Journey to the center of GW170817

Isabel J. Rodriguez, Oregon State University
Major advisor: Davide Lazzati
Minor advisor: Robert Thompson

Master's Thesis Defense | 02.26.2021

Alma Thomas, *Grassy Melodic Chant*, 1976

Oregon State University is a land grant institution that benefits from the dispossession of land from multiple tribal nations, including the Ampinefu Band of the Kalapuya, on whose traditional homelands OSU currently occupies.

Despite having raised millions from this land grab, Oregon State University does not offer free tuition for its Indigenous students, nor has it meaningfully addressed the calls to action raised by the Ethnic Studies department this past summer, which is the only department on campus comprised almost entirely by Indigenous faculty and faculty of color.

I stand in solidarity with local and international Indigenous struggles for the reclamation of sovereignty, stewardship of natural resources, and collective liberation.

Who Am I?

Isabel J. Rodriguez they/them/elle or she/her/ella

(Astro)physics

Ethnic Studies

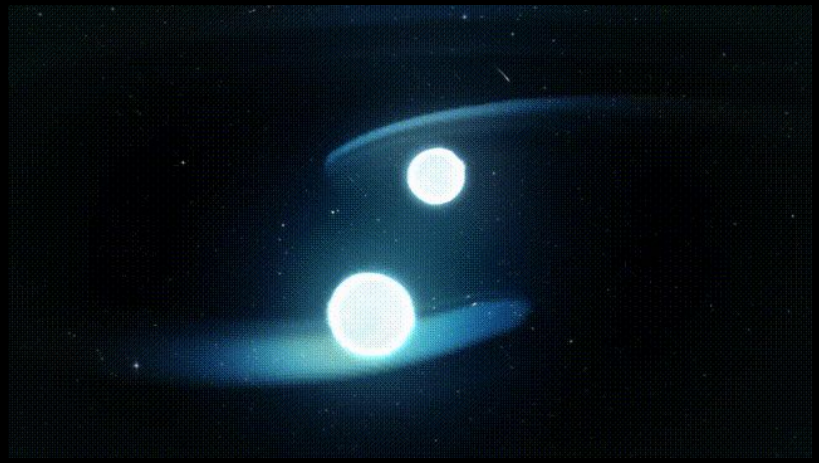
A story about extremes

Extreme cosmic speeds

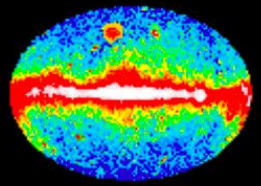
How do relativistic jets form and become structured?

Matter at extreme densities

What happens when two neutron stars collide and merge?

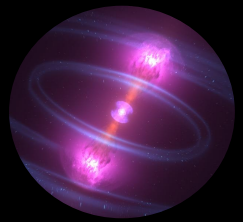


A story in 4 parts



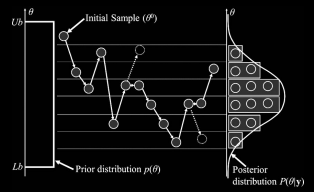
BACKGROUND

Gamma-Ray Bursts



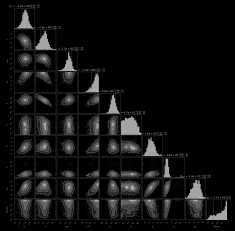
MOTIVATION

GW170817



METHODOLOGY

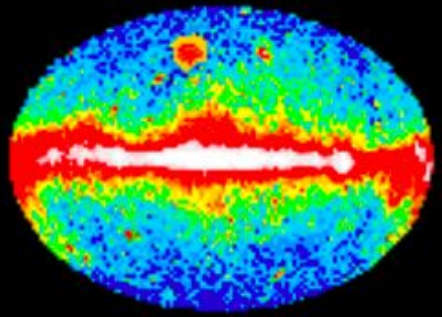
Bayesian parameter estimation

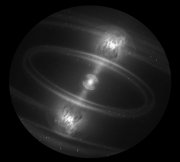


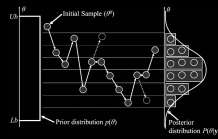
RESULTS + IMPLICATIONS

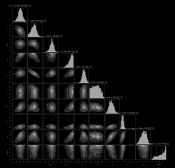
Between the years 1973 and 2015, less than one hundred Black women were awarded PhDs in physics. Less than ten were awarded to Indignous women.

– National Science Foundation



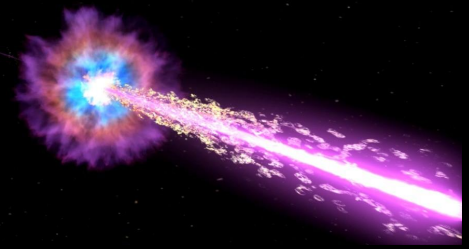






BACKGROUND

Gamma-Ray Bursts

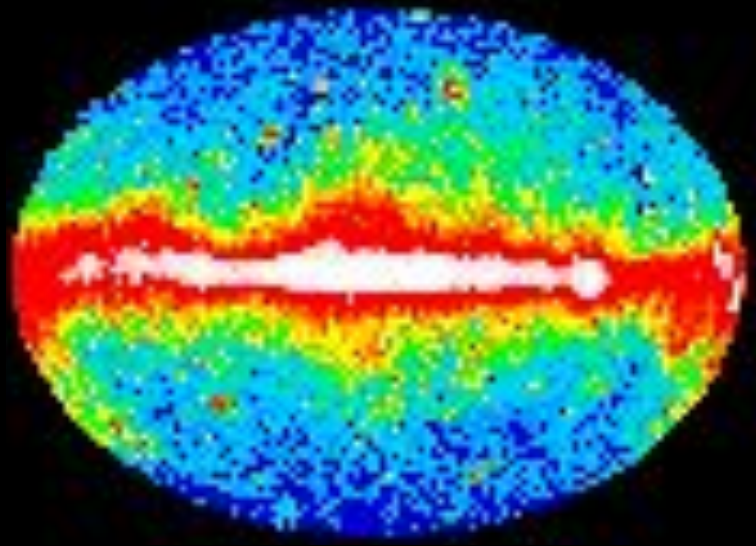


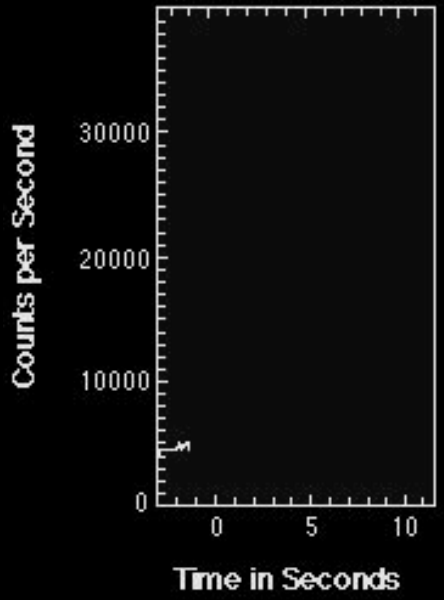
“cosmic superweapon”

“silent killer”

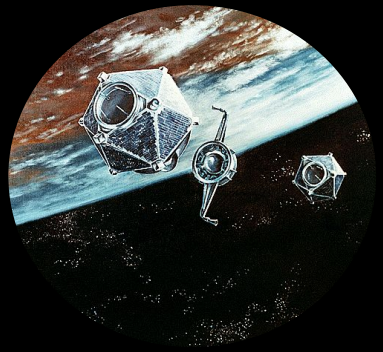
“cosmic sniper’s bullet”

“cosmic raygun”



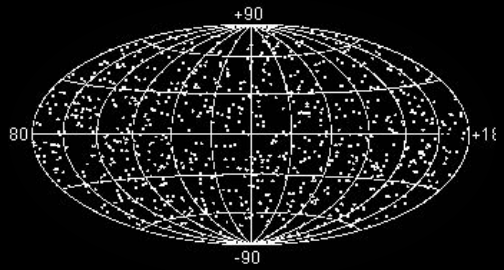

Counts per Second
30000
20000
10000
0
0
5
10
Time in Seconds

Gamma-Ray Bursts: A timeline



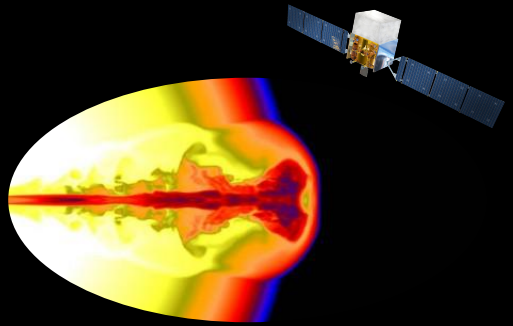
Vela satellites

1960's



BATSE observations

1990's

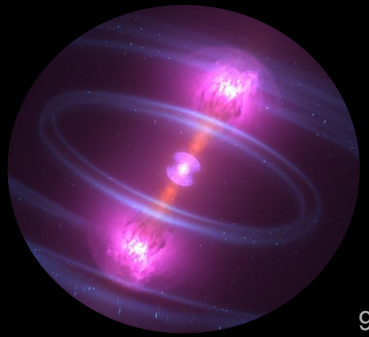


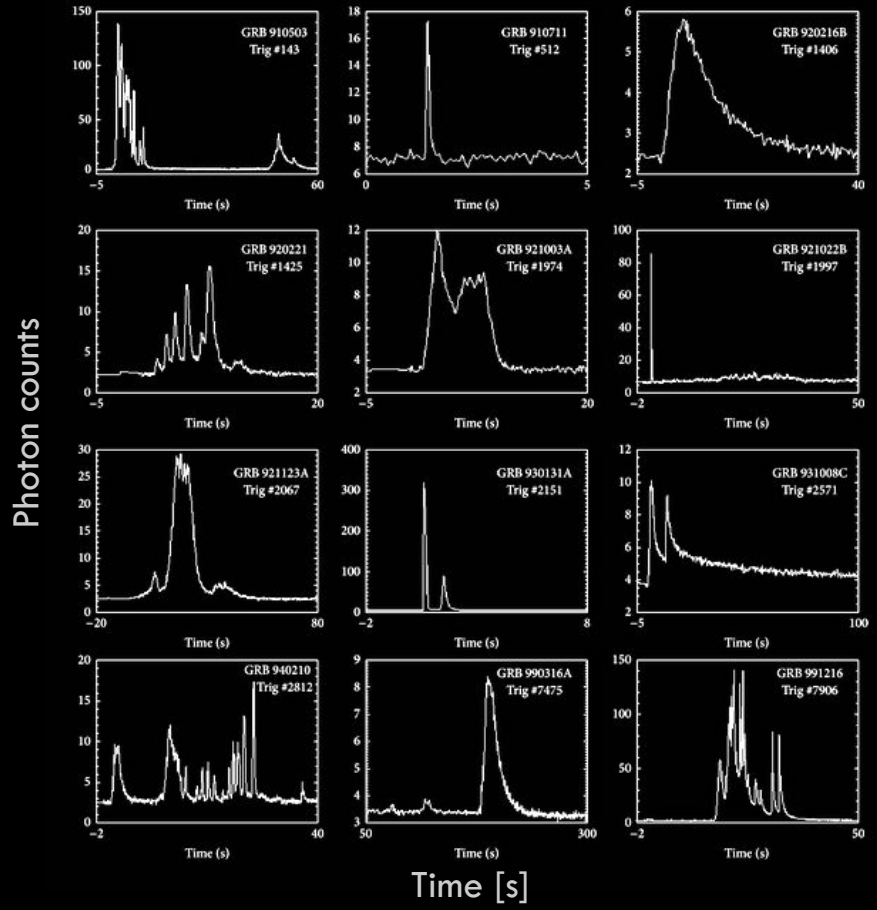
Fermi & GRB simulations

2000's

GRB170817A

2017

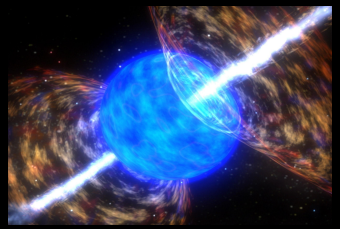




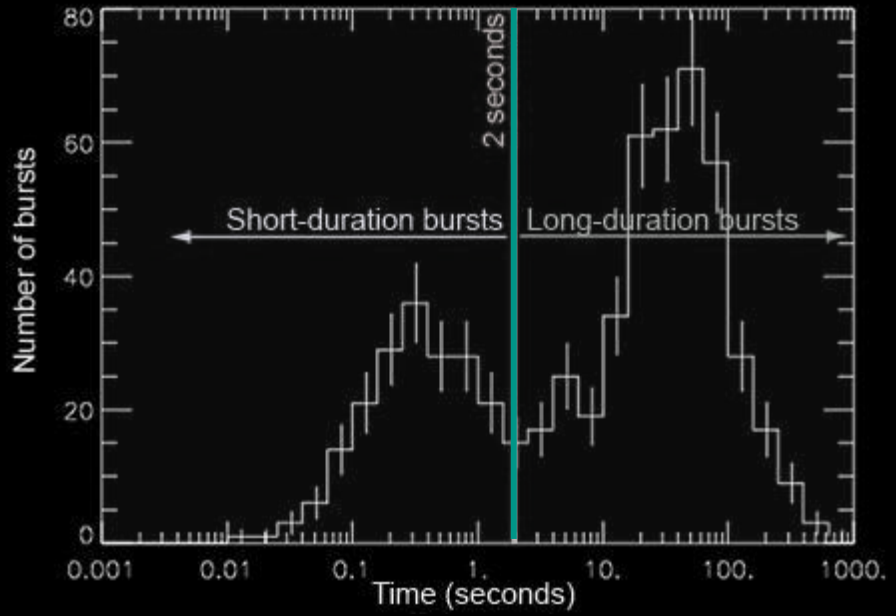
Our observations of GRBs:

- bright
- non-repeating
- observed ~1/day
- unique profiles

Long-duration GRBs
(LGRBs)

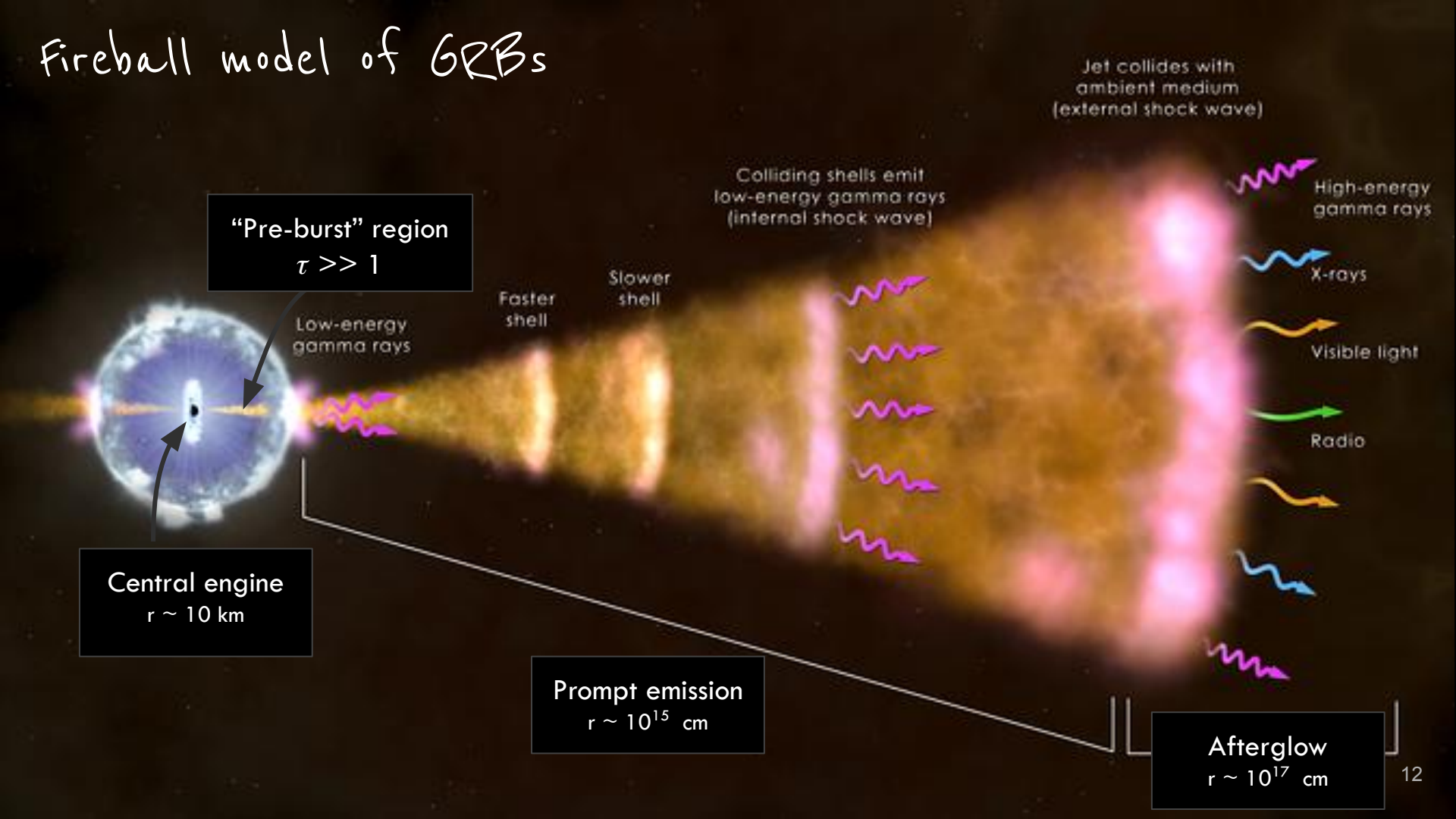


Short-duration GRBs
(SGRBs)

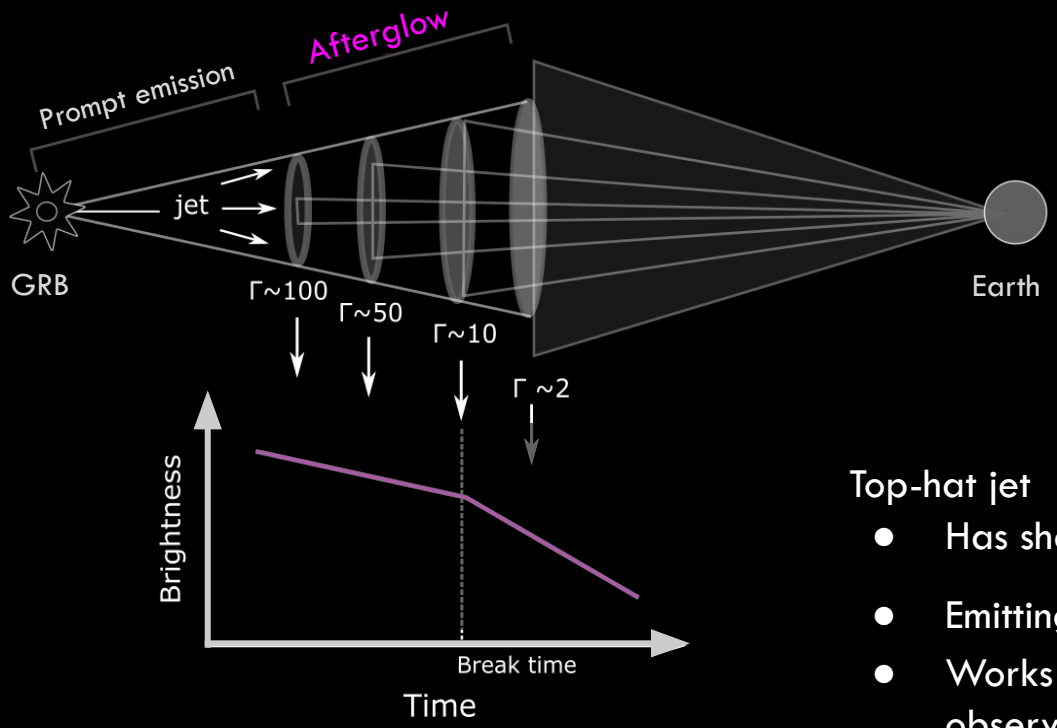


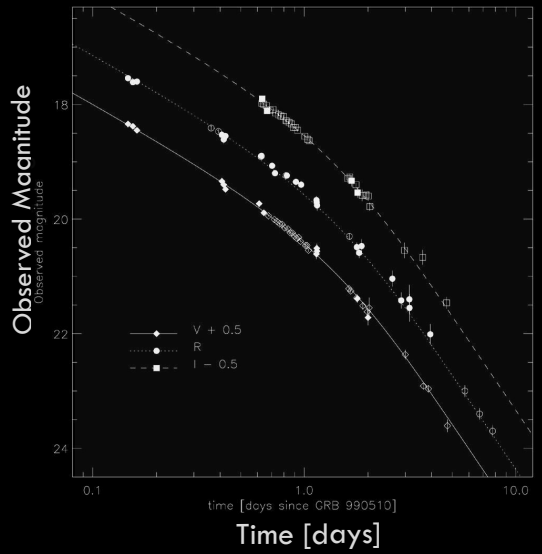
Meegan et al., 2005/NASA

Fireball model of GRBs



From a model to lightcurves and spectra

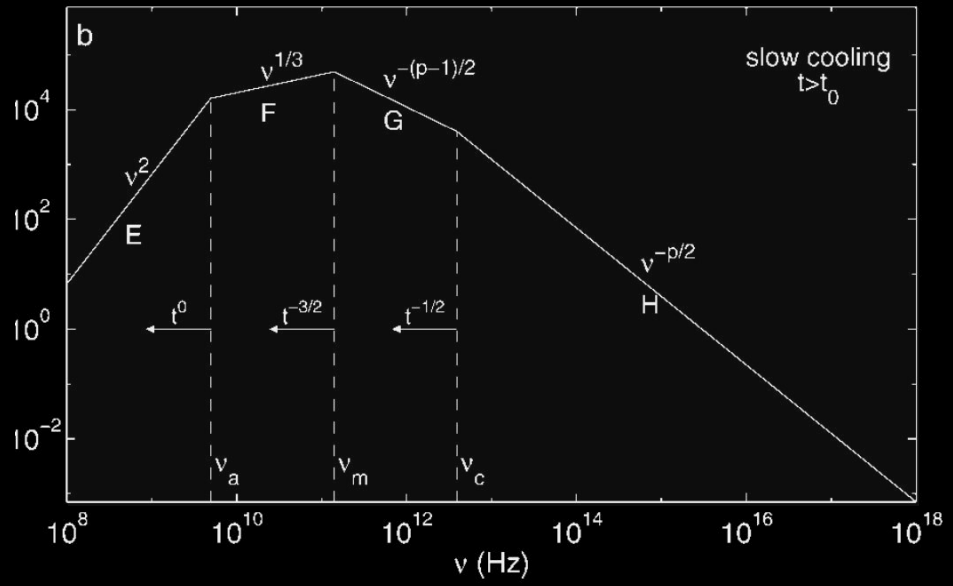




Top-hat jet

- Has sharp edges (unphysical)
- Emitting region $\propto 1/\Gamma$
- Works for on-axis observations

From a model to lightcurves and spectra

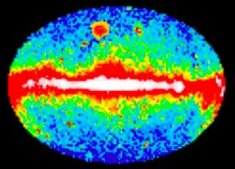


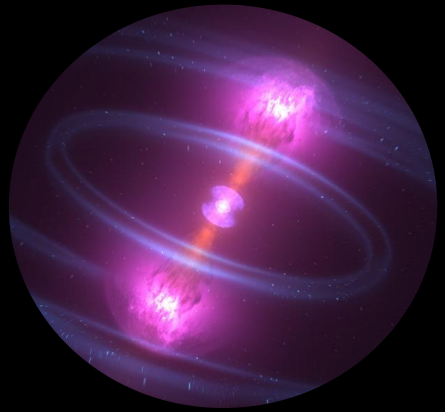
time

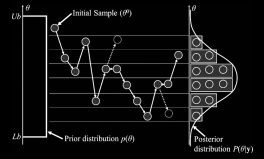
Synchrotron emission depends on:

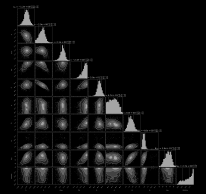
- Environment (n)
- Shock physics (ε_e , ε_B)
- Total energy (E)
- Electron index (p)
- Redshift (z)

Need observations in R, O, X





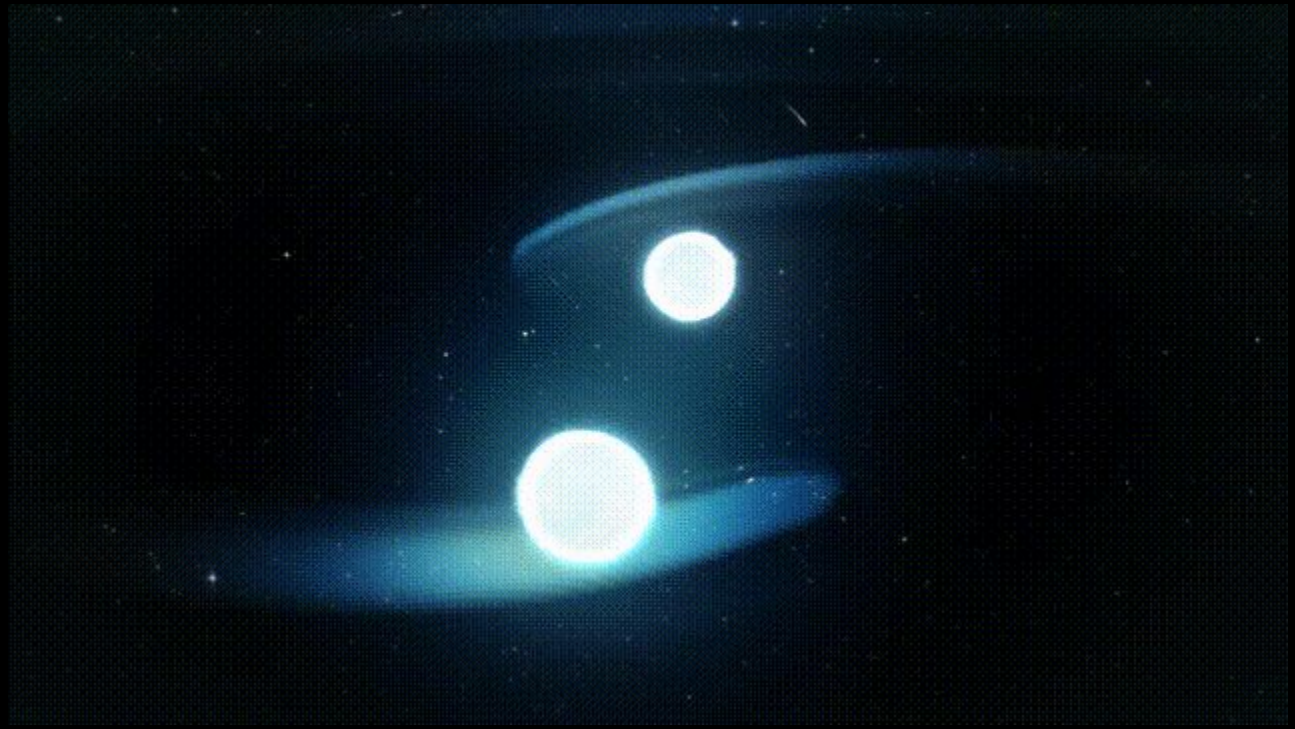




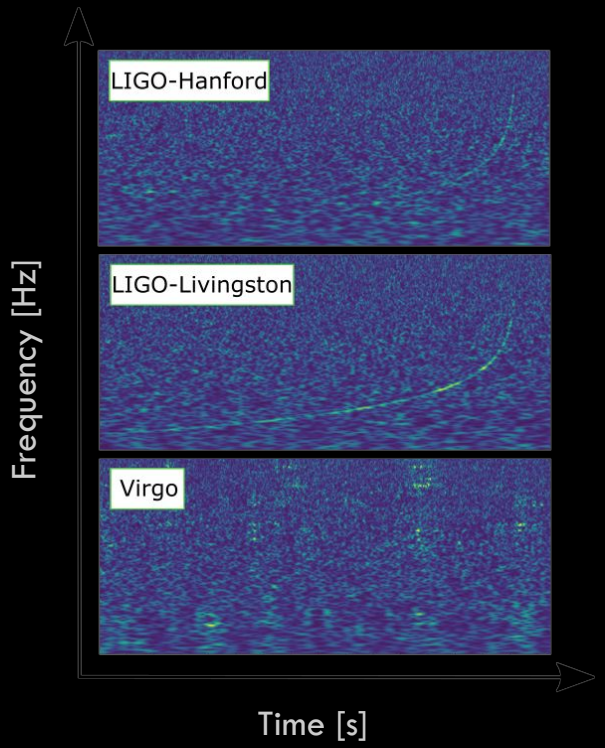
MOTIVATION

GW170817

130(ish) million years ago

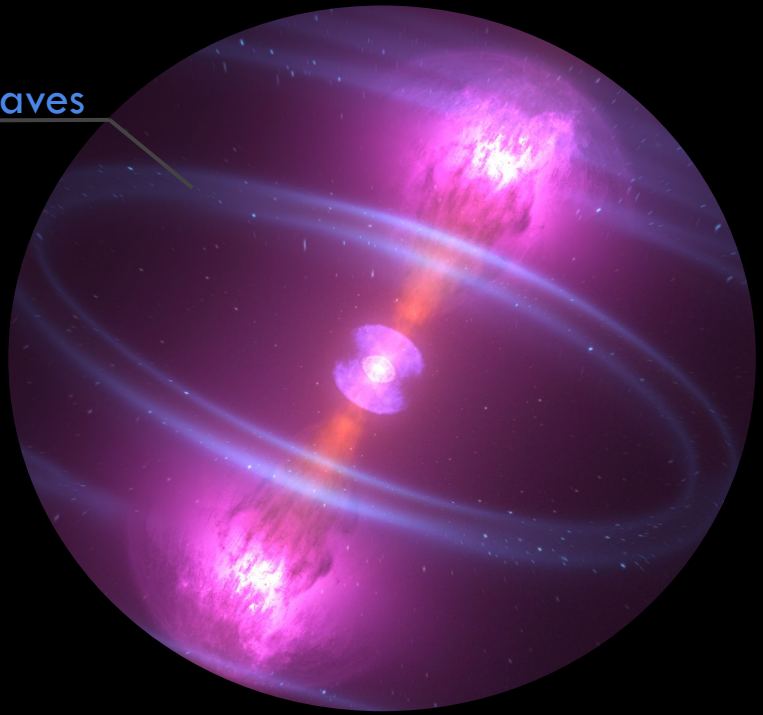


A chance GW detection on Aug. 17, 2017

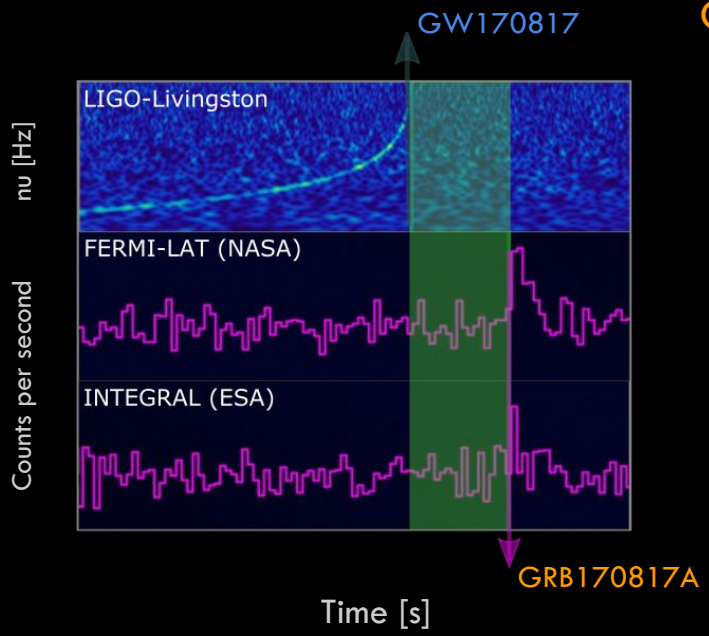


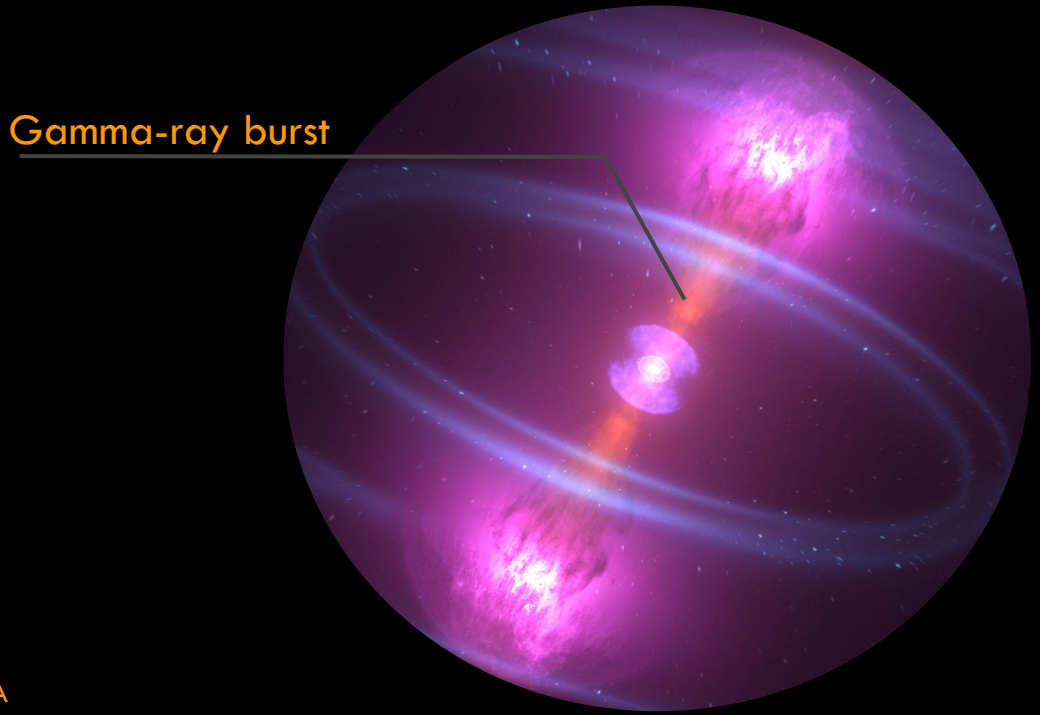
Gravitational waves

GW170817



followed by a flash of gamma-rays 1.74 s later.

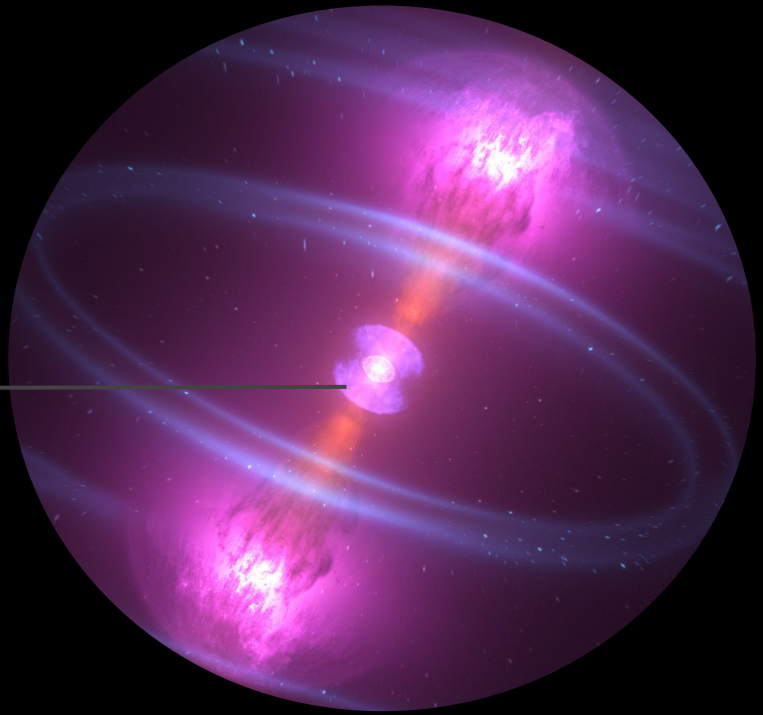




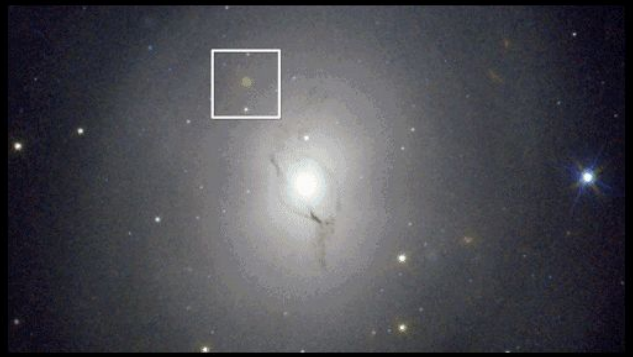
The kilonova was imaged by Hubble 11 hours later,

NASA/ESA

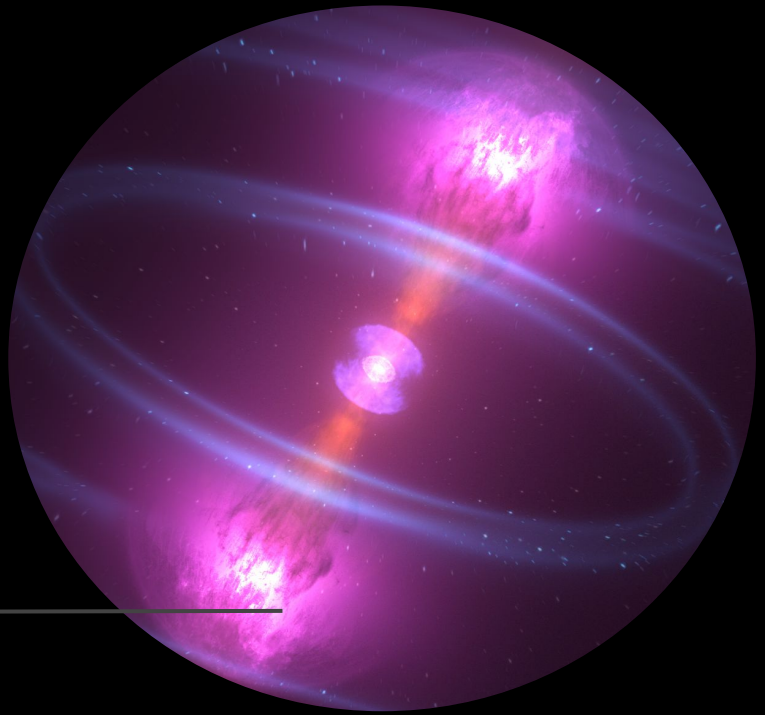
Kilonova



and the afterglow was imaged by Chandra after ~9 days.



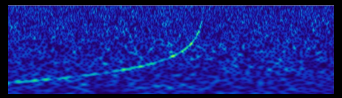
NASA/CXC/ E. Troja



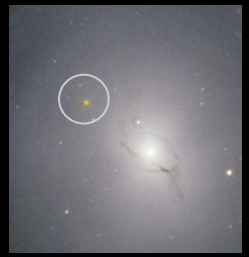
GRB Afterglow

(Fun Fact: X-rays were still being detected as of Dec. 2020)

Our first ever multimessenger NS merger event.

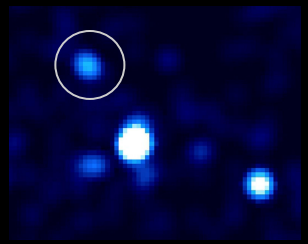


Space-time ripples (GWs)

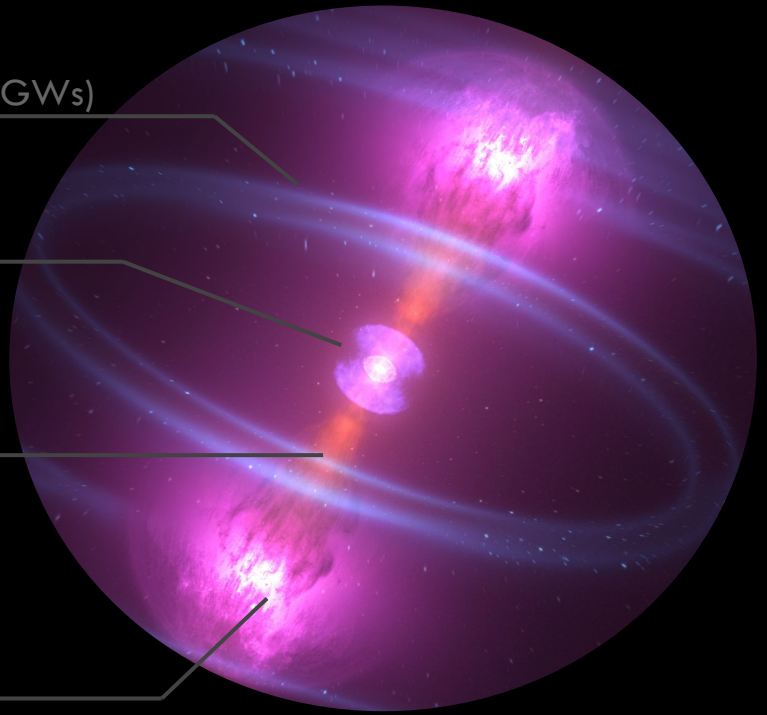


Expanding debris (kilonova)

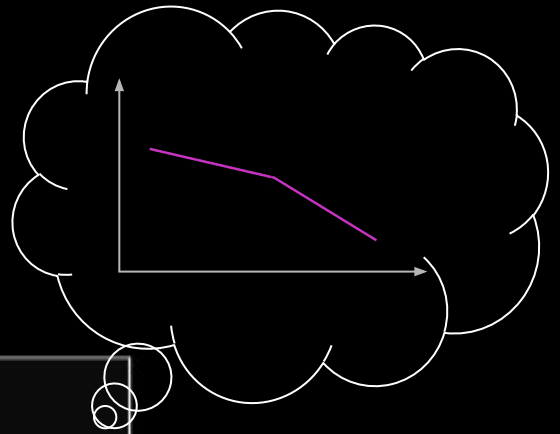
Relativistic Jet (GRB)

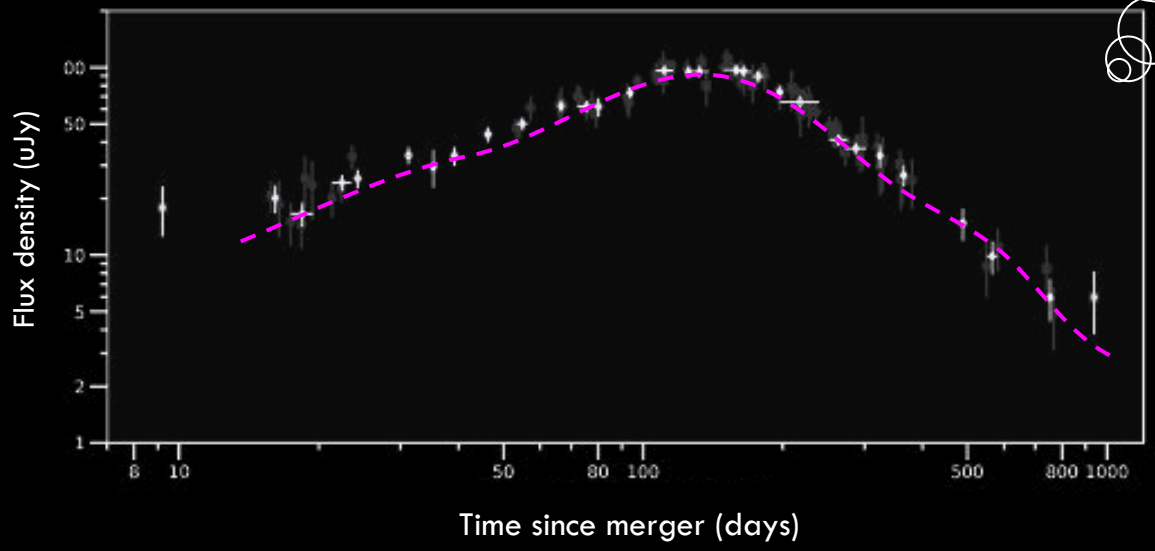


Shockwave (GRB afterglow)



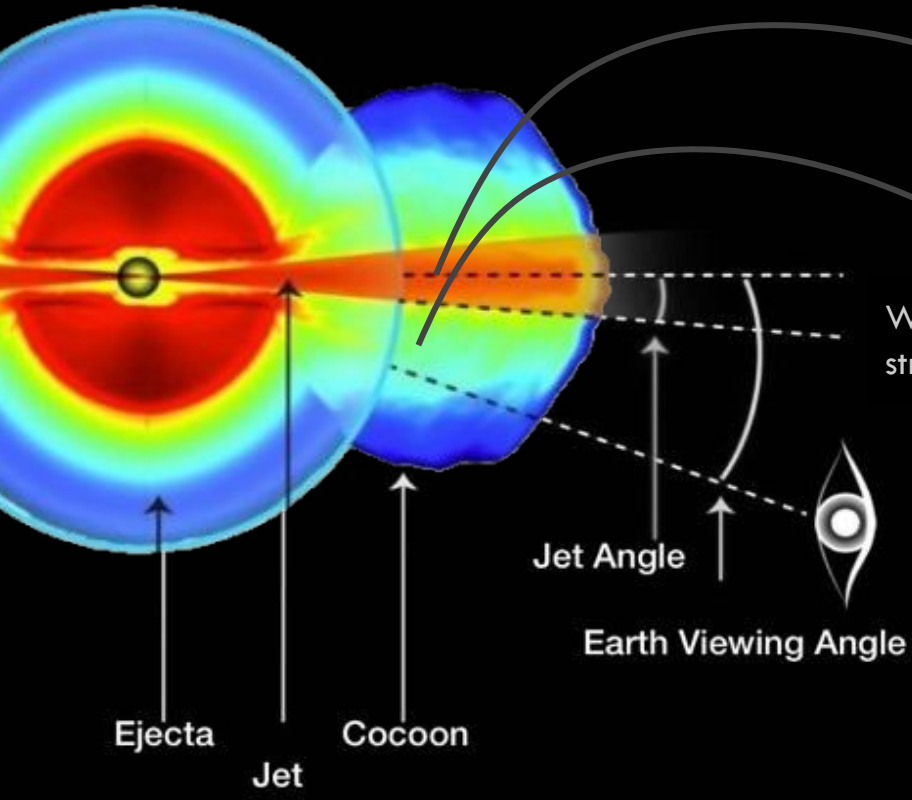
Unusual phenomenology





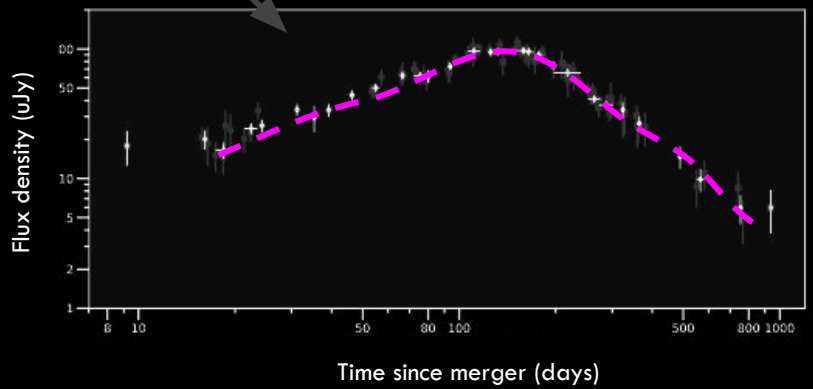
Makhatini et al. (2020)

A structured jet viewed off-axis

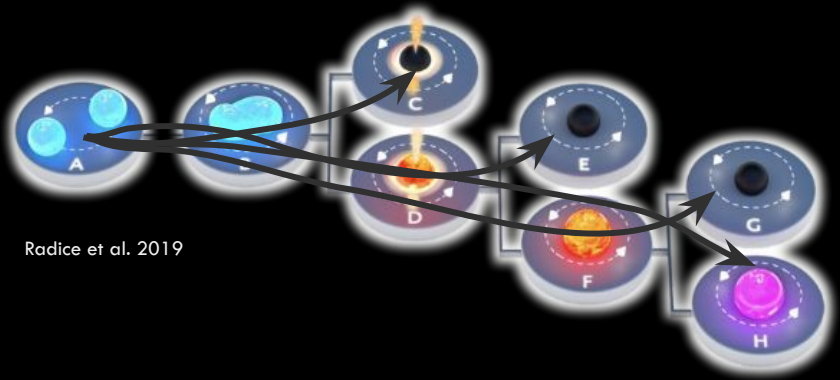


We observe the cocoon structure at early times,

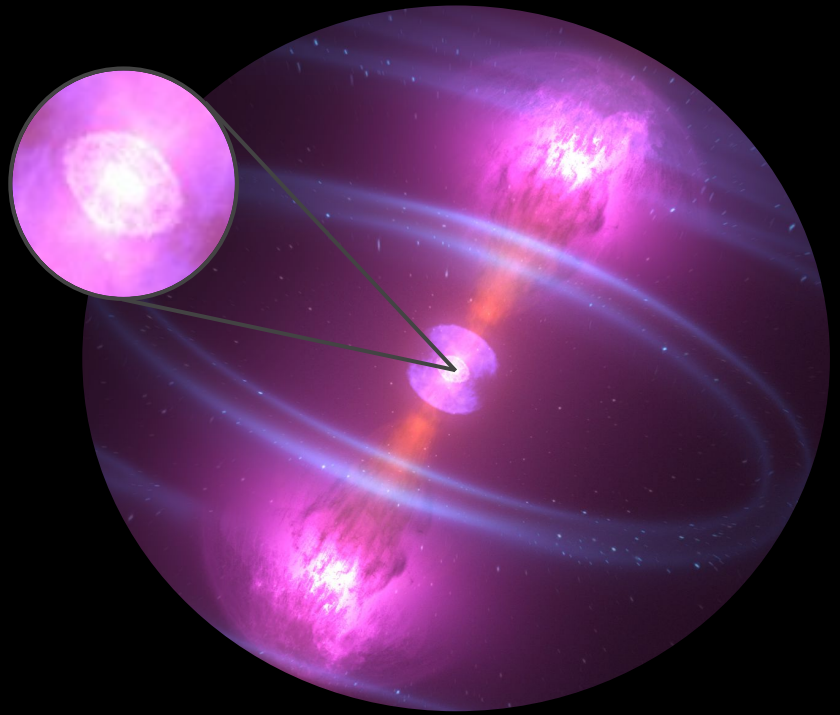
and the jet at late times.



What does a merger leave behind?



Radice et al. 2019



The "what"

What can we learn about properties of:

- the structured jet?
- the early jet?
- neutron star ejecta?
- the central engine?

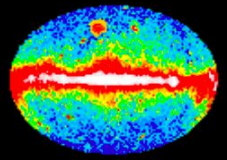
The aim

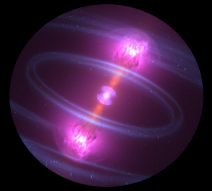
1) Use observational data & afterglow model to constrain properties of:

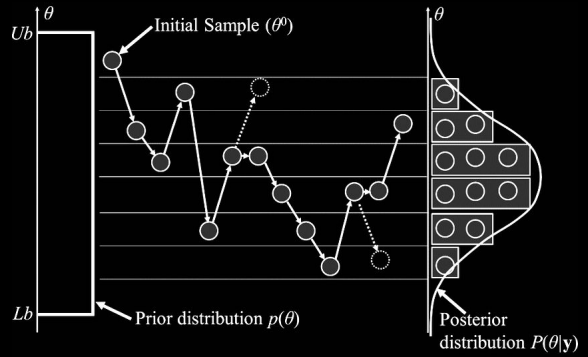
- structured jet
- external medium
- observer parameters

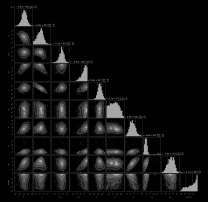
2) Use an outflow model & (1) constrain properties of:

- initial jet
- NS ejecta
- central engine









METHODOLOGY

Bayesian parameter estimation

"When you measure include the measurer."

– MC Hammer

Guiding framework: Bayesian statistics

Prior: What previous knowledge do we have of these parameters?

$$P(\Theta|D) \propto P(D|\Theta)P(\Theta)$$

Posterior: Given a set of parameters, how *probable* are their values given observational data?

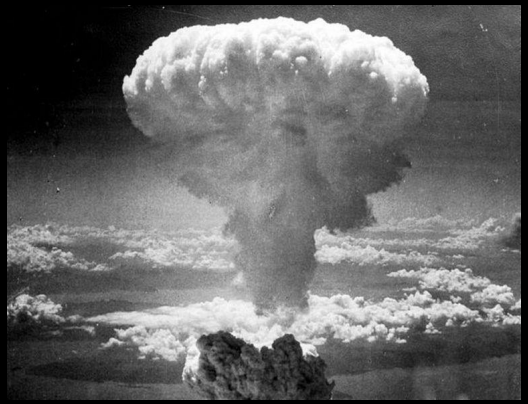
Likelihood: How probable is the observed data given a set of model parameters?

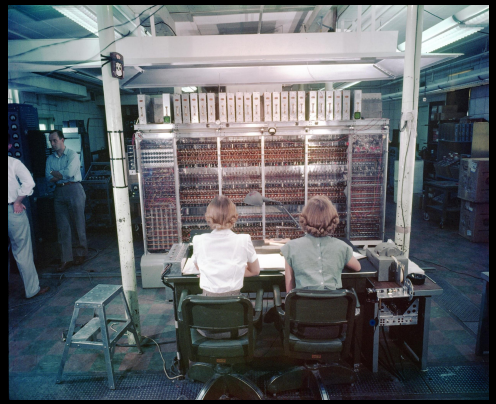
D = Data 

Θ = Set of parameters

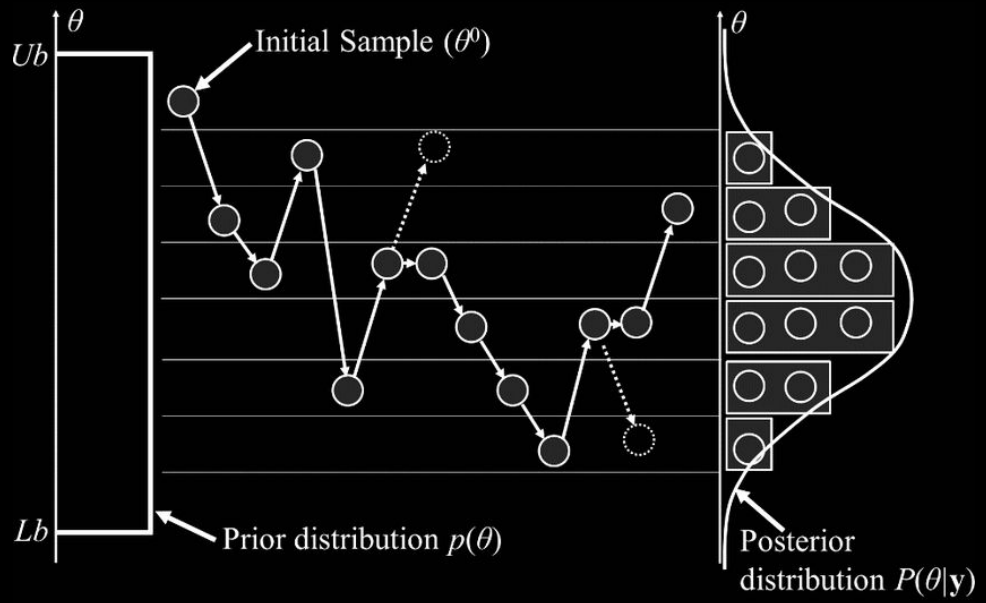
... E_j, E_c, θ_j, θ_c ...

The Markov Chain Monte Carlo method





A scheme to apply our framework in multiple dimensions.



Lee et al 2015

And a computational tool to implement it.

`emcee`: The MCMC Hammer (Python)

`emcee` outputs:

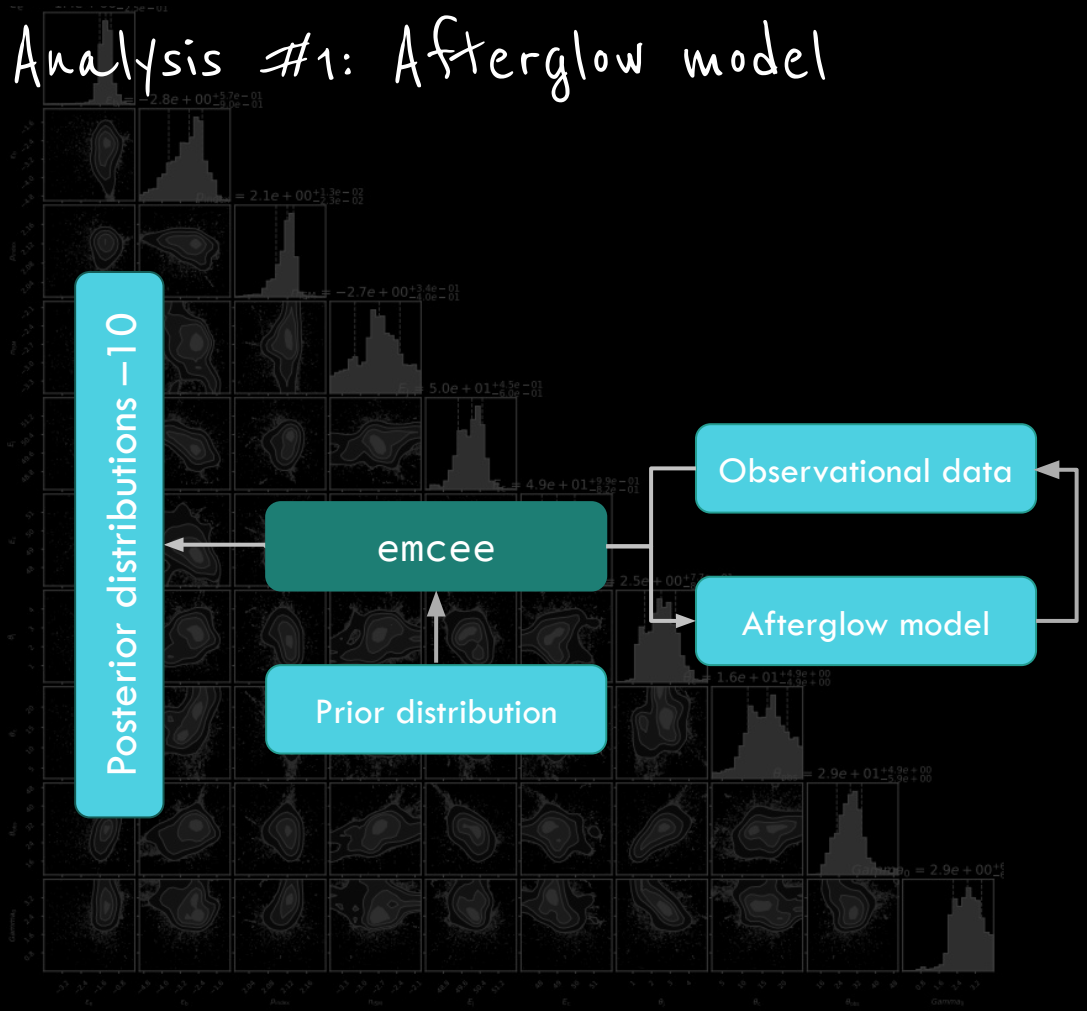
- samples of the posterior

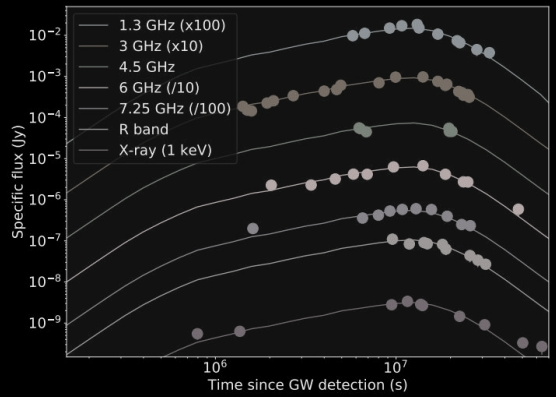
User inputs:

- log likelihood function
- log prior function
- data
- a model

`emcee` walkers explore the parameter space

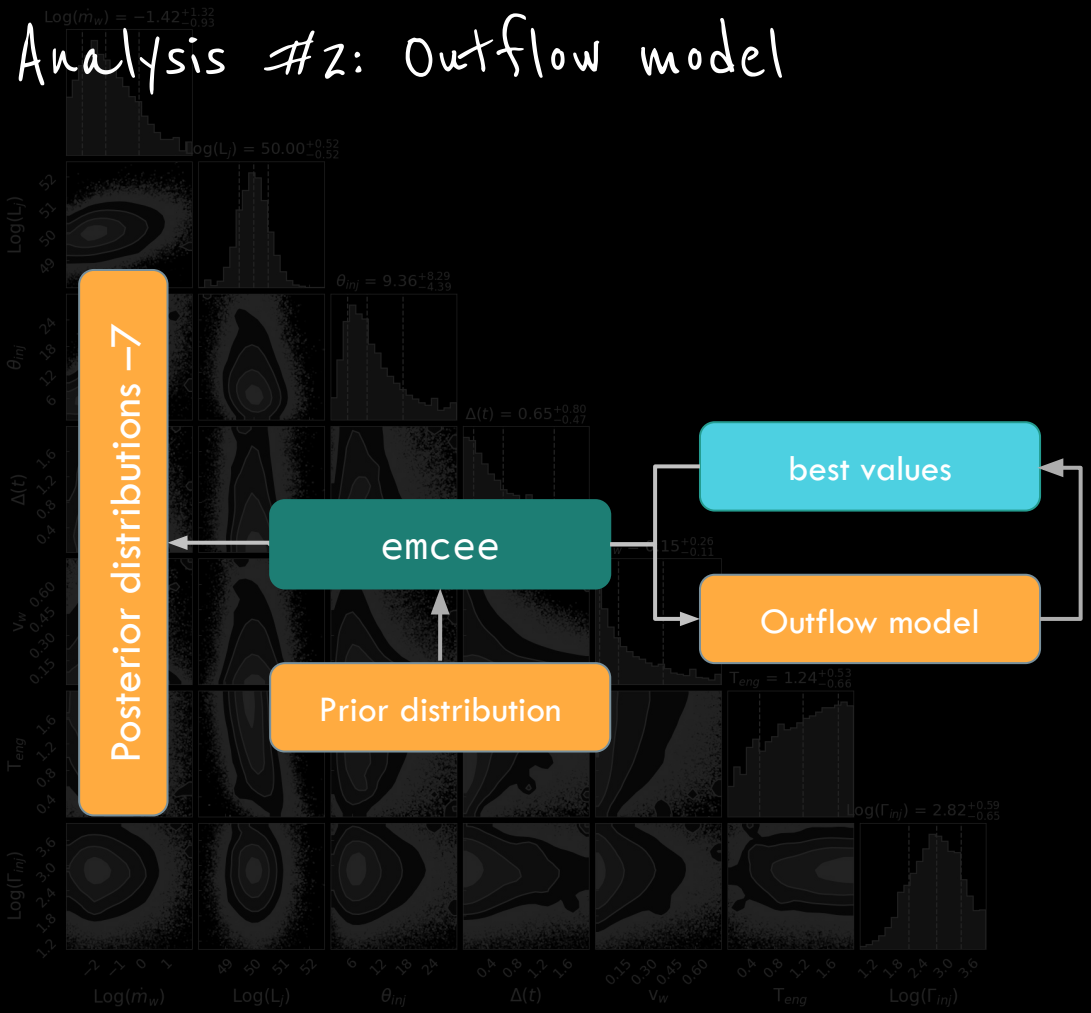
Analysis #1: Afterglow model

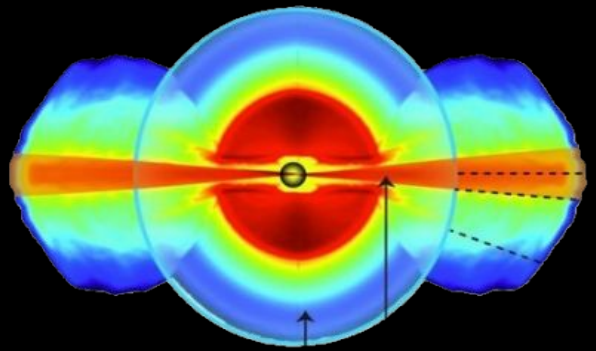




AIM: Constrain jet, environment & observer parameters using observational data + afterglow model.

Analysis #2: Outflow model

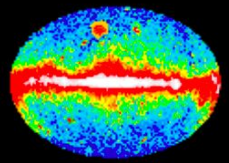


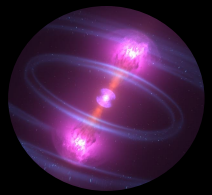


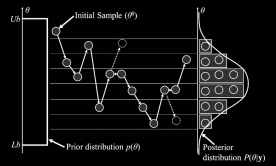
AIM: Constrain properties of the initial jet, NS ejecta, and central engine using analysis data + an outflow model.

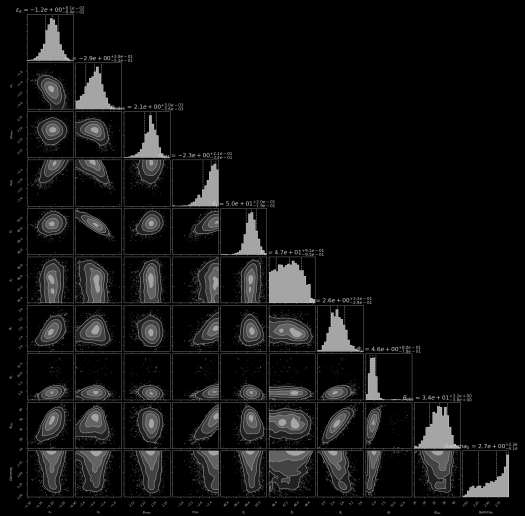
“White empiricism has an impact not just on the empirical choices on the part of non-Black physicists but also on the choices of Black women physicists, including whether they continue to participate in physics at all.”

– Chanda Prescod-Weinstein (2020, p.430)



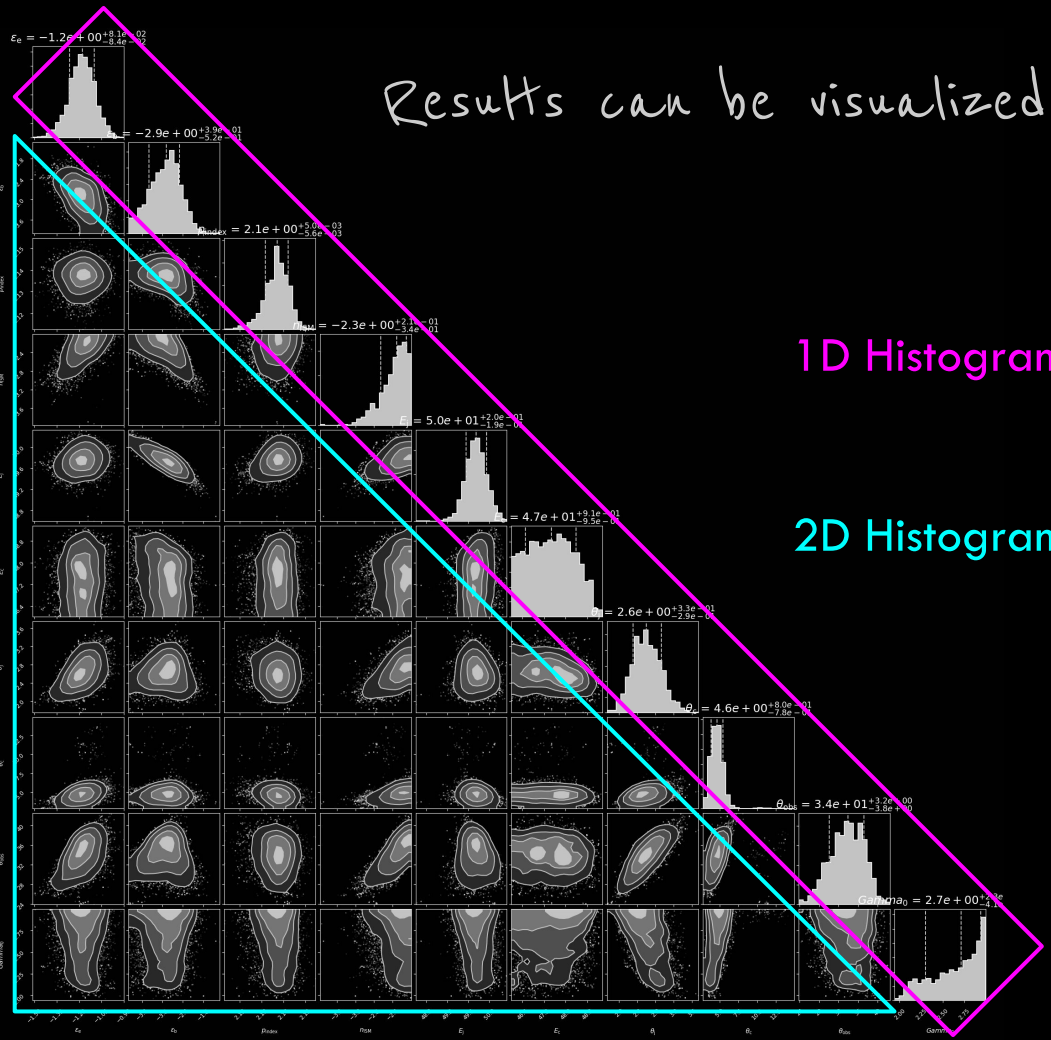






RESULTS + IMPLICATIONS

Results can be visualized using a corner plot



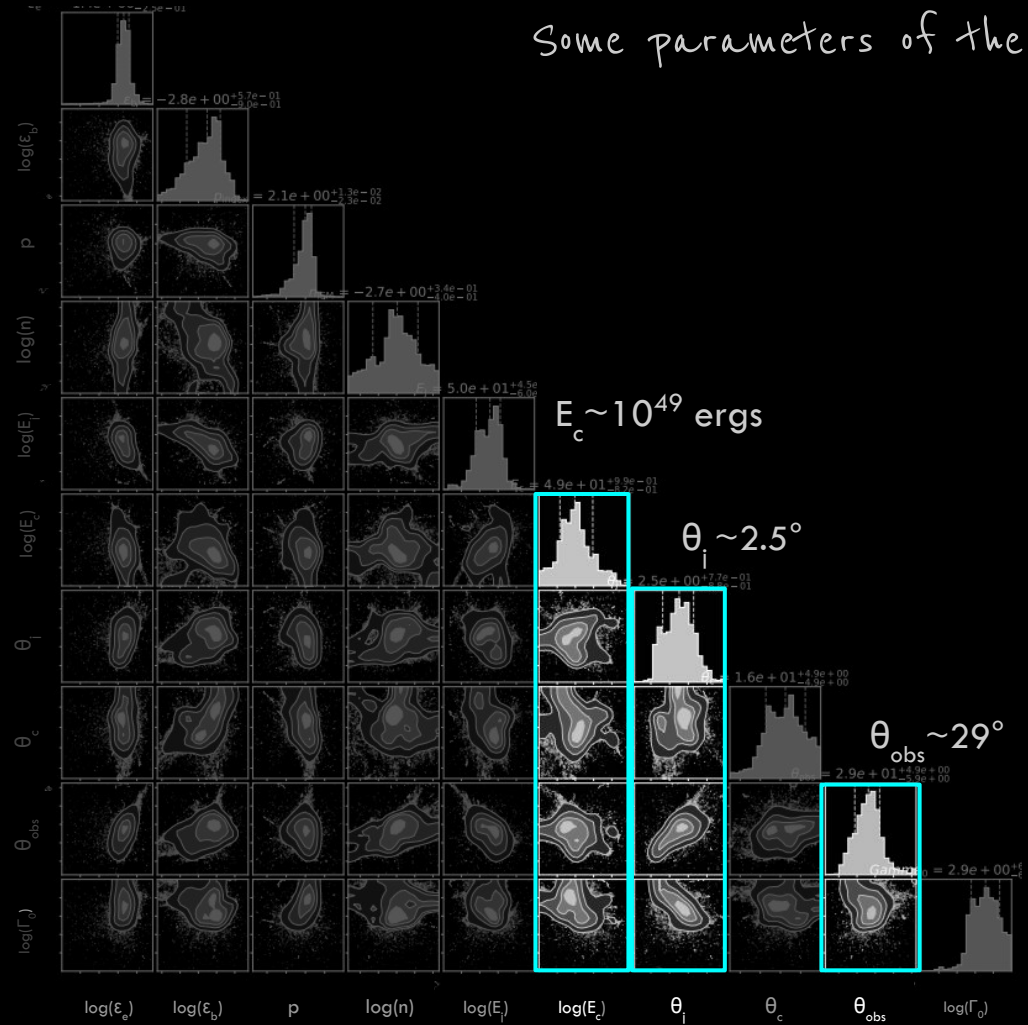
1D Histograms: distribution of each individual parameter (posterior)

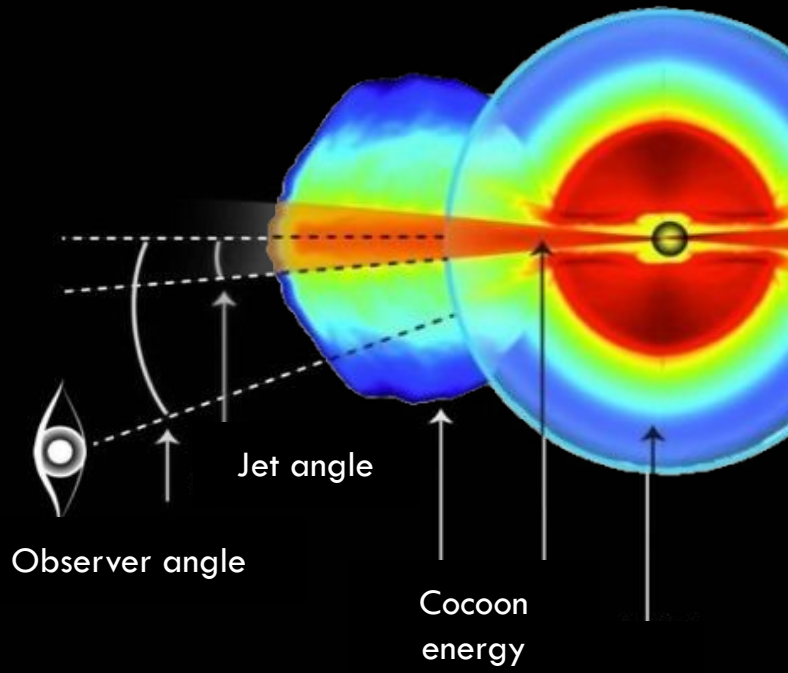
2D Histograms: shows the relationships between parameters (covariance)

Analysis #1

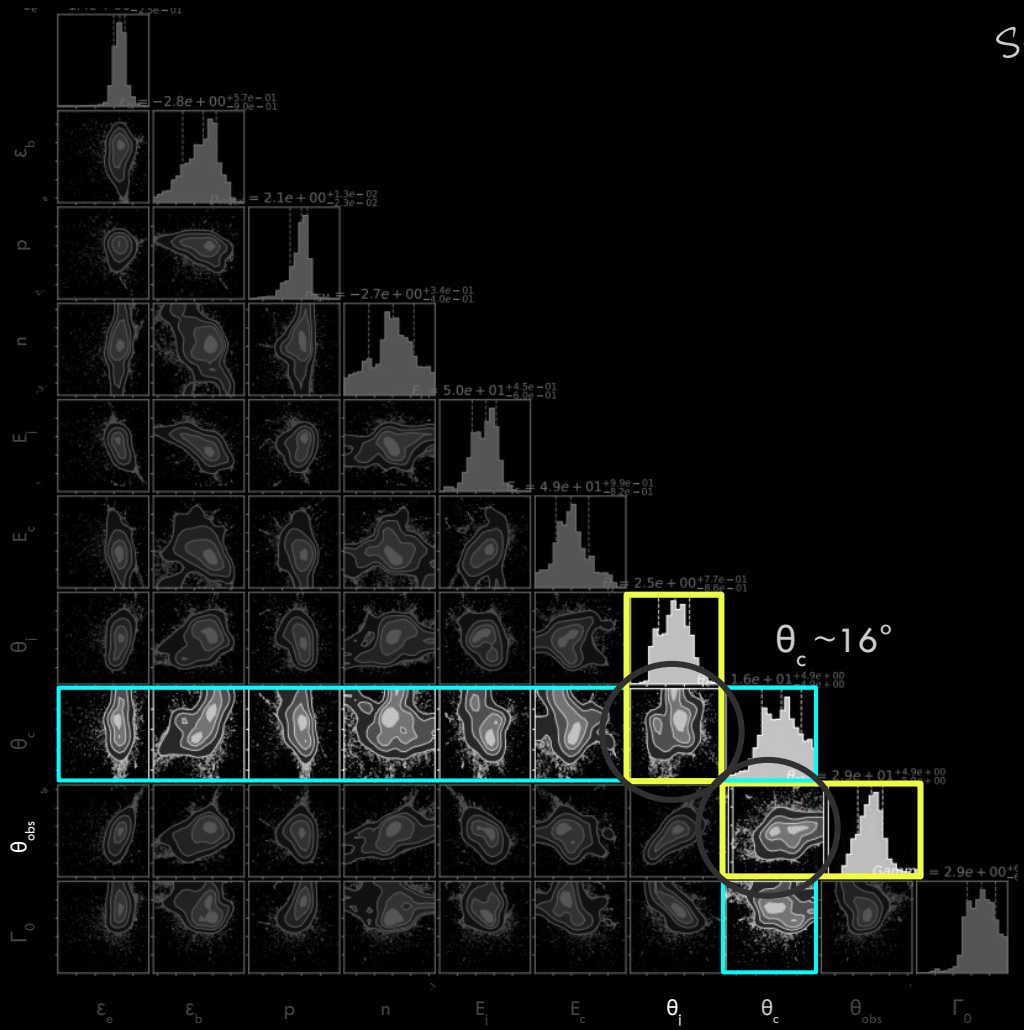
(structured jet → afterglow)

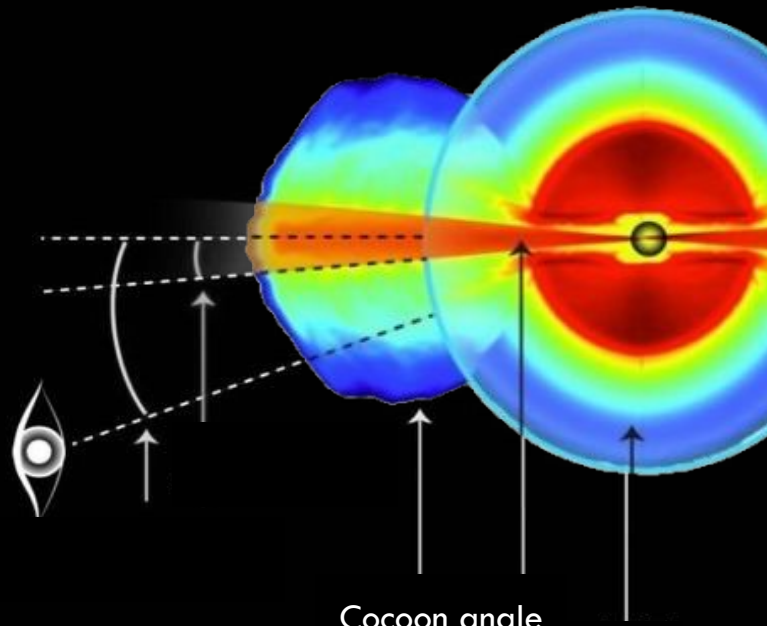
Some parameters of the structured jet are are well-constrained.





Some parameters are less well constrained.

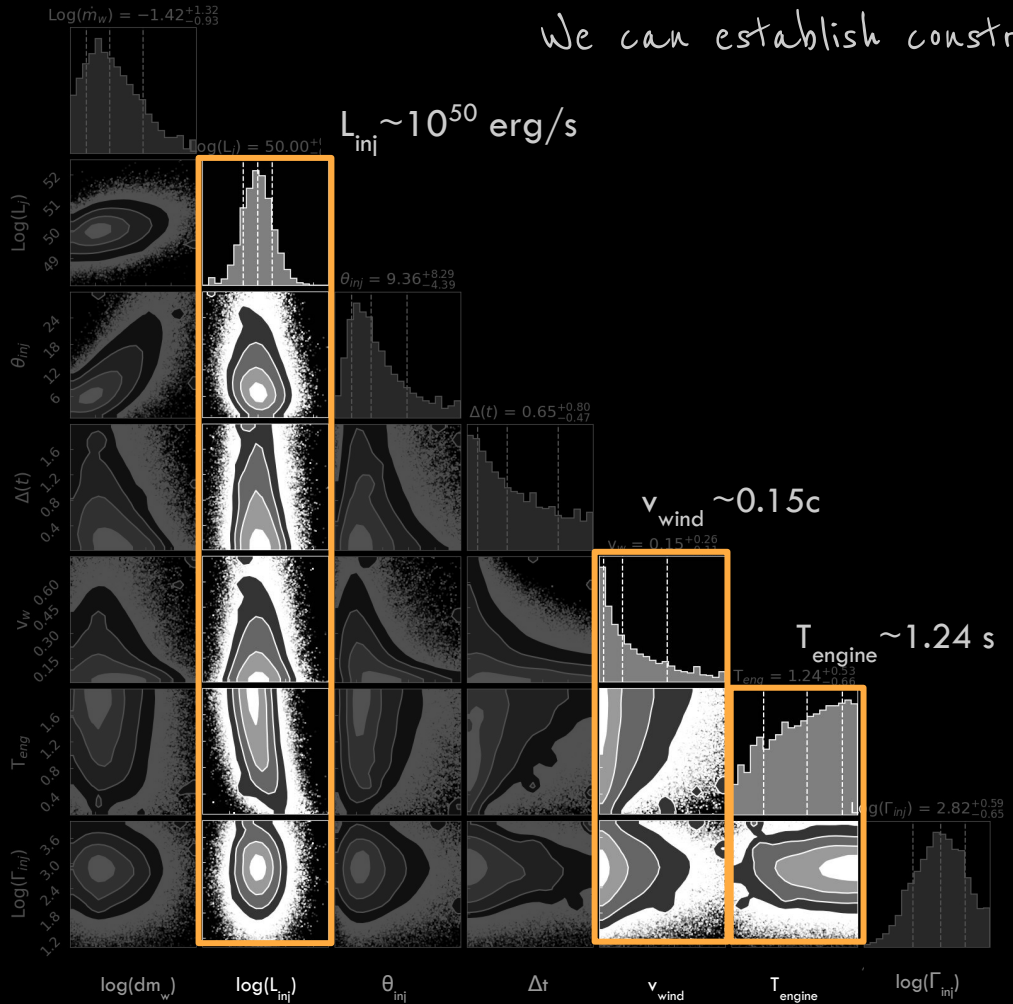


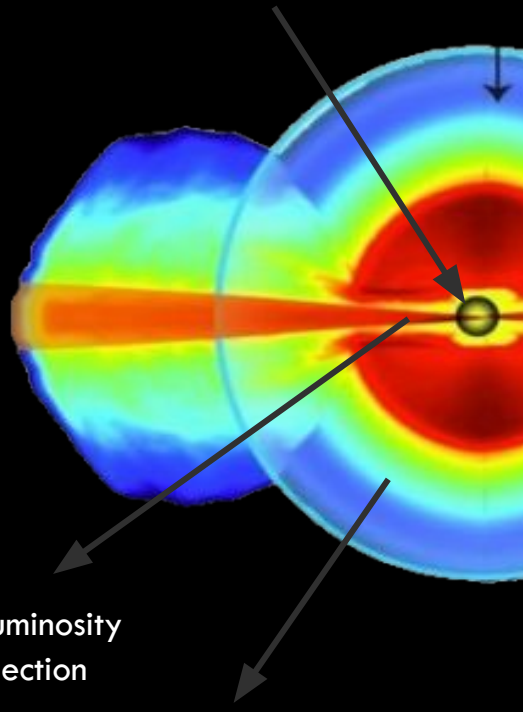


Analysis #2

(outflow → structured jet)

We can establish constraints & upper/lower limits on unobservables





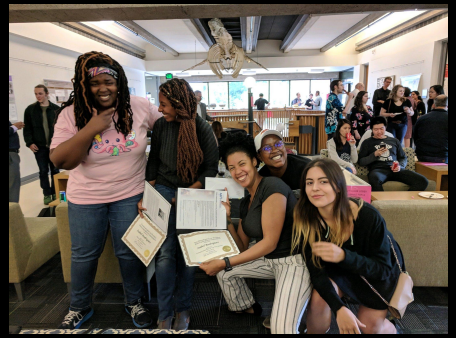
Summary of results

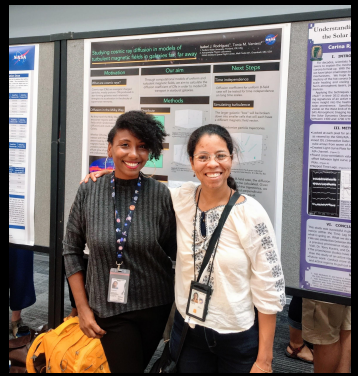
- We constrained a total of 17 parameters
- Place constraints on the geometry and energy of a structured jet.
- We can place constraints on unobservable BNS merger properties.
- A more robust mulitband observational dataset may help to break parameter degeneracies in our afterglow model.

Future work & Open Q's

- Incorporating machine learning algorithms and or high-performance computing techniques.
- How would a more robust observational dataset of GW170817's afterglow have impacted the outcome of this analysis?
- Are there parameter estimates that could be improved with the addition of GW data?

My academic journey





and some things I've done along the way.

- Founder, *WE are STEM Coworking*
- Founding member, *OSU College of Science Multidisciplinary Antiracism Coalition*
- Vice President, *Black Graduate Student Association (BGSA)*
- Representative, *Physics Graduate Student Council*
- Member, *3D Dam Diverse Dance*
- Executive Board Member, *PSU Physics Society*
- Peer mentor, *PSU BUILD EXITO Program*
- Workshop leader & LA, *PSU Physics Department*
- Mentor, *Oregon Math Engineering and Science Achievement (MESA)*
- Program Technician Intern, *Multnomah County Elections*
- Volunteer, *Oregon Museum of Science and Industry (OMSI)*

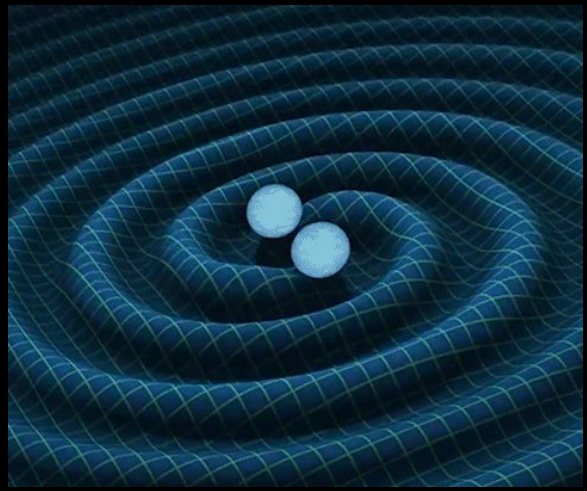
Thank you!

- We explored the largest parameter space using a structured jet.
  - Placed constraints on the jet geometry and energy
  - Placed constraints on unobservable BNS merger properties.
- A more robust mulitband observational dataset may help to break parameter degeneracies in our afterglow model.
- The current underrepresentation of Black, Indigenous women and non-binary people of color stems from a history of exclusion and is a symptom of STEM culture (Isler et al. 2021).

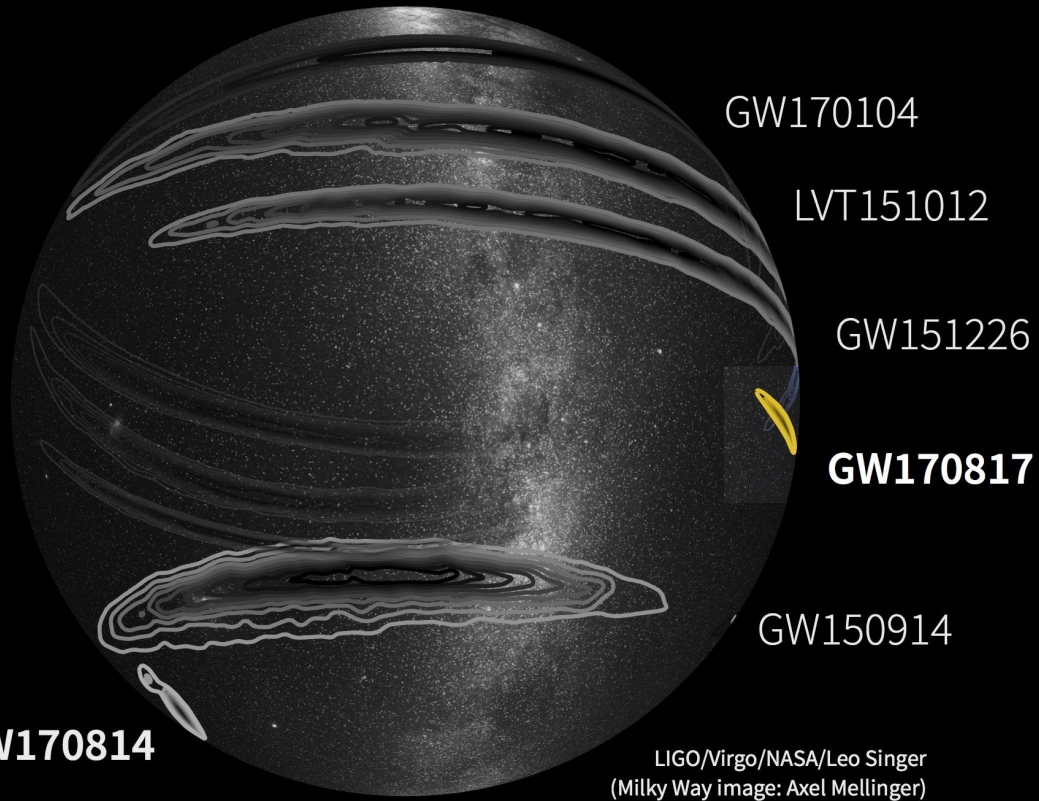
Tell me more about...

The "why"

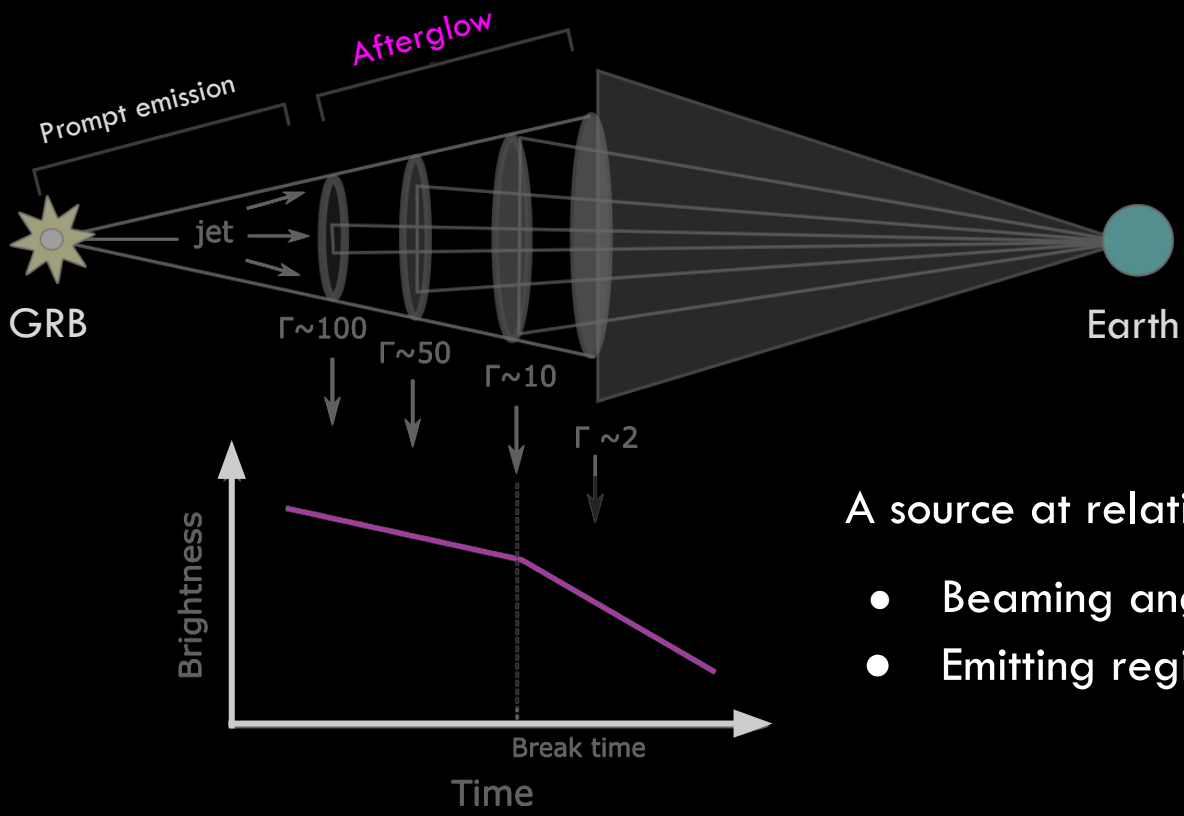
- Primary sites of the r-process
  - Create heavy elements such as Au, Pt, etc.
- Progenitors of short gamma-ray bursts
- Possibility for more (off-axis) multimessenger detections
- Probe the nature of:
  - neutron star matter
  - the central engine (NS/BH)



Localizing GW170817



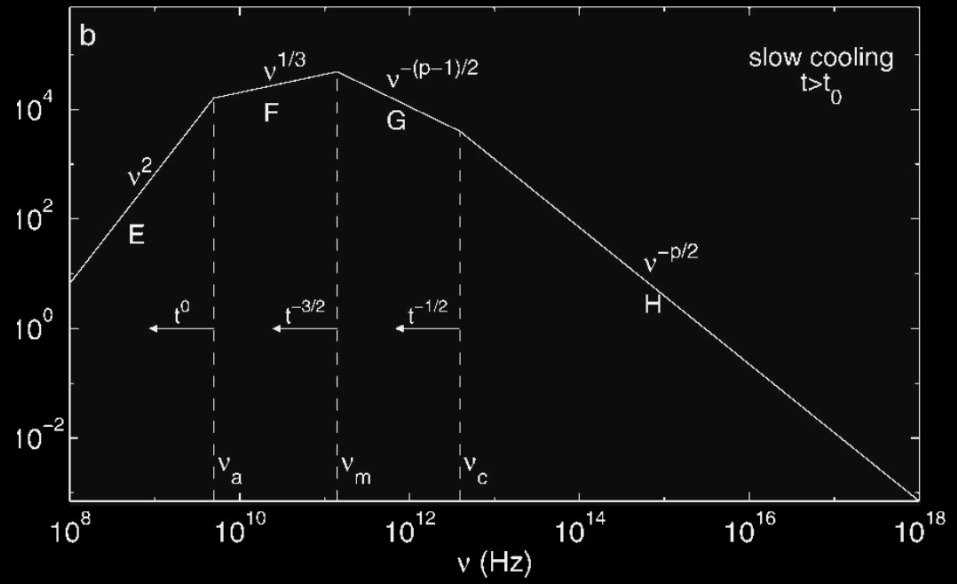
Relativistic beaming



A source at relativistic speeds:

- Beaming angle: $1/\Gamma$
- Emitting region w/ radius R: R/Γ

The broadband synchrotron spectrum



time

$$\nu_a = f_a(\epsilon_e, \epsilon_B, n, E, p, z) \text{ Hz},$$

$$\nu_m = f_m(\epsilon_e, \epsilon_B, n, E, p, z) t^{-3/2} \text{ Hz},$$

$$\nu_c = f_c(\epsilon_e, \epsilon_B, n, E, p, z) t^{-1/2} \text{ Hz},$$

$$F_m = f_F(\epsilon_e, \epsilon_B, n, E, p, z) \text{ Hz}.$$

Your dataset

Table 4.2: The set of multiband observational data used in the afterglow analysis.

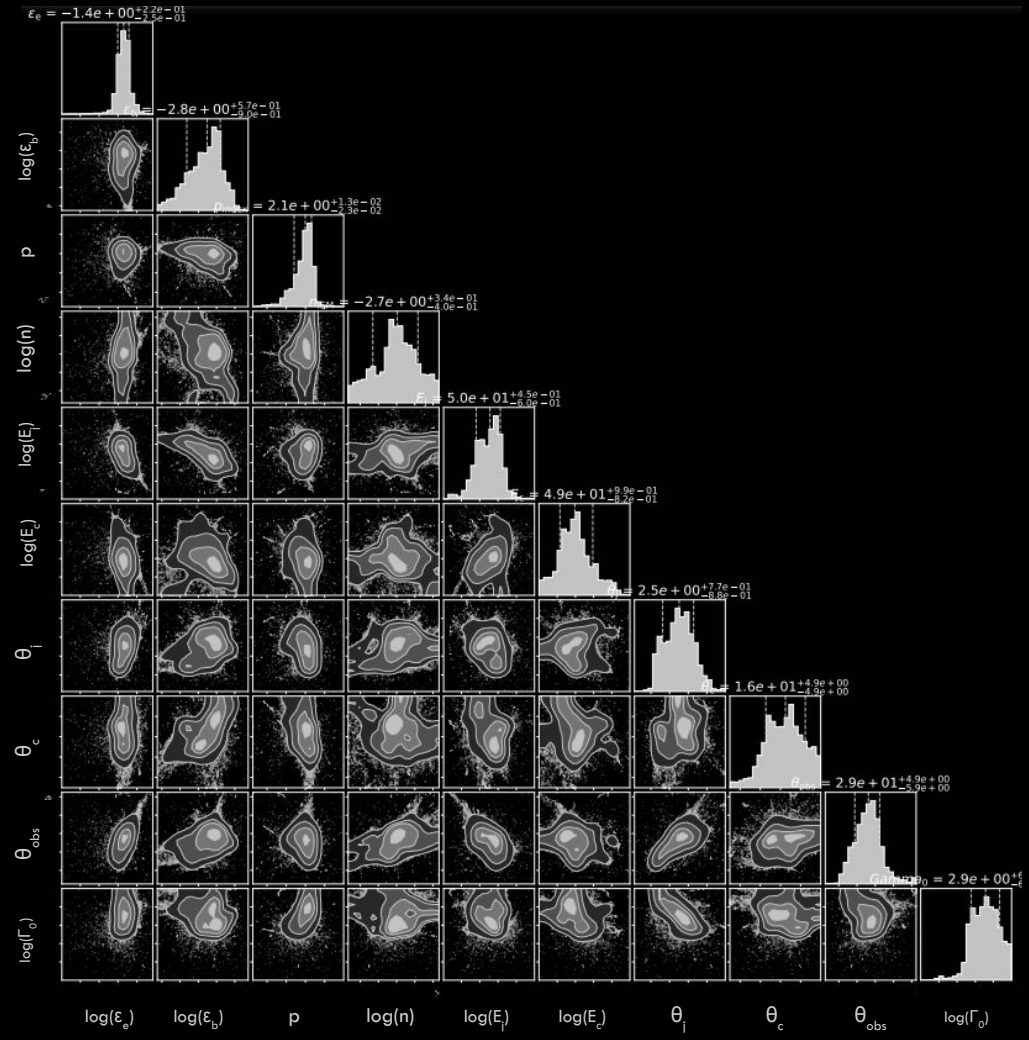
Band	Frequency	Number of datapoints
3.00 GHz	Radio	20
6.0 GHz	Radio	11
4.50 GHz	Radio	7
15.0 GHz	Radio	4
11.0 GHz	Radio	4
2.42×10^{17} Hz	X-ray	10
4.99×10^{14} Hz	Optical	9

Makhatini et al. (2020)

Parameters from Analysis #1

Table 5.1: Bayesian parameter estimation results using our afterglow model.

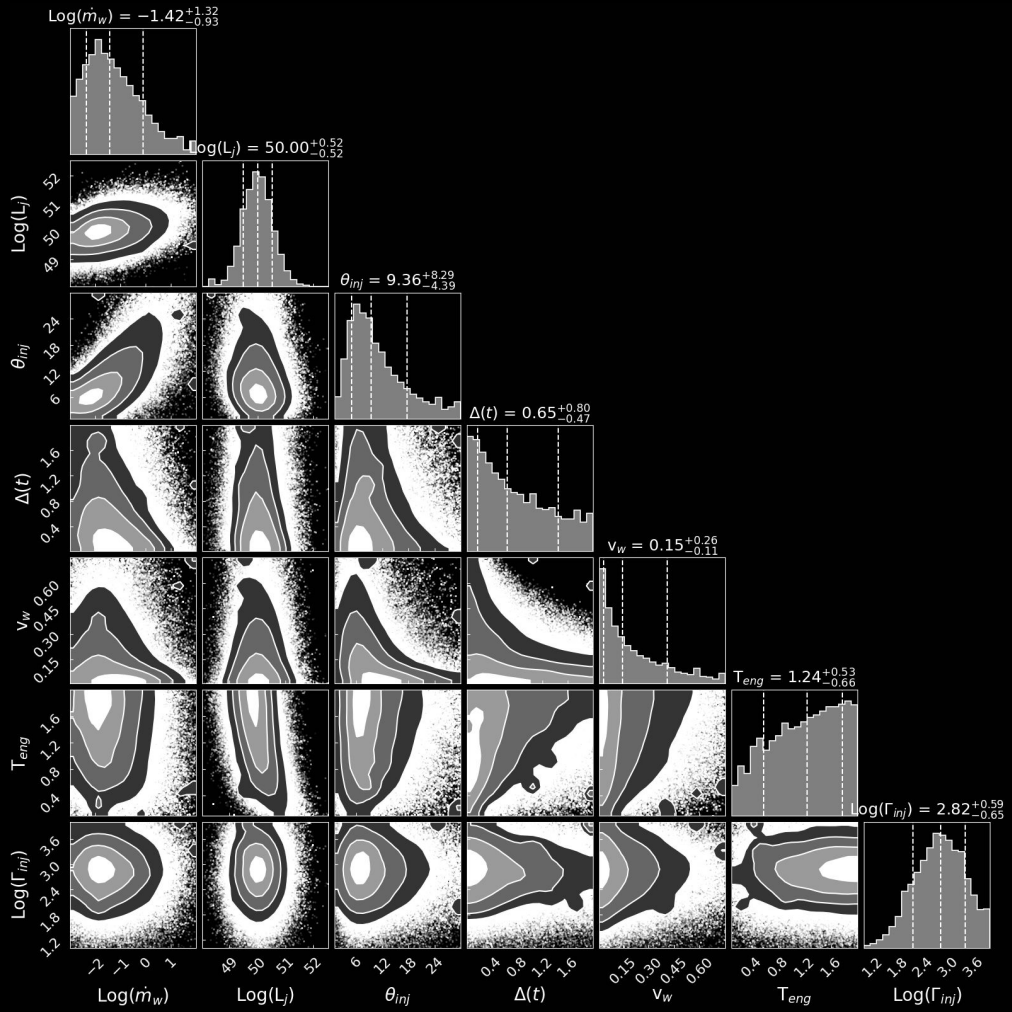
Prior bounds	**emcee** estimate	Units	Description
$-4 \leq log(\epsilon_e) \leq -0.3$	$-1.18^{+0.08}_{-0.09}$	–	fraction of energy of electrons
$-4 \leq log(\epsilon_B) \leq -0.3$	$-2.90^{+0.42}_{-0.53}$	–	fraction of energy of magnetic field
$2 \leq p_{index} \leq 2.5$	$2.14^{+0.01}_{-0.01}$	–	electron slope
$-4 \leq log(n_{ISM}) \leq -0.3$	$-2.34^{+0.22}_{-0.34}$	cm^3	external number density of ISM
$-4 \leq log(E_j) \leq 50$	$49.75^{+0.21}_{-0.20}$	erg	relativistic (core) jet energy
$-4 \leq log(E_c) \leq 49$	$47.42^{+0.91}_{-0.92}$	erg	relativistic cocoon energy
$0 \leq \theta_j \leq 10$	$2.56^{+0.32}_{-0.27}$	deg	jet (core) opening angle
$\theta_j + 0.6 \leq \theta_c \leq 20$	$4.68^{+0.76}_{-0.78}$	deg	cocoon opening angle
$-4 \leq log(\Gamma_0) \leq 2.70$	$2.76^{+0.19}_{-0.39}$	–	terminal Lorentz factor
$0 \leq \theta_{obs} \leq 90$	$33.61^{+3.13}_{-3.69}$	deg	observer angle


$\varepsilon_e = -1.4e+00^{+2.2e-01}_{-2.5e-01}$
$\varepsilon_b = -2.8e+00^{+5.7e-01}_{-9.0e-01}$
$p = 2.1e+00^{+1.3e-02}_{-1.3e-02}$
$n = -2.7e+00^{+3.4e-01}_{-4.0e-01}$
$E_j = 5.0e+01^{+4.5e-01}_{-6.0e-01}$
$E_c = 4.9e+01^{+9.9e-01}_{-8.2e-01}$
$\theta_j = 2.5e+00^{+7.7e-01}_{-8.8e-01}$
$\theta_c = 1.6e+01^{+4.9e+00}_{-4.9e+00}$
$\theta_{obs} = 2.9e+01^{+4.9e+00}_{-5.9e+00}$
$\Gamma_0 = 2.9e+00^{+$
log(ε_e)
log(ε_b)
p
log(n)
log(E_j)
log(E_c)
θ_j
θ_c
θ_obs
log(Γ_0)

Parameters from Analysis #2

Table 5.2: Bayesian parameter estimation results using our outflow model.

Prior bounds	emcee estimate	Units	Description
$-3 \leq \log(\dot{m}_w) \leq 2$	$0.27^{+0.57}_{-0.58}$	$M_\odot$ /s	rate of mass loss
$0.01 \leq v_w \leq 0.75$	$0.49^{+0.17}_{-0.17}$	c	wind velocity
$1 \leq \theta_0 \leq 30$	$22.99^{+4.72}_{-6.06}$	deg	jet angle at injection
$1 \leq \log(\Gamma_0) \leq 4$	$2.63^{+0.37}_{-0.50}$	–	jet Lorentz factor at injection
$0.01 \leq \Delta_t \leq 2$	$0.06^{+1.32}_{-0.04}$	s	time delay to jet launch
$48 \leq \log(L_0) \leq 53$	$49.66^{+0.62}_{-0.36}$	erg/s	jet luminosity at injection
$0.1 \leq T_{engine} \leq 2$	$1.35^{+0.45}_{-0.63}$	s	activity time of central engine


Log($\dot{m}_w$) = $-1.42^{+1.32}_{-0.93}$
Log(L_j) = $50.00^{+0.52}_{-0.52}$
θ_{inj} = $9.36^{+8.29}_{-4.39}$
$\Delta(t)$ = $0.65^{+0.80}_{-0.47}$
v_w = $0.15^{+0.26}_{-0.11}$
T_{eng} = $1.24^{+0.53}_{-0.66}$
Log(Γ_{inj}) = $2.82^{+0.59}_{-0.65}$
Log($\dot{m}_w$)
Log(L_j)
θ_{inj}
$\Delta(t)$
v_w
T_{eng}
Log(Γ_{inj})

The emcee module

$$\ln(p(\Theta|D) = \ln(p(\Theta) + \ln(p(D|\Theta)),$$

Posterior: Given a set of parameters, how *probable* are their values given observational data?

$$\ln p(\Theta_i) = \begin{cases} 0, & \text{if } \Theta_{i,LB} \leq \Theta_i \leq \Theta_{i,UB} \\ -\infty, & \text{otherwise,} \end{cases}$$

Prior: What previous knowledge do we have of these parameters?

$$\ln(p(D|\Theta)) = -\frac{1}{2}\sum_i \left(\frac{\text{data} - \text{model output}}{\text{data uncertainty}}\right).$$

Likelihood: How probable is the observed data given a set of model parameters?

White empiricism

"White empiricism is the phenomenon through which only white people (particularly white men) are read has having a fundamental capacity for objectivity and Black people (particularly Black women) are produced as an ontological other."

(Prescod-Weinstein 2020)