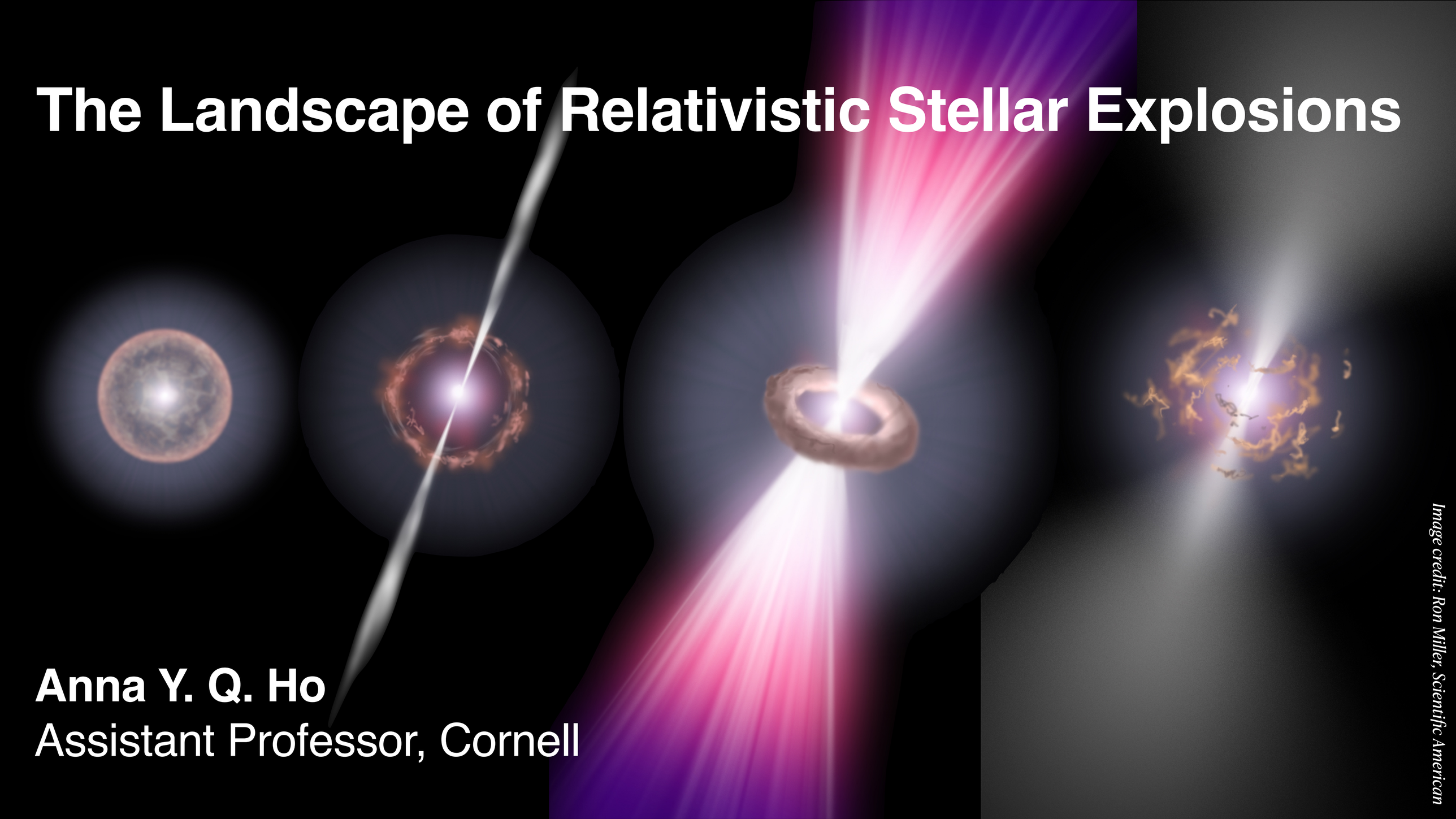
The Landscape of Relativistic Stellar Explosions

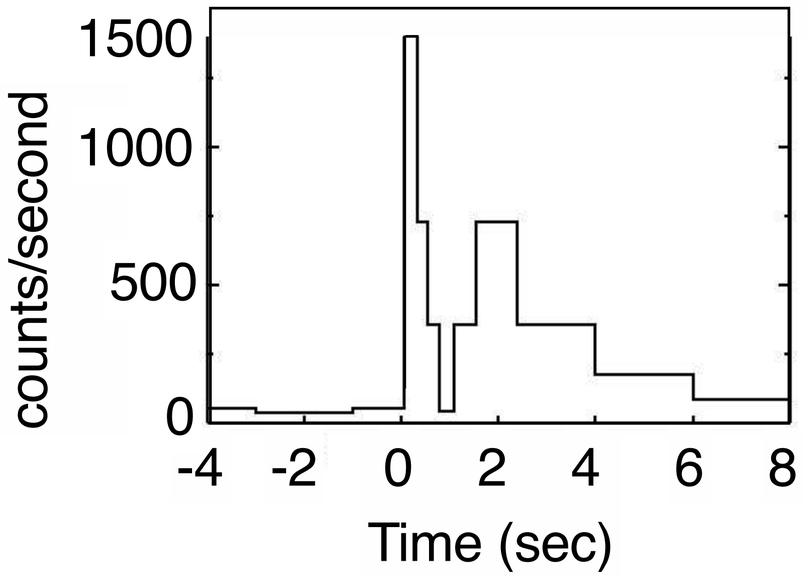


Anna Y. Q. Ho
Assistant Professor, Cornell

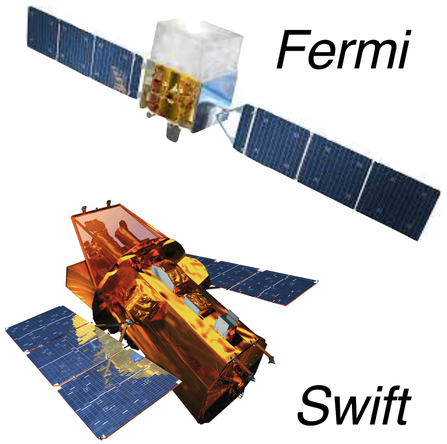
Image credit: Ron Miller, Scientific American

Gamma-ray bursts (GRBs)

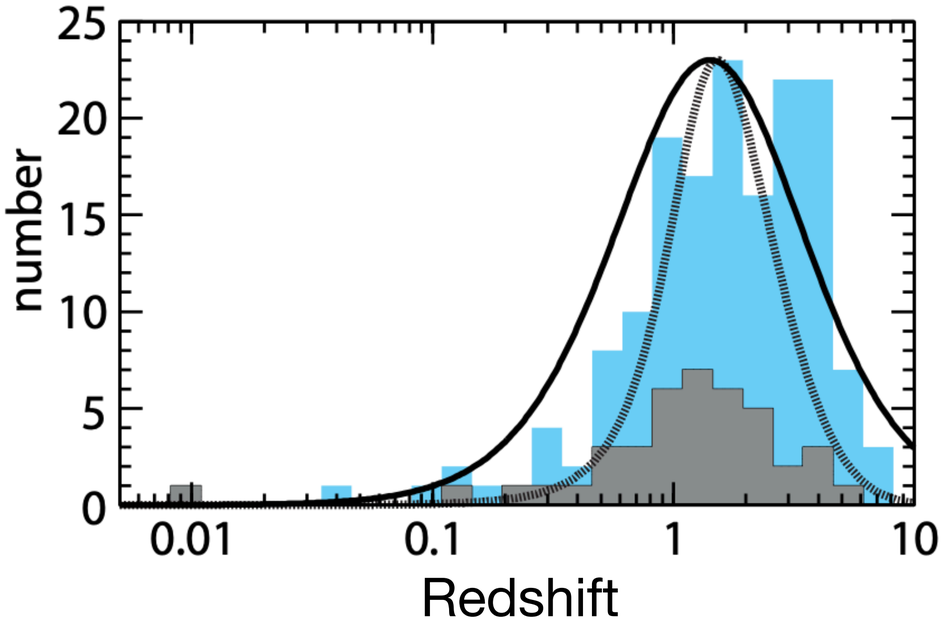
Vela 4a Event — July 2, 1967



Since then: 2173* discovered



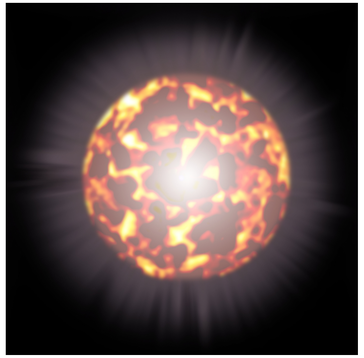
Gehrels+09



Short (< 2 sec): compact object mergers (NS-NS), e.g., GW170817 & GRB 170817A

NASA / ESA / D. Player, STScI

Long (>2 sec): collapse of massive star



* Jochen Greiner website, https://www.mpe.mpg.de/~jcg/grbgen.html

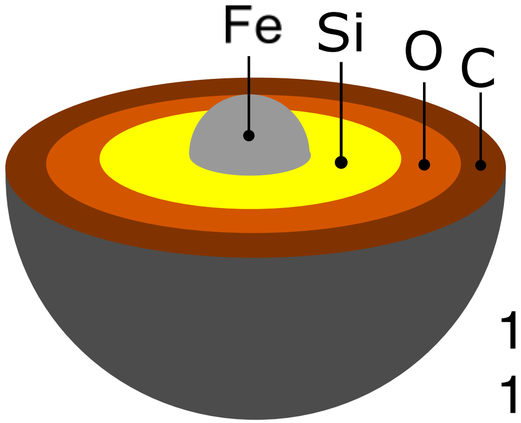
Traditional GRB model

1. “Central engine” (compact object)
2. Ultra-relativistic flow
3. GRB: collisions in jet
4. Afterglow: collisions w/ environment

NASA’s Goddard Space Flight Center

Longstanding problem: GRBs should be tip of iceberg

Type Ic SN (~10% SNe)



10^{51} erg;
10,000 km/s

— Type Ic-BL SN (~10% Ic; 10^{52} erg; >20,000 km/s)
— GRB (~10% Ic-BL)

Many requirements & predicted (GRB-dark) phenomena

The observed iceberg (past 2 decades)
- Relativistic Ic-BL SNe
- LLGRBs
- Jets in Type II SNe
- Ultra-long-duration GRBs
- GRBs w/o SNe
- X-ray flashes
- Candidate orphan afterglows

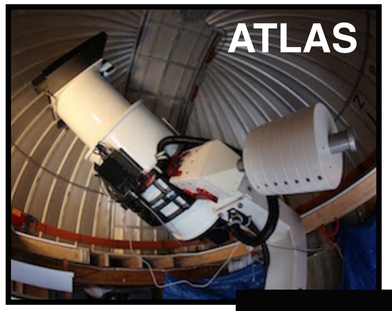
See talks by S. Kulkarni, D. Dong, O. Gottlieb, M. Shrestha…

Underlying physical connections unclear

SN-GRB: Woosley & Bloom (2006), Modjaz+16, Cano+17
Rates: AYQH PhDT(2020)
Iceberg: Gal-Yam 19 (SLSN); Cano+ 17 (Ic-BL/LLGRB/GRB/XRF); Smith+12 (II); Levan+14 (ULGRB)

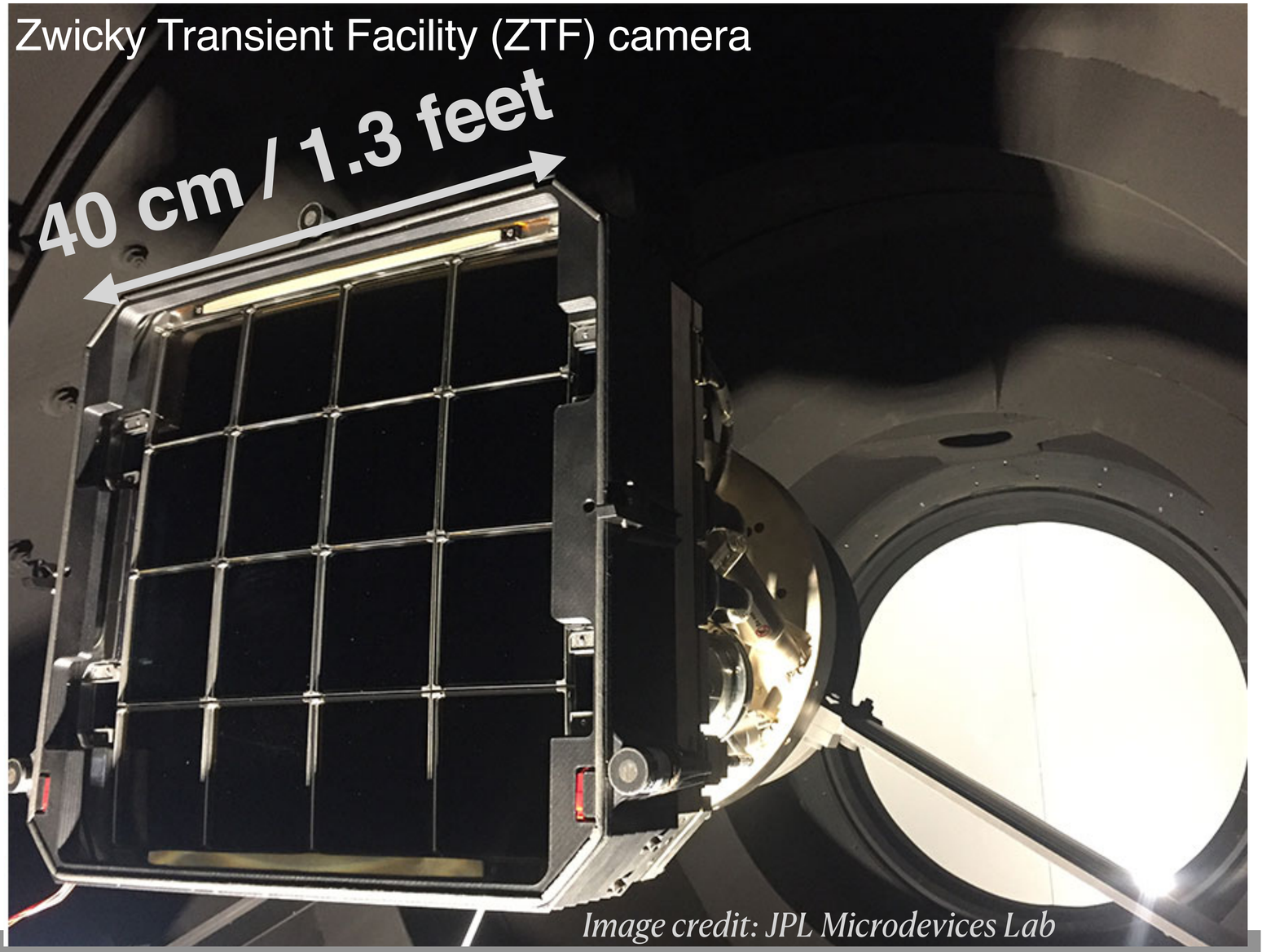
Why now? New capabilities (optical TDA)

Map wide areas of sky, quickly



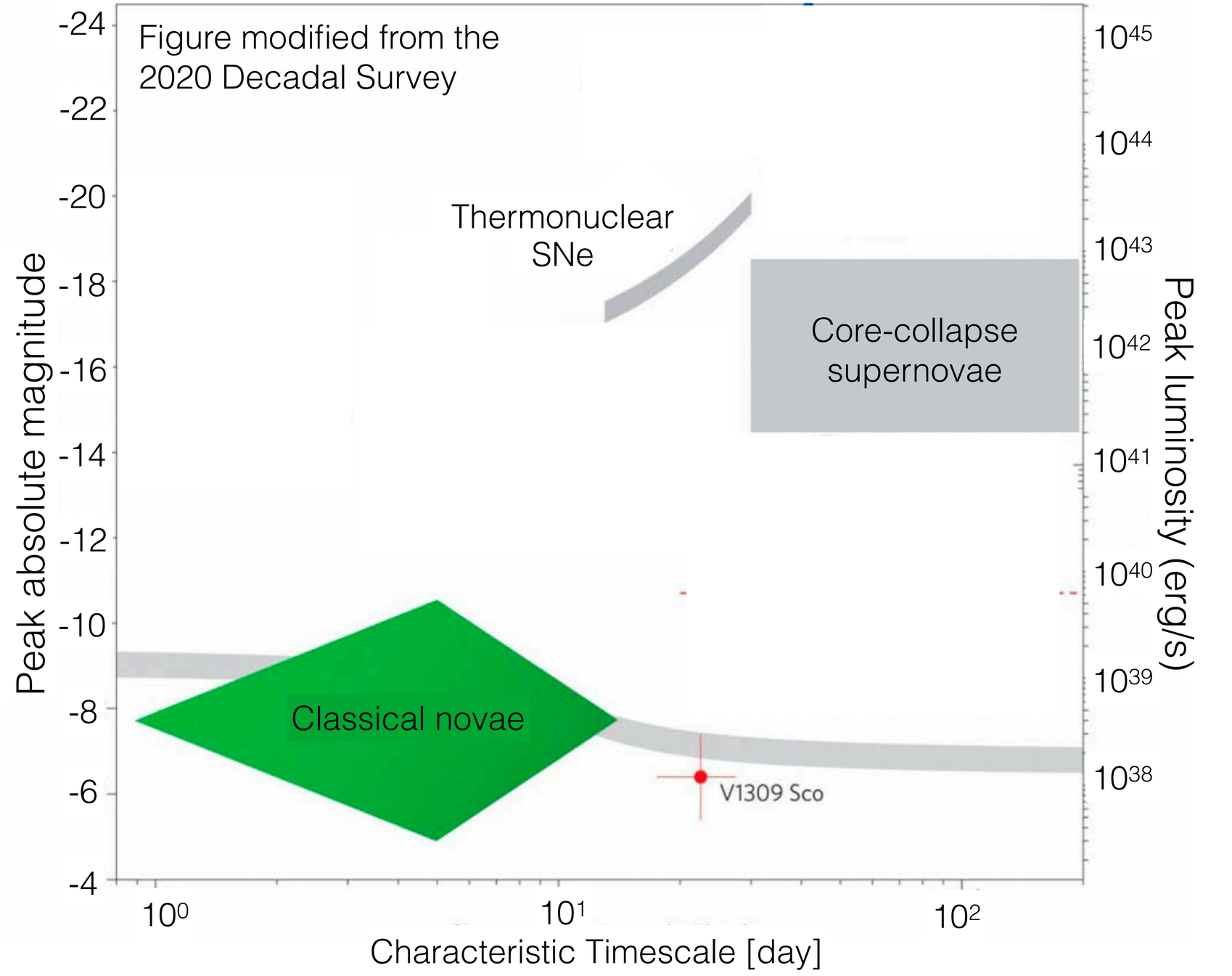
ASAS-SN

ZTF



ATLAS: Tonry+18; ASAS-SN: Shappee+16;
ZTF: Graham+19, Bellm+19, Dekany+19

Last few years: discovery as *optical* transients



Last few years: discovery as *optical* transients

Afterglows — **Part 1**

Cows (& flares) — **Part 2**

Relativistic shock breakout / low-luminosity GRBs

“FBOTs”

Ic-BL SNe

Part 1: Dirty Fireballs and “Orphan” Afterglows

Part 2: The Cow and a New Class of Relativistic Explosions

The “Dirty Fireball” Hypothesis

$\Gamma_{\rm init} \gtrsim 100$ (Normal GRB)

$E = \Gamma_{\rm init} M c^2$

$M \approx M_{\rm Earth}$ (“Clean” jet)

$\Gamma_{\rm init} \sim$ few to tens (“Dirty” fireball)

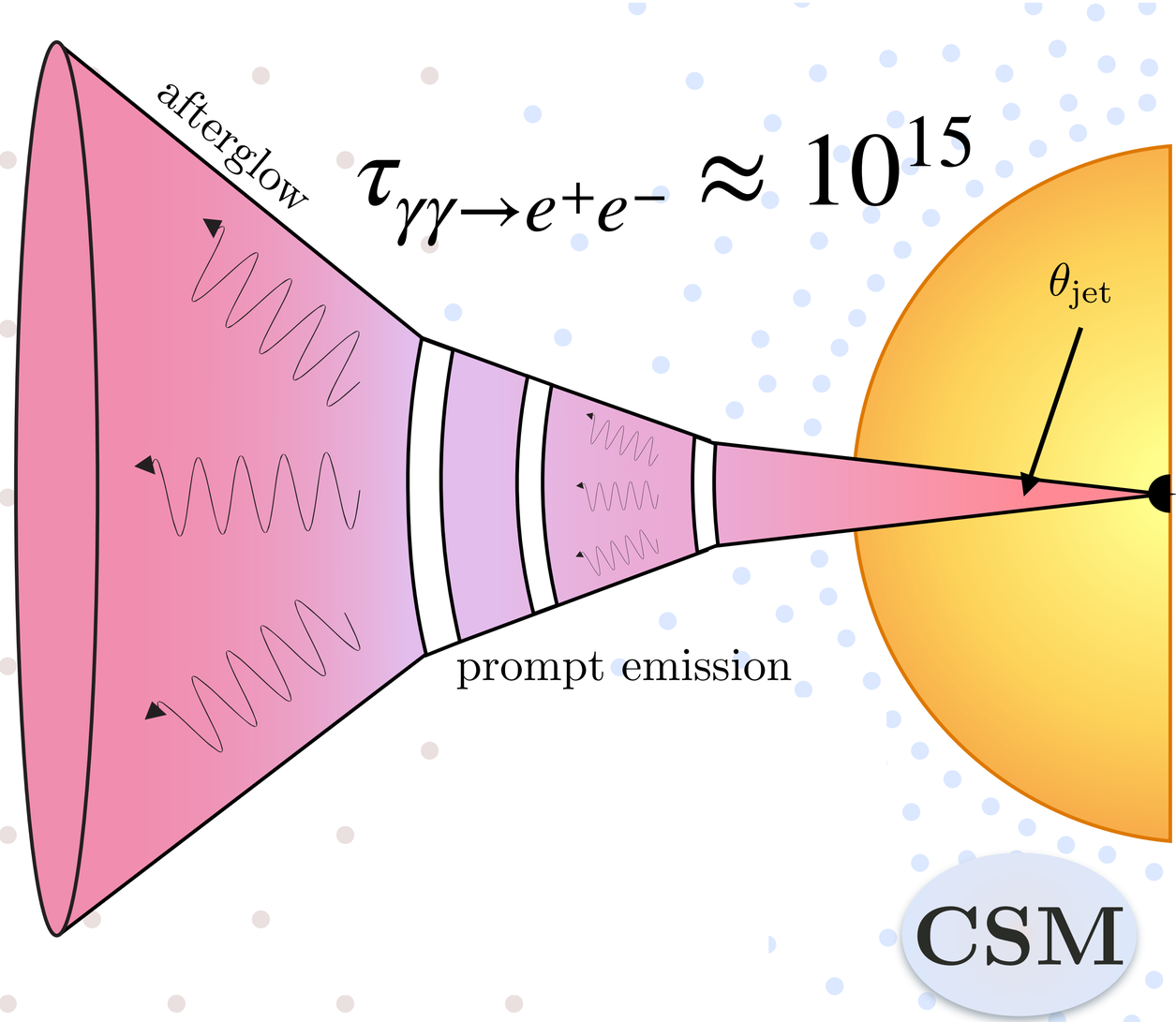
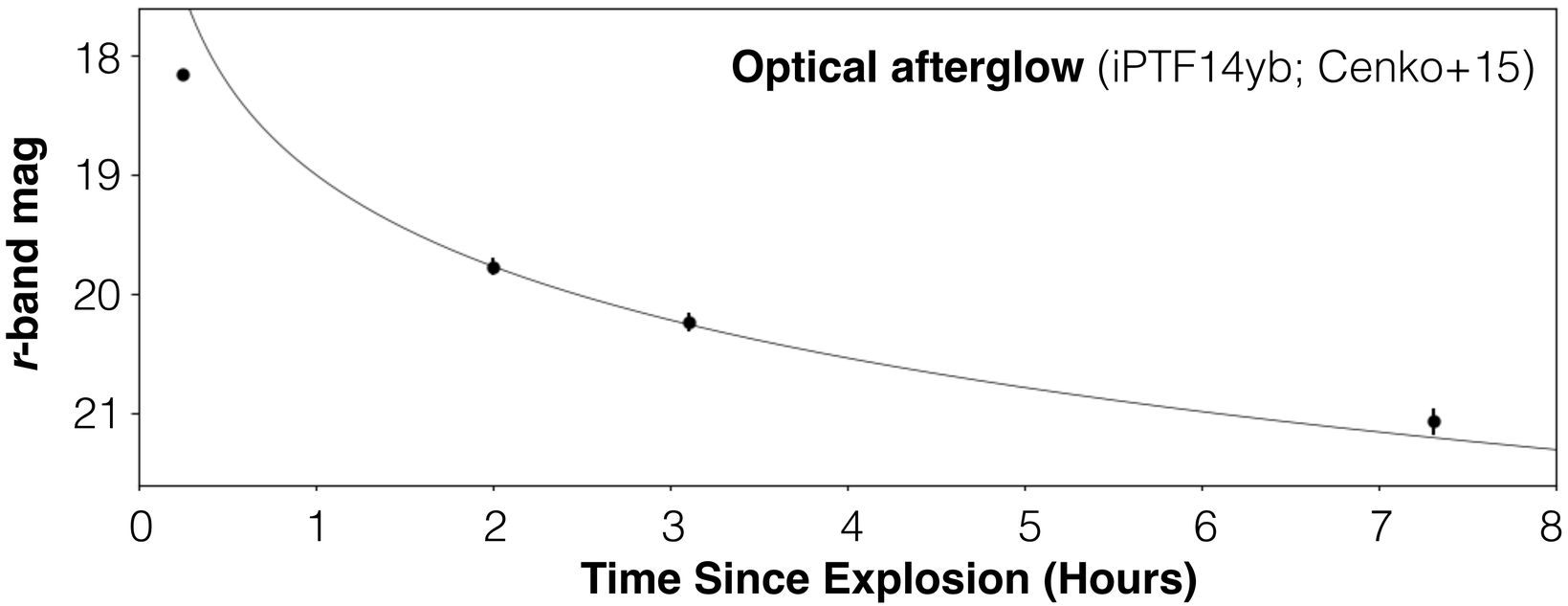


image credit: Brittany Miller

Compactness Problem: Ruderman (1975), Paczynski (1986), Baring & Harding (1997).
Mass-loading Problem: Shemi & Piran (1990)
Dirty fireballs: Dermer et al. (1999), Huang et al. (2002), Rhoads et al. (2003)

Finding dirty fireballs as optical transients



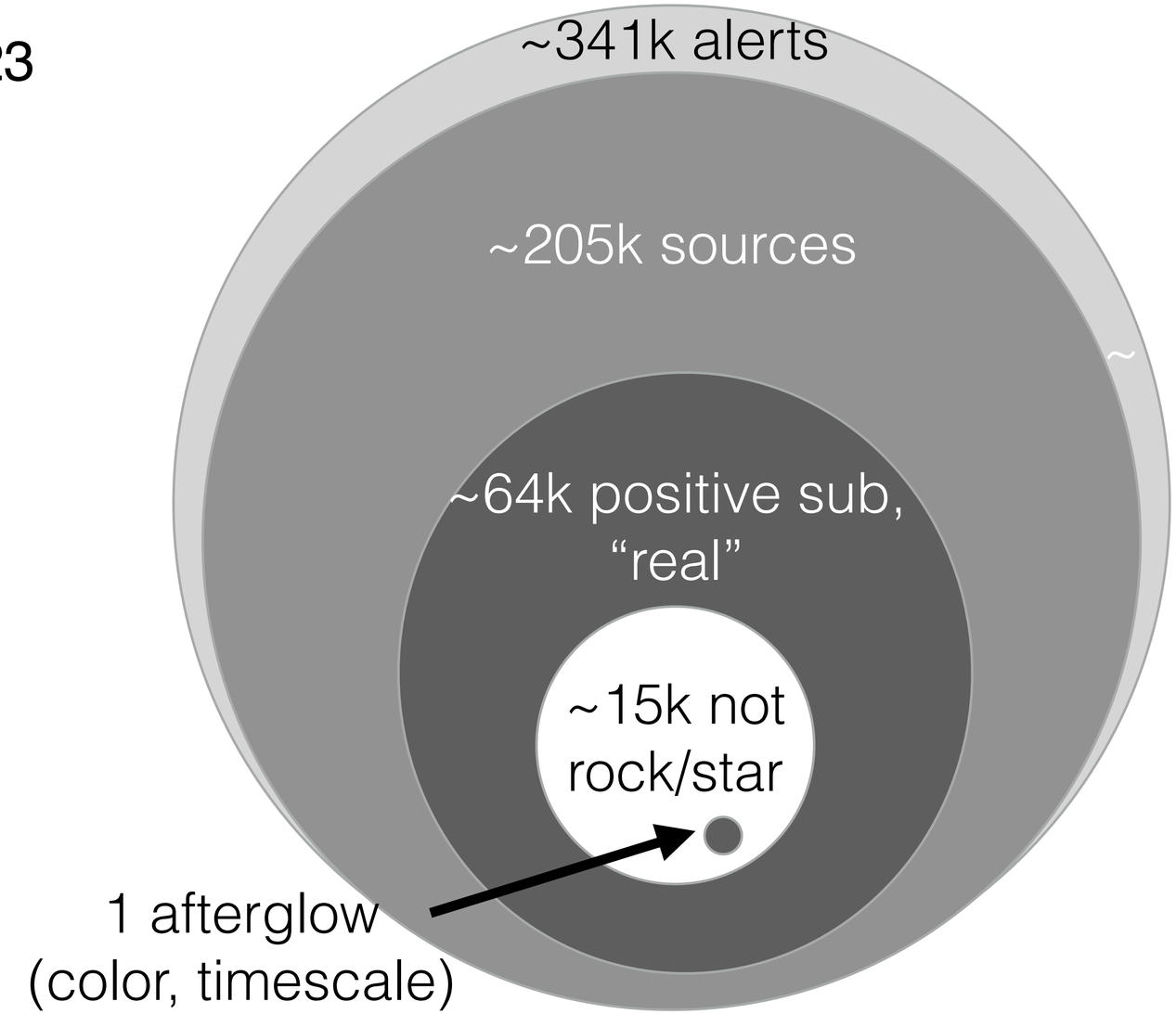
- Dirty fireball: afterglow with no associated GRB
- Fast optical transient

Pre-2019: 3 discoveries (2 GRB afterglows, one with z)

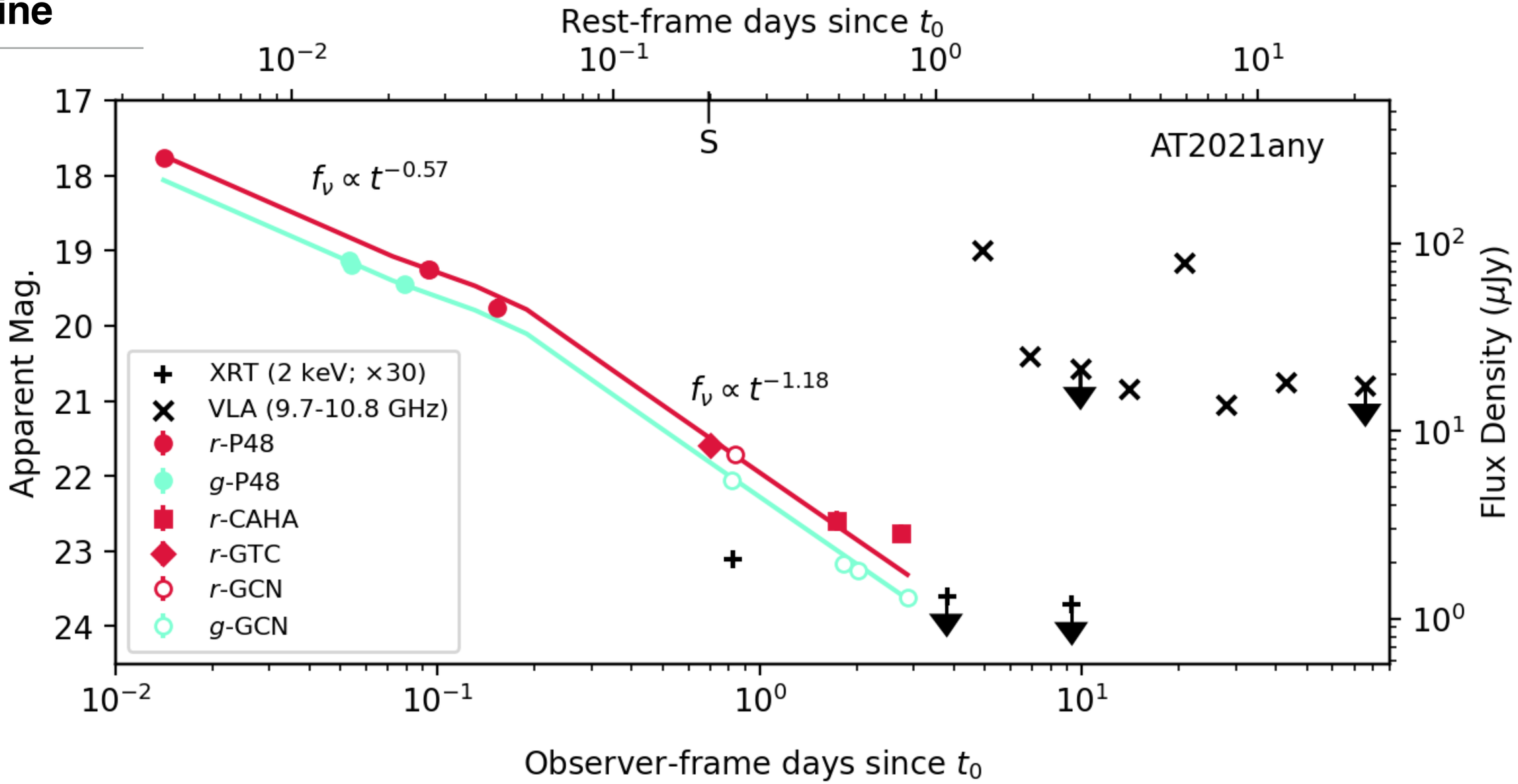
Afterglow Reviews: Piran et al. (2004), Kouveliotou et al. (2012), Kumar & Zhang (2015)
Pre-ZTF optical afterglow discoveries: Cenko+13, Cenko+15, Stadler+17, Bhalerao+17
"On-axis orphan afterglows:" Nakar & Piran (2003)

Finding afterglows using ZTF

18 June 2023



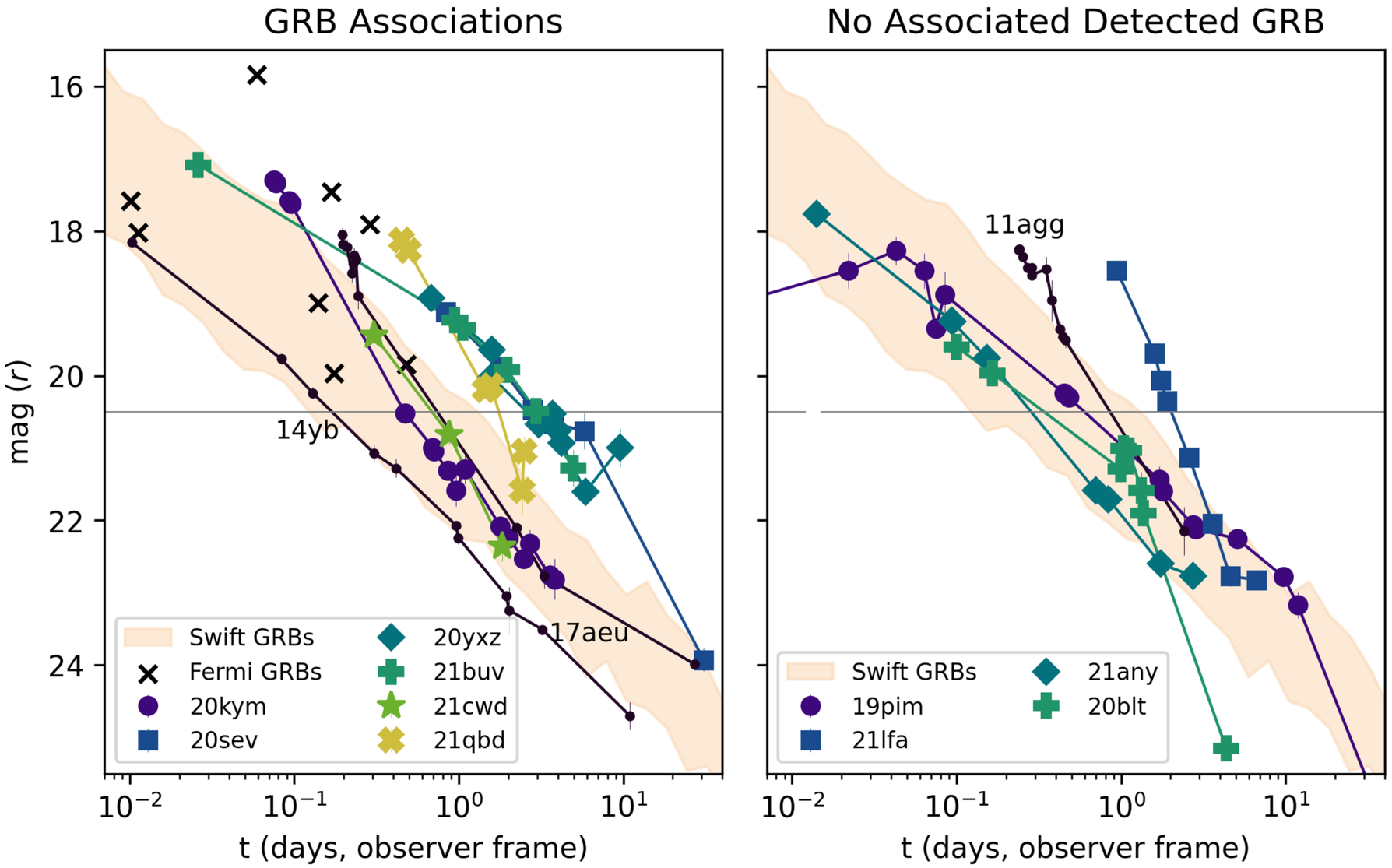
Timeline


Rest-frame days since t_0
10^{-2}
10^{-1}
10^{0}
10^{1}
S
AT2021any
$f_\nu \propto t^{-0.57}$
$f_\nu \propto t^{-1.18}$
XRT (2 keV; ×30)
VLA (9.7-10.8 GHz)
r-P48
g-P48
r-CAHA
r-GTC
r-GCN
g-GCN
Apparent Mag.
17
18
19
20
21
22
23
24
Flux Density (μJy)
10^{2}
10^{1}
10^{0}
Observer-frame days since t_0

2020-2023: Ten afterglows

Figure: AYQH et al. 2022b

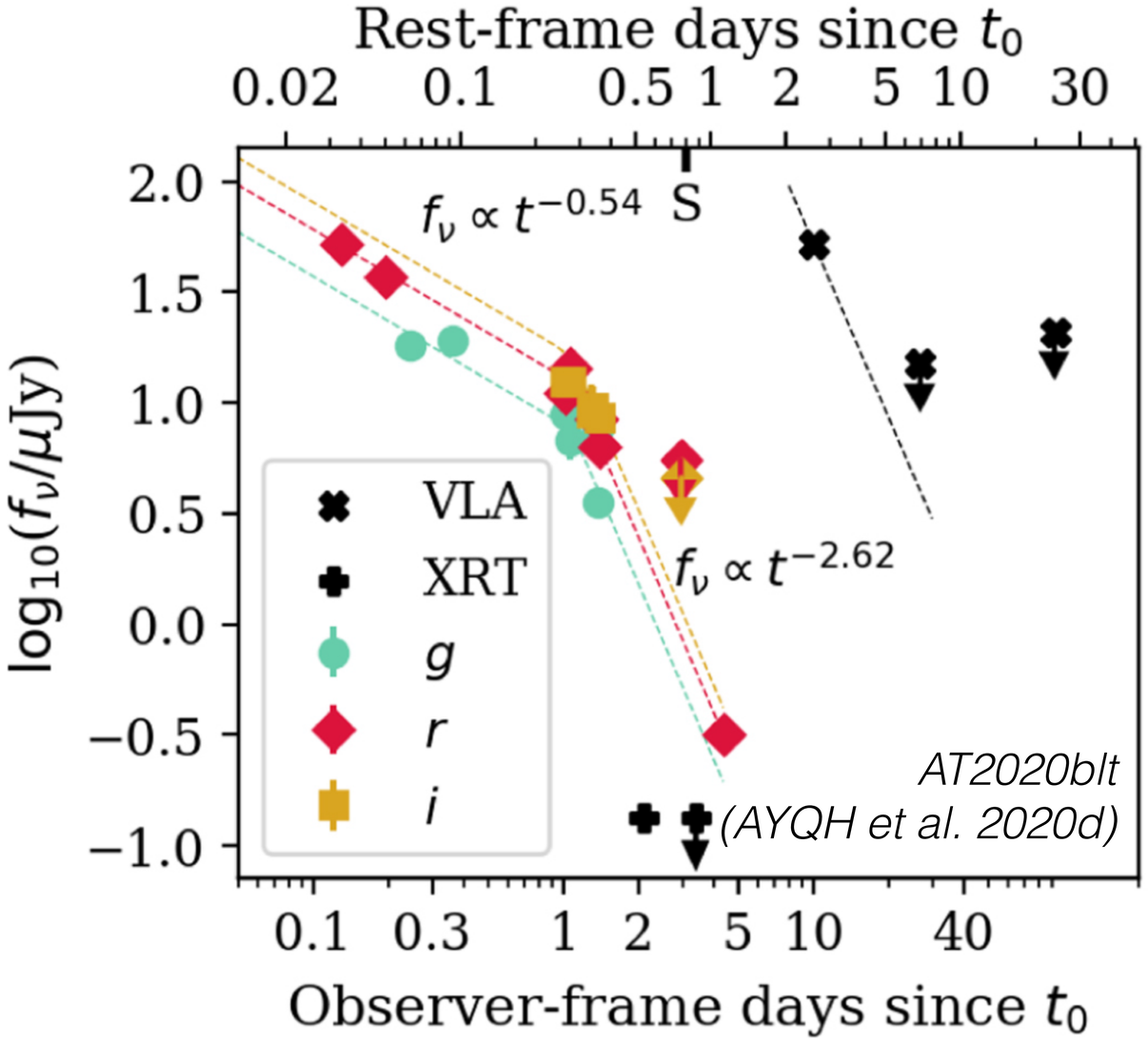
- Fastest transients discovered optically
- Redshifts: z=0.3-2.9
- Optically discovered afterglows with z: 1→8
- 6/10: associated GRB



See also: Andreoni et al. 2020, 2021; Kasliwal et al. 2020; Perley, AYQH et al. in prep.

Four “orphan” afterglows

- Redshifts: 1.3 to 2.9
- Data: optical, X-ray, radio
- Look like on-axis GRB afterglows
  - Two have a prominent “jet break”
- Can’t rule out a GRB
- GRB missed? Slightly off-axis? Dirty fireball? Low gamma-ray efficiency?



Conclusions

- Optical fast cosmological transients: half are GRBs
- Jets w/ GRB energetics & collimation: rate ~ GRBs *(Huang et al. 2002, Rhoads 2003)*
- Material producing gamma-rays & early optical afterglow: similar opening angle

- Consistent with
  - GRB flux distribution (Eichler 2011)
  - Optical upper limits & X-ray searches (optical: Cenko et al. 2015, Ho et al. 2018; X-ray: Grindlay 1999, Dermer et al. 1999, Greiner et al. 2000, Nakar & Piran 2003)
  - Blind radio afterglow searches (Mooley et al. 2022)
  - Searches for relativistic ejecta in supernovae ("Ic-BL") (Corsi et al. 2015; Corsi, AYQH et al. 2023)

Discussion

Highly relativistic ejecta is rare

- GRBs (~0.1% SNe)
- On-axis “orphan” afterglows (AYQH+22)
- Relativistic Ic-BL SNe (Corsi, AYQH+23; AYQH+20c)
- “FBOTs” (/18cows; next section) (AYQH+23)

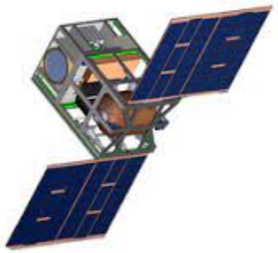
Results hint at bimodal distribution

Pressing questions—

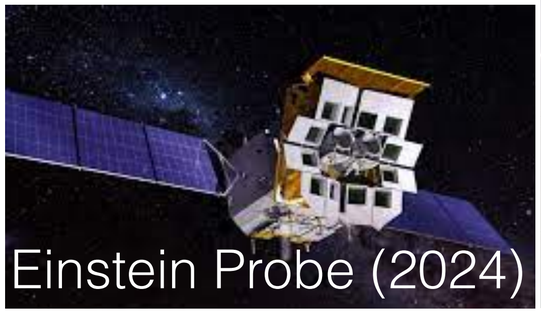
- What would bimodality imply about launch/propagation/structure?
- What are the “normal” Ic-BL SNe?
- Do dirty fireballs exist? What do they look like?
- How can we identify “choked” jets? (Bromberg+12, Lazzati+12, Sobacchi+17, Petropoulou+17)

The Future

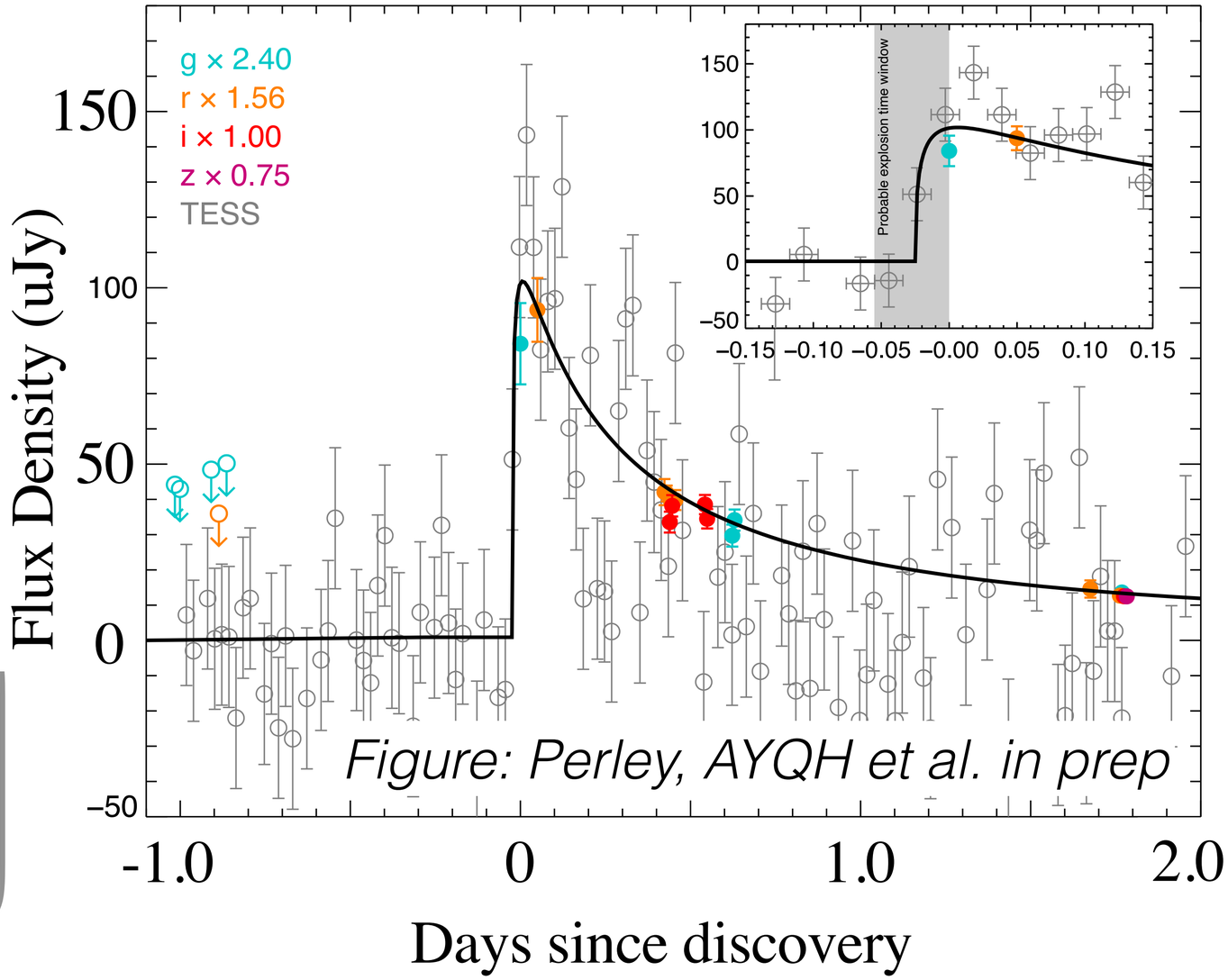
- Wide-field high-energy coverage



- …Including in soft X-rays



- Minute-cadence UV/optical observations (TESS, LAST, Argus, ULTRASAT, …)



SVOM: Wei+16, Cordier+16; EP: Yuan+18
Starburst: Kocevski+22; Argus: Law+22

Part 1: The Search for Dirty Fireballs

Part 2: The Cow and a New Class of Relativistic Explosions

ALMA (Credit: ESO/C.Malin)

June 2018: ATLAS survey discovered AT2018cow (d=60 Mpc)

nature IN FOCUS NEWS

NEWS · 02 NOVEMBER 2018 · CORRECTION 30 NOVEMBER 2018

Holy Cow! Astronomers agog at mysterious new supernova

NewScientist

Strange 'space cow' explosion may have been the birth of a black hole

Forbes

Jan 17, 2019, 10:00am EST | 2,907 views

Astronomers Can't Agree On What Caused This Extreme Burst, And Literally 'Have A Cow'

See talk by Y. Chen

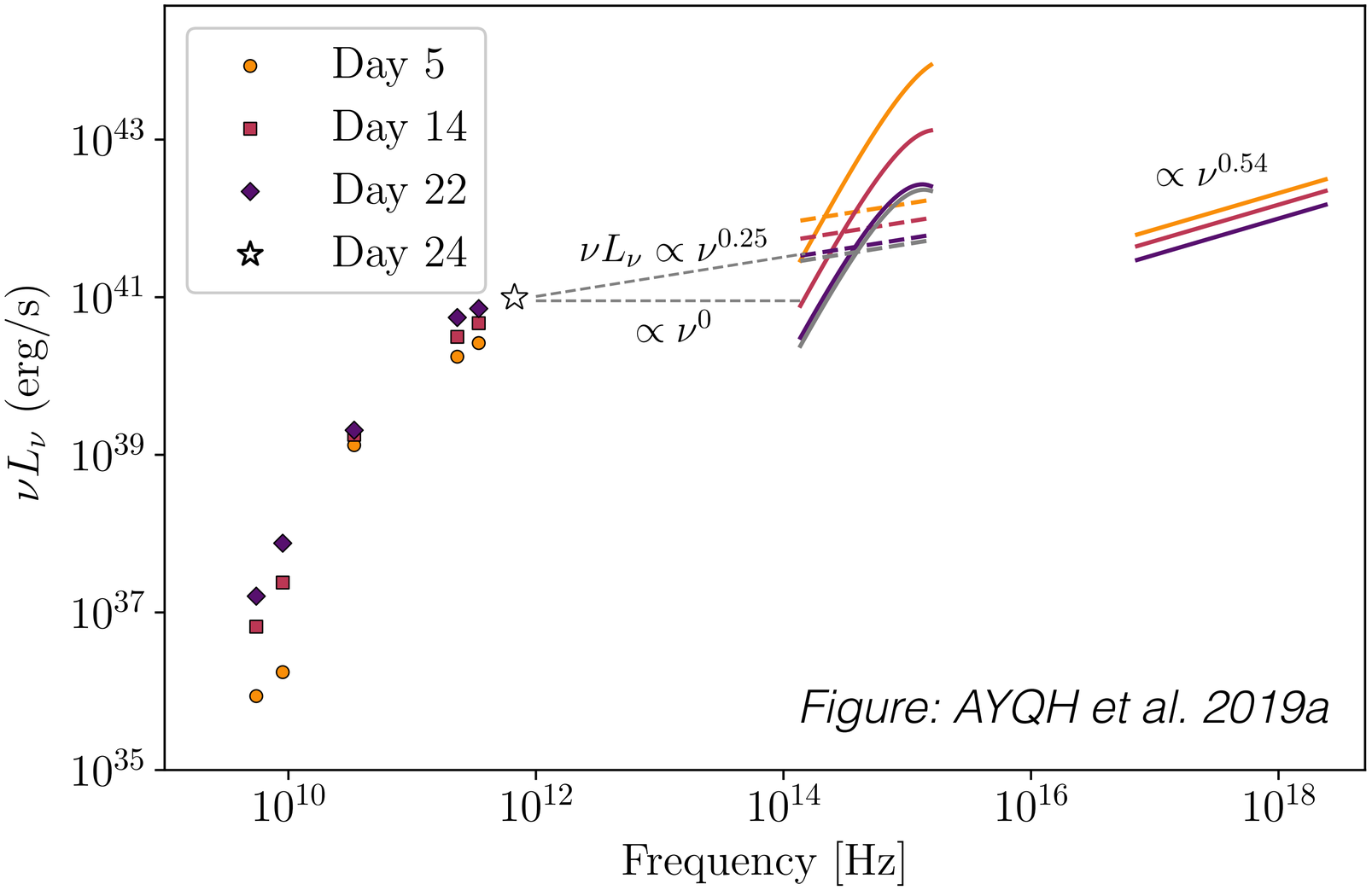


Figure: AYQH et al. 2019a

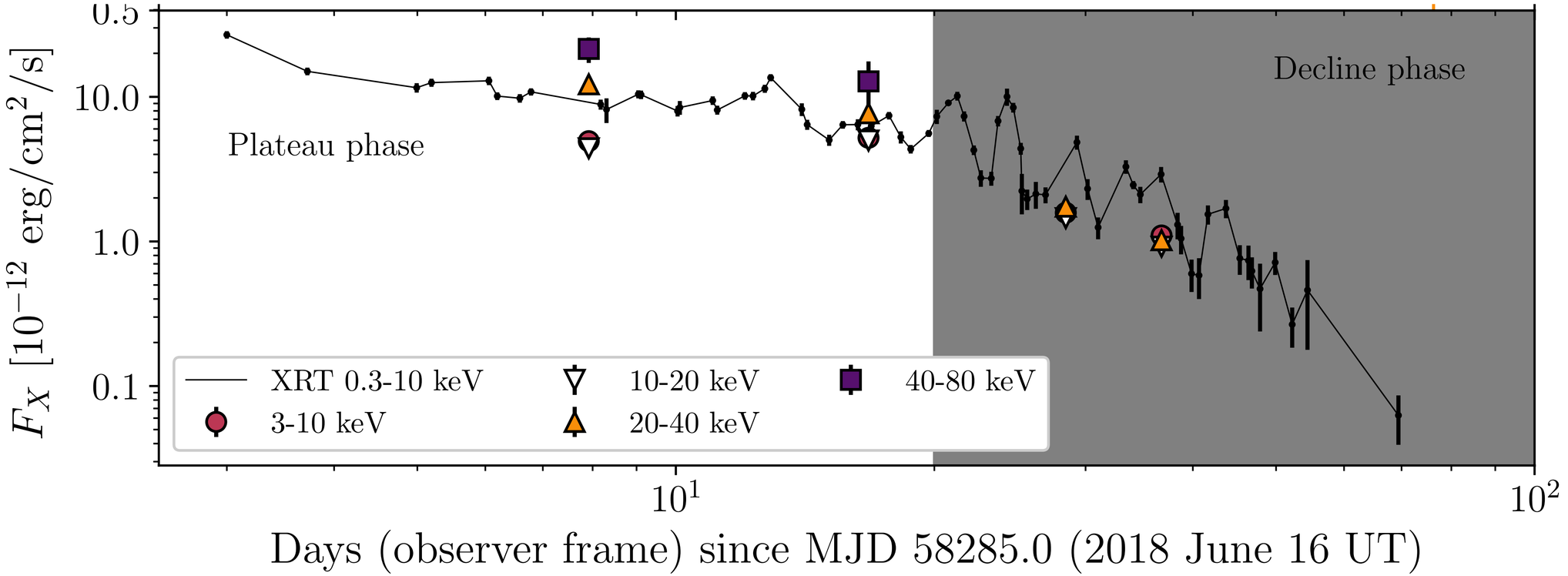
Tonry et al. (2018), Prentice et al. (2018)

Multiwavelength observations: Rivera-Sandoval+19, Kuin+19, Perley+19, Margutti+19, AYQH+19b, …

Engine-powered transient

Figure: AYQH et al. 2019a

10^{43} erg/s



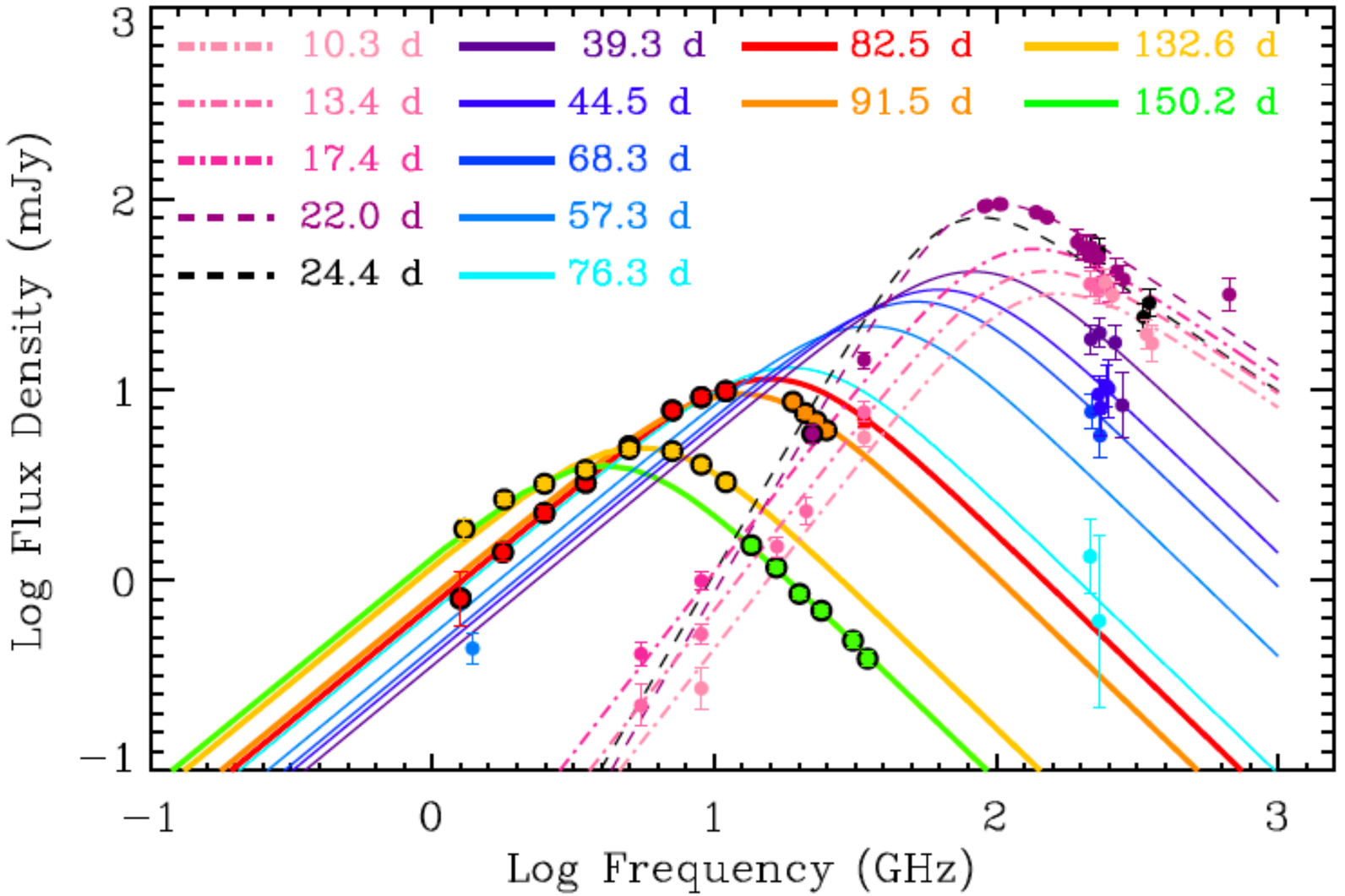
Unlike GRBs: H & He in spectrum, Sub-relativistic (v~0.1c), Nickel mass < 0.1 $M_\odot$, Exposed engine

Models: failed SN (supergiant)? Pair-instability SN? IMBH TDE? Stellar TDE? WD AIC? …

Multiwavelength observations: Rivera-Sandoval+19, Kuin+19, Perley+19, Margutti+19, AYQH+19b, …
Model comparison & summary: Metzger (2022)

Outstanding questions after 18cow

- Progenitor
  - Volumetric rate (1%?)
  - Relationship to other “FBOTs”
  - Diversity of properties
- Interpreting the emission
  - Power source
  - Strange mm SED (steep + deviation from radio)



Finding more Cows (2018-2023)

- Day-timescale transients
- Require host association (CVs)
- Require high luminosity (IIb, Ibn)


Gemini


LT


VLT

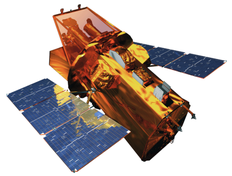

Keck

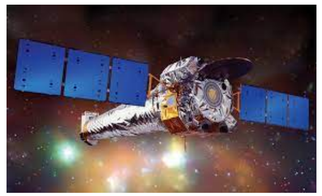

NOEMA

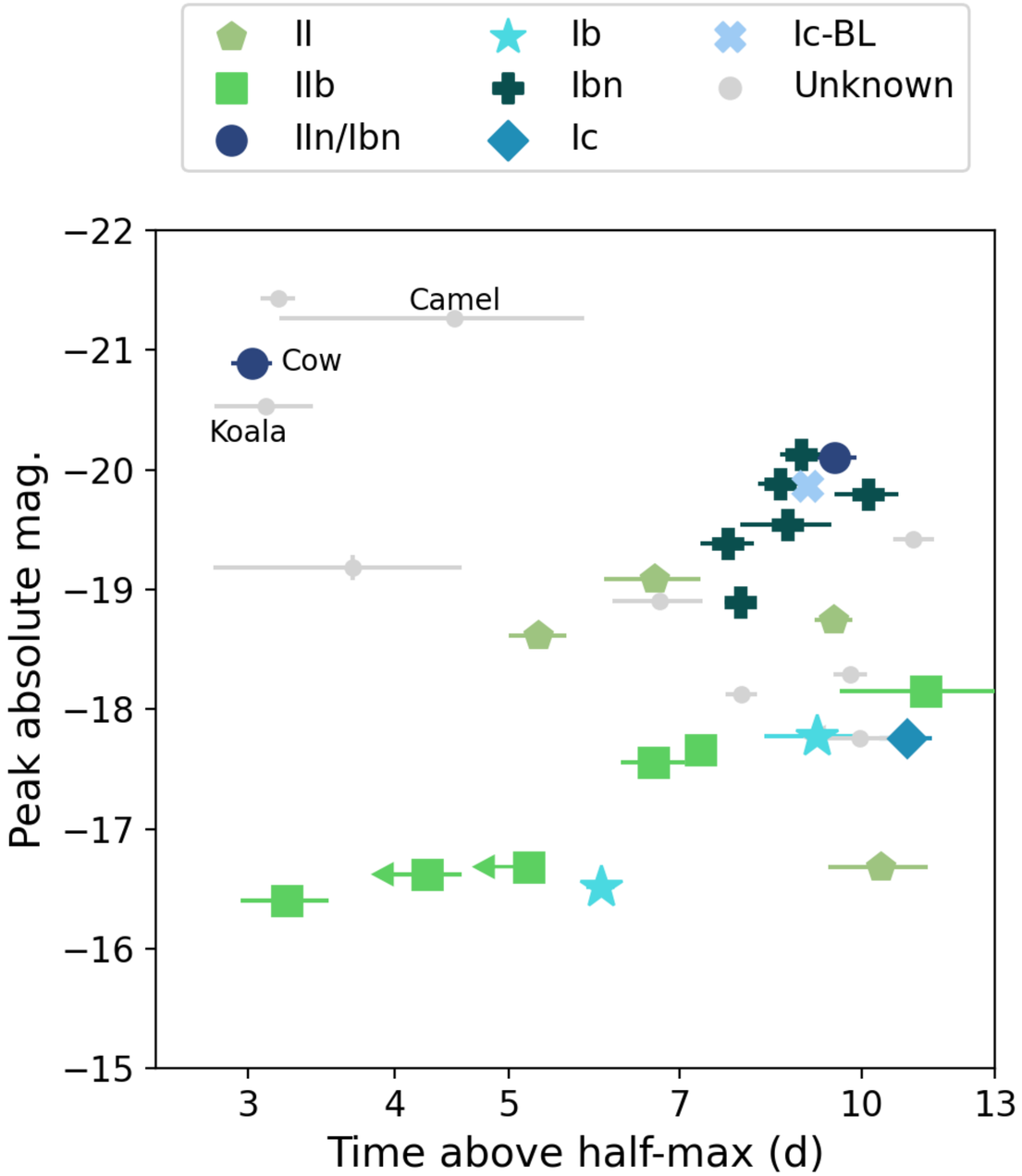

VLA


ALMA


GMRT


Swift

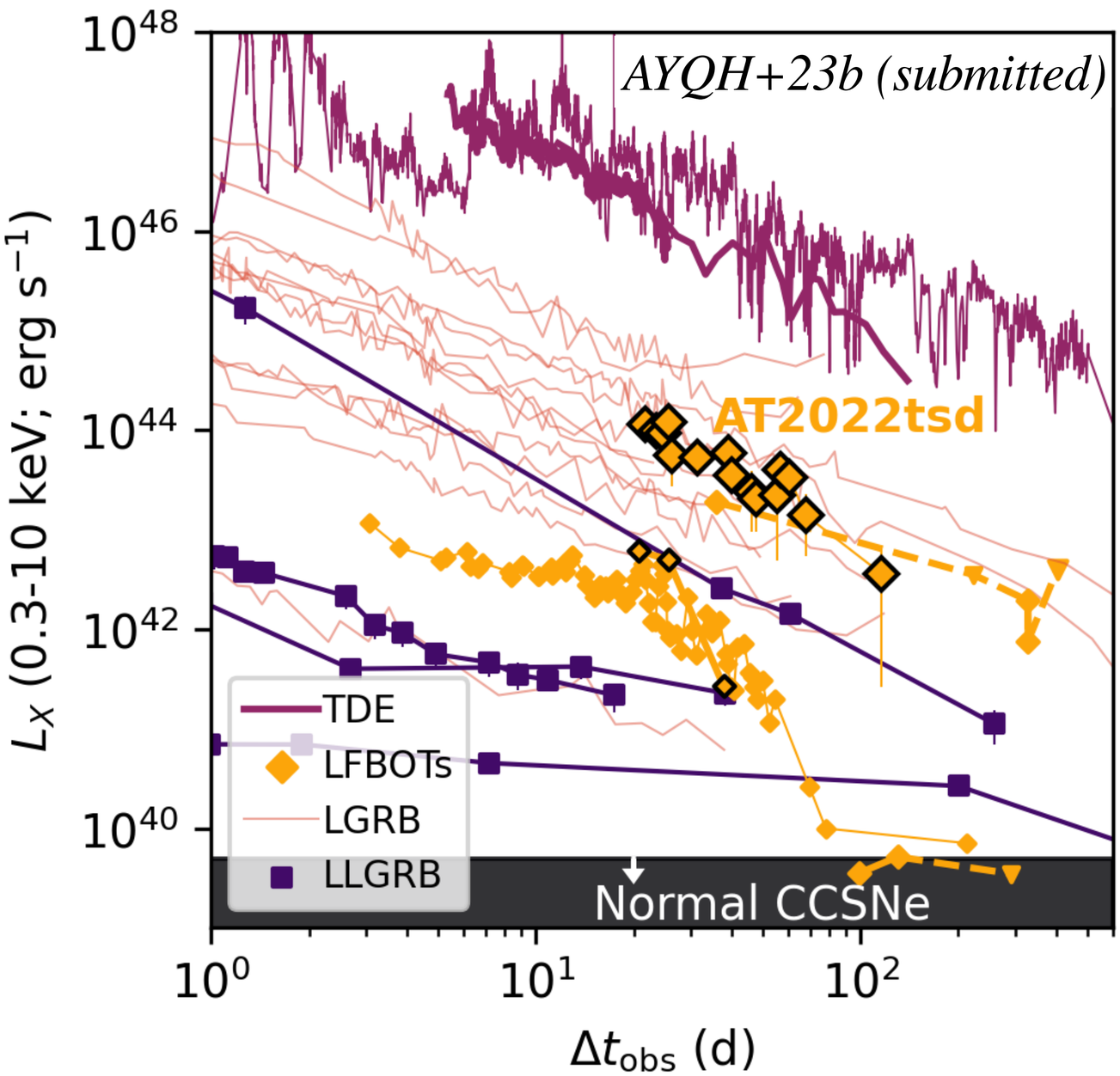

Chandra



Eight additional events; ten total

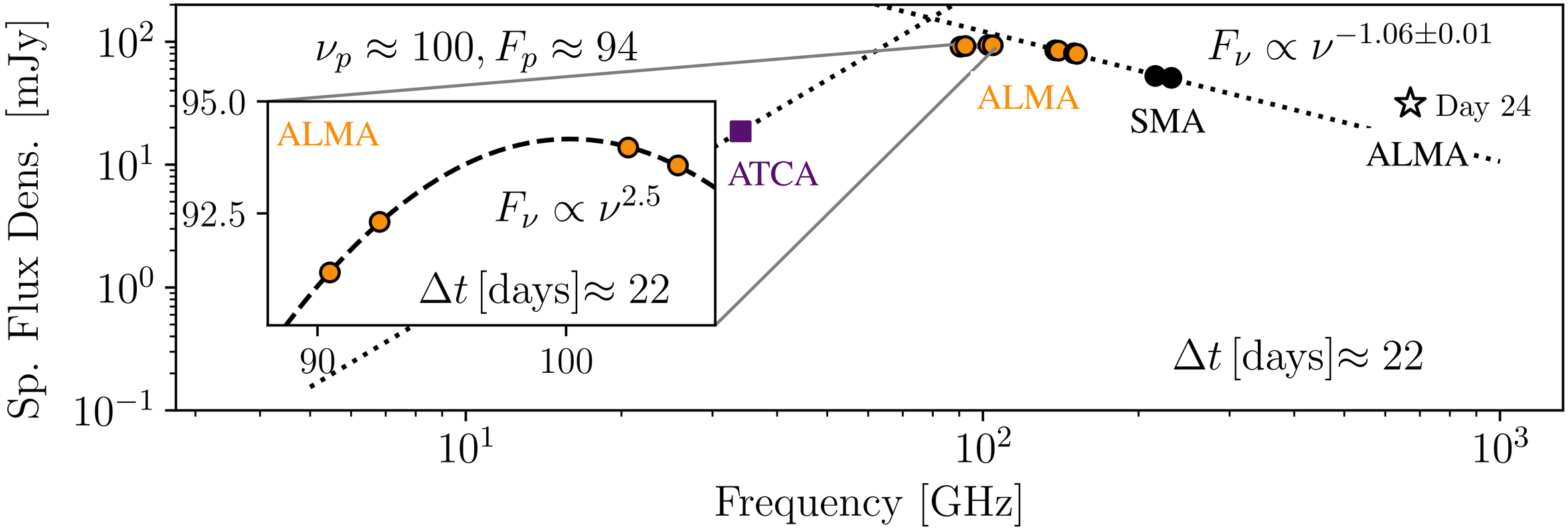
& CSS161010 (Coppejans+2020)

- Redshifts: $z = 0.03$ to $z = 0.34$
- Radio: nine (10^{38} to 10^{40} erg/s)
- X-rays: five (10^{42} to 10^{44} erg/s)
- Rate < 0.1% CC SN rate
- SF (10^{-3}-7 Msun/yr) galaxies (10^{7}-10^{10} Msun); few kpc offset



Submillimeter Transients

Figure from AYQH et al. 19a

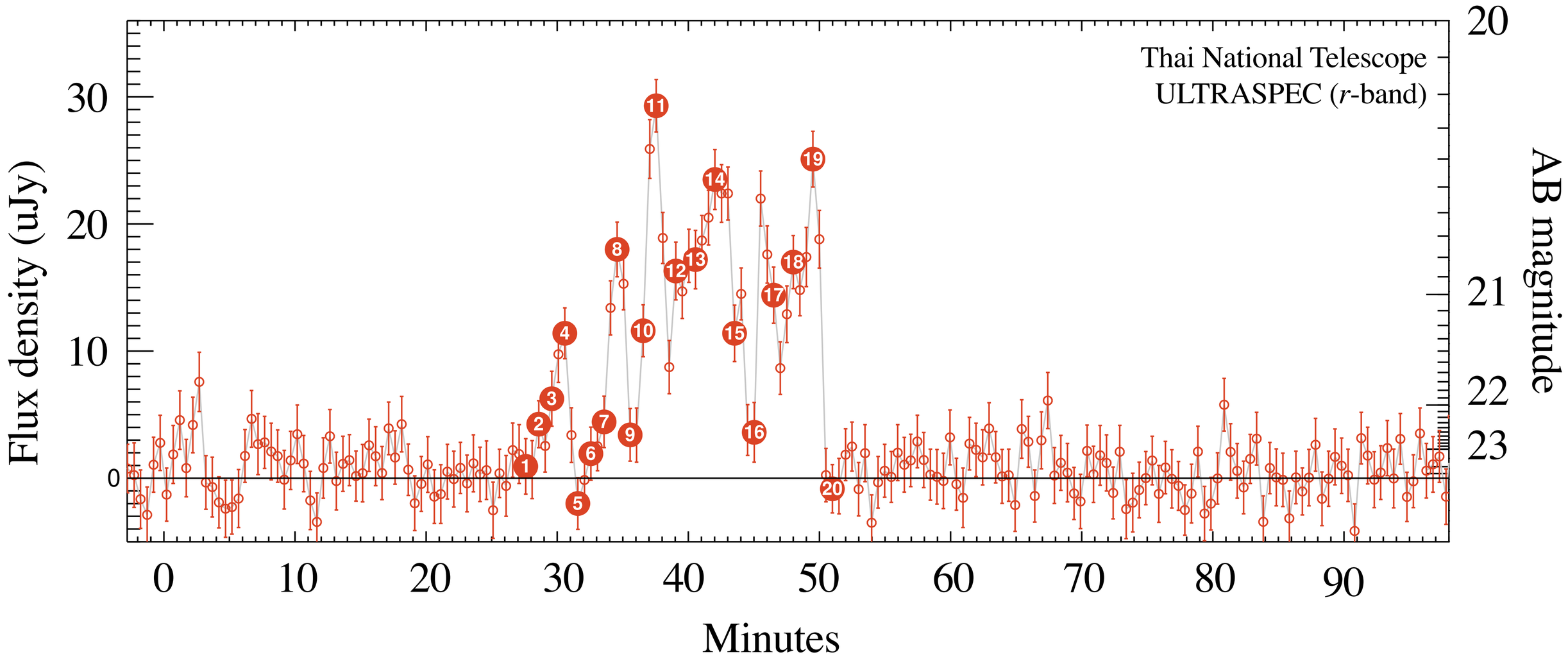


- Conventional SSA: high B / n_e
- Relativistic Maxwellian?

SSA modeling: Margutti+19, AYQH+19b, Coppejans+20, AYQH+20, Nayana+21, Yao+22, Bright+22, AYQH+22b

Relativistic Maxwellian: Margalit & Quataert (2021), AYQH+22b

Long-lived central engine (~10^2 days)



Conclusions / Discussion

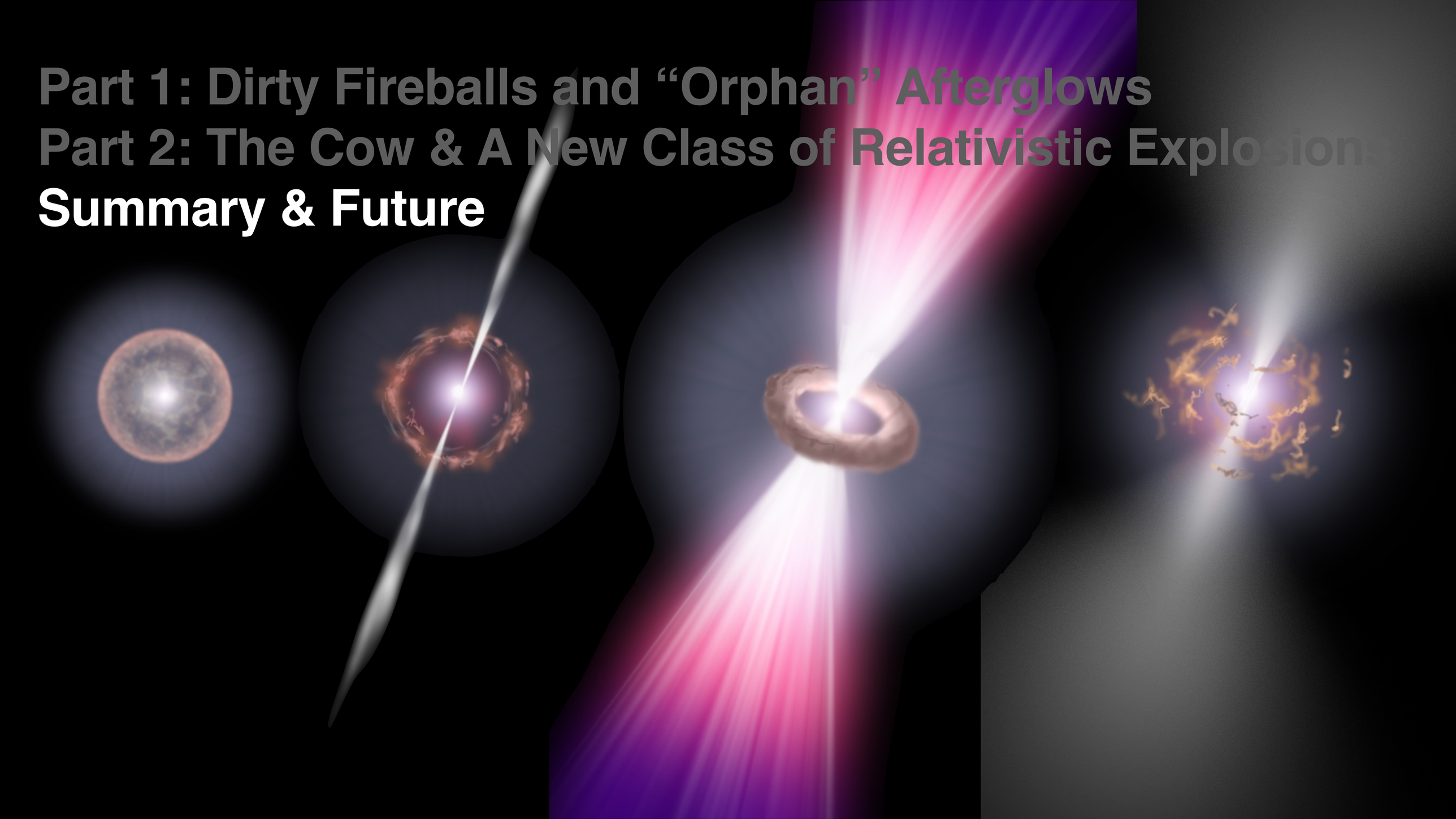
- Simplest explanation: stellar mass compact object
  - Supergiant collapse and accretion
  - Magnetar
  - Merger and tidal disruption

- Motivates:
  - Multi-exposure survey observations (flare detection)
  - Sub-ms UVOIR (compact object)
  - UV spectroscopy (composition)
  - High-energy coverage (outflow)
  - High-cadence UV (much earlier discovery)

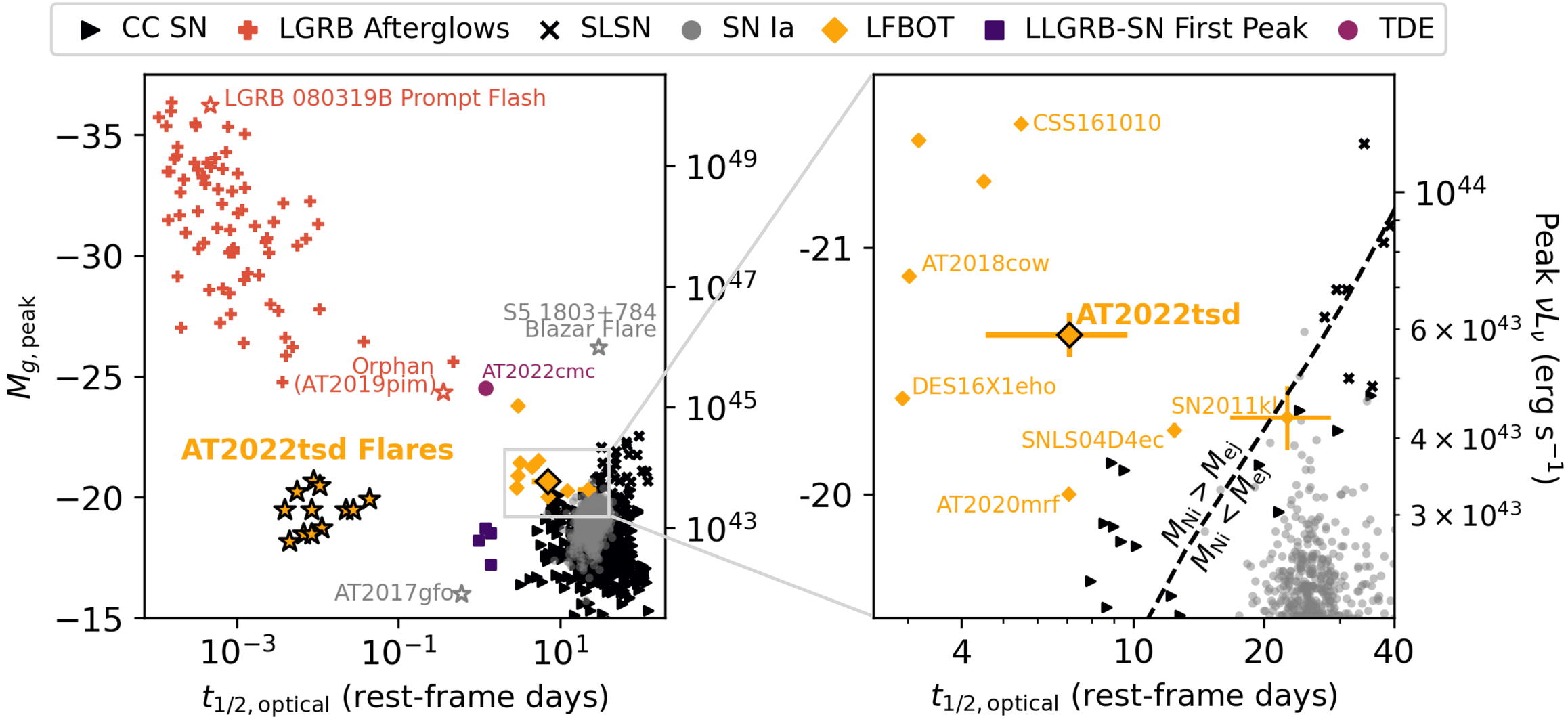
Part 1: Dirty Fireballs and “Orphan” Afterglows

Part 2: The Cow & A New Class of Relativistic Explosions

Summary & Future



Development: relativistic explosions outside gamma-ray band



+ dozens of Ic-BL SNe (Corsi, AYQH et al. 2023, submitted)

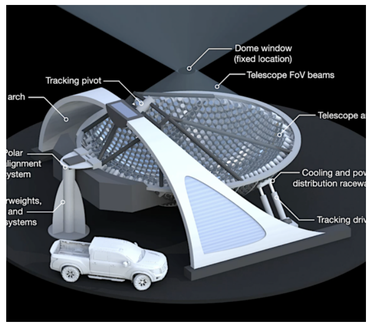
The upcoming landscape (2023-2030)

(1) High-energy coverage

(2) Sub-ms to min-cadence UVOIR

See talk by J. Cooke

LAST



Argus

TESS

(3) Submillimeter surveys

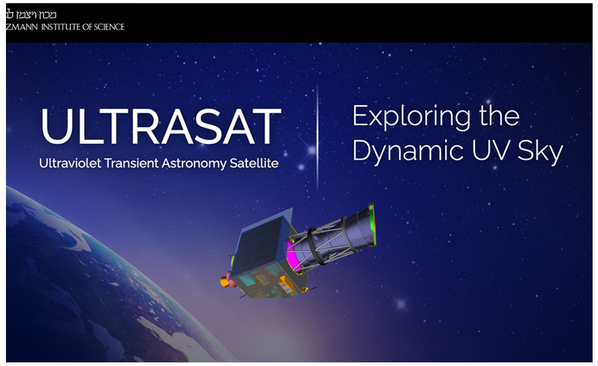
See talks by E. Biermann, Y. Li, C. Hervias-Caimapo, S. Guns, K. Phadke, Y. Wan, C. Tandoi

SIMONS OBSERVATORY

CMB-S4
Next Generation CMB Experiment

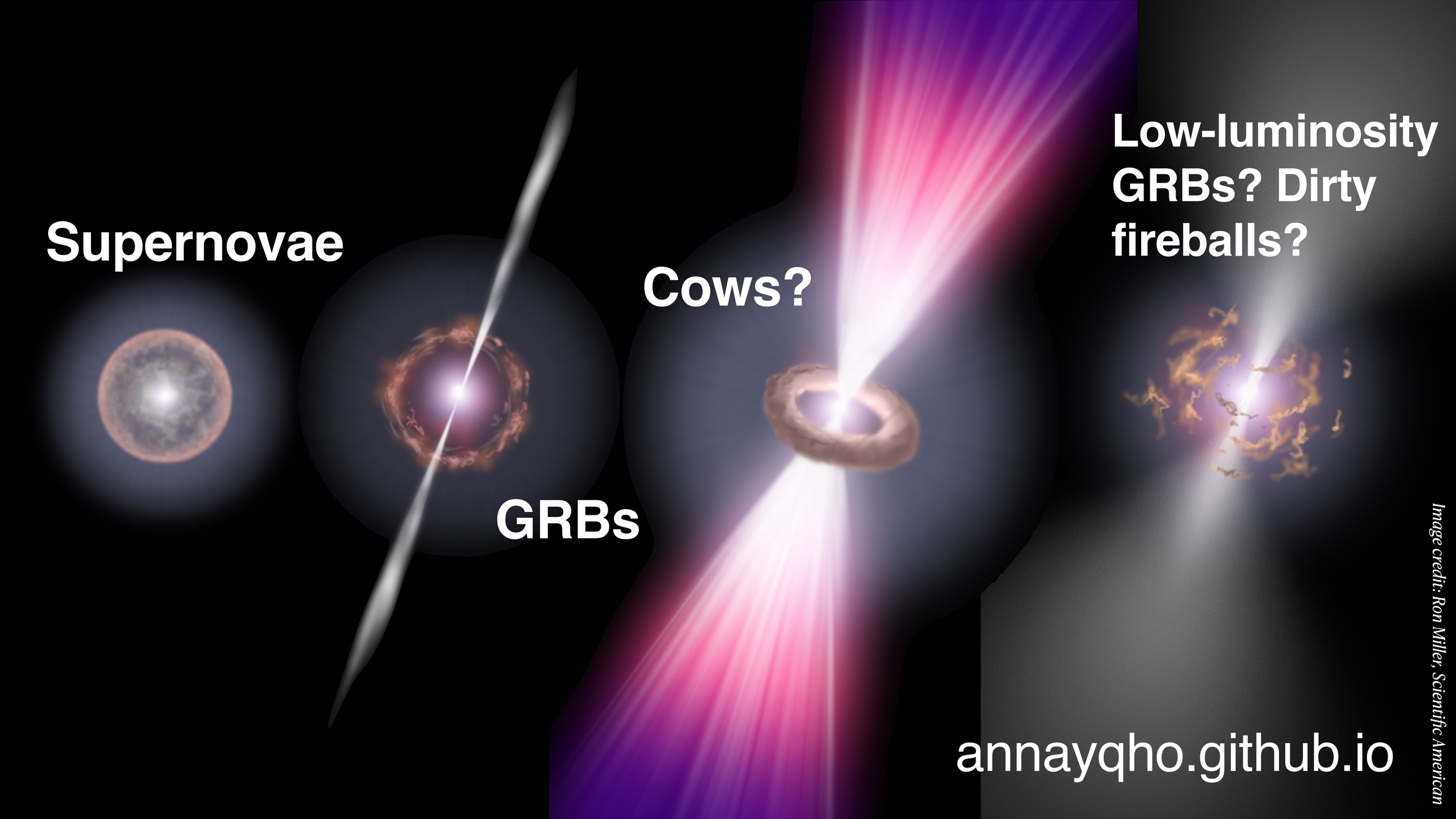
(4) UV discovery & spectroscopy

See talk by S. Kulkarni



UVEX

ZTF collaboration


Supernovae
GRBs
Cows?
Low-luminosity GRBs? Dirty fireballs?
annayqho.github.io
Image credit: Ron Miller, Scientific American