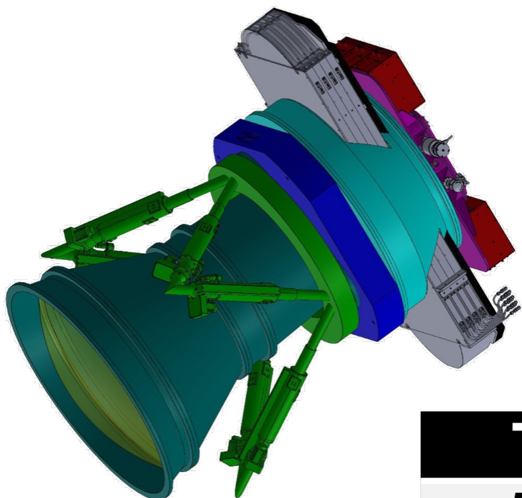
Resolving the supernova UV crisis with Roman:
Enabling science with z > 4 supernovae

Jeff Cooke
Swinburne University

UV-O WFI
Wide-Field Imager

UV-sensitive optical wide-field imager
Goes head-to-head with Roman *(optical vs. IR)*

The most powerful wide-field optical imager on Earth or in space for the foreseeable future (2+ decades)



- Wide fields to depths *(including blue)* of m ~ 29 – 30
- 0.145" per pixel resolution, ~10s readout, ~10s filter change
- Slots for 8 filters: broadband, medium- and narrowband
- Extreme u-band, sensitivity to the near-UV (CMOS chips, too)
- Real-time data reduction pipeline and analysis *(minutes)*
- Minutes-later spectroscopy with deployable secondary mirror

Similar values for Keck or GTC observatories

Time	u	g	r	i	z
5 min	26.7	27.0	26.4	25.7	24.9
30 min	27.7	28.0	27.4	26.7	25.9
2 hr	28.4	28.8	28.1	27.4	26.6
20 hr	29.7	30.0	29.4	28.7	27.9

5 sigma depths, 0.8" FWHM seeing, 3 days from New Moon

Main take-aways

We have entered the **z ~ 2–20** supernova era: Euclid, JWST, Rubin, Roman, and ELT(s)
Note: we have been in the z ~ 2–5 supernova era since ~2009

High-redshift supernovae have high utility *in stellar evolution, galaxy formation and evolution (outflows/feedback, induce/arrest star formation, etc,), cosmic star formation rates and chemical enrichment, impact on the epoch of reionization, measure the high-mass end of the stellar initial mass function, CGM and IGM study, Population III star deaths, pair-instability supernovae, cosmology, etc.*

z ~ 2–10+ supernova detections are *"easy"* *(spectra are harder, but doable)*

- ***However****, we only have a* ***rest-frame optical*** *classification system*
- *Rest-frame optical is redshifted out of the near-IR by z ~ 4, and the mid-IR by z ~ 9*

The largest pressing problem: We have no supernova UV classification system

We currently cannot do science with the ~100 existing z > 2 supernovae, nor the many 1000s to be discovered with Rubin and Roman

- **z ~ 2–4** is where to do build the UV classification system *(but need deep u-band)*
- Roman + ground-based optical can solve this for light curve classification
- 8-10m telescopes, JWST and the ELTs can solve this for spectroscopic classification

The problem

In the 20th century, supernovae SNe were detected by optical surveys
As such, all SNe are classified by their optical light
No classification scheme at any other wavelength

Core collapse SNe (CCSNe) and superluminous SNe (SLSNe) are UV-luminous (much brighter than Type Ias) and can be detected to $z \sim 6$ (CCSNe) and $z \sim 20$ (SLSNe) in deep 8-10m, Rubin, Euclid, and Roman surveys and JWST and ELT programs. Lensed events can be detected farther. These surveys/programs will detect many 1000s at $z \sim 2$–20

- **By $z \sim 4$, SN optical classification features are redshifted out of the near-IR**
- **By $z \sim 9$, SN optical classification features are redshifted out of the mid-IR**

→ Wide-field optical surveys **only observe the rest-frame far-UV**
→ Wide-field near-IR surveys **observe the rest-frame optical to $z \sim 4$, and only the UV at $z \gtrsim 4$**
→ By $z > 9$, all supernovae are detected **only by their rest-frame UV**
(no matter what telescope, mid-IR, etc.)

A UV classification scheme is essential to classify SNe and do science

Why z ~ 2-4?

z ~ 2-4 is the **'sweet spot' -** can observe the rest-frame UV and rest-frame optical for the same supernovae. Can gather 100s of SNe to establish a classification system

Doing this at low redshift is hard

- No extremely deep wide-field UV supernova searches
- UV is triggered after optical detection – miss the rise
  UV evolves faster than optical, need to get full light curves
- Only Hubble can get rest-frame UV spectra, limited lifetime, and only to very low z
- Relatively small volume and low cosmic star formation rate
- Redshift evolution?

Non-intuitively, this is easier at high redshift

- Deep wide-field surveys probe large cosmological volumes, get 100s per deg^2
- The cosmic star formation rate is much higher (and possibly top-heavy IMF)
- Cadenced surveys get the full UV light curve from outburst, peak, and fade
- Time dilation helps in observing epochs, data density, coordinating spectra, etc.
- z ~ 2-4 supernovae more similar to higher redshift events

Detection

Traditional image subtraction method *(has gotten a single or a few data points)*
HST+ Type Ia efforts to z ~ 2 for H_0 *(many authors)*
HST z ~ 2-3 CCSN detections *(e.g., Strolger+15)*
JWST z ~ 2-3 SN detections *(e.g., Frye+24, Pierel+24, DeCoursey+25)*
Unless a well studied field with a wide range of wavelengths, you need to get spectra of each event to know its redshift

Galaxy selection and monitoring method *(full light curves, known redshifts)*
It all started with this method and is the most *efficient* Cooke 08, Cooke+ 09, 12
Know the redshifts ahead of time

If you can detect high-redshift galaxies, you can find UV-luminous SNe
SLSNe and CCSNe are as bright as, or brighter than, their high-z hosts

What is needed to do this effectively
- Wide-field optical for rest-frame UV light curves,10m/ELT for rest-frame UV spectra
- Roman for rest-frame optical light curves and JWST/ELTs for rest-frame optical spectra

Galaxy selection and monitoring

Advantages:

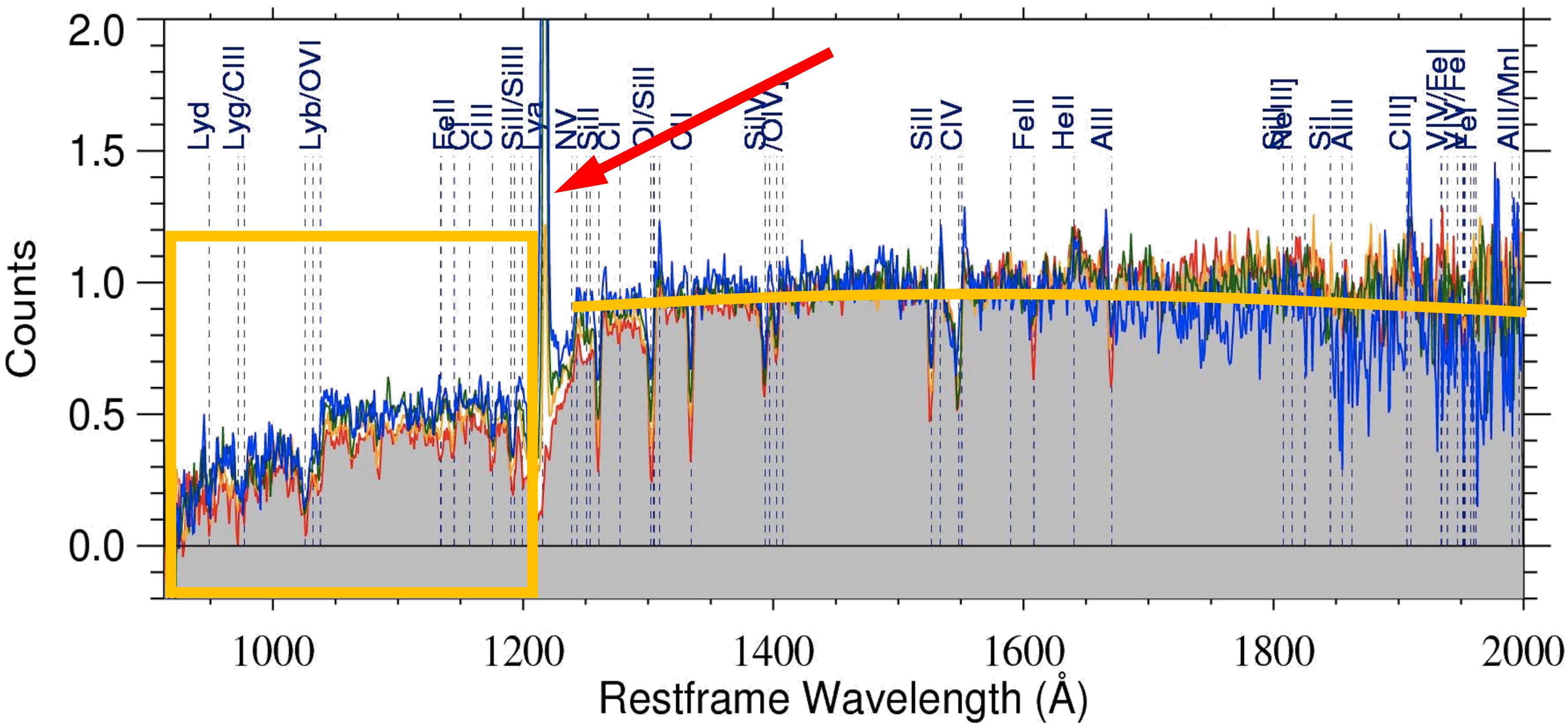
- Avoids ‘fog’ of low-z events and contaminants (and nearly all AGN)
- Get the full UV rise (pre-peak bumps, etc.)
- Know the redshift to z +/- 0.3 – even with a few broadband filters
- Identifies (fast) which transients you should follow up, i.e., with JWST/ELT
  especially when there is only a few broadband filter coverage
  (SED photometry for phot-zs does not exist for very high redshift galaxies)
- Well-defined volume and well-defined galaxy population (SFR, IMF, etc.)
- Depth grows with survey – to reach fainter hosts

Disadvantages:

- Limited to the selected galaxies
  (> 70% of all galaxies and reaches down to ~dwarf galaxies)
- Can miss events with large host separations

z > 2 galaxy selection and monitoring

Lyman break galaxy (star-forming galaxy) far-UV spectra



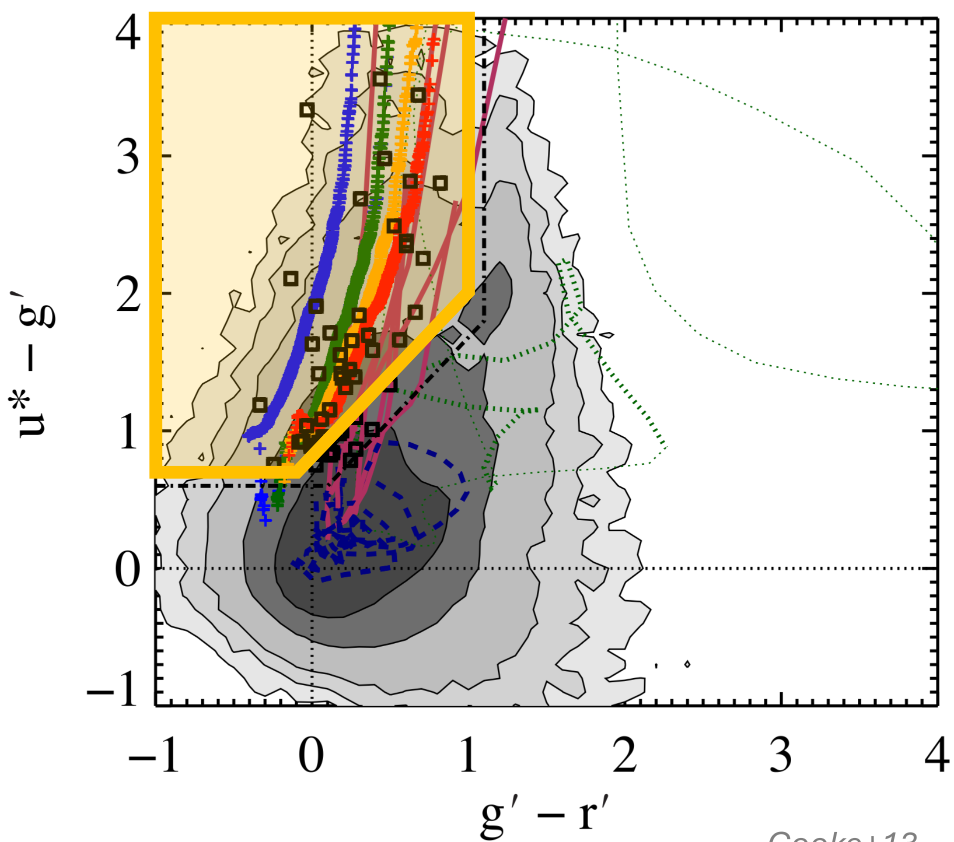
z > 2 galaxy selection and monitoring

(1) Identify high-z galaxies in deep images

Lyman break galaxy selection
Targets star forming galaxies at z > 2
~95% efficient, eliminates nearly all AGN

(2) Monitor the galaxies for flux changes

Time dilation enables
Stacked data (monthly) → detection
Daily or weekly → phot identification
LCs help eliminate any remaining AGN
> 85% spectroscopic confirmation rate

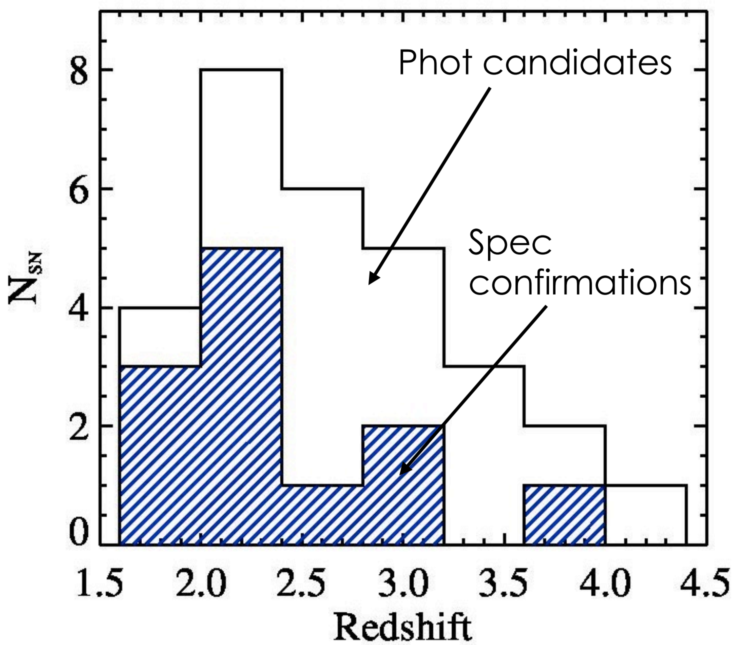


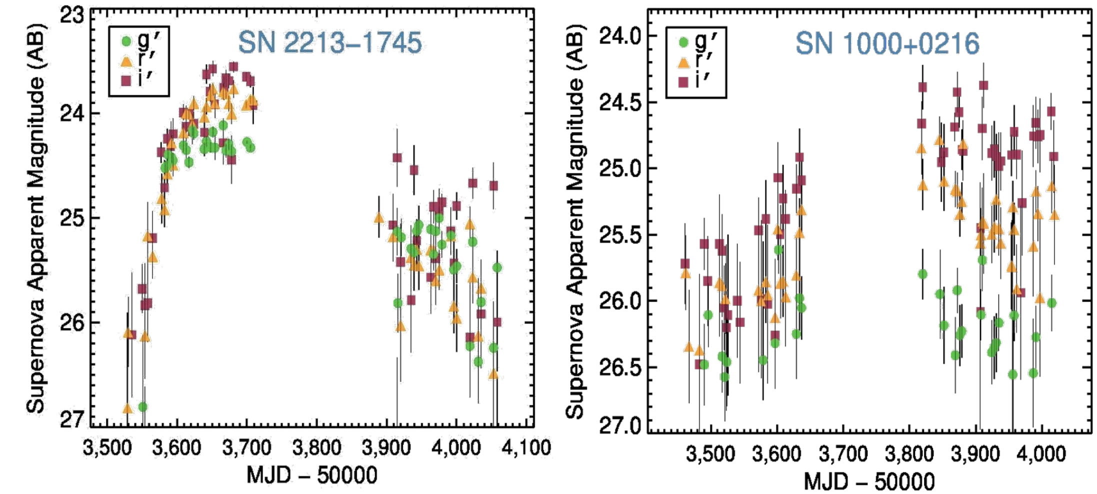
Cooke+13

Detections

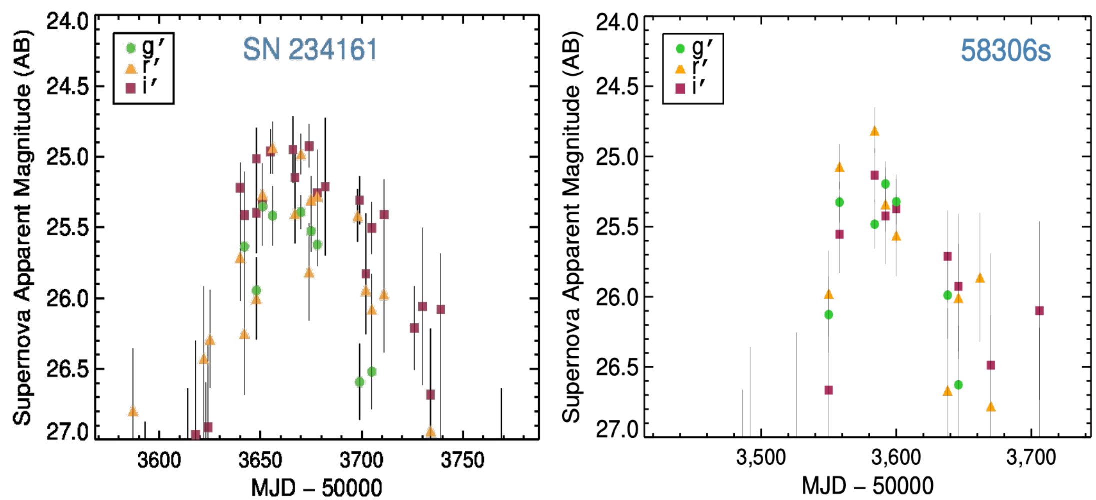
CFHTLS (**3.6m**) – archival search
Deep u-band to m ~27.5

- Five SLSN phot cands, 2 spec-zs
  z = 2.04, 2.5, 3.89, 4.0, 4.5
- ~30 CCSN phot cands, 13 spec-zs



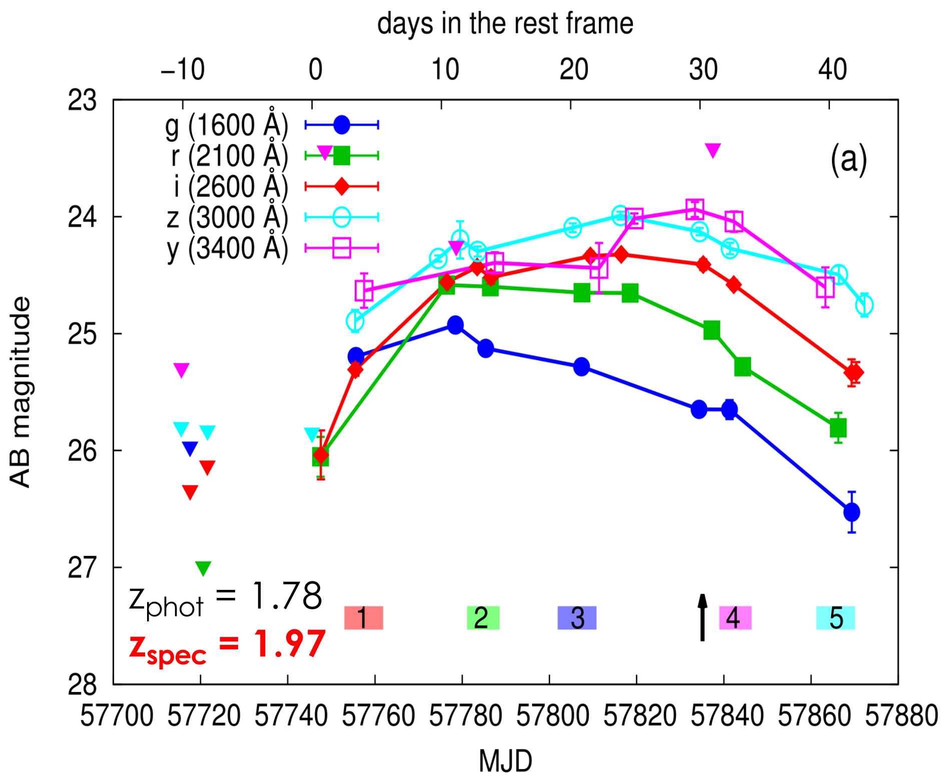


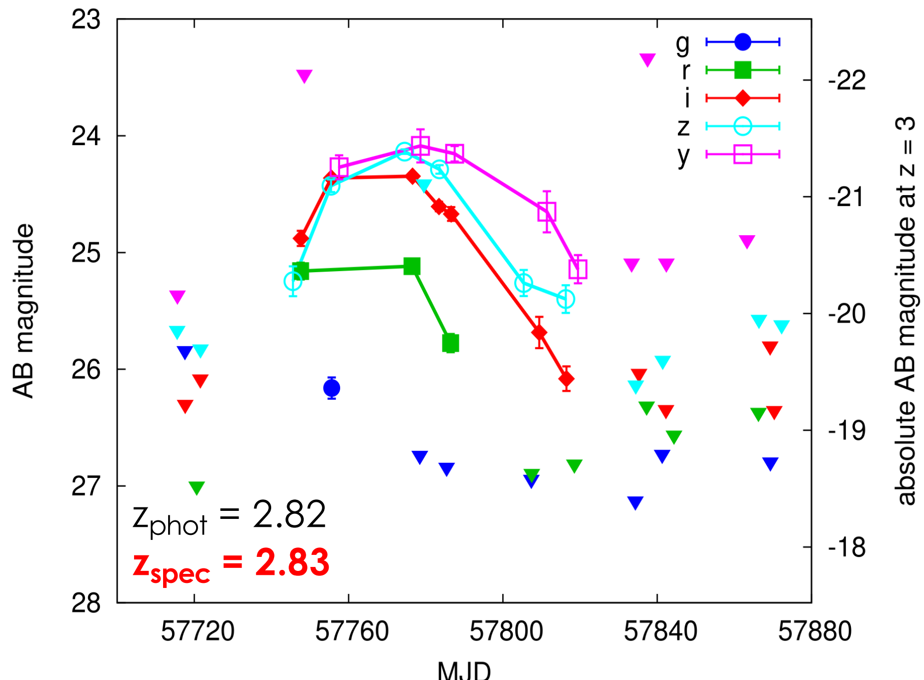
Cooke+12



Detections

SHIZUCA – Subaru (8.2m) HSC-SSP Ultra-Deep + CFHT u-band via the CLAUDS program + Keck spectroscopy





Moriya+19

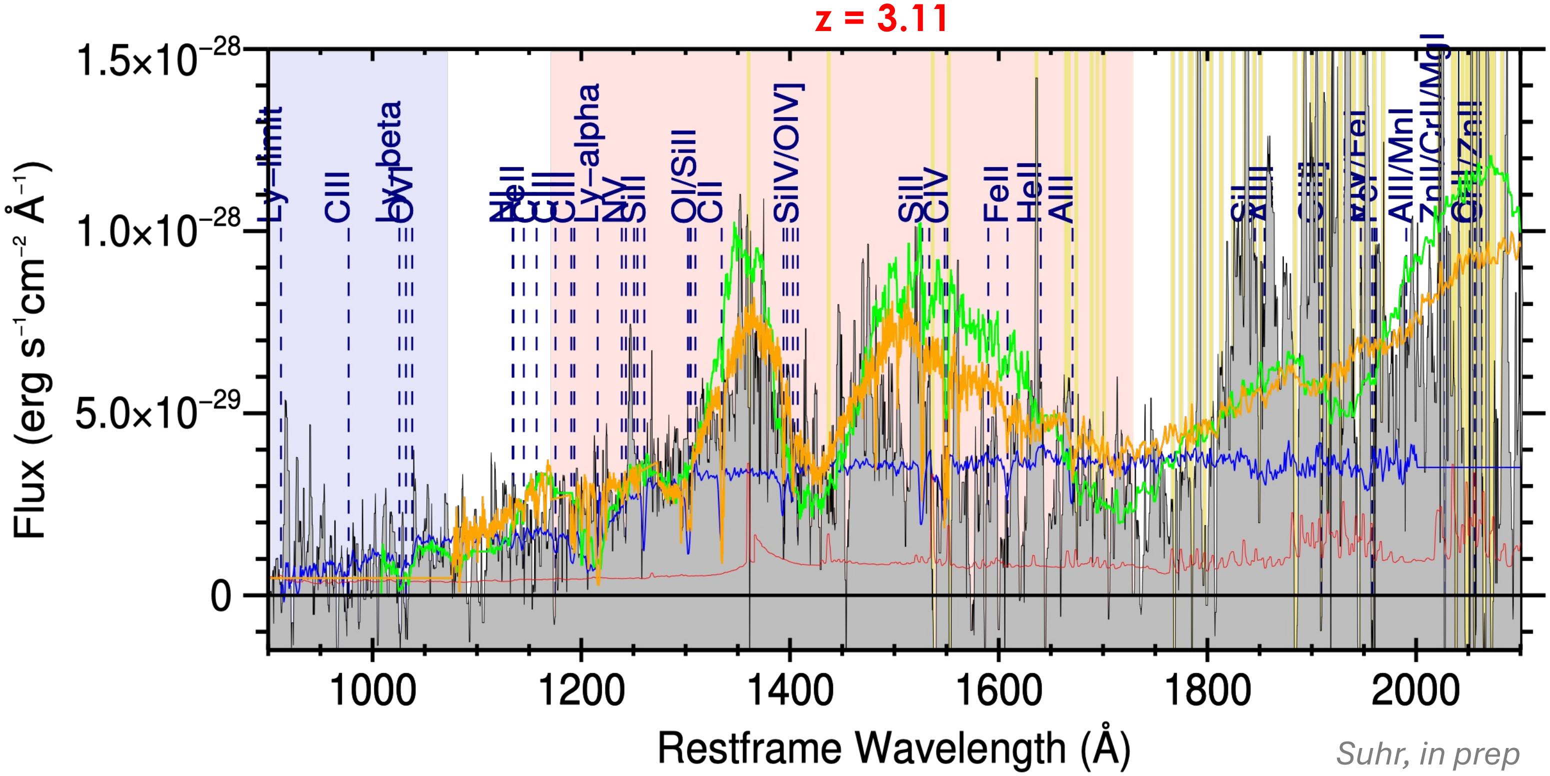
Detections

SHIZUCA – Subaru (8.2m) HSC-SSP Ultra-Deep + CFHT u-band via the CLAUDS program + Keck spectroscopy

SLSN-I faded post-peak

Green spectrum Gaia16apd (peak) *Yan+17*

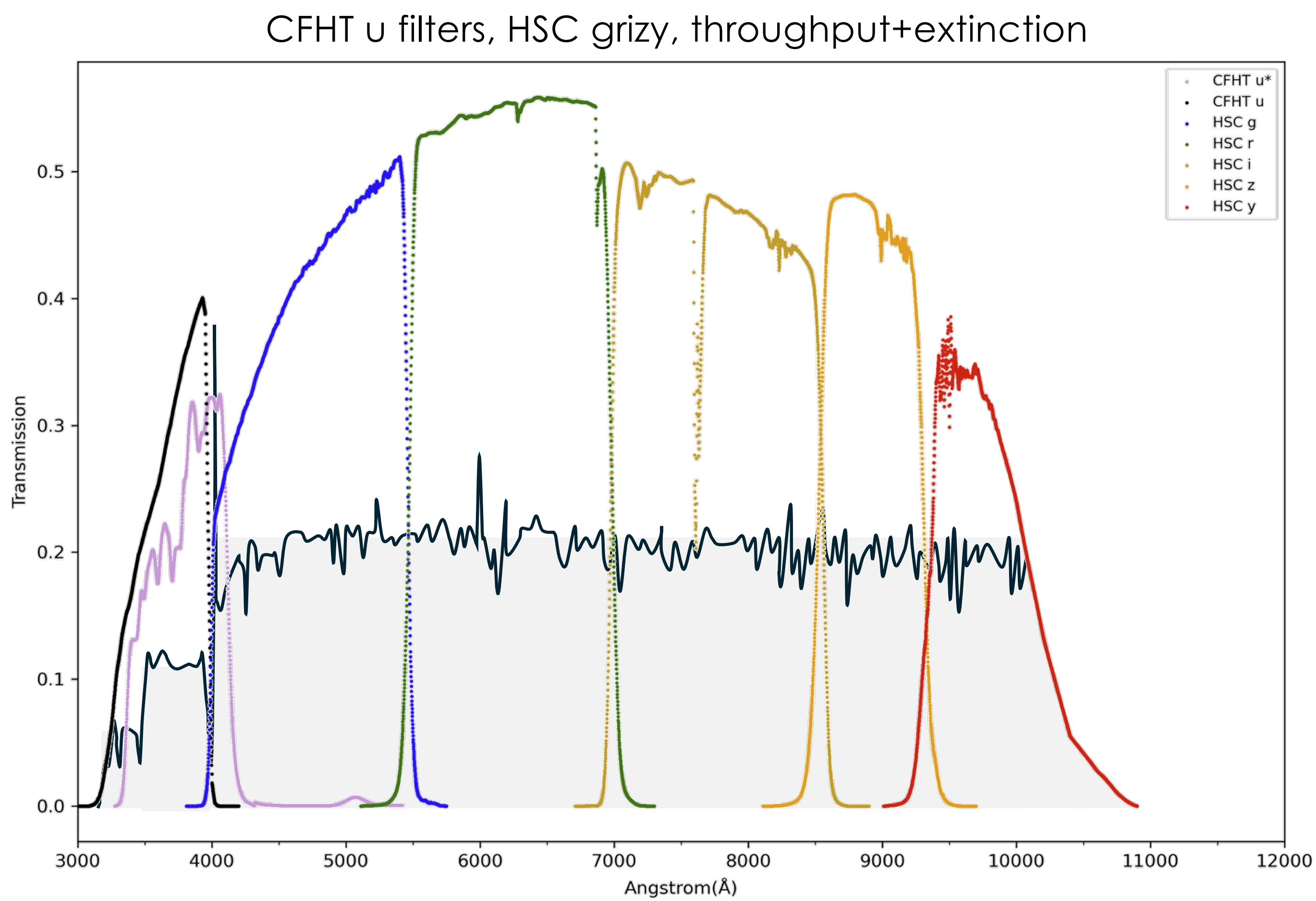
Orange spectrum SN 2017egm (peak) *Yan+18*



Suhr, in prep

Detection

z ~ 2.3

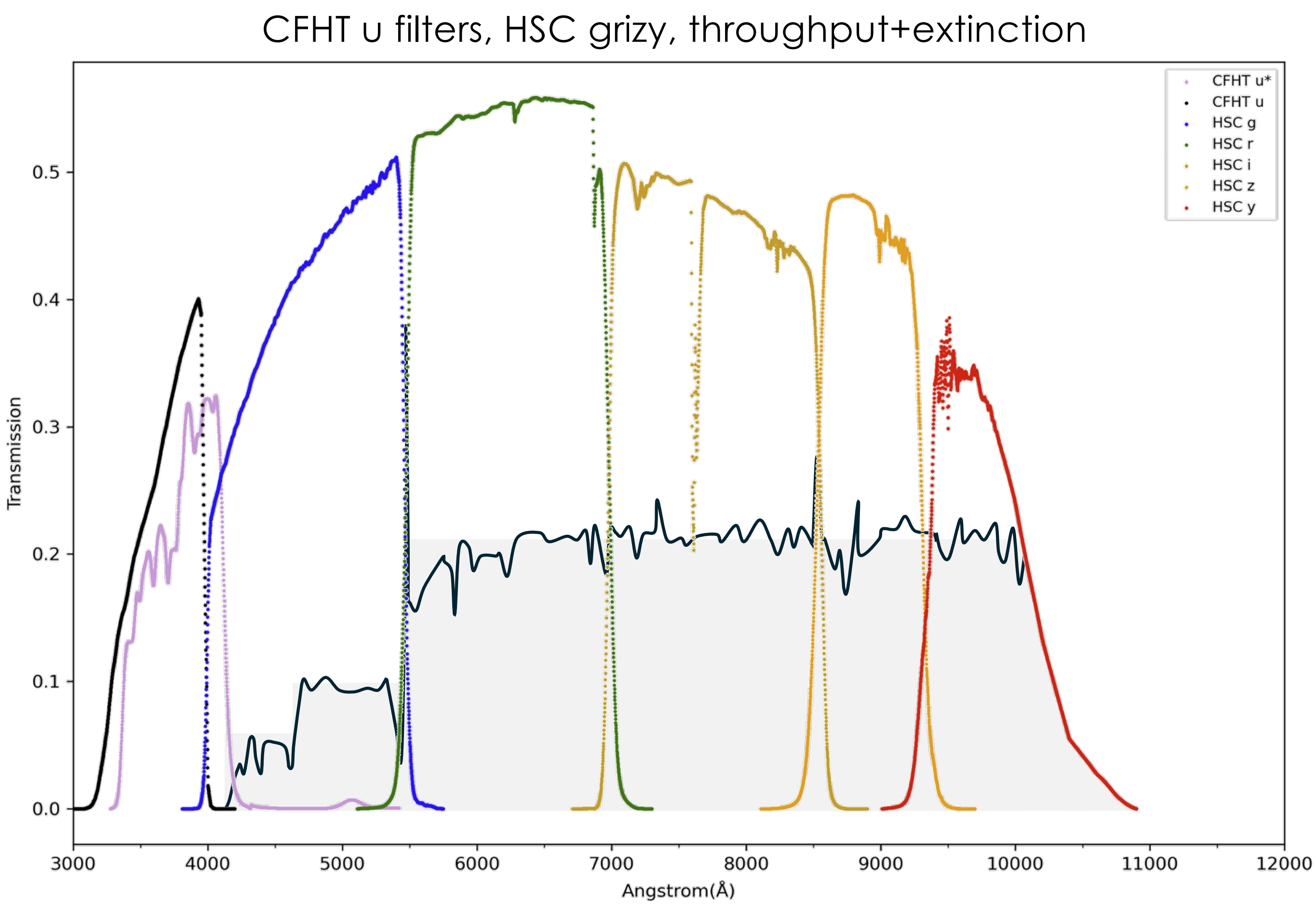


Redshift
Apparent mag of an M = -21 event
Apparent mag of an M = -18 event

z	M = -21	M = -18
2	23.82	26.82
3	24.57	27.57
4	25.07	28.07
5	25.45	28.45
6	25.74	28.74
7	25.99	28.99
8	26.19	29.19
9	26.37	29.37
10	26.53	29.53
11	26.67	29.67
12	26.79	29.79
13	26.91	29.91
14	27.01	30.01
15	27.11	30.11
16	27.20	30.20
17	27.29	30.29
18	27.36	30.36
19	27.44	30.44
20	27.51	30.51

Detection

z ~ 3.5



Redshift

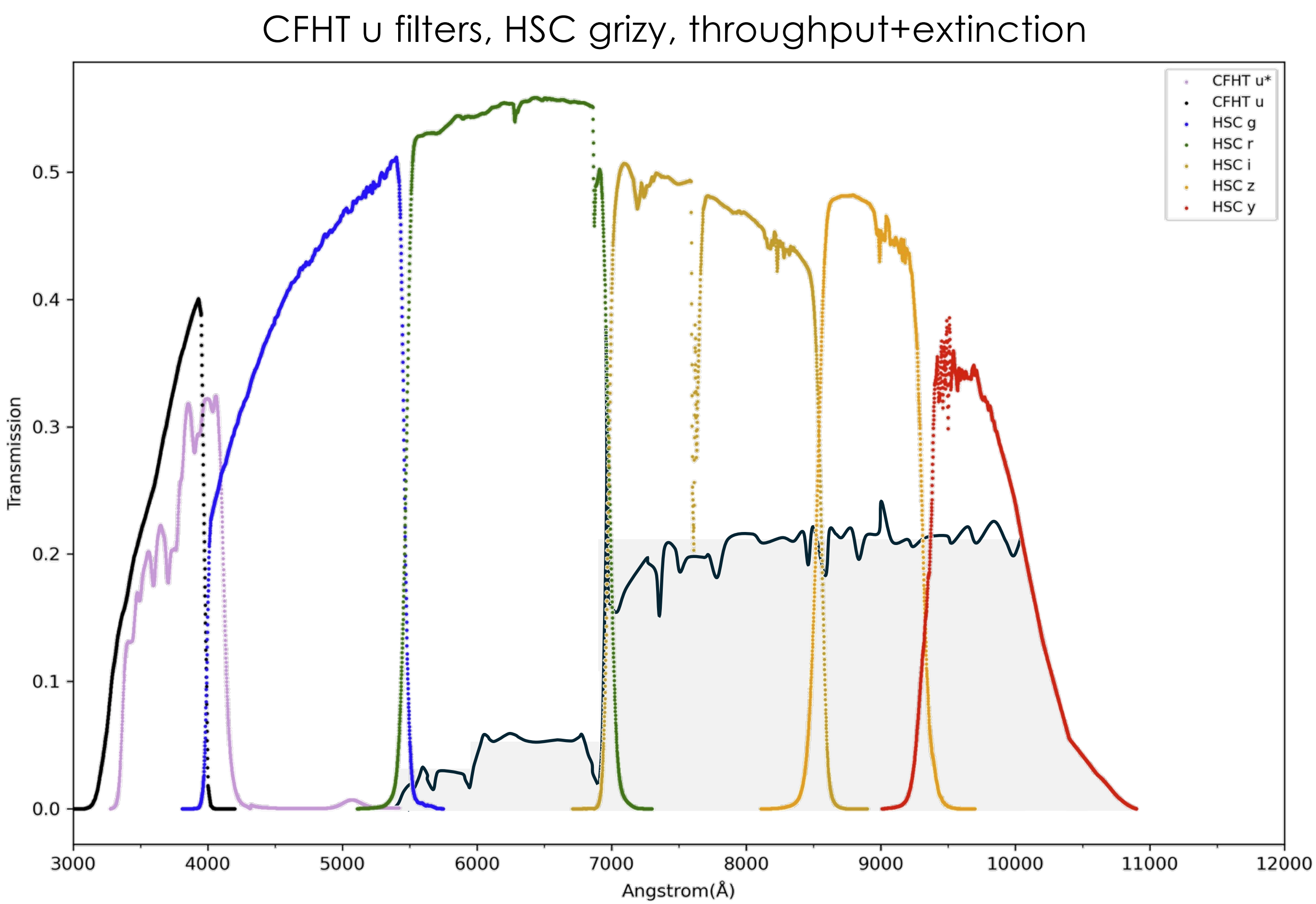
Apparent mag of an M = -21 event

Apparent mag of an M = -18 event

z	M = -21	M = -18
2	23.82	26.82
3	24.57	27.57
4	25.07	28.07
5	25.45	28.45
6	25.74	28.74
7	25.99	28.99
8	26.19	29.19
9	26.37	29.37
10	26.53	29.53
11	26.67	29.67
12	26.79	29.79
13	26.91	29.91
14	27.01	30.01
15	27.11	30.11
16	27.20	30.20
17	27.29	30.29
18	27.36	30.36
19	27.44	30.44
20	27.51	30.51

Detection

z ~ 4.7



Redshift

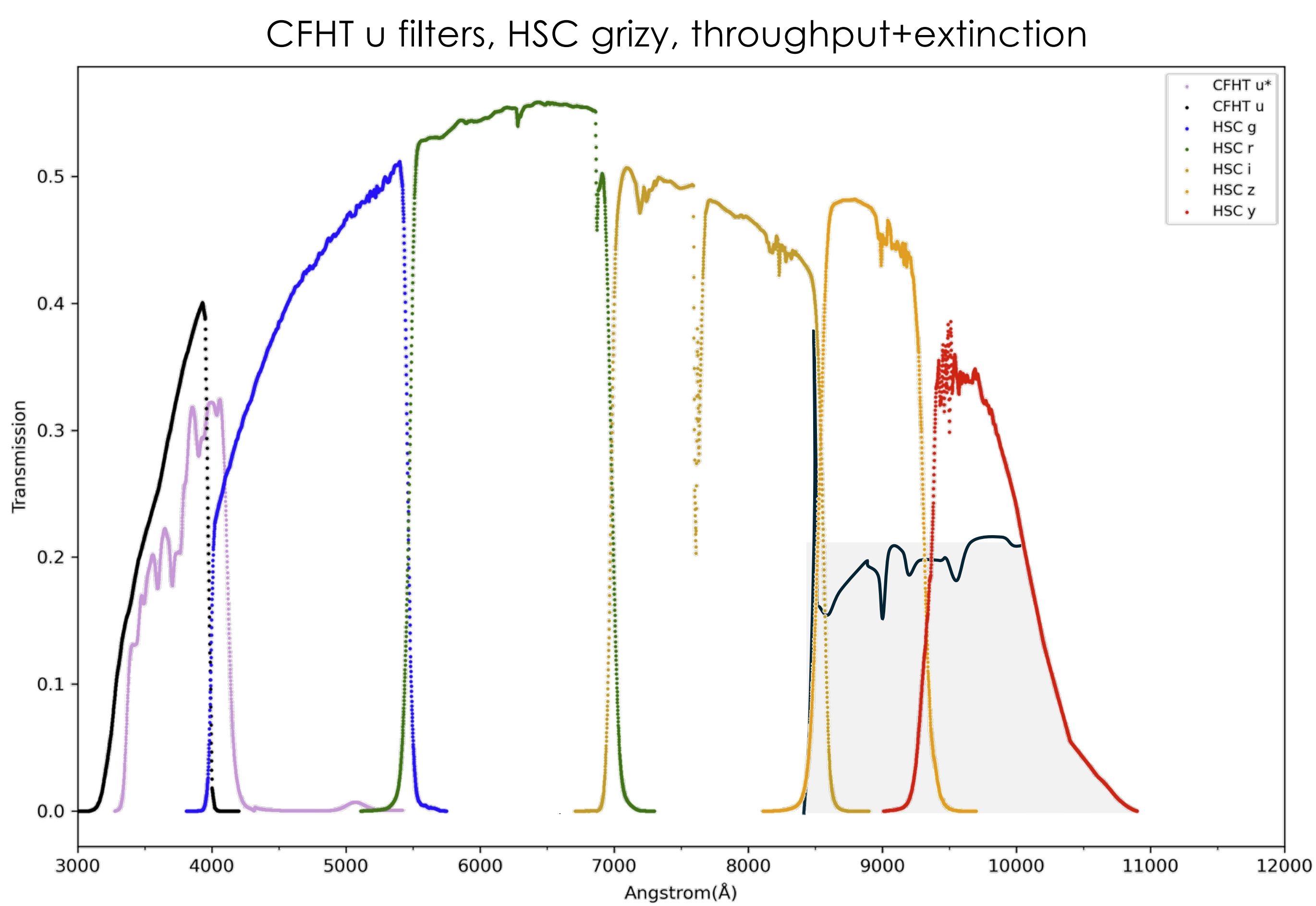
Apparent mag of an M = -21 event

Apparent mag of an M = -18 event

z	M = -21	M = -18
2	23.82	26.82
3	24.57	27.57
4	25.07	28.07
5	25.45	28.45
6	25.74	28.74
7	25.99	28.99
8	26.19	29.19
9	26.37	29.37
10	26.53	29.53
11	26.67	29.67
12	26.79	29.79
13	26.91	29.91
14	27.01	30.01
15	27.11	30.11
16	27.20	30.20
17	27.29	30.29
18	27.36	30.36
19	27.44	30.44
20	27.51	30.51

Detection

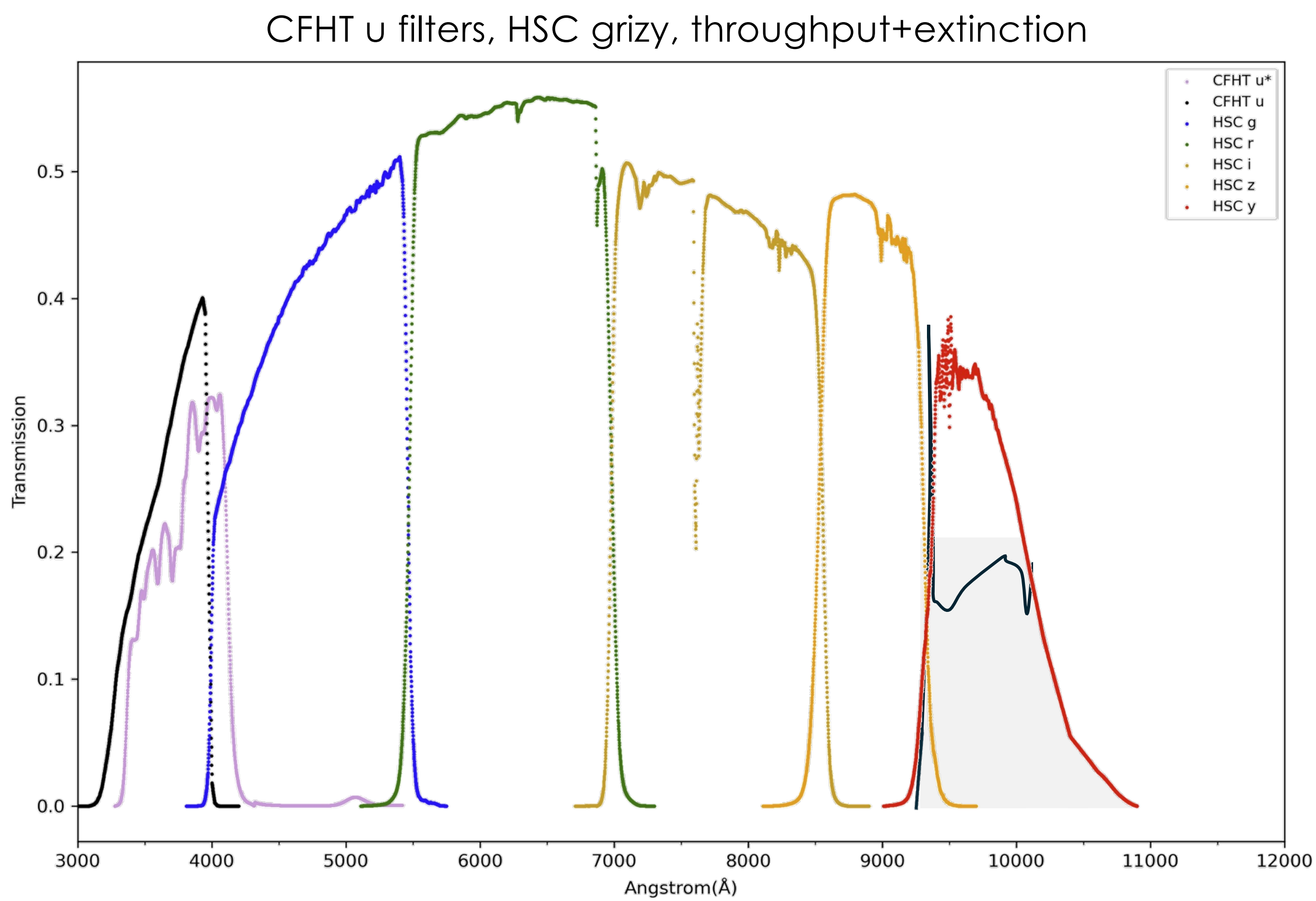
z ~ 6.9



z	M = -21	M = -18
Redshift	Apparent mag of an M = -21 event	Apparent mag of an M = -18 event
2	23.82	26.82
3	24.57	27.57
4	25.07	28.07
5	25.45	28.45
6	25.74	28.74
7	25.99	28.99
8	26.19	29.19
9	26.37	29.37
10	26.53	29.53
11	26.67	29.67
12	26.79	29.79
13	26.91	29.91
14	27.01	30.01
15	27.11	30.11
16	27.20	30.20
17	27.29	30.29
18	27.36	30.36
19	27.44	30.44
20	27.51	30.51

Detection

z ~ 7.7

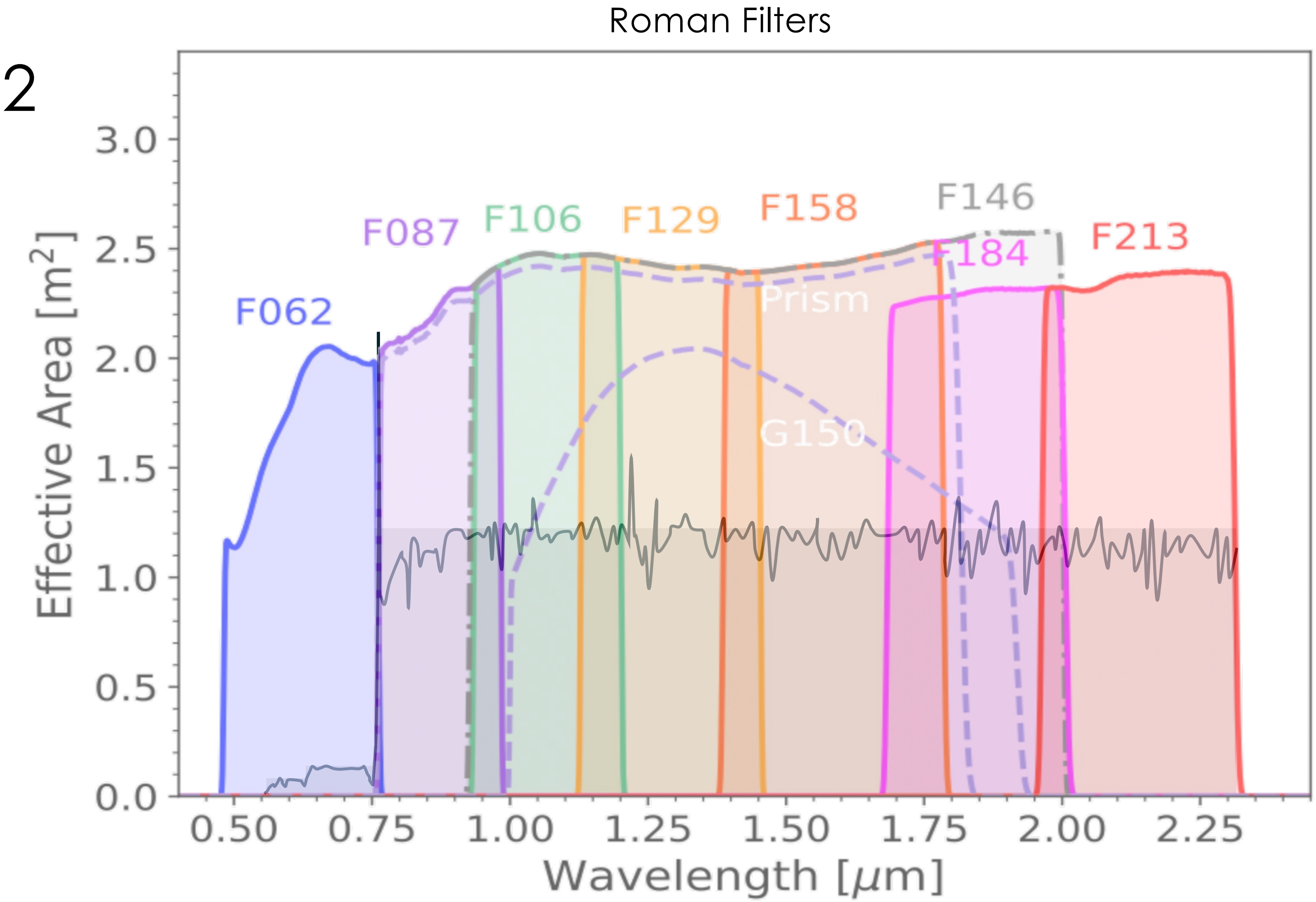


Redshift | Apparent mag of an M = -21 event | Apparent mag of an M = -18 event

z	M = -21	M = -18
2	23.82	26.82
3	24.57	27.57
4	25.07	28.07
5	25.45	28.45
6	25.74	28.74
7	25.99	28.99
8	26.19	29.19
9	26.37	29.37
10	26.53	29.53
11	26.67	29.67
12	26.79	29.79
13	26.91	29.91
14	27.01	30.01
15	27.11	30.11
16	27.20	30.20
17	27.29	30.29
18	27.36	30.36
19	27.44	30.44
20	27.51	30.51

Detection

z ~ 5.2

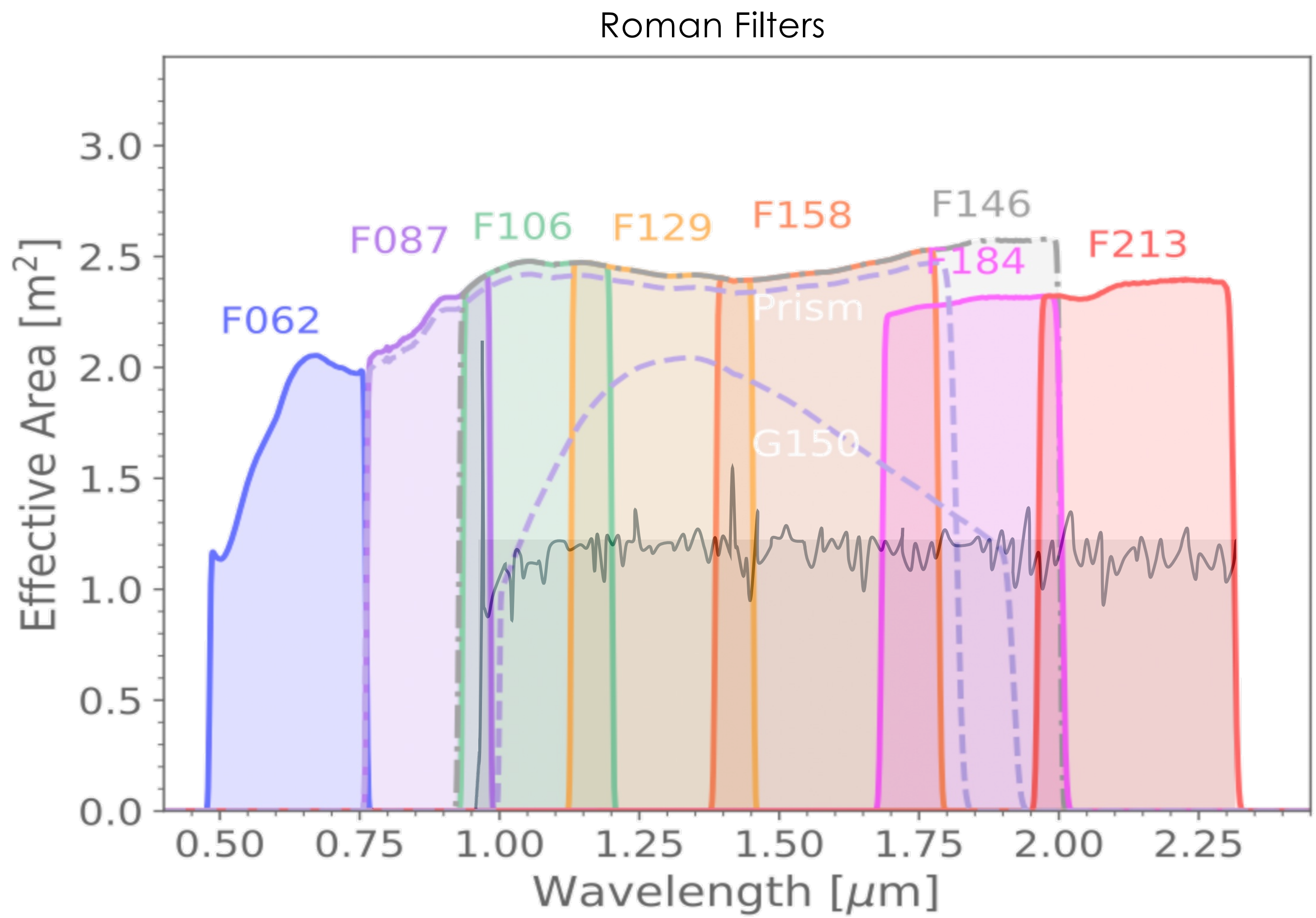


Redshift
Apparent mag of an M = -21 event
Apparent mag of an M = -18 event

z	M = -21	M = -18
2	23.82	26.82
3	24.57	27.57
4	25.07	28.07
5	25.45	28.45
6	25.74	28.74
7	25.99	28.99
8	26.19	29.19
9	26.37	29.37
10	26.53	29.53
11	26.67	29.67
12	26.79	29.79
13	26.91	29.91
14	27.01	30.01
15	27.11	30.11
16	27.20	30.20
17	27.29	30.29
18	27.36	30.36
19	27.44	30.44
20	27.51	30.51

Detection

z ~ 7

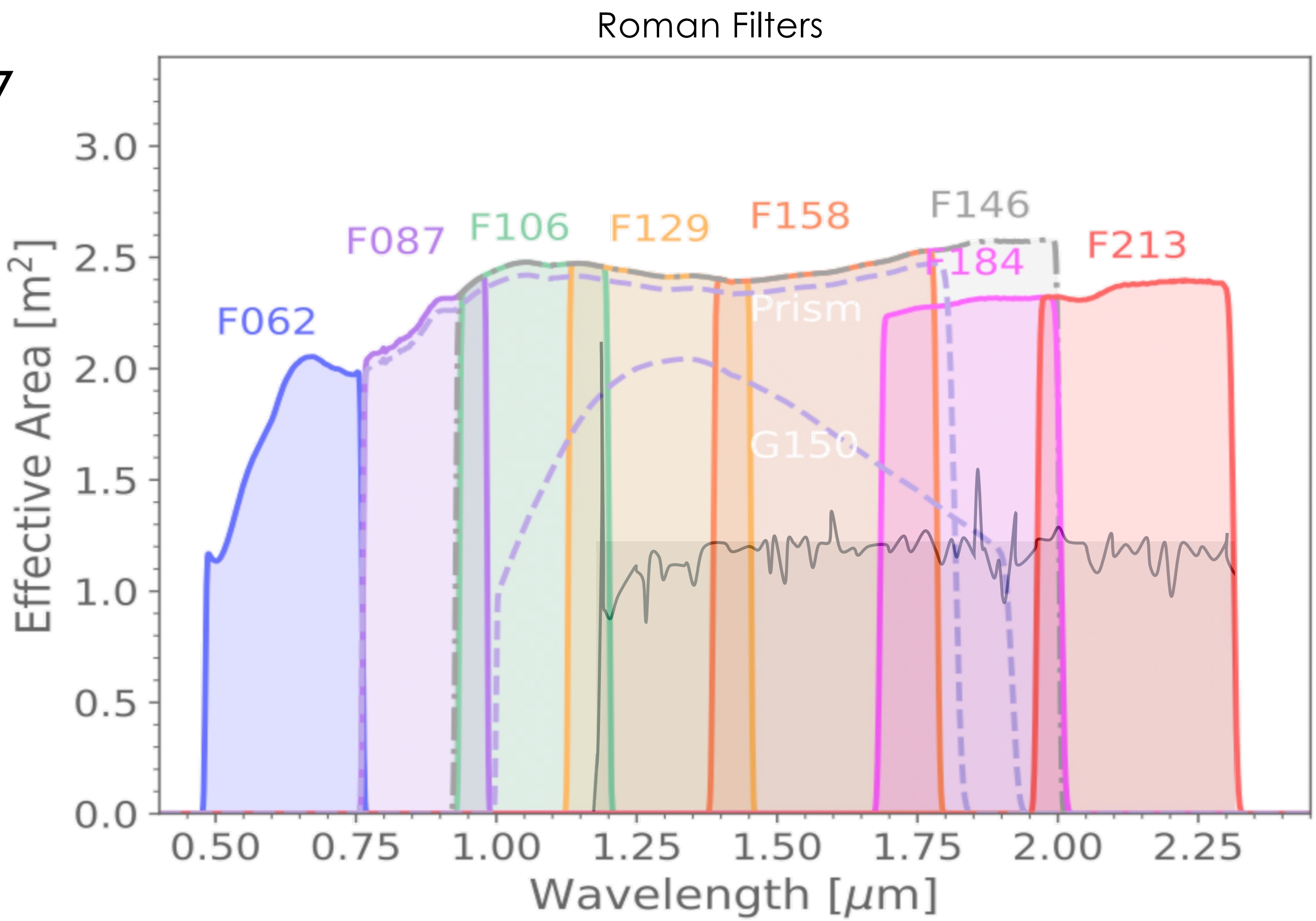


Redshift
Apparent mag of an M = -21 event
Apparent mag of an M = -18 event

z	M = -21	M = -18
2	23.82	26.82
3	24.57	27.57
4	25.07	28.07
5	25.45	28.45
6	25.74	28.74
7	25.99	28.99
8	26.19	29.19
9	26.37	29.37
10	26.53	29.53
11	26.67	29.67
12	26.79	29.79
13	26.91	29.91
14	27.01	30.01
15	27.11	30.11
16	27.20	30.20
17	27.29	30.29
18	27.36	30.36
19	27.44	30.44
20	27.51	30.51

Detection

z ~ 8.7



Redshift

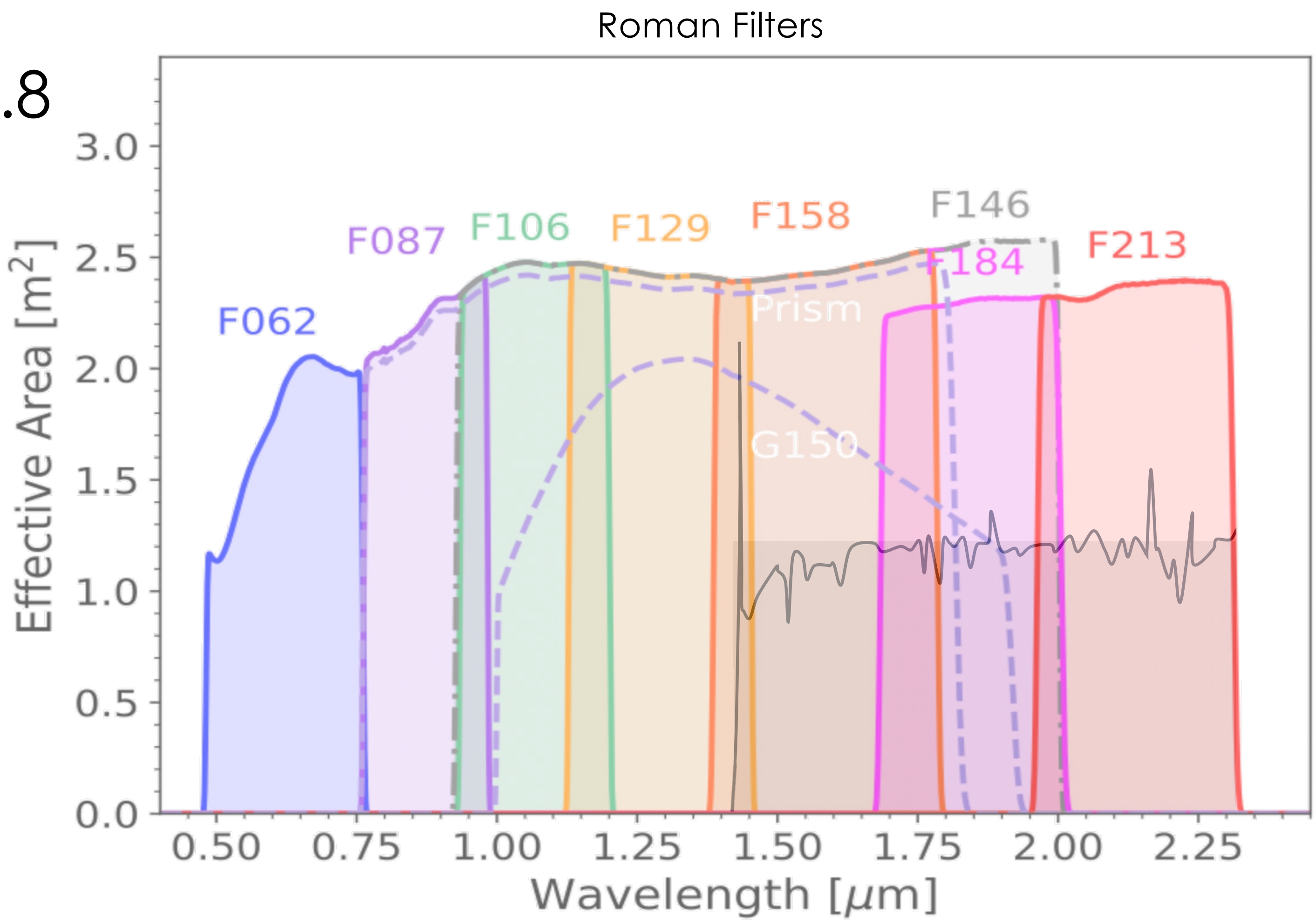
Apparent mag of an M = -21 event

Apparent mag of an M = -18 event

z	M = -21	M = -18
2	23.82	26.82
3	24.57	27.57
4	25.07	28.07
5	25.45	28.45
6	25.74	28.74
7	25.99	28.99
8	26.19	29.19
9	26.37	29.37
10	26.53	29.53
11	26.67	29.67
12	26.79	29.79
13	26.91	29.91
14	27.01	30.01
15	27.11	30.11
16	27.20	30.20
17	27.29	30.29
18	27.36	30.36
19	27.44	30.44
20	27.51	30.51

Detection

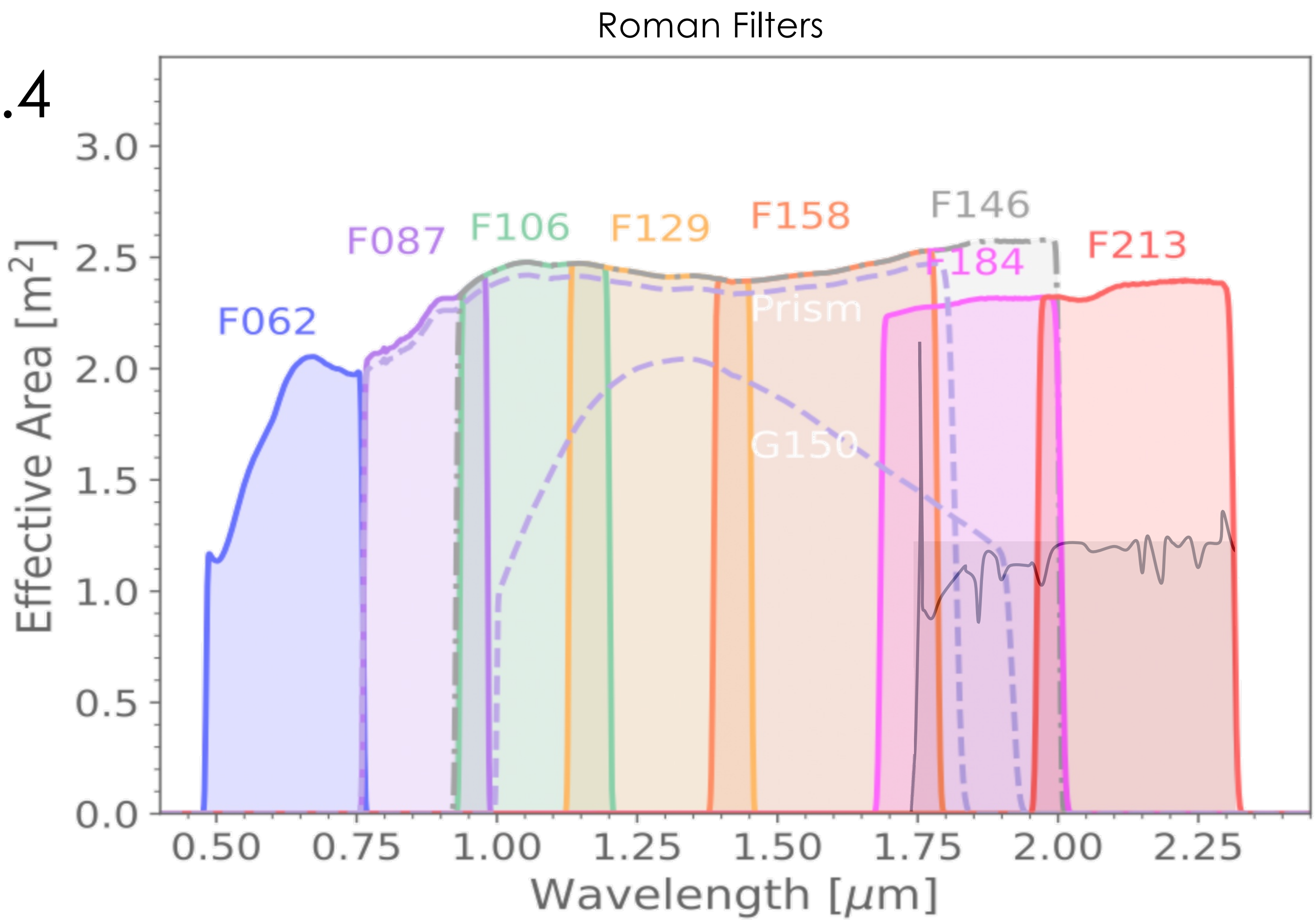
z ~ 10.8



z	M = -21	M = -18
Redshift	Apparent mag of an M = -21 event	Apparent mag of an M = -18 event
2	23.82	26.82
3	24.57	27.57
4	25.07	28.07
5	25.45	28.45
6	25.74	28.74
7	25.99	28.99
8	26.19	29.19
9	26.37	29.37
10	26.53	29.53
11	26.67	29.67
12	26.79	29.79
13	26.91	29.91
14	27.01	30.01
15	27.11	30.11
16	27.20	30.20
17	27.29	30.29
18	27.36	30.36
19	27.44	30.44
20	27.51	30.51

Detection

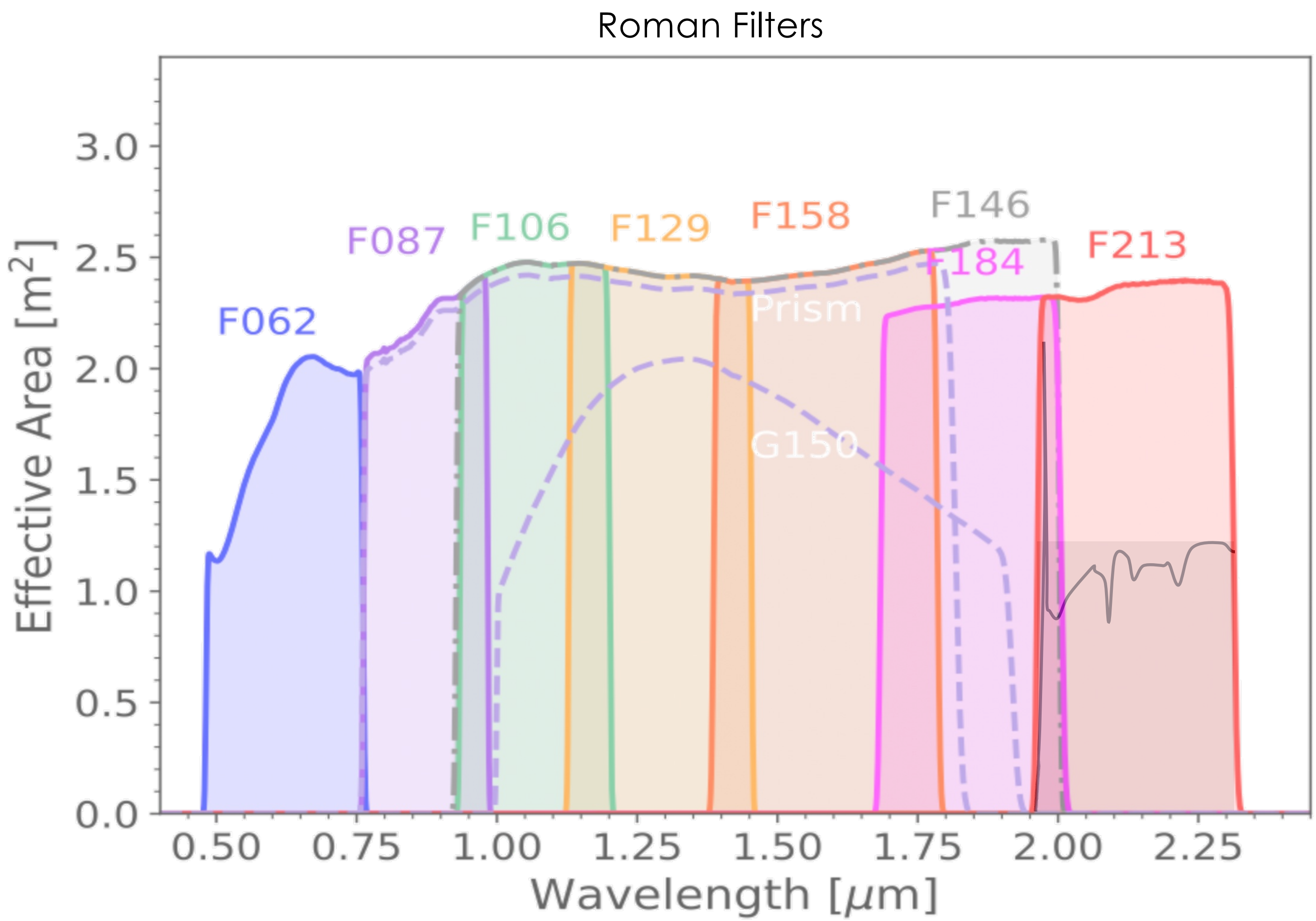
z ~ 13.4



Redshift	Apparent mag of an M = -21 event	Apparent mag of an M = -18 event
z	M = -21	M = -18
2	23.82	26.82
3	24.57	27.57
4	25.07	28.07
5	25.45	28.45
6	25.74	28.74
7	25.99	28.99
8	26.19	29.19
9	26.37	29.37
10	26.53	29.53
11	26.67	29.67
12	26.79	29.79
13	26.91	29.91
14	27.01	30.01
15	27.11	30.11
16	27.20	30.20
17	27.29	30.29
18	27.36	30.36
19	27.44	30.44
20	27.51	30.51

Detection

z ~ 15



Redshift

Apparent mag of an M = -21 event

Apparent mag of an M = -18 event

z	M = -21	M = -18
2	23.82	26.82
3	24.57	27.57
4	25.07	28.07
5	25.45	28.45
6	25.74	28.74
7	25.99	28.99
8	26.19	29.19
9	26.37	29.37
10	26.53	29.53
11	26.67	29.67
12	26.79	29.79
13	26.91	29.91
14	27.01	30.01
15	27.11	30.11
16	27.20	30.20
17	27.29	30.29
18	27.36	30.36
19	27.44	30.44
20	27.51	30.51

Need for Roman

HLTDS - Deep ~6.5 deg^2, 10d cadence, ~26.6 per epoch, stack m ~ 29.2
Wide ~18.3deg^2, 10d cadence, ~25.4-26.4 per epoch, stack m ~ 28-29

Help detect SNe for other facility follow up

RXDF in the NEP: JWST NEXUS, Euclid Ultra-Deep Field, other wavelength data
RXDF (deeper and wider wavelength range than NEXUS)
Area – ~700 arcmin^2 (full), >1200 arcmin^2 (m > 28.5), 3 yrs, 3 epochs per yr (~10 d apart)
Per epoch depths – about a mag less

	(U)	(G)	F062 (R)	F087 (Z)	F106 (Y)	F129 (J)	F158 (H)	F184 (F)	F213 (K)
RXDF			30.6 hrs	53.5 hrs	55.4 hrs	65.4 hrs	73.2 hrs	36.5 hrs	60.4 hrs
5σ, $r = 0.2''$			30.0 mag	30.0 mag	30.0 mag	30.0 mag	30.0 mag	29.0 mag	28.0 mag
UV-O **WFI** $5\sigma, r = 0.2''$	30.4 hrs	19.5 hrs							
	30.0 mag	30.0 mag							

(0.8" seeing, near New Moon, single pointing covers more than the RXDF field)

Need for Roman

The depth and wide field of Roman is essential for high-z SN ***detection and light curves***

- ***Roman will get rest-frame optical for z ~ 2–4***
  to connect with the UV from optical surveys to establish a UV classification system
- ***Roman will get rest-frame near-UV and far-UV for z ~ 4–9****,*
  tying the two regimes
- ***Roman will get rest-frame far-UV for z ~ 4–15***
  JWST can get mid-IR rest-frame optical imaging and spectroscopy up to z ~ 9

Host galaxies *– Roman high-res imaging, morphology, star forming regions, SN location, etc. Also, eliminate any line-of-sight contaminants*

The Community programs and Cycle 1-2(3) RXDF will enable hundreds of z ~ 2–15 SNe

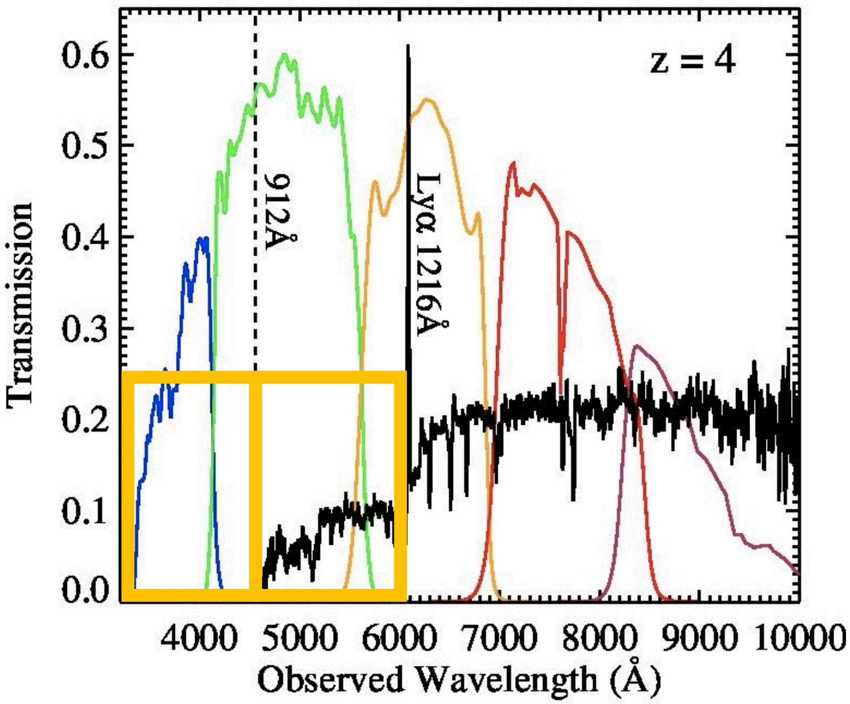
Other programs will complement Roman observation cadence

Summary

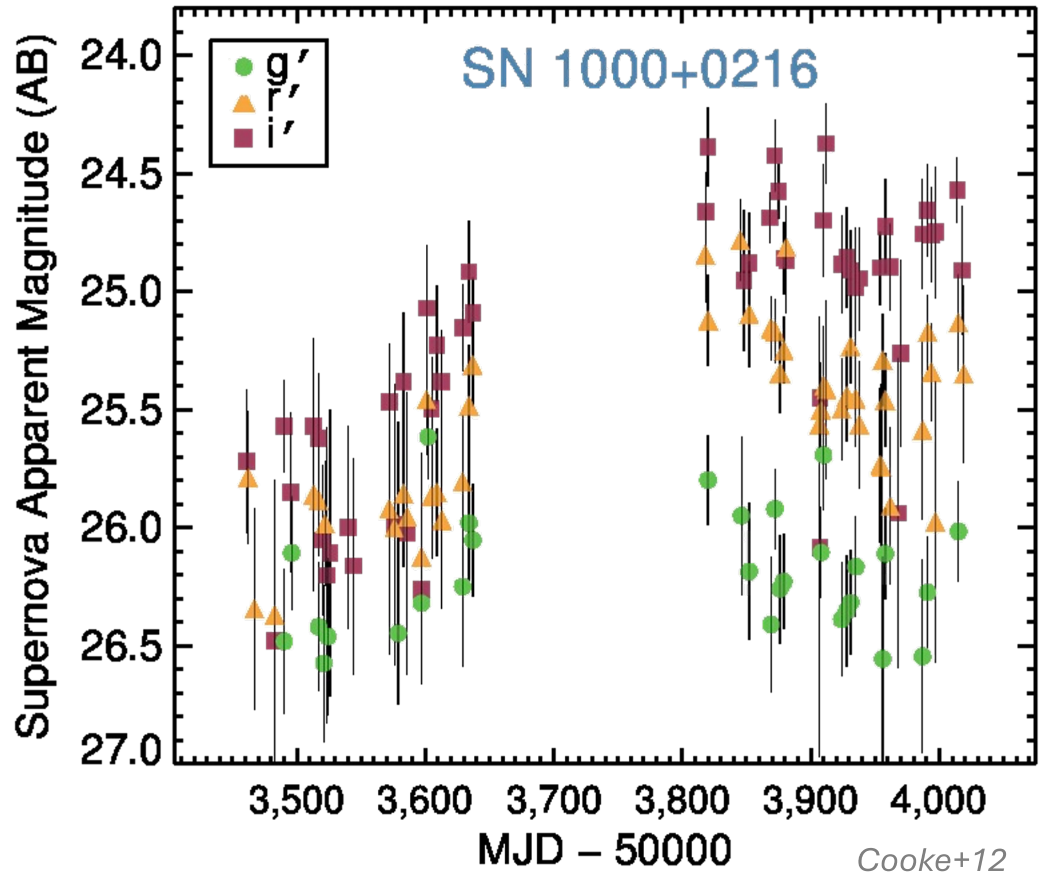
- CCSNe can be detected to z ~ 6+ with current technology and Roman
  SLSNe can be detected to z ~ 20+ *(z ~ 15 with Roman, higher with JWST)*
- Supernova detections are *"easy" using galaxy selection & monitoring*
- *Best to use galaxy selection & monitoring along with traditional methods*
- The largest pressing problem: **UV classification scheme**
  - Solution is to get optical and infrared (rest-frame UV and optical) light curves and spectra of the same z ~ 2–4 SNe
  - Need a large number to get samples of all types and various phases
- Roman Community programs and the RXDF, along with coordinated efforts from ground-based 8-10m telescope *(also UV-WFI)* and, later, the ELTs are needed to establish a UV classification system and enable us to do science with all existing and future z > 2 SNe

Lyman α forest / continuum

CFHT Megacam filters



z = 3.9



Cooke+12

Lyman α forest decreases with redshift,
Universe fully opaque by z ~ 6