SEARCH FOR ORPHAN GAMMA-RAY BURST AFTERGLOWS WITH THE VERA C. RUBIN OBSERVATORY

- PhD Seminar -

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11 April, 2023

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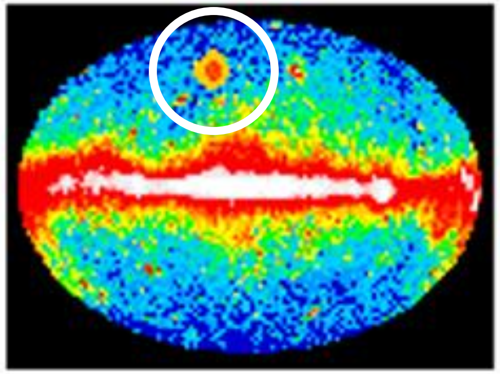
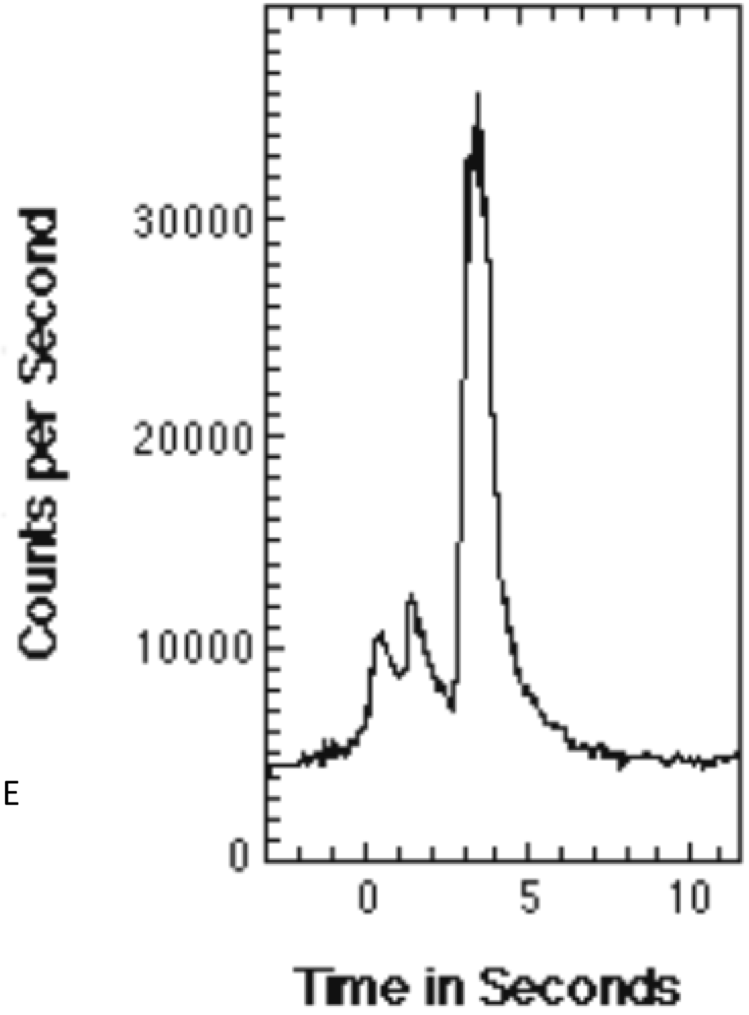
WHAT IS A GAMMA-RAY BURST (GRB)?



(DATA FROM THE COMPTON GAMMA-RAY OBSERVATORY IN THE 20 KeV – 1 MeV ENERGY RANGE)



- Discovered on July 2, 1967 by the Vela satellites
- Short gamma-ray flashes from the sky

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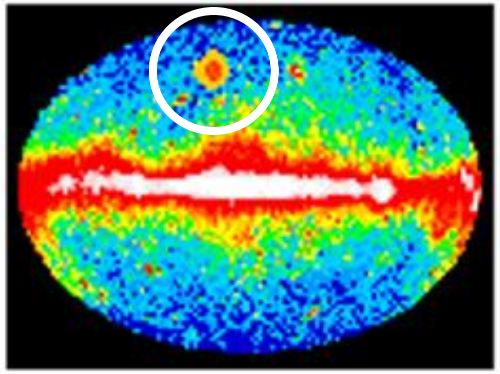

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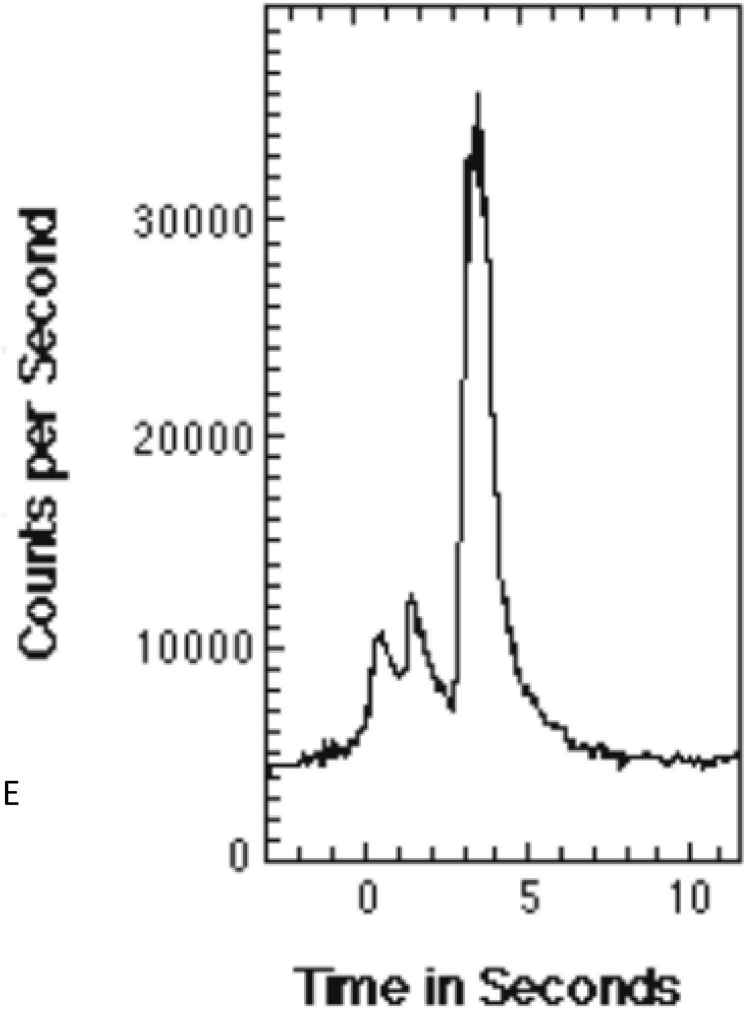
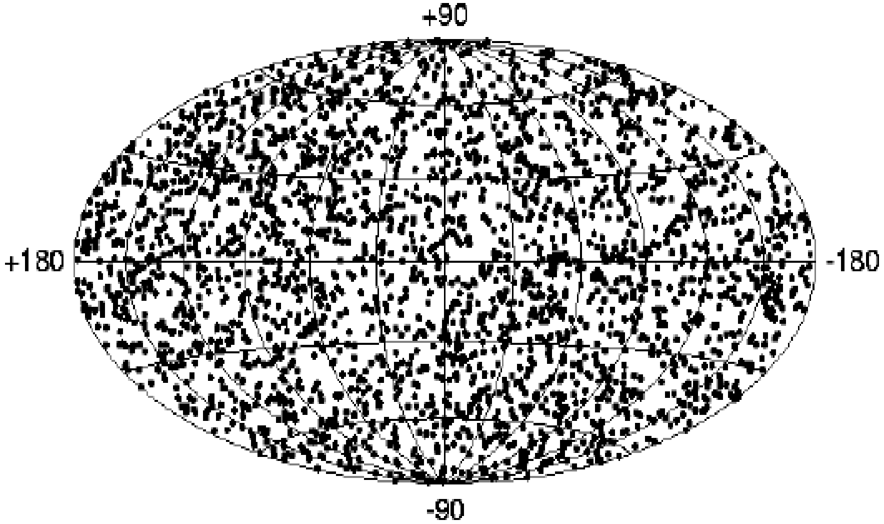


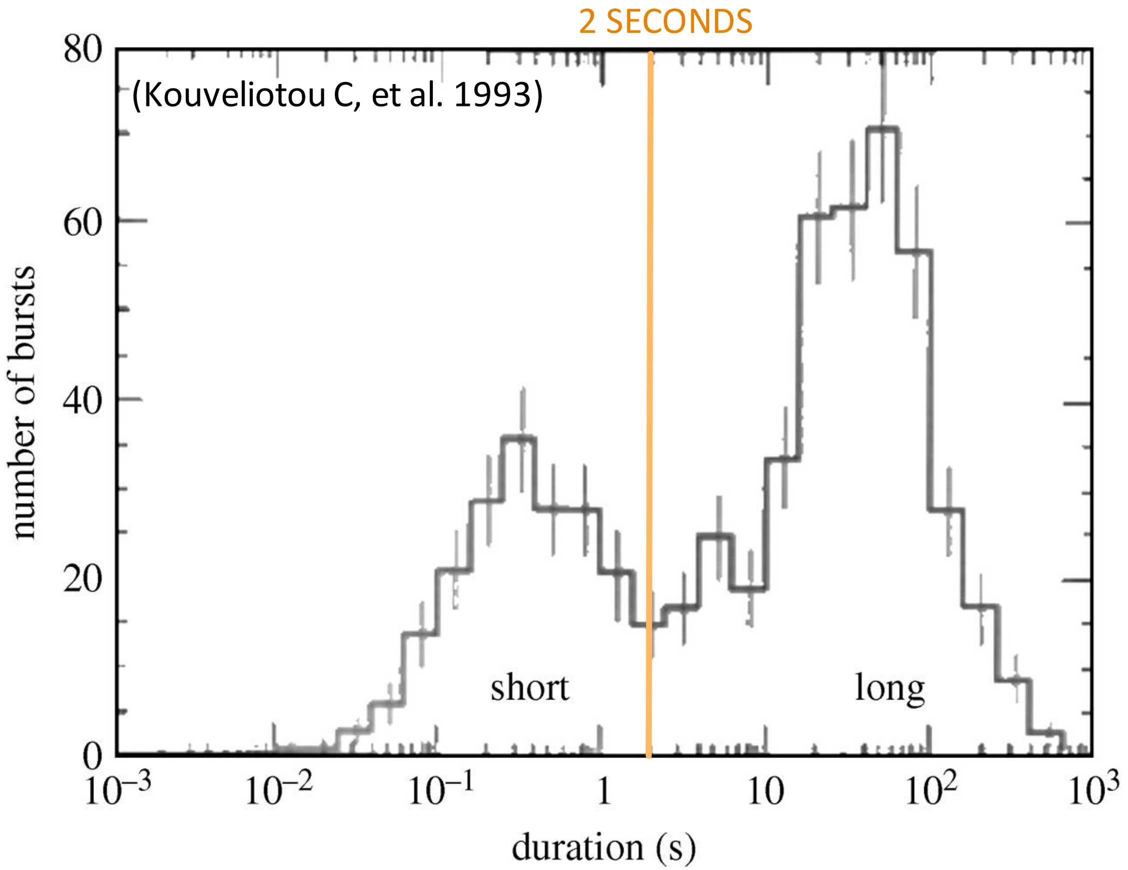
- Discovered on July 2, 1967 by the Vela satellites
- Short gamma-ray flashes from the sky
- Isotropic distribution in the sky $\Longrightarrow$ cosmological origin (Paczyński B. 1995)



(2704 BATSE GRBS)

GAMMA-RAY BURSTS PROGENITORS

Bimodal duration distribution of GRBs ⟹ at least 2 different progenitors



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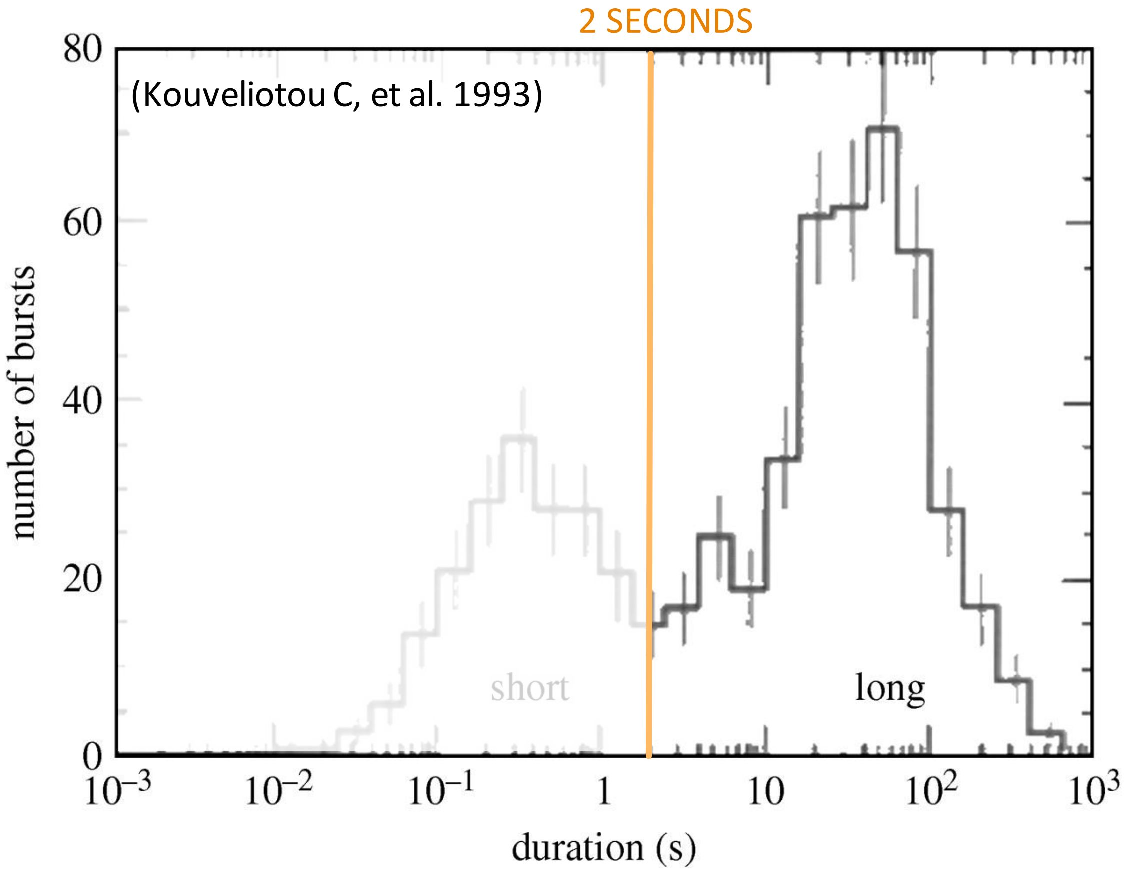


LONG

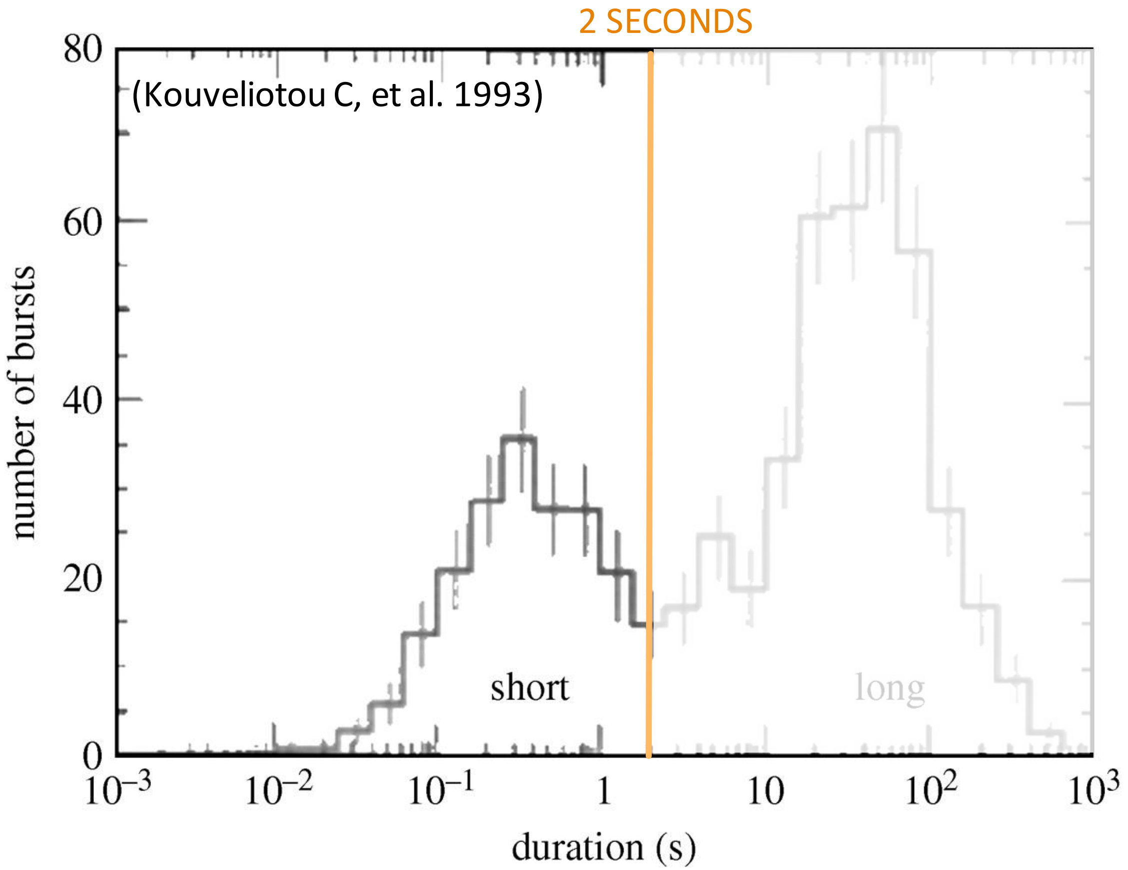
- Duration > 2 seconds
- Progenitor: connected to core-collapse supernova (SN)
- First event: GRB980425 + SN1998bw (Galama et al. 1998)

GAMMA-RAY BURSTS PROGENITORS

Bimodal duration distribution of GRBs ⟹ at least 2 different progenitors

SHORT

- Duration < 2 seconds
- Progenitor: connected to neutron star (NS) mergers
- First (& golden) event: GRB170817A + GW170817 (Abbott et al. 2017)



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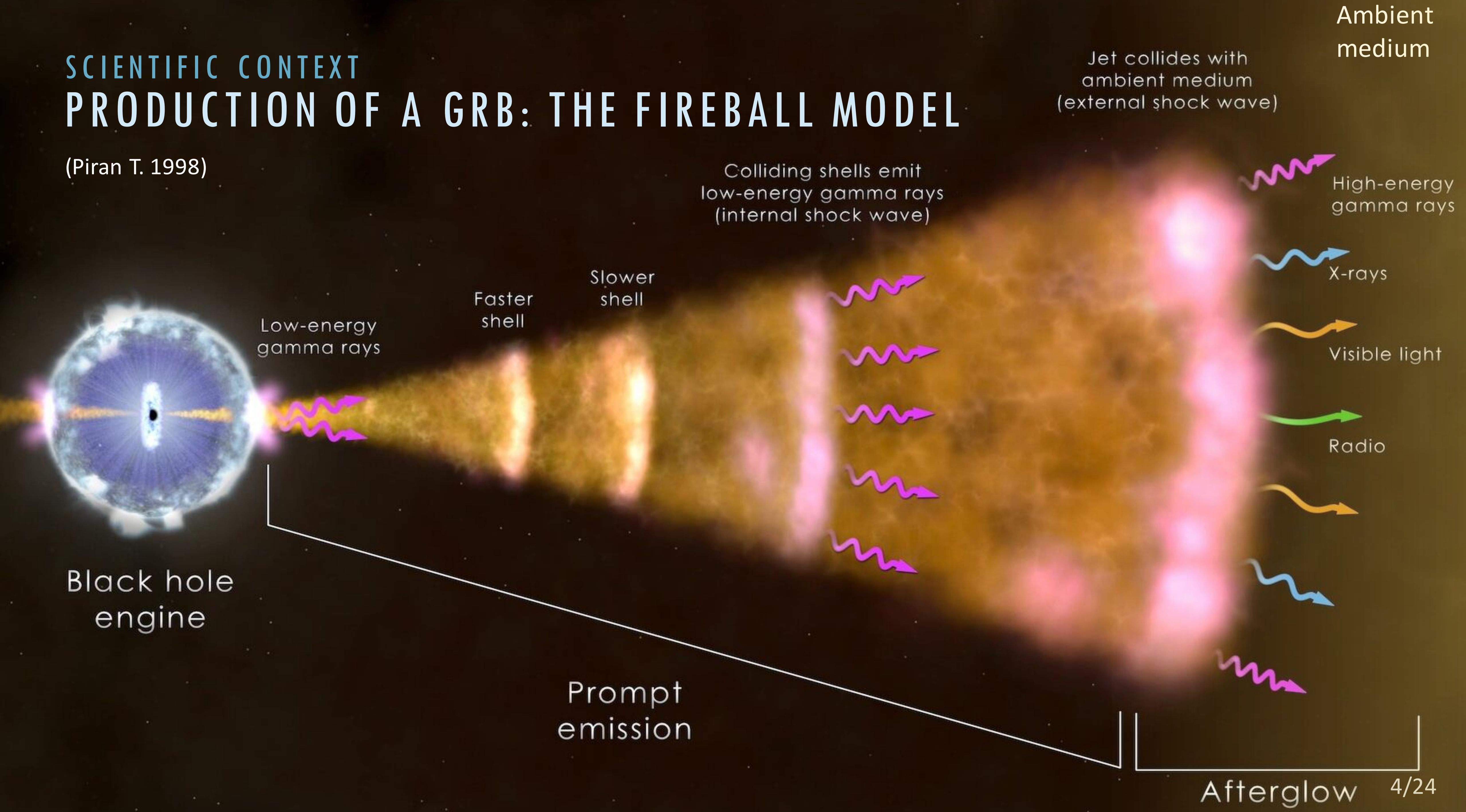
SCIENTIFIC CONTEXT

PRODUCTION OF A GRB: THE FIREBALL MODEL

(Piran T. 1998)



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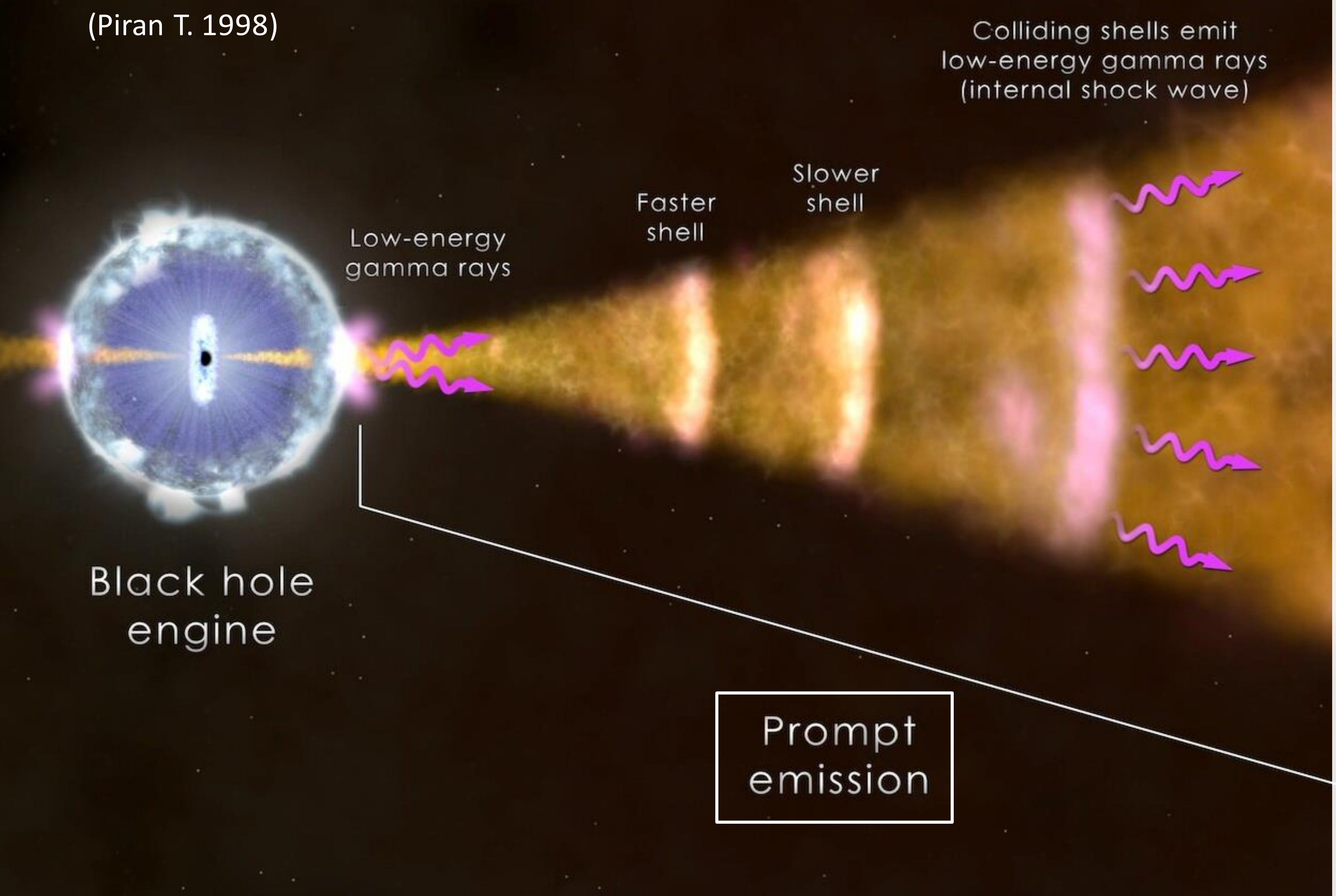
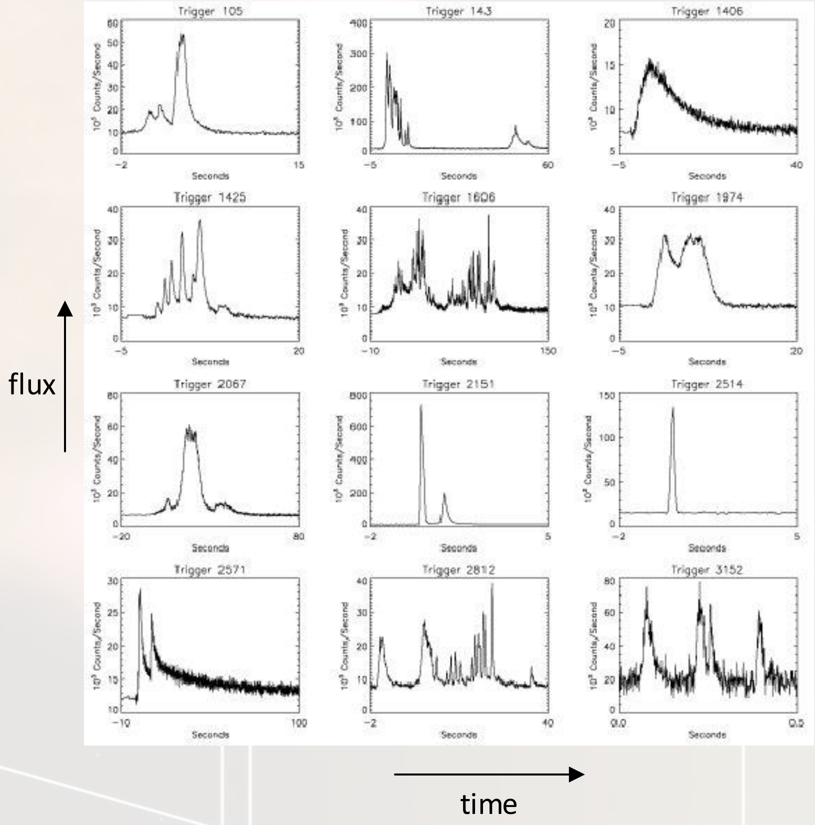


GRB (prompt emission) = short and highly energetic (~ 10^{51} erg) gamma-ray flashes (observed with Fermi or Swift in keV – GeV)

SAMPLE OF BATSE LIGHT CURVES



SCIENTIFIC CONTEXT

PRODUCTION OF A GRB: THE FIREBALL MODEL

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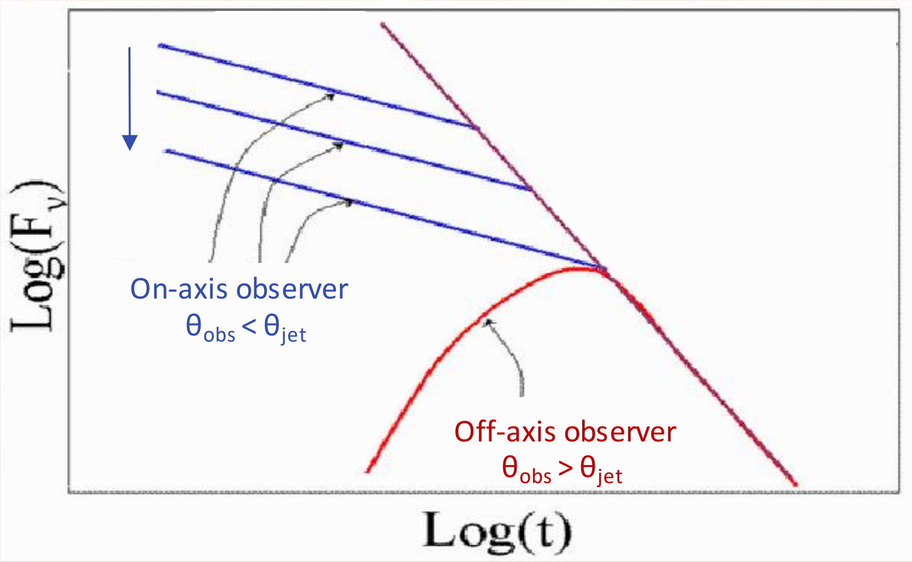
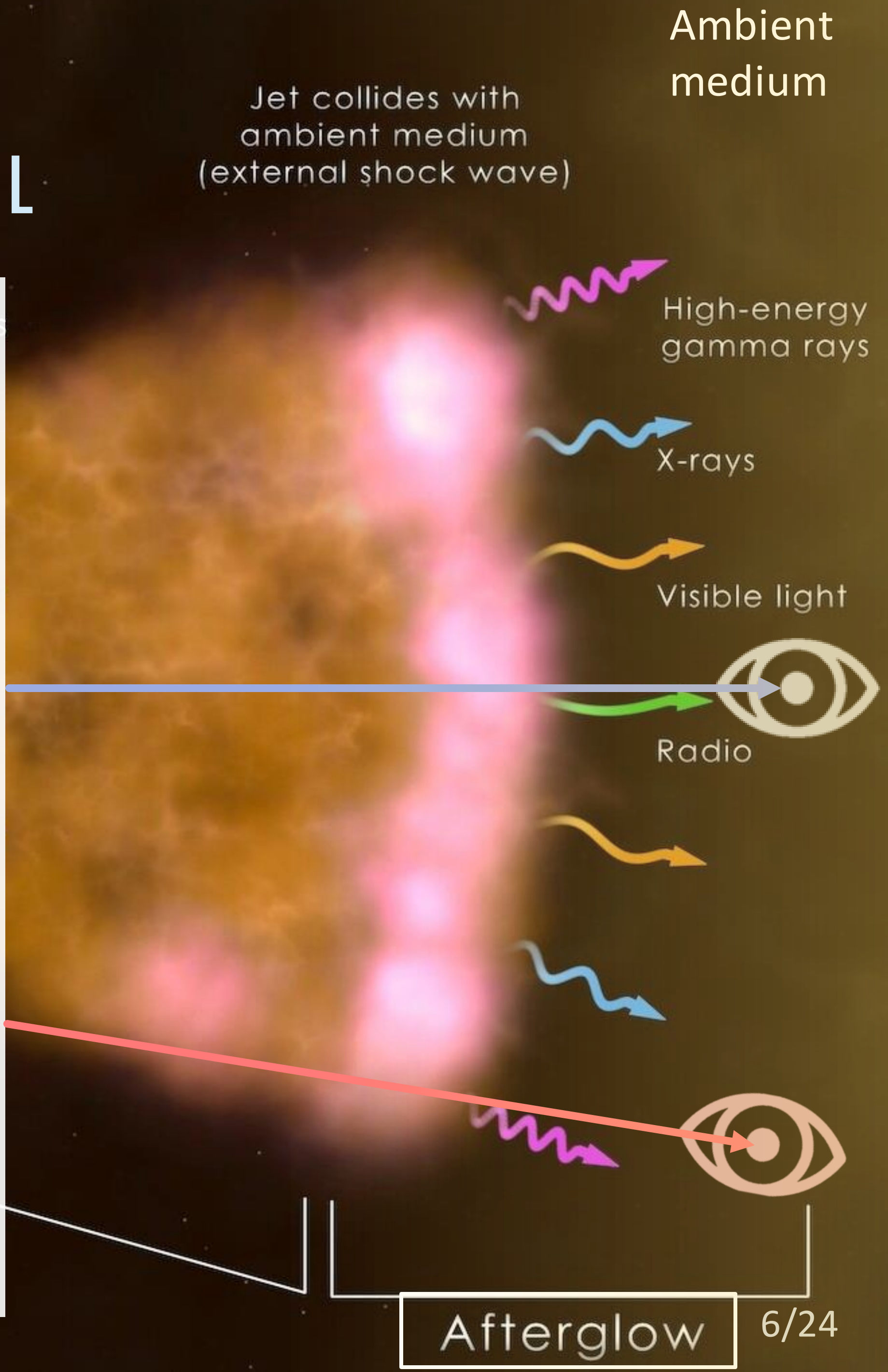
Afterglow = long-lasting and fading emission following the gamma prompt emission
- Emitted in multiple wavelengths
- Longer
- Wider

SCHEMATIC AFTERGLOW LIGHT CURVE



Black hole engine



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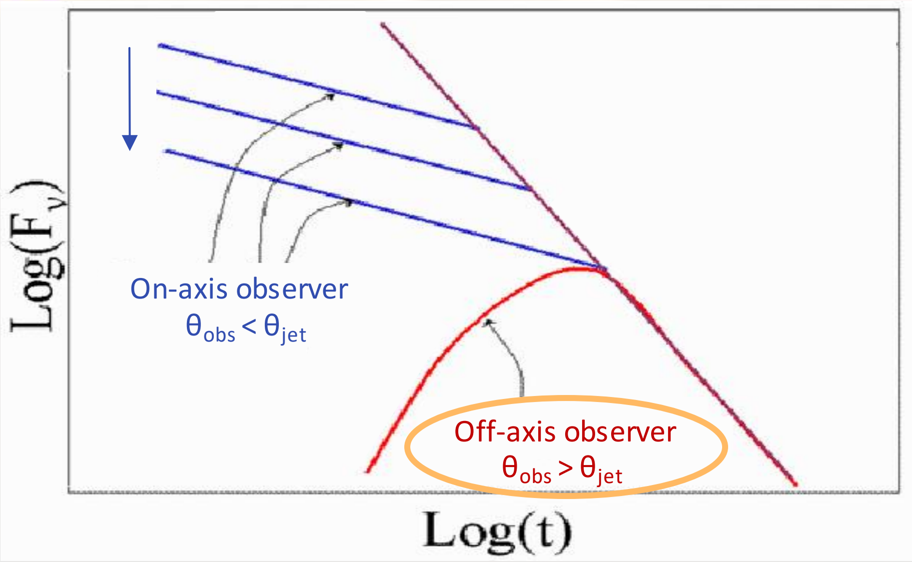
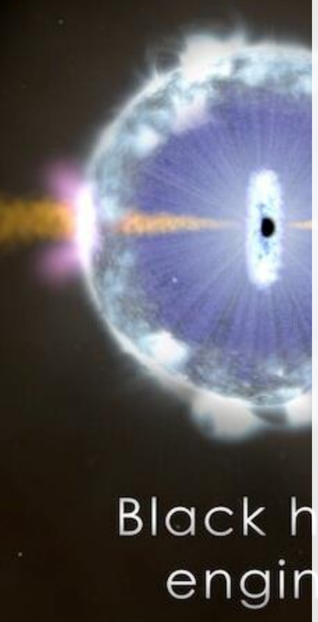
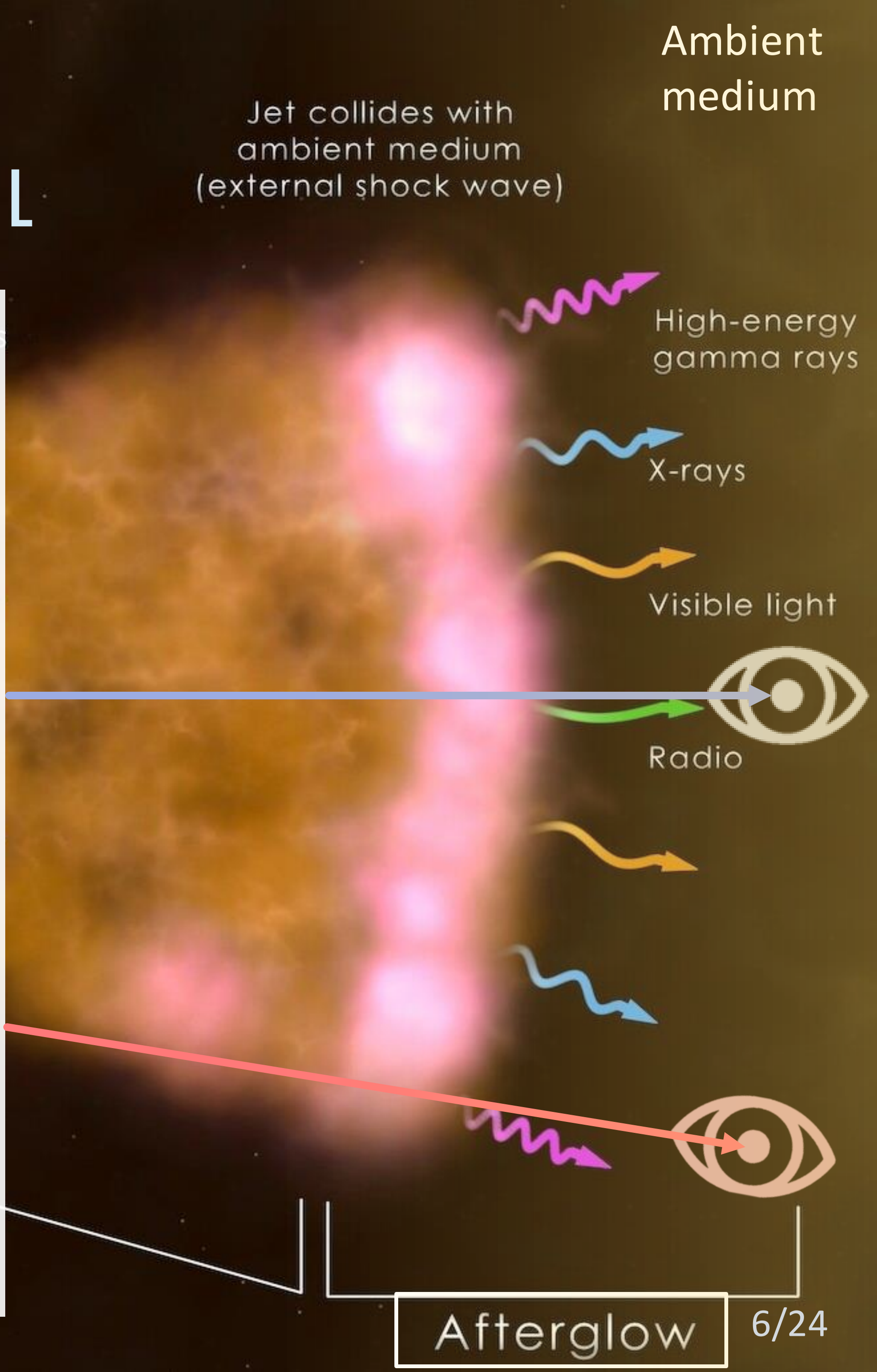
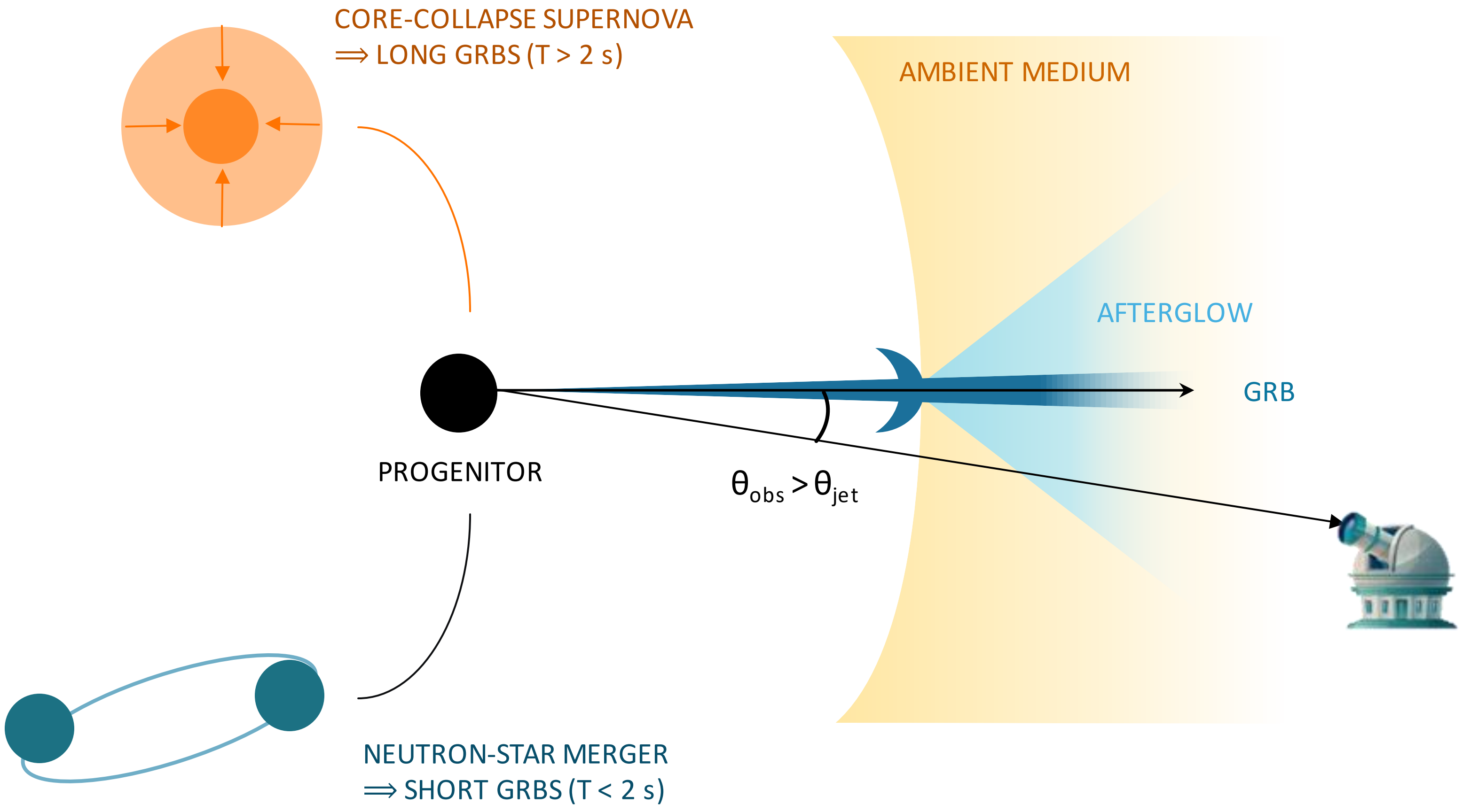






SCIENTIFIC CONTEXT

THE ORPHAN AFTERGLOW: A GRB VIEWED OFF-AXIS

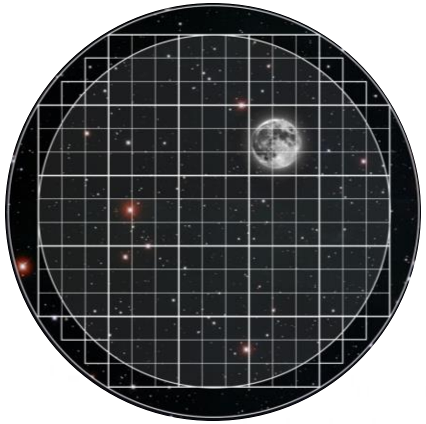


Orphan afterglow = afterglow observed off-axis (without gamma-ray emission)
⟹ **No orphan afterglow confirmed so far!** (Some candidates)

Why?
- Faint events
- No gamma prompt emission to identify them

THE VERA C. RUBIN OBSERVATORY

https://www.lsst.org/



VERA C. RUBIN OBSERVATORY

- Will perform the 10-year **Legacy Survey of Space and Time (LSST)**

⟹ **Explore the transient optical sky** (first data expected for **2026**)

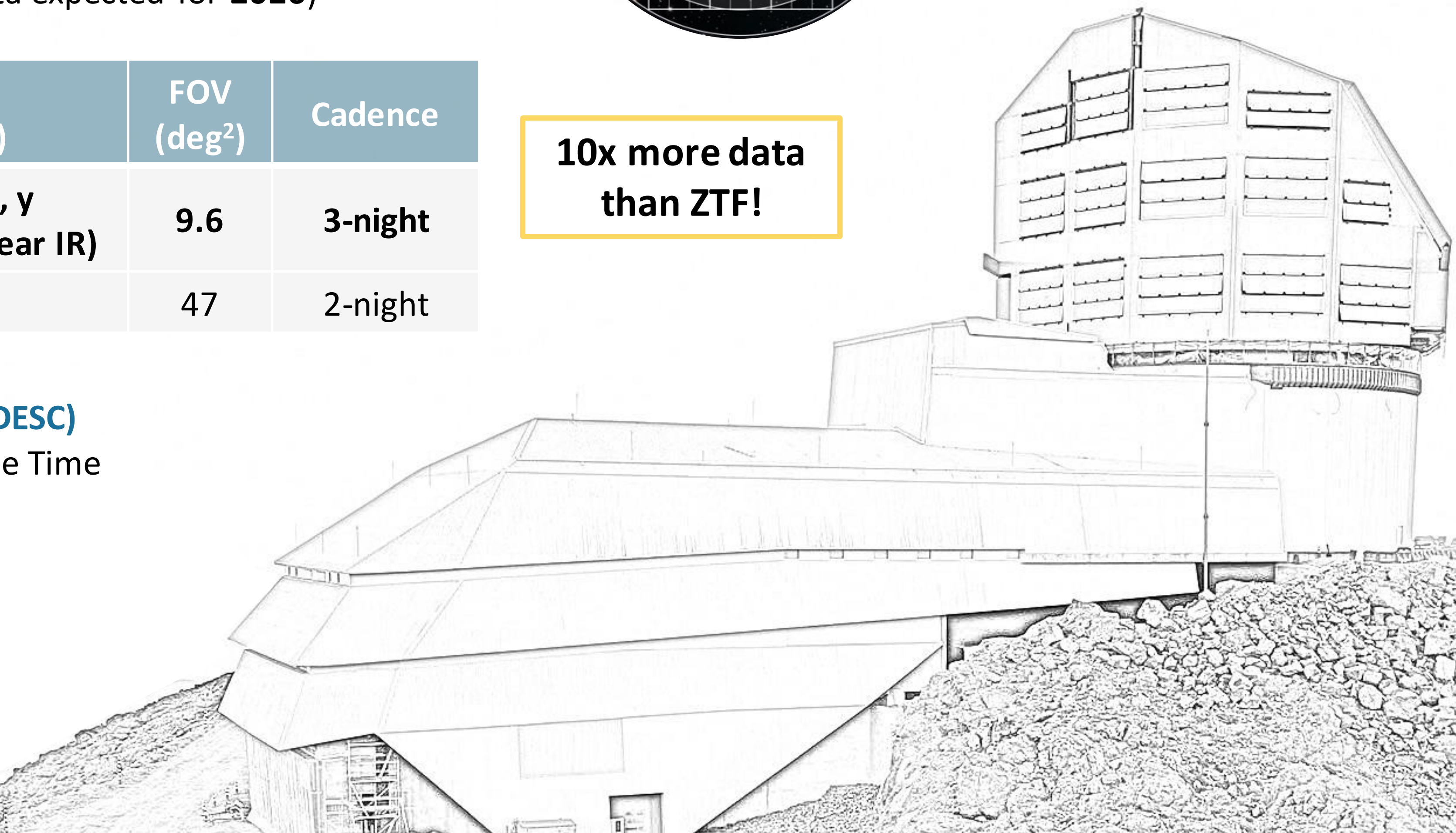
Survey	Nightly limiting magnitude	Filters (optical)	FOV (deg²)	Cadence
LSST	**24.5**	**u, g, r, i, z, y (near UV → near IR)**	**9.6**	**3-night**
ZTF	20.5	g, r, i	47	2-night

10x more data than ZTF!

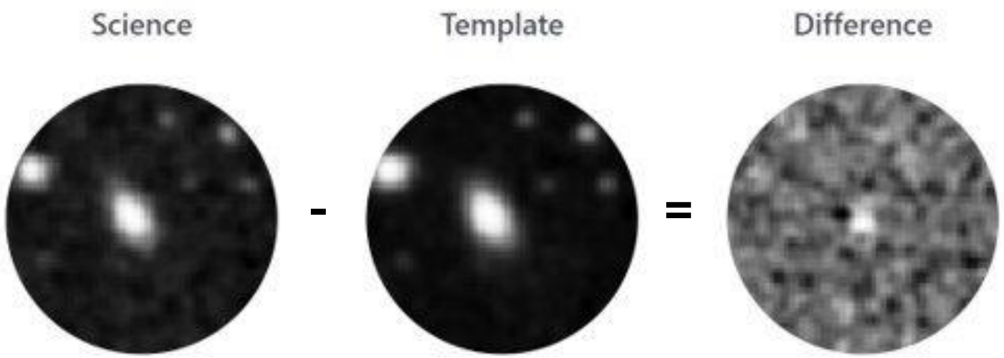
- **The Dark Energy Science Collaboration (DESC)**

Orphan afterglow project approved within the Time Domain working group (https://lsstdesc.org/)

LSST DESC Dark Energy Science Collaboration



THE ALERT BROKER FINK

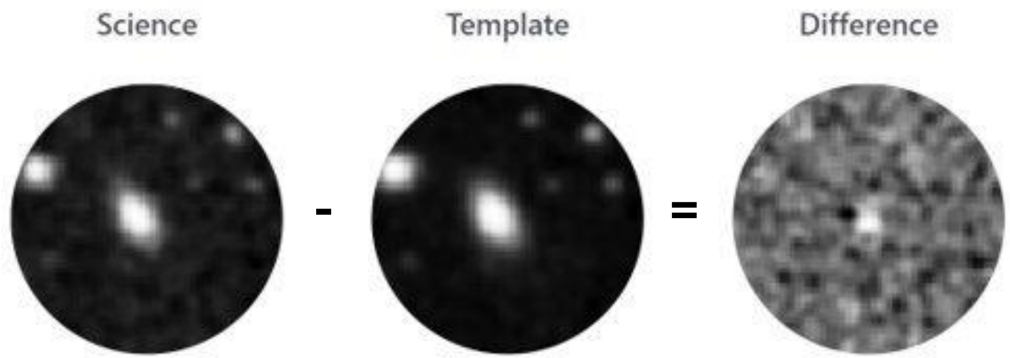


Detection of a source > specified detection threshold in the difference image ⟹ **something has changed in the sky = alert**

COLLABORATIVE CONTEXT

THE ALERT BROKER FINK

https://fink-portal.org/



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Alert broker = software that process data from a telescope:

- Cross-matches with catalogues
- Generate photometric classification based on light curve analyses

FINK = one of the official alert broker of Rubin LSST, developed by the IJCLab IN2P3

SURVEY

LSST — Legacy Survey of Space and Time

20 TB of data / night

10 million alerts / night →

ALERT BROKER

FINK

Filters →

IDENTIFICATION OF THE ALERTS

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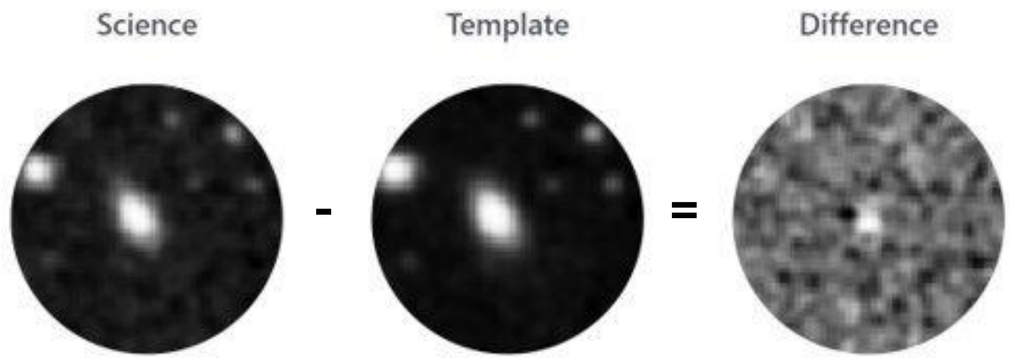

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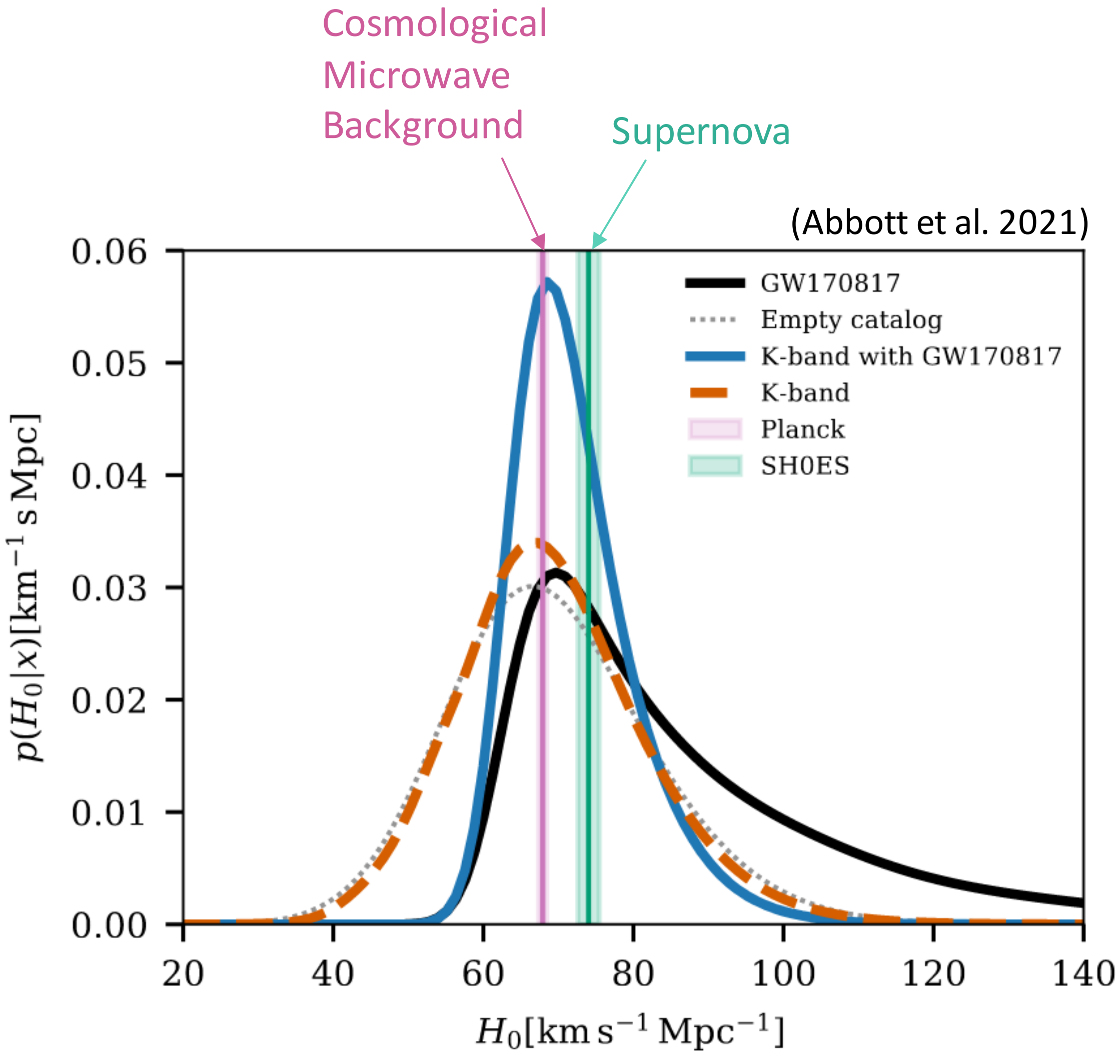
20 TB of data / night

MOTIVATIONS

Goal = **To implement a filter in FINK to identify orphan afterglows in the Rubin LSST data**

Why study orphan afterglows?

- More information on the **GRB physics and their progenitors** (acceleration of particles, jet formation and structure…)
- **Multi-messenger analysis with gravitational waves:** estimate the Hubble constant H_0 (expansion rate of the Universe)

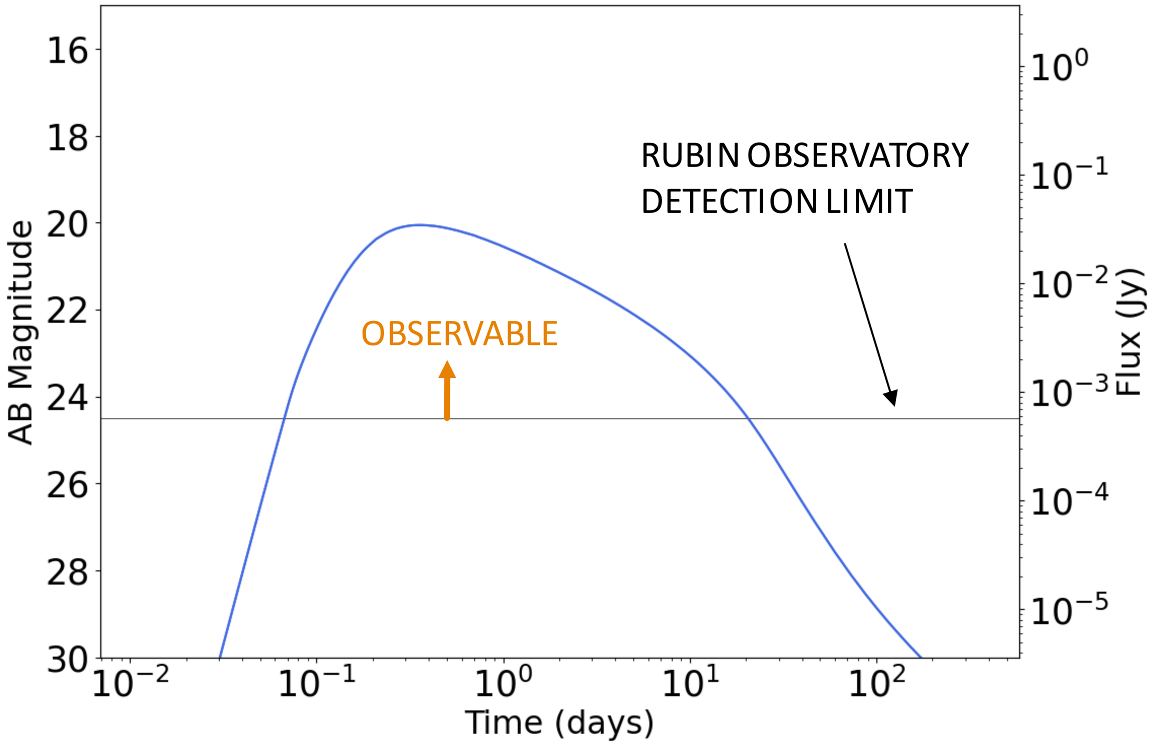


MODEL OF GRB AFTERGLOW EMISSION

MAGNITUDE

- mag ∝ $-\log_{10}$(flux)
- Limit for naked eye ~ 7.2

Identification of orphans based on their light curve



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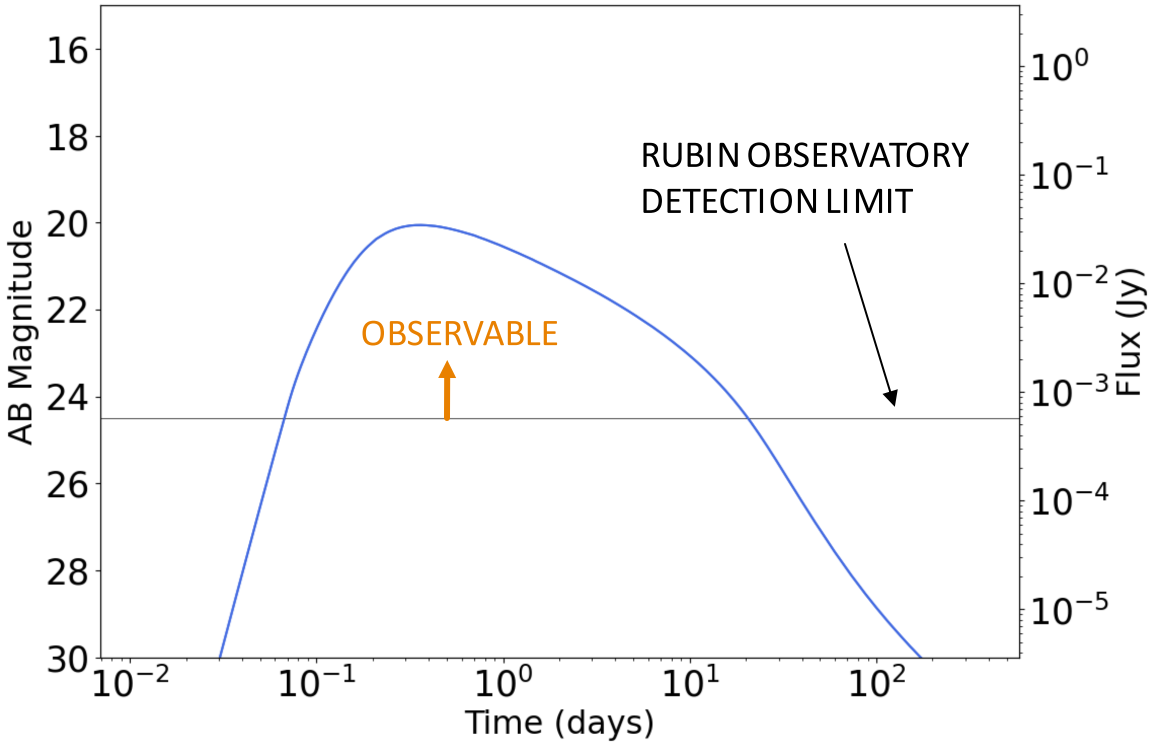
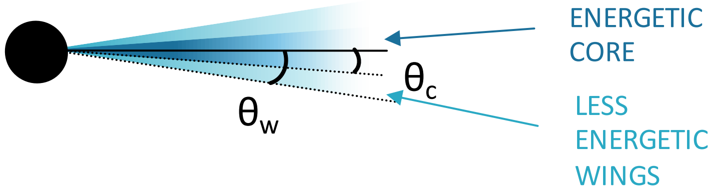


Forward shock model
+ electron synchrotron
(Van Eerten et al. 2010)

Parameters of the model:

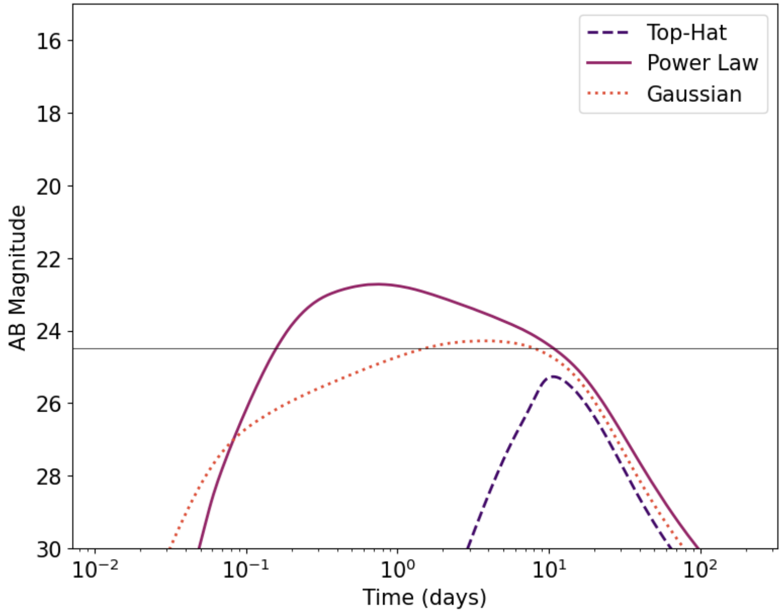
- Energy of the jet E_0
- Ambient medium density n_0
- Redshift z ~ distance
- Observer angle θ_{obs}
- Structure of the jet
  - Core angle θ_c
  - Truncature angle θ_w



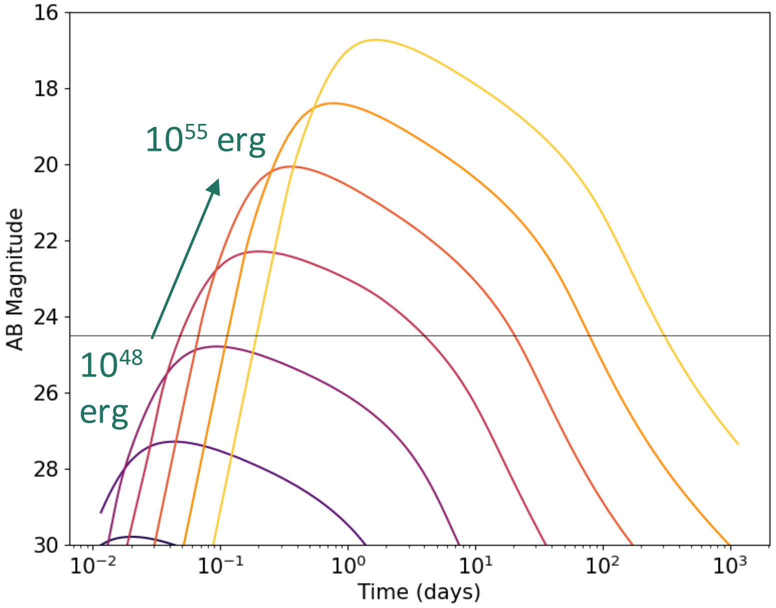
IMPACT OF THE MODEL PARAMETERS ON THE LIGHT CURVE

Scan of the model parameters ⟹ study their impact on the observability of the afterglow

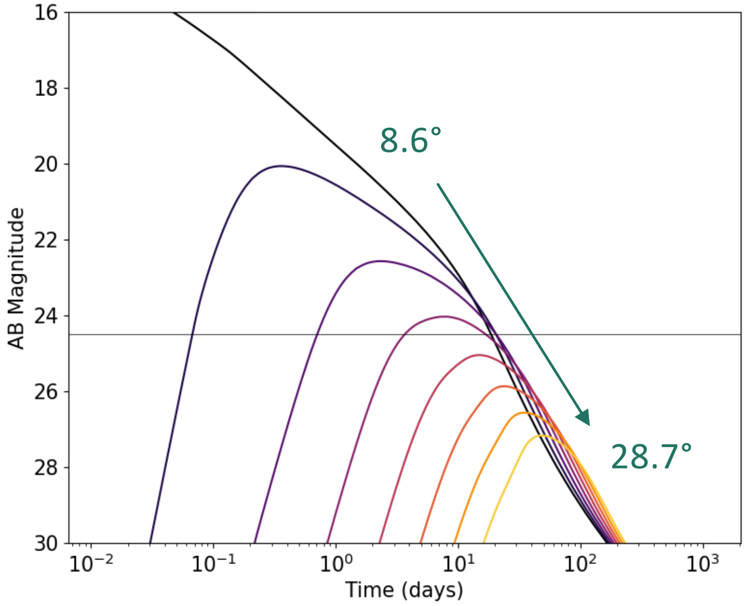
JET STRUCTURE



ENERGY

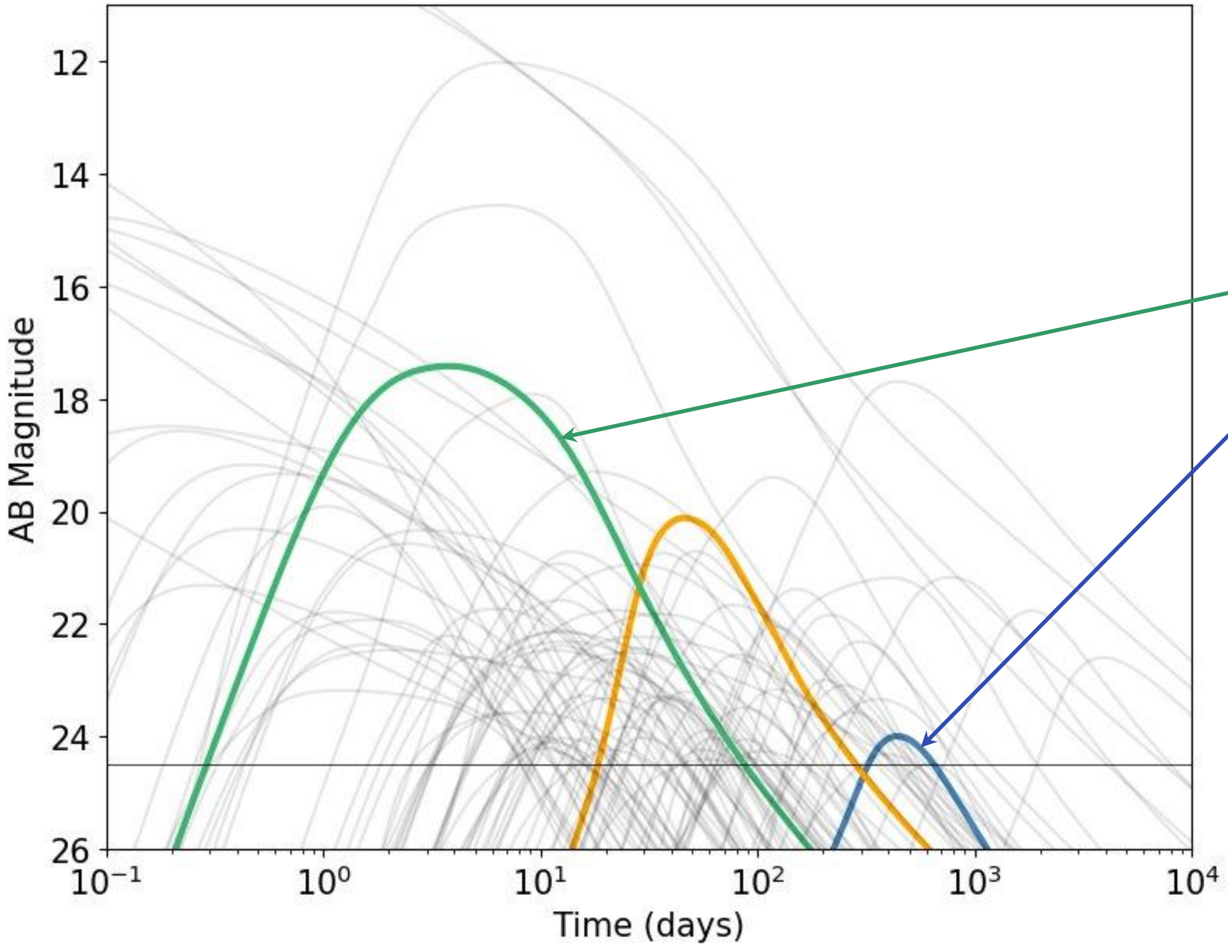


OBSERVER ANGLE



⟹ Impact of parameters on observability may balance out each other
⟹ The parameters space is very large

ORPHAN LIGHT CURVES



Large diversity of light curves:

- Bright and short orphans
- Faint and long orphans
- ...

⟹ Characterizing orphan light curves is not that easy...

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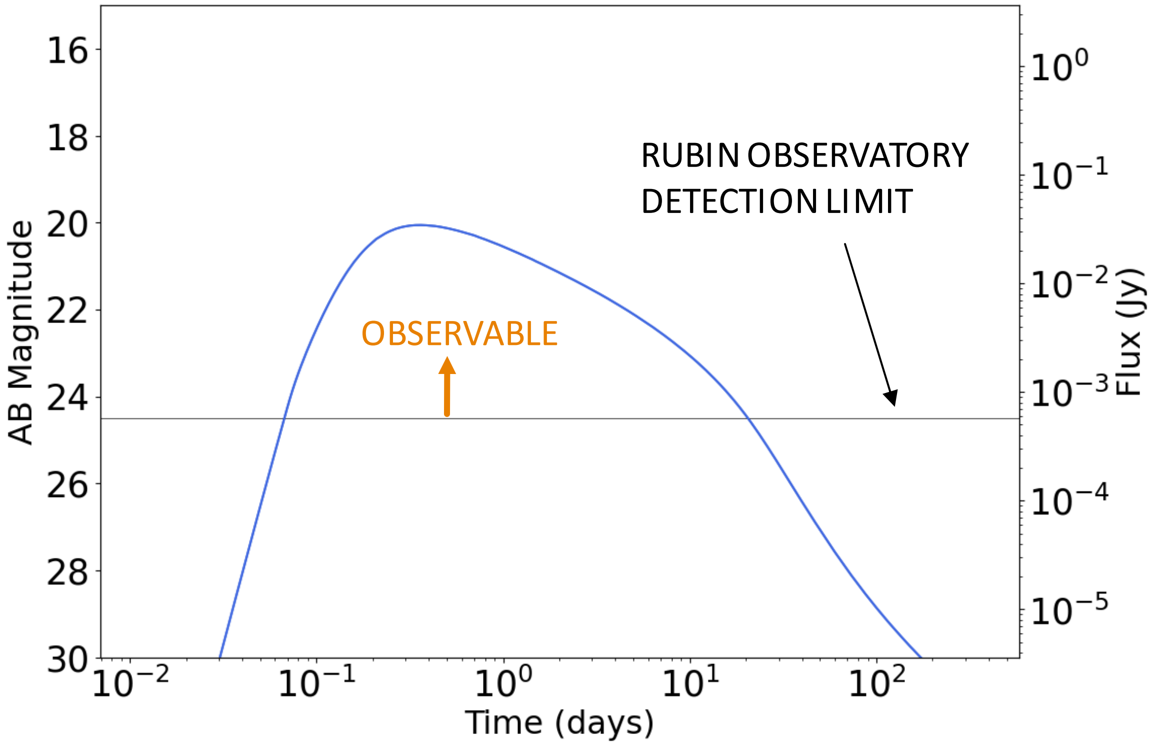

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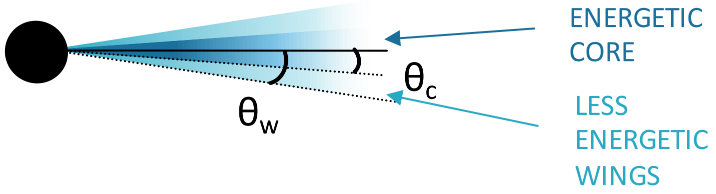
⟹ Need some parameters distributions!

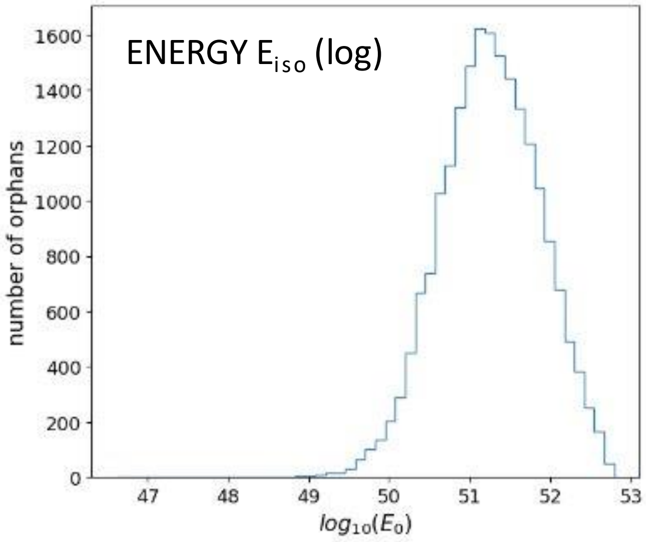


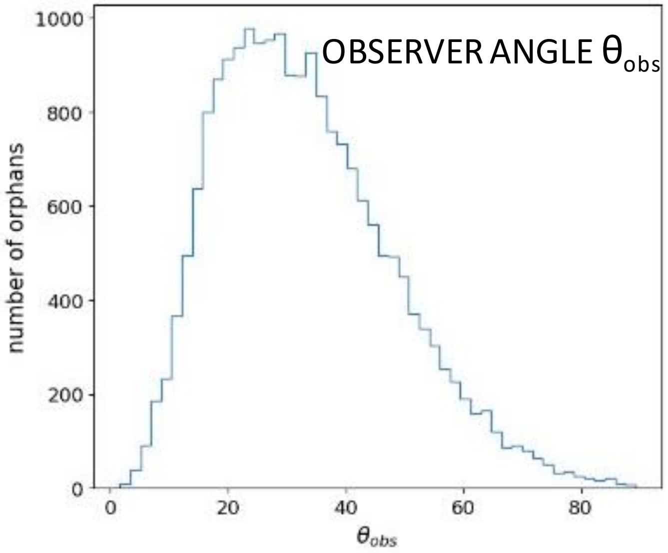
POPULATION OF GRBS BASED ON SBAT4 AND BAT6 CATALOGUES

Goal: To simulate realistic distributions for GRBs

SBAT4 catalogue (D'Avanzo et al. 2014) = selected sample of **short** GRBs observed by the Swift satellite up to June 2013

- Detected in the **15-150 keV energy band**
- Selection criteria: peak flux $\mathbf{PF_{64} > 3.5}$ **ph/s/cm²**





Generate configurations of parameters with uniform distributions

↓

Compute gamma flux that would be received by Swift

↓

GRBs with peak flux > 3.5 ph/s/cm²

↓

Simulated SBAT4-like GRB population: ~500,000 GRBs

SIMULATION OF AN OBSERVATION: A "PSEUDO-OBSERVATION"

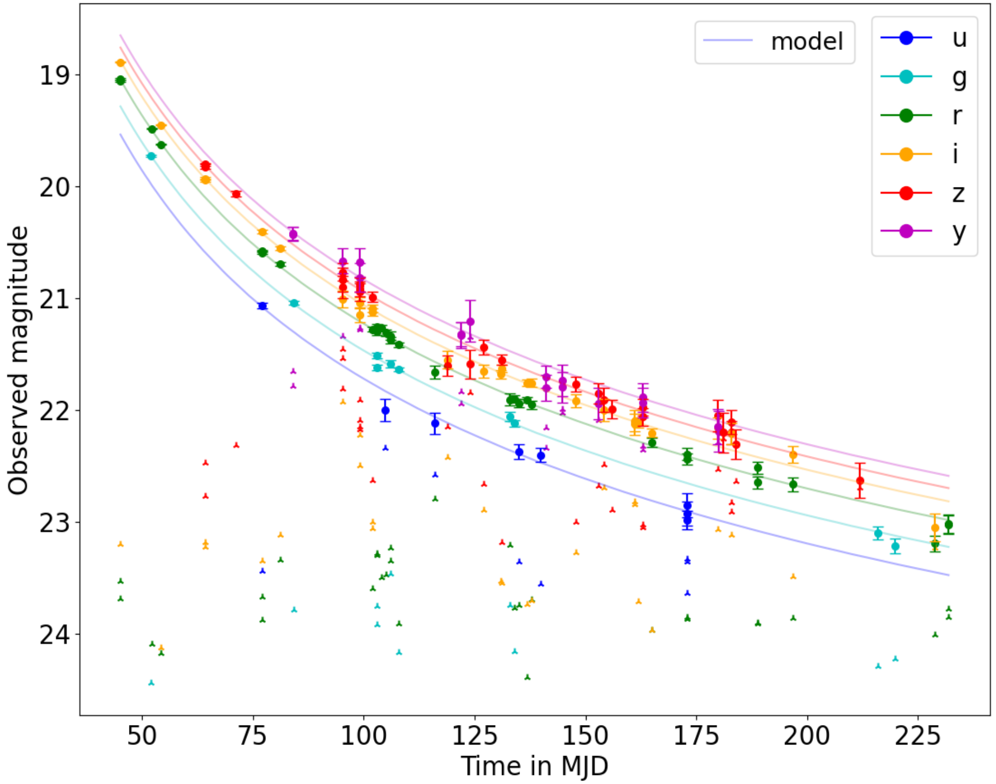
rubin_sim package ⟹ Realisation of the scheduler simulation for the 10 years of LSST (https://github.com/lsst/rubin_sim)

GRB date: 12 March, 2030

GRB coordinates: (19h00m55.04s, -53d23m42.38s)

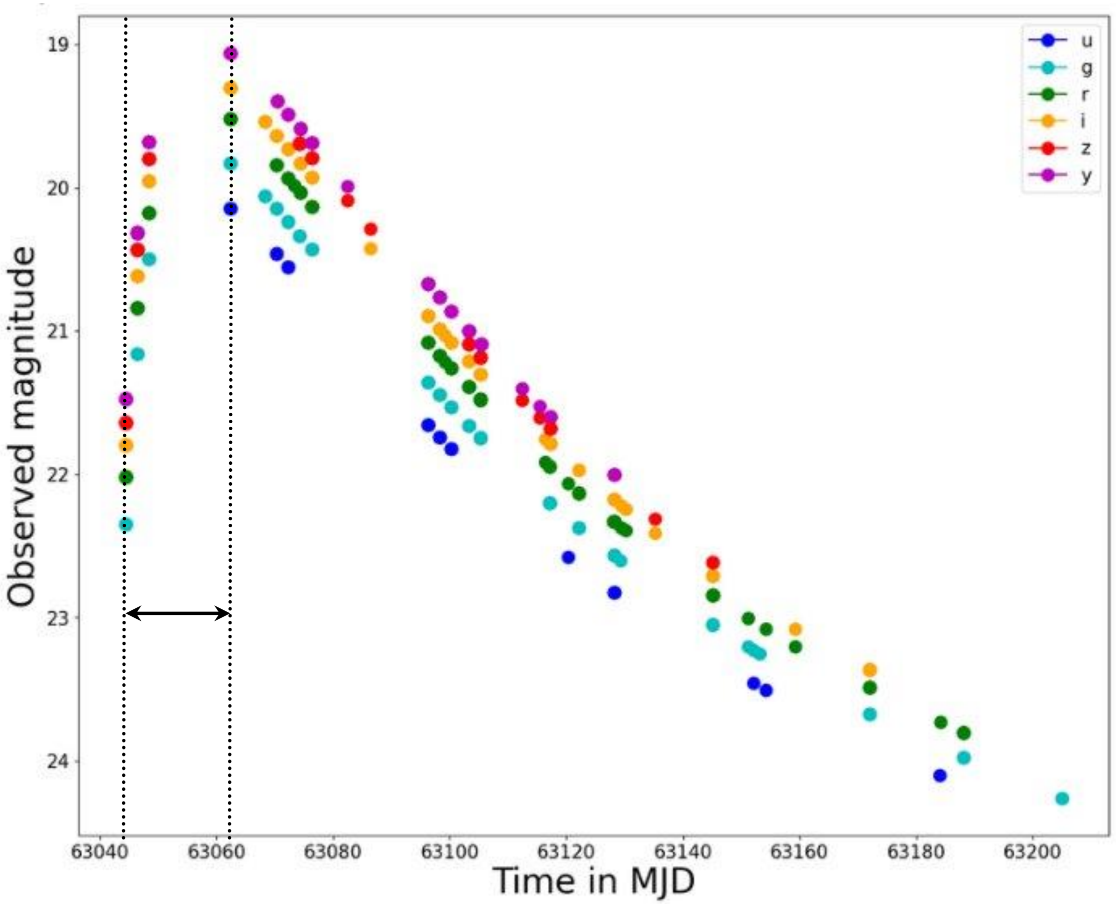
Parameters:

- Power-Law jet
- E_{iso} = 1.3 x 10^{52} erg
- θ_{obs} = 21.2 °
- θ_c = 2.9°
- θ_w = 8.6°
- n_0 = 0.45 cm^{-3}
- z = 0.001 (really close)



⟹ Only ~4 % of orphans have > 1 point in their simulated observations

CHARACTERISATION OF LIGHT CURVES



Defined features:

- **Duration between the first detection and the peak**
- Increase rate of the magnitude
- Decrease rates of the magnitude in the 1st third and the last third of the light curve
- g-r colour (expected value for synchrotron emission ~0.3)

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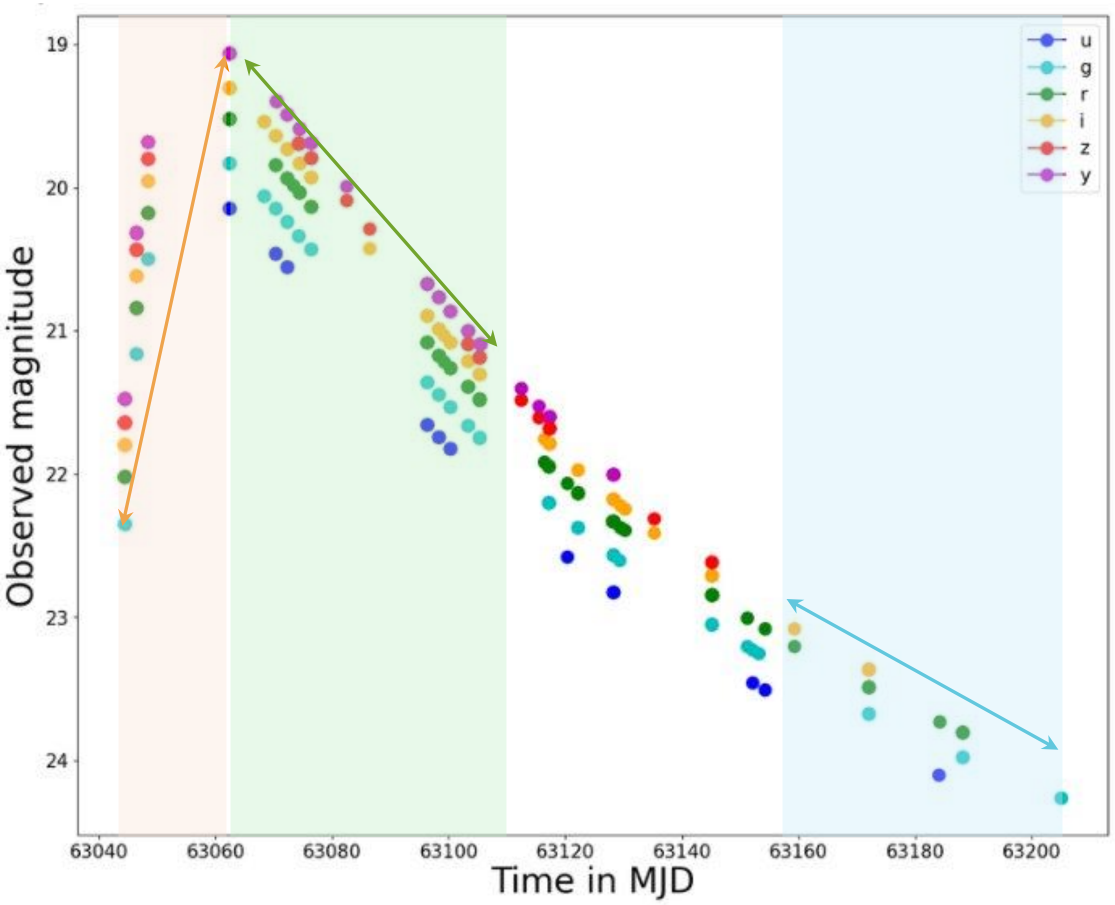

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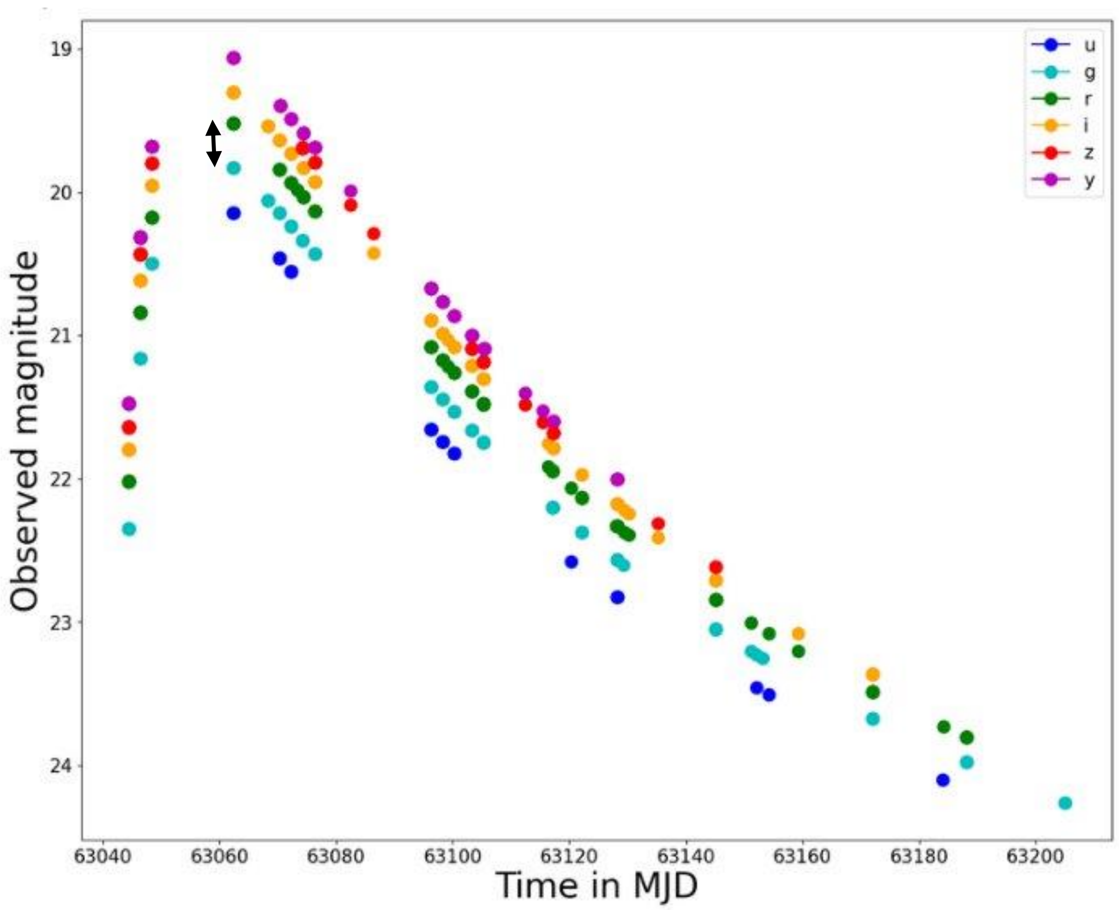

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g-r colour = $mag_{g\text{-}band} - mag_{r\text{-}band}$

FIT OF PSEUDO-OBSERVED LIGHT CURVES

Fit data with a function with free parameters (Russeil et al. (arXiv:2402.04298)):

$$mag(t) = A \times t + B + C \times \exp(-D \times t)$$

Points are rescaled to be on the r-band

RESCALING DATA TO THE R-BAND

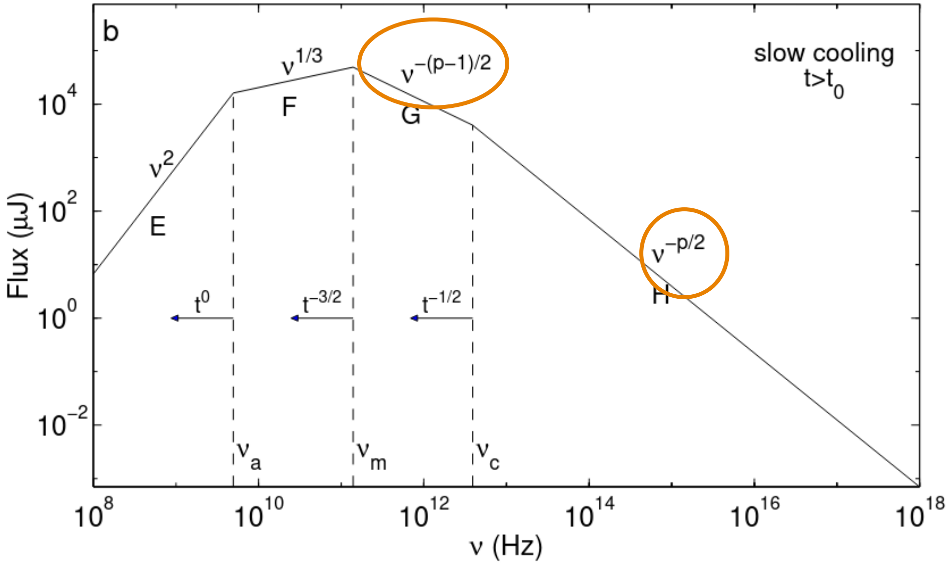
$F_\nu \propto \nu^{-\beta}$

β spectral index

- β = -(p-1)/2 when $\nu_m < \nu < \nu_c$
- β = -p/2 when $\nu_c < \nu$

ν_c decreases with time $\Longrightarrow$ we don't know which value of β we have to use

Sari & Piran 1998



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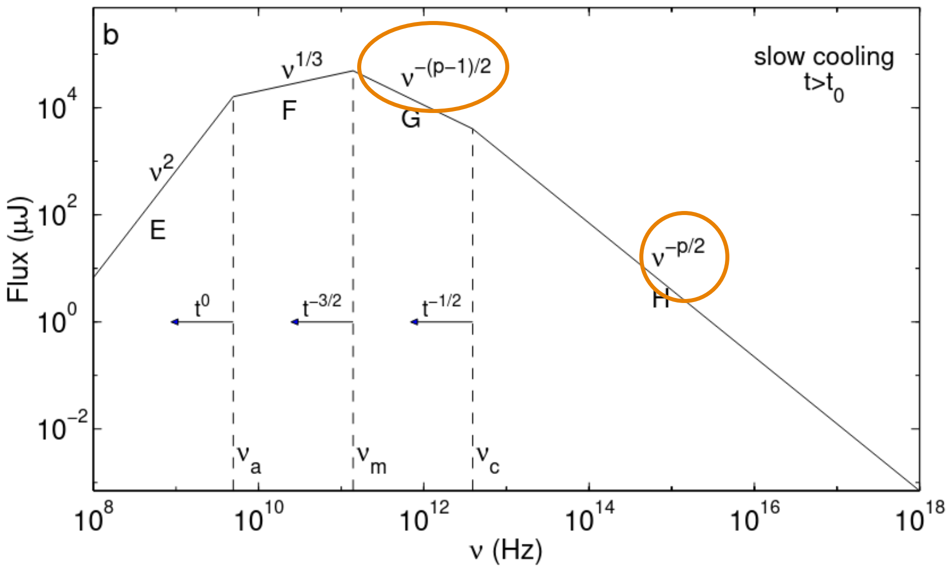
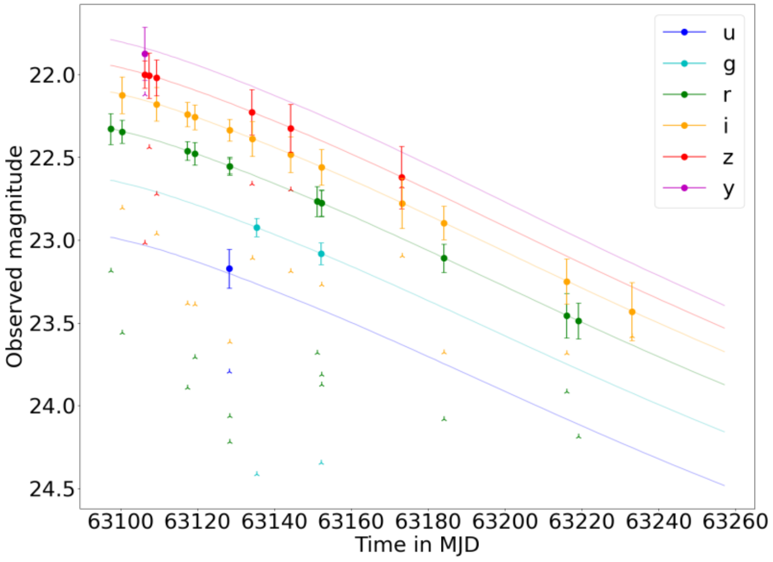
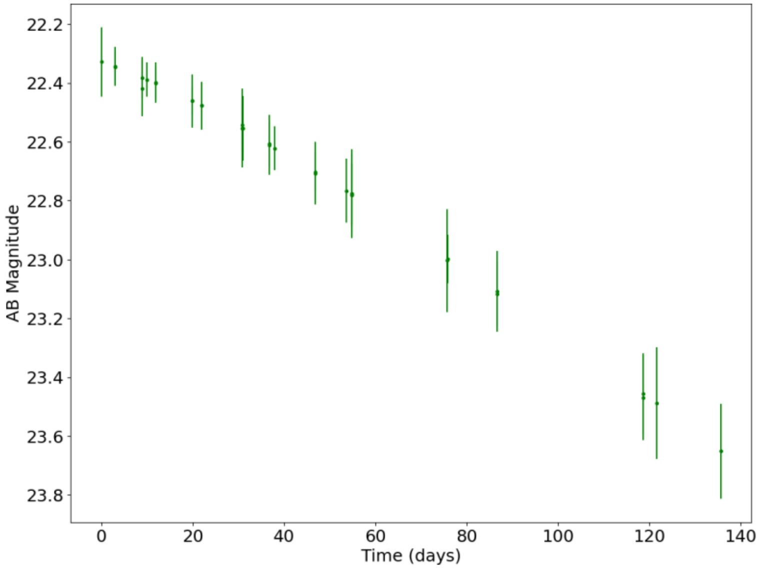


What we do:

1. Test several values of β between -(p-1)/2 and -p/2

2. Keep the one that minimize the distance between the re-scaled points and the true r-band points





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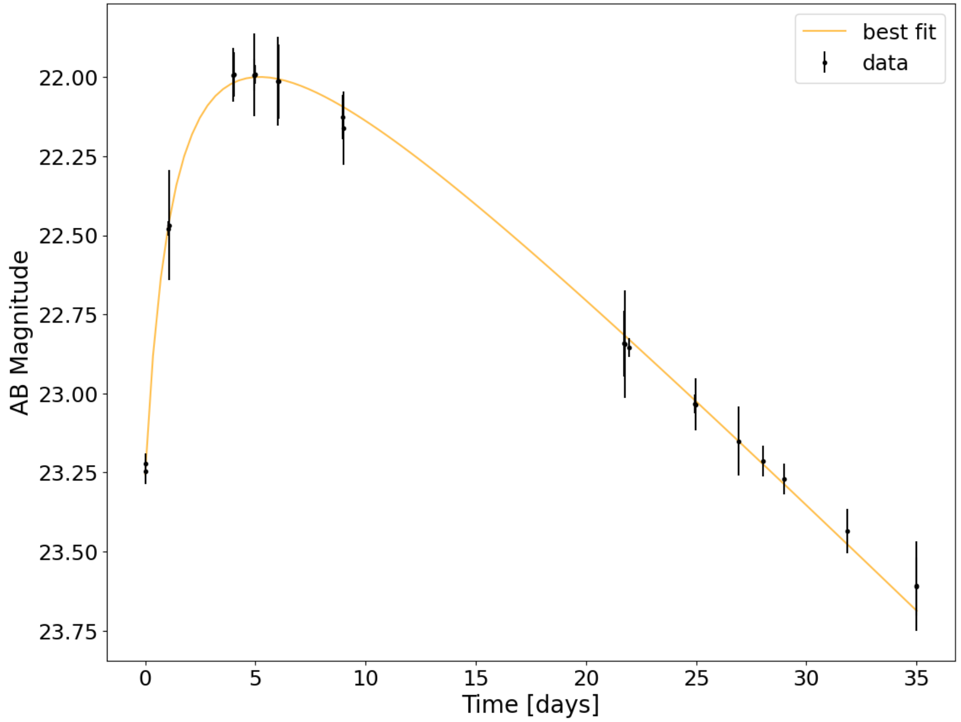


All features used to characterize one event:

$(t_{peak}-t_0)$	Increase rate	Decrease rate (1/3)	Decrease rate (3/3)	Colour	A	B	C	D	χ^2

CREATION OF A CLASSIFIER

USING ELASTICC DATA AS A BACKGROUND

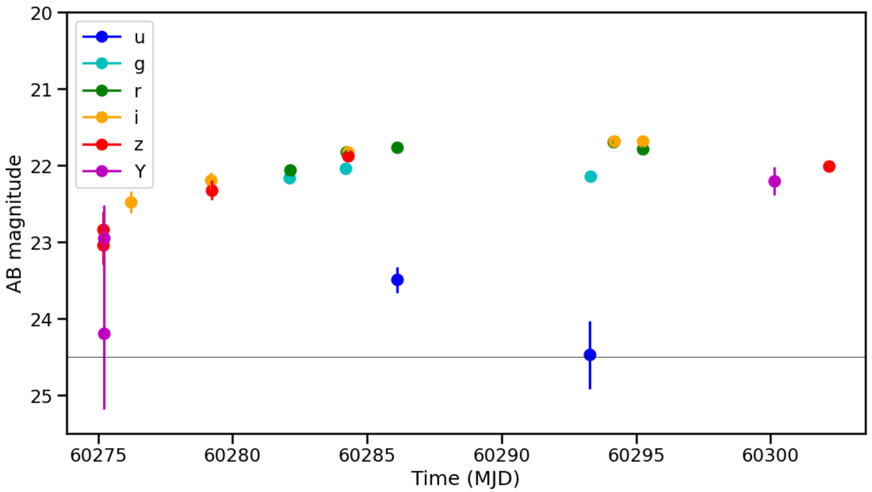
https://portal.nersc.gov/cfs/lsst/DESC_TD_PUBLIC/ELASTICC/

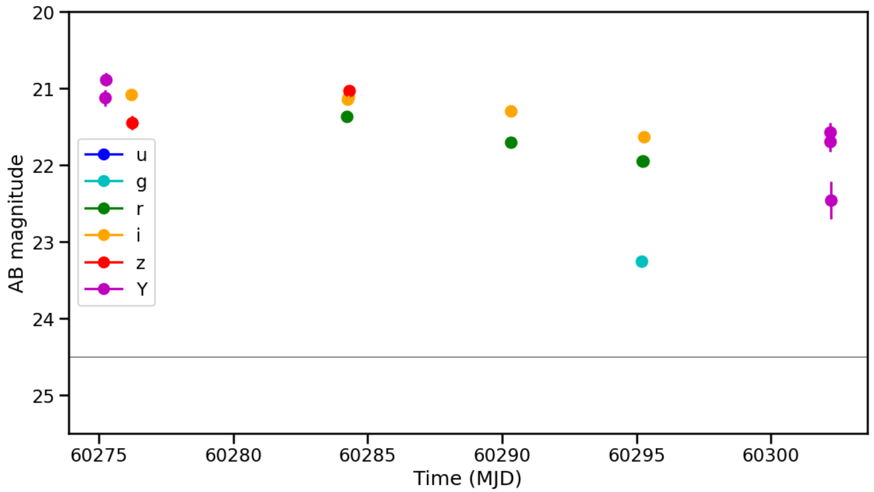
ELAsTiCC = DESC simulation of LSST alerts
(**E**xtended **LSST** **A**stronomical **T**ime-**S**eries **C**lassification **C**hallenge)

Synthetic transient light curves and host galaxies for:

- Supernovae
- Active galactic nuclei
- Tidal disruption events
- Kilonovae
- M-dwarf flares
- Cepheid variables
- …
- **But no orphans!**

⟹ Create a realistic data stream to test broker alert systems and classifiers





EXAMPLES OF ELASTICC LIGHT CURVES

CREATION OF A CLASSIFIER

FIRST TEST OF A MACHINE LEARNING ALGORITHM

TRAINING

500 orphans
5000 ELAsTiCC events

(only non-periodic events)

→ **features** →

ML CLASSIFIER
scikit.learn Gradient Boosting Classifier

→

TESTING

679 orphans
10000 ELAsTiCC events

FIRST TEST OF A MACHINE LEARNING ALGORITHM

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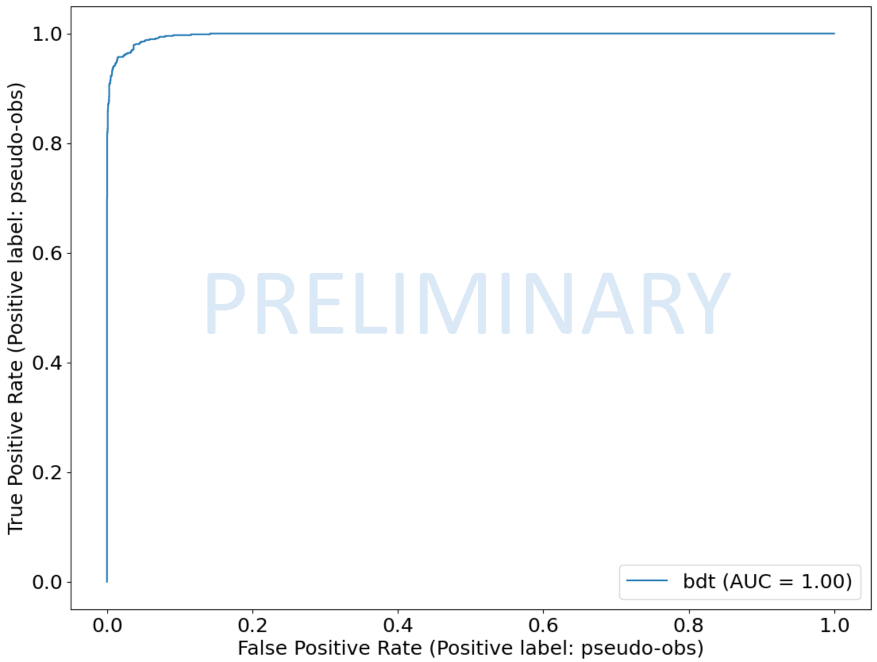
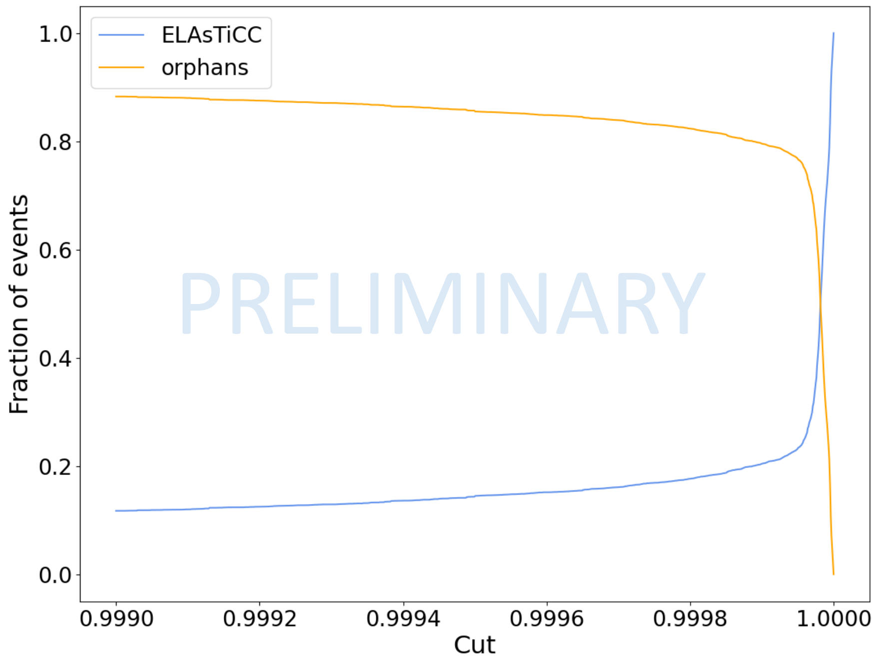
→ **cut = 0.999** →

PRELIMINARY

453/679 orphans
1/10000 ELAsTiCC

(only non-periodic events)





FIRST TEST OF A MACHINE LEARNING ALGORITHM

(Work presented to the Rencontres de Moriond conference 2024)

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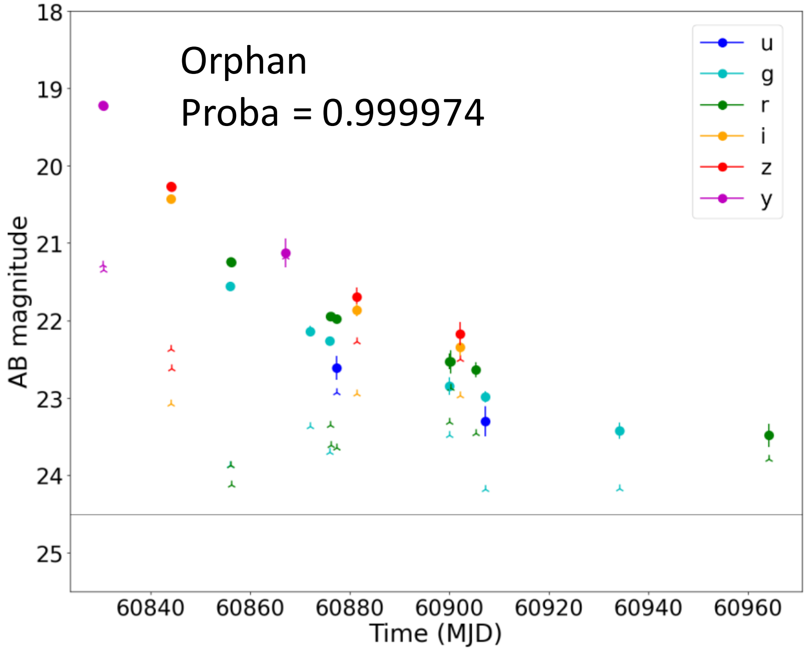

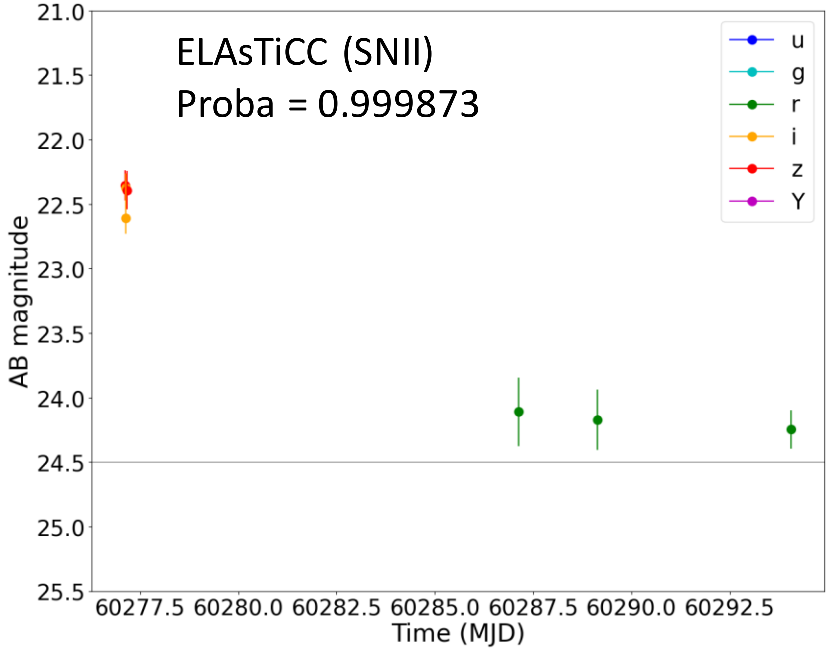

CONCLUSION & PERSPECTIVES

GOAL **Implement a filter in FINK to identify orphan GRB afterglows among Rubin LSST data** (code available on Gitlab)

CONCLUSION

Simulation of a population of GRBs based on Swift BAT catalogues and their observations by Rubin LSST

Characterise "pseudo-observed" light curves of orphan GRBs

Create ML filter to discriminate orphans among LSST data

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THANK YOU FOR YOUR ATTENTION!

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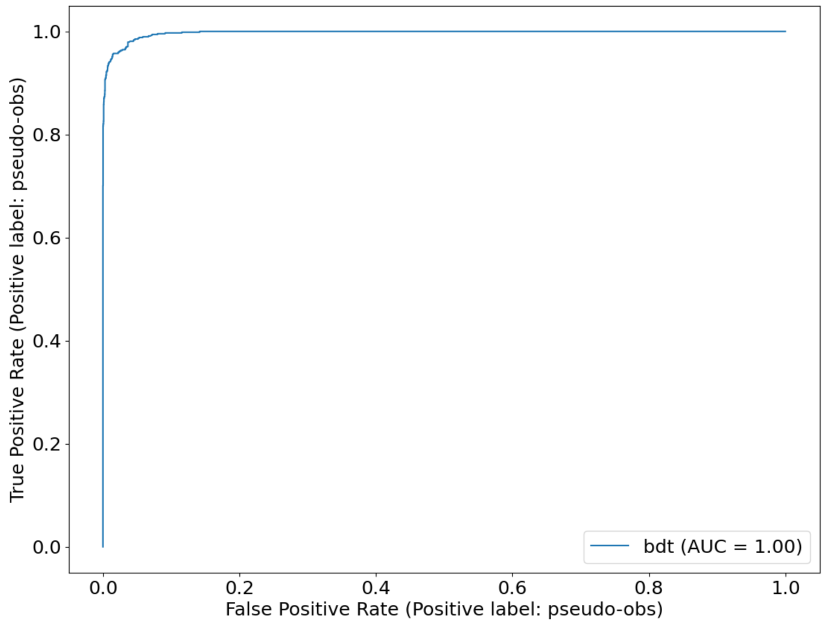
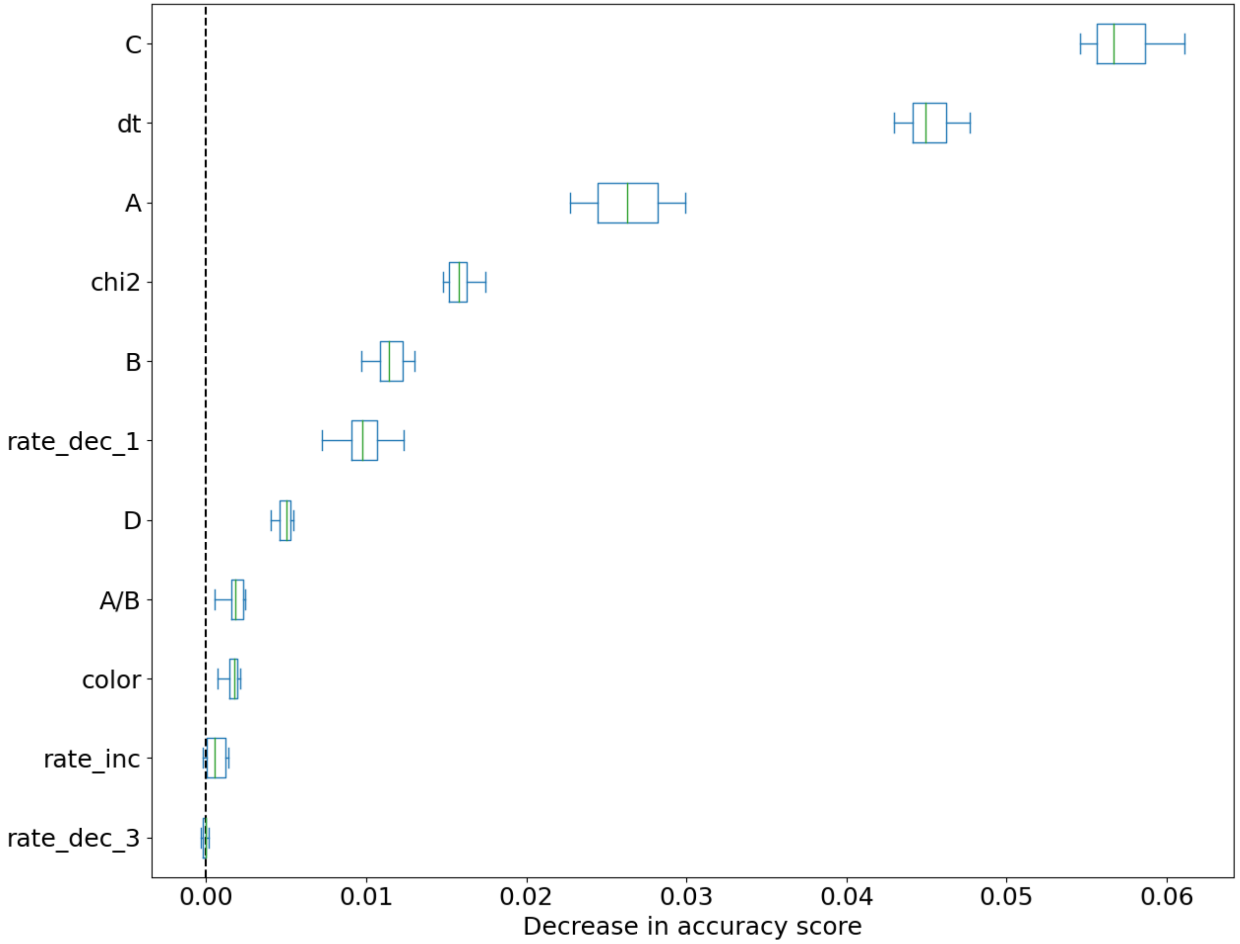
BACKUP SLIDES

MORE DETAILS ON THE CLASSIFIER

150 decision trees
learning_rate = 0.1
max_depth = 5

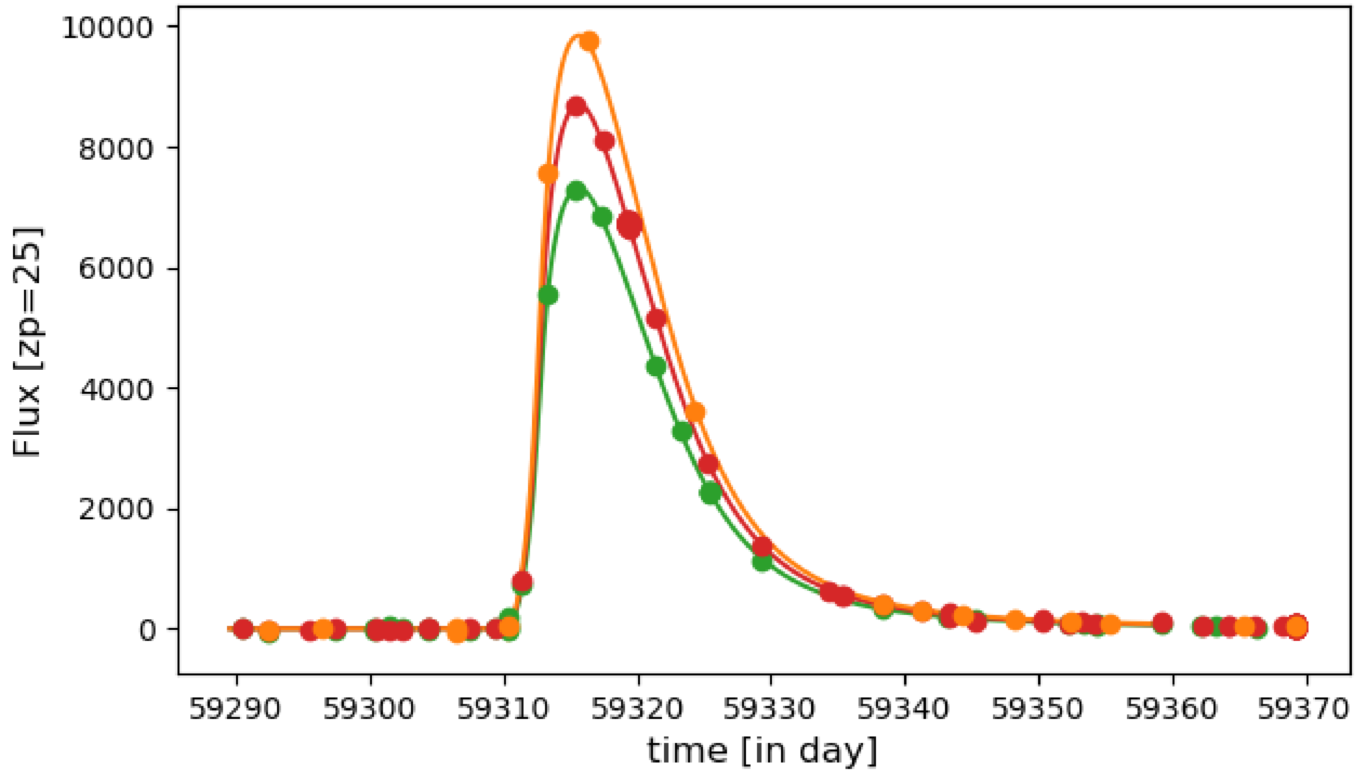




LOOKING INTO ZTF DATA

`skysurvey` package ⟹ Simulate astronomical targets as they would be observed by a survey (https://github.com/MickaelRigault/skysurvey)

Survey	Nightly limiting magnitude (r-band)	Filters	FOV (deg^2)	Cadence
LSST	24.5	u, g, r, i, z, y	9.6	3-night
ZTF	**20.5**	**g, r, i**	**47**	**2-night**

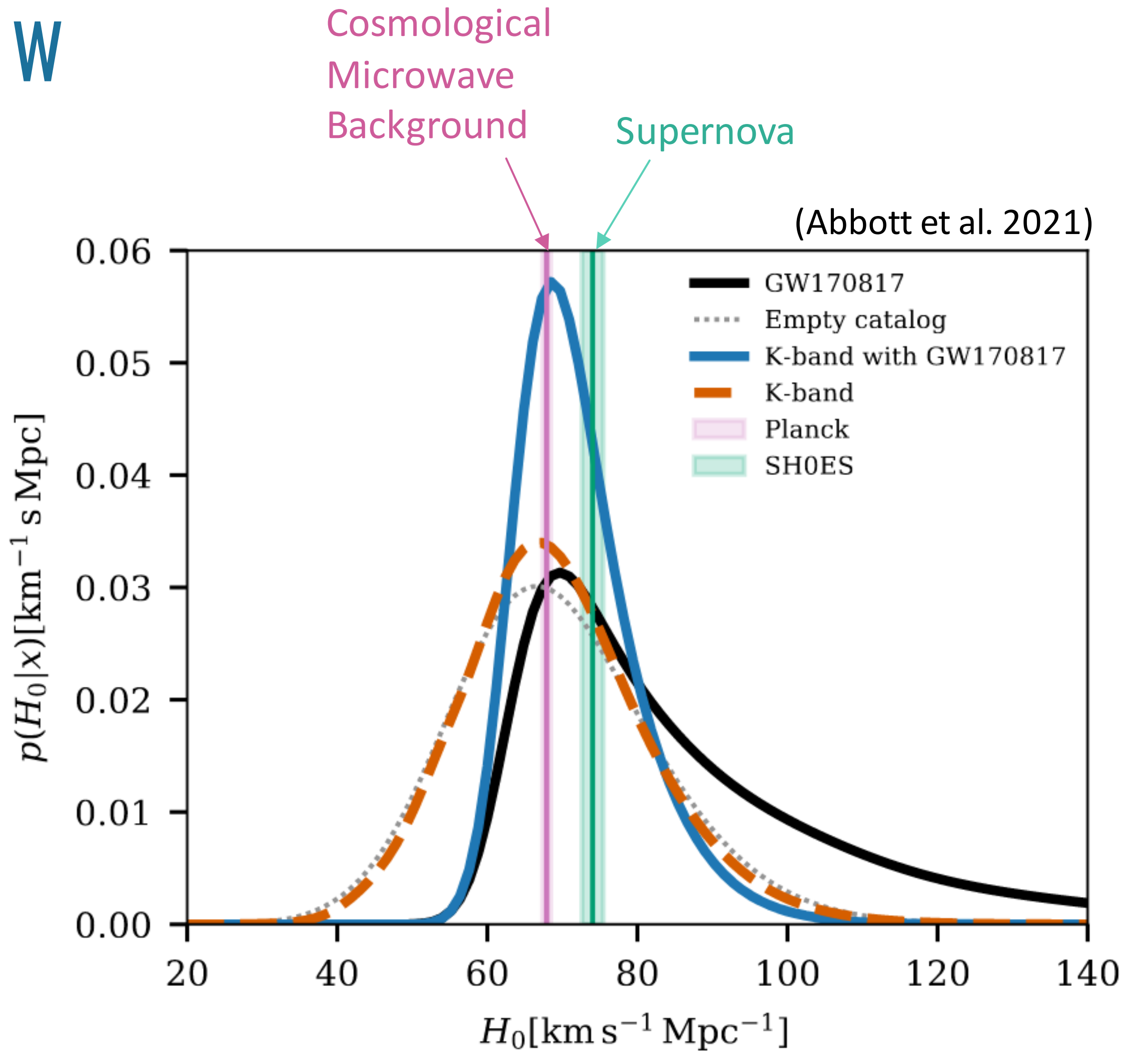


MULTI-MESSENGER ANALYSIS WITH GW

Multi-messenger analysis with gravitational waves: estimate the Hubble constant H_0 (expansion rate of the Universe)

For $z << 1$:

$$d_L \approx \frac{cz}{H_0}$$



GRAVITATIONAL WAVE COUNTERPART

- Specific analysis needed because we have a precise position but large uncertainties on T_0 for orphans

- GWTC-3 catalogue all-sky triggers: given a position, look for synchronised GW signals

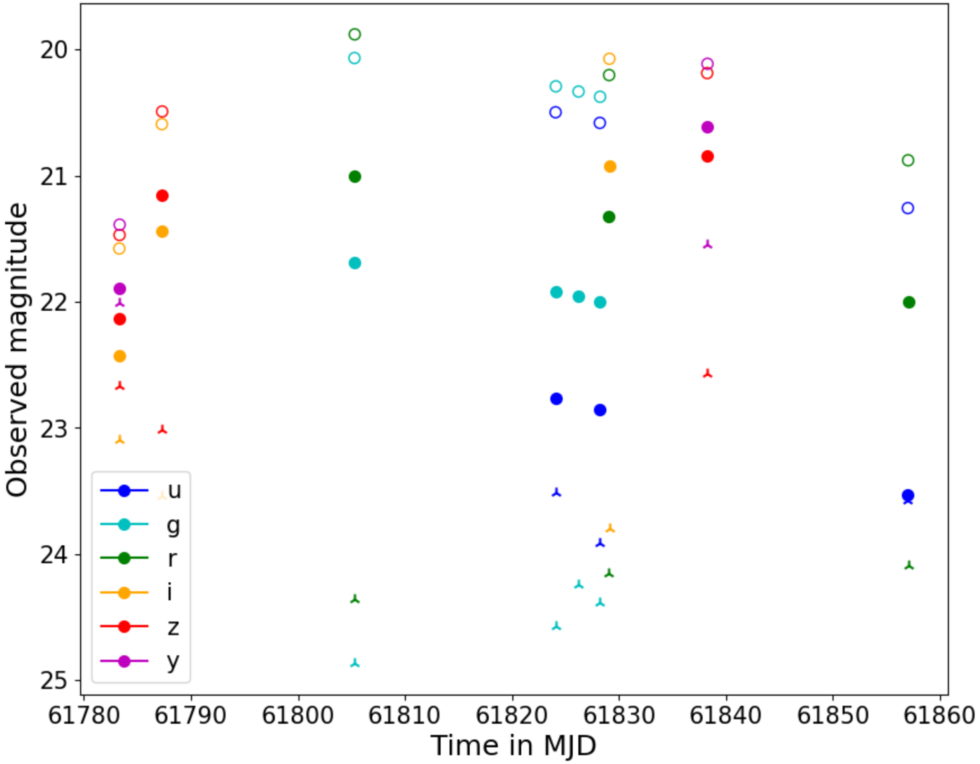
- How the size of the time window for the PyCBC coherent analysis impacts the number of detected events?

HOST EXTINCTION

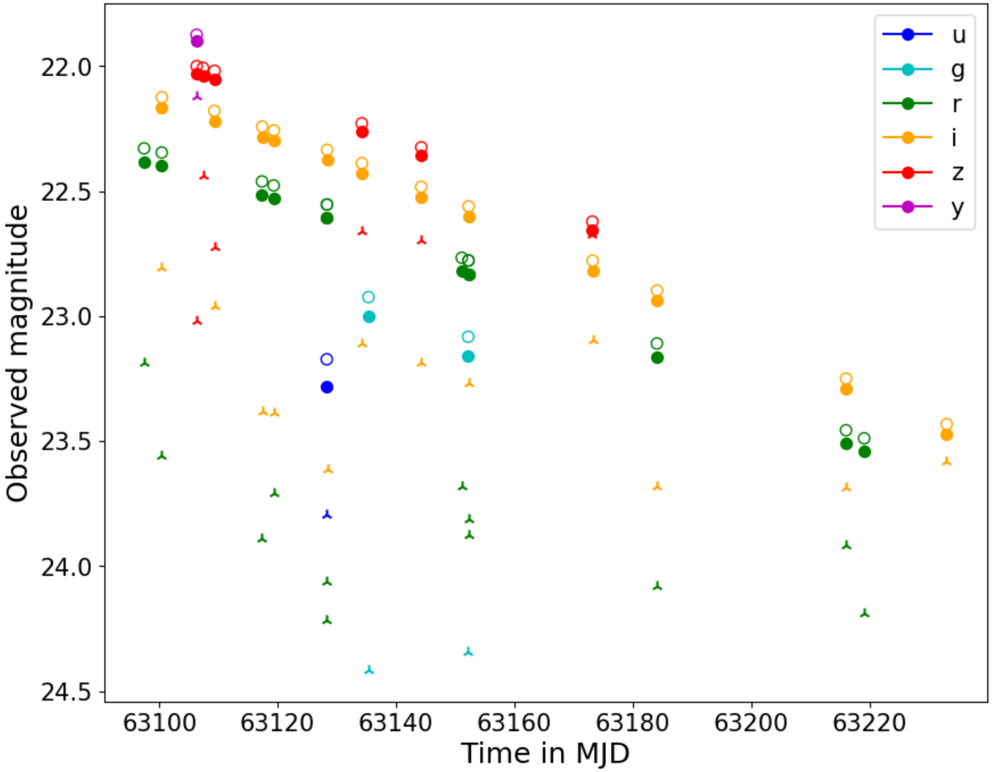
Without extinction

With extinction

Host extinction more important for long GRBs than for short GRBs



LONG



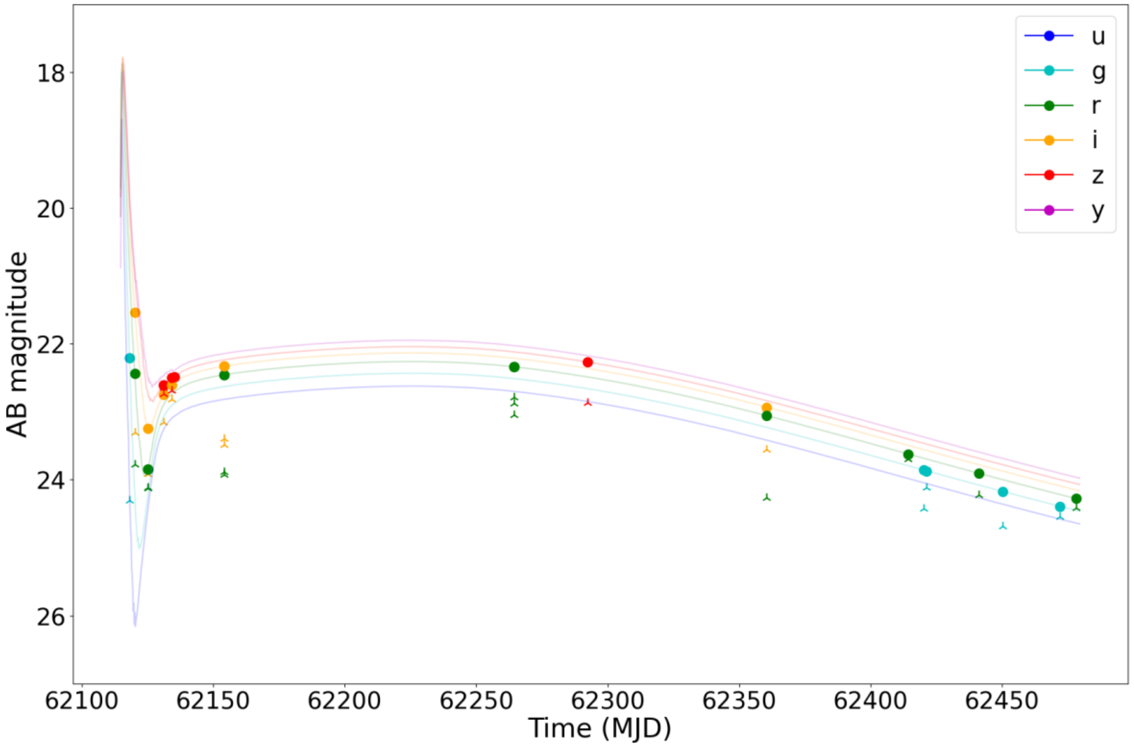
SHORT

KILONOVA OVERLAP

CORE-COLLAPSE SUPERNOVA
⟹ long GRBs + supernova
(GRB980425 + SN1998bw)

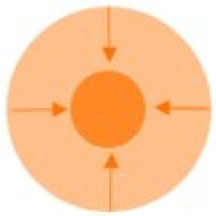
NEUTRON STAR MERGER
⟹ short GRBs + kilonova
(GRB 170817 + AT 2017gfo)

Collaboration with the Osservatorio Astronomico di Brera, Italy



⟹ KN light curve may appear at early times
⟹ Quantify impact of KN on light curve features

SUPERNOVA OVERLAP



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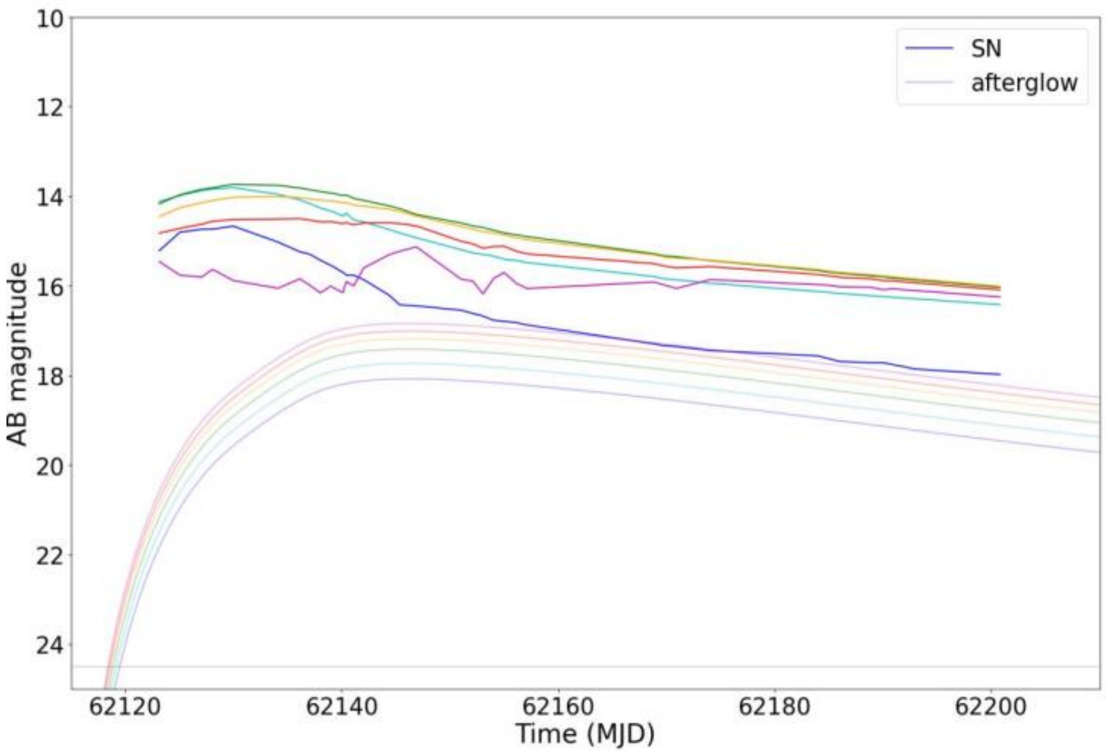

⟹ Orphan light curve "hidden" by the SN light curve
⟹ Impact of the orphan on the SN light curve seen at later times