Study of the time delay between star formation and short gamma-ray bursts

in a hierarchical Bayesian framework

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LIÈGE université
STAR Institute

SGRB redshift distribution

- Convolution between cosmic star formation history (CSFR) and time delay distribution (DTD)
  - Fixed star formation history parameters (Madau & Fragos 2017)

$$\dot{\rho}(z, \vec{\lambda}'_{\rm pop}) \propto \int_z^\infty \psi(z) P\left(t(z) - t(z')|\vec{\lambda}'_{\rm pop}\right) \frac{{\rm d}t}{{\rm d}z'} {\rm d}z'$$

$$\psi(z) \propto \frac{(1+z)^{a_\psi}}{1 + \left(\frac{1+z}{1+z_\psi}\right)^{b_\psi}}$$

$\tau_d = t(z) - t(z')$

Power-law with minimum time delay

$$P(\tau_d|\vec{\lambda}'_{\rm pop}) \propto \begin{cases} 0\,, & \tau_d < \tau_d^{\rm min} \\ \tau_d^{-\alpha_t}, & \tau_d \geq \tau_d^{\rm min} \end{cases}$$

Log-normal distribution

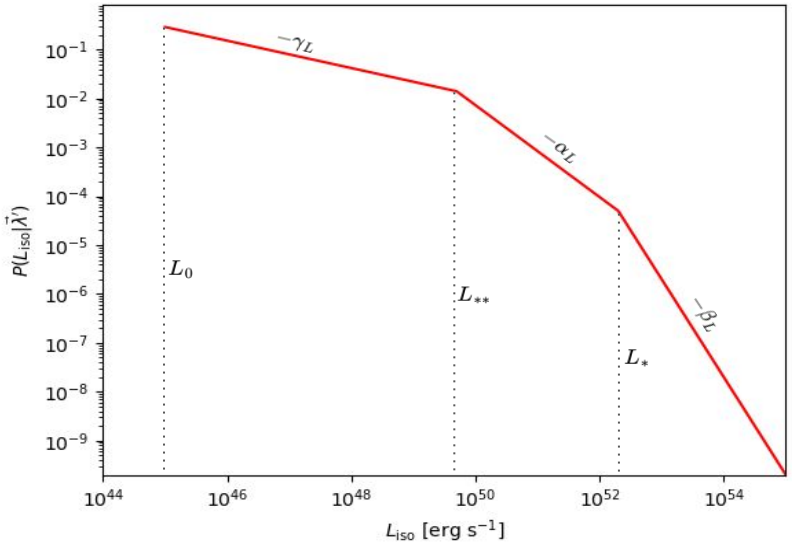
$$P(\tau_d|\vec{\lambda}'_{\rm pop}) = \exp\left[-\frac{1}{2}\left(\frac{\ln \tau_d - \ln \mu_t}{\sigma_t}\right)^2\right](\tau_d\sqrt{2\pi\sigma_t^2})^{-1}$$

$$P(z|\vec{\lambda}'_{\rm pop}, R_0) \propto \frac{\dot{\rho}(z, \vec{\lambda}'_{\rm pop}, R_0)}{1+z}\frac{dV}{dz}$$

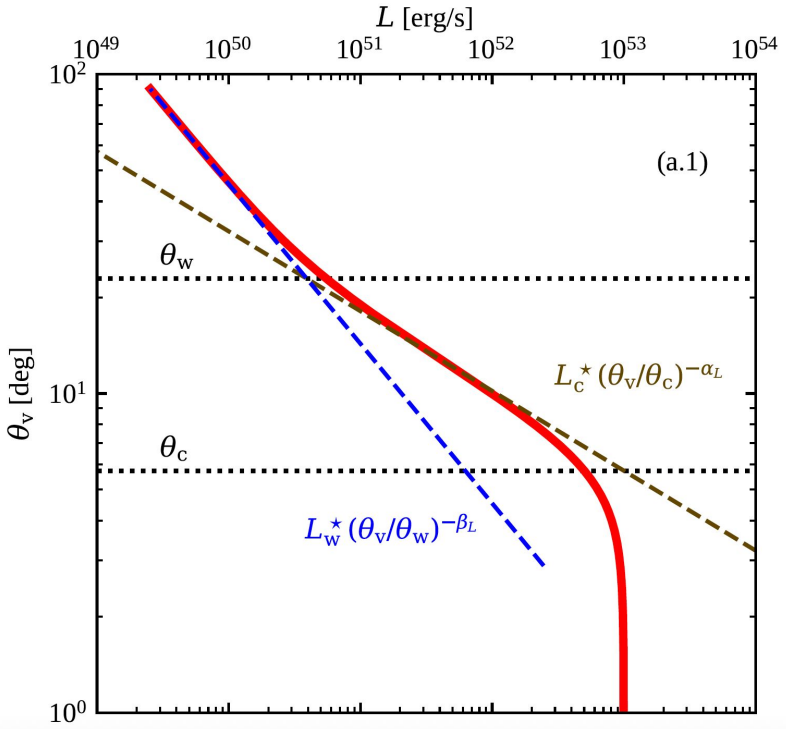
Luminosity distribution models

Empirical broken power-law (BPL)

$$P(L|\vec{\lambda}'_{\rm pop}) \propto \begin{cases} 0, & L < L_0 \\ \left(\frac{L}{L_{**}}\right)^{-\gamma_L-1}\left(\frac{L_{**}}{L_*}\right)^{-\alpha_L-1}, & L_0 \le L \le L_{**} \\ \left(\frac{L}{L_*}\right)^{-\alpha_L-1}, & L_{**} < L \le L_* \\ \left(\frac{L}{L_*}\right)^{-\beta_L-1}, & L > L_* \end{cases}$$



Quasi-universal jet structure (Jet)



Credit: Salafia et al. 2023

Hierarchical bayesian framework

From: Mandel I., Farr W. M., Gair J. R., “Extracting distribution parameters from multiple uncertain observations with selection biases”, 2019, MNRAS, 486, 1086

$$p(\vec{\lambda}_{\rm pop}|\{\vec{d}_i\}) = \frac{p(\{\vec{d}_i\}|\vec{\lambda}_{\rm pop})\pi(\vec{\lambda}_{\rm pop})}{p(\{\vec{d}_i\})}$$

Likelihood of having measured source parameters given “true” parameters

Likelihood for “true” source parameters

Poissonian probability distribution

$$p(\{\vec{d}_i\}|\vec{\lambda}_{\rm pop}) = \prod_{i=1}^{N_{\rm obs}} \frac{\int p(\vec{d}_i|\vec{\lambda}_{\rm src}) p_{\rm pop}(\vec{\lambda}_{\rm src}|\vec{\lambda}'_{\rm pop}) {\rm d}\vec{\lambda}_{\rm src}}{\int p_{\rm det}(\vec{\lambda}_{\rm src}) p_{\rm pop}(\vec{\lambda}_{\rm src}|\vec{\lambda}'_{\rm pop}) {\rm d}\vec{\lambda}_{\rm src}} e^{-N_{\rm det}} (N_{\rm obs})^{N_{\rm det}}$$

Detection efficiency of the detector(s)

SGRB Samples

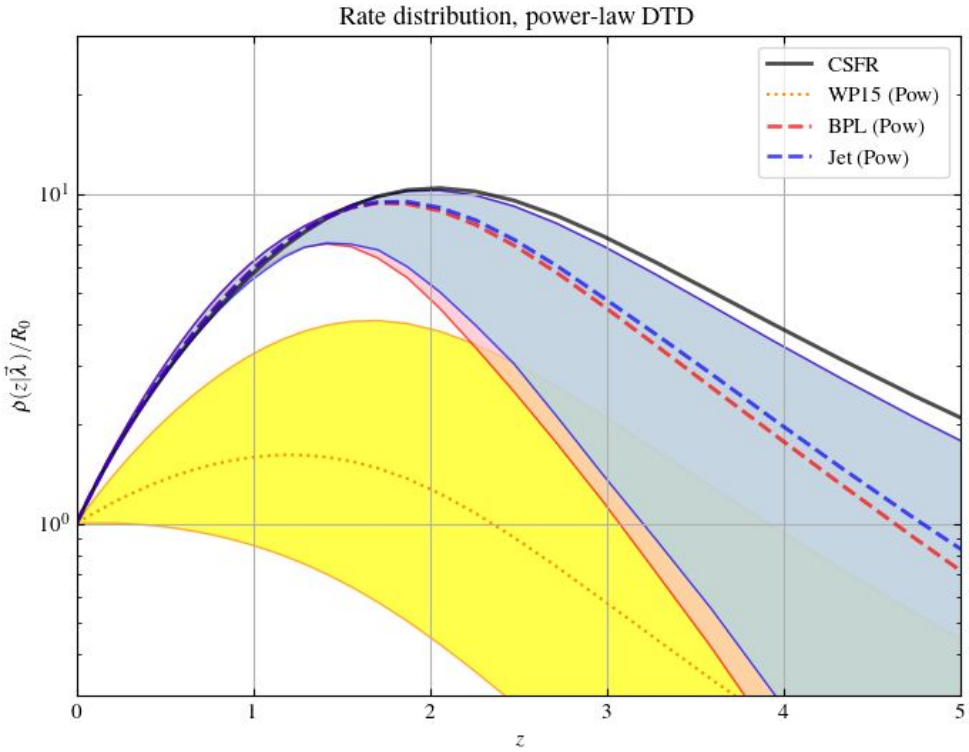
Following: Salafia O. S., Ravasio M. E., Ghirlanda G., Mandel I., “The short gamma-ray burst population in a quasi-universal jet scenario”, 2023, A&A, 680, A45

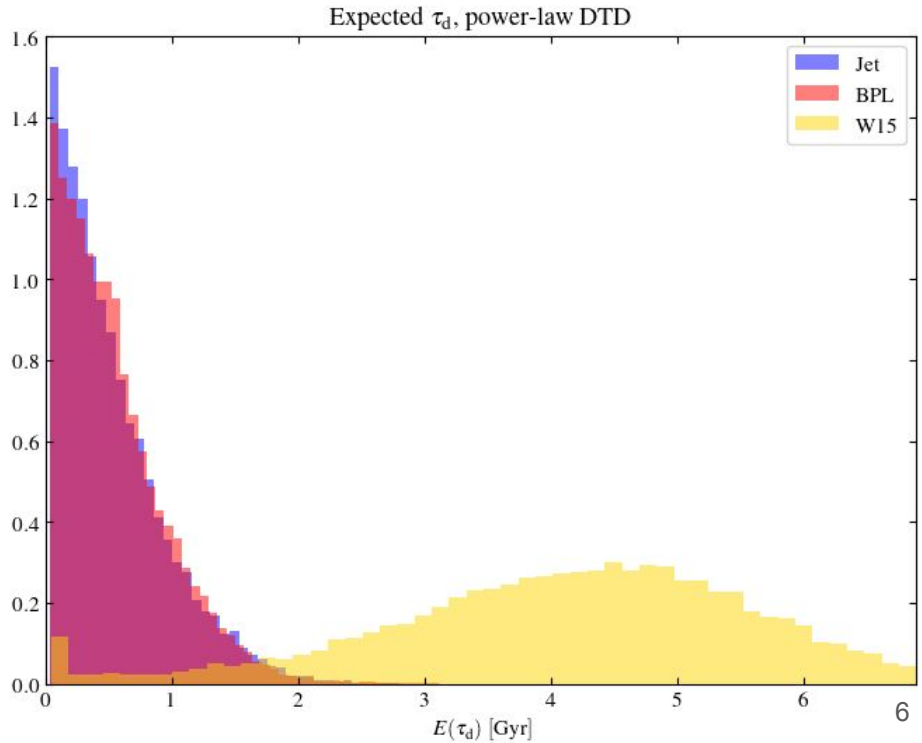
- SGRBs detected by Fermi/GBM in first 10 years of observations
  - Spectral peak photon energy available
  - Events with measured 64ms peak photon-flux above 3.5 cm^{-2} s^{-1}
    - Same as detector photon flux threshold
    - Sample complete in flux (210 events)
    - No GRB 170817A
- Measured redshift sample of Swift/BAT SGRBs jointly observed by Fermi/GBM
  - Selected SGRBs observed with favorable conditions (Ferro et al. 2023)
  - Sample highly complete in redshift
    - ~89% (16 over 18) of those SGRBs have measured redshift

Redshift distribution and time delays

- Power-law DTD favors time delays below 1 Gyr

$$E[\tau_{\rm d}|\vec{\lambda}'_{\rm pop}] = \int \tau_{\rm d} P(\tau_{\rm d}|\vec{\lambda}'_{\rm pop}) {\rm d}\tau_{\rm d}$$

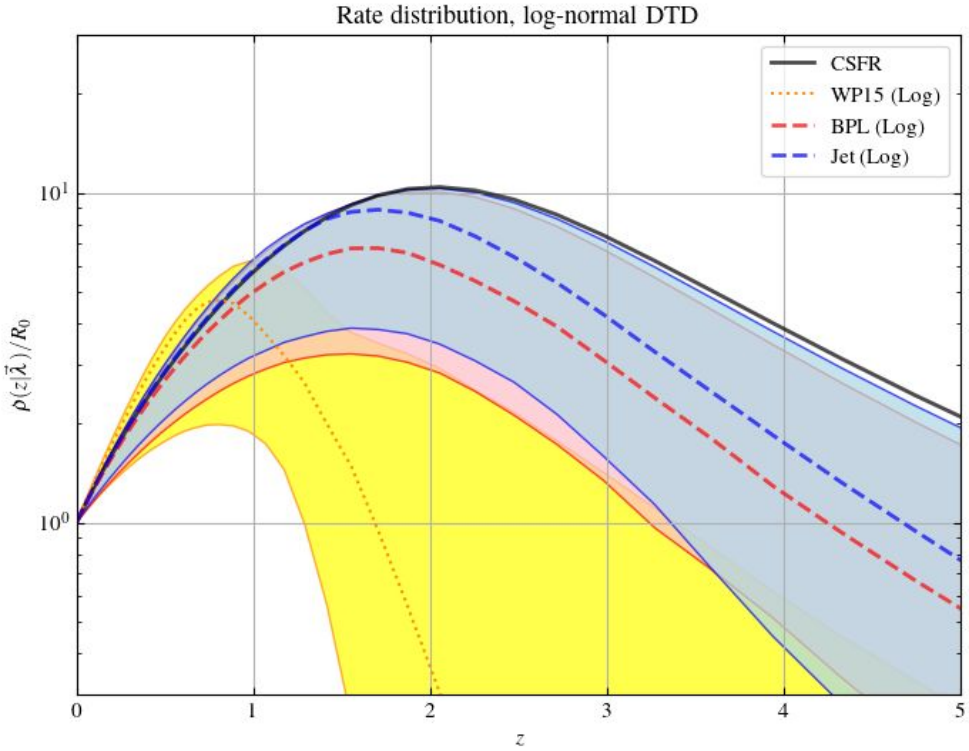


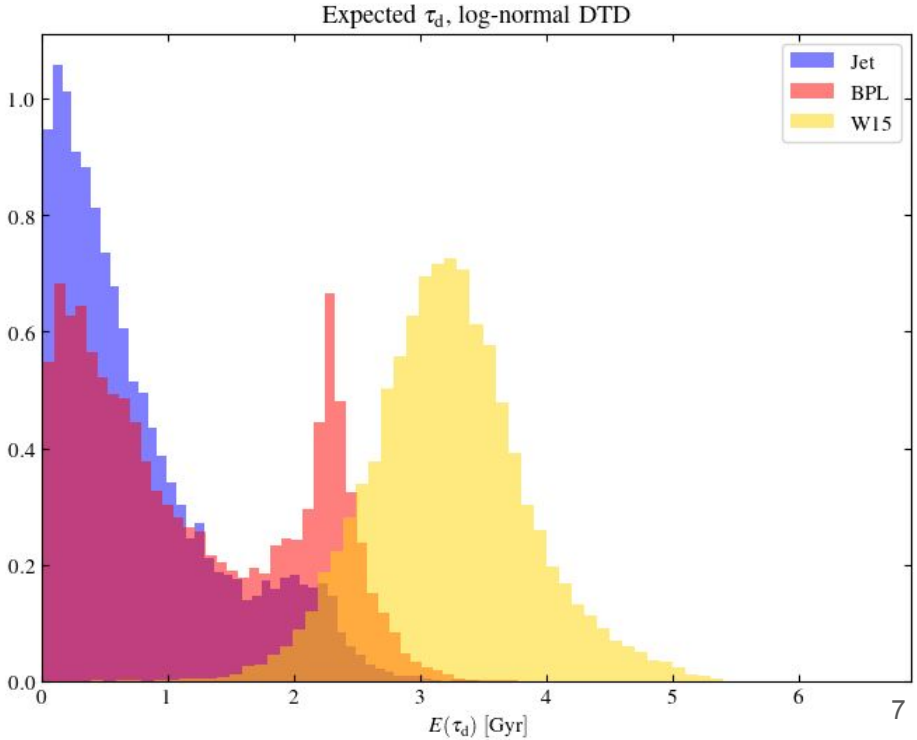


Redshift distribution and time delays

- Log-normal DTD allows for longer time delays

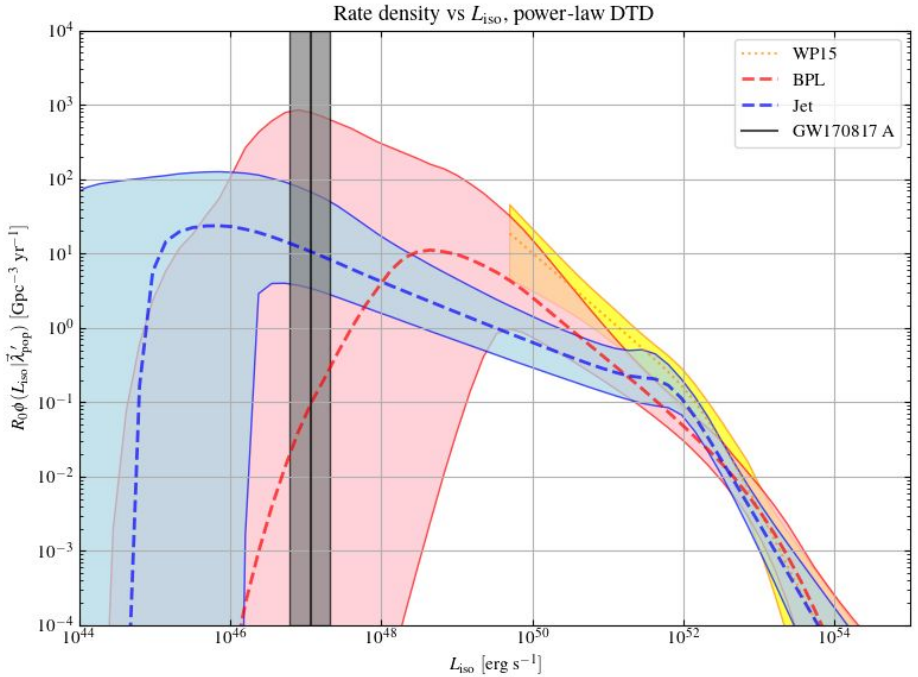
$$E[\tau_{\rm d}|\vec{\lambda}'_{\rm pop}] = \int \tau_{\rm d} P(\tau_{\rm d}|\vec{\lambda}'_{\rm pop}) {\rm d}\tau_{\rm d}$$

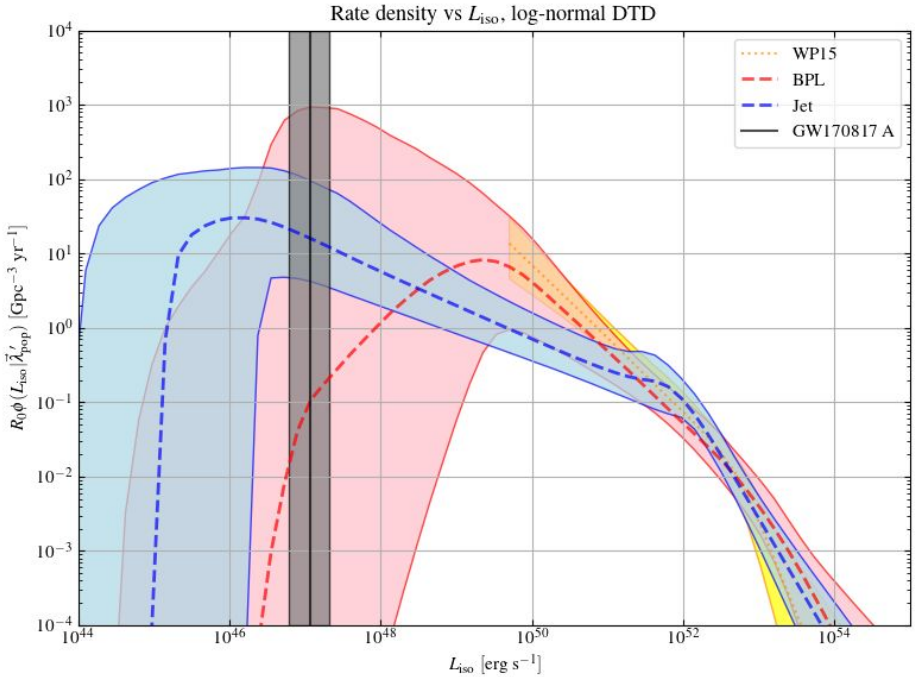




Luminosity distribution

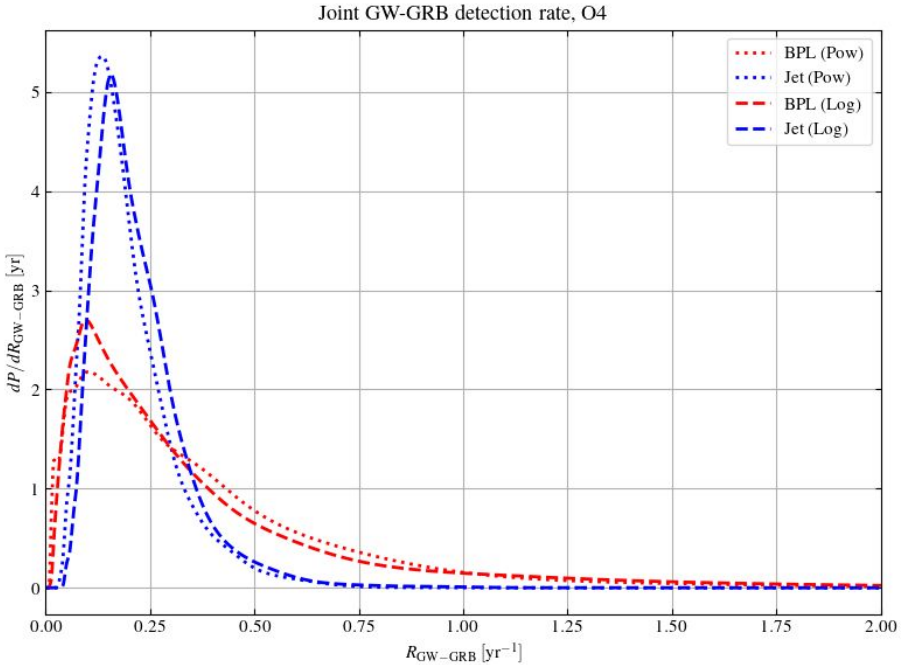
- Results in good agreement above L~10^{52} erg s^{-1}
- Rate uncertainty larger below L~10^{49} erg s^{-1}

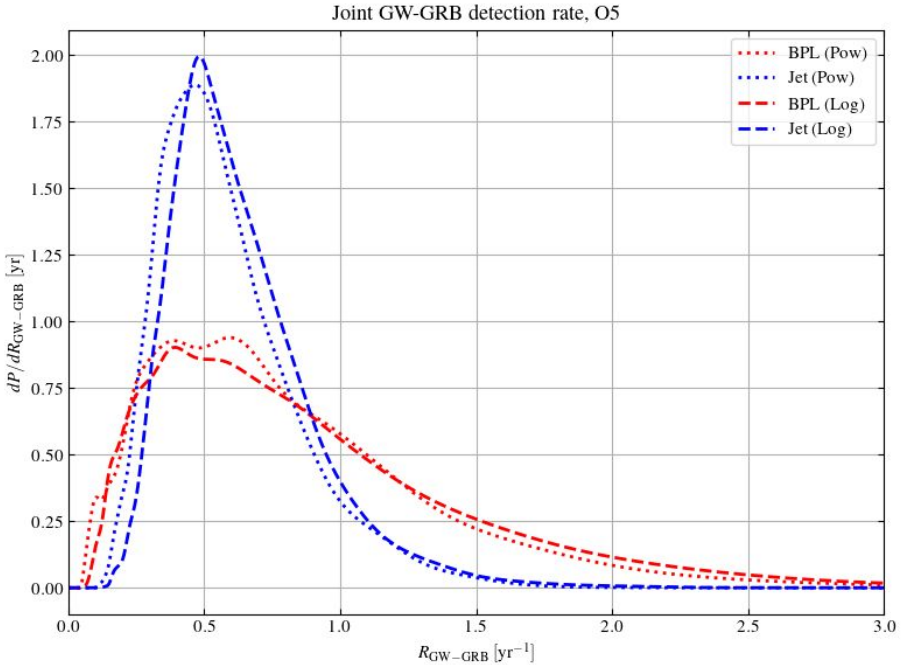




GW-GRB joint detection rates

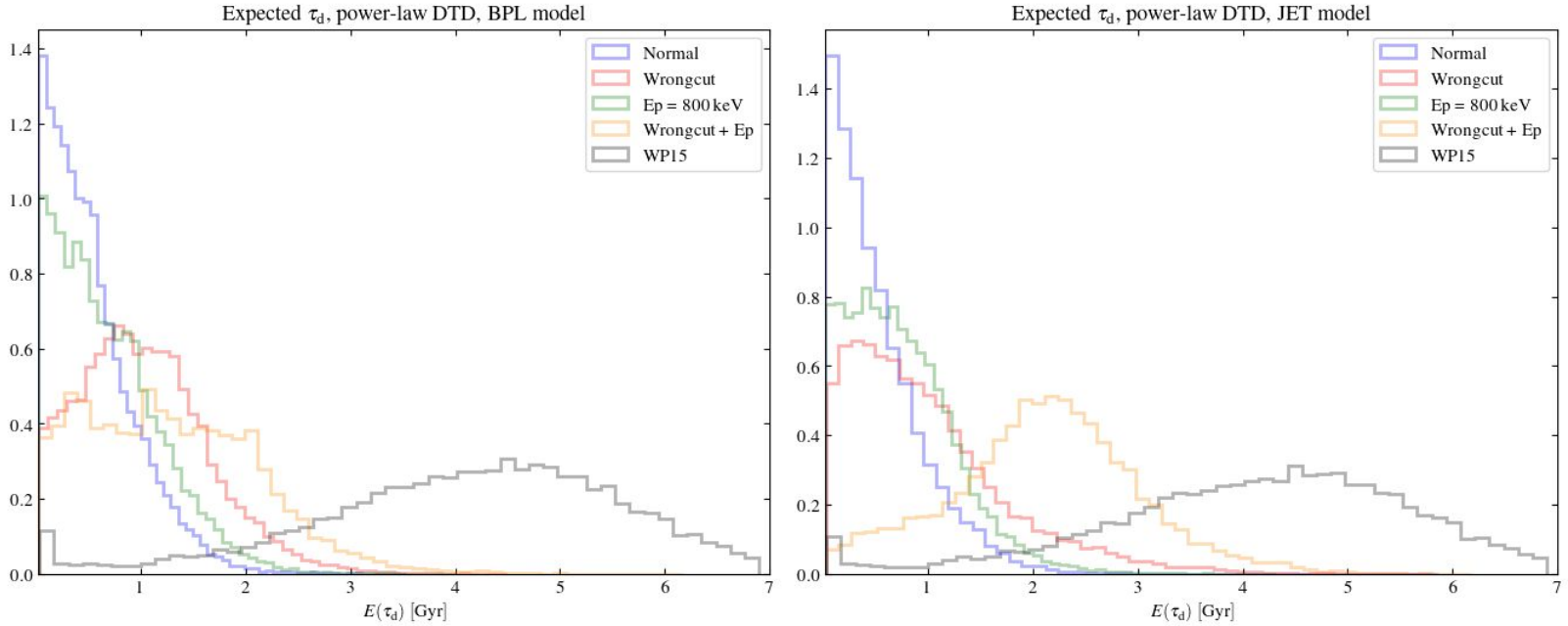
- LIGO-Virgo design sensitivity for O4 and O5
- Expecting 1 to 3 GW-GRB joint detections for O5!





Biases on expected time delays

- Incorrect modeling of selection effects can induce biases on time delay estimates
  - Photon flux threshold lower than completeness threshold
  - Spectral peak photon energy fixed to a single value



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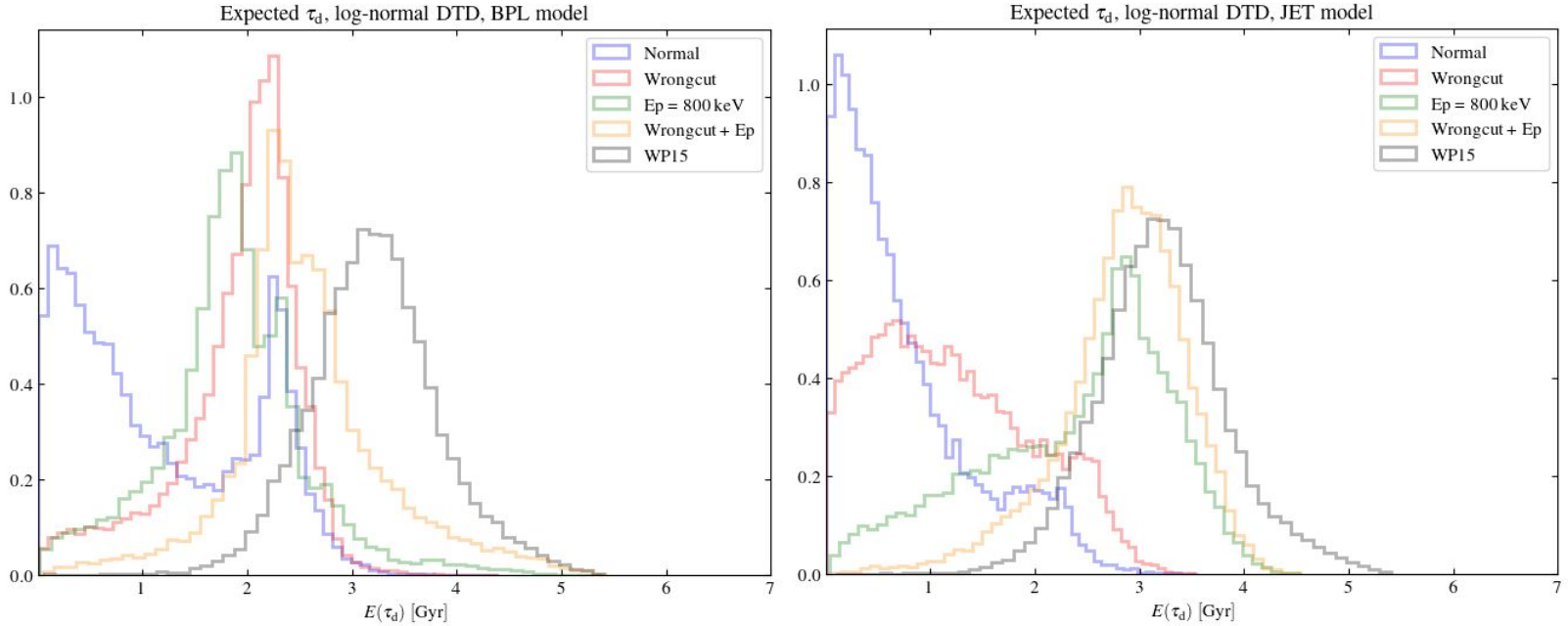


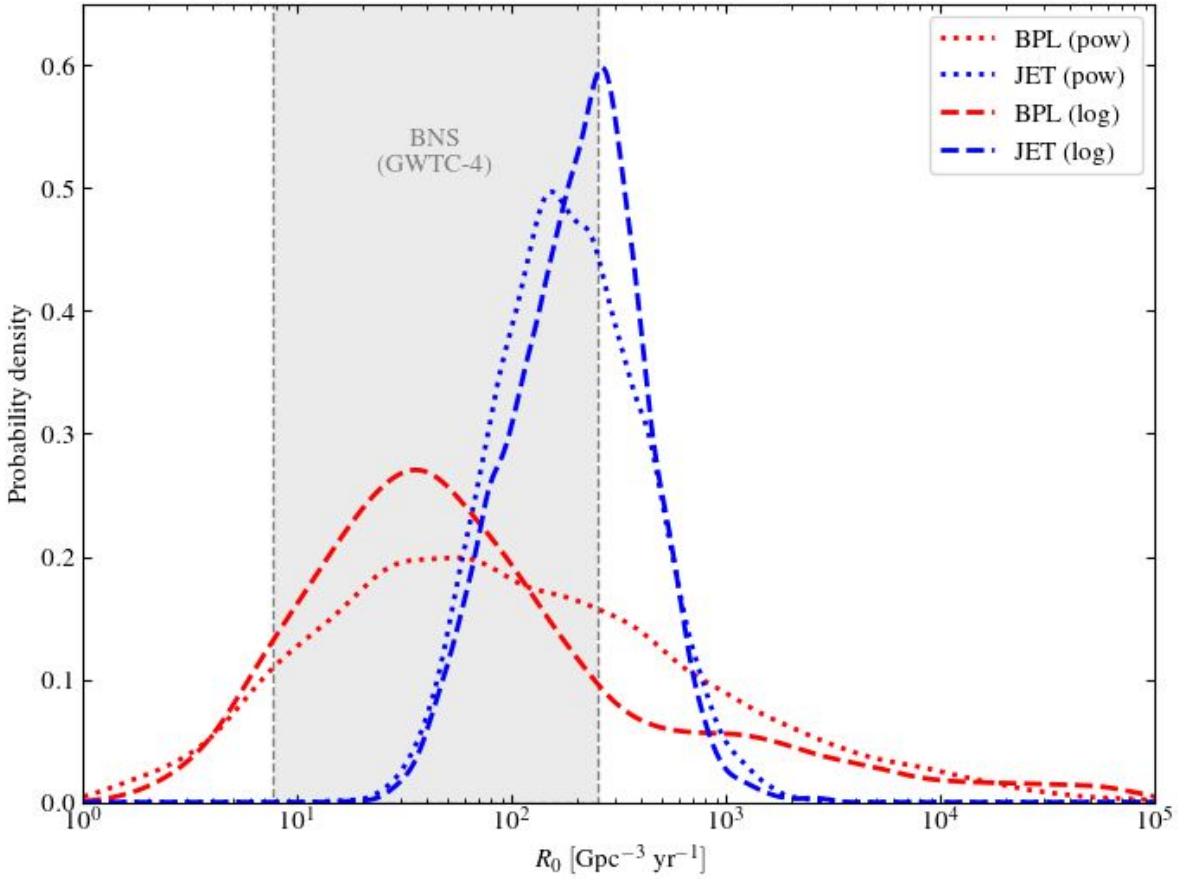
Conclusions

- Time delays between CSFR and SGRBs generally below 2 Gyr
  - Longer time delays with log-normal DTD model
- Incorrect modeling of selection effects might bring to a wrong estimate of time delays
  - Time delays generally longer when using a fixed peak photon spectral energy and/or a too low flux threshold
- We expect between 1 and 3 GW-GRB joint detections for O5!
- Paper in preparation!

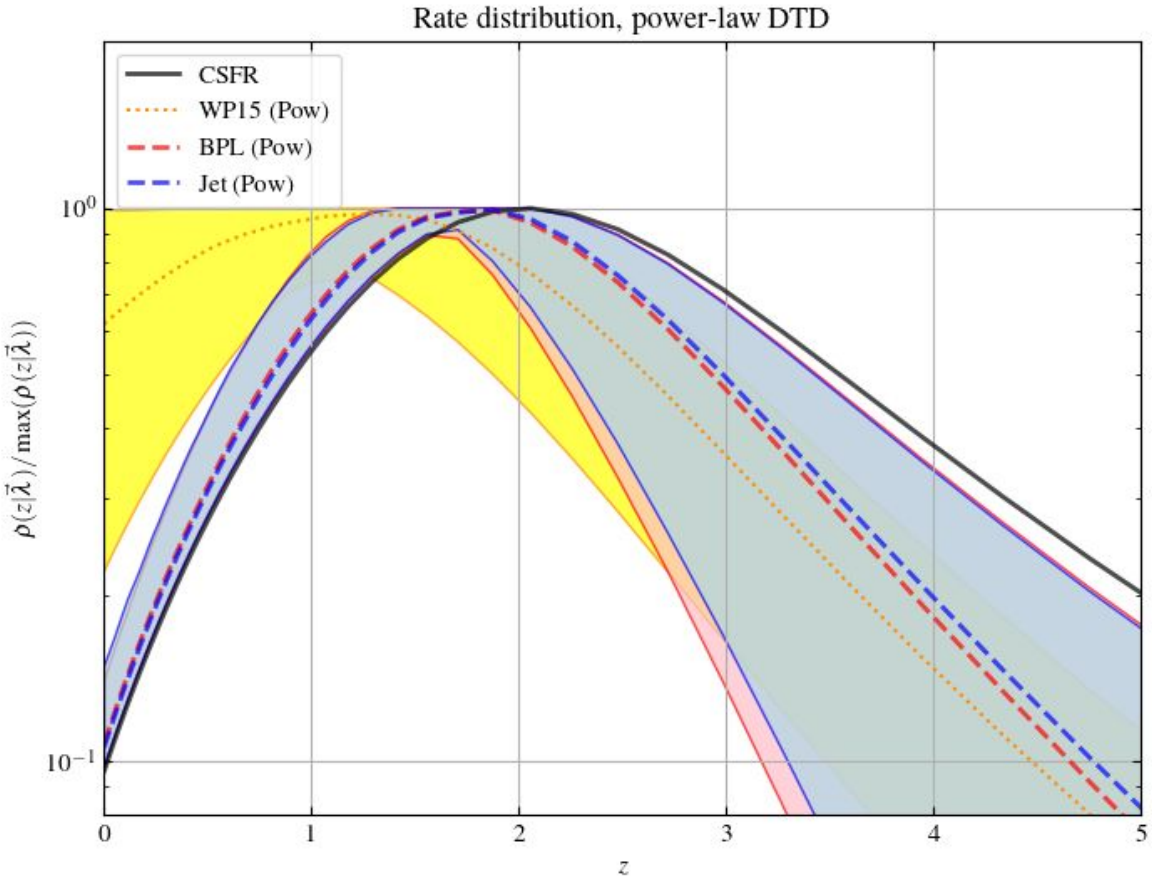
Thank you for your attention!

Backup Slides

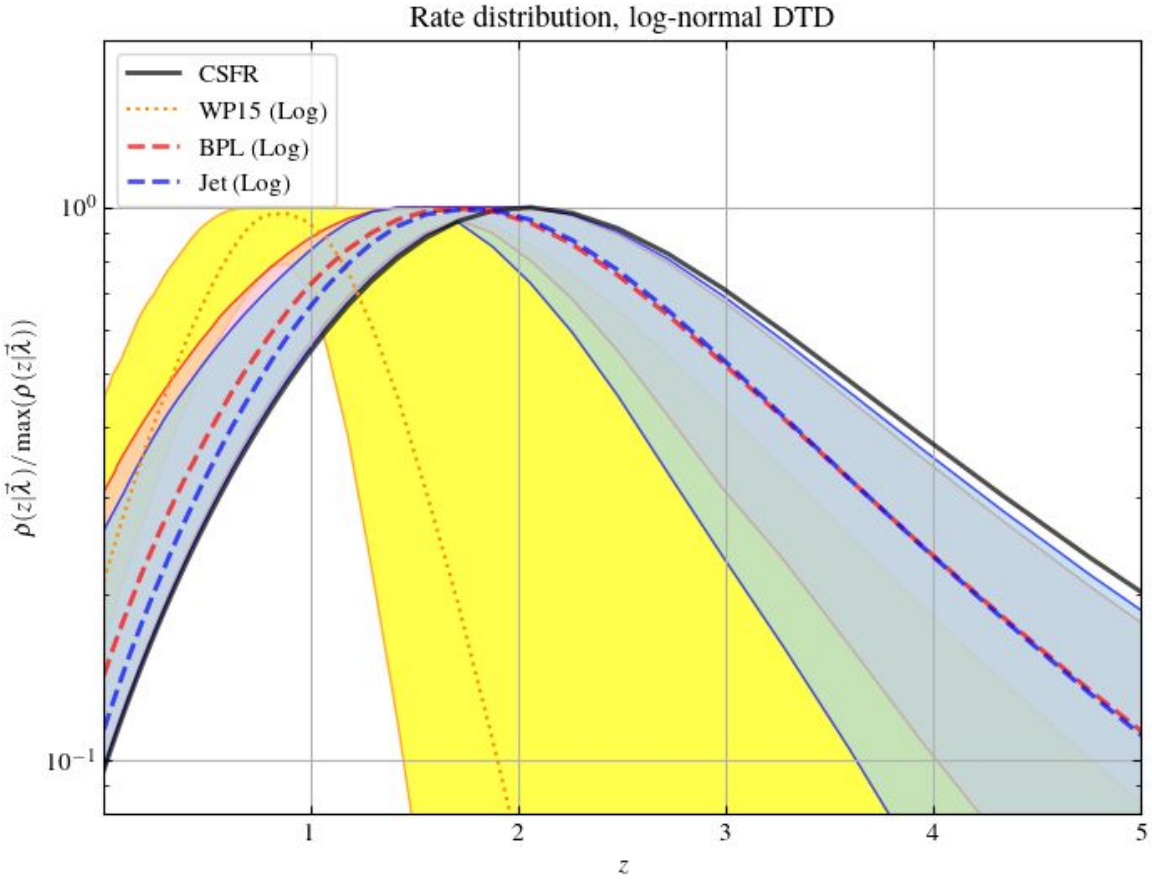
Local rate density



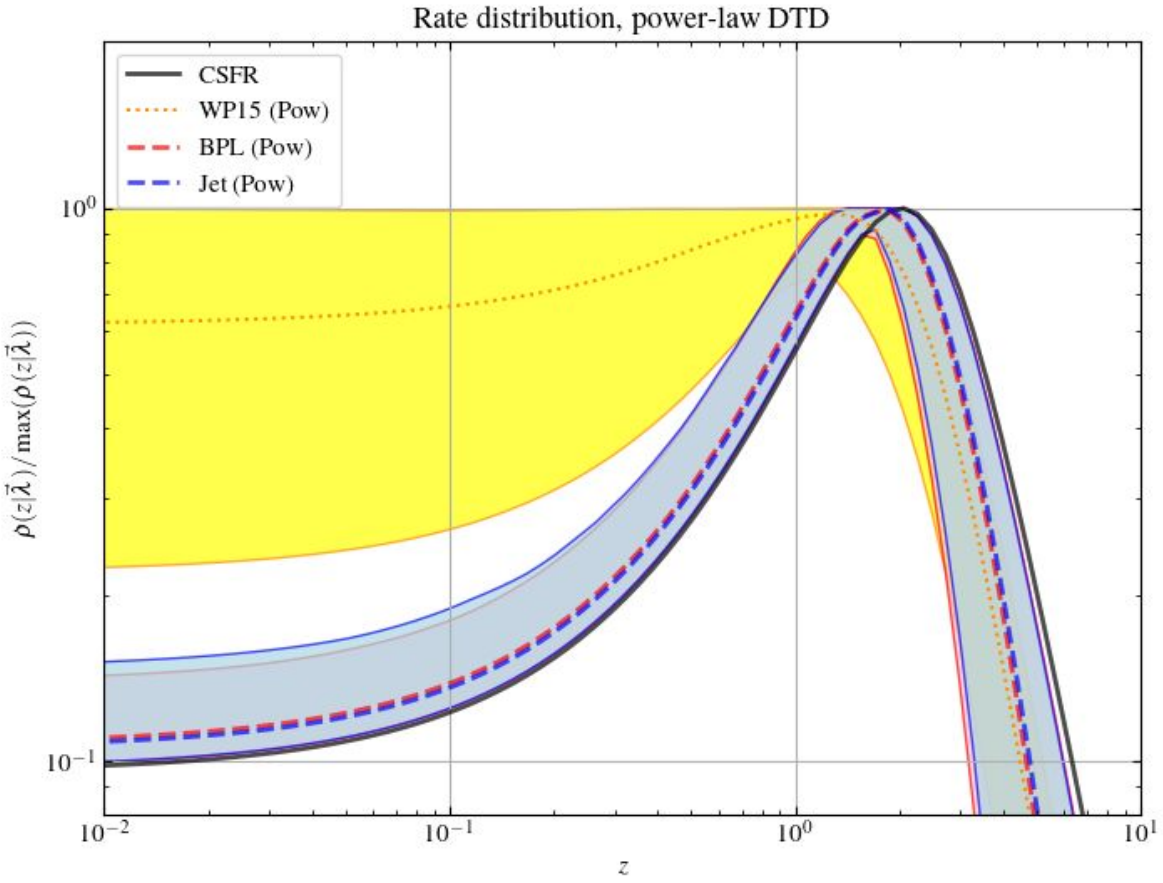
Rate curves normalized to peak (Pow)



Rate curves normalized to peak (Log)



Rate curves normalized to peak (Pow)



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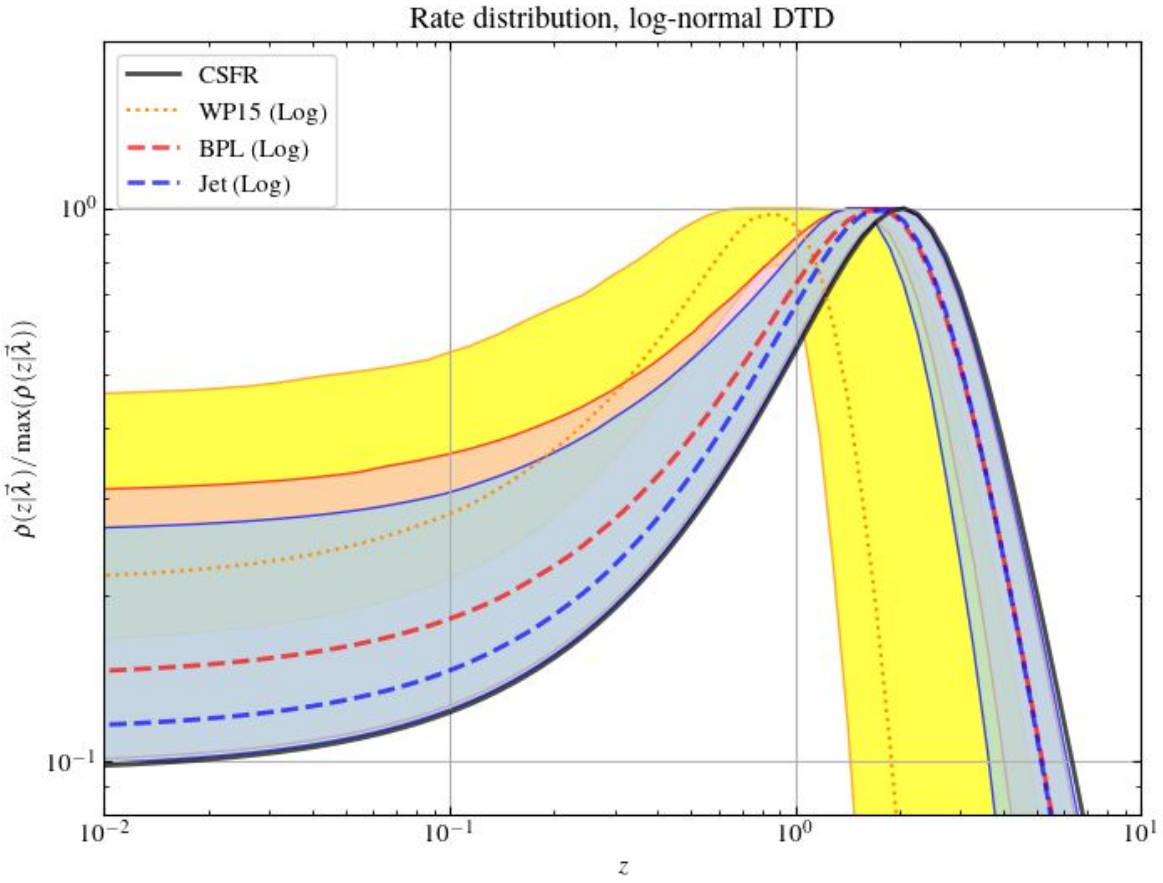
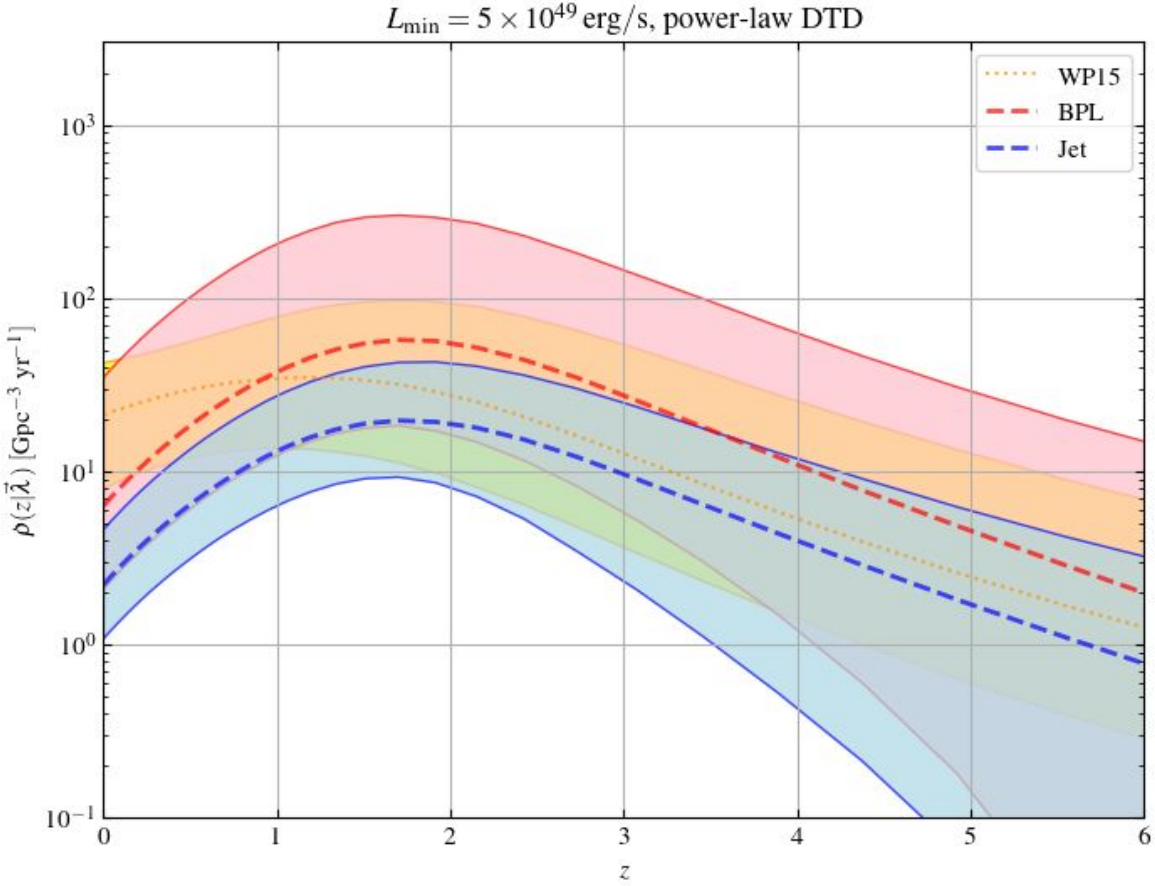


Redshift distribution



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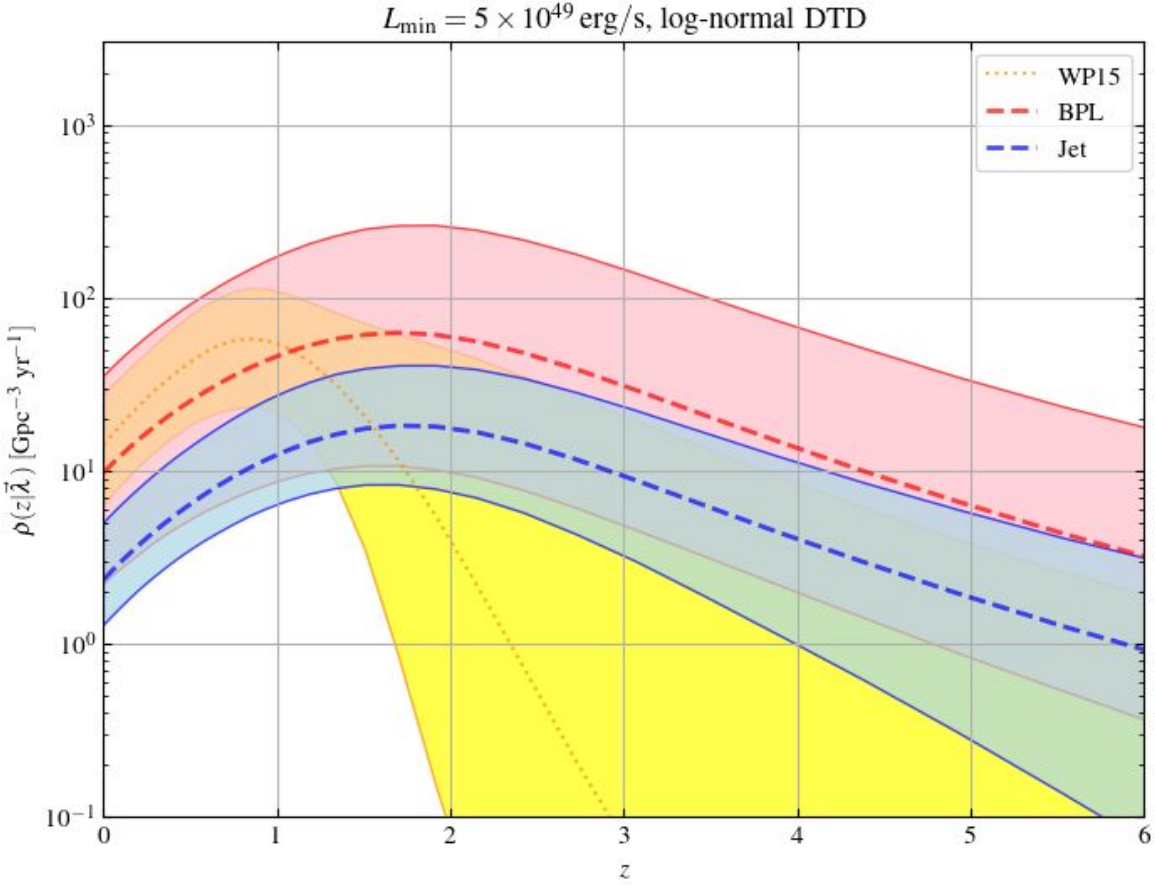
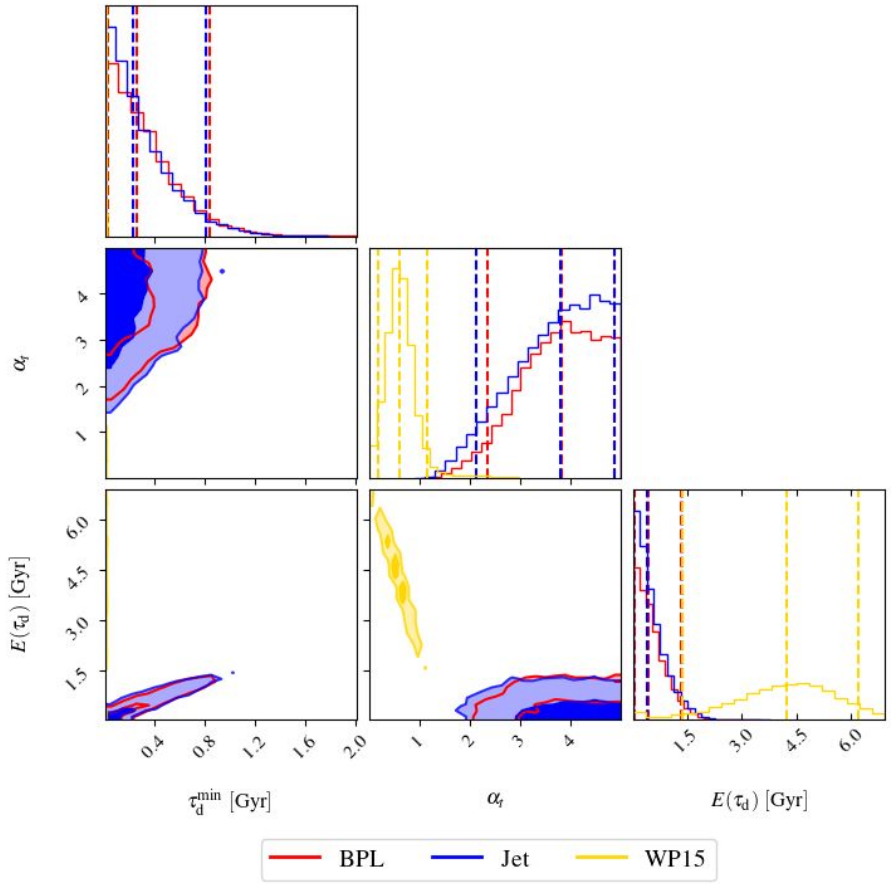


DTD parameters



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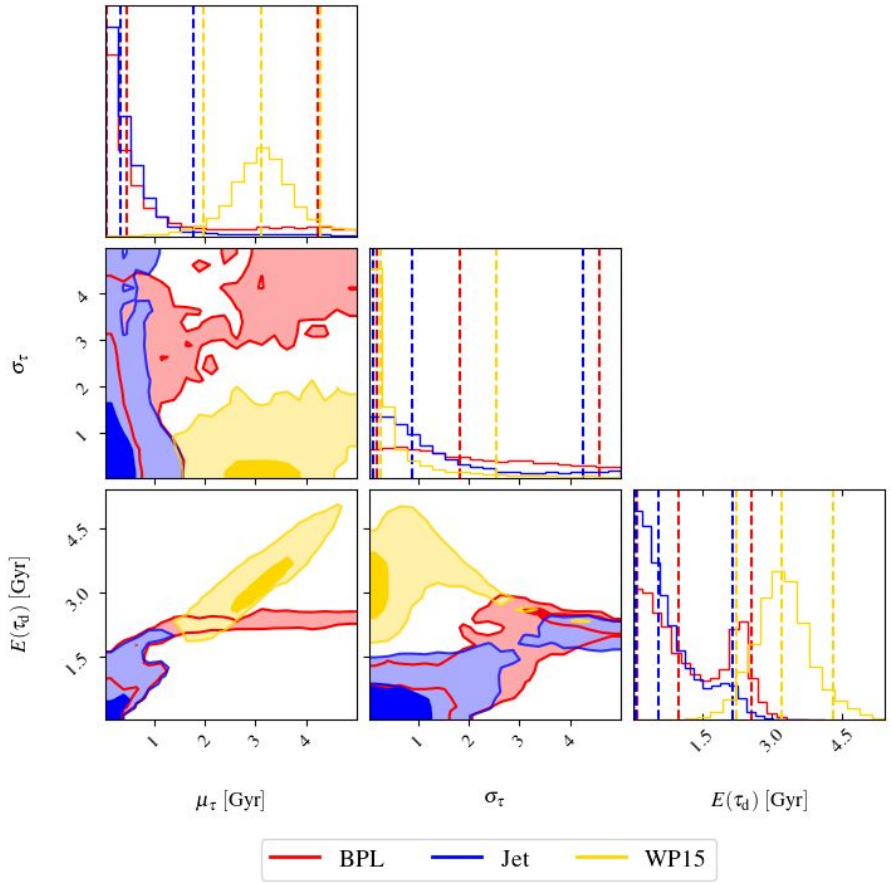
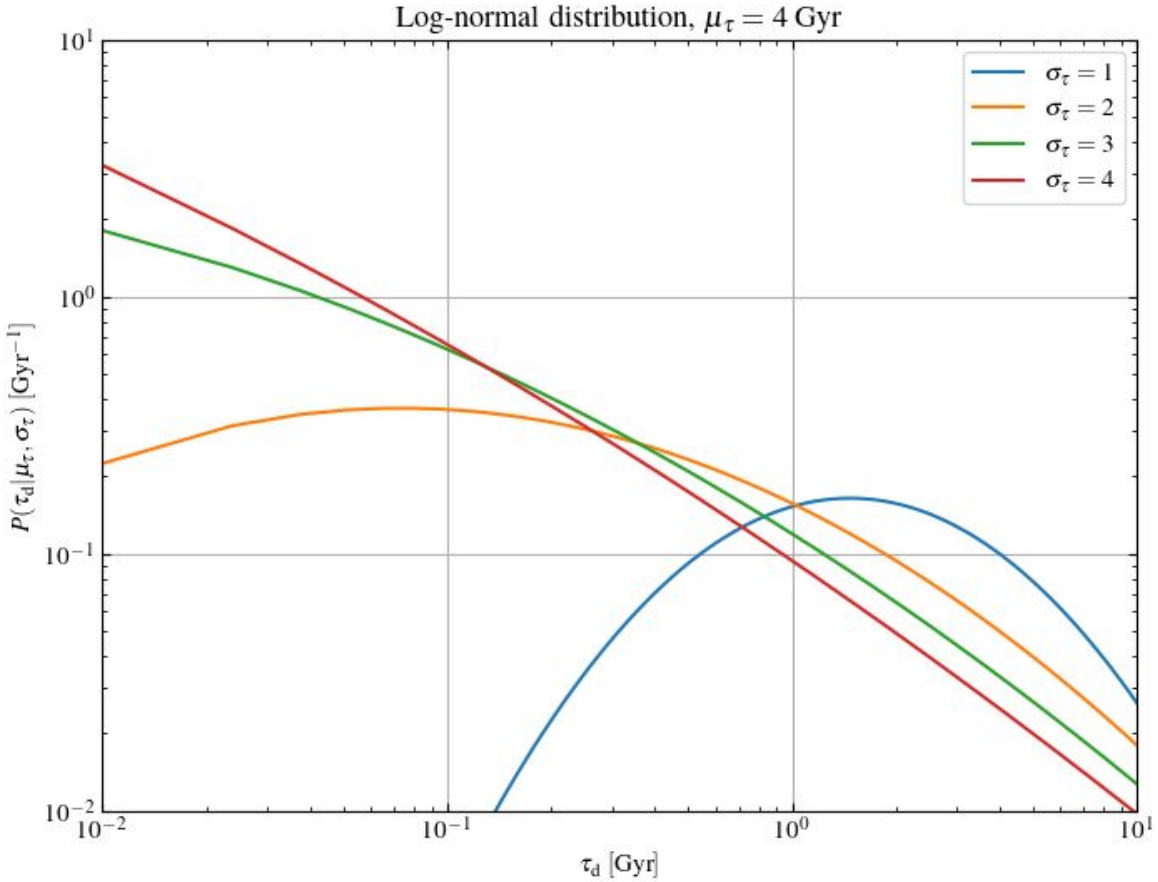
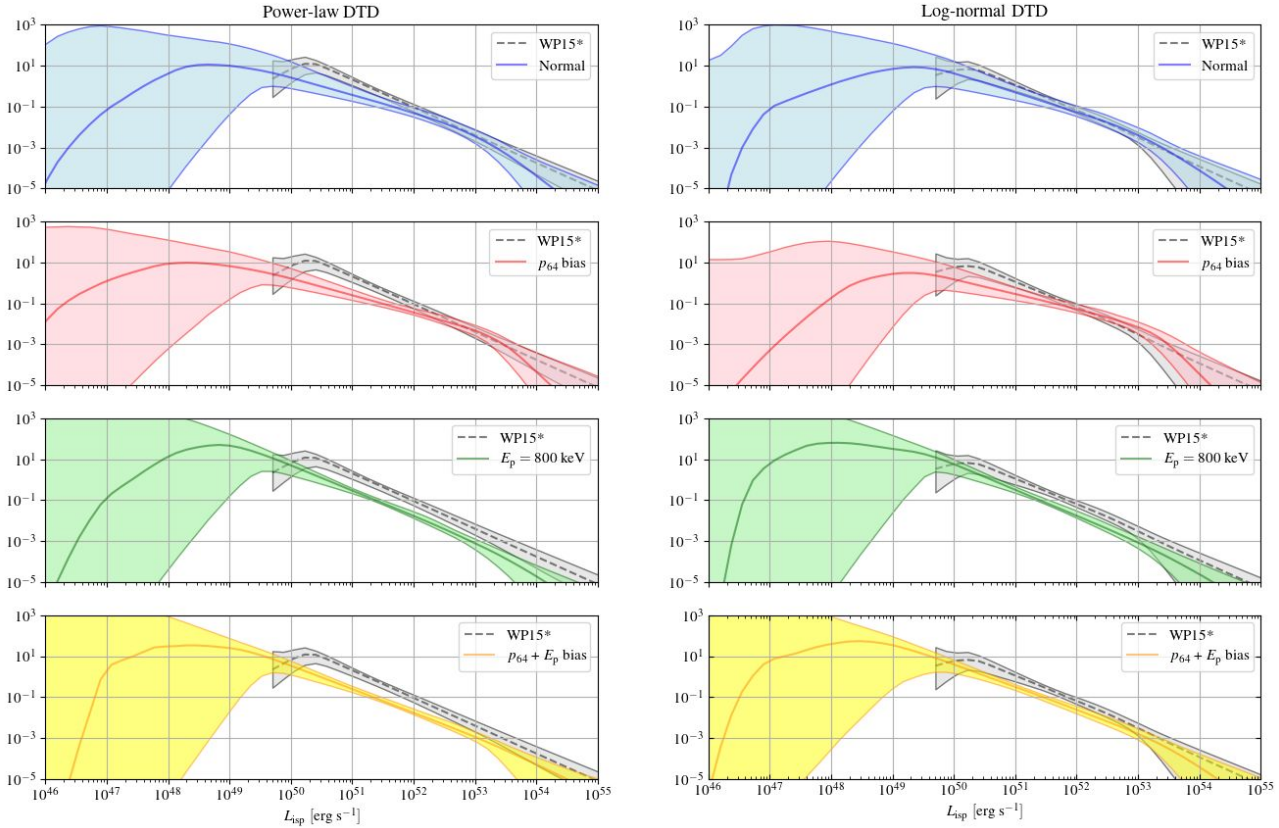


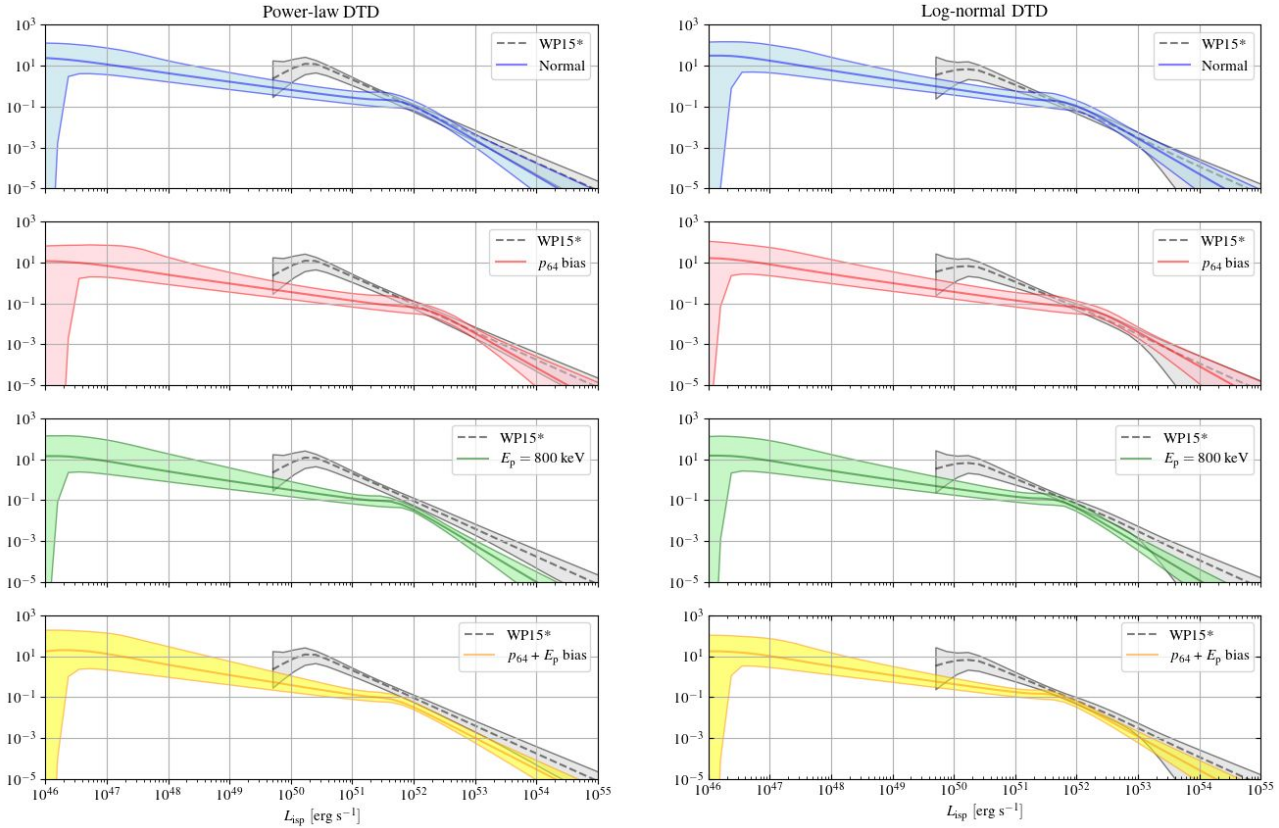
Log-normal for large sigma values



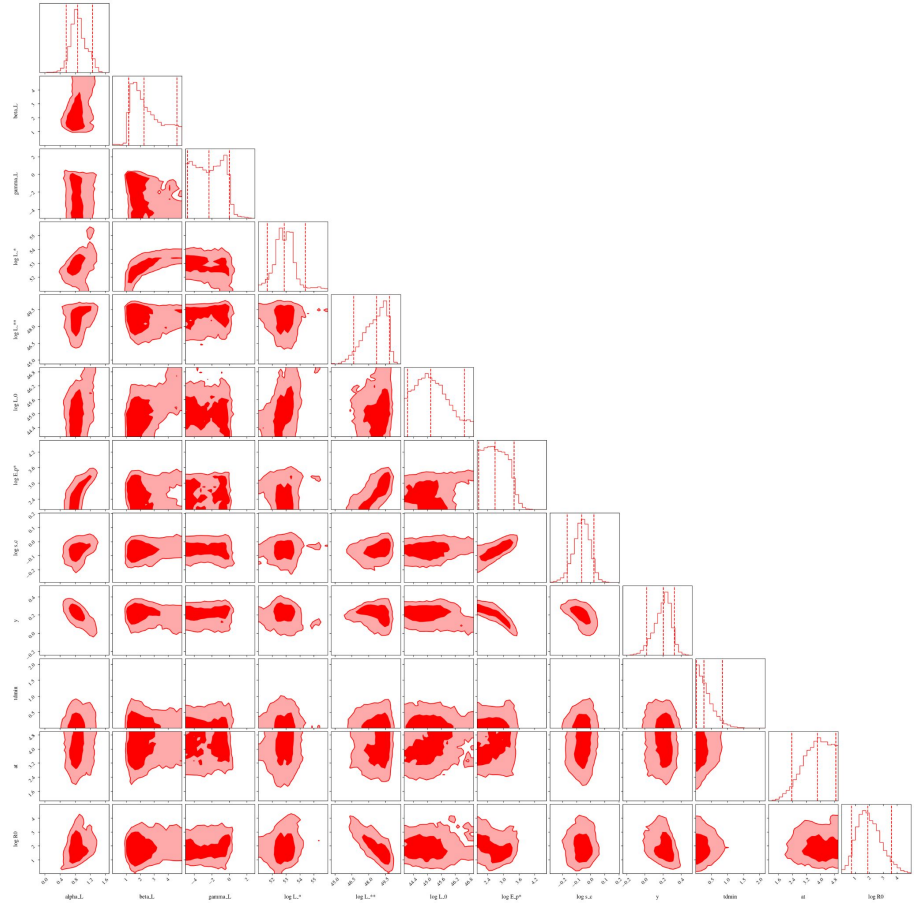
Luminosity function and biases (BPL)



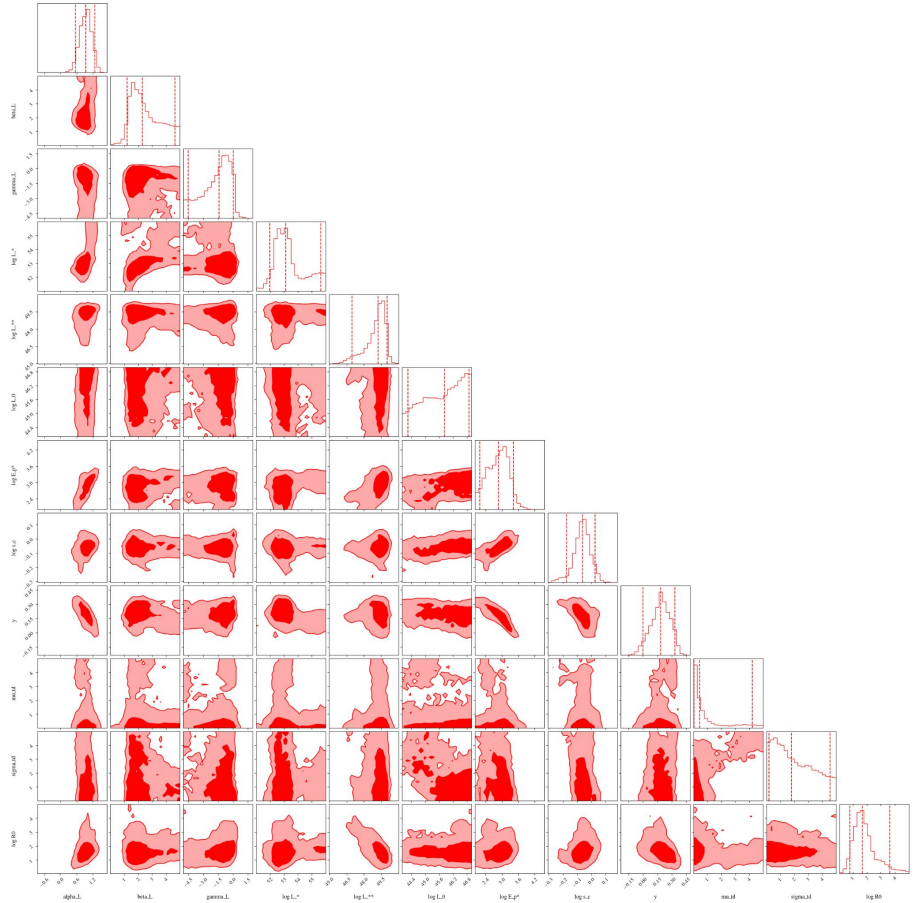
Luminosity function and biases (Jet)



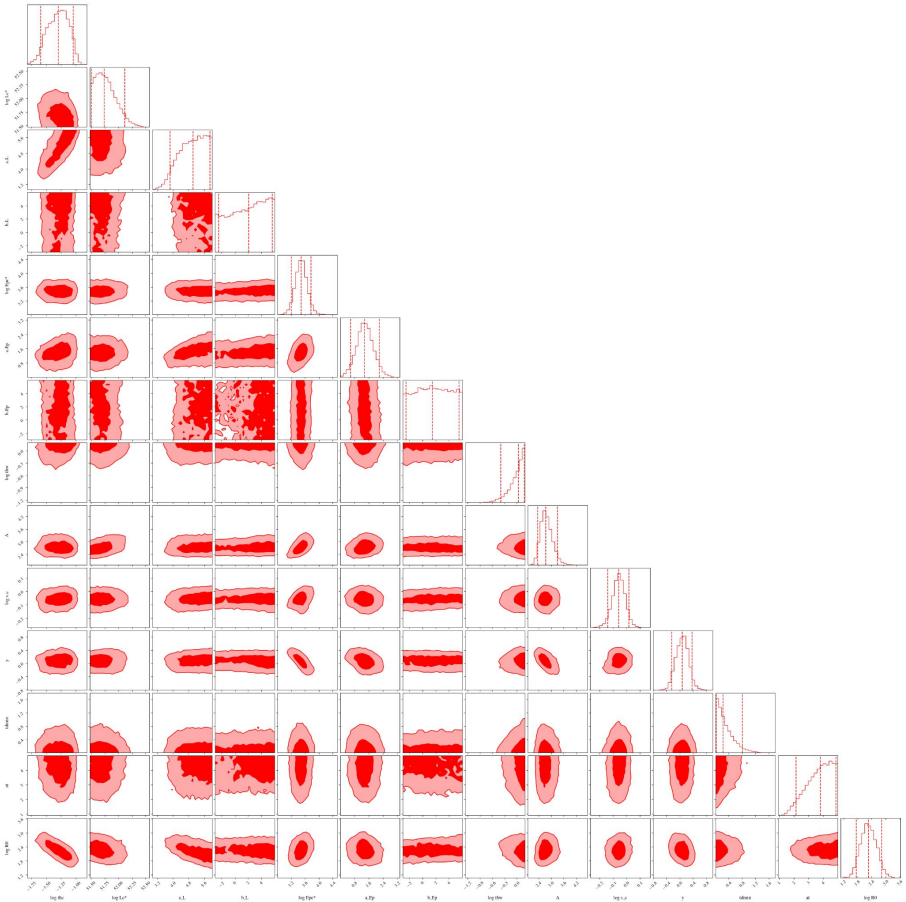
Posterior PDF (BPL, Pow)



Posterior PDF (BPL, Log)



Posterior PDF (Jet, Pow)



Posterior PDF (Jet, Log)