On the jet structure of GRBs through X-ray light curve modeling

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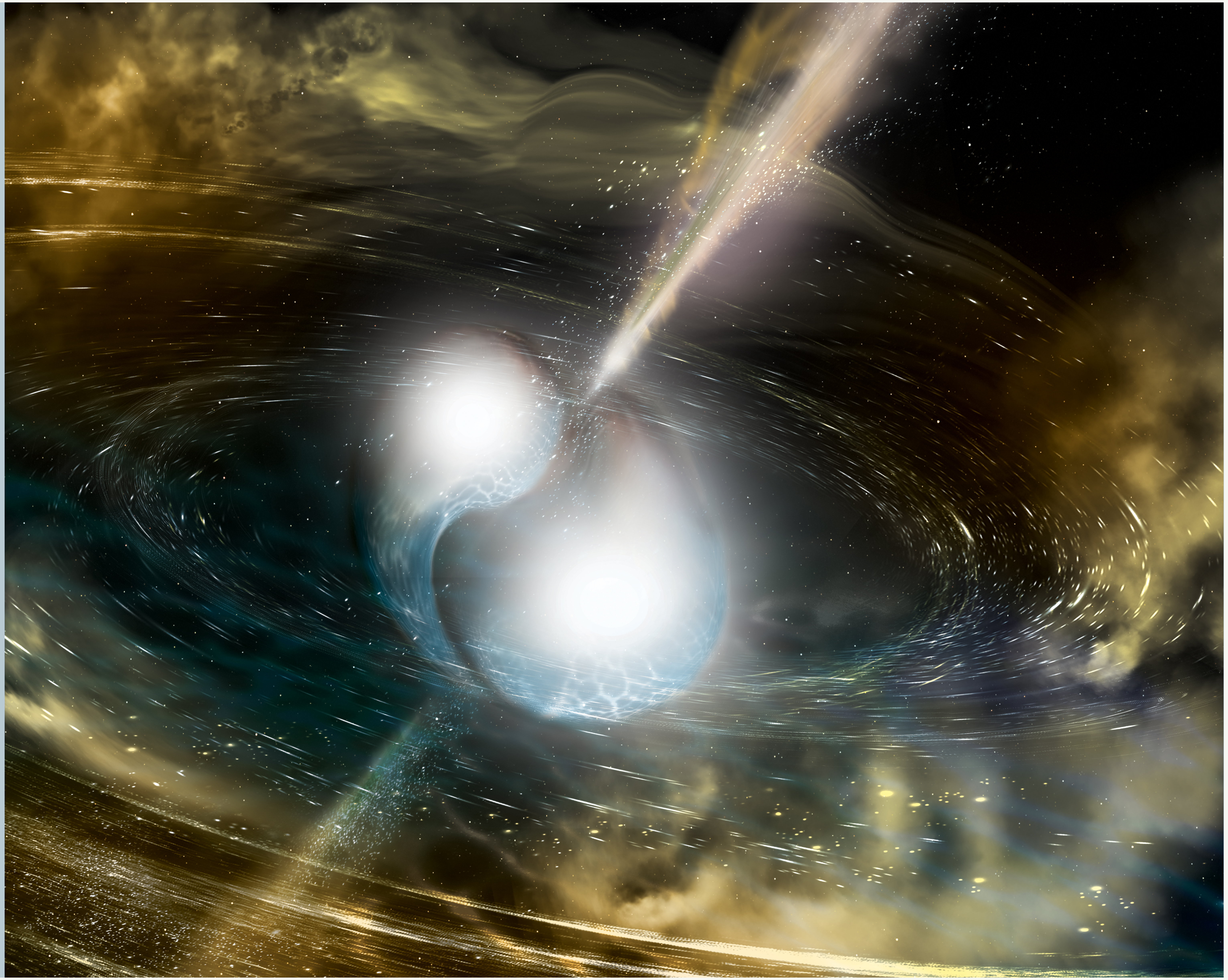
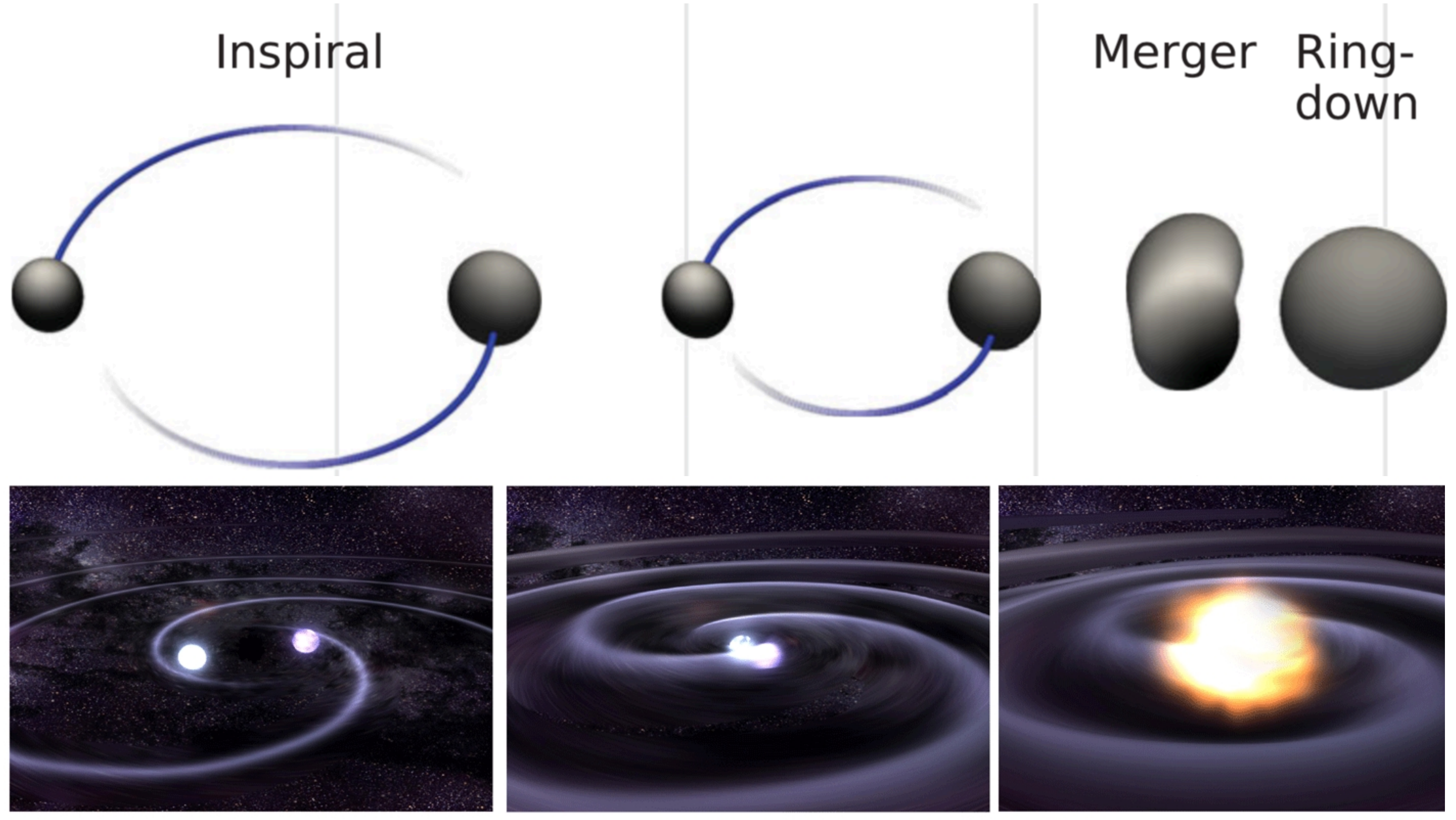
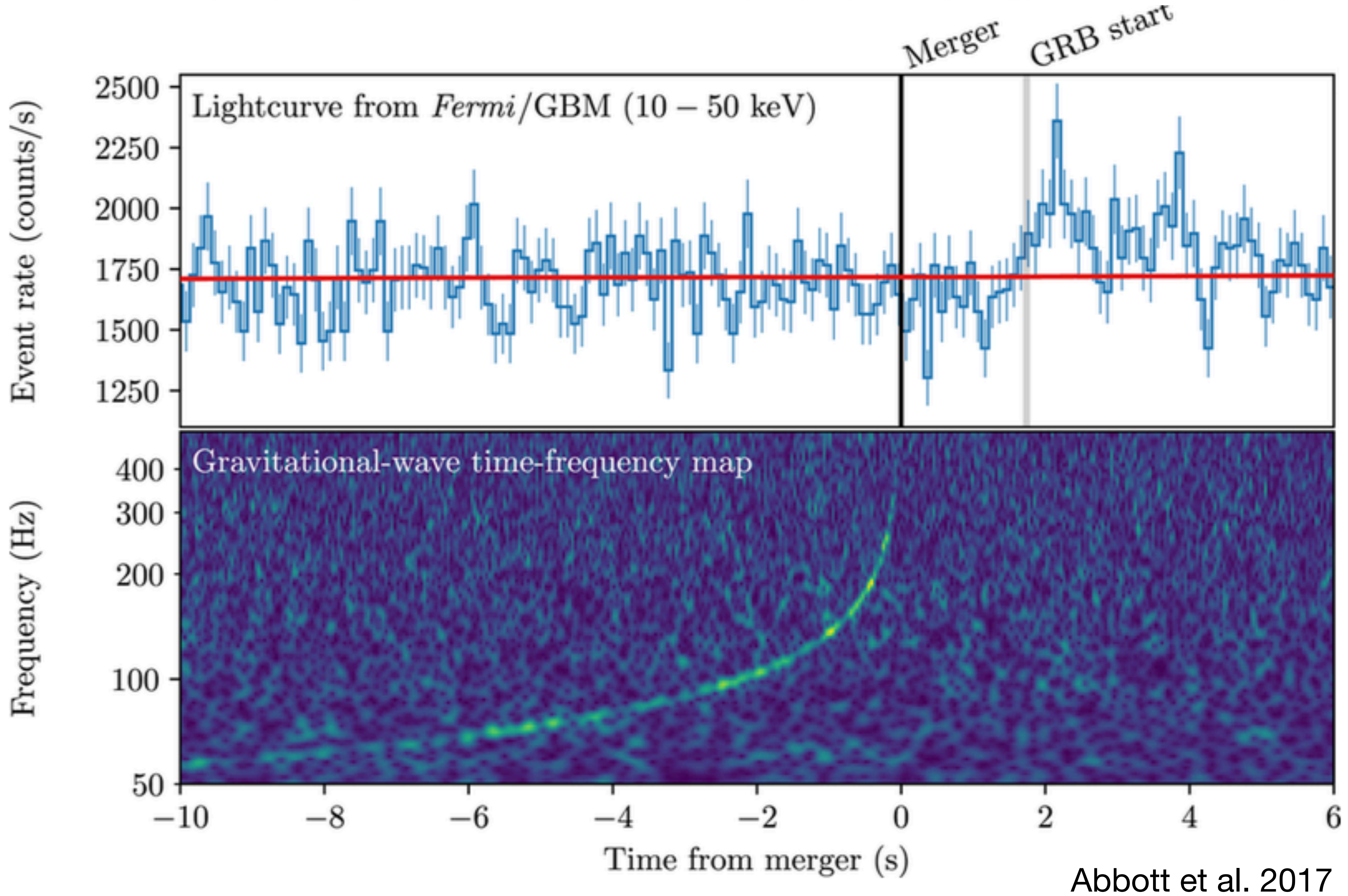
Binary Neutron Star Mergers
as progenitors of short GRBs



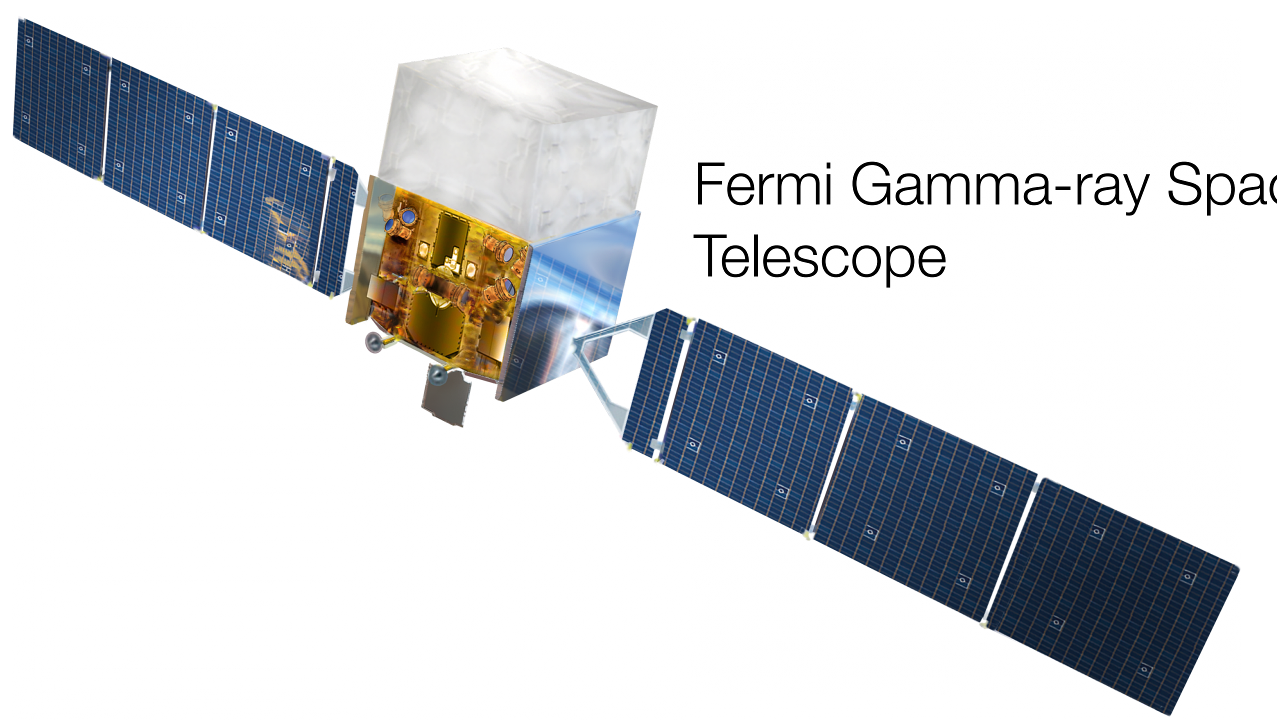
GW170817



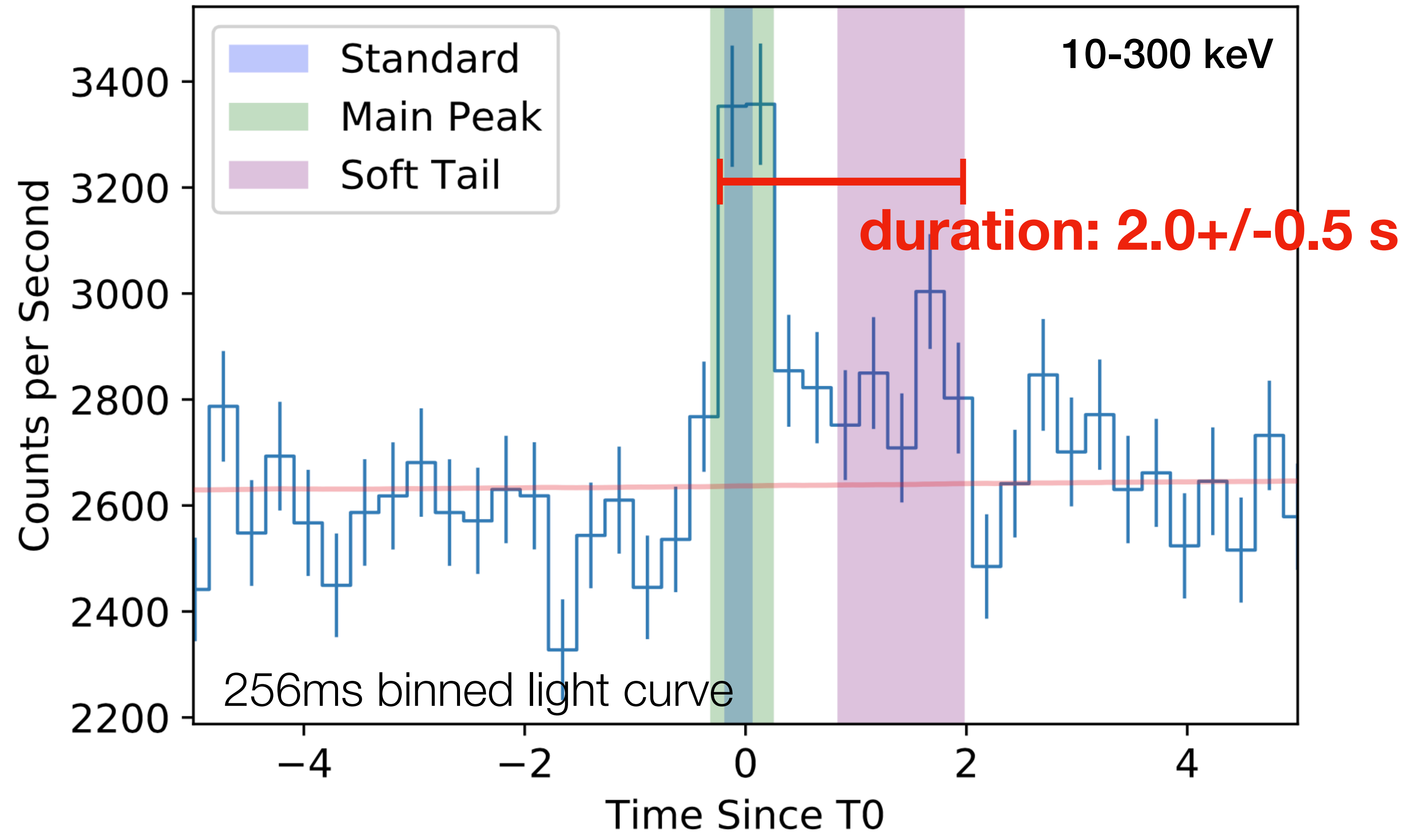


Abbott et al. 2017

- LIGO/VIRGO detected 11 confirmed compact binary coalescences in observing run O1 and O2
  - 10 Binary black hole mergers
  - 1 Binary neutron star merger
- Binary neutron star merger GW170817
- Short GRB association confirmed by Fermi Gamma-ray Space Telescope (Goldstein et. al, 2017)



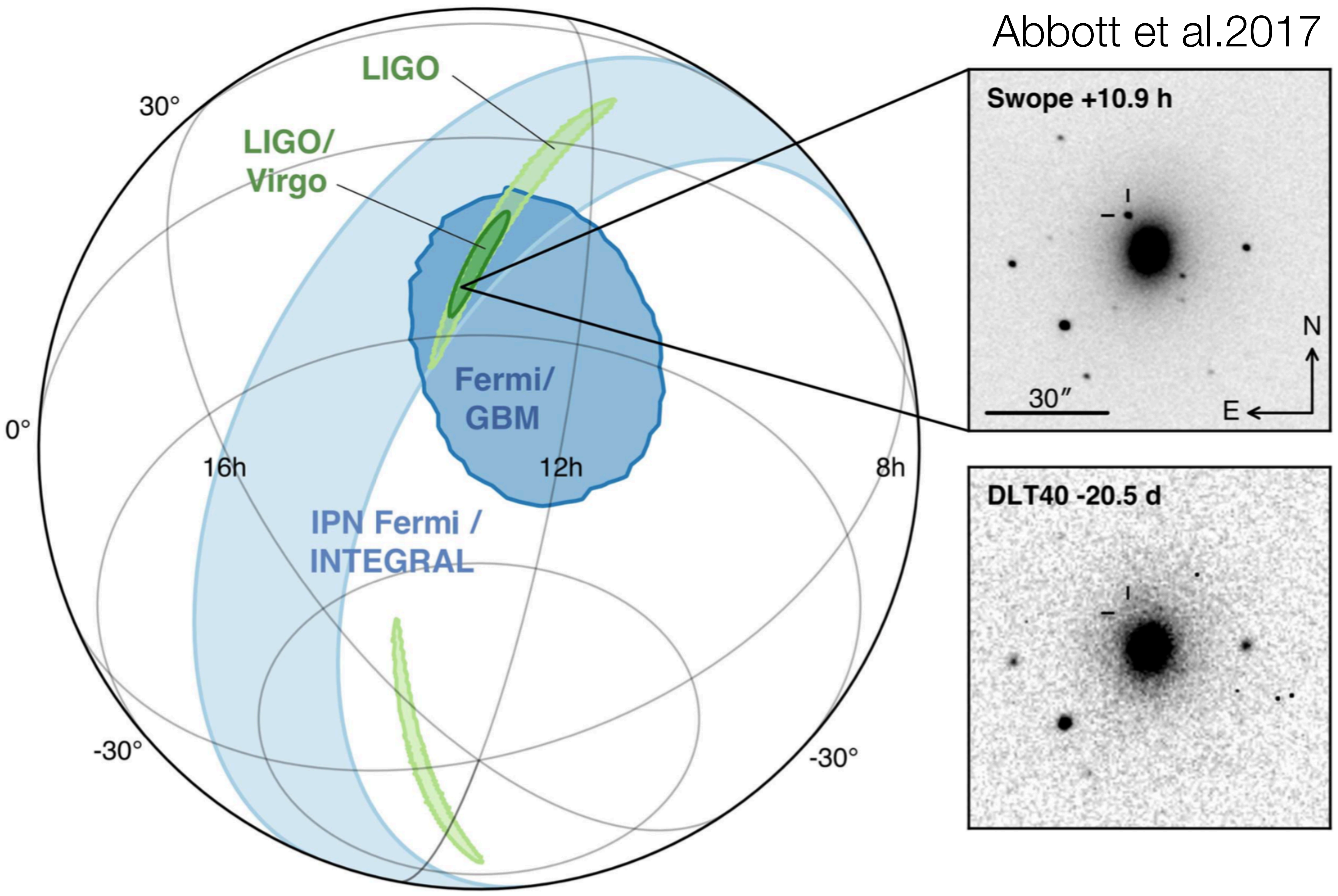
Fermi Gamma-ray Space Telescope



Multi-messenger Astrophysics

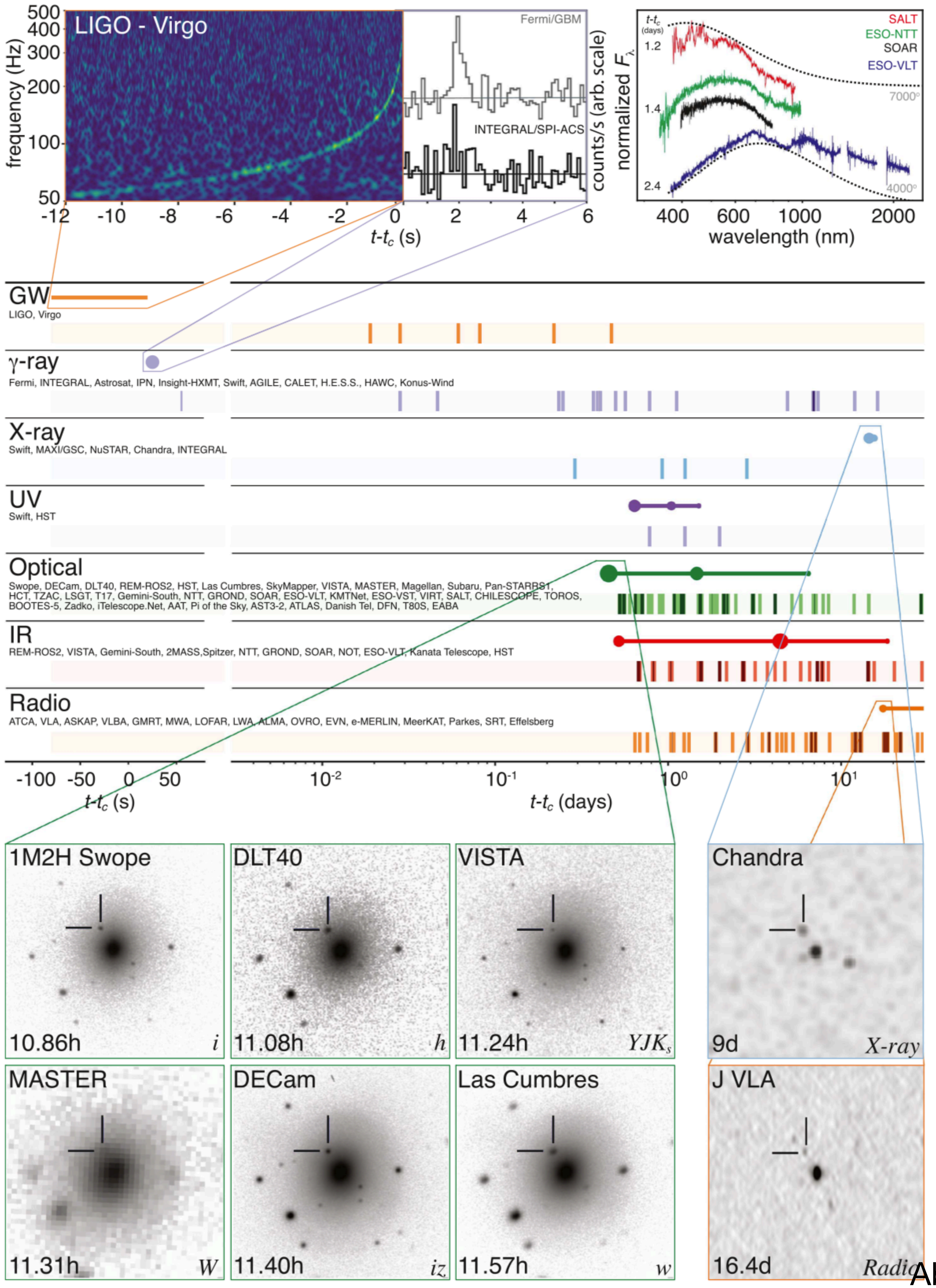
GW + EM observation

Abbott et al.2017



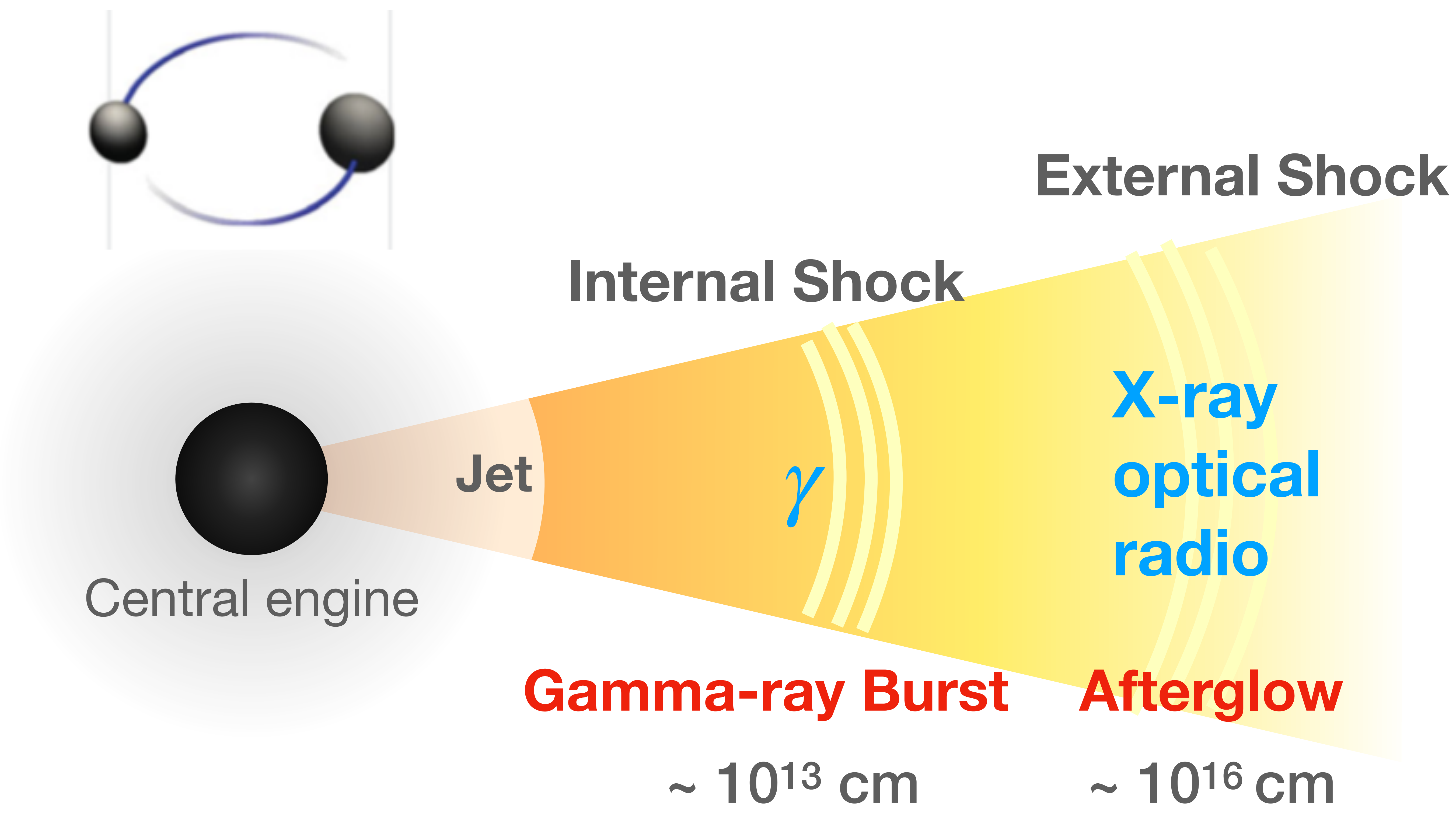
Multi-messenger Astrophysics

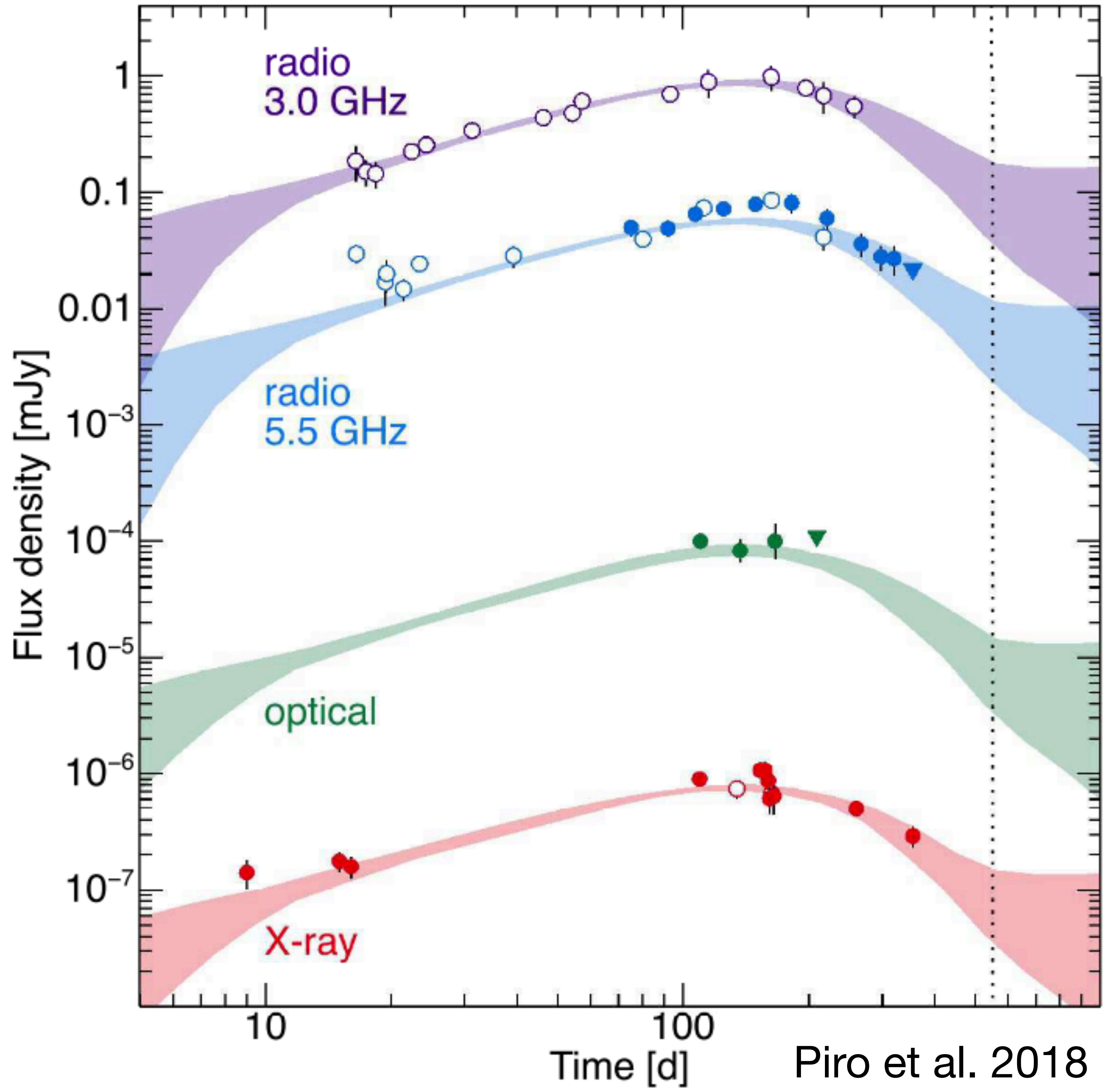
GW + EM observation



Abbott et al. 2017

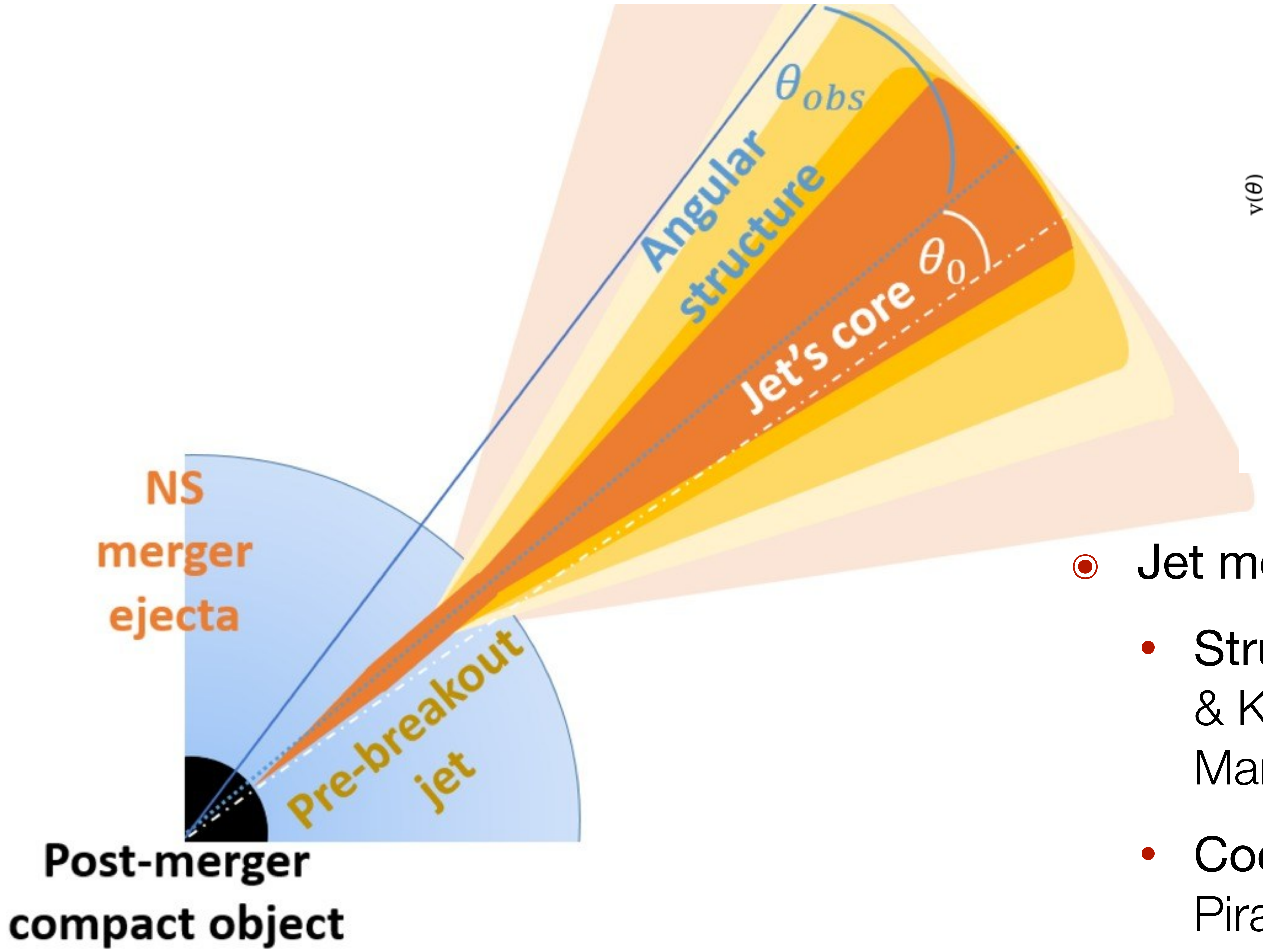
GRB afterglow light curves



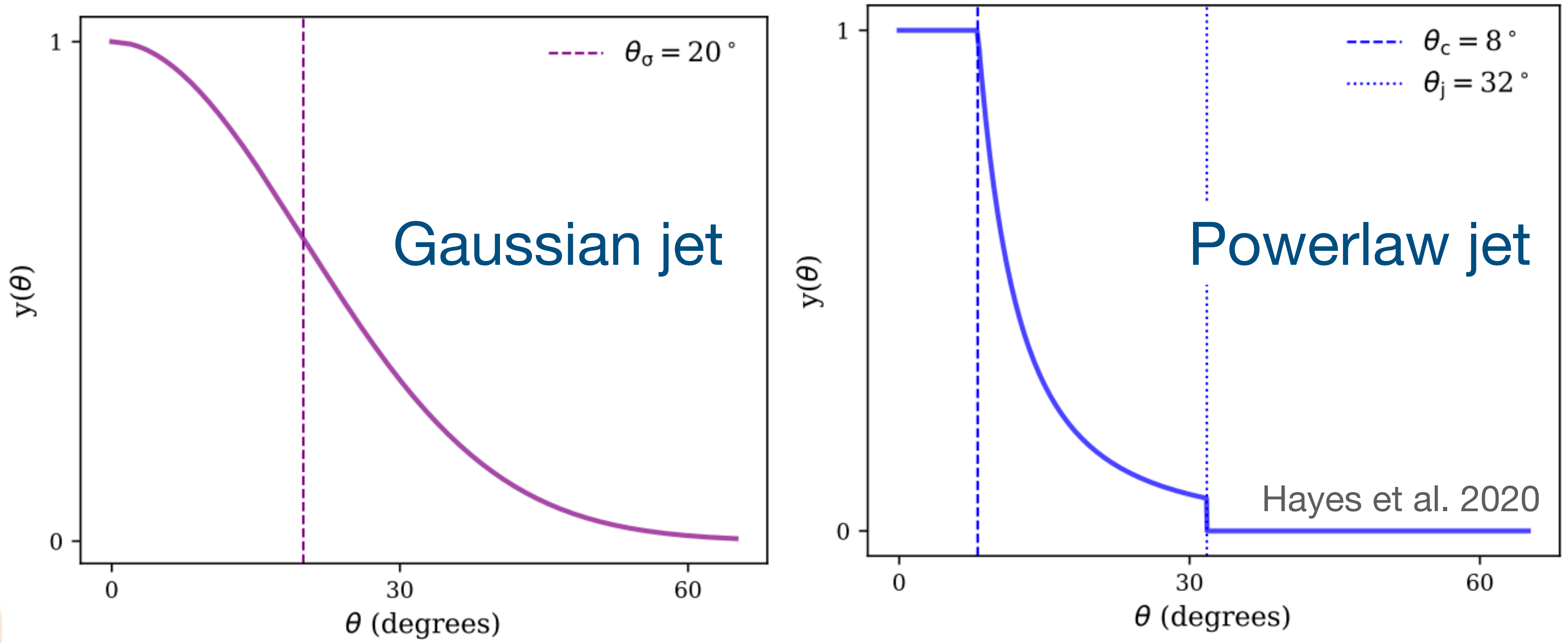


Piro et al. 2018

Afterglow light curves as hints to jet structure



Beniamin et al. 2019



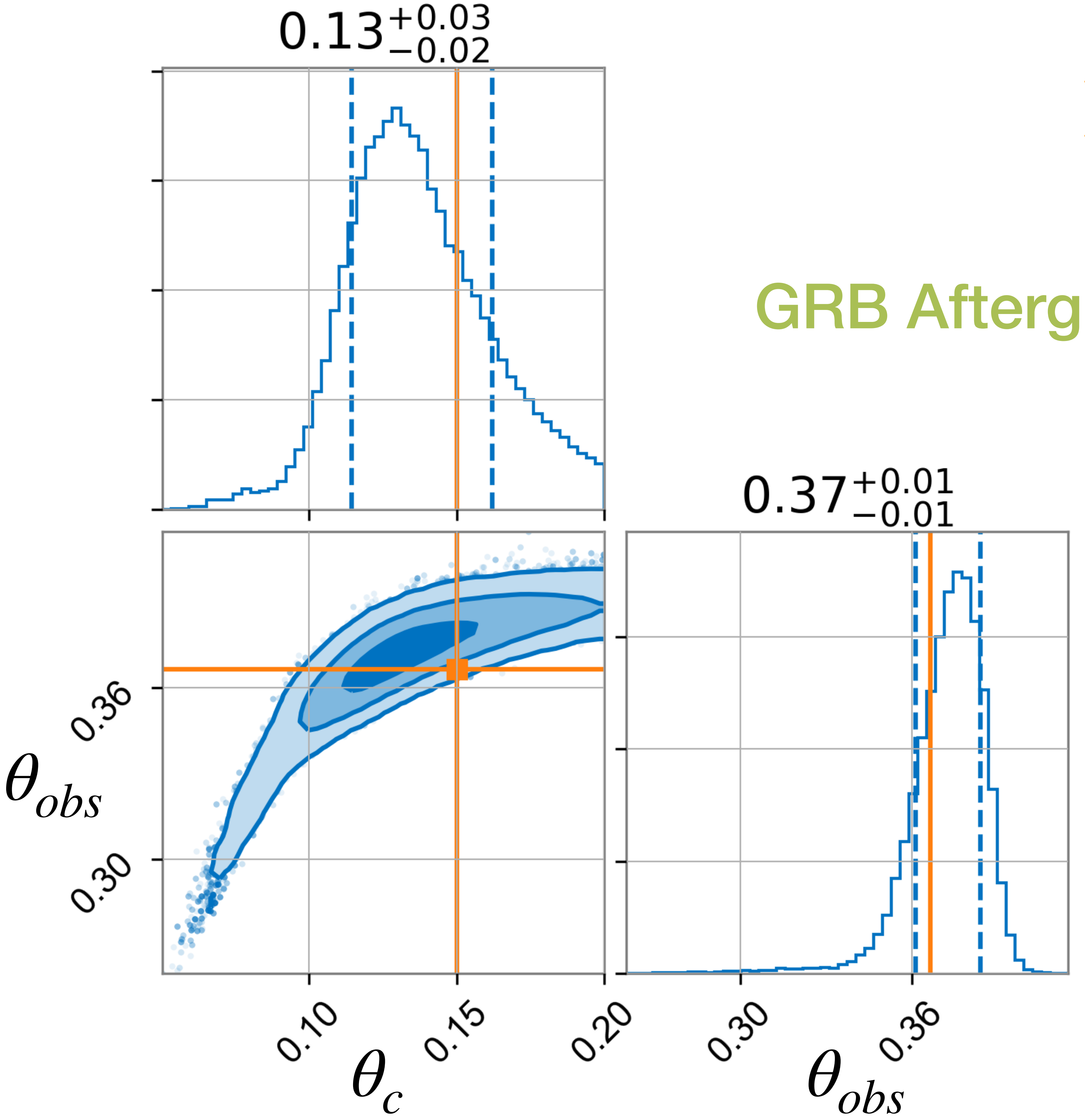
Hayes et al. 2020

- Jet models
  - **Structured jet** (D'Avanzo et al. 2018; Gill & Granot 2018; Lamb & Kobayashi 2018; Lazzati et al. 2018; Lyman et al. 2018; Margutti et al. 2018; Troja et al. 2018, etc.)
  - **Cocoon jet/top-hat jet** (Kasliwal et al. 2017; Gottlieb, Nakar & Piran 2018; Mooley et al. 2018)
  - **Refreshed shock model** (Lamb et al. 2020)

On the jet structure of GRBs through X-ray light curve investigation

- Objective
  - Jet structure
- Research framework
  - Generate X-ray afterglow light curves
  - Parameter estimation
  - Model comparison

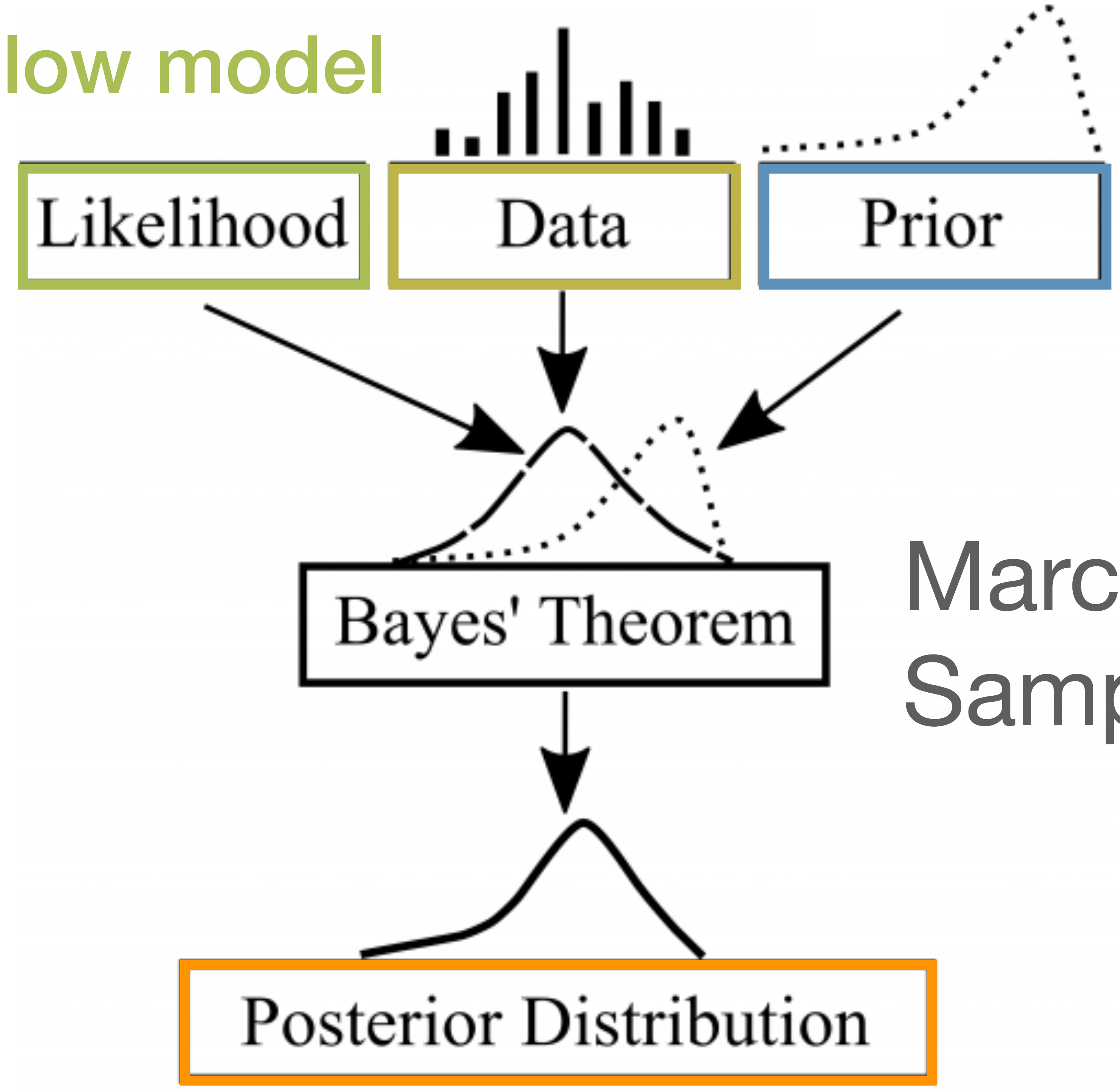
Parameter Estimation

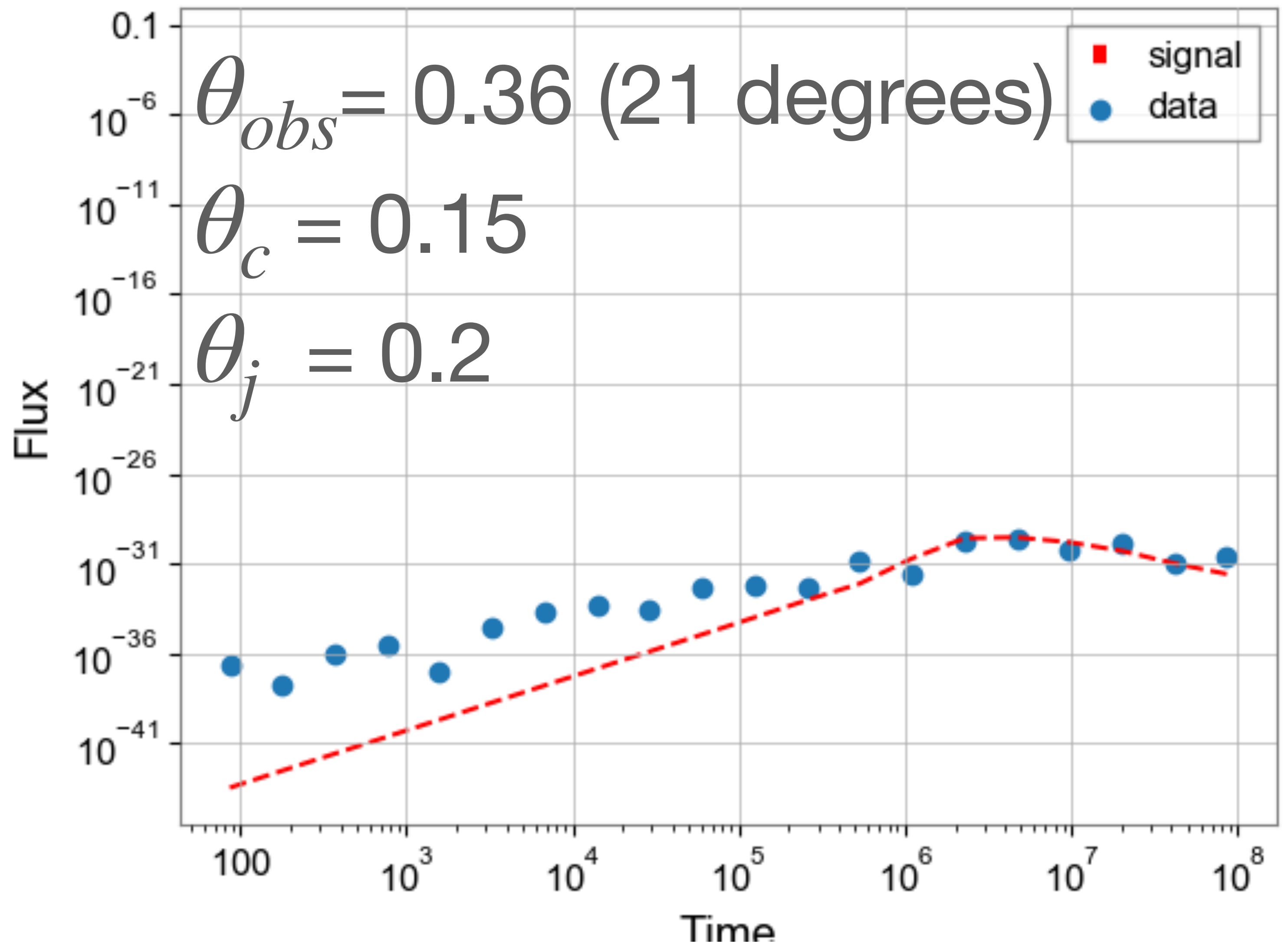


Bayes Rule:

$$P(\theta|D) = \frac{P(D|\theta)\, P(\theta)}{P(D)}$$

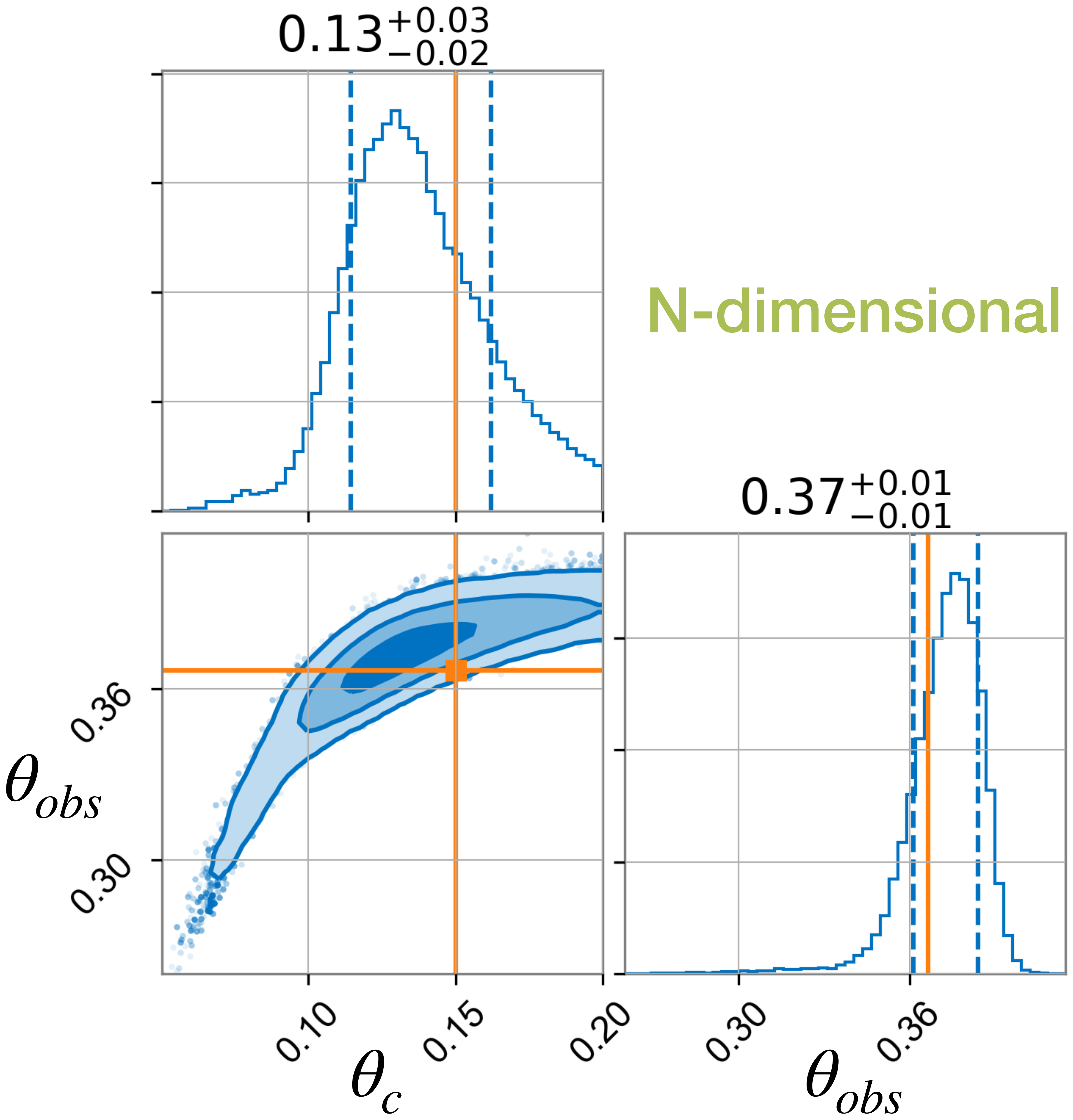
GRB Afterglow model





Marcov Chain Monte Carlo Sampling Method

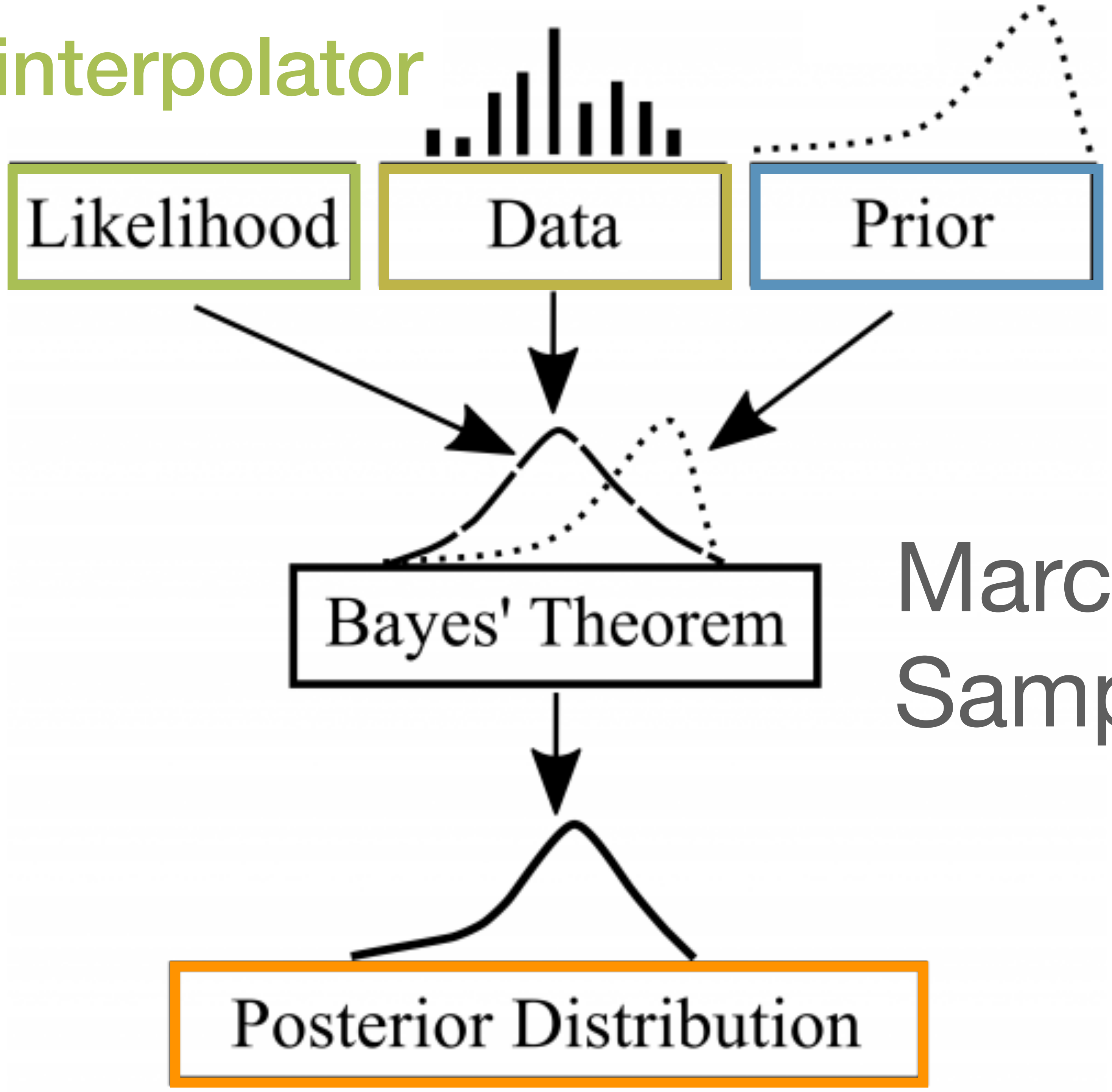
Parameter Estimation



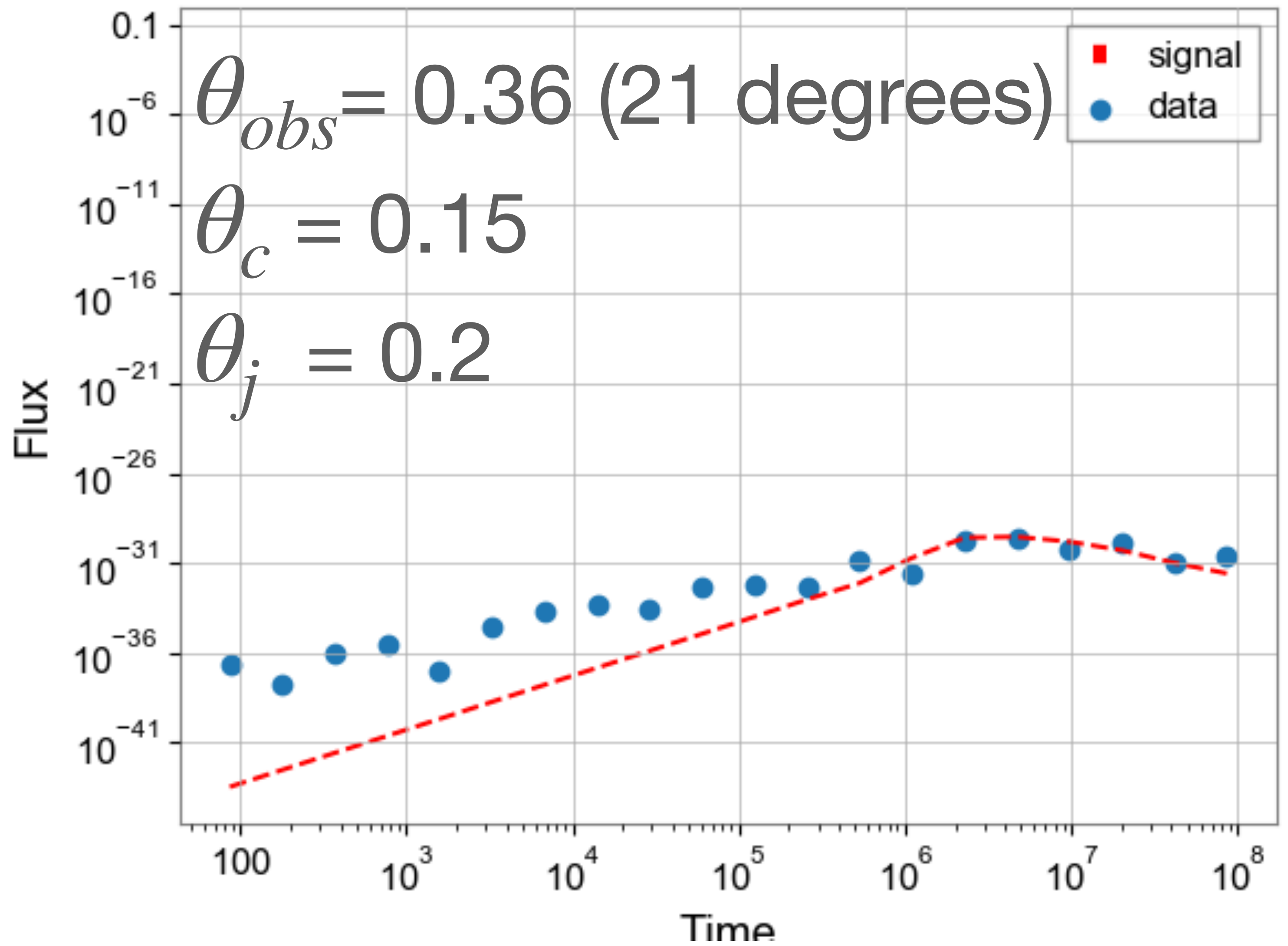
Bayes Rule:

$$P(\theta|D) = \frac{P(D|\theta)\,P(\theta)}{P(D)}$$

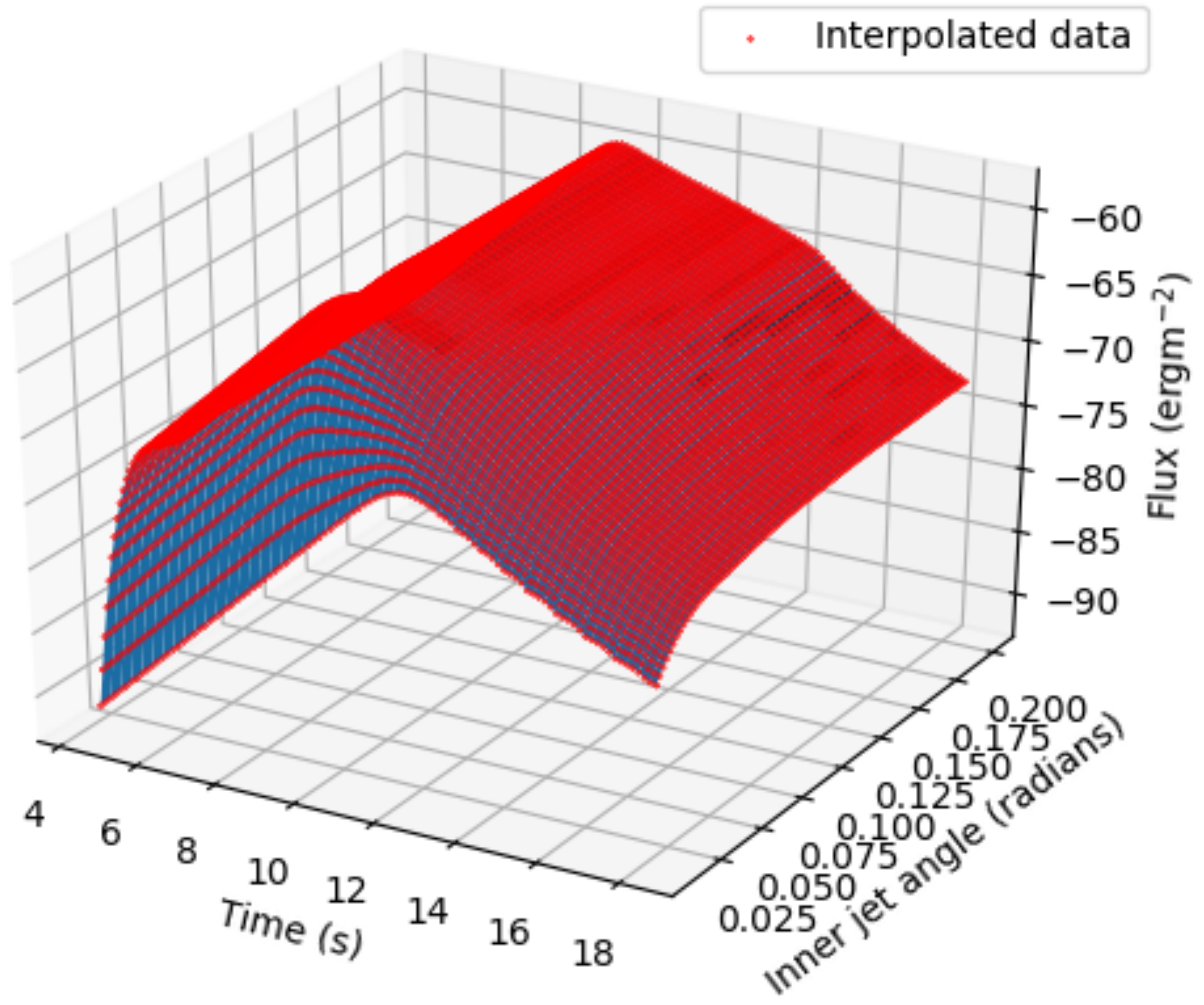
N-dimensional interpolator

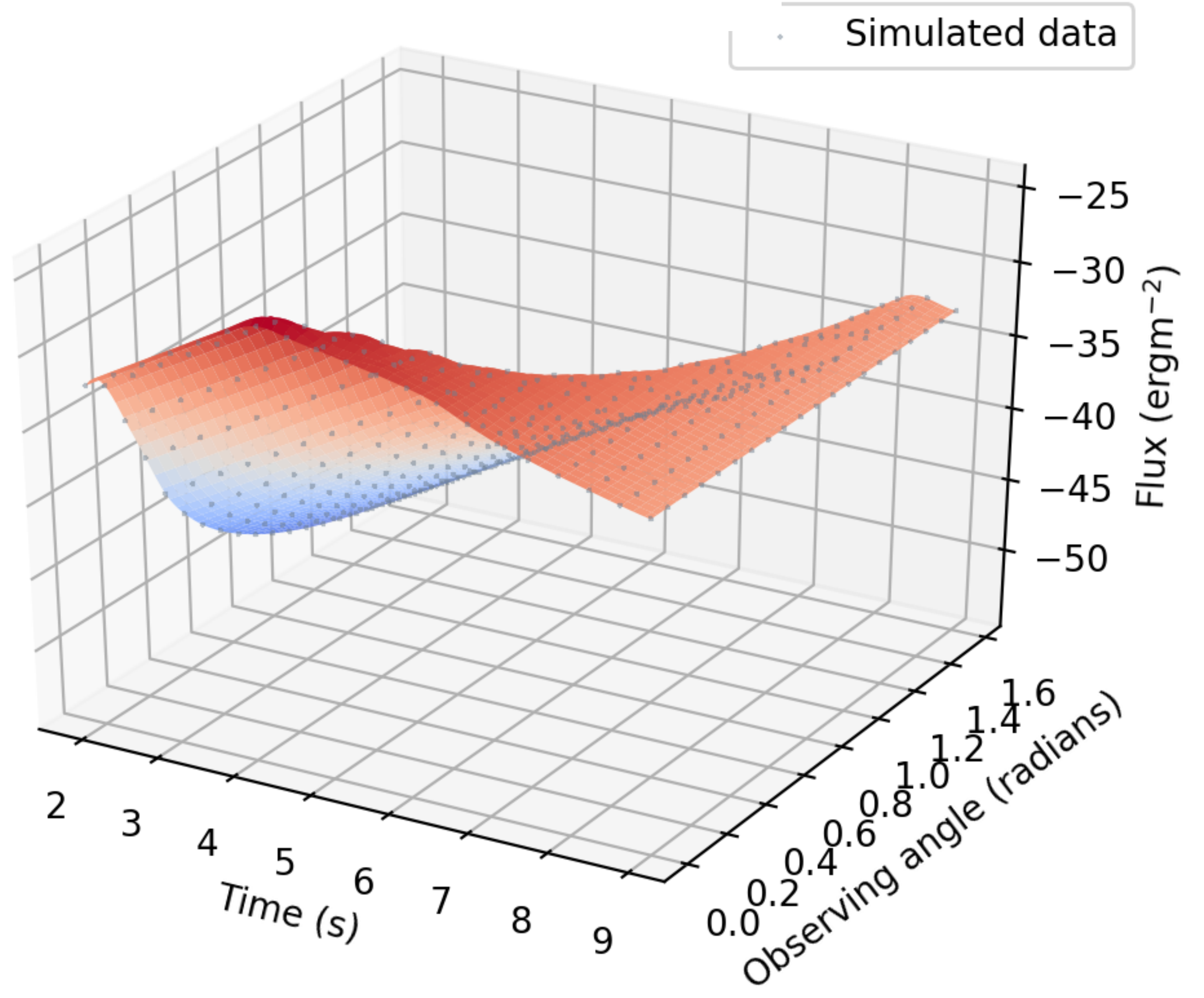


Marcov Chain Monte Carlo Sampling Method



Multi-dimensional grids across parameter space



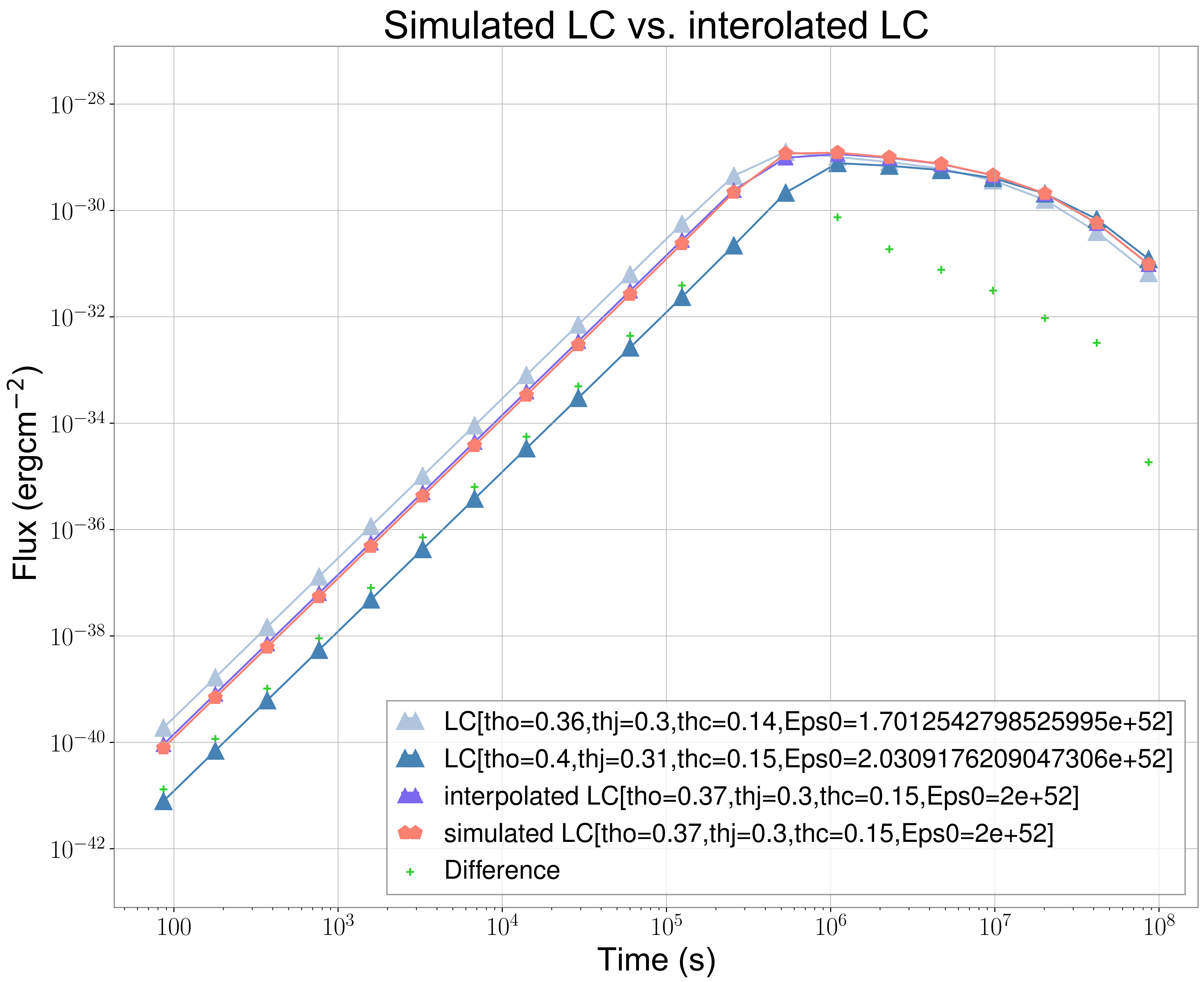


Multi-dimensional grids across parameter space

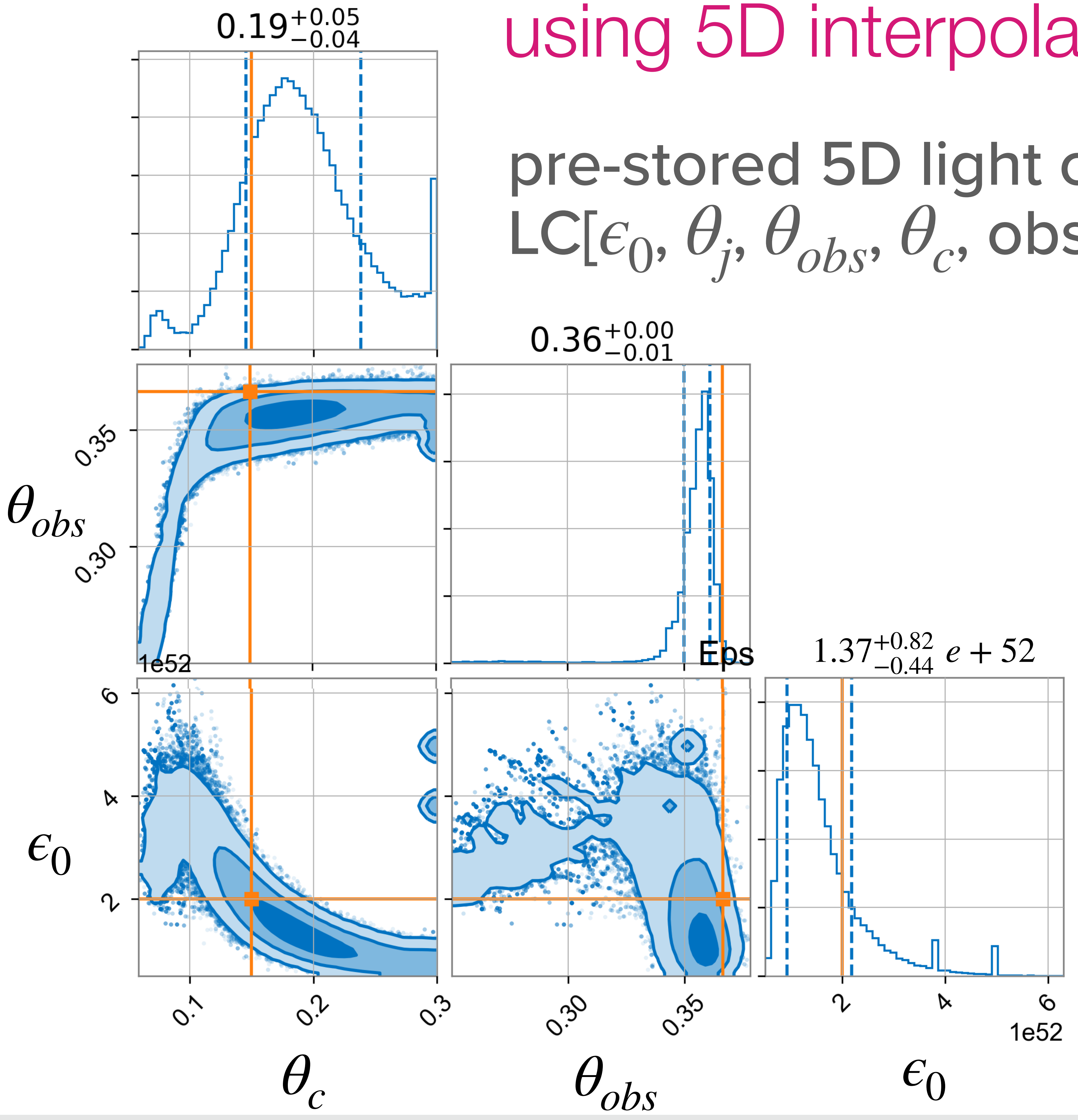
- θ_{obs} ~ [0.01, $\pi/4$]
- θ_j (jet opening angle) ~ [0.01, $\pi/6$]
- θ_j (jet core angle) ~ [0.01, $\pi/6$]
- ϵ_0 (kinetic energy of central segment) ~ [1e50,1e53]
- obs_times ~ [0.001,1000]

5D light curves:

LC[ϵ_0, θ_j, θ_{obs}, θ_c, obs_time] =40x40x40x40x20

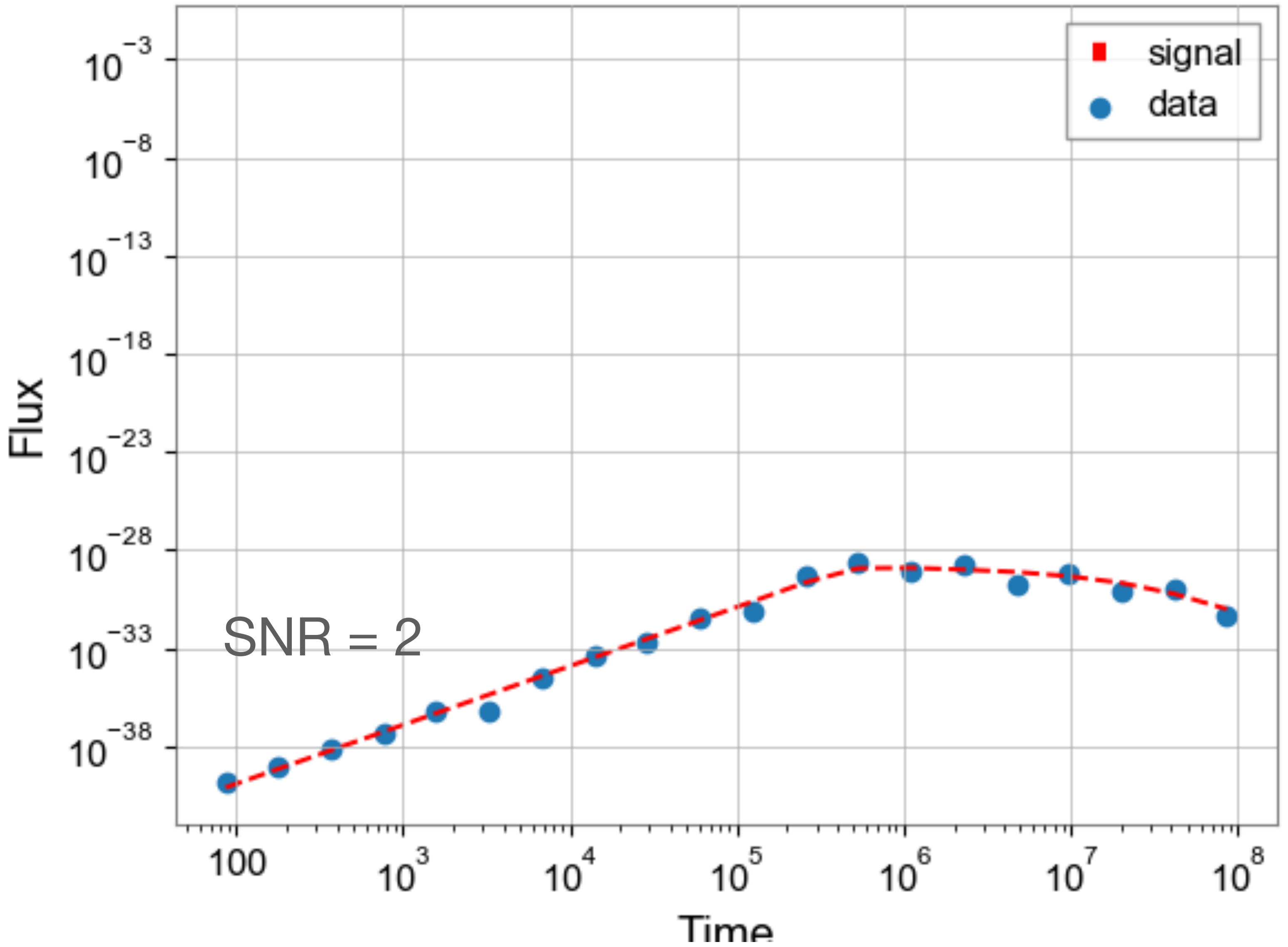


Probability distribution of jet parameters



using 5D interpolation function as likelihood

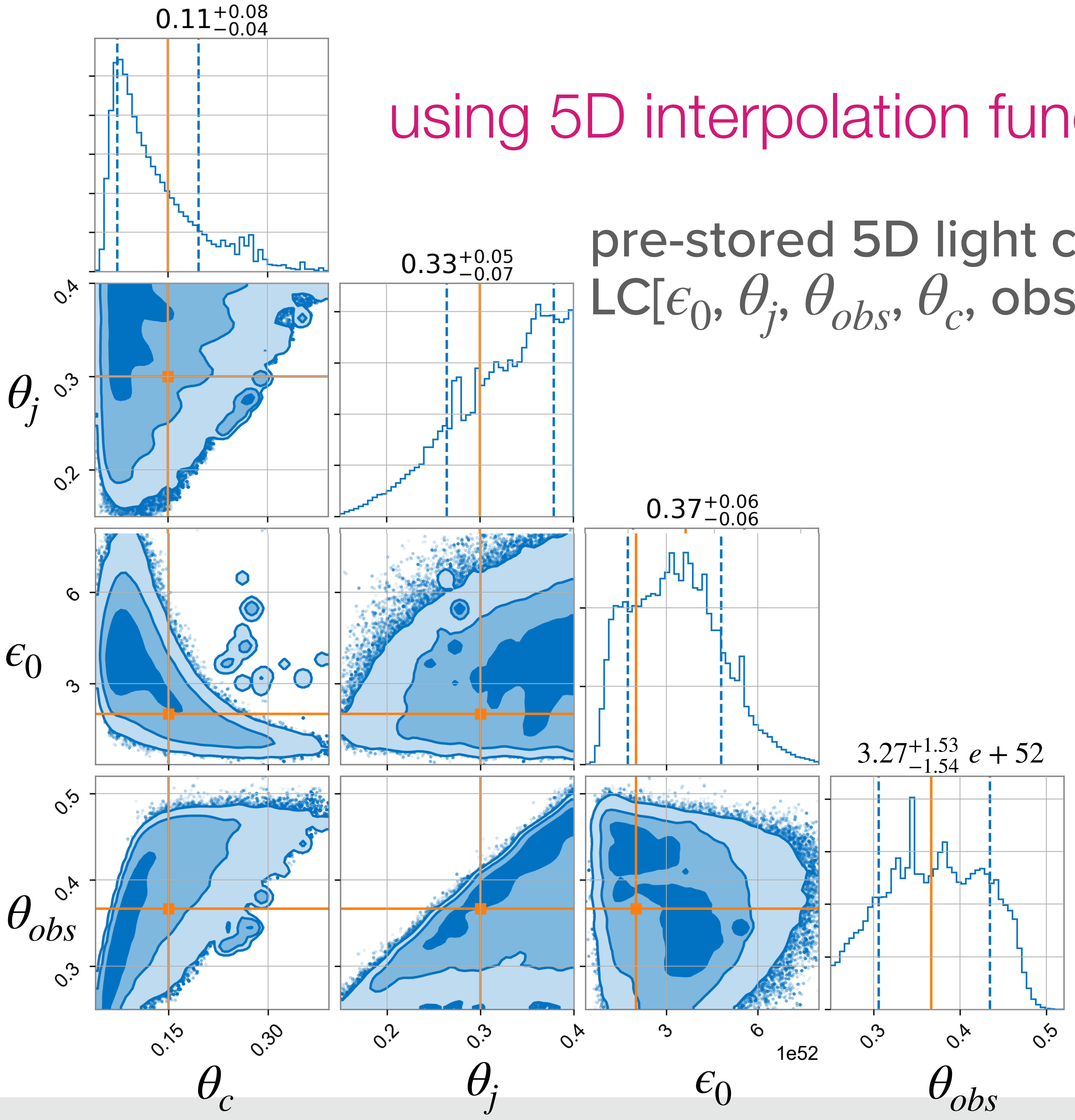
pre-stored 5D light curves:
LC[ϵ_0, θ_j, θ_{obs}, θ_c, obs_time] =40x40x40x40x20



Injected values:

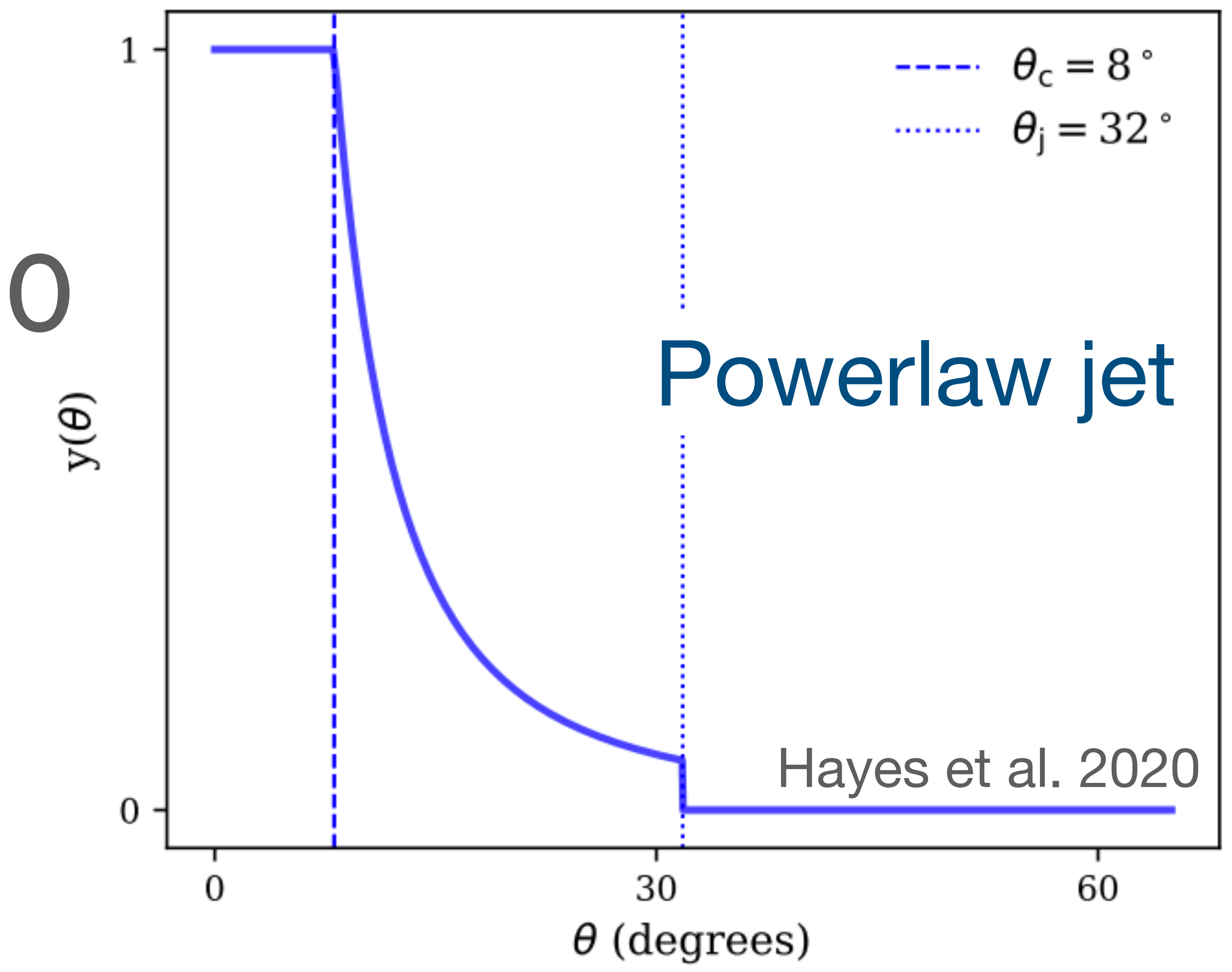
- θ_{obs} = 0.36 (21 degrees)
- θ_c (jet core angle) = 0.15
- ϵ_0 (kinetic energy) = 2e52

Probability distribution of jet parameters



using 5D interpolation function as likelihood

pre-stored 5D light curves:
LC[ϵ_0, θ_j, θ_{obs}, θ_c, obs_time] =40x40x40x40x20



Injected values:

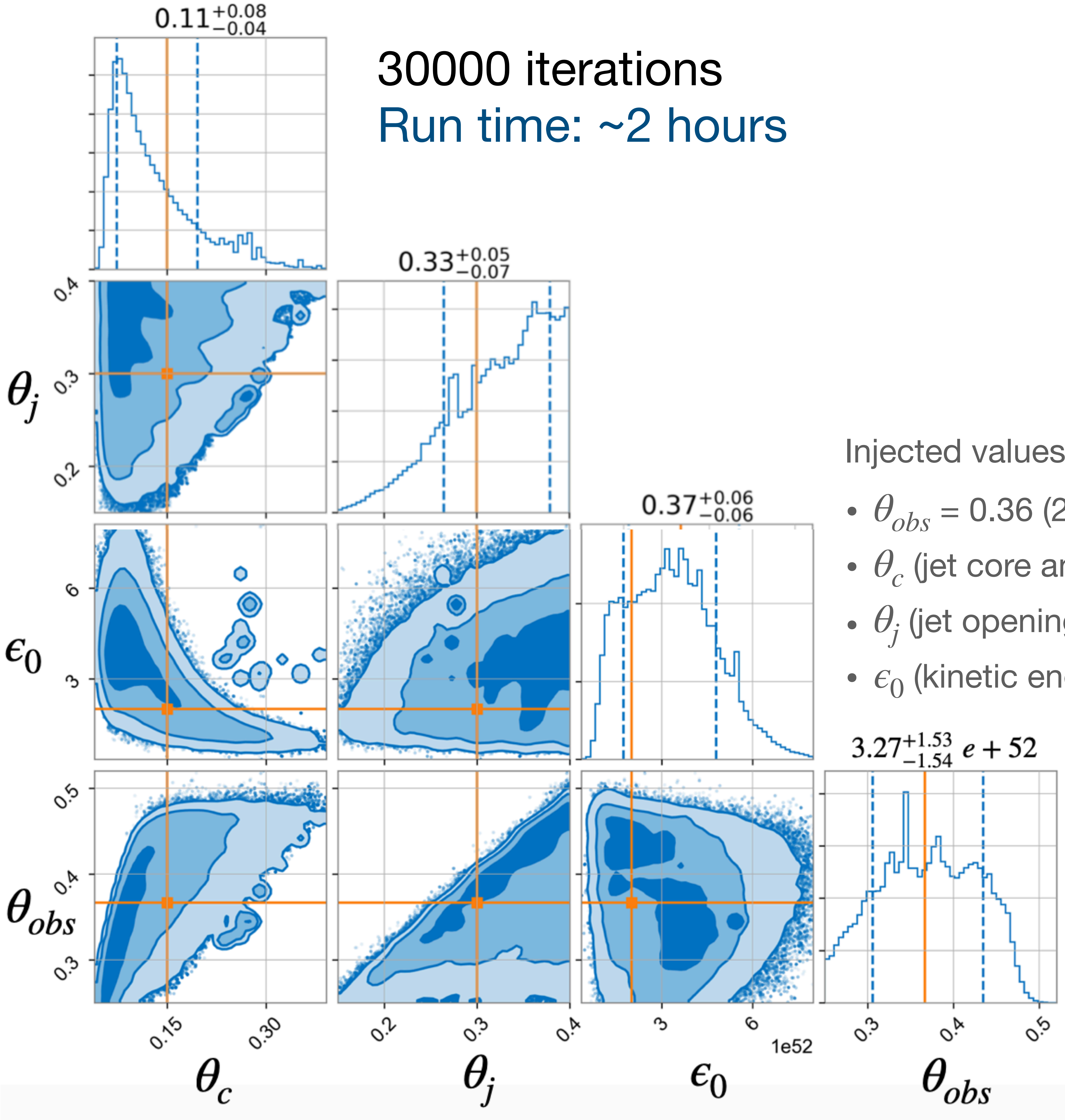
- θ_{obs} = 0.36 (21 degrees)
- θ_c (jet core angle) = 0.15
- θ_j (jet opening angle) = 0.3
- ϵ_0 (kinetic energy) = 2e52

A comparison between two methods

Interpolated GRB model

30000 iterations

Run time: ~2 hours



Injected values:

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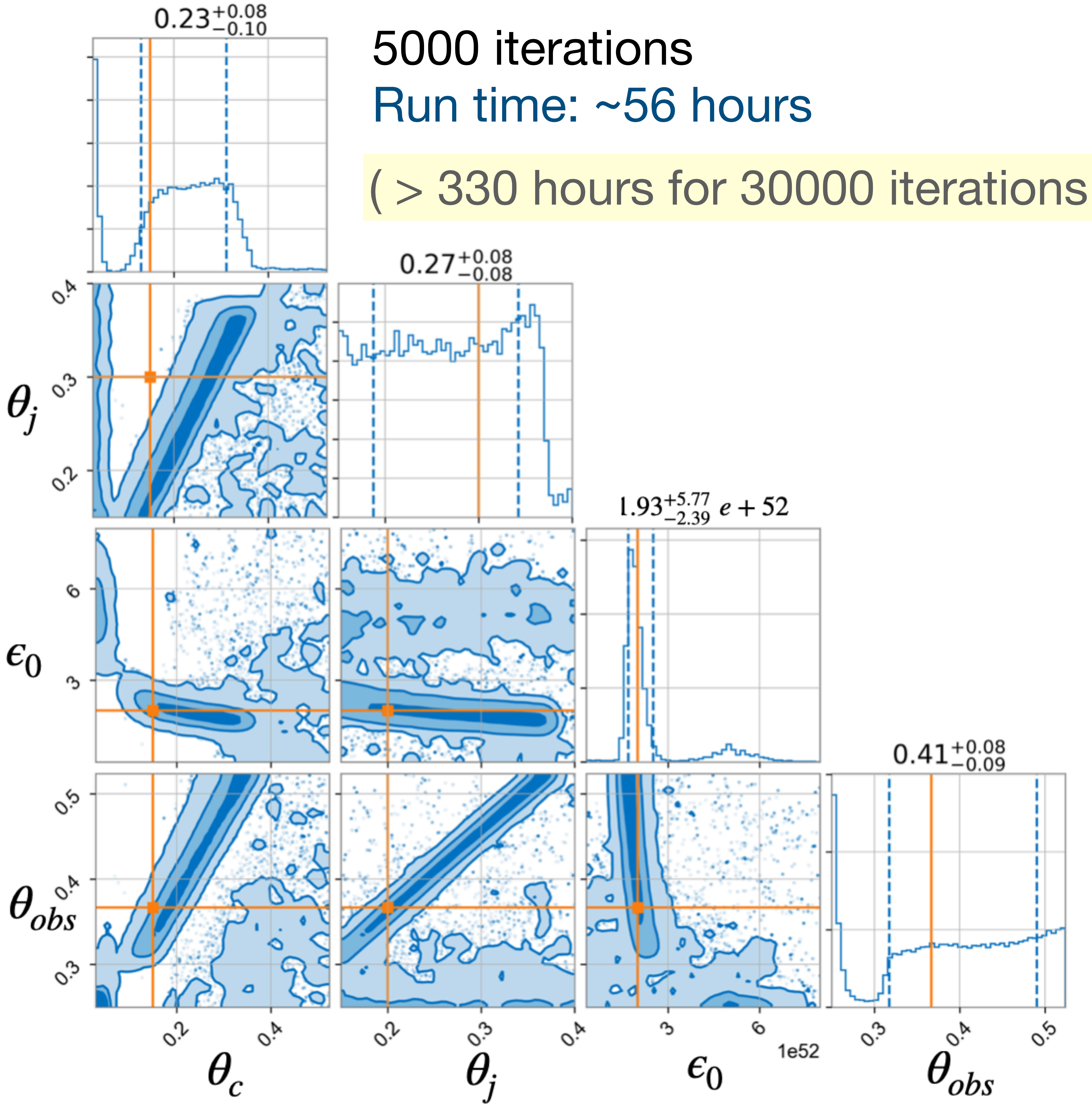
GRB afterglow model

5000 iterations

Run time: ~56 hours

(> 330 hours for 30000 iterations)



Takeaways

- The joint discovery of GW170817 and GRB170817A opened the window for multi-messenger astronomy
- Modeling the afterglow light curve of GRBs can help us understand the structure of the jets
- We simulated high-D afterglow light curves with values across the parameter space and replaced the likelihood with a interpolation function
- The interpolated GRB model has the ability to constrain jet parameters
  - ➡ Advantages
    - Only have to simulate light curves one time
    - > 150 times faster than original method!
    - Model comparison (future work)