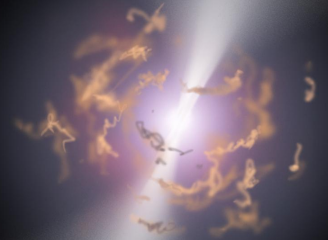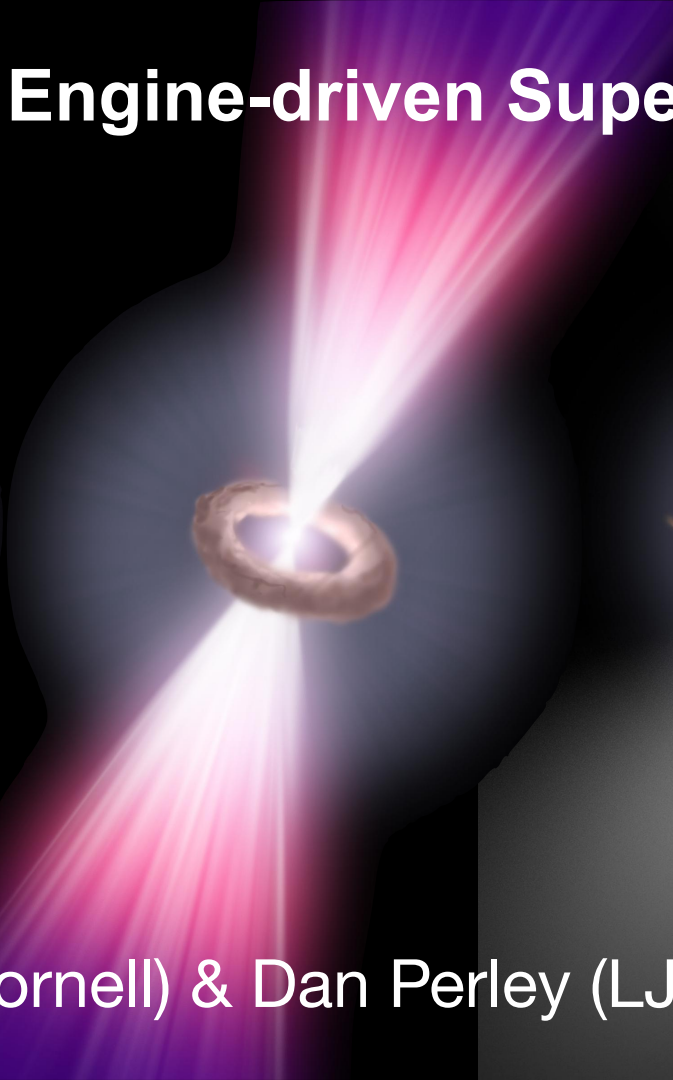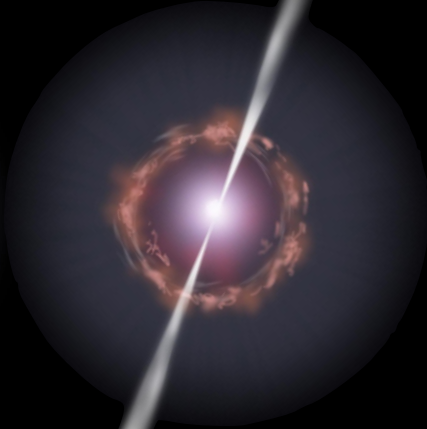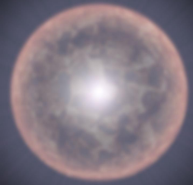# Jetted Transients: Engine-driven Supernovae

Anna Y. Q. Ho (Cornell) & Dan Perley (LJMU)

➡ Landscape Overview

Orphan Afterglows and Dirty Fireballs

Low-luminosity GRBs

New Classes (FBOTs)

Summary

Exemplar jetted engine-driven SN: long-duration GRB

Vela 4a Event — July 2, 1967

counts/second vs Time (sec)
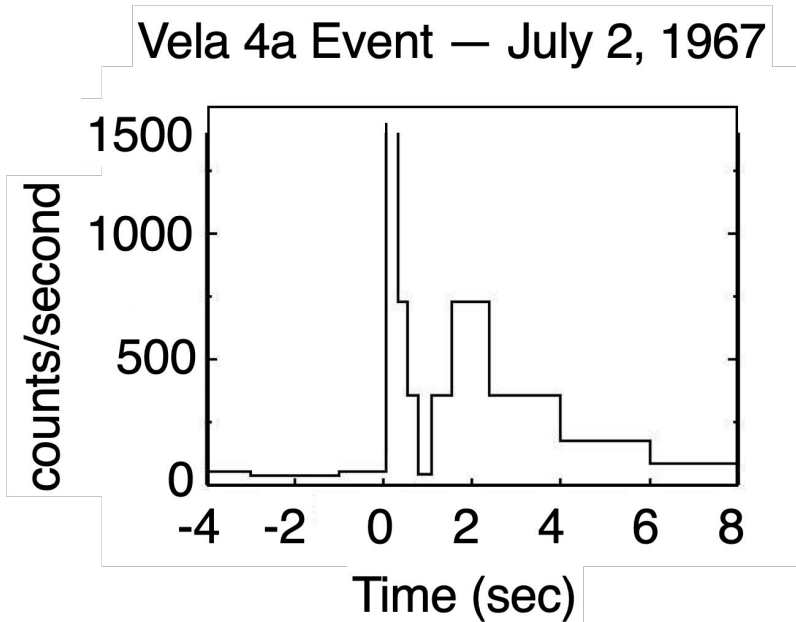
Observations:
- Seconds-long flashes
- >2000 since 1967
- Brightest photon sources
- Multiλ counterparts

Origin:
- Massive-star death
- Relativistic jet from NS/BH

Reviews: Piran (2004), Mészáros (2006) Kouveliotou et al. (2012), Kumar & Zhang (2015)

GRB Fireball Model

$E \sim 10^{51}$ erg

$\theta \sim 10°$

$\Gamma \sim 300$

Jet collides with ambient medium (external shock wave)

Colliding shells emit gamma rays (internal shock wave model)

Faster shell

Slower shell

Very high-energy gamma rays (> 100 GeV)

High-energy gamma rays

X-rays

Visible light

Radio

Black hole engine

low-energy (< 0.1 GeV) to high-energy (to 100 GeV) gamma rays

Prompt emission

$t_{pk} \sim 10$ seconds

$t_{pk} \sim 1$ minute
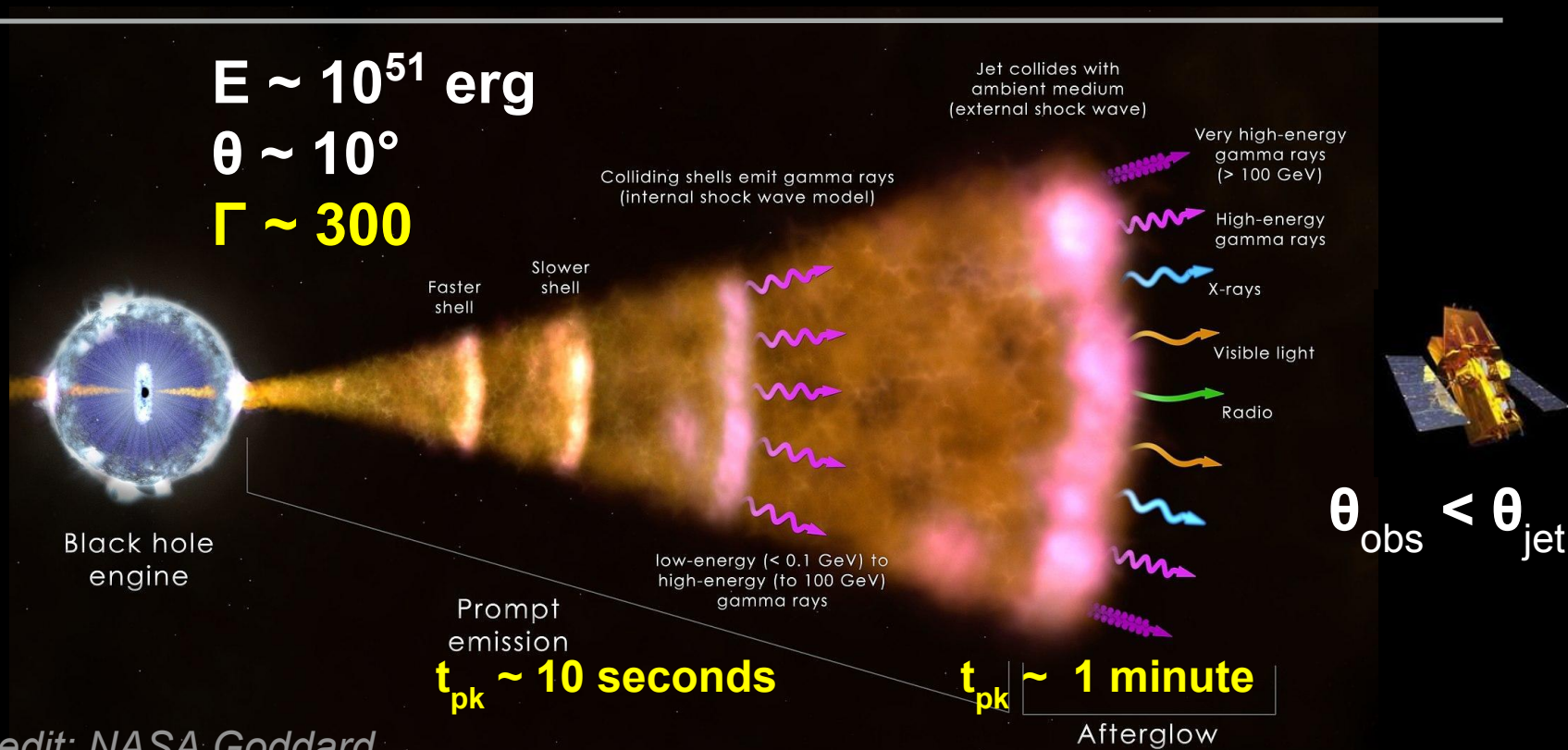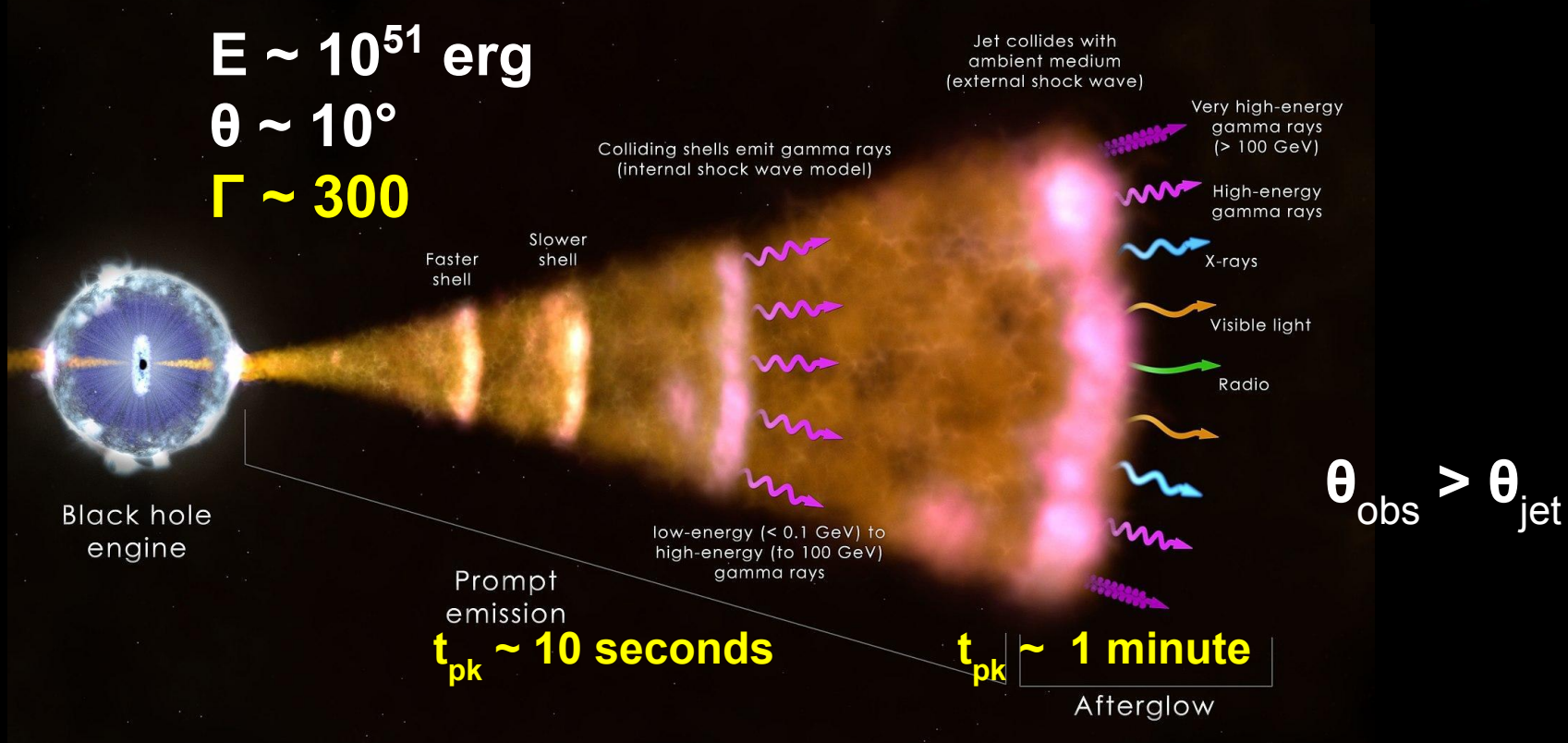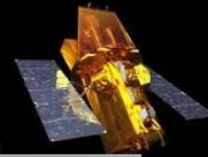
$\theta_{obs} < \theta_{jet}$

Afterglow

Image credit: NASA Goddard

Reviews: Piran (2004), Mészáros (2006) Kouveliotou et al. (2012), Kumar & Zhang (2015)

$E \sim 10^{51}$ erg
$\theta \sim 10°$
$\Gamma \sim 300$

Colliding shells emit gamma rays
(internal shock wave model)

Jet collides with
ambient medium
(external shock wave)

Very high-energy
gamma rays
(> 100 GeV)

High-energy
gamma rays

X-rays

Visible light

Radio

Faster
shell

Slower
shell

Black hole
engine

Prompt
emission

low-energy (< 0.1 GeV) to
high-energy (to 100 GeV)
gamma rays

$t_{pk} \sim$ 10 seconds

$t_{pk} \sim$ 1 minute

Afterglow

$\theta_{obs} > \theta_{jet}$

Reviews: Piran (2004), Mészáros (2006) Kouveliotou et al. (2012), Kumar & Zhang (2015)

Low Lorentz factor (mass loaded): "dirty fireball"

E ~ 10^{51} erg

θ ~ 10°

Γ ~ 300 Γ ~ 10

Jet collides with ambient medium (external shock wave)

Colliding shells emit gamma rays (internal shock wave model)

Faster shell

Slower shell

Very high-energy gamma rays (>100 GeV)

High-energy gamma rays

X-rays

Visible light

Radio

Black hole engine

Prompt emission

low-energy (< 0.1 GeV) to high-energy (to 100 GeV) gamma rays

$θ_{obs} < θ_{jet}$

t_{pk} ~ hour

Afterglow

Dermer et al. (1999), Huang et al. (2002), Rhoads et al. (2003)

6

"Failed" or "choked" jets

A mildly relativistic shock

Shock breakout

Extended mass

Core

~10^{11} cm 10^{13}-10^{14} cm

An Ultra-Relativistic jet
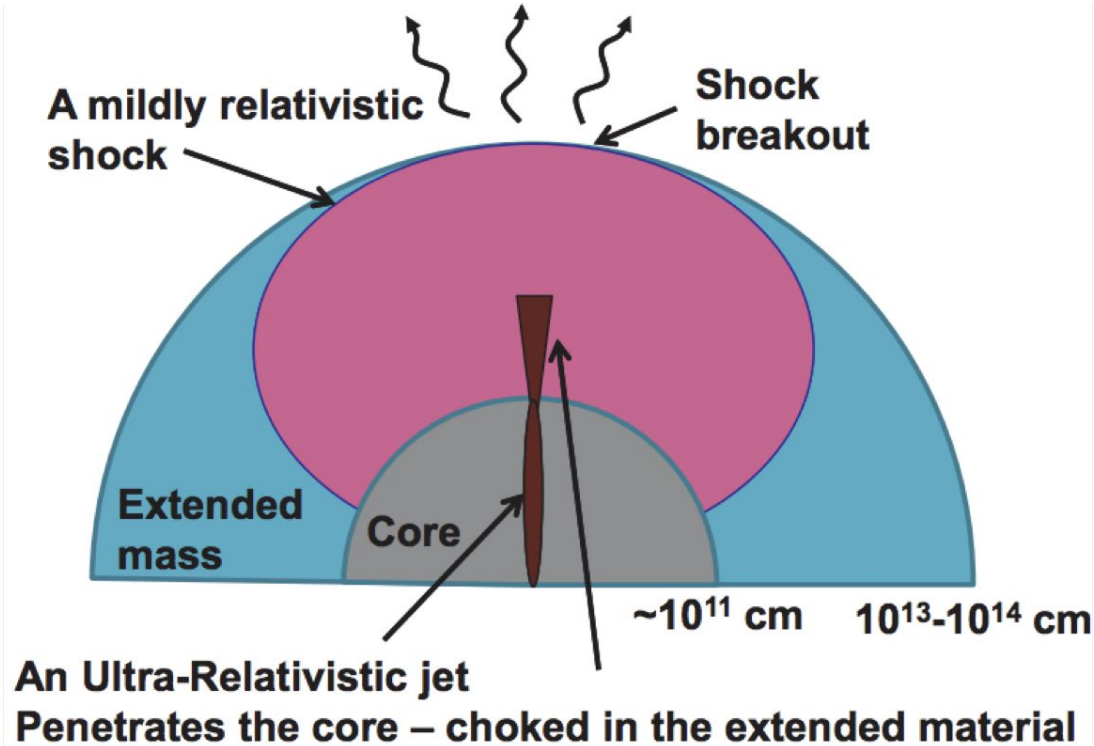Penetrates the core – choked in the extended material

Figure modified from Nakar (2015)
Other references: Mészáros & Waxman (2001), Lazzati et al. (2012), Sobacchi et al. (2017)

The Zoo of Jetted and/or Engine-driven SNe

- Low-luminosity GRBs (e.g., GRB 980425 / SN1998bw)
- Ultra-long Duration GRBs
- X-ray Flashes (HETE-2)
- Fast X-ray Transients (Chandra, SRG/eROSITA)
- Fast Blue Optical Transients (e.g., AT2018cow)
- "Hypernovae" (Ic-BL SNe)
- Superluminous supernovae
- "Orphan" optical afterglows
- Radio-loud SNe (e.g., SN2009bb)
- Luminous radio transients in the local universe

Fundamental Questions (B-Q2 & Q3, G-Q1 & Q2)

1. GRB progenitor channel(s) (~0.1% CC SNe, no H/He)
2. Diversity of jetted supernovae (GRB-SN connection)
3. Rates / prevalence (*r*-process, SN mechanism)
4. Central engine (NS or BH) & jet launch
5. Jet composition, structure, propagation
6. Relativistic shocks, particle acceleration

Dirty Fireballs and Off-axis Jets

Several observational approaches:

Search for "bursts" at lower energies (easiest in **X-ray**)
→ *dirty fireballs*

Search for orphan afterglows at early times (easiest in **optical**)
→ *dirty fireballs and marginally off-axis GRBs*

Search for orphan afterglows at late times (easiest in **radio**)
→ *highly off-axis GRBs*

("Orphan" afterglow: one without accompanying prompt emission)

X-Ray Candidates

Several archival **Chandra** X-ray transients have been reported (Quirola-Vásquez+2022, Lin+2022), some plausibly cosmological

- Rise times ~10-1000 sec (too slow for GRB, too fast for dirty FB?)
- Host (candidates) all very faint - no firm redshifts known
- Interpretation still unclear

SRG/eROSITA should be very efficient at finding afterglows (Khabibullin+2012, Ghirlanda+2015)

- Sparingly few reported?   (One GCN: GRB200120A)
- False positives likely a challenge

MAXI and **HETE-2** have detected GRBs with Epk < 25 keV ("XRFs") in modest numbers, some apparently cosmological (e.g. Stratta+2007) - not clear if rate dominates GRBs or if Γ is low

Optical Candidates

Many discoveries of cosmological transients from ground-based surveys (iPTF, ATLAS, **ZTF**) – many with confirmed redshifts and extensive follow-up (Ho+2020,2022)

- About half have (known) GRB associations, the others do not
- Apparent "orphans" could still be missed/underluminous GRBs, GRBs seen off axis, or could be dirty fireballs
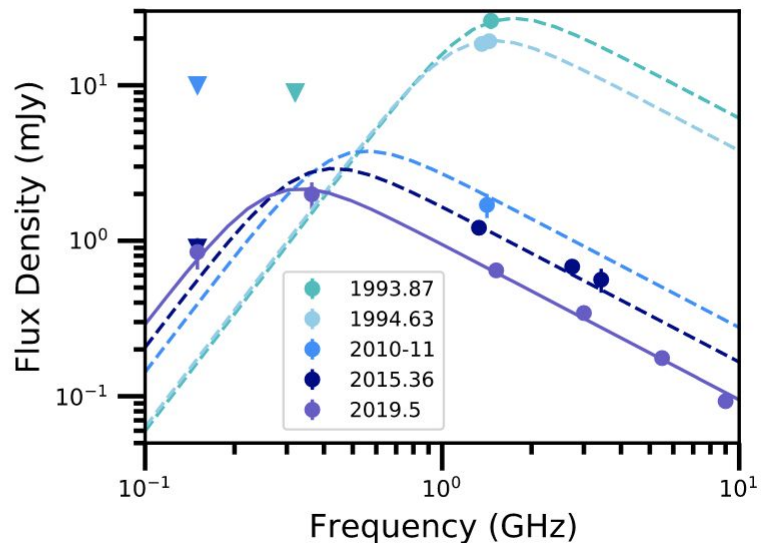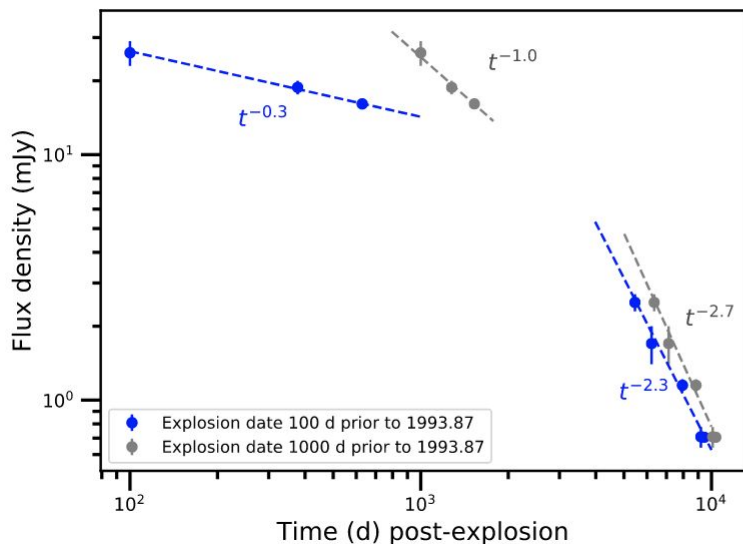
Serendipitous TESS observations of one event *hint* at a slow rise time, but also consistent with rapid rise (Perley+2022 in prep)
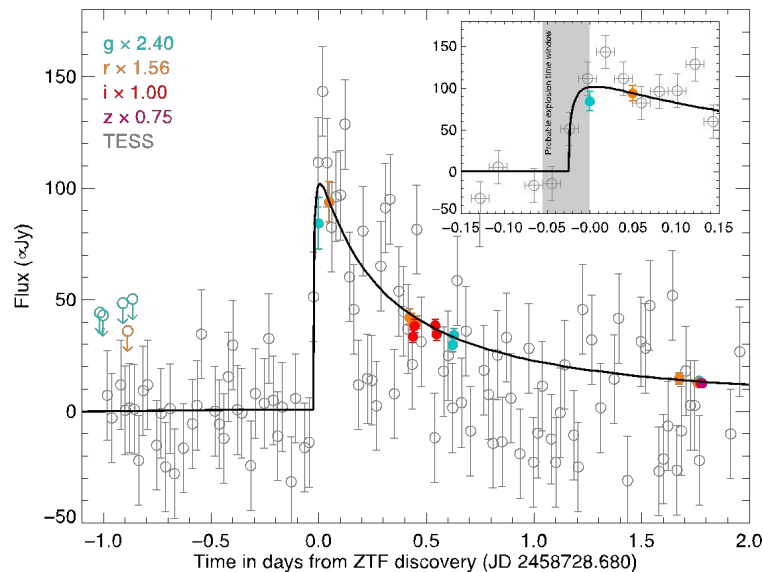
Radio Candidates

One promising off-axis afterglow candidate: FIRST J1419+3940 (from **VLA;** Law+2018, Mooley+2022)

Luminosity, host, evolution all consistent with off-axis GRB in 2003

Dirty Fireballs & Off-axis Afterglows

No firm evidence *yet* that dirty fireballs are common.

If outflow energy & physics are similar to GRBs, rate is limited to < few x GRB rate (Ho+2022)

> Rate could be higher if characteristic E is lower, but if it's much lower they are simply LLGRBs!

No firm constraint yet on GRB rate (or beaming) from off-axis methods

What Observations are Needed

Multiwavelength, multi-cadence observations for a multiwavelength, multi-cadence problem.

Gamma-rays / Hard X-rays:

More sensitive **all-sky GRB coverage** (to *exclude* GRB associations)

Soft X-rays:

Wide scan survey with **rapid alerts to observers**

Intermediate-FOV, **high-sensitivity, fast-cadence survey** at <25 keV

Continued **fast-response X-ray facility** (for follow-up)

Optical, radio: Wide/deep/fast surveys with rapid alert distribution;
Deep all-sky photo-z catalog (for cross-matching)

Multimessenger Prospects

GRBs do not appear to be prolific neutrino sources (Abbasi+2012, Blaufuss+2013, Gao+2013)

Dirty fireballs may be more promising, if they exist (Mezsaros+2015)

GW radiation likely not detectable from LGRB progenitors
(but off-axis afterglow searches may also detect nearby
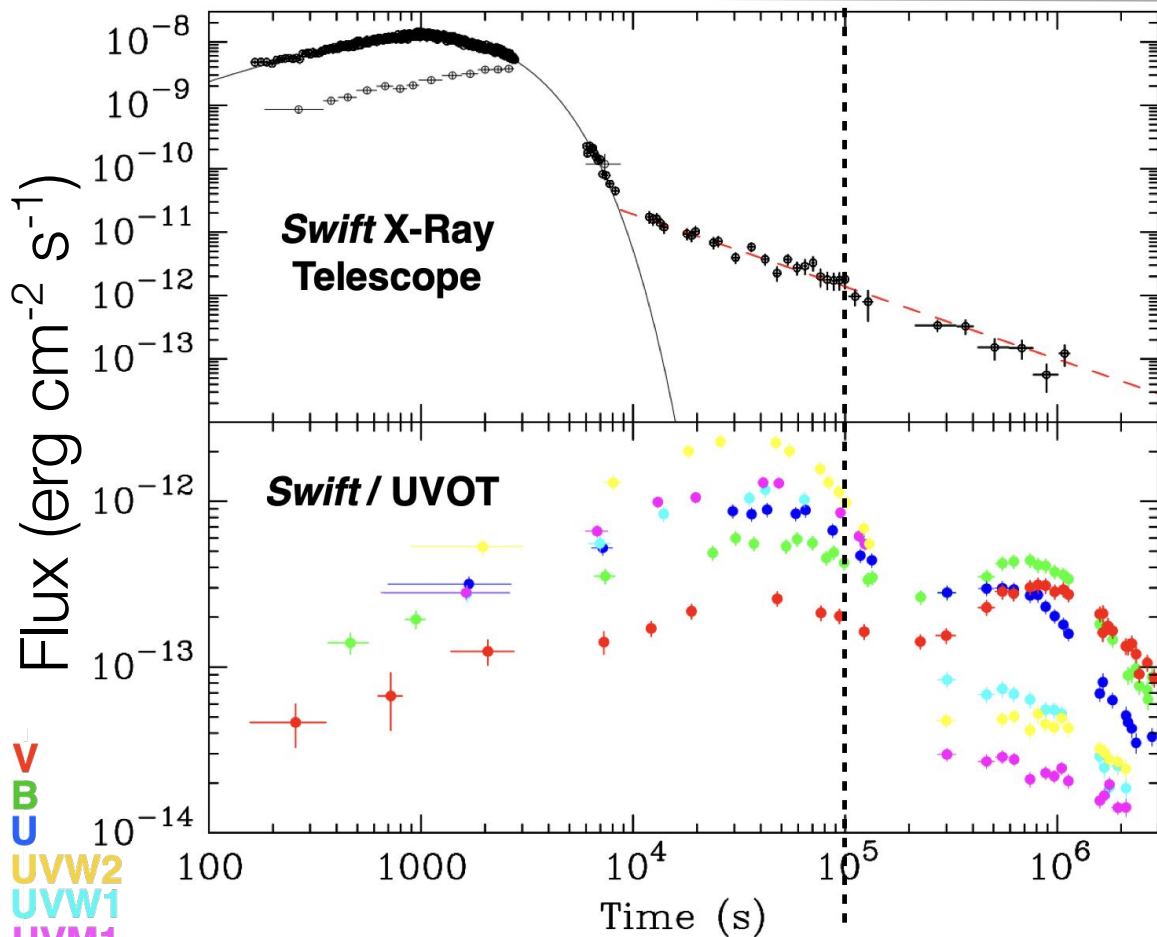 NS-NS mergers)

Landscape Overview

Orphan Afterglows and Dirty Fireballs

➡ Low-luminosity GRBs
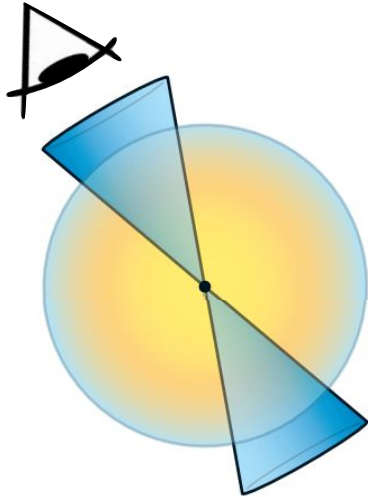
New Classes (FBOTs)

Summary

Low-luminosity GRBs

- Subluminous, smooth, low E_{peak}
- 10-100x more common than GRBs?
- 2-3 OOM smaller relativistic E release

Kulkarni et al. (1998), Soderberg et al. (2006), Cobb et al. (2006), Liang et al. (2007), Guetta & Della Valle (2007), Virgili et al. (2009), Bromberg et al. (2011), Margutti et al. (2013), Nakar (2015)
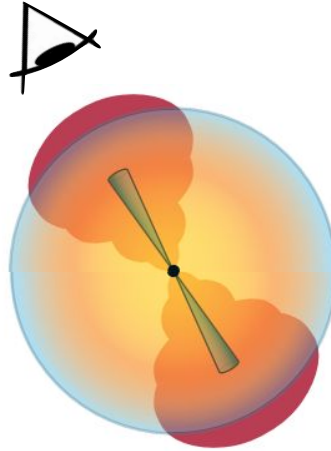
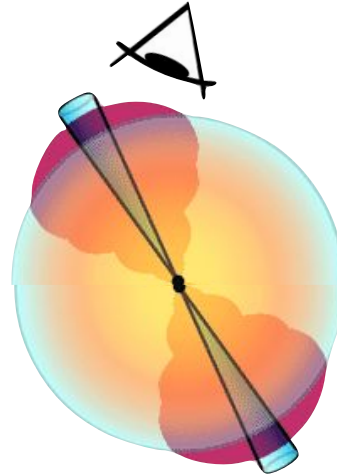# LLGRBs: jet and/or shock breakout?

Low-luminosity jet?   Choked jet?   Off-axis jet?

(cartoons modified from Kasliwal+2017)

Kulkarni et al. (1998), Campana et al. (2006), Soderberg et al. (2006), Waxman et al. (2007), Guetta & Della Valle (2007), Bromberg et al. (2011), Margutti et al. (2013), Nakar (2015), Irwin & Chevalier (2016), Bromberg et al. 2018), Izzo et al. (2019)

Limitation: rate of discovery

- Inefficient discovery by existing GRB satellites
    - Low E_{peak}, long duration, low luminosity
  - Searches via the supernova (Type Ic-BL)
    - Radio obs. of nearby Ic-BL SNe (Soderberg et al. 2010, Corsi et al. 2016, Marongiu et al. 2019)
    - High-cadence optical surveys (AYQH et al. 2020)

What observations are needed

-Discovery: wide-field detector optimized for low-luminosity, long-duration bursts peaking in soft X-rays or UV

-Follow-up:
- Targeted X-ray (shock breakout, engine activity)
- UV (shock breakout/cooling)
- Multi-band optical (shock-cooling, supernova)
- Submillimeter & radio (relativistic ejecta)

Multimessenger prospects

Expect high-energy neutrinos
- Lower luminosity but more numerous than GRBs (Murase et al. 2006, Gupta & Zhang 2007, Murase & Ioka 2013, Mészáros 2015)
- Choked jets (Mészáros & Waxman 2001, Horiuchi & Ando 2008, Senno et al. 2016, He et al. 2018)

Prospects for detection in next decade
- Primarily diffuse background (Mészáros & Waxman 2001, Senno et al. 2016, Mészáros et al. 2015)
- Maybe a coincidence at low-z (Murase et al. 2006, Mészáros et al. 2015)
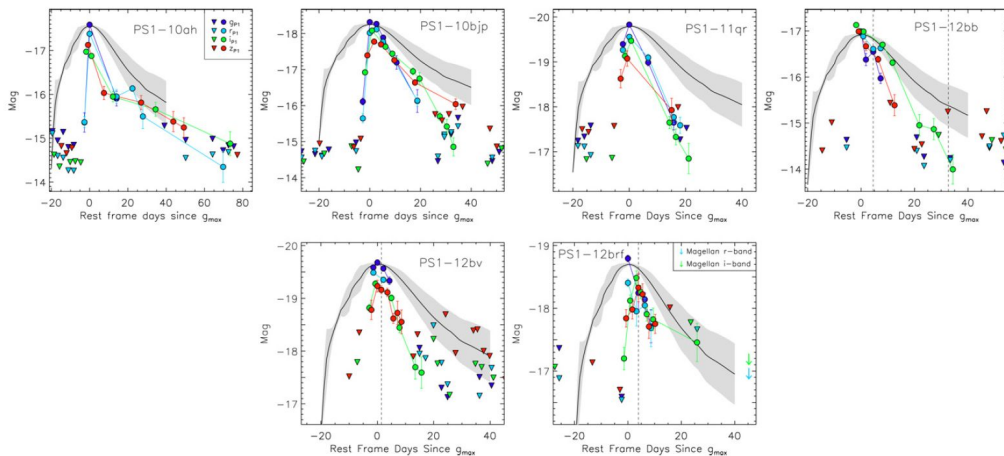
Landscape Overview

Orphan Afterglows and Dirty Fireballs
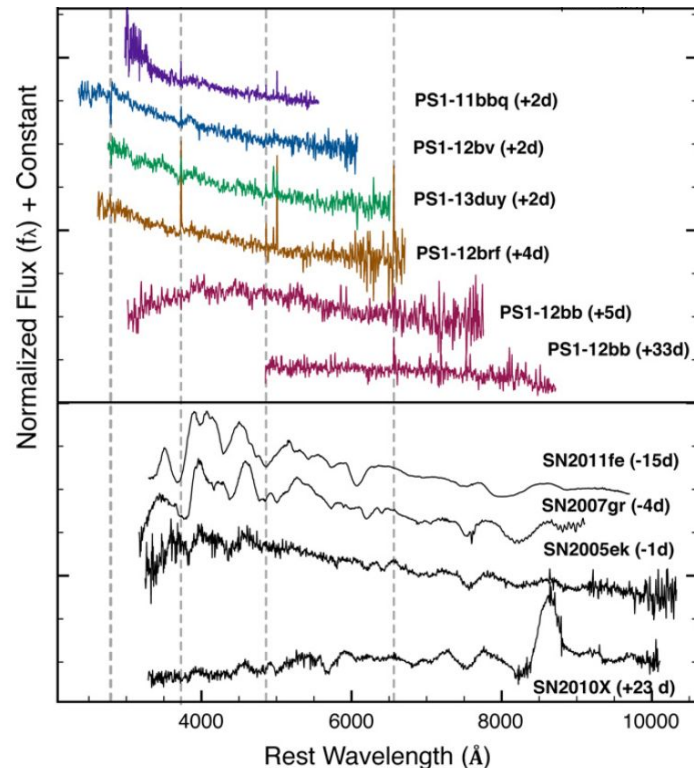
Low-luminosity GRBs

➡ New Classes (FBOTs)

Summary

Fast, Blue Optical Transients

e.g., Drout+ 2014, Tanaka+2016, Rest+2018, Pursaianen+2018

General properties:
    < 12 days duration (above half-max)
    SN-like or greater luminosity (M < -17)
    Blue/featureless at peak
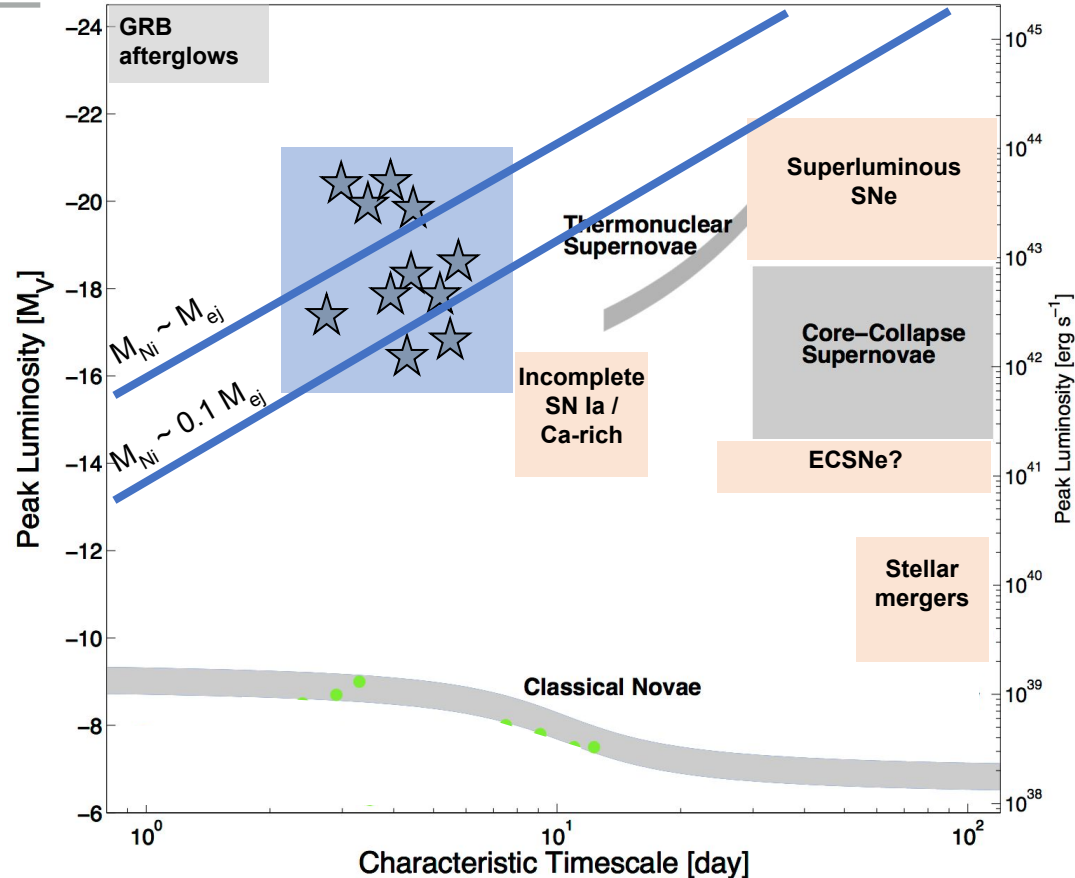   Rates ~1% CCSN

Drout+ 2014

A distinct power source

Luminosity scales as radioactive mass:
$$L_{SN, peak} \sim M_{56Ni}$$

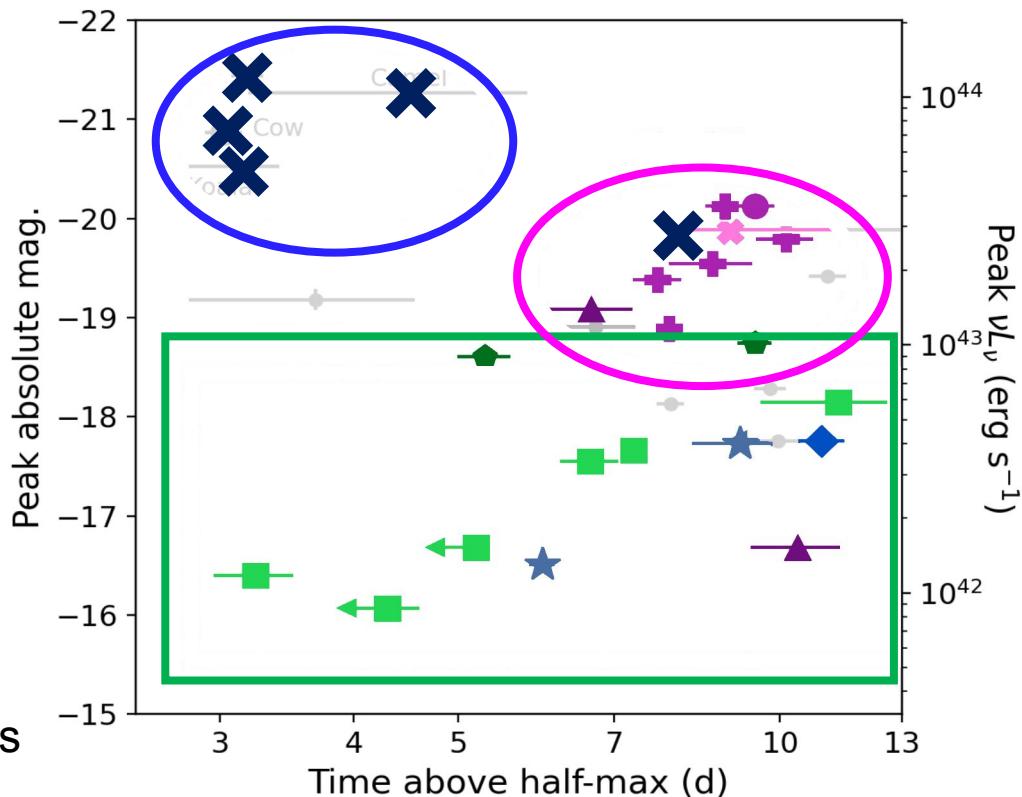But timescale varies as ejecta mass:
$$t_{SN} \sim M_{ejecta}$$

Fast+luminous:
dominant energy source at peak is not radioactivity

Observationally heterogeneous

Ibn/Icn (+IIn/Ic-BL):
**Slower, interaction
driven; no radio or X-rays**

Cow-like
("LFBOT"):
**featureless,
radio-loud,
X-ray bright**

IIb/Ib:
**Stripped
progenitor
w/inflated
envelope**

Legend:
- ⬠ II
- ⬛ IIb
- ▲ ● IIn
- ✚ Ibn/Icn
- ★ Ib
- ◆ Ic
- ✕ Ic-BL+int
- ✖ featureless

Ho+2021 (+ additions)

Observationally heterogeneous

Ibn/Icn (+IIn/Ic-BL):
Slower, interaction driven; no radio or X-rays

Cow-like ("LFBOT"):
featureless, radio-loud, X-ray bright

IIb/Ib:
Stripped progenitor w/inflated envelope

II
IIb
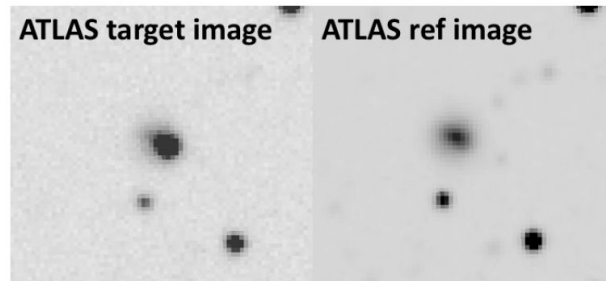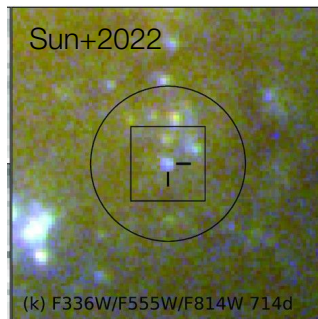IIn
Ibn/Icn
Ib
Ic
Ic-BL+int
featureless
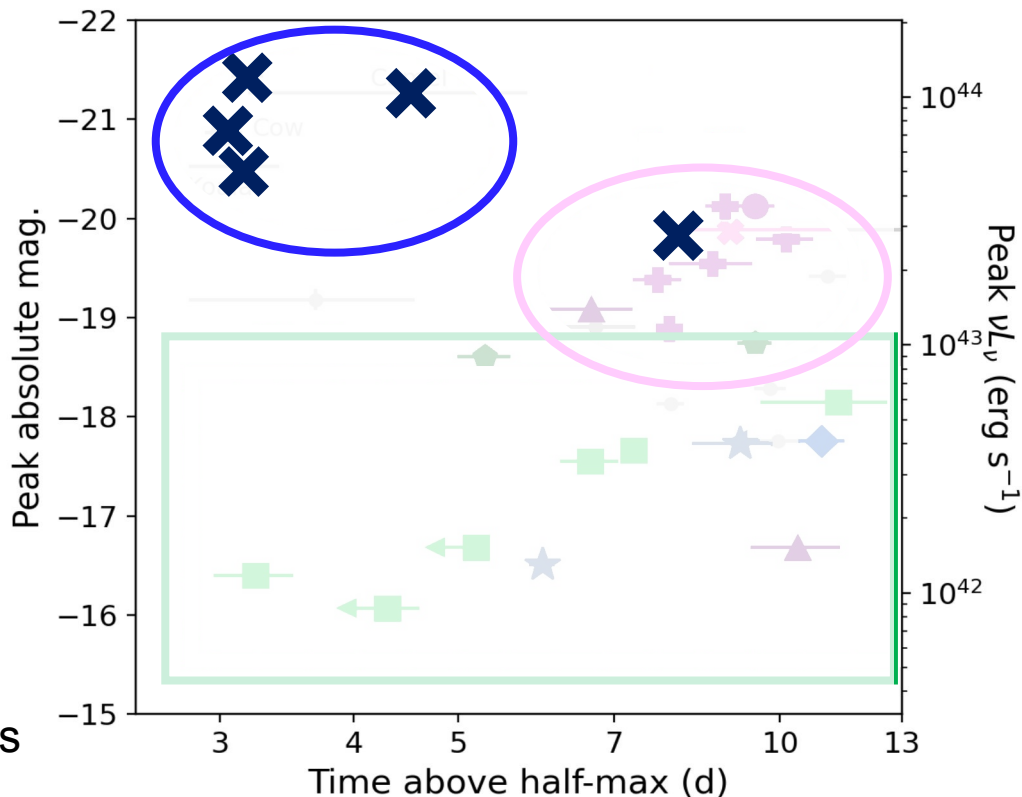
Ho+2021 (+ additions)
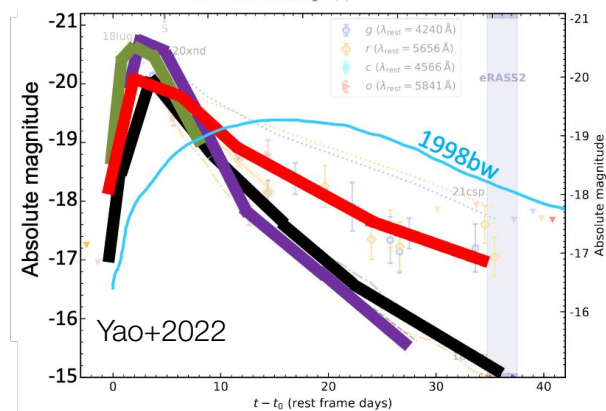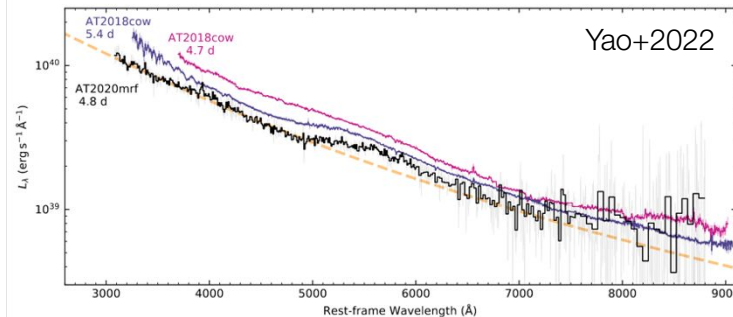
AT 2018cow & kin

Five well-studied events, AT2018cow is by far the closest

- Very fast rise (2d), very luminous (-20 mag)
  (Prentice+2018)

- Persistently hot, featureless spectra at all phases, some narrow H+He late
  (Perley+2019, Margutti+2019, Xiang+2021)

- Optically faint at late times – no SN bump
  (Perley+2018,2021)

- Low-mass star-forming hosts
 (Coppejans+2018, Perley+2021, Wiseman+2020, Lyman+2021)

ATLAS target image   ATLAS ref image

Prentice+2018

Yao+2022

Sun+2022

(k) F336W/F555W/F814W 714d

1998bw

Yao+2022

AT 2018cow & kin

Ho+2019

- Luminous fast-varying (~1d) **X-rays**, possibly w/ millisecond QPO
  (Rivera Sandoval+2018, Ho+2019, Margutti+2019, Pasham+2022)

- Luminous **submm/radio**
  (Ho+2019,2022b, Margutti+2019, Nayana+2021, Bright+2022)

- Population is fairly homogeneous (Ho+2022b), but one notable recent exception (Yao+2022): AT2020mrf was *much* more X-ray luminous at late times

- Rate: <~0.1% CCSN (Ho+2022b)

Ho+2020
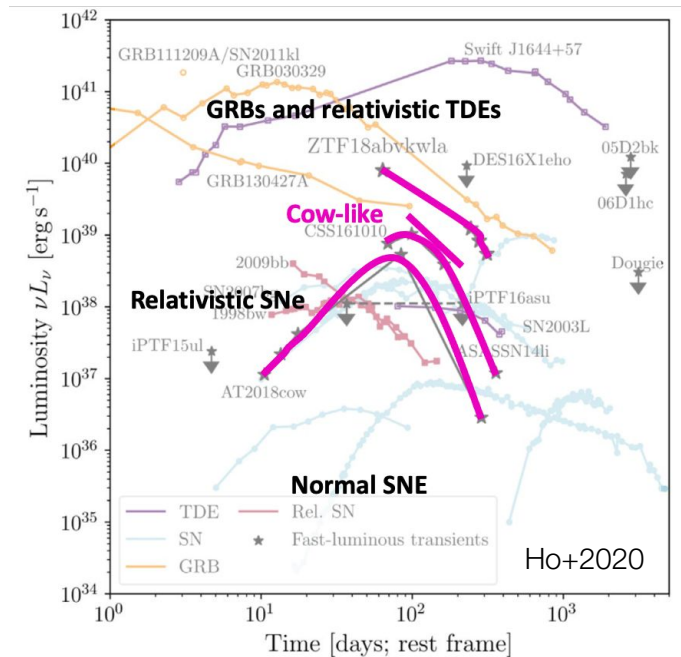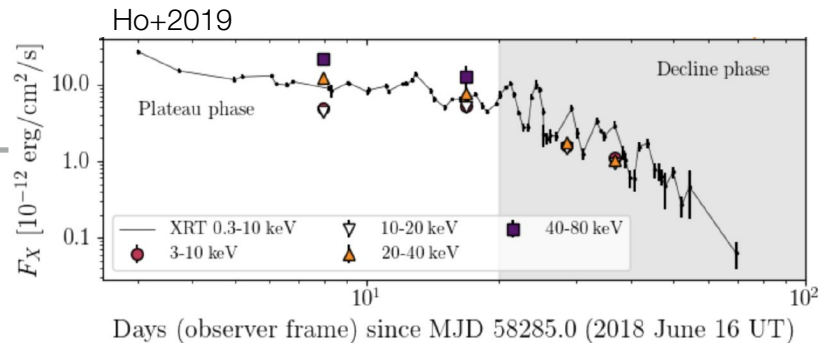
A Mystery Progenitor

- Almost certainly engine-driven

- Requires substantial CSM

- Probably massive-star related

- Probably involves a stellar mass black hole

- Minimal radioactive elements released

Many theoretical models!   (Failed/fallback SN, magnetar, WD TDE, IMBH TDE, WD AIC, PPISN, common-envelope WR TDE…)
(prev. citations plus: Soker+2019, Yu+2019, Kuin+2019, Lyutikov+2019, Mohan+2020, Uno+2020, Leung+2020, Kremer+2021, Xiang+2021, Metzger 2022)

What Observations are Needed

AT2018cow-like events are **primarily UV transients** - energetically dominated by UV at all epochs; optical shows few features.

UV survey (<2d cadence) - Discover early, better constrain rise

UV follow-up - Needed at all phases to track energy output

UV spectroscopy - Better constrain composition and nature of pre-explosion CSM

Also very luminous in **X-rays**, sometimes for months (AT2020mrf)

X-ray survey (3-30d cadence) - Find extremes of population

X-ray follow-up critical for confirming optical candidates

X-ray **timing** and **spectroscopy** provides unique insights (but sensitivity-limited)

+ optical, radio surveys and photo-z catalogs

Multi-messenger prospects

Could be significant sources of neutrinos
(Fang+2019,2020, Guarini+2022)

Landscape Overview

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Low-luminosity GRBs

New Classes (FBOTs)

➡ Summary

Jetted engine-driven explosions

LGRBs: stripped massive star, central engine, ultra-relativistic jet

Theoretical
- GRBs should be the tip of the iceberg: dirty fireballs, choked jets, off-axis GRBs, different stellar progenitors, …
- No *bona fide* discovery of these predicted phenomena

Observational
- Diverse phenomena (GRBs, LLGRBs, XRFs, FBOTs, …)
- Underlying physical connections (Lorentz factor, jet power, progenitor size, viewing angle, …) unclear

Critical time-domain/multi-wavelength observations

- Sensitive all-sky GRB coverage
- High-cadence time-domain surveys w/ alerts:
    - Soft X-rays (~hours)
    - UV (~day)   (+ optical & radio)
- Rapid-response follow-up:
    - X-ray pointed obs., also timing + spectroscopy
    - UV imaging + spectroscopy
- Deep all-sky photo-z catalog

Multi-messenger Prospects in the Next Decade

- Expect significant contribution to the HE diffuse neutrino background from choked jets, LLGRBs
- If we're lucky, coincident event at low redshift