Relativistic Explosions Without GRBs

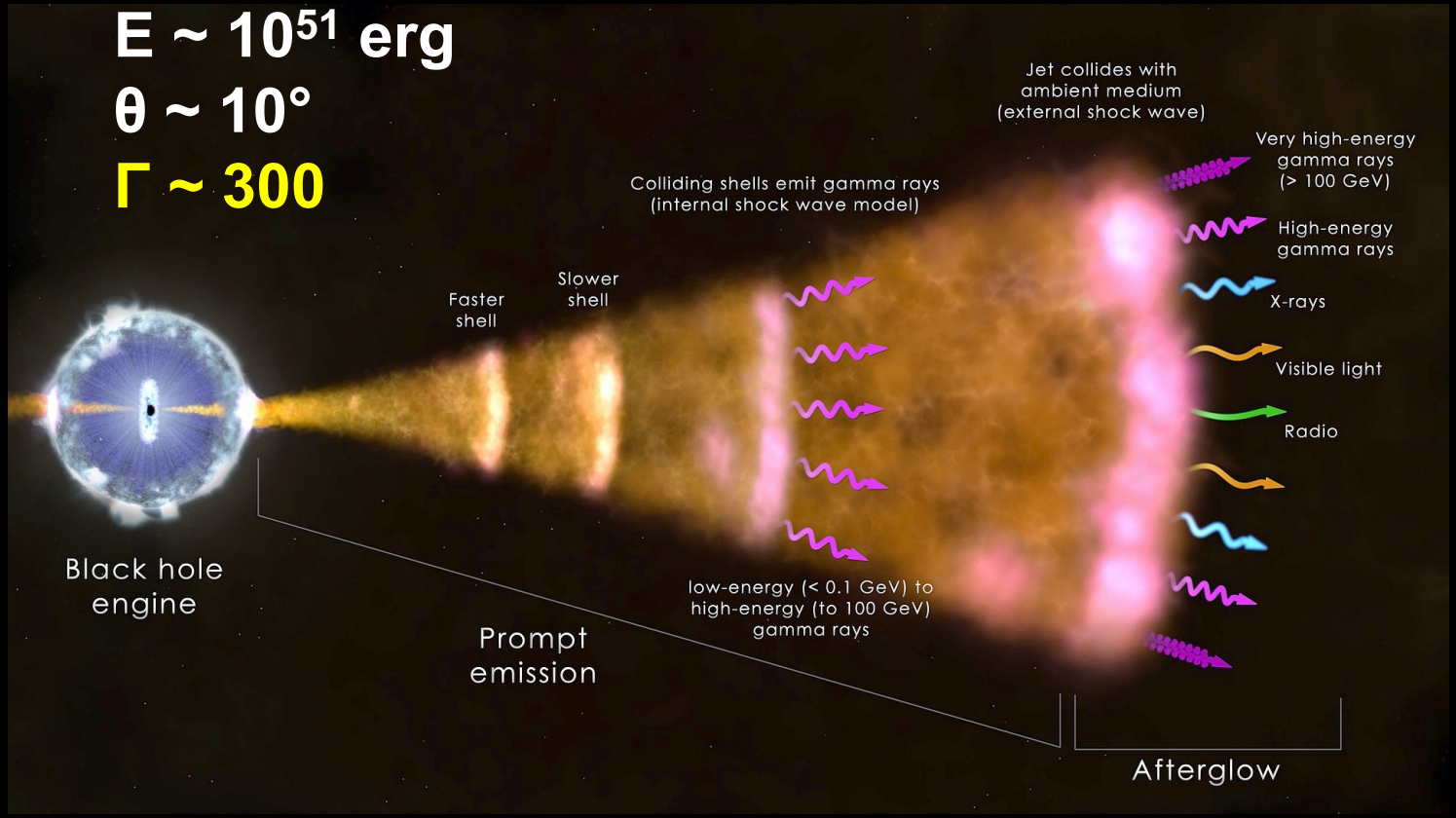
Daniel Perley

Liverpool John Moores University

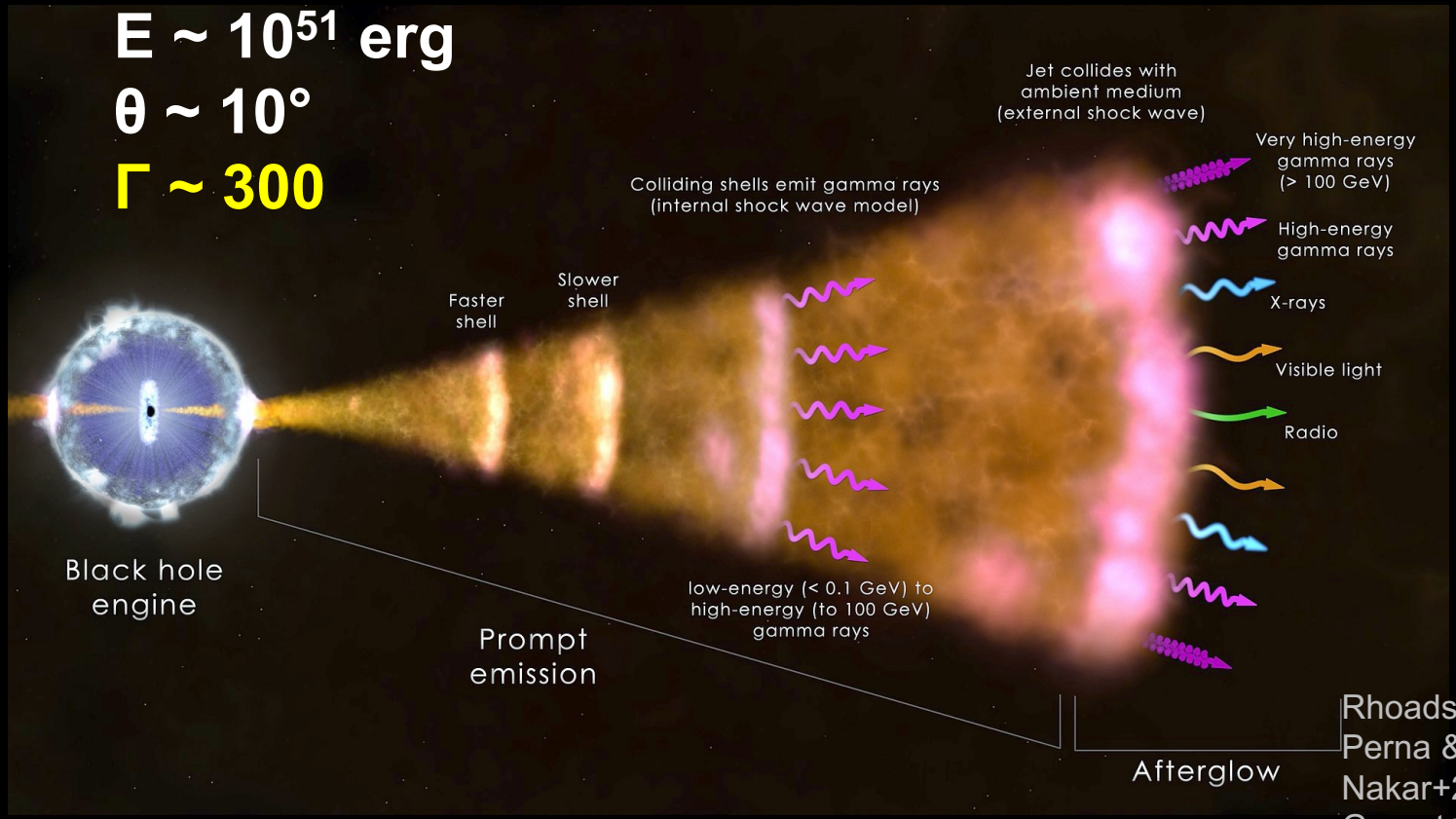
LIVERPOOL JOHN MOORES UNIVERSITY

ZTF

GRB Fireball Model

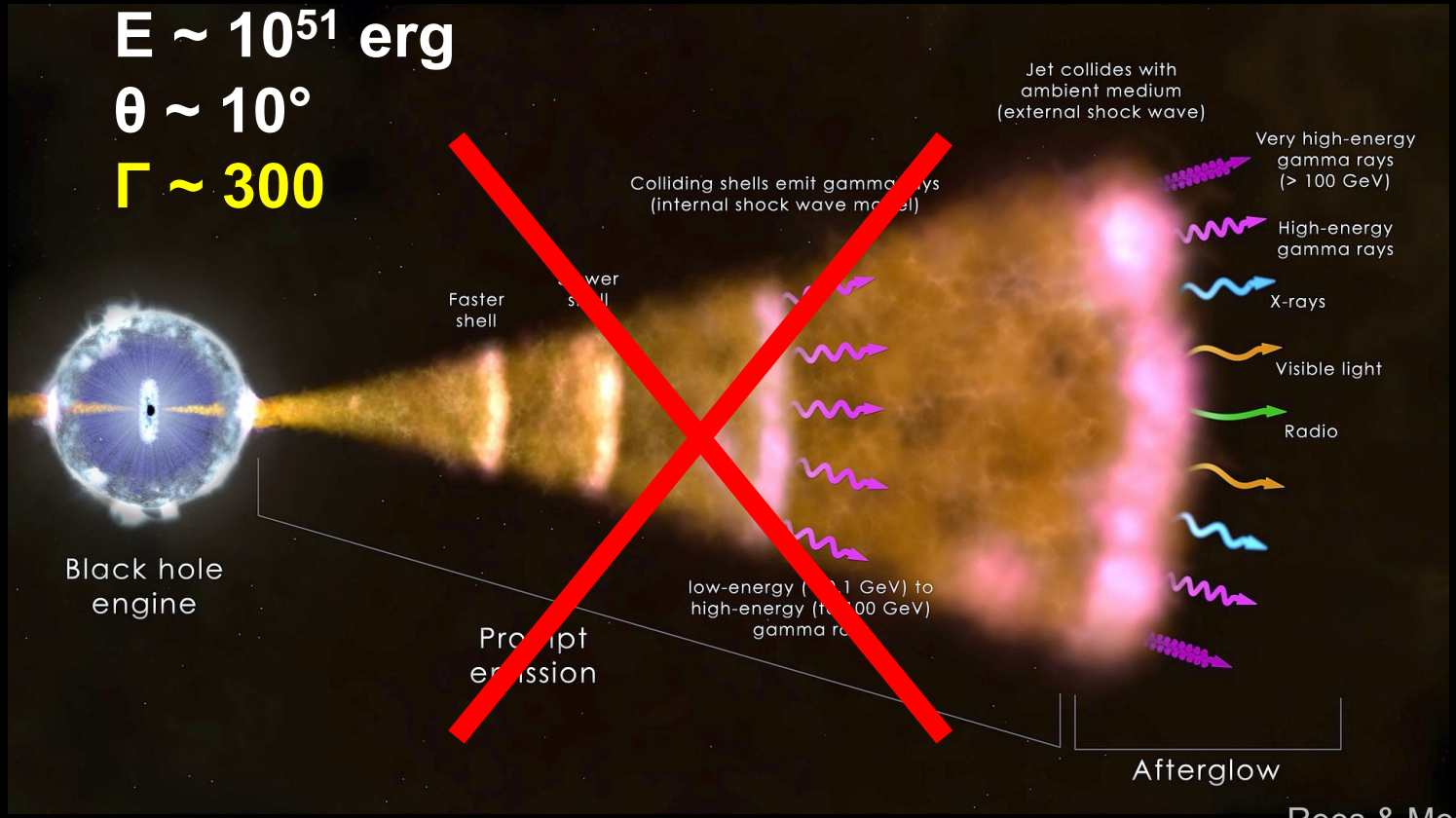


Off-axis Afterglow



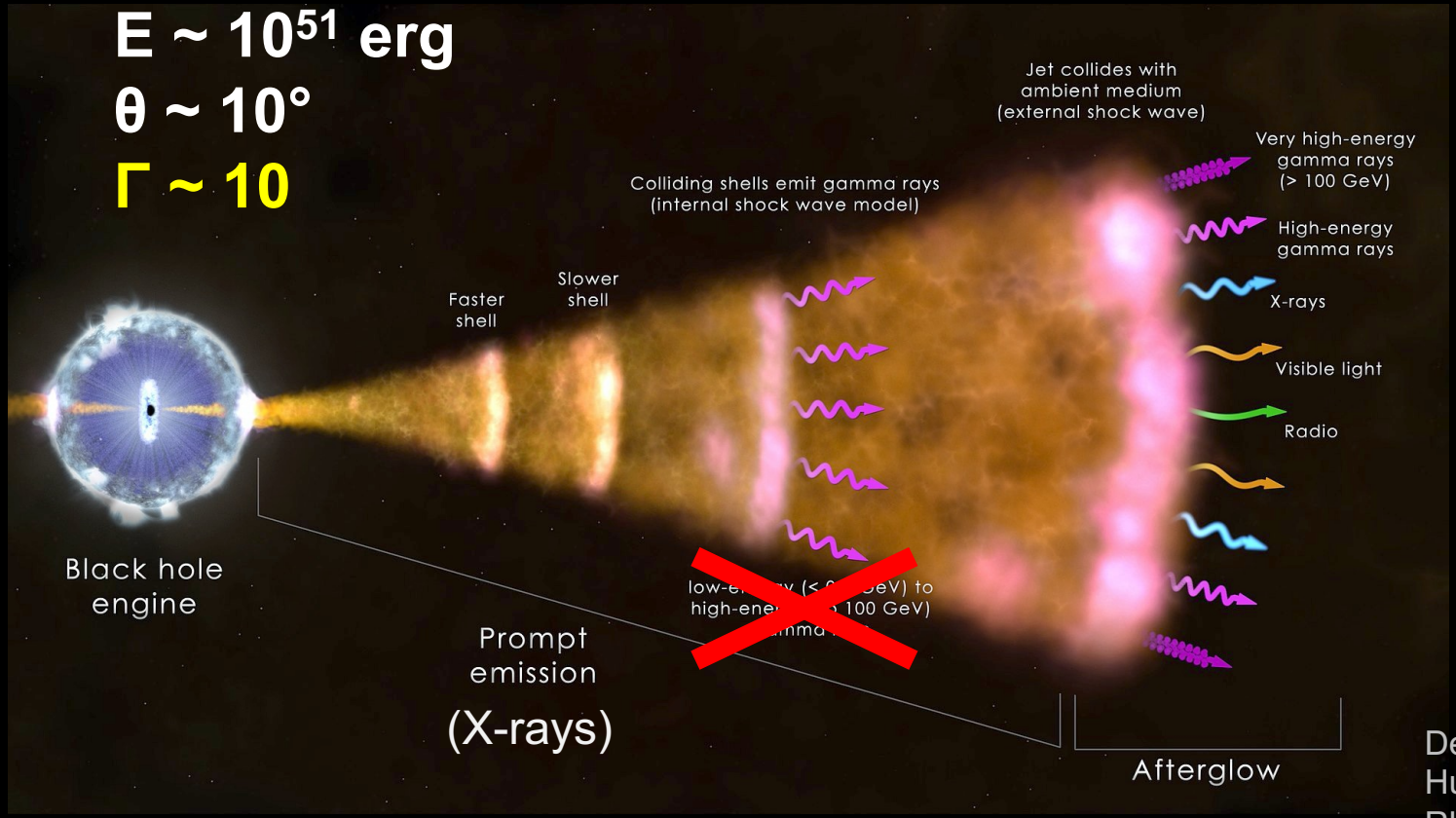
Rhoads 1997
Perna & Loeb 1998
Nakar+2002
Granot+2002

Inefficient Internal Shocks



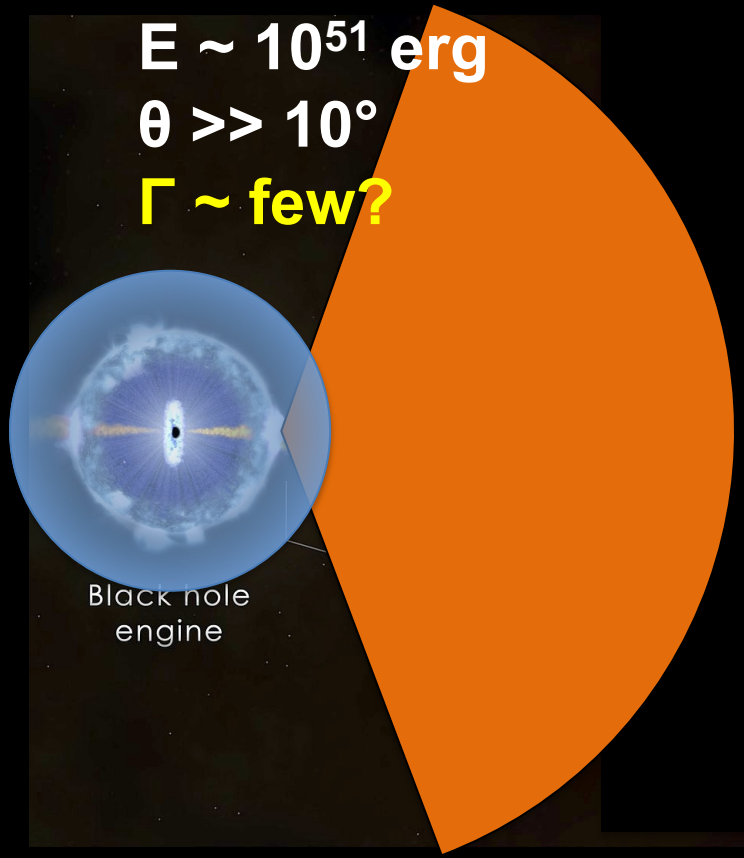
Rees & Meszaros 1994

Dirty Fireball



Dermer+2000
Huang+2002
Rhoads 2003

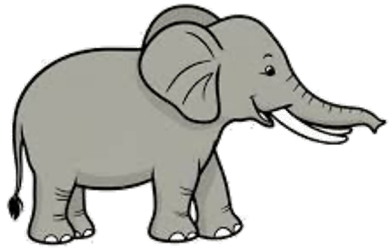
Choked Jet



MacFadyen+2001
Meszaros & Waxman 2001
Nakar+2015

Predicted (non-GRB) jet phenomena

- Off-axis jet
- "Dirty fireballs" (Low Γ)
- Inefficient outflows
- "Choked" jets



Most of these models do not produce luminous high-energy emission. Where do we look?

Searching for Hidden Jets

- X-ray prompt emission: XRFs and FXTs
- Untargeted afterglow searches
  - Optical
  - X-ray
  - Radio
- Constraints from comparative GRB/SN rates
- SN-targeted radio afterglow searches

Searching for Hidden Jets

- X-ray prompt emission: XRFs and FXTs

Bauer+2017,
Quirola-Vásquez+2023
Sun+2024,
van Dalen+2024,
Srivstav+2024,
Bright+2024
(+LLGRBs?)

- Untargeted afterglow searches
  - Optical
  - X-ray
  - Radio Law+2018, Mooley+2022
- Constraints from comparative GRB/SN rates
- SN-targeted radio afterglow searches

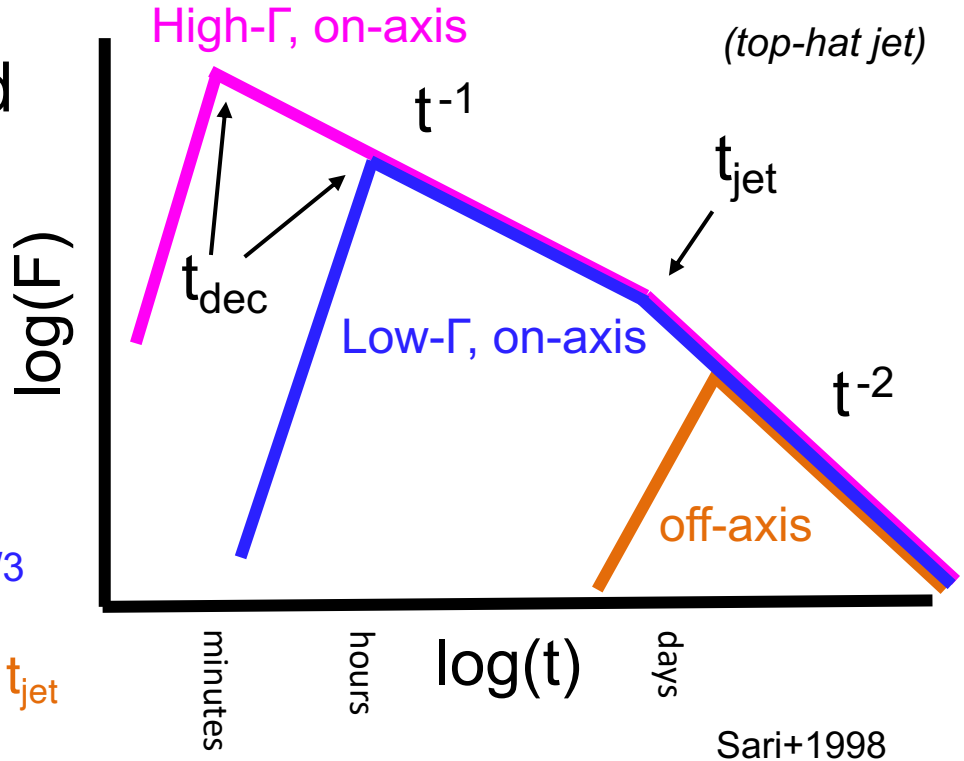
Soderberg+2006, 2010
Corsi+2016,2023

"Orphan" Afterglows

- Any energetic jet should produce a luminous afterglow ($L_{\nu,max} \sim \varepsilon_B^{1/2} E_K n^{1/2}$)
- Peak time delayed if...

  Γ low: $t_{peak} \sim E^{1/3} n^{-1/3} \Gamma^{-8/3}$

  off-axis: $t_{peak} \sim (\theta_{obs}/\theta_{jet} - 1)^2 t_{jet}$

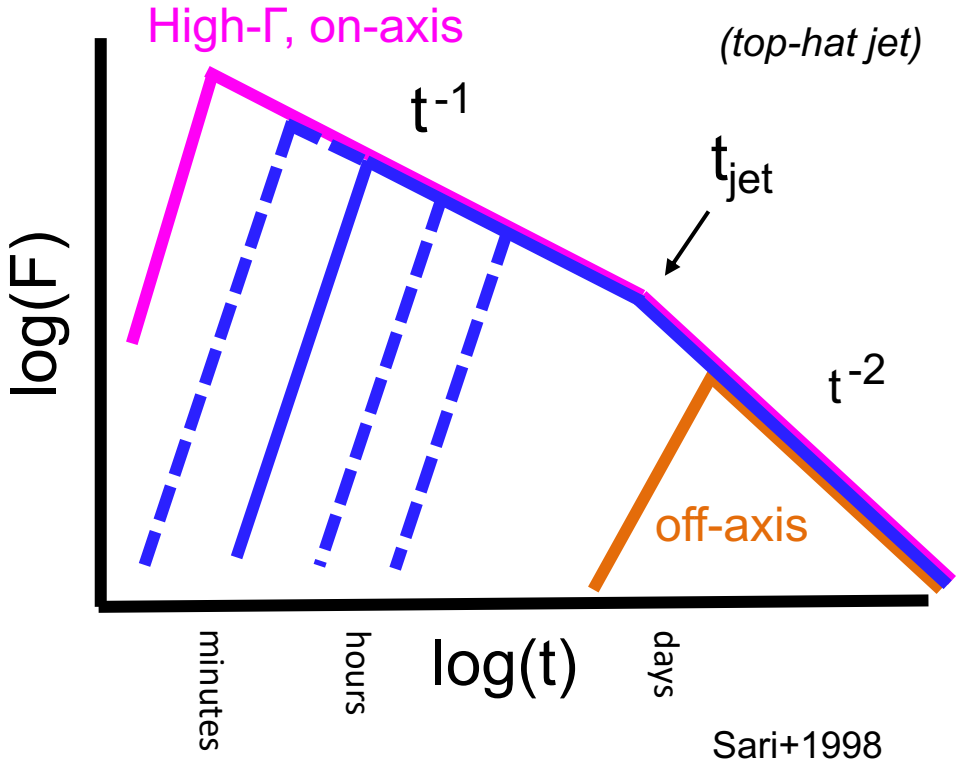


Sari+1998
Granot+2002
Rhodes+2003
Meszaros+2006

Dirty Fireball Signatures

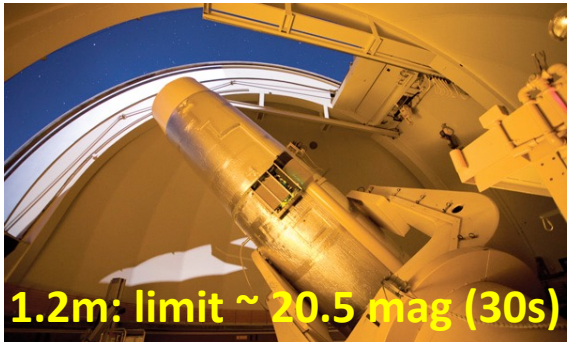
Characteristic afterglow rise times ($\sim \Gamma^{-8/3}$):

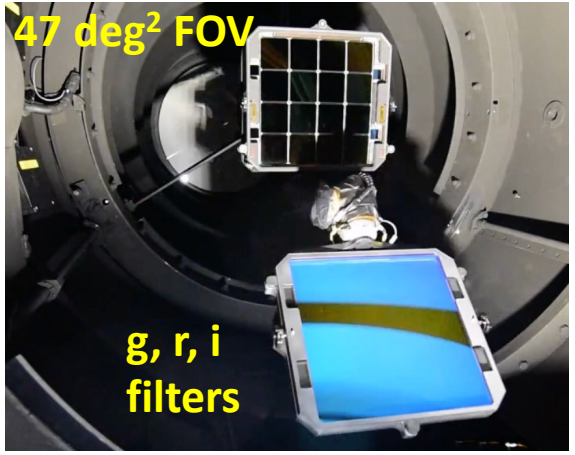
- ~ 10s for Γ=300
- ~ 2 hours for Γ=30
- ~ 0.5 day for Γ=15



Sari+1998
Granot+2002
Rhodes+2003
Meszaros+2006

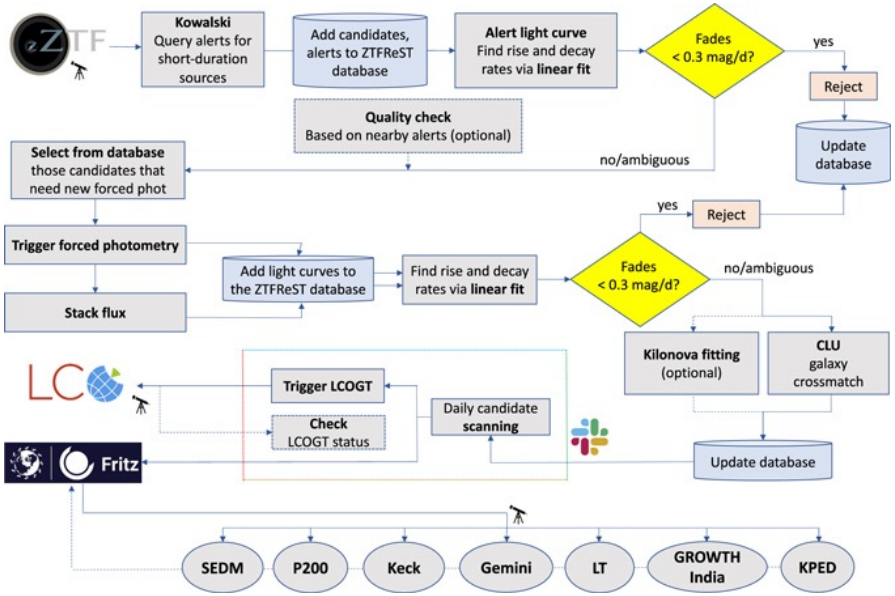
ZTF: Finding Fast Transients in Real Time





ZTF: Finding Fast Transients in Real Time

- Use timescale, crossmatch, and colour to isolate afterglow candidates from new SNe and flare stars



Anna Ho | Igor Andreoni | Michael Coughlin



Ho+2022
Andreoni+2021

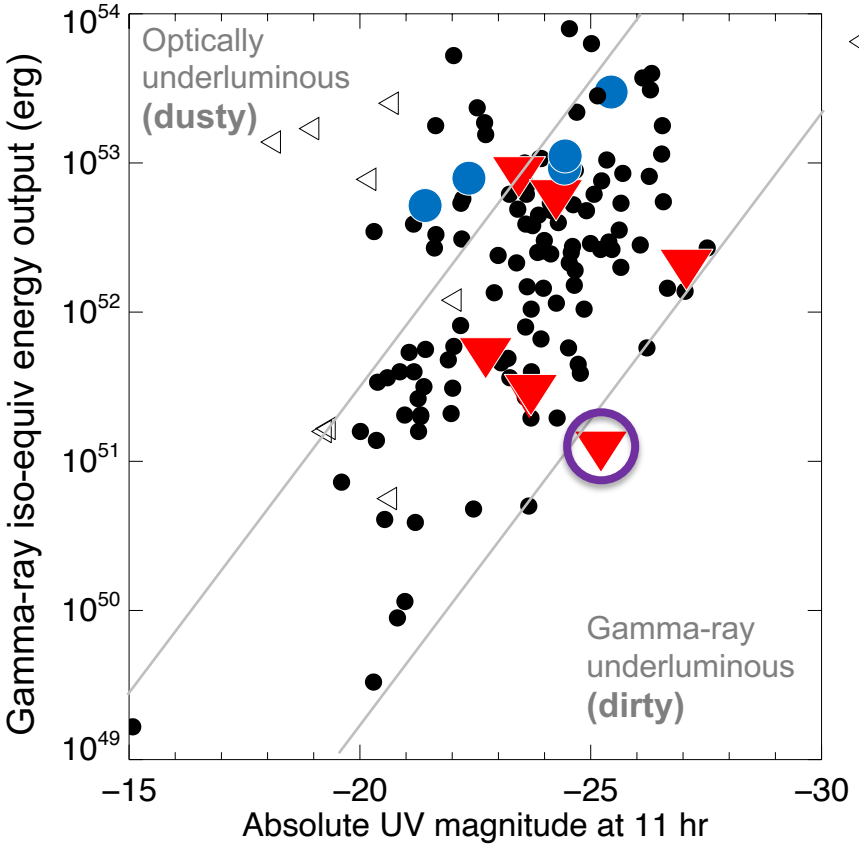
Spectroscopy needed: have to act fast and be confident of candidates!

Afterglow Discoveries

So far: **22** afterglows detected in general survey operations (i.e., *not* TOO follow-up)

- 12 with accompanying GRB (7 found "blind")
- **10** with no identifiable GRB
  - 6 with redshifts

ZTF Afterglows vs. GRB afterglows



◁● *Swift* GRB afterglow

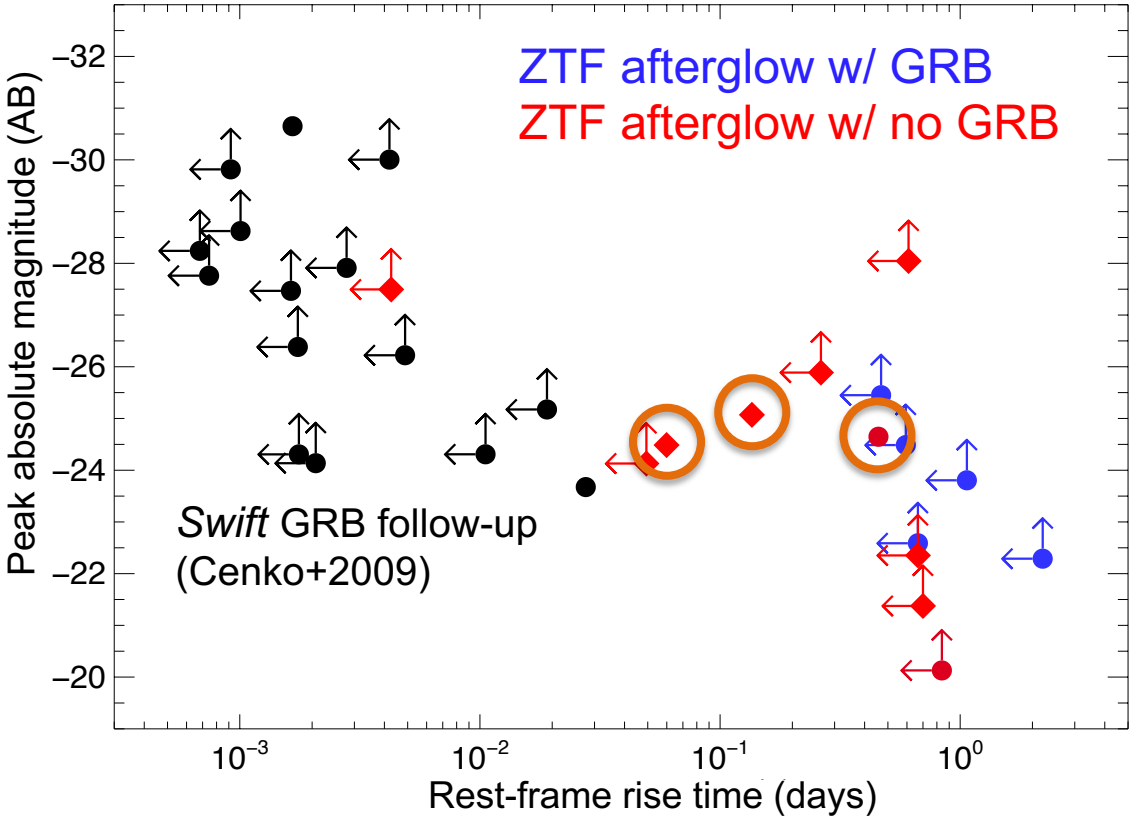
● ZTF afterglow w/ GRB association

▼ ZTF afterglow w/ no GRB association (limit)

For most ZTF afterglows, can't rule out association with a "normal" GRB

One exception (23lcr) – but looks like a "normal" GRB afterglow in all other respects (fast rise, etc.)

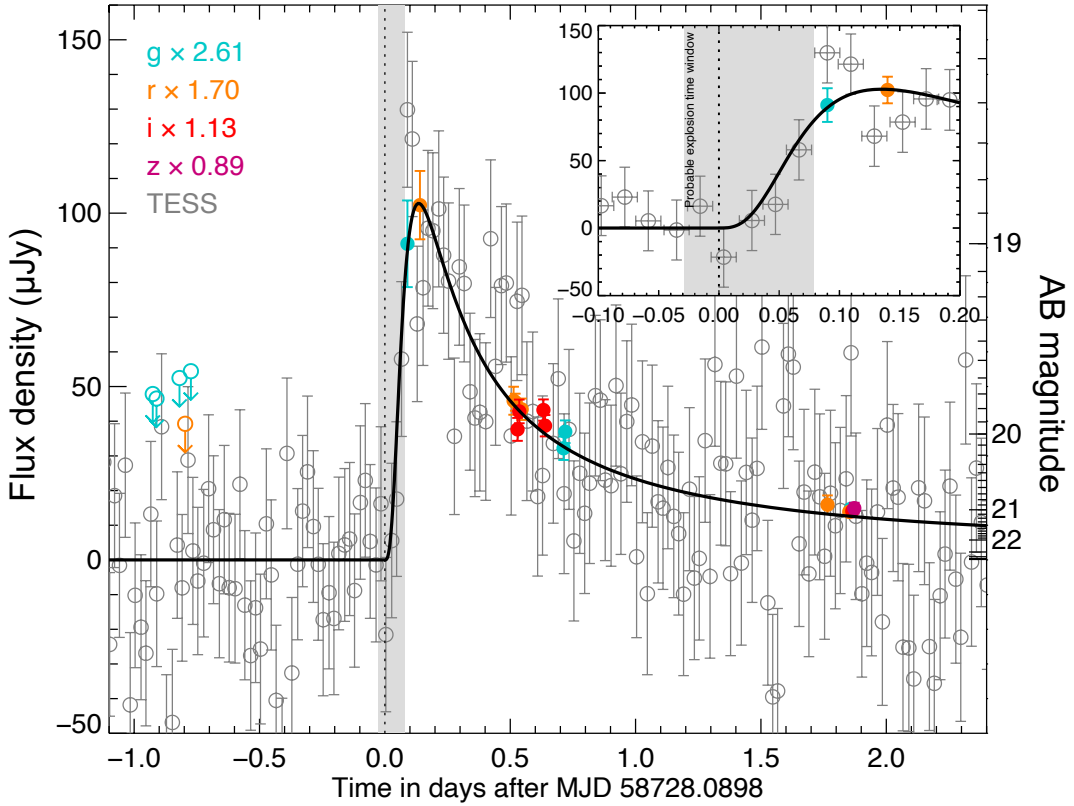
Luminosity / Rise Time



Rise usually missed; limits not usually constraining

But there are three exceptions...

AT2019pim: a resolved ZTF+TESS rise

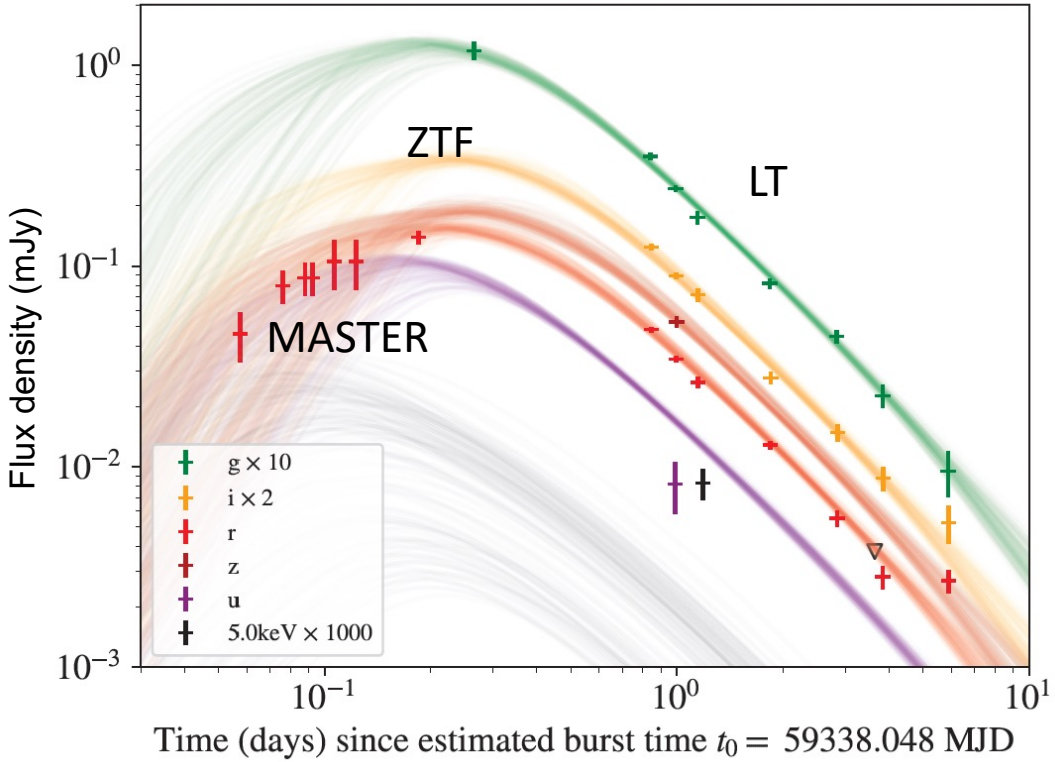


Slow rise (1-2 hours): consistent with a moderate Lorentz factor ($\Gamma \sim 30$)

Radio monitoring also suggests low Γ... But could also be structured jet off-axis

Perley+2024 (arXiv:2401.16470)

AT2021lfa: an excellent "dirty" candidate

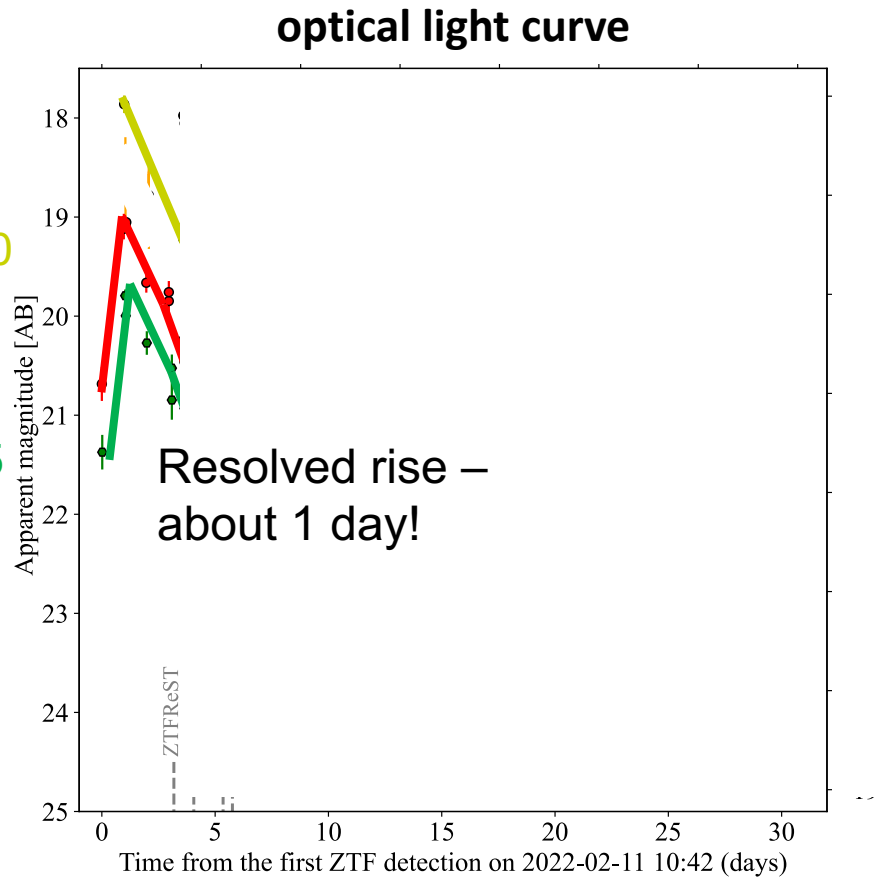


Slow rise (3 hours): consistent with a low Lorentz factor ($\Gamma \sim 10$)

Structured off-axis jet also fits the data

Li+ 2024, arXiv:/2411.07973
(also Lipunov+2023)

AT2022cmc: A very slow rise



Andreoni+2022

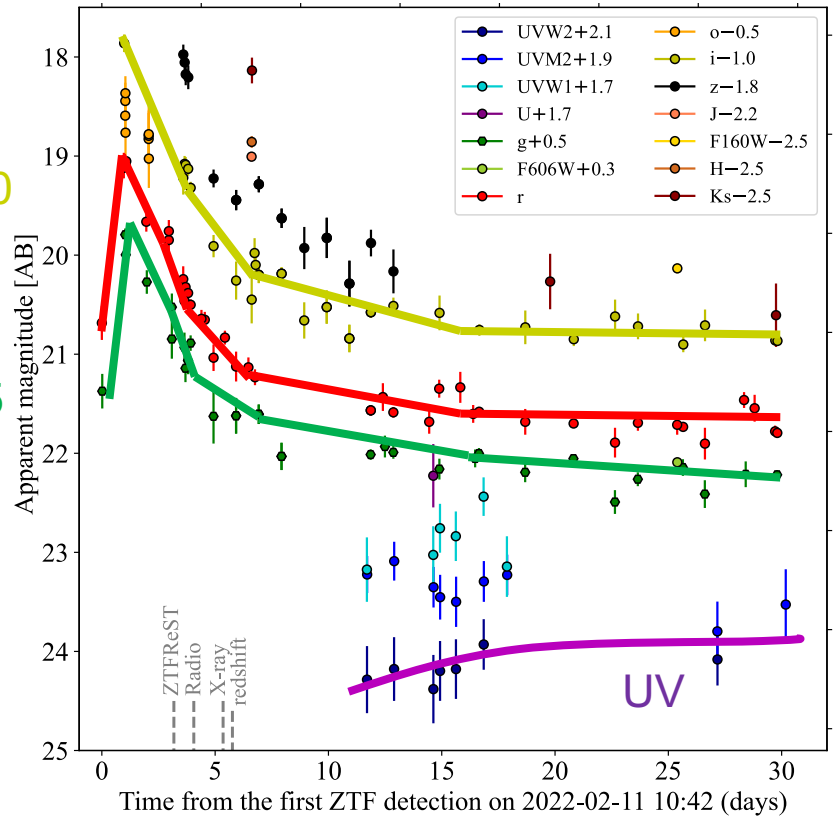
AT2022cmc: A relativistic TDE!

optical light curve

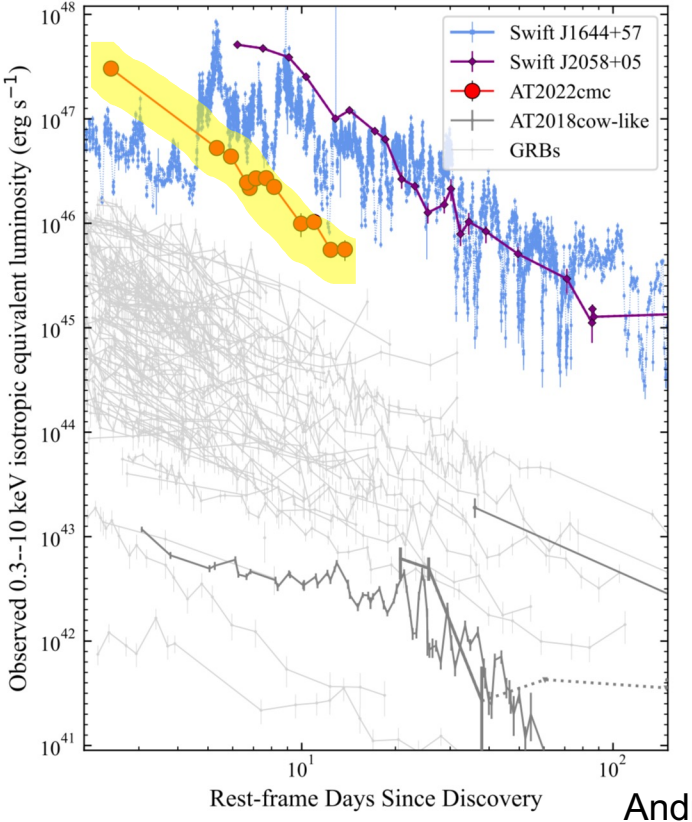
i – 1.0

r

g+0.5



X-Ray light curve



Andreoni+2022

Dirty fireball rates: not high

About **half** of optically-discovered afterglows have detected GRB emission (and we are sensitive to only the brightest bursts...):

Dirty fireballs are rare or underenergetic.

Rate of ZTF detectable afterglows across the whole sky

$$\frac{R_{afterglow}}{R_{BAT}} = 1 - 7$$

Rate of Swift-BAT detectable GRBs with ZTF-detectable afterglow across the whole sky (~500/yr)

Searching for Hidden Jets

- X-ray prompt emission: XRFs and FXTs

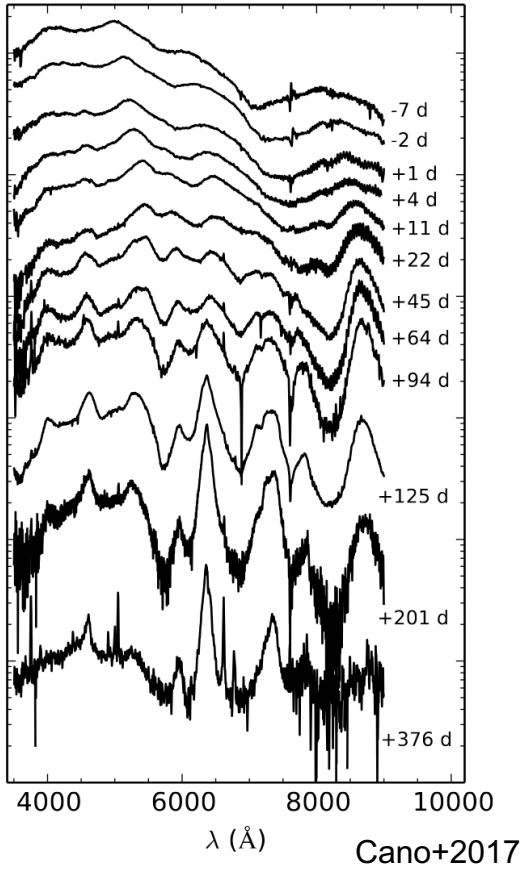
Bauer+2017,
Quirola-Vásquez+2023
Sun+2024,
van Dalen+2024,
Srivstav+2024,
Bright+2024
(+LLGRBs?)

- Untargeted afterglow searches
  - Optical
  - X-ray
  - radio Law+2018, Mooley+2022
- Constraints from comparative GRB/SN rates
- SN-targeted radio afterglow searches

Soderberg+2006, 2010
Corsi+2016,2023

The GRB-SN Connection

- Most* LGRBs show SNe when discovered close enough to detect SN emission ($z \lesssim 0.4$)
- The stellar explosion is **always**:
  - H/He-free (stripped envelope)
  - Broad-lined (fast ejecta velocity)
  - Luminous (abundant ^{56}Ni)



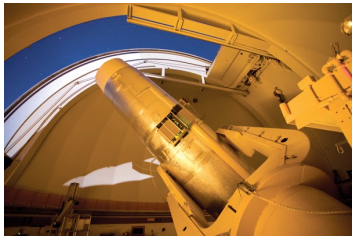
Cano+2017

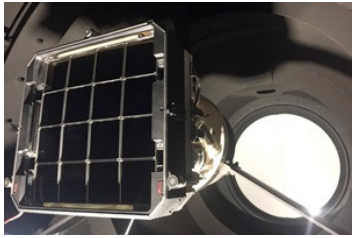
* Exceptions attributed to mergers (SN is absent, not faint)

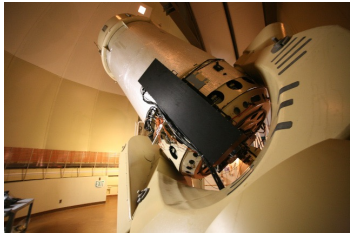
Finding GRB candidates via SNe

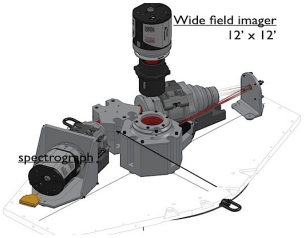
- SN emission is isotropic – can discover independent of viewing angle
- SN **rate** sets maximum GRB "supply"
- Can search for off-axis signatures (typically in radio)

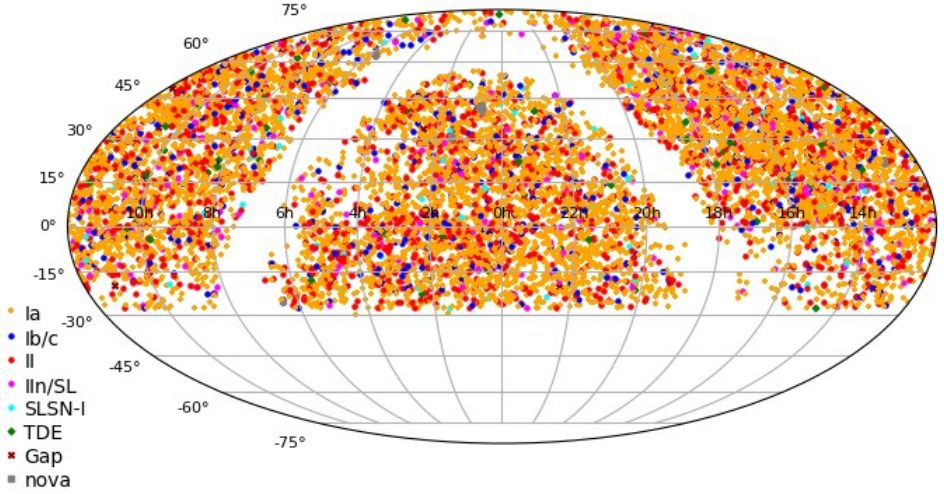
ZTF: Systematic SN Search











https://sites.astro.caltech.edu/ztf/bts/bts.php

Rates from ZTF

Ic-BL rate exceeds GRB rate by a factor of 5-20... but...

Class	Rate (Gpc^{-1} yr^{-1})
CCSN	**80,000**
Ic	**8,000**
Ic-BL	**740 - 2600**

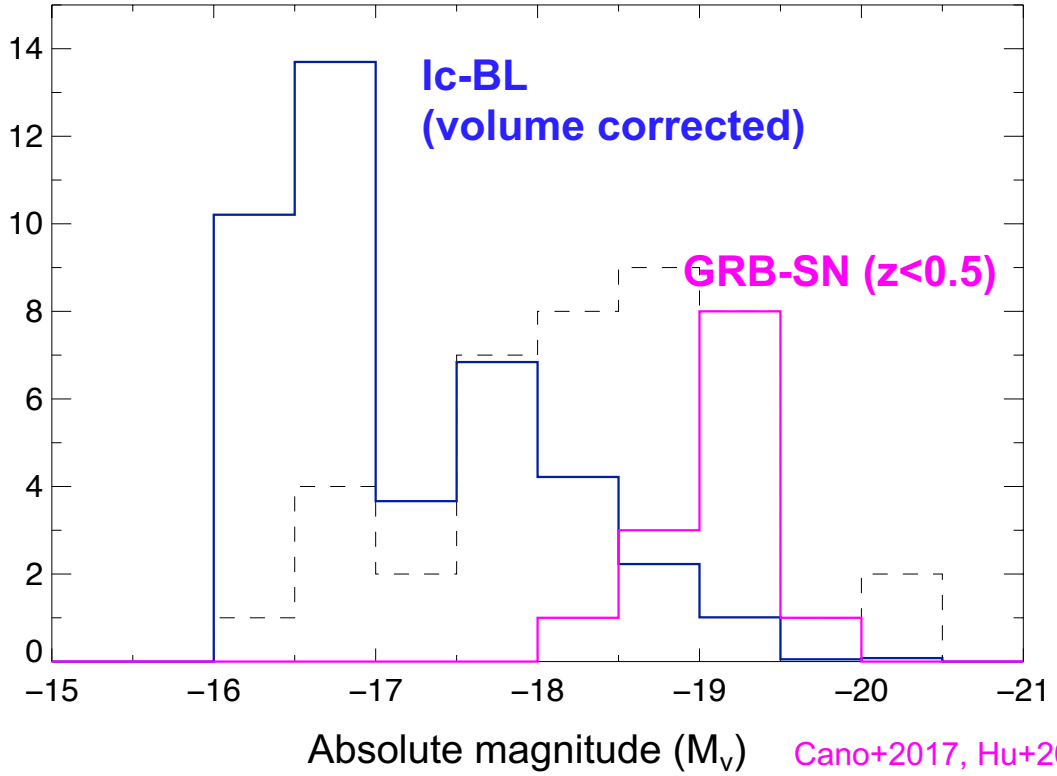
GRB rates from the literature:

LLGRB	~200*
GRB ($L_{iso} > 10^{50}$ erg/s)	~1** / 50-100^{+}

* Soderberg+2006, Liang+2007, Virgili+2008
** Wanderman+2010, Lien+2014, Howell+2014
$^{+}$ Ghirlanda+2022

GRB SNe are highly overluminous

- GRBs sample only the **most luminous subgroup** (10%) of Ic-BL SNe

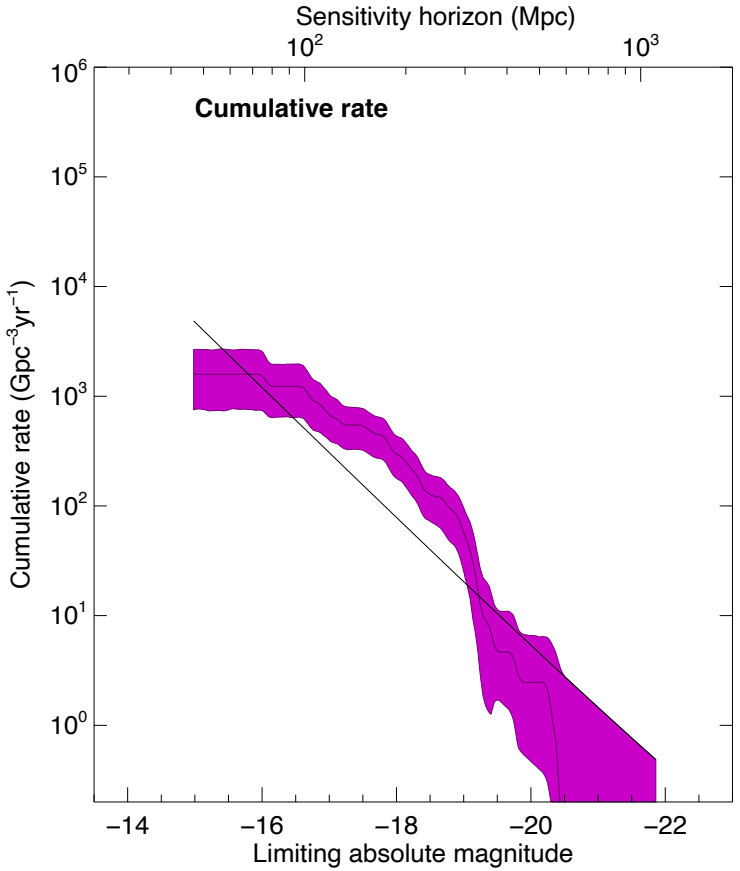


Cano+2017, Hu+2021, Melandri+2019 Srinivasaragavan+2024

Not a selection effect: dimmer SN would be easily detectable for most z<0.5 GRBs if present

Luminous Ic-BL rate ≈ GRB Rate

Class	Rate (Gpc^{-1} yr^{-1})
All Ic-BL	**740 - 2600**
$M_{V,pk} < -18.5$	**80 - 200**
$M_{V,pk} < -19$	**25 - 90**
LLGRB	~200*
GRB ($L_{iso} > 10^{50}$ erg/s)	~1** / 50-100^{+}



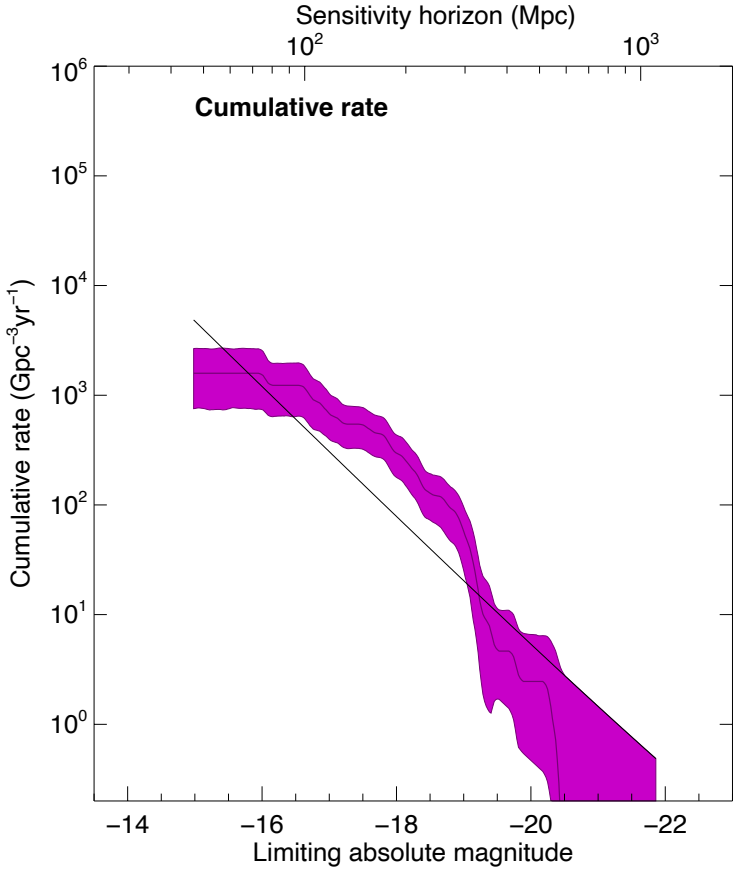
* Soderberg+2006, Liang+2007, Virgili+2008

** Without beaming correction: Wanderman+2010, Lien+2014, Howell+2014

$^{+}$ With beaming correction: Ghirlanda+2022

Luminous Ic-BL rate ≈ GRB Rate

Class	Rate (Gpc^{-1} yr^{-1})
All Ic-BL	**740 - 2600**
$M_{V,pk} < -18.5$	**80 - 200**
$M_{V,pk} < -19$	**25 - 90**
LLGRB	~200*
GRB ($L_{iso} > 10^{50}$ erg/s)	~1** / 50-100+



* Soderberg+2006, Liang+2007, Virgili+2008

** Without beaming correction: Wanderman+2010, Lien+2014, Howell+2014

+ With beaming correction: Ghirlanda+2022

Some Implications

- Limited "headroom" for GRB-peripheral phenomena
  - Dirty fireball rate cannot exceed GRB rate by much
    (unless SN properties differ or GRB rate overestimated)
- Most (all?) **luminous** Ic-BL produce GRBs,
  even if not directly observed (LL or off-axis)
- Producing a jet also produces abundant ^{56}Ni
  (and probably vice versa)
- Fast SN ejecta can be produced without a jet

Conclusions

- Dirty fireballs, inefficient outflows, and choked jets could exist... but cannot be abundant (and may not exist?)
- Tight link between luminous+energetic SNe and jet formation

- Future directions: X-ray searches, Rubin/LSST, improved SN targeting