MODELLING OF GRB 221009A THROUGH AN ANALYTICAL DESCRIPTION OF VHE AFTERGLOW LIGHT CURVES

Claudio Gasbarra
claudio.gasbarra@roma2.infn.it

Università di Roma Tor Vergata
INFN Sezione di Roma Tor Vergata

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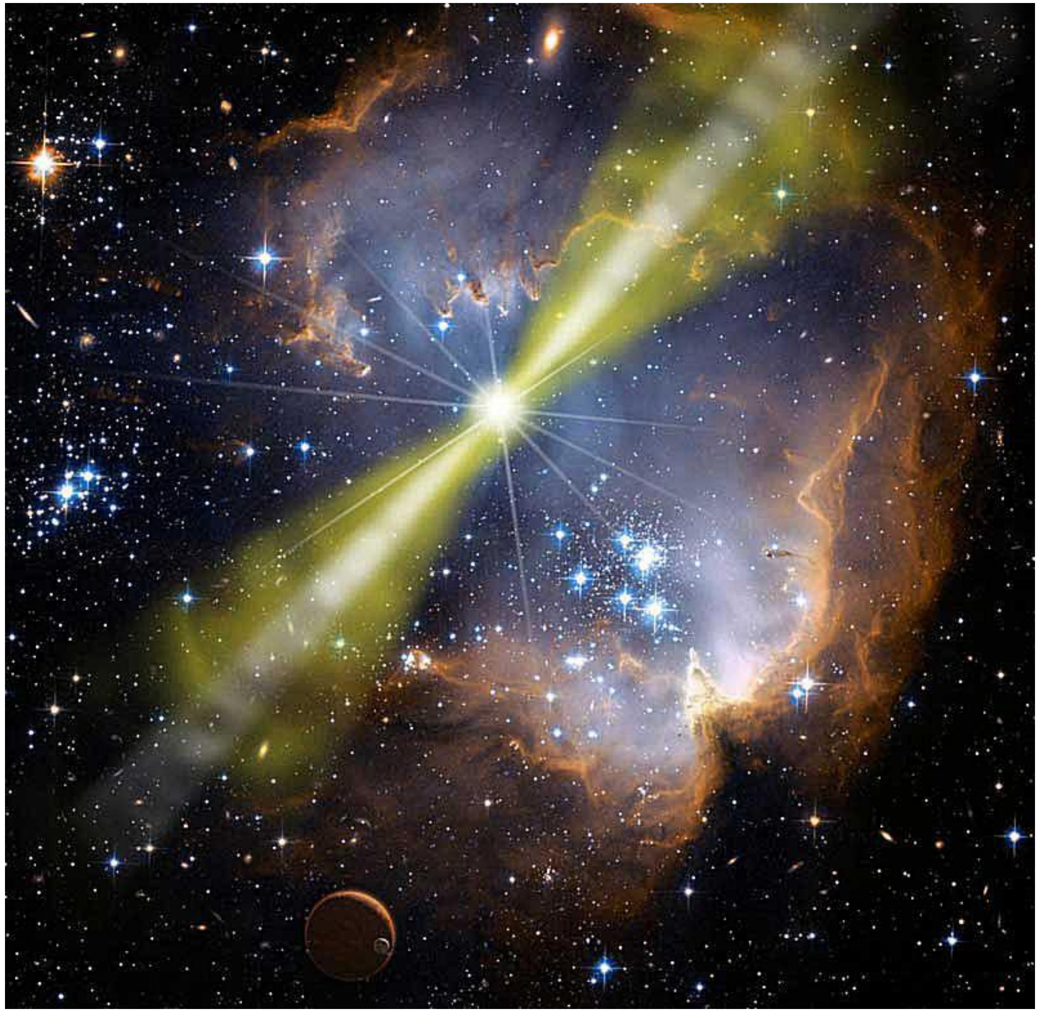
C. Gasbarra*[ab], D. Belardinelli[b], V. Fafone[ab], D. Miceli[c], A. Morselli[b], G. Rodriguez Fernandez[b]

a Università degli studi di Roma Tor Vergata, *b* INFN Sezione di Roma Tor Vergata, *c* Università degli studi di Padova e INFN

OUTLINE

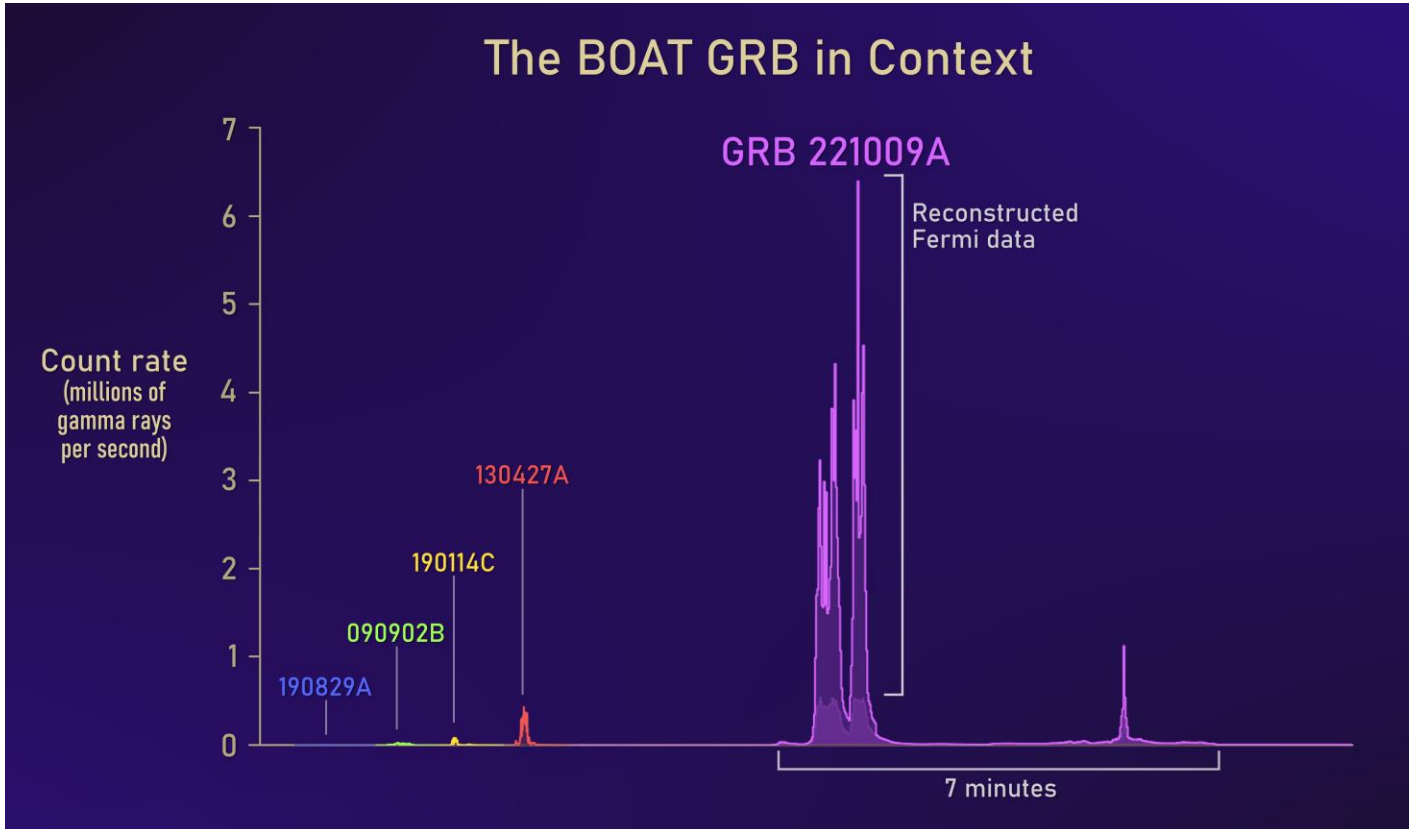
- GRB 221009A
- Numerical model
- Analytical description
- Workflow: how to model GRB 221009A
- Parameter estimation: Maximum Likelihood
- Markov-Chain Monte Carlo
- Conclusions



Credits: NASA/Swift/Mary Pat Hrybyk-Keith and John Jones

GRB 221009A: THE B.O.A.T.

- On date 9th of October 2022 several ground- and space-based observatories detected a GRB signal
- Exceptionally bright GRB! (**B**rightest **O**f **A**ll **T**ime)
- Redshift: $z = 0.151 \quad (724\ Mpc)$
- $E_{k,iso} \approx 10^{55} erg$
- Once-in-a-10^4 yr event!

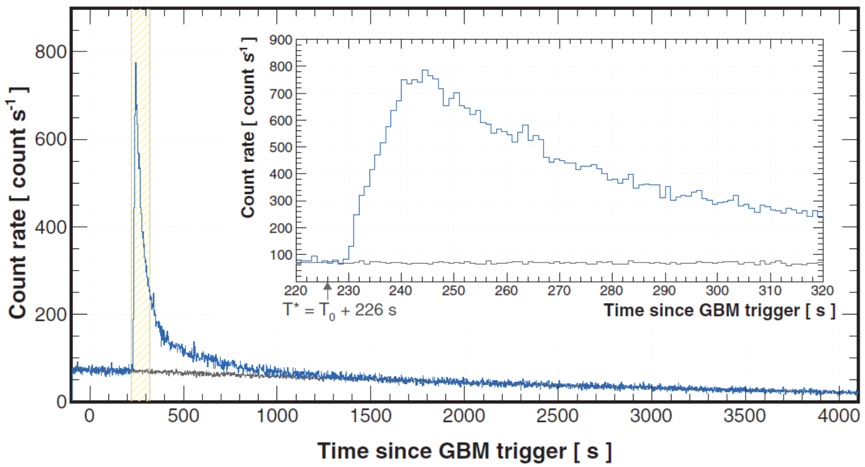


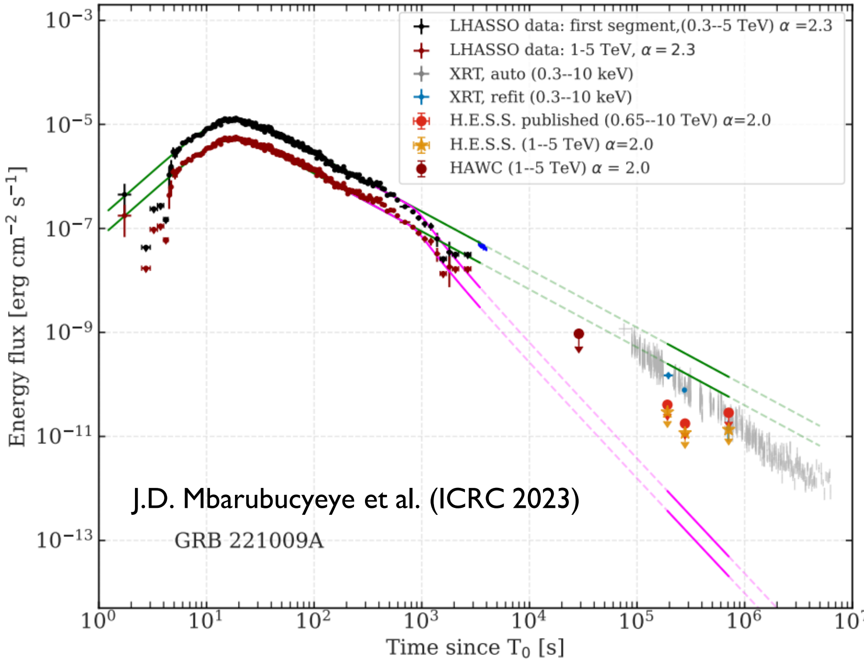
Credit: NASA's Goddard Space Flight Center and Adam Goldstein (USRA)

GRB 221009A DETECTION

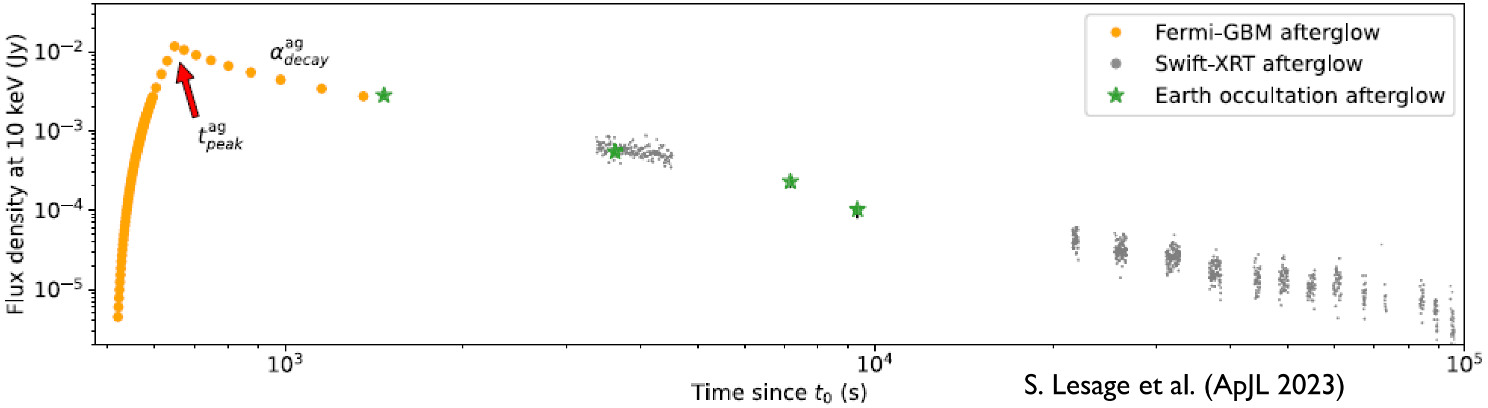
- Very high count rate!
- HE detection for ~10 d
- LHAASO detection up to ~10 TeV

LHAASO Collab. (Science 2023)

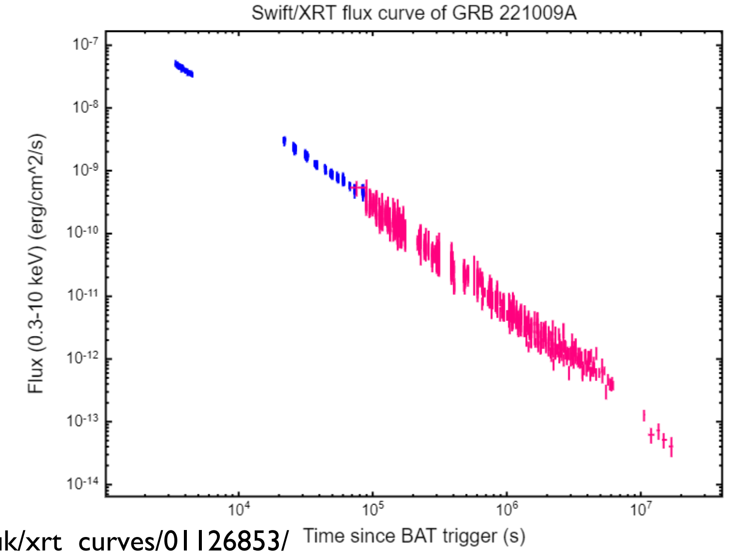




J.D. Mbarubucyeye et al. (ICRC 2023)



S. Lesage et al. (ApJL 2023)



https://www.swift.ac.uk/xrt_curves/01126853/

LHAASO DATA

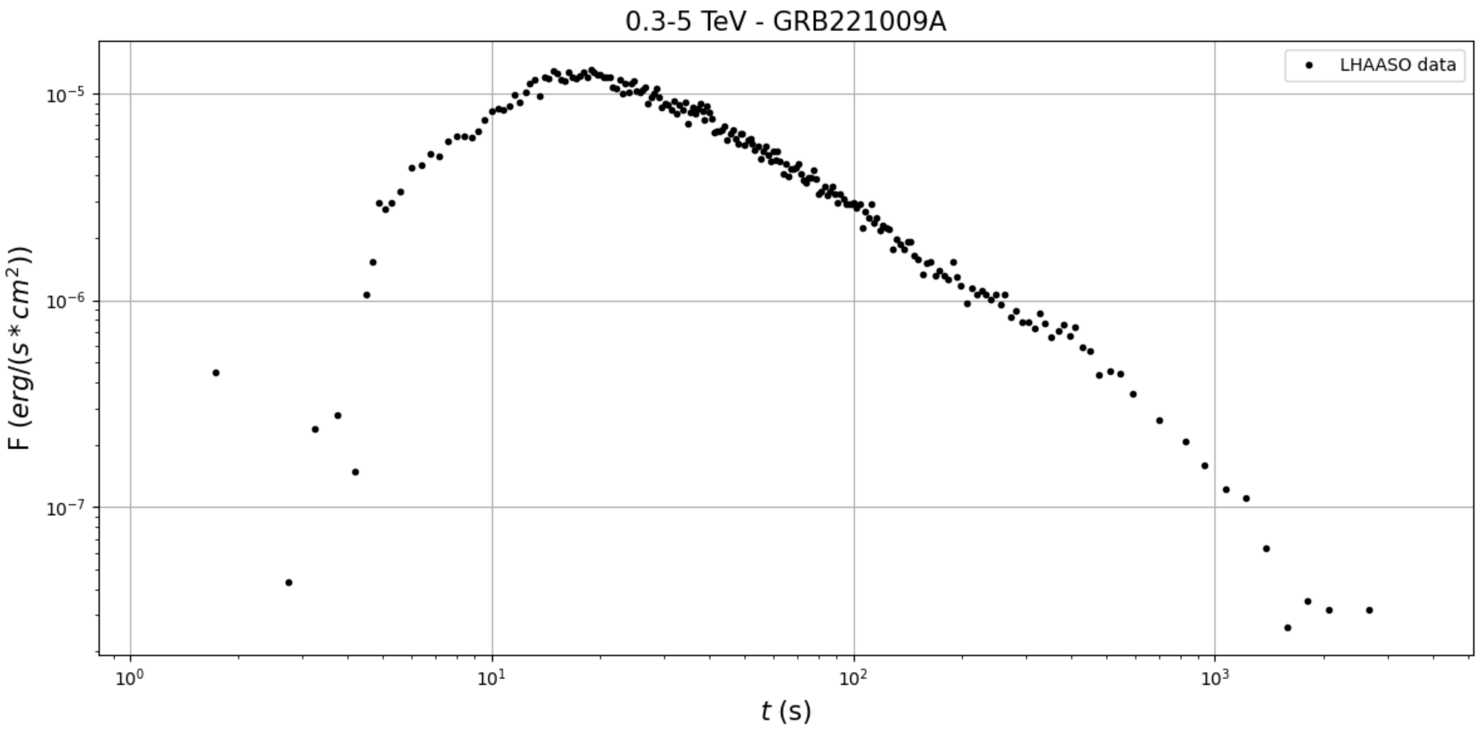
- Available dataset:

  LHAASO-WCDA

  $[T_0 \,, T_0 + 3000\ s]$

  0.3 – 5 TeV

  $\sigma > 250$



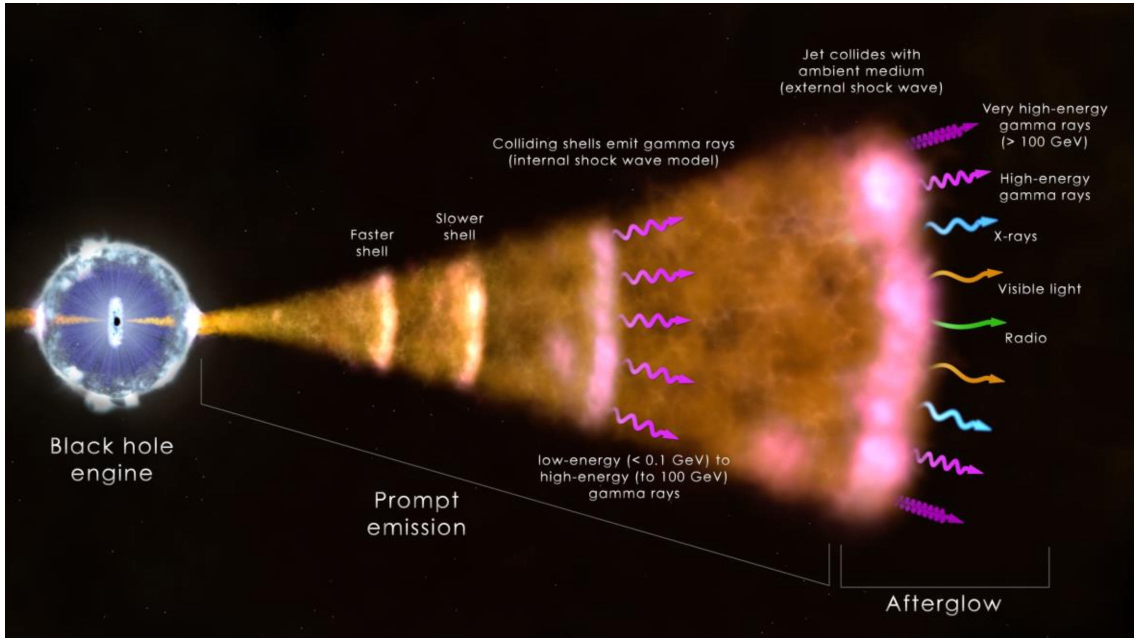
Data from: https://www.nhepsdc.cn/files/20230518/Figure3A_4.txt

LHAASO Collab. (Science 2023)

NUMERICAL MODEL

Following: *Miceli, Nava – Galaxies 2022, 10, 66*

- Expansion governed by a self-similar solution for an adiabatic blast wave
- Relativistic fireball with a homogeneous shell approximation (neglected internal structure)
- Shock front described by an evolution of the Bulk Lorentz Factor
- e^+e^- subsequently accelerated over a (broken) power-law distribution
- VHE afterglow emission due to Synchrotron and Synchrotron Self-Compton (SSC) radiation



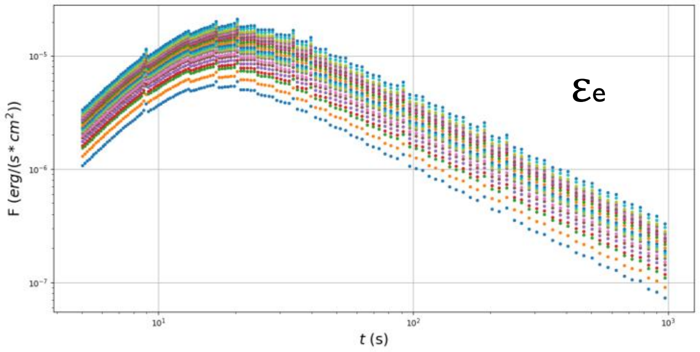
Credits: NASA/GSFC

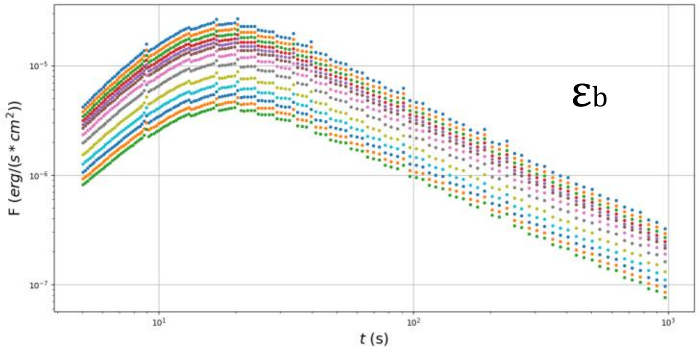
SIMULATED AFTERGLOW LIGHTCURVES

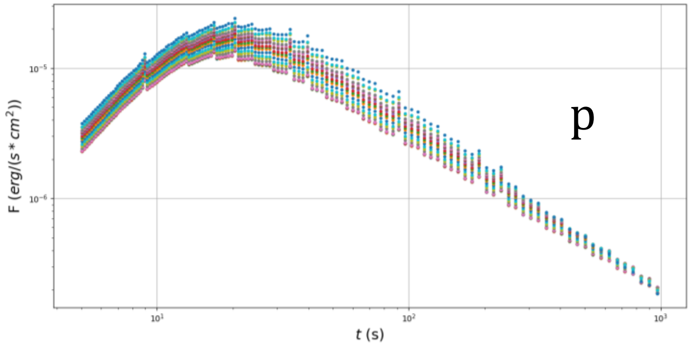
- We can produce curves based on a set of parameters, of which we choose to let vary:

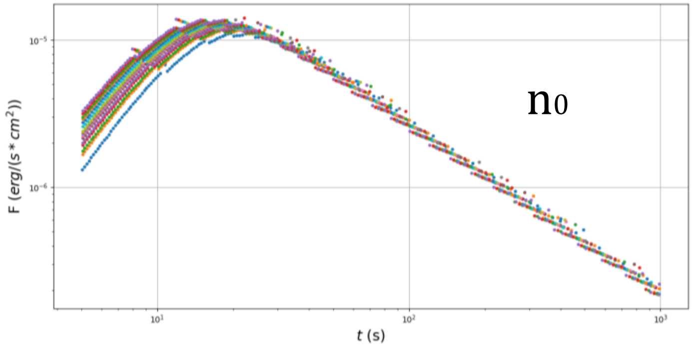
  ε_e = electron energy fraction
  ε_b = magnetic energy fraction
  Γ_0 = bulk Lorentz factor
  n_0 = ISM density [cm^{-3}]
  p = injected electrons index

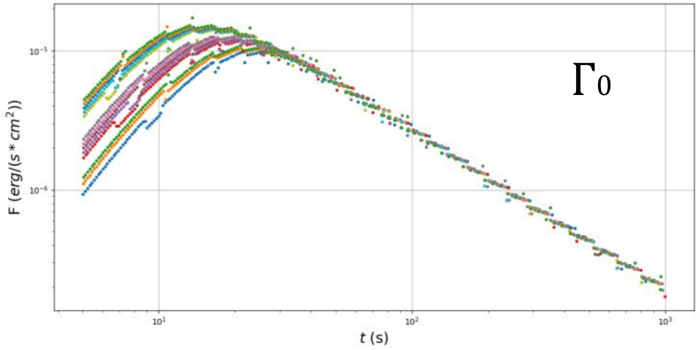
- Varying these *physical* parameters, we can find set of values able to reproduce the LCs of chosen GRBs











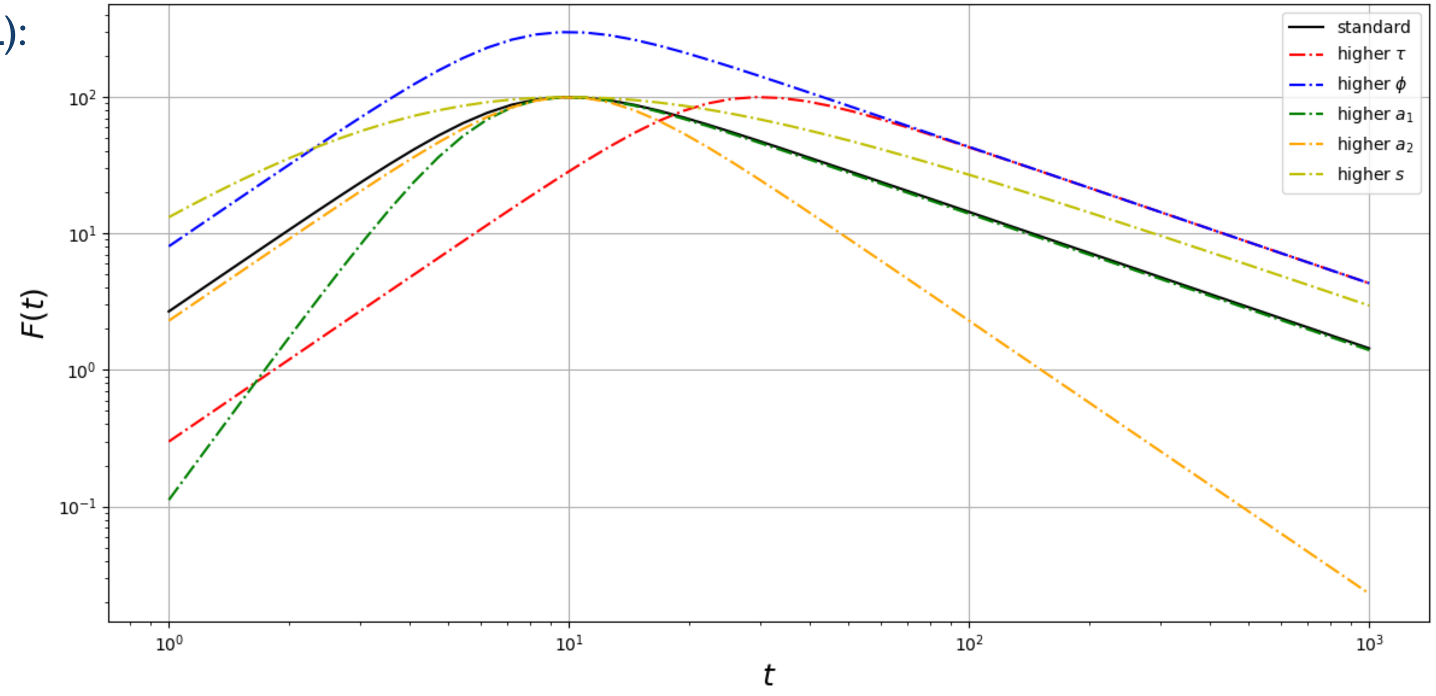
ANALYTICAL DESCRIPTION

- We can define a smooth broken power law (BPL):

$$F(t) = \Phi \left(\frac{t}{\tau}\right)^{a_1} \left[\frac{a_1 \left(\frac{t}{\tau}\right)^{1/s} + a_2}{a_1 + a_2}\right]^{-(a_1+a_2)s}$$

Where (*Fit parameters*):

τ = peak time
Φ = peak flux
a_1 = low time PL index
a_2 = high time PL index
s = smoothing parameter



ANALYTICAL DESCRIPTION

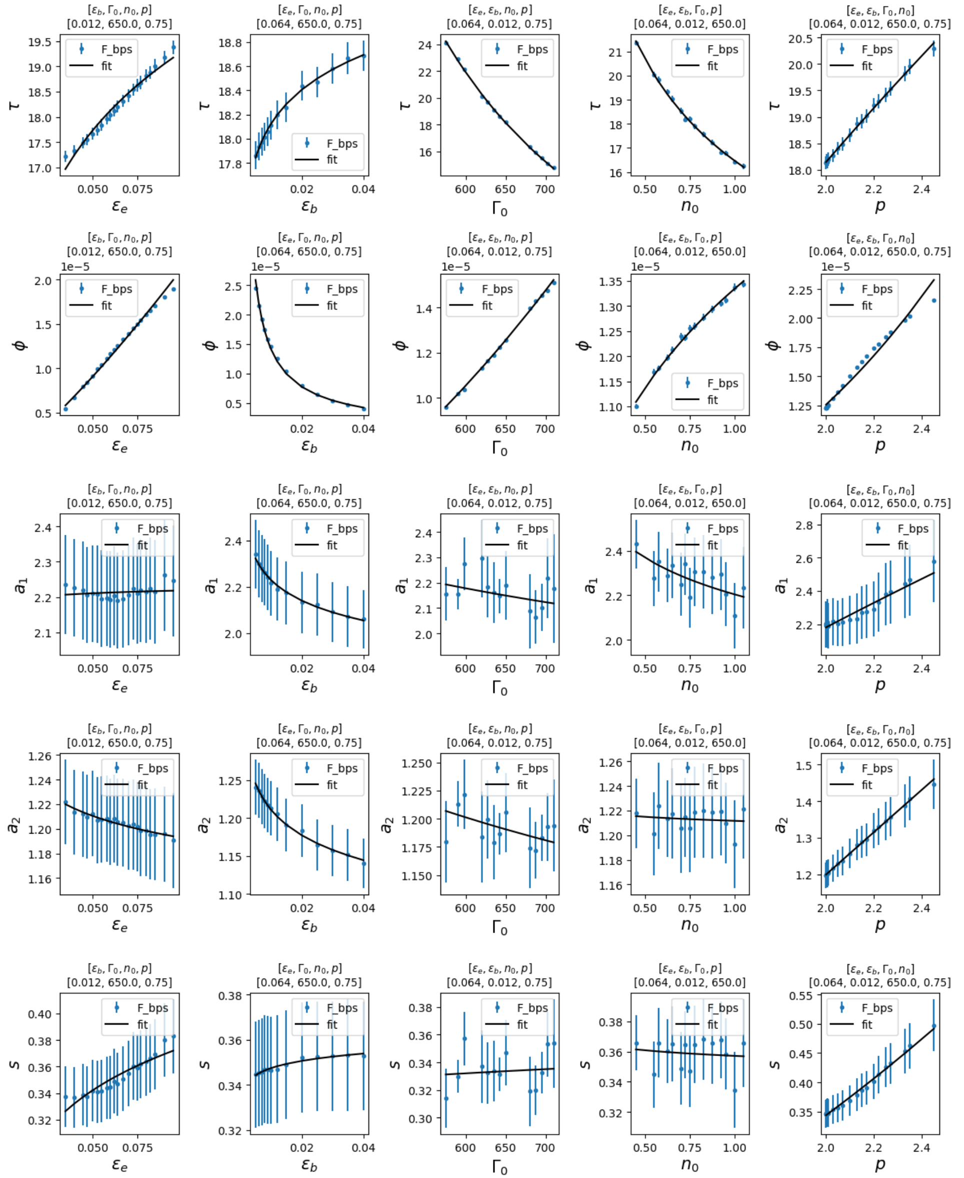
- We need to describe the LCs as dependent on the *physical parameters*!
- Link each fit par to each phys par through:

$$y = A \ x^b$$

- To have, ultimately:

$$(fit\ par) = A \left(\frac{\epsilon_e}{\overline{\epsilon_e}}\right)^{b_e} \left(\frac{\epsilon_b}{\overline{\epsilon_b}}\right)^{b_b} \left(\frac{\Gamma_0}{\overline{\Gamma_0}}\right)^{b_\Gamma} \left(\frac{n_0}{\overline{n_0}}\right)^{b_n} \left(\frac{p}{\overline{p}}\right)^{b_p}$$

	τ	Φ	a₁	a₂	s
A	18.2	1.2×10^{-5}	2.2	1.2	0.3
b_e	0.12	1.24	5.1×10^{-3}	-2.2×10^{-2}	0.13
b_b	2.2×10^{-2}	-0.87	-5.9×10^{-2}	-4.1×10^{-2}	1.3×10^{-2}
b_Γ	-2.4	2.2	-0.16	-0.11	5.9×10^{-2}
b_n	-0.3	0.2	-0.1	-3.9×10^{-3}	-1.5×10^{-2}
b_p	0.6	3.0	0.7	1.0	1.8



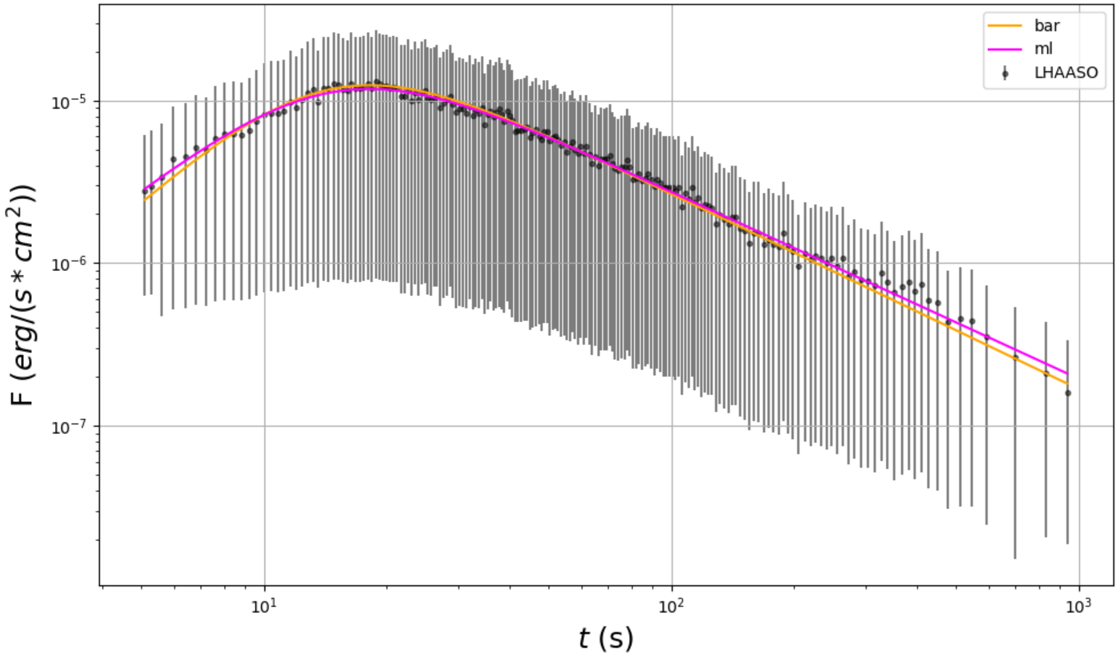
WORKFLOW ON MODELLING GRB 221009A

- Production of LCs around an initial set of values
- Derivation of the dependences between *physical* and *fit* parameters
- Writing down the analytical expression of the Flux, now expressed as *F(phys) = F(fit (phys))*
- Estimation of the parameters through a Maximum Likelihood Estimation
- Markov-Chain Monte Carlo to gain a confidence interval for the parameters

MAXIMUM LIKELIHOOD ESTIMATION

- We have now all ingredients linking fit parameters to physical parameters!
- Possible to write the log-likelihood

$$\ln P\,(y \mid t, \sigma, \epsilon_e, \epsilon_b, \Gamma_0, n_0, p) = -\frac{1}{2}\sum_n \left[\frac{(y_n - F(phys))^2}{\sigma^2} + \ln(\sigma^2)\right]$$



- We maximise it, and get a first good estimate for the physical parameters:

$\overline{\epsilon_e} = 6.5 \times 10^{-2}$	$\overline{\epsilon_b} = 1.0 \times 10^{-2}$	$\overline{\Gamma_o} = 650$	$\overline{n_o} = 0.75$	$\overline{p} = 2.01$
$\boldsymbol{\epsilon_e^{ML} = 1.0 \times 10^{-1}}$	$\boldsymbol{\epsilon_b^{ML} = 2.5 \times 10^{-2}}$	$\boldsymbol{\Gamma_0^{ML} = 580}$	$\boldsymbol{n_0^{ML} = 2.1\ (cm^{-3})}$	$\boldsymbol{p^{ML} = 2.0}$

MARKOV-CHAIN MONTE CARLO

- We can now run a MCMC
- “ML” as initial values
- Walkers: 32 × # par (5 physical parameters)
- 2 × 10⁴ steps

ϵ_e^{ML}	1.0×10^{-1}
ϵ_b^{ML}	2.5×10^{-2}
Γ_0^{ML}	580
n_0^{ML}	$2.1\ (cm^{-3})$
p^{ML}	2.0

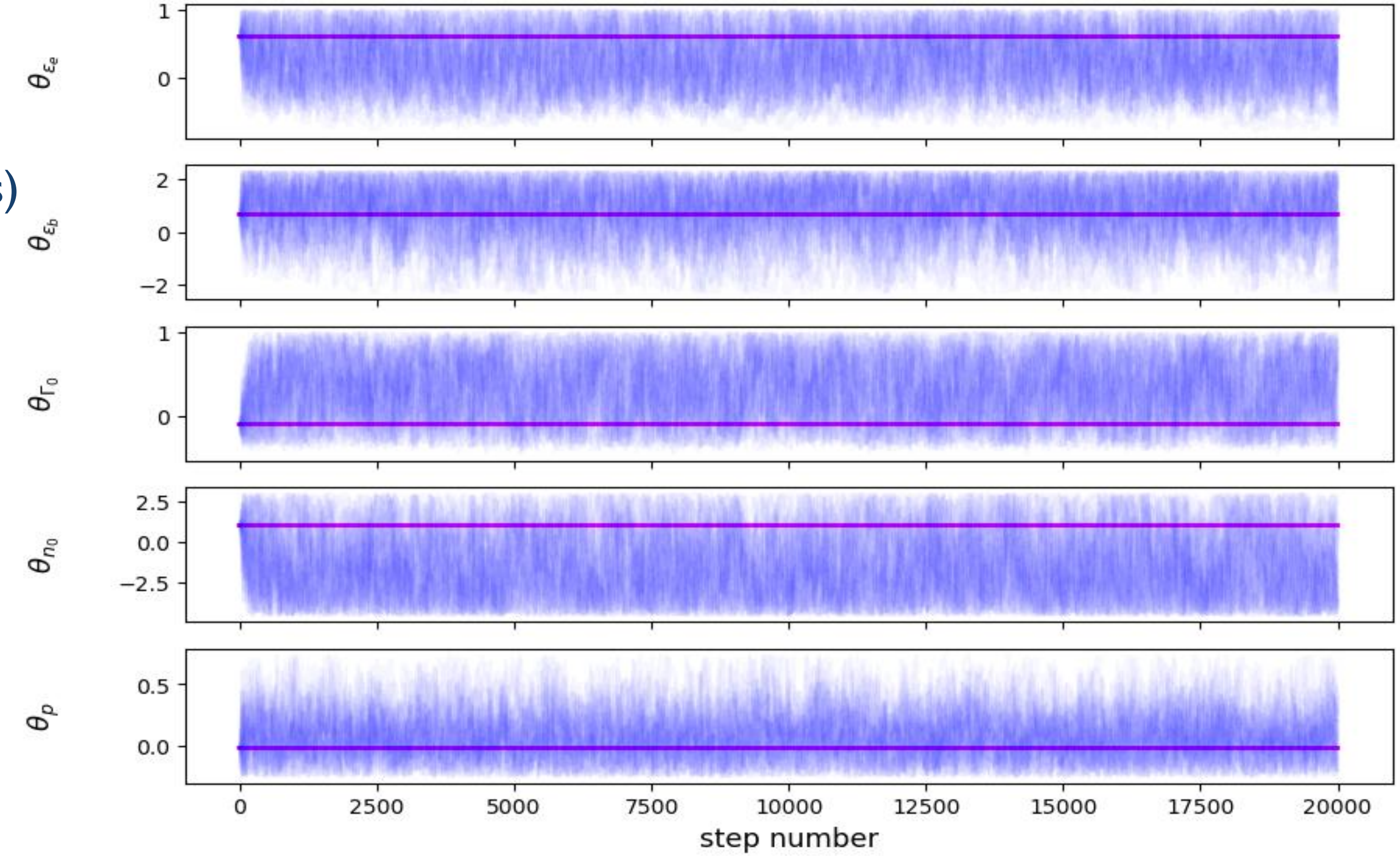
$$\theta_{\epsilon_e} = \frac{\epsilon_e}{\overline{\epsilon_e}} - 1$$

$$\theta_{\epsilon_b} = \ln\left(\frac{\epsilon_b}{\overline{\epsilon_b}}\right)$$

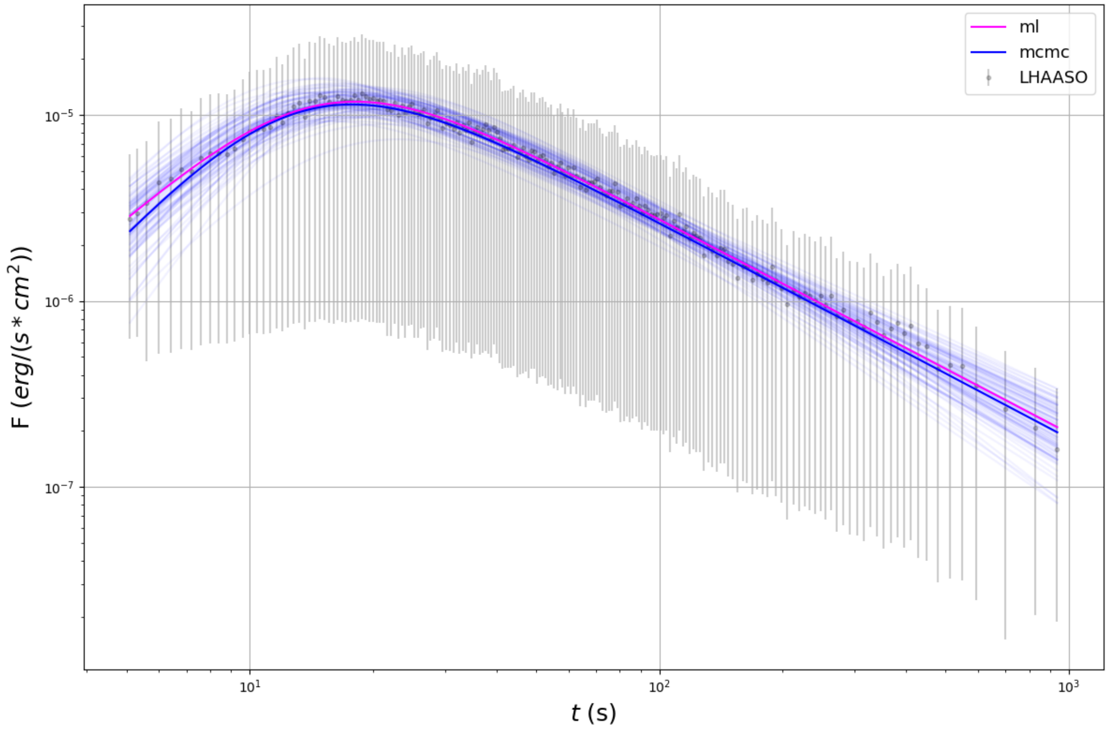
$$\theta_{\Gamma_0} = \frac{G_0}{\overline{G_0}} - 1$$

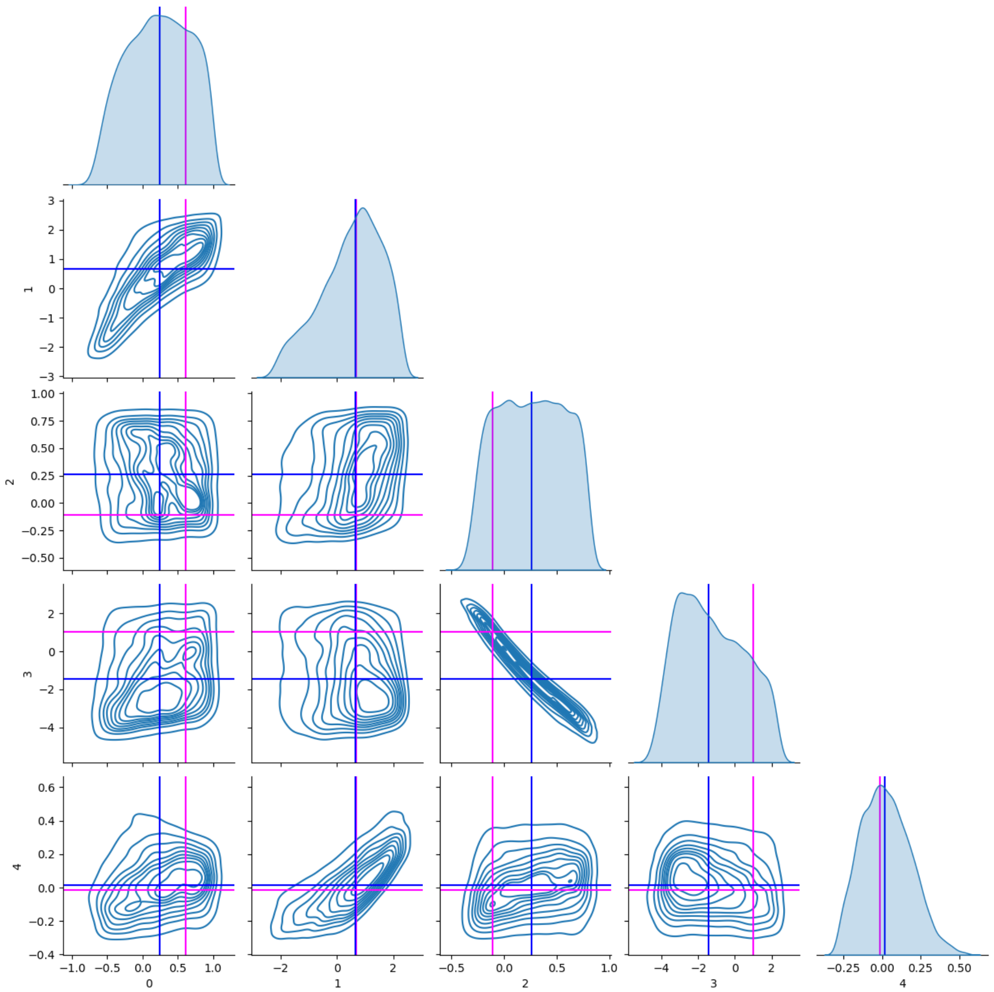
$$\theta_{n_0} = \ln\left(\frac{n_0}{\overline{n_0}}\right)$$

$$\theta_p = \ln\left(\frac{p}{\overline{p}}\right)$$



MARKOV-CHAIN MONTE CARLO





MCMC results: $\epsilon_e = 0.079^{+0.03}_{-0.03}$, $\epsilon_b = 0.023^{+0.038}_{-0.017}$, $\Gamma_0 = 820^{+240}_{-240}$, $n_0 = 0.18^{+1.55}_{-0.15}$, $p = 2.04^{+0.39}_{-0.29}$

CONCLUSIONS AND PERSPECTIVE

- In this work, we got two main results:
  - we showed the developed analytical method to describe generic broken power law LCs, explaining the workflow for the modelisation of a GRB, with precise estimates of the parameters driving the emission,
  - performed a preliminar study of GRB 221009A - quite good agreement

- To do:
  - production of new data for other sets of parameters
  - try a different function for the *fit – physical parameters* relation

- Better results soon to come!

Thanks for your attention!