X-ray Flares During the Steep Decay Phase of GRB Afterglows

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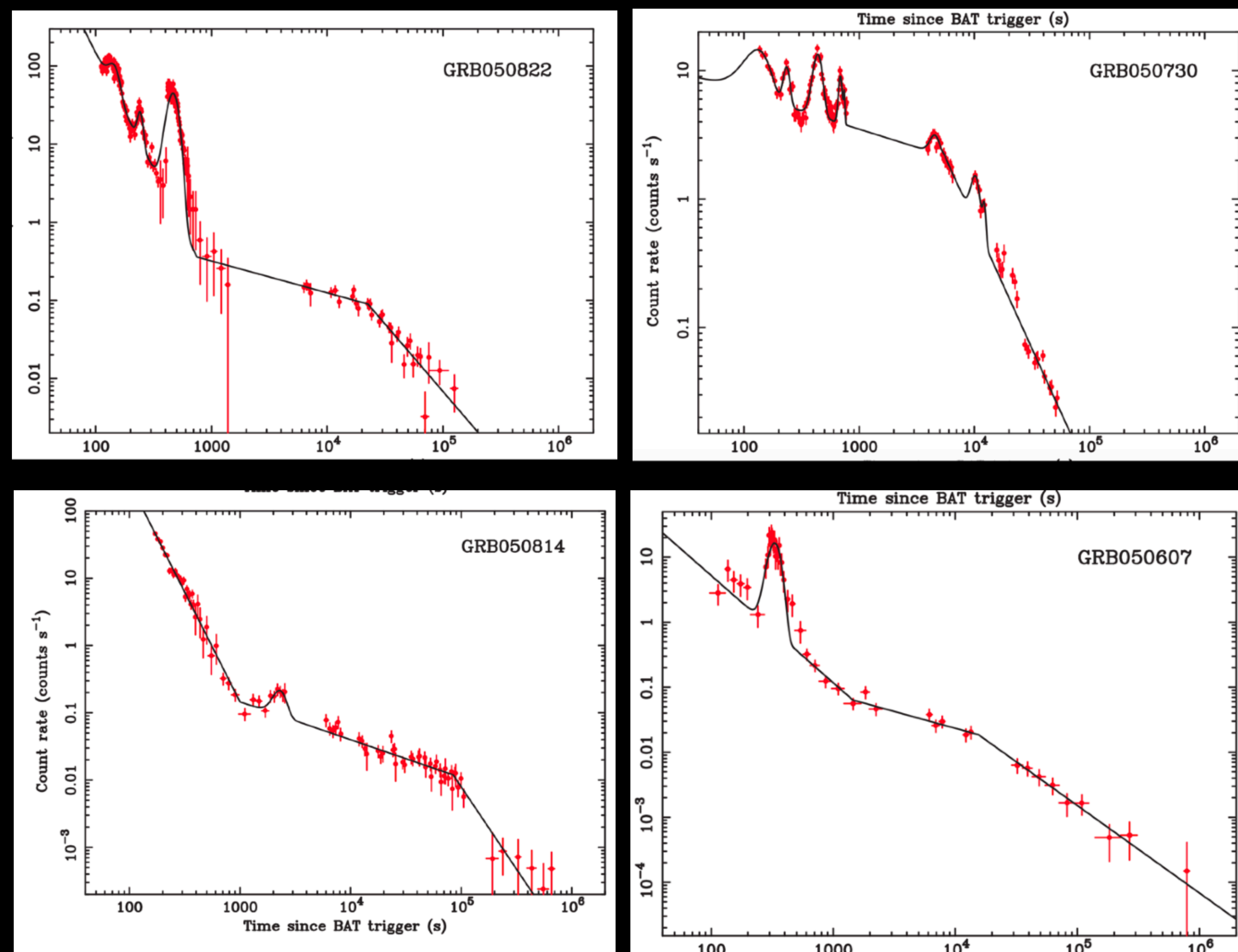
with Ehud Nakar (TAU) and Tsvi Piran (HUJI)

X-Ray Flare Observations

- Light curves
- Why study flares?
- Timescale
- Average flare behavior

Chincarini+ 07



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- GRB prompt emission has long remained a mystery
- X-ray flares share several characteristics with the prompt emission, suggesting they may have a similar physical origin
  - Lag-luminosity relation: Emission peaks later in lower energy bands
  - X-ray flares have a similar shape as prompt pulses, with a fast rise and slower decay

X-Ray Flare Observations

Chincarini+ 10

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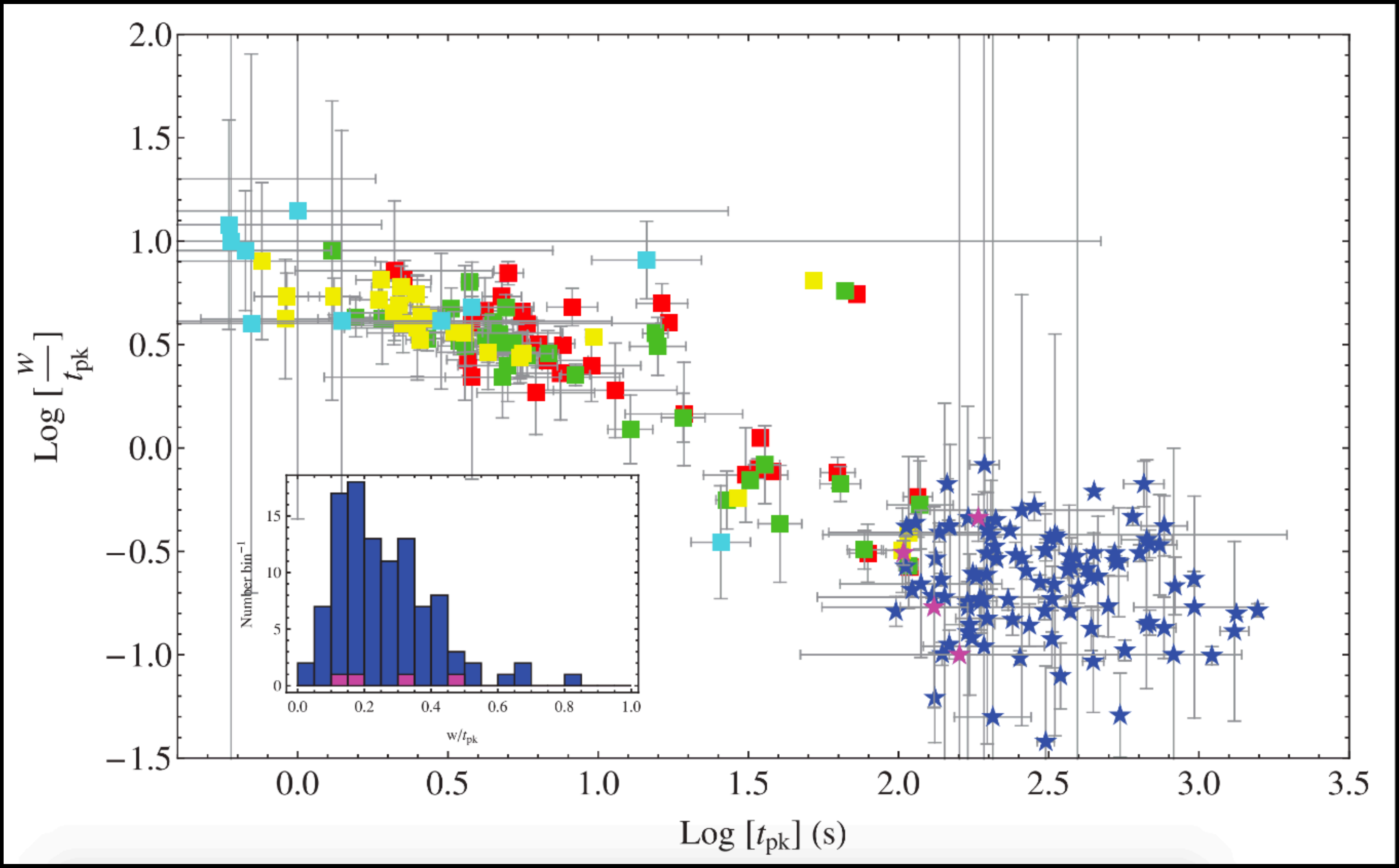

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Bernardini+ 11

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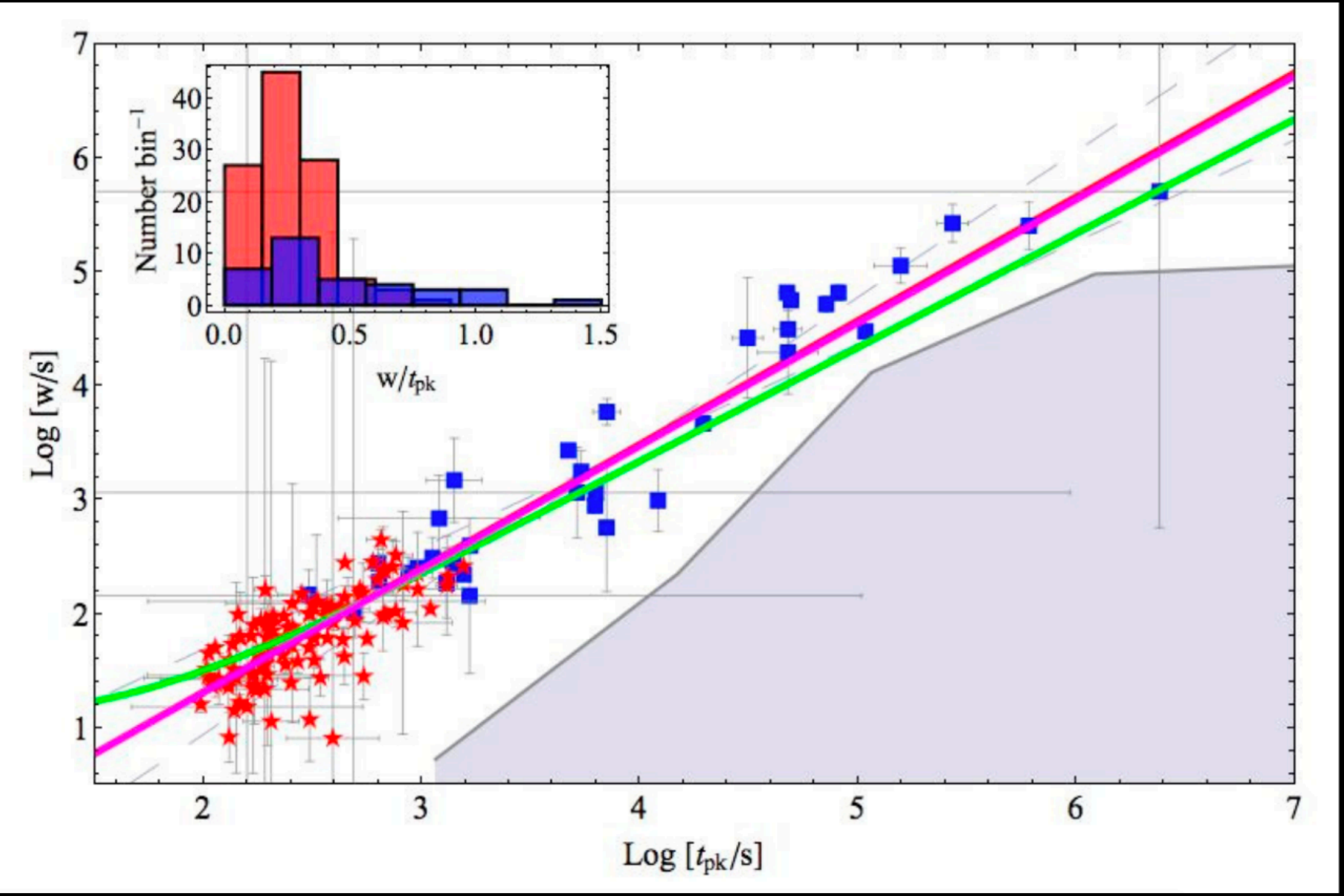

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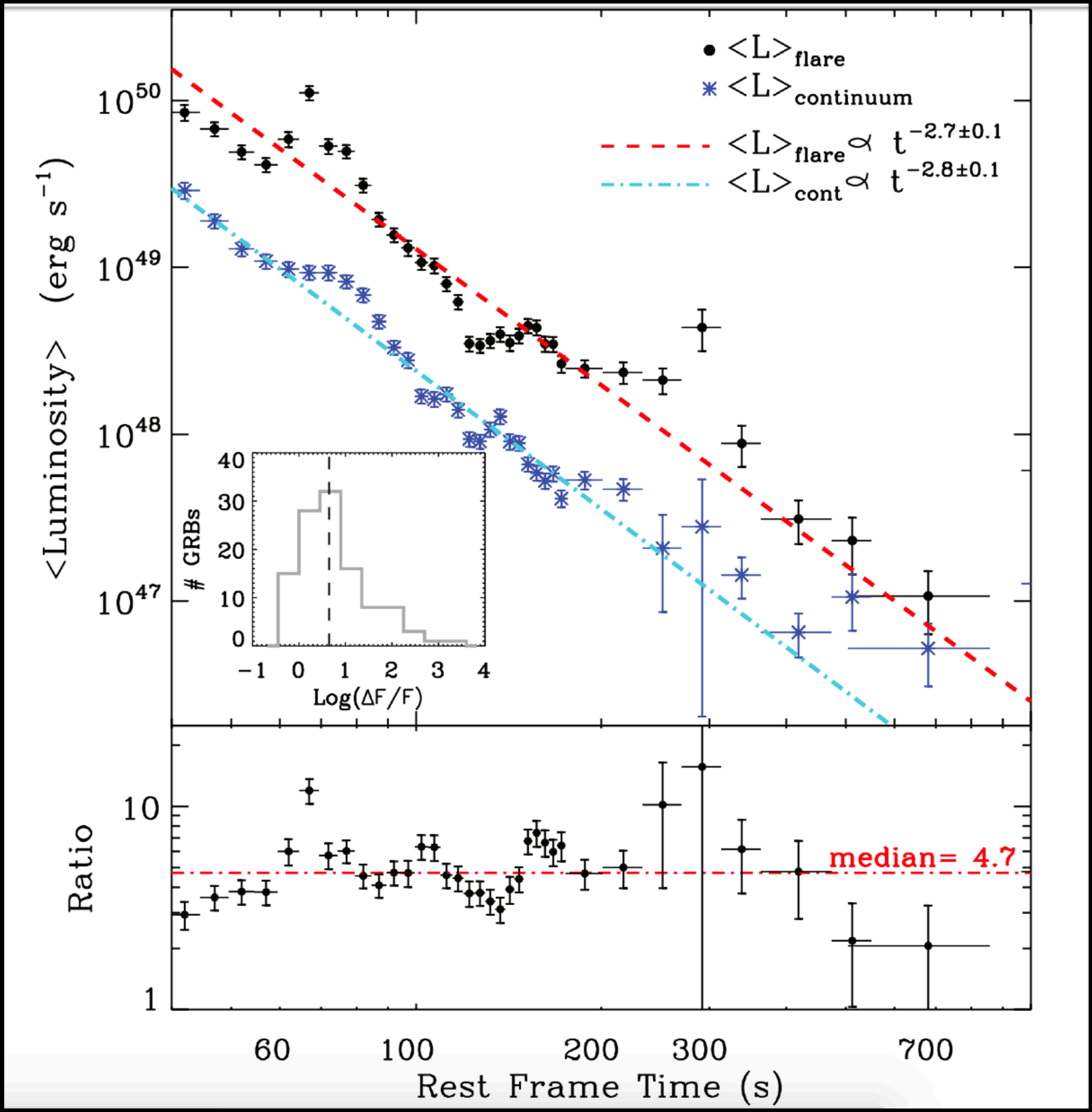
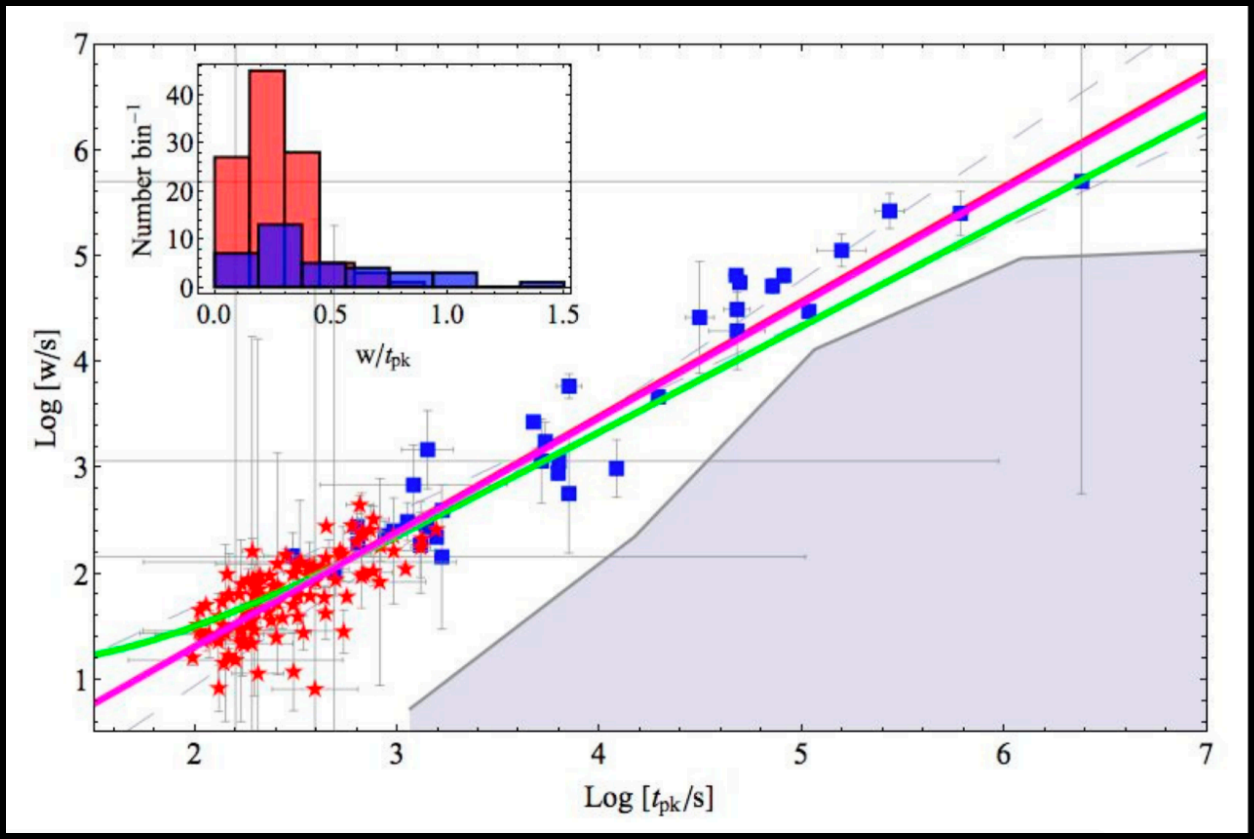
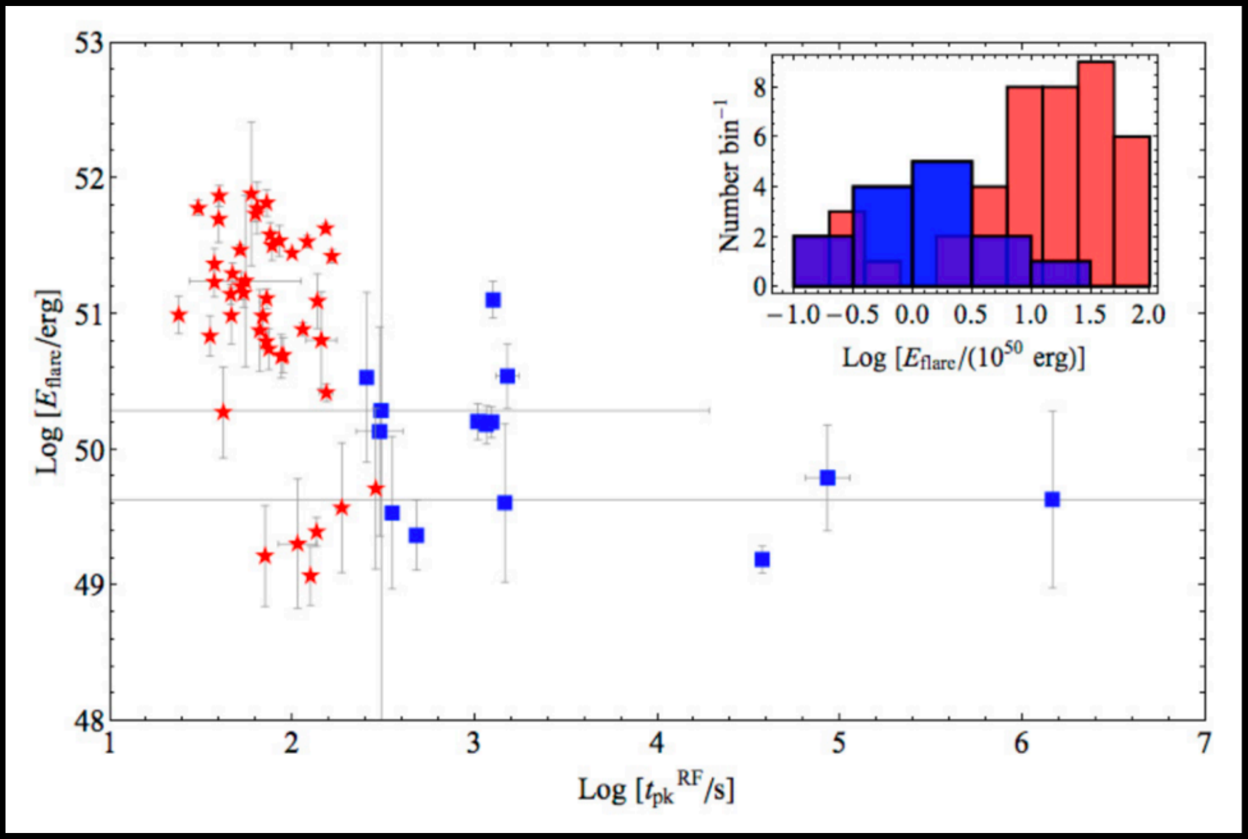


Margutti+ 11

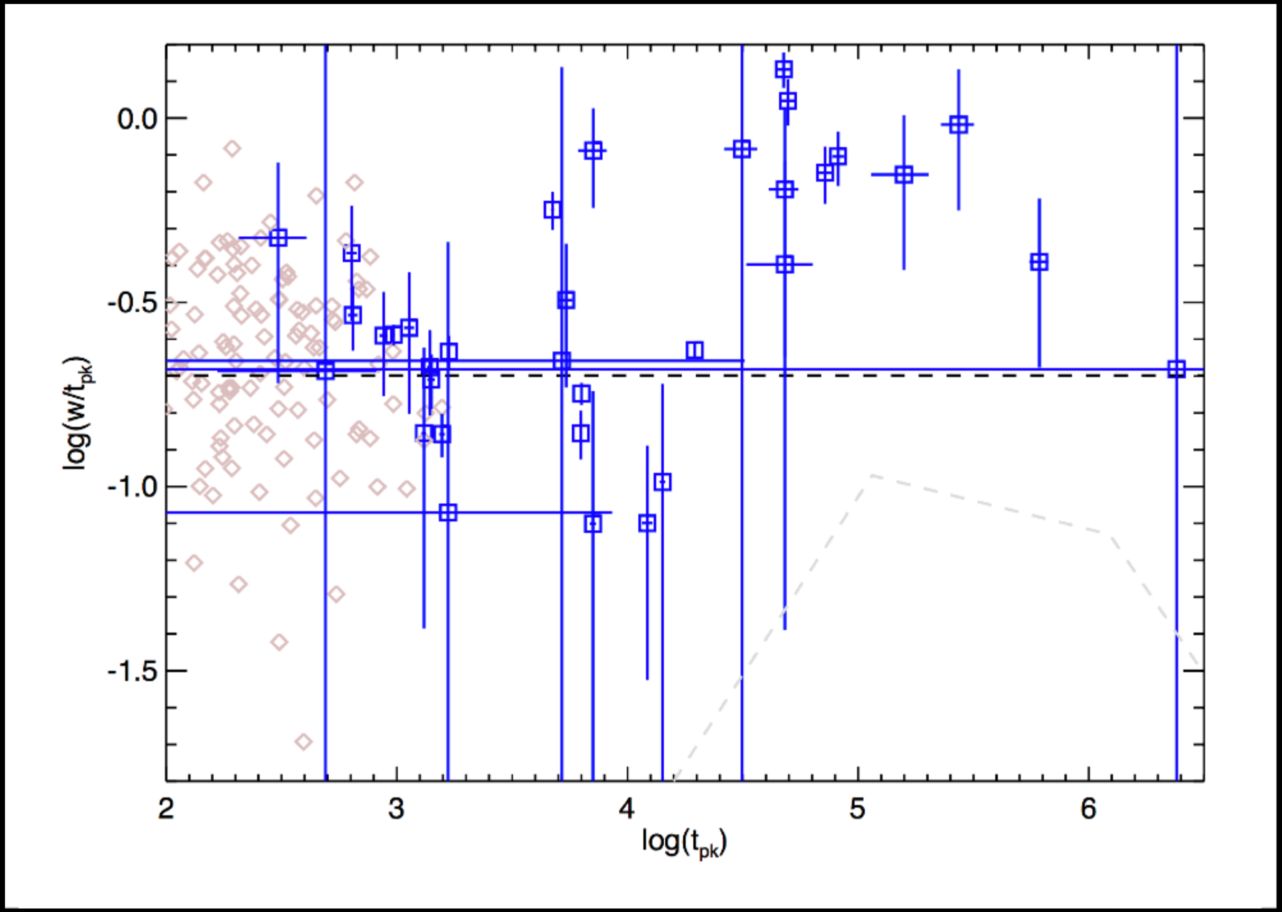
Late Time Flares

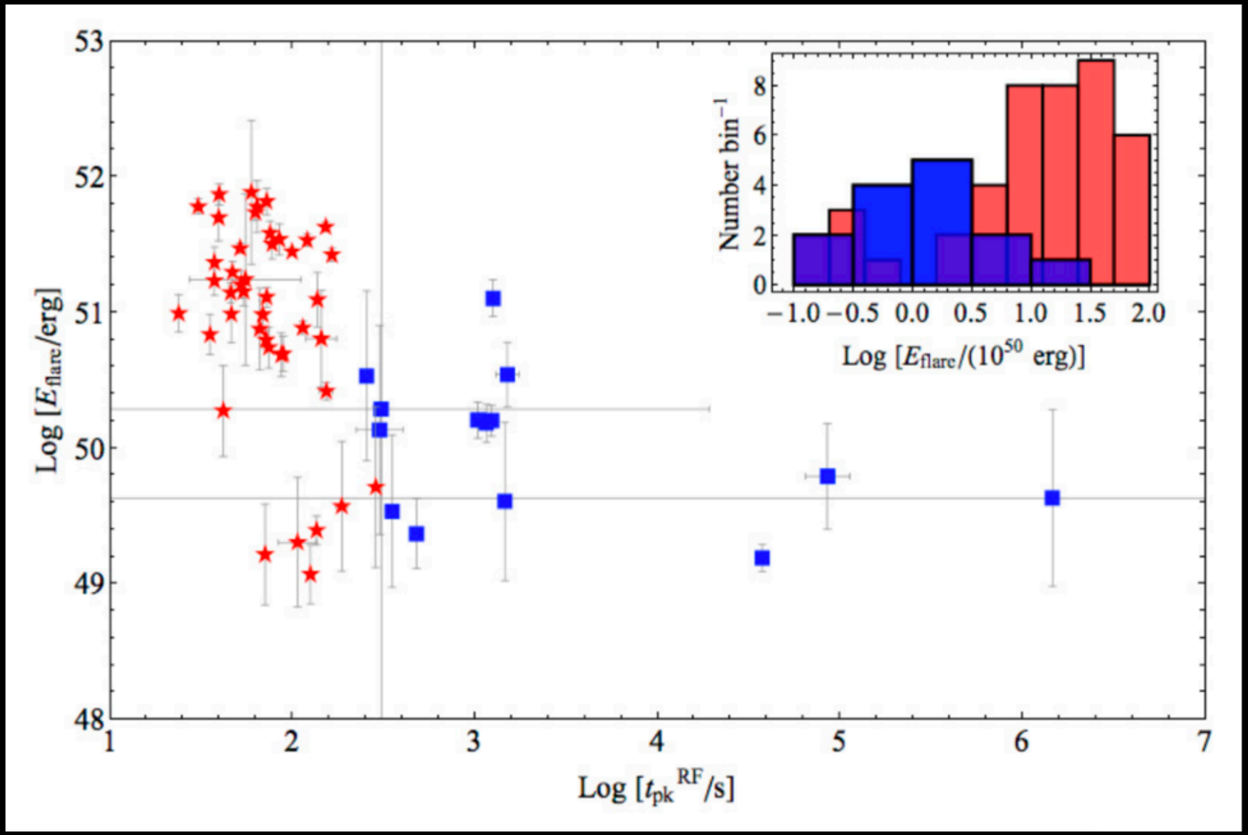




Bernardini+ 11

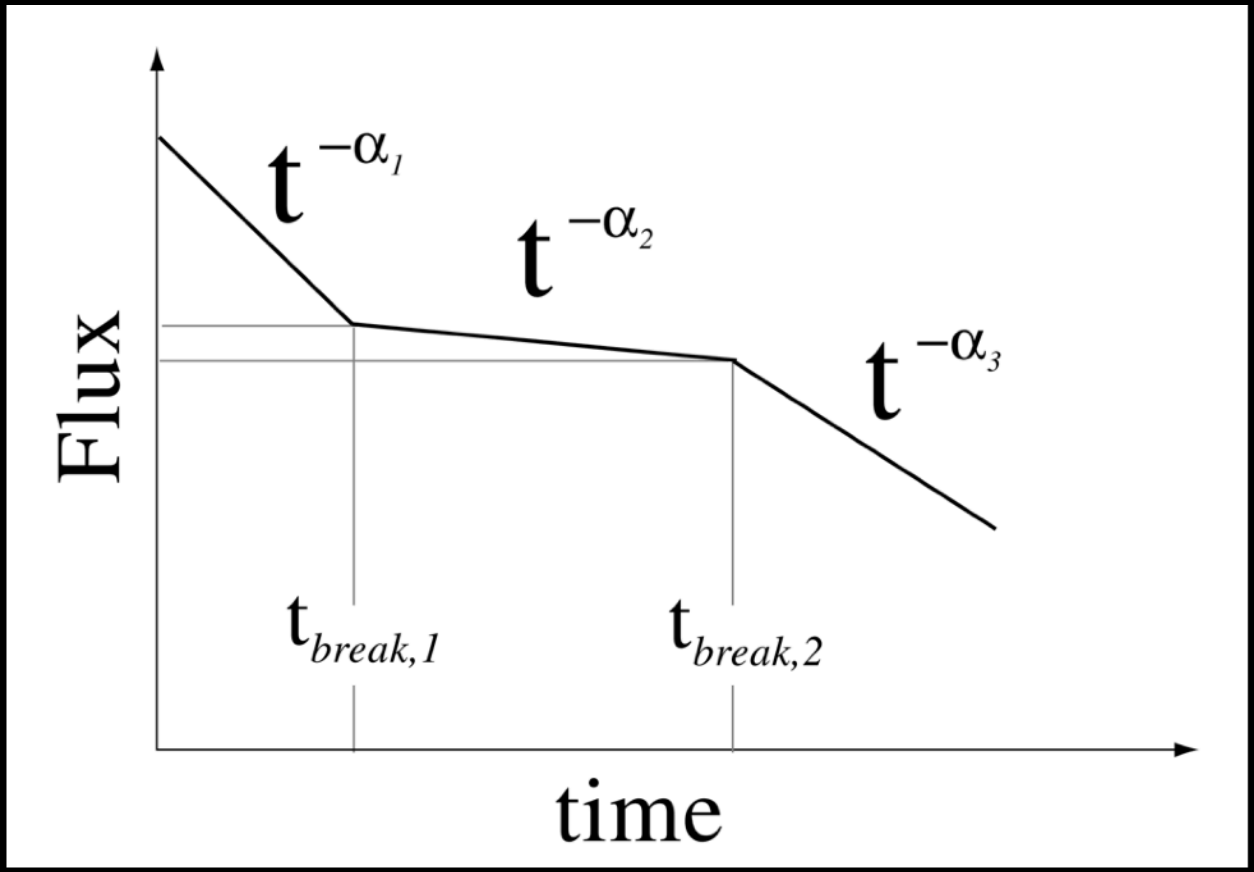
Late Time Flares

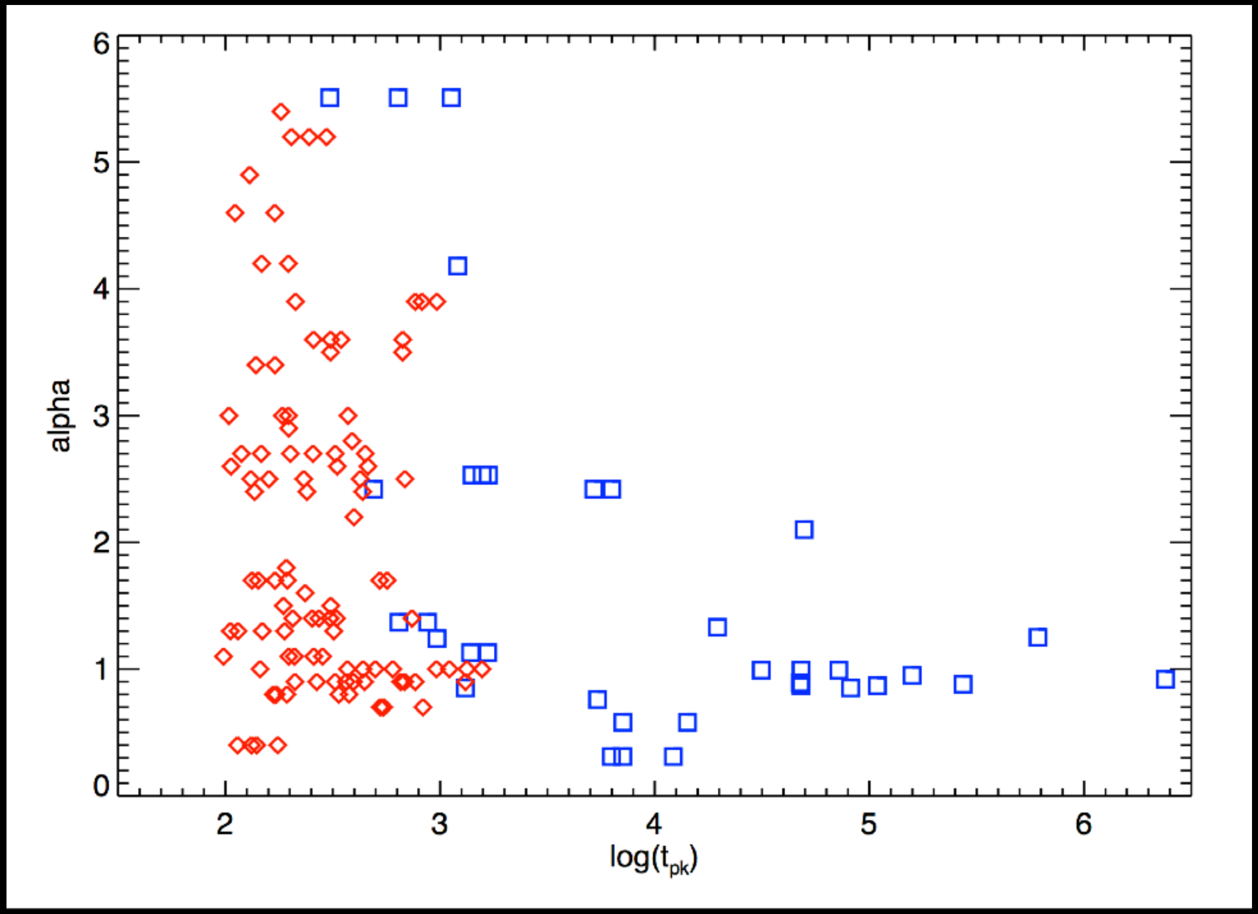




Bernardini+ 11

Late Time Flares

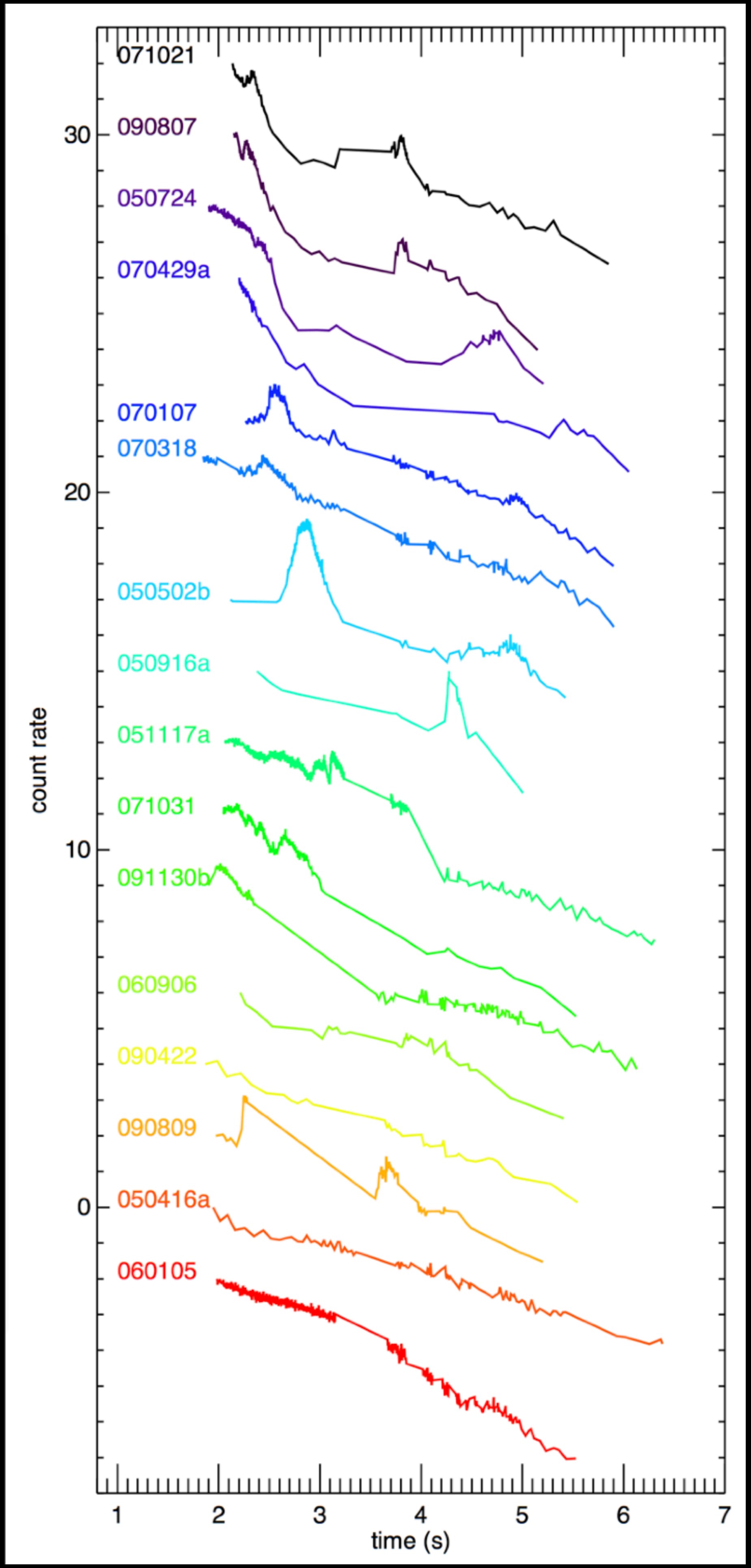




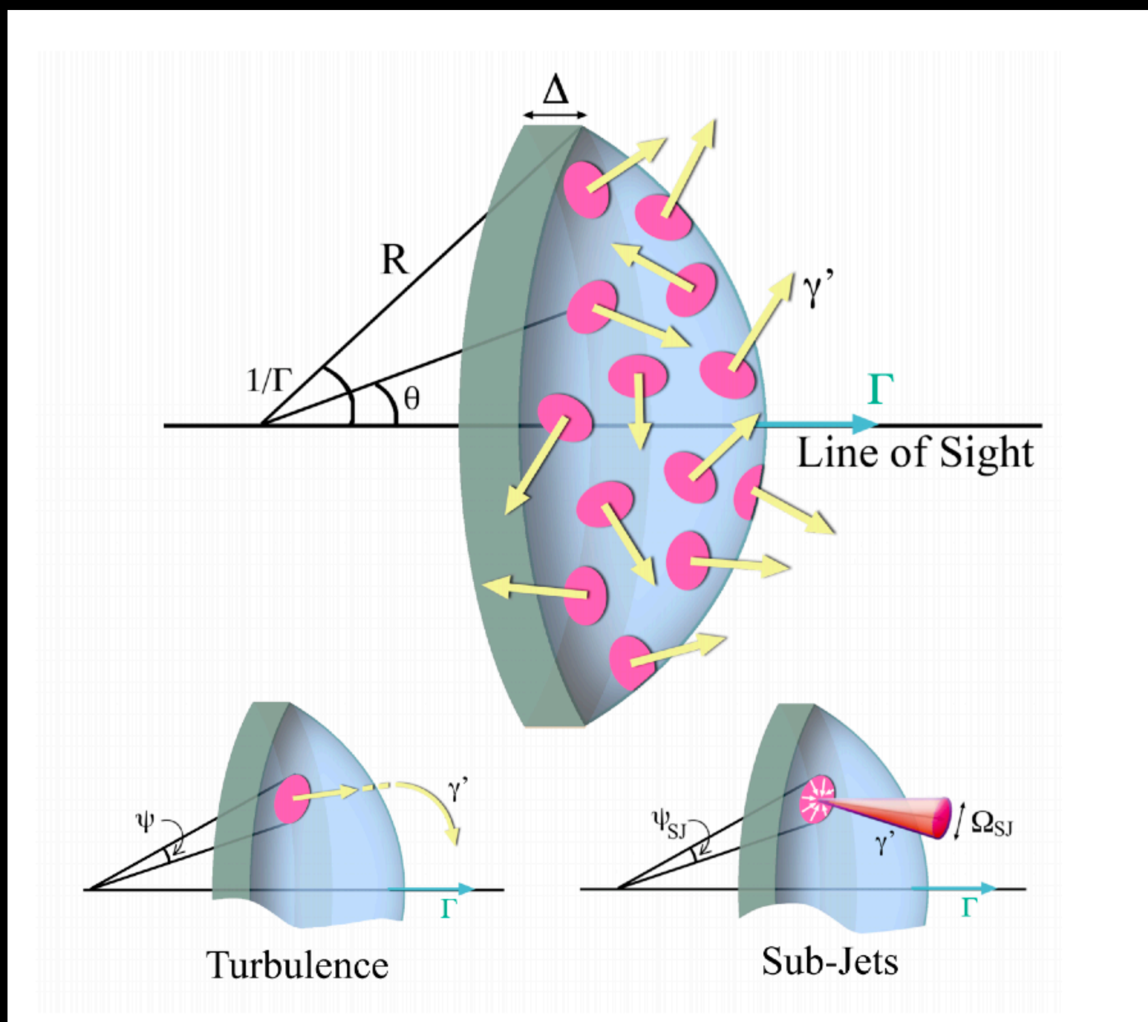
- Bursts with a steep decay *do not have flares after ~1000 s*

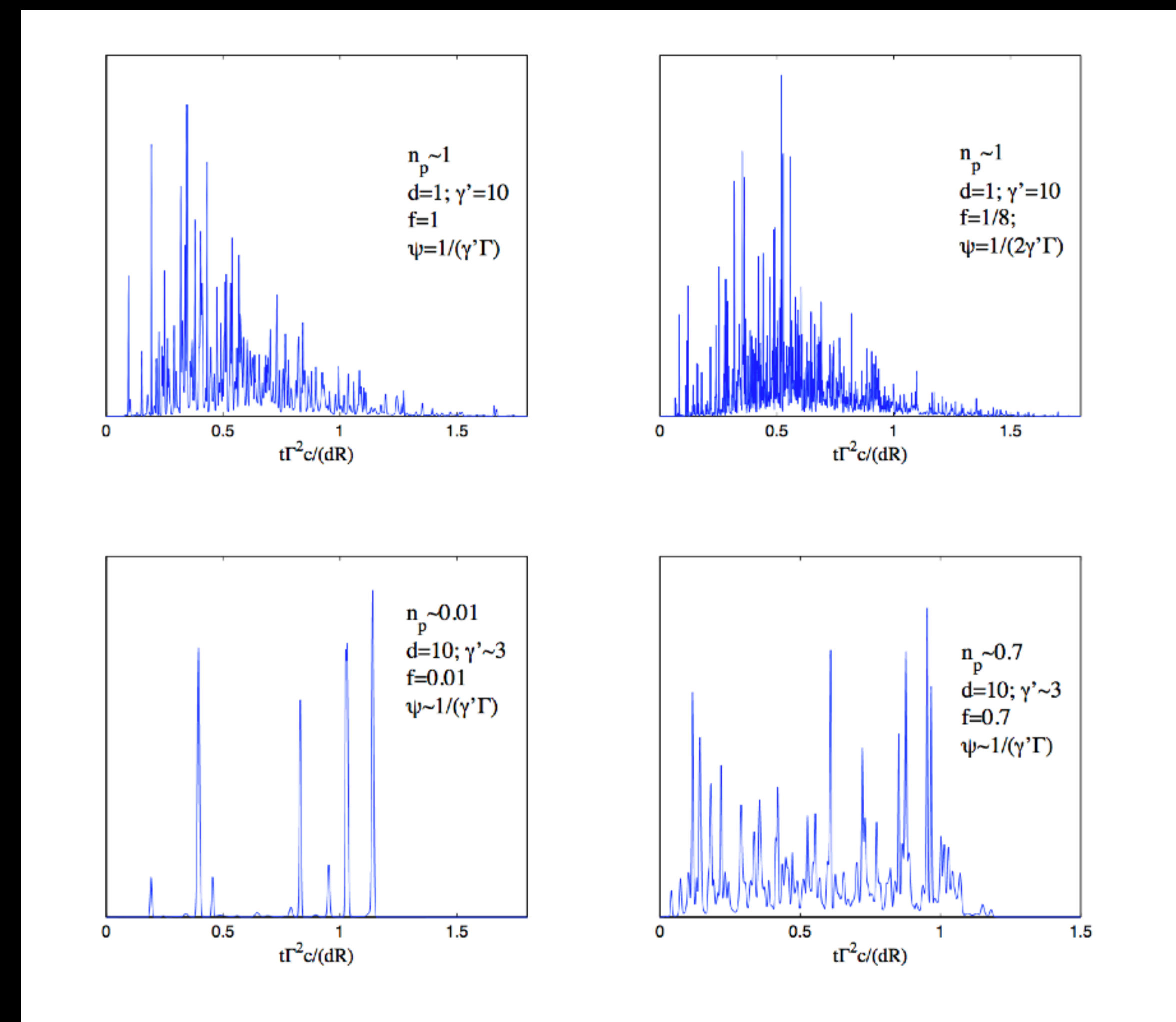
blue: Bernardini+ 11
red/gray: Chincarini+ 10

- Similarly, bursts showing flares after ~1000 s *do not have canonical light curves*
- However, there are a few exceptions where a flare is seen at the end of the plateau phase



GRB Prompt Emission: Subjets





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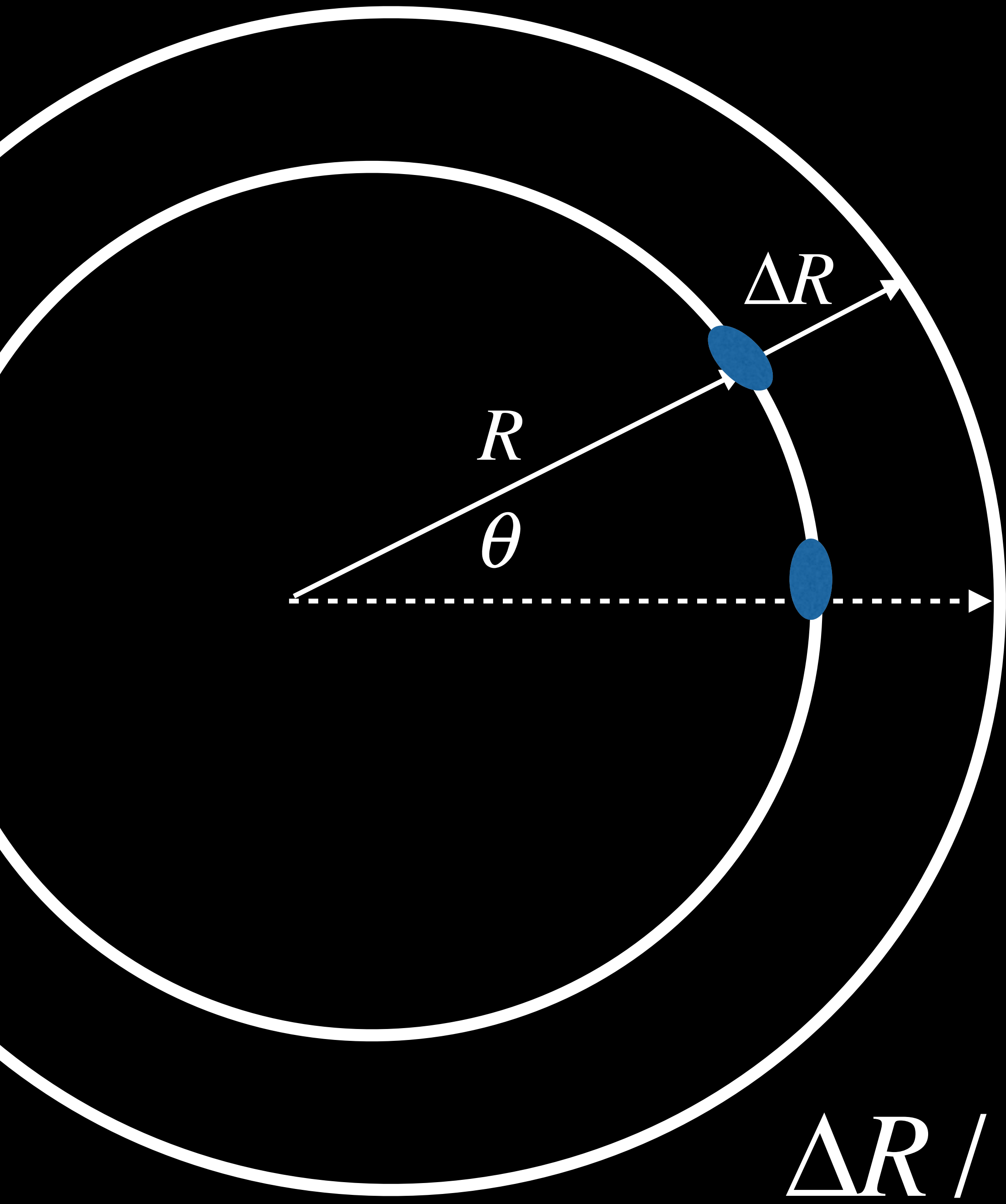
Model: Timescales



$$\Delta t = \frac{\Delta R}{c}(1 - B\cos\theta)$$

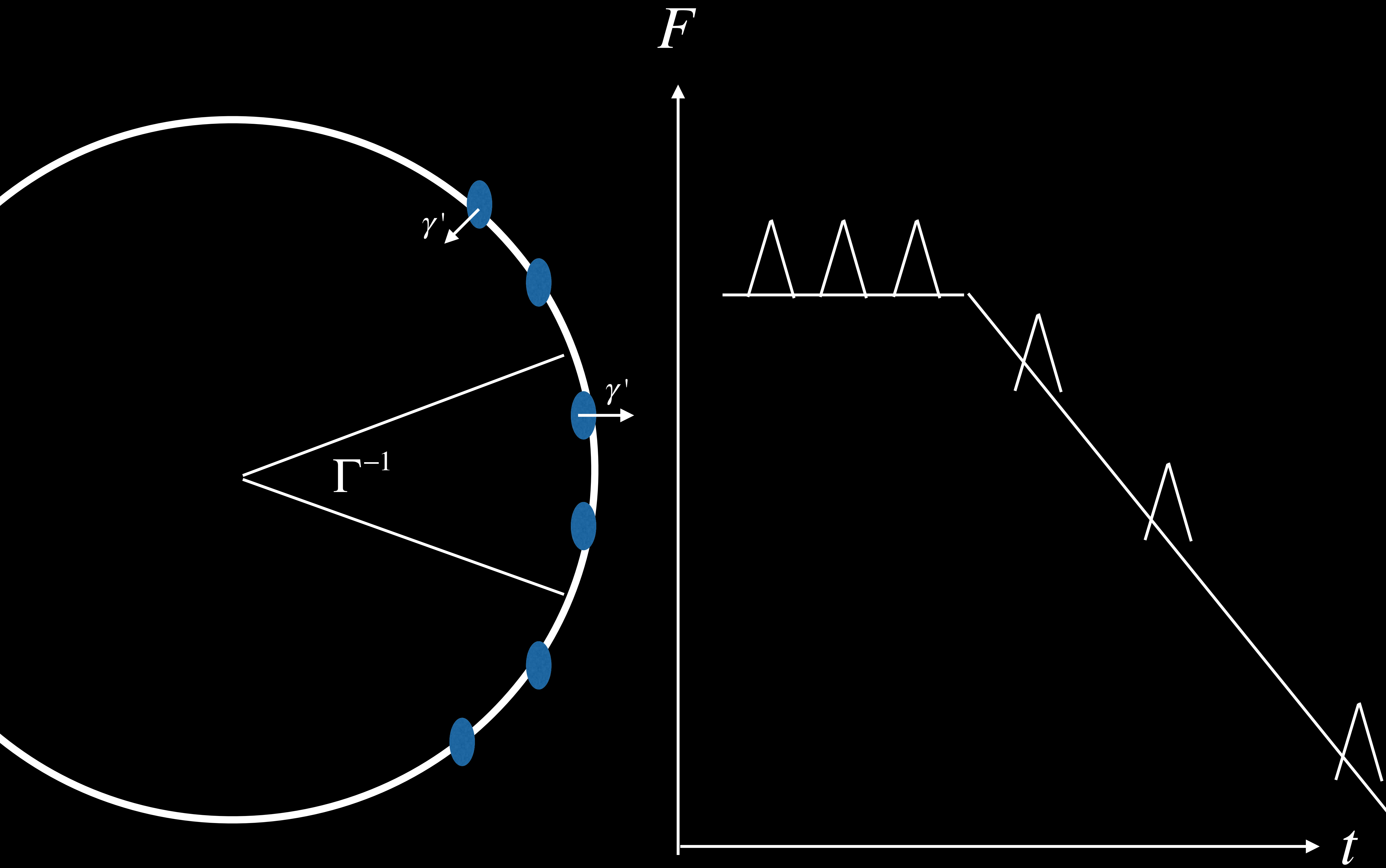
$$\Delta t \approx \frac{\Delta R}{2\Gamma^2 c}(1 + (\theta\Gamma)^2)$$

$$\Delta t \propto t^0, \theta < \Gamma^{-1}$$

$$\Delta t \propto t, \theta > \Gamma^{-1}$$

$$\Delta R / R \simeq 0.2$$

Model: Flare Frequency



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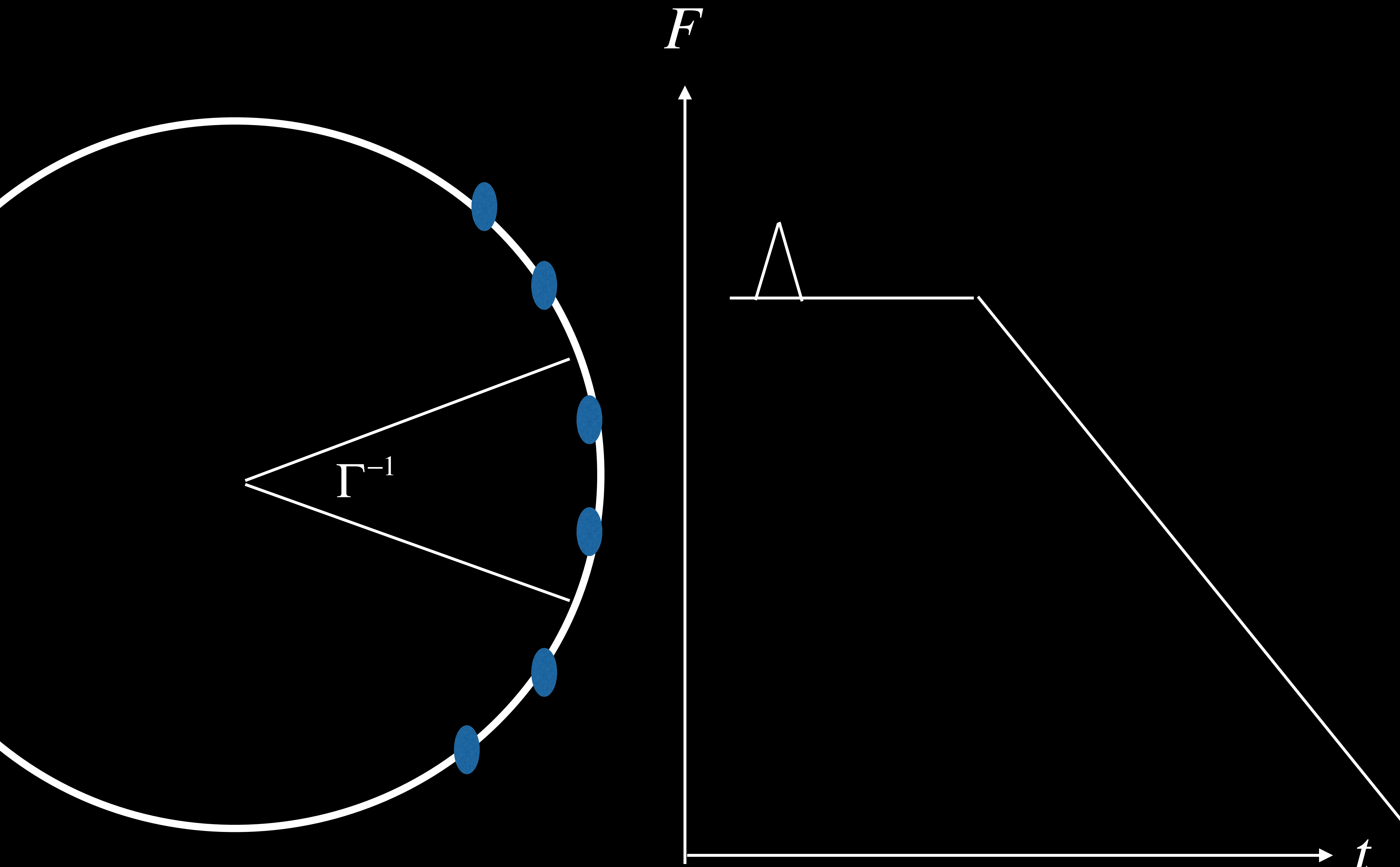

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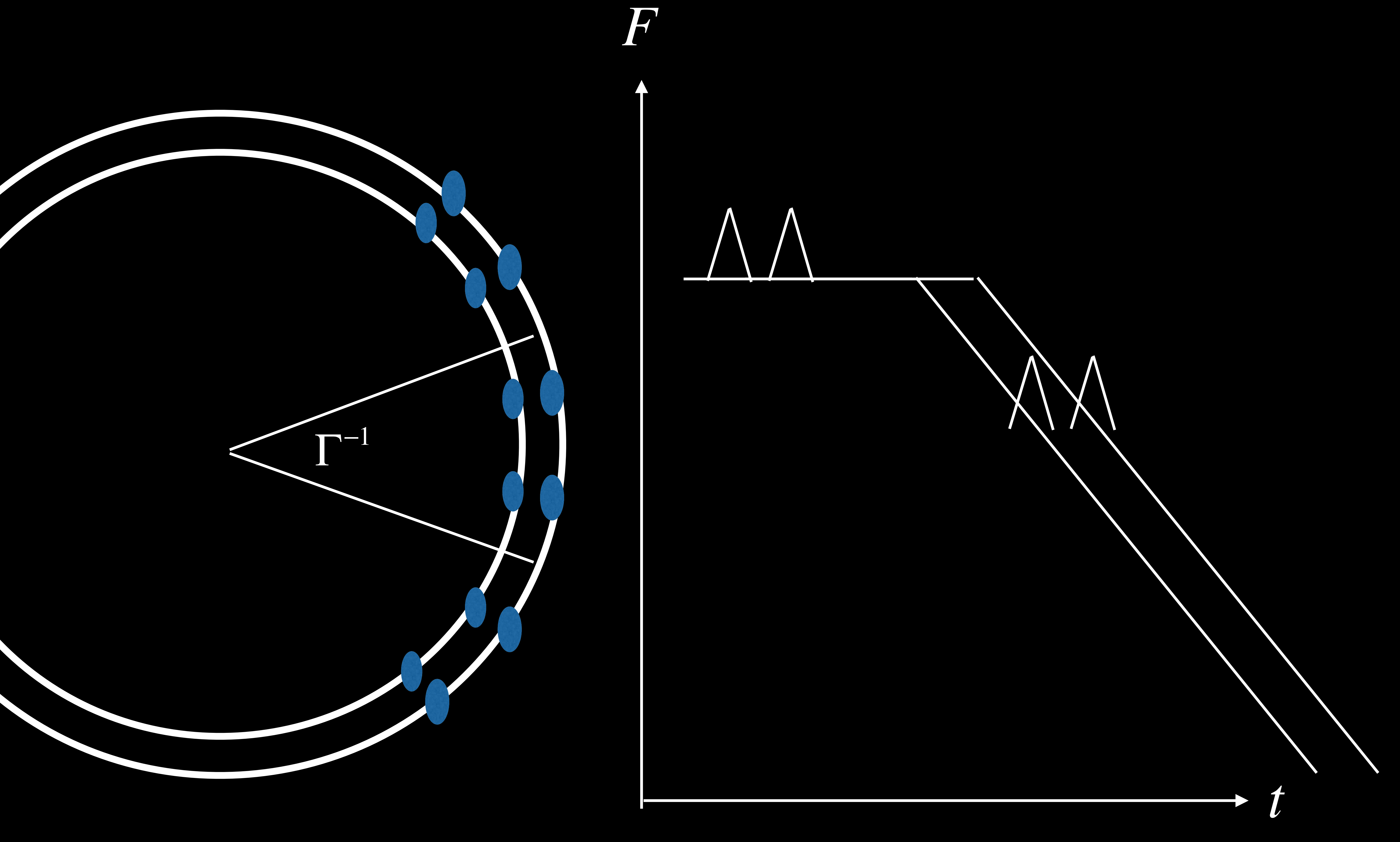

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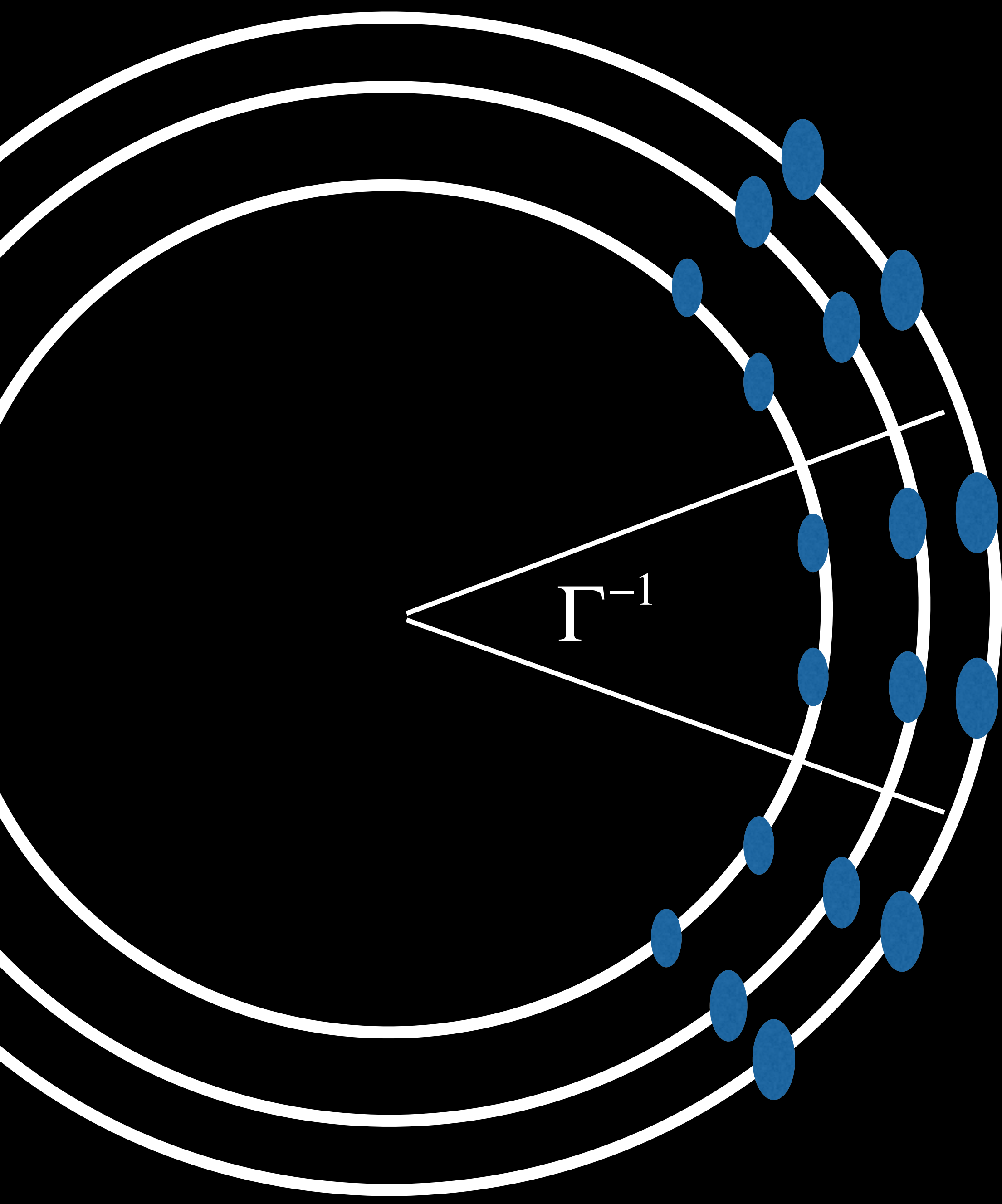

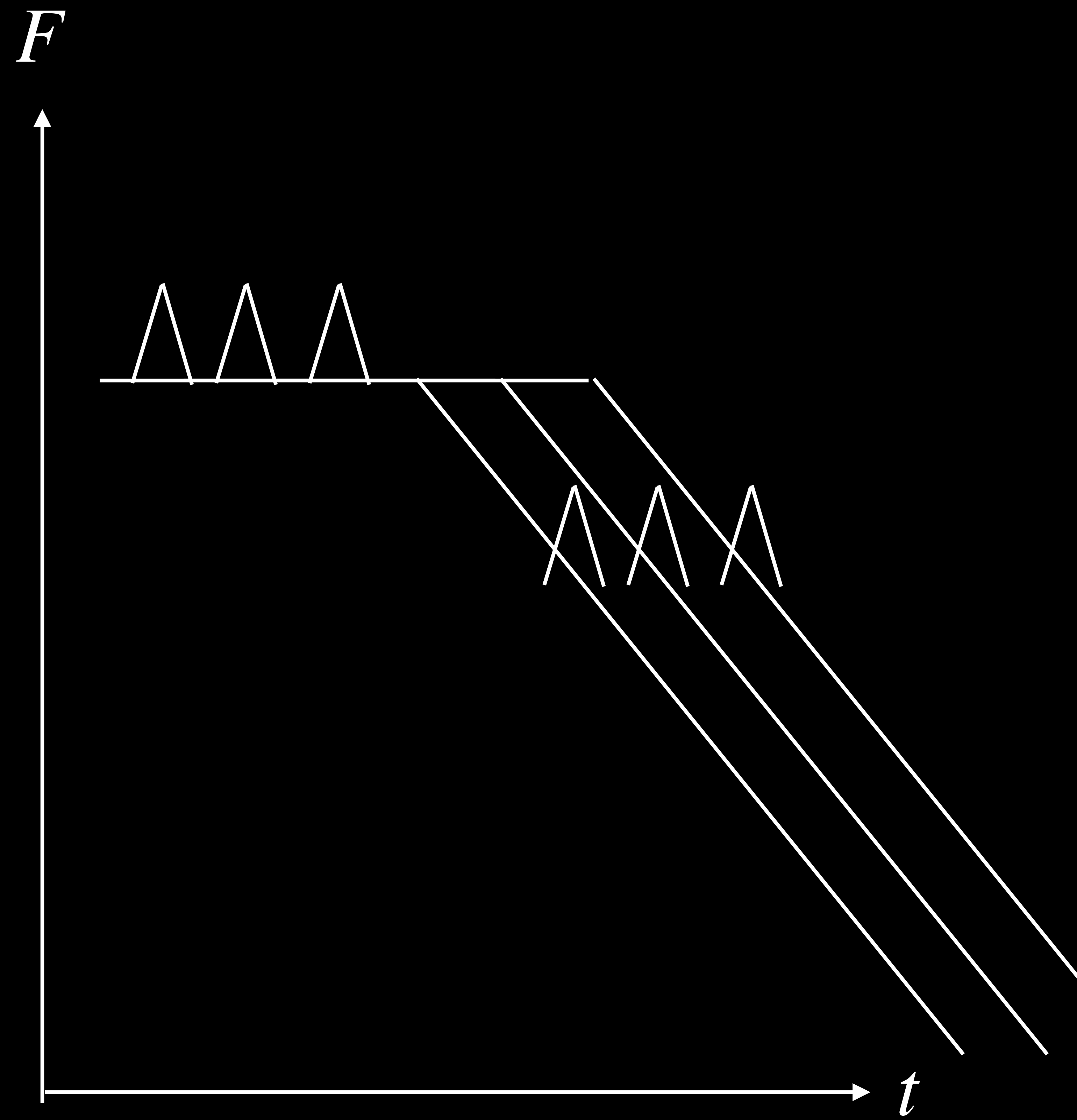

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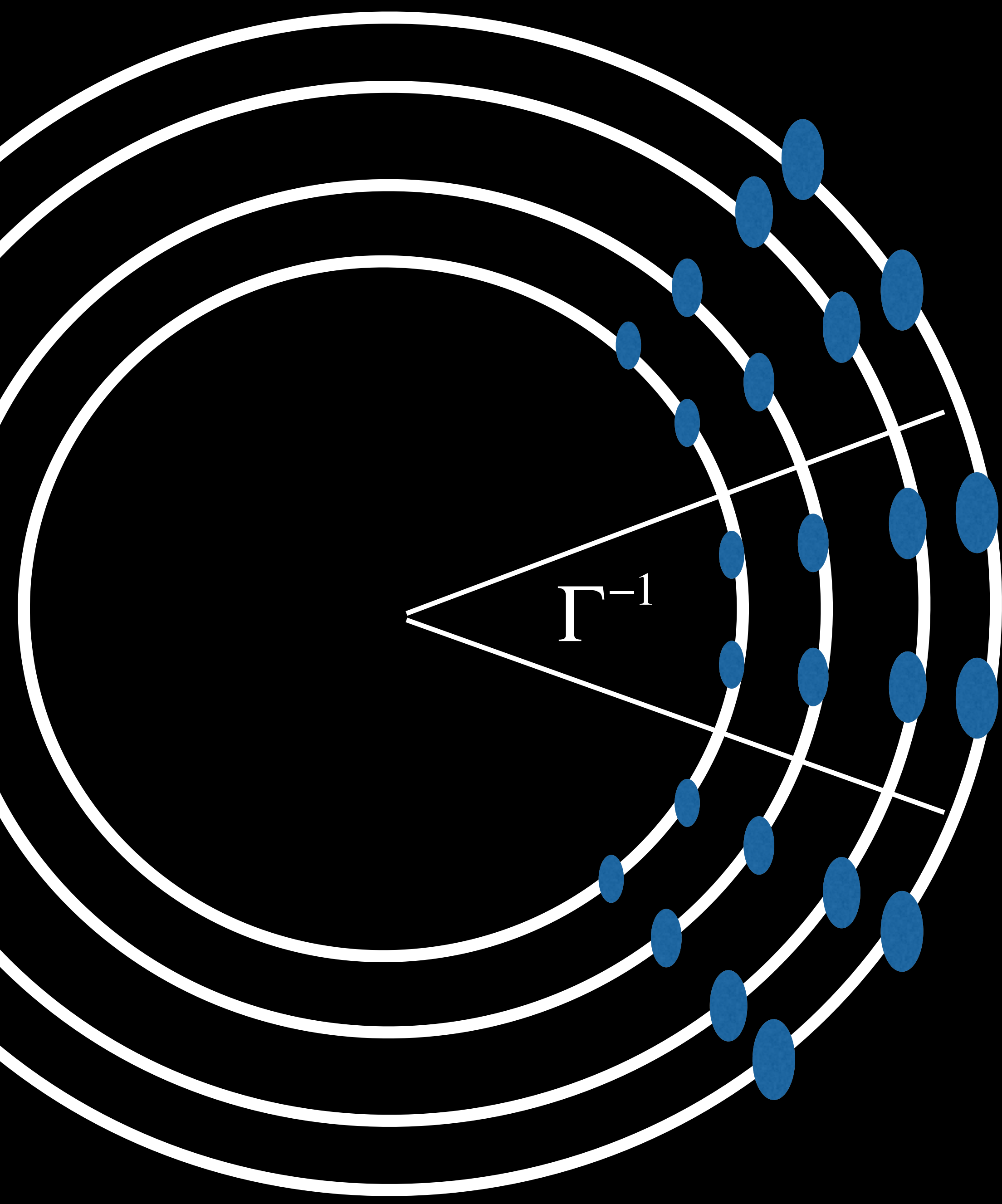
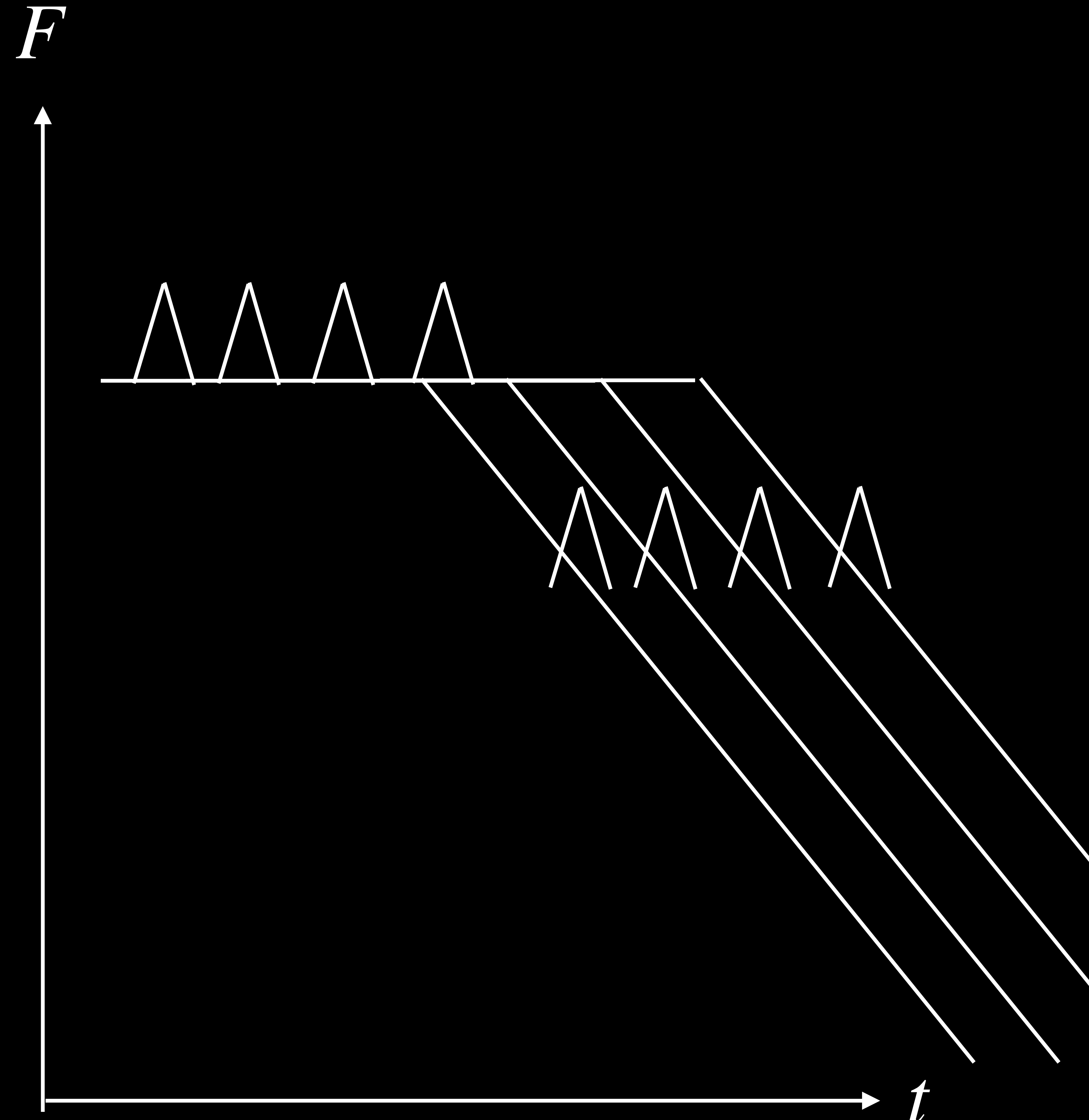


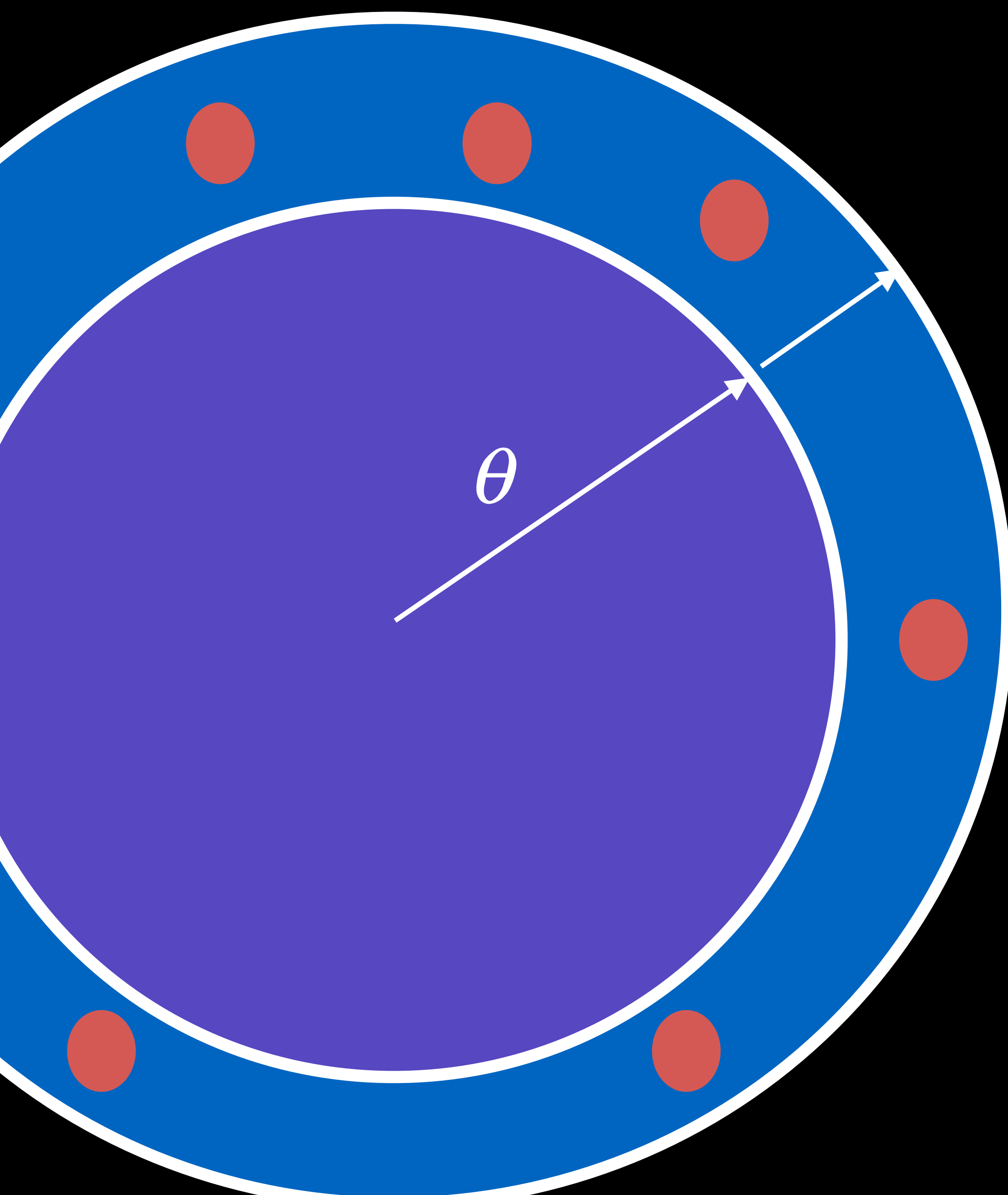


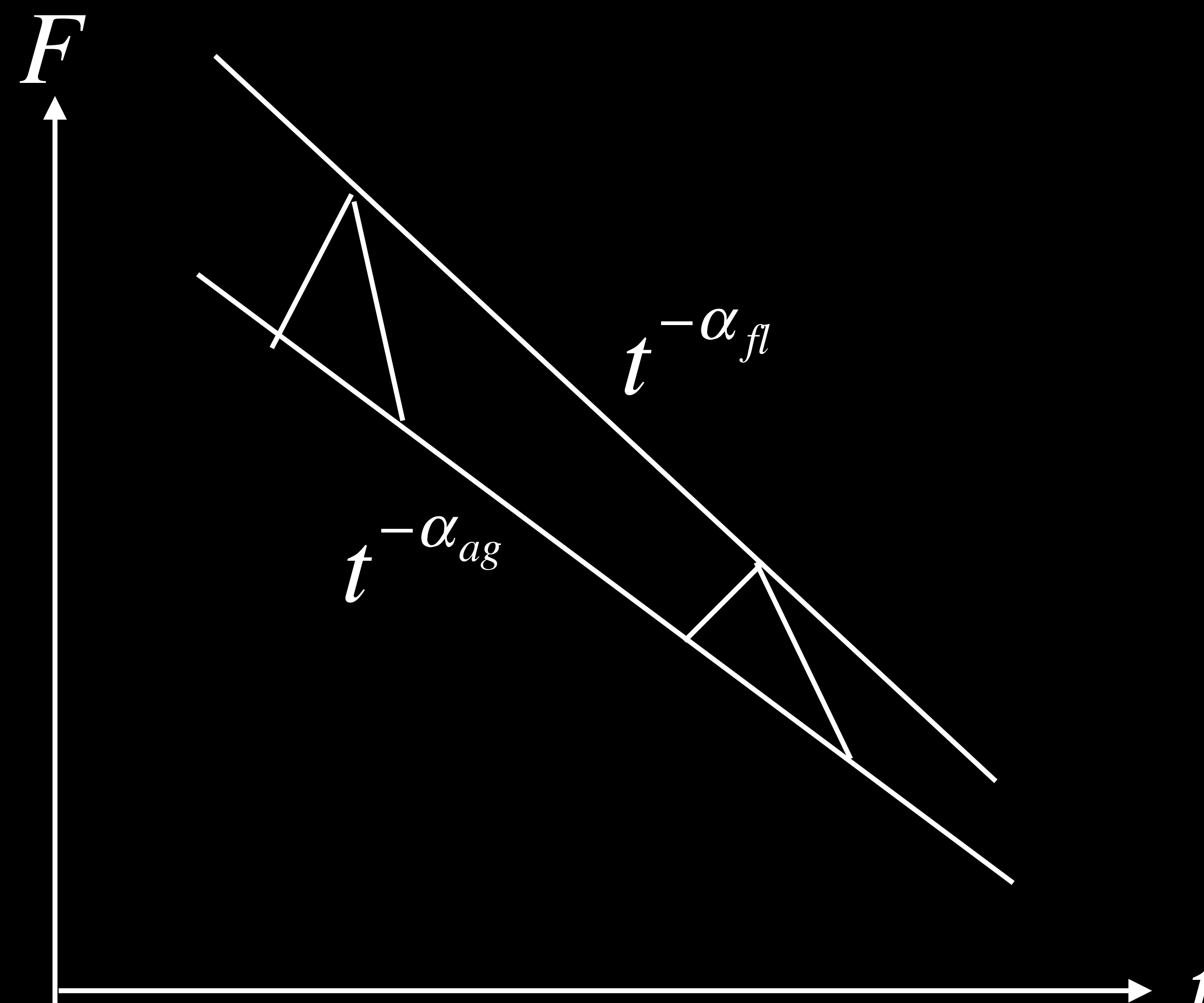
What do we see?

- In the subjet model, we expect to see an order of magnitude fewer flares for every dex in time
- We find:
  - 115 flares with $t < 10^3$ s
  - 19 flares with 10^3 s $< t < 10^4$ s
  - 10 flares with 10^4 s $< t < 10^5$ s
  - 5 flares with $t > 10^5$ s
- Consistent with subjet flares up to about 10^3 s, and another process responsible for ~5-10 flares in each bin, and dominating at late times

Model: Flare Flux

$$\Lambda_{fl,\max} / \Lambda_{ag} = \gamma(1+\beta)$$

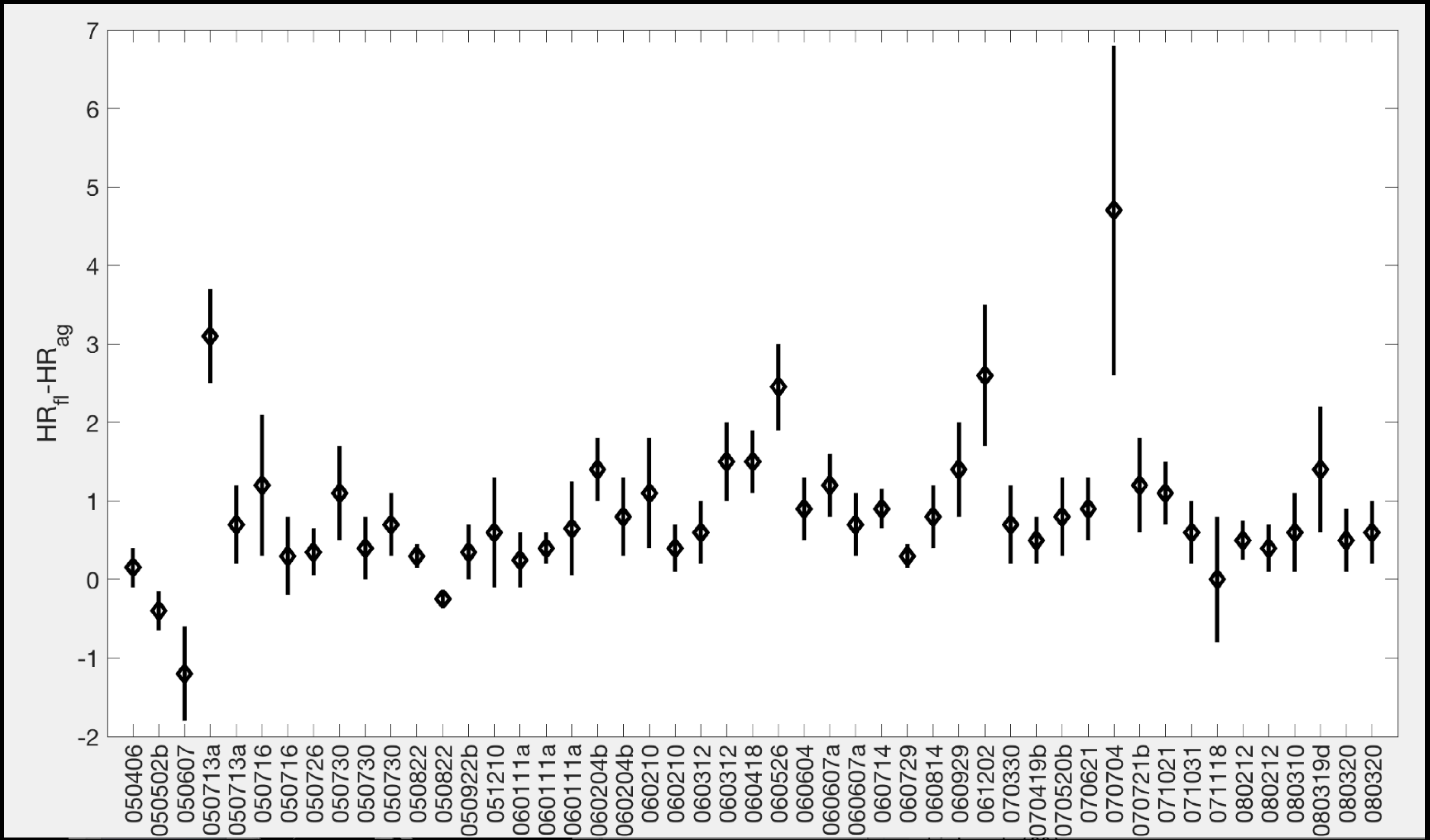




$$\alpha_{ag} \simeq -(2+\beta_{ag})$$

$$\alpha_{fl} \simeq -(3+\beta_{fl})$$

$$\alpha_{ag} \approx \alpha_{fl} \Rightarrow \beta_{fl} \approx \beta_{ag} - 1$$



- Flares are clearly harder than the afterglow
  - The difference in HR is typically ~1, for frequency ranges 0.3-1.5 keV and 1.5-10 keV
- However, for $\beta_{ag} = 0.7 - 1.0$, we find $\Delta\beta = 0.2 - 0.3$
  - There is tension!

Conclusions

- We find clear evidence for (at least) two different mechanisms powering X-ray flares
  - One mechanism creates flares before ~1000 s. The flares track the steep decay of the afterglow light curve and have a typical width of dT/T ~ 0.2
  - The other process dominates at late times, although it may also produce flares at early times. These flares have a typical width dT/T ~ 1, and are only seen in GRBs that do NOT have a steep decay phase
- We explore a subjet model to link the flares during the early steep decay phase to the prompt emission
  - The model can explain the timescale and frequency of these early flares
  - However, there is tension between the temporal decay index and the flare spectral index