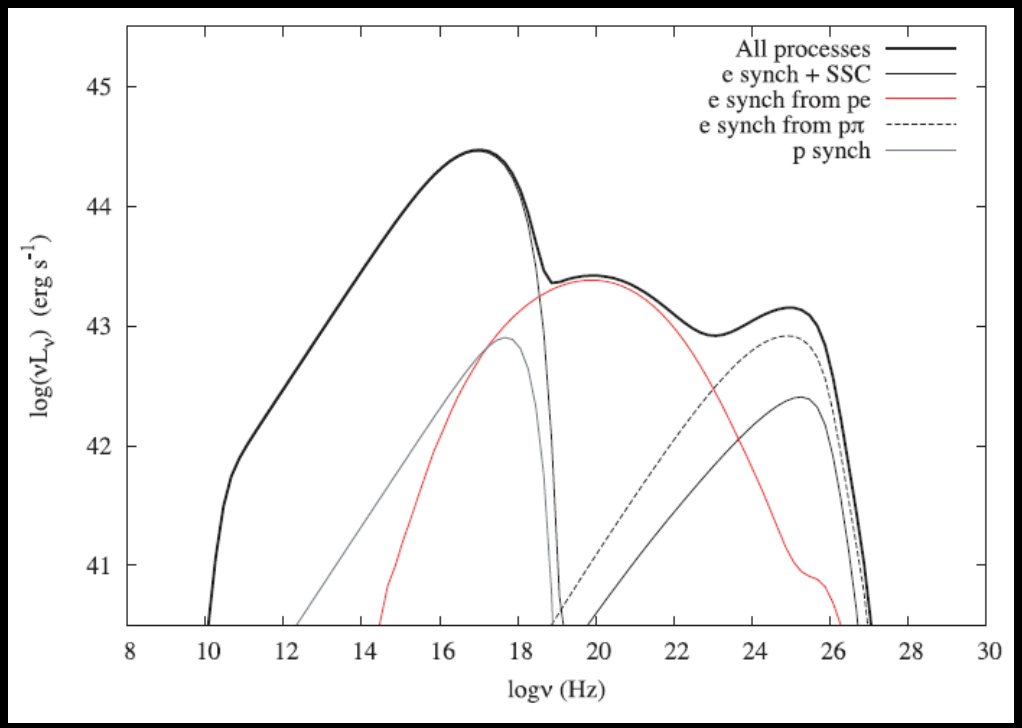
afterglow GRB 190114C

(img credit: Petropoulou)

A role for the protons in the SED?



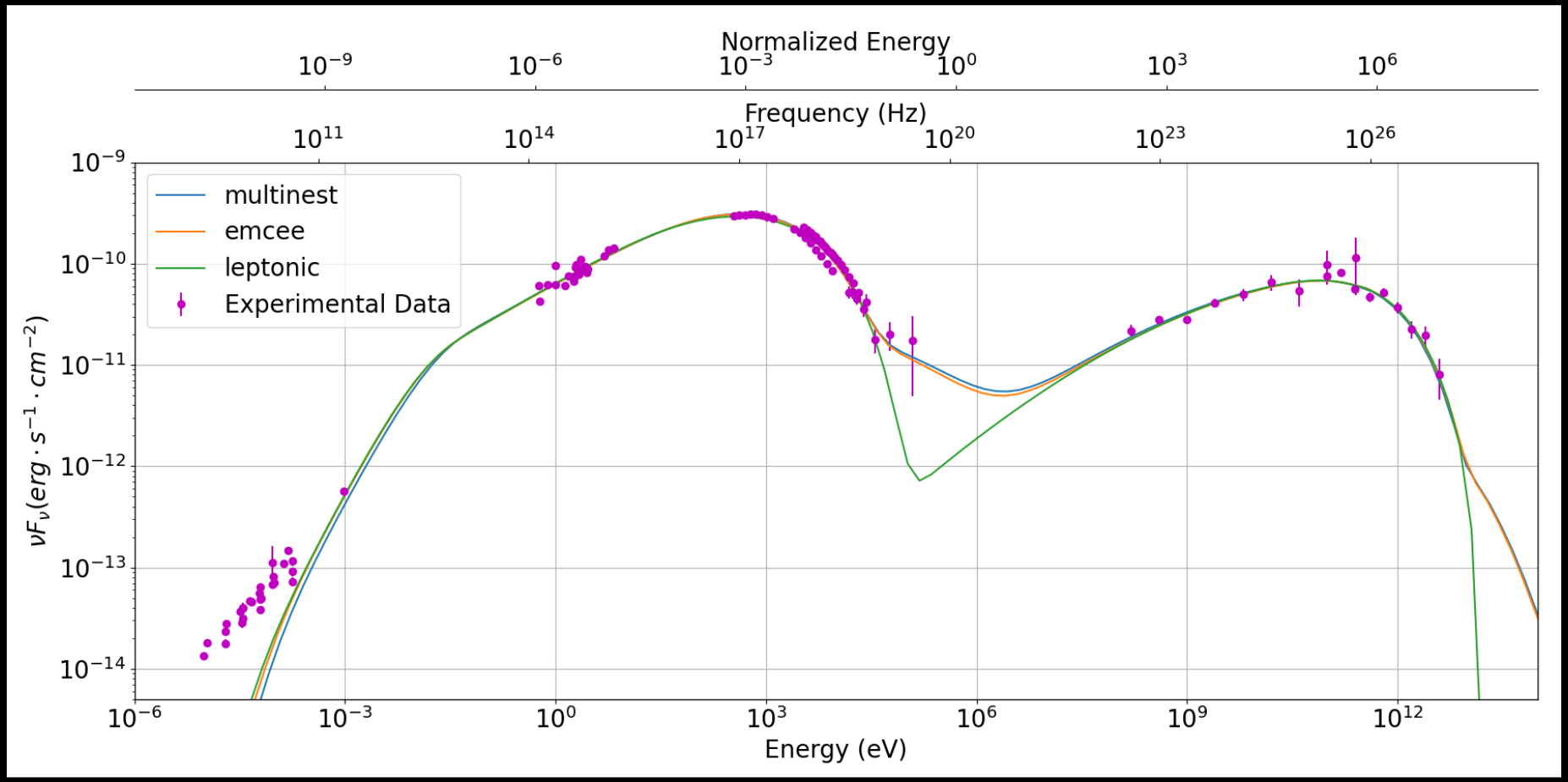
Petropoulou & Mastichiadis 2015



Bethe-Heitler ("pe") process creates electron / positrion pairs that can subsequently produce synchrotron radiation

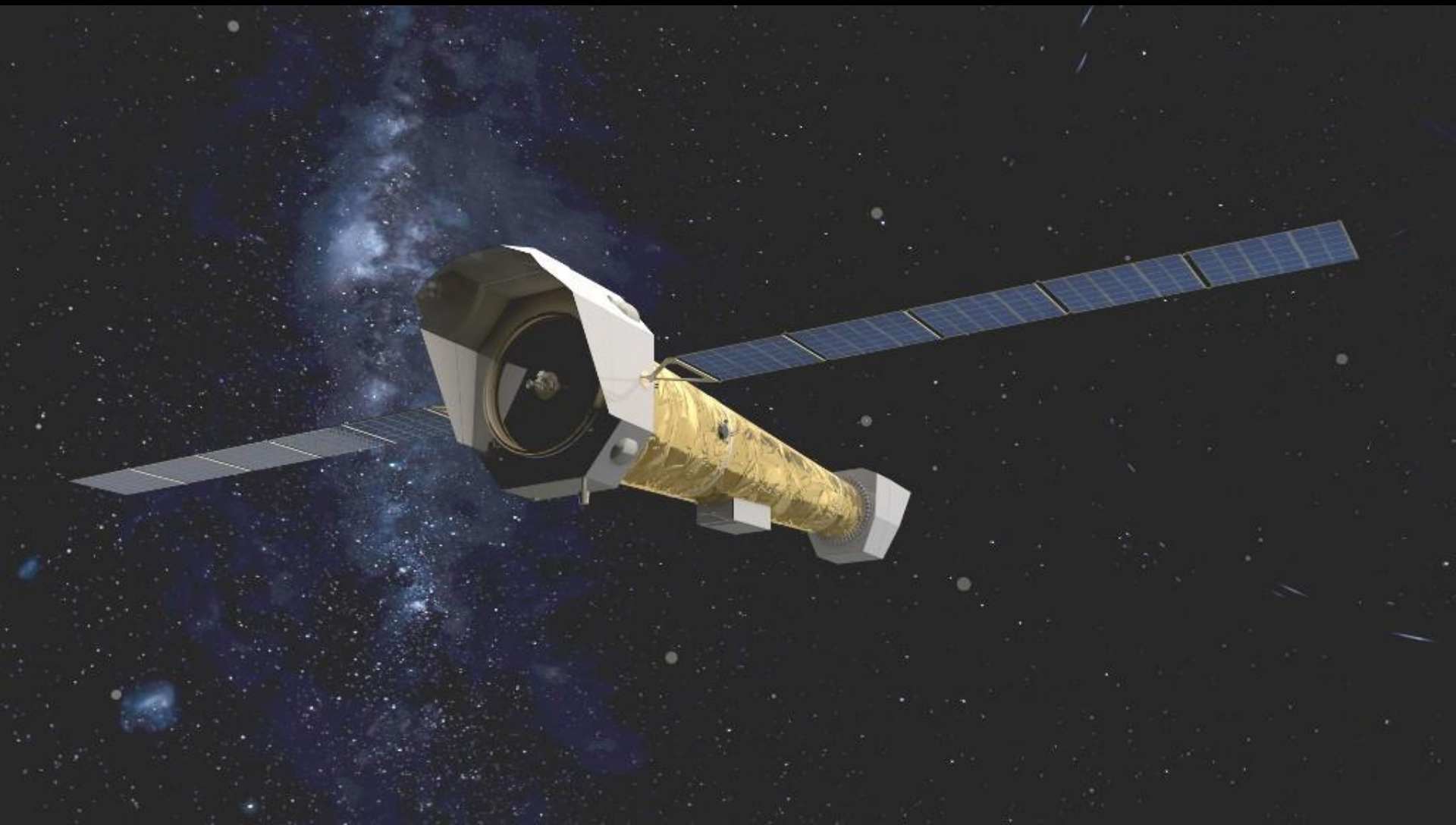
$p + \gamma \rightarrow p + e^{+} + e^{-} \rightarrow synchrotron\ emission$

A toy-model example: Leptonic and lepto-hadronic models for Mrk 421

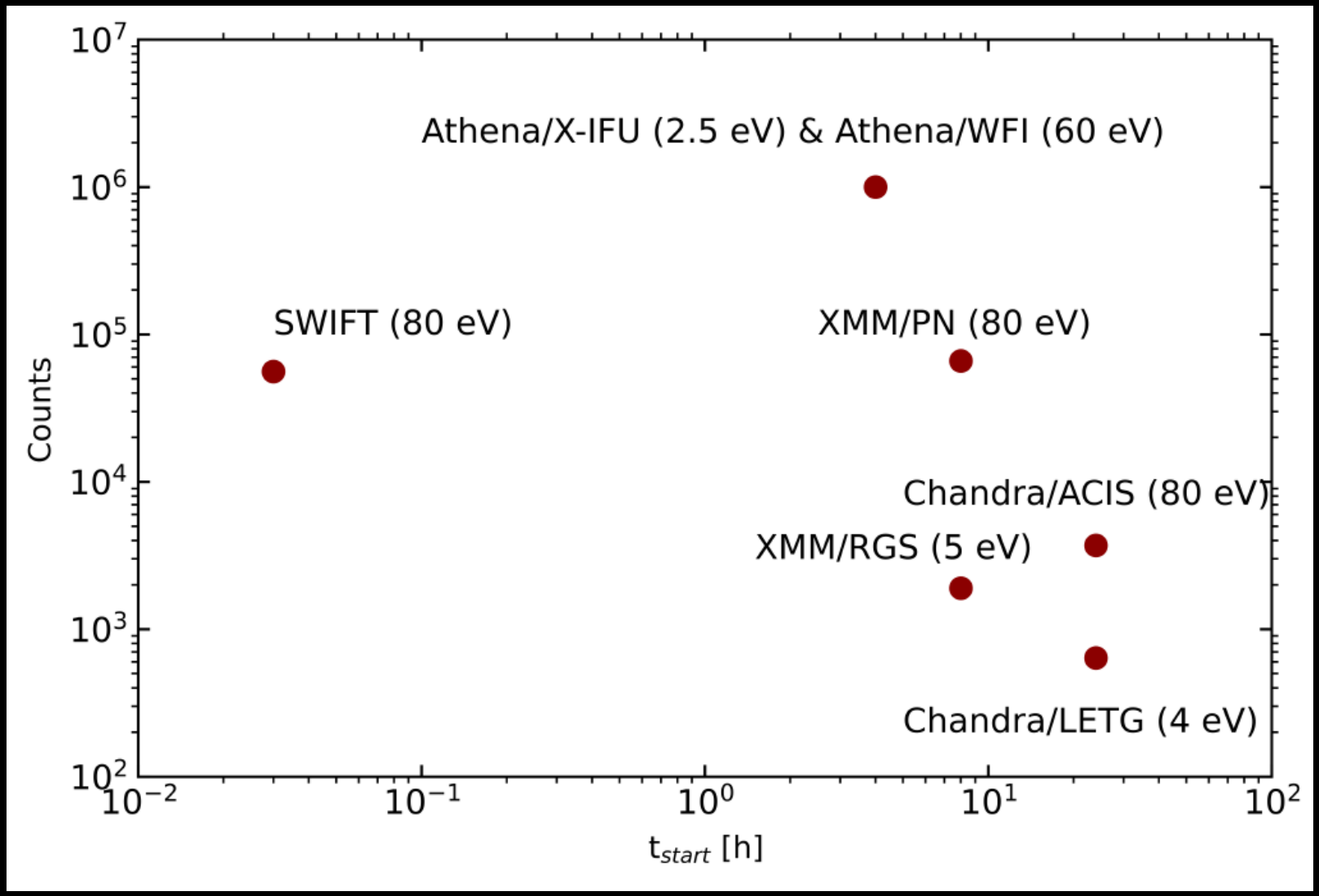


Jimenez-Fernandez & van Eerten 2021, submitted

Athena

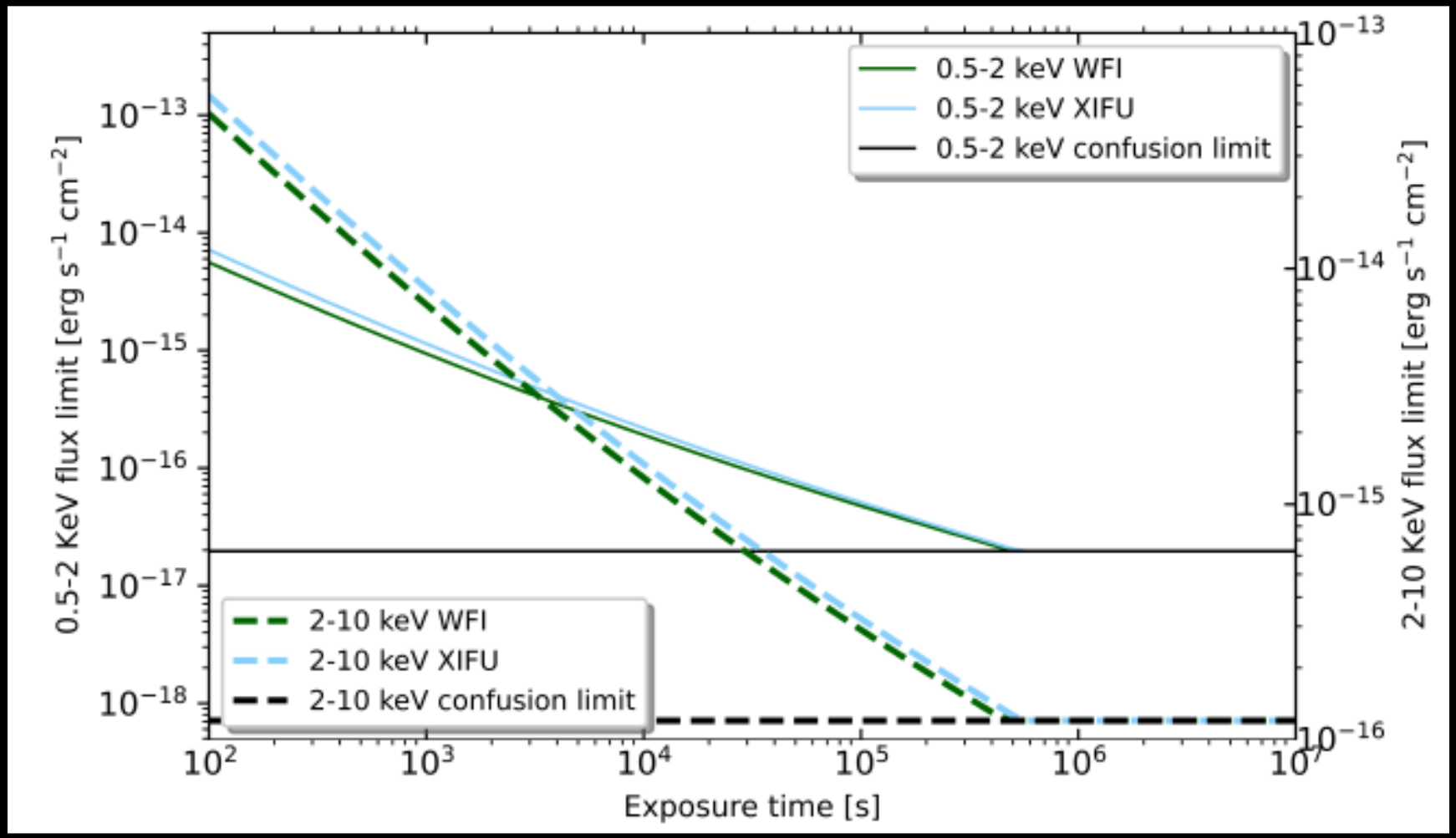


Athena: not a transient chaser



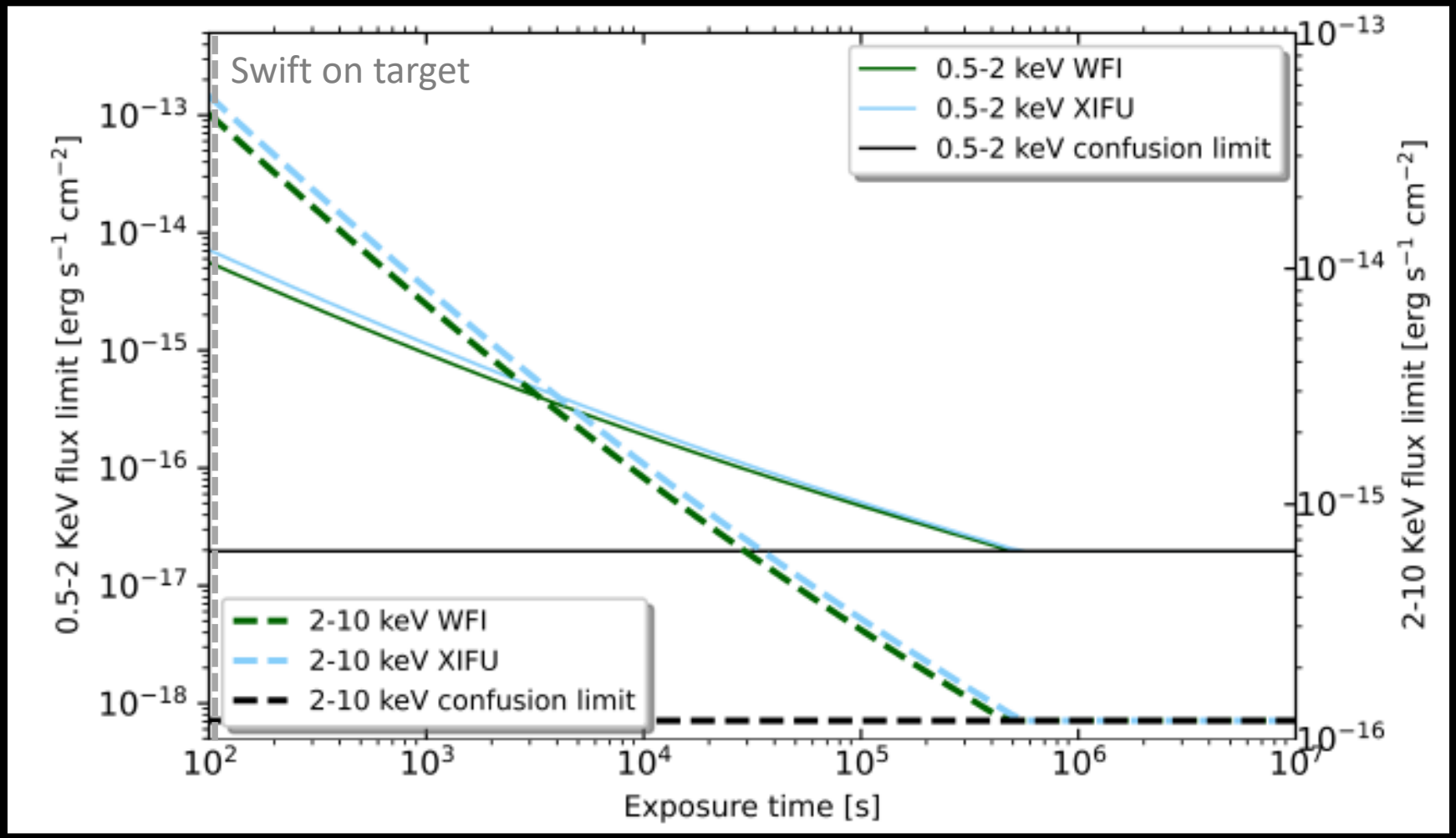
Athena multi-messenger white paper 2021

The sensitivity of Athena



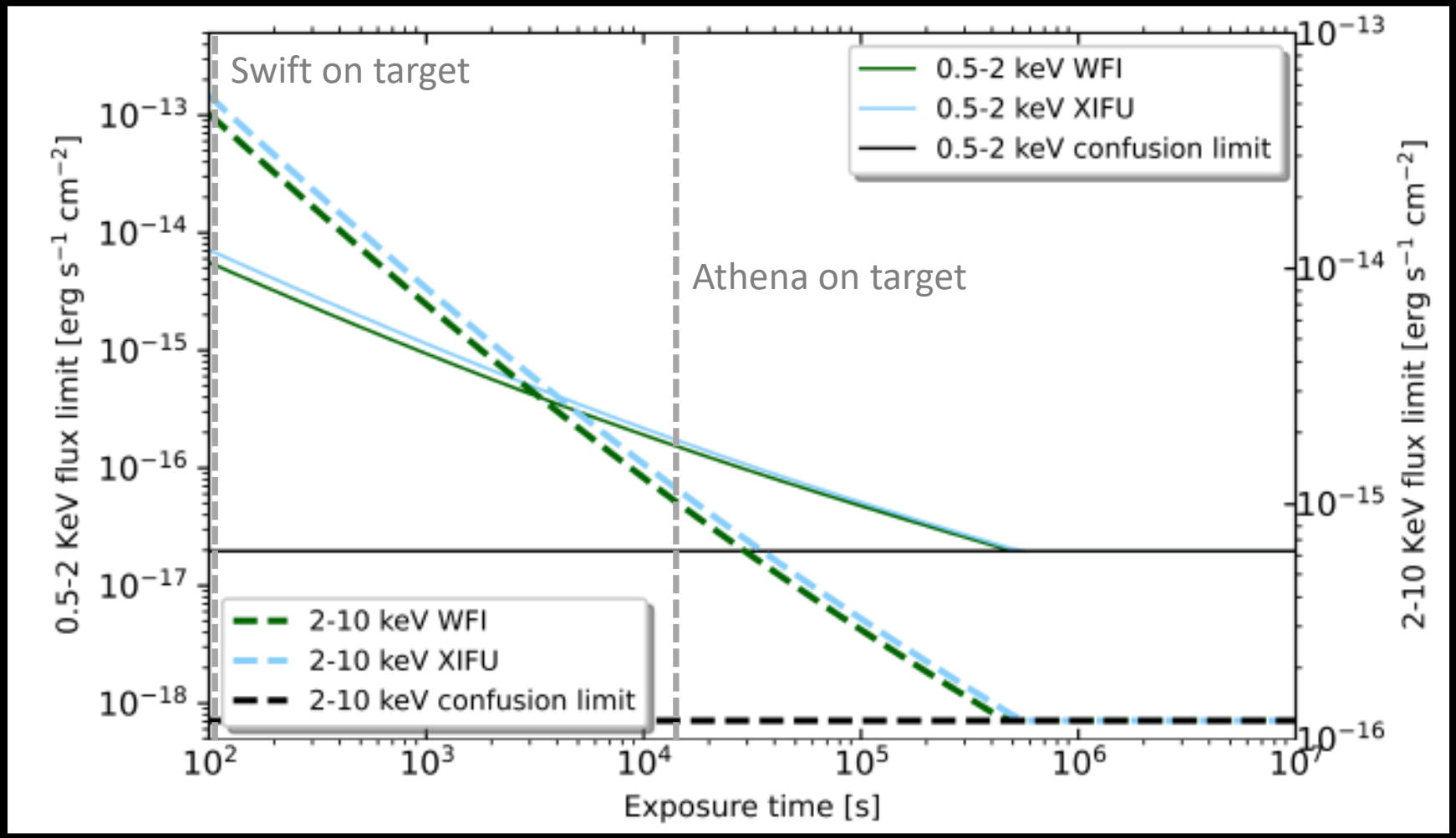
Athena multi-messenger white paper 2021

The sensitivity of Athena



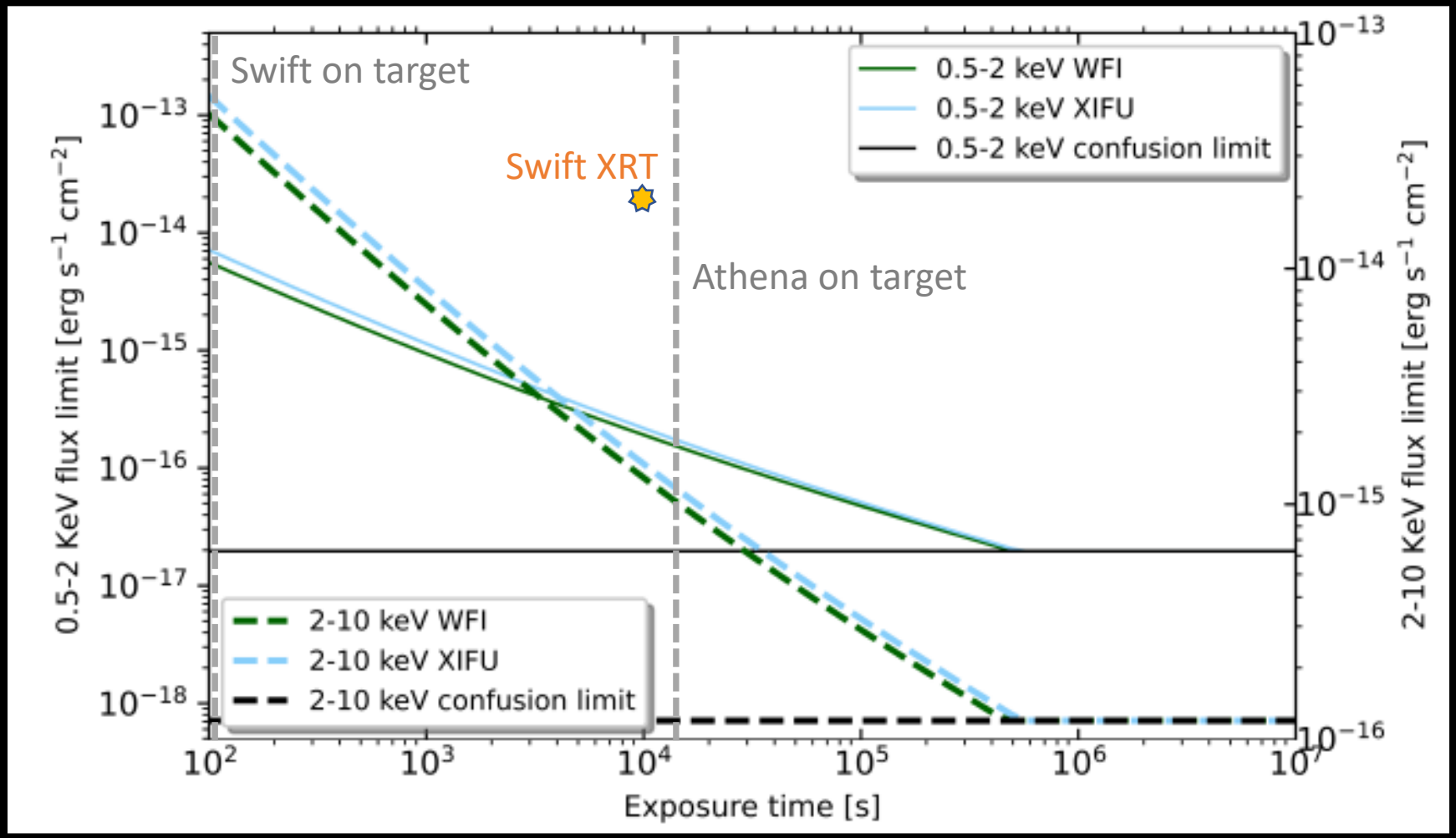
Athena multi-messenger white paper 2021

The sensitivity of Athena



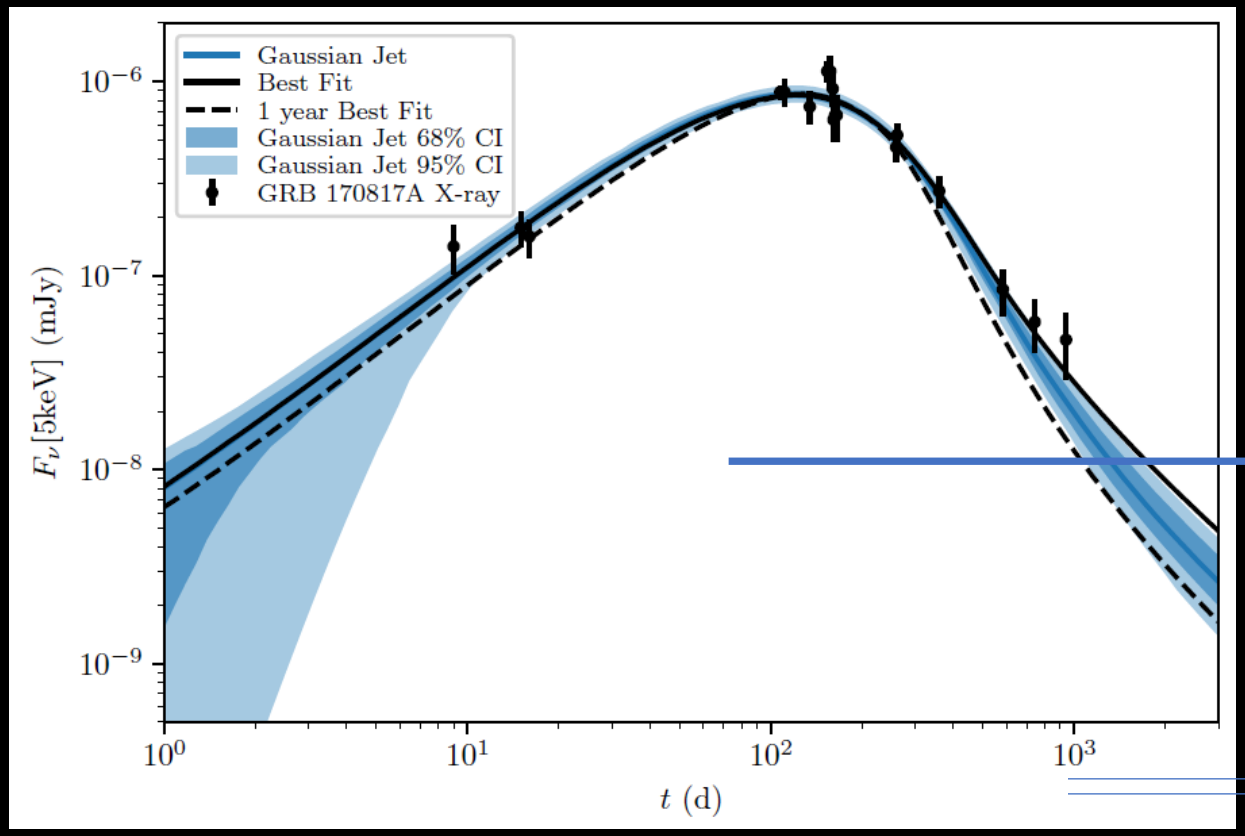
Athena multi-messenger white paper 2021

The sensitivity of Athena



Athena multi-messenger white paper 2021

GRB 170817A and Athena



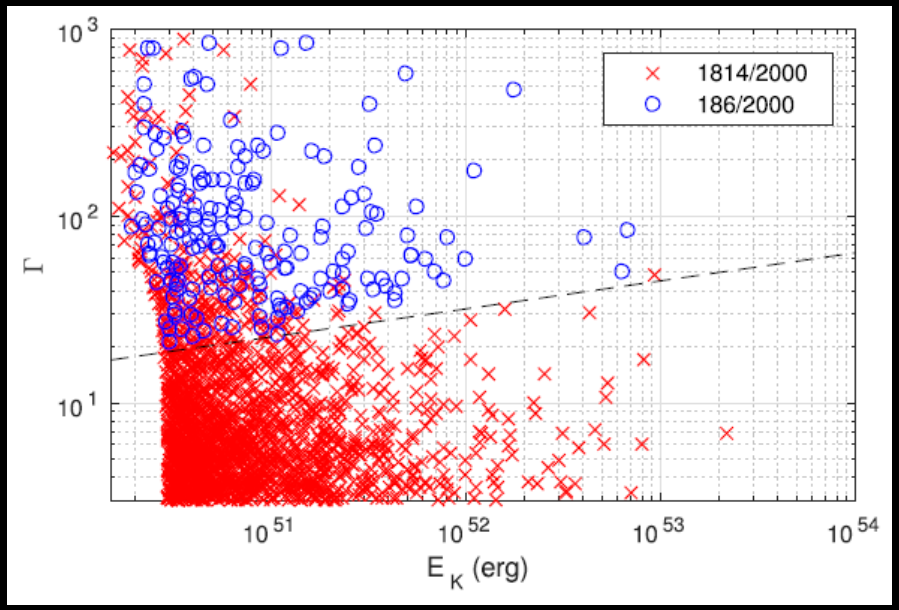
Broadband observations from radio with VLA to X-rays with Chandra (and MANY more instruments across the broadband).
Shown left here are X-rays.

Athena sensitivity

2030-2040

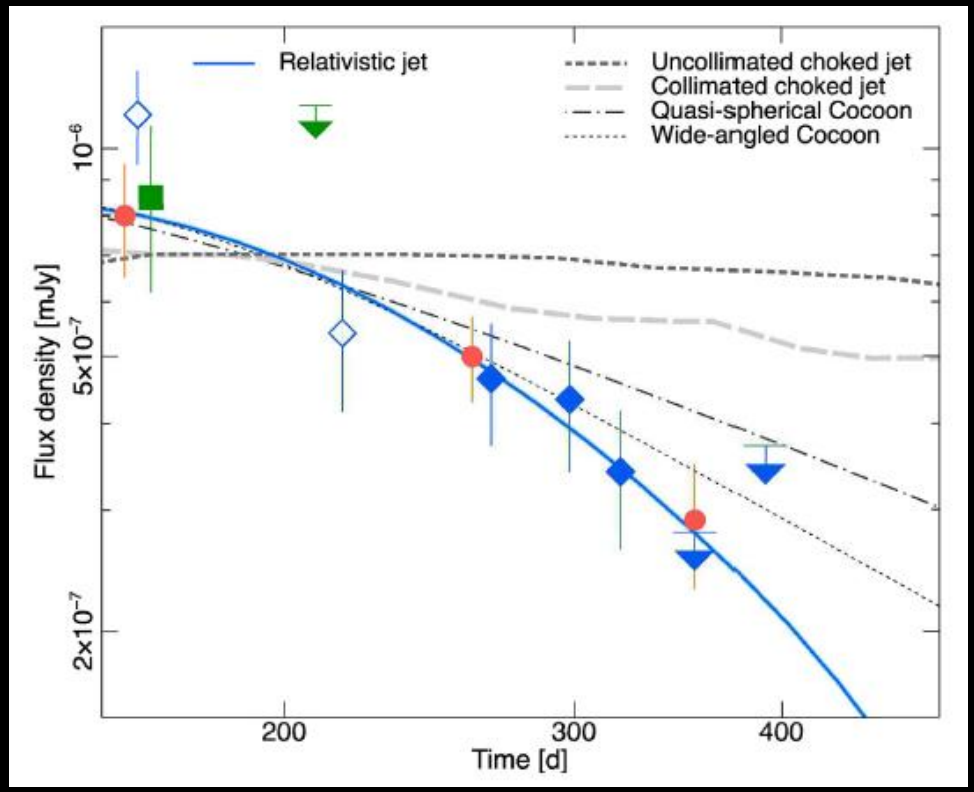
Athena and the rate of successful jets

The VLBI results for GRB 170817A are wonderful, but this might not always be available in order to tell whether there is a directed outflow



Lamb & Kobayashi 2016
blue: successful burst; red: failed bursts

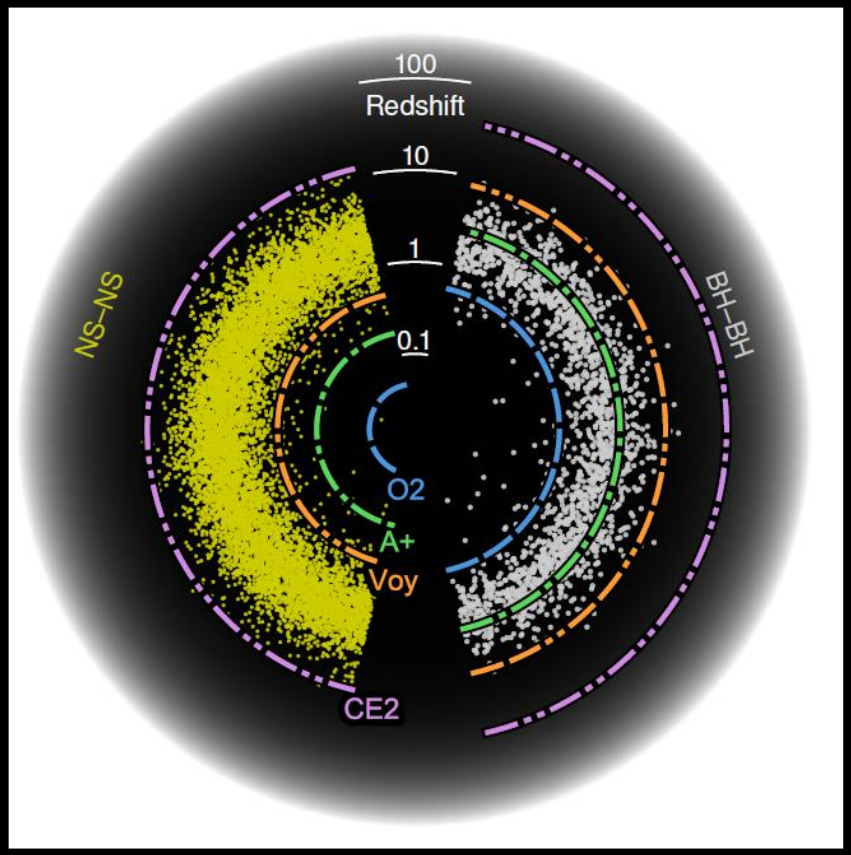
If the jet Lorentz factor distribution has a tail to low values, many GRB jets will remain opaque to their prompt emission. A failure to break out (a "choked jet") will lead to a quasi-spherical shock-wave

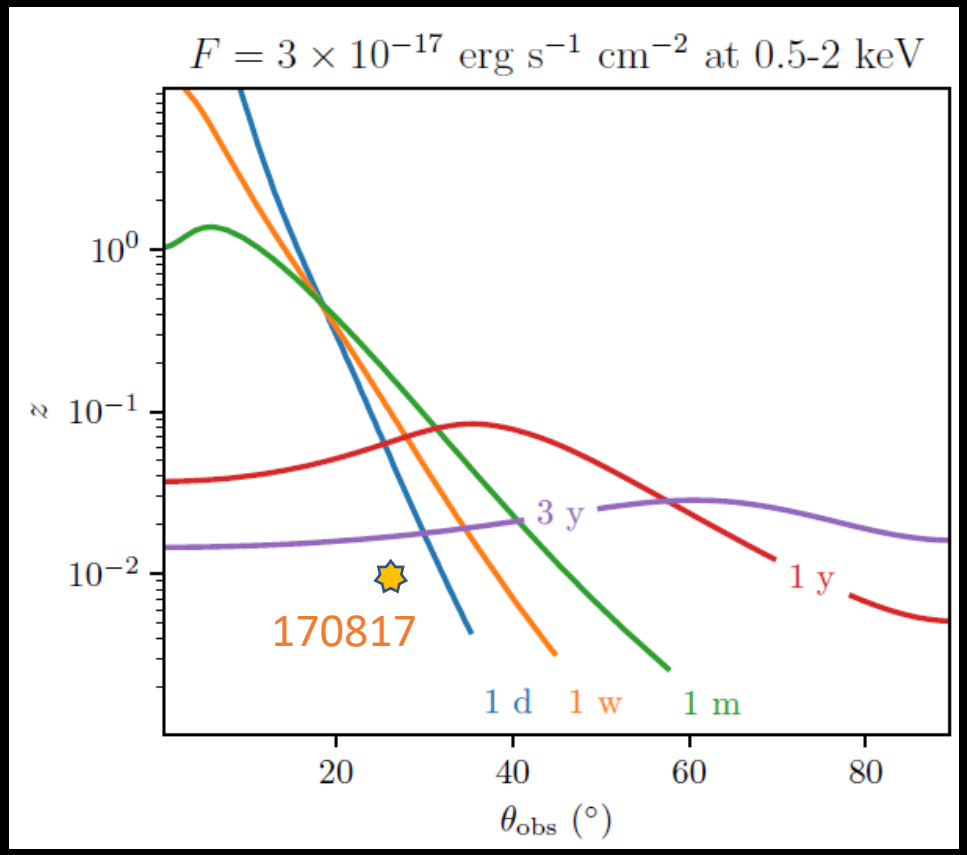


Troja, van Eerten+ 2019

The late-time (ie *faint*) light curve slope will reveal whether the jet is collimated or not. Athena can capture this slope best.

Neutron star mergers with Athena





Athena multi-messenger white paper 2021

Summary:
The joys of X-rays

- An extra perspective on GRB prompt emission
- Probe the nature of particle shock-acceleration (across many decades for e.g. GRB 170817A)
- Revealing the lateral energy structure of GRB jets
- A detectable afterglow for resonance shattering flares from NS-NS & NS-BH mergers
- Part of the toolkit for constraining the signatures of hadronic emission models (e.g. in blazars), and thus the origin of neutrinos & cosmics rays
- a promising future for transients studies with ATHENA