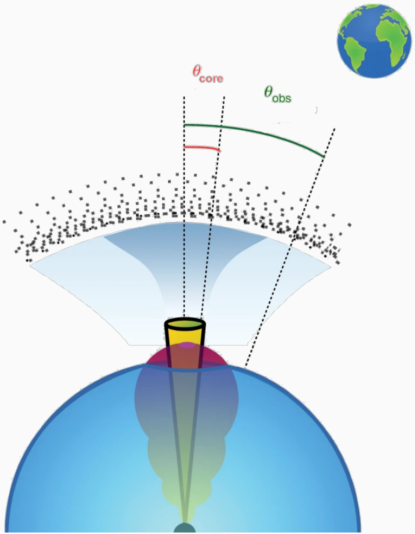
How Well Can We Determine the Geometry of Off-Axis GRB's?

Taya Govreen-Segal
Ehud Nakar

August 2022

Tel-Aviv University

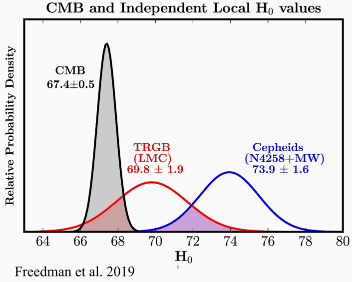


Why Study the Geometry of Off-Axis GRB's?

To Better Understand Jets

- Energetics
- Launching mechanism (collimation)
- Jet propagation in the ejecta
- ...

The Hubble Tension



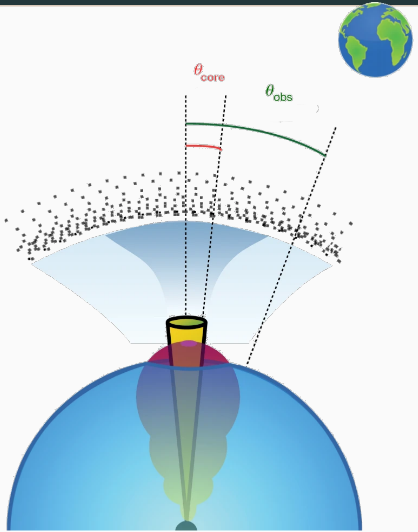
GW-EM Events are Standard Sirens (Schutz 1986)

- Independent probe of H_0, significant if error(H_0)<2%
- GW Signal $\propto \frac{\cos\theta_{obs}}{d_L}$; $\theta_{obs} \lesssim 70°$

Plan

Observables

- Light-curve - $\theta_{core}/\theta_{obs}$
- VLBI observations - flux centroid displacement - $\theta_{obs} - \theta_{core}$



Mooley et al. 2018

Model Assumptions

Afterglow Model

- Relativistic forward shock
- Uniform external density
- Constant $\epsilon_e, \epsilon_b, p$
- $\nu_m < \nu < \nu_c$ (as expected for radio)
- Jets with various angular energy structures

This worked very well for GW170817

Analytical Model

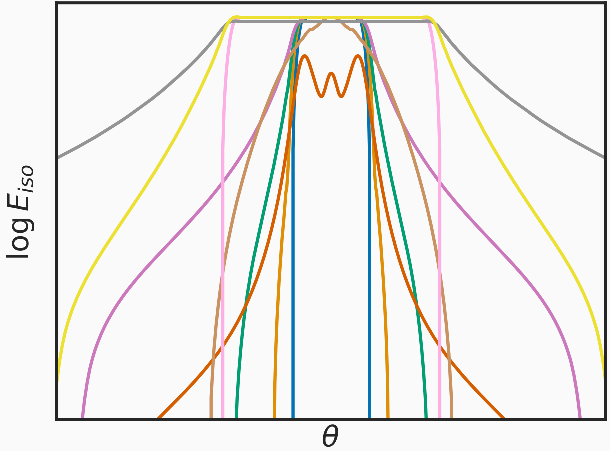
- Assuming every angle evolves as part of a spherical blast wave - $\gamma \propto t^{-\frac{3}{2}}$

Numerical Simulations

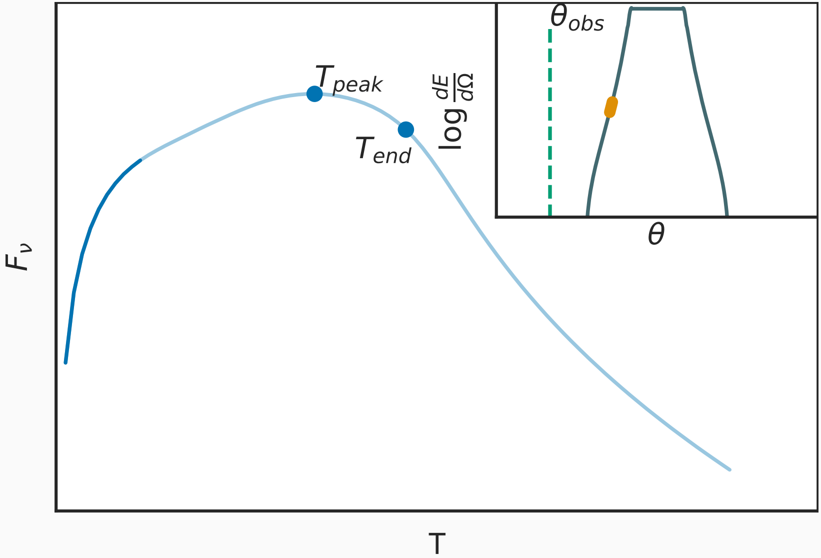
- 2D relativistic hydro simulations with Gamma (Ayache et al. 2021)
- Used to calibrate $\mathcal{O}(1)$ constants

Simulated Structures

Jet structures at $\gamma_{core} = 20$

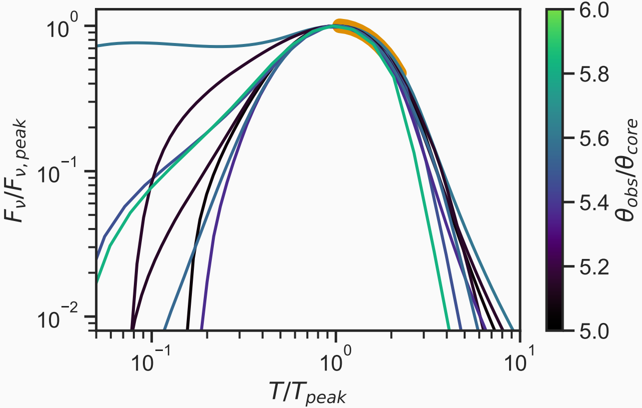


The Light-Curve



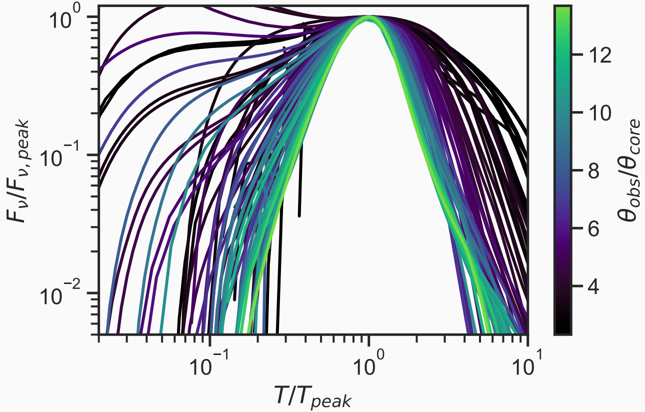
The Light-Curve

$$\frac{\theta_{core}}{\theta_{obs}} = \frac{(T_{end}/T_{peak})^{0.4} - 1}{(T_{end}/T_{peak})^{0.4} + 1}$$



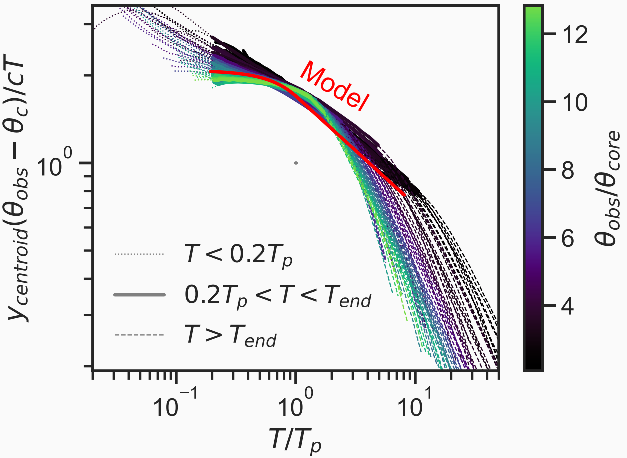
The Light-Curve

$$\frac{\theta_{core}}{\theta_{obs}} = \frac{(T_{end}/T_{peak})^{0.4} - 1}{(T_{end}/T_{peak})^{0.4} + 1}$$

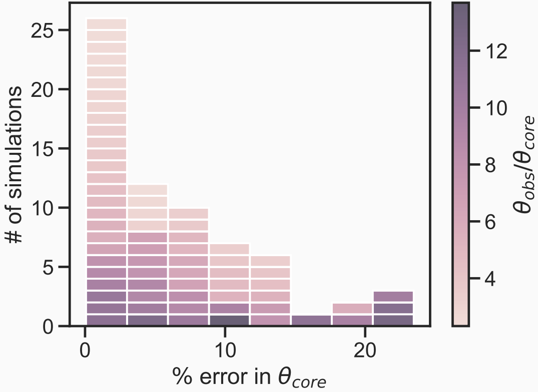


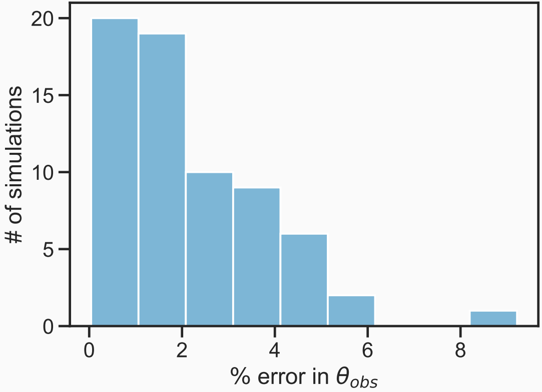
Centroid Motion

$$y_{centroid} = \frac{cT}{\theta_{obs} - \theta_c} \cdot f\left(\frac{T}{T_{peak}}\right) \quad ; \quad 0.2T_{peak} \leq T \leq T_{end}$$



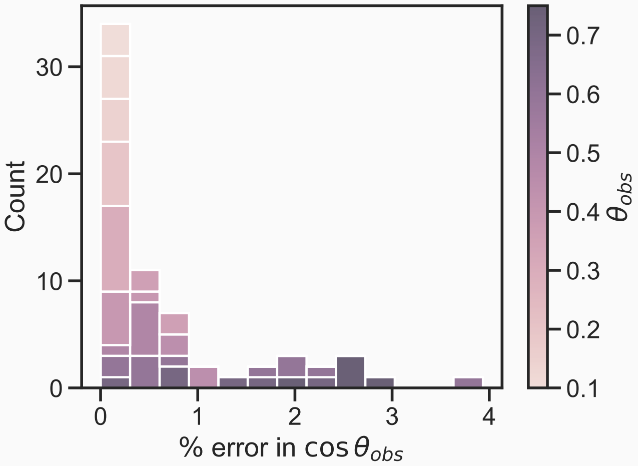
Errors in θ_{core} and θ_{obs}





Error in $\cos\theta_{obs}$

$$\text{GW signal} \propto \frac{\cos\theta_{obs}}{d_L}$$



Summary

To constrain the geometry, we need:

- T_{peak} and T_{end} from the Light-Curve
- 2 VLBI observations - between $0.2T_{peak}$ and T_{end}

Assuming infinite observation cadence:

- θ_{obs}, θ_{core} can be measured independently of the jet structure outside the core
- θ_{obs} with $\leq 9\%$ error
- θ_{core} with $\leq 25\%$ error

The systematic error in $\cos\theta_{obs}$ is $\lesssim 4\%$

- If other errors are under control, it may be possible to determine H0 to 2% using ~ 10 mergers with a detectable jet.

Sources of Error in measuring H_0

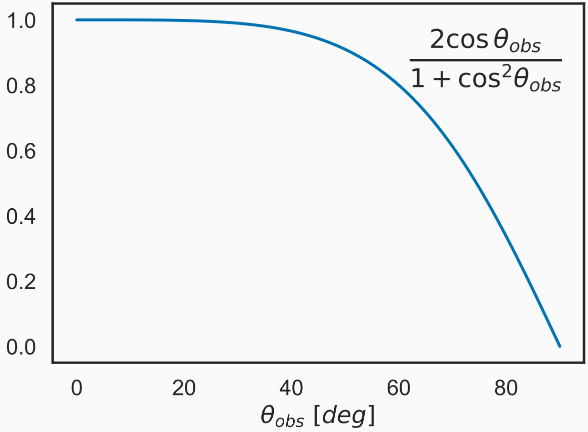
Errors in H_0 (1 σ)

- GW signal systematic error: $\epsilon_{GW,sys} \approx 1\%$
- GW signal statistical error: $\epsilon_{GW,stat} \approx \frac{1}{SNR} \propto \frac{D}{\cos\theta_{obs}}$
- Host peculiar velocity: $\epsilon_{vp} \approx 2\% \left(\frac{\sigma_{vp}}{150\,\frac{km}{s}}\right)^{-1} \left(\frac{D}{100Mpc}\right)^{-1}$

If θ_{obs} is known, the smallest error is when $\epsilon_{GW,stat} = \epsilon_{vp}$, so the total error $\simeq 3\%$

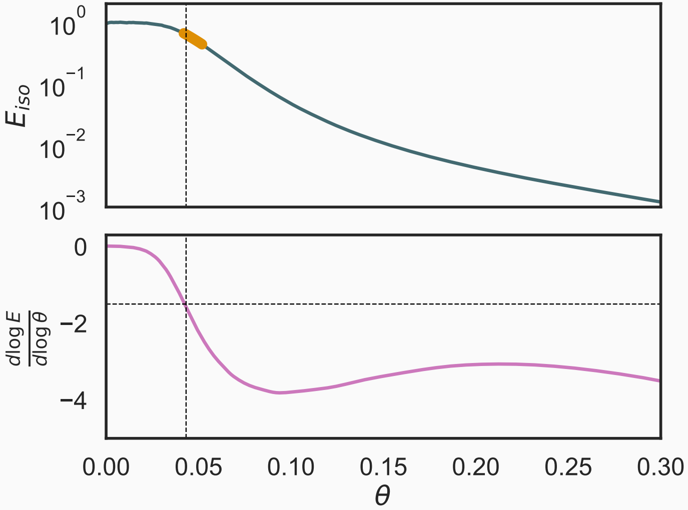
GW Polarization

$$h_+ \propto \frac{1+\cos^2\theta}{2d_L}, h_\times \propto \frac{\cos\theta}{d_L}$$

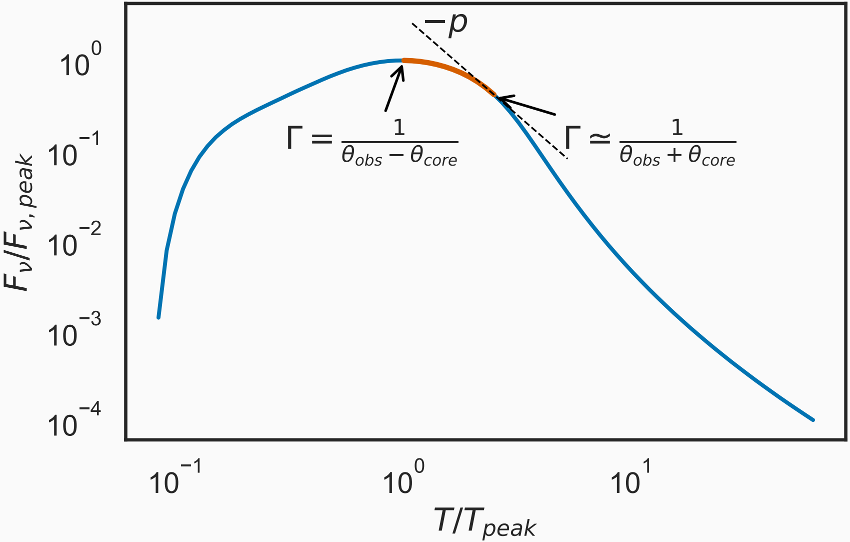


Definition for θ_{core}

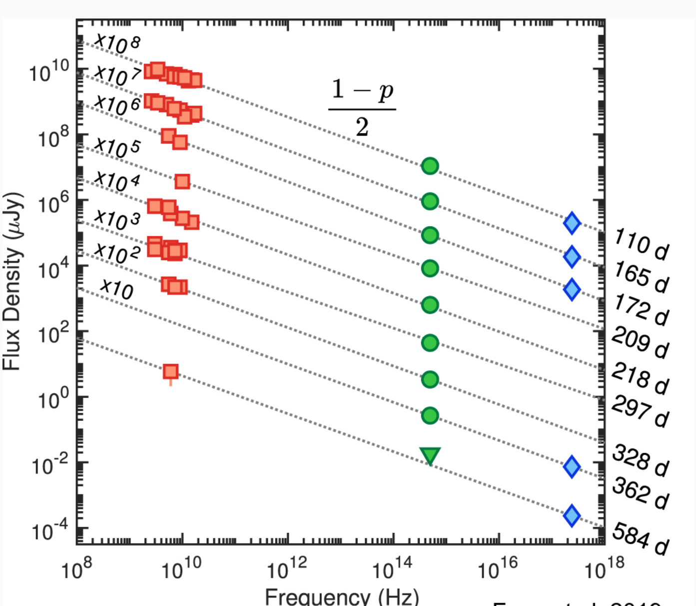
$$\theta_{core} \equiv \theta\left(\frac{d\log E}{d\log\theta} = -1.5\right) \simeq \text{the angle dominating the peak of the light curve.}$$



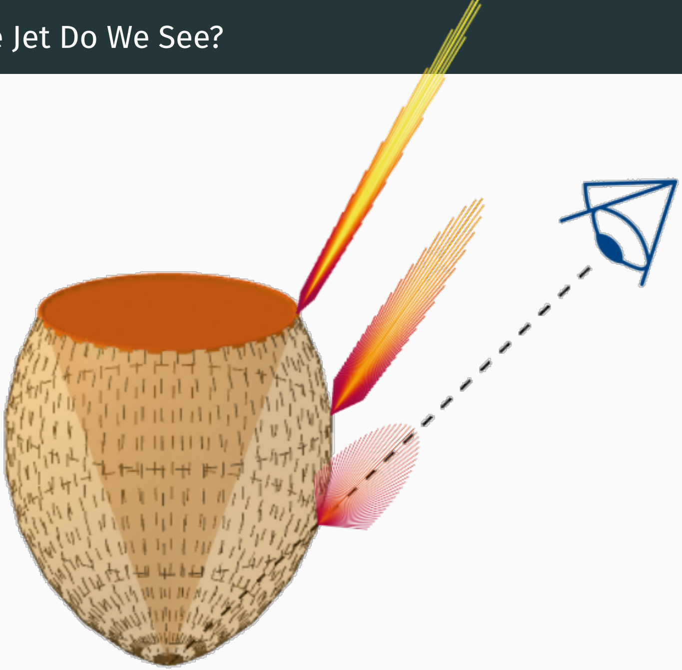
Finding T_{end}



GW170817 Spectrum



Which Part of the Jet Do We See?



Which Part of the Jet Do We See?