Looking for orphans (and their cousins) in wide fields

James E. Rhoads

NASA Goddard Space Flight Center

NASA Time Domain and Multimessenger Astrophysics Workshop

Annapolis, Maryland, August 2022

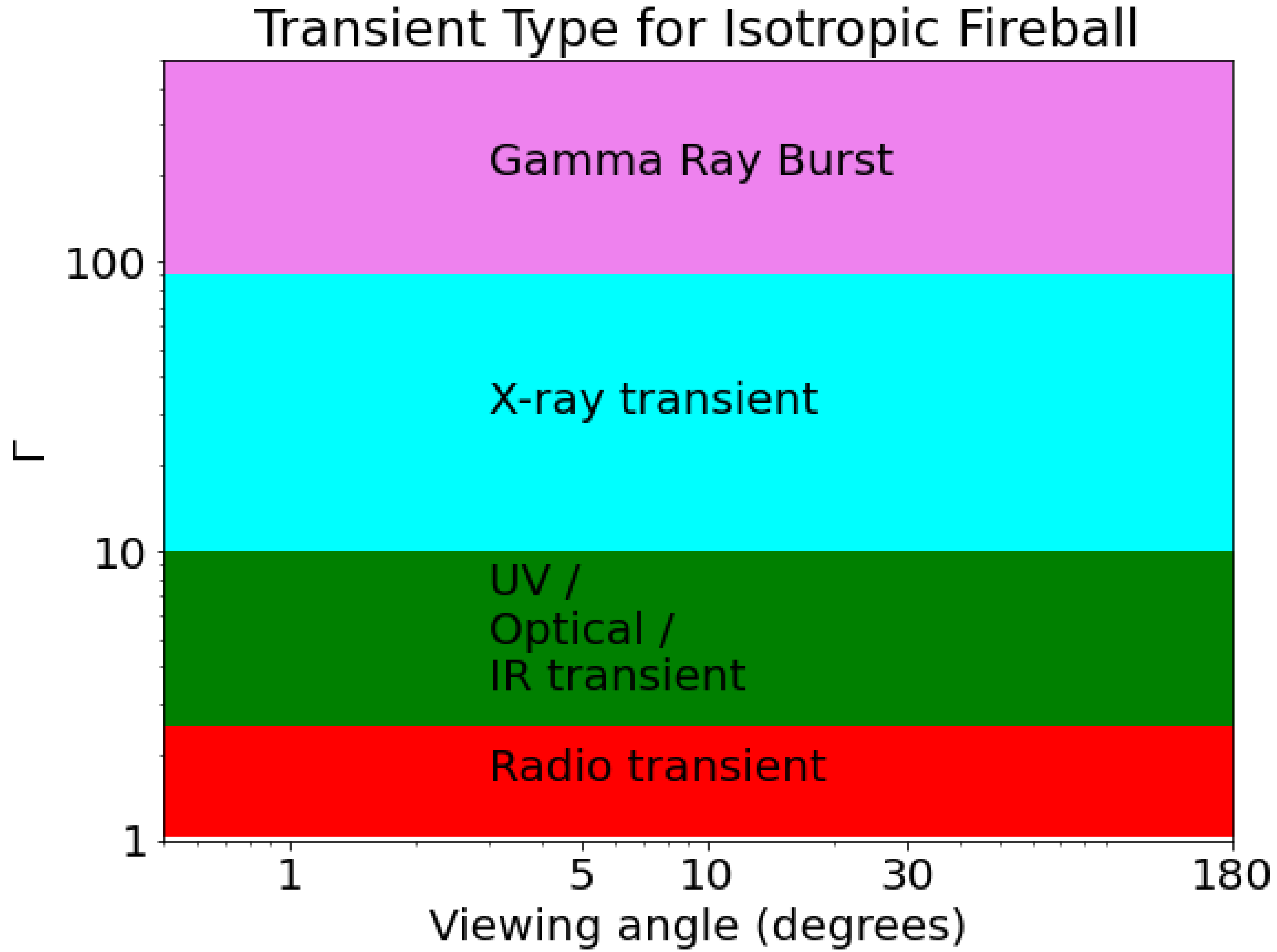
Relativistic Fireballs (1)

- Relativistic fireballs result when a large amount of energy (~ 1 GRB worth) is released into a small volume with some baryons.
- Optically thick --> energy ends up as kinetic energy of the baryons.
- If the baryon loading is small enough (~ 1 planet's worth), the ejecta are highly relativistic (Lorentz factor $\Gamma > 100$), and shocks in the ejecta can then produce a gamma ray burst.
- This model was extensively developed in the context of GRB and GRB afterglow modeling.

- **Question: What fireballs are we missing when we count GRBs?**

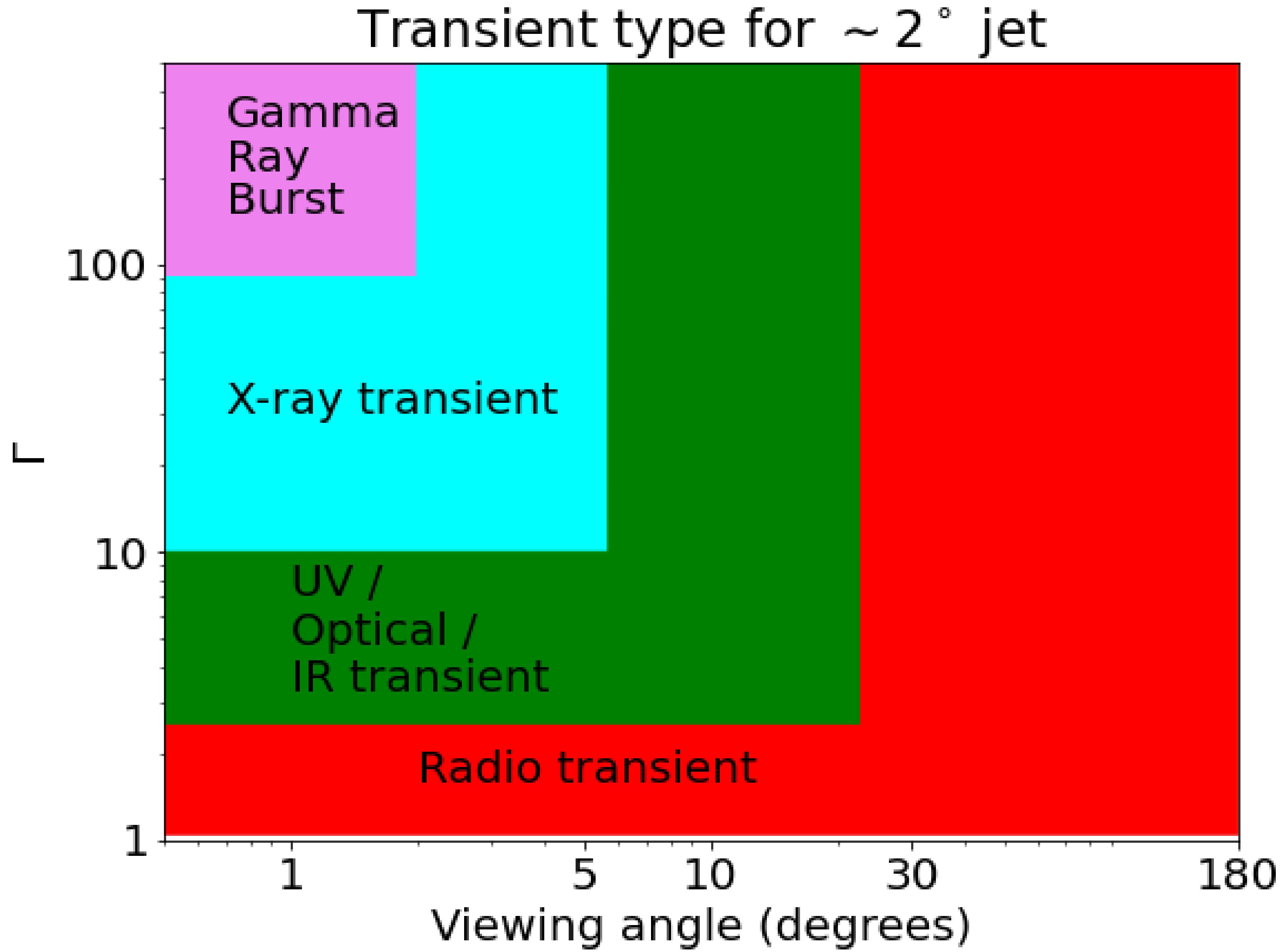
Relativistic Fireballs (2) – Dirty Fireballs

- Such a small baryon loading probably requires special conditions, as suggested by the relatively low ratio of GRB to supernova event rates.
- If the baryon loading is substantially larger, the peak Lorentz factor of the ejecta may be in the range $2 \lesssim \Gamma \lesssim 100$.
- The resulting “dirty fireball” will not produce a GRB (see, e.g., Woods & Loeb 1995), but will produce some or all of radio, infrared, optical, ultraviolet, and X-ray emission (with the shortest wavelength following from the peak Γ).

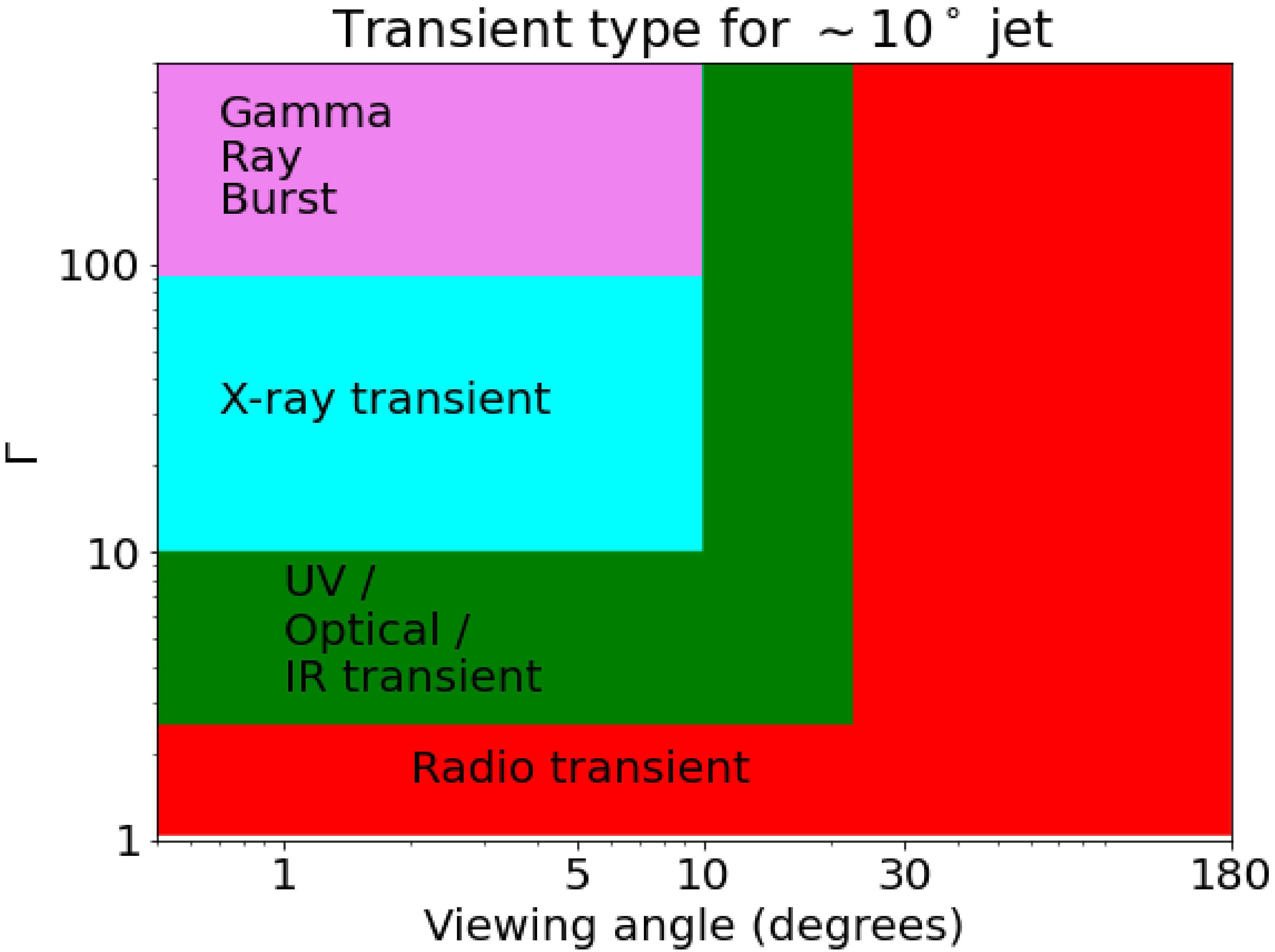

Transient Type for Isotropic Fireball
Gamma Ray Burst
X-ray transient
UV /
Optical /
IR transient
Radio transient
100
10
1
Γ
1
5
10
30
180
Viewing angle (degrees)

Relativistic Fireballs (3) – Collimation

- GRB explosions are thought to be collimated, presumably bipolar, outflows
  - Observed GRB fluences combined with cosmological distances would imply energies much exceeding supernova energies if isotropy is assumed.
  - The very small baryon loading may be produced along the rotation axis in collapsar models for long GRBs, or perpendicular to the orbital plane for an NS-NS merger.
- Afterglow emission from collimated ejecta is expected over a wider angle than the gamma ray emission.
  - Relativistic beaming → $\theta_{em} \sim 1/\Gamma$ (e.g. Rhoads 1997)
  - Sideways expansion of decelerating jet material once $\Gamma < 1 / \theta_{jet}$. (Rhoads 1999)
- Simplest toy model: "Top hat" jets, where Γ is independent of θ, and $dE/d\Omega$ is a step function.



Note, this illustration assumes a hard-edged ("top hat") jet.



Note, this illustration assumes a hard-edged ("top hat") jet.

Orphan Afterglows

- Broad definition: An orphan afterglow is a transient that resembles the long-wavelength afterglow of a gamma ray burst (GRB), but that is observed without the benefit of a GRB trigger.
- Classes:
  - Untriggered GRB Afterglows:
    - In this case, gamma rays from the event were observable from Earth orbit, but simply not observed (no appropriate detector was looking)
  - Afterglows of off-axis GRBs (true orphans):
    - Gamma ray emission was produced by the event, but not directed towards Earth.
    - The longer-wavelength afterglow illuminates a larger solid angle that includes Earth.
  - Dirty fireballs:
    - No gamma ray emission was produced, only an afterglow-like transient
    - Under a fireball model of GRBs, this can happen if baryon loading is high and the peak Lorentz factor of the event is $\Gamma \ll 100$.

Orphan Afterglows: Basic Rate Expectations

- BATSE event rate ~ 1000 GRB/Sky/year
- If collimated to 1% of sky, in principle could expect 100x more radio afterglows, and ~ 10x more optical transients
- If distribution of peak Lorentz factors favors dirty fireballs over clean GRBs, could again expect much higher event rates at Xray through radio wavelengths.

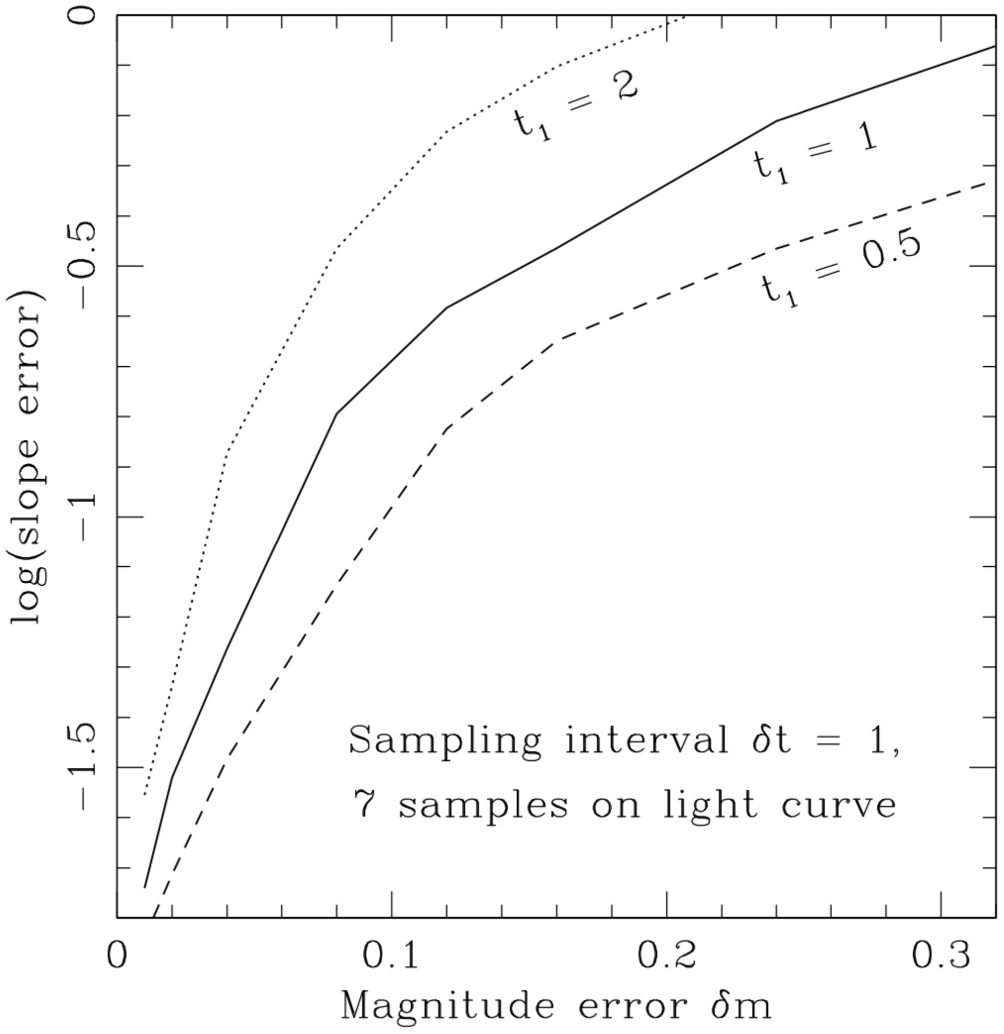
- So an interesting experiment is one that can
  - A) detect at least a few afterglows from the known GRB population, and
  - B) Hopefully distinguish them from other transient events.

- For (A), to get one event, need to monitor ~ 40 sq. deg*year with sufficient cadence and sensitivity to detect the afterglow

Distinguishing Orphan Afterglow Types

Detailed observations of fireball transients can distinguish between different classes of orphans.

- Off-axis orphans and on-axis dirty fireballs have different light curves, and different relations between light curve slope and spectral slope.
- A major uncertainty for off-axis fireballs is the true trigger time, which must be fitted along with decay slope (+1 "nuisance" parameter).
- *Right: Figure 1 from Rhoads 2003: Slope error for realistic O/UV/IR monitoring campaign for orphan afterglow.*



2003ApJ...591.1097R , DOI: 10.1086/368125

Worked example from ZTF

Journal, 918:63 (16pp), 2021 September 10 Andreoni et al.

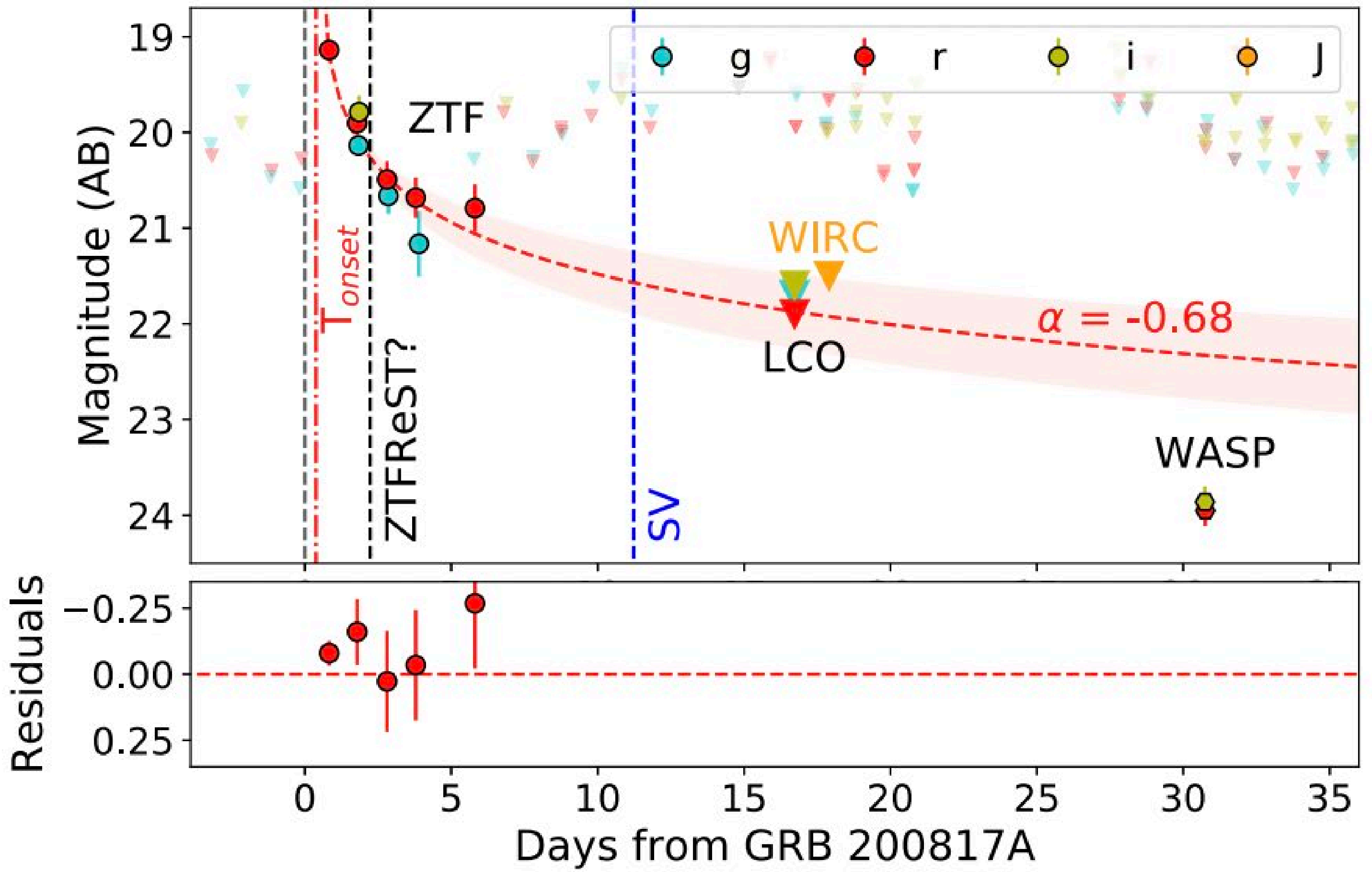


Fig 3 of Andreoni et al 2021: ZTF (+) light curve for an optically identified afterglow.

See distinction between T_onset from power law fit, and trigger time of likely associated GRB.

Decay slope $\alpha = -0.68 \pm 0.124$
Age at discovery 11 +- 4 hours

Distinguishing Orphan Afterglow Types

Certain characteristics of afterglow light curves & spectra evolve differently pre-break and post-break.

"Classical" off-axis orphans are only observed in the post-break regime, and any orphan showing "pre-break" behaviors is either an untriggered GRB or a dirty fireball.

Uncertainty in trigger time can affect measured slopes, but cannot change the sign of a measured slope. *Radio light curve slope is thus promising.*

Table 1. Indicators of Orphan Afterglow Origins

Quantity	Conditions: $t < t_{jet}$ uniform	$t < t_{jet}$ wind	$t > t_{jet}$
$f_{\nu,m}$	0	-1/2	-1
ν_c	-1/2	+1/2	0
ν_a	0	-3/5	-1/5
f_{radio}[a]	1/2	0	-1/3

[a] "f_{radio}" is here defined as the flux density for frequencies ν such that $\nu_a < \nu < \nu_m$. This corresponds to cm-wave and mm-wave radio frequencies for typical GRB afterglows.

Table 1, Rhoads 2003

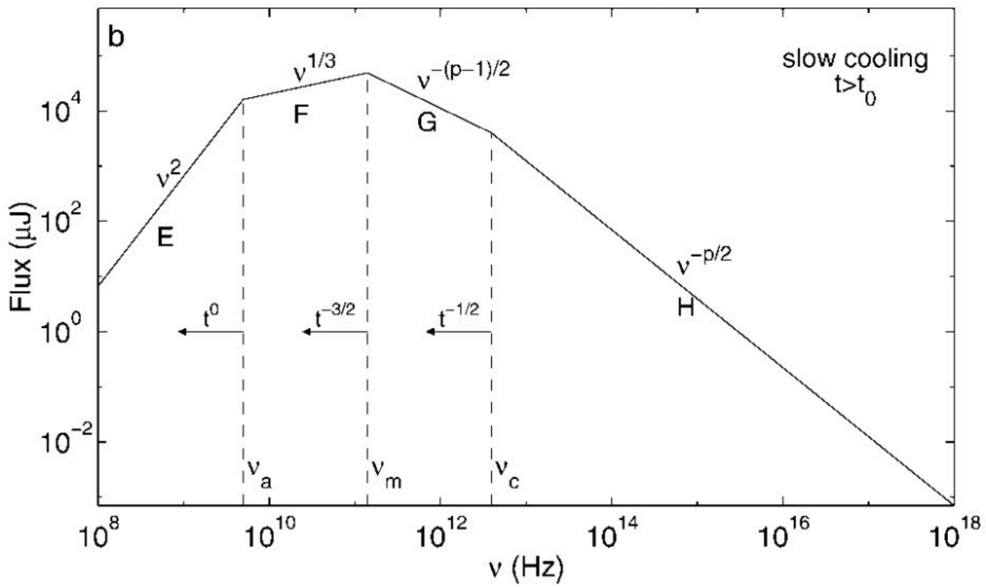
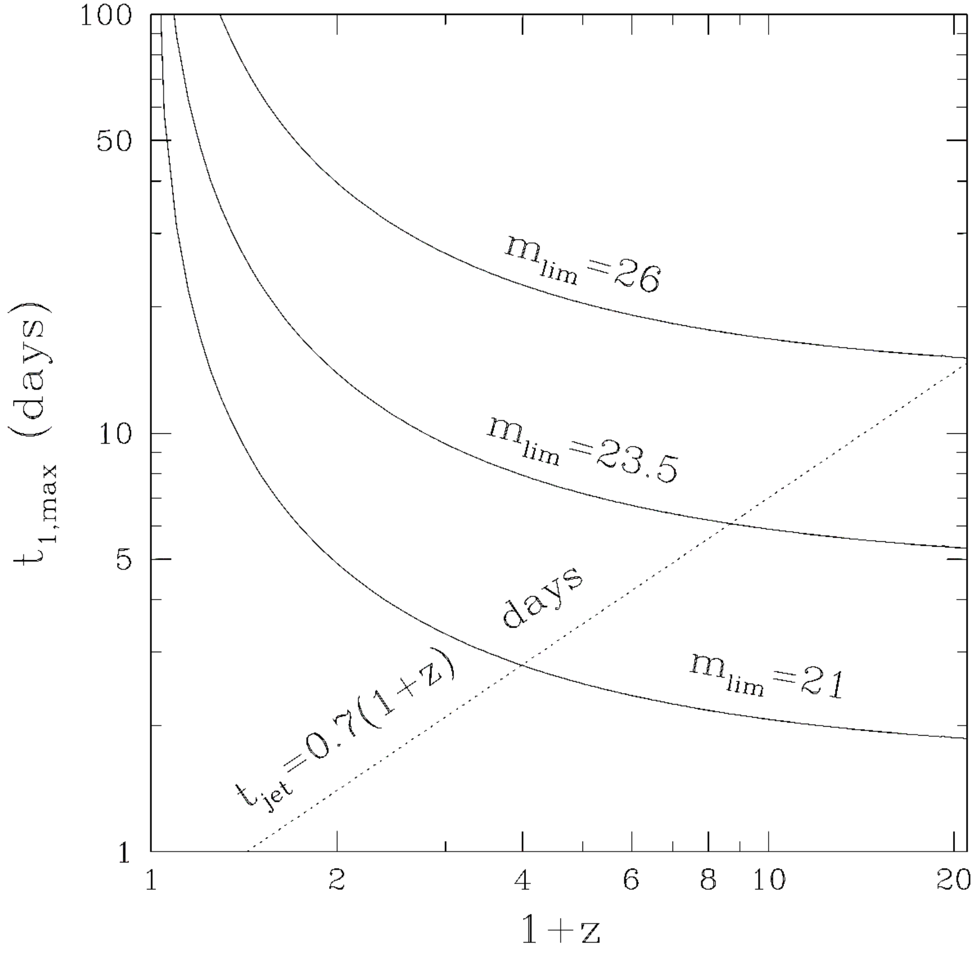
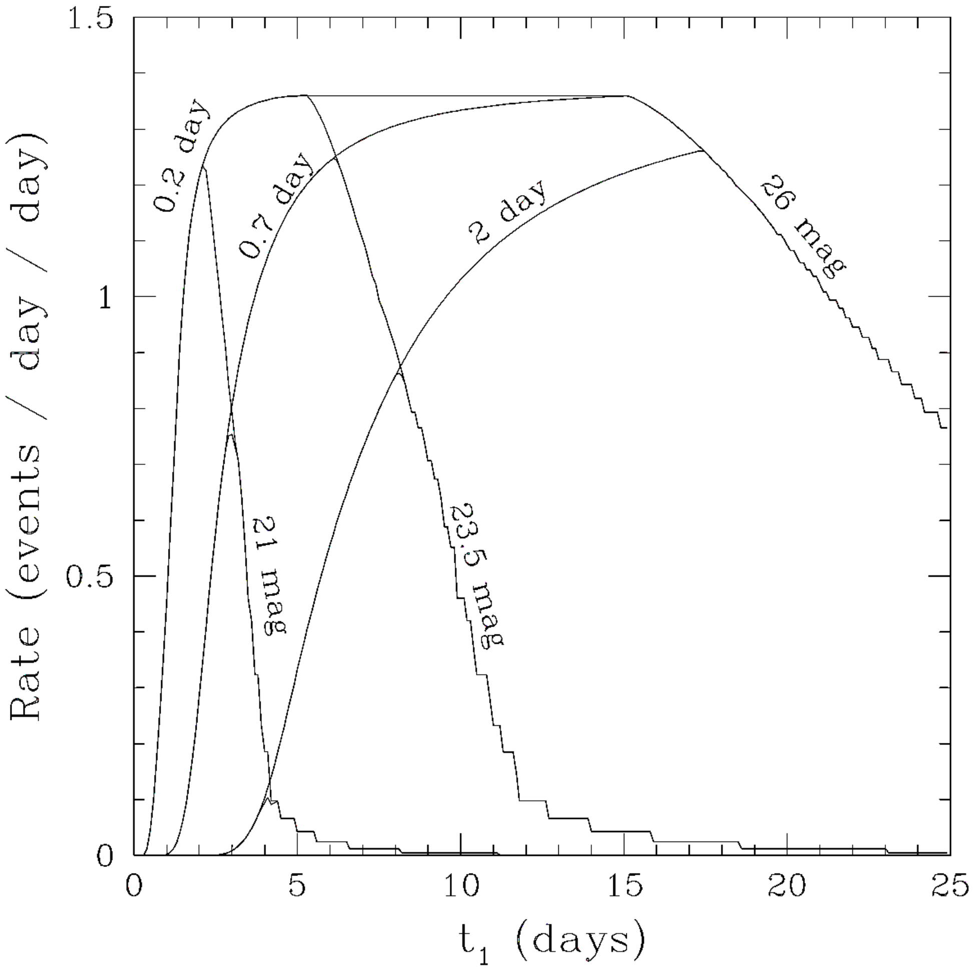


Figure 1b, Sari et al 1998

Population predictions from a “standard” jet model



Latest time at which an off-axis jet would become observable above a particular magnitude.



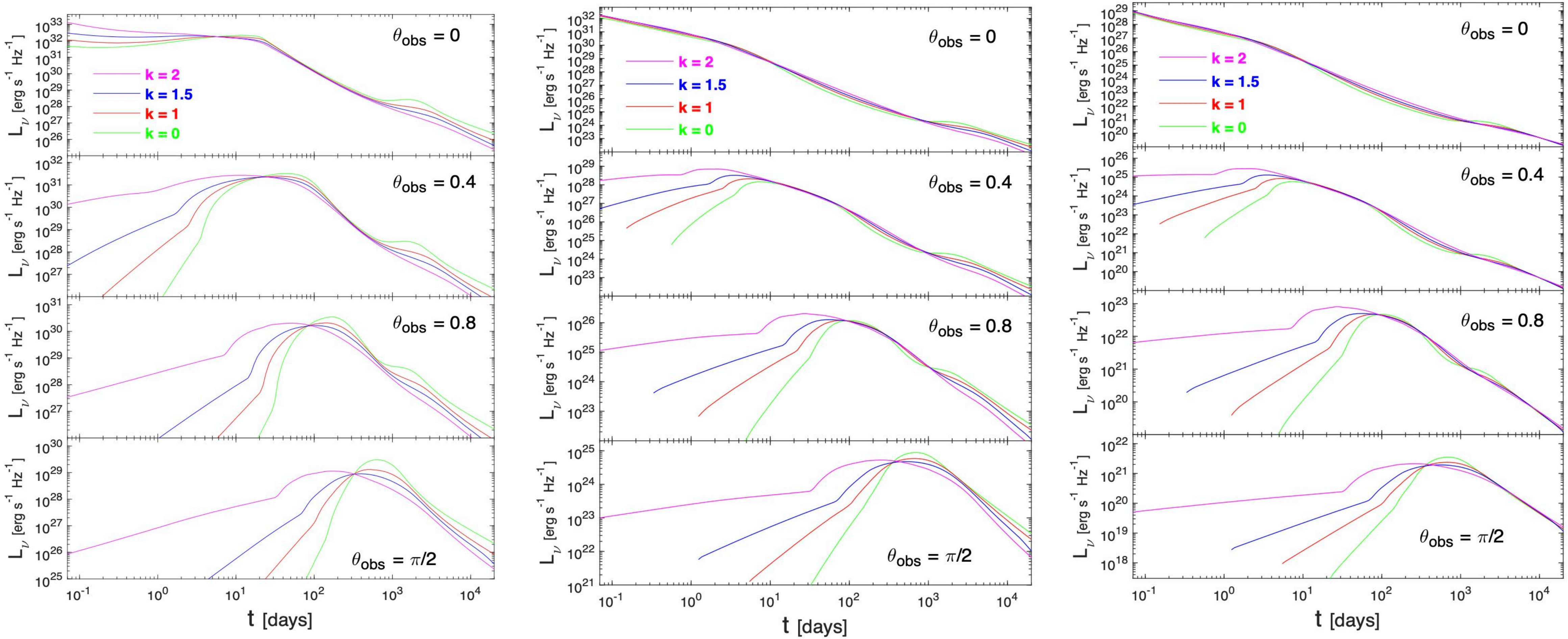
Event rate for off-axis orphan discovery *as a function of age at discovery*, above a particular flux threshold

Figures 3-4, Rhoads 2003

More realism: Structured jets

- The top-hat approximation is simplistic, and “structured jet” models (e.g. Rossi et al 2002) are more plausible.
- We can consider a general fireball model by specifying
  - $\frac{dE}{d\Omega}(\theta)$
  - $\Gamma(\theta)$
- This allows a fully structured bipolar jet model.
- Common simplifications include
  - “Top hat” jets, where Γ is independent of θ and ${}^{dE}/_{d\Omega}$ is a step function
  - Jets where one or both quantities decline as power laws away from the jet axis (usually with some kind of core so that neither quantity diverges on axis)

Relativistic Hydrodynamic Simulation Results



- Radio, Optical, X-ray. Different opening angles & ambient density profiles.
- Figures from Granot et al 2018, MNRAS 481, 2711

Fireball Populations

- Suppose we describe each fireball with its total energy E, collimation angle θ, and peak Lorentz factor Γ.
- We would like to know the event $R(E, \theta, \Gamma, z)$

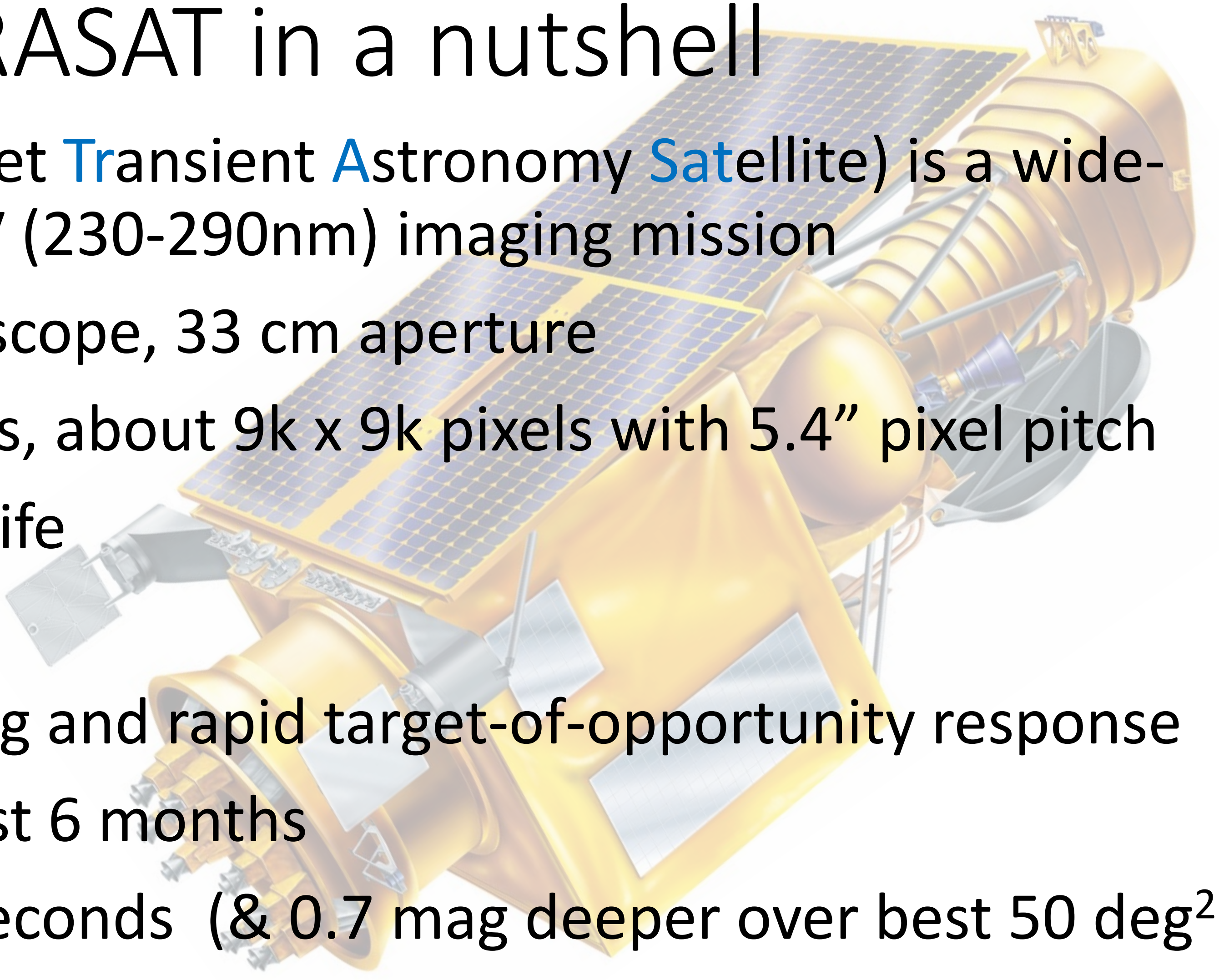
- GRB experiments constrain this distribution for the $\Gamma \gtrsim 100$ portion of parameter space, with thresholds in fluence ~ $E / (\theta^2 \ d(z)^2)$
- Multiwavelength monitoring of GRB afterglows yields constraints on the distribution of θ.
- Constraints from optical regime are getting better thanks to recent time domain experiments, notably the Zwicky Transient Factory (cf. Ho + Perley's talk, in this workshop)

The Coming Era of Time Domain Astronomy

The next years will see the inception of critical new observational capabilities:

- Ultraviolet: ULTRASAT (2025)
- Near-infrared: The Nancy Grace Roman Space Telescope (2026)
- Optical: The Vera Rubin Observatory (2023)
- Latest news: X-ray from X-STAR, or UV from UVEX (2028)

ULTRASAT in a nutshell



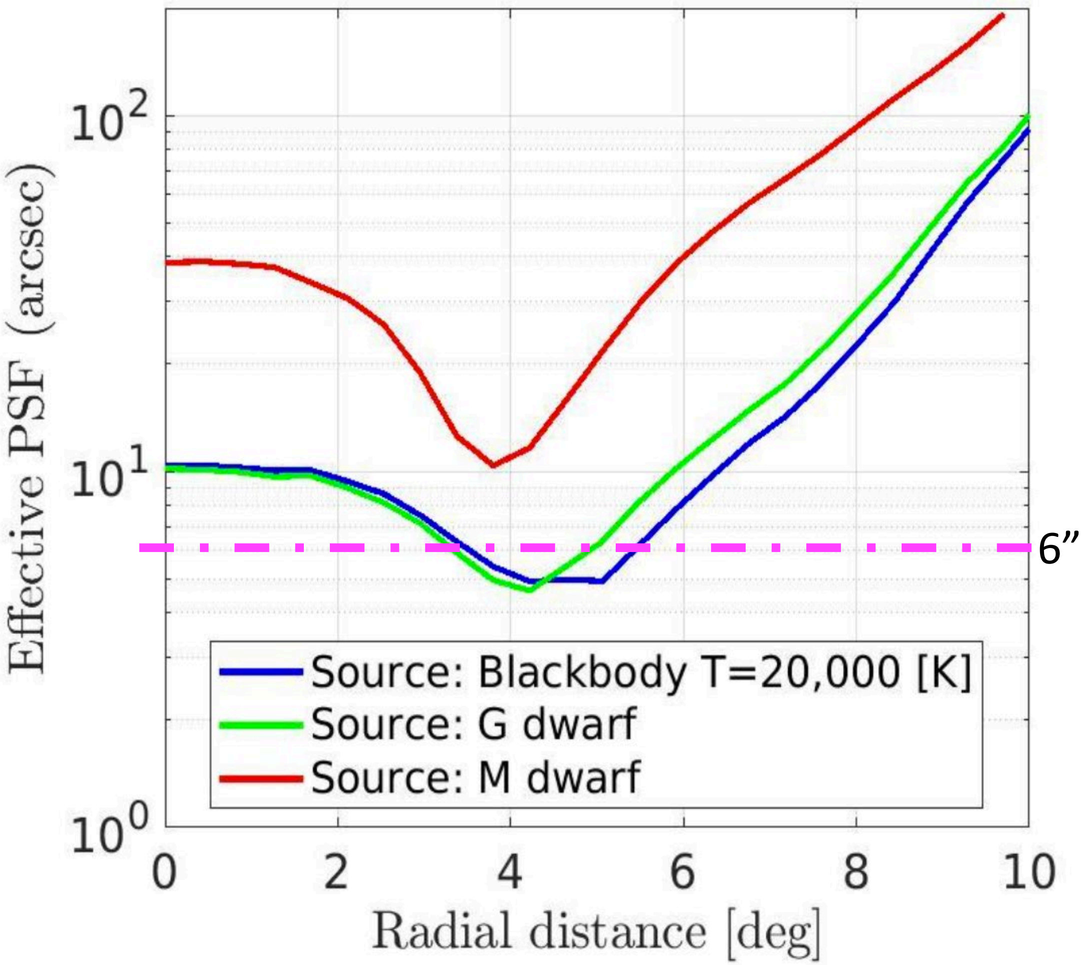
- ULTRASAT (the Ultraviolet Transient Astronomy Satellite) is a wide-field (200 deg^2) near-UV (230-290nm) imaging mission
- Wide field Schmidt telescope, 33 cm aperture
- High QE CMOS detectors, about 9k x 9k pixels with 5.4” pixel pitch
- 3 year primary mission life
- Geostationary orbit
- High cadence monitoring and rapid target-of-opportunity response
- All-sky survey during first 6 months
- 22.3 AB mag in 3x300 seconds (& 0.7 mag deeper over best 50 deg^2)

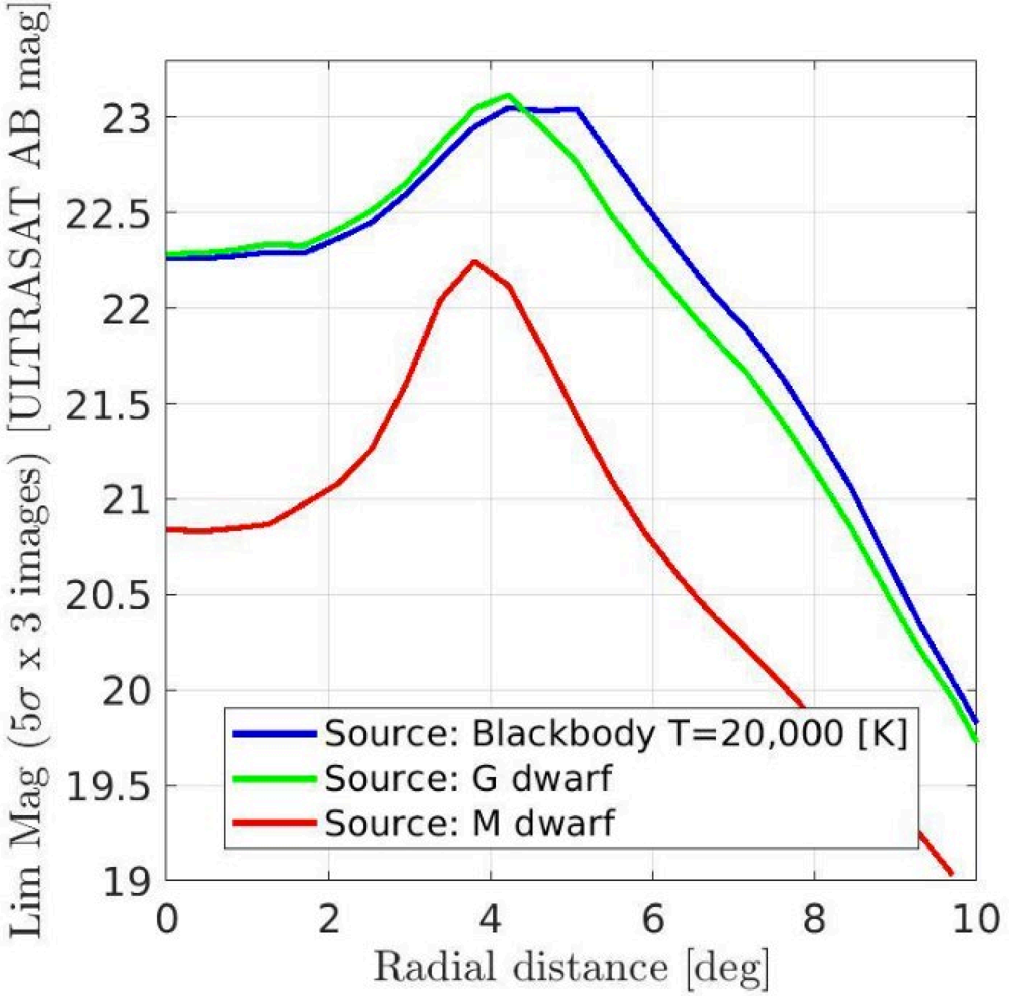
ULTRASAT Partnership

ULTRASAT is an Israeli mission with NASA & German partnership.

- NASA’s roles:
  - Launch ULTRASAT
  - Select and fund participating scientists who will join ULTRASAT working groups, and have data access during the 1-year limited access period
  - Provide a US based science archive
  - Participate in alerts
- ULTRASAT is also negotiating a partnership with the Vera Rubin Observatory / LSST.

ULTRASAT Performance vs. field position

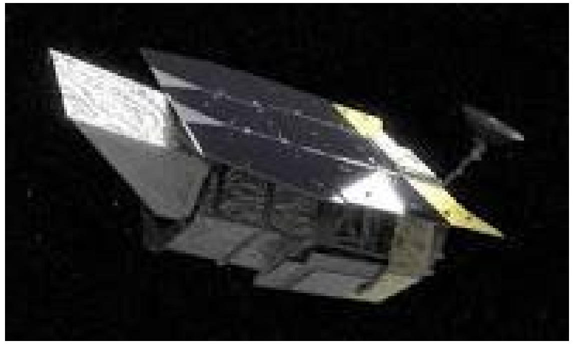




Operations Concept

- Survey mode:
  - Deep / high cadence. 21 hours/day over 1 ULTRASAT field per semester
  - Wide / low cadence.   3 hours/day; 40 ULTRASAT fields on a 4 day cadence.
- Target of Opportunity mode:
  - Responsive to triggers from LIGO, and potentially other trigger sources
  - Can reach > 50% of sky within < 15 minutes.
- All Sky Map mode:
  - Replaces the wide / low cadence survey during first 6 months of operations.
  - 7x deeper than GALEX all sky survey, reaching AB = 23-23.5 mag over the high Galactic latitude sky, |b| > 30 deg; covers low latitude sky also (just not as deeply; limit AB=21.7 – 22.2 mag).

Roman Space Telescope in a nutshell



- The Nancy Grace Roman Space Telescope, formerly WFIRST.
- 8 near-IR and optical filters, plus slitless grism (R~1000) and prism (R~100)
- Three-mirror anastigmat, HST light-gathering and image quality
  - 0.28 square degree field of view
- 18 H4RG10 detectors, total 300 Mpix, with 0.11” pixel pitch
- 5 year primary mission, all expendibles sized for 10 year+ life
- L2 orbit
- Notional Core Community Surveys with time domain components:
  - Galactic Bulge Time Domain Survey: ~ 2 deg^2 with 15 min cadence, seven seasons of 72 days each, one primary filter W149 and two other filters for color info
  - High Latitude Time Domain Survey: ~ 10 deg^2, monitoring with 5 day cadence in several filters + prism, total of 6 months’ data spread over 2 years
  - High Latitude Wide Area Survey: ~ 1700 deg^2, four filters + grism, 2- 4 passes enables some basic variability tests

Vera Rubin Observatory Capabilities

- 8m telescope in Chile
- 7 sq. degree, ugrizy filters
- Survey of full southern sky, plus deep drilling fields
- Depths of 24 - 25 mag per single epoch, with revisits on ~ 0.25-2 hour cadence and on ~ 2 day cadence
  - Some complexity in cadence for single filters.
  - Deep drilling fields, minisurveys, weather, etc

Looking Forward

- ULTRASAT represents an improvement of ~ 1000x in near-UV survey efficiency compared to GALEX
- Roman represents an improvement of 100 - 500x in near-IR survey efficiency compared to HST
- Rubin represents an order-of-magnitude improvement in Optical survey efficiency compared to ZTF (and much larger compared to SDSS or other fore-runners)
- Combined, these capabilities will unlock the ability to search for afterglow-like transients independent of high energy triggers.

Looking Forward

- ULTRASAT:
  - Expect ~ 15 on axis GRBs in high cadence field, plausibly ~ 60 jetted orphans, + ?? DF.
  - Wide area survey: ~ 500 on-axis GRBs (w. detection of a fraction); plausibly ~ 700 jetted orphans above threshold, + ?? DF
- Roman High Latitude Time Domain Survey
  - Expect ~ 1 on-axis GRB; plausibly ~ 12 jetted orphans, + ?? DF.
- Rubin:
  - Expect ~ 5k on-axis GRBs in LSST survey; plausibly 50k jetted orphans, + ?? DF.
- The resulting population statistics will greatly illuminate our understanding of relativistic fireballs– their energetics, collimation, baryon loading, and progenitor populations.
- Multiwavelength followup of triggers from these sources will greatly enhance their value.

Closing thoughts for this workshop

- Orphan afterglow populations (including off-axis GRBs and dirty fireballs) are in reach with our new facilities.
- ULTRASAT, Rubin, and Roman provide the needed UV/O/IR capability for the mid-to-late 2020s.
- By the end of the decade, we should know whether GRBs dominate the relativistic fireball population, or are just the tip of a (very hot) iceberg.
- There is definite multimessenger potential,
  - After all, GRB170817A = GW170817.
  - And, GW are likely more isotropic than gamma rays, similar to radio afterglows.
- These are panchromatic events; constraints from gamma ray to radio are incredibly valuable.

  ➔Maintain a strong Time Domain capability across the spectrum, including wide area monitoring and responsive Target-of-Opportunity capabilities.