# Relativistic Stellar Explosions:

## The Landscape Revealed by Wide-field, High-cadence Optical Surveys

*Image credit: Ron Miller, Scientific American*


Anna Y. Q. Ho (Cornell)


11 February 2026


THE DAVID & LUCILE Packard Foundation

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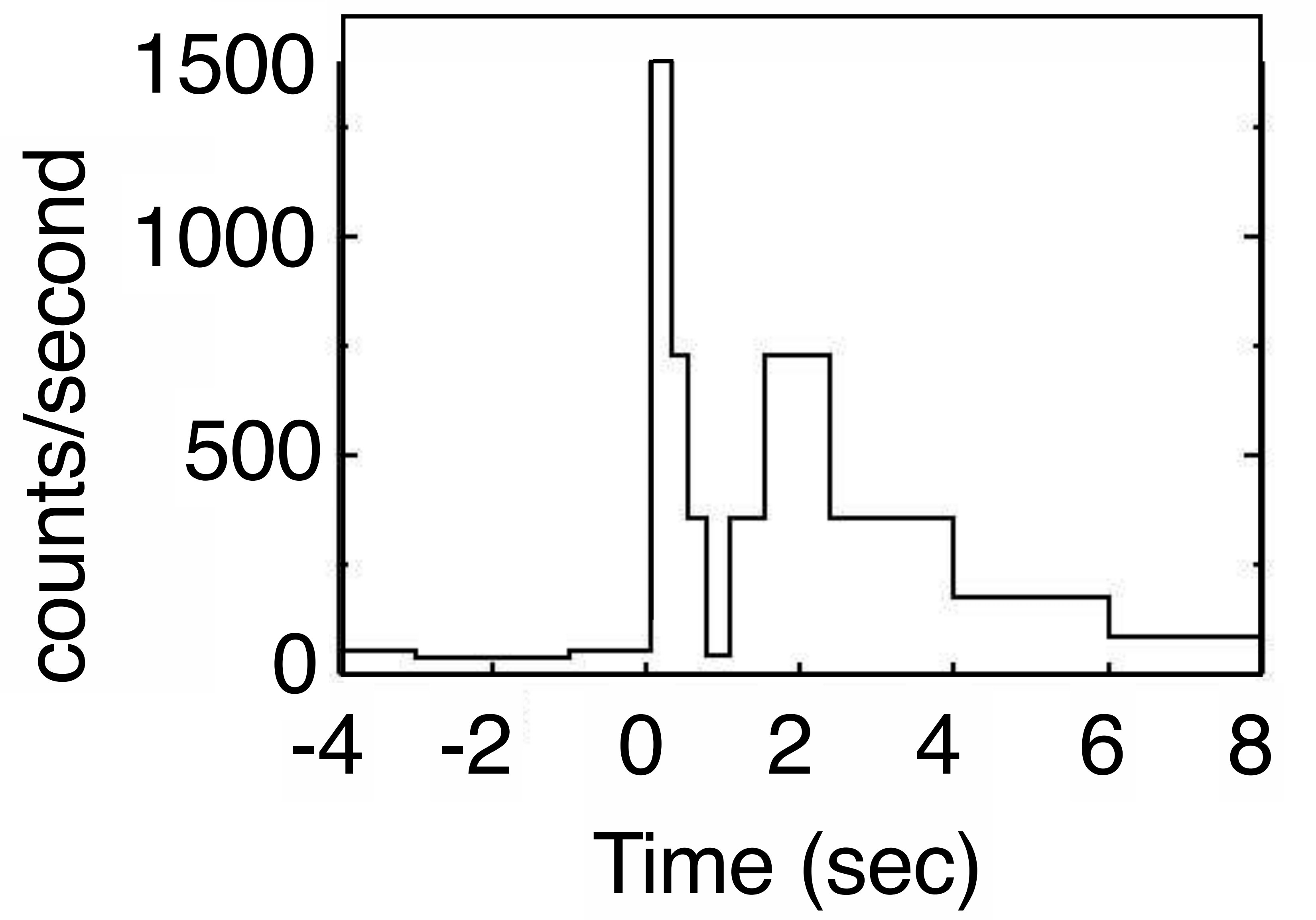
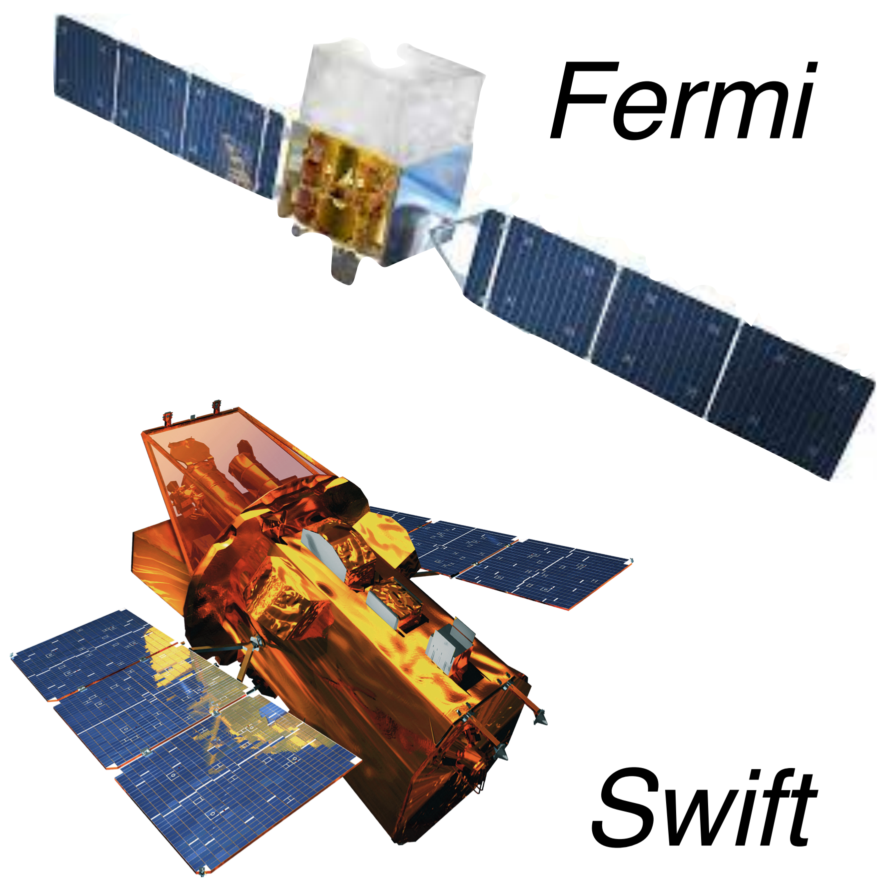
# Exemplar relativistic stellar explosion: long-duration gamma-ray bursts (GRBs)

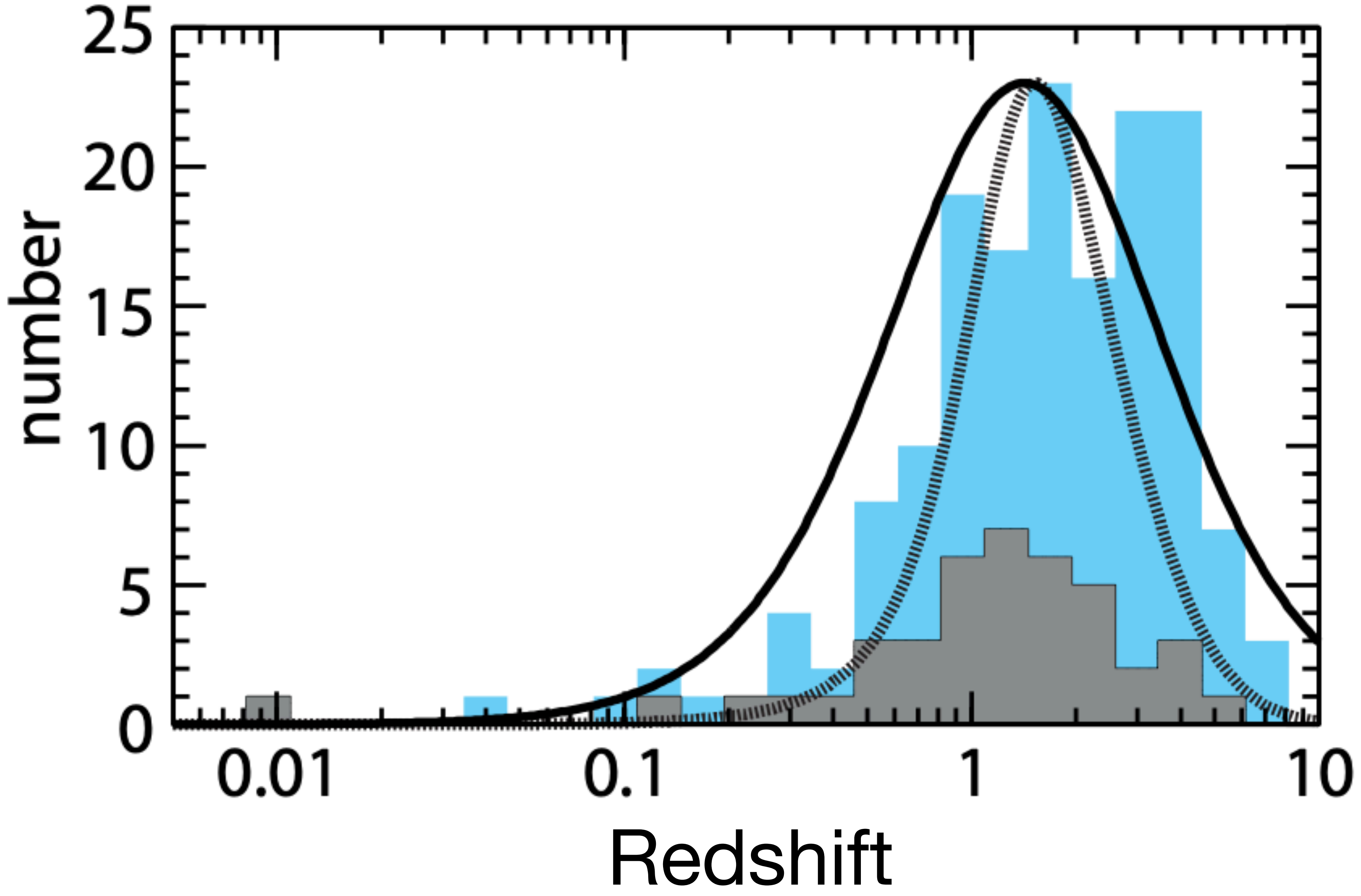
Vela 4a Event — July 2, 1967



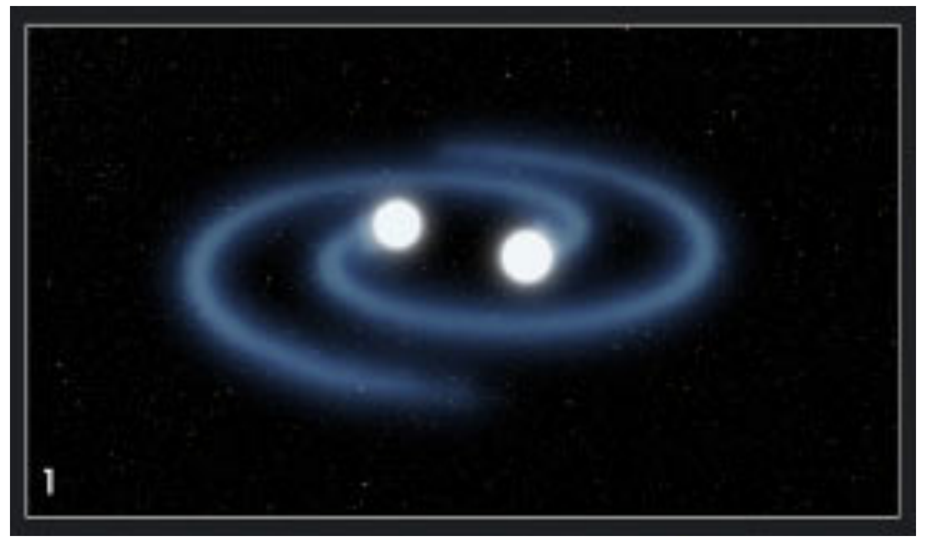

Since then: thousands discovered




*Gehrels+09*




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

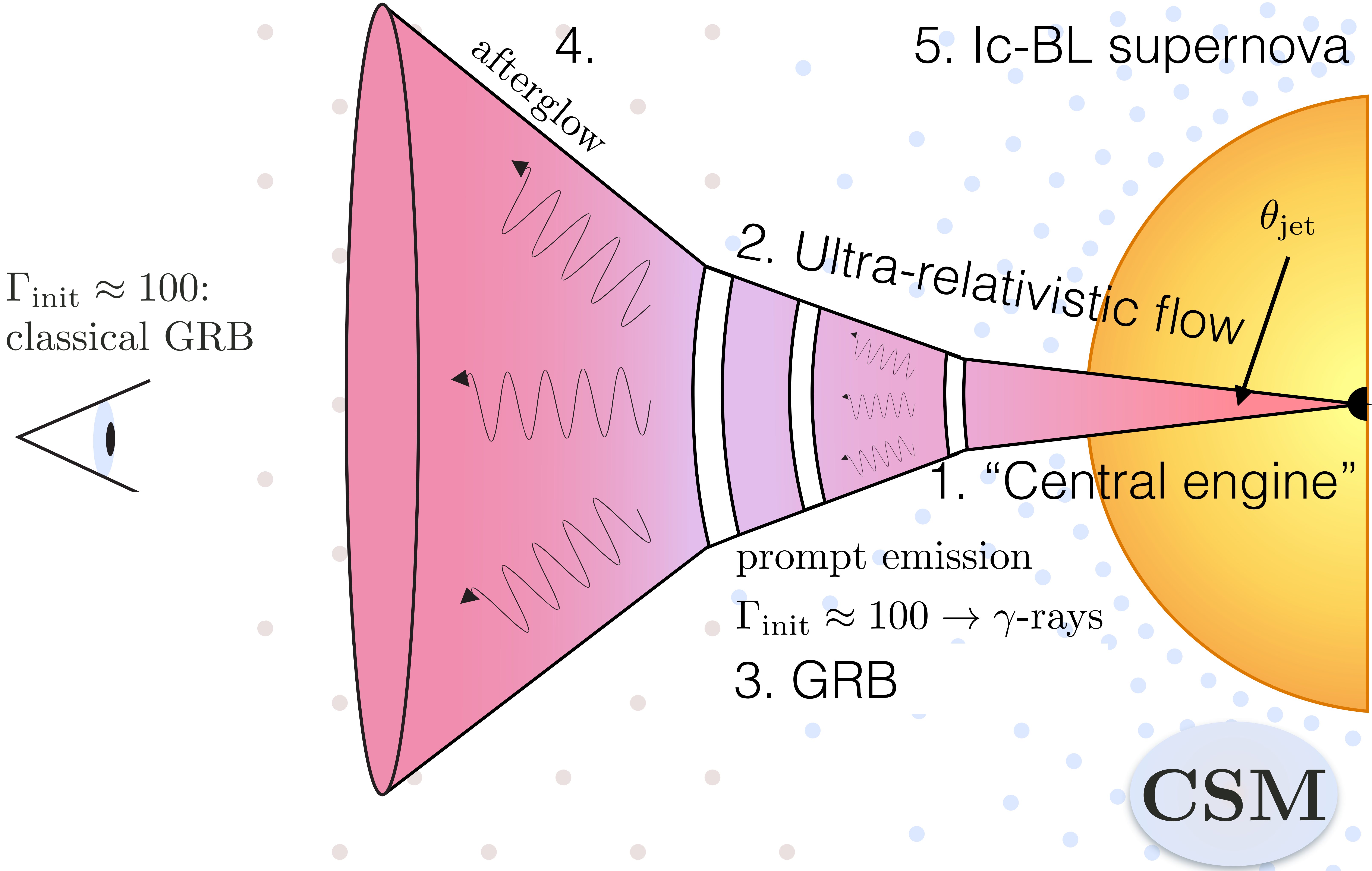


*NASA / ESA / D. Player, STScI*

Long (>2 sec): collapse of massive star

Reviews: Mészáros (2002, 2006); Piran (2004), Kouveliotou et al. (2012), Berger et al. (2014), Kumar & Zhang (2015), Levan (2025)

# Traditional model for long-duration GRBs




***See talk by Todd Thompson***

*Cartoon by Brittany Miller*

Reviews: Mészáros (2002, 2006); Piran (2004), Kouveliotou et al. (2012), Kumar & Zhang (2015), Levan (2025)

# Big questions

What phenomena lie between “ordinary” supernovae and GRB-supernovae?

What is the central engine?

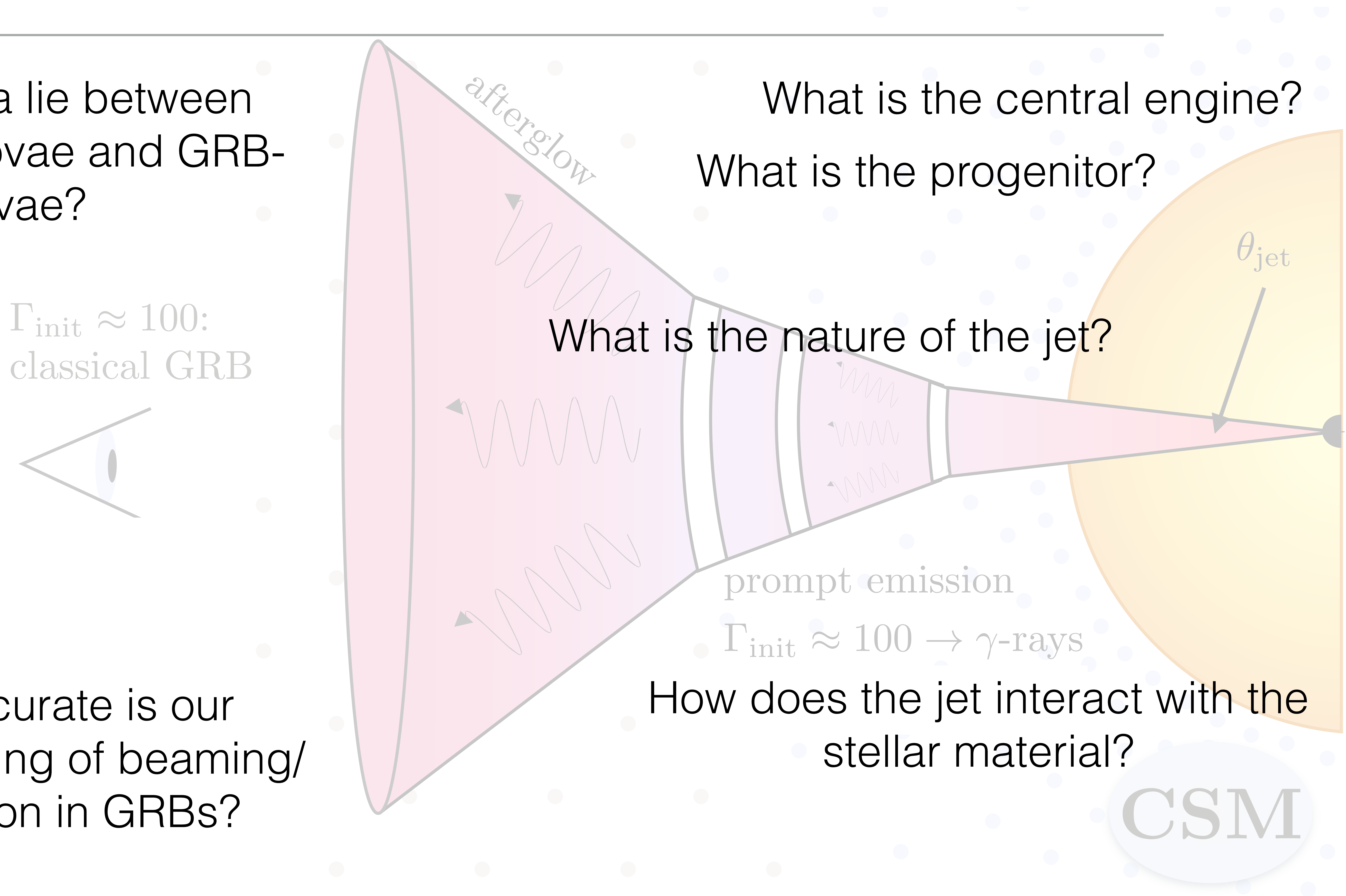
What is the progenitor?

What is the nature of the jet?

Is there a continuum of bursts with lower Lorentz factor?

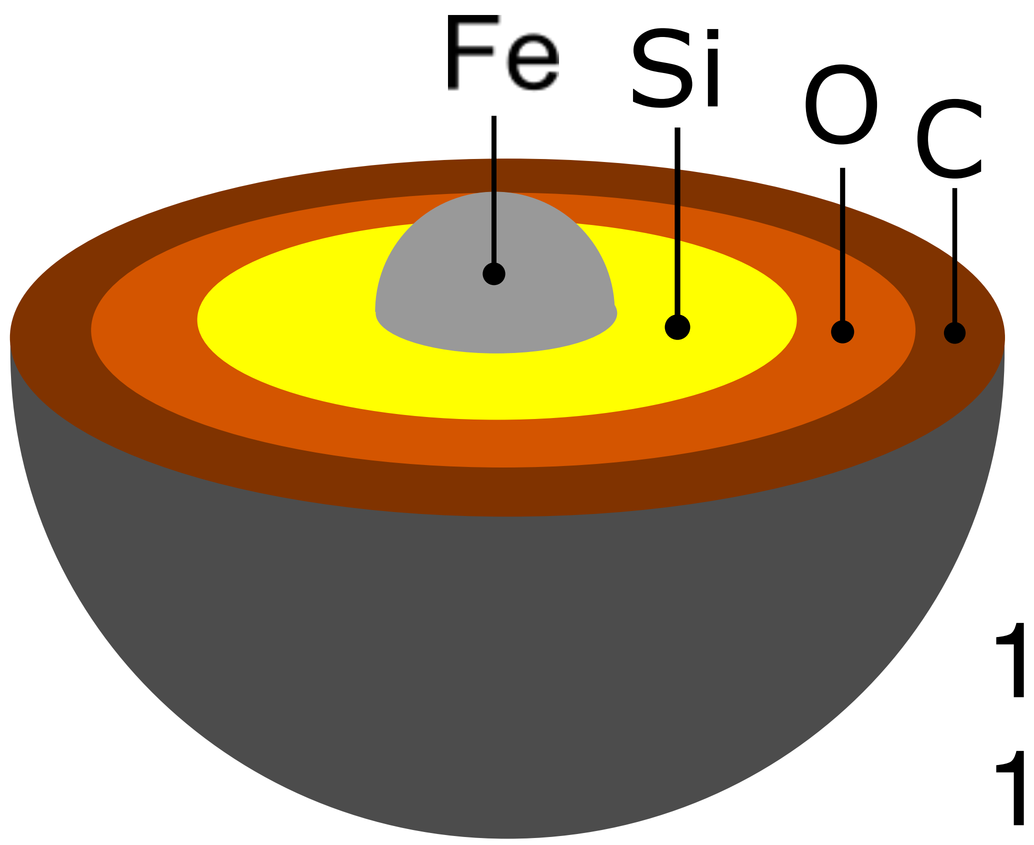
How accurate is our understanding of beaming/ collimation in GRBs?

How does the jet interact with the stellar material?



## Decades-long prediction: GRBs should be the tip of the 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)

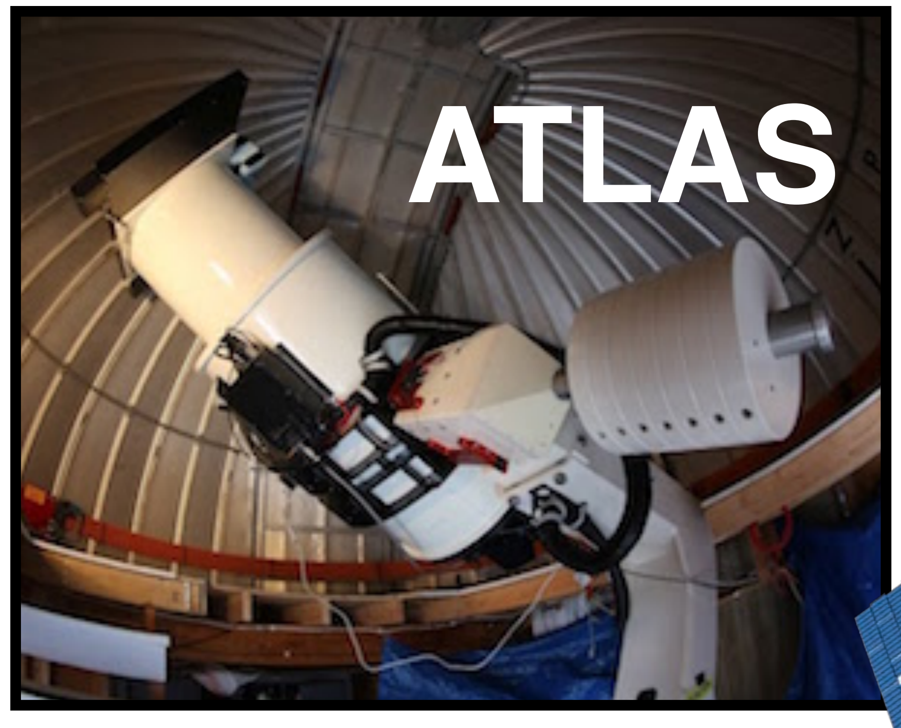
- Relativistic Ic-BL SNe
- Low-luminosity GRBs
- Jets in Type II SNe
- Ultra-long-duration GRBs
- GRBs without supernovae
- X-ray flashes
- Candidate orphan afterglows

Underlying physical connections unclear

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

# Why now? Wide-field, high-cadence optical surveys

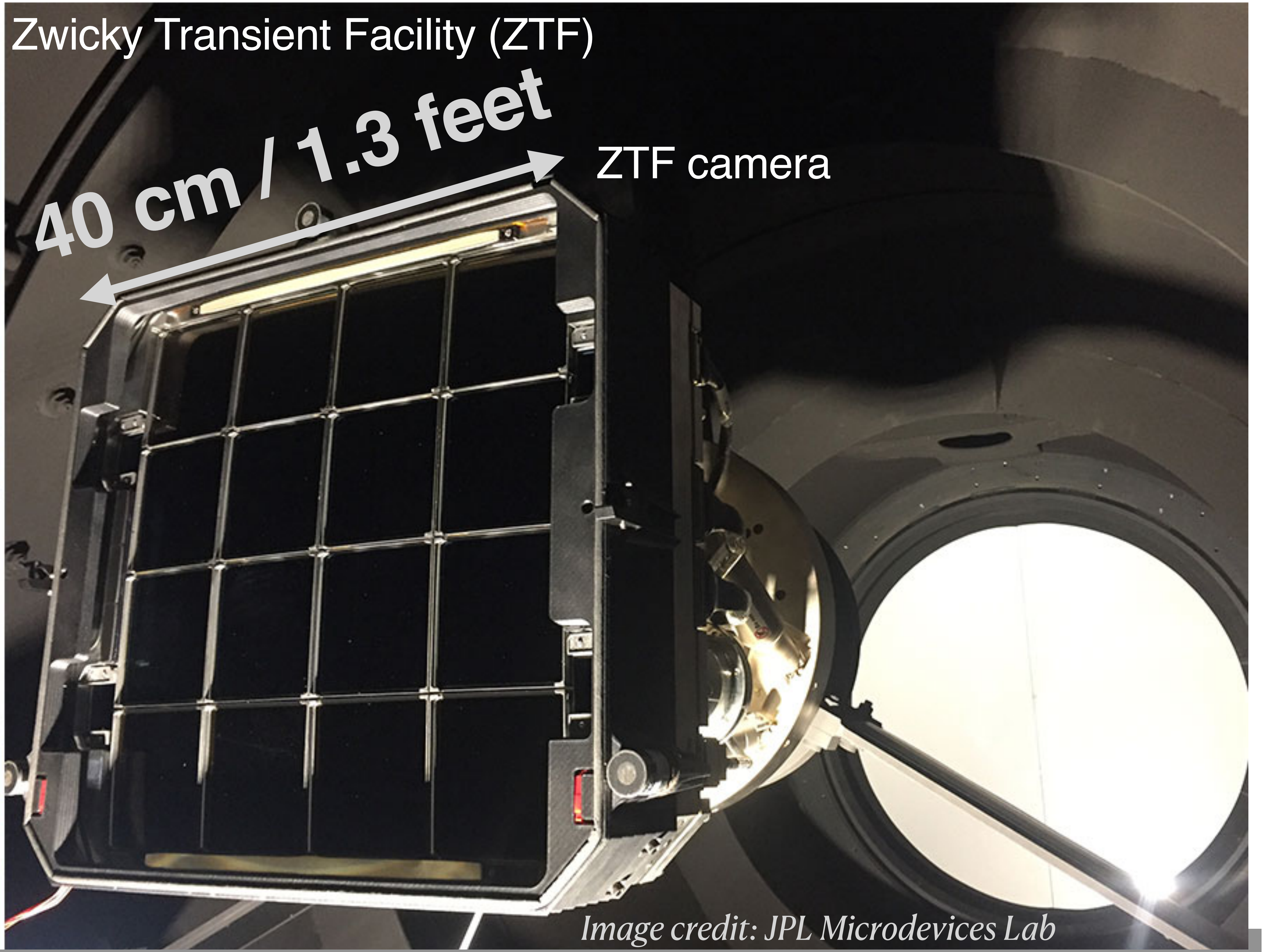
Map wide areas of sky, quickly



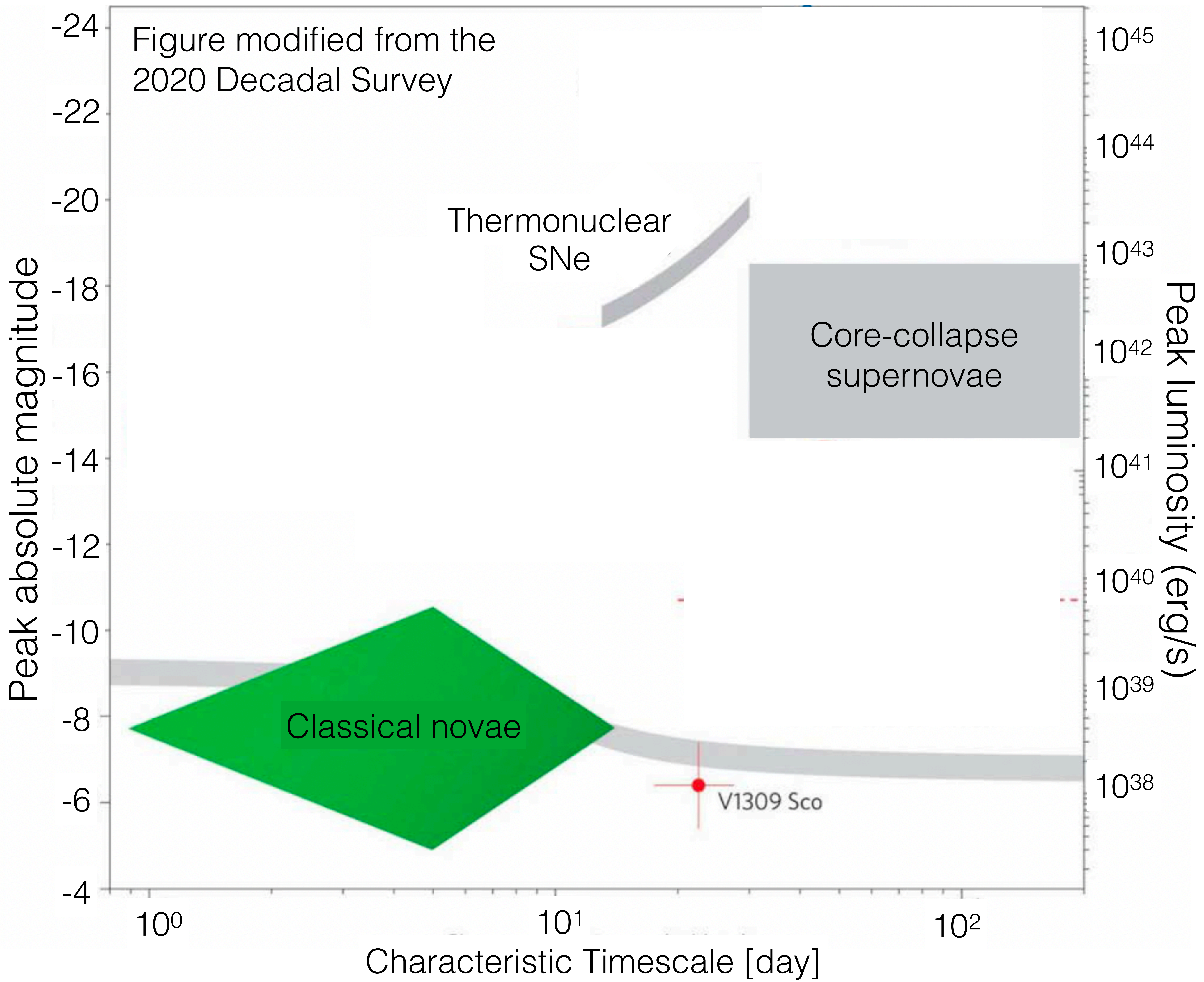

TESS

GOTO
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER

ASAS-SN



# Optical Transients: Observed Landscape



# Optical Transients: Observed Landscape

**Afterglow (GRB)**

**Afterglow (TDE)**

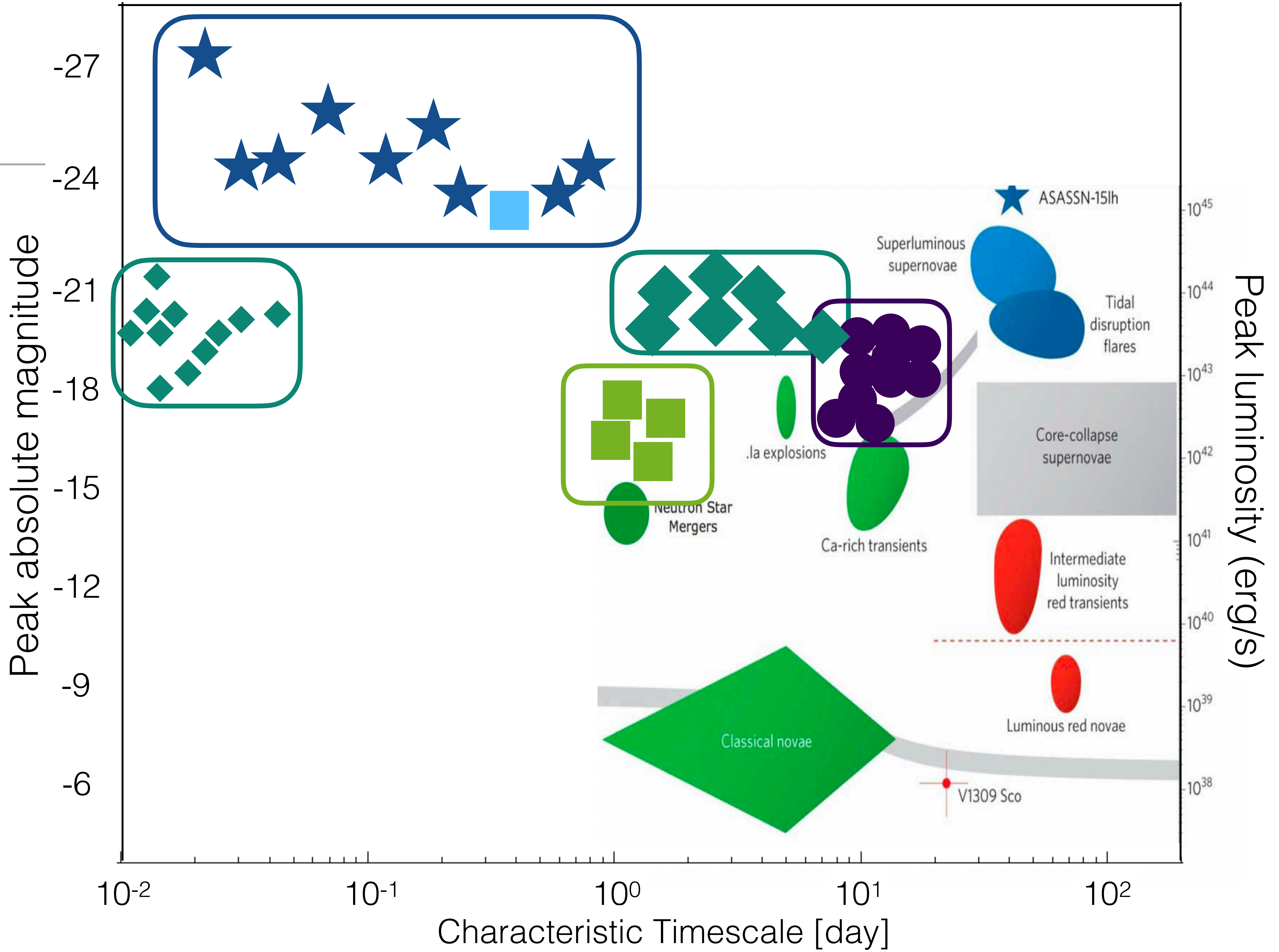
**“Luminous FBOTs”**

**Luminous fast coolers**

**Flares**

**Stripped-envelope supernovae with dense CSM**

**Relativistic shock breakout / low-luminosity GRBs**



# Part 1: Dirty Fireballs and Orphan Afterglows

## Part 2: Cows and Tasmanian Devils (“FBOTs”)

→ **The Dirty Fireball Hypothesis**

Afterglow searches with ZTF

Rates of broad-lined Ic supernovae

# "Cleanliness" of GRBs seems finely tuned

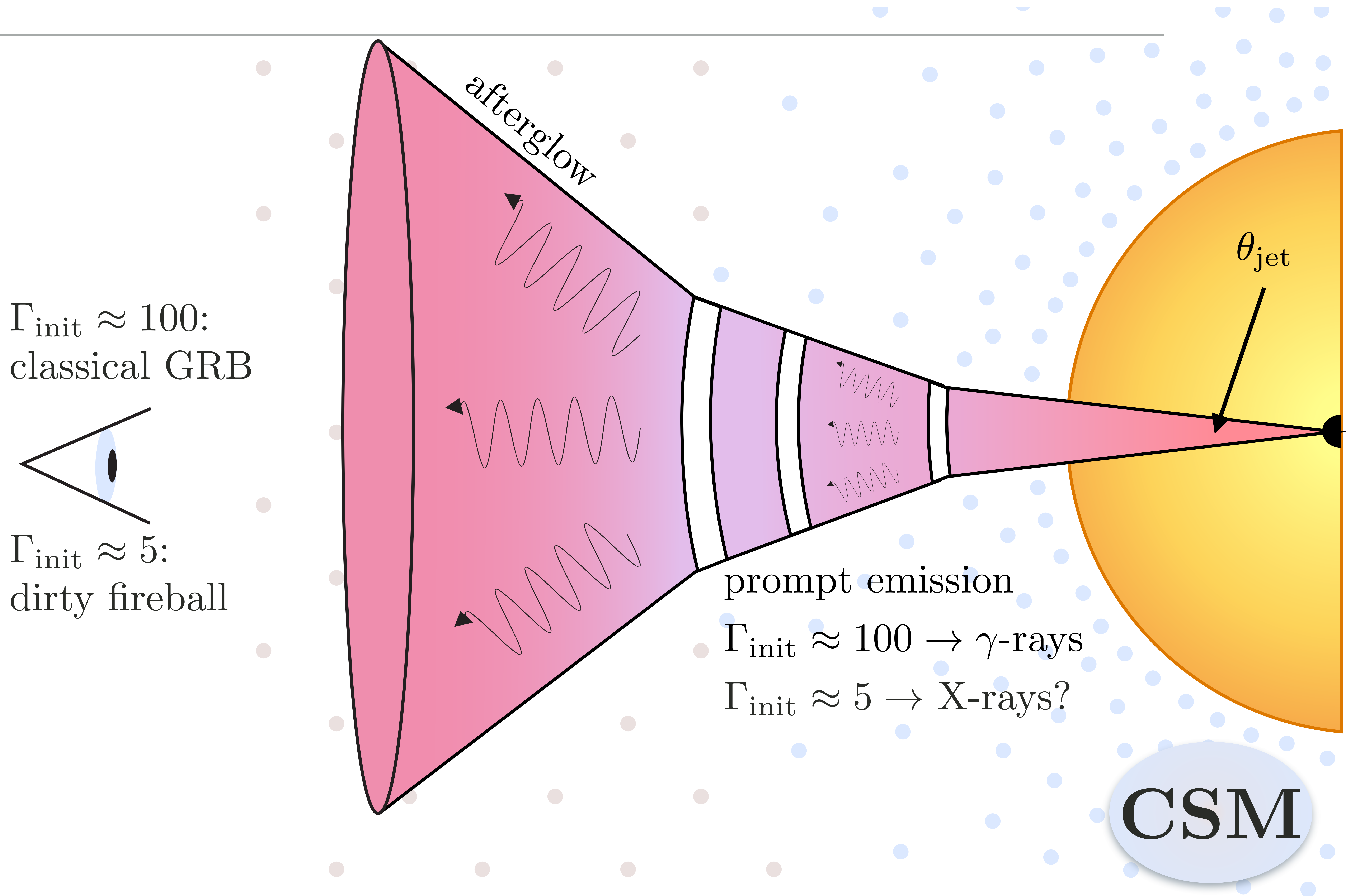
$$\tau_{\gamma\gamma \to e^+e^-} \approx 10^{15}$$

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

$$M \approx M_{\rm Earth}$$

("Clean" jet)

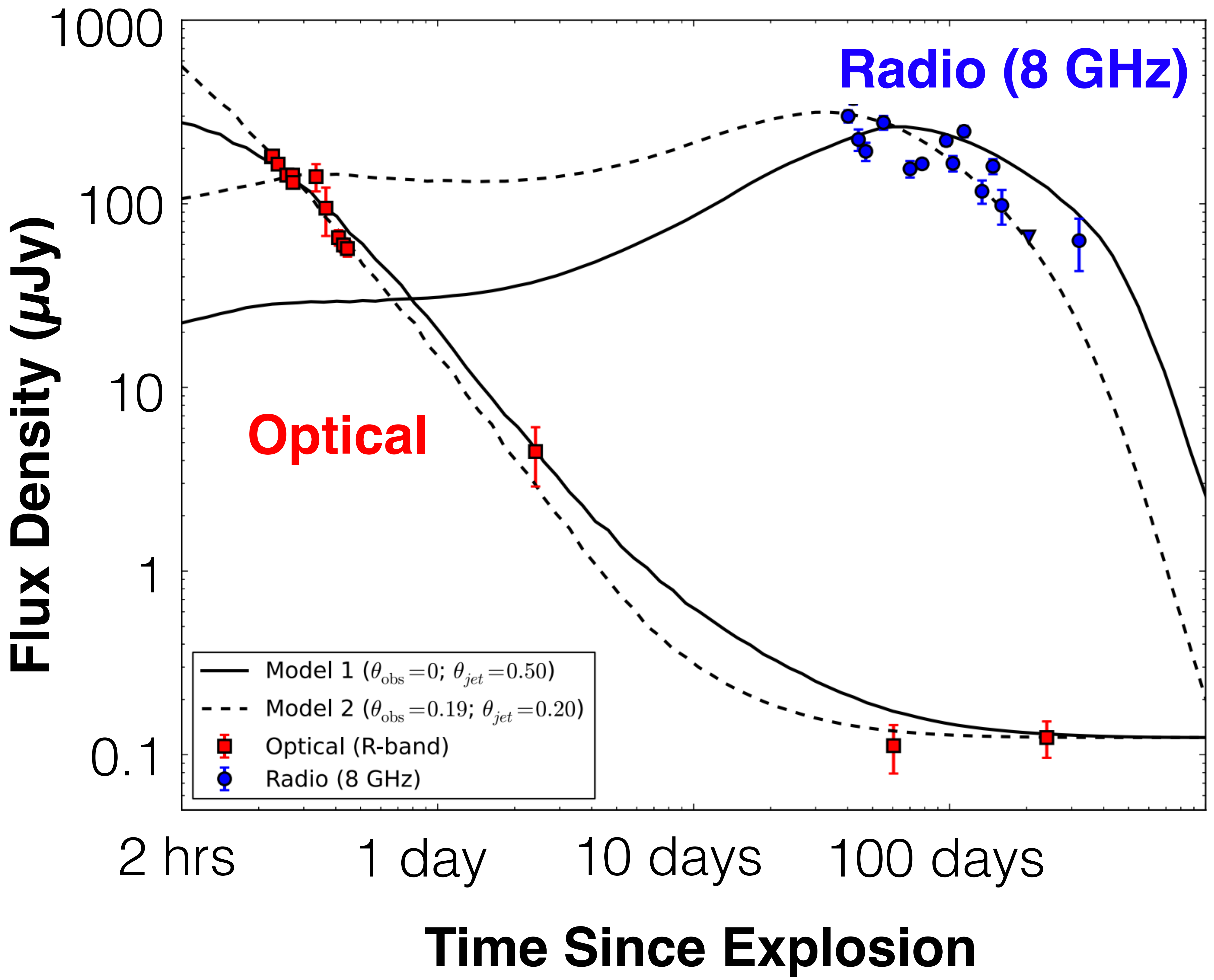
Jet has too much mass —
**dirty fireball**

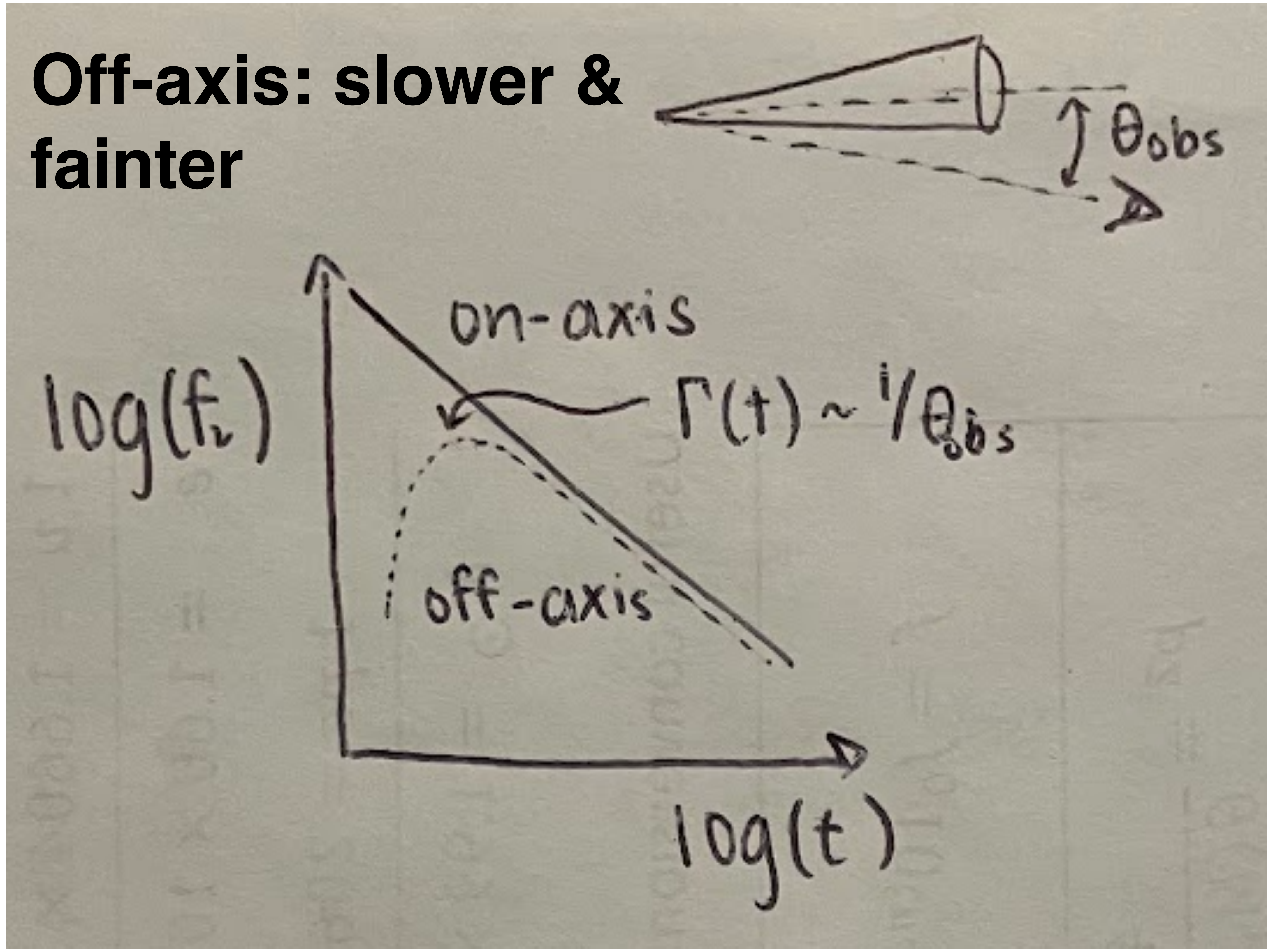



*Compactness Problem:* Ruderman (1975), Paczynski (1986), Baring & Harding (1997).
*Mass-loading Problem:* Shemi & Piran (1990)
*Dirty fireballs:* Dermer et al. (1999), Huang et al. (2002), Rhoads et al. (2003)

*Cartoon by Brittany Miller*

# Approach: search for dirty fireballs as "orphan" afterglows



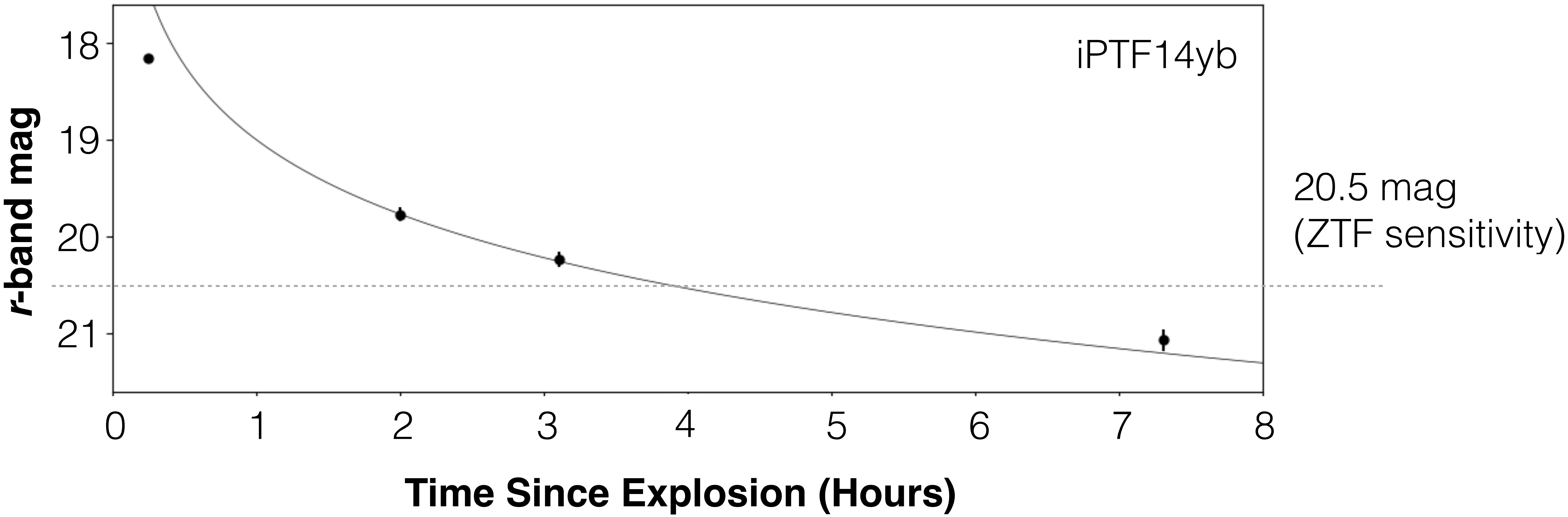

*Searches: Grindlay+99, Greiner+00, Levinson+02, Nakar&Piran+03, Gal-Yam+06, Rau+06,08, Kulkarni & Rau 06, Khabibullin+12, Berger+13, Cenko+13,15, AYQH+18, Huang+20*

## Optical searches: technical challenge

1. Rare (one every few months): needle in the haystack

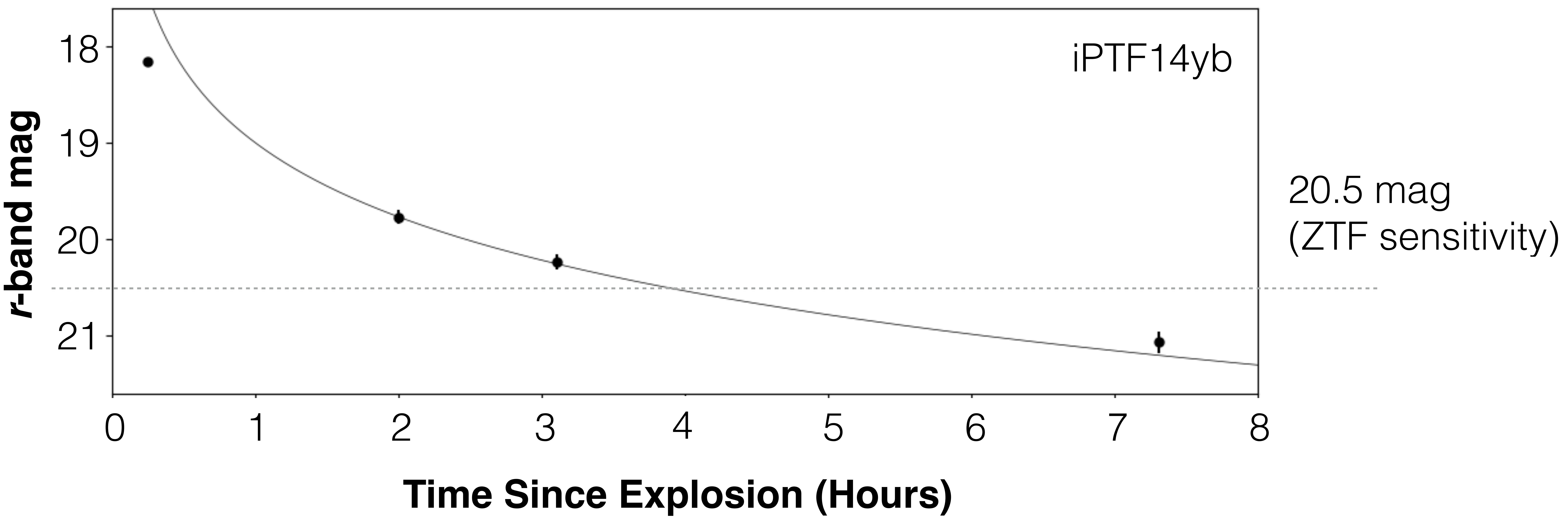
# Optical searches: technical challenge

1. Rare (one every few months): needle in the haystack
2. Fast (optically thin synchrotron radiation): hours (for on-axis)
   - Supernova timescale: weeks (diffusion through optically thick ejecta)



# Optical searches: technical challenge

1. Rare (one every few months): needle in the haystack
2. Fast (optically thin synchrotron radiation): hours (for on-axis)
3. Rapid follow-up (<days) for redshift, multi wavelength modeling (X-ray, radio)

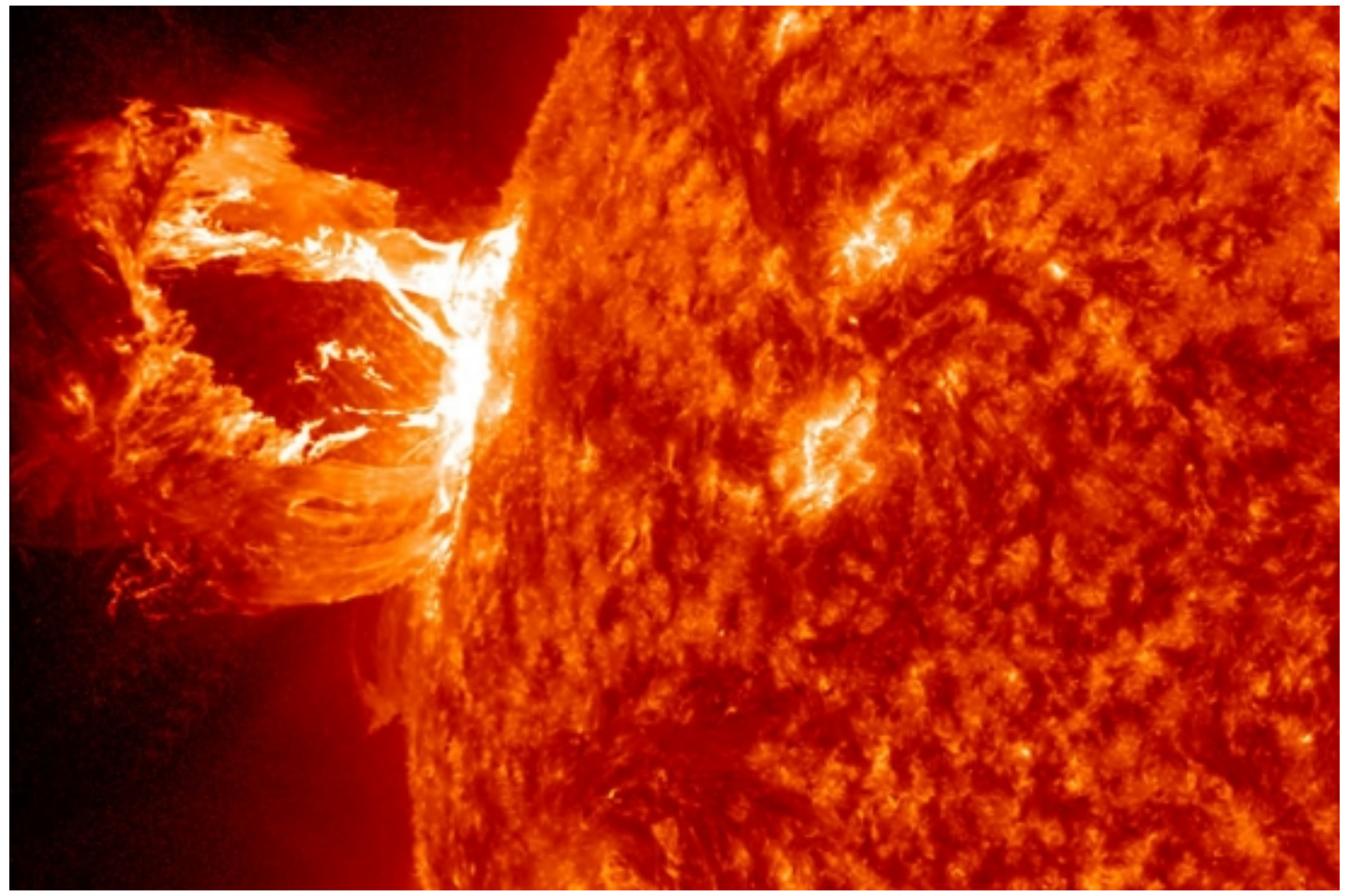



Optically discovered afterglows: Cenko et al. 2013, 2015; Stalder et al. 2017; Bhalerao et al. 2017



Anna Y. Q. Ho (Cornell)

# False positives: M-dwarf flares



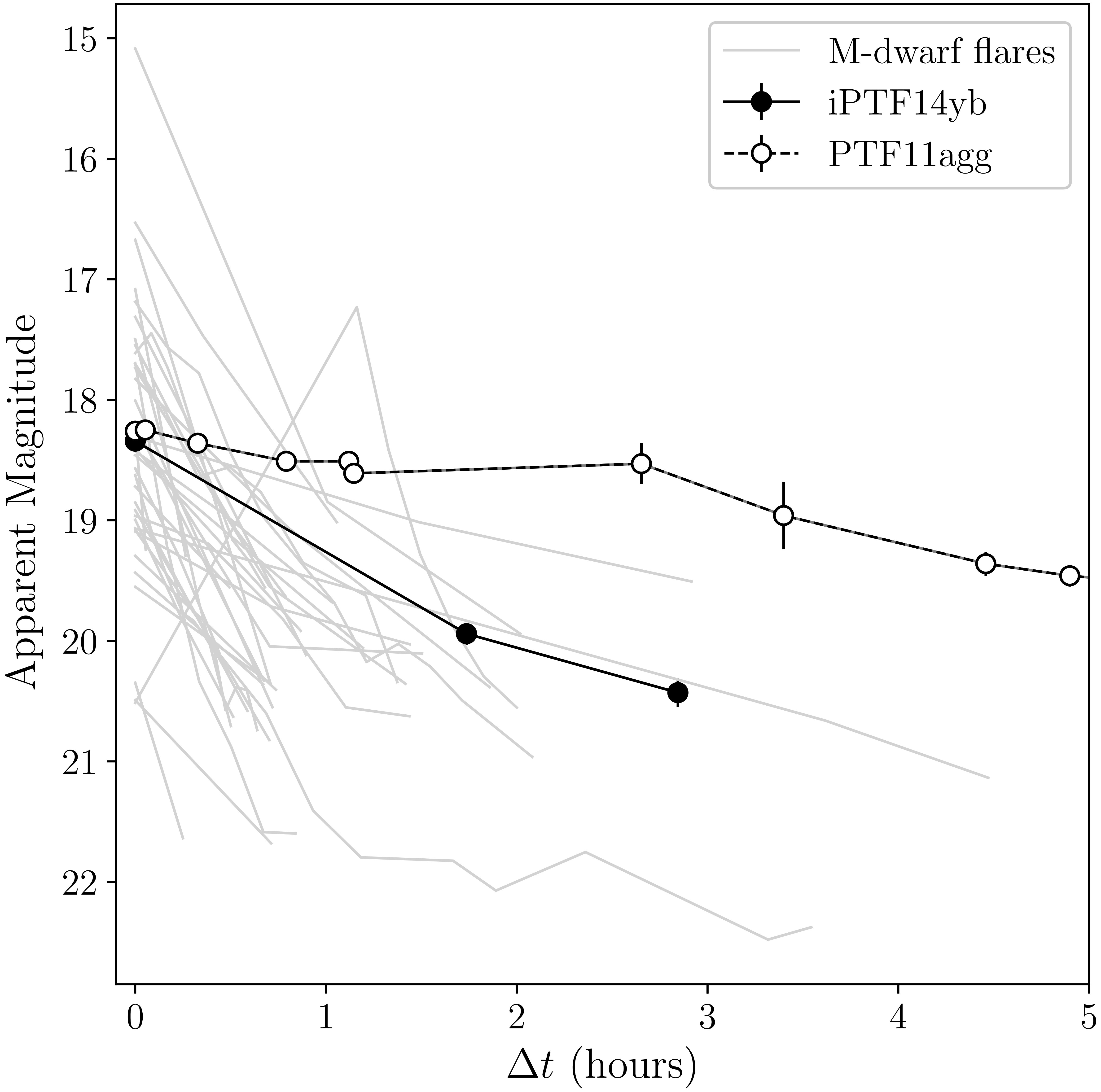



Figure from AYQH et al. 2018, ApJ, 854, 13

Foreground of stellar flares: Greiner et al. (1999), Kulkarni & Rau (2006), Rau et al. (2008), Berger et al. (2013)

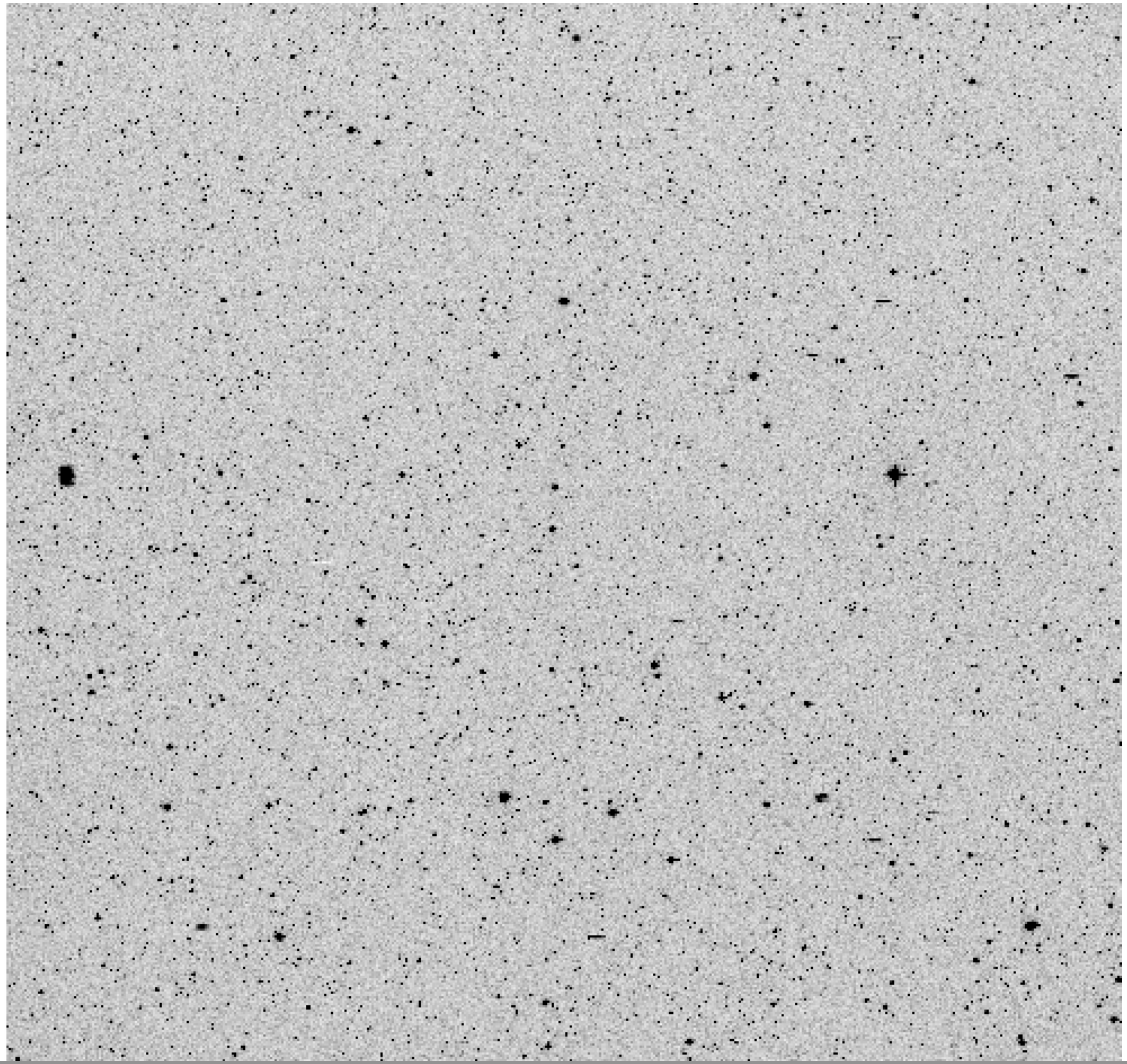
The Dirty Fireball Hypothesis

→ **Afterglow Searches with ZTF**

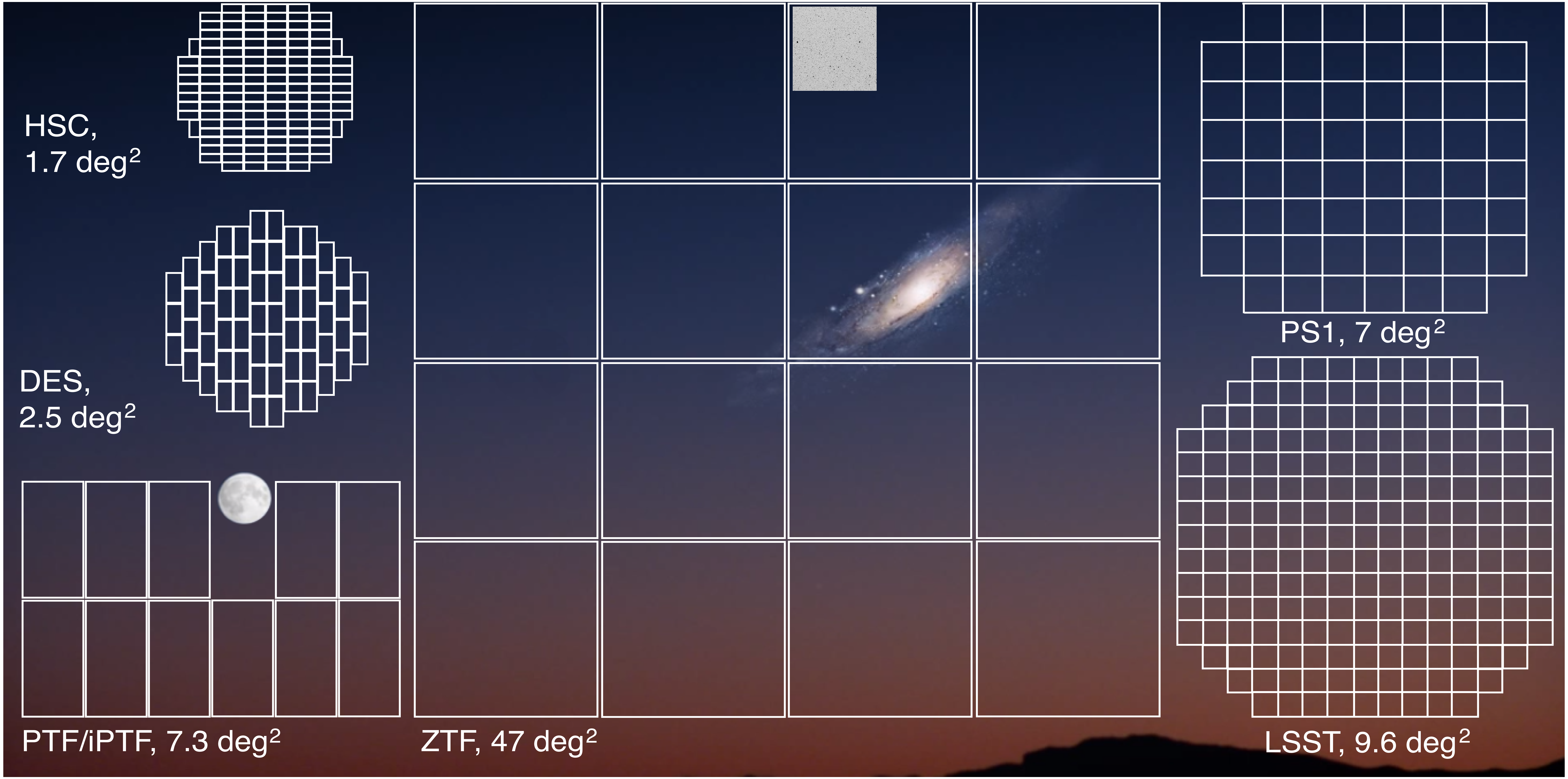
Rates of broad-lined Ic supernovae

# Large field of view

**1/64 of a real image!**



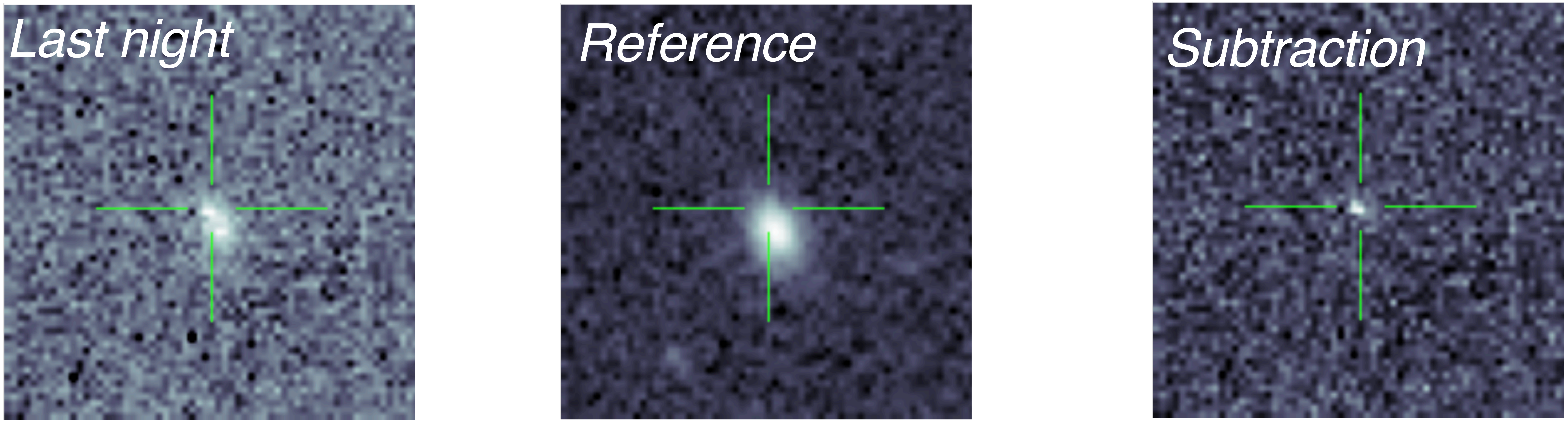
# Large field of view



## Surveys & transient identification

- Several different surveys down to ~20.5 mag
  - 10,000 $deg^2$ overlapping with Rubin LSST, *gr* each night
  - Tiered surveys of the Northern sky

- Automated subtraction; 5-sigma change issues “alert” (format of Rubin)

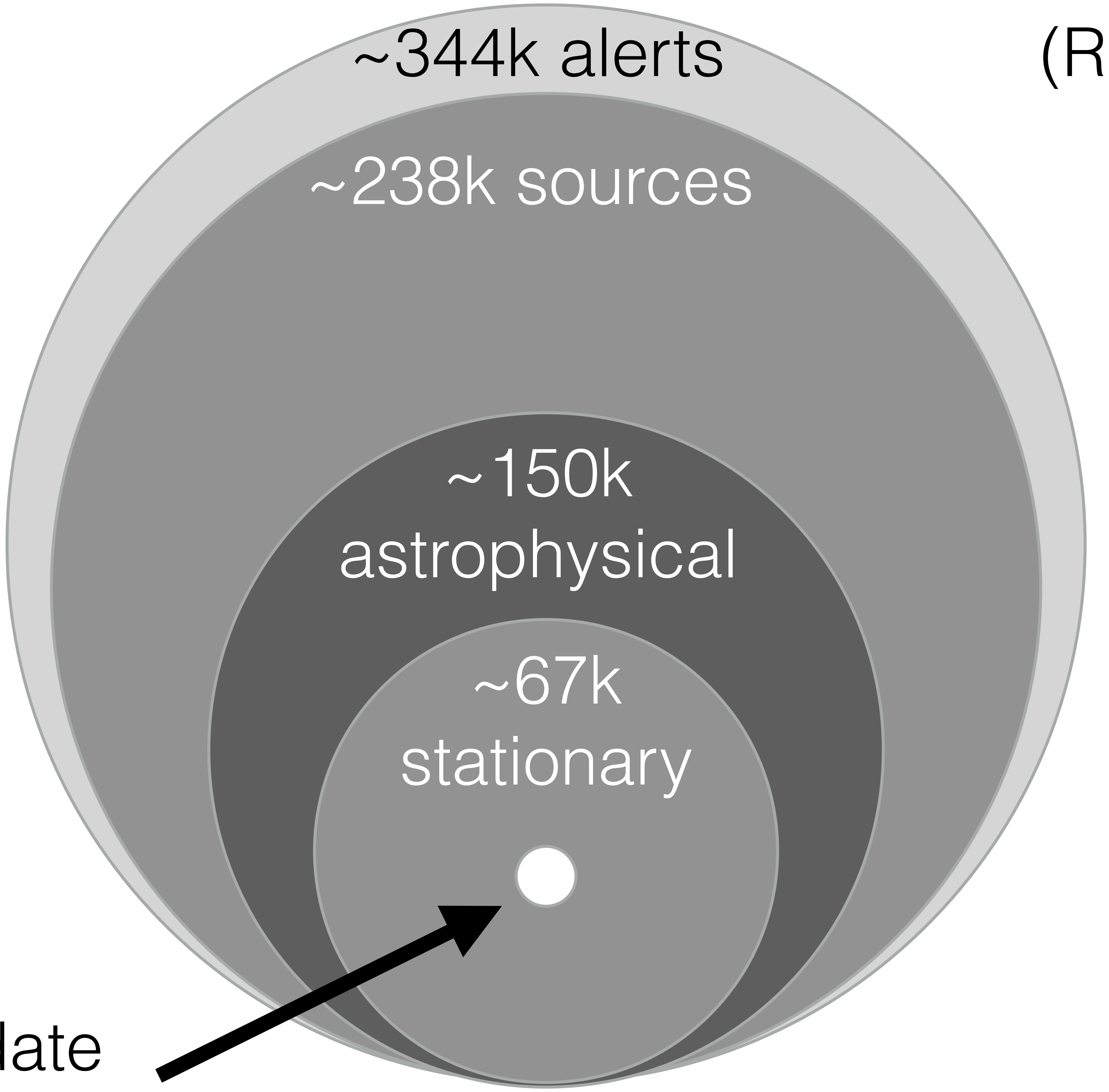



- Close of shutter to alerts: 8 minutes (Rubin: 60 seconds)

## Finding afterglows with ZTF

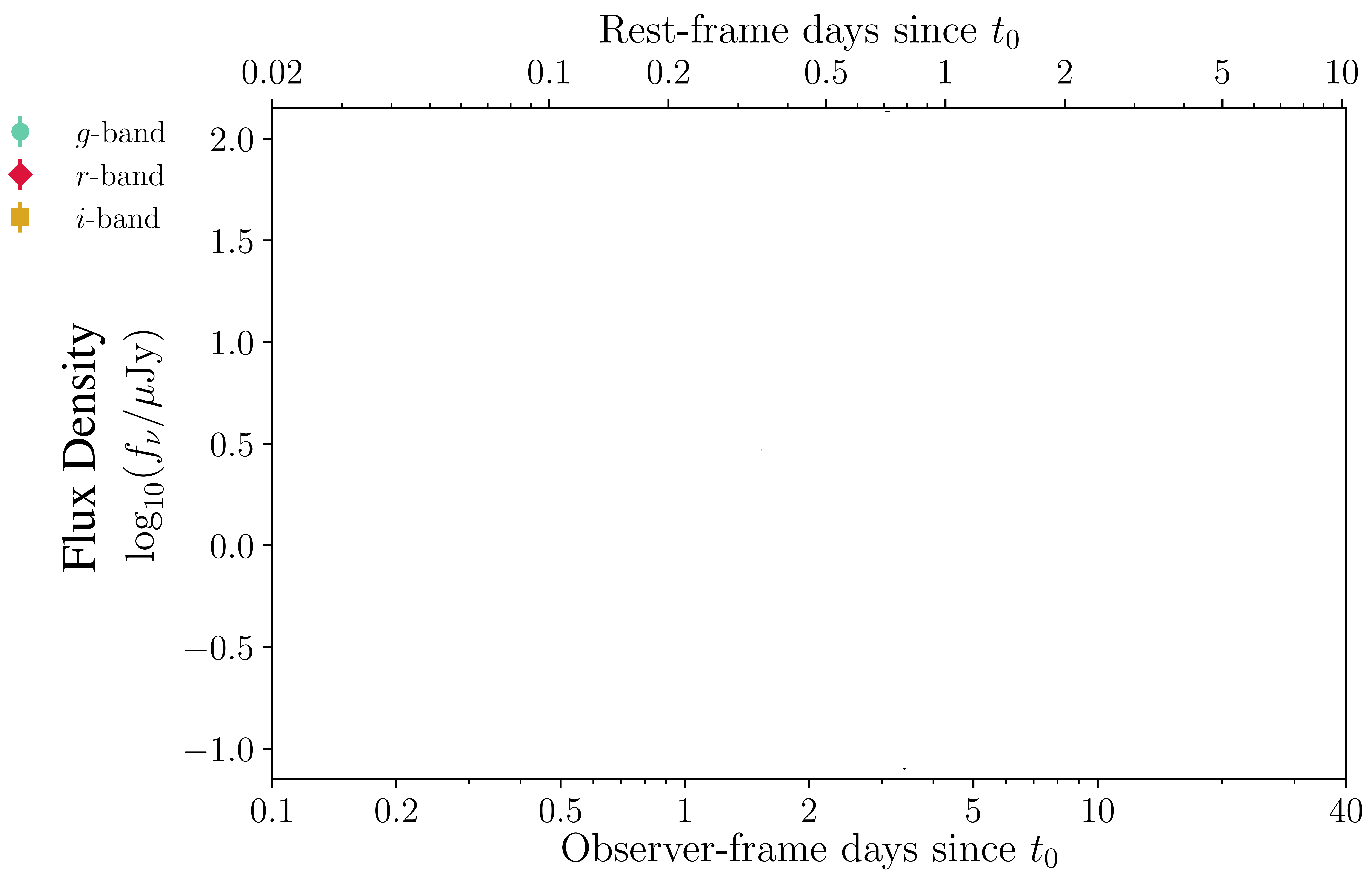
8 February!

(Rubin: 10 million per night*)




~5358 candidate extragalactic, **1 afterglow**

# Confirming candidates




## Optical imaging: color & timescale (<24 hours)

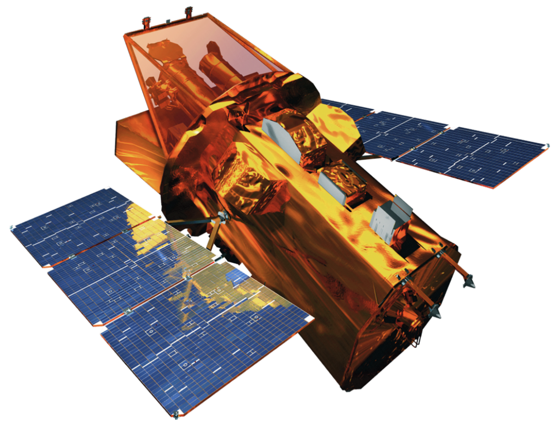
LT

GIT

## Confirmation: redshift/X-rays

Gemini

Keck



*Swift*

## Detailed study (months)

GMRT

VLA

NOEMA

ALMA

# 20 optically selected afterglows so far

8 “orphan”

Redshifts: $z$=0.3-2.9

Pre ZTF: only 1 orphan candidate, and no redshift measurement

Note: these are close to on-axis (by design)

Optical light curves

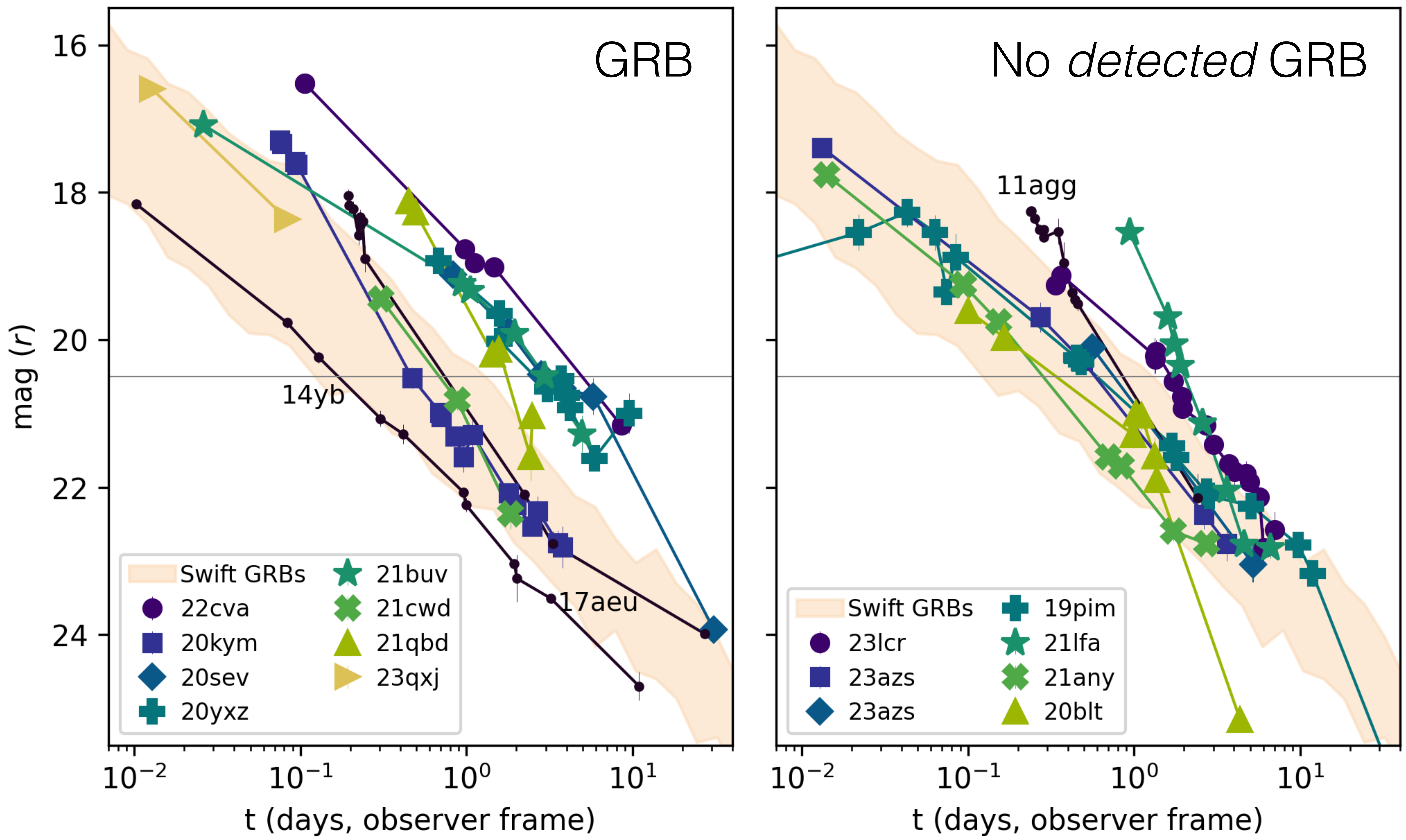


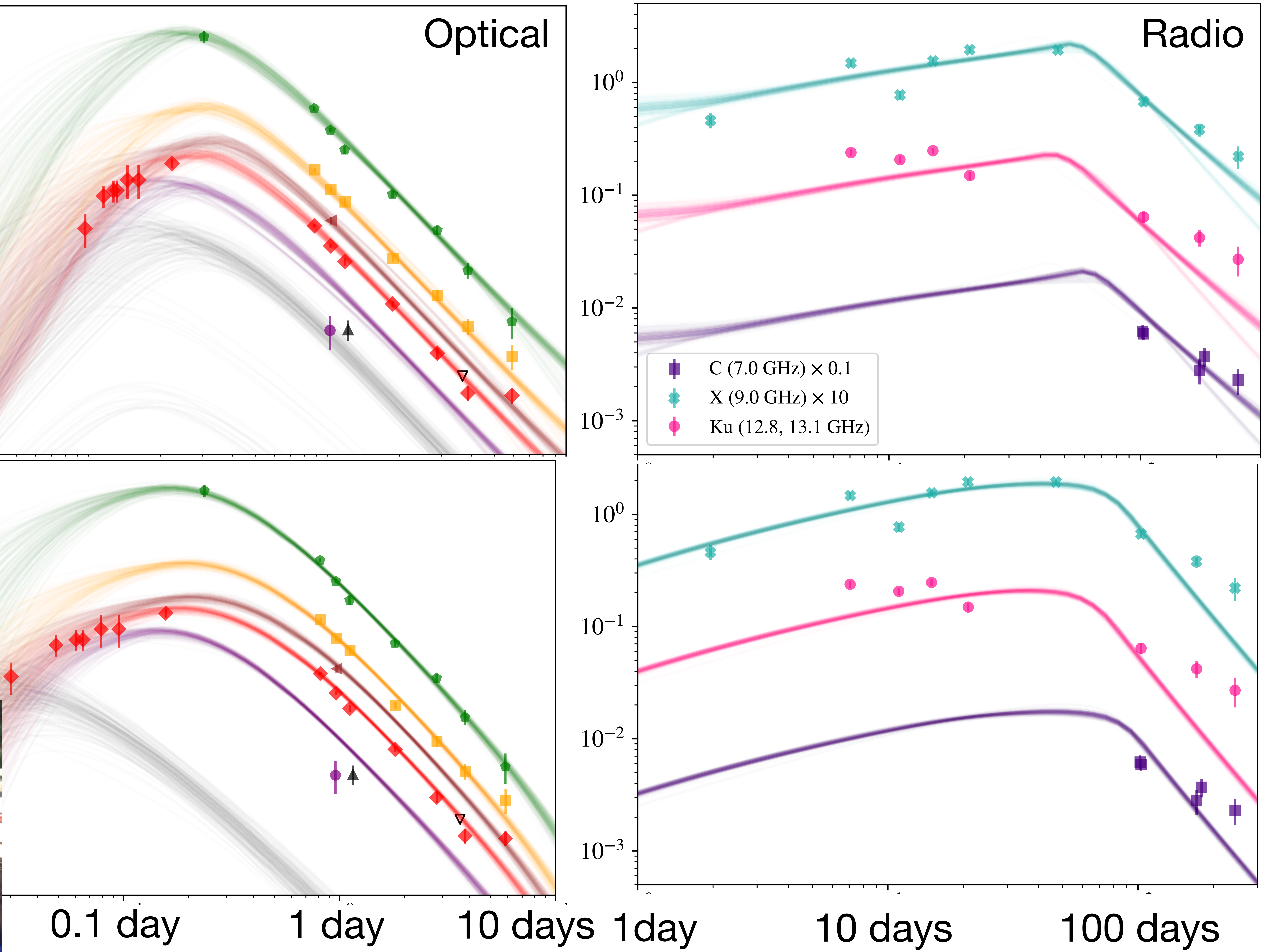

Figure updated from AYQH et al. 2022, ApJ, 938, 85

Data includes: Kann+10, Cenko+13, Stalder+17, Bhalerao+17, Melandri+18, AYQH+20, Andreoni+20,21, Kasliwal+20, Perley+25

# “Orphan” afterglows: probably off-axis

*On-axis, Gamma~10*

*Off-axis (2θ), Gamma~150*




Maggie Li
Cornell physics undergrad
Bethe Thesis Prize
Now Caltech PhD student

Figure from Li, AYQH et al. (2025); see also Perley, AYQH et al. (2025); discussed in Rhoads (2003) and Nakar & Piran (2002)

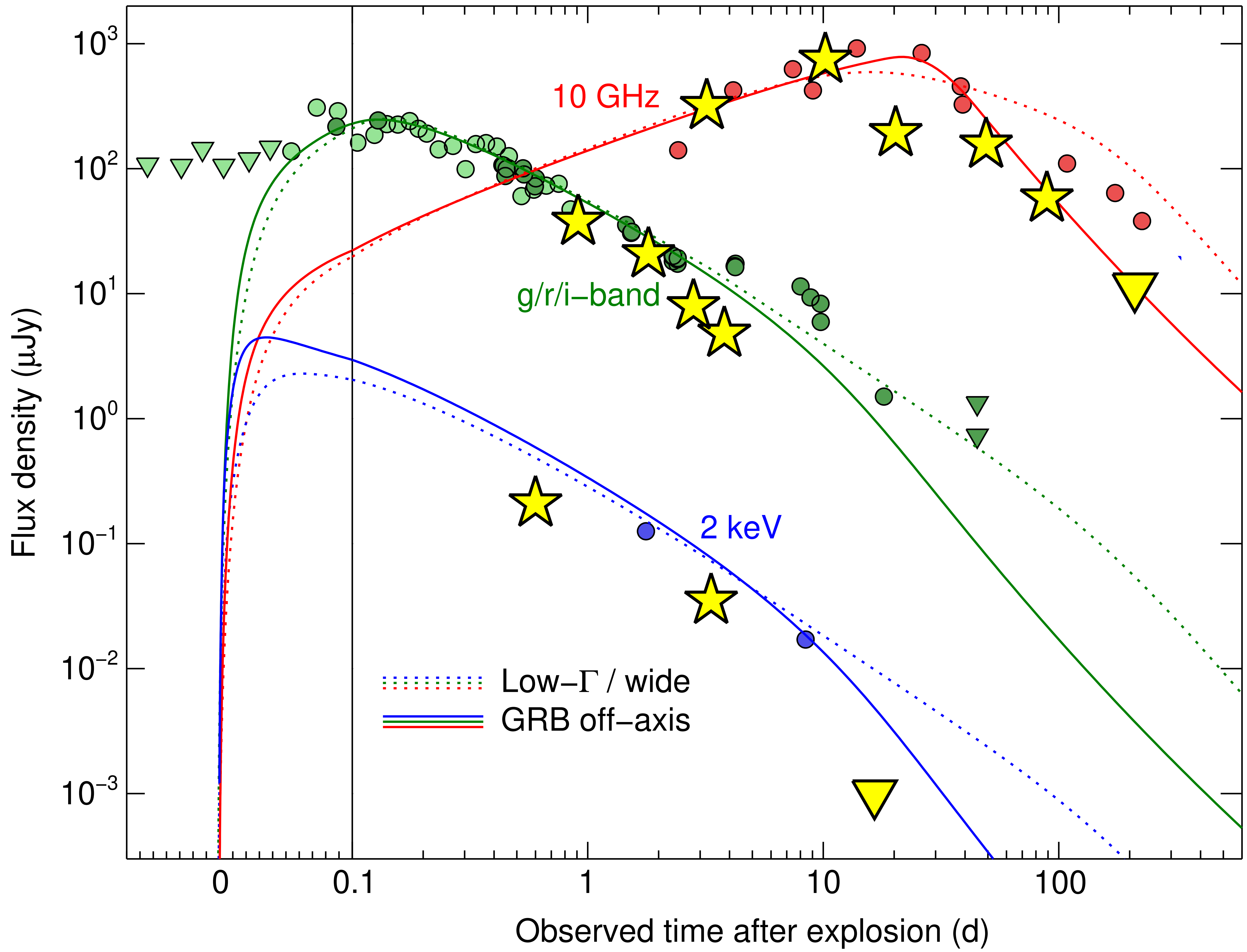
## Implications

Collimated relativistic jets: ≤ few x GRB rate (no big missing continuum of dirty fireballs)
Early optical "beaming" ~ $\gamma$-ray beaming

- Consistent with other approaches & jet structure from theory (Eichler 2011, Cenko et al. 2015, AYQH et al. 2018, Grindlay 1999, Dermer et al. 1999, Greiner et al. 2000, Nakar & Piran 2003, Mooley et al. 2022, Corsi et al. 2025, Corsi, AYQH et al. 2023, Ramirez-Ruiz et al. 2002, Nakar & Piran 2017, De Colle et al. 2018)

## Path Forward: wide-field X-ray surveys with good localization capabilities

***See talk by Weimin Yuan***





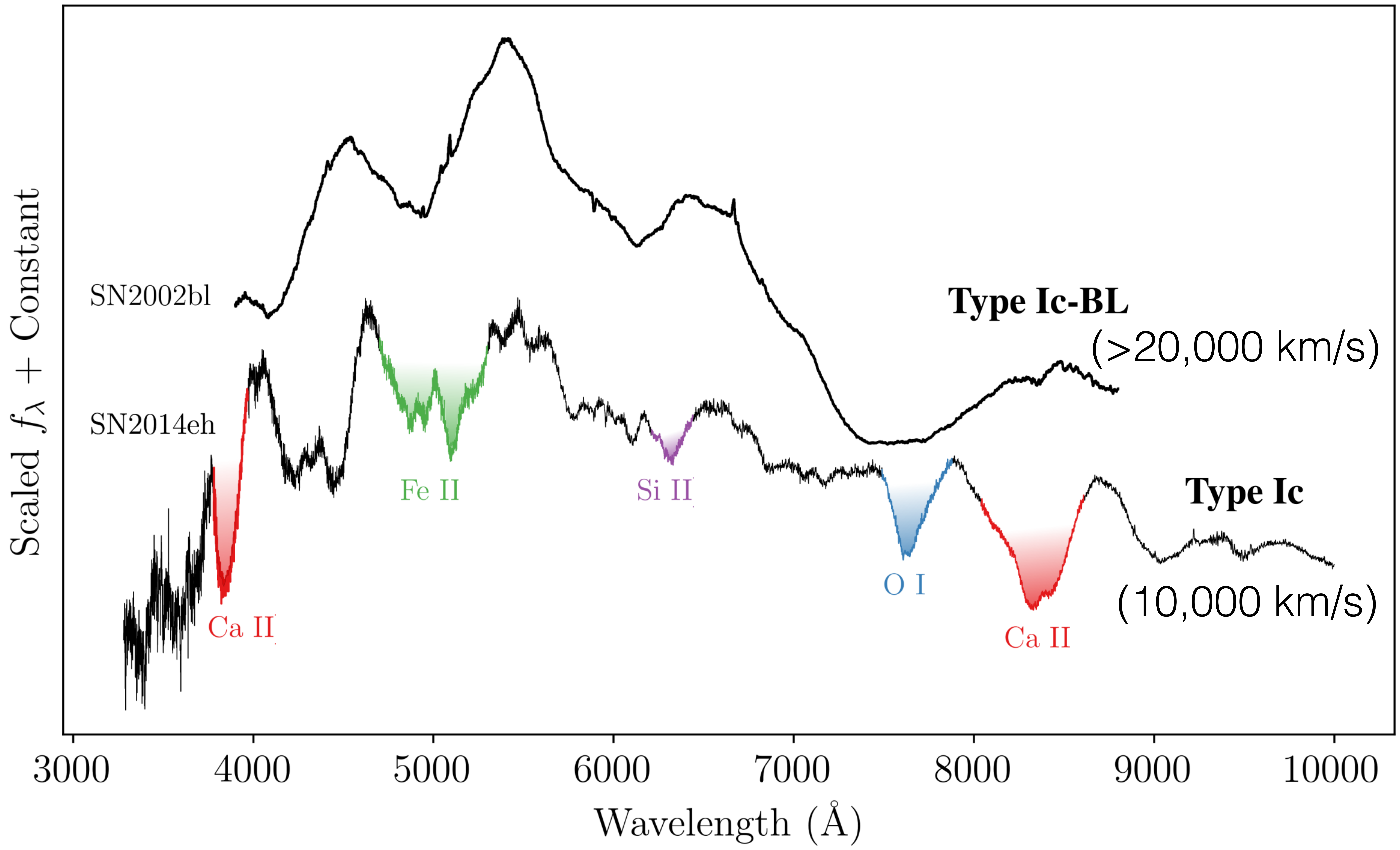
Ongoing VLA+XMM-Newton+HST program

*Genevieve Schroeder (Postdoc)*

GRB 250419a (z=0.845): Schroeder, AYQH et al. in prep

The Dirty Fireball Hypothesis
ZTF Afterglow Searches
→ **Rates of broad-lined Ic supernovae**

# Broad-lined Ic supernovae ("hypernovae")




- All GRB-SNe are Type Ic-BL
- Most Type Ic-BL SNe have no (detected) GRB

Figure from AYQH (2020)
Spectra from UC Berkeley Supernova Database

# Recent development: large samples of nearby ($z < 0.1$) Ic-BL supernovae

- First large, untargeted sample (34 objects): Taddia et al. (2018)
  - Not selected in a well-understood way
- ZTF: **flux-limited sample (100 objects so far)**

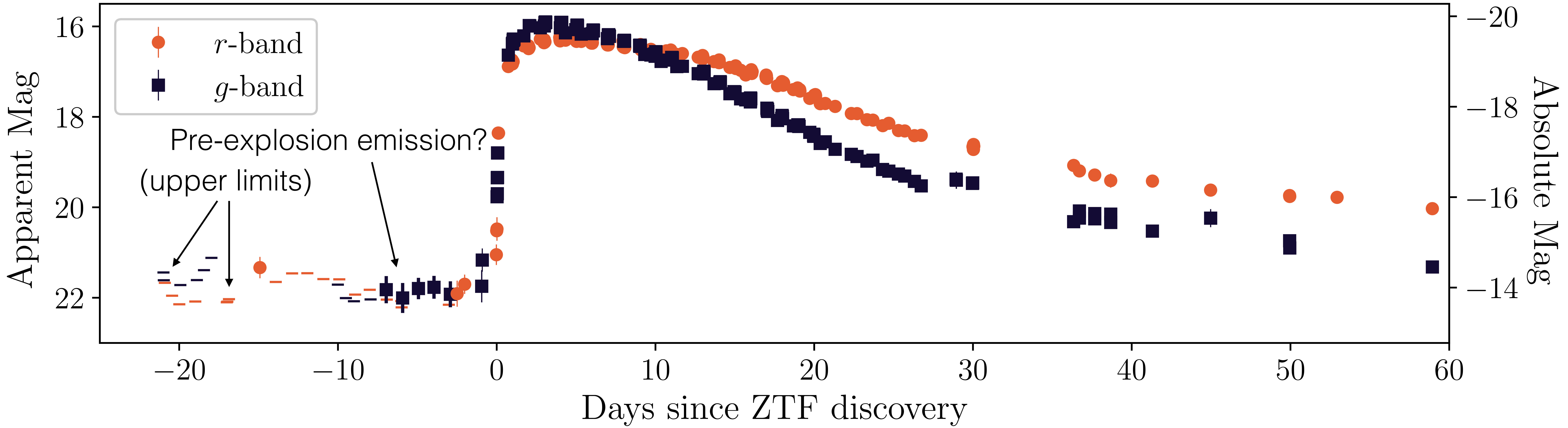


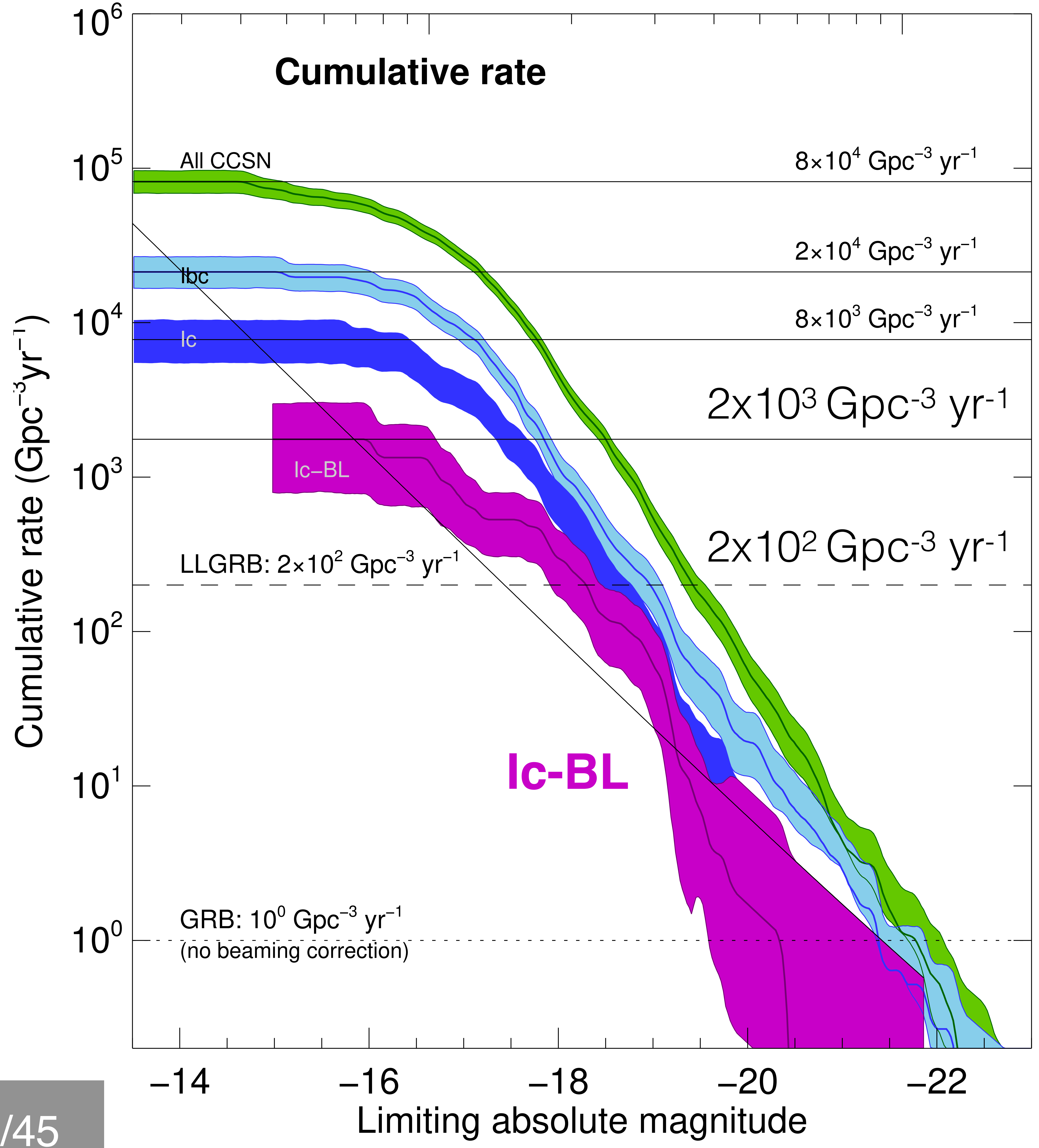

Figure of SN2018gep from AYQH et al. 2020, ApJ, 887, 169
See also Pritchard et al. (2021), Leung et al. (2021)
PTF sample: host galaxies (Modjaz et al. 2020)
ZTF sample: for a subset, optical (Srinivasaragavan et al. 2024), radio (Corsi et al. 2023), NIR (Anand et al 2024) properties

# Ic-BL supernova luminosity function (preliminary)

- All GRB-associated Ic-BL SNe are luminous (M < -18.5 mag)
- The luminous ones are rare (~10%)

- Need to investigate classifications in more detail, continuum of velocities inferred, KE…

Figure from Dan Perley (LJMU)



## Volumetric rates: status

| Class | Local Rate ($yr^{-1}$ $Gpc^{-3}$) | % of CC SN |
|---|---|---|
| Core-collapse SN | $8 \times 10^4$ | |
| Ic-BL supernova | $2 \times 10^3$ | 3% |
| M < -18.5 mag | $\sim 2 \times 10^2$ | **~0.3%** |
| Early shock-cooling | $\sim 2 \times 10^2$ | **~0.3%** |
| Low-luminosity GRB | $\sim 1\text{-}5 \times 10^2$ | **~0.1-0.6%** |
| On-axis GRB | 1 | 0.001% |
| GRBs, total | ~100 | **~0.1%** |

$(1 - \cos\theta_{jet})$

Updated from AYQH (2020); rates from Soderberg et al. (2006), Liang et al (2007), Lien et al. (2014), Perley et al. (2020); Vail, AYQH et al. (in prep), Perley et al. (in prep)

# Searching for off-axis jets: long-term radio monitoring

*Genevieve Schroeder (Postdoc)*

Targeted VLA (radio) observations of 10 Ic-BL supernovae in GRB-like host galaxy environments

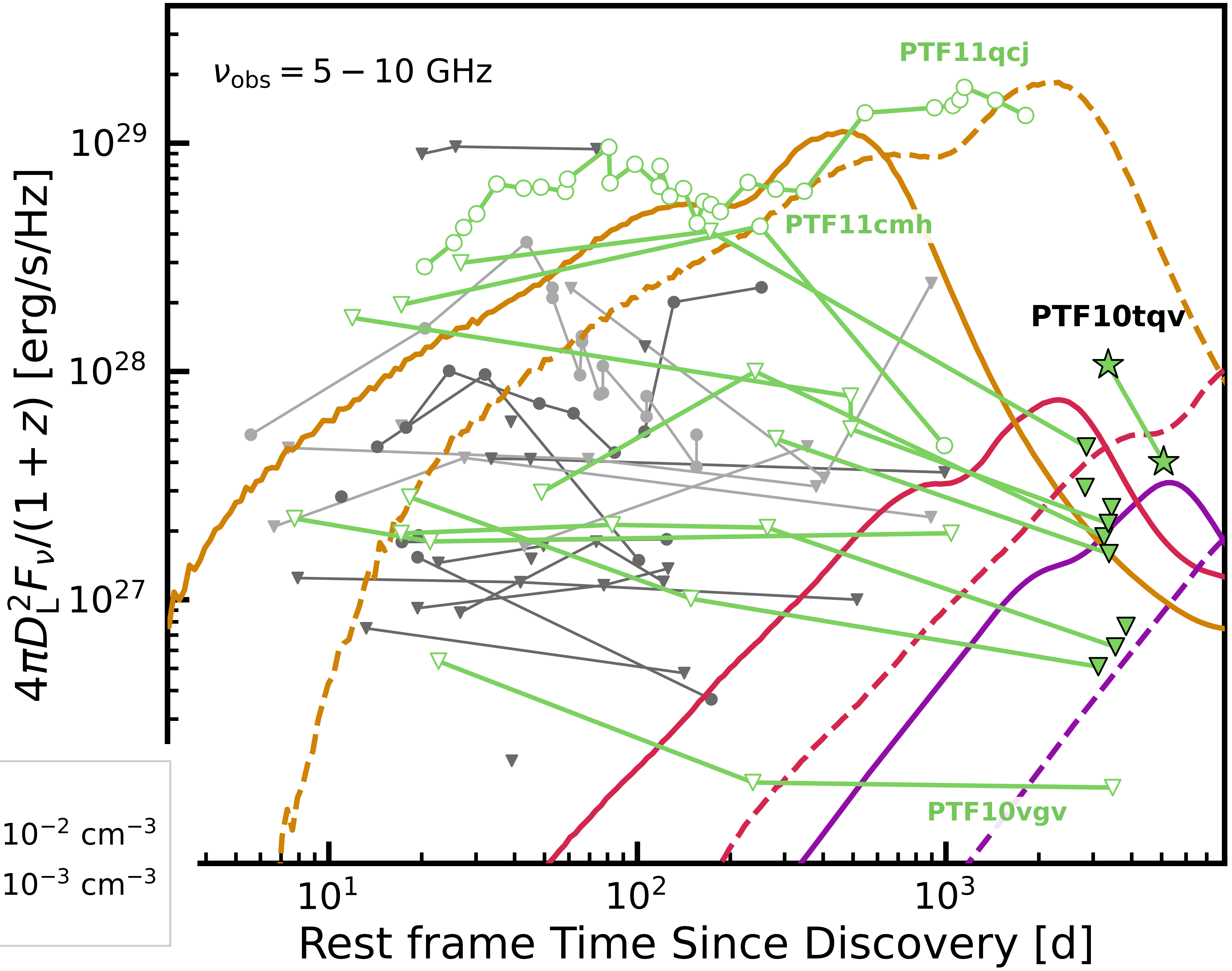
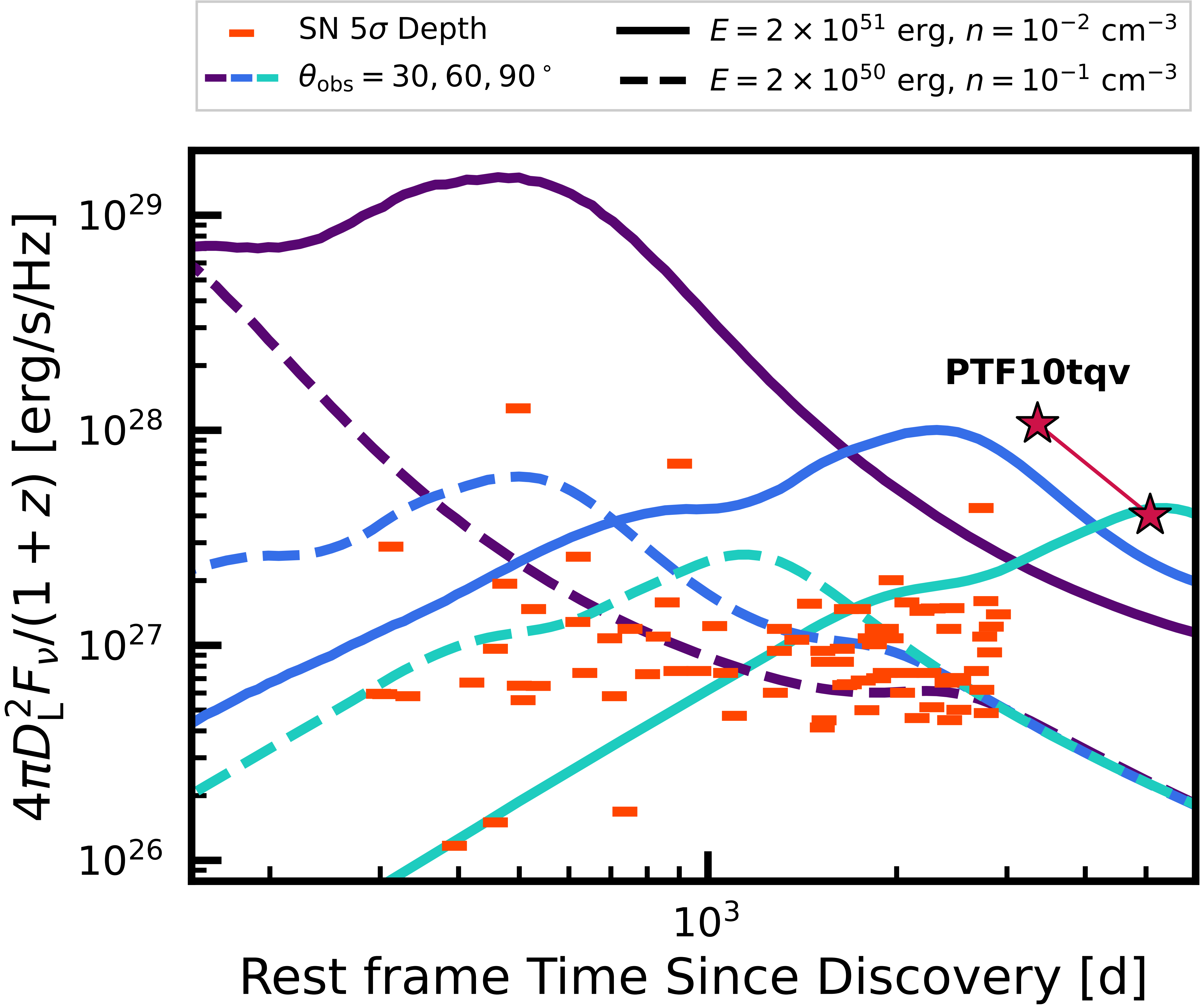



Figure from Schroeder, AYQH et al. 2025
Sample from Modjaz et al. (2020)

# Path forward

Starting soon (February 20):
- VLA observations of 81 nearby Ic-BL SNe (remainder of ZTF flux-limited sample)
- Most have well-observed optical light curves

(PI Genevieve Schroeder)



# Summary of Part 1

- Routine discovery of cosmological ($z \gtrsim 1$) afterglows outside gamma-ray band
- Several orphan optical afterglows, likely from off-axis jets
- Jetted transients with similar collimation & energy to GRBs: no big hidden population
- Future: nearby ($z < 1$) universe
  - Dirty fireballs: high-cadence wide-field X-ray surveys
  - Off-axis GRBs: systematic radio follow-up of large numbers of Ic-BL supernovae

Part 1: Dirty Fireballs and Orphan Afterglows

# Part 2: Cows and Tasmanian Devils (“FBOTs”)

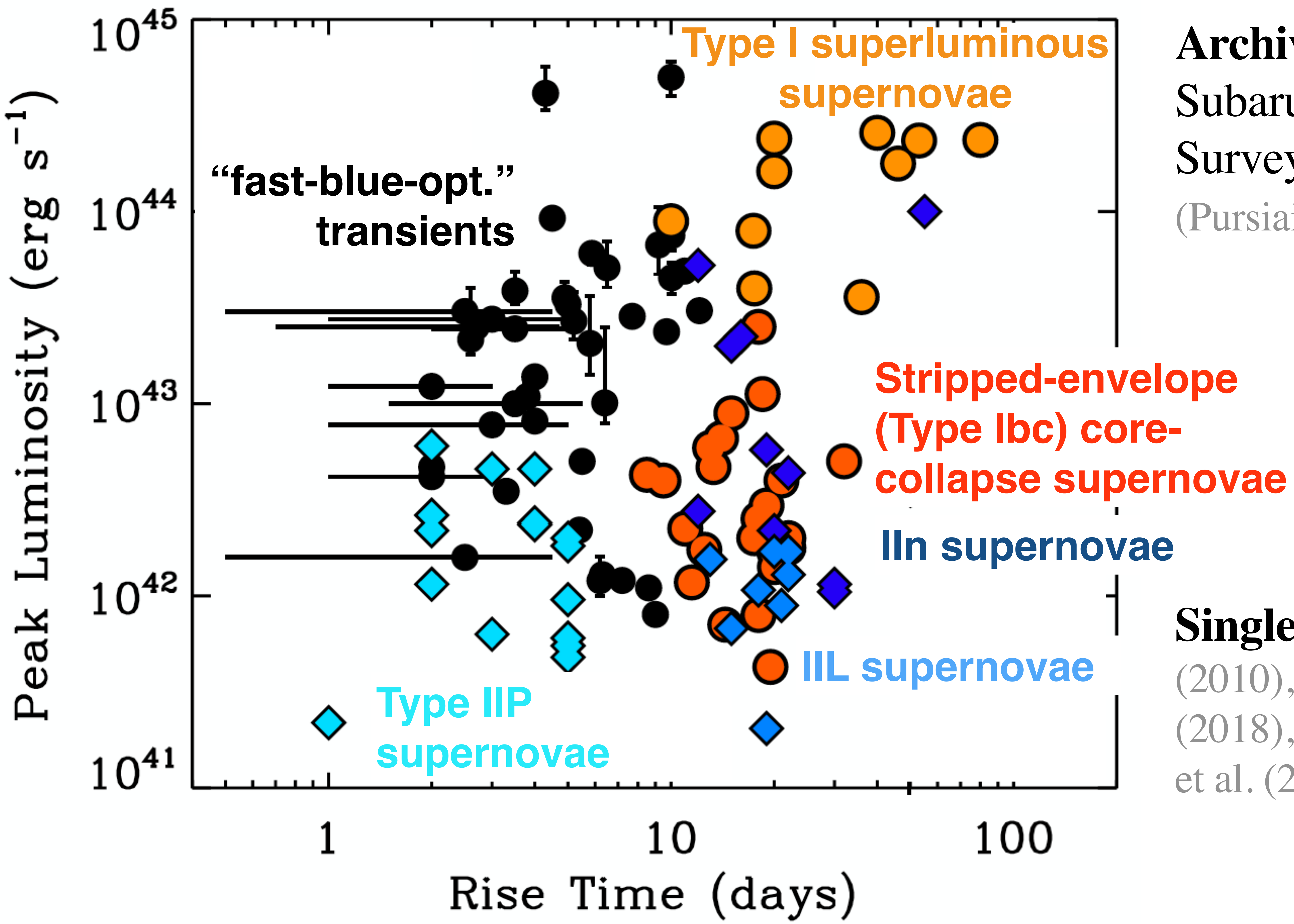
**“FBOTs” & The Cow**

Submillimeter emission

Minutes-duration optical flares

Progenitors

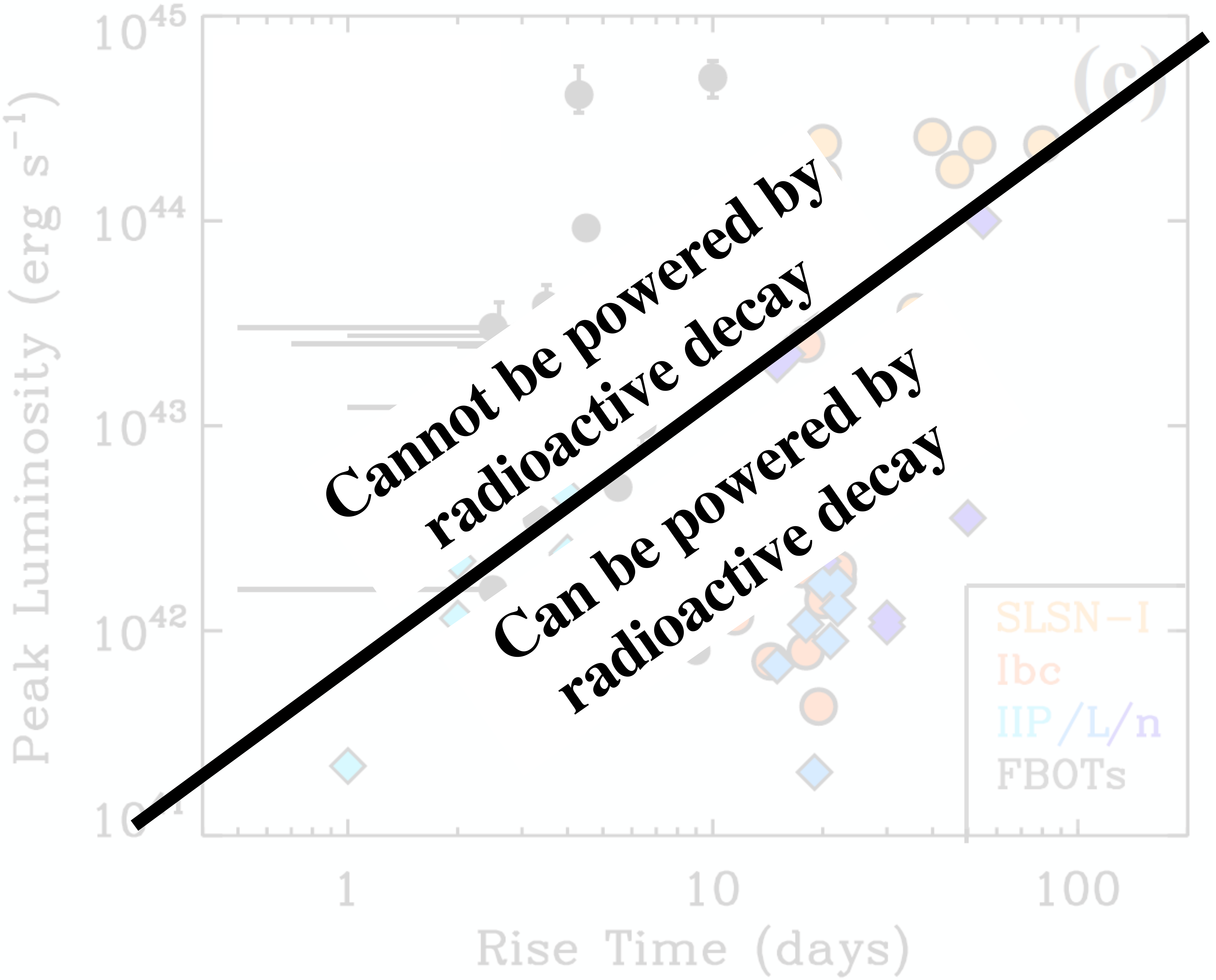
# “Fast Blue Optical Transients” / “Rapidly Evolving Luminous Transients” / “Rapidly Rising Transients”




**Archival Samples:** PanSTARRS (Drout et al. 2014), Subaru HSC (Tanaka et al. 2016), Supernova Legacy Survey (Arcavi et al. 2016), Dark Energy Survey (Pursiainen et al. 2018), & others

**Single Objects**: Matheson et al. (2000), Ofek et al. (2010), Drout et al. (2013), Vinkó et al. (2015), Rest et al. (2018), AYQH et al. (2019), Pritchard et al. (2021), Nicholl et al. (2023), & others

# “Fast Blue Optical Transients” / “Rapidly Evolving Luminous Transients” / “Rapidly Rising Transients”

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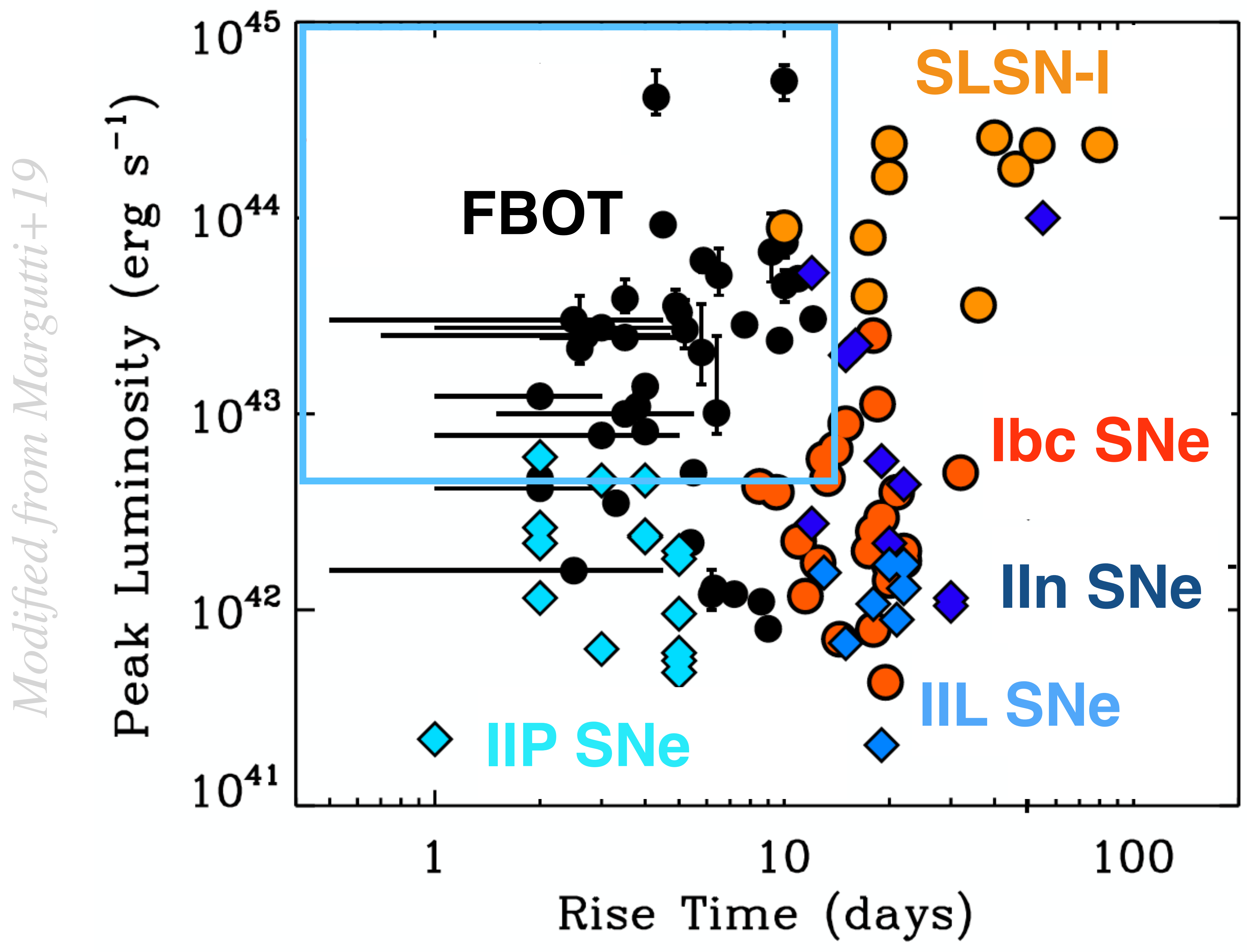
# Most “FBOTs” are core collapse supernovae



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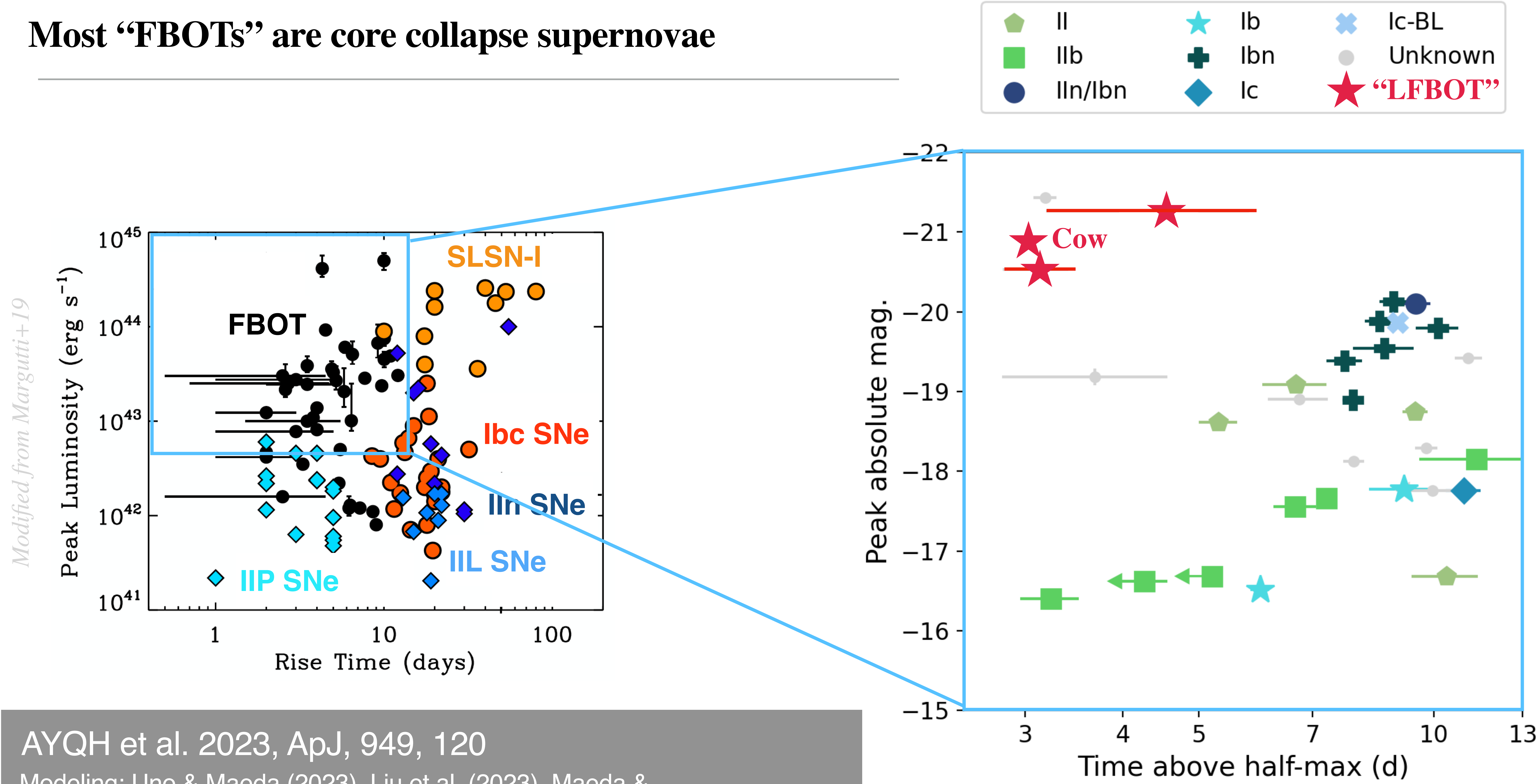
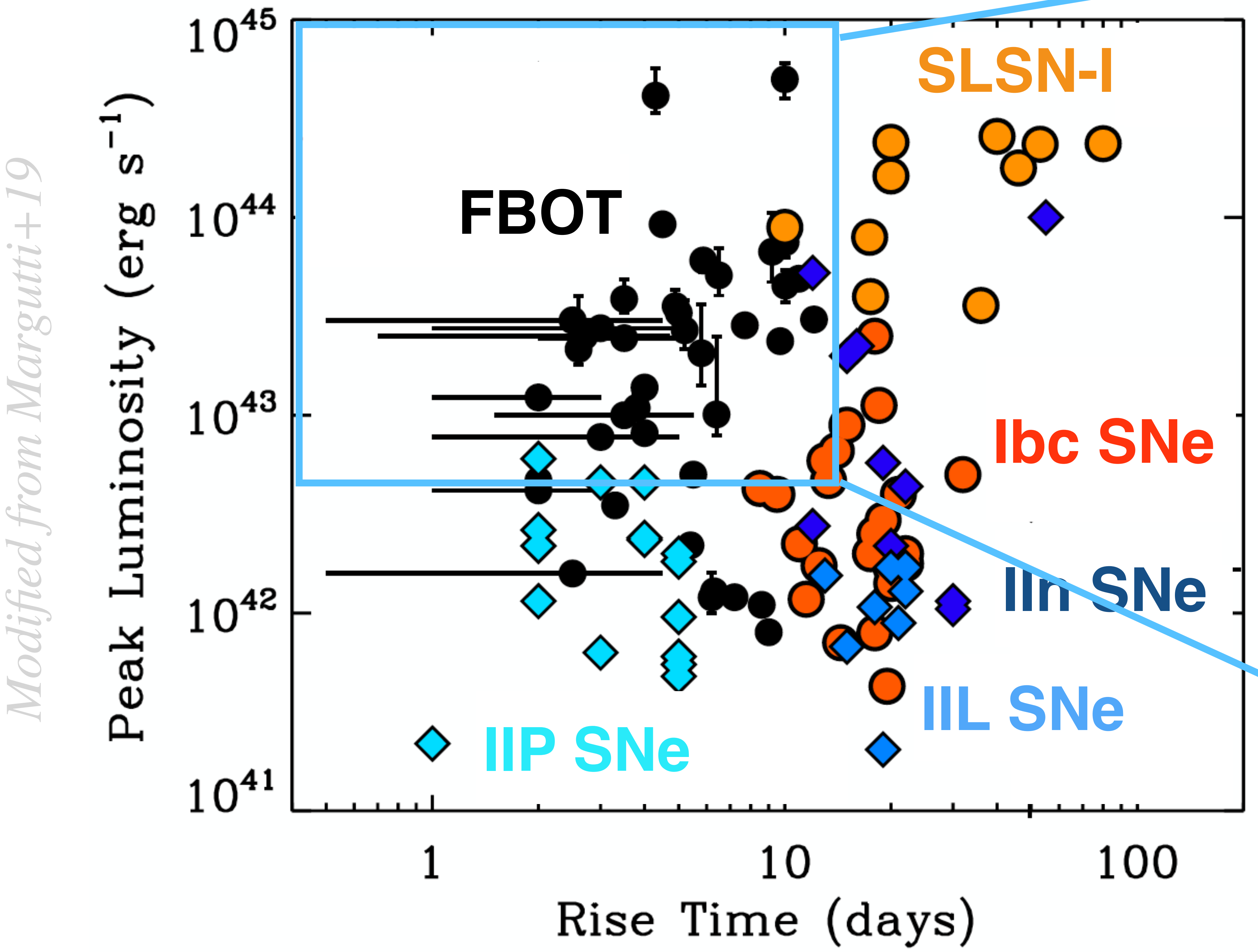


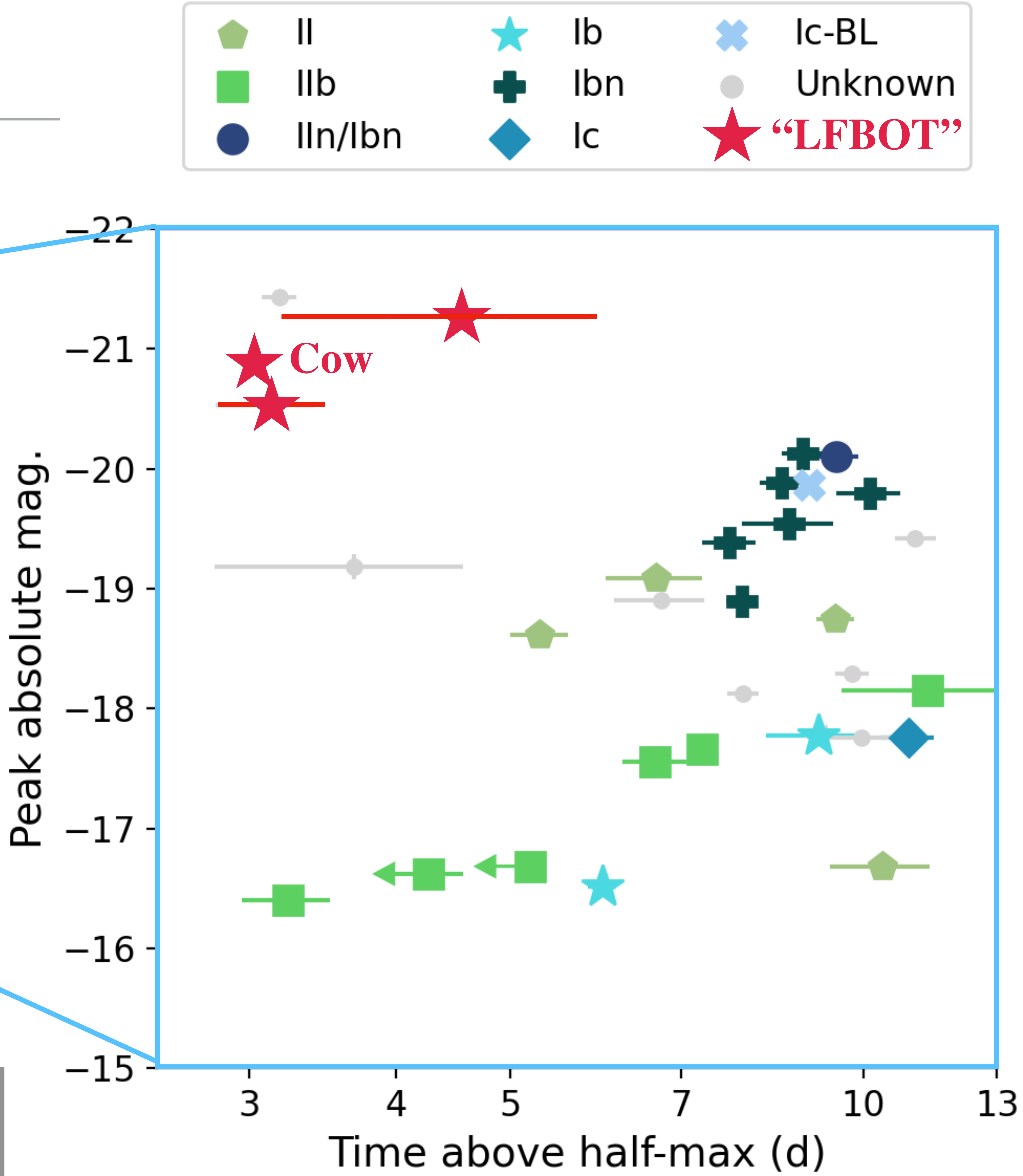

AYQH et al. 2023, ApJ, 949, 120

Modeling: Uno & Maeda (2023), Liu et al. (2023), Maeda & Moriya (2022), Ofek et al. (2021), Wang et al. (2019), Pellegrino et al. (2022), …

# Most “FBOTs” are core collapse supernovae

Power source: shock breakout/cooling, CSM interaction
Interesting single objects: ultra-stripped (Yao et al. 2020),
~10kpc offset from elliptical galaxy (Nicholl et al. 2023), …




AYQH et al. 2023, ApJ, 949, 120
Modeling: Uno & Maeda (2023), Liu et al. (2023), Maeda & Moriya (2022), Ofek et al. (2021), Wang et al. (2019), Pellegrino et al. (2022), …

# Likely exception: discovery of AT2018cow by ATLAS ($d$=60 Mpc)

nature IN FOCUS NEWS

NEWS · 02 NOVEMBER 2018 · CORRECTION 30 NOVEMBER 2018

## Holy Cow! Astronomers agog at mysterious new supernova

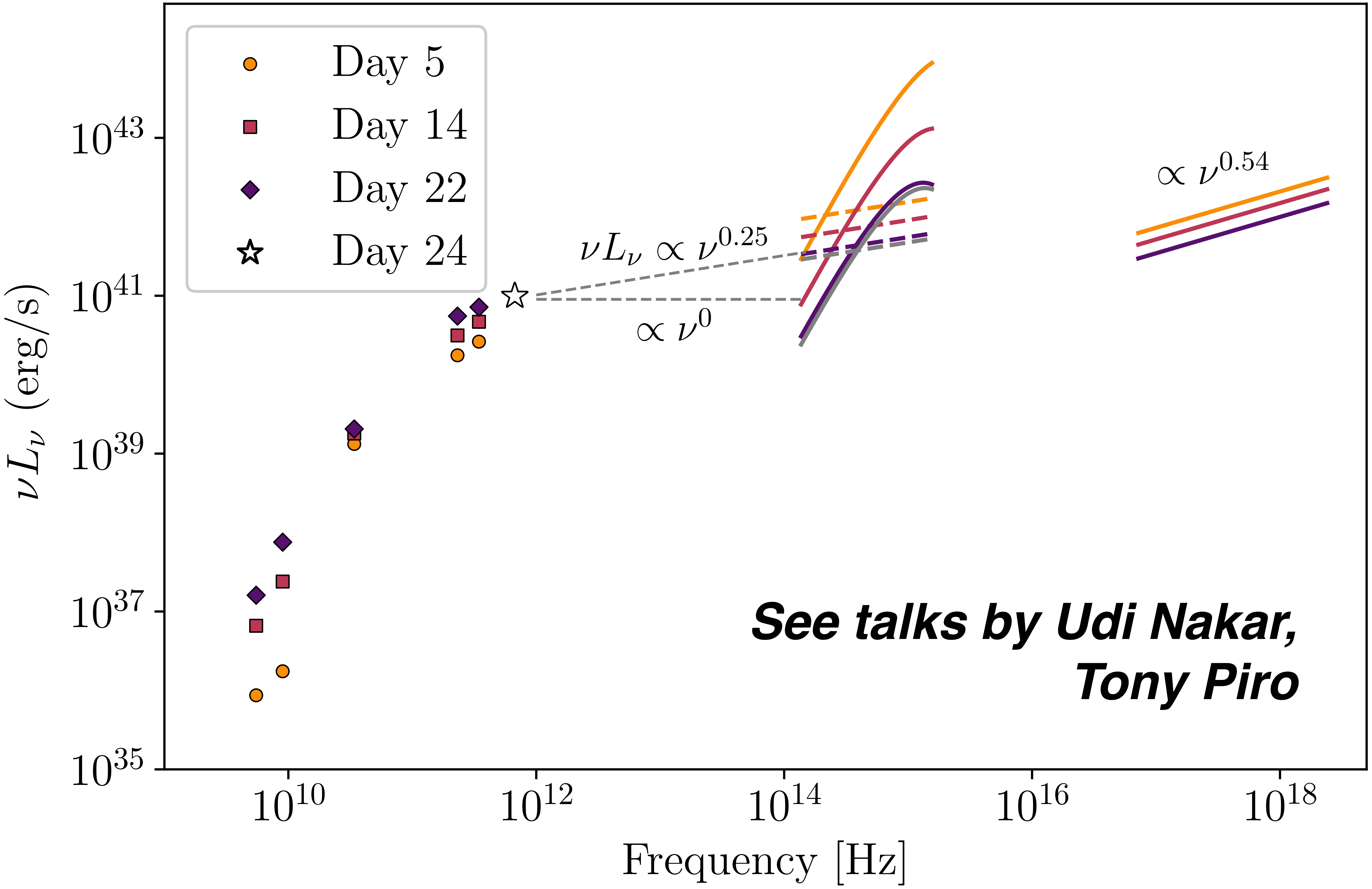
NewScientist

## 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 talks by Udi Nakar, Tony Piro***

# ZTF searches: 11 transients similar to AT2018cow (13 total)


Gemini


LT

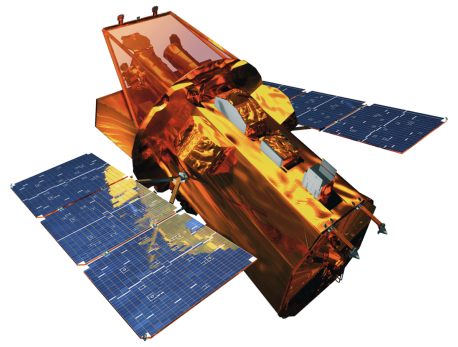

VLT

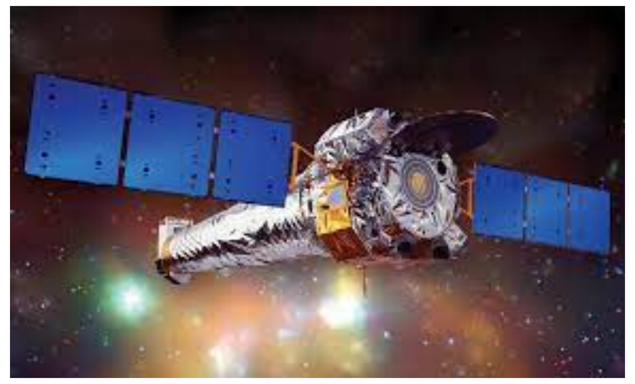

NOEMA

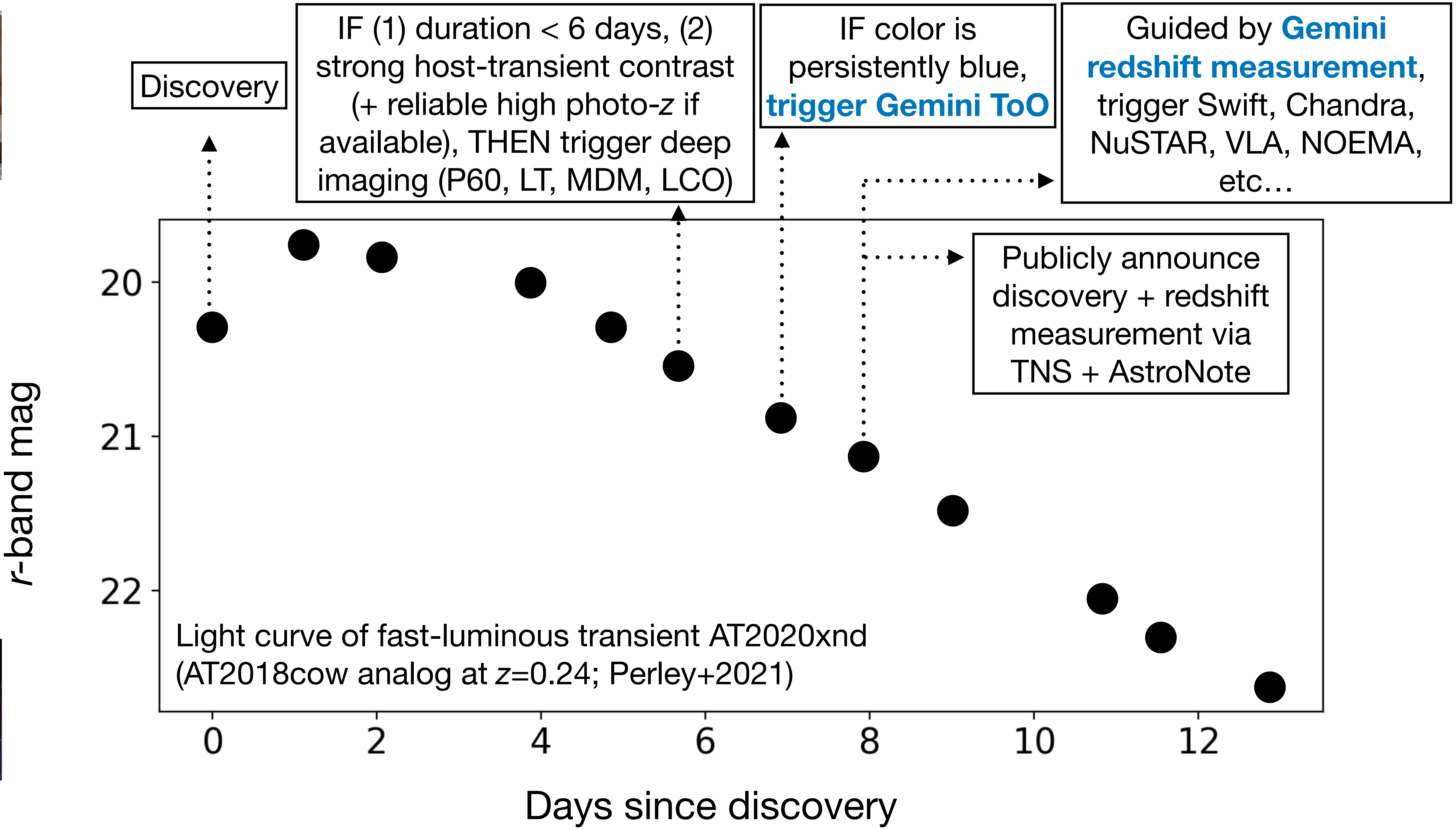

VLA


ALMA


GMRT


*Swift*


Chandra

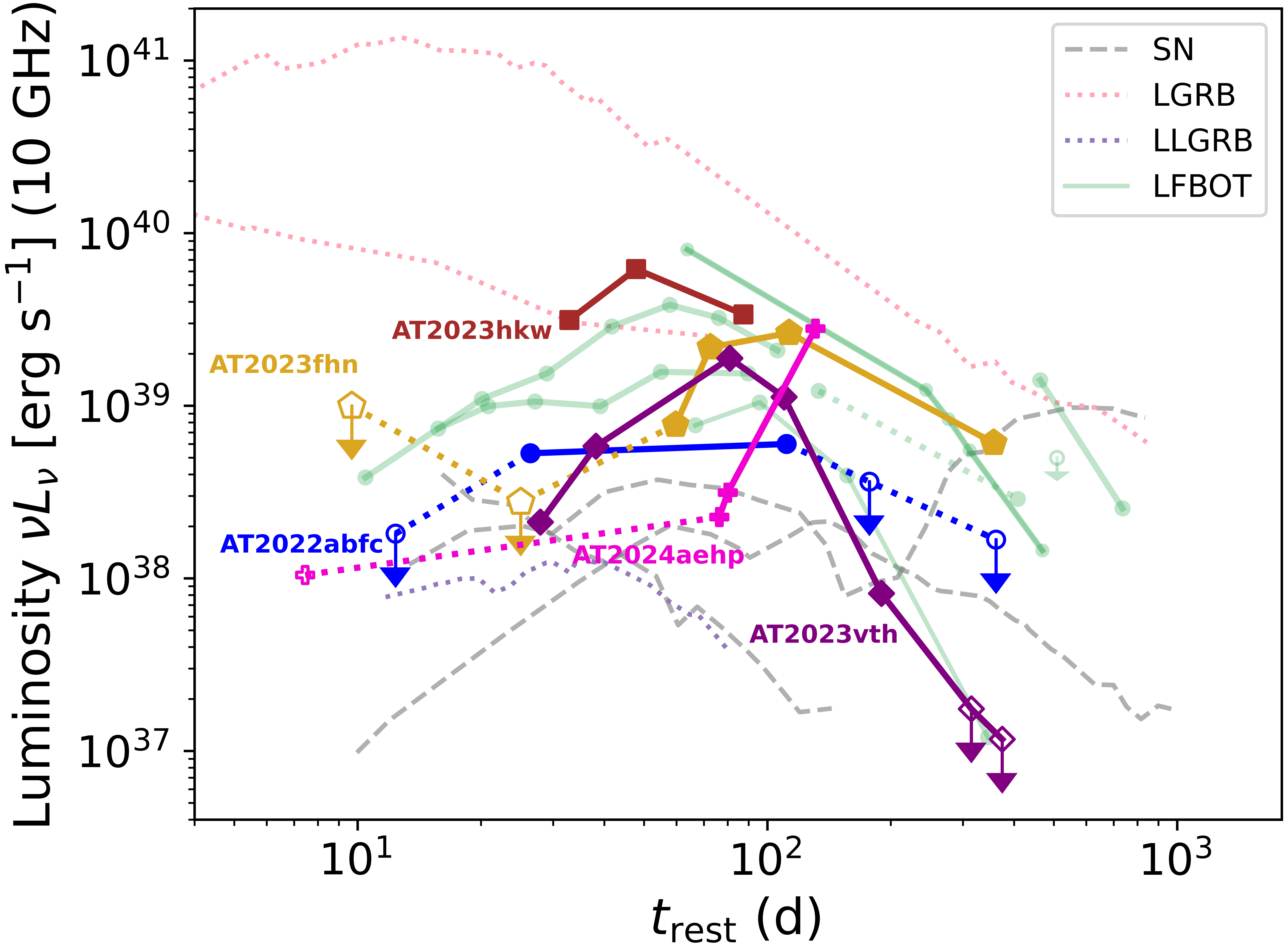



AYQH et al. 2020, Coppejans et al. 2020, Perley et al. 2021, Yao et al. 2021, AYQH et al. 2023a&b, Chrimes et al. 2023, Gutierrez et al. 2024, Perley et al. 2026, Sevilla et al. 2026

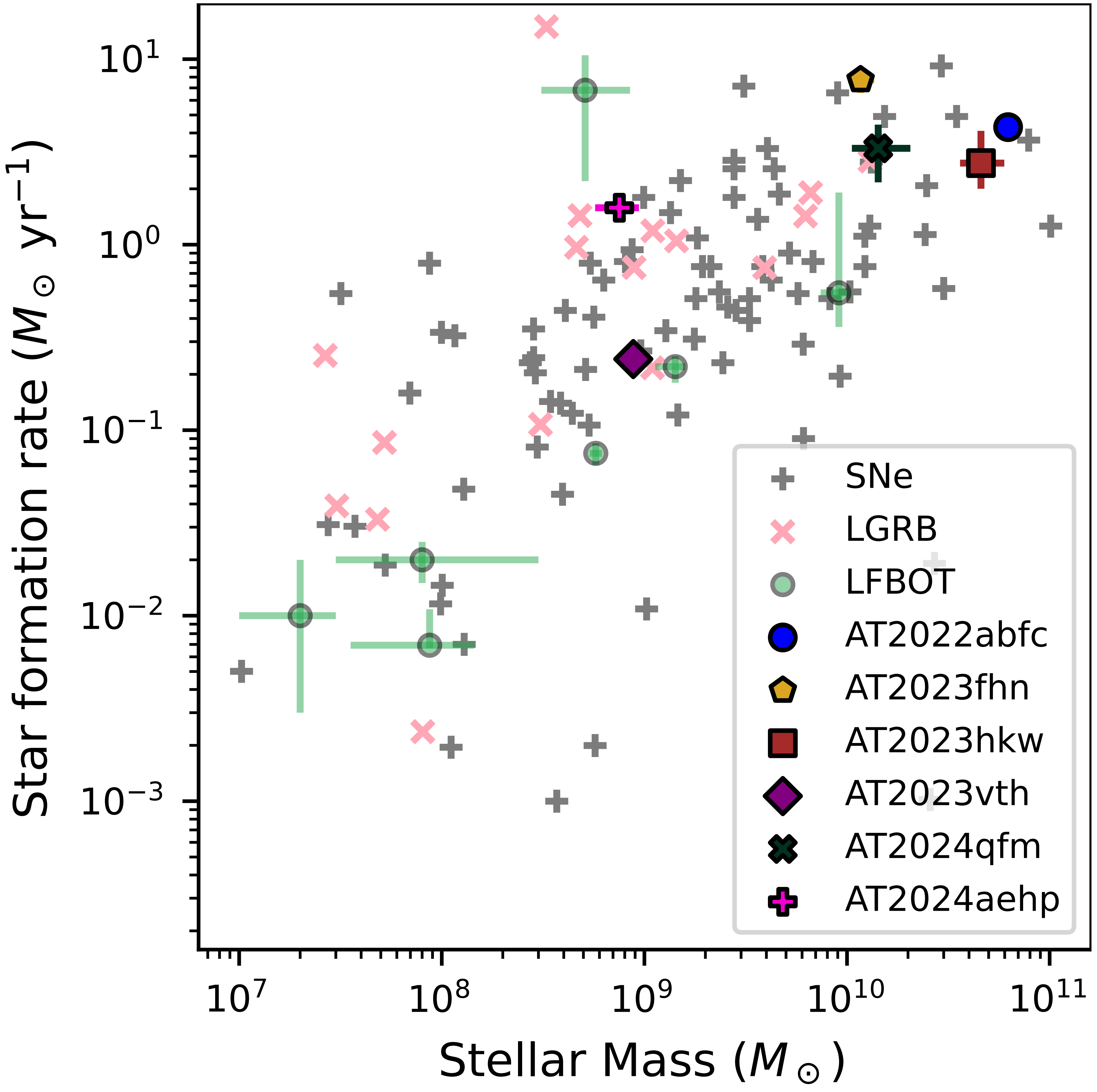
# “LFBOTs”: results from optical selection

Cassie Sevilla
(PhD student)

## Similar radio light curves




## Starforming galaxies



“FBOTs” & The Cow

**Sub-millimeter emission**

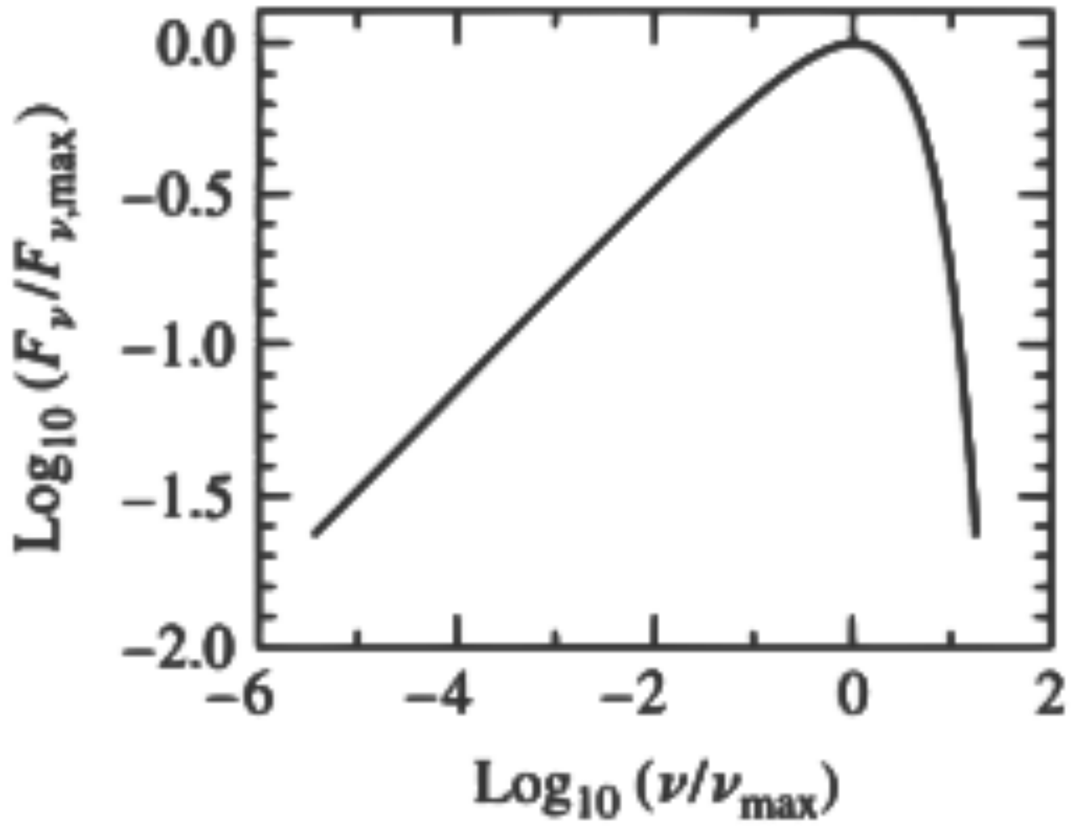
Minutes-duration optical flares

Progenitors

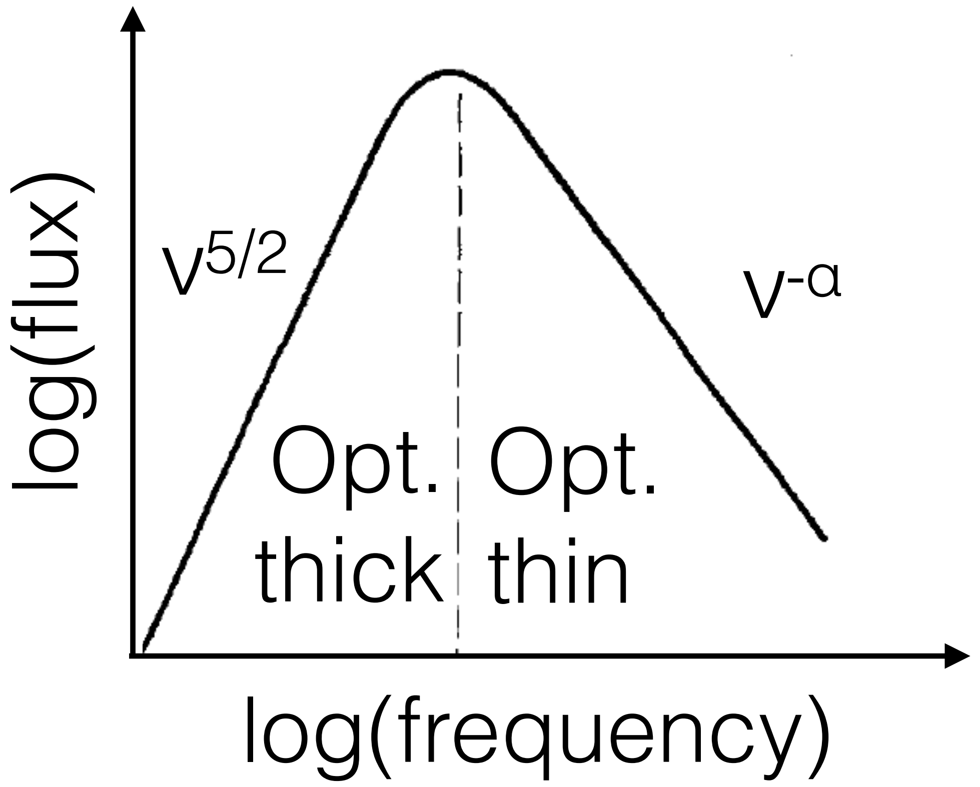
# Primer: supernova radio emission

Explosion in pre-supernova wind —> relativistic electrons, magnetic fields —> synchrotron radiation

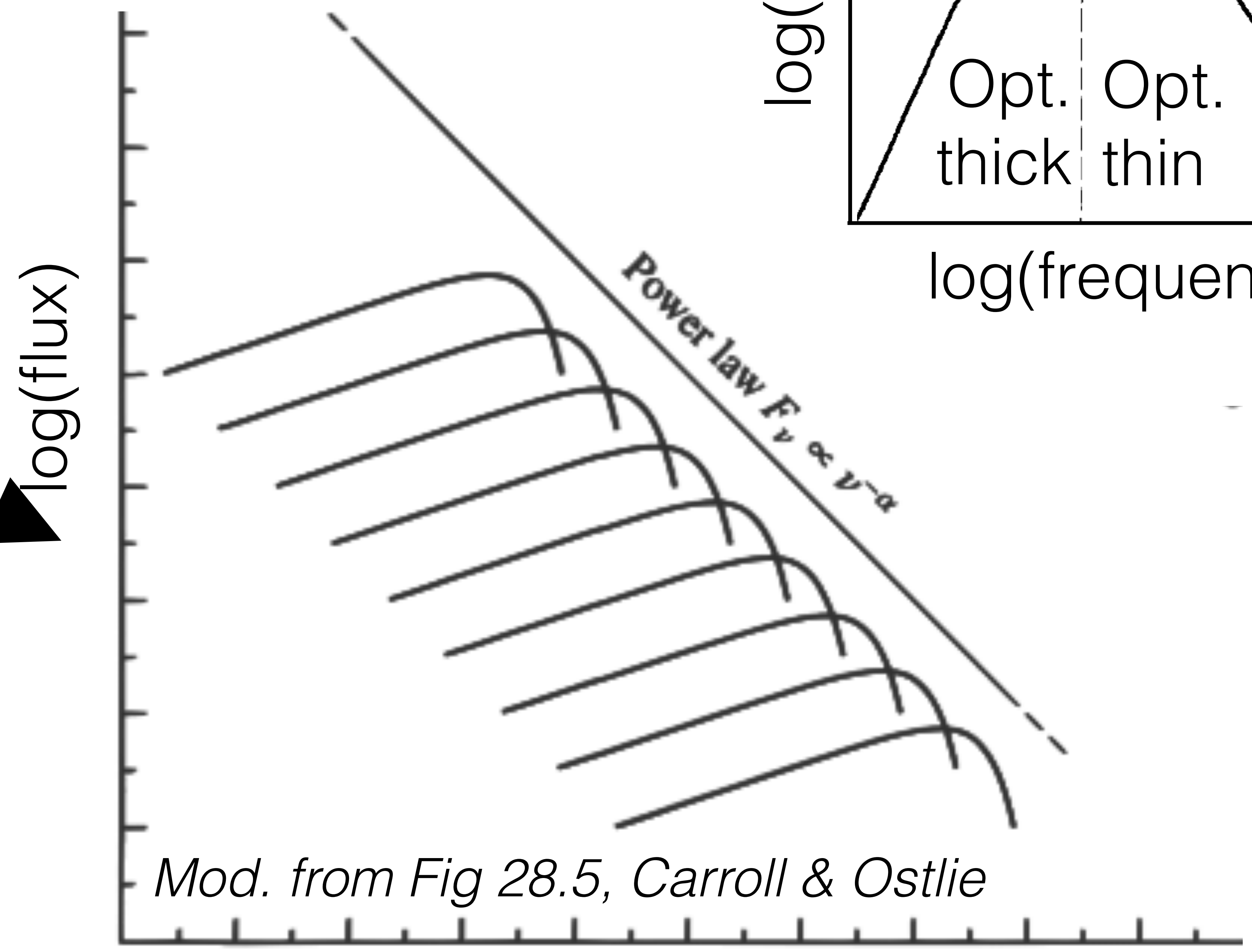
Single-electron spectrum




Net (observed) spectrum

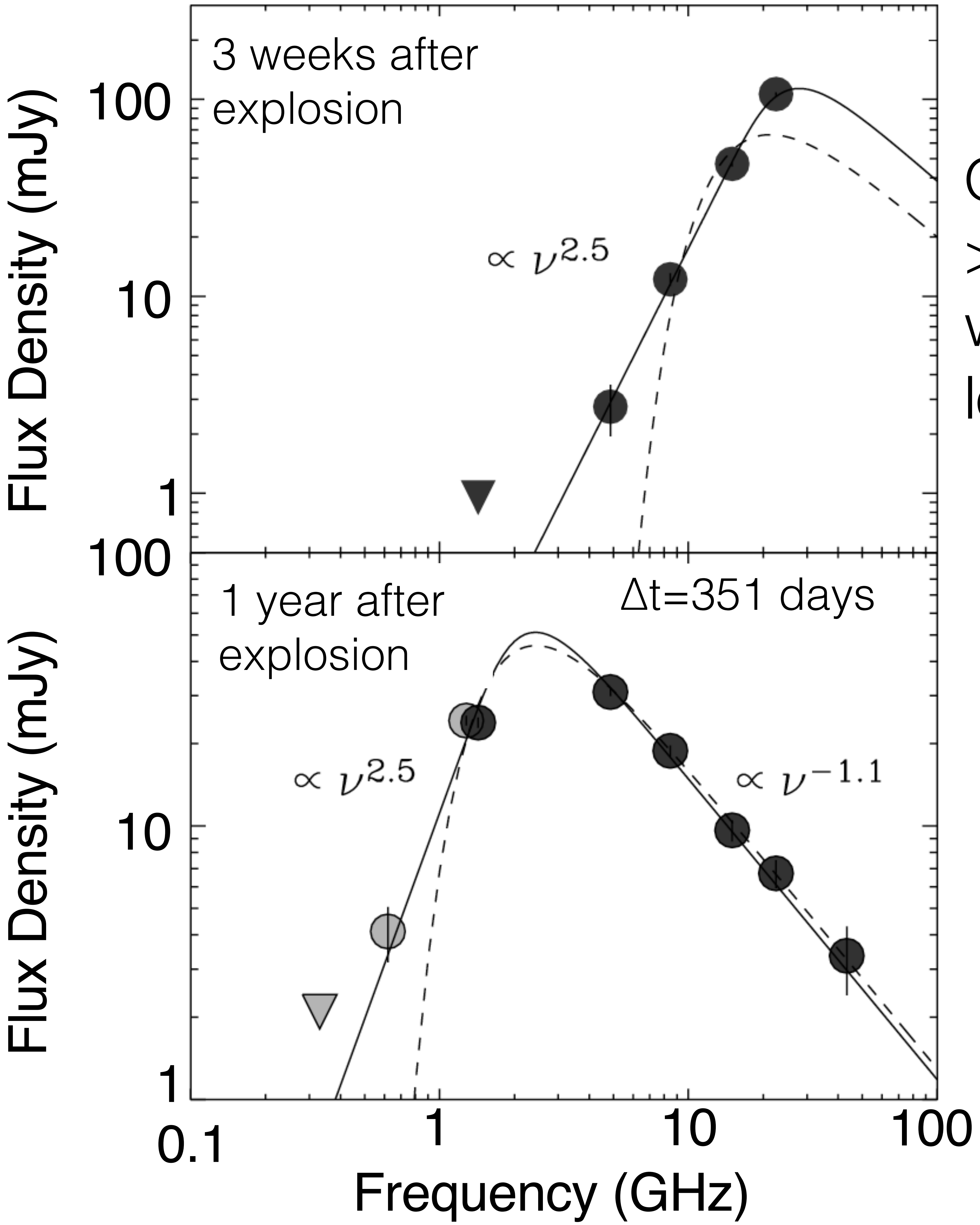



**IF electrons have a power-law energy distribution**



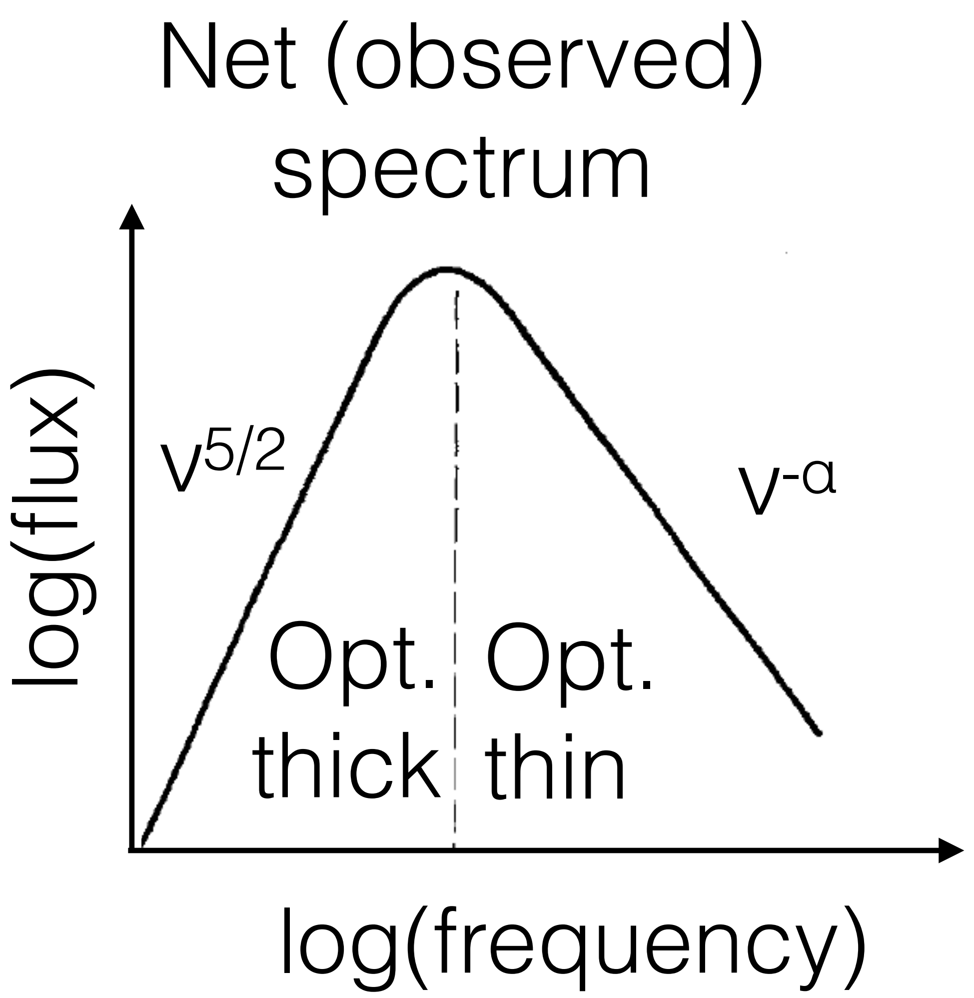

*Mod. from Fig 28.5, Carroll & Ostlie*

# Long history of cm-wave observations of explosive transients



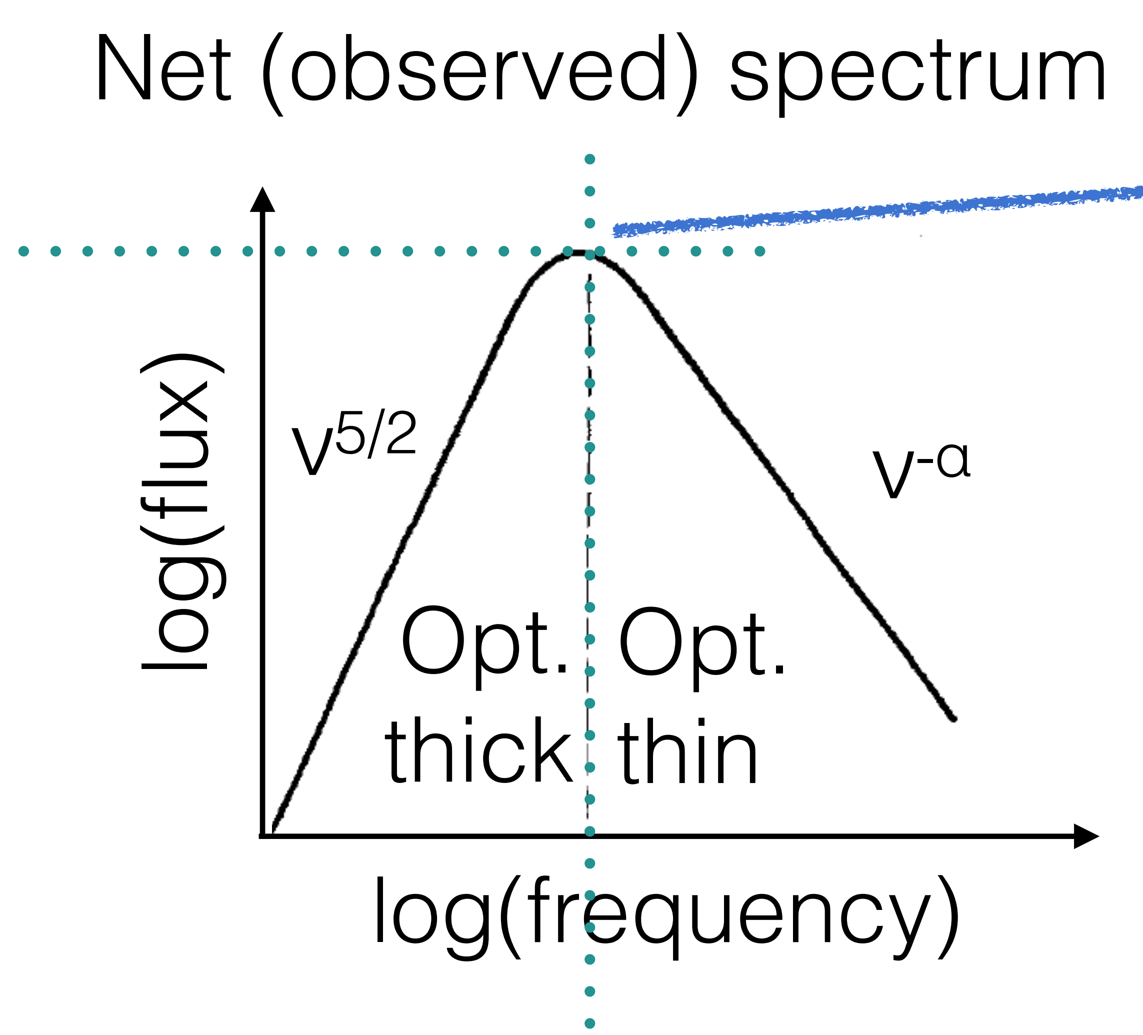

Observations at >30 GHz (mm wavelengths) far less common

*The Very Large Array (of radio telescopes)*




***See talk by Poonam Chandra***

# Inferring physical parameters




At time $t_p$, peak brightness $F_p$ & frequency $\nu_p$ set by shock radius $R$, magnetic field strength $B$

$$R \propto F_p^{9/19} \nu_p^{-1} \qquad B \propto F_p^{-2/19} \nu_p$$

$$v = \frac{R}{t_p} \propto F_p^{9/19} (\nu_p t_p)^{-1} \qquad U = \frac{U_B}{\epsilon_B}$$

Conserve momentum:

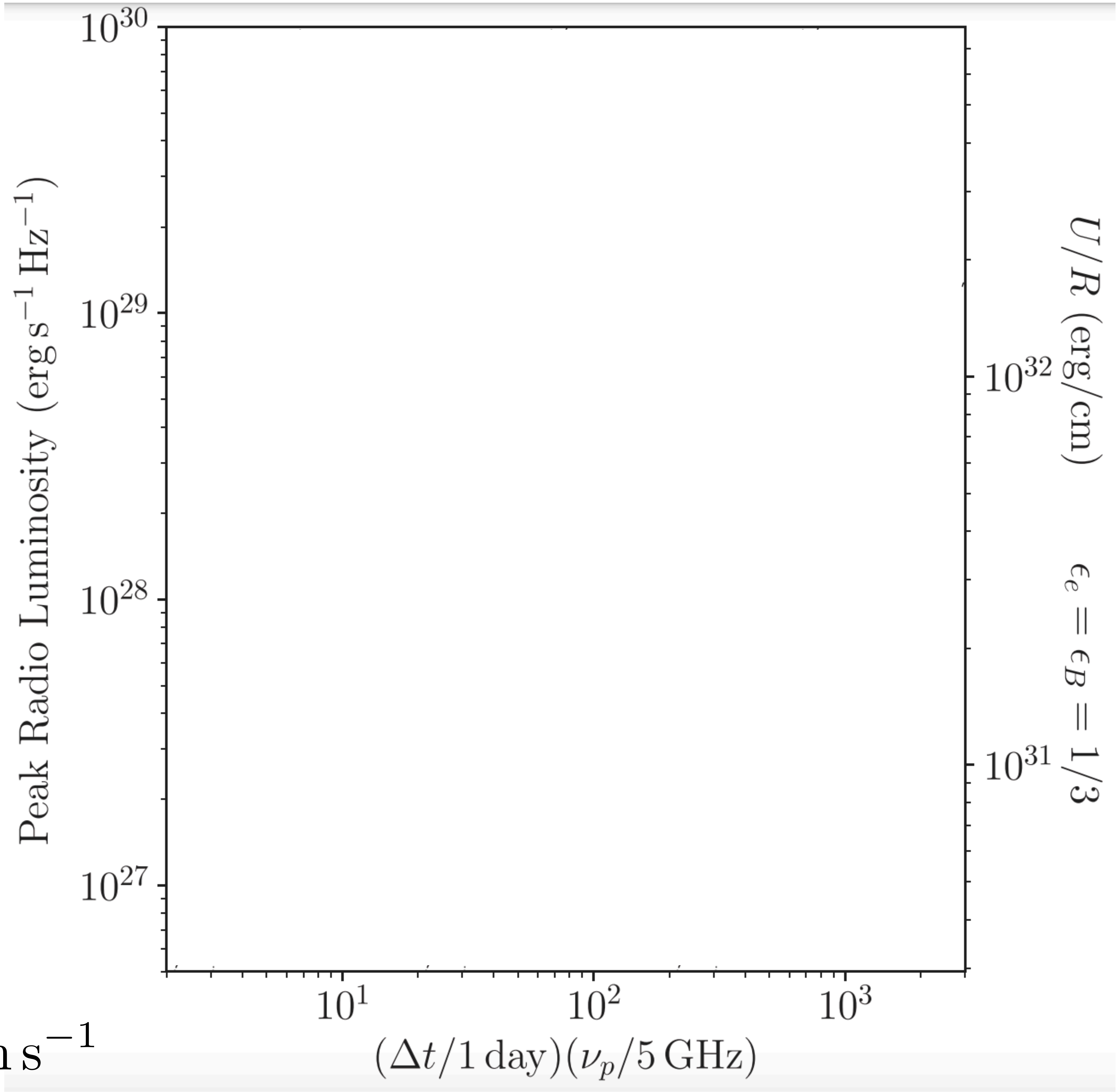
$$n_e \propto F_p^{-22/19} \nu_p^4 t_p^2$$

Assume wind velocity $v_w$

$$\frac{\dot{M}}{v_w} \propto F_p^{-4/19} (\nu_p t_p)^2$$

# Inferring physical parameters

increasing ambient density (mass-loss rate) →




mass-loss rate in units of

$10^{-4}\,M_\odot\,\mathrm{yr}^{-1}/1000\,\mathrm{km\,s}^{-1}$

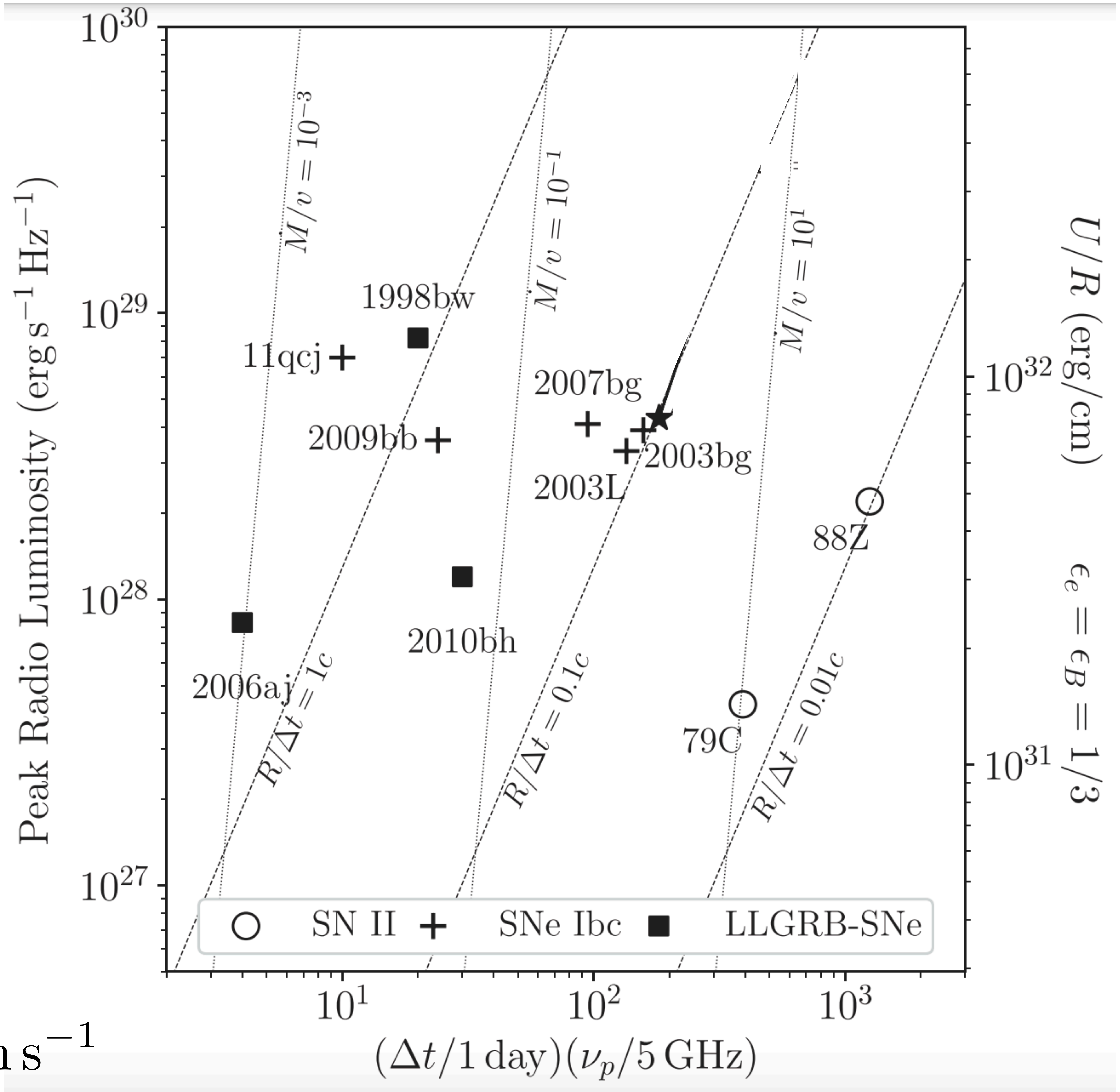
Chevalier (1998), Jencson et al. (2018);
fig. from AYQH et al. 2019, ApJ, **871**, 73

# Inferring physical parameters

Decades of supernova radio observations

(e.g., Weiler+86, Fransson+96, Kulkarni+98, Soderberg+06, Soderberg+10, Corsi+14, Margutti+17, Maeda+21, Dong+21)

increasing ambient density (mass-loss rate)




mass-loss rate in units of

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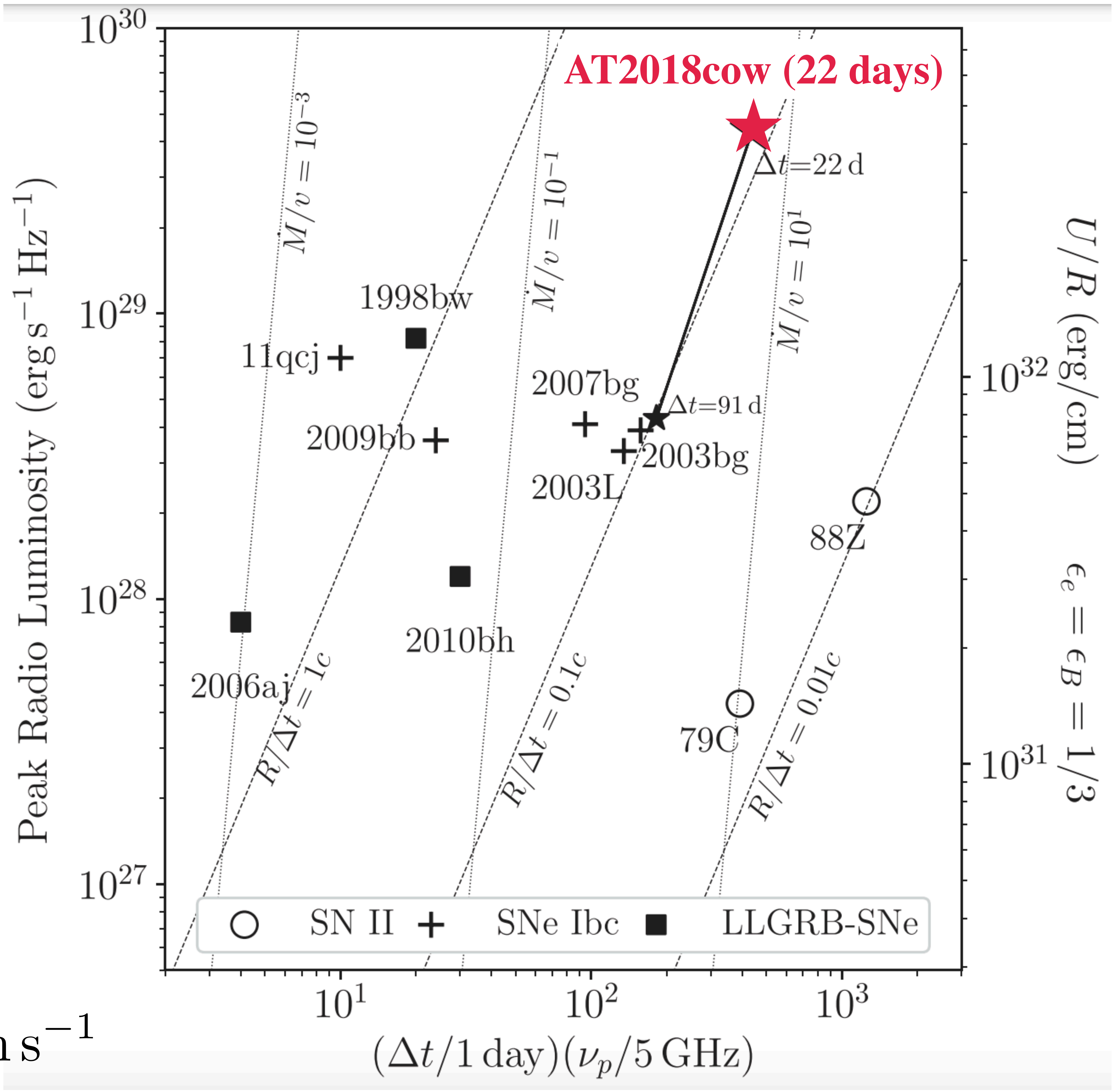
Chevalier (1998), Jencson et al. (2018); fig. from AYQH et al. 2019, ApJ, **871**, 73

# Inferring physical parameters

Interpretation: high mass-loss rate, high explosion energy

Also: novel features of synchrotron modeling parameters, variable sub-mm spectral index at early times, steep optically thin spectral index

increasing ambient density (mass-loss rate) →

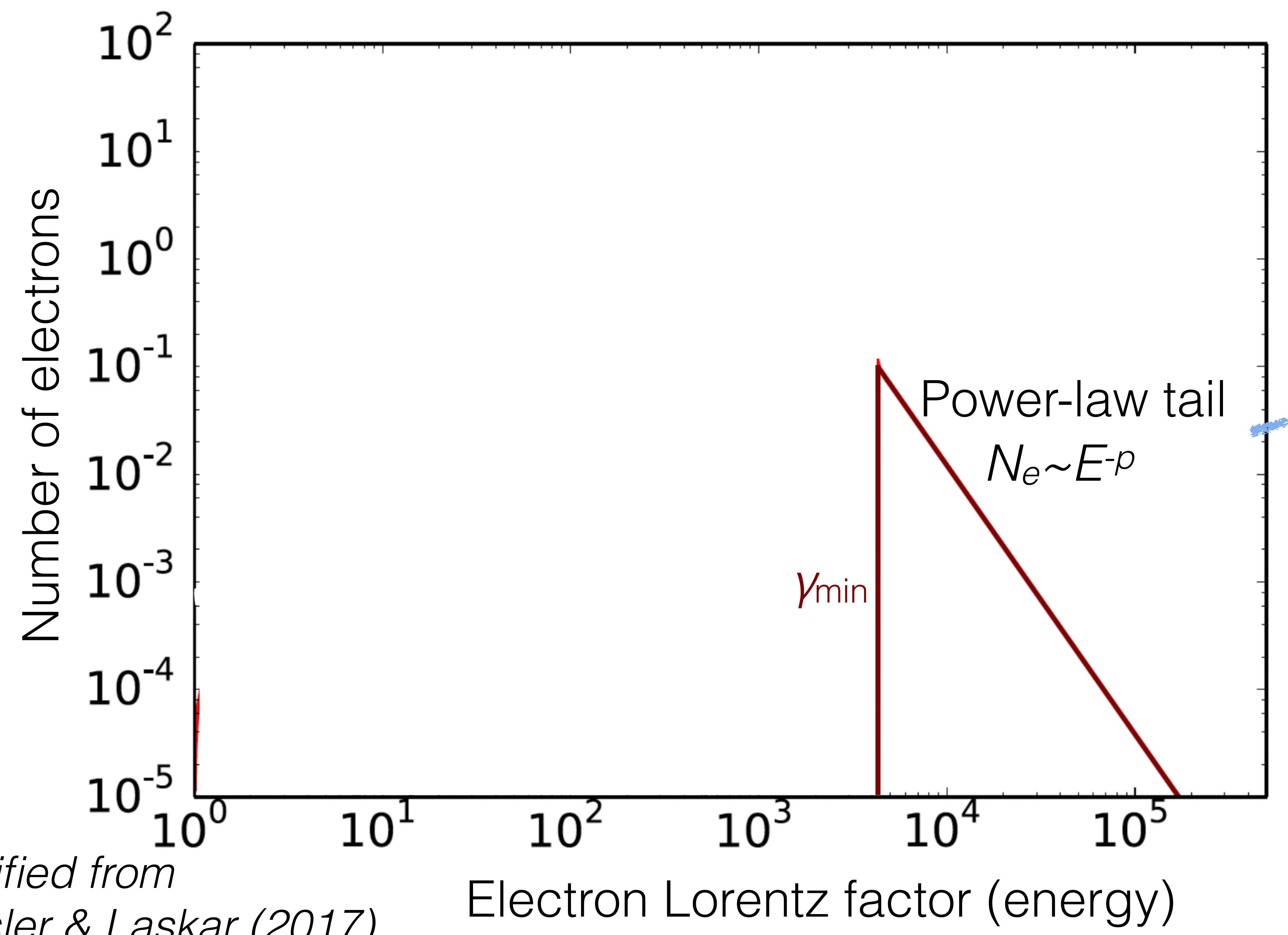



mass-loss rate in units of

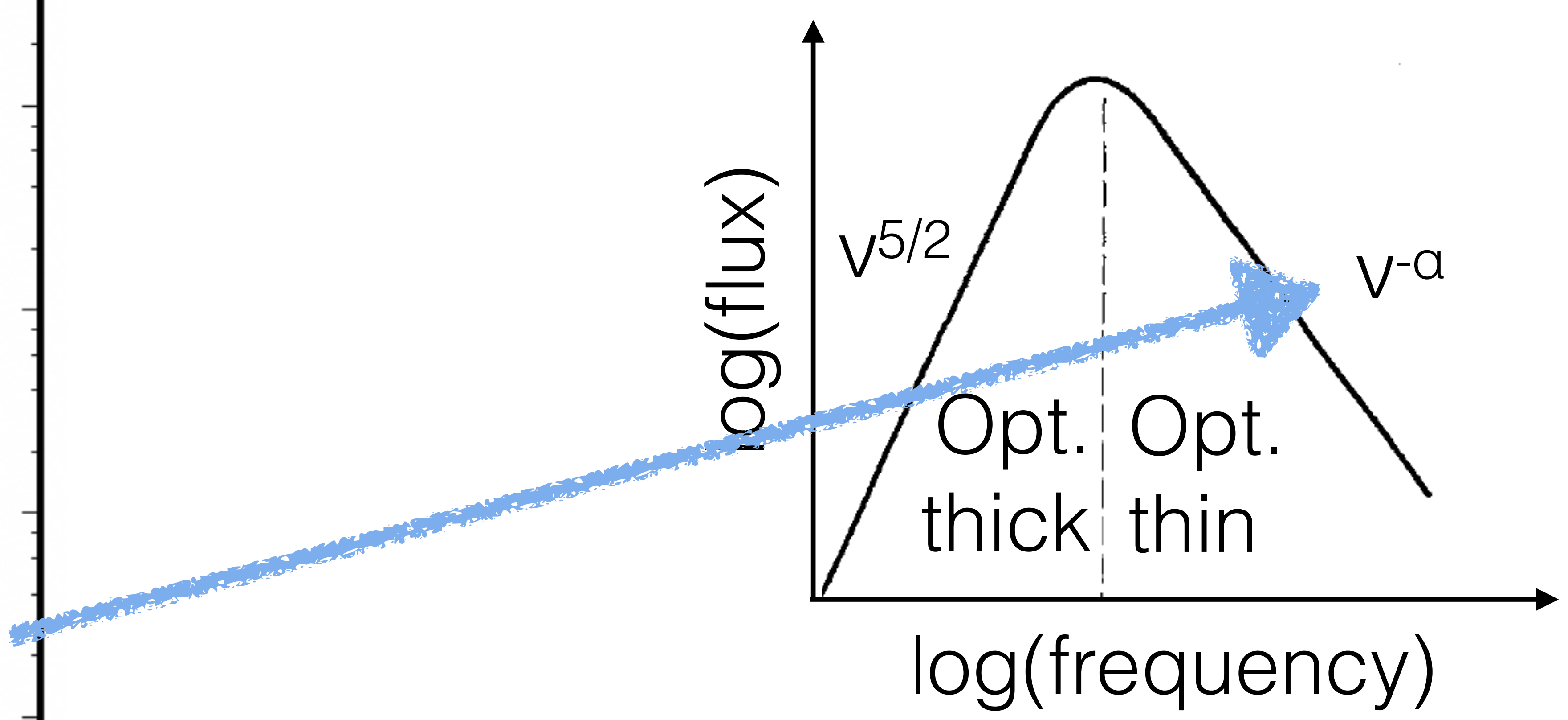
$$10^{-4}\, M_\odot\, \mathrm{yr}^{-1} / 1000\, \mathrm{km\, s}^{-1}$$

## A steep electron energy distribution?

In modeling supernovae, it's assumed that all electrons are accelerated into a power law…
Fermi acceleration: $p$=2.3




*Modified from Ressler & Laskar (2017)*




Spectral index:

α=(p-1)/2

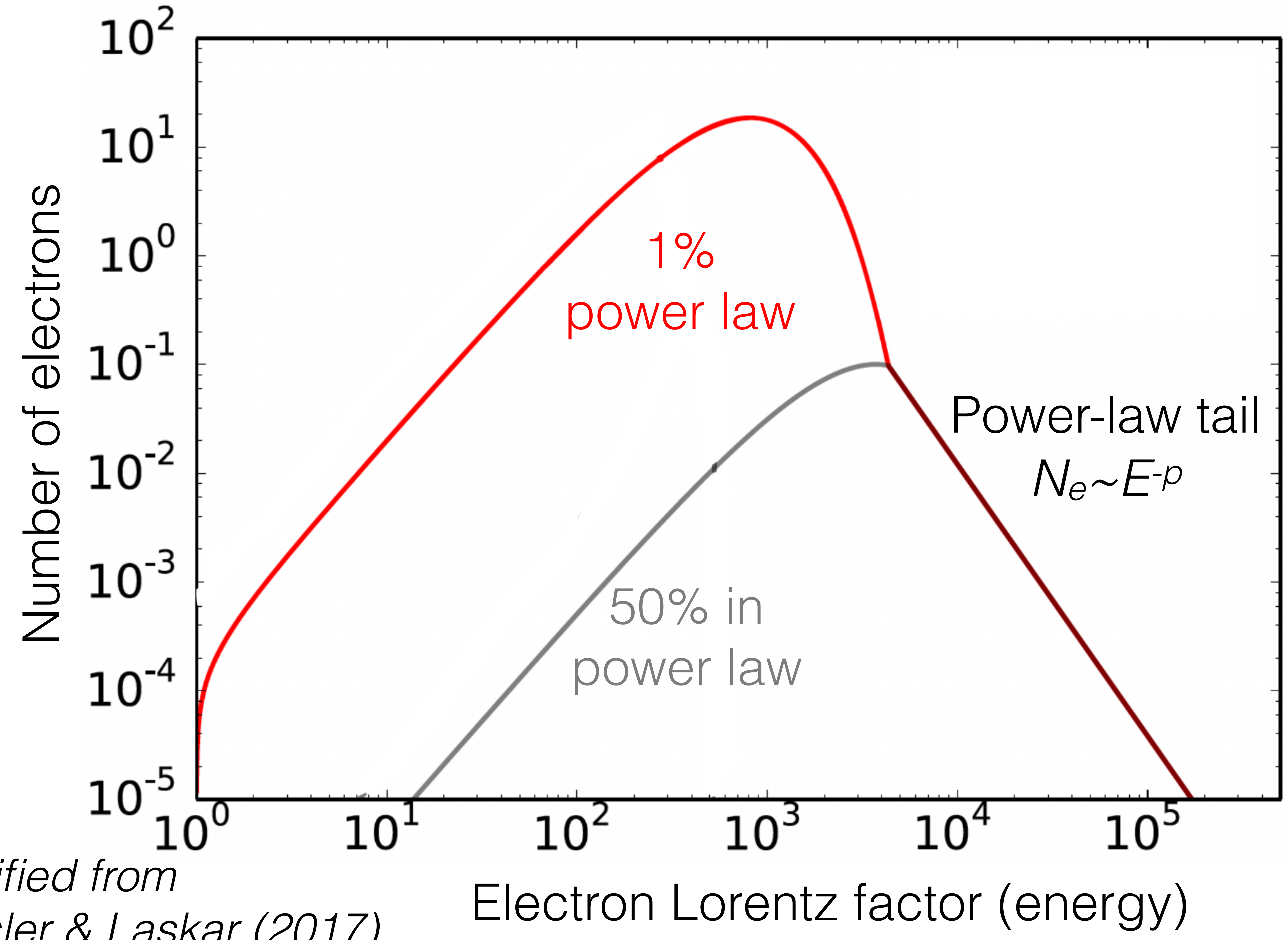
Expect $p$=2-3

α=0.5-1

Eichler & Waxman (2005), Spitkovsky (2008), Giannios & Spitkovsky (2009), Ressler & Laskar (2017), Jóhannesson & Björnsson 2018, Warren et al. (2018), Yuan et al. (2003)

## A steep electron energy distribution?

Expectation from simulations: some % of e-s are accelerated into a power law… but most end up in a relativistic Maxwellian




*Modified from Ressler & Laskar (2017)*

***See talk by Anatoly Spitkovsky***

Eichler & Waxman (2005), Spitkovsky (2008), Giannios & Spitkovsky (2009), Ressler & Laskar (2017), Jóhannesson & Björnsson 2018, Warren et al. (2018), Yuan et al. (2003)

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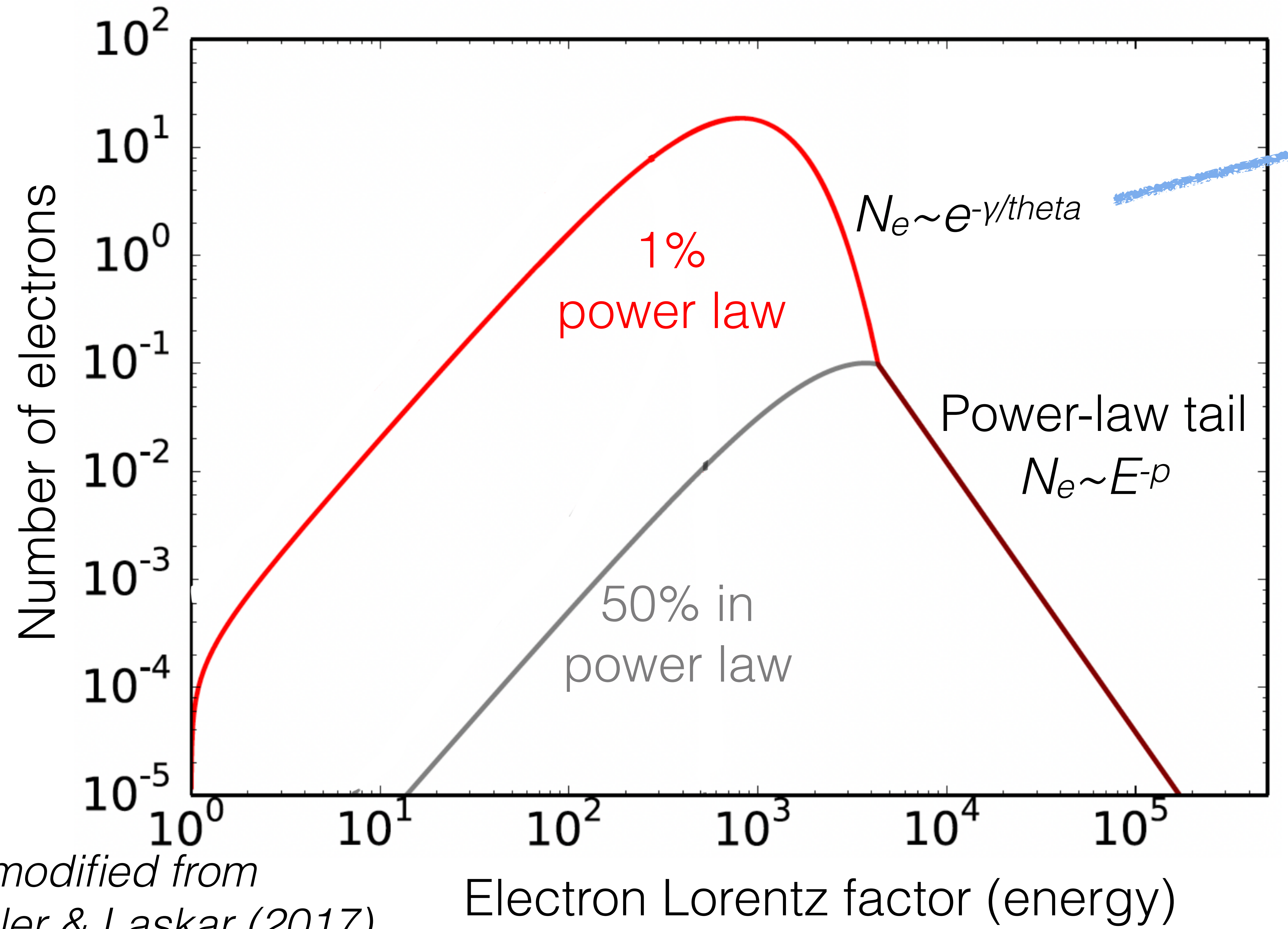



Steeper spectrum: an exponential in frequency

*Fig. modified from Ressler & Laskar (2017)*

Discussed in the context of
- GRB afterglows
- Sgr A*

Mahadevan (1998), Ozel et al. (2000), Yuan et al. (2003), Eichler & Waxman (2005), Spitkovsky (2008), Giannios & Spitkovsky (2009), Ressler & Laskar (2017), Jóhannesson & Björnsson 2018, Warren et al. (2018)

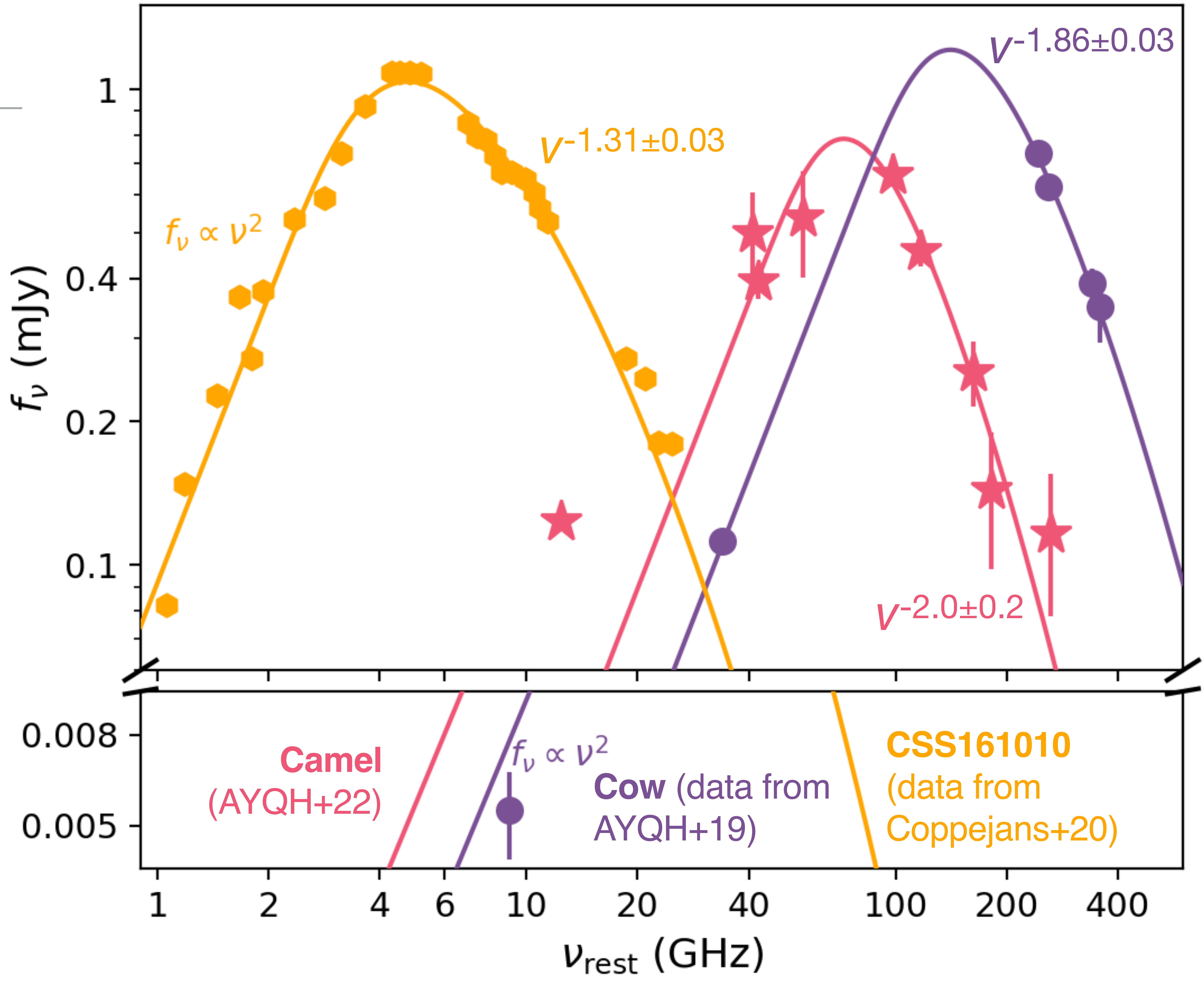
## A relativistic Maxwellian?

Inferred shock properties:
$v \sim 0.2\text{-}0.4c$, $n_e \sim 10^2$ to $10^5$ cm$^{-3}$

% of electrons in power law <20%

Shock speed + ambient density
(Margalit & Quataert 2021, 2024)

Test: observe transition from
Maxwellian to power law electrons



“FBOTs” & The Cow

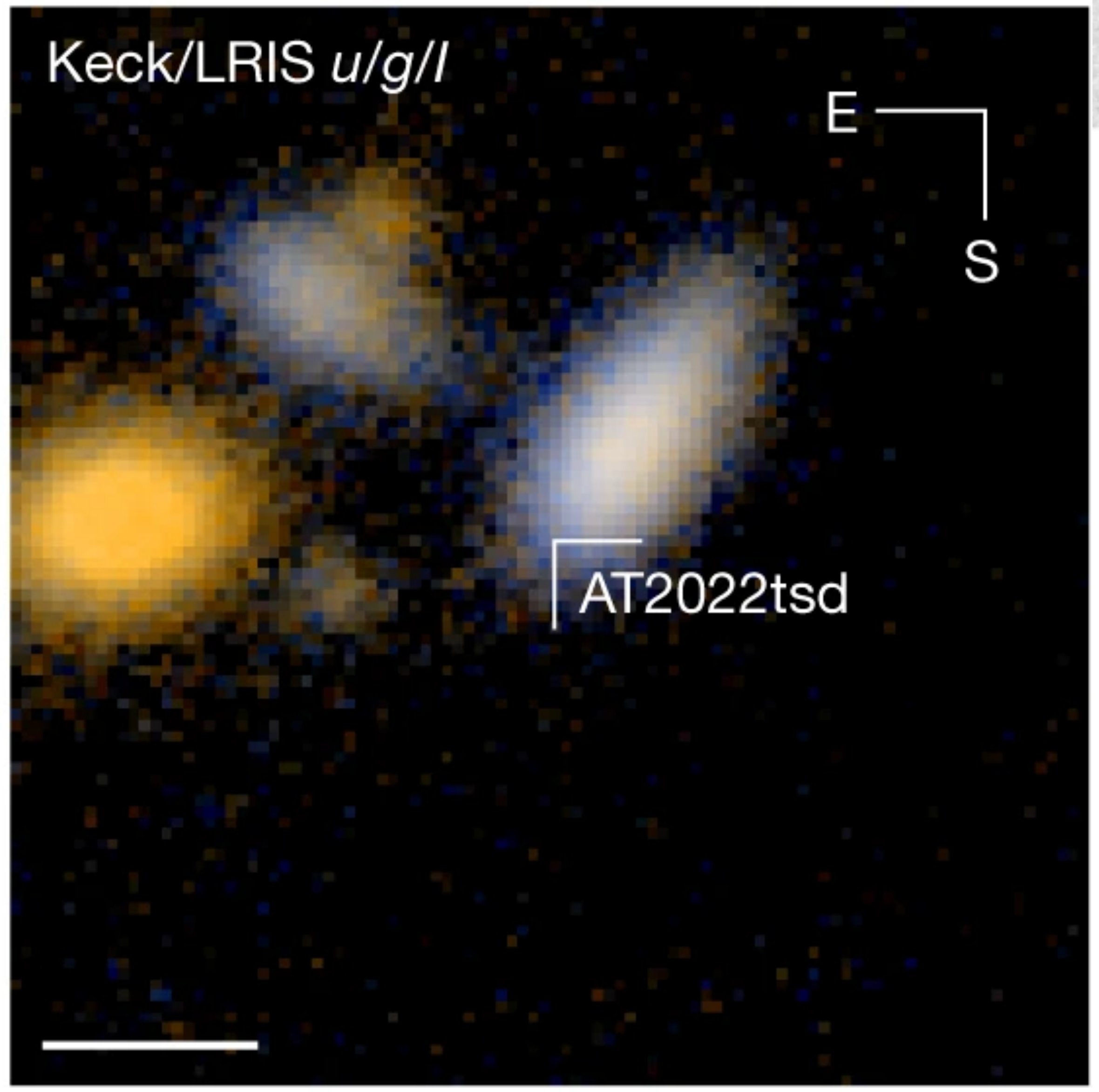
Sub-millimeter emission

→ **Minutes-duration optical flares**

Progenitors

# *100 days* after AT2022tsd ("The Tasmanian Devil")

5 x 3min *g*-band exposures with Magellan/IMACS



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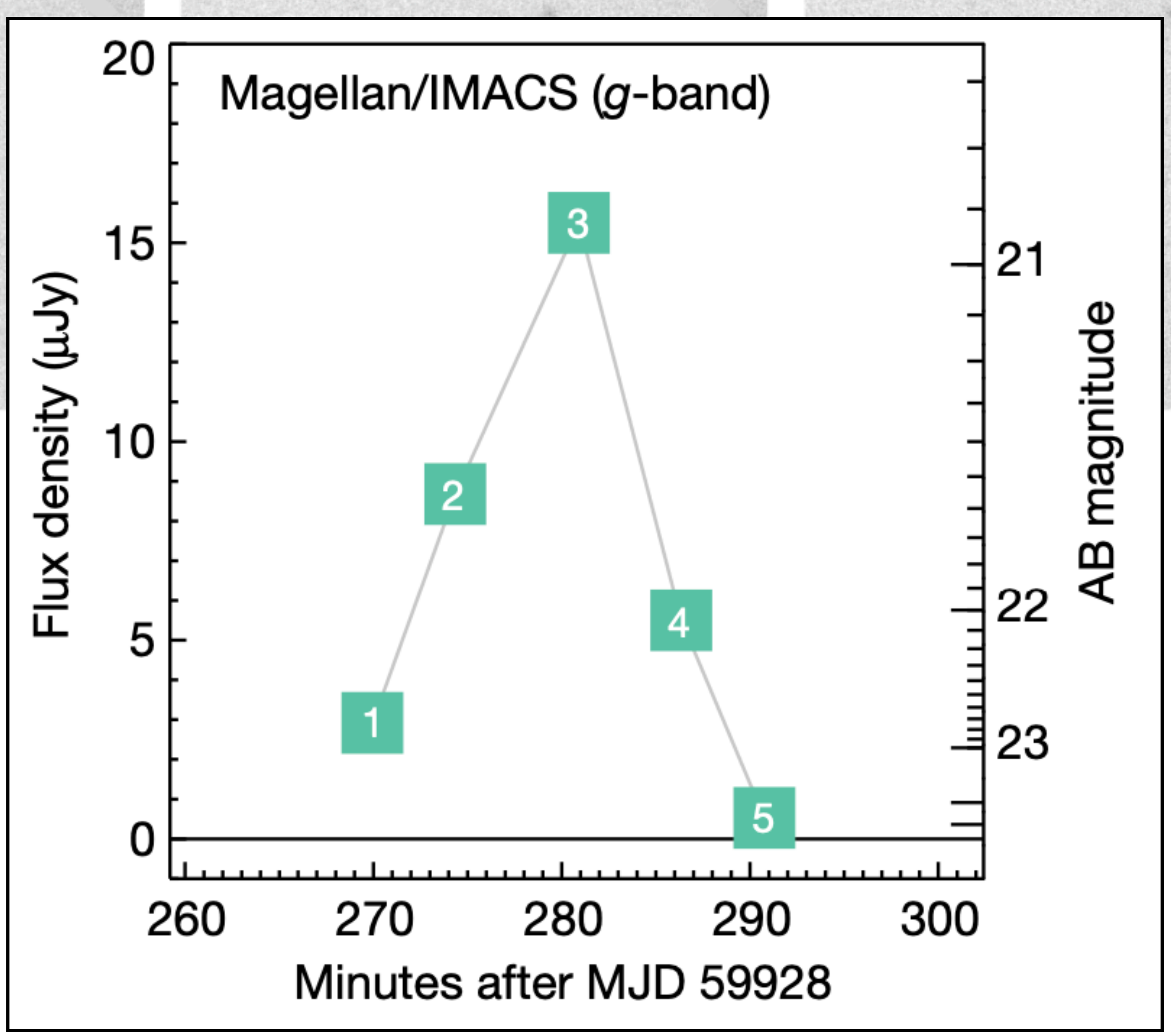
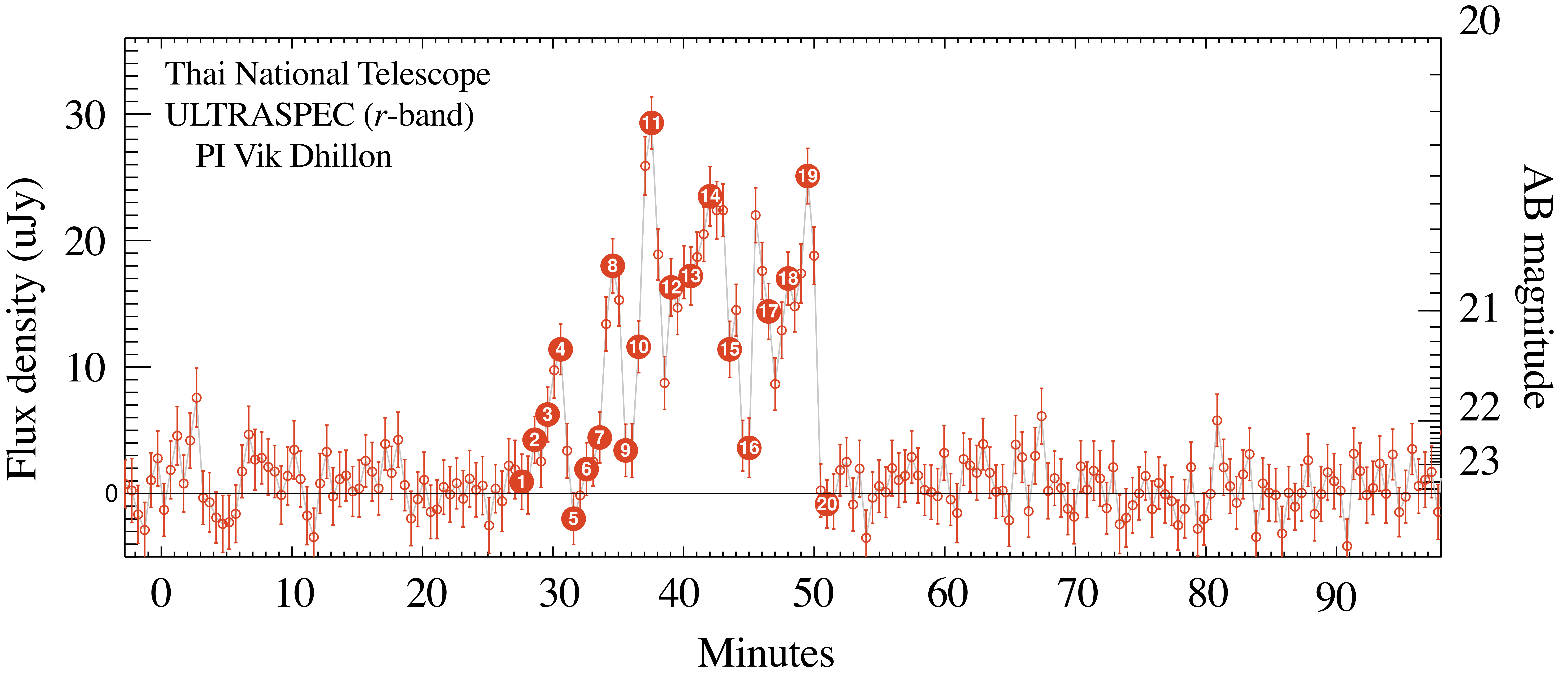



At $z = 0.256$, M = -20 mag ($\nu L_\nu \sim 10^{44}$ erg/s)

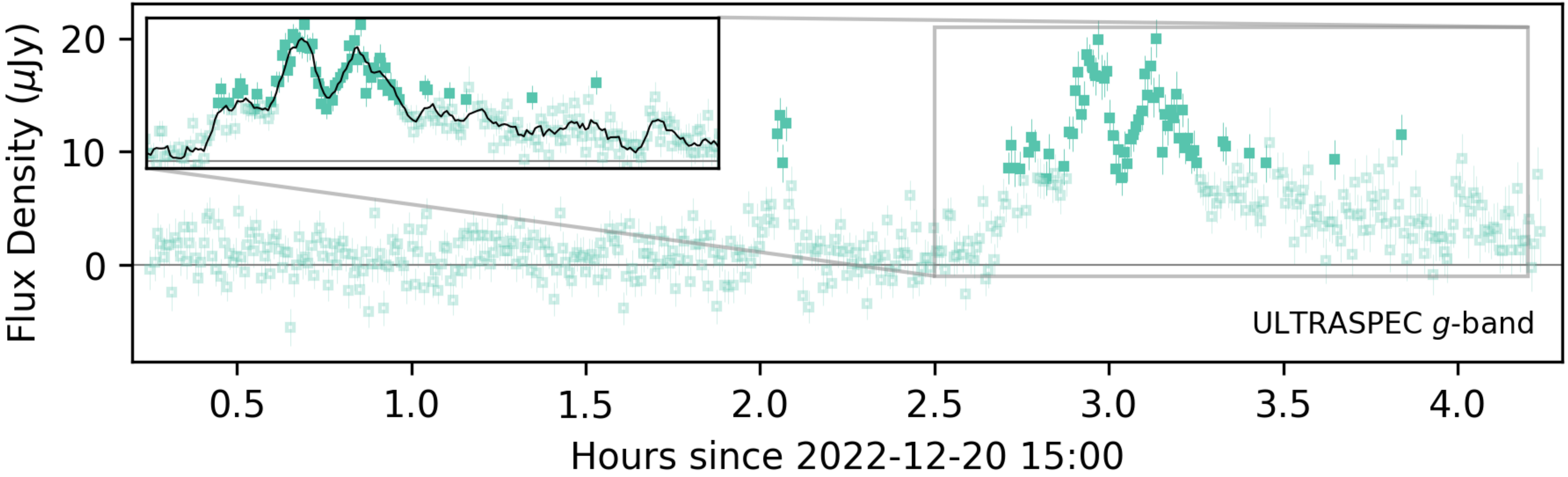
Same luminosity as original transient!

# High-cadence imaging: no clear periodicity

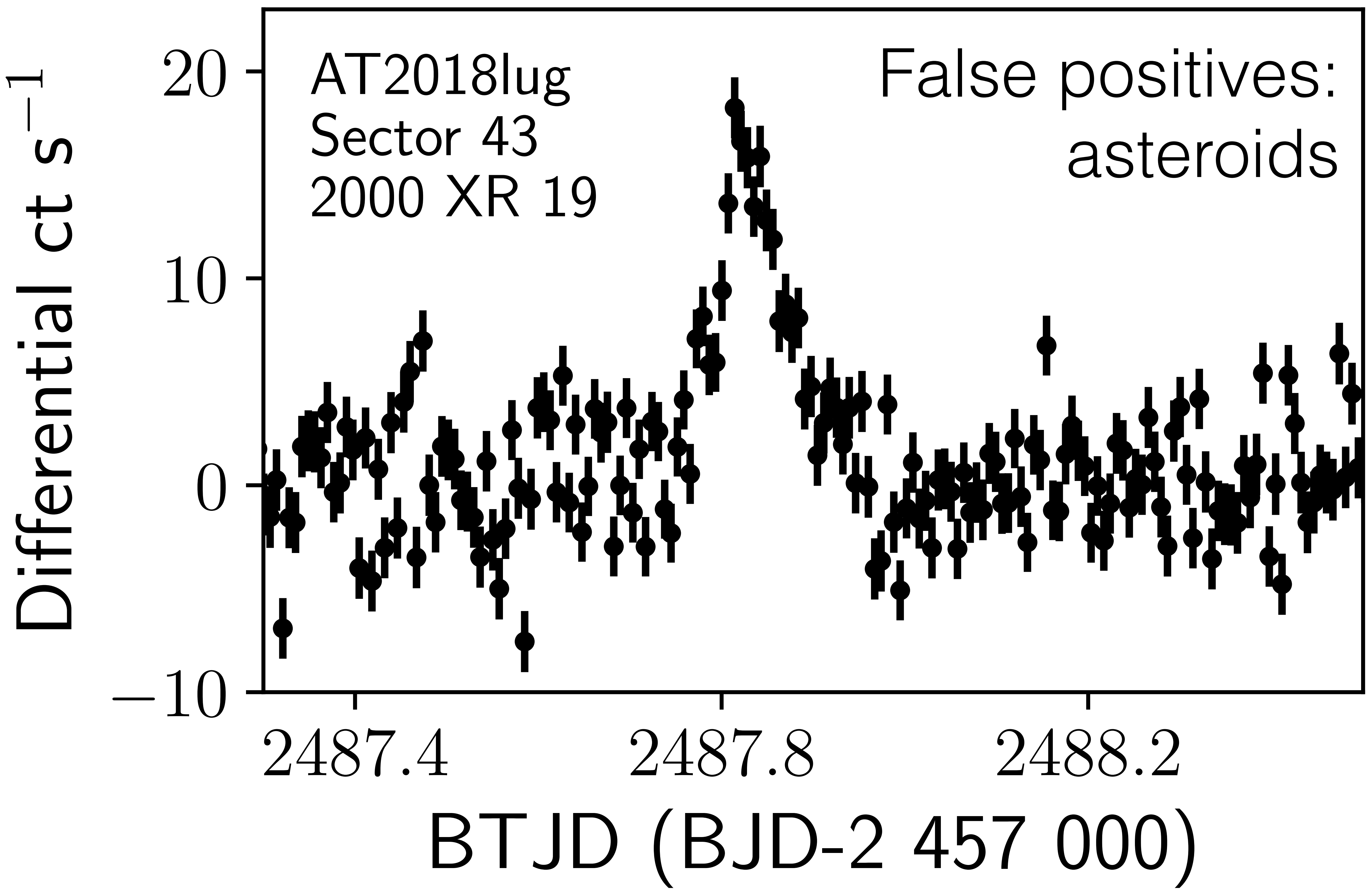


# Summary of flare observations & properties

- 14 flares: 8 telescopes, 60 hours, 20 nights (30-120 days)
- Durations: 10-80 minutes
- No clear periodicity
- Duty cycle 1-10%, time between flares ~ hours
- Red colors (non thermal, near-relativistic)



# TESS search: no additional flares so far (in progress…)




Rahul Jayaraman
(Cornell Klarman
Postdoctoral Fellow)

Next step: blind search (~20 per year?)

“FBOTs” & The Cow
Sub-millimeter emission
Minutes-duration optical flares
→ **Progenitors**

## Literature models

Tidal disruption event

- Intermediate-mass black hole (Kuin+19, Perley+19, Gutiérrez+24)
- Stellar mass black hole (Kremer+21, Metzger 2022, Tsuna & Lu 2025)

Massive star

- Failed supernova (Margutti+19, Perley+19, Quataert+19)
- Merger of Wolf-Rayet star & compact object (Metzger 2022, see also Fryer & Woosley 1998)
- Pulsational pair-instability supernova (Leung+20)
- Magnetar-powered (Mohan+20, Li+24)

Accretion induced collapse of white dwarfs (Lyutikov+19, 22)

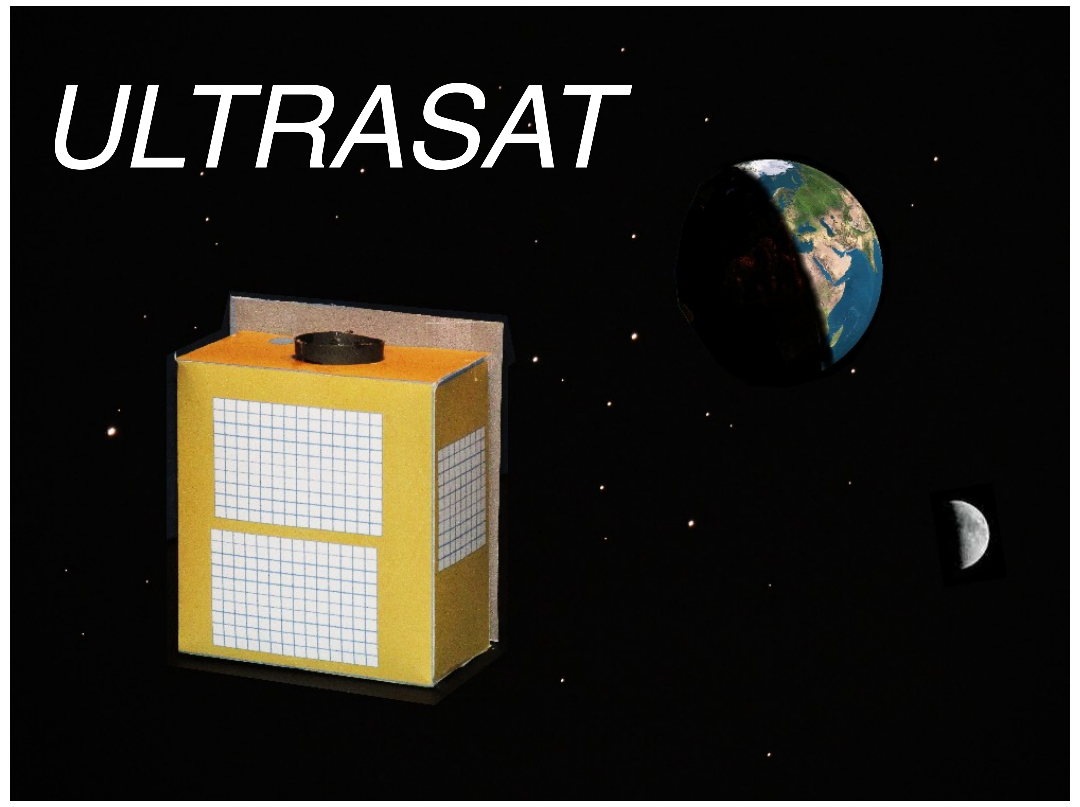
> The only feature that all but one (and perhaps all) of the very many proposed models have in common is that they will not be the explanation of gamma-ray bursts.
>
> *M. Ruderman 1975*

# Path Forward: Wide-field UV Surveys (Upcoming New Capability)

***See talk by Eli Waxman***

ULTRASAT (launch 2027)

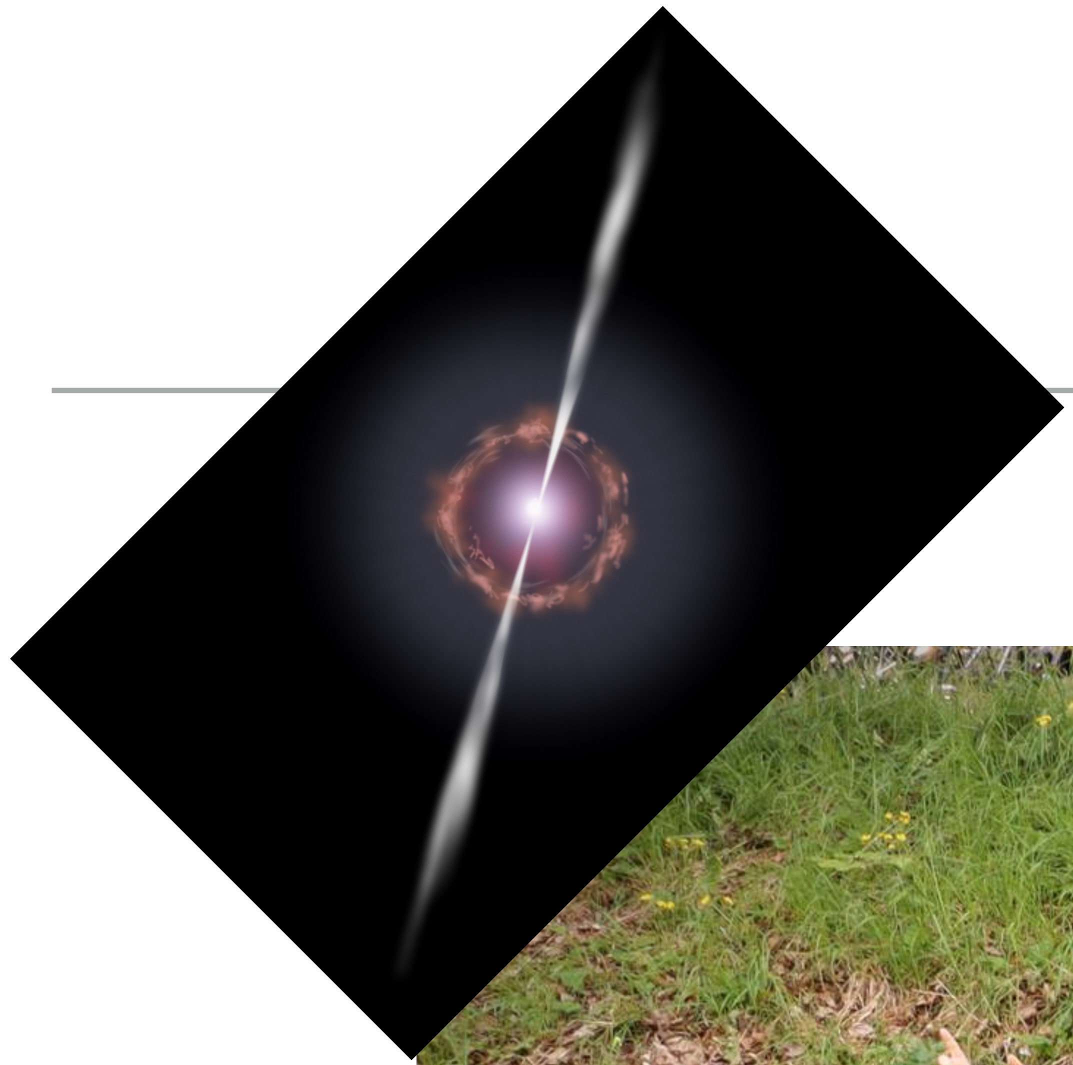
- 22.5 AB mag (5-sigma, 900s)
  - 200 deg$^2$, 5-min cadence
  - 8000 deg$^2$, 4-day cadence




UVEX (launch 2030): NASA MIDEX

- NUV+FUV imaging (12 deg$^2$ FOV, >24.5 AB in 900s 5-sigma)
- Long-slit spectrograph for ToO observations

# Thank you!



**Zwicky Transient Facility Collaboration**

**Long-term collaborators & group members**

Dan Perley, Yuhan Yao, Josh Grajales, Maggie Li, Harlan Phillips, Jack Pope, Marquice Sanchez-Fleming, Genevieve Schroeder, Jason Sevilla, Jada Vail, Kailai Wang

# Summary


2017
Peak Absolute Magnitude
−28
−26
−24
−22
−20
−18
−16
Superluminous supernovae
Tidal disruption flares
RET
Ia SN
.Ia explosions
Core collapse supernovae
Neutron star mergers
Calcium-rich transients
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
Characteristic Timescale (days)
2026
Orphan Afterglows (collapsars)
Orphan Afterglow (TDE)
FBOT Flare
FBOT (18cow-like)
FBOT (SN with dense CSM)
$10^{13}$
$10^{12}$
$10^{11}$
$10^{10}$
$10^{9}$
$10^{8}$
Peak Luminosity ($L_\odot$)
Characteristic Timescale (days)

# Summary

Are GRBs the tip of the iceberg?
- No evidence yet for “dirty fireballs”
- Probably finding slightly off-axis GRBs
- GRBs ~10x less common than Ic-BL SNe

Where are the off-axis GRBs?
- Recent development: large Ic-BL samples
- Systematic radio follow-up out to years
- Promising candidates (stay tuned!)

The Cow & similar events
- Central engine operates for 100 days
- Consistent CSM structure
- Merger of star & compact object?