The Origin of X-ray Plateaus in the Structured Jet Scenario

Stefano Ascenzi

Image Credit: ESA/Hubble, M. Kornmesser

Oganesyan, G., **SA,** Branchesi, M., Salafia, O. S., Dall'Osso, S., Ghirlanda, G. , 2020, ApJ, 893, 10

SA, Oganesyan, G., Salafia, O. S., Branchesi, M., Ghirlanda, G., Dall'Osso, S. , 2020, A&A, 641, 15

V Congresso Nazionale GRB - 12-15 Settembre 2022

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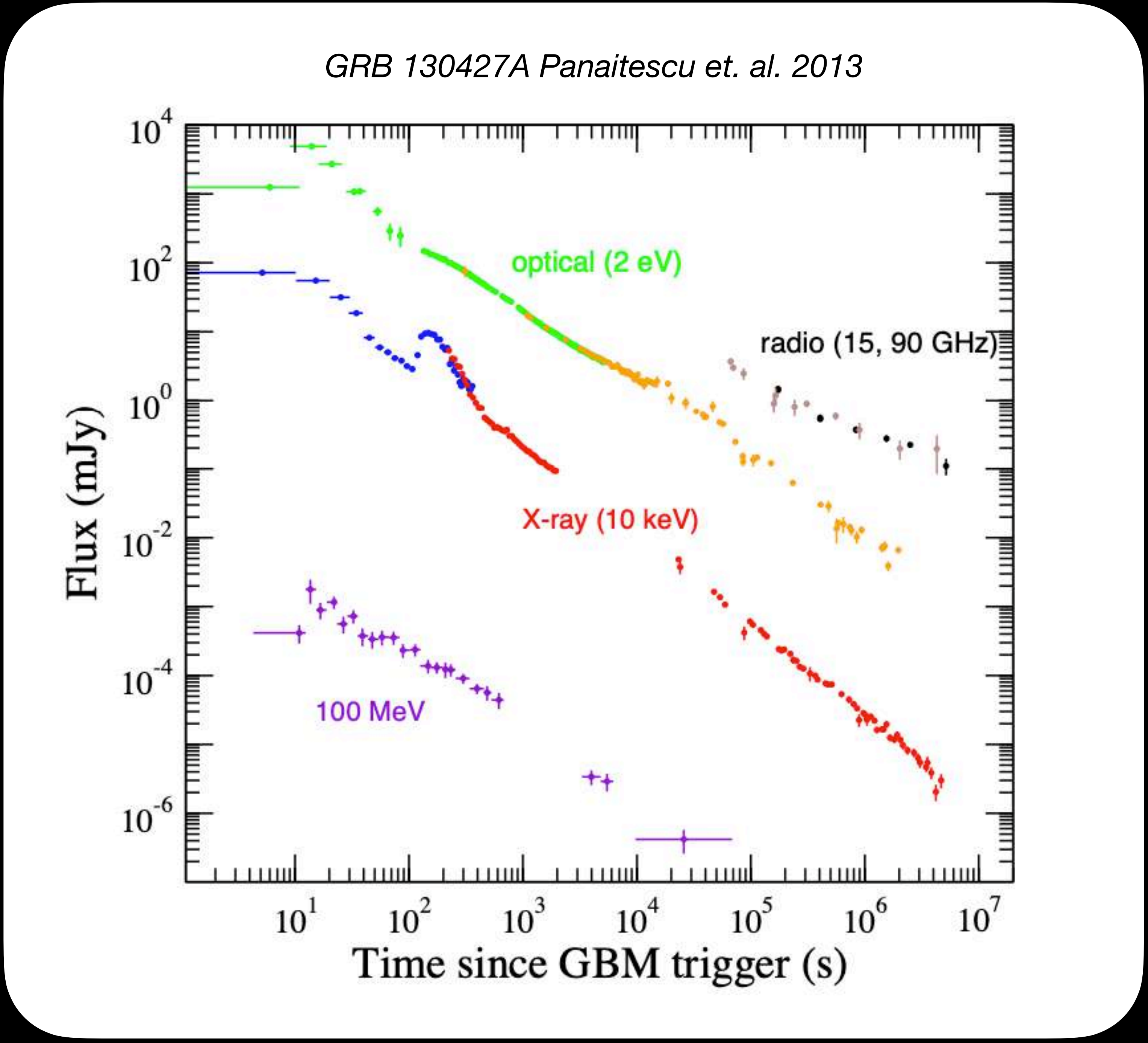
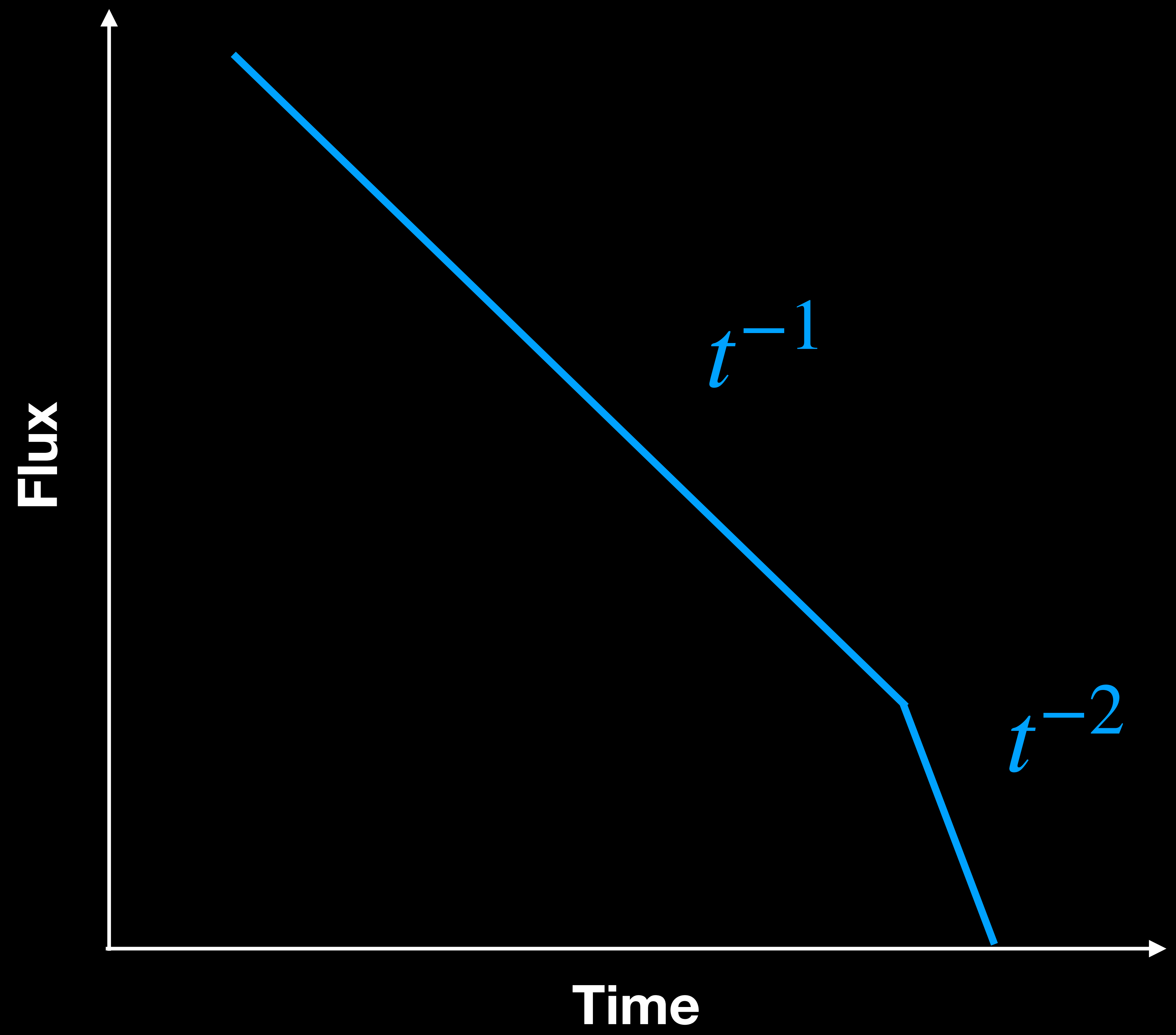
Afterglow

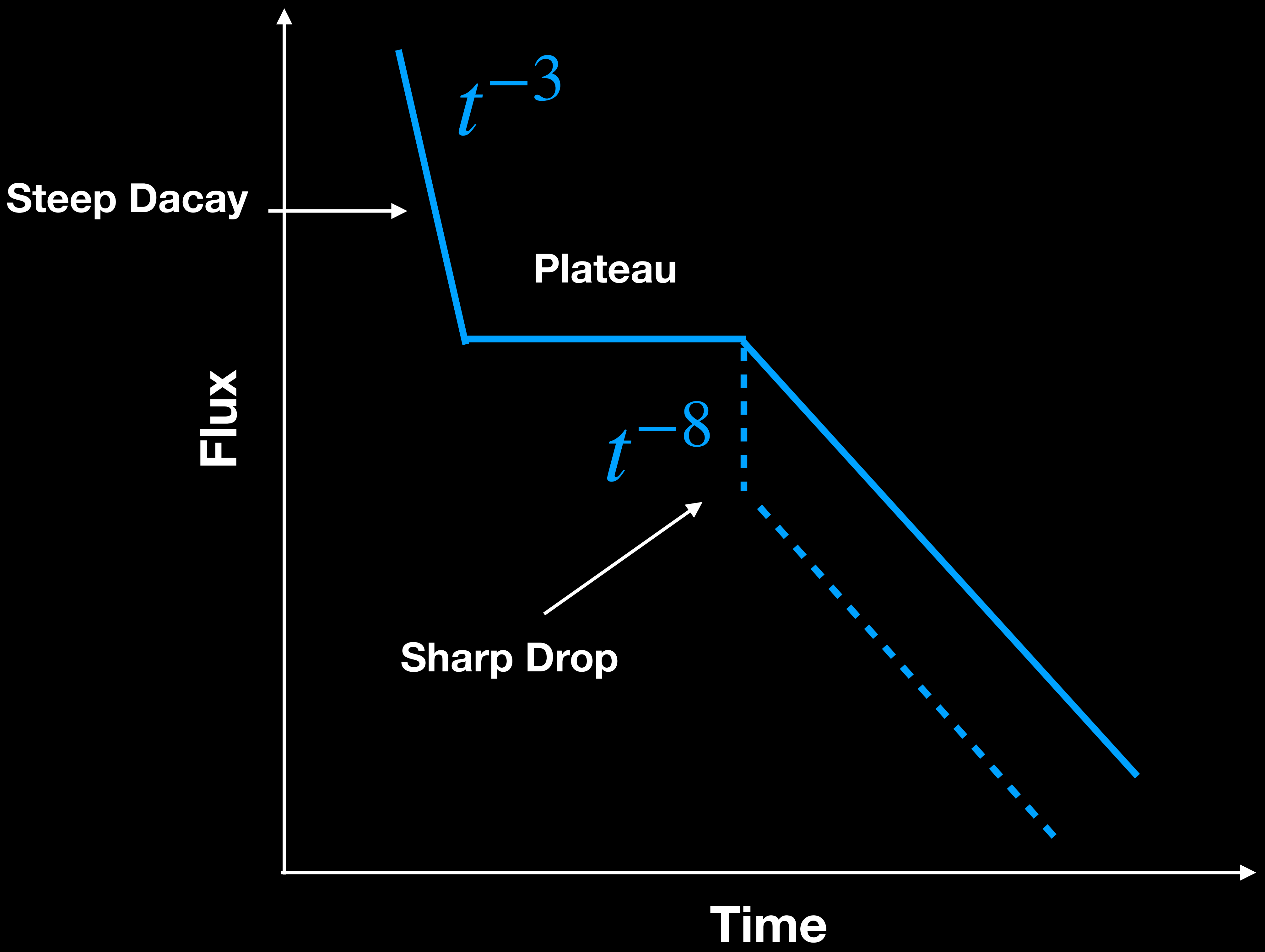


- **Observed from Radio to TeV**
- **Lasting days after the prompt emission**

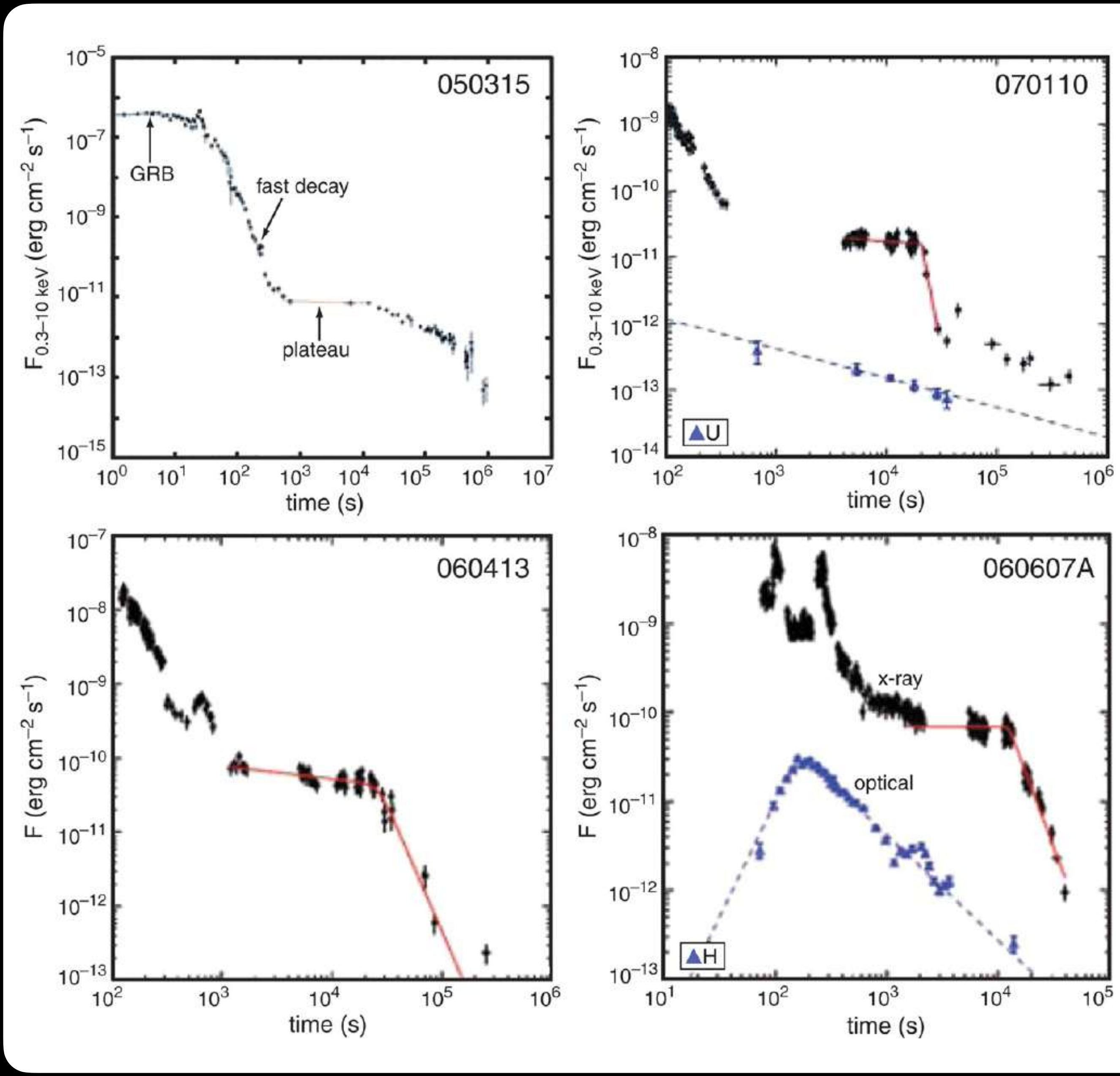
Open problem: the mystery of X-ray emission



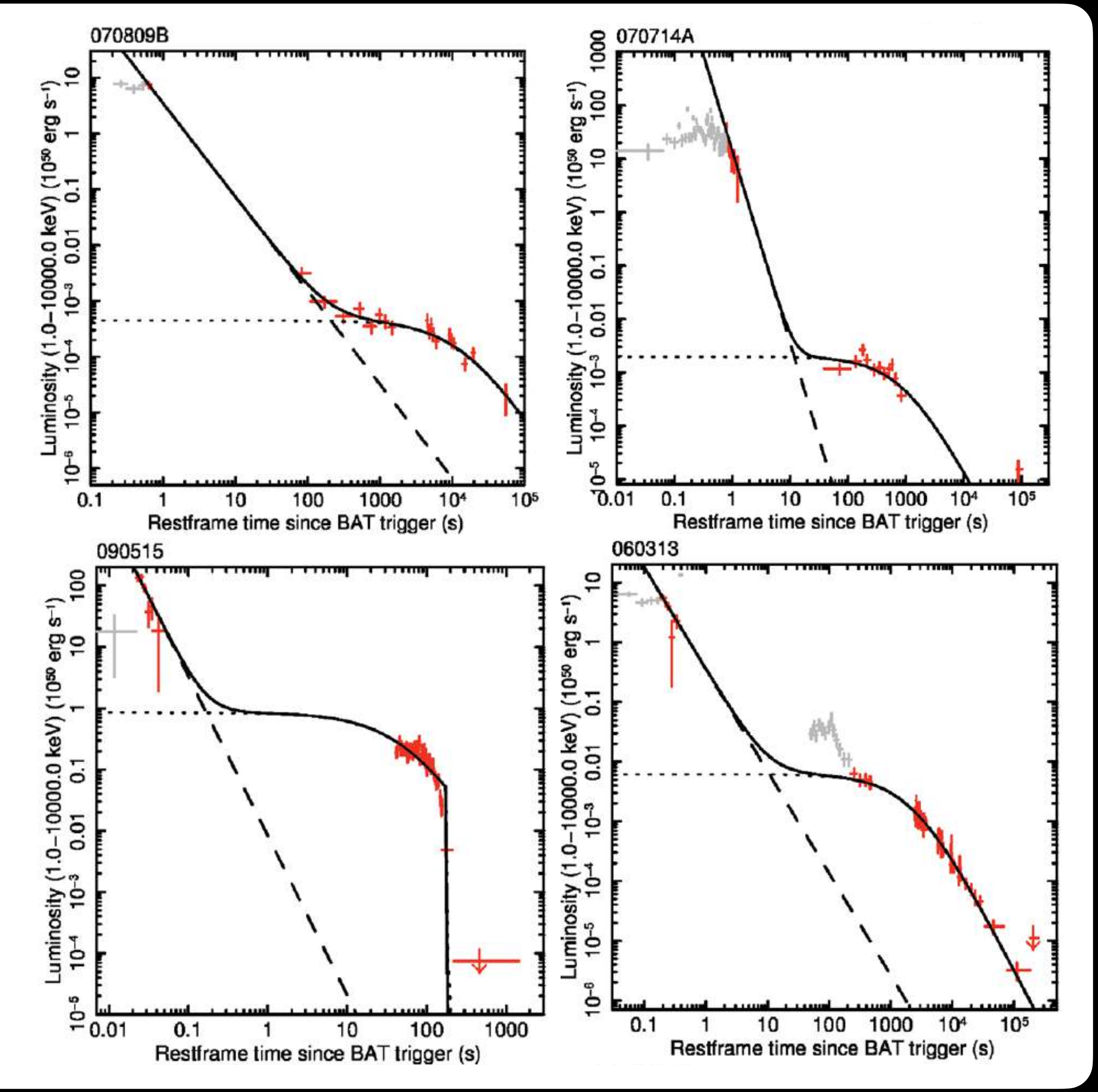
Open problem: the mystery of X-ray emission



X-ray afterglow emission



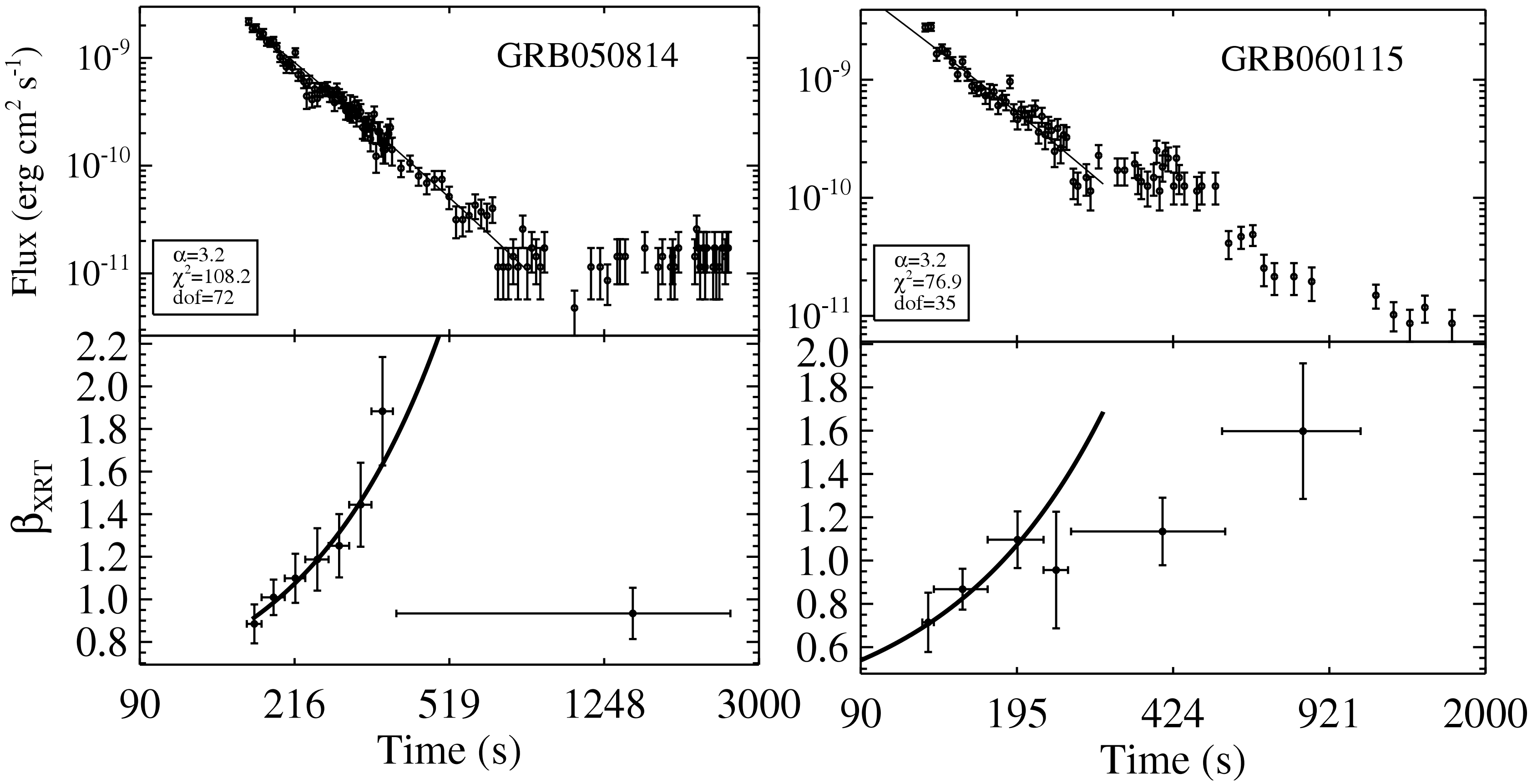
Kumar et al. 2008



Rowlinson et al. 2013

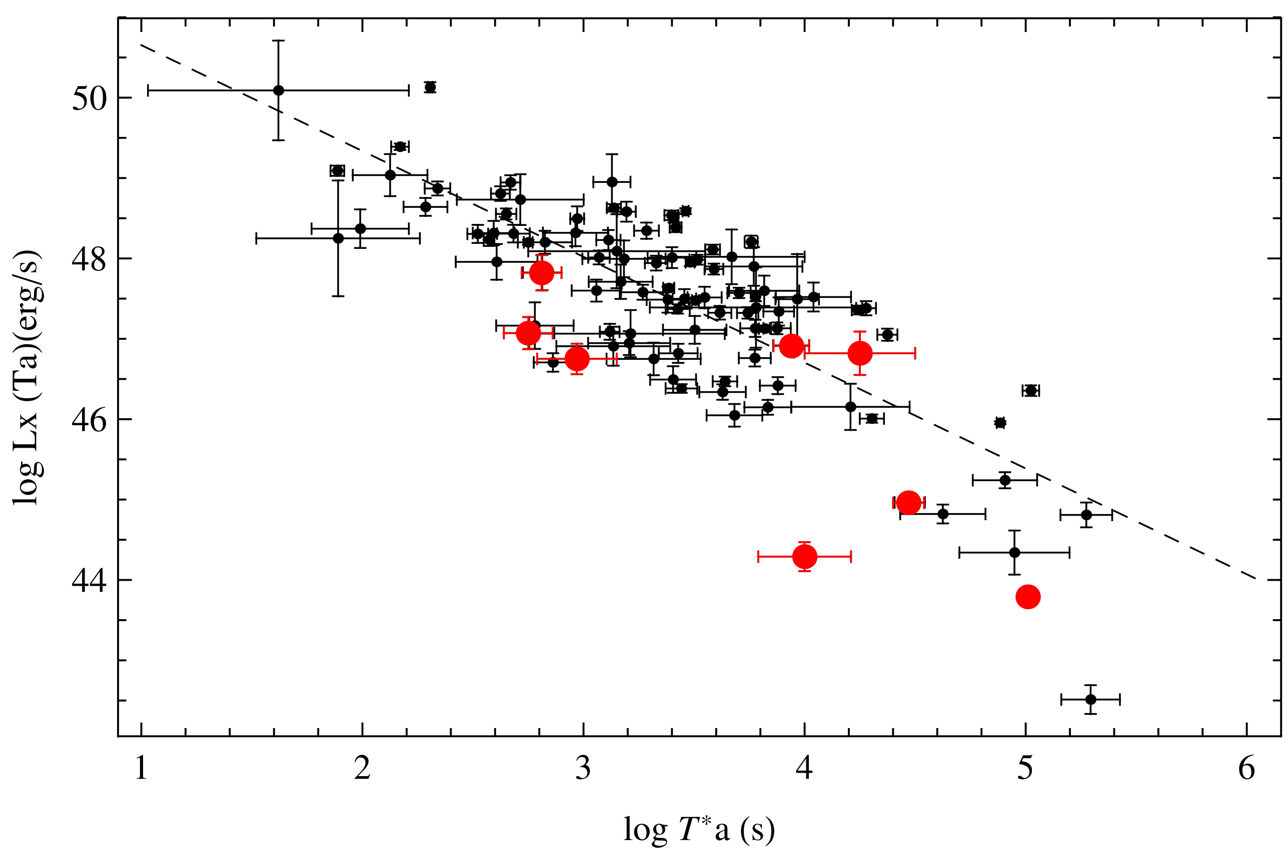
- Duration up to $\mathcal{O}(10^4\ \mathrm{s})$
- Abrupt or smooth decay
- Chromaticity with optical

Other Features



Spectral Evolution

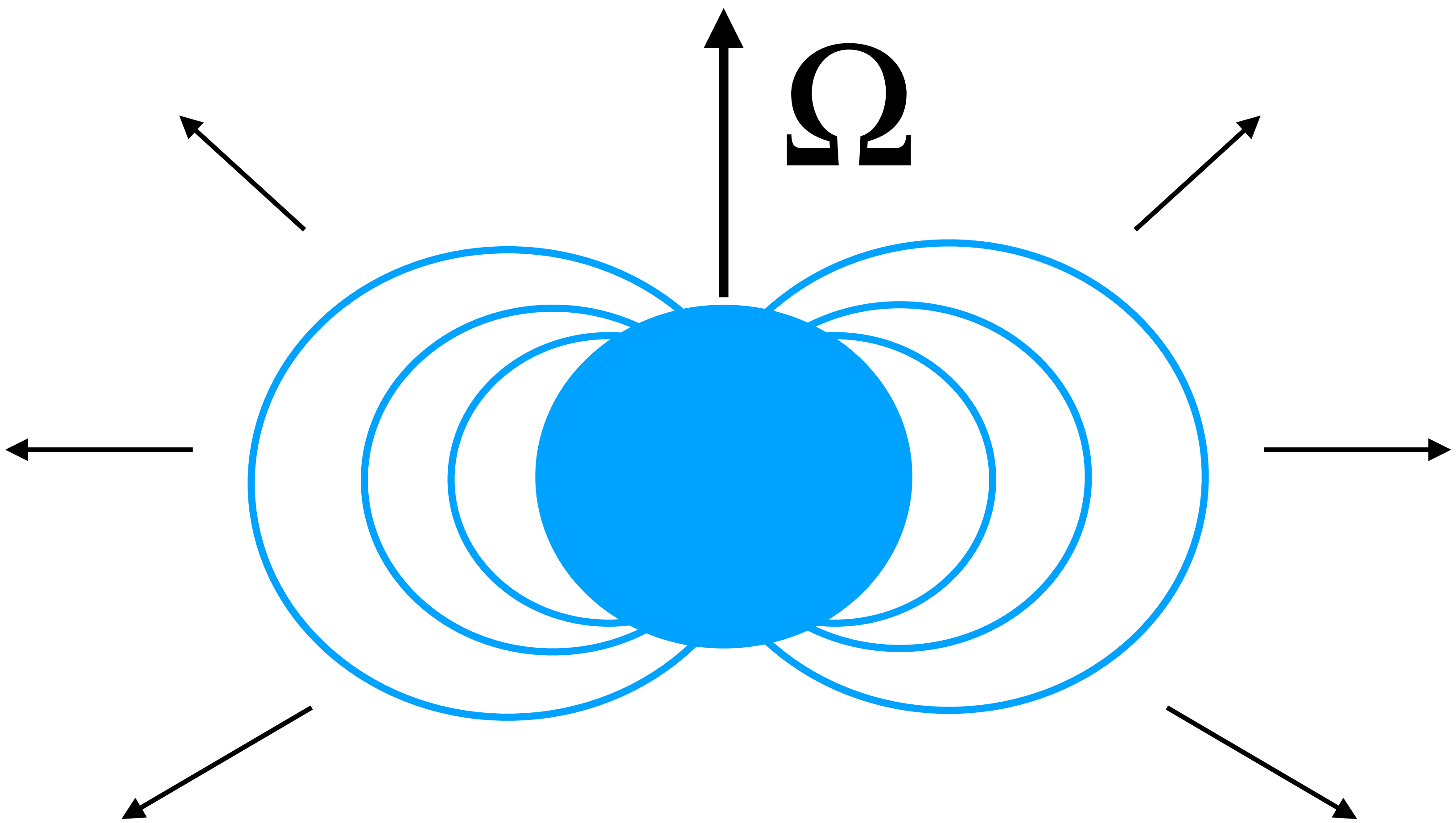
Zhang et al. 2007



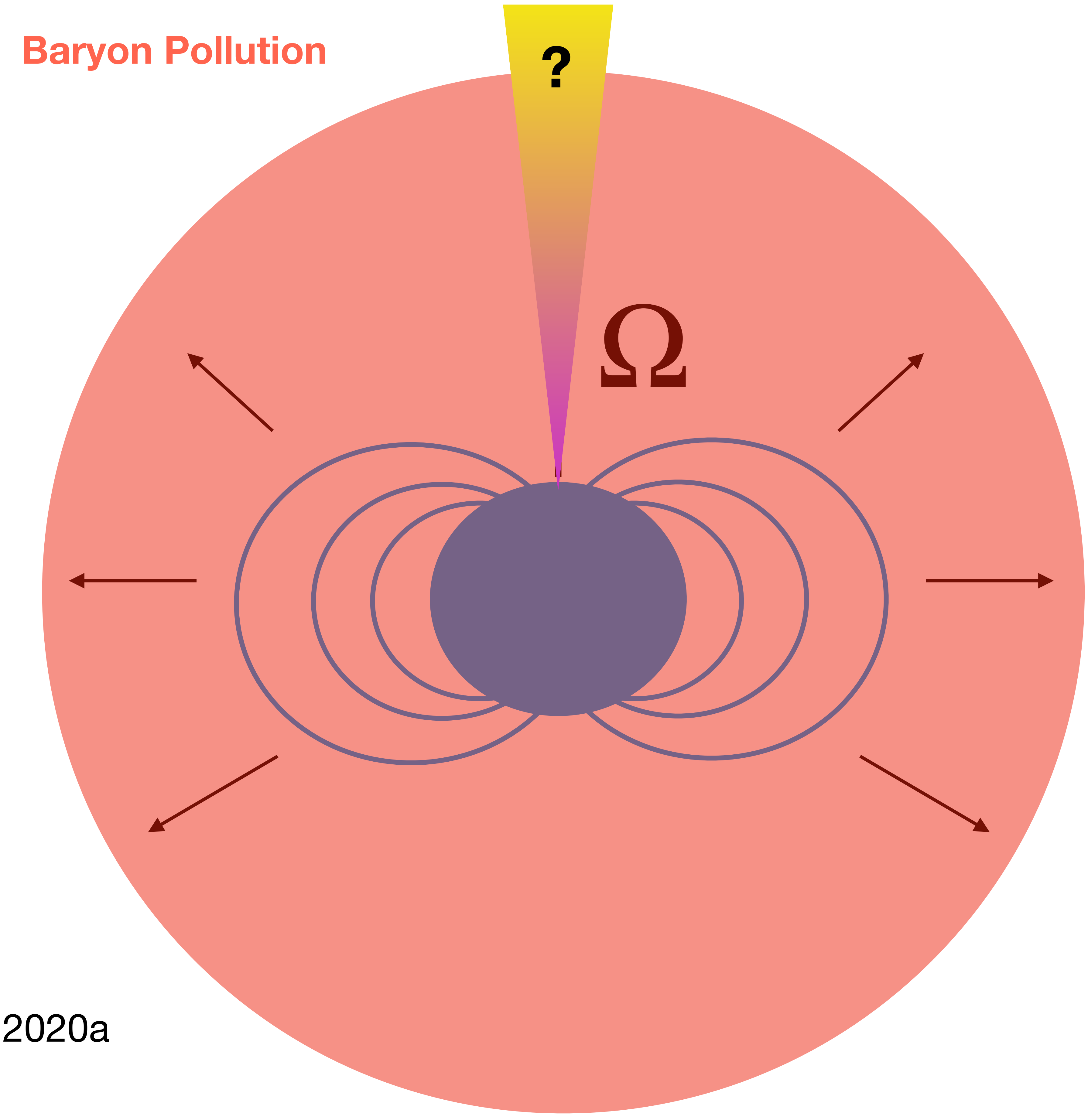
$L_X - T(-E_\gamma)$ correlation

Dainotti et al. 2013

Magnetar as GRB central engine

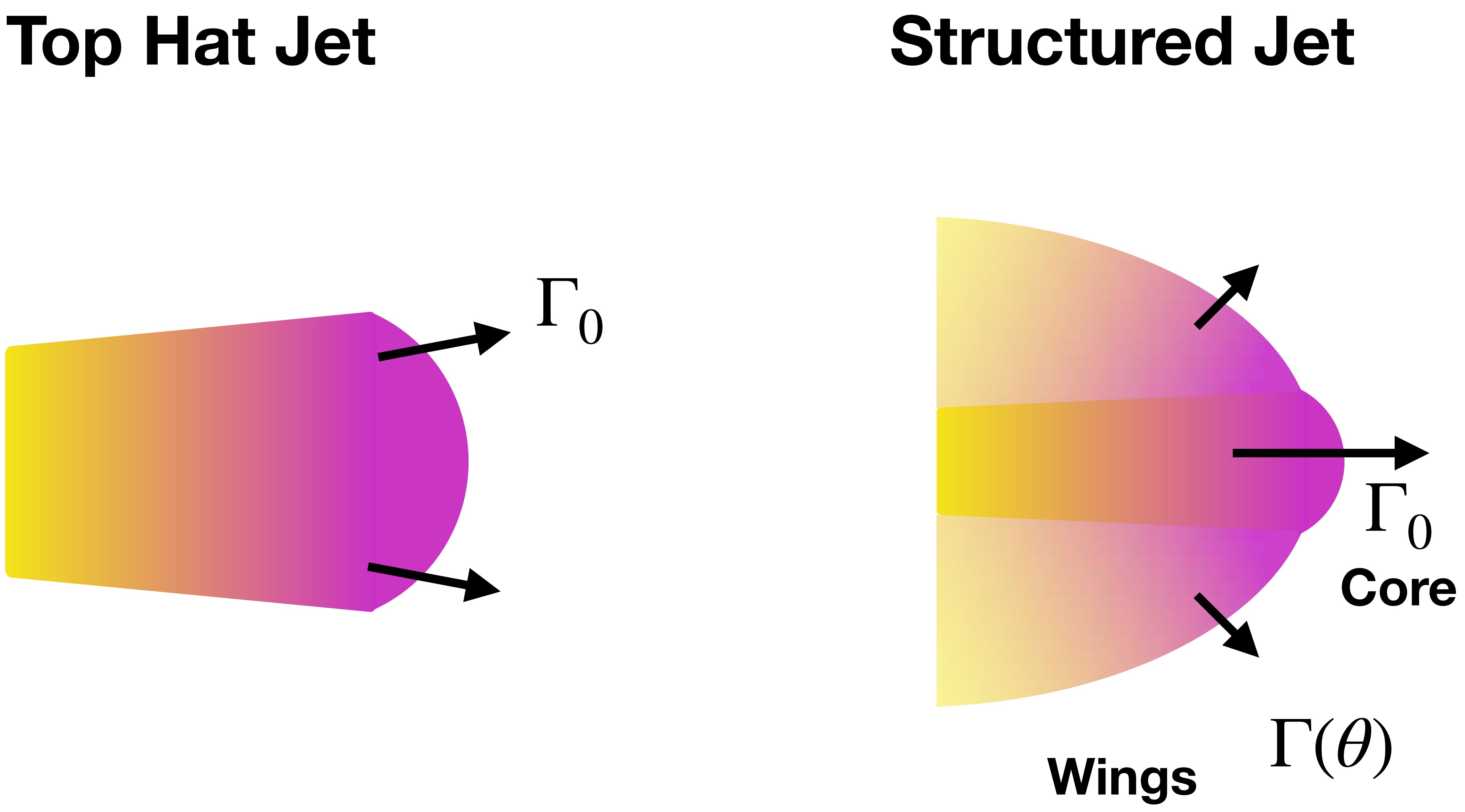


Magnetar as GRB central engine



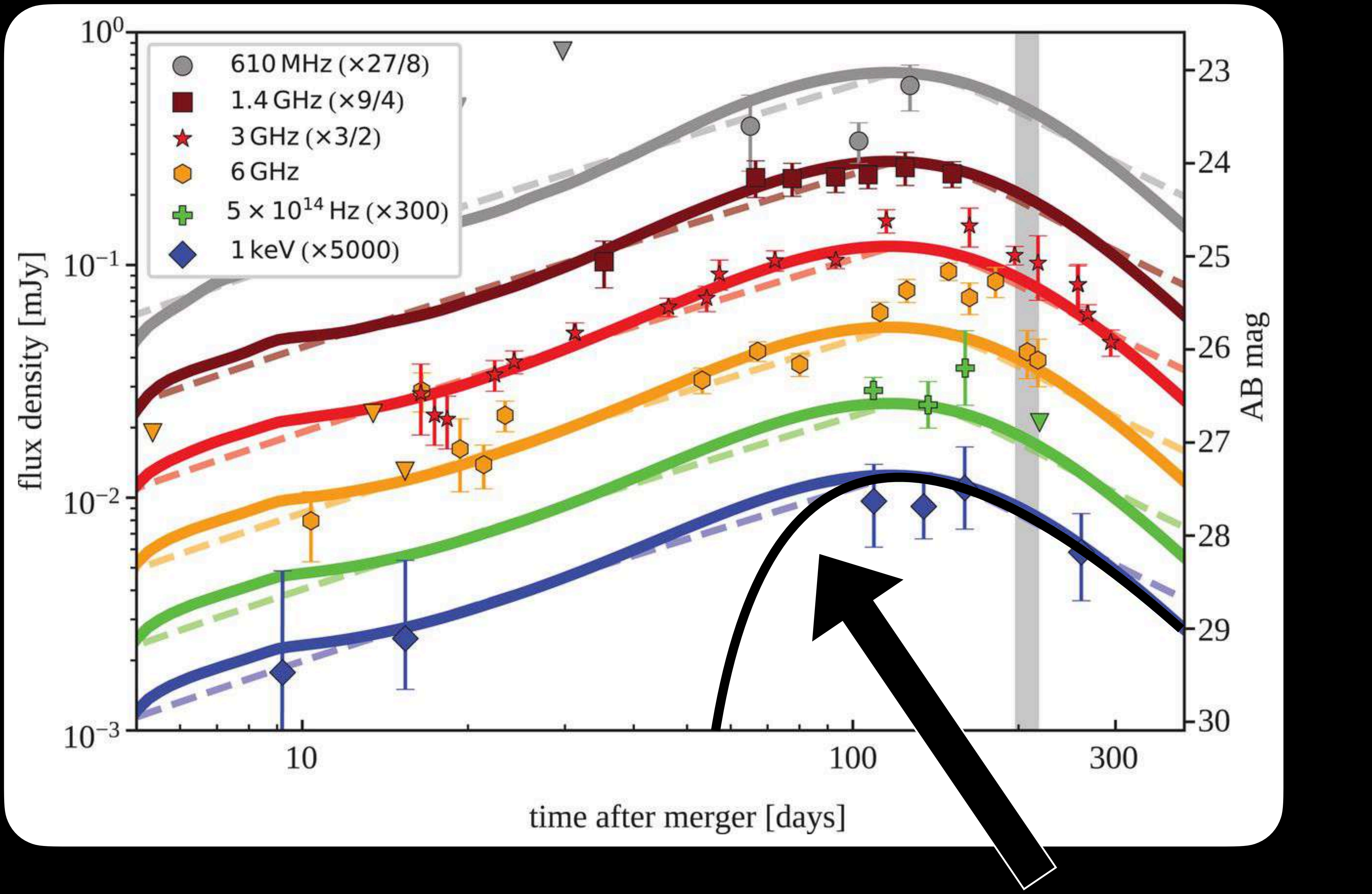
See e.g. Ciolfi 2020a

How is a GRB Jet?



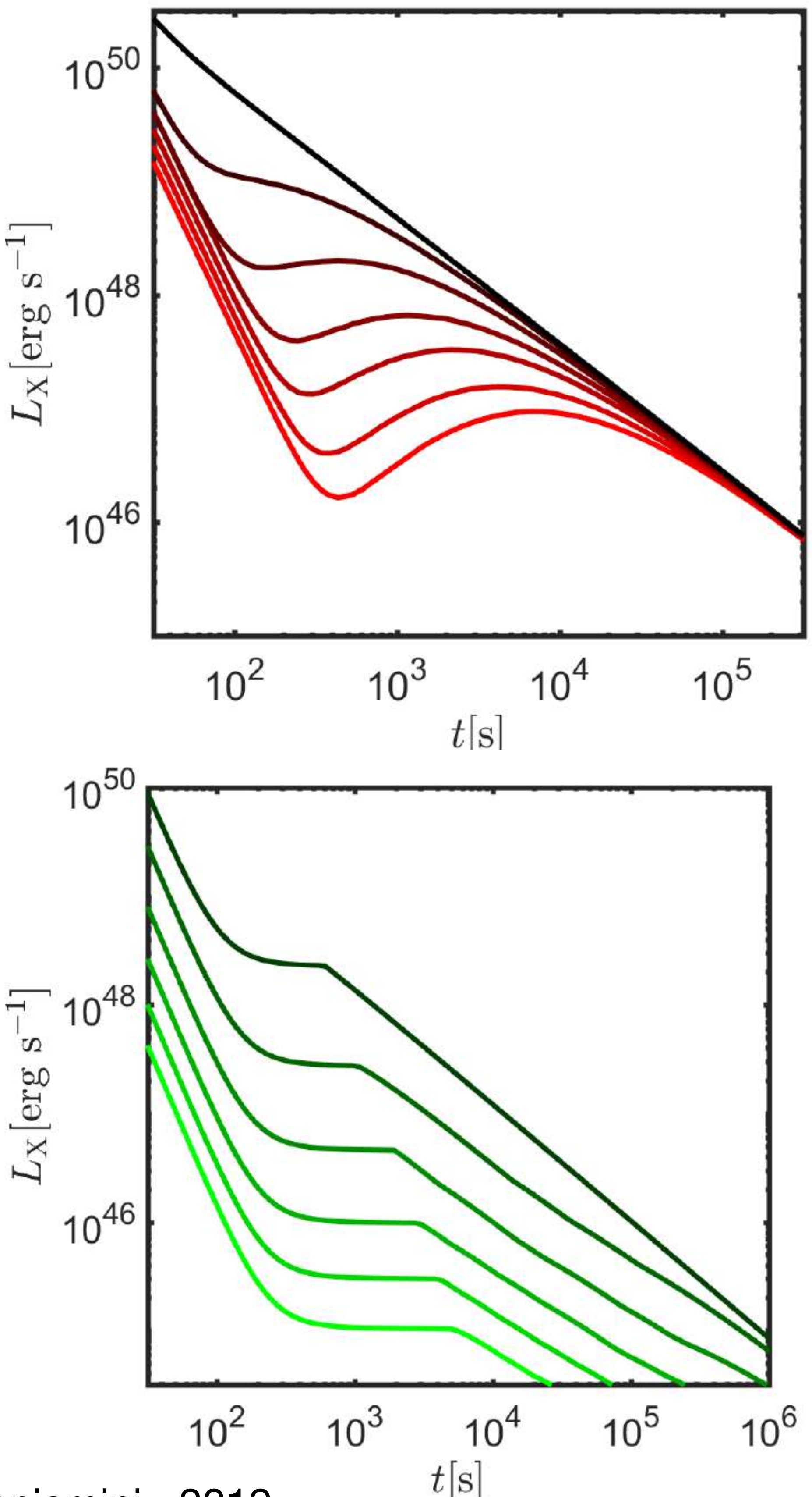
Structured Jets Confirmed!

GRB 170817/GW 170817 afterglow



D'Avanzo et al. 2018, Dobie et al. 2018,
Alexander et al. 2018, Troja et al. 2018
.....

Off-axis forward shock (Beniamini+ 2020)



Beniamini+ 2019

Plateau originated by the **forward shock** (external dissipation) from a structured jet observed slightly off-axis

Two possible mechanisms:

1) Off-axis emission from the core (initially beamed away) that becomes progressively visible while the jet decelerates.

2) On-axis emission from portions of the jet that have not stat to decelerate yet (only for wind-like medium)

- Correlations reproduced
- Chromaticity explained assuming different position of the X-ray and optical bands with respect to the synchrotron frequencies
- Sharp drop not explained

Our Model

Steep Decay

The High Latitude Emission (HLE) Model

Kumar & Panaitescu 2000, Ap. J., 541, 2, L51-L54

The Recipe

The steep decay is the tail (in X-ray) of the **prompt emission**. The energy is released instantaneously by a curved surface in highly relativistic motion. The difference in the time of flight of photons from different regions of the emitting surface shapes the lightcurve

The Main Ingredients

- Difference in time of flight of photons
- Relativistic motion

The Assumption

- Instantaneous emission
- Spherical emitting surface
- (Power law spectrum)

Steep Decay

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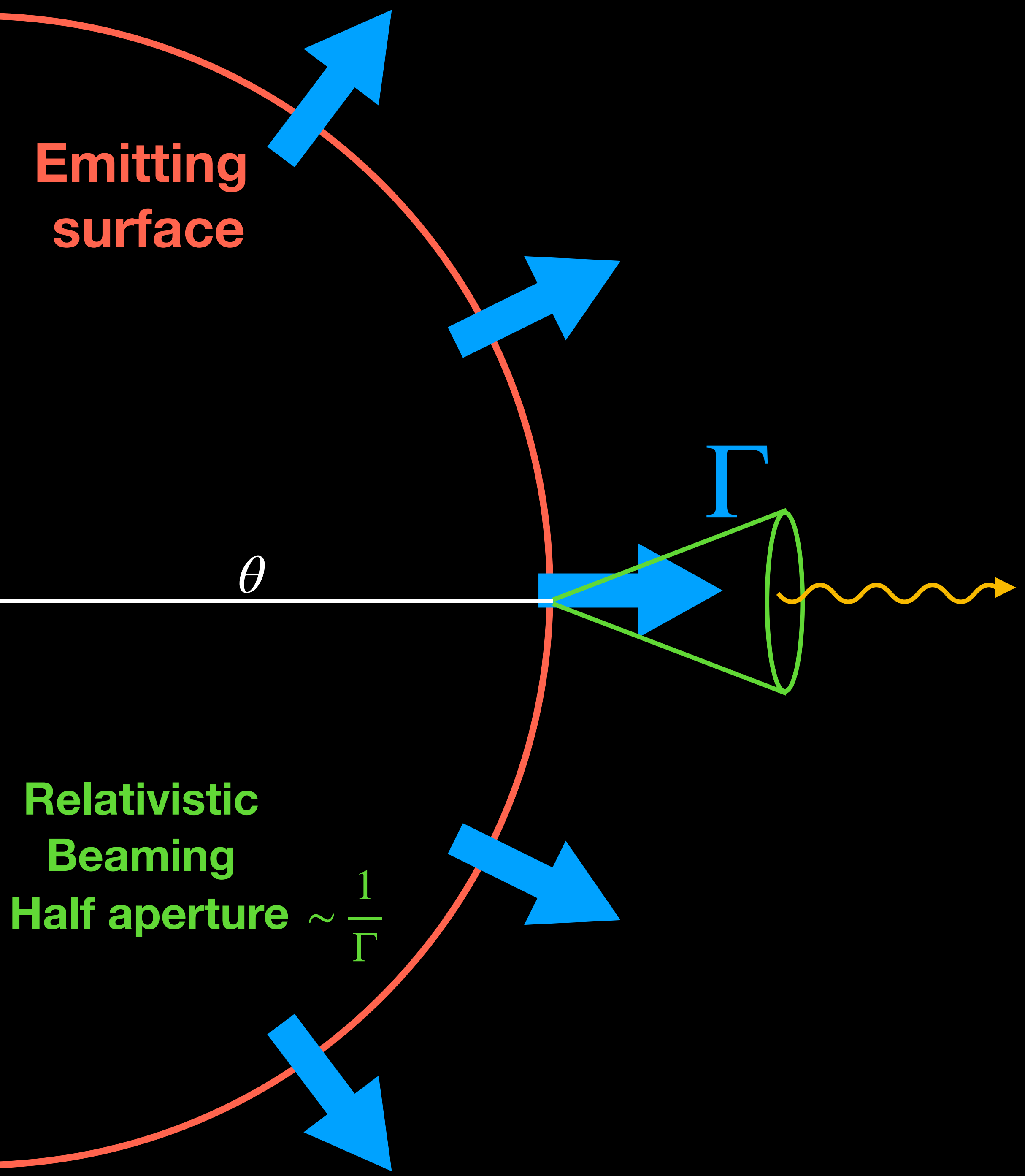

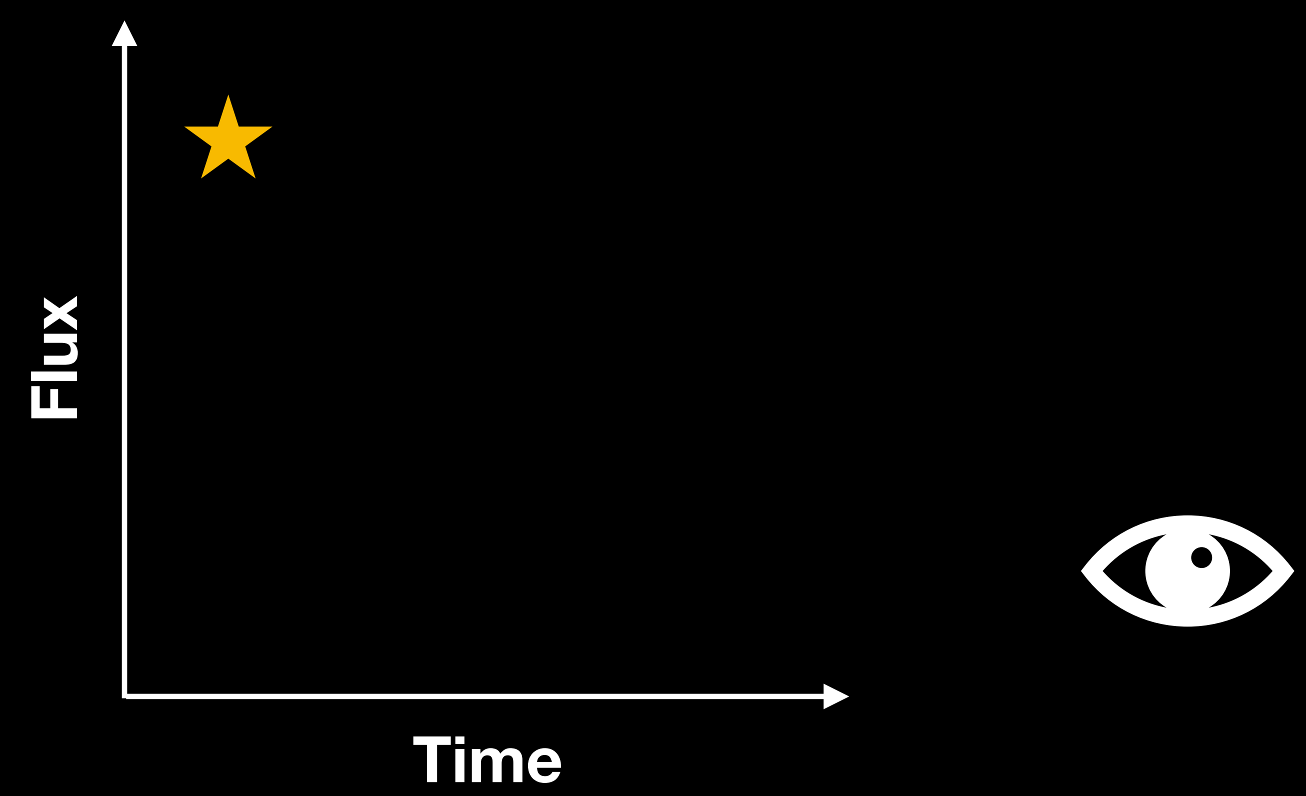

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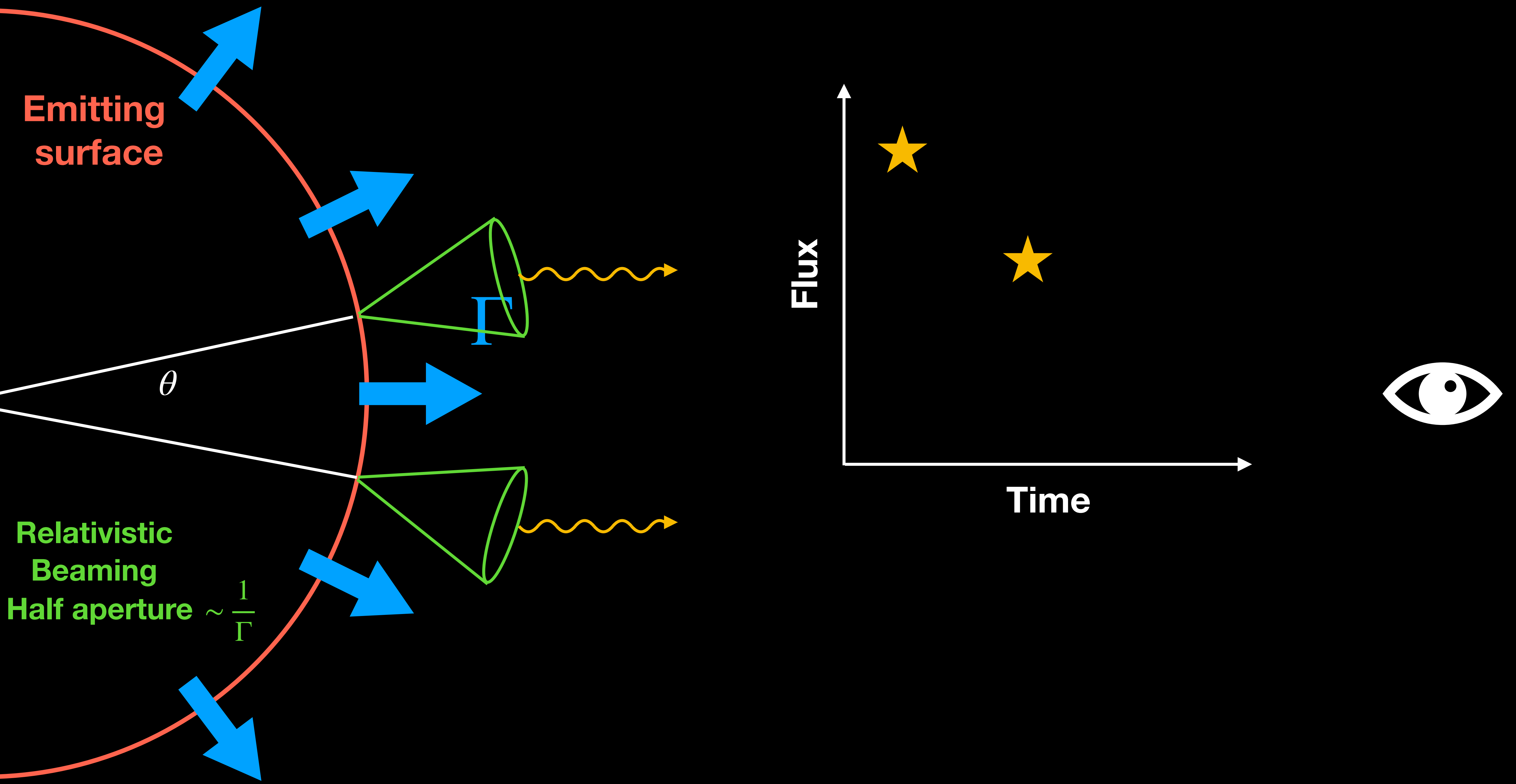

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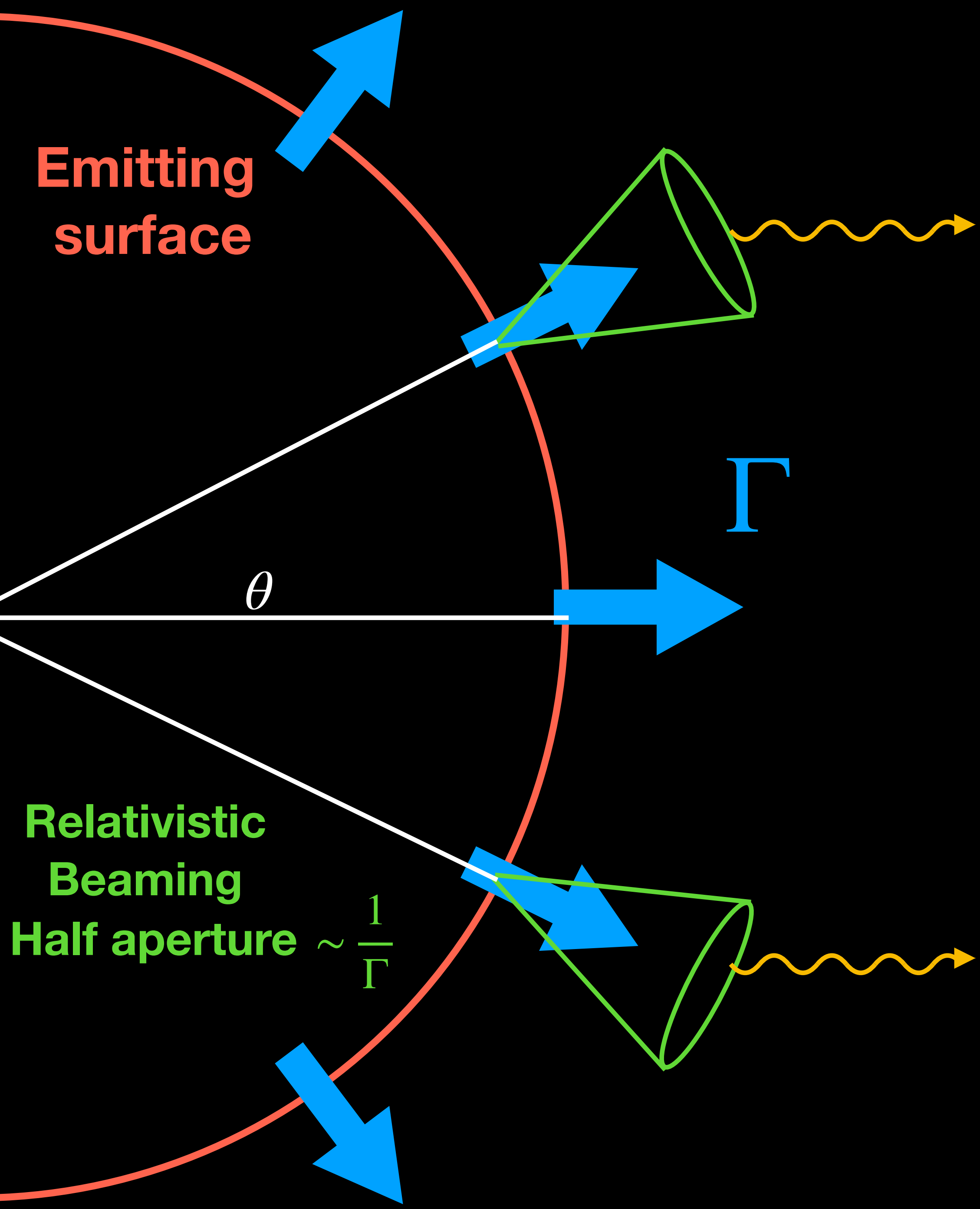

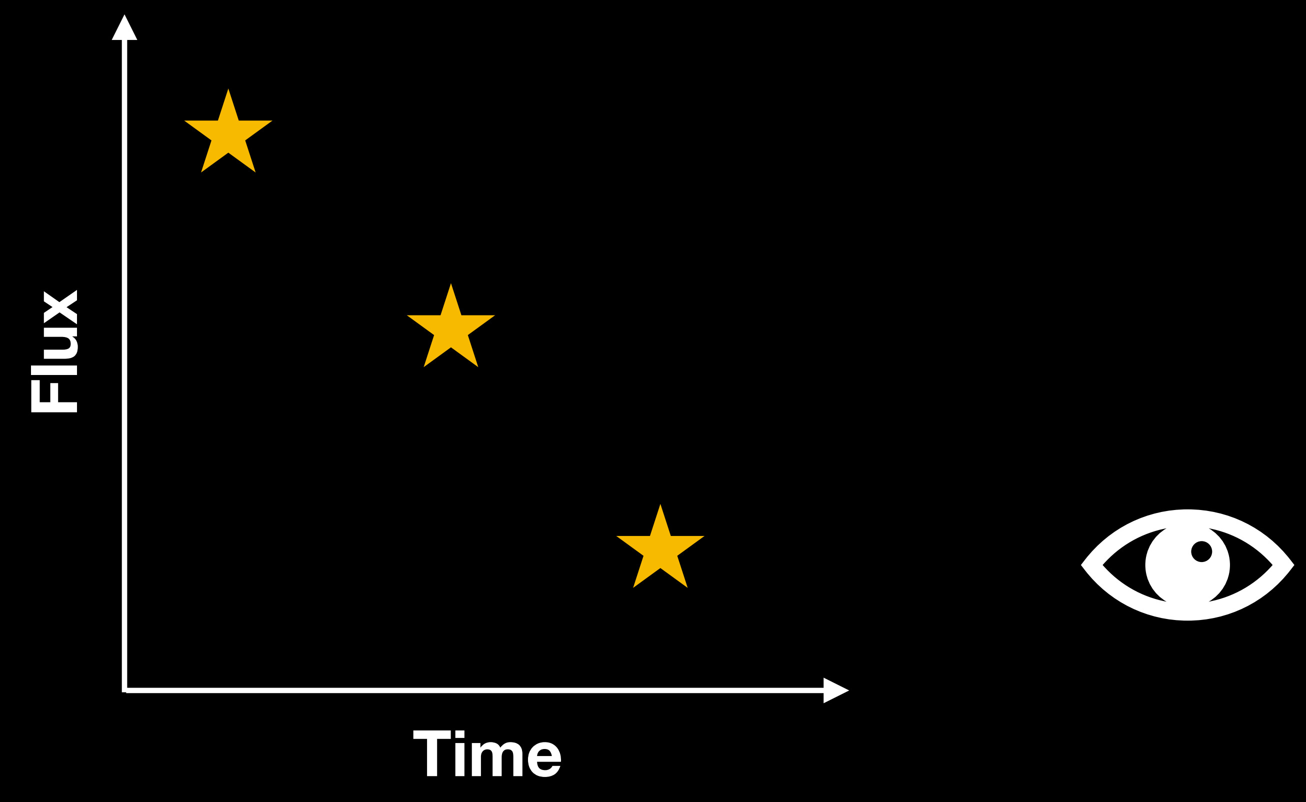

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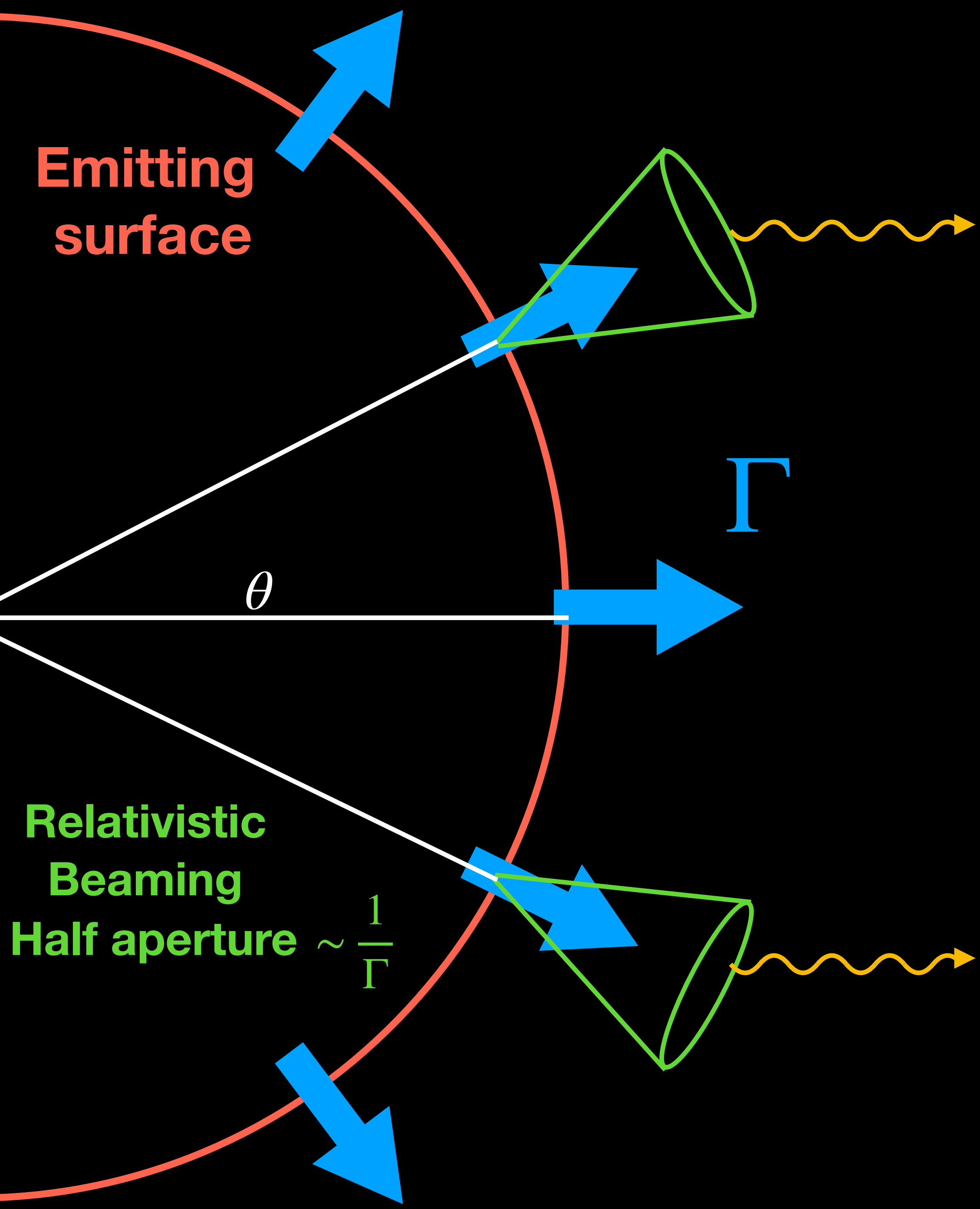
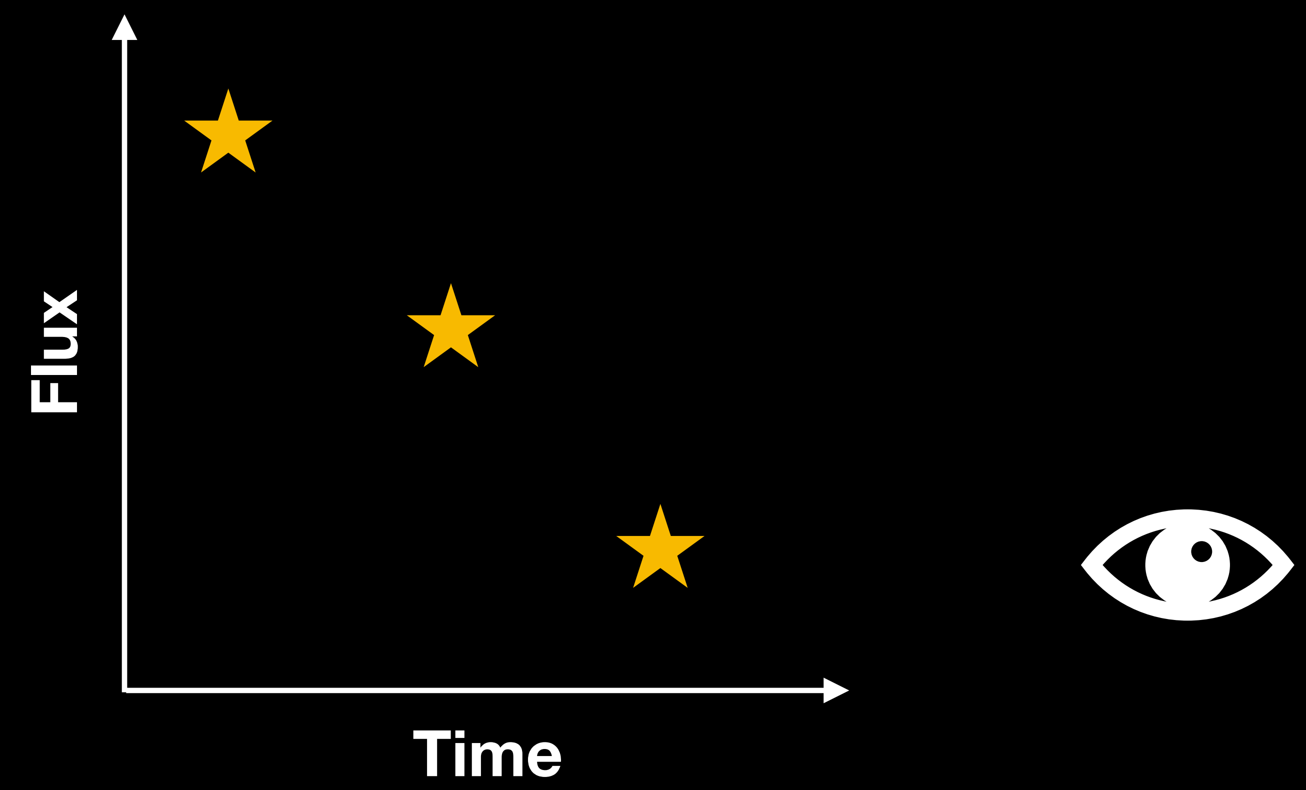




$$F_\nu = \int_S I_\nu \cos\theta_{obs} d\Omega_{obs} \quad \propto \nu^{-\beta} t^{-(2+\beta)}$$

Steep Decay + Plateau

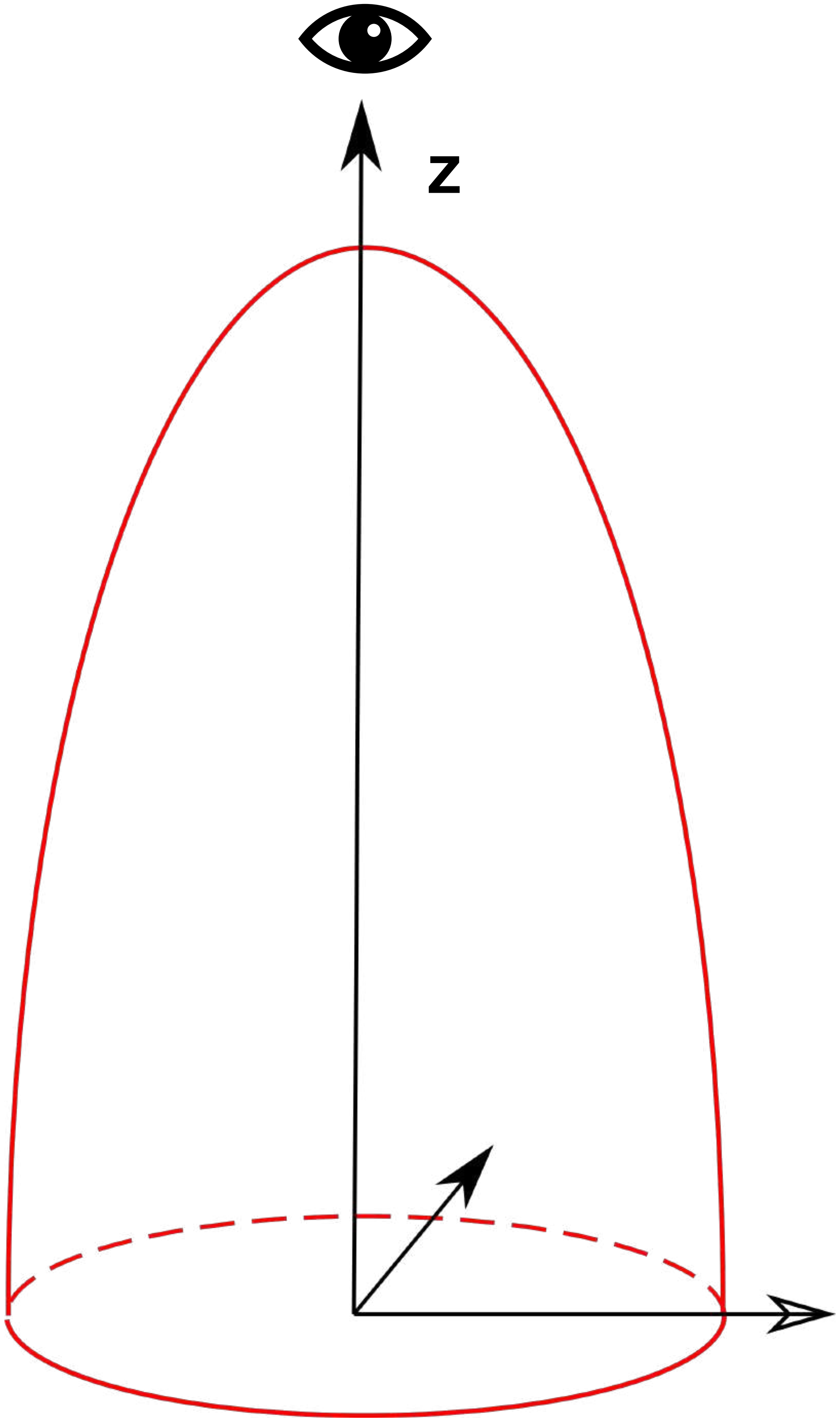
The High Latitude Emission (HLE) Model

Oganesyan, **SA** et al. 2020

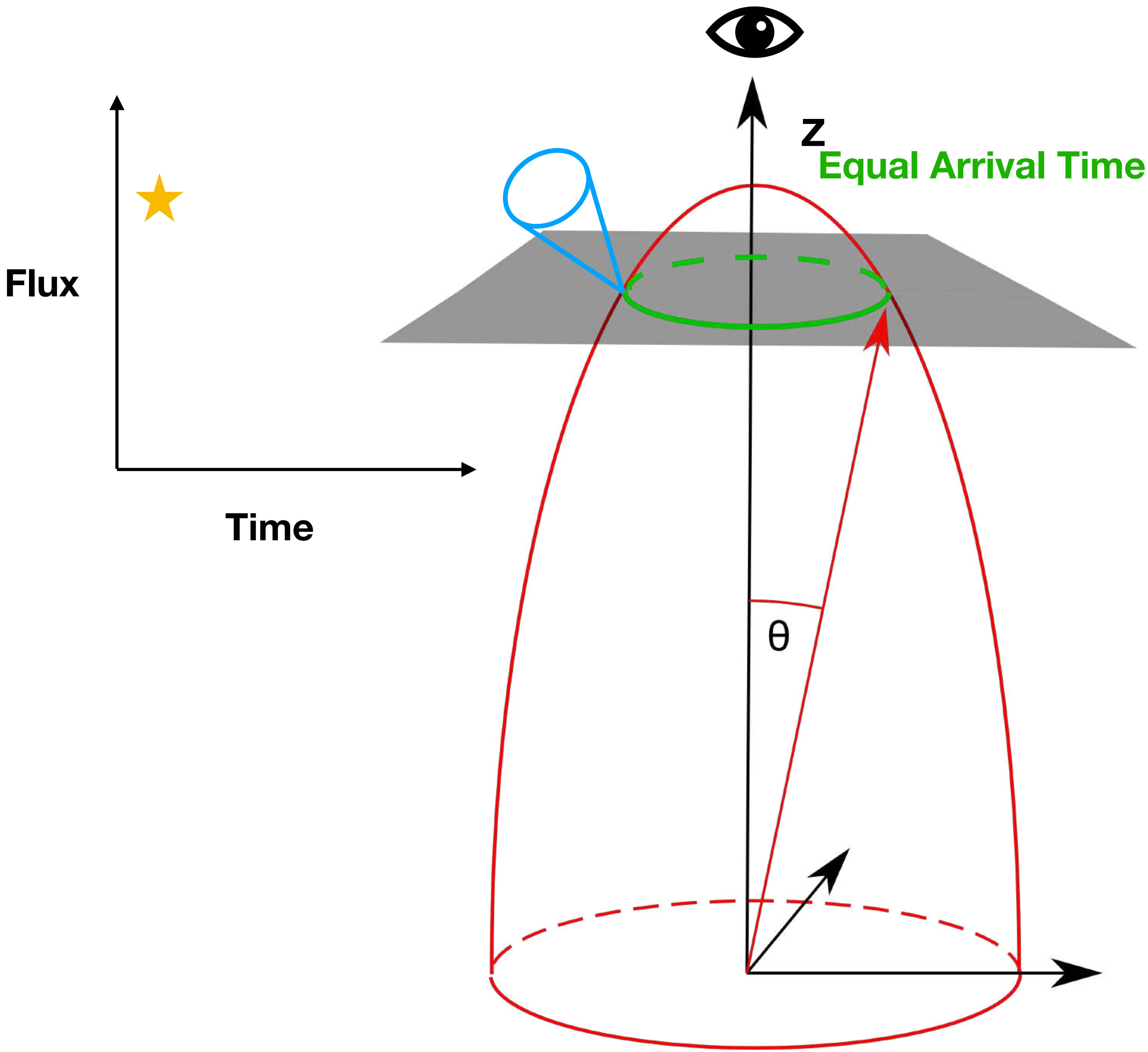
The Assumptions

- Instantaneous emission
- Structured emitting surface
- Negligible opacity everywhere
- Observer along the jet axis
- Same spectrum everywhere

High latitude emission- Structured Jet



High latitude emission- Structured Jet



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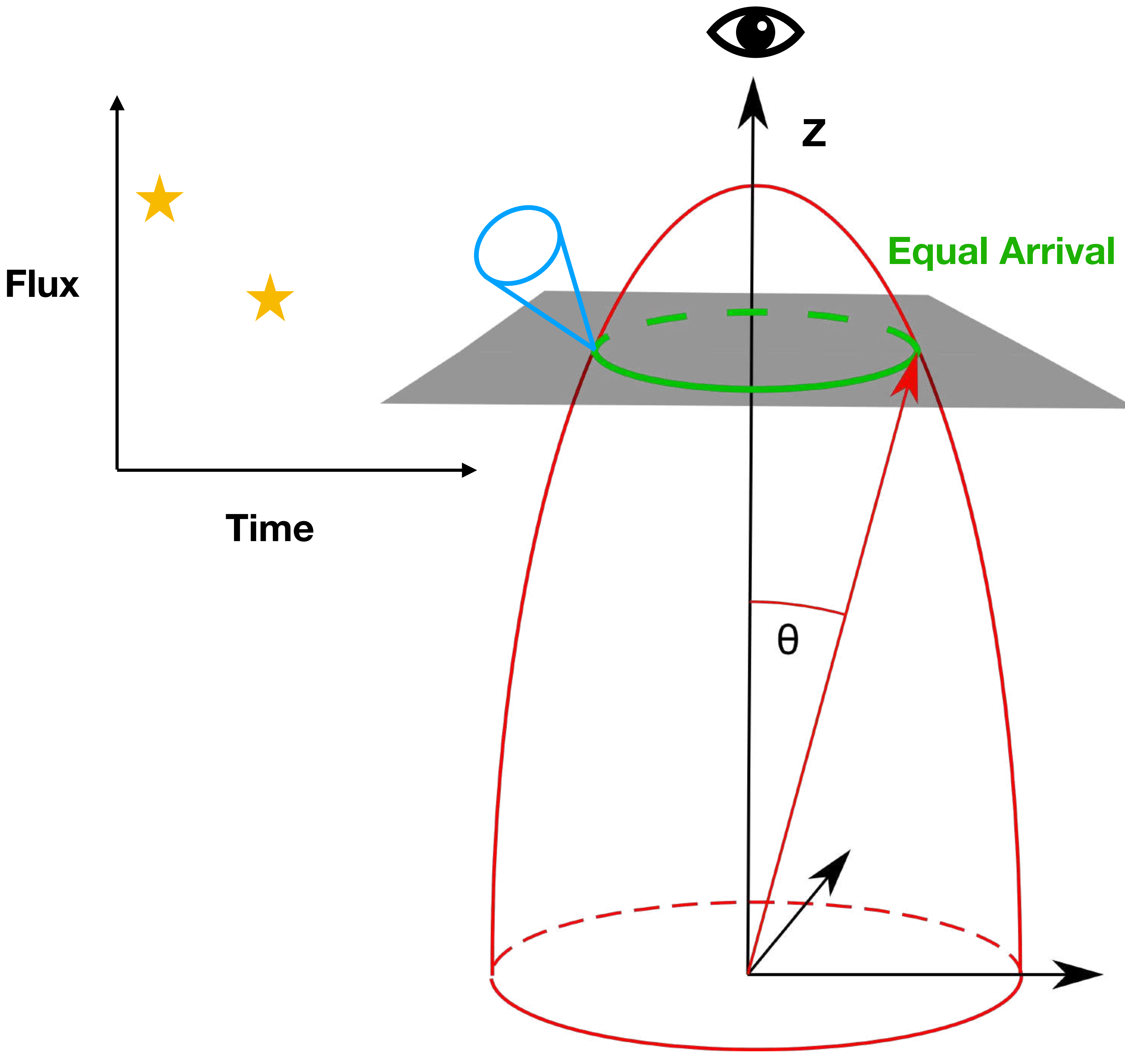

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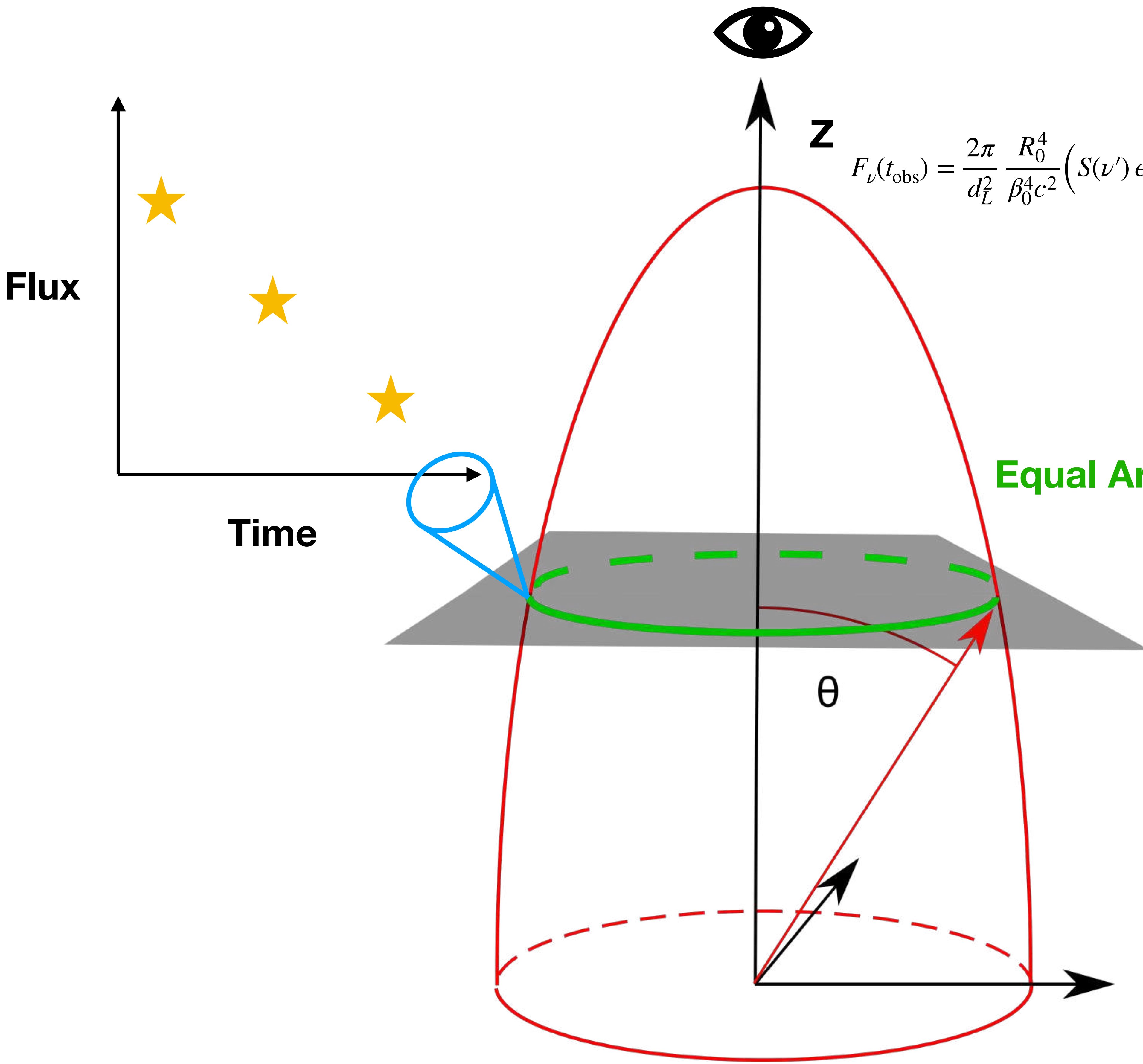


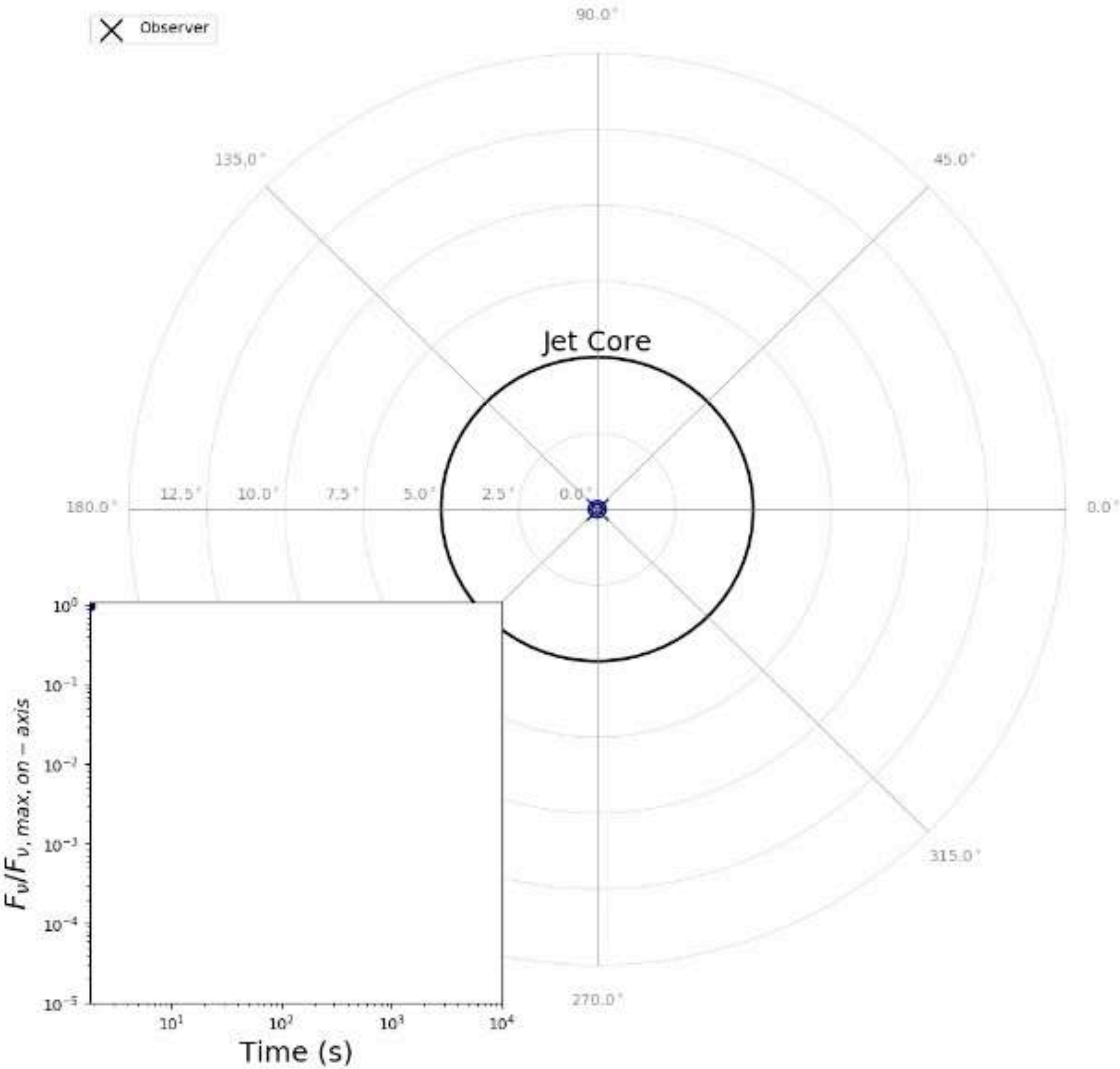
$$F_\nu(t_{\rm obs}) = \frac{2\pi}{d_L^2}\frac{R_0^4}{\beta_0^4 c^2}\left(S(\nu')\,\epsilon(\theta)\,\frac{\beta^2(\theta)}{\Gamma^3(\theta)}\;\cos\theta\,\sin\theta\,\frac{d\theta}{dt_{\rm obs}}\right)_{\theta=\theta(t_{\rm obs})} t_{\rm obs}^{-2}$$

Gaussian structure $\Gamma(\theta) = 1 + (\Gamma_c - 1)\exp\left[-\frac{\theta^2}{\theta_c^2}\right]$

$\Gamma_c = 100$

$\theta_c = 5^\circ$

$R_0 = 10^{15}\,\mathrm{cm}$



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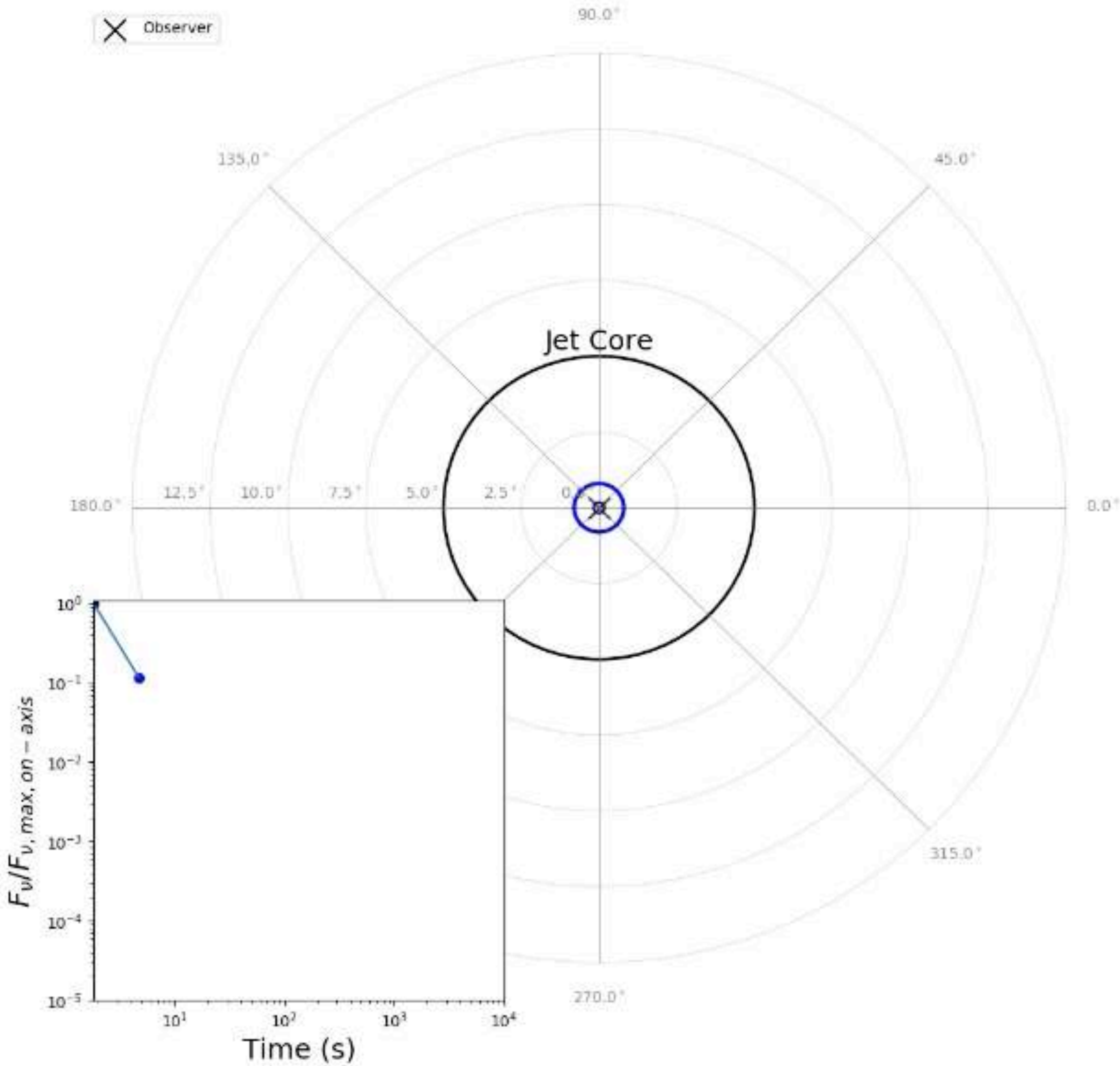

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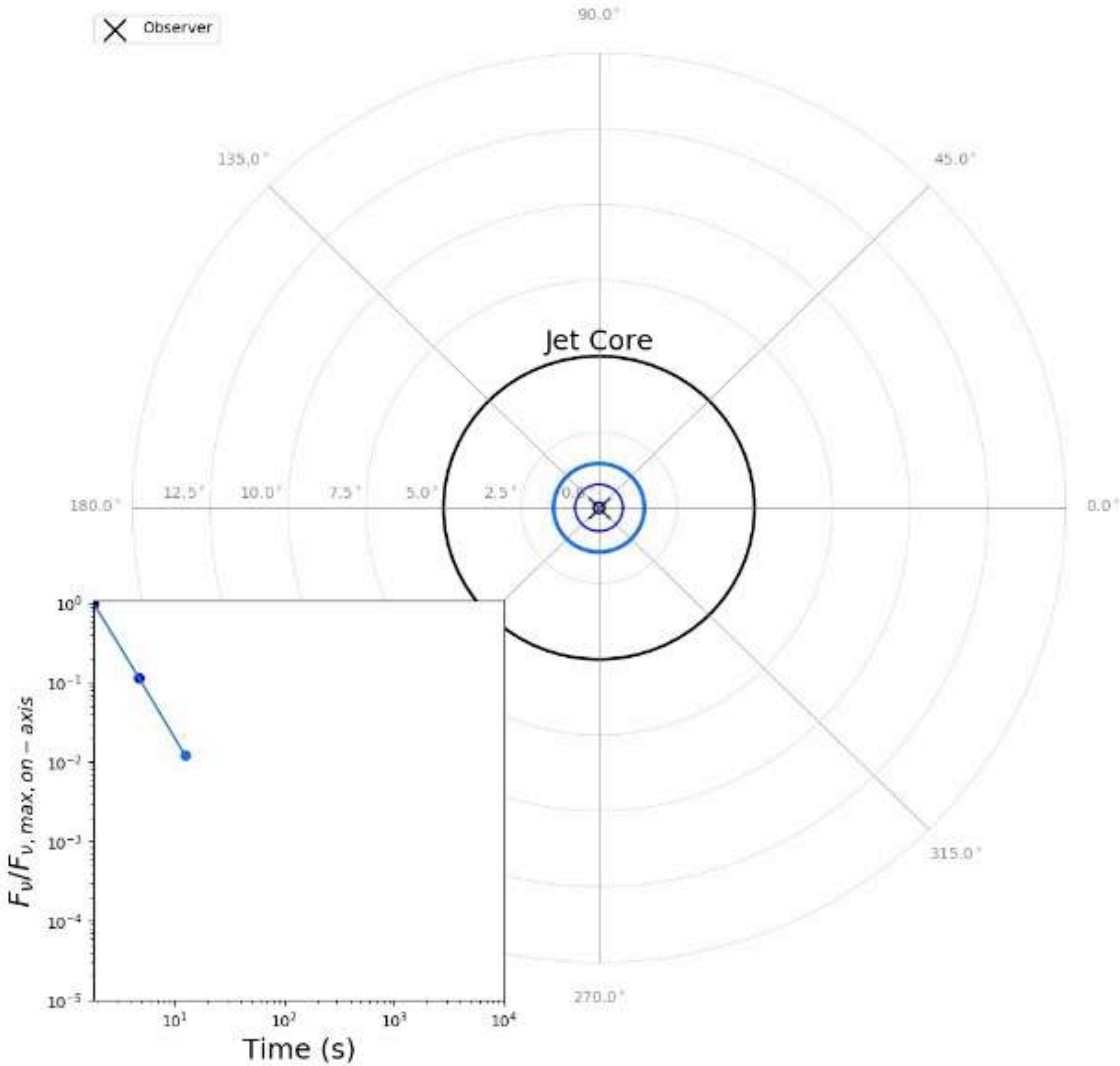

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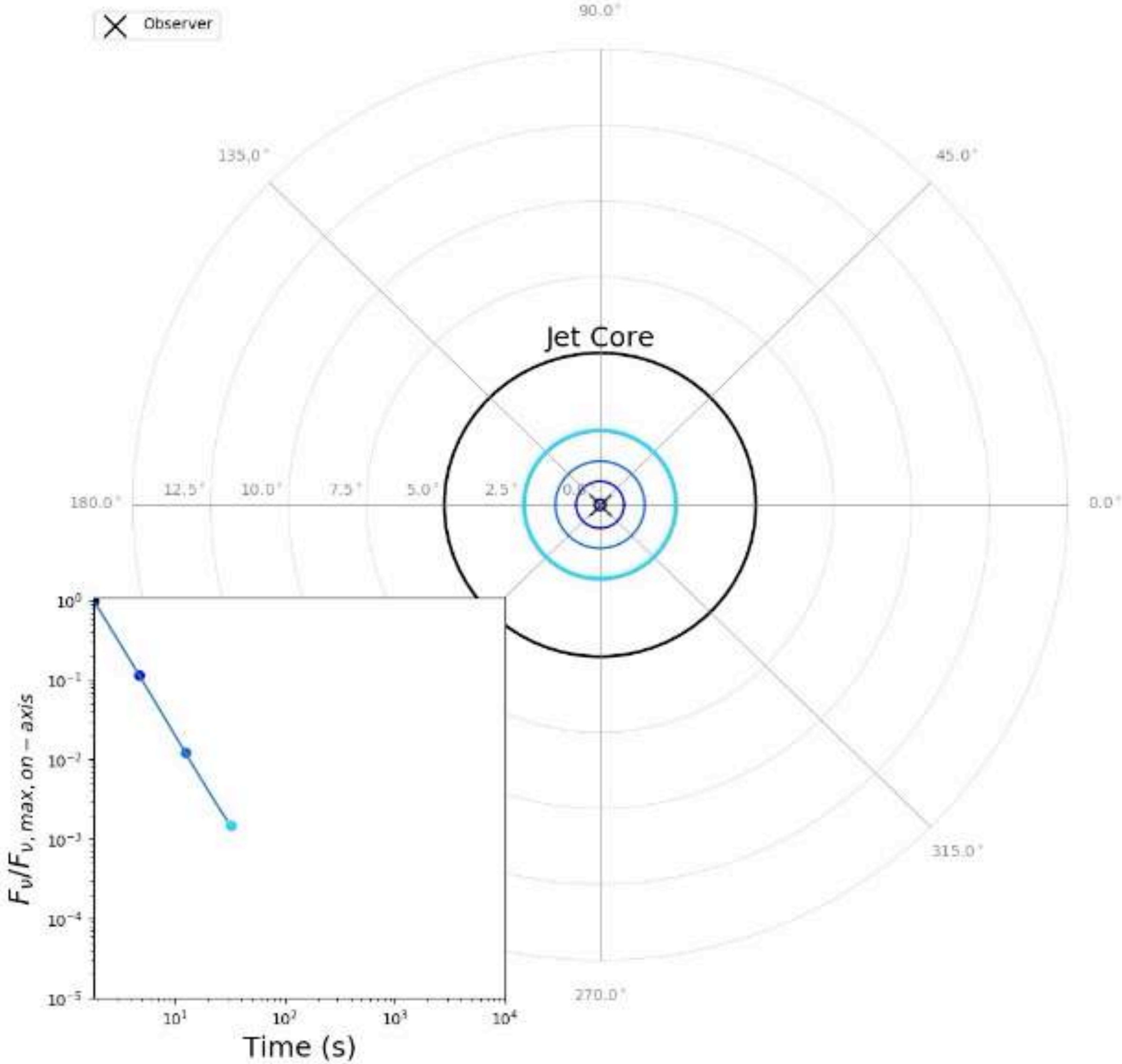

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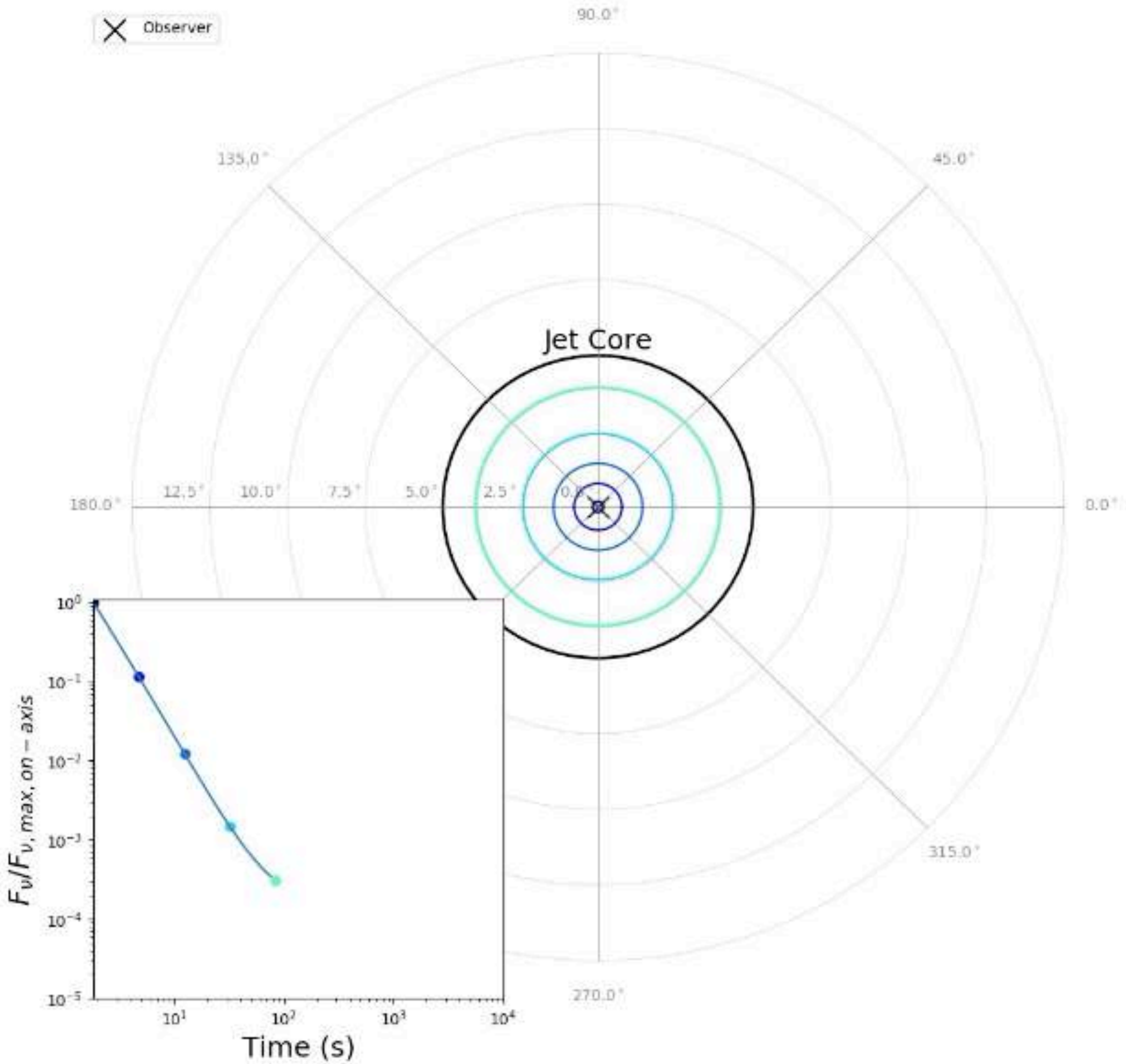

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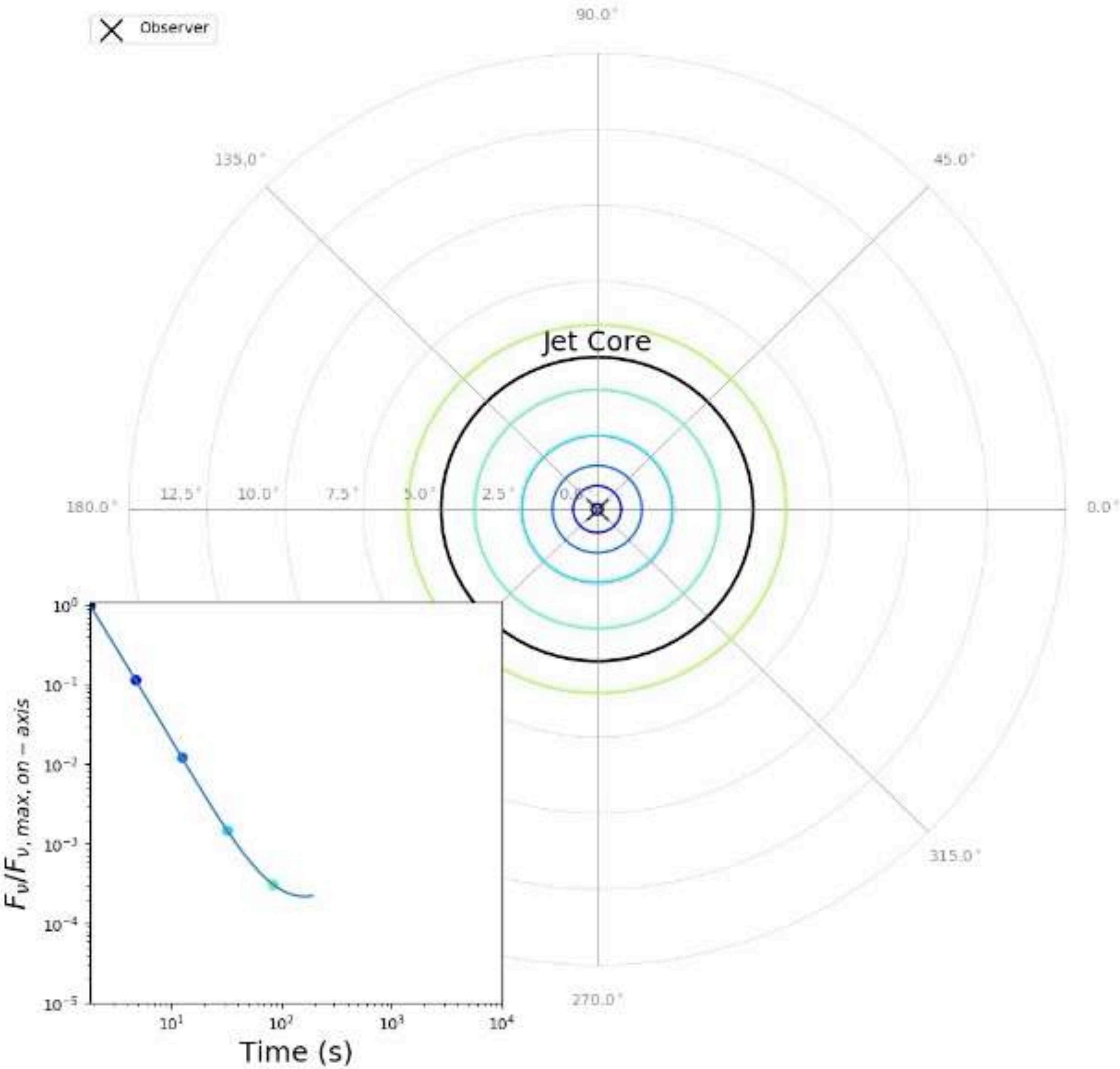

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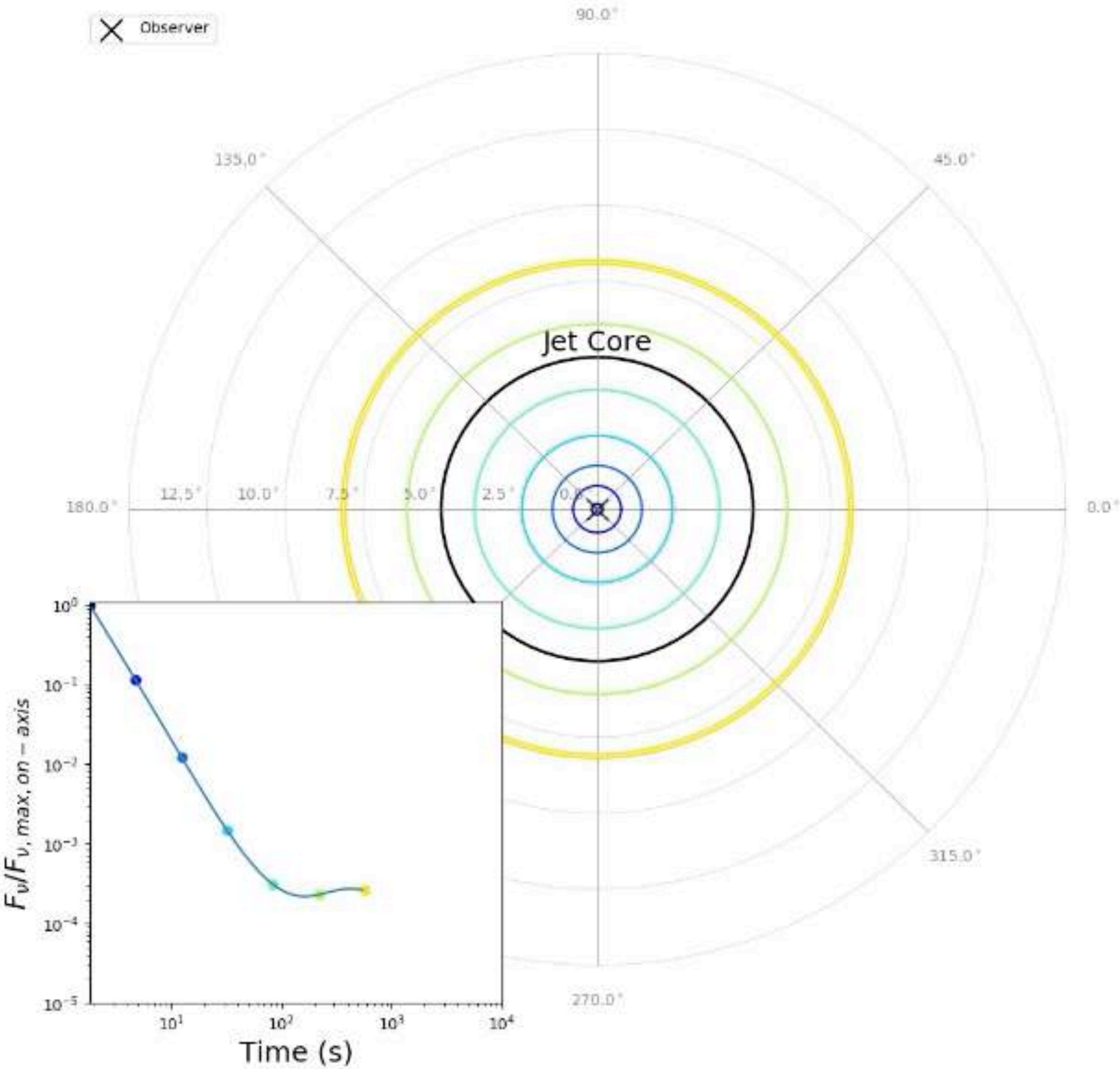

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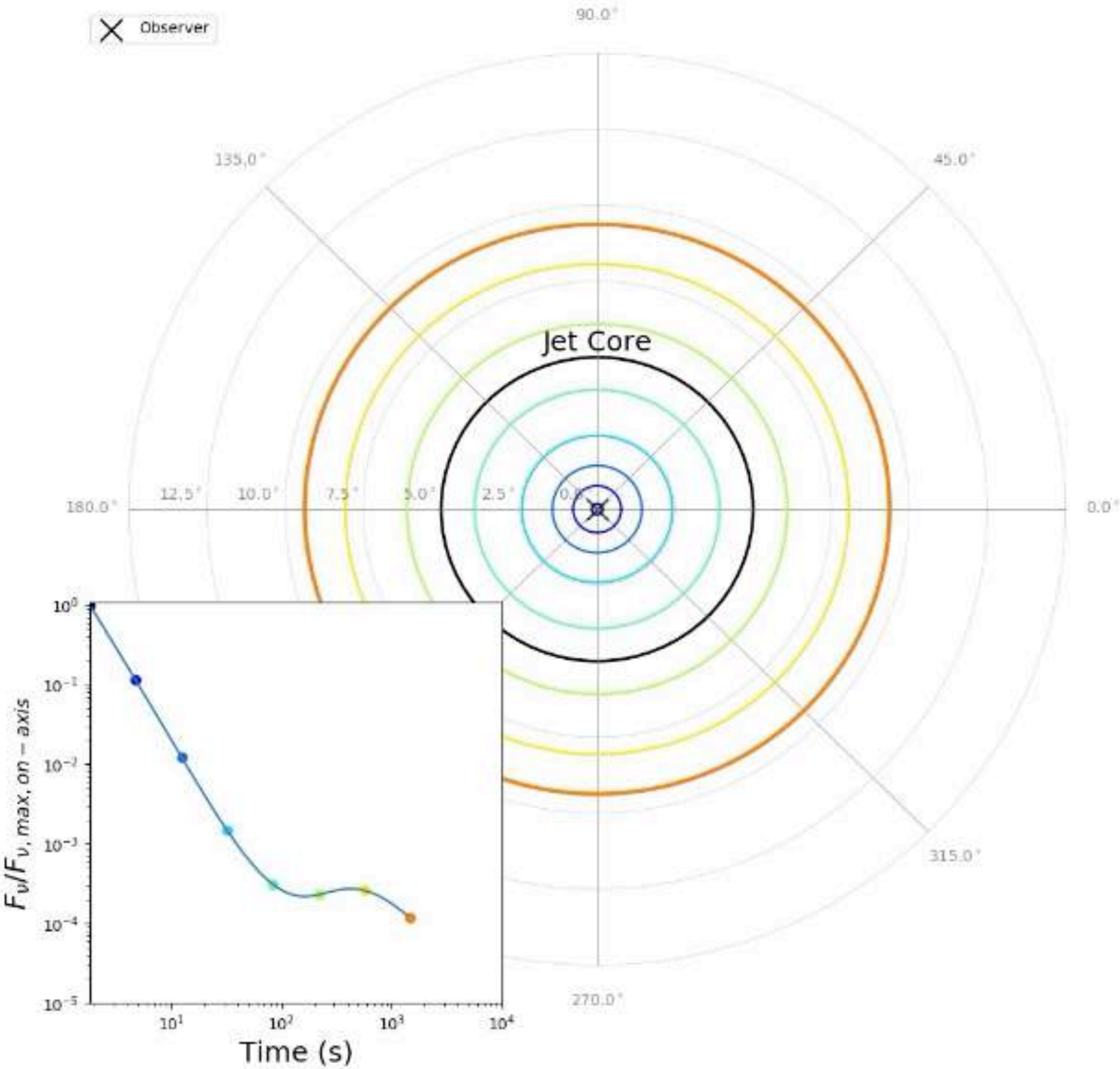

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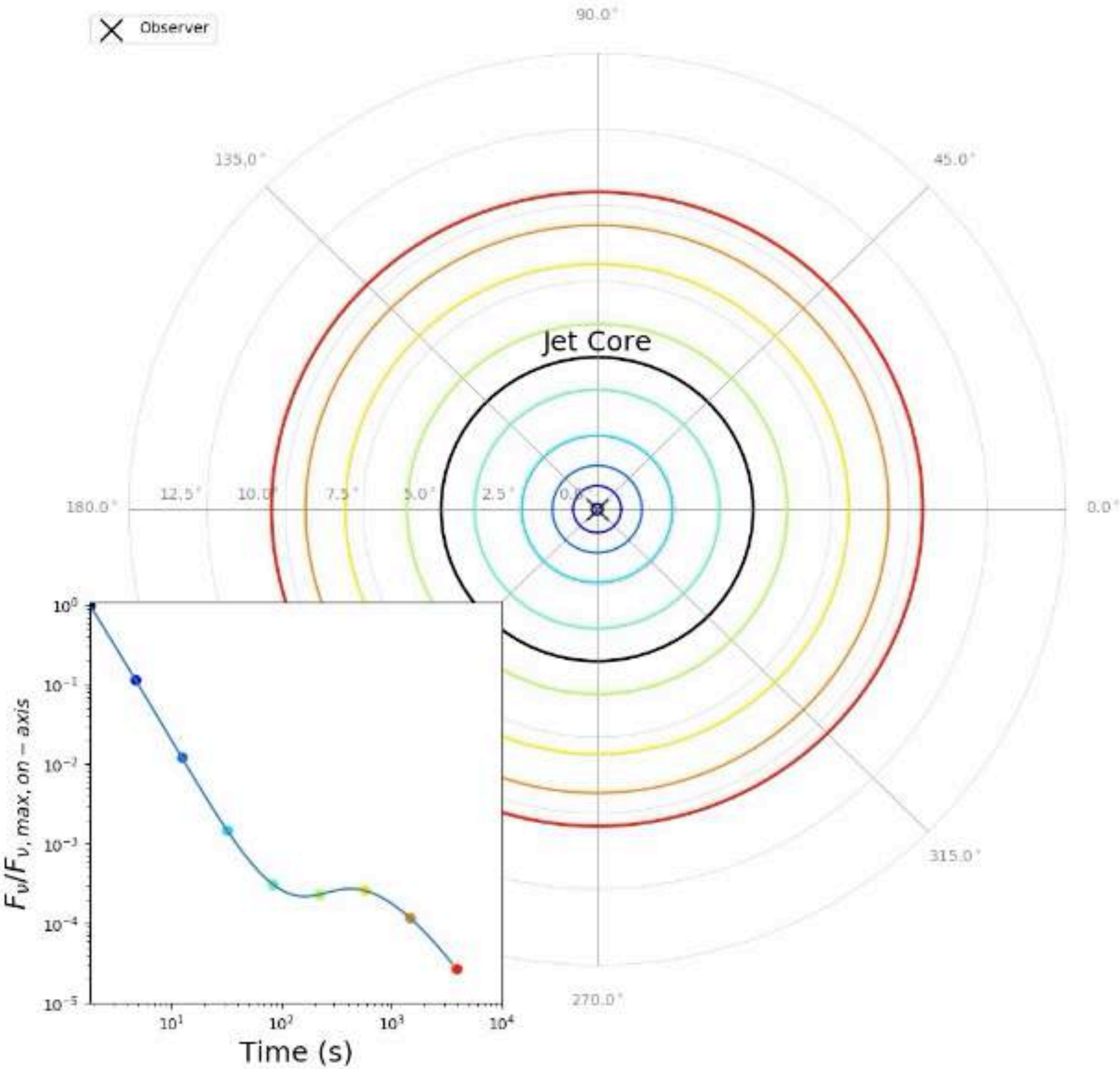

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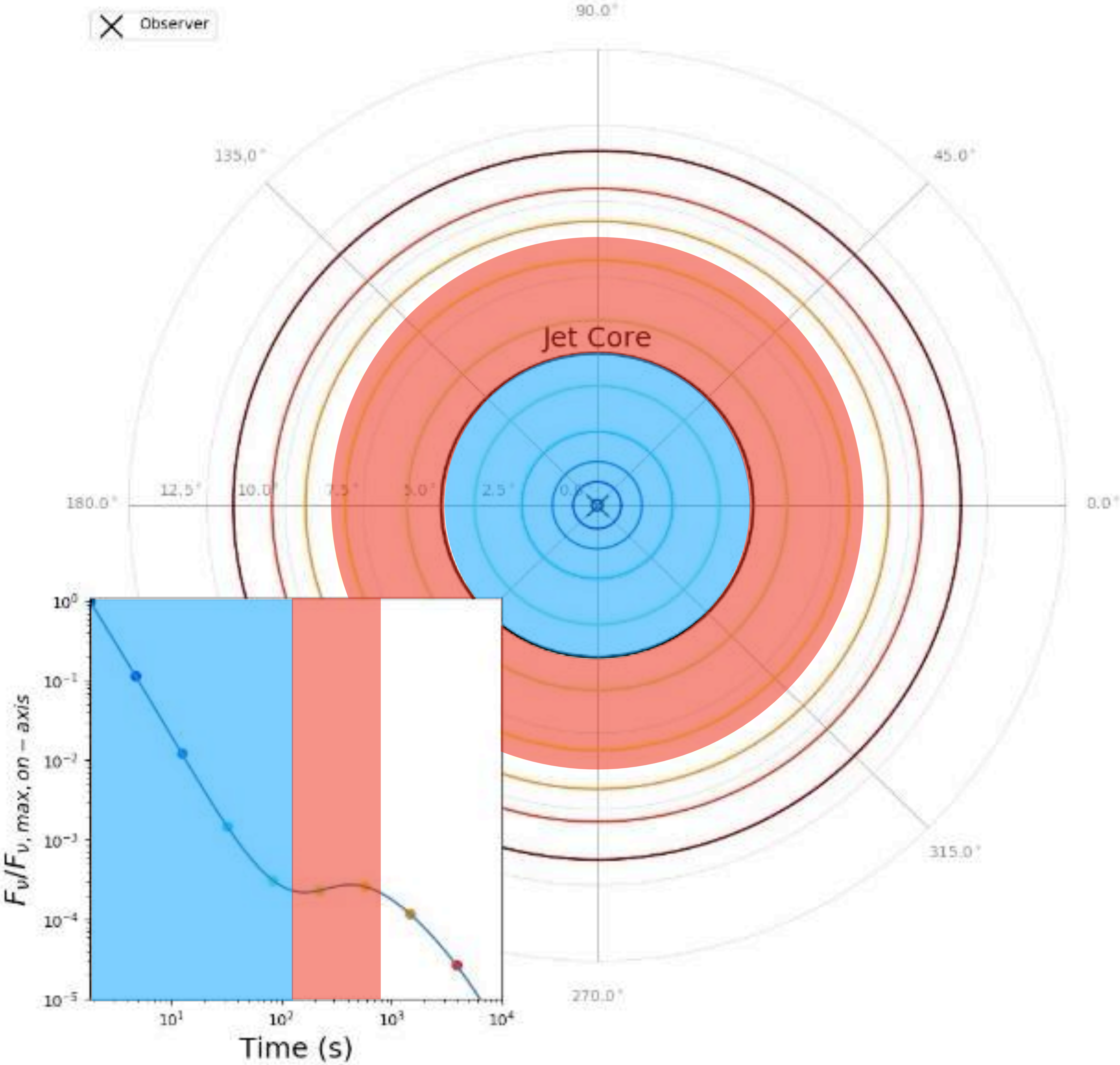
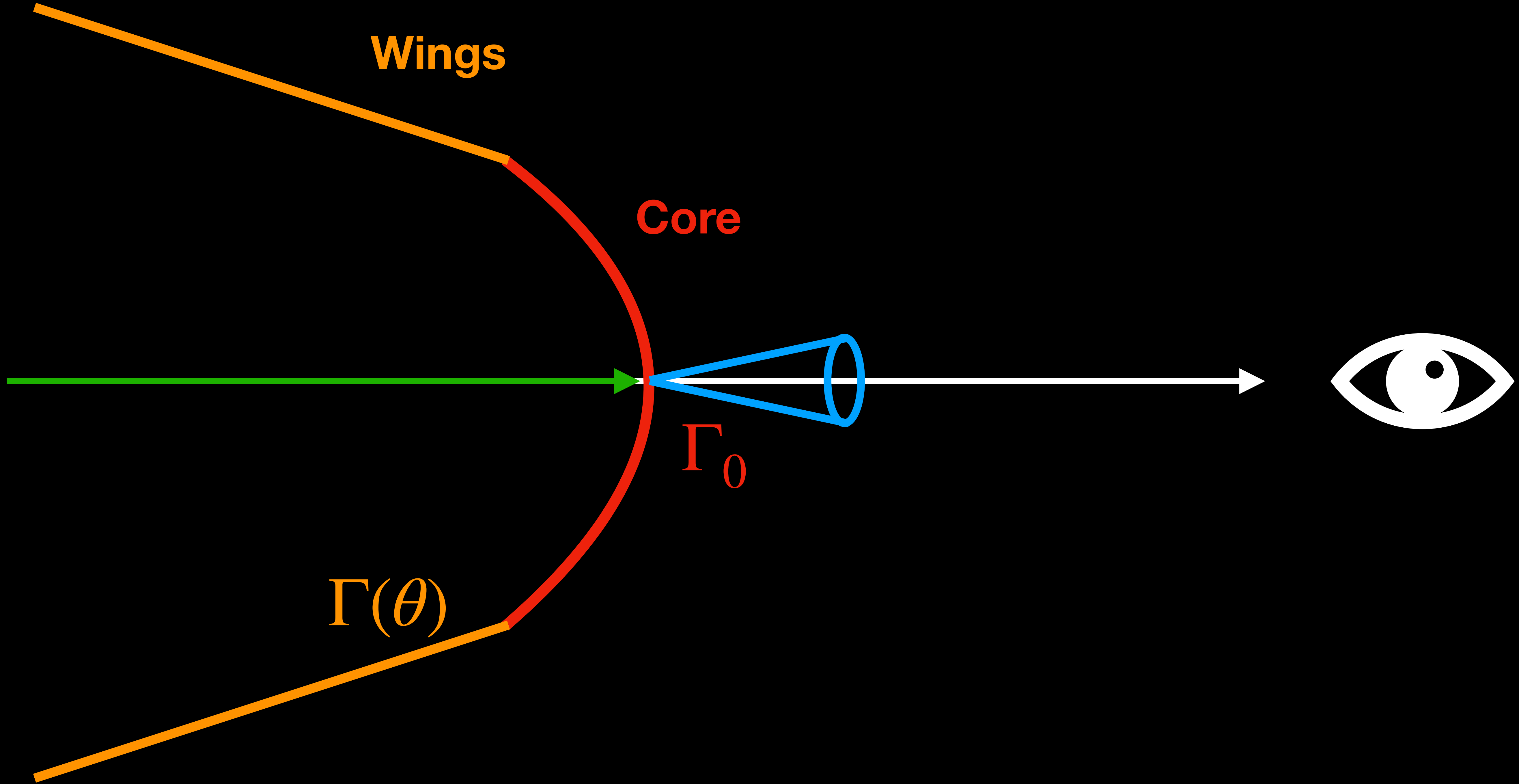


Interpretation



Oganesyan, **SA**, et al. 2020

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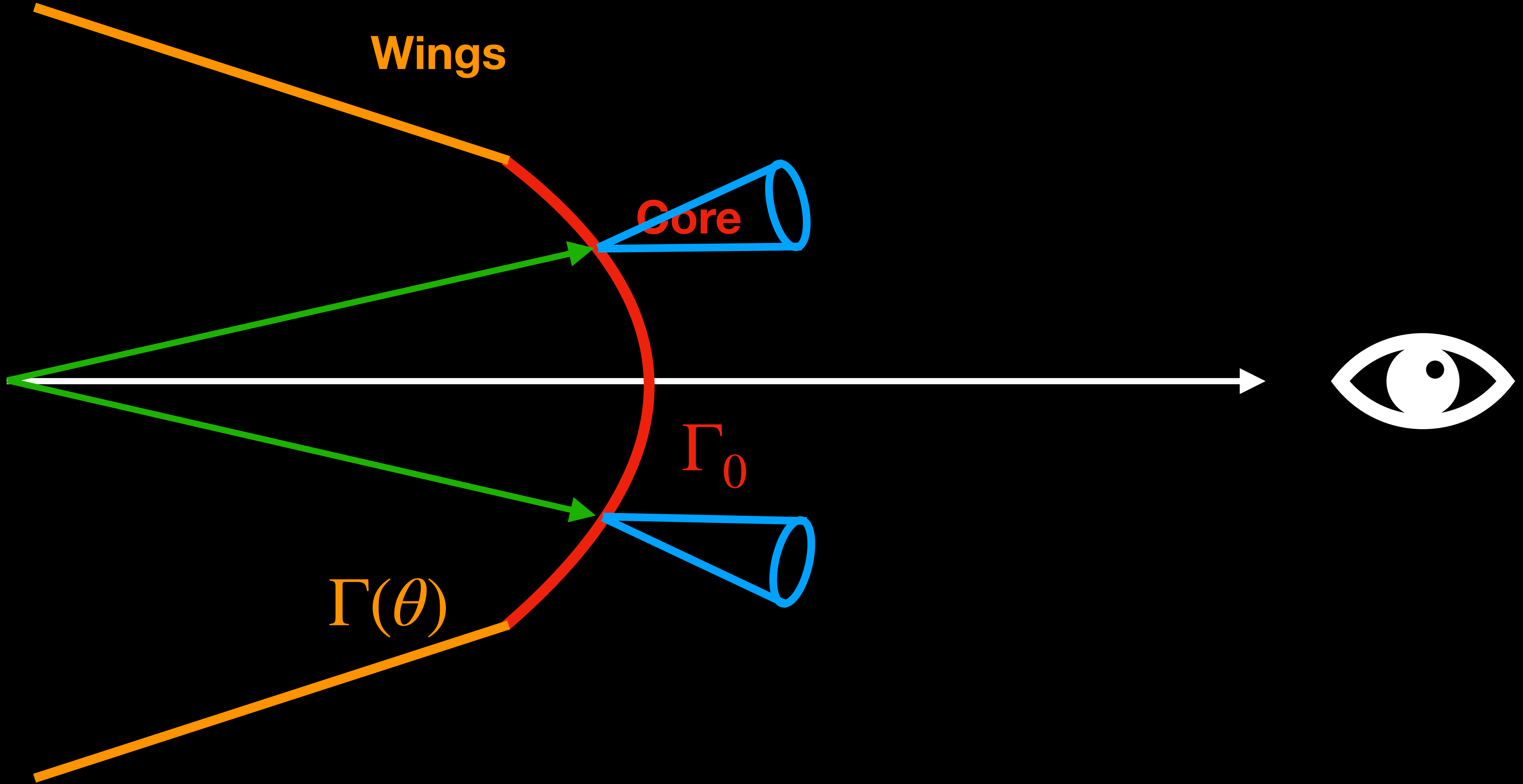

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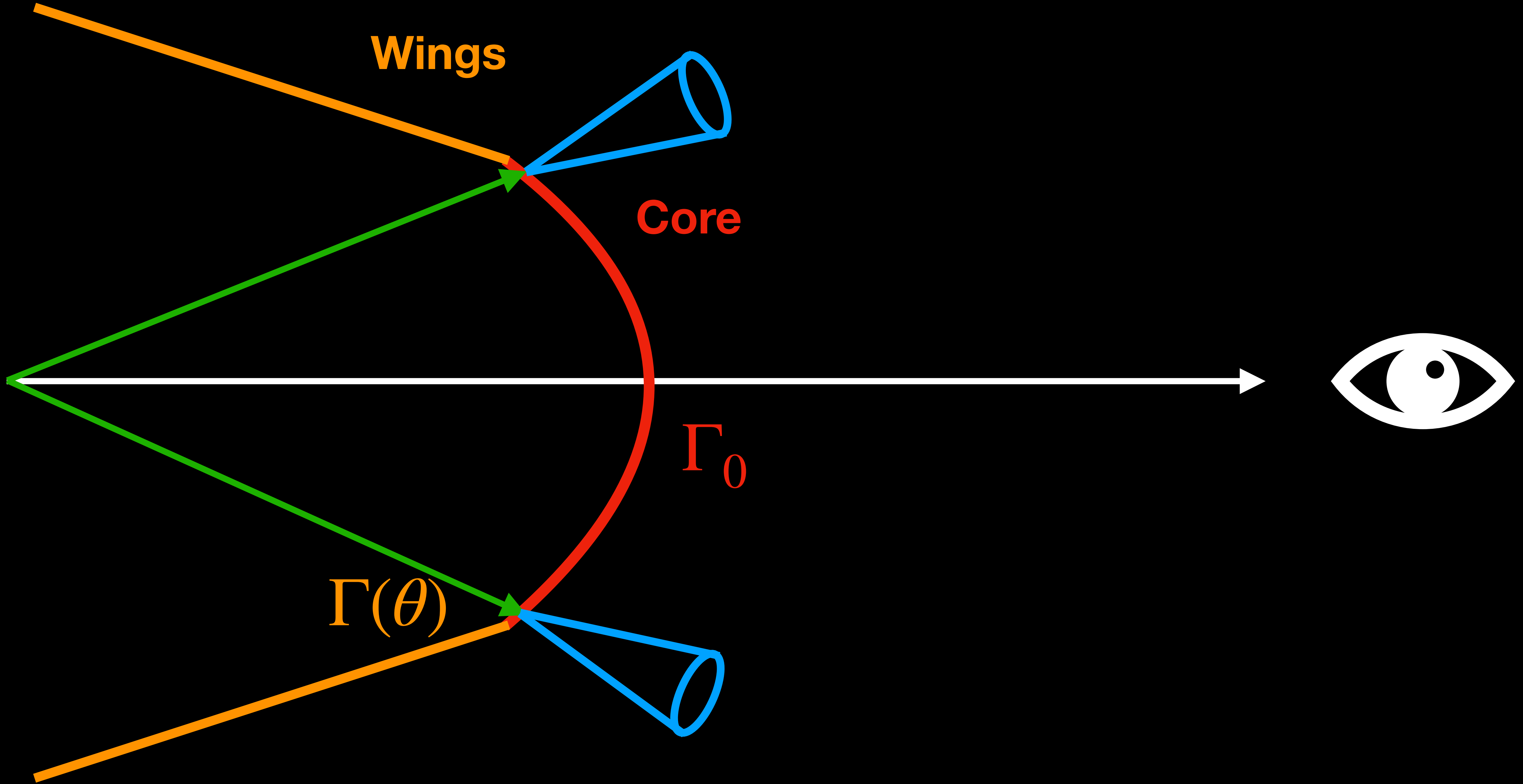

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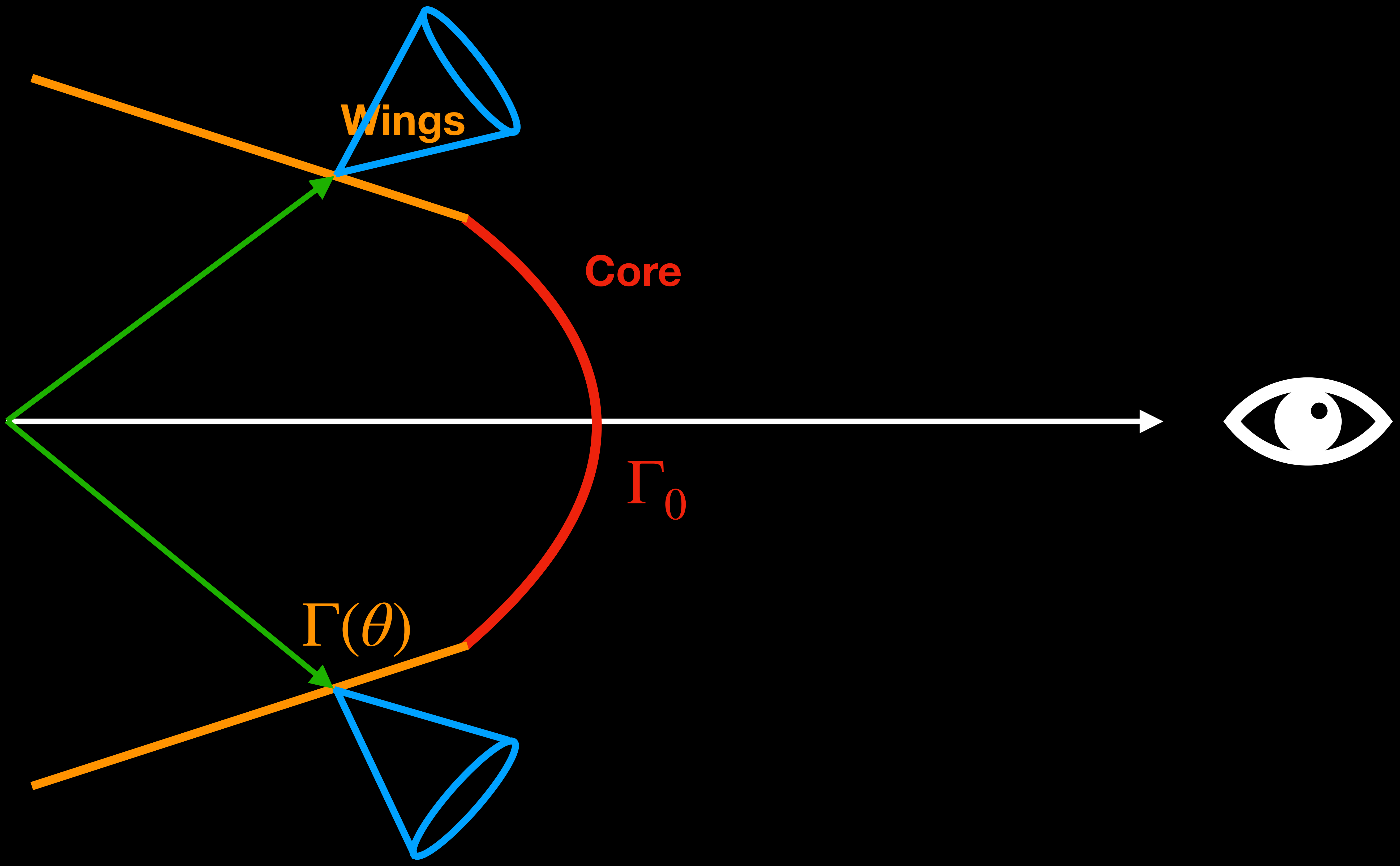

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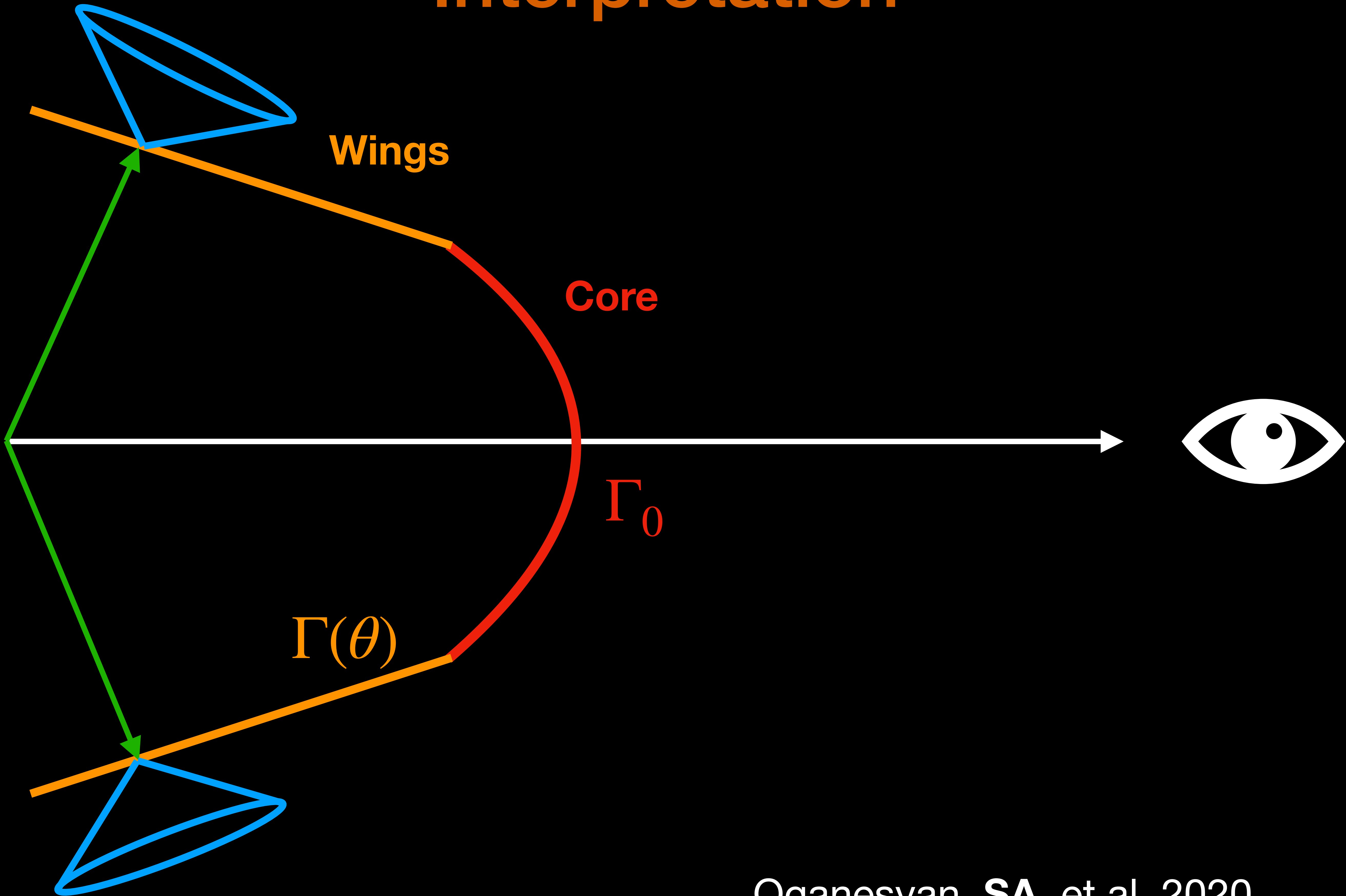
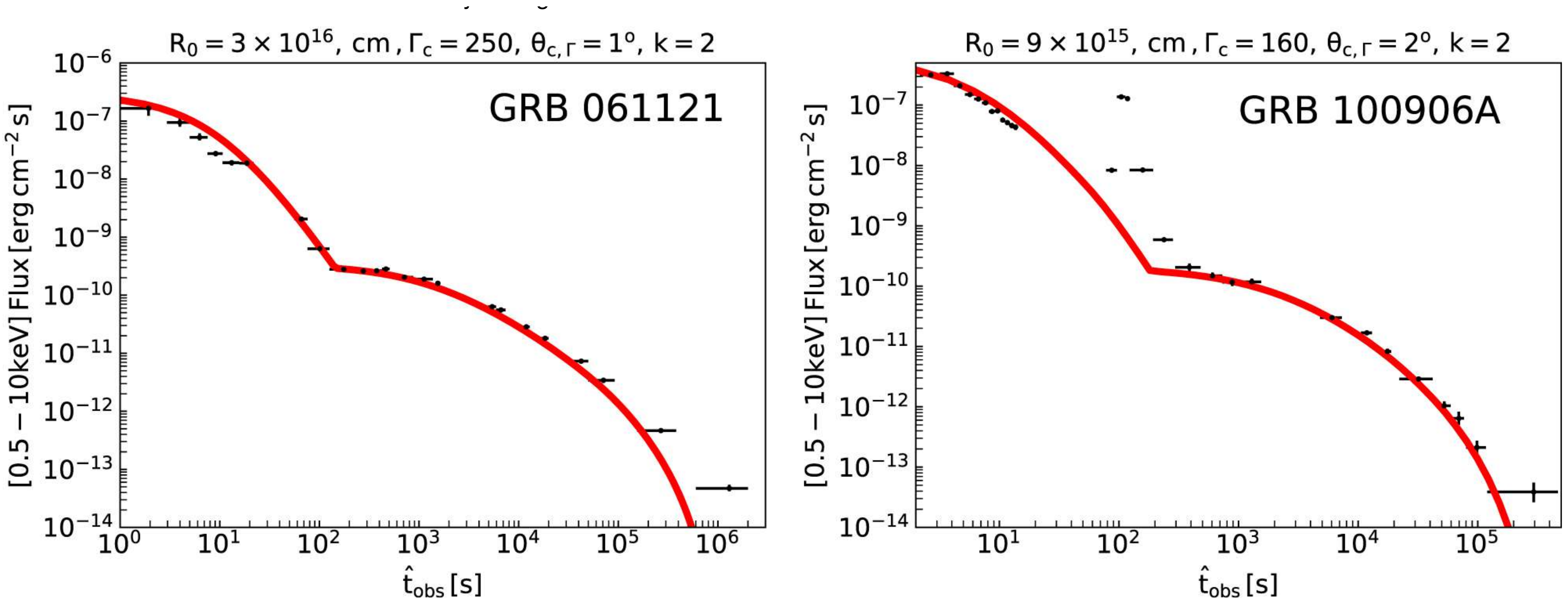


Oganesyan, **SA**, et al. 2020

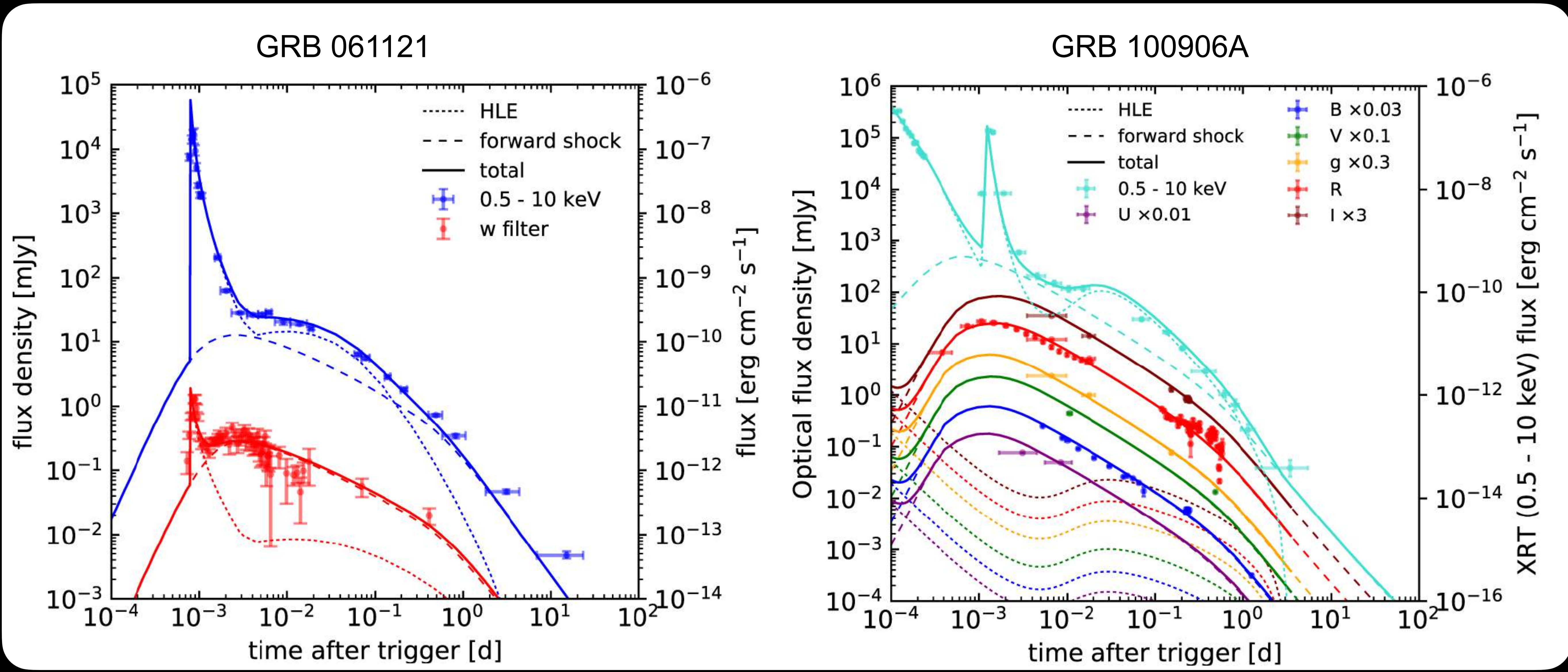
Comparison with Data



Oganesyan, **SA**, et al. 2020

Comparison with Data and the Forward Shock

Oganesyan, **SA**, et al. 2020



Conclusions

- The FS can contribute to the Plateau
- The HLE contributes (or domininates) the X-ray light curve, but the optical light curve is due to FS. This explains the chromaticity!

Steep Decay + Plateau

The High Latitude Emission (HLE) Model

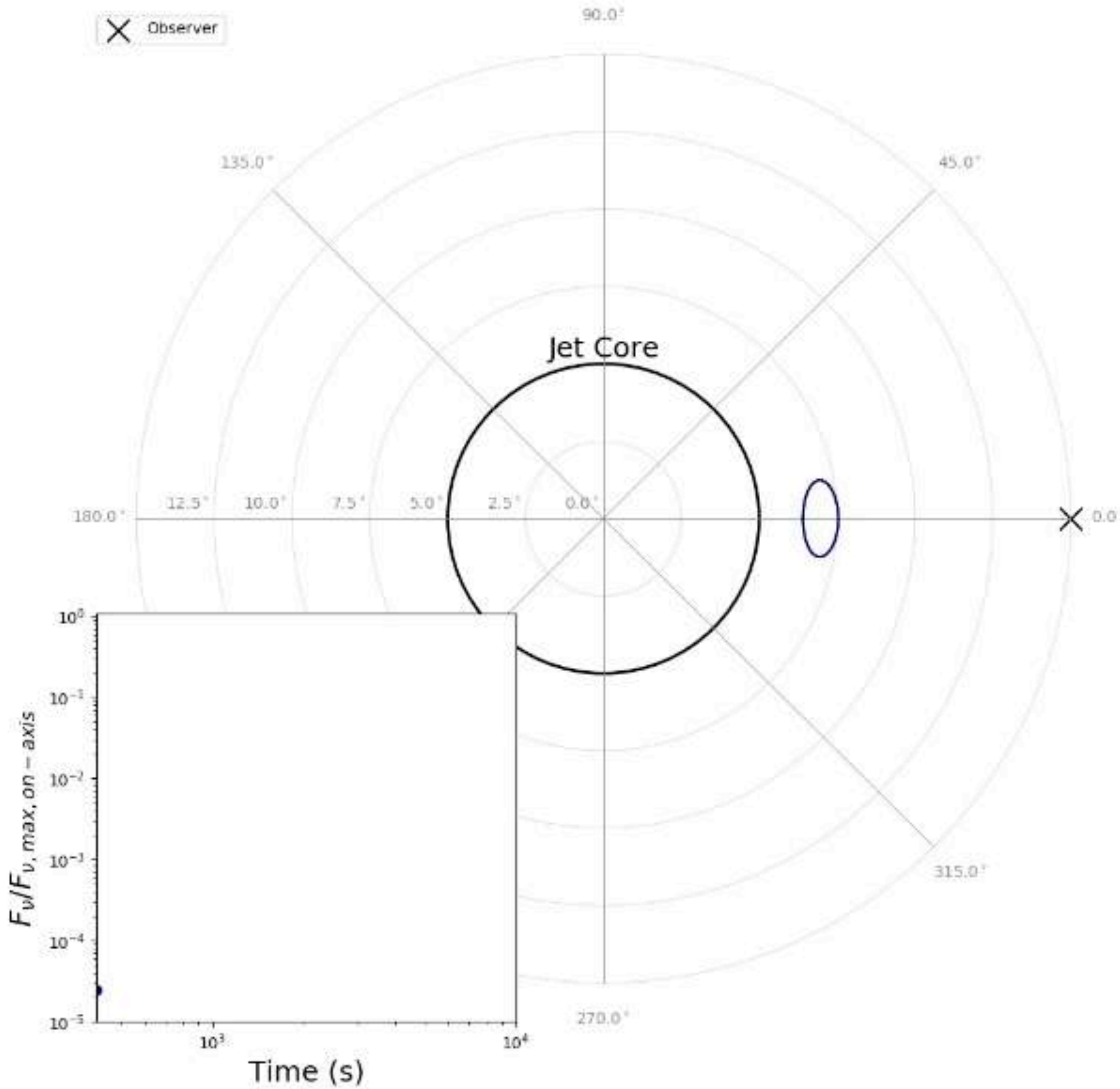
SA, Oganesyan et al. 2020

Same Assumptions

- Structured emitting surface
- Same spectrum everywhere

Relaxed Assumptions

- Instantaneous and non-instantaneous emission
- Structured opacity
- Arbitrary observer



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$F_\nu/F_{\nu,\,max,\,on-axis}$
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10^{-2}
10^{-3}
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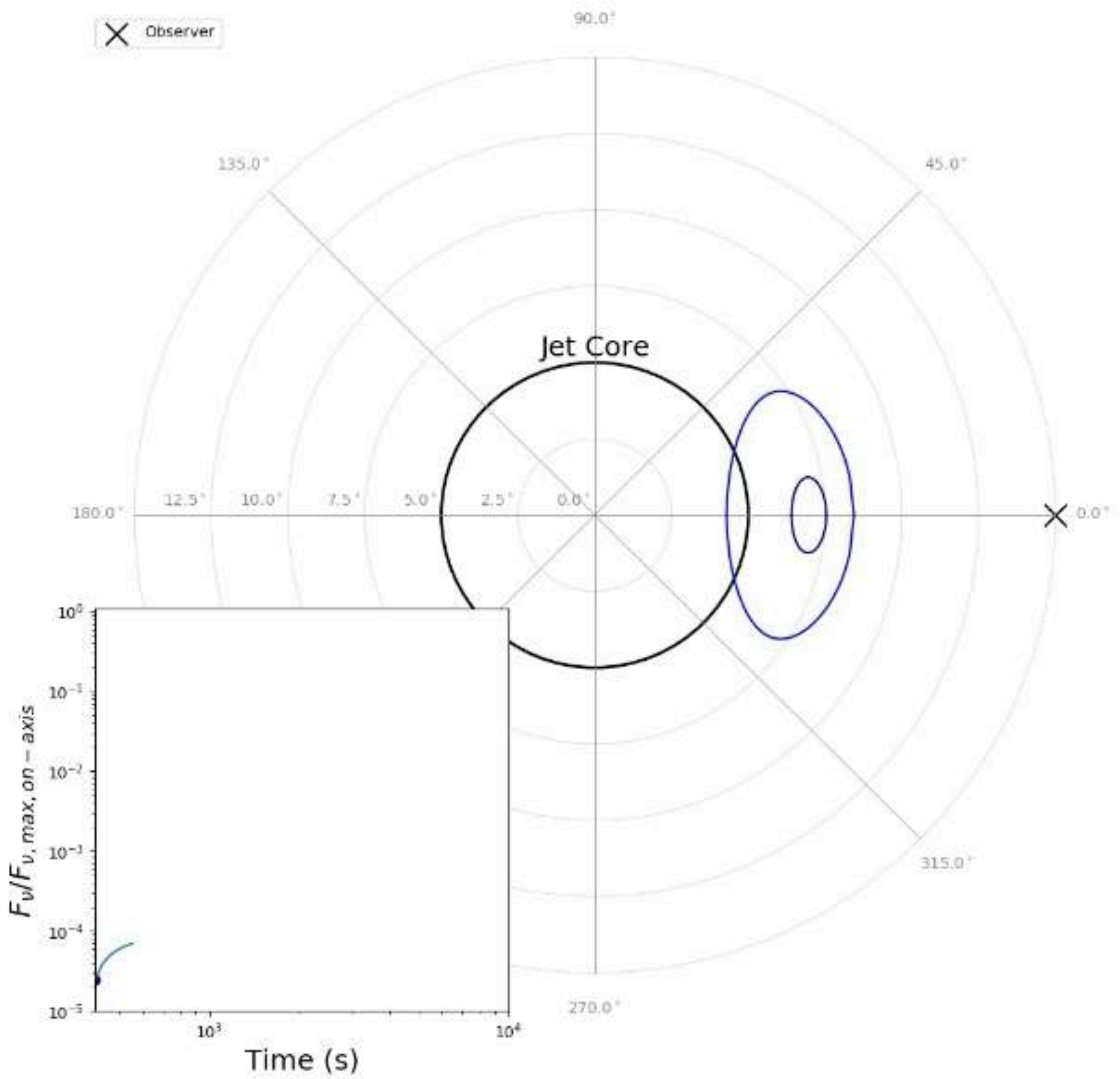
10^{-5}
10^3
10^4
Time (s)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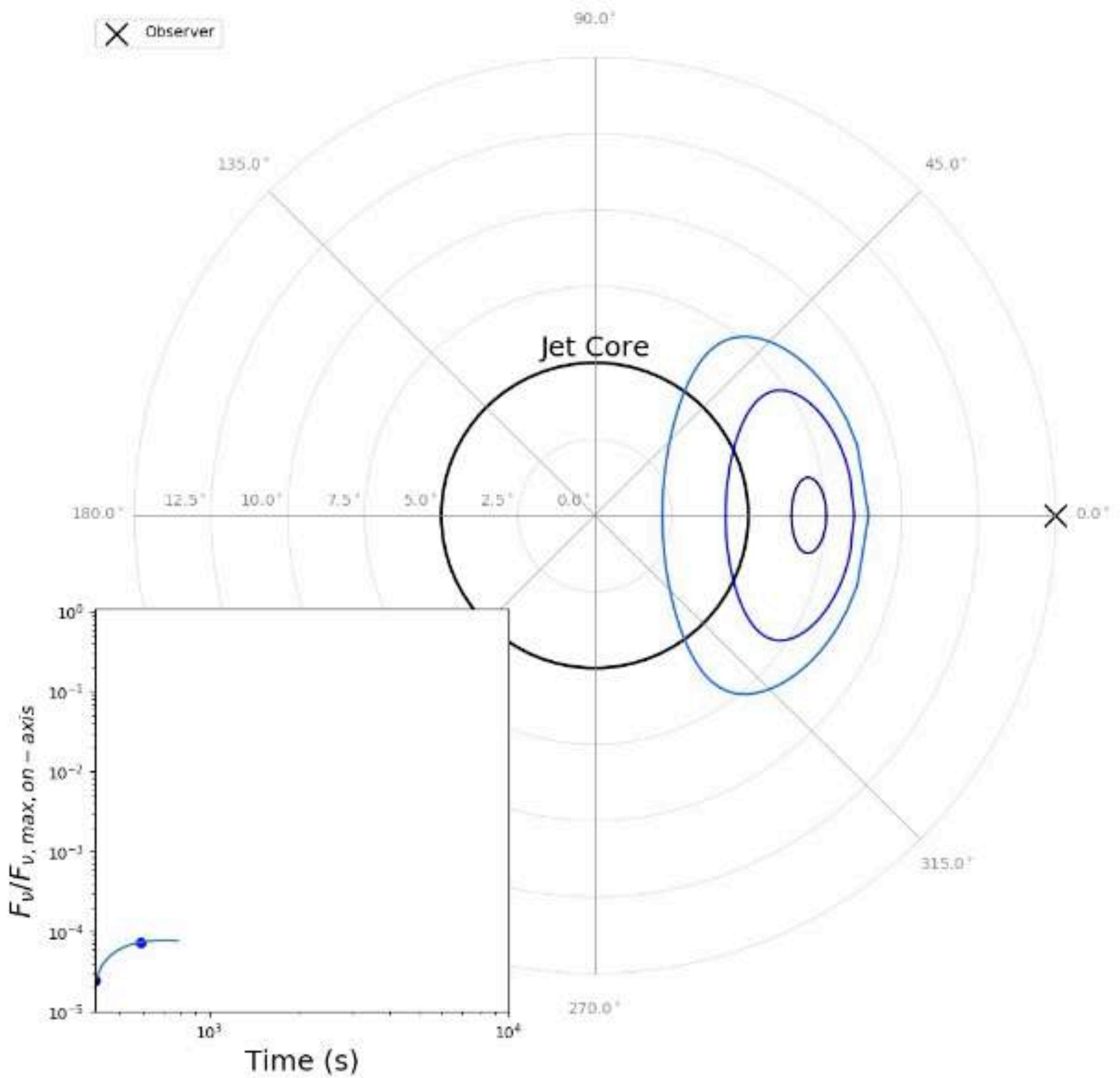

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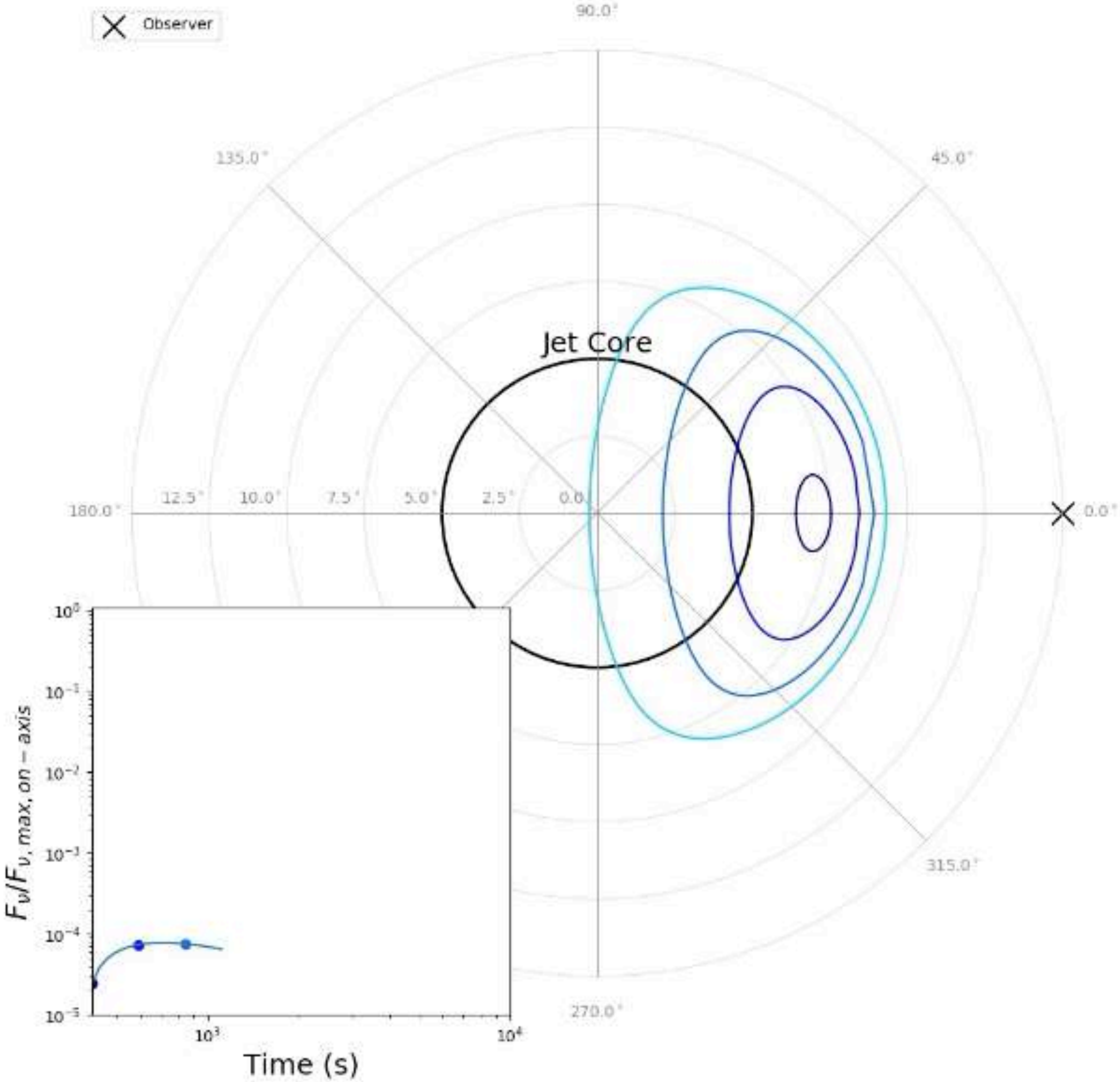

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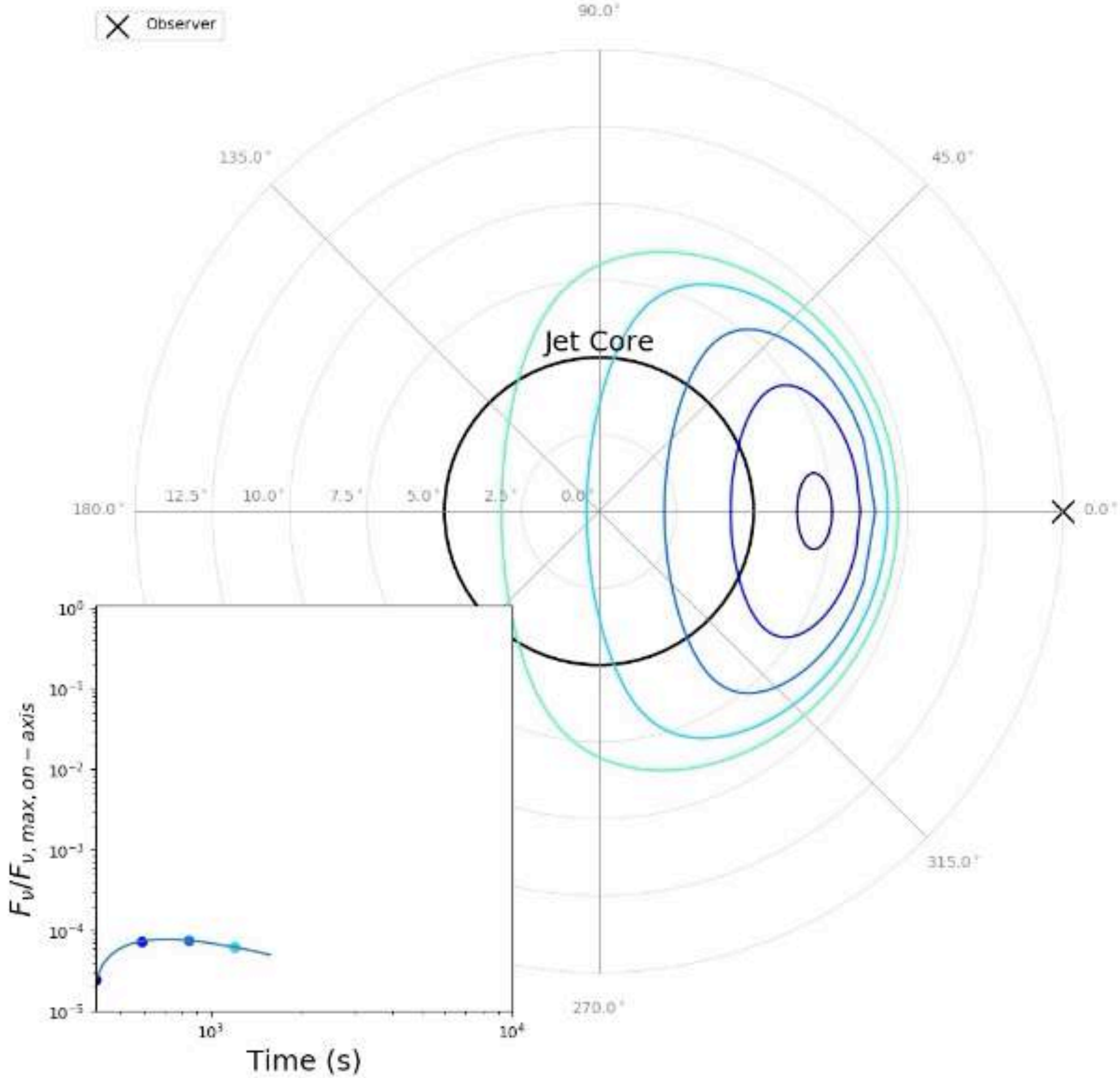

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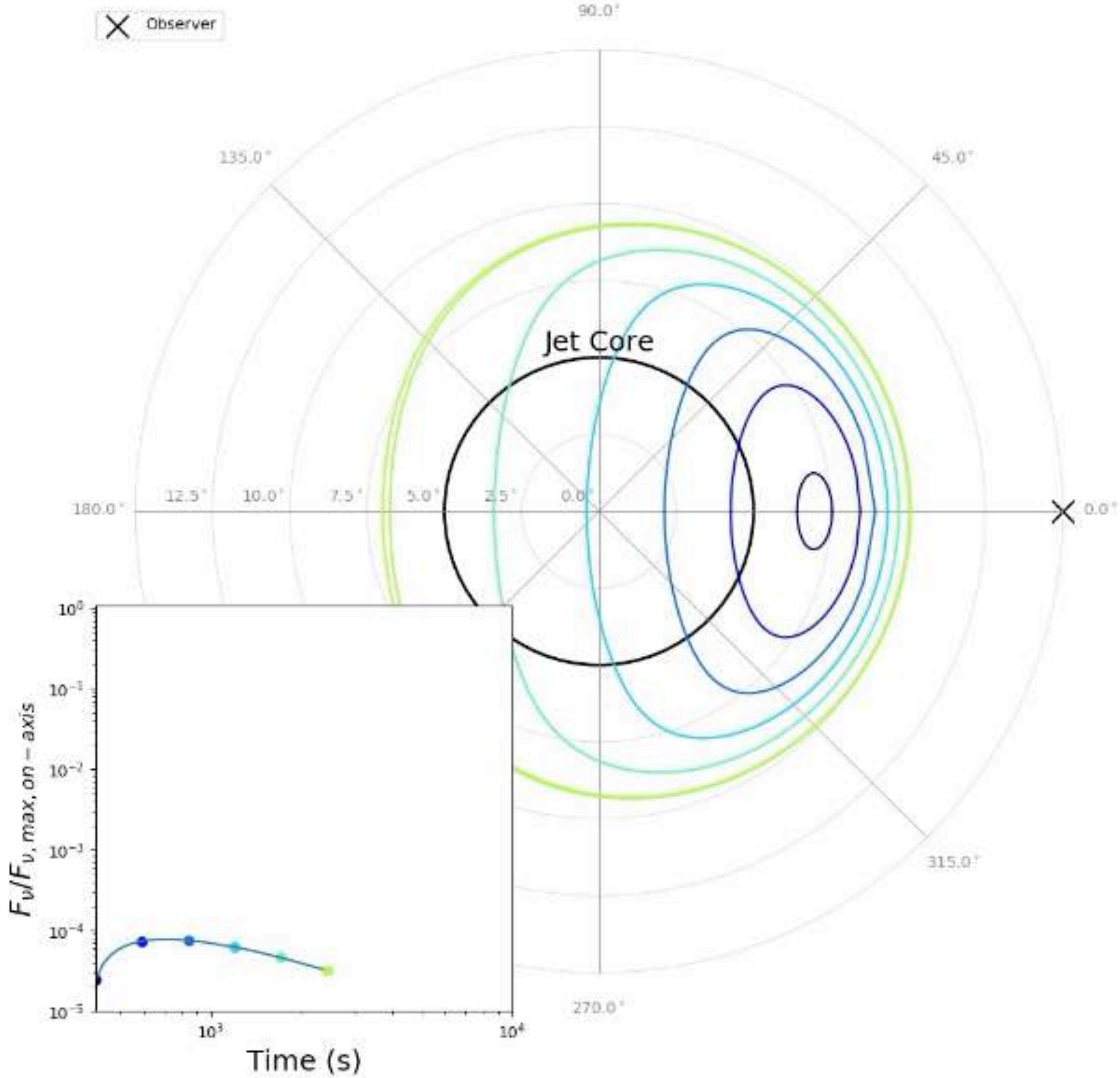

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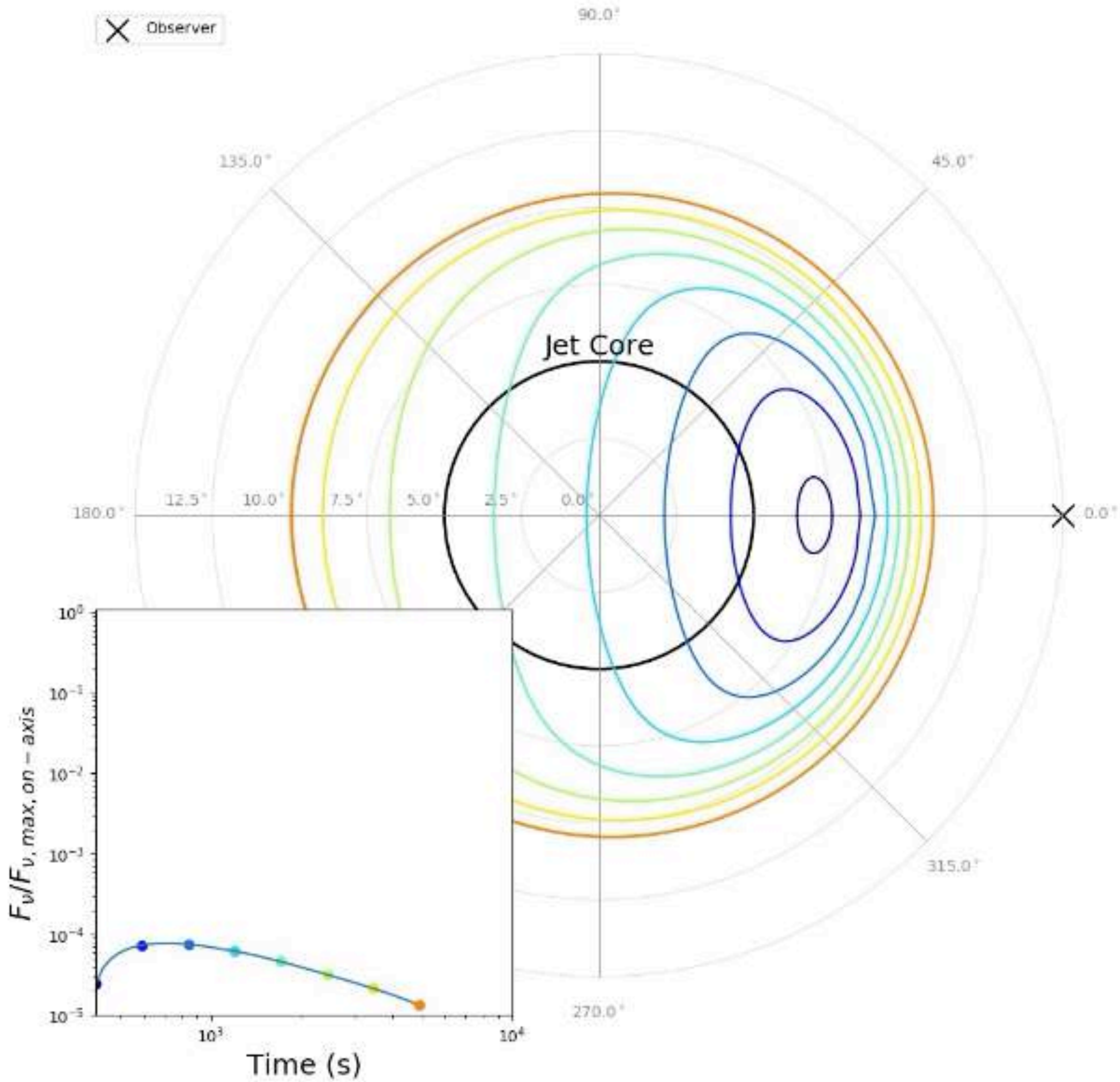

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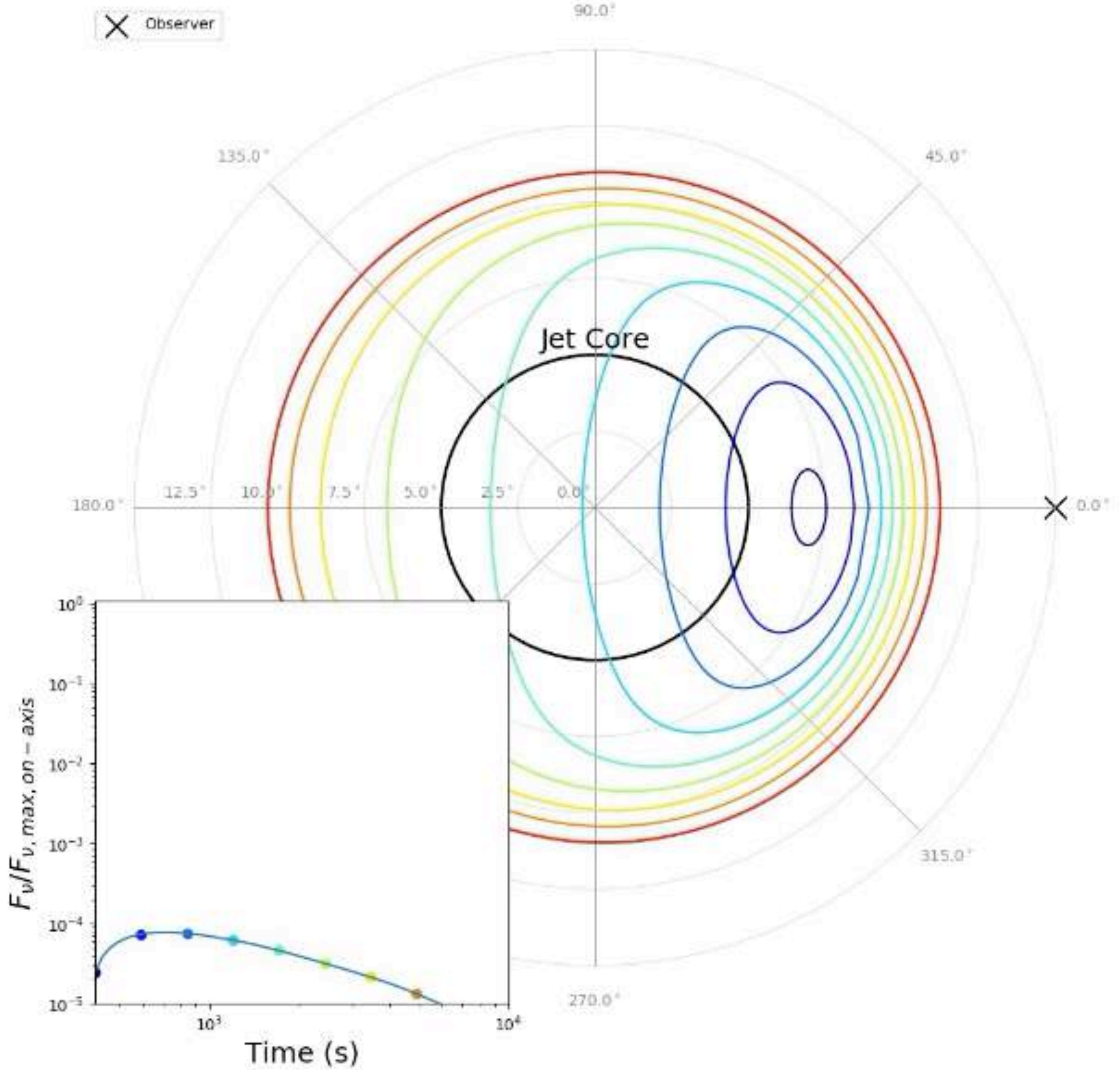
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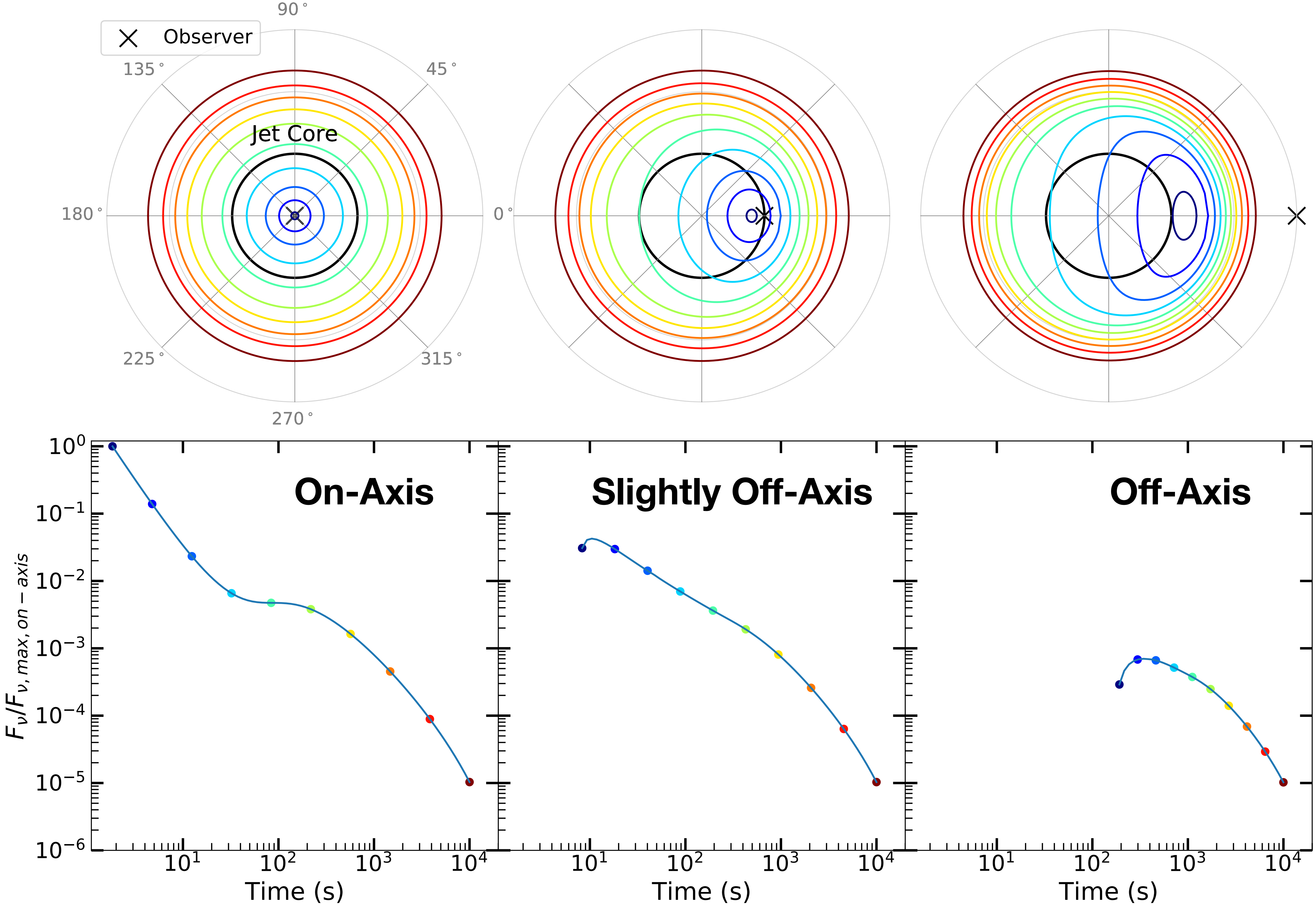
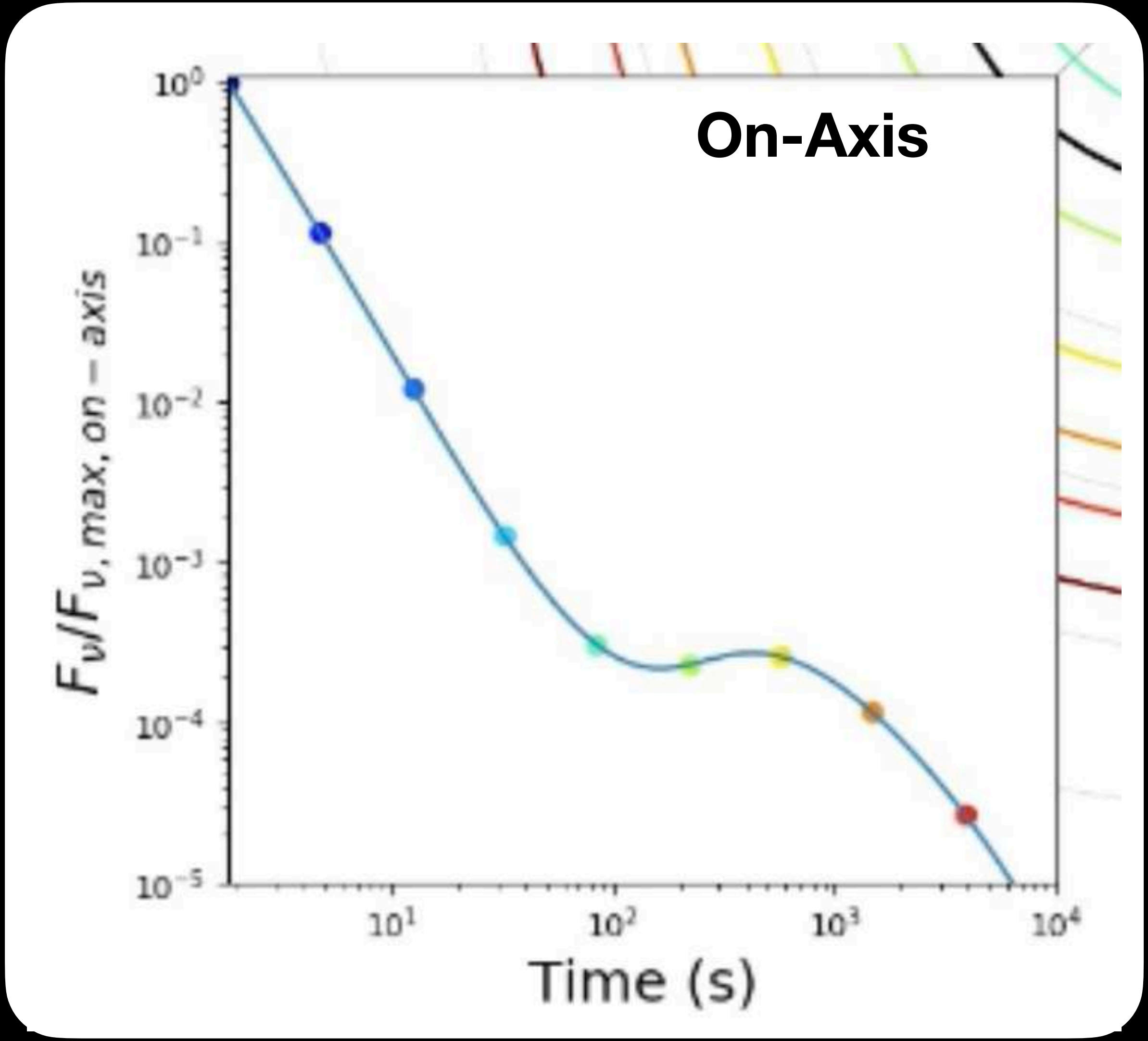
7.5°
5.0°
2.5°
0.0°
0.0°
315.0°
270.0°
$F_\nu/F_{\nu,\,max,\,on-axis}$
Time (s)

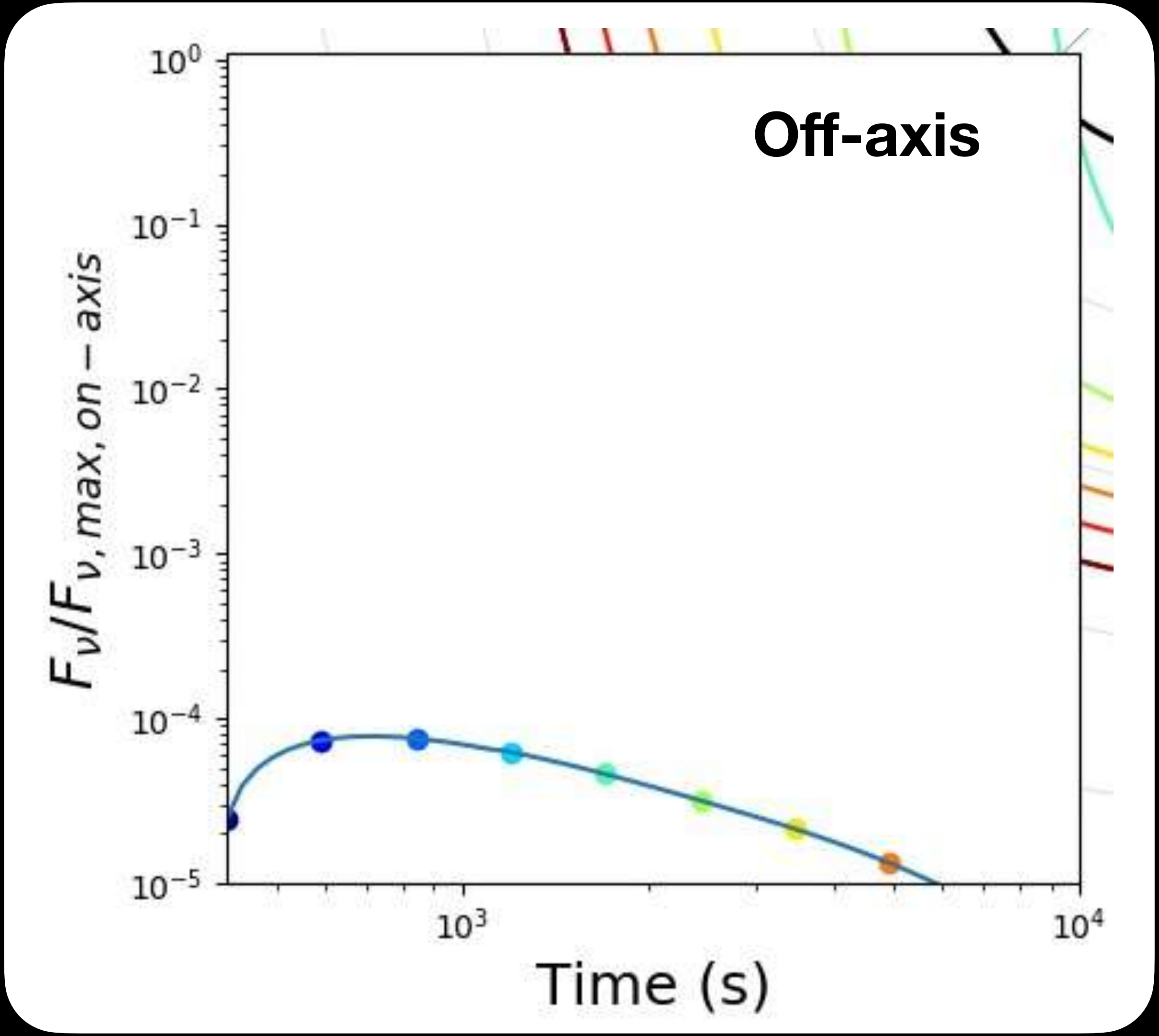


SA, Oganesyan et al. 2020

ON-AXIS →
- Both steep decay and plateau are due to prompt emission!

OFF-AXIS →
- No steep decay + plateau phases
- Lower luminosity
- Later onset





ON-AXIS

- Both steep decay and plateau are due to prompt emission!

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- No steep decay + plateau phases
- Lower luminosity
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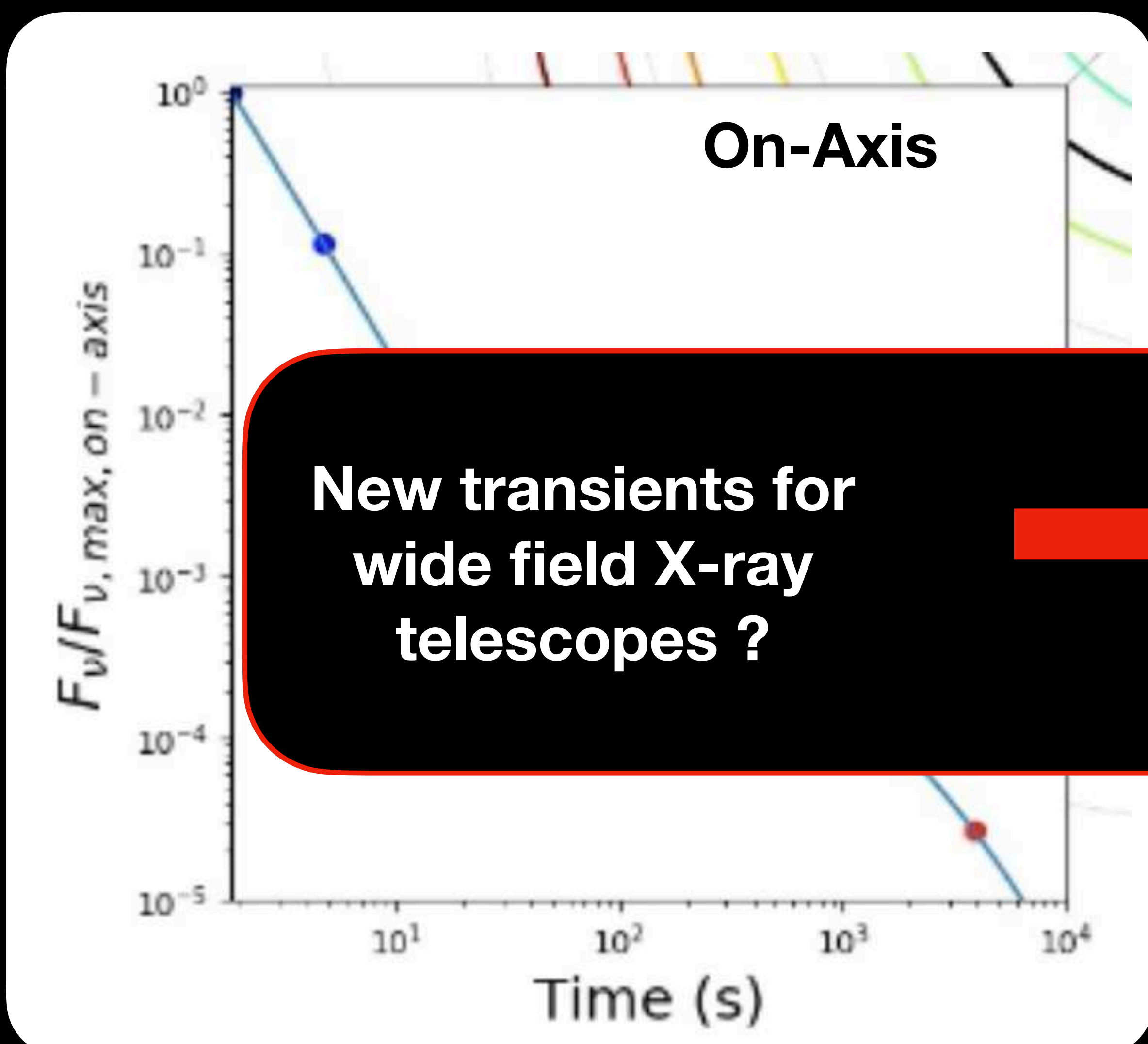
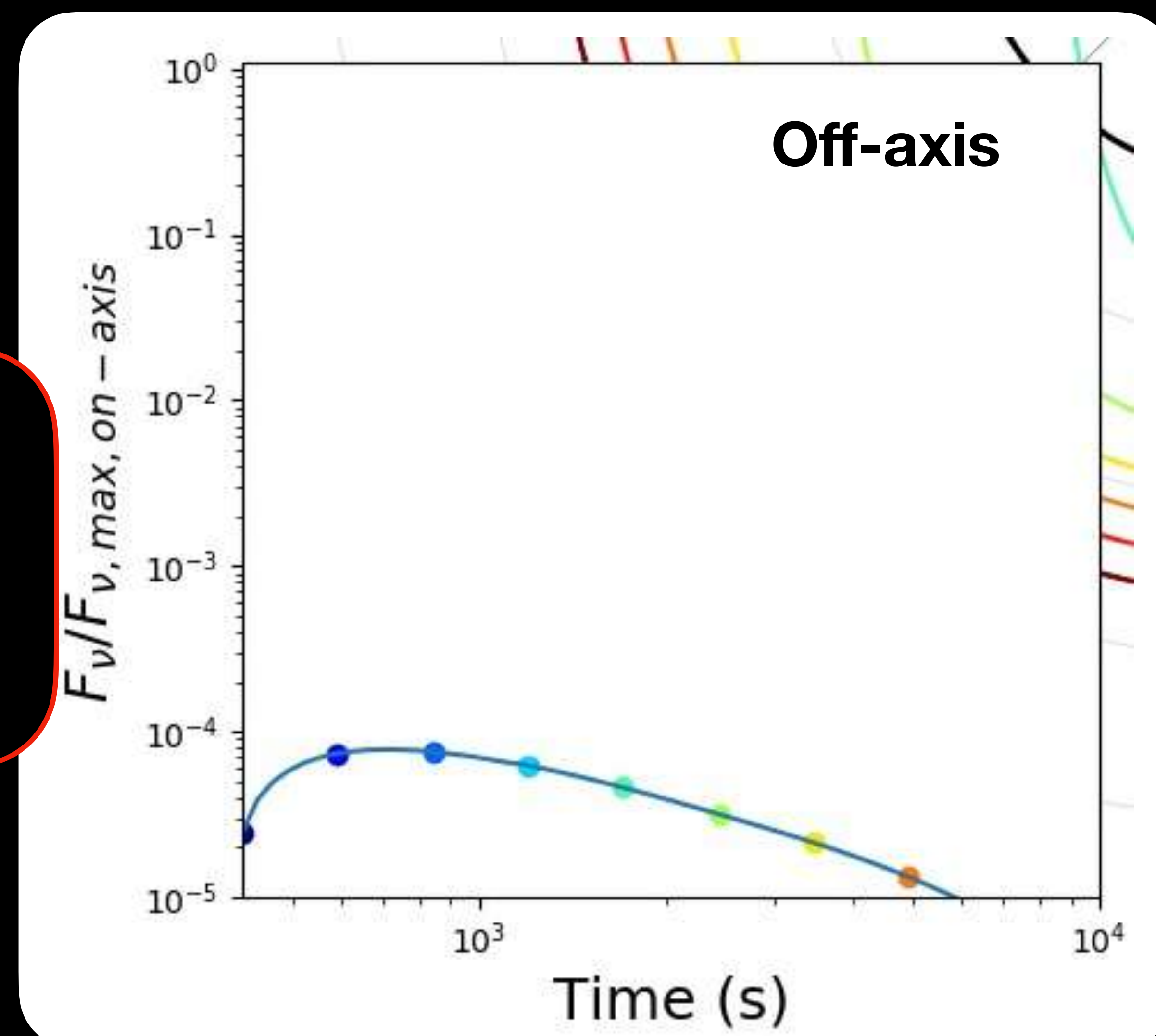
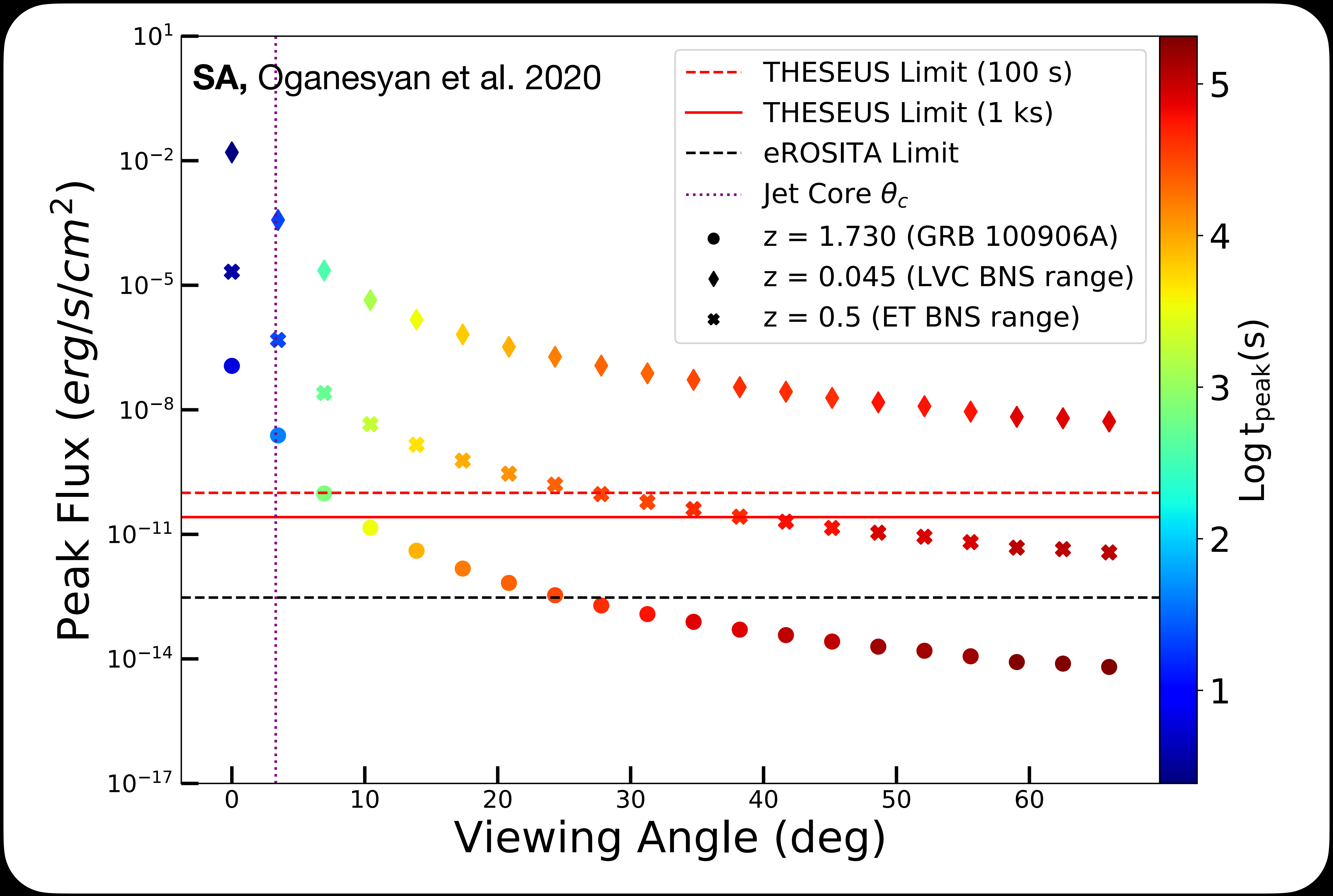


New transients for wide field X-ray telescopes ?



Prospect for Detection



Open Problems

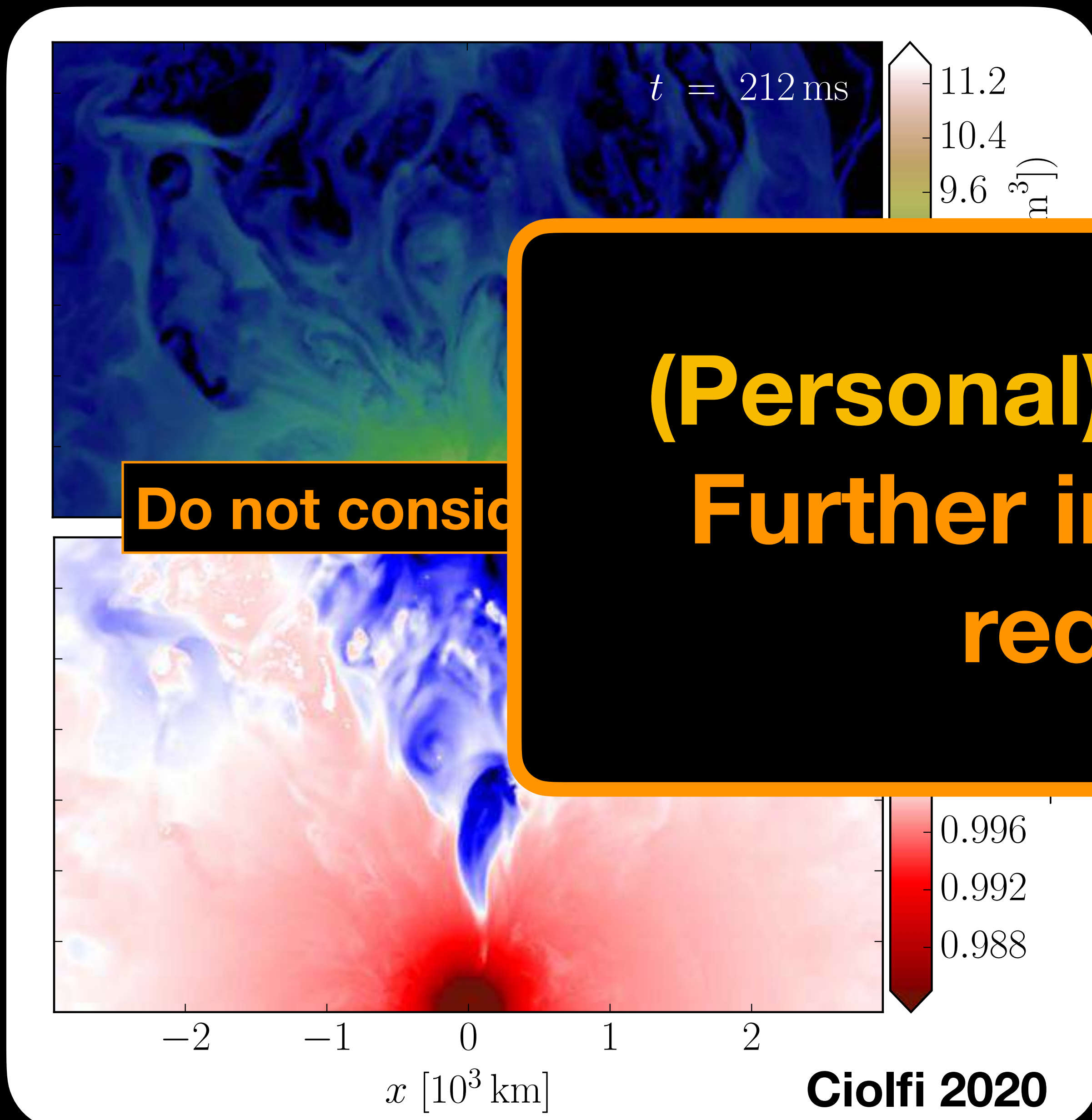
- Correlations NOT tested. To explains difference in duration and luminosities, non-universal jet structure is required
- Our model cannot easily explain an hardening of spectrum during plateau
- Our model cannot easily explain very long duration ($> 10^4\ s$) plateaus

Summary

- We proposed a model based on **High Latitude Emission** effect that predicts a softening after the steep decay, occurring when the jet is structured
- The X-ray flux is comparable to the forward shock emission (standard afterglow), while the forward shock dominates in optical. This explain the **chromaticity**
- This emission can be observed **off-axis**. Therefore, in the case of Short GRBs, it can constitute a promising electromagnetic counterpart of gravitational waves

Thank you for your attention!

Magnetar as GRB central engine



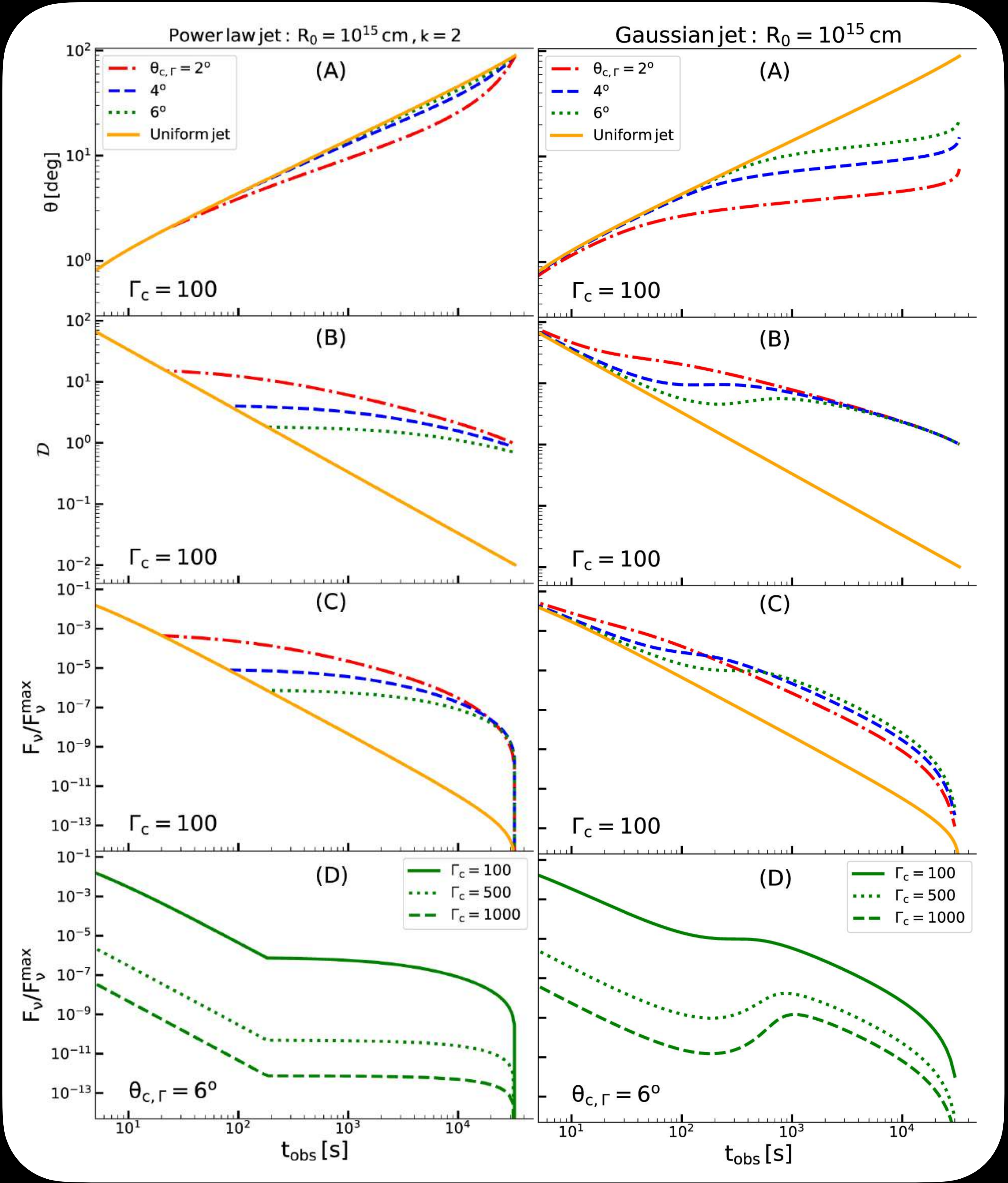
(Personal) Conlcusion: Further investigation required!

A collimated outflow is produced, but it is far too heavy to be accelerated to $\Gamma \geq 10$

Magnetars cannot power GRBs!

When neutrinos are included they sweep away material around the axis, helping the jet formation

Magnetars can power GRBs!



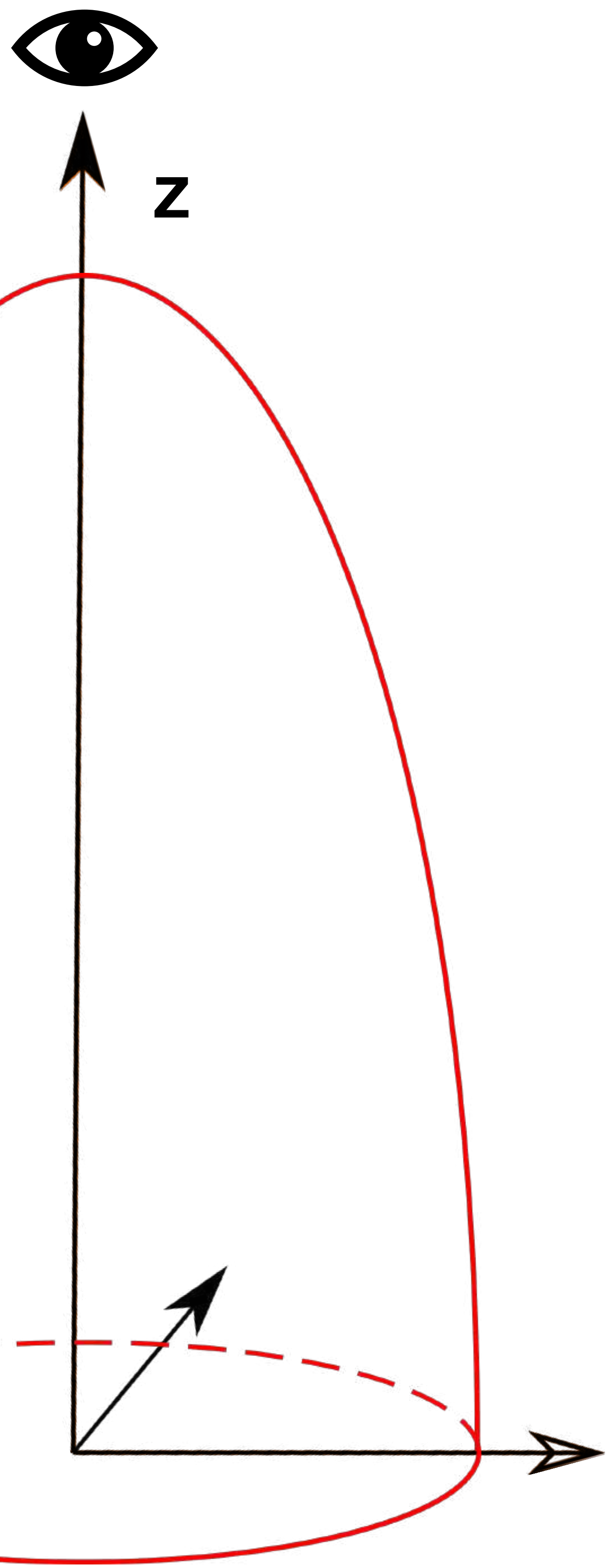
Doppler Factor

$$D(\theta) = \frac{1}{\Gamma(\theta)[1 - \beta(\theta)\cos\theta]}$$

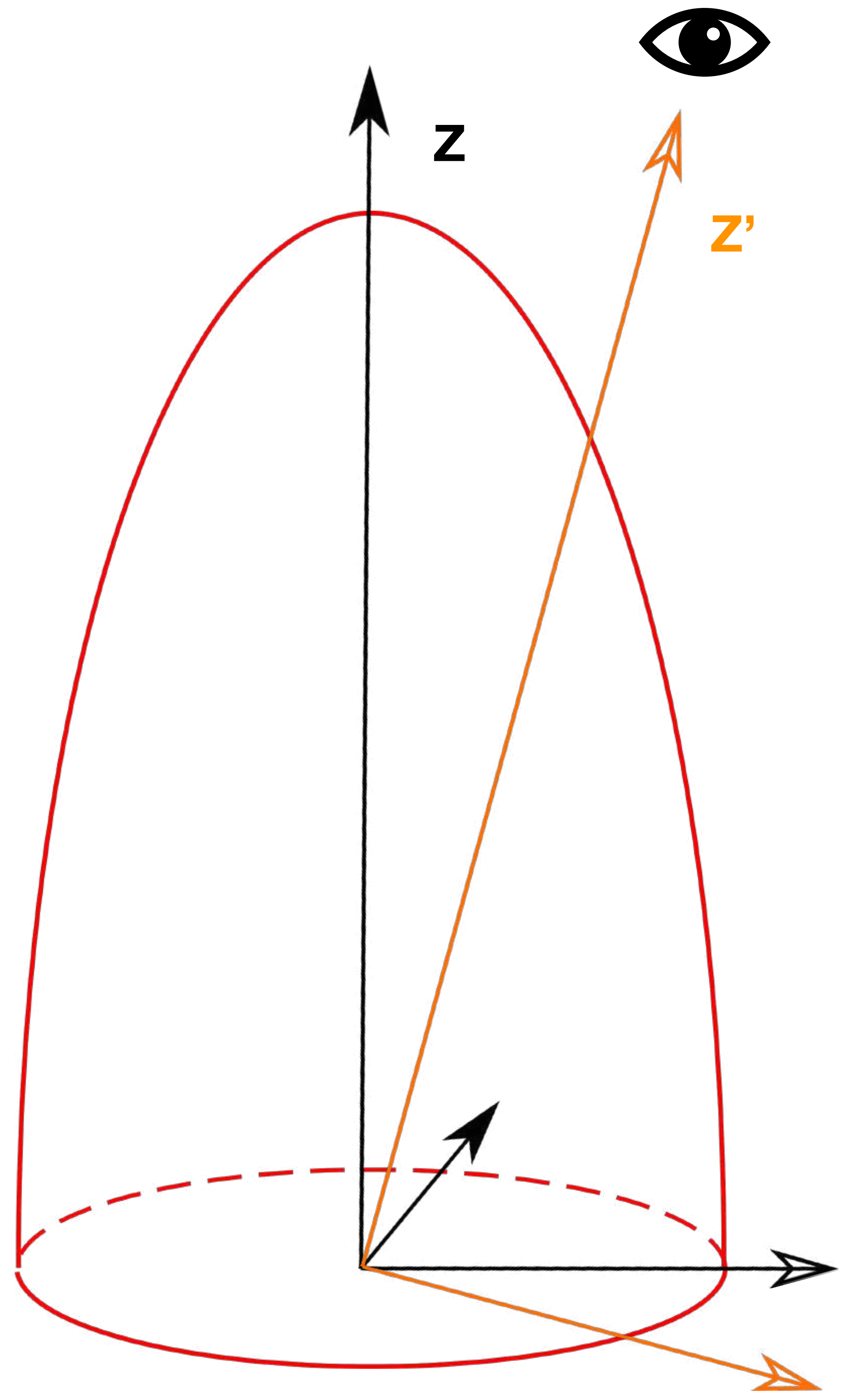
Lightcurves

Oganesyan, **SA**, et al. 2020

Off-Axis case



Off-Axis case



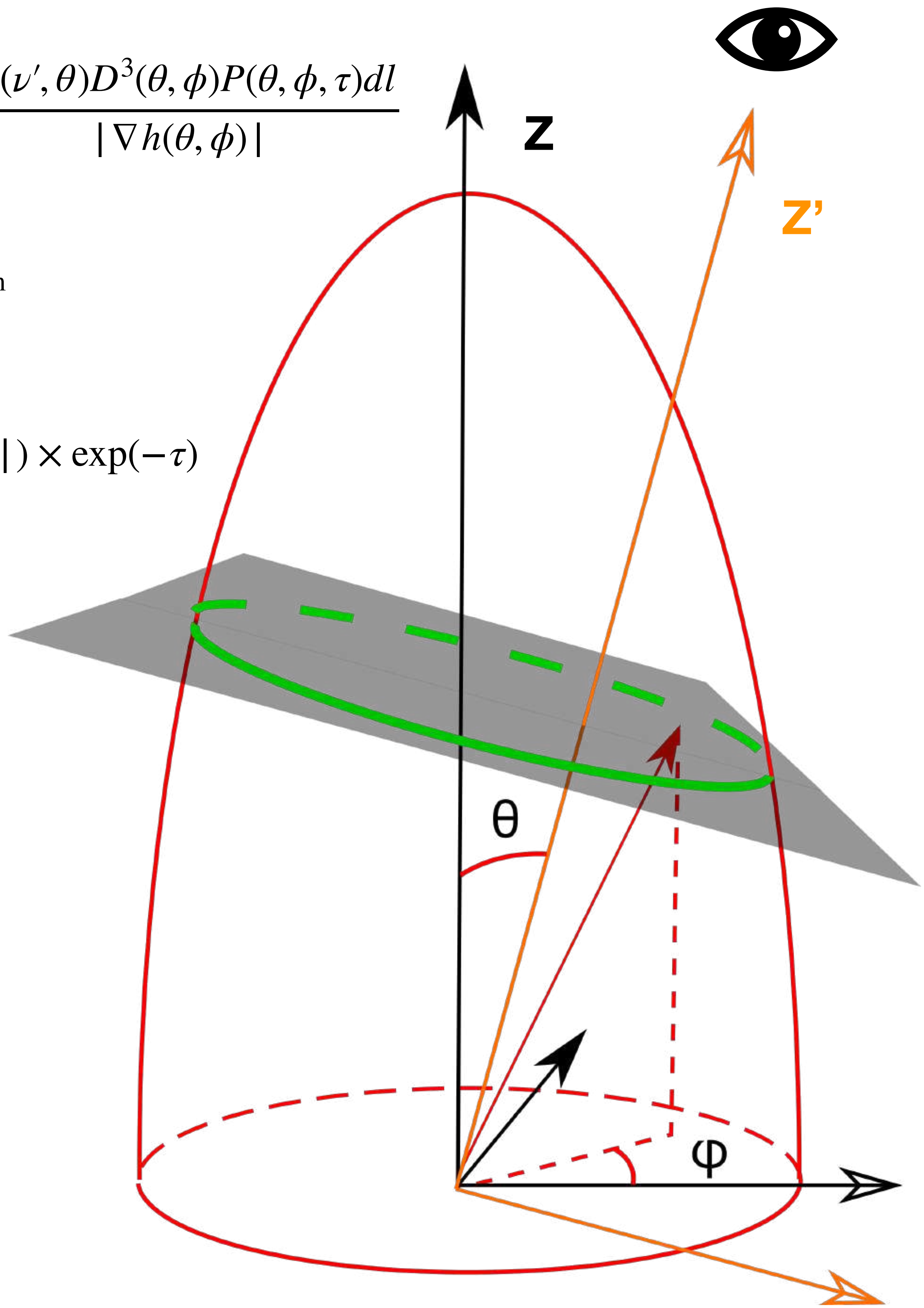
Off-Axis case

$$F_\nu = \int_S I_\nu P(\theta, \phi, \tau) d\Omega_{\rm obs}$$

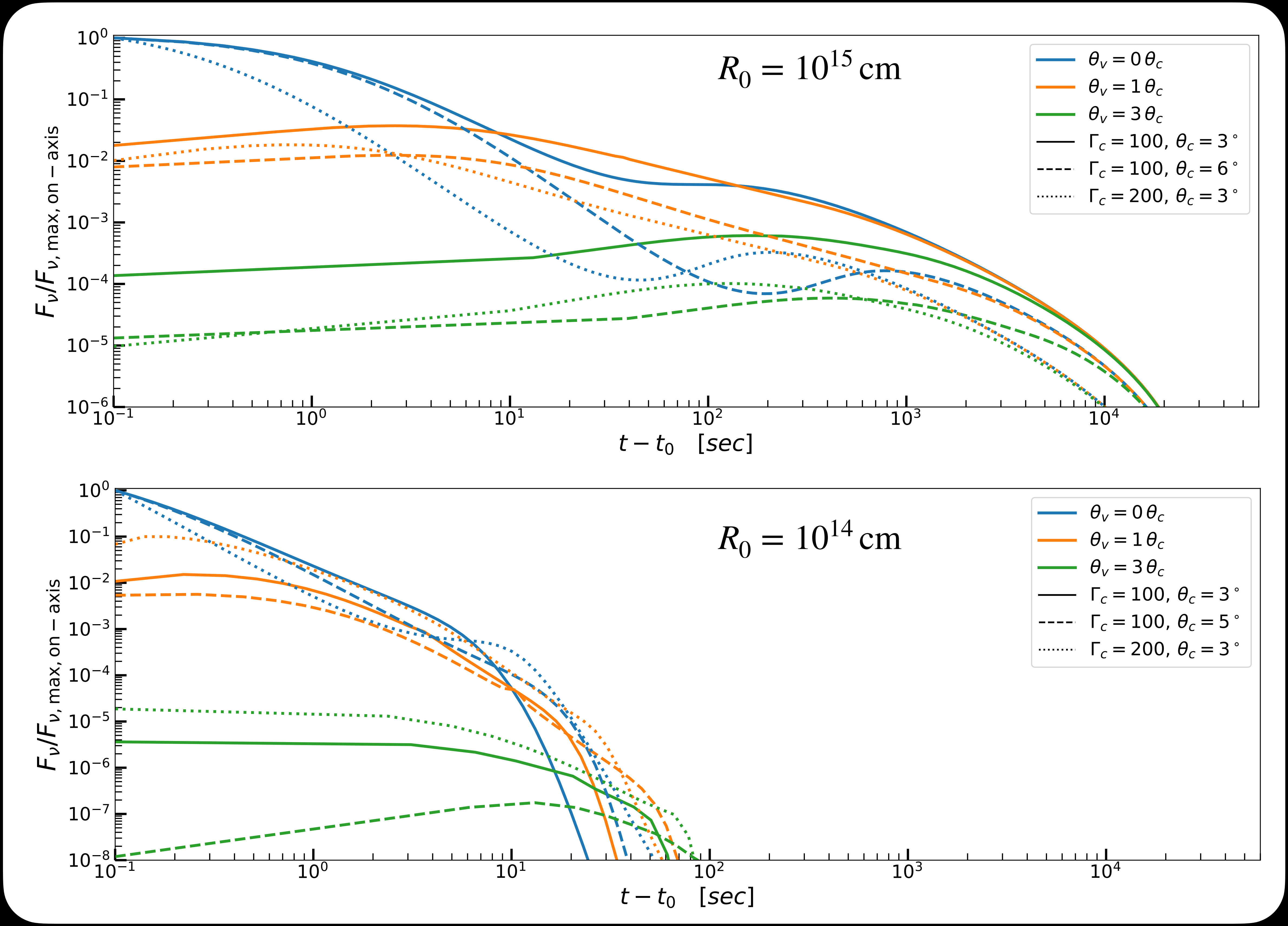
$$F_\nu(t_{obs}) = \frac{1}{d_L^2(1+z)^3} \oint_{EATR} \frac{\eta'_{\nu'}(\nu', \theta) D^3(\theta, \phi) P(\theta, \phi, \tau) dl}{|\nabla h(\theta, \phi)|}$$

$$h(\theta, \phi) \equiv D(\theta, \phi)\Gamma(\theta) t_{\rm obs} - t_{\rm em}$$

$$P(\theta, \phi, \tau) \equiv |\hat{k}' \cdot \hat{n}(\theta, \phi)| + \\ +(1 - |\hat{k}' \cdot \hat{n}(\theta, \phi)|) \times \exp(-\tau)$$

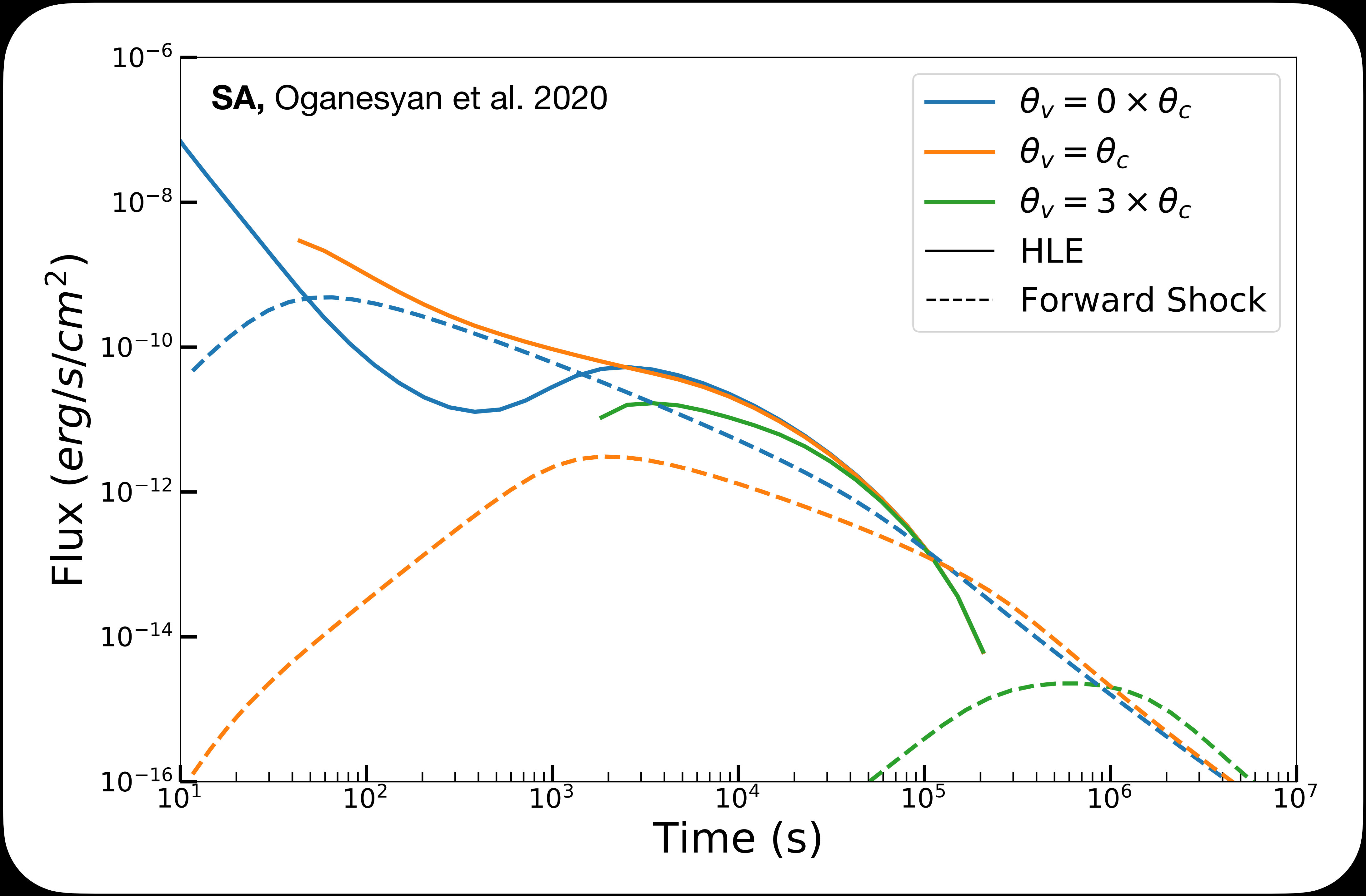


SA, Oganesyan et al. 2020

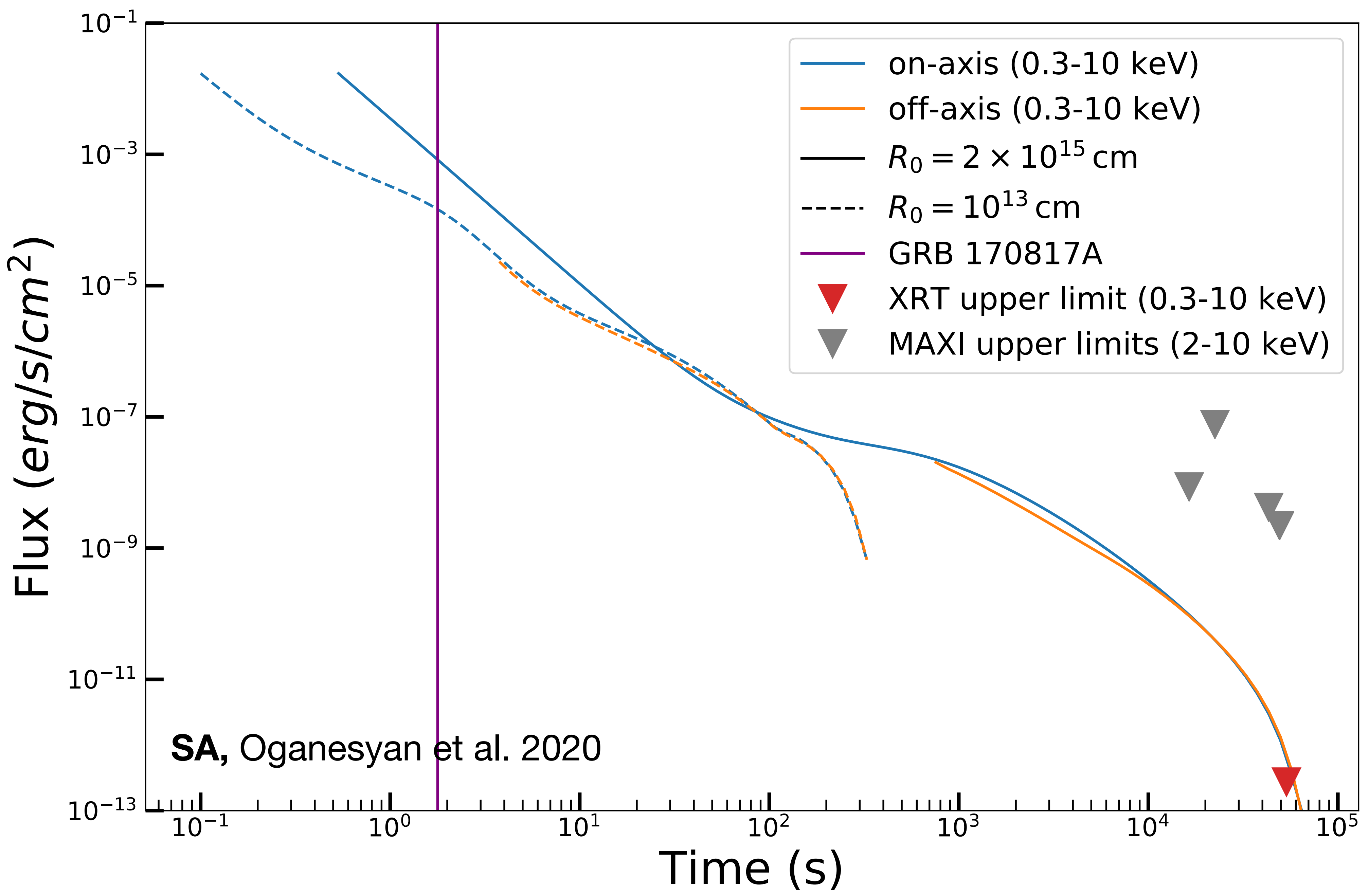


SA, Oganesyan et al. 2020

Comparison with Forward-Shock

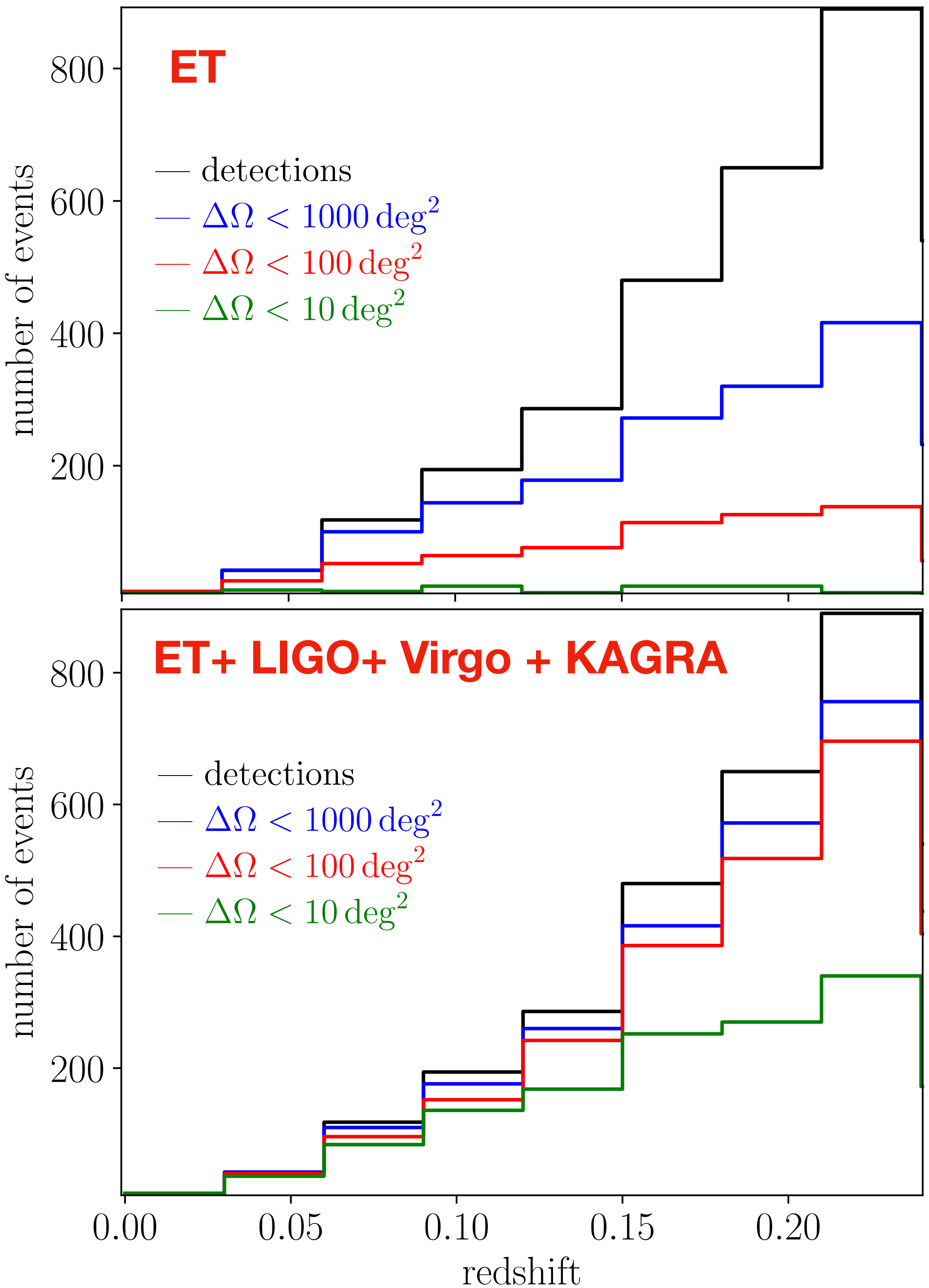


The case of GW170817



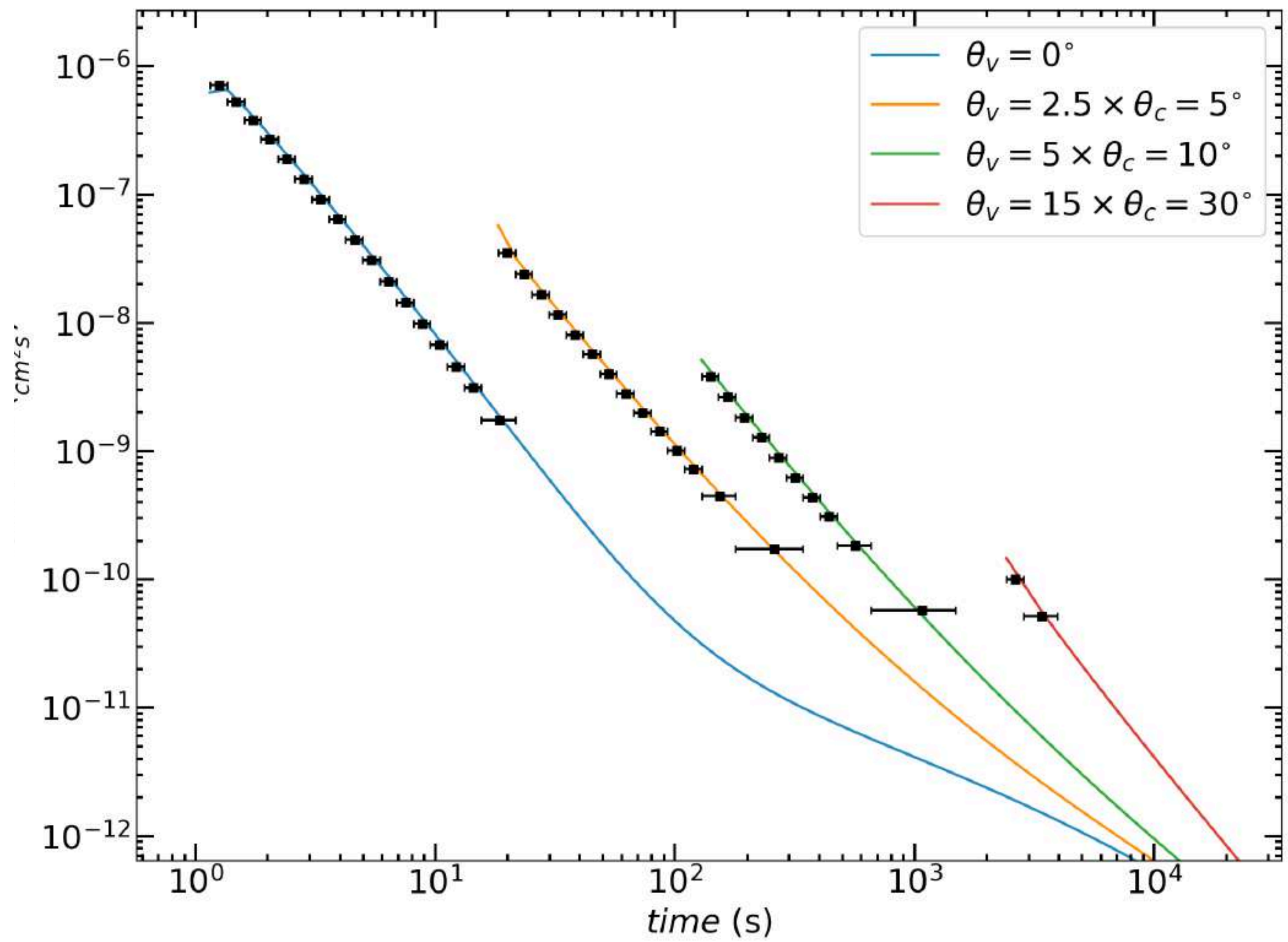
Prospect for Detection

Gravitational Wave



Grimm et al. (in prep.)

THESEUS - SXI

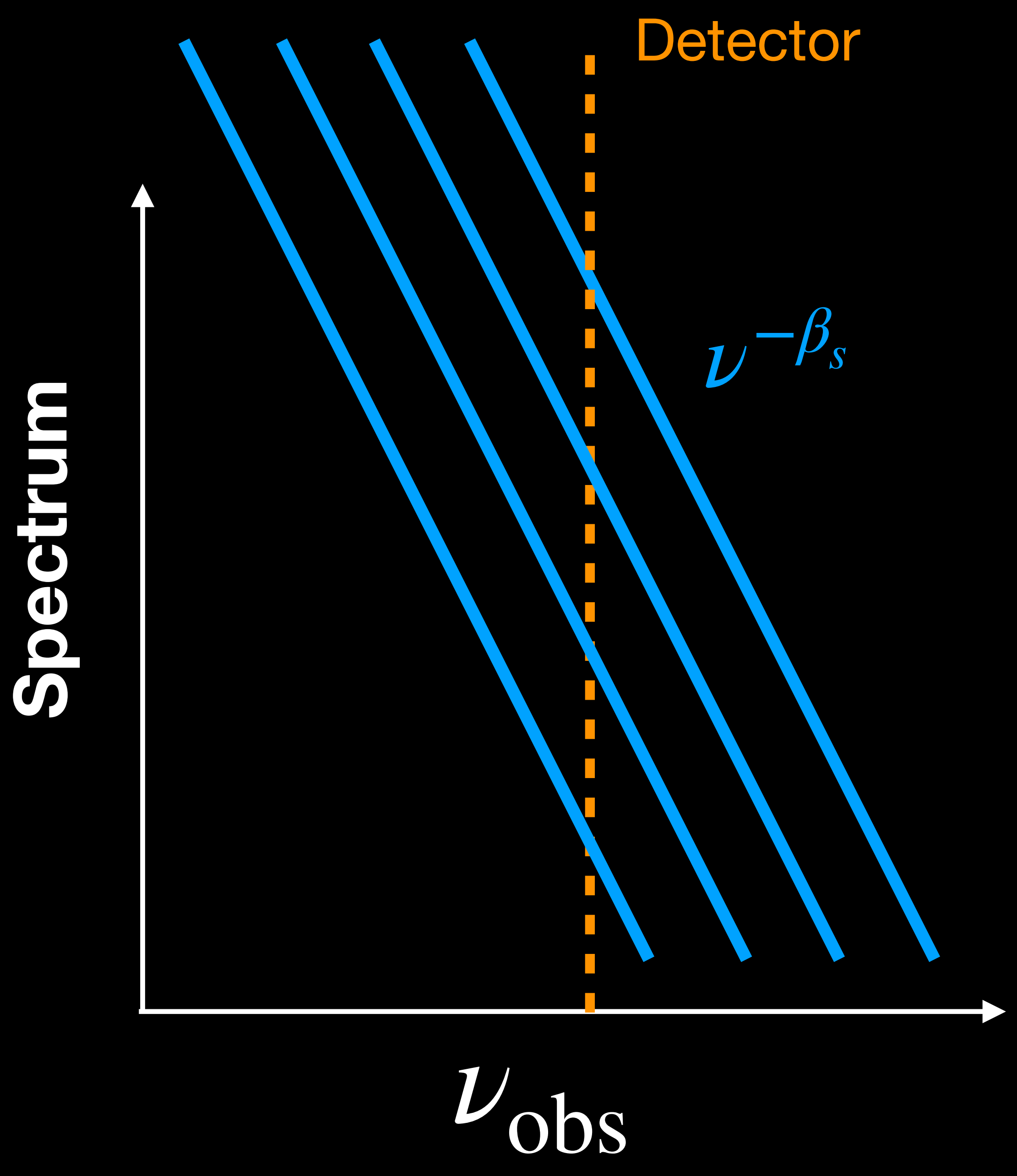


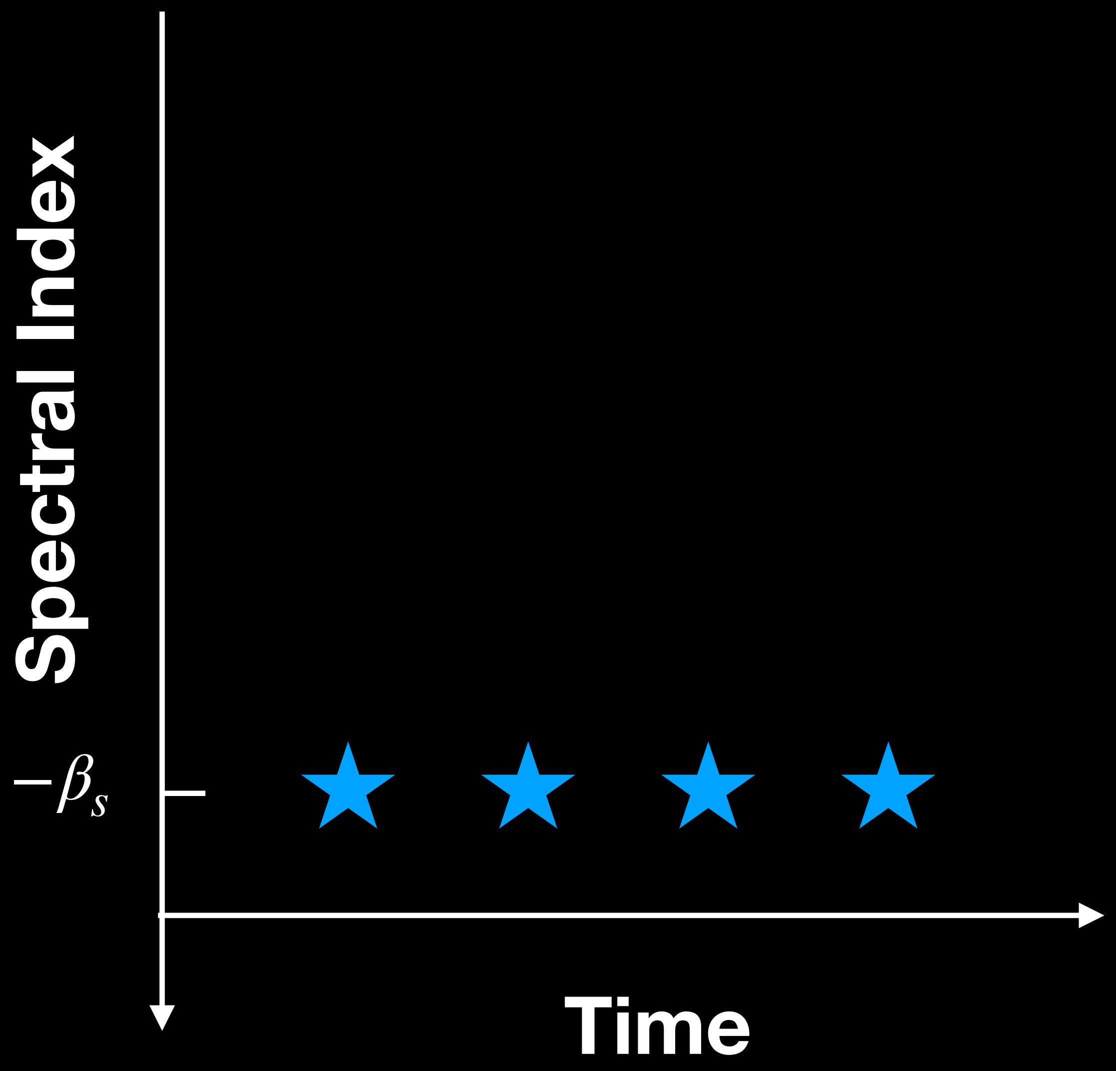
GRB 140903A placed at z=0.5
0.5-10 keV lightcurves

Adapted from Ghirlanda+2021

Spectral Evolution

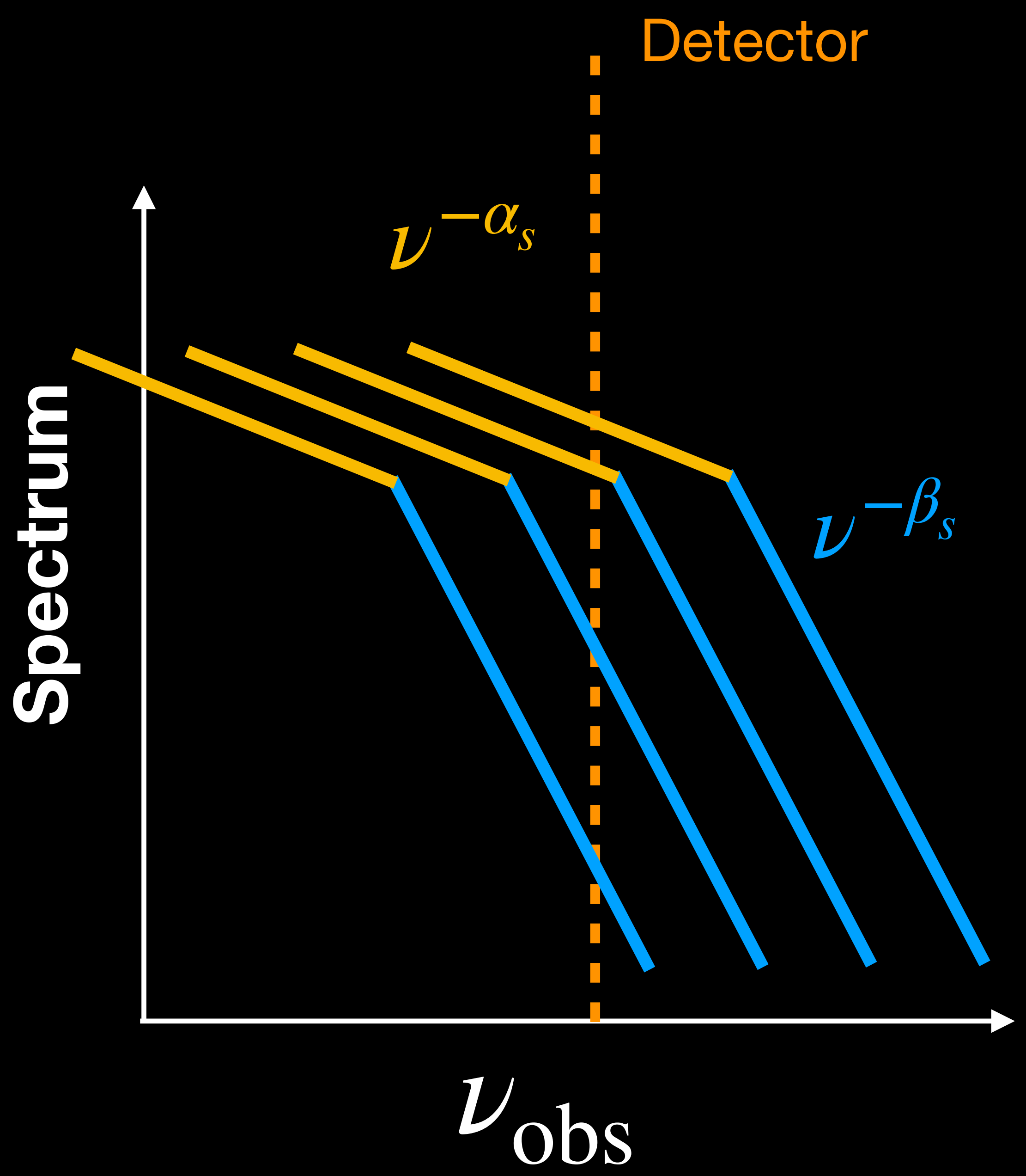
$$\nu_{\rm obs} = D(\theta)\,\nu$$

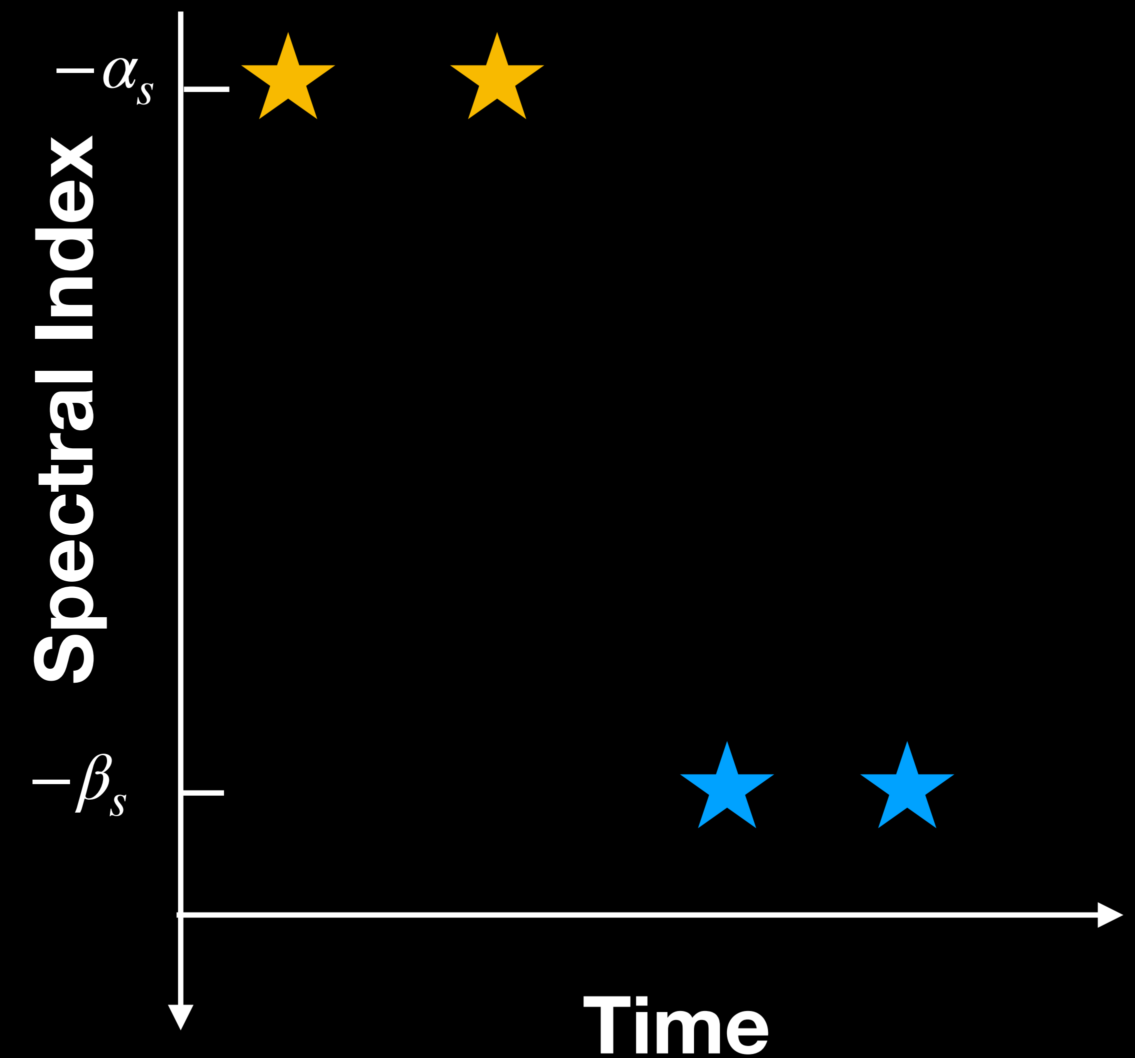




Spectral Evolution

$$\nu_{\rm obs} = D(\theta)\,\nu$$





Spectral Evolution

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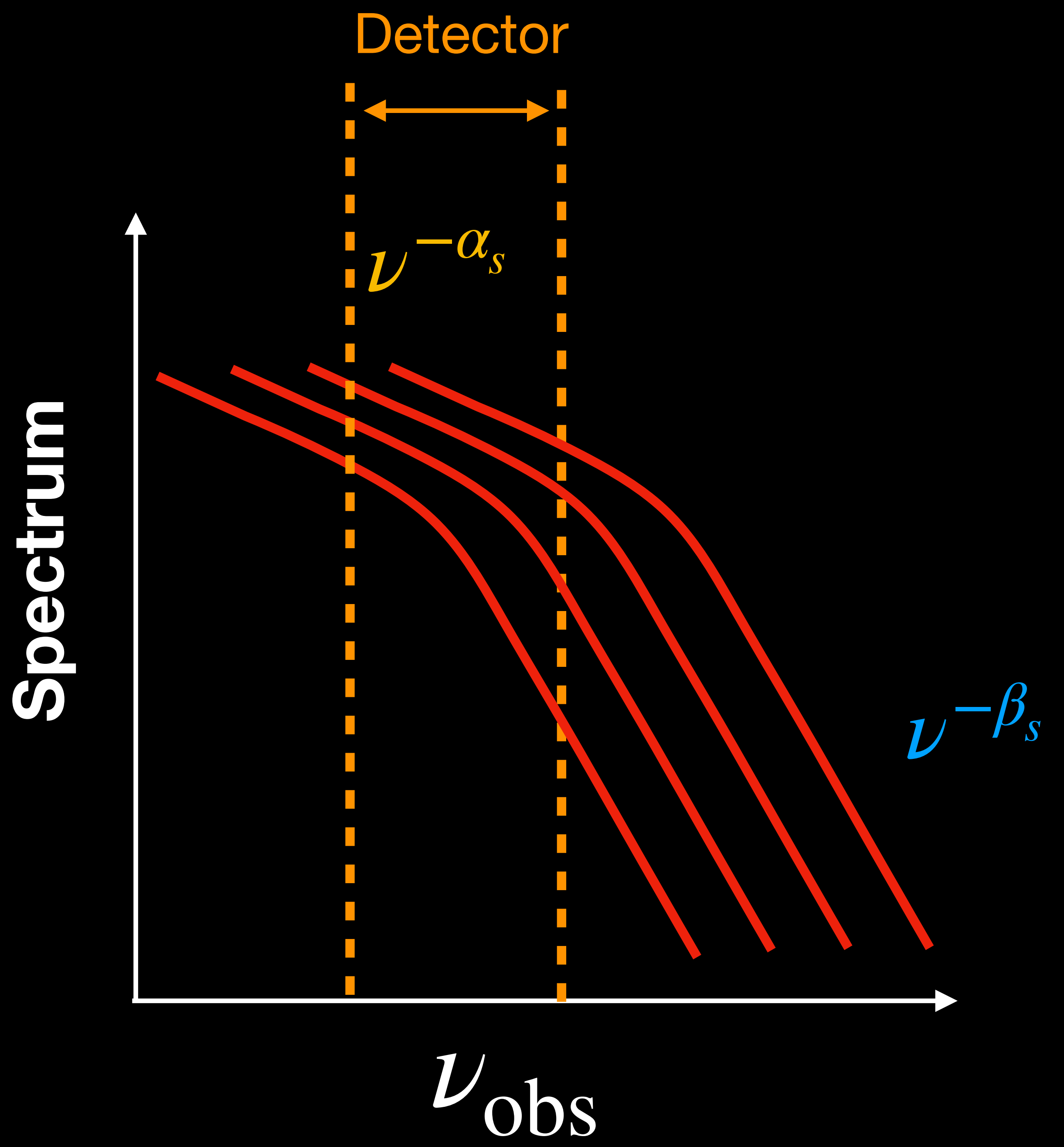
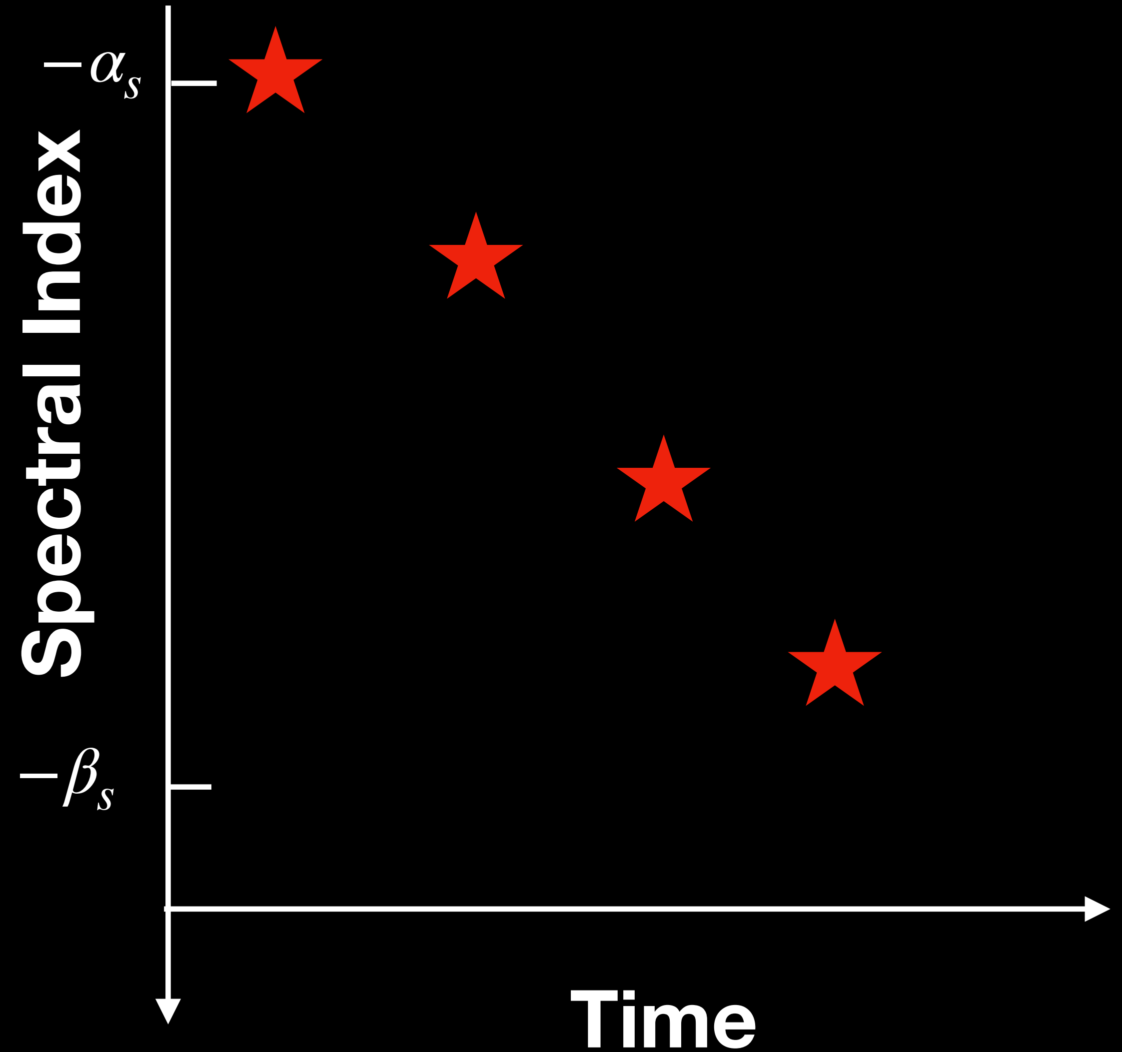
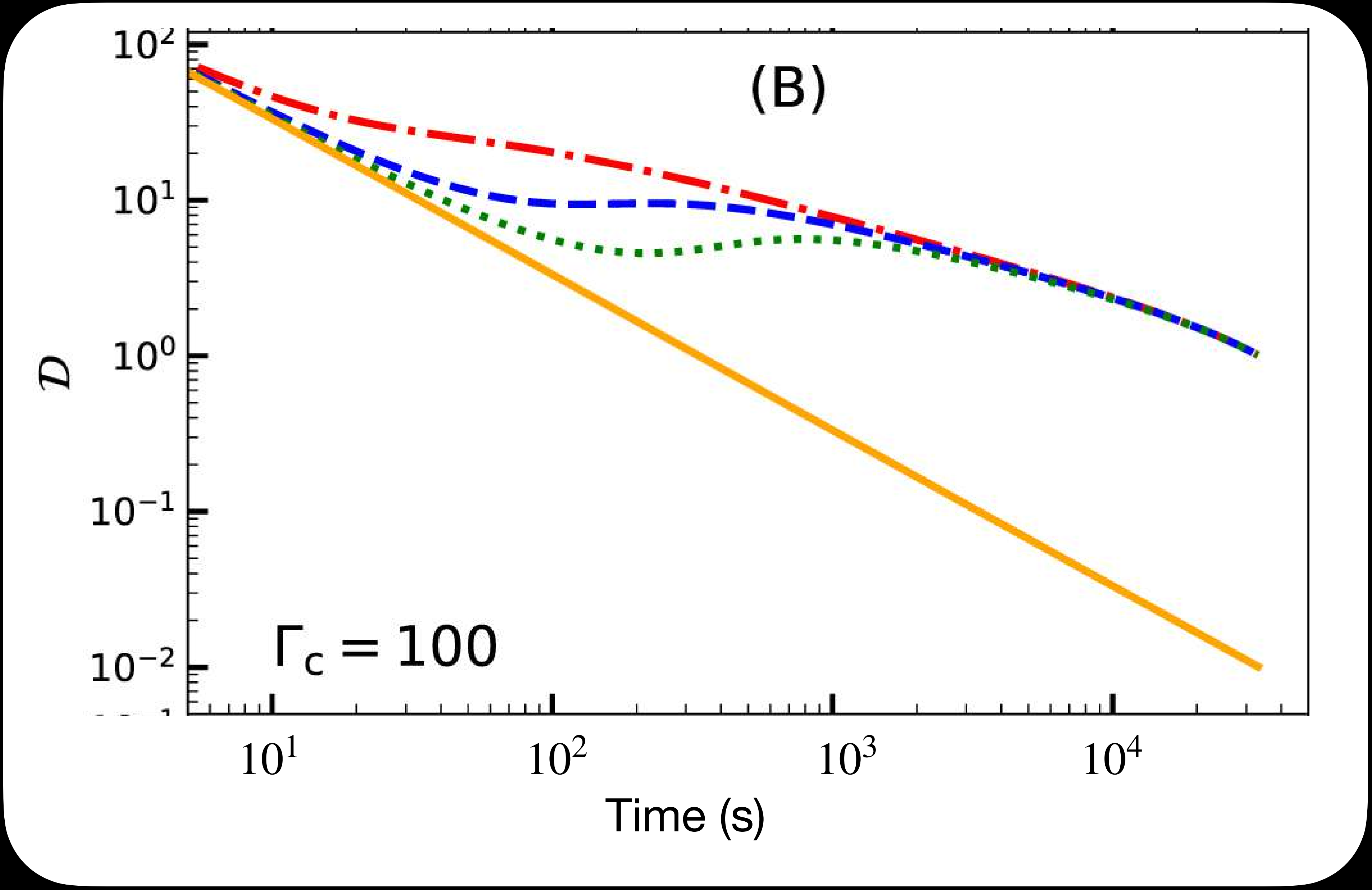


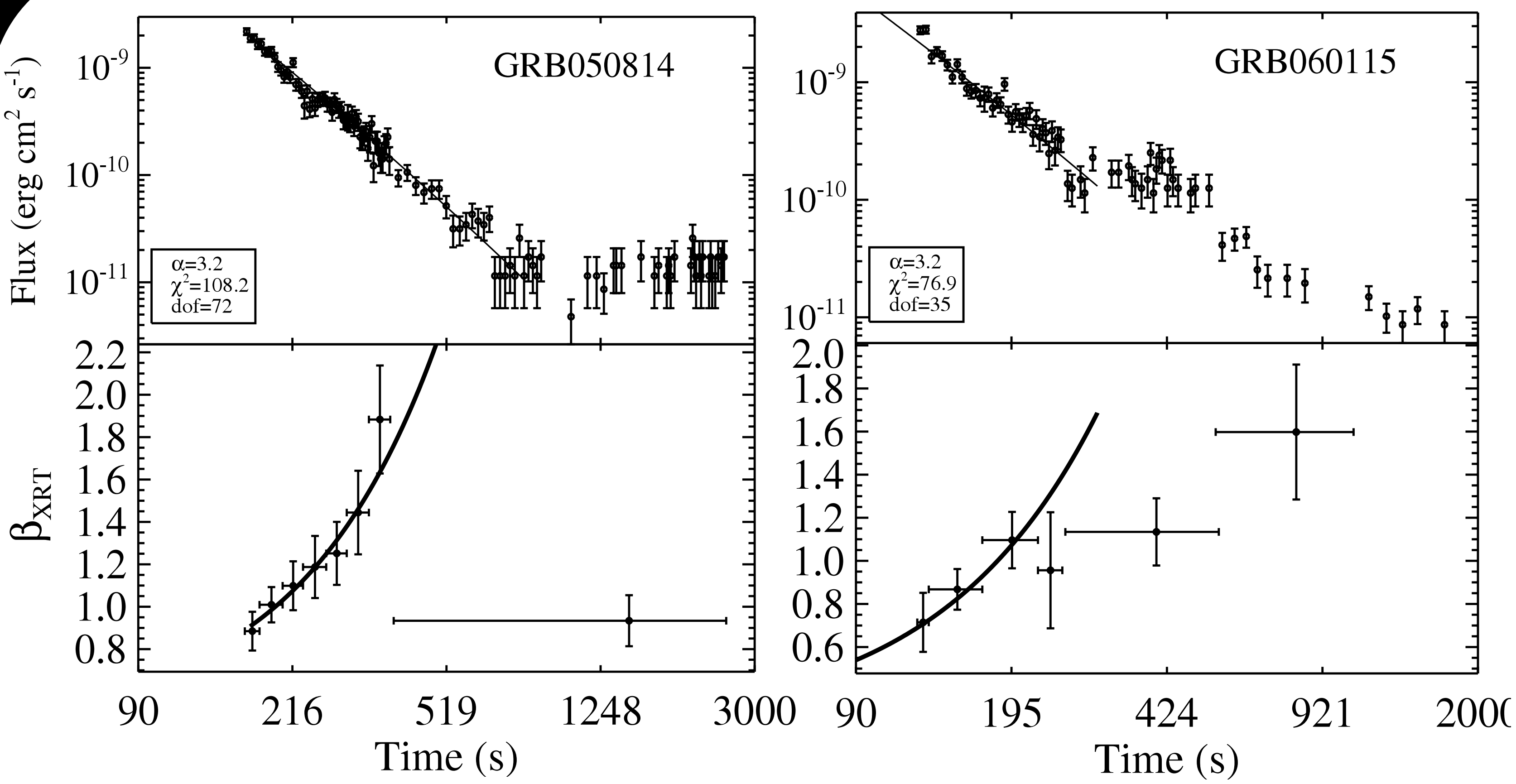


Spectral Evolution

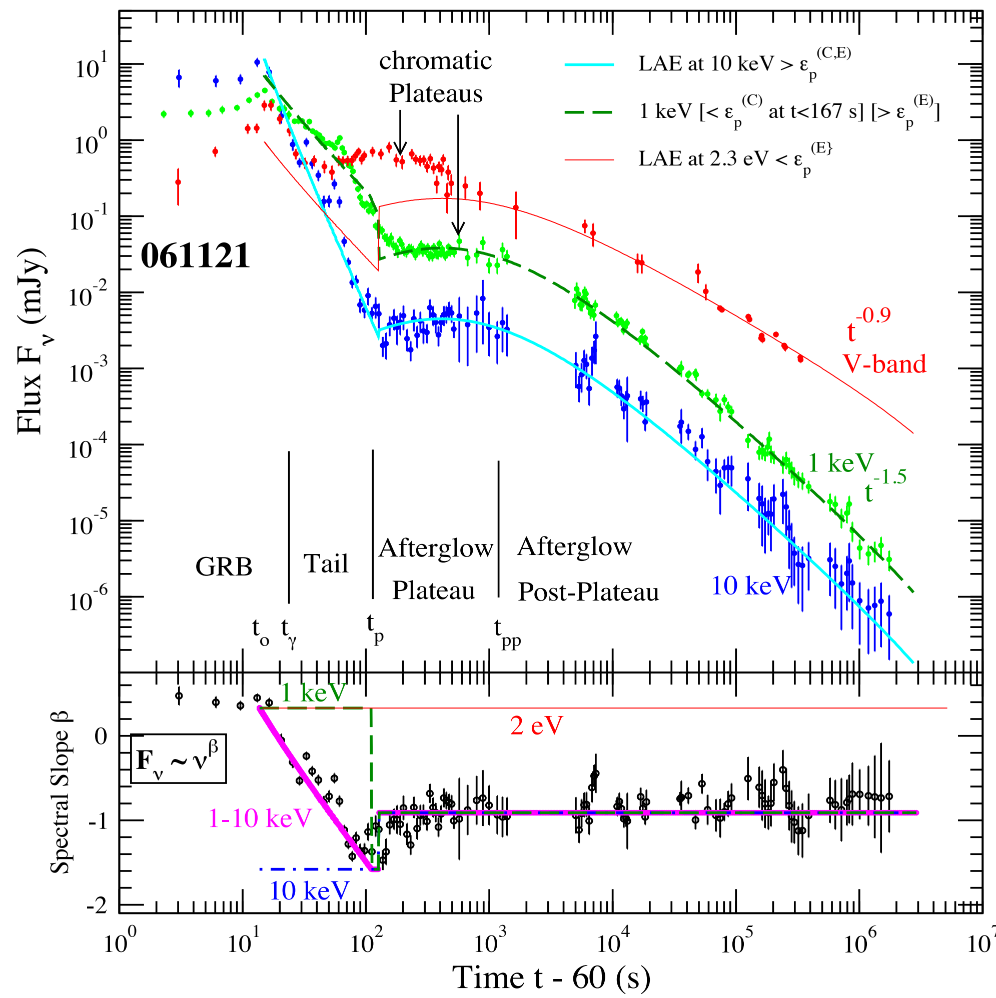
The Spectral Evolution follows the Doppler factor evolution. When the Doppler factor decreases the spectrum softens, when the Doppler factor increases the spectrum hardens.



Spectral Evolution - Data

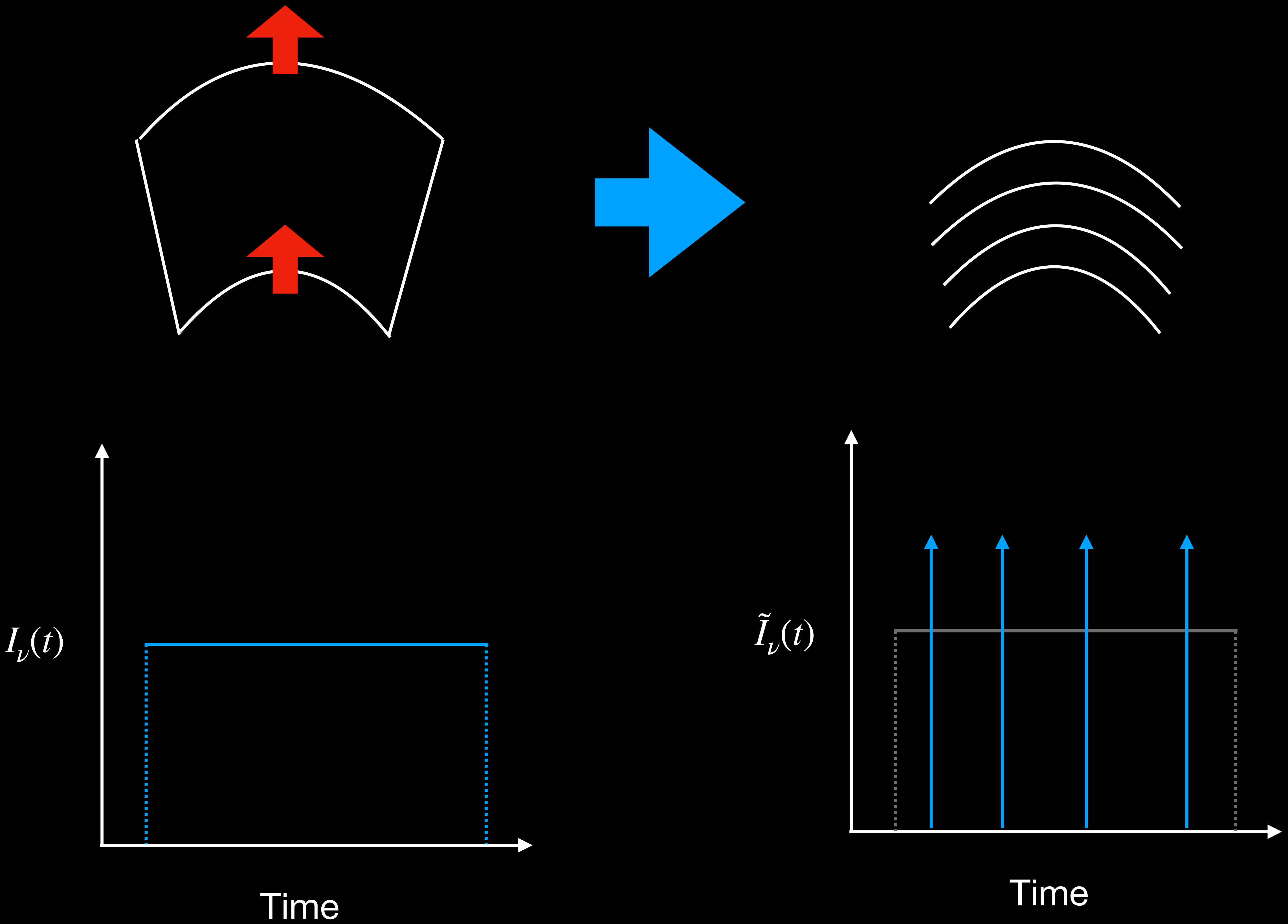


Zhang et al. 2007

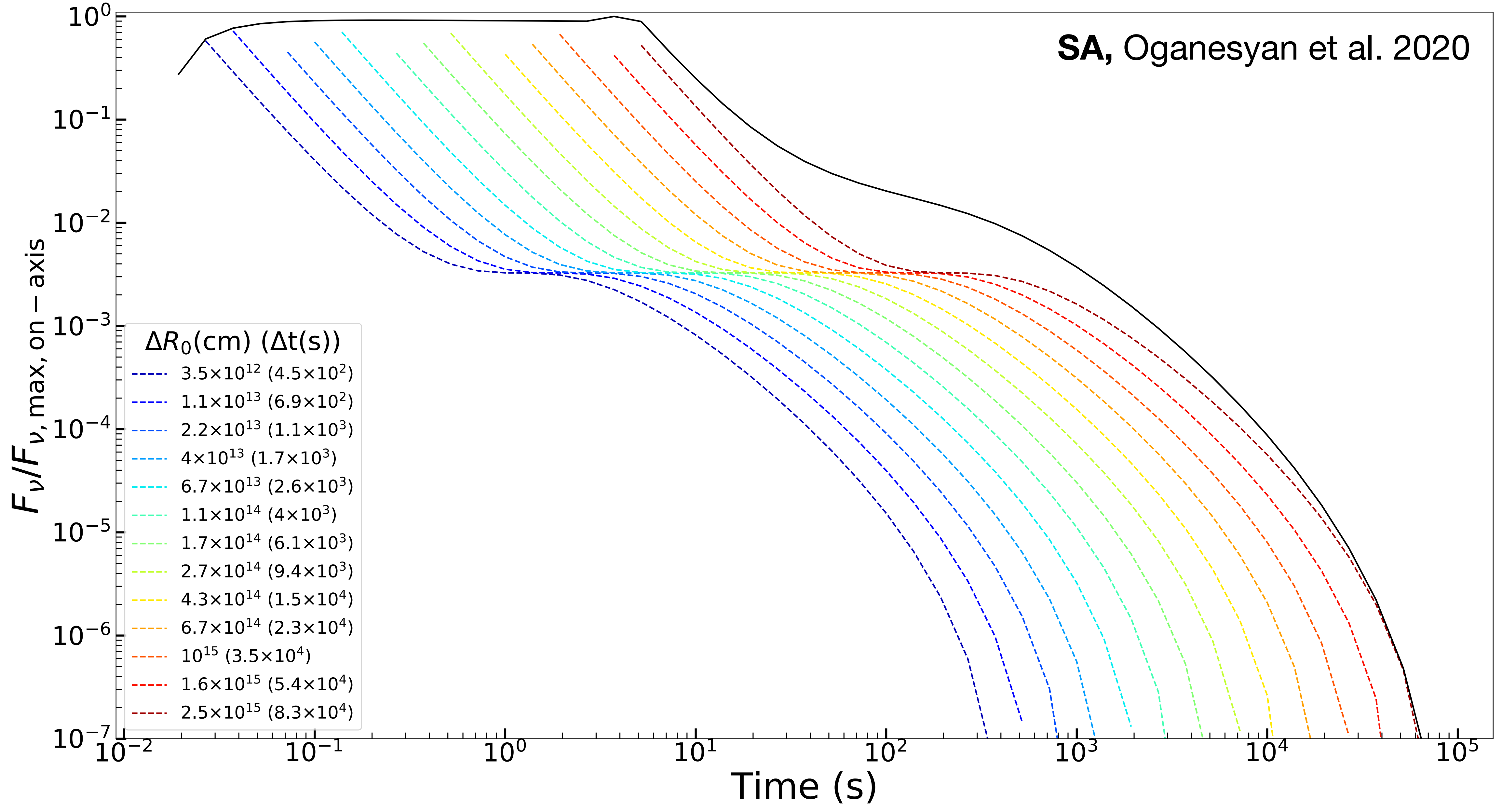


Panaitescu 2020

Finite Duration

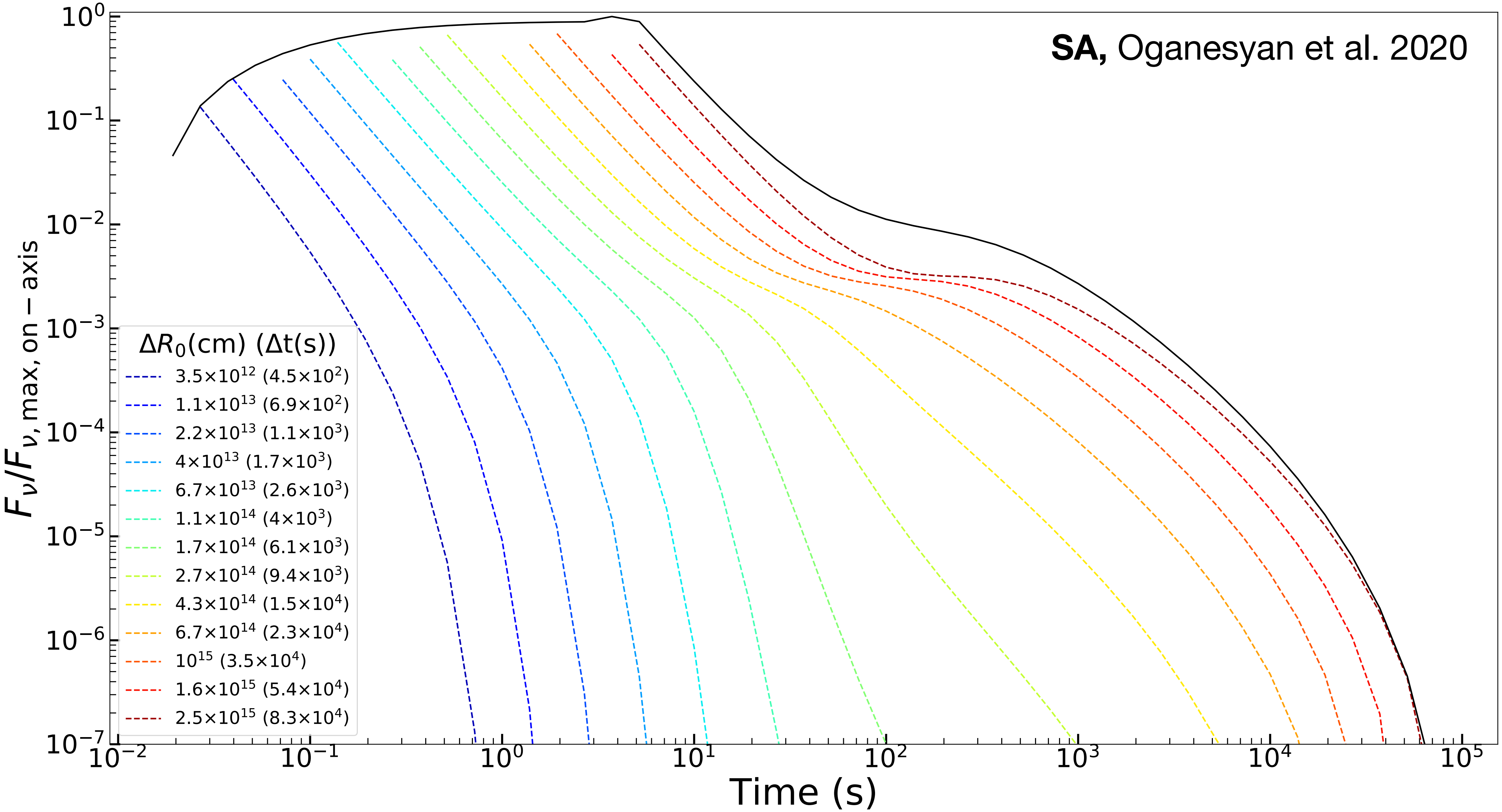


Finite Duration



Opacity

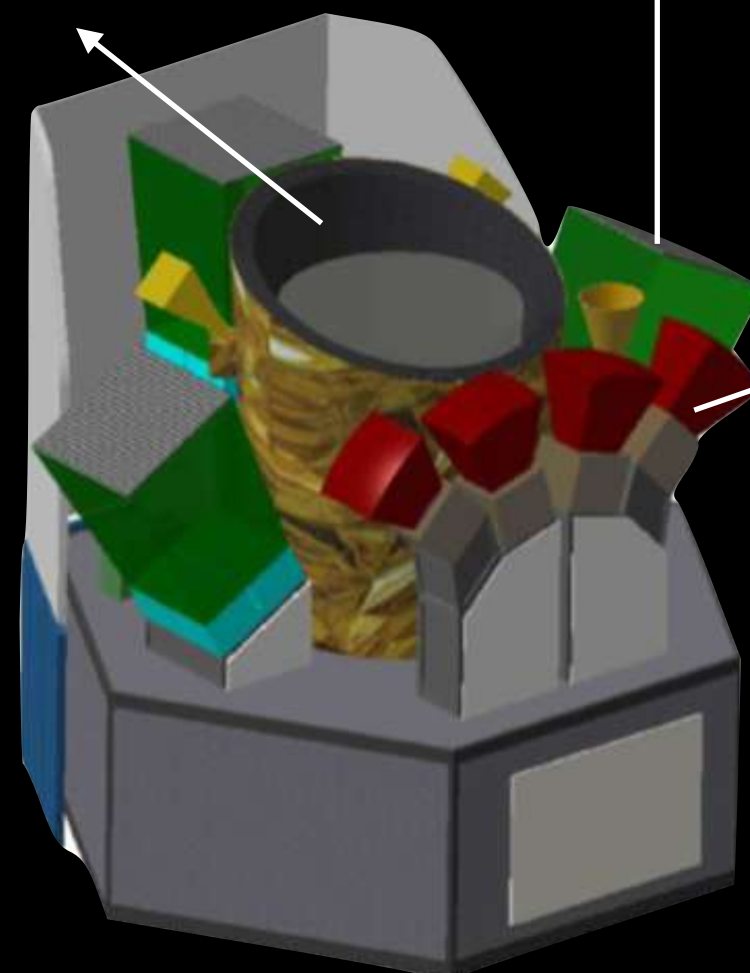
$$\tau(\theta) = \frac{Y_e \sigma_T L_{\mathrm{K,ISO}}}{4\pi m_p c^3 \Gamma^2 (\Gamma - 1)(1+\beta)} \left[\frac{1}{R} - \frac{1}{R + \Delta R (1+\beta)\Gamma^2} \right]$$



Theseus

IRT $(0.7 - 1.8\,\mu m)$
FoV = 10 x 10 arcmin

XGIS (2 keV- 20 MeV)
FoV = 1.5 sr
Res = 5 arcmin (2-30 keV)



SXI (0.3-6 keV)
FoV = 1 sr
Res < 1-2 arcmin

Rates

	THESEUS XGIS/SXI joint GW+EM observations			
	BNS range	BNS rate (yr^{-1})	XGIS/sGRB rate (yr^{-1})	SXI/X-ray isotropic counterpart rate (yr^{-1})
LIGO-Virgo	~200 Mpc	~40*	~5-15	~1-3 (simultaneous) ~6-12 (+follow-up)
ET	~15-20 Gpc	>10000	~15-35	$\gtrsim$100