Unveiling GRB Orphan Afterglows in Rubin LSST data with the FINK alert broker
PUMA22

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CNRS/IN2P3/LPSC and Univ. Grenoble–Alpes

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Overview

Context

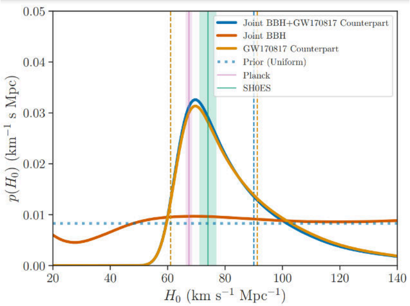
- The Vera C. Rubin Observatory
- The Legacy Survey of Space and Time
- The Dark Energy Science Collaboration
- The FINK alert broker

GRB orphan afterglows with Rubin

- Orphan afterglow
- Afterglow emission model: **afterglowpy**
- Jet structure
- Optical light curves and geometry
- Observability matrices
- A population of short GRBs

Conclusions and work ahead

Science driver



- Improve the measurement of the Hubble constant by increasing the number of GW-EM events associations Abbott et al. 2021 (arXiv:1908.06060)
- Look for orphan afterglows in Rubin LSST survey data to search for sub–threshold GW counterparts in EGO data

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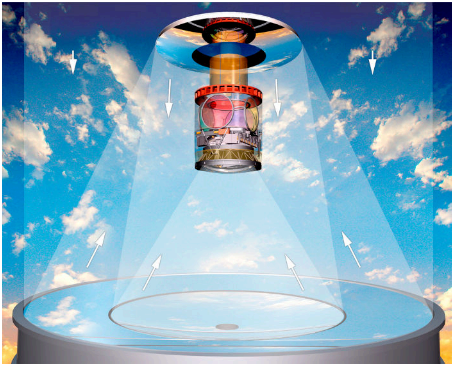
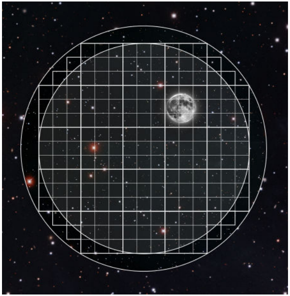
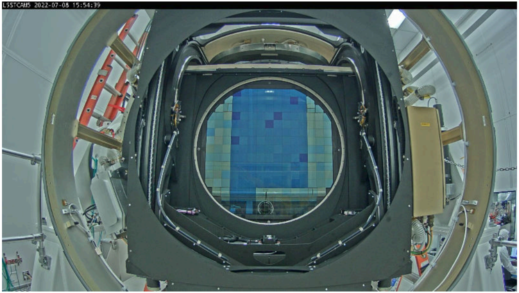
Rubin site and telescope

- Cerro Pachón, Chile
- 8.4 m primary mirror, 5 m tertiary $\Rightarrow$ 6.5 m effective
- 3 mirrors, 3 lenses and 5 filters (out of 6) on the wheel
- https://www.lsst.org/



Camera and field of view

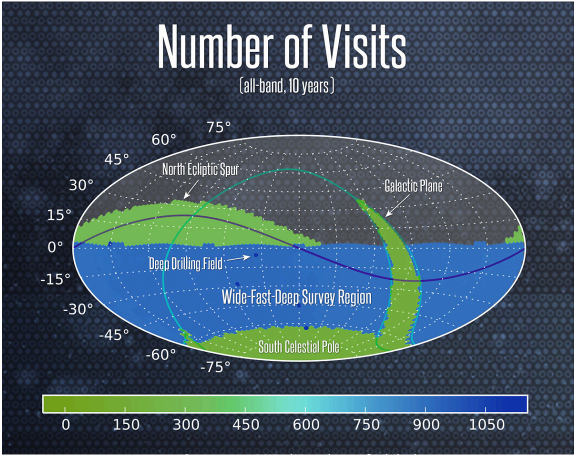




- Very large field–of–view: 10 sq degrees
- Biggest CCD camera ever: 3.2 GPx for ⌀64 cm
  - 21 rafts of 9 CCDs, 16 amplifiers per CCD
  - high througput (90% fill factor)
  - fast readout (2 s)
  - low noise (10 e^-)

⇒ lots of data: 15 TB/night

Rubin Legacy Survey of Space and Time

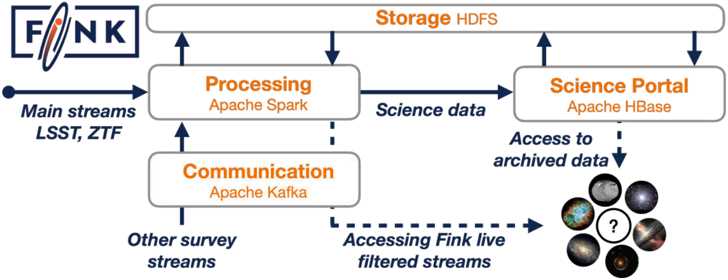


- Main survey: Deep, Wide and Fast
- "Full Southern sky every 3 days", in multiple filters
- Millions of "alerts" per night

The Dark Energy Science Collaboration

- 1100+ members in 20+ countries, 49 published papers to date
- https://lsstdesc.org/
- Orphan afterglow project approved by the collaboration within the Time Domain working group

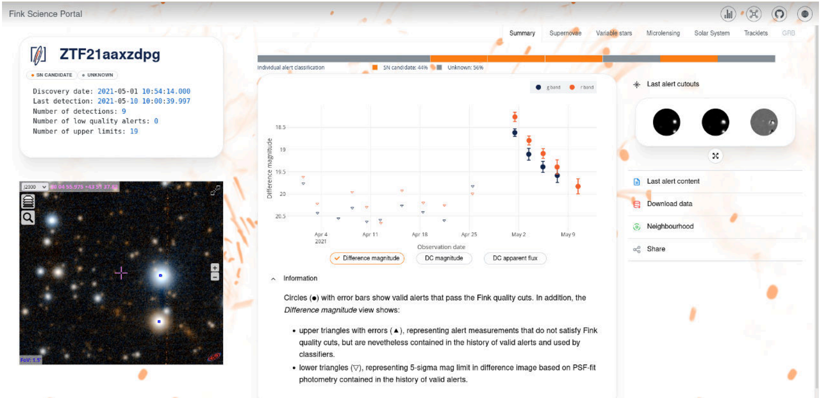
FINK Broker



- The FINK alert broker (Möller, Peloton, Ishida et al. (2021))
- One of the 6 alert brokers chosen by the Rubin project to receive the full alert stream
- Infrastructure hosted at IN2P3 Computing Center in Lyon
- A collaboration and community driven project

⇒ fink-broker.org

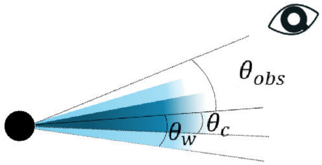
FINK Broker interfaces



- Science portal, REST API, tutorials
- Xmatch service, science driven filter (Machine Learning)
- Now running on the ZTF public alert stream

Overview

Orphan afterglows



GRBs seen off–axis

- no γ rays for no jet boost
- should exist if GRBs are relativistic and jetted... but none firmly confirmed so far!
- $\sim 100\times$ more the number of known GRBs

An entire new population of "GRBs" to discover

- should provide complimentary information
- overall geometry and energetic of the system
- jet structure, choked jets, cocoons
- progenitor population models

Off–axis optical flux

- optical emission peaks later (hours to days)
- but maximum flux is dimmer.

$\Rightarrow$ prime target for Rubin survey

$\Rightarrow$ ~ 50/year (Ghirlanda 2015)

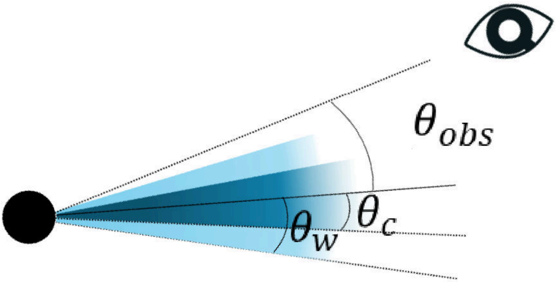
Afterglow emission model: **afterglowpy**

- Synchrotron emission from the forward shock model as implemented in the [`github:geoffryan/afterglowpy`] package
    - "Ryan, G., van Eerten, H., Piro, L. and Troja, E., 2019" arXiv:1910.11691
- includes
    - approximate prescription for jet spreading
    - arbitrary viewing angles
    - angularly structured jets, ie. $E(\theta)$
- does **not** include
    - external wind medium, i.e. $n \propto r^{-2}$
    - synchrotron self-absorbtion
    - reverse shock emission

→ simulate both flux light curves and spectral energy densities on the full specrum

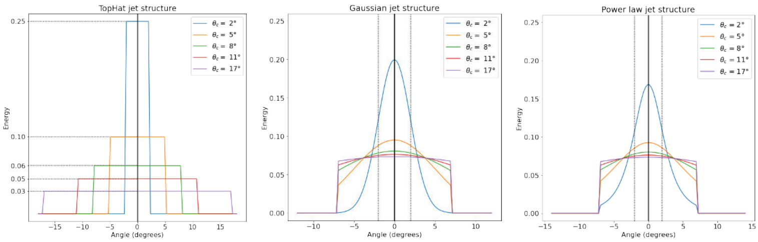
+ easy to use, fast, efficient and open source!

Jets geometrical parameters



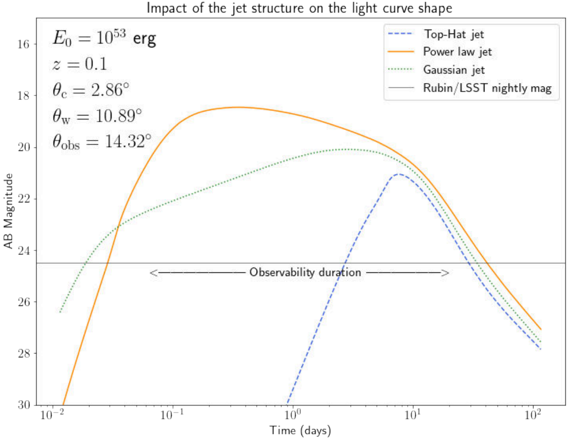
- θ_c: Core of the jet energy distribution
- θ_w: "Wing", where the jet energy distribution stops.
- θ_obs: Angle of the observer with respect to the jet axis

Jet structure



- Top hat was the default choice for a long time
- Jet structure has come back under scrutiny in the past year
- Significant impact on the light curve shape, in particular for jets seen off–axis

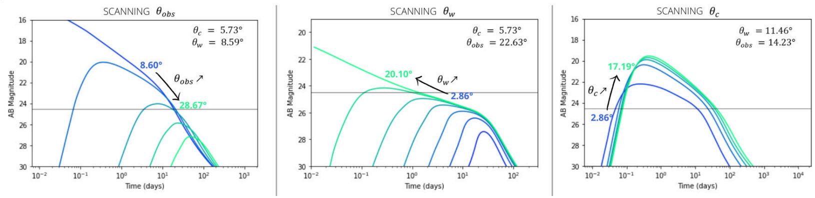
Structured jet light curve



- Structured jet light curve has a different shape at early times, the observed light flux rises earlier.
- Power law jet is different to Gaussian jet when $\theta_w >>> \theta_c$

Light curve dependency on angles

- Power law jet structure

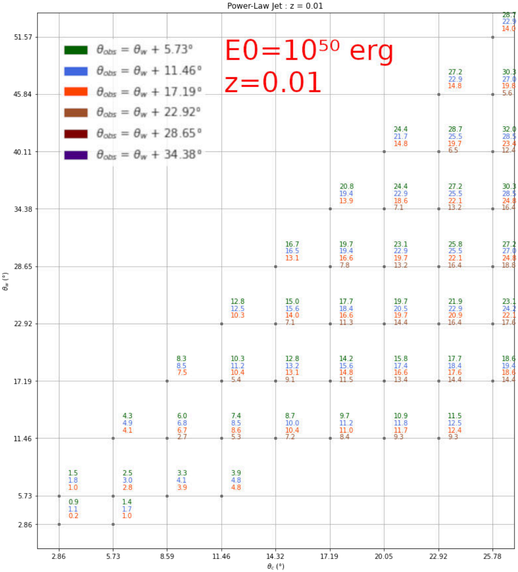


As θ_{obs} increases, the peak flux decreases.

As θ_{w} increases, the peak flux increases.

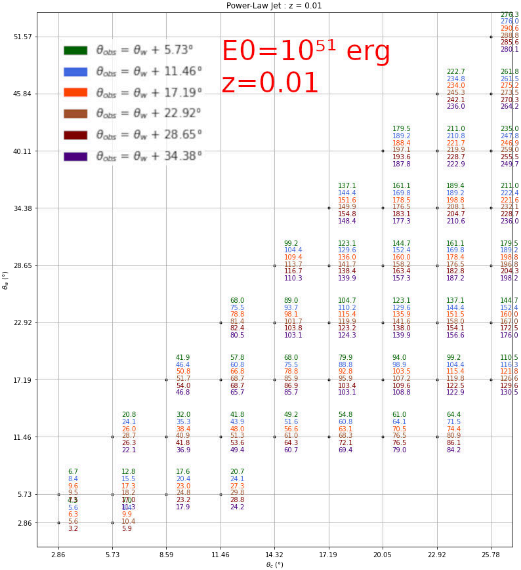
As θ_{c} increases, the peak flux increases. . .
if θ_{w} is $\sim$ "small"

Observability matrices



- Matrix: $(\theta_c, \theta_w, \theta_{obs})$
- Orphan afterglow: $\theta_{obs} > \theta_w$
- $\theta_w < 2 \times \theta_c$
- Observability can be longer when θ_{obs} increases (b/c of the light curve shape)
- Energy and redshift are obviously key parameters

Observability matrices



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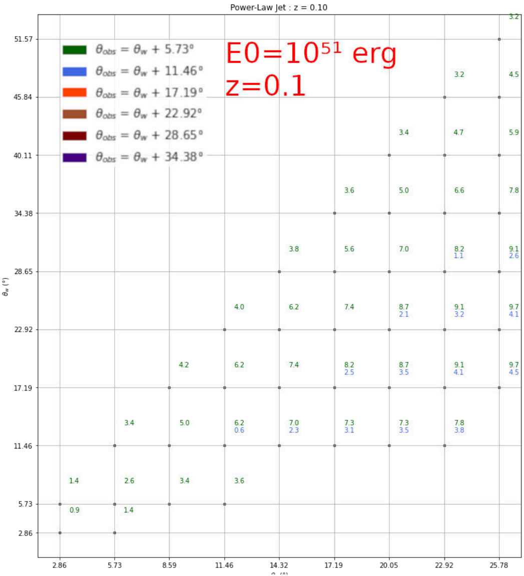

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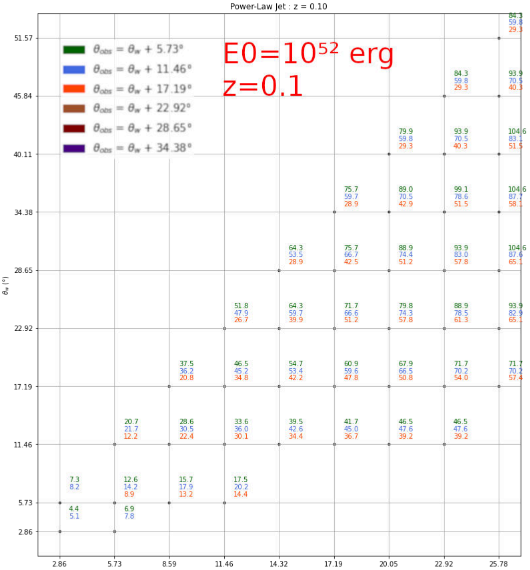

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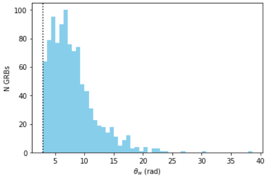
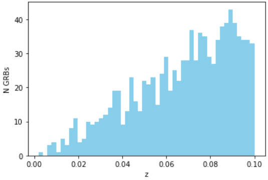
Simulating a population of Short GRBs

- "Pseudo–reasonable" population of 1000 SGRBs
  - → should be ok at first order...
- Distributions
  - Core angle (θ_w): 2 values, 2.86° and 8.60°
  - Observer angle (θ_obs): uniform distribution $[0; \pi/2]$ rad
  - Circumburst density: uniform distribution $[0.001; 1.0]$ cm
  - Limit redshift to 0.1, as O5 range is 300 Mpc
    - very roughly corresponds to 10% of all short GRBs

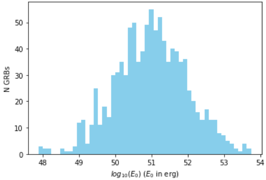
Truncature angle $\theta_\mathrm{w} > \theta_\mathrm{c}$



Redshift z



Isotropic equ. energy E_0



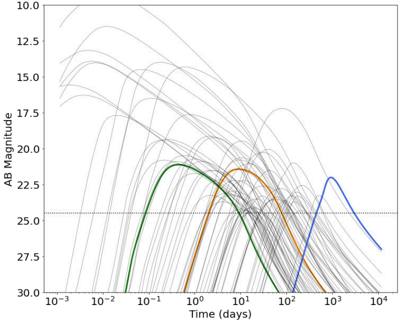
Simulated light curves

- Only show **off–axis** GRBs, observable more than 7 days

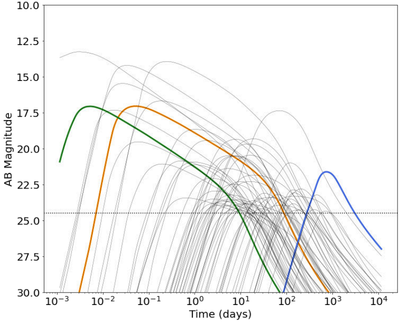
→ large variety of light–curve shapes

→ from "faint and long" to "bright and short" OAs

Top Hat jet



Power law jet



Observability table

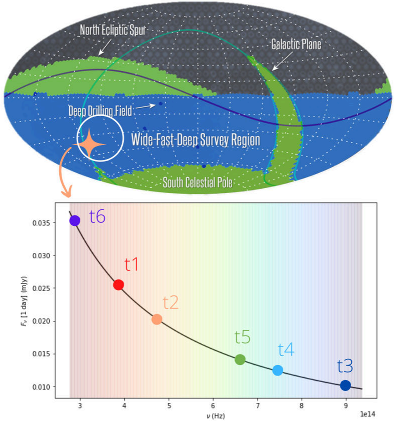
Jet Type	θ_c	Axis	t_{obs}	Number of observable afterglows (/1000)
TOP-HAT	0.15 radians	ON	> 7 days	32
	(~ 8.60 degrees)	OFF	> 7 days	69
POWER LAW	0.05 radians	ON	> 7 days	14
	(~ 2.86 degrees)	OFF	> 7 days	29
	0.15 radians	ON	> 7 days	49
	(~ 8.60 degrees)	OFF	> 7 days	66

- Fraction of "observable" orphan afterglow $\sim 5\%$.
- OA light curve sensitive to jet structure, but statistically the impact on observability numbers is limited.
- More GRB afterglows observable off–axis than on–axis!
- Note that for O5, $\sim$30 BNS are expected to be detected each year.

Going further with pseudo–observations

- Start with the 10 years long simulated schedule of Rubin/LSST (*lsst/rubin_sim* package)

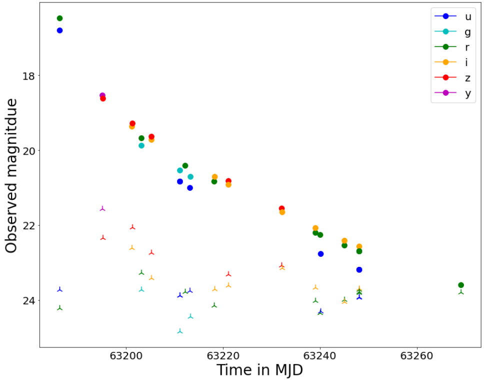
1. Choose a time and sky coordinates of a short GRB
2. Keep only observations inside the Rubin/LSST field of view
3. Compute GRB spectrum at each observation time
4. Compute magnitude through the correct filter of each observation
5. Build pseudo–observed afterglow light curve



Pseudo–observed light curve

- GRB observed on November 15$^{\mathrm{th}}$2031 at (Ra, Dec) = (03h40m31.6s, -13d44m34.2s)

```
Z = {'jetType':    4,
     'specType':   0,
     'b':          4,
     'thetaObs':   0.1694977553300254,
     'E0':         7.791161758307381e+52,
     'thetaWing':  0.15478575129181205,
     'thetaCore':  0.15,
     'n0':         0.09182964074183593,
     'p':          2.2,
     'epsilon_e':  0.1,
     'epsilon_B':  0.01,
     'xi_N':       1.0,
     'd_L':        1.3721135634076648e+27,
     'z':          0.094}
```



- The nightly magnitude is rarely 24.5
- There is a nice diversity of filters, good for color estimation!

$\rightarrow$ good starting point to simulate an alert stream

Overview

Work ahead

- Short term
  - Increase statistics on simulation and pseudo–observed light curves
  - Design and implement a filter in FINK
    - simple cuts, machine learning, active learning, deep learning
    - likely work on a proper "color" module as well
  - Reorganize public code: https://gitlab.in2p3.fr/johan-bregeon/orphans
- Medium term
  - Systematics on emission models
  - Improve on the population model
  - Understand the multi–wavelength aspect...
- (Slightly) longer term
  - Get ready for LSST commissioning data in 2024!

What to do with the best candidates?

- Multi-wavelength
  - optical, radio, spectroscopy, interfometry, X and gamma!
- Multi–messenger: GW, Neutrino, CRs
- Consider excellent space localization but bad time localization (no T_0)
  - still possible to look for sub-threshold signals
  - engage discussion with the GW community
- Need to define the best strategy to be able to confirm that objects are really orphan afterglows
- Need for coordination with other groups looking for on–axis GRBs and kilonovæ (talks within the FINK collaboration)

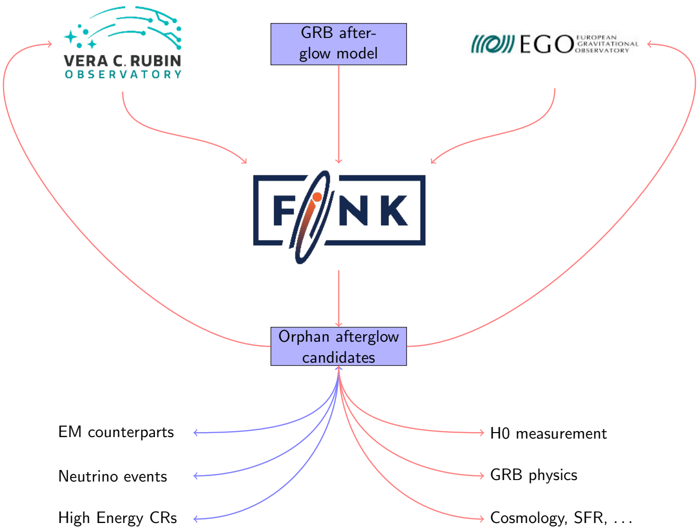
→ optimise use of observation resources

(Quick) Conclusions

- Rubin LSST data should contain O(10) orphan afterglows from GRBs each year
- Identifying these GRB OA is key toward great multi–messenger science
- Detection of sub–threshold gravitational wave signals matching Rubin orphan afterglows could greatly enhanced constraints on H_0.
- A lot will be learned about gamma–ray bursts physics as well!
- But a lot of work is still to be done to achieve such a feat. . .

⇒ M. Masson PhD thesis starting next week

Summary

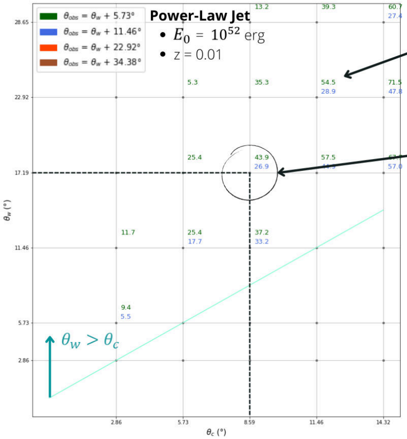

VERA C. RUBIN
OBSERVATORY
GRB after-glow model
EGO EUROPEAN GRAVITATIONAL OBSERVATORY
FINK
Orphan afterglow candidates
EM counterparts
Neutrino events
High Energy CRs
H0 measurement
GRB physics
Cosmology, SFR, . . .

Backup

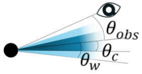
Long Conclusions

- The Rubin observatory will be a prime tool of the decade to study the optical variable sky.
- The "Wide, deep and fast" survey is well adapted to observe orphan afterglows from gamma–ray bursts in great details.
- The phase space of orphan afterglow observability is large, and many parameters distribution are not well known.
- Careful work is needed to prepare alert stream filters to identify the best orphan afterglow candidates during the survey.
- Only a well designed multi–wavelength and multi–messenger campaign will lead to unequivocal identification of orphan afterglows.
- Detection of sub–threshold gravitational wave signals matching Rubin orphan afterglows could greatly enhanced constraints on H_0.
- A lot will be learned about gamma–ray bursts physics as well!

Observability matrices explained



Observability duration for each combination $(\theta_c, \theta_w, \theta_{obs})$ in days



EXAMPLE: θ_c = 8.59°
θ_w = 17.19°

$\theta_{obs} = \theta_w + 5.73° = 22.92°$
$\Longrightarrow$ OA observable during 43.9 days

$\theta_{obs} = \theta_w + 11.46° = 28.65°$
$\Longrightarrow$ OA observable during 26.9 days

1 matrix created for each combination of:

- **z = 0.01 and 0.1**
- **$E_0 = 10^{51}, 10^{52}$ and 10^{53} erg**

For $(\theta_c, \theta_w, \theta_{obs})$: parameters space is large
$\Longrightarrow$ Simulation of a population of GRBs!

Orphan afterglow detection rates

Table 2. Transient surveys in the optical and X-ray bands.

Survey	FOV (deg^2)	Cadence	$F_{\rm lim}$ (mJy)	Coverage (deg^2 night^{-1})	Lifetime days	$R_{\rm OA}$ (deg^{-2} yr^{-1})	$\langle T \rangle$ days	# OA yr^{-1}
PTF	7.8	1m–5d	1.17×10^{-2}	1000		1.5×10^{-3}	1[0.2–3.8]	1.5
ROTSE–II	3.4	1d	1.17×10^{-1}	450		5.2×10^{-4}	0.4[0.1–1.7]	0.1
CIDA–QUEST	5.4	2d–1yr	4.60×10^{-2}	276		8.0×10^{-4}	0.5[0.1–2.3]	0.1
Palomar–Quest	9.4	0.5h–1d	1.17×10^{-2}	500	2003–2008	1.5×10^{-3}	1[0.2–3.8]	0.8
SDSS–II SS	1.5	2d	2.68×10^{-3}	150	2005–2008	3.2×10^{-3}	1.6[0.4–6.3]	0.8
Catilina	2.5	10m–1yr	4.60×10^{-2}	1200		8.0×10^{-4}	0.6[0.1–2.4]	0.6
SLS	1.0	3d–5yr	5.60×10^{-4}	2	2003–2008	5.2×10^{-3}	2.8[0.8–11]	0.03
SkyMapper	5.7	0.2d–1yr	7.39×10^{-2}	1000	2009–...	6.4×10^{-4}	0.5[0.2–2.0]	0.3
Pan–STARRS1	7.0	3d	7.39×10^{-3}	6000	2009–...	2.0×10^{-3}	1[0.3–4.4]	12
LSST	9.6	3d	4.66×10^{-4}	3300	2022–...	5.1×10^{-3}	3[0.8–11]	50
Gaia	0.5×2	20d	3.00×10^{-2}	2000	2014–2019	10^{-3}	1[0.5–5]	2
ZTF *	42.0	1d	2.00×10^{-2}	22 500	2017–...	1.1×10^{-3}	0.8[0.4–4.8]	20
RASS	3.1	...	4.00×10^{-5}	12 000	6 months	8.0×10^{-4}	1[0.3–4.4]	10
eROSITA	0.8	6 months	2.00×10^{-6}	4320*	4 years	3.0×10^{-3}	2[0.5–6.5]	26

Notes. Ongoing and future surveys are marked in boldface. Parameters of the optical surveys, field of view (FOV), cadence, limiting flux $F_{\rm lim}$, coverage and lifetime are from the compilation of Rau et al. (2009). The rate of orphan afterglow $R_{\rm OA}$ above the survey limiting flux is obtained through the flux density distribution reported in Fig. 2. The average OA duration above this flux limit $\langle T \rangle$ is derived from Fig. 3 and from the parameters of the linear fits reported in Table 1 (minimum and maximum durations are shown in brackets). The last column shows the number of OAs per year detectable by the reported surveys. For the X-ray the sky coverage is intended for 24 h. (*) See http://www.ptf.caltech.edu/ztf and Bellm (2014).

- ZTF of interest already (use public alert stream)
- Rubin LSST is the most promising

More ideas. . .

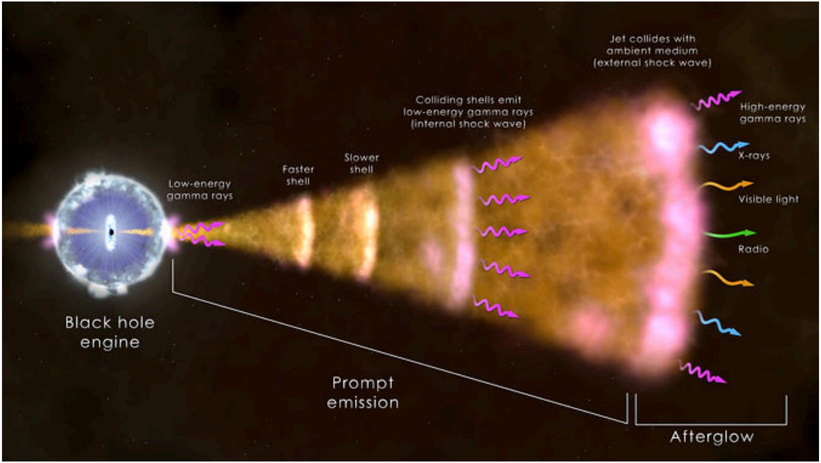
- Identify ‘optical’ orphan afterglows
  - multi-wavelength data needed for Rubin candidates
  - optical, radio, spectroscopy
- Find origin of some orphan afterglows
  - consider excellent space localization and sub-threshold signals
  - but bad time localization (no T_0)
  - multi–messenger: GW, GRB, CR, Radio, Neutrino

  → lots of stuff to do if any signal found
- GRB and progenitors physics
  - need theoretical modeling
  - system geometry, jet structure, star environment, population
  - kilonovae and supernovae
- Cosmology (reionization)
  - population of (Pop III) massive stars as a function of redshift (Long GRBs)

Non exhaustive list of OA candidates

- **PTF11agg**: *"Discovery of a Cosmological, Relativistic Outburst via its Rapidly Fading Optical Emission"* [2013ApJ...769..130C]
- **ZTF19abvizsw** (AT2019pim): *"Liverpool Telescope observations of ZTF19abvizsw, a candidate untriggered GRB afterglow "*[GCN 25643] and all GCNs associated to [Kool et al., GCN 25616]
- **ZTF20aajnksq** (AT2020blt): *"ZTF20aajnksq (AT 2020blt): A Fast Optical Transient at z $\sim$ 2.9 with No Detected Gamma-Ray Burst Counterpart"* [2020ApJ...905...98H]
- **SN2020bvc**: *"The broad-line type Ic SN 2020bvc: signatures of an off-axis gamma-ray burst afterglow"* [2020A&A...639L..11I]
- **ZTF21aaeyldq** (AT2021any): *"Revealing nature of GRB 210205A, ZTF21aaeyldq (AT2021any), and follow-up observations with the 4K$\times$4K CCD Imager+3.6m DOT"* [Nov. 2021, Journal of Astrophysics and Astronomy]
- But things are not so clear:
  "Low–efficiency long gamma–ray bursts: a case study with AT2020BLT" [2021arXiv210601556S]

GRB fireball model



EGO schedule