Magnetic Fields & NS Merger Disks

Ian Christie

CIERA (Northwestern University)

December 5th, 2019

In Collaboration with:

A. Lalakos (CIERA) **A. Tchekhovskoy** (CIERA)

R. Fernandez (Alberta) **E. Quataert** (Berkeley)

F. Foucart (New Hampshire) **D. Kasen** (Berkeley)

E. Kaufman (IIT)

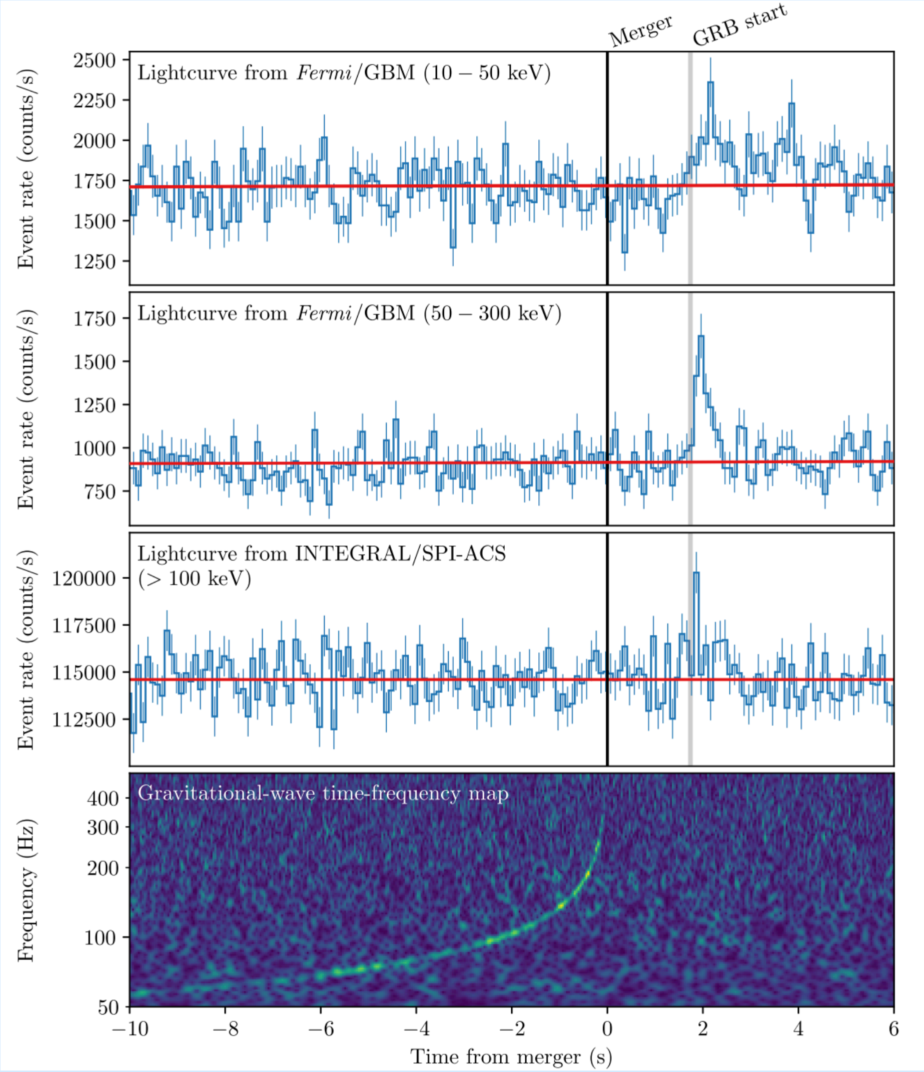
NS Mergers

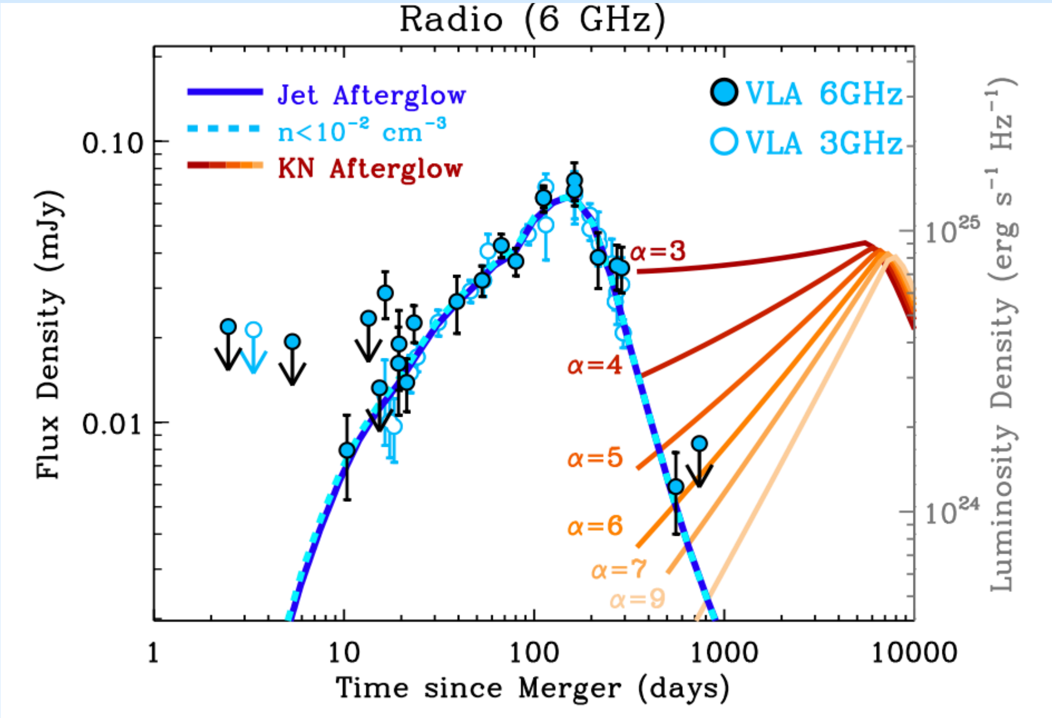
Image Credit: Paz Beniamini

- ❖ Environments of:
  - i. Mass Accretion
  - ii. Outflows (relativistic jets & disk winds)
  - iii. r-process nucleosynthesis

Fernandez & Metzger 2015
Kasen et al. 2017
Alexander et al. 2018
Hajela et al. 2019

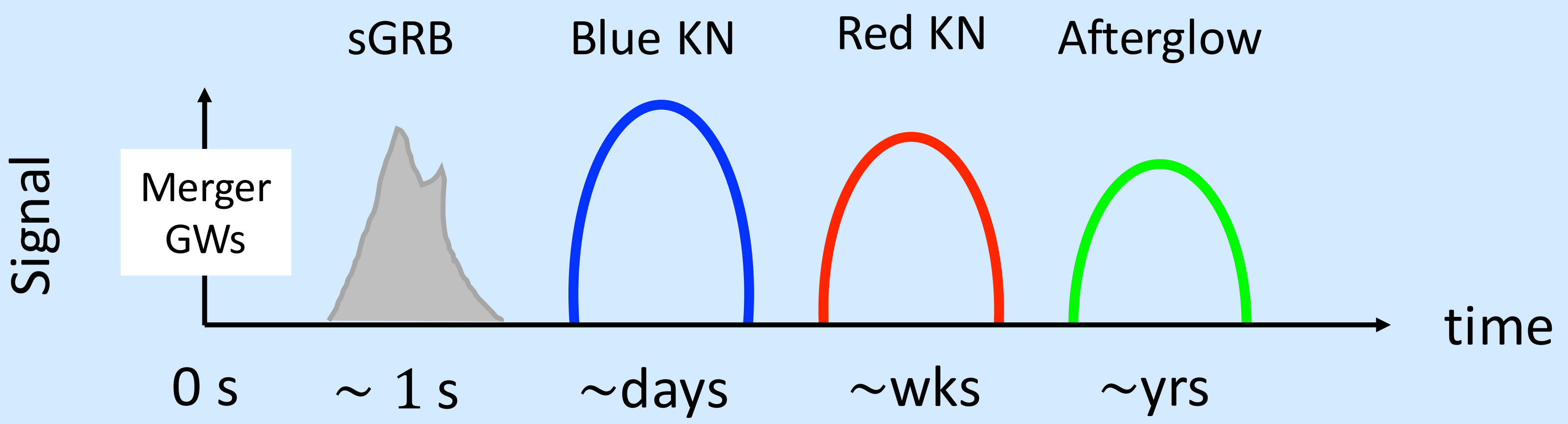
NS Mergers:
GW 170817 / GRB 170917A





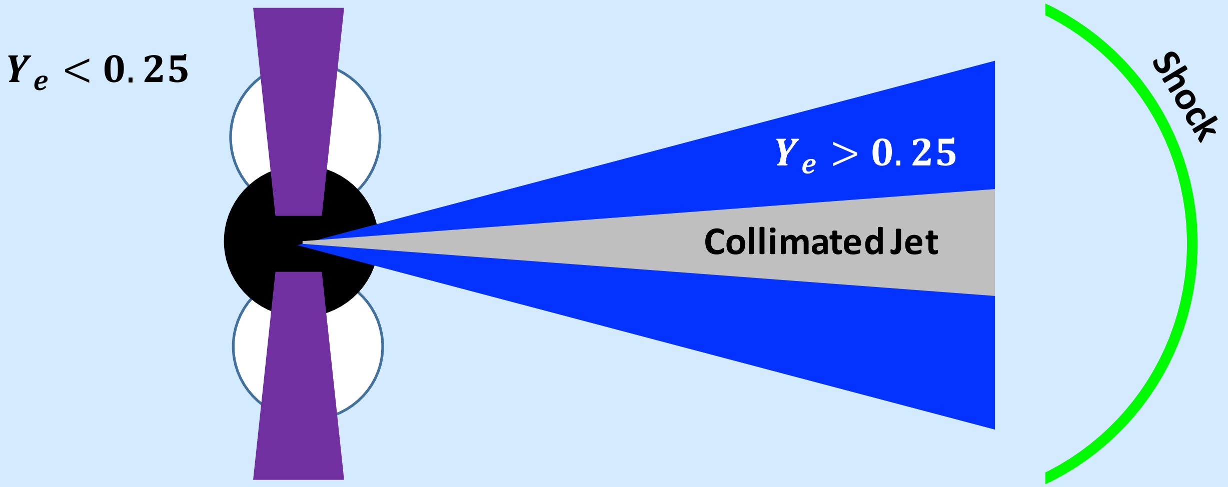
Abbott et al. 2017
Alexander et al. 2018
Hajela et al. 2019

What is required to reproduce a NS merger event?



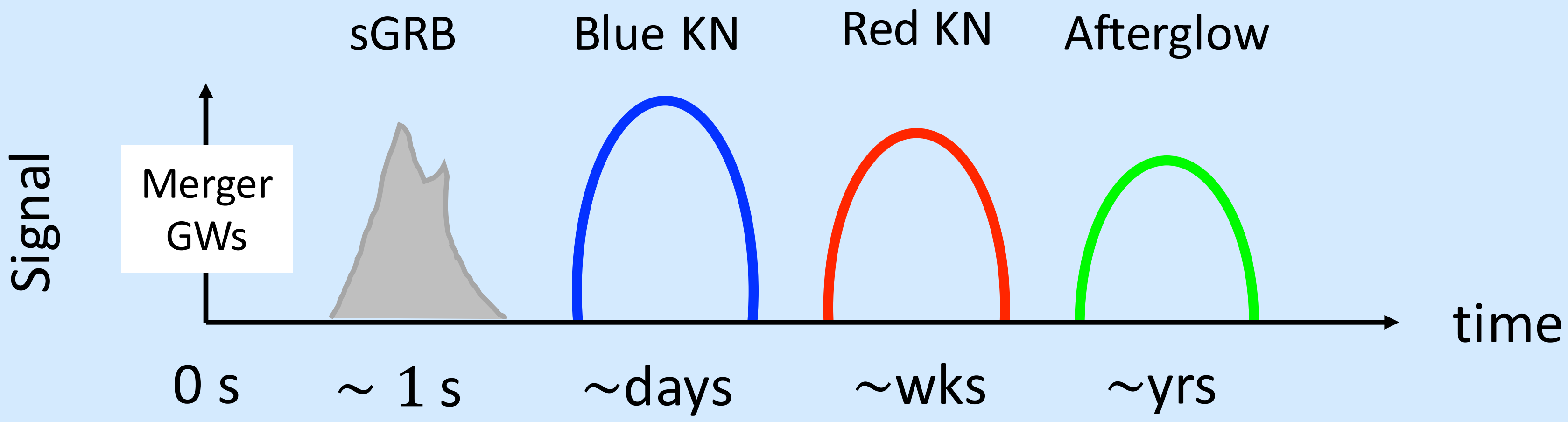
Electron Fraction:

$$Y_e = \frac{n_e}{n_B}$$



Fernandez & Metzger 2015

What is required to reproduce a NS merger event?



- GRB 170817A engine active for ~few seconds
  Requires simulation times of ~ 4 s ($\sim 2.5 \times 10^5\, r_g/c$)

- NS merger event prefers a predominantly toroidal post-merger magnetic field geometry
  Previous studies have shown that toroidal fields produce very weak jets and little outflows

- sGRBs characteristically have small opening angles ($\theta_j \sim 16° \pm 10°$):
  How can we obtain such tightly collimated jets with little mass ($\sim 0.1\, M_\odot$)?

Beckwith et al. 2008
Fernandez & Metzger 2015
Fong et al. 2015
McKinney et al. 2012

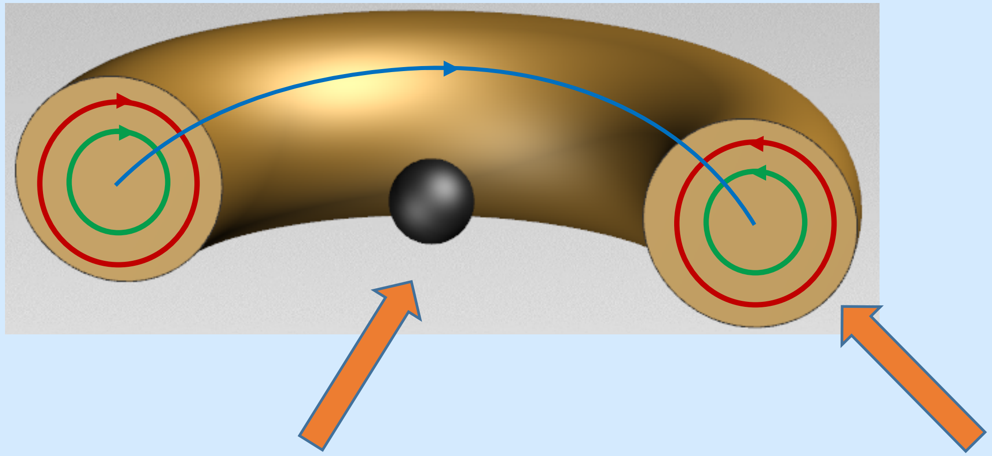
Simulation Setup

- Included neutrino cooling and nuclear recombination

- **Longest running simulations to date**, extending. $4.4 \rightarrow 9\ s \sim 3 \rightarrow 6 \cdot 10^5\ {}^{R_g}\!/_{c}$

- Variation only in the post-merger magnetic field geometry:
  i. Strong & Weak Poloidal Fields
  ii. Toroidal Field

Diagram of Magnetic Field Geometries

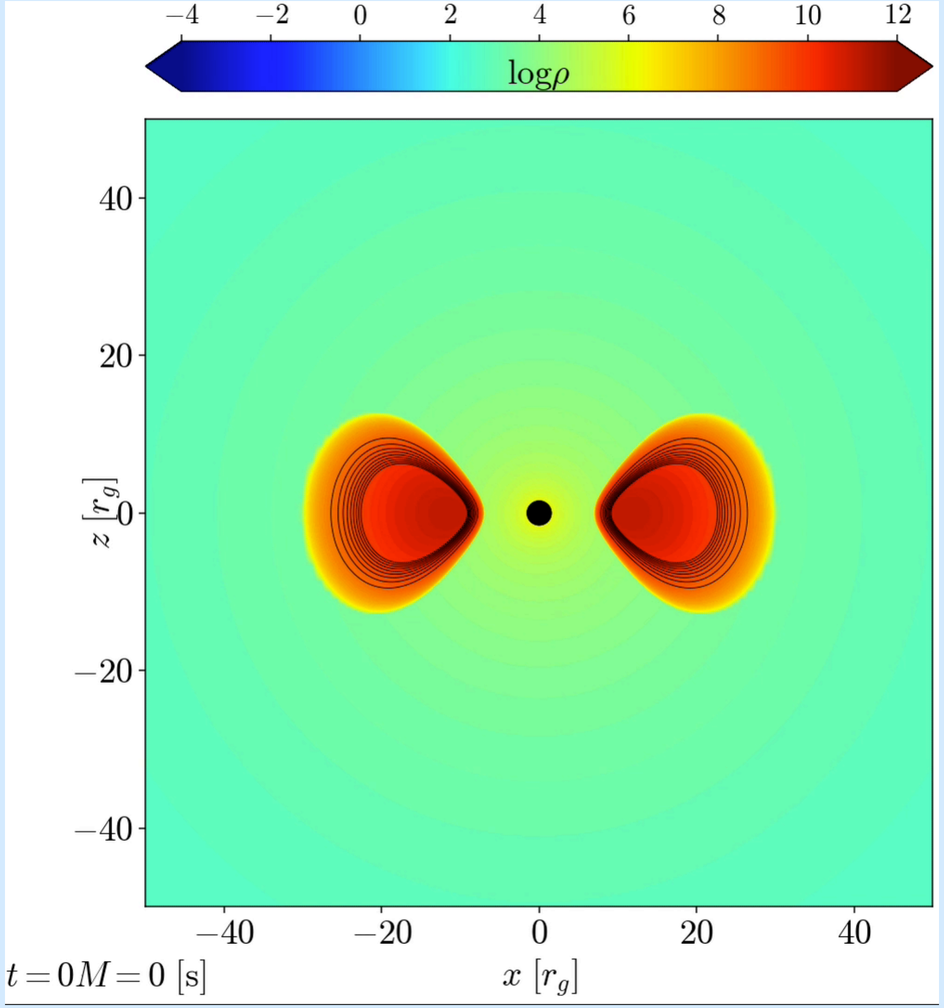


$M_{BH} = 3\ M_{\odot}$
$a = 0.8$

$M_{torus} = 0.033\ M_{\odot}$
$Y_e = 0.1$

U.S. DEPARTMENT OF ENERGY | Office of Science   NERSC

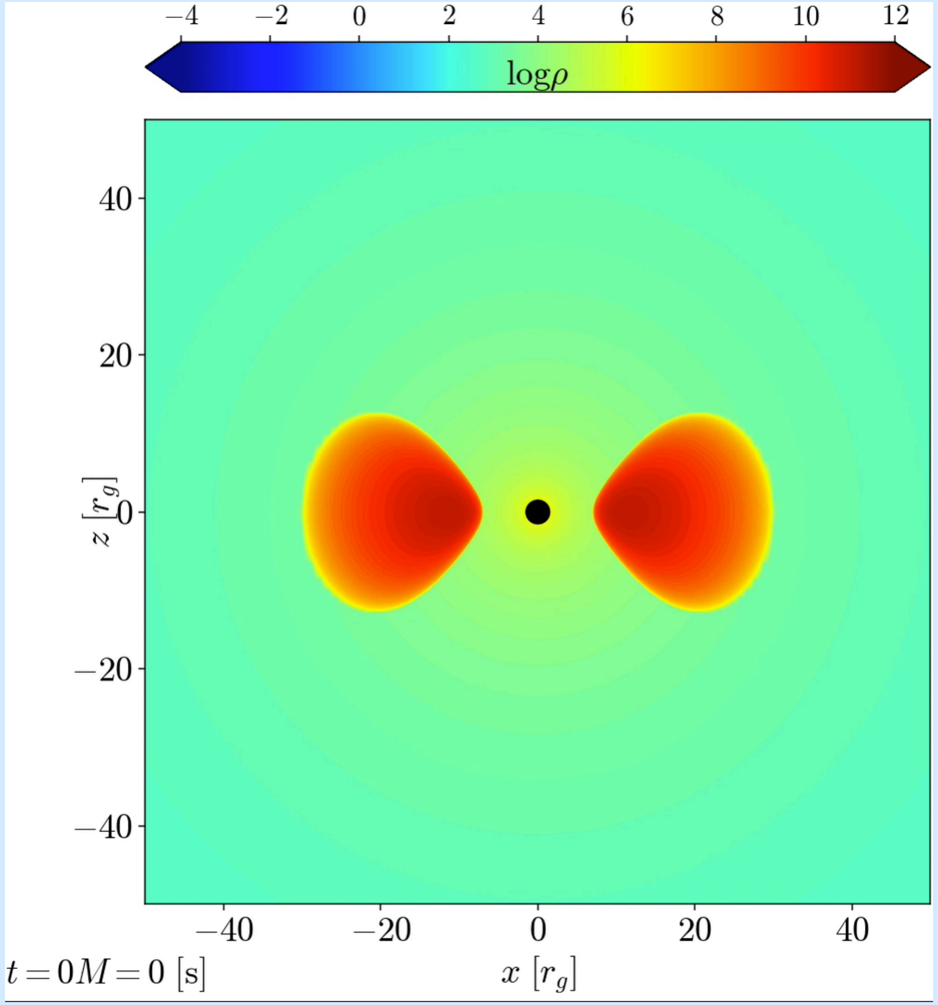
Poloidal Geometries



❖ Initially starting with poloidal magnetic flux → accretion and jet formation begin at earlier times

Fernandez et al. 2018
Christie et al. 2019

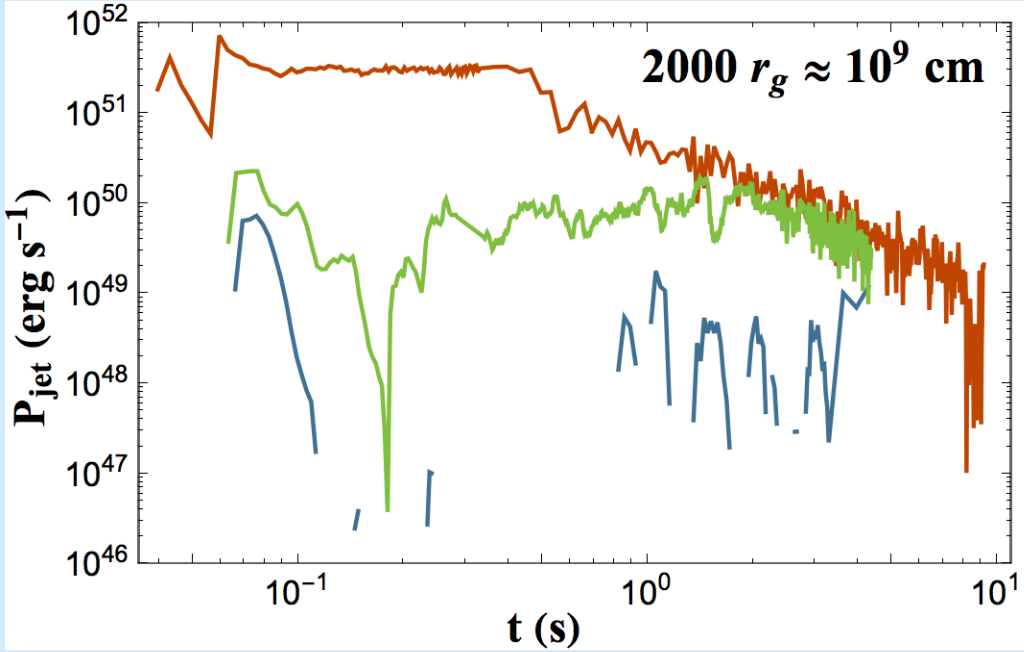
Toroidal Geometry



- ❖ Undergoes dynamo-like process for toroidal → large-scale poloidal magnetic flux
- ❖ For the first time for initially toroidal fields, we have the production of jets!

Christie et al. 2019

Jet Power



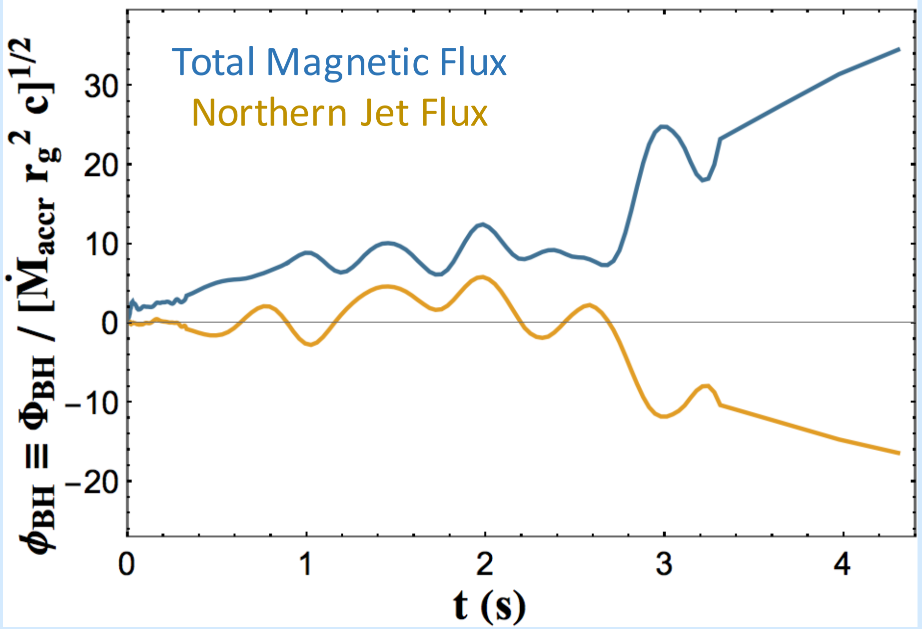
Christie et al. 2019

- ❖ Initially poloidal fields produce powerful jets
- ❖ Toroidal fields produce weak **and** intermittent jets!

Post-Merger Geometry:
Strong/Weak Poloidal
Toroidal

Toroidal Fields Lead to Striped Jets!

Normalized Poloidal Magnetic Flux on BH

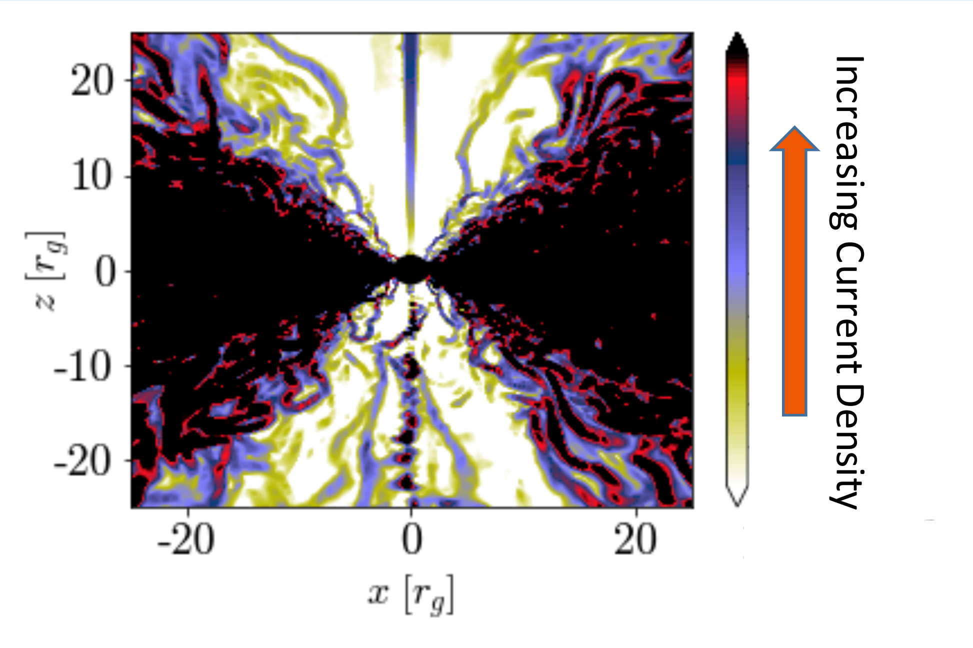


Christie et al. 2019

- Randomness in dynamo leads to alternating magnetic polarity on BH
- Production of current sheets on BH which propagate through the jet

Toroidal Fields Lead to Striped Jets!

Simulation Snapshot of Current Density

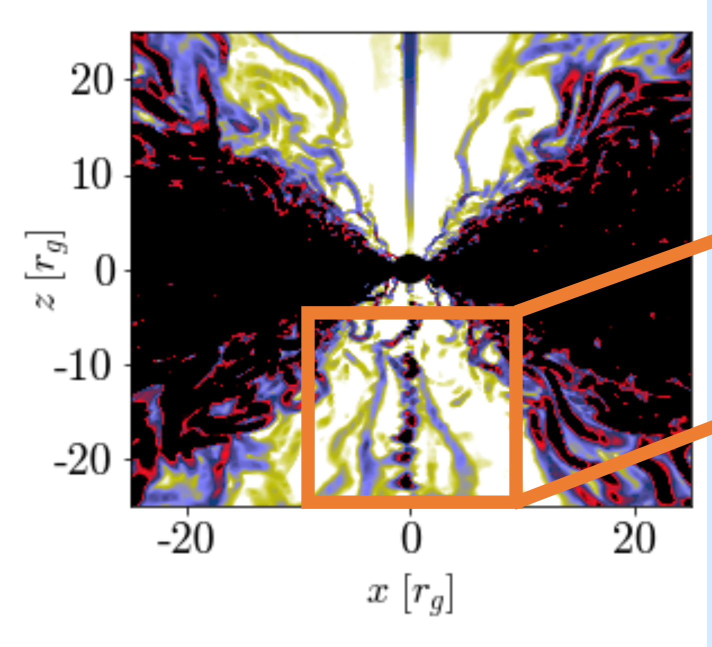


Christie et al. 2019
(Image Credit: Nick Kaaz)

- ❖ Randomness in dynamo leads to alternating magnetic polarity on BH
- ❖ Production of current sheets on BH which propagate through the jet

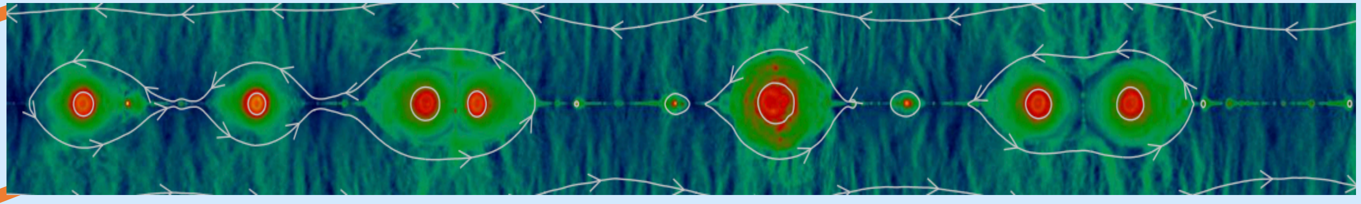
Toroidal Fields Lead to Striped Jets!

Simulation Snapshot of Current Density



Christie et al. 2019
(Image Credit: Nick Kaaz)

Plasmoids Within Reconnection Layer



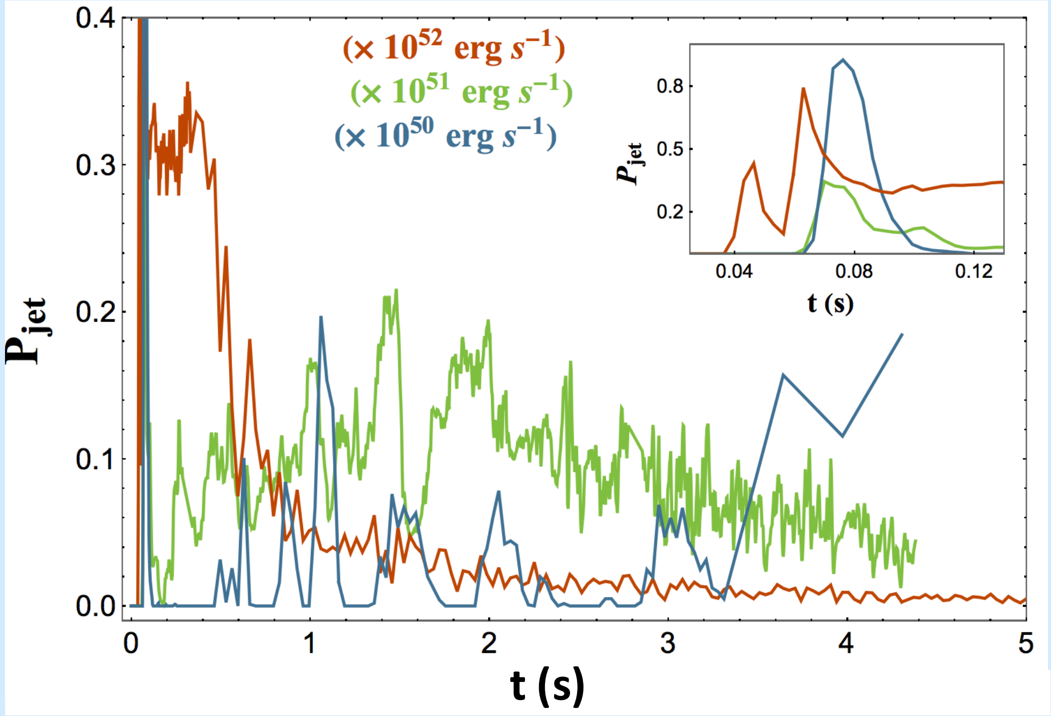
Petropoulou & Sironi, 2018

- Current sheets can potentially lead to dissipation and particle acceleration via magnetic reconnection

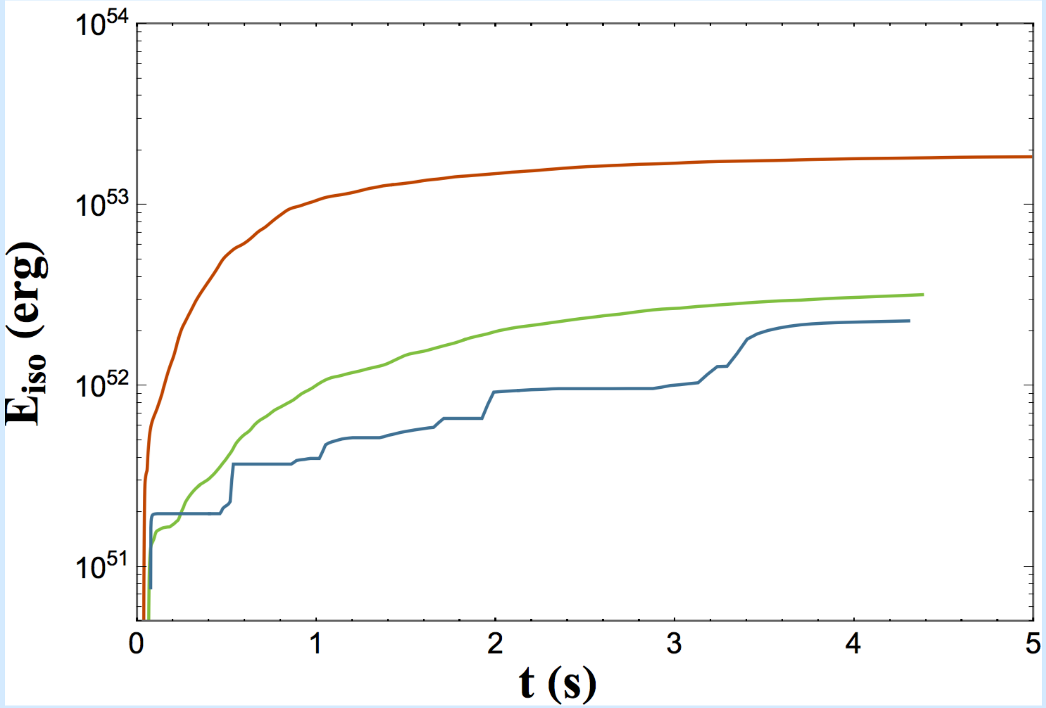
Isotropic Energy

Post-Merger Geometry:
Strong/Weak Poloidal
Toroidal

Jet Power



Isotropic Energy

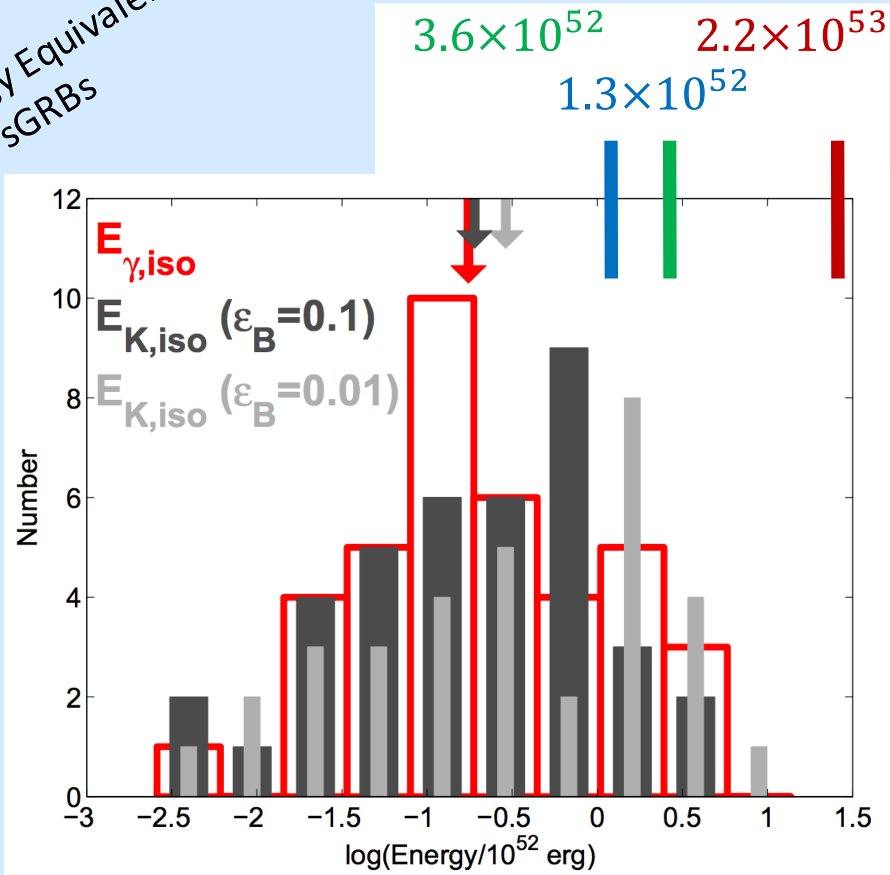


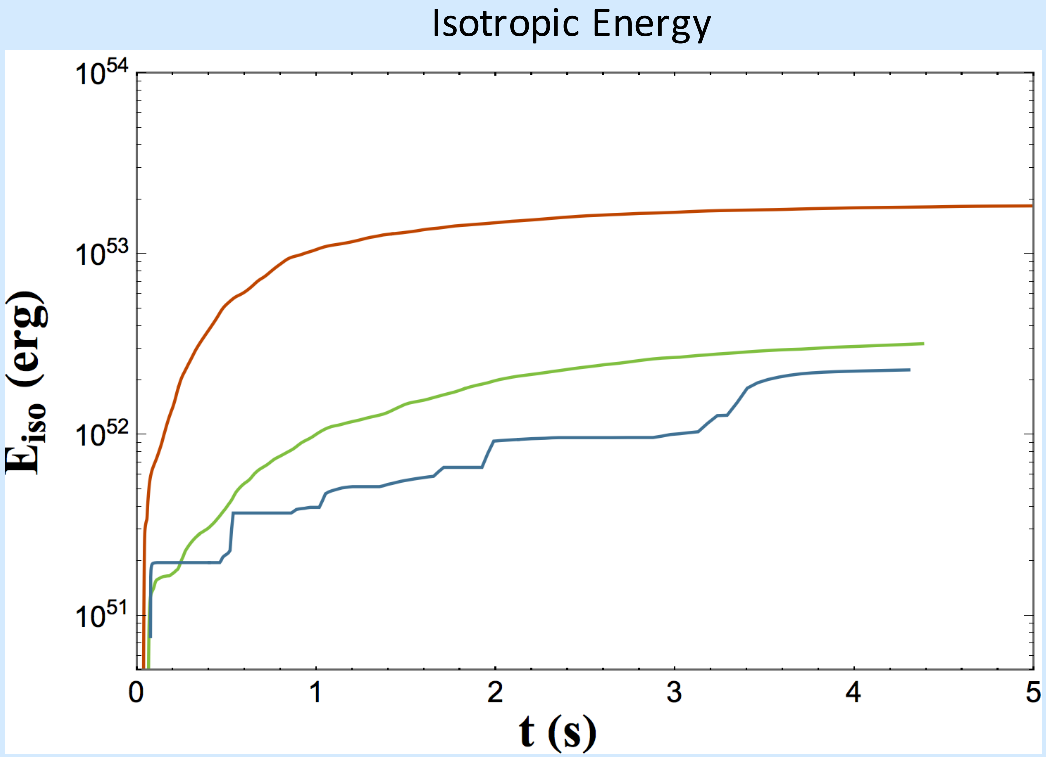
Christie et al. 2019

Isotropic Energy

Post-Merger Geometry:
Strong/Weak Poloidal
Toroidal

Isotropic Energy Equivalent
for 38 sGRBs



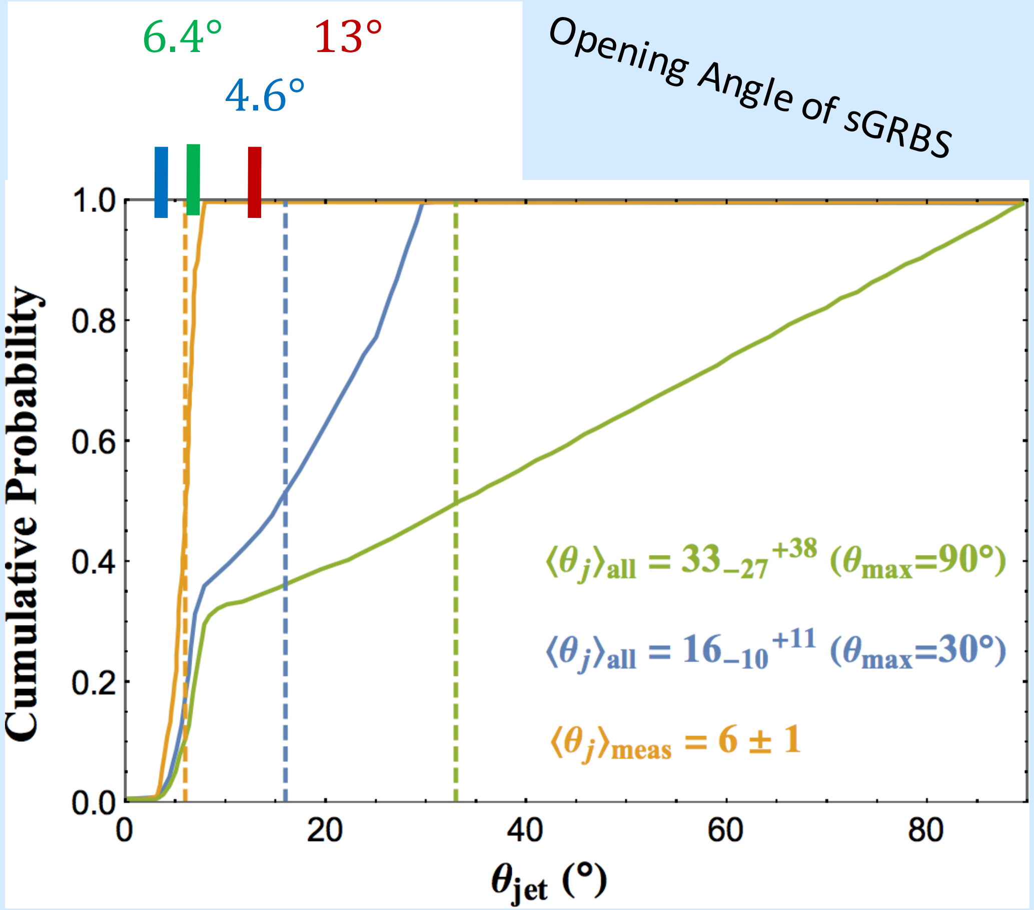


Christie et al. 2019
Fong et al. 2015

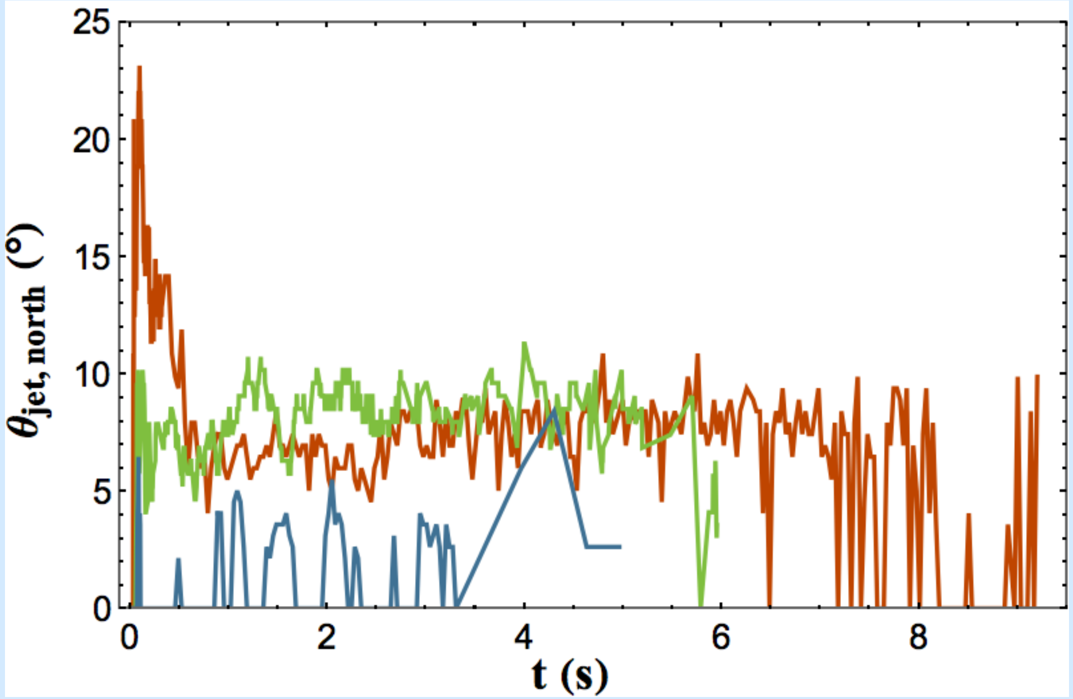
Jet Opening Angle

Post-Merger Geometry:
Strong/Weak Poloidal
Toroidal

Opening Angle of sGRBS



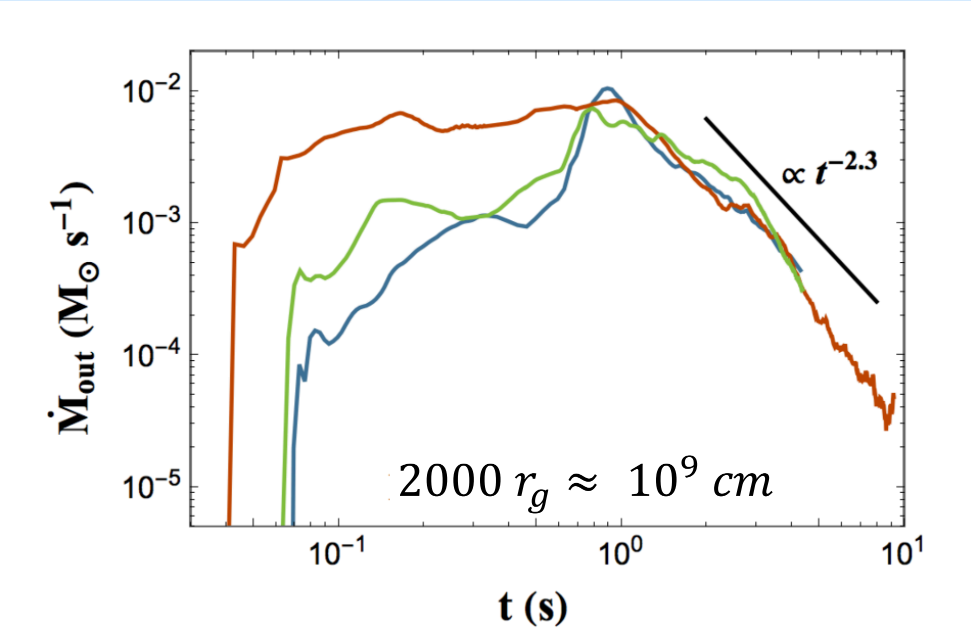
Opening Angle of Northern Jet



Christie et al. 2019
Fong et al. 2015

Mass Accretion & Outflow Rate

Outflow Rate for All Geometries



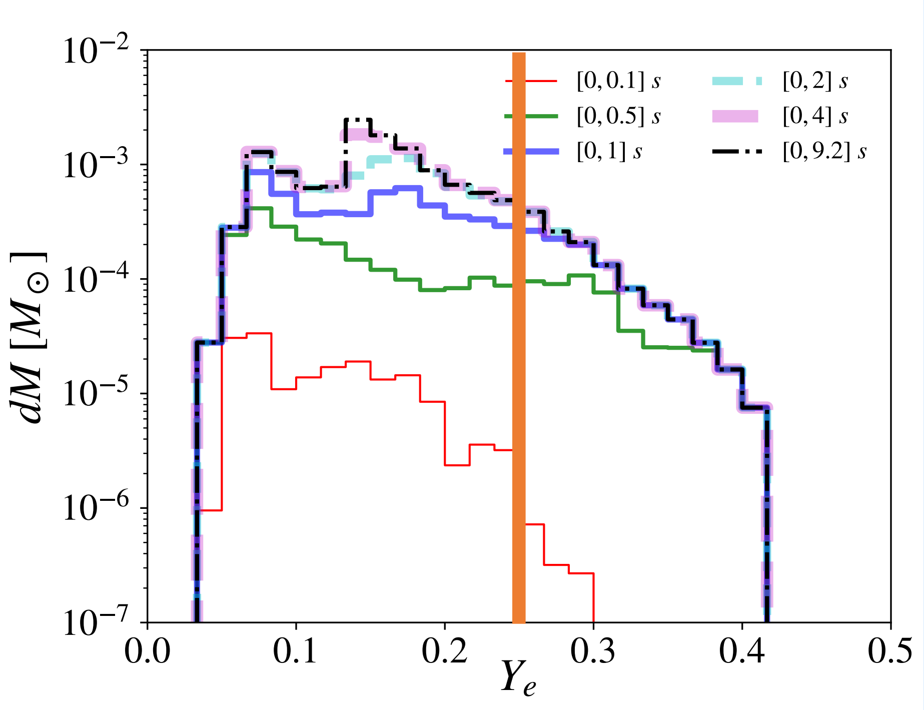
Model Name	M_{accr} (%)	M_{accr} ($10^{-2}\ M_\odot$)	M_{ejec} (%)	M_{ejec} ($10^{-2}\ M_\odot$)
BPS	60	2	40	1.3
BPW	67	2.2	30	0.99
BT	71	2.3	27	0.89

Post-Merger Geometry:
Strong/Weak Poloidal
Toroidal

Christie et al. 2019

Relativistic Ejecta: Electron Fraction Distribution

Strong Poloidal Field



Model Name	$M_{\rm ejec,red}$ (%)	$M_{\rm ejec,red}$ ($10^{-2}\ M_\odot$)	$M_{\rm ejec,blue}$ (%)	$M_{\rm ejec,blue}$ ($10^{-2}\ M_\odot$)
BPS	37	1.2	3	0.1
BPW	27	0.89	3	0.1
BT	25	0.83	2	0.066

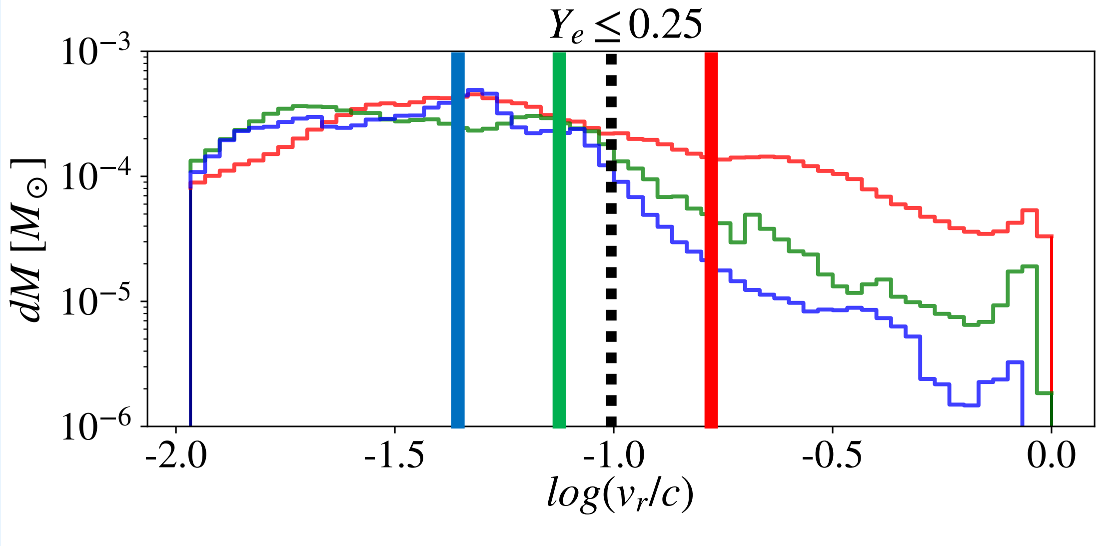
- From GW 170817/GRB 170817A, we can infer:

$$M_{red} \approx 0.04\ M_\odot$$
$$M_{blue} \approx 0.025\ M_\odot$$

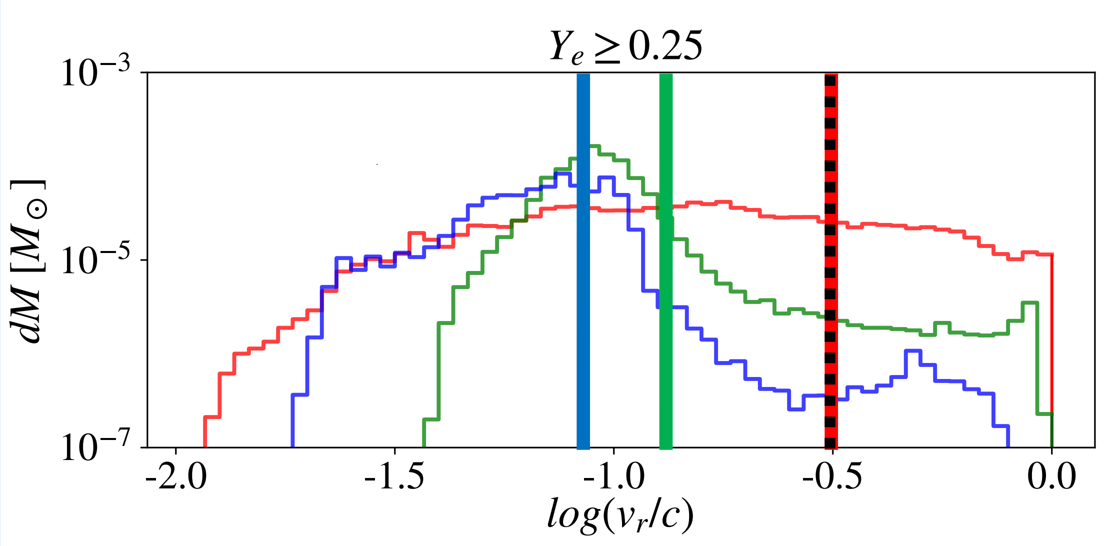
Christie et al. 2019

Relativistic Ejecta: Velocity Distribution

Neutron-Rich Material



Electron-Rich Material

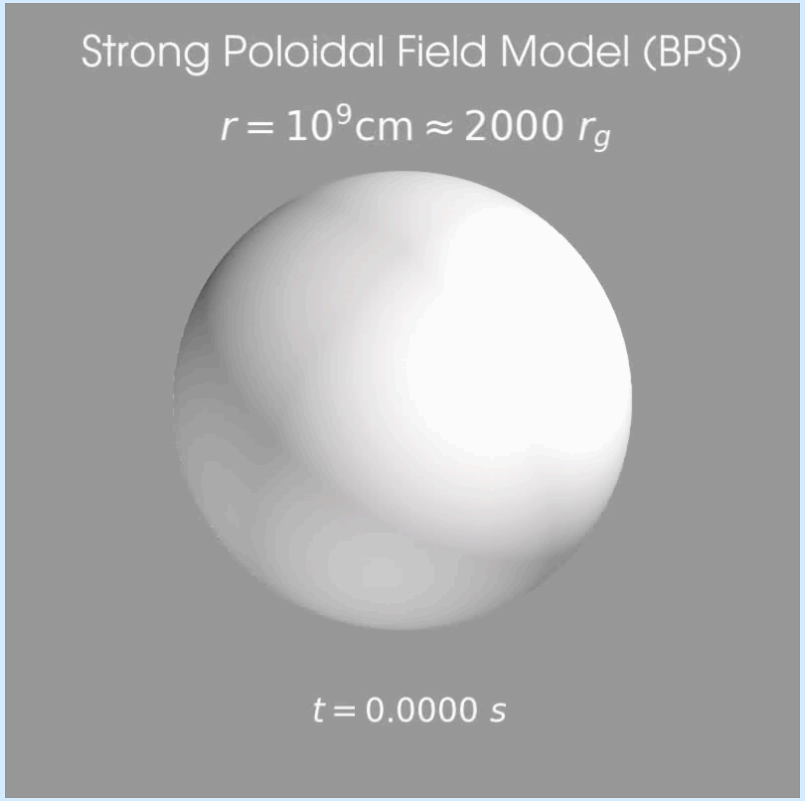


Post-Merger Geometry:
Strong/Weak Poloidal
Toroidal

GW 170817

Christie et al. 2019

How can we see the kilonova?



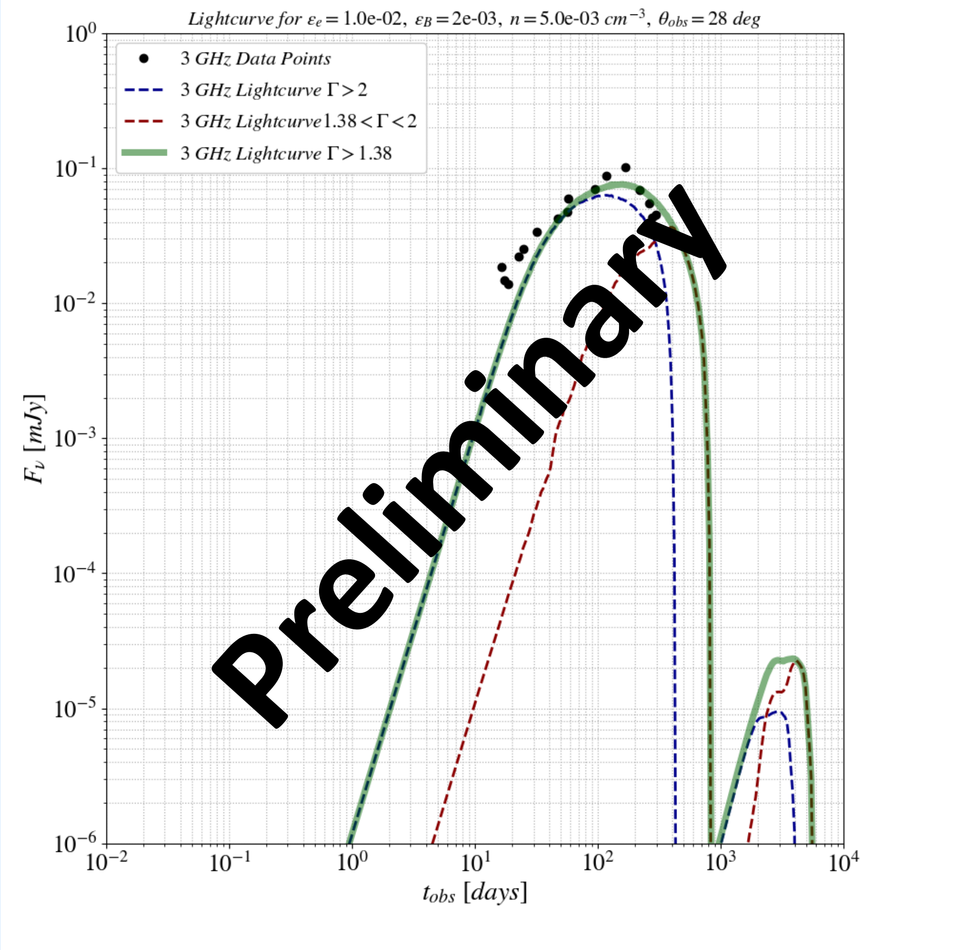
- For all post-merger geometries:
  i. Red material is spread along equatorial plane
  ii. Blue material is confined within $\Delta\theta \sim 15 - 25°$

Red $(Y_e < 0.25)$ Material
Blue $(Y_e \geq 0.25)$ Material
Relativistic Jet

Christie et al. 2019

Can we decipher the field geometry from afterglow?

3 GHz Light Curve for Strong-Poloidal Geometry



Lalakos, Christie et al. in prep.

- ❖ The velocity and amount of outflows is sensitive to the post-merger geometry
- ❖ Can we use long-term afterglow observations to constrain the geometry and parameter space?

Summary

- Post-merger geometries drastically affect mass accretion, mass outflow, and jet power!
- Jet properties fall within sGRB observations but underpredict those of GW 170817
- Initially toroidal magnetic fields can produce striped jets!

Outlook

- Inclusion of more realistic initial conditions (e.g. neutrino physics)
- Future simulations to include dynamical ejecta

arXiv: 1907.02079

ichristi231@gmail.com

Caveats (for now!)

- ❖ Improvement on the neutrino transport and include neutrino absorption
  - ➡ Could provide larger amount of blue material
- ❖ Realistic equation of state(e.g. Helmholtz EOS)
  - ➡ Change composition and velocities of outflows
- ❖ Inclusion of dynamical ejecta
  - ➡ Could provide large fraction of blue material

How Can Toroidal Fields Make Jets?

- Previous toroidal simulations showed little outflows and no jets
  (Beckwith et al. 2008, McKinney et al. 2012)

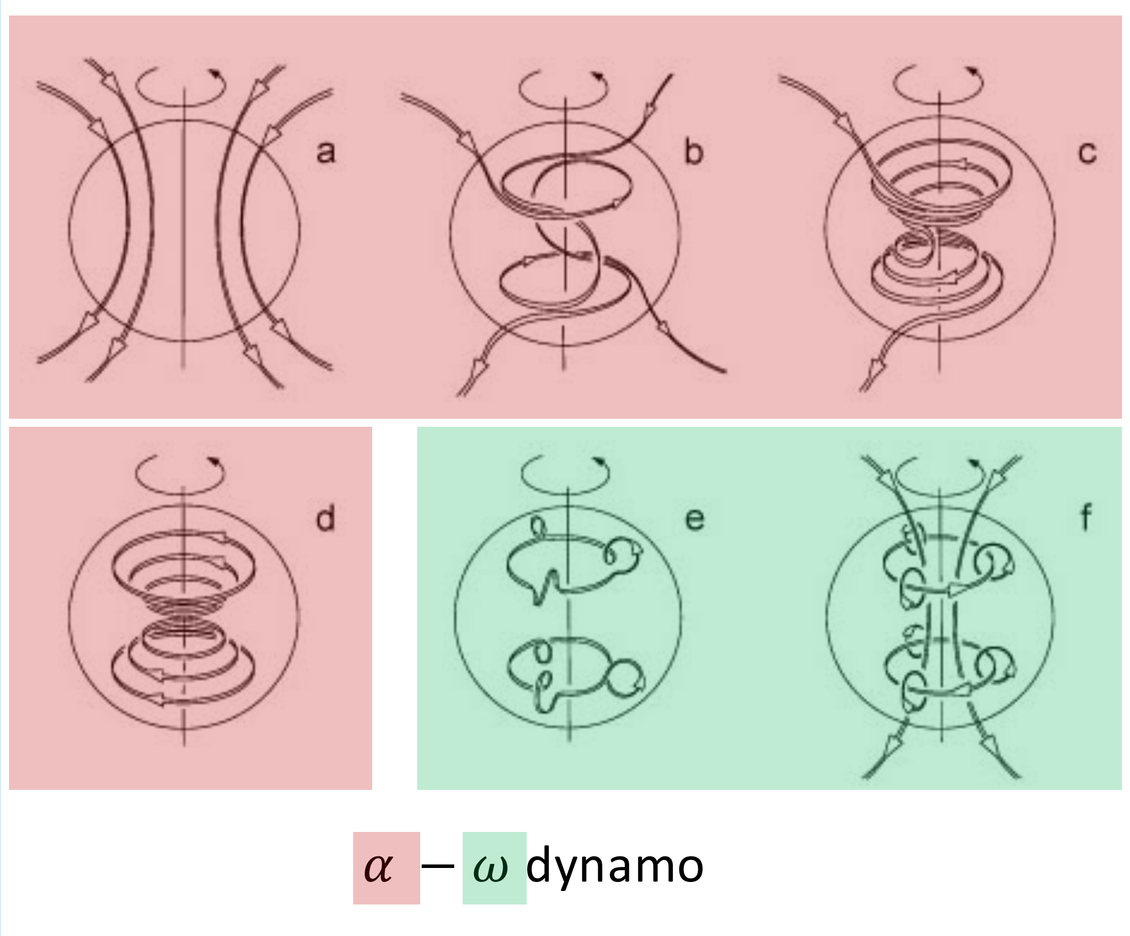
- A possible mechanism for jets w/o large-scale poloidal flux:

  $\boldsymbol{\alpha - \omega}$ **dynamo**

  i. α-effect: poloidal ➡ toroidal via differential rotation

  ii. ω-effect: toroidal ➡ poloidal via twisting of magnetic field lines

(Moffat 1978, Parker 1979)

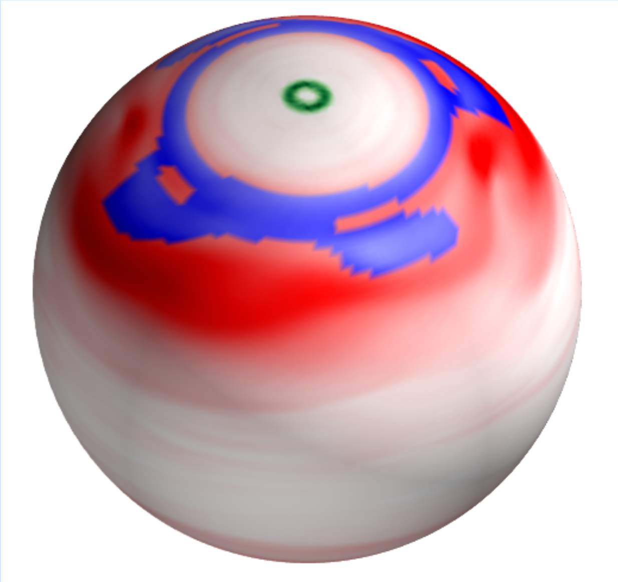


Love, 1999

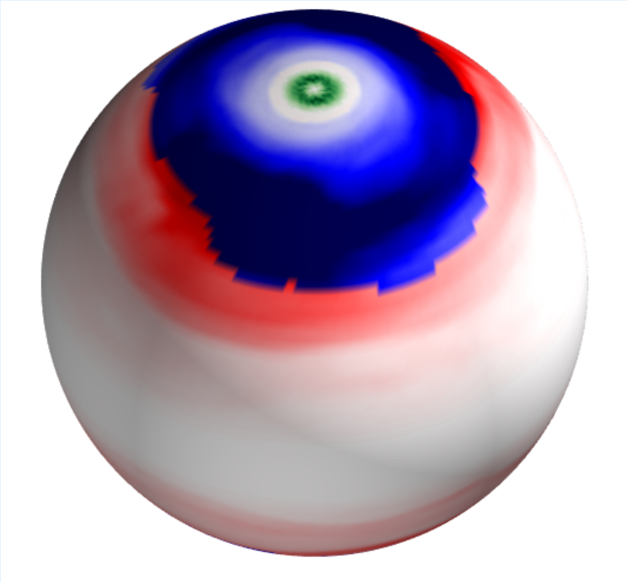
How can we see the kilonova?

Evaluated at:
$2000\ r_g \approx 10^9\ cm$
$t \sim 0.8\ s$

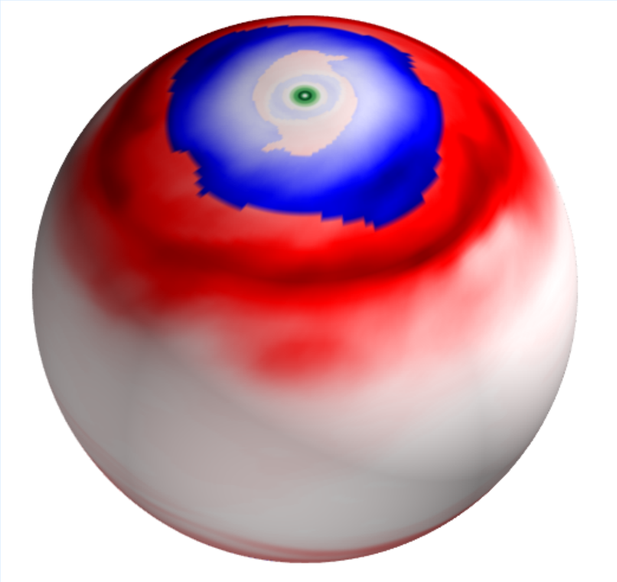
Strong-Poloidal Field



Weak-Poloidal Field



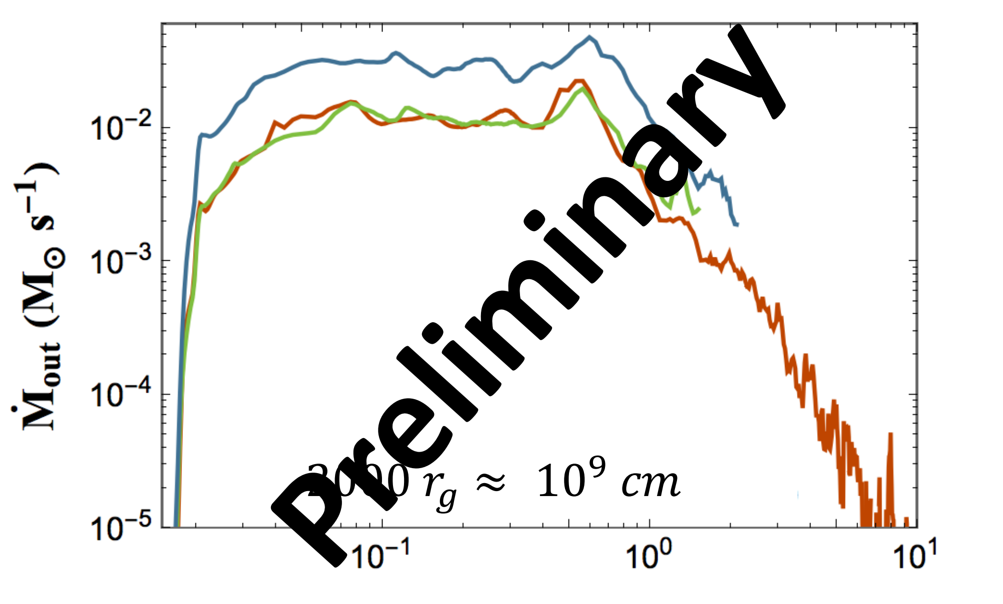
Toroidal Field



Christie et al. 2019

Are there any additional mechanisms worth exploring?

Mass Outflow Rate: Strong Poloidal Geometry



Original
Larger Disk Mass
No Nuclear Recombination

- How do properties of outflows (e.g. mass accretion/ejection, composition) vary for increasing torus mass ($0.033\ M_\odot \rightarrow 0.1 M_\odot$)?
- Can we pinpoint the dominant mechanisms for mass ejection? *MRI-driven turbulence or Nuclear Recombination*

Christie et al., in prep. (2)
Siegel & Metzger 2017, 2018