# Binary Neutron Star Merger rate via the Luminosity Function of short Gamma Ray Bursts

Debdutta Paul

Tata Institute of Fundamental Research, Mumbai, India

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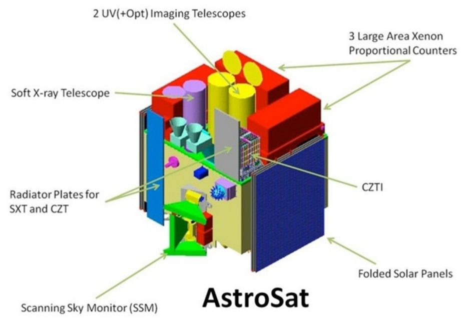
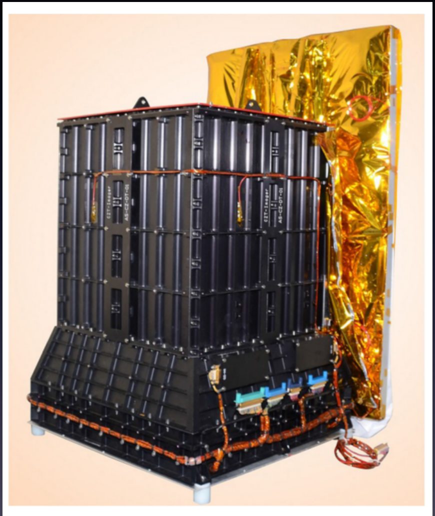
# *AstroSat*

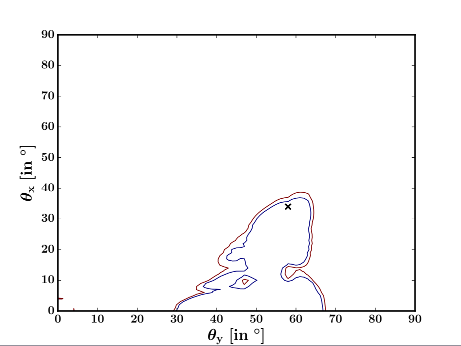



*AstroSat* team

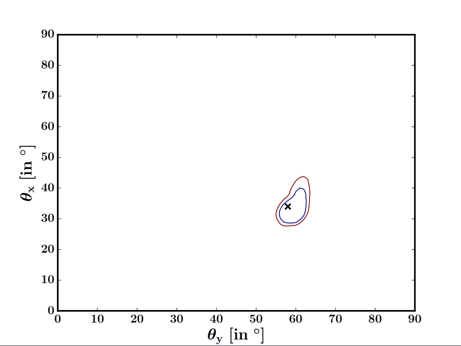


Bhalerao+'17

# GRB151006A



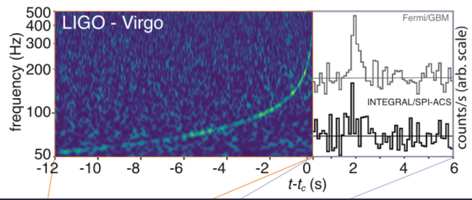

Data



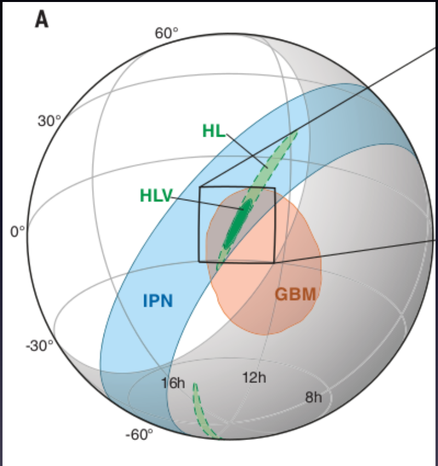

Simulations

Rao+'16

# How many GRBs can it detect?




Abbott+'17e




Kasliwal+'17

# The Luminosity Function (LF), $\Phi(L)$

$$\mathrm{d}N \equiv T\,\Delta\Omega \times \dot{R}(z)\mathrm{d}V \times \Phi(L)\mathrm{d}L,$$

with

$$\dot{R}(z) = f_{\mathrm{B}}\,C\,\Psi(z),$$

$$\Psi(z) = \int_{z_{\min}(z)}^{\infty} \dot{\rho}_{\star}(z')\,P\left(\tau[z,z']\right)\frac{\mathrm{d}\tau}{\mathrm{d}z'}\mathrm{d}z'.$$

**Aim**: To model $\Phi(L)$.

**Motivations**:

- To measure the true source rate.
- To predict the number distribution for newer instruments.

# Review: Proposed methods

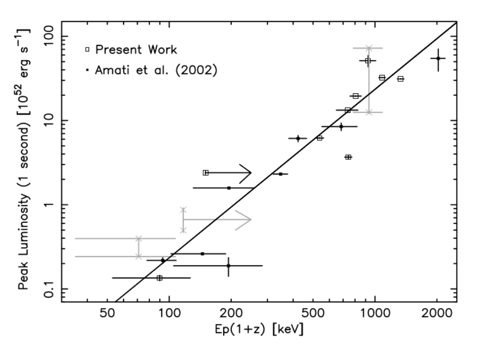
- Measured redshift ($z$) distribution:
  Statistical limitation + selection bias.
- Measured flux ($P$) distribution:
  Intrinsic parameters ($z$, $L$) $\rightarrow$ Measured parameter ($P$)?
  - Limit to “flux-complete” sample: Statistical limitation.
- Different instruments give different results.

| Reference | $\dot{R}(0)$ $\mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$ |
|---|---|
| Ghirlanda+’16 model [a] | 0.13-0.24 |
| Guetta & Piran ’05 | 0.1-0.8 |
| Yonetoku+’14 | 0.24-0.94 |
| Ghirlanda+’16 model [c] | 0.65-1.10 |
| Coward+’12 | 5-13 |
| Guetta & Piran ’06 | 8-30 |

# Yonetoku correlation

$$L = P\,4\pi d_L(z)^2 \times k(z;\,\mathrm{spectrum})$$

$z$ is measured only for a small fraction of GRBs.

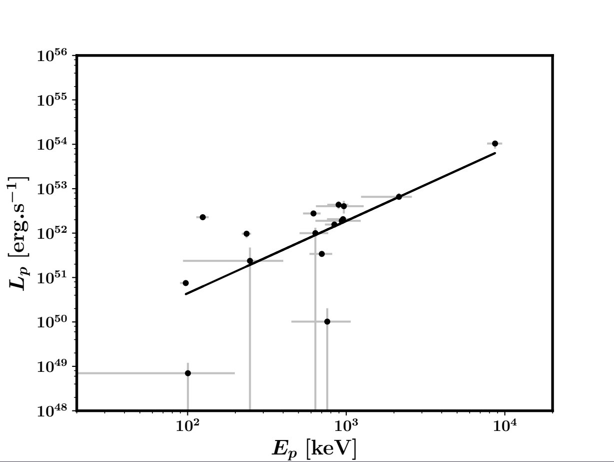



Yonetoku+'04

# Long GRBs

| Reference | $\dot{R}(0)$ $\mathrm{yr^{-1}Gpc^{-3}}$ |
|---|---|
| Amaral-Rogers+'17 | 0.04-0.24 |
| Paul'18a | 0.12-0.20 |

# Short GRBs – the correlation



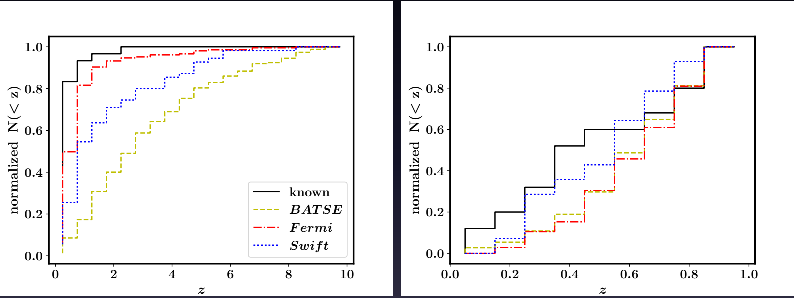

The correlation is tight, in spite of outliers.

# Number of GRBs used

| mission | redshift | number |
|---|---|---|
| *CGRO*-BATSE | pseudo | 468 |
| *Fermi*-GBM | pseudo | 209 |
| | measured | 2 |
| *Swift*-BAT | pseudo | 59 |
| | measured | 19 |
| TOTAL | | 757 |

# Redshift distributions

There are only **30** GRBs with known redshift.




- Observed number of GRBs too small (30/25).
- Heavily biased due to redshift measurement selection effects.

# The Luminosity Functions: models tested

1. **S**imple **P**ower **L**aw (SPL) model: $\Phi(L) = \Phi_0 (L)^{-\nu}$.
2. **B**roken **P**ower**L**aw (BPL) model: $\Phi(L) = \Phi_0 \begin{cases} \left(\frac{L}{L_{\rm b}}\right)^{-\nu_1}, & L \leq L_{\rm b} \\ \left(\frac{L}{L_{\rm b}}\right)^{-\nu_2}, & L > L_{\rm b}. \end{cases}$
3. **E**xponential-**C**utoff **P**ower**L**aw (ECPL) model:
   $\Phi_z(L) = \Phi_0 \left(\frac{L}{L_{\rm b}}\right)^{-\nu} \exp\left[-\left(\frac{L}{L_{\rm b}}\right)\right]$

# The Luminosity Functions: models fit

## SPL

- **Ruled out for all $\nu$,**
- against claim of Yonetoku+'14 [$\nu = 1$],
- extending Ghirlanda+'16 [$\nu > 2$ ruled out].

## BPL

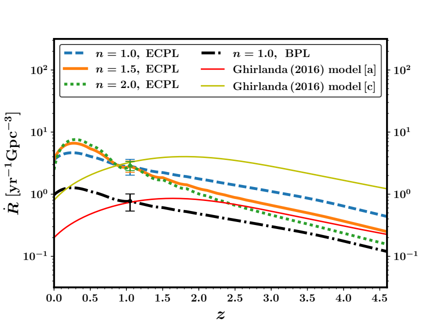
- $\nu_1$ loosely bound below
- $\nu_2 \sim 1.85$; $L_{\rm b} \sim 1.50$
- consistent with 68% HDIs of G16
- no $z$-dependence

## ECPL

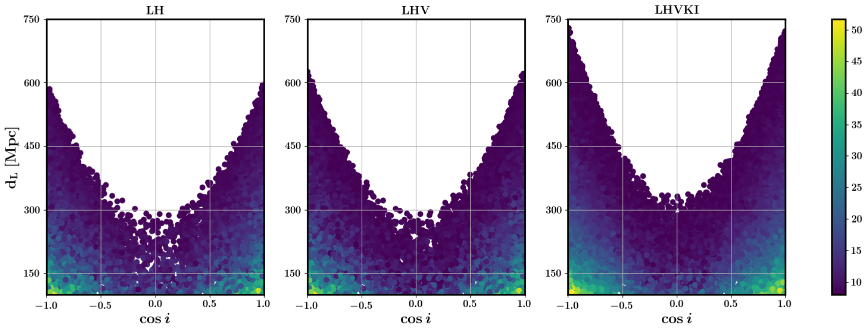
- $L_{\rm b}$ loosely bound above
- $\nu \sim 0.65$
- both $\sim$ same for long GRBs
- no $z$-dependence

# Formation rate

| Reference | $\dot{R}(0)$ [$\mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$] |
|---|---|
| Ghirlanda et al. (2016), model [a] | 0.13-0.24 |
| Guetta & Piran (2005) | 0.1-0.8 |
| Yonetoku et al. (2014) | 0.24-0.94 |
| Ghirlanda et al. (2016), model [c] | 0.65-1.10 |
| present work | 0.61-3.89 |
| Coward et al. (2012) | 5-13 |
| Guetta & Piran (2006) | 8-30 |

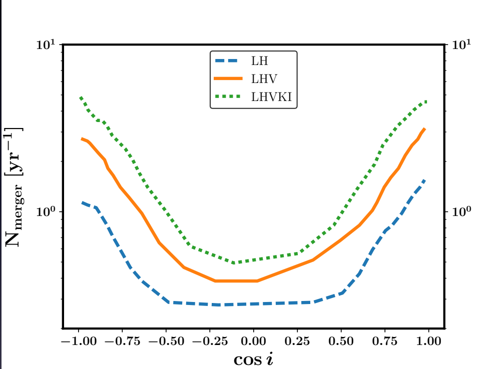


# Binary neutron star merger (BNSM) rate – aLIGO/VIRGO




Saleem+'18

# Binary neutron star merger (BNSM) rate – aLIGO/VIRGO




- **lower limits** [$\rm yr^{-1}$]: LH: 0.95; LHV: 1.87; LHVKI: 3.11.
- Inferred rate from GW/EM170817: $1\,\rm yr^{-1} \implies \gtrsim 2\,\rm yr^{-1}$ from the next observing runs.

# True sGRB and BNSM rates

- $f_{\rm B} = 1 - \cos\theta_j$, where $\theta_j$ is the jet opening angle.
- $\theta_j = $ 3-26$^\circ$ (Margutti+'12; Fong+ '12, '15).
- sGRB formation rate, $R_0 = \frac{\dot{R}(0)}{f_{\rm B}} = $ 6-2838 $\rm yr^{-1} Gpc^{-3}$.
- Abbott+'17e: BNSMr $=$ 320-4740 $\rm yr^{-1} Gpc^{-3}$.
- Each BNSM creates a sGRB : allowed.

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- Abbott+'17e: BNSMr = 320-4740 $\mathrm{yr^{-1}Gpc^{-3}}$.
- Each BNSM creates a sGRB : allowed.
- However, slight tension...
- What could it imply? Choked jets (Kasliwal+'17).

# *AstroSat*-CZTI

**Prediction**: 14-42 $\mathrm{yr}^{-1}$.

**Observed**: $\sim$ 36* in 2 yr.

* Subjective:
initial triggered searches by Vidushi Sharma +
latter systematic searches by Ajay Ratheesh
[Feb’16 – Oct’17].

**Publicly available tool for any new instrument.**

*Daksha* (proposal accepted by ISRO):

- Soft [1-10 keV]: 11-12 $\mathrm{yr}^{-1}$.
- Hard [20-200 keV]: 34-35 $\mathrm{yr}^{-1}$.

# Thank You!

# Review: Ghirlanda+'16

- $P$, $F$ (fluence), $T_{90}$, $E_p$ from *Fermi*;
- D'Avanzo+'14 "flux-complete" *Swift* sample: $z$, $L_{iso}$, $E_{iso}$.
- Assumptions:
  - Short GRB lightcurve = triangle.
  - Amati correlation and Yonetoku correlation – parametrized.
  - Progenitor rate – parametrized.
- Rules out SPL for $\nu > 2$.

# The star formation rate is delayed...

$$\dot{R} = f_{\mathrm{B}}\, C\, \Psi,$$

where

$$\Psi(z) = \int_{z_{\mathrm{min}}(z)}^{\infty} \dot{\rho}_{\star}(z')\, P\left(\tau[z, z']\right) \frac{d\tau}{dz'} dz',$$

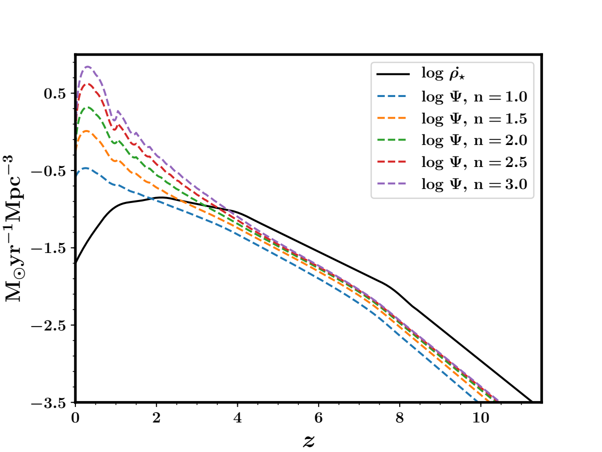
$$\tau[z, z'] = t_{\mathrm{age}}(z) - t_{\mathrm{age}}(z'),$$

$z_{\mathrm{min}}(z)$ given by

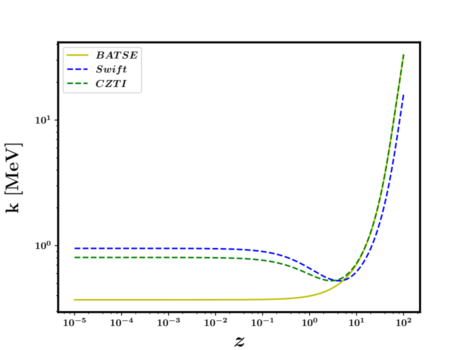
$$t_{\mathrm{age}}(z) - t_{\mathrm{age}}(z_{\mathrm{min}}) = \tau_{\mathrm{min}}.$$

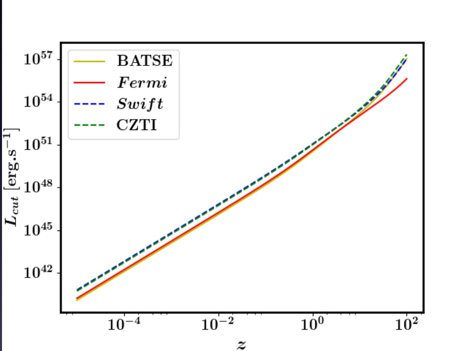
# ...to the GRB formation rate

$$P(\tau) = \tau^{-n}$$

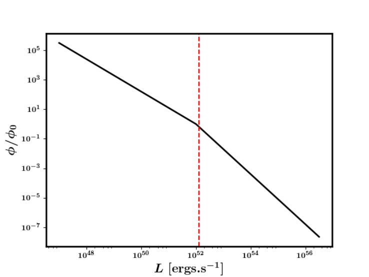


# $k(z)$ and $L_c(z)$



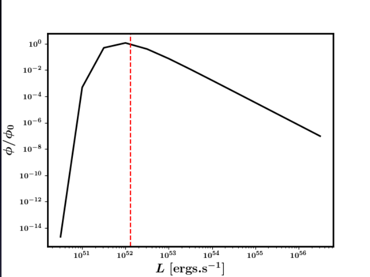



# Models tested against data




**B**roken **P**ower**L**aw (BPL):

$$\Phi(L) = \Phi_0 \begin{cases} \left(\frac{L}{L_\mathrm{b}}\right)^{-\nu_1}, & L \leq L_\mathrm{b} \\ \left(\frac{L}{L_\mathrm{b}}\right)^{-\nu_2}, & L > L_\mathrm{b}. \end{cases}$$




**E**xponential-**C**utoff **P**ower**L**aw (ECPL):

$$\Phi_z(L) = \Phi_0 \left(\frac{L}{L_\mathrm{b}}\right)^{-\nu} \exp\left[-\left(\frac{L}{L_\mathrm{b}}\right)\right]$$

# Fits: SPL details

| $n$ | parameters | BATSE | *Fermi* | *Swift* |
|---|---|---|---|---|
| 1.0 | $\nu$ | 1.121 | 1.232 | 1.374 |
| | $\chi^2_{\text{red}}$ | 233.1 | 26.5 | 10.1 |
| 1.5 | $\nu$ | 1.103 | 1.198 | 1.331 |
| | $\chi^2_{\text{red}}$ | 276.5 | 35.4 | 10.9 |
| 2.0 | $\nu$ | 1.094 | 1.184 | 1.314 |
| | $\chi^2_{\text{red}}$ | 300.6 | 39.4 | 11.2 |

- Simple Power Law model **ruled out for all $\nu$**,
- against claim of Yonetoku+'14 [$\nu = 1$],
- extending Ghirlanda+'16 [$\nu > 2$ ruled out].

# Fits: BPL details

| $n$ | parameters | | *Fermi* | *Swift* | BATSE |
|---|---|---|---|---|---|
| 1.0 | $\nu_1$ | $0.48^{+0.22}_{-0.48}$ | | | |
| | $\nu_2$ | $1.86^{+1.08}_{-0.20}$ | | | |
| | $L_b$ | $1.52^{+1.58}_{-0.67}$ | | | |
| | $\Gamma$ | | 0.00 | 0.00 | $0.17^{+0.05}_{-0.05}$ |
| | $\chi^2_{red}$ | | 0.10 | 0.42 | 1.09 |
| 1.5 | $\nu_1$ | $0.38^{+0.23}_{-0.38}$ | | | |
| | $\nu_2$ | $1.85^{+1.04}_{-0.19}$ | | | |
| | $L_b$ | $1.46^{+1.36}_{-0.62}$ | | | |
| | $\Gamma$ | | 0.00 | 0.00 | $0.16^{+0.04}_{-0.05}$ |
| | $\chi^2_{red}$ | | 0.10 | 0.39 | 1.09 |
| 2.0 | $\nu_1$ | $0.34^{+0.23}_{-0.34}$ | | | |
| | $\nu_2$ | $1.85^{+1.03}_{-0.19}$ | | | |
| | $L_b$ | $1.45^{+1.32}_{-0.60}$ | | | |
| | $\Gamma$ | | 0.00 | 0.00 | $0.15^{+0.04}_{-0.05}$ |
| | $\chi^2_{red}$ | | 0.10 | 0.39 | 1.09 |

- $\nu_1$ loosely bound below
- $\nu_2 \sim 1.85$; $L_b \sim 1.50$
- $\nu_2$, $L_b$ independent of $n$
- no $z$-dependence
- consistent with 68% HDIs of Ghirlanda+'16

Cannot be distinguished with ECPL.

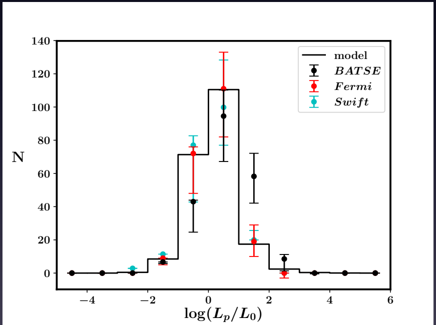
# Fits: ECPL details

| $n$ | parameters | | *Fermi* | *Swift* | BATSE |
|---|---|---|---|---|---|
| 1.0 | $\nu$ | $0.71^{+0.05}_{-0.36}$ | | | |
| | $L_b$ | $7.42^{+7.21}_{-1.96}$ | | | |
| | $\Gamma$ | | 0.00 | 0.00 | $0.41^{+0.15}_{-0.12}$ |
| | $\chi^2_{red}$ | | 0.31 | 0.21 | 0.75 |
| 1.5 | $\nu$ | $0.64^{+0.05}_{-0.39}$ | | | |
| | $L_b$ | $6.84^{+6.73}_{-1.58}$ | | | |
| | $\Gamma$ | | 0.00 | 0.00 | $0.38^{+0.13}_{-0.10}$ |
| | $\chi^2_{red}$ | | 0.39 | 0.19 | 0.82 |
| 2.0 | $\nu$ | $0.60^{+0.05}_{-0.38}$ | | | |
| | $L_b$ | $6.61^{+6.09}_{-1.53}$ | | | |
| | $\Gamma$ | | 0.00 | 0.00 | $0.36^{+0.12}_{-0.09}$ |
| | $\chi^2_{red}$ | | 0.41 | 0.19 | 0.84 |

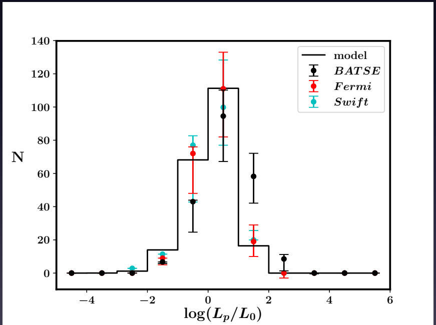
- generally over-fit
- $L_b$ loosely bound above
- $\nu \sim 0.65$
- both $\sim$ same for lGRBs!
- no $z$-dependence

# Fits: BPL & ECPL

$$\mathrm{d}N \equiv T\,\Delta\Omega \times D(L,z) \times \dot{R}(z)\mathrm{d}V \times \Phi(L)\mathrm{d}L; \quad D(L,z) \propto P^{\Gamma}.$$




**B**roken **P**ower**L**aw (BPL)



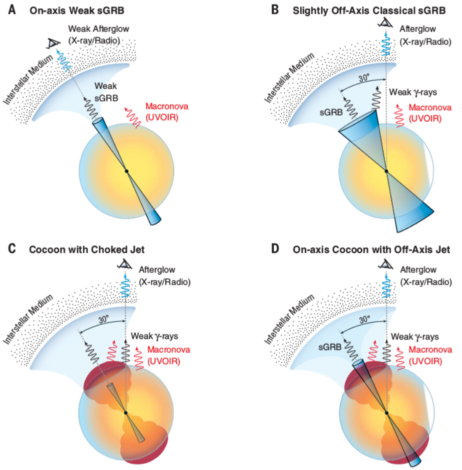

**E**xponential-**C**utoff **P**ower**L**aw (ECPL)

# Formation efficiency

| $n$ | model | $f_{\rm B} C(0)$ $[10^{-9}\,{\rm M}_\odot^{-1}]$ | $\dot{R}(0)$ $[{\rm yr}^{-1}{\rm Gpc}^{-3}]$ |
|---|---|---|---|
| 1.0 | ECPL | $13.7^{+1.2}_{-3.9}$ | 0.68-3.89 |
| | BPL | $3.74^{+3.76}_{-1.15}$ | |
| 1.5 | ECPL | $6.45^{+0.39}_{-1.32}$ | 0.82-3.80 |
| | BPL | $2.05^{+1.73}_{-0.58}$ | |
| 2.0 | ECPL | $3.65^{+0.26}_{-0.61}$ | 0.61-2.66 |
| | BPL | $1.23^{+0.94}_{-0.34}$ | |

# Choked jets...?

**Fig. 5. Model schematics considered in this paper.** In each panel, the eye indicates the line of sight to the observer. (**A**) A classical, on-axis, ultrarelativistic, weak short-hard gamma-ray burst (sGRB). (**B**) A classical, slightly off-axis, ultrarelativistic, strong sGRB. (**C**) A wide-angle, mildly relativistic, strong cocoon with a choked jet. (**D**) A wide-angle, mildly relativistic, weak cocoon with a successful off-axis jet.




Kasliwal+'17