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

- ACME Workshop -

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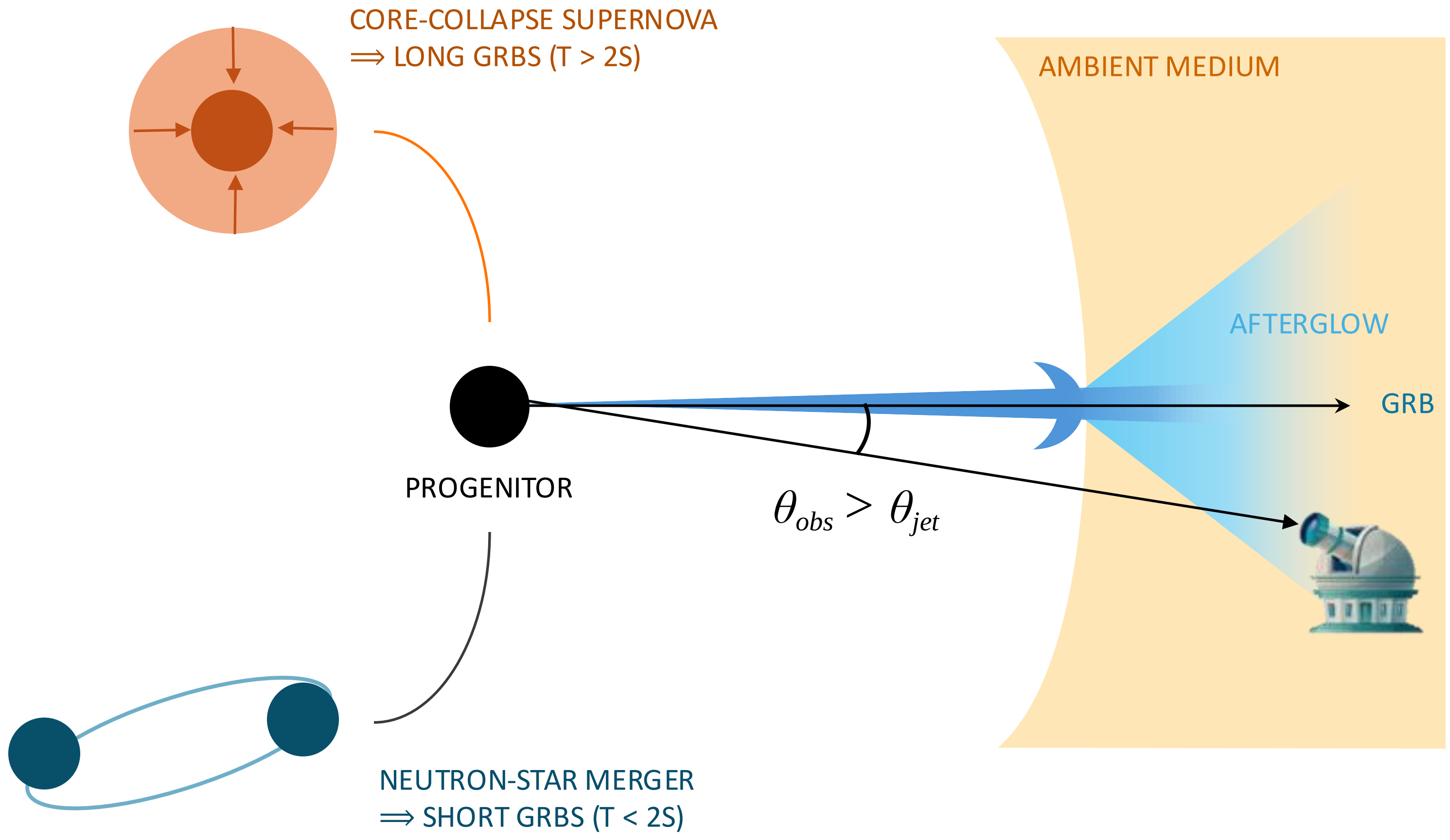
** Institute of Engineering Univ. Grenoble Alpes*

7-11 April, 2025

THE ORPHAN AFTERGLOW: A GRB VIEWED OFF-AXIS



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

Afterglow = long-lasting and fading emission following the gamma prompt emission

Orphan afterglow = afterglow observed off-axis (without gamma-ray emission)
⟹ **Hard-to-find, faint and slow transients!**
(Just a few candidates discovered so far)

https://www.lsst.org/

THE VERA C. RUBIN OBSERVATORY

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

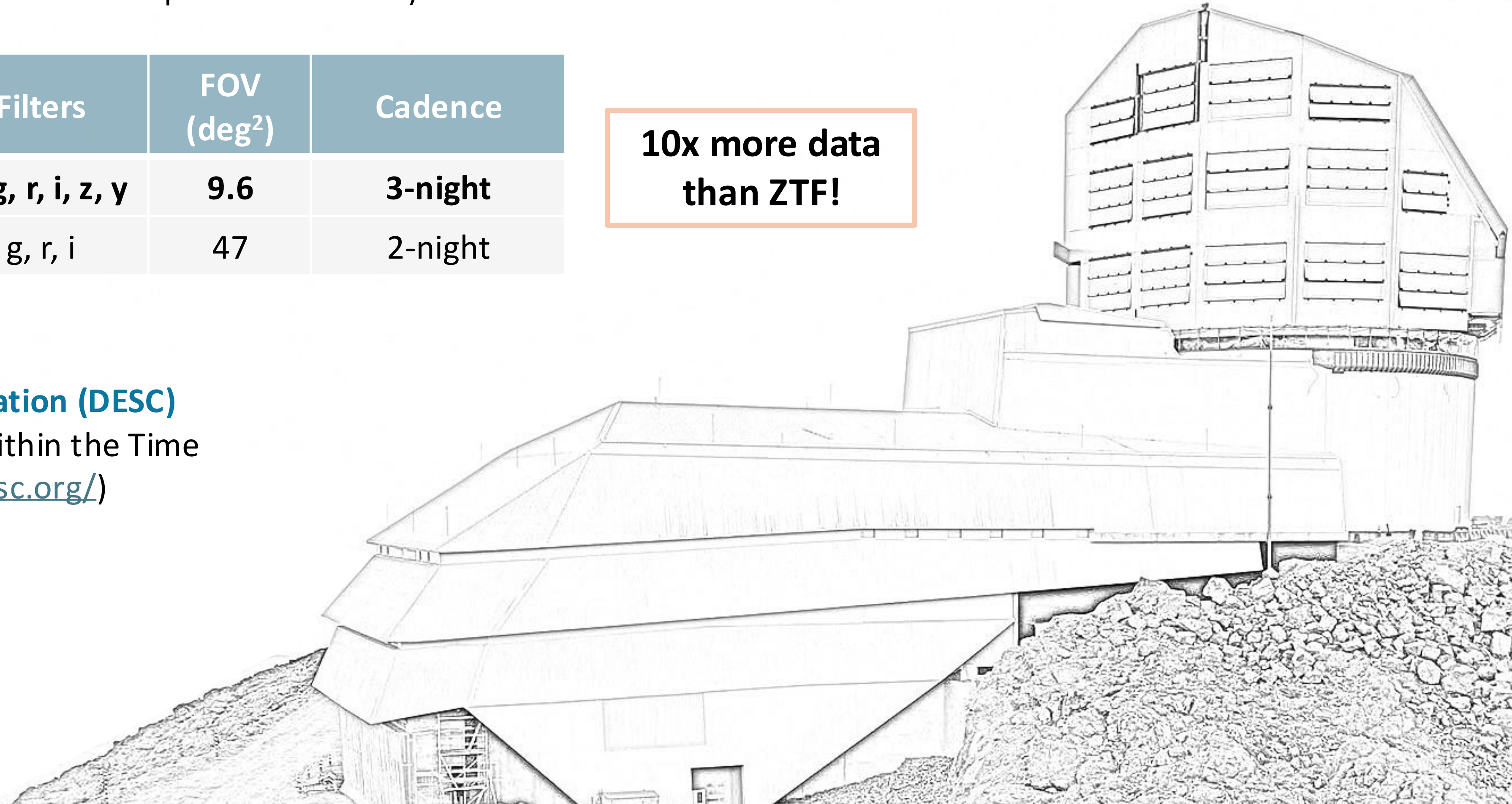
⟹ **Explore the transient optical sky** (first data expected for **2025!**)

Survey	Nightly limiting magnitude	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

10x more data than ZTF!

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

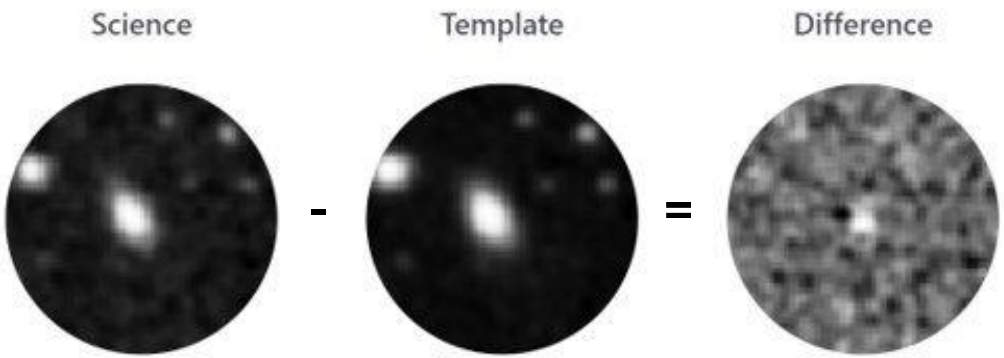
Orphan afterglow project approved within the Time Domain working group (https://lsstdesc.org/)



THE ALERT BROKER FINK

https://fink-portal.org/

See Emille's talk



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

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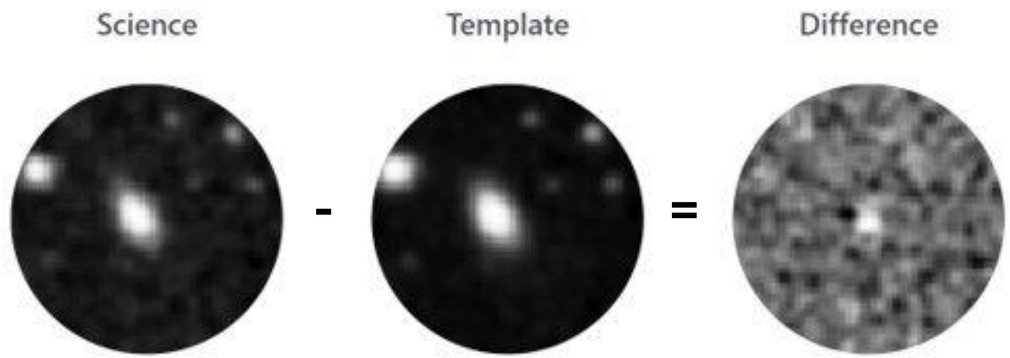

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Alert broker = software that process data from a telescope:

- 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

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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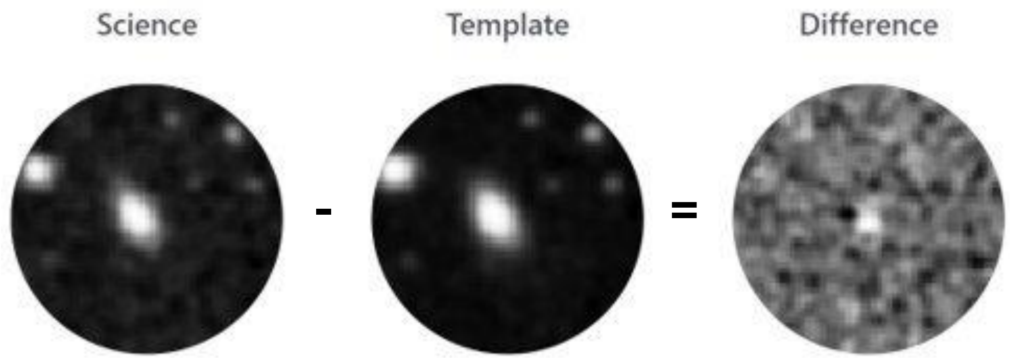

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FINK

This work!

Filters →

IDENTIFICATION OF THE ALERTS

MOTIVATIONS

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

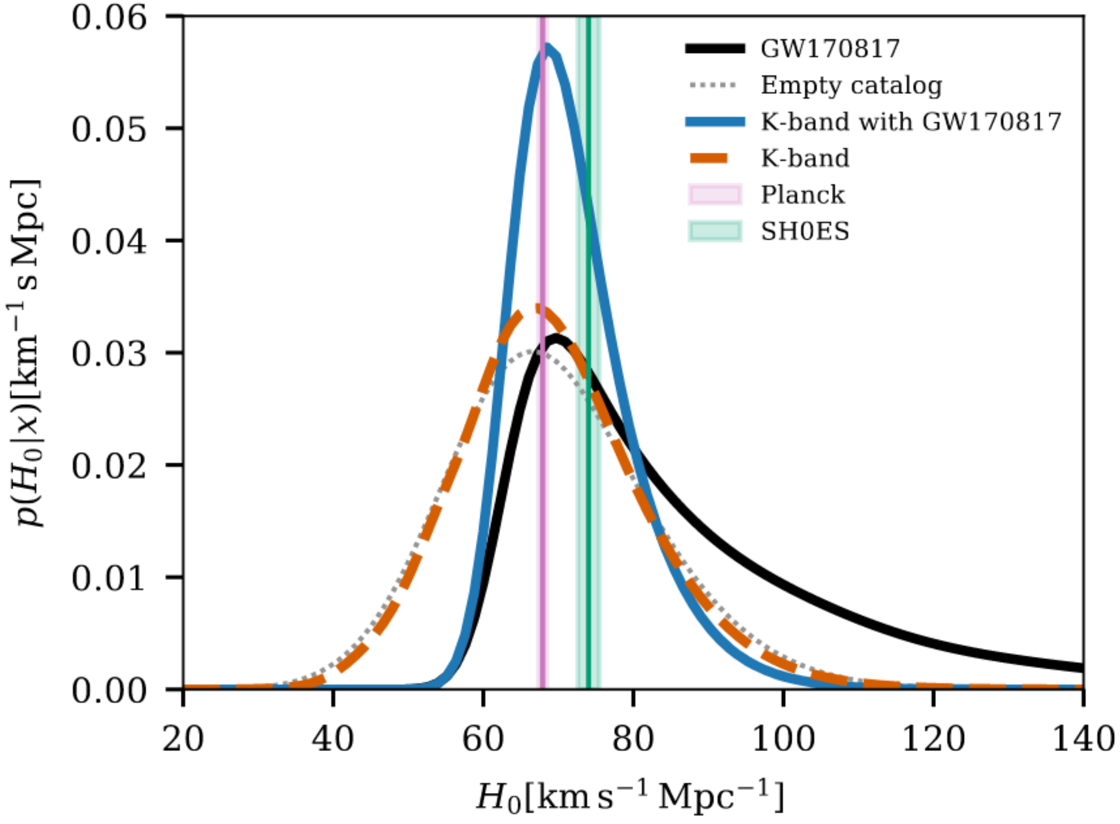
Why study orphan afterglows?

- More information on the **GRB physics and their progenitors** (acceleration of particles, jet formation and structure...)

- **Multi-messenger analysis with gravitational waves: separate measure of the distance and the redshift to calculate the Hubble constant H0**

$$d_L(z) = \frac{cz}{H_0}$$

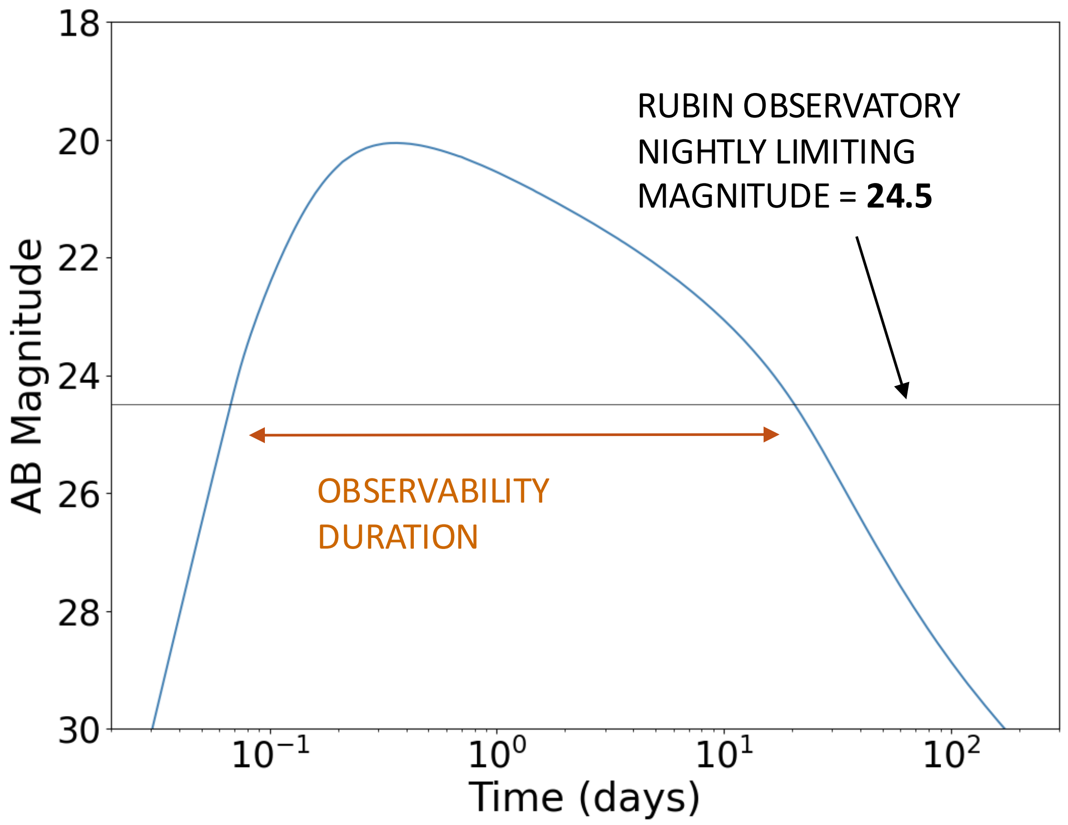
Abbott et al. 2021



https://github.com/geoffryan/afterglowpy

MODEL OF GRB AFTERGLOW EMISSION

Identification of orphans based on their light curve



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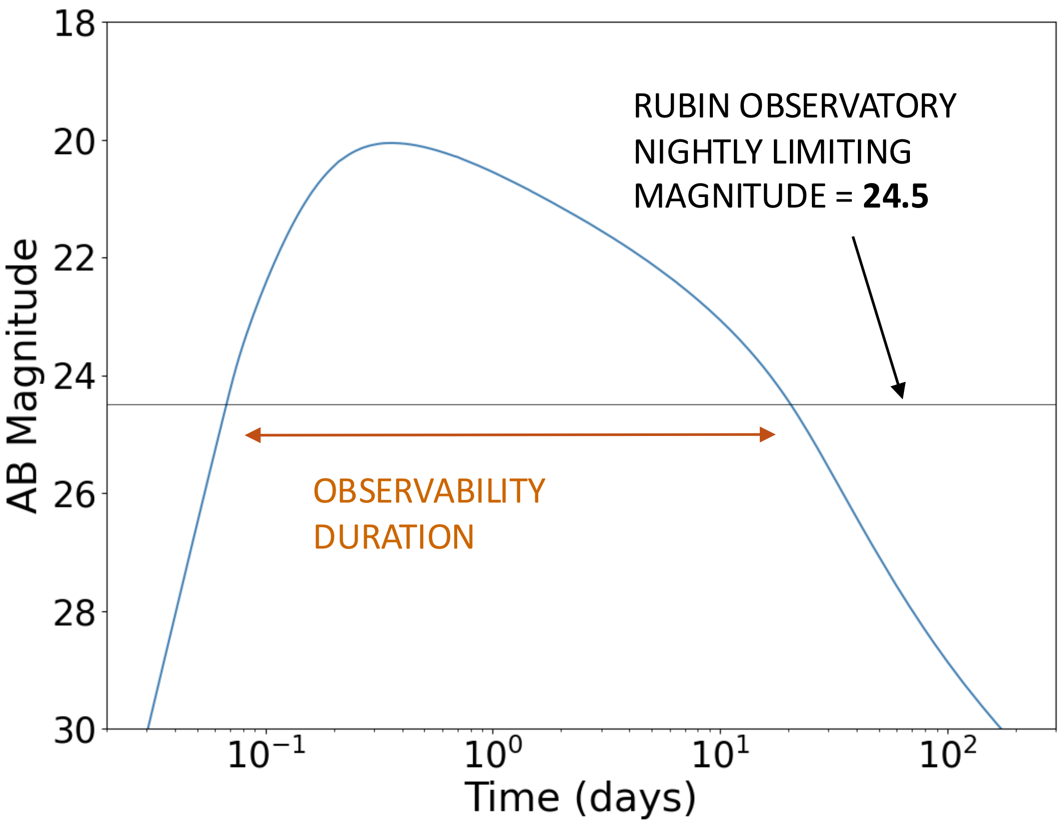
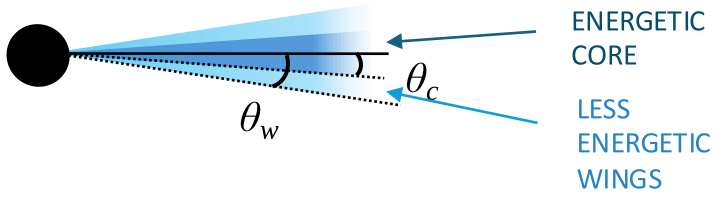


Forward shock model
+ electron synchrotron model
(Van Eerten et al. 2010)

Studied parameters:

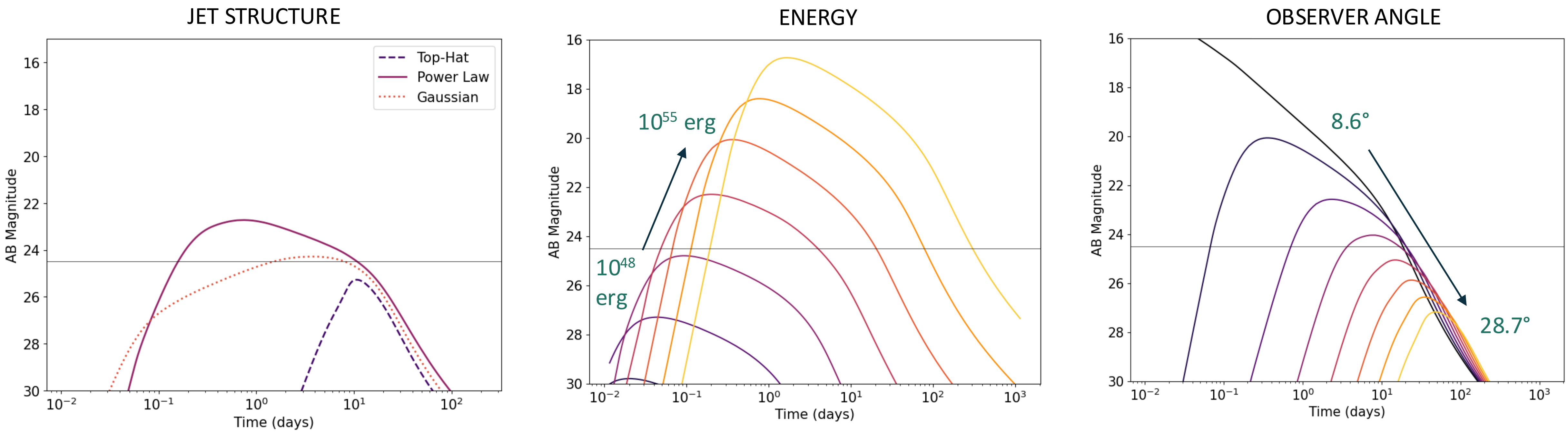
- Energy E_0
- Circumburst medium density n_0
- Redshift z
- Observer angle θ_{obs}
- Jet type (uniform or **structured**)
  - Core angle θ_c
  - Truncature angle θ_w

See Clément's talk



IMPACT OF THE MODEL PARAMETERS ON THE LIGHT CURVE

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



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

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MODEL OF GRB AFTERGLOW EMISSION

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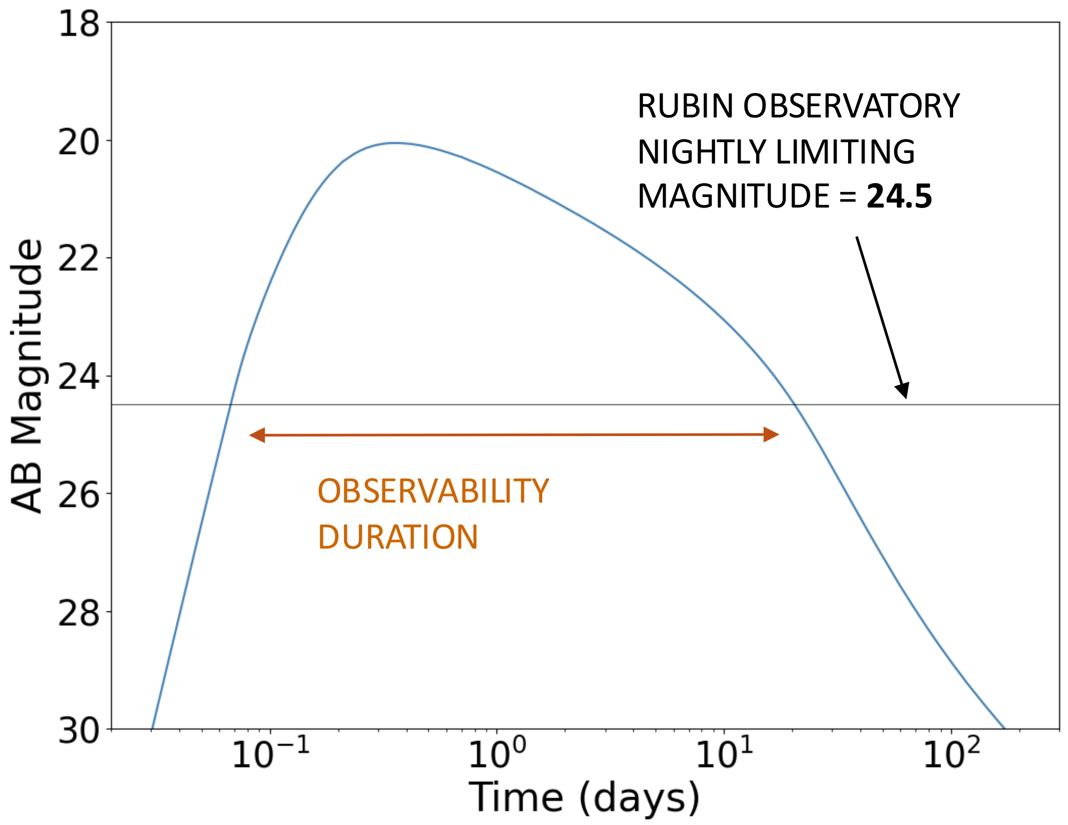

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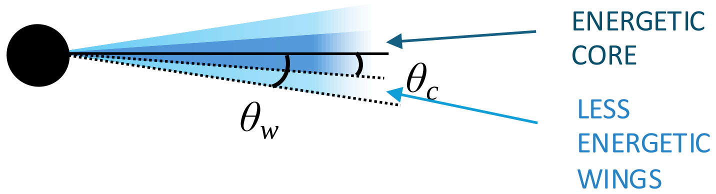
⟹ Need some parameters distributions!

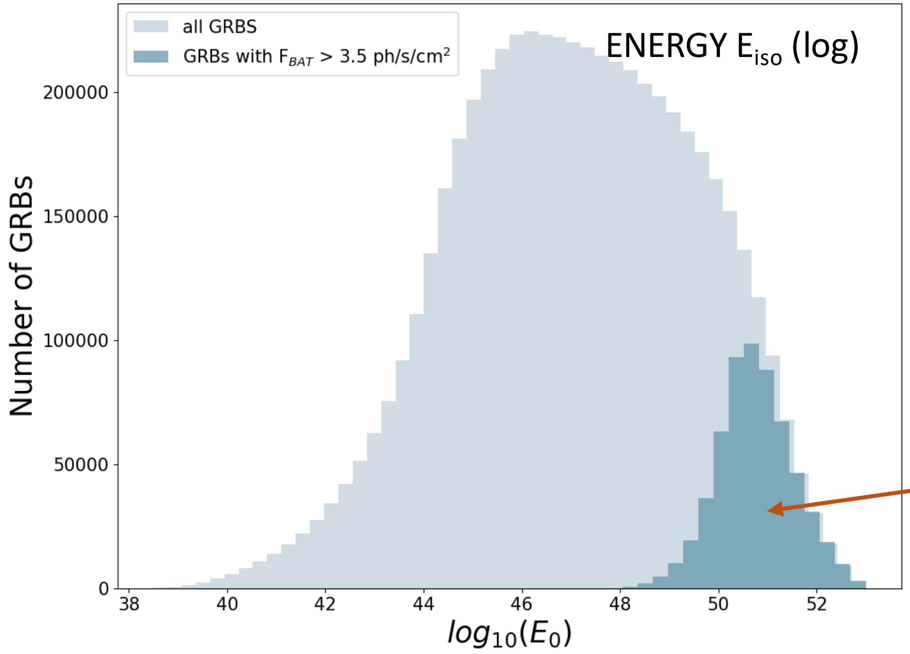


POPULATION OF SHORT GRBS BASED ON SBAT4

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 **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: ~ 1,000,000 GRBs

POPULATION OF SHORT GRBS BASED ON SBAT4

~ SBAT4 GRB population

↓

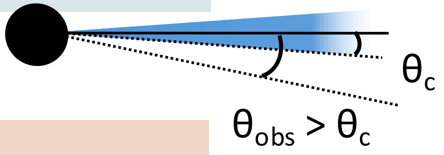
Keep afterglows not detectable by Fermi

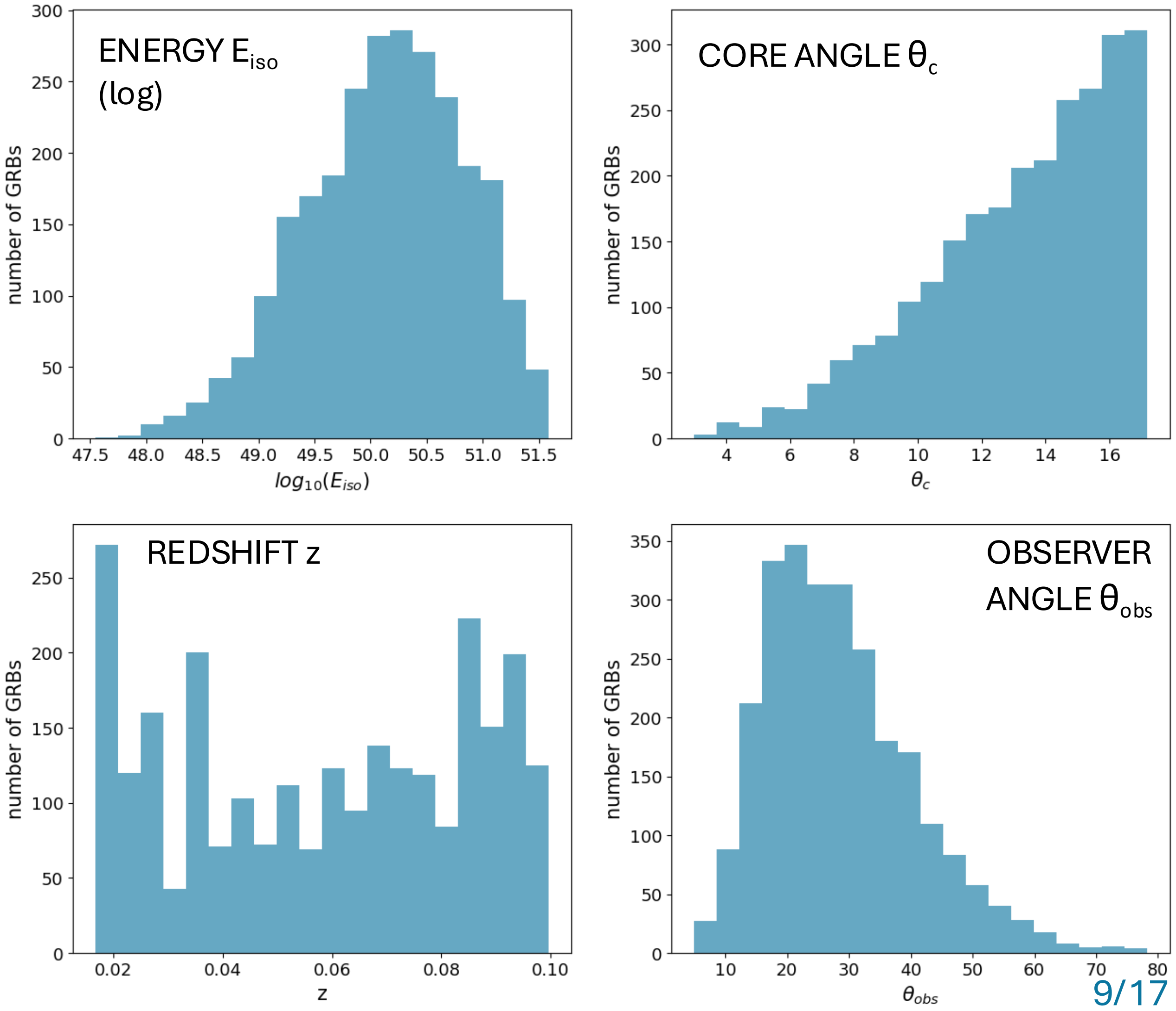
↓

$\theta_c < \theta_{obs}$ and $z < 0.1$

↓

~ SBAT4 orphan GRB population





* Fermi GBM minimal detection flux

POPULATION OF SHORT GRBS BASED ON SBAT4

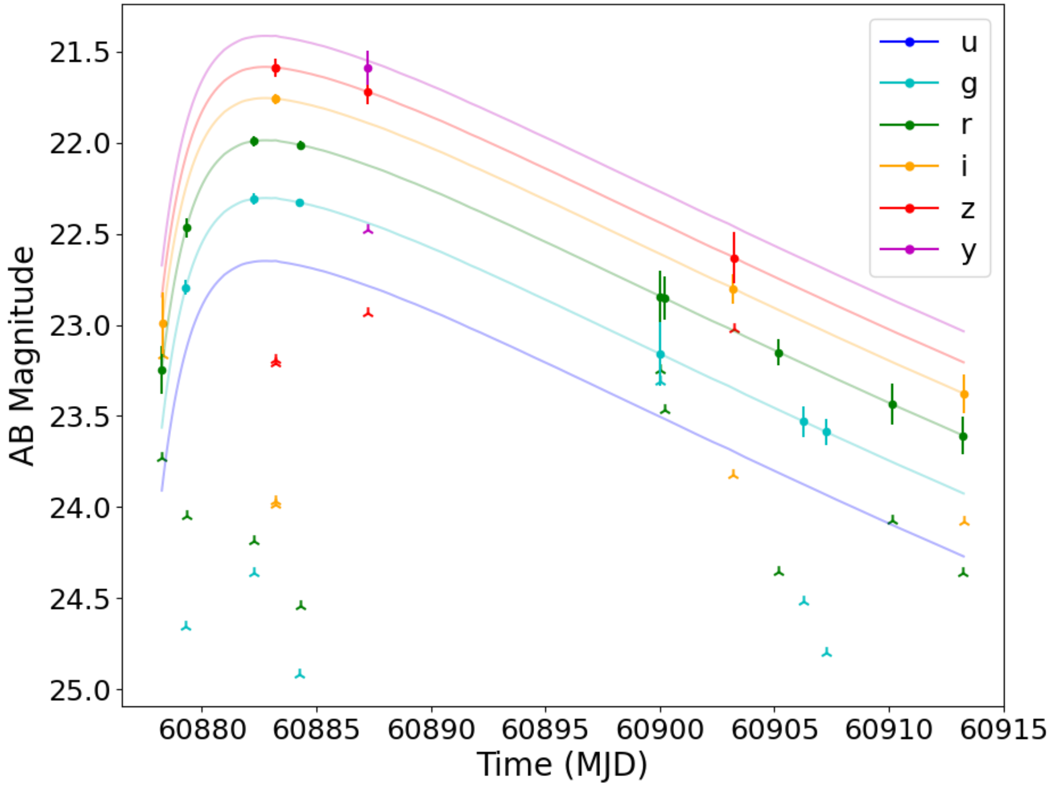
`rubin_sim` package ⟹ Realisation of the scheduler simulation for the 10 years of LSST (https://github.com/lsst/rubin_sim)

GRB date: 12 March, 2030

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

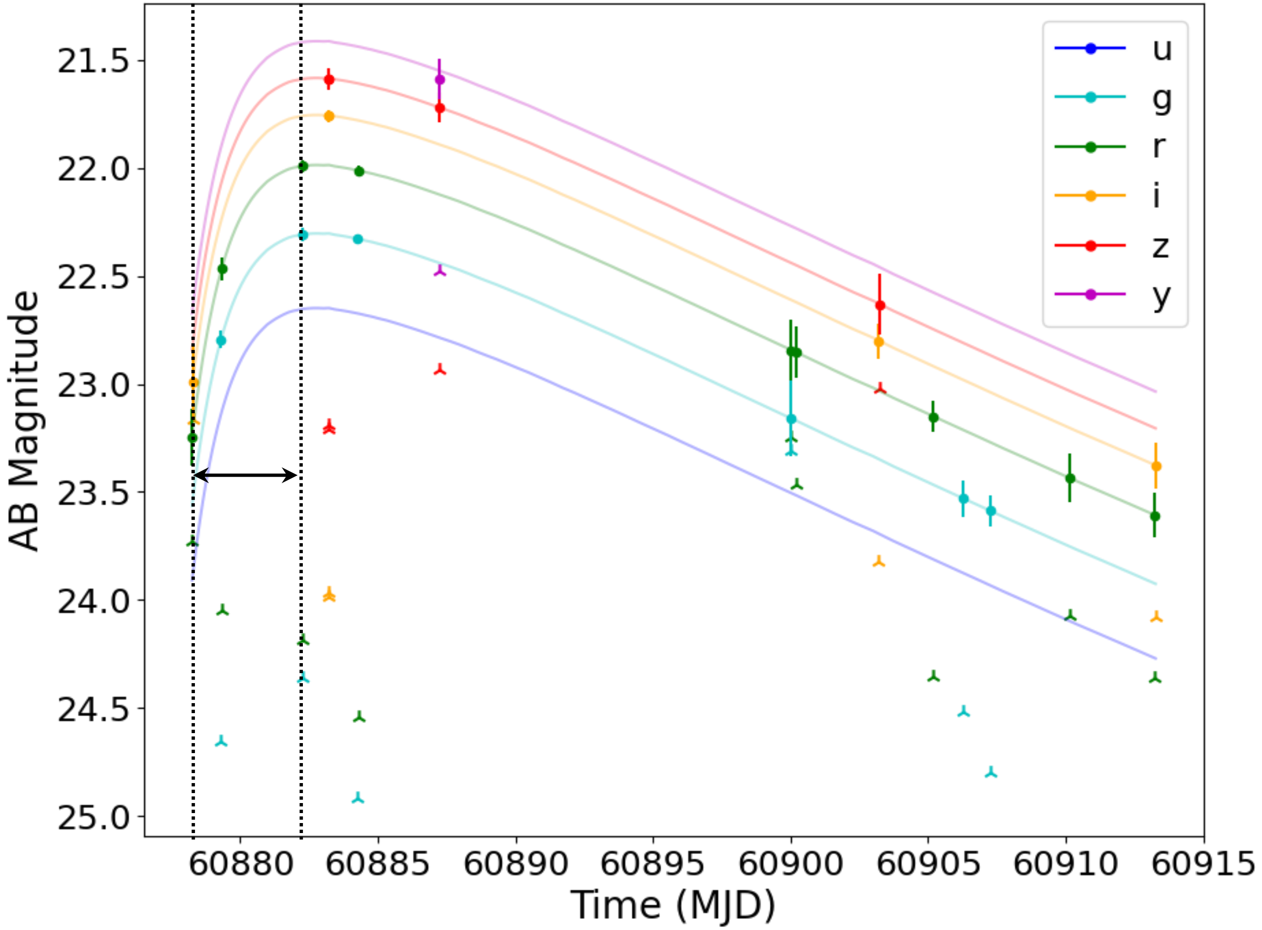
Parameters:

- 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



⟹ Only ~ 4 % of the simulated orphans have > 1 point in their "observed" light curve

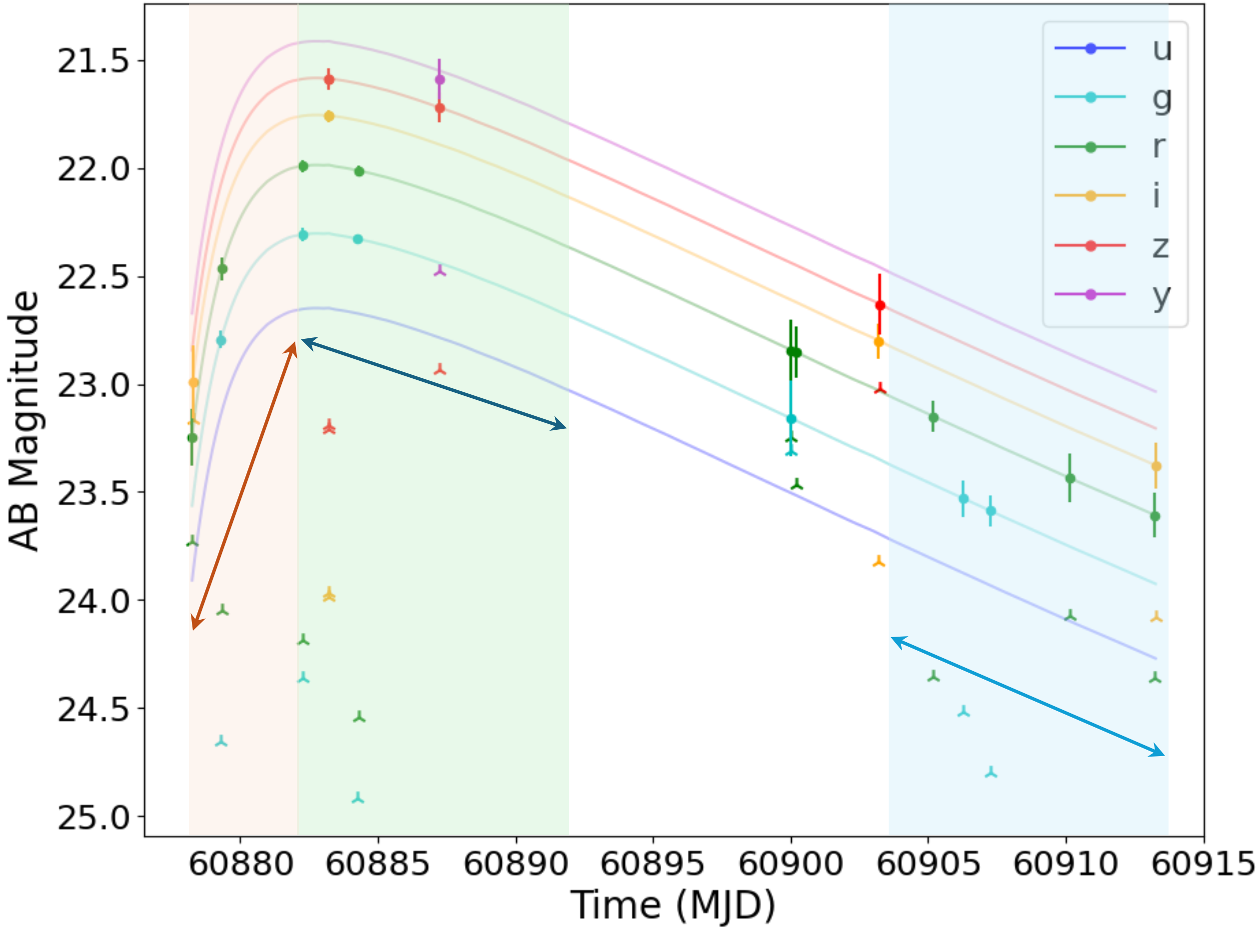
CHARACTERISATION OF LIGHT CURVES



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
- Colours (g-r and r-i)

CHARACTERISATION OF LIGHT CURVES



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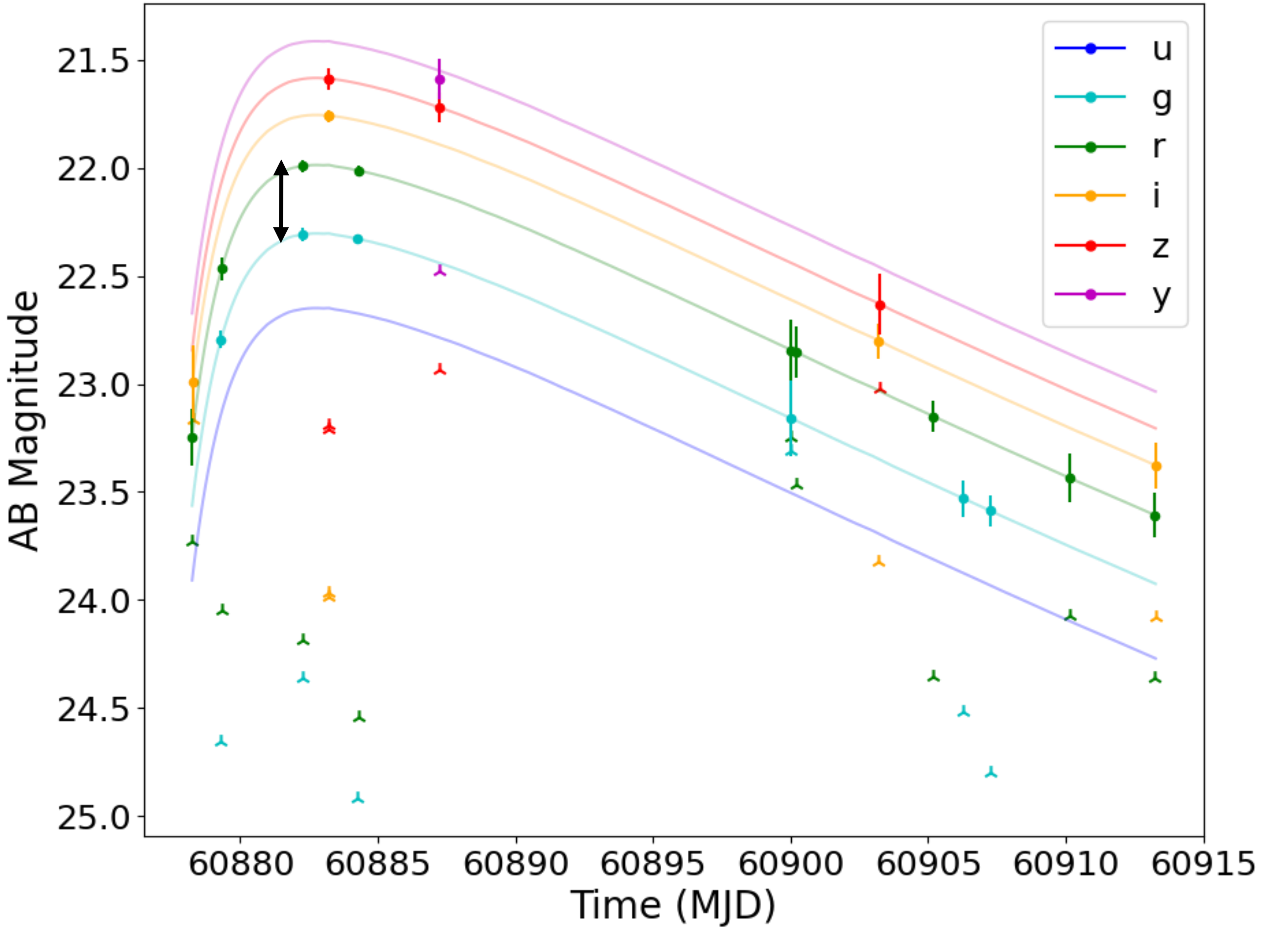

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RESCALING DATA TO THE R-BAND

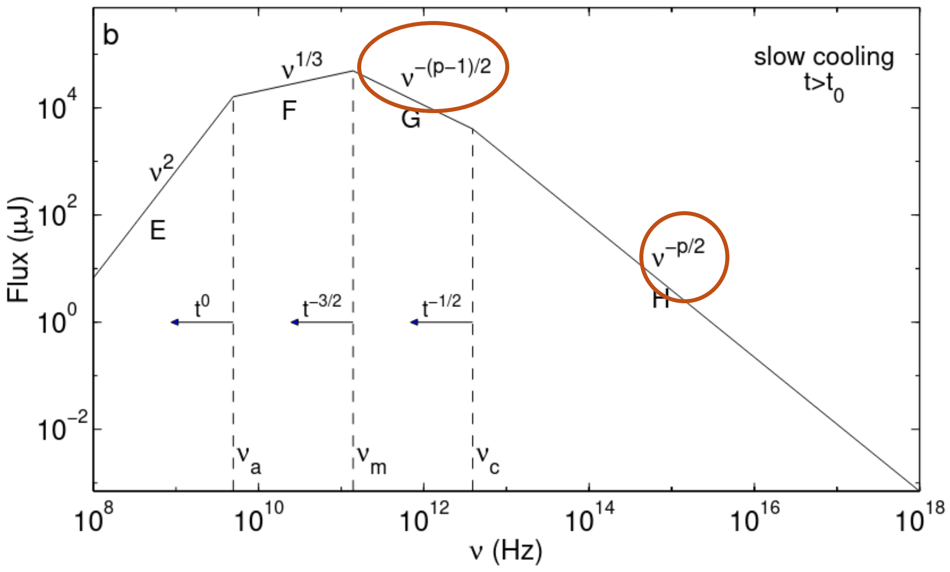
$$F_\nu \propto \nu^{-\beta}$$

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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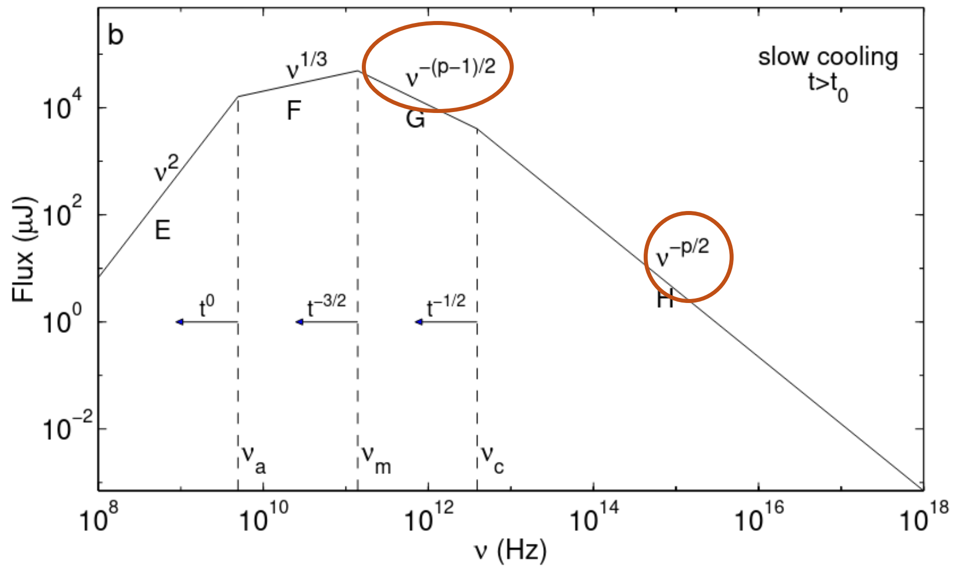

$\boxed{F_\nu \propto \nu^{-\beta}}$ **β spectral index**

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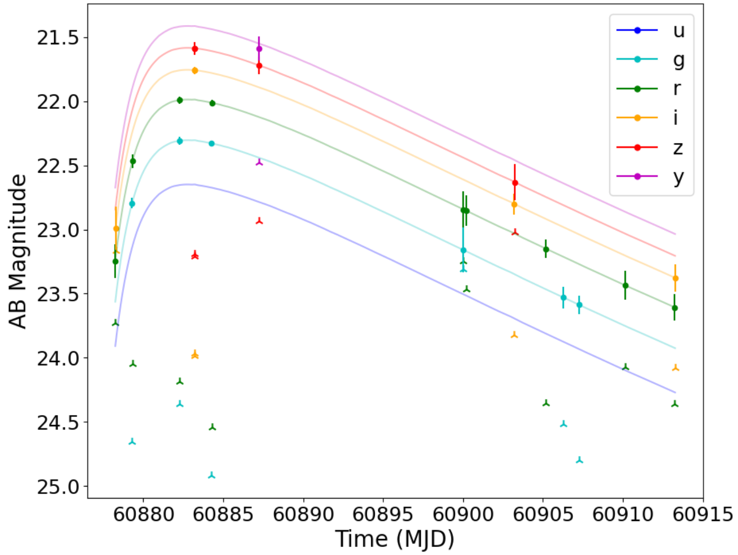
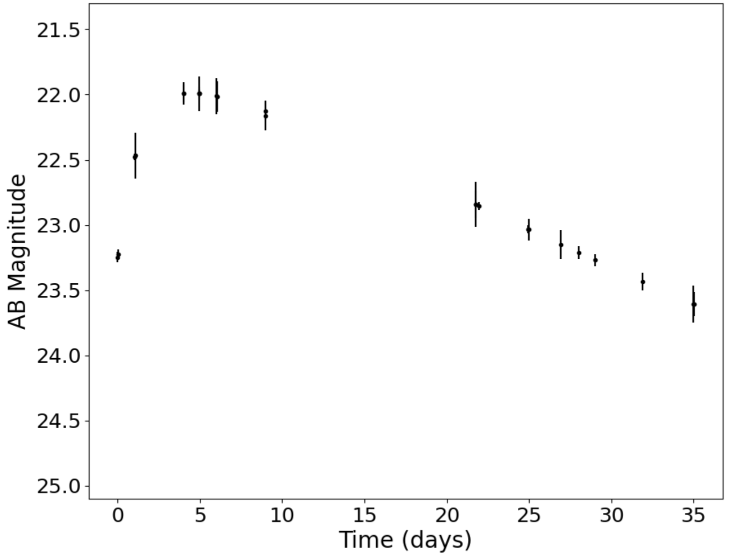
ν_c decreases with time $\Longrightarrow$ we don't know which value of β we have to use

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





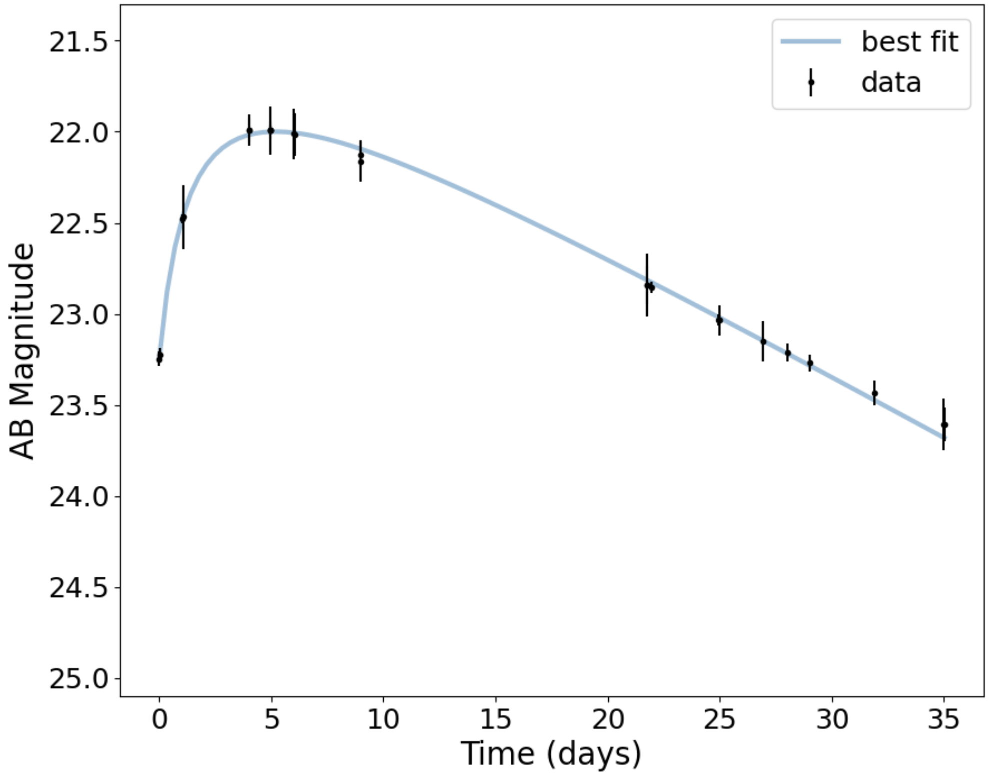
FIT OF PSEUDO-OBSERVED LIGHT CURVES

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

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

Points are rescaled to be on the r-band:

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



All features used to characterize one event:

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

CREATION OF A CLASSIFIER

USING ELASTICC DATA AS A BACKGROUND

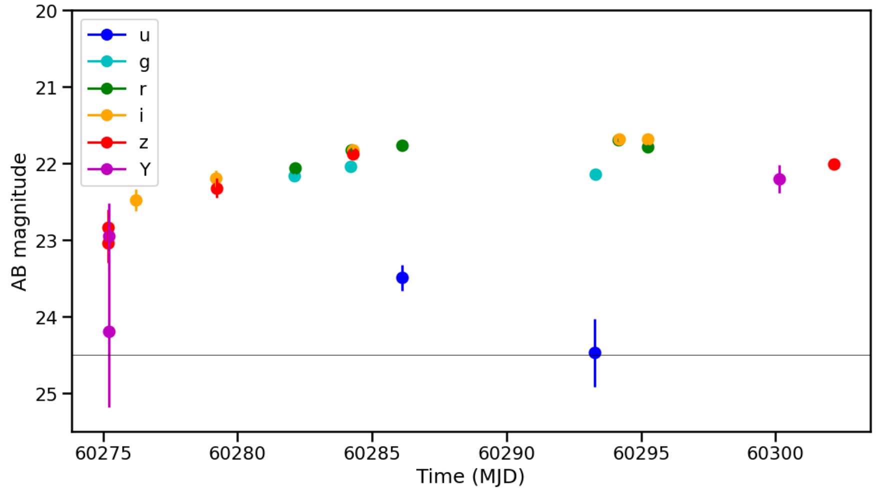
https://portal.nersc.gov/cfs/lsst/DESC_TD_PUBLIC/ELASTICC/

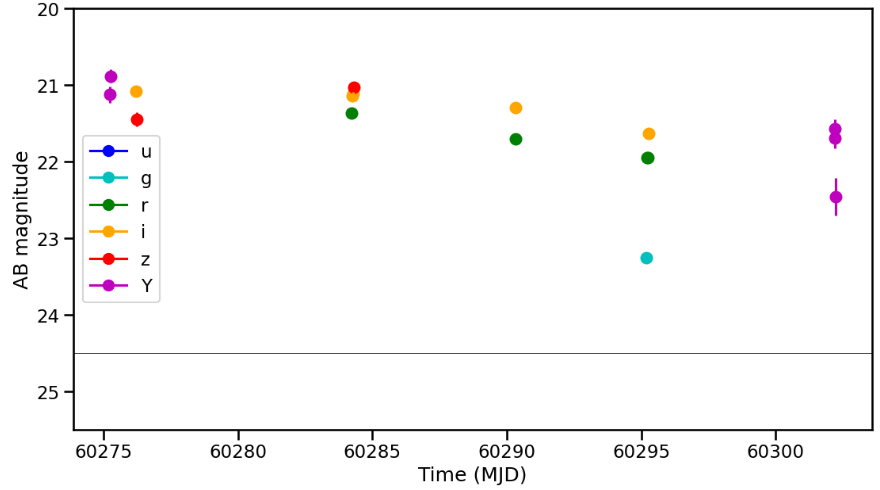
ELAsTiCC = DESC simulation of LSST alerts
(**E**xtended **L**SST **A**stronomical **T**ime-**S**eries **C**lassification **C**hallenge)

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

FIRST TEST OF A MACHINE LEARNING ALGORITHM

TRAINING

500 orphans
5000 background events

features →

ML CLASSIFIER
`scikit.learn` **Gradient Boosting Classifier**

→

TESTING

1915 orphans
> 650,000 background events

(only non-periodic events)

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84% orphans
~ **100%** of background rejected
⟹ **99.99% precision**

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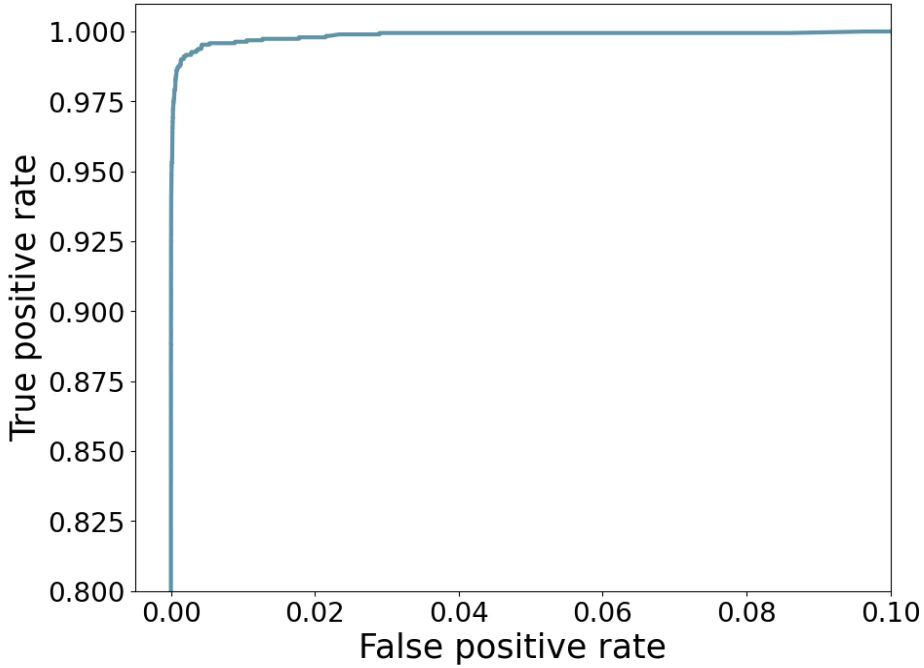

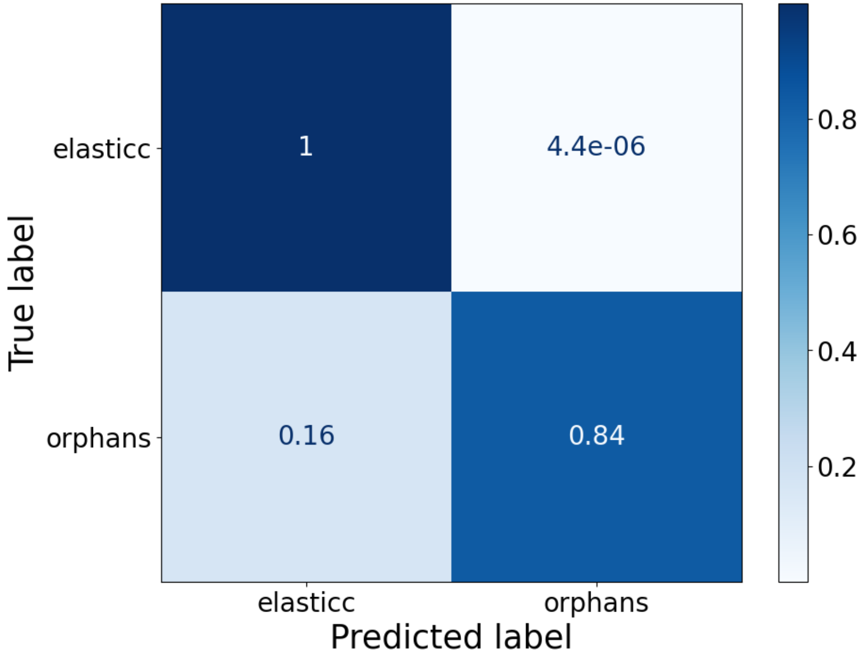

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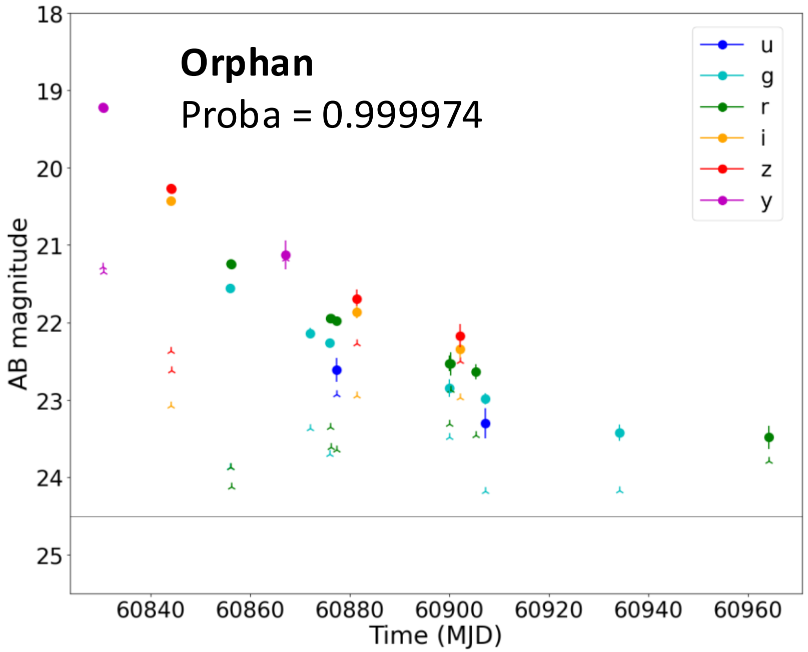

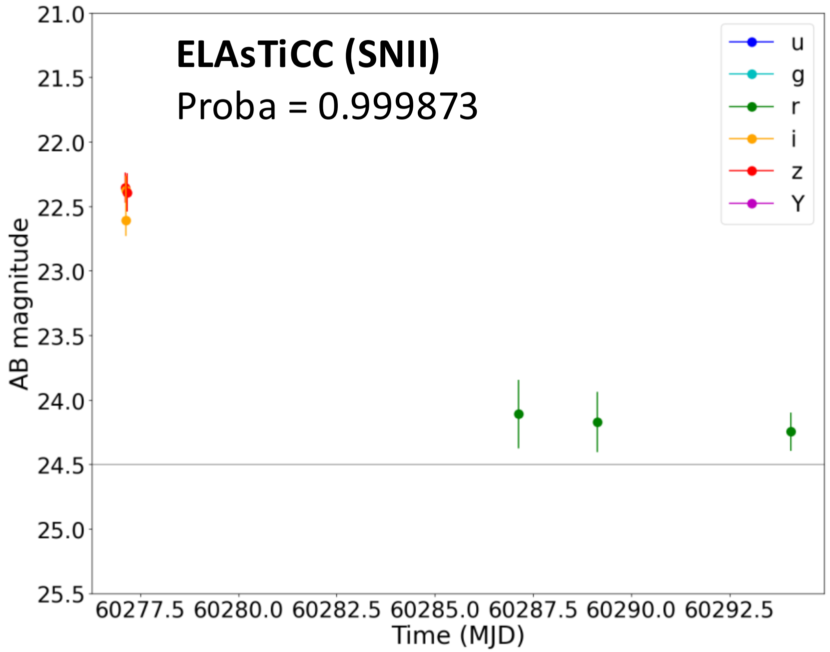

CONCLUSION & PERSPECTIVES

GOAL Implement a filter in Fink to identify orphan afterglows in Rubin LSST data (code available on github)

CONCLUSION

- Simulation of a population of short GRBs based on Swift BAT4 catalogue and their observation by Rubin LSST
- Characterise "pseudo-observed" light curves of orphan afterglows
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- Adapt our filter and test it on ZTF data
- Compare with another implemented model
- Discussion on GW-orphan joint detection

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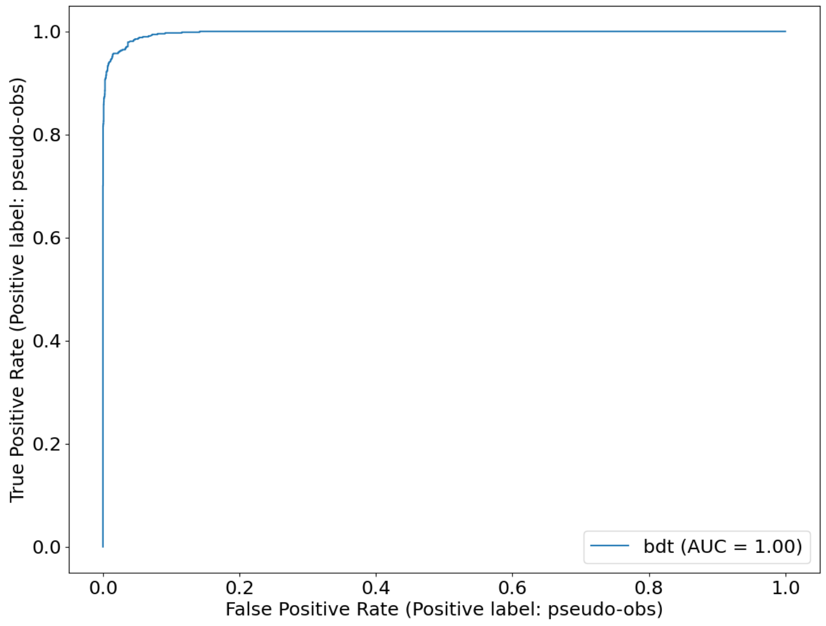
THANK YOU FOR YOUR ATTENTION!

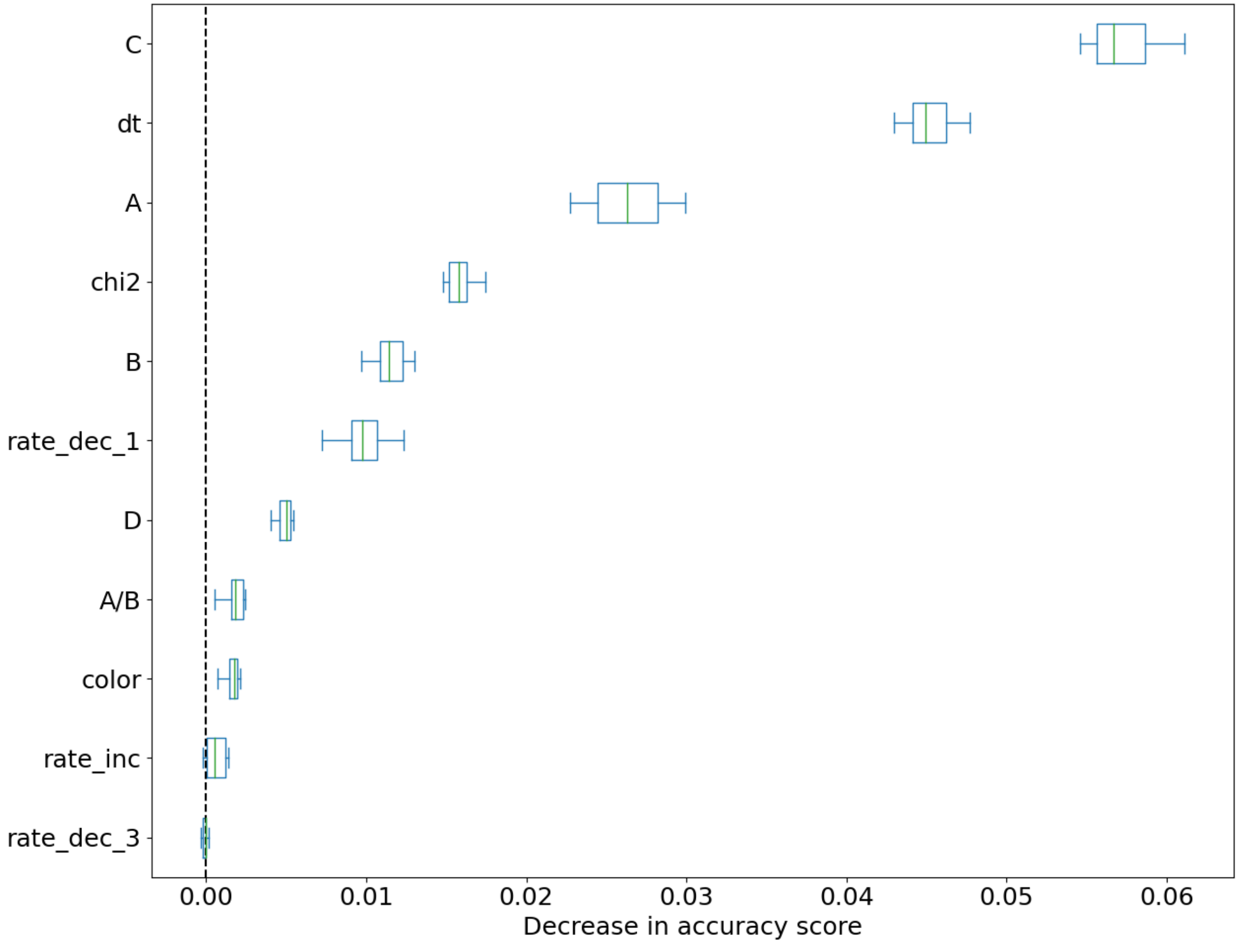
BACKUP SLIDES

MORE DETAILS ON THE CLASSIFIER

HYPER PARAMETERS

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
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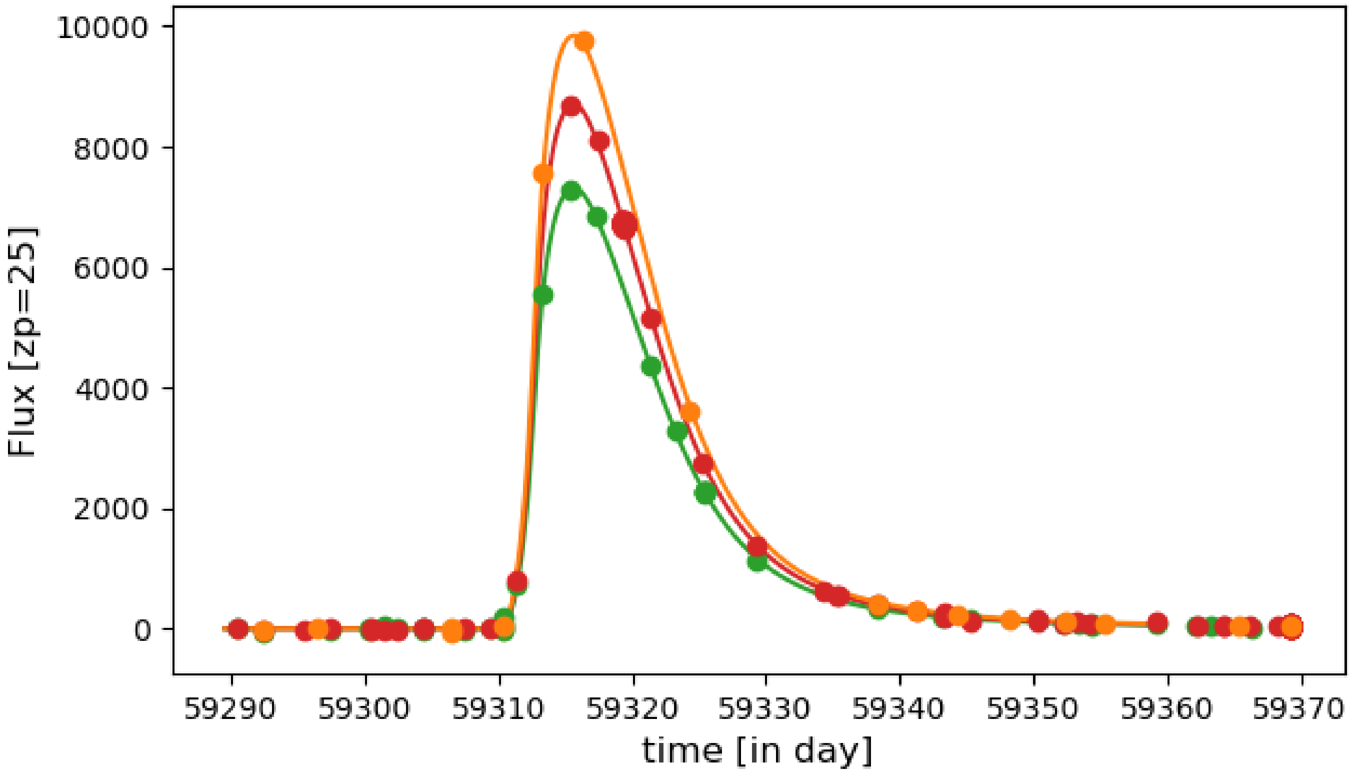
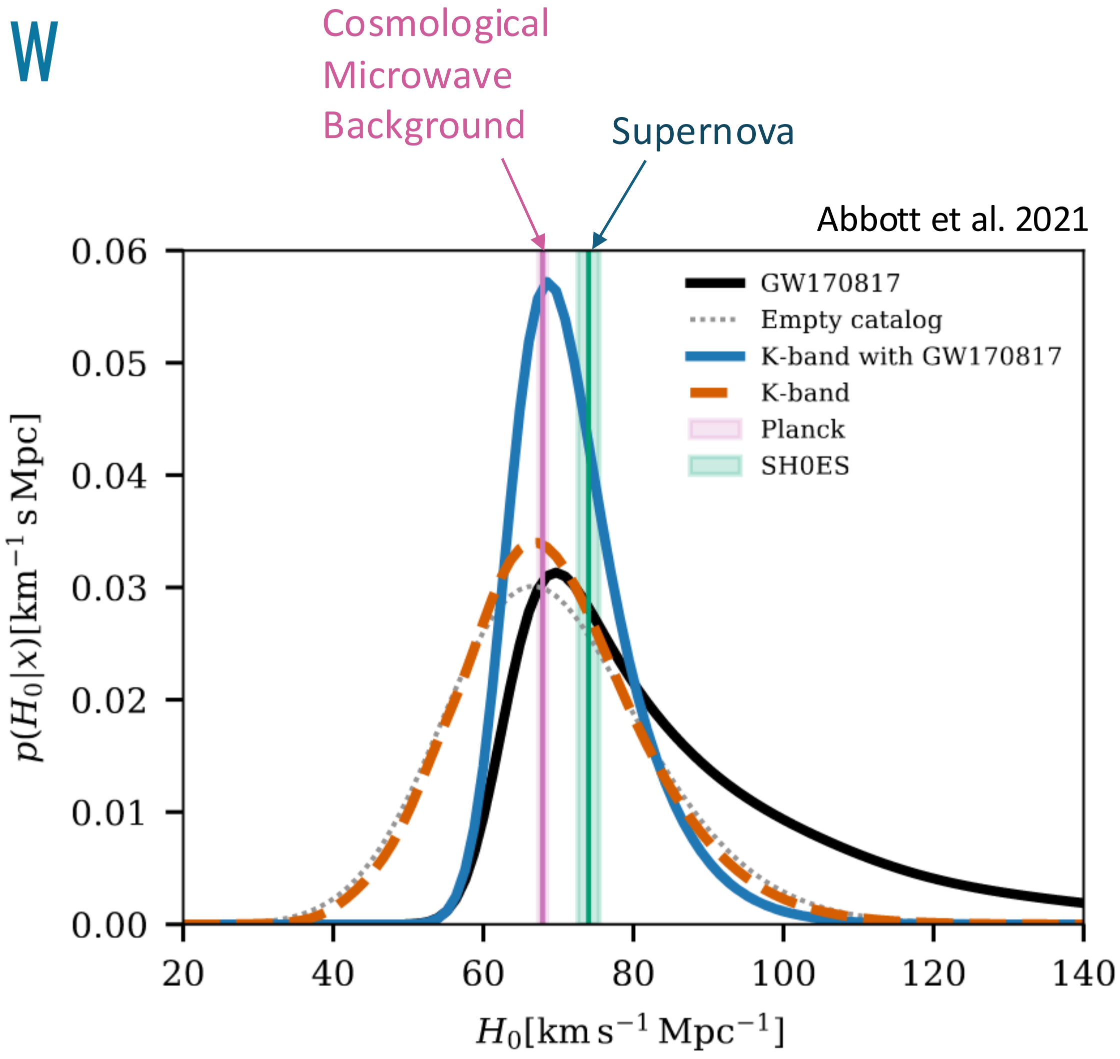


MULTI-MESSENGER ANALYSIS WITH GW

Multi-messenger analysis with gravitational waves: estimate the Hubble constant H_0

For $z << 1$:

$$\boxed{d_L(z) = \frac{cz}{H_0}}$$



GRAVITATIONAL WAVE COUNTERPART

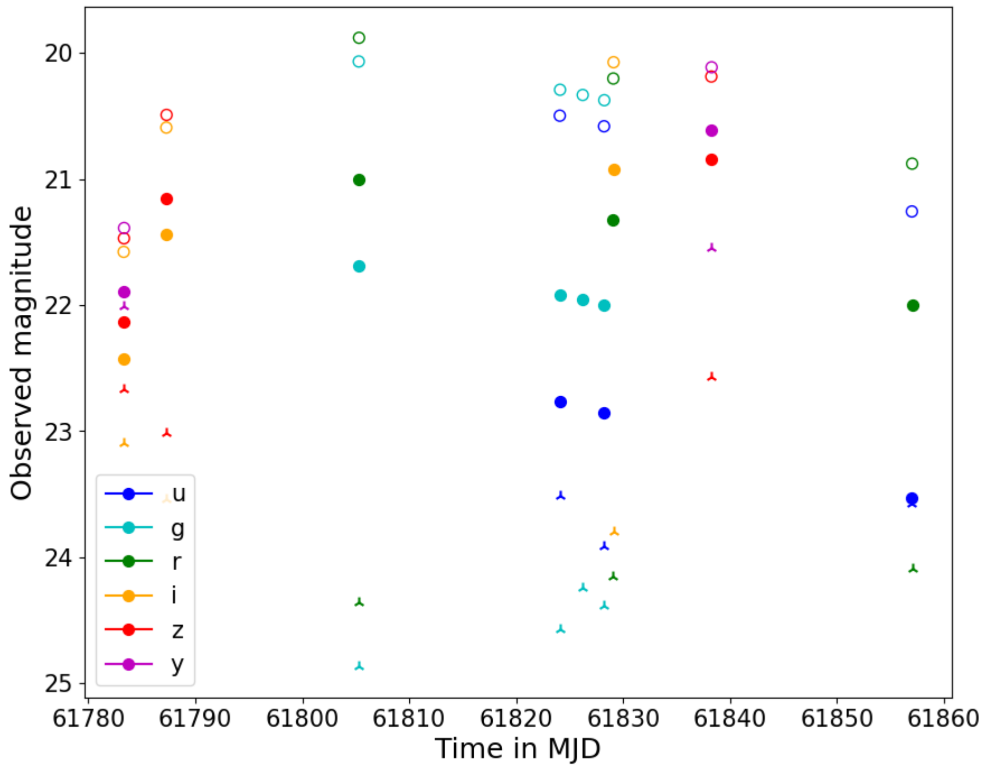
- Specific analysis needed because we have a precise position but large uncertainties on T_0 for orphans
- GWTC-3 catalogue all-sky triggers: given a position, look for synchronised GW signals
- How the size of the time window for the PyCBC coherent analysis impacts the number of detected events?

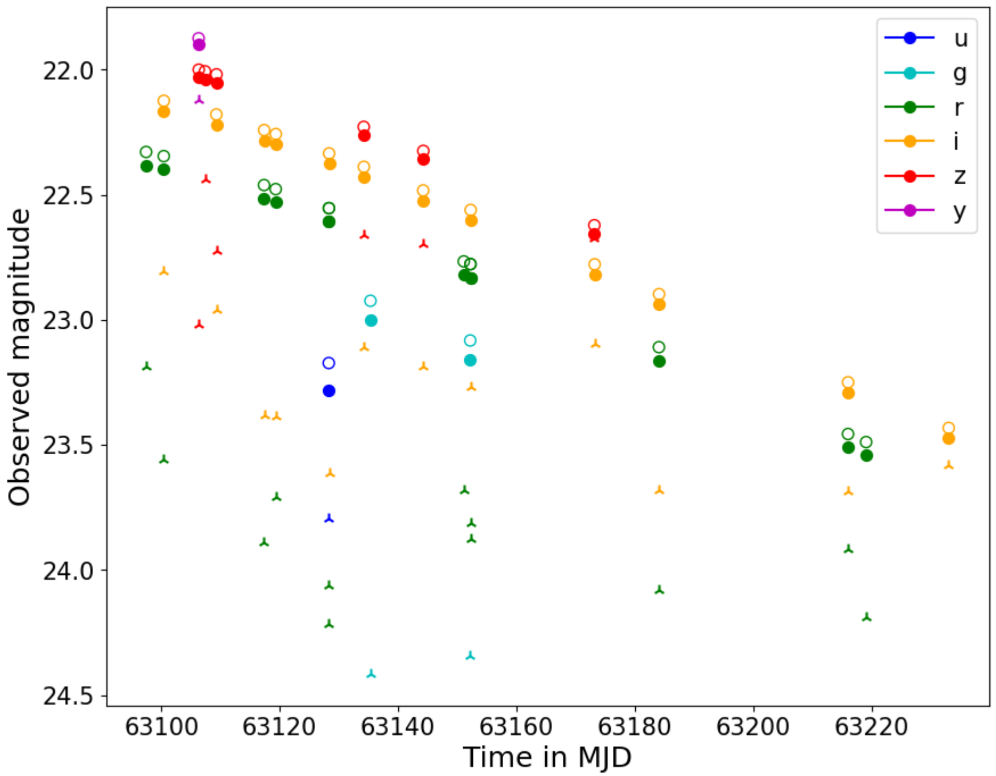
HOST EXTINCTION

Without extinction

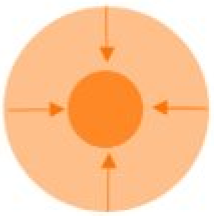
With extinction

Host extinction more important for long GRBs than for short GRBs





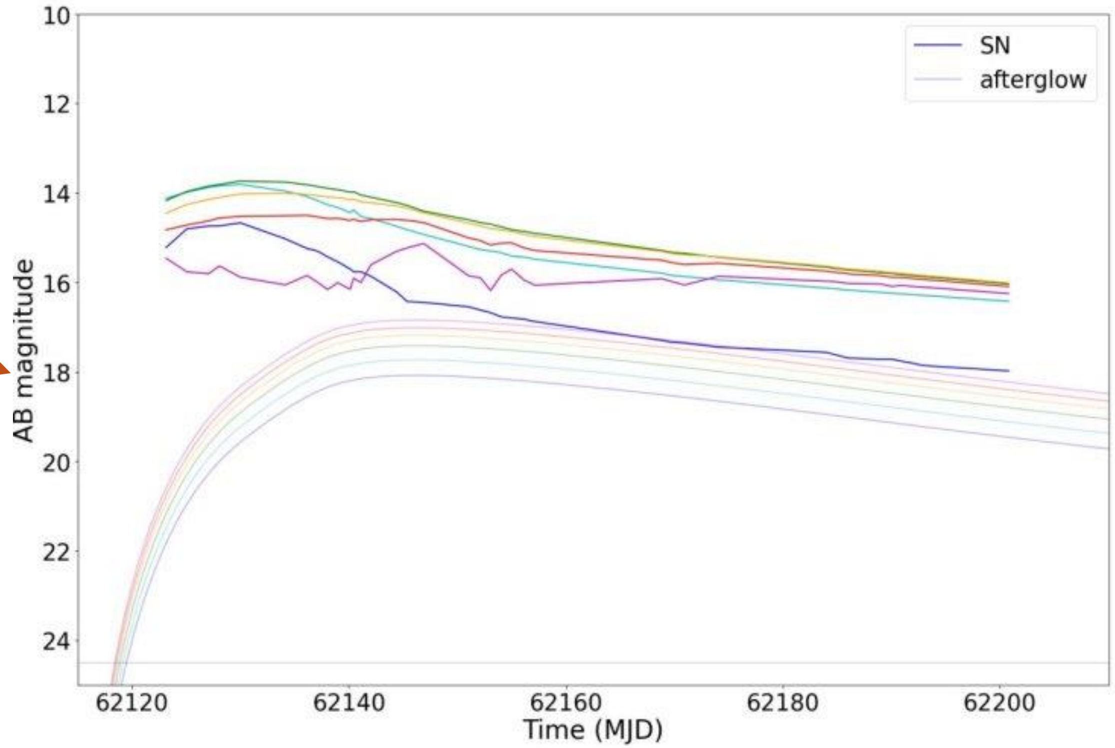
KILONOVA OVERLAP



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



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

KILONOVA OVERLAP

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⟹ long GRBs + supernova
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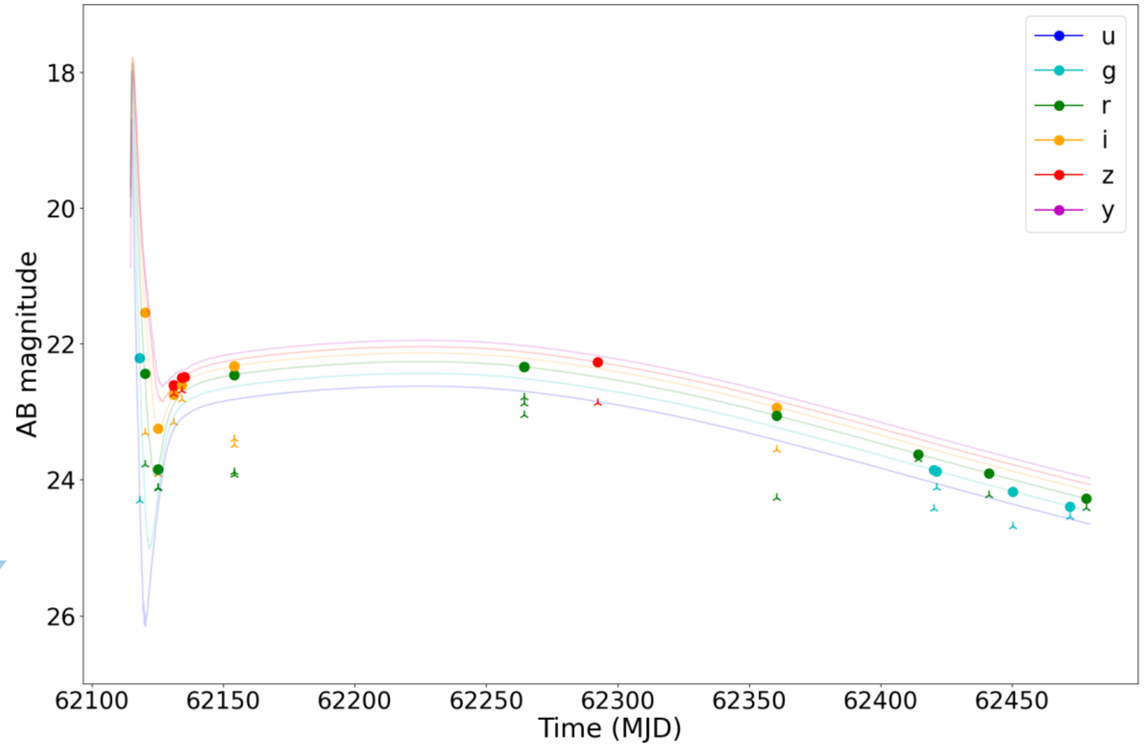

⟹ KN light curve may appear at early times
⟹ Quantify impact of KN on light curve features