Astro 2020 Decadal Survey White Paper: Can JWST Detect Pop III Objects Directly via Caustic Transits?

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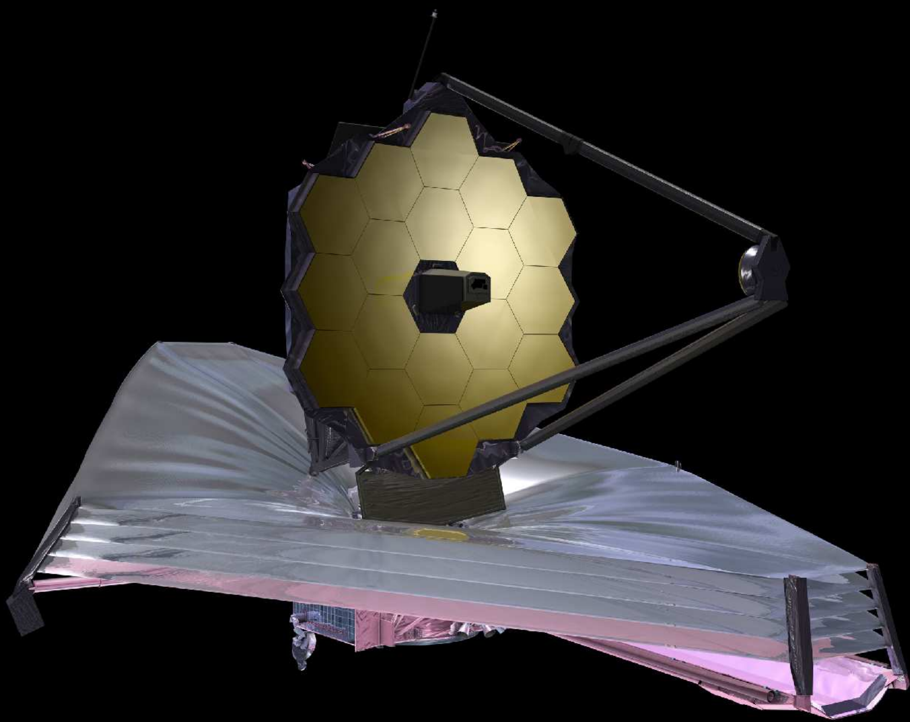

- Today, the JWST science remains as compelling as it was ∼20 years ago.
- In fact, the JWST science is far more exciting today than we could have imagined or planned for ∼20 years ago.

Talk at the JWST Science Working Group — Apr. 3, 2019

Talk is on: `http://www.asu.edu/clas/hst/www/jwst/jwsttalks/jwst_caustictransitsWP_03apr19.pdf`

Outline & Conclusions

(1a) The principle of cluster caustic transits: Extreme magnifications.

(1b) HST observations of OB-star caustic transits at $z \simeq 1$–1.5

(2a) Limits to the SKY-SB of Pop III objects: First Stars

(2b) Limits to the SKY-SB of Pop III objects: Black Holes

(3) Conclusions:

- In the best lensing clusters, JWST may detect caustic transits of Pop III stars and their stellar-mass black hole accretion disks at $z \gtrsim 7$.

- It will need to monitor $\gtrsim 3$ clusters for years to see this.

(1a) The principle of cluster caustic transits: Extreme magnifications.

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On the Observability of Individual Population III Stars and Their Stellar-mass Black Hole Accretion Disks through Cluster Caustic Transits

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Abstract

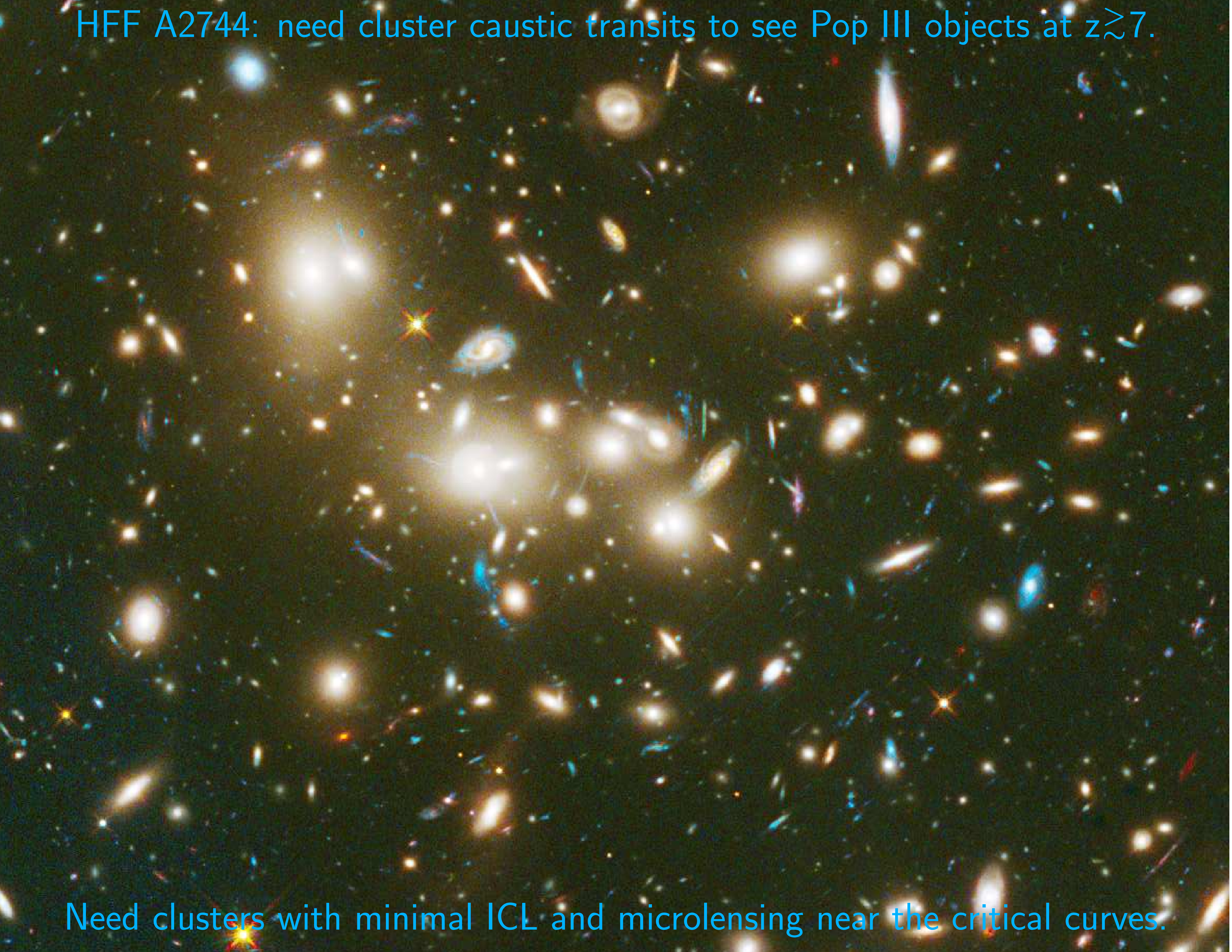
We summarize panchromatic Extragalactic Background Light data to place upper limits on the integrated near-infrared surface brightness (SB) that may come from Population III stars and possible accretion disks around their stellar-mass black holes (BHs) in the epoch of First Light, broadly taken from $z \simeq 7$–17. Theoretical predictions and recent near-infrared power spectra provide tighter constraints on their sky signal. We outline the physical properties of zero-metallicity Population III stars from MESA stellar evolution models through helium depletion and of BH accretion disks at $z \gtrsim 7$. We assume that second-generation non-zero-metallicity stars can form at higher multiplicity, so that BH accretion disks may be fed by Roche-lobe overflow from lower-mass companions. We use these near-infrared SB constraints to calculate the number of caustic transits behind lensing clusters that the *James Webb Space Telescope* and the next-generation ground-based telescopes may observe for both Population III stars and their BH accretion disks. Typical caustic magnifications can be $\mu \simeq 10^4$–10^5, with rise times of hours and decline times of $\lesssim$1 year for cluster transverse velocities of $v_T \lesssim 1000$ km s^{-1}. Microlensing by intracluster-medium objects can modify transit magnifications but lengthen visibility times. Depending on BH masses, accretion-disk radii, and feeding efficiencies, stellar-mass BH accretion-disk caustic transits could outnumber those from Population III stars. To observe Population III caustic transits directly may require monitoring 3–30 lensing clusters to AB $\lesssim$ 29 mag over a decade.

Key words: accretion, accretion disks – galaxies: clusters: general – gravitational lensing: strong – infrared: diffuse background – stars: black holes – stars: Population III

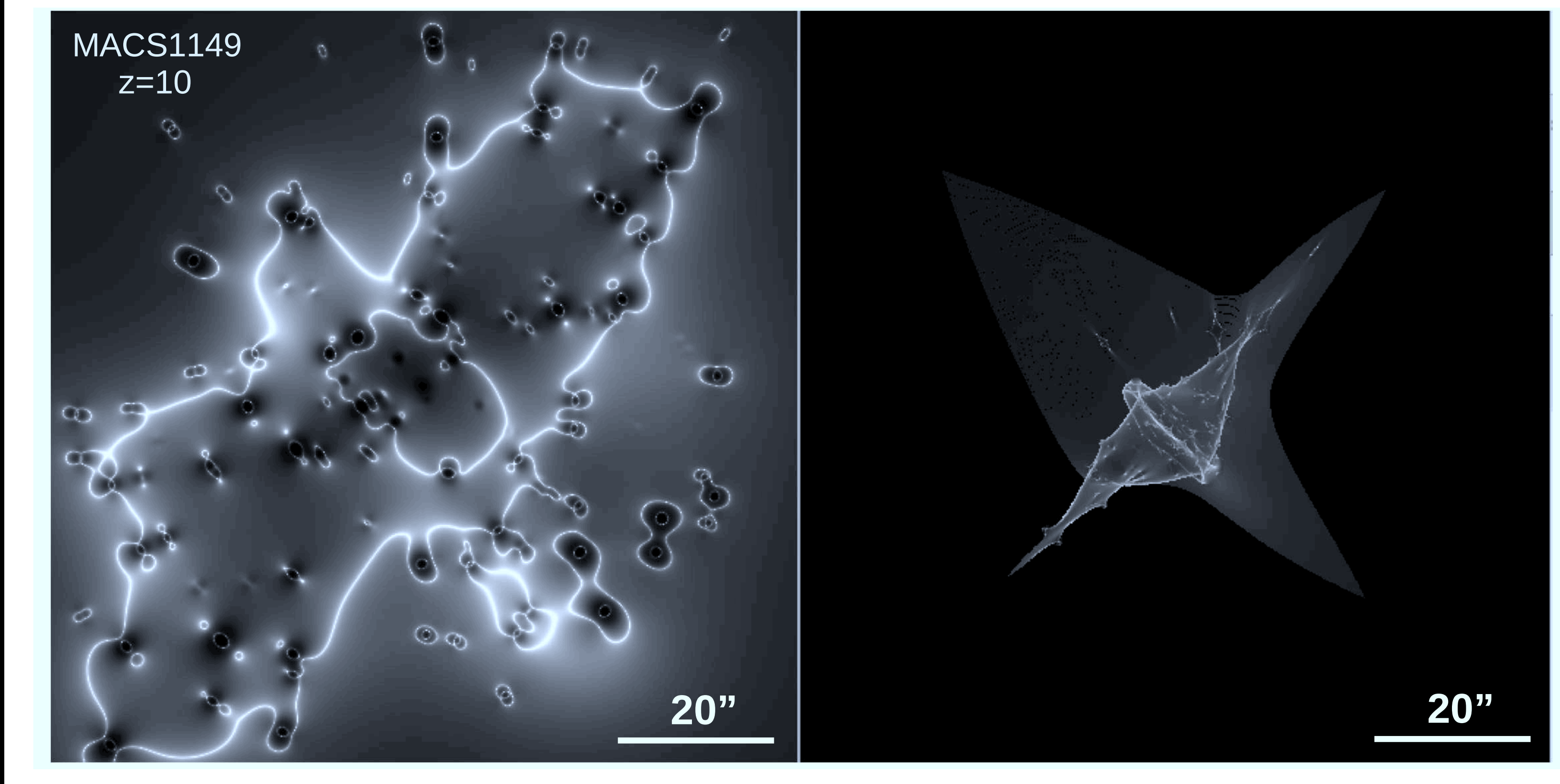
Windhorst$^+$ (2018, ApJS, 234, 41): JWST (and 25–39 m ground-based telescopes?) may detect Pop III stars and their stellar-mass BH accretion disks *directly* to AB$\lesssim$28–29 mag via caustic transits in the right clusters.

- JWST GO community should anticipate this and build on it.

HFF A2744: need cluster caustic transits to see Pop III objects at $z \gtrsim 7$.



Need clusters with minimal ICL and microlensing near the critical curves.



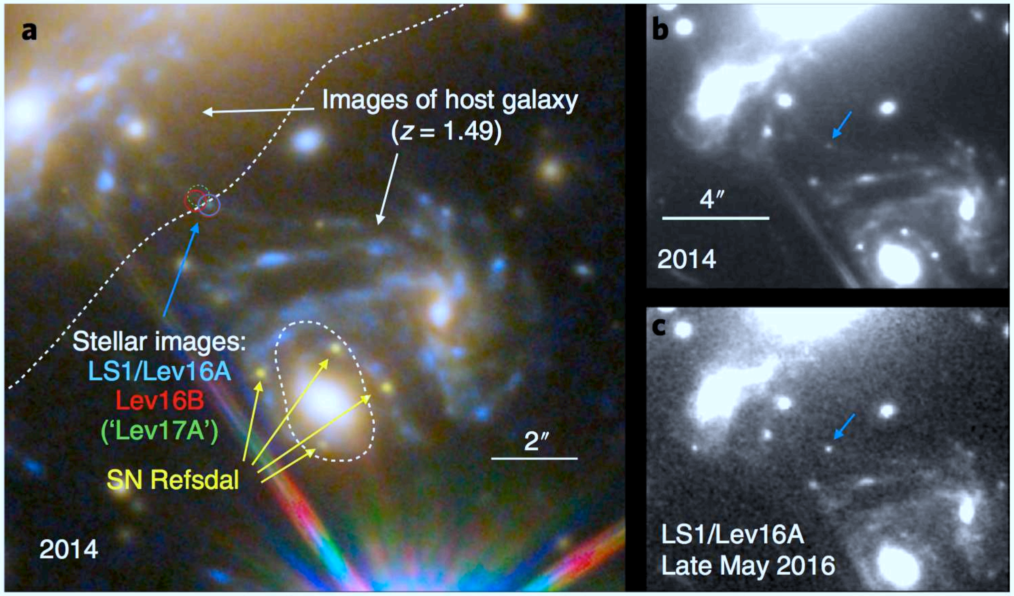
For source at z=10, critical curves for HFF cluster MACS 1149 at z≃0.54 [LEFT], and main cluster caustics [in the source plane; RIGHT].

• Transverse cluster (sub-component) velocities can be $v_T \lesssim 1000$ km/s (Kelly+ 2018; Nature Astr. 2, 334; Windhorst+ 2018, ApJS, 234, 41).

• Main caustic magnification: $\mu \simeq 10/\ (\mathrm{d}_{caustic}/'')^{1/2}$. For Pop III objects at z≳7 with 1–30 $R_{\odot}$, μ can then be $\gtrsim 10^4$–10^5 for ≲0.4 year.

• Must use clusters with minimal ICL near the critical curves, since ICL microlensing dilutes the main caustics (Diego+ 2018, ApJ, 857, 25).

(1b) HST observations of OB-star caustic transits at z≃1–1.5



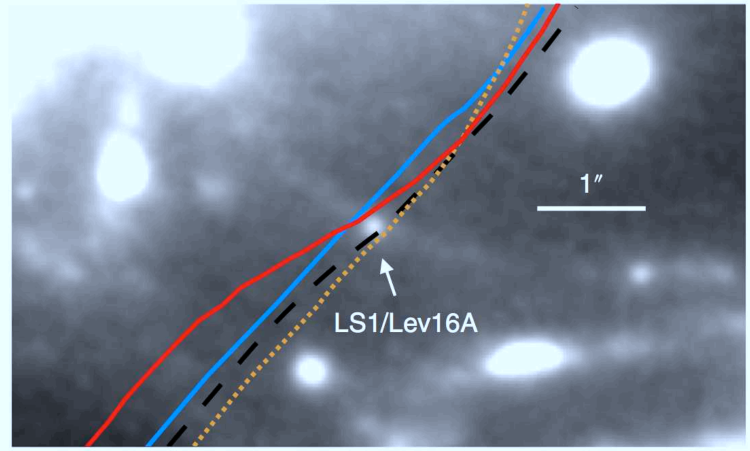


Fig. 2 | Proximity of LS1/Lev16A to the MACS J1149 galaxy cluster's critical curve for multiple galaxy-cluster lens models. Critical curves for models with available high-resolution lens maps including ref. [8] (CATS;

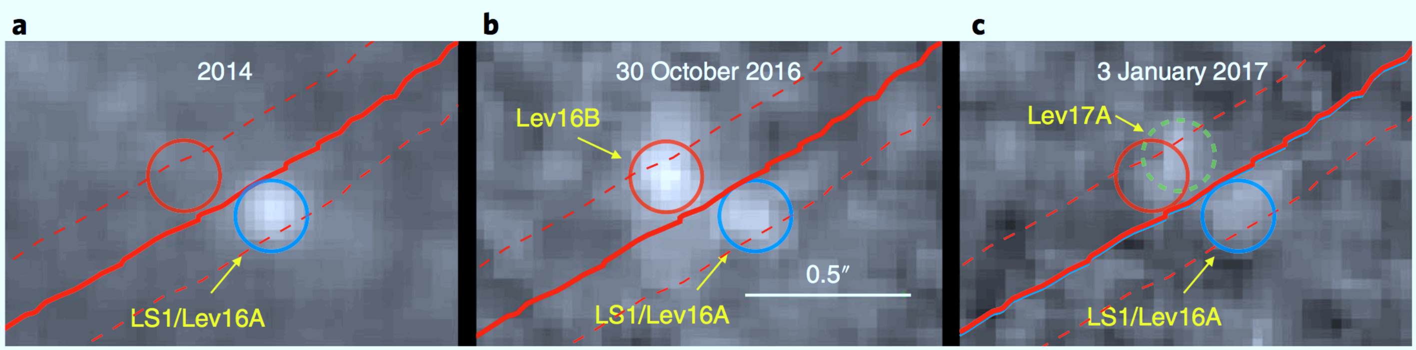


Fig. 5 | Highly magnified stellar images located near the MACS J1149 galaxy cluster's critical curve. a, LS1 in 2014; we detected LS1 when it temporarily brightened by a factor of ~4 in late April 2016, and its position is marked by a blue circle. **b**, The appearance of a new image dubbed Lev16B on 30 October 2016, whose position is marked by a red circle. The solid red line marks the location of the cluster's critical curve from the CATS cluster model[8], and the dashed red lines show the approximate 1σ uncertainty from comparison of multiple cluster lens models[5-10]. Lev16B's position is consistent with the possibility that it is a counterimage of LS1. **c**, The candidate named Lev17A at the location of the green dashed circle had a ~4σ significance detection on 3 January 2017. If a microlensing peak, Lev17A must correspond to a different star.

Kelley et al. 2018 (Nat. Astr. 2, 334): caustic transit of a B-star at z≃1.49.

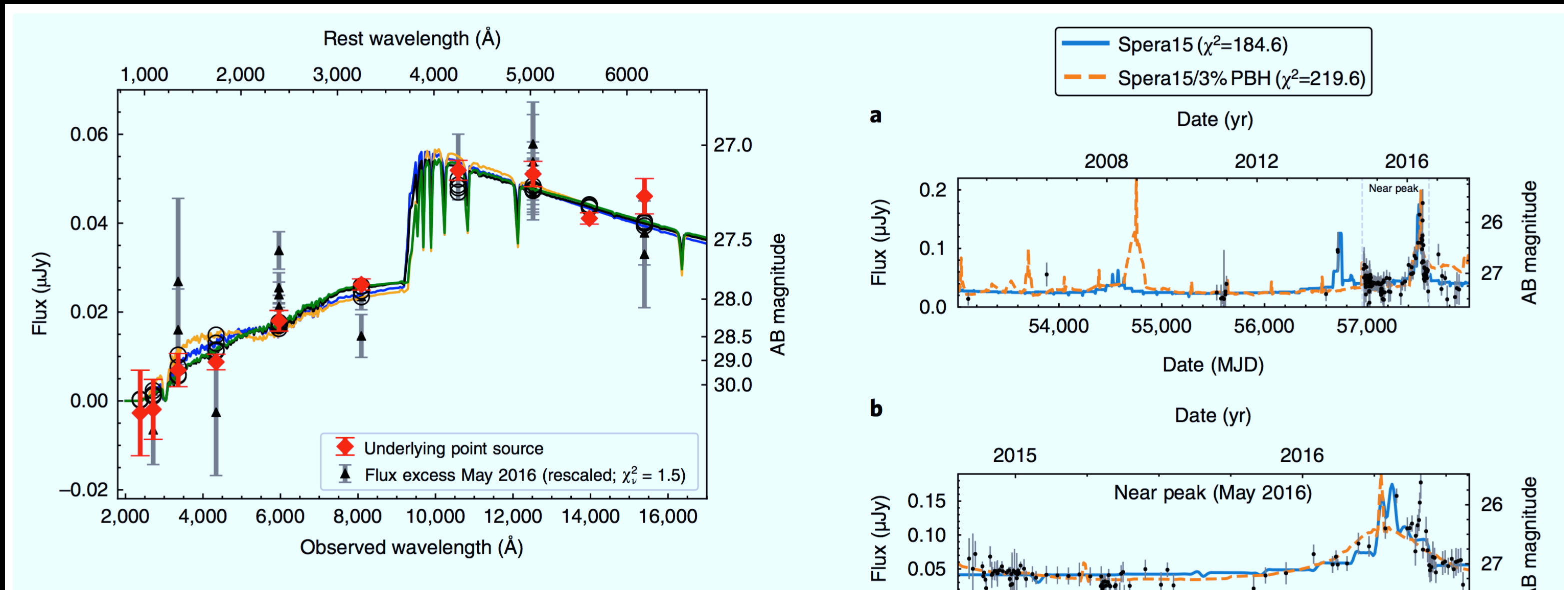


Fig. 3 | The SEDs of LS1 measured in 2013–2015 and of the rescaled excess flux density at LS1's position close to its May 2016 peak. Rescaling the SED of the flux excess (Lev16A; black triangles) to match that of the

Kelley et al. 2018 (Nat. Astr. 2, 334): caustic transit of a B-star at z≃1.49.

THE ASTROPHYSICAL JOURNAL, 857:25 (27pp), 2018 April 10 — Diego et al.

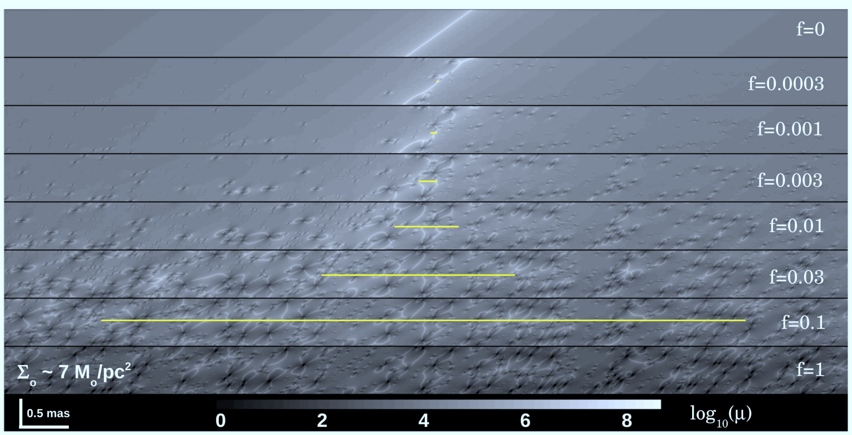
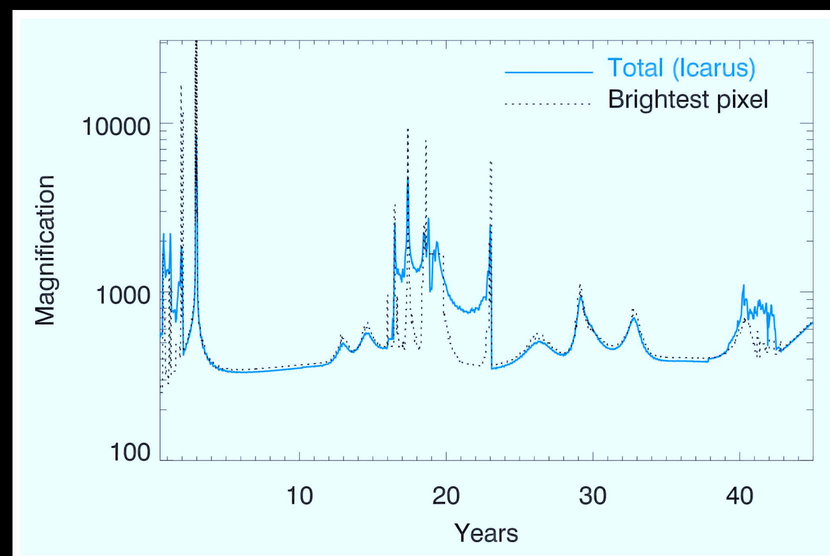
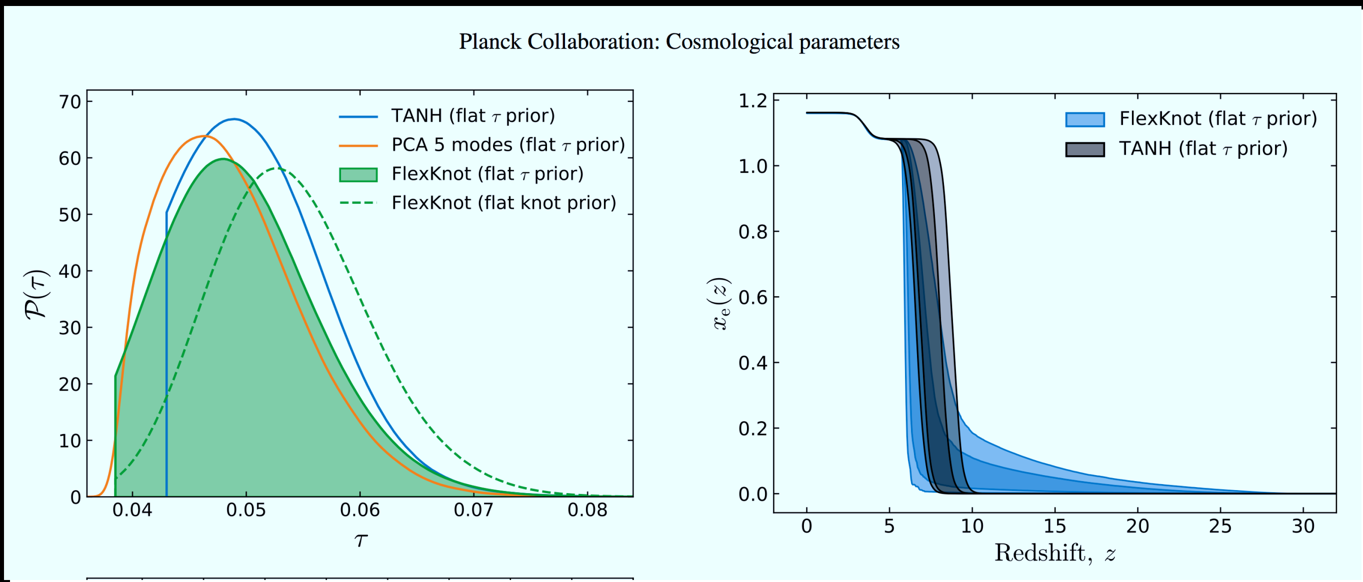


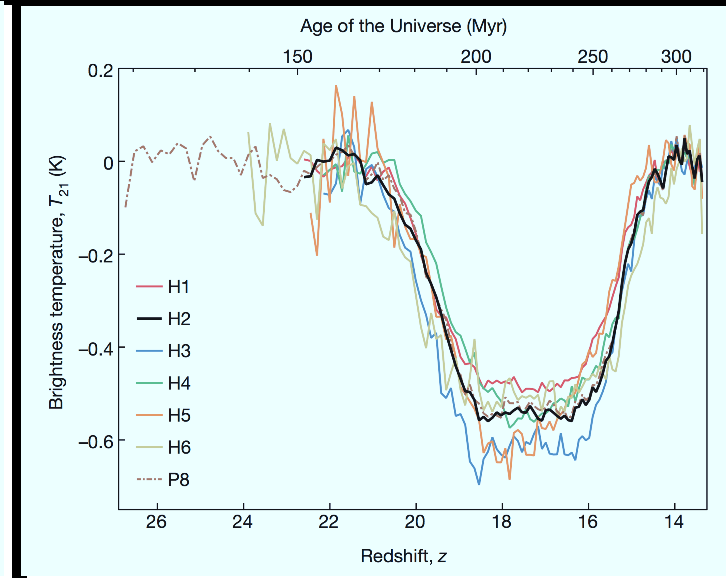
Figure 9. Disruption of the CC as a function of microlens surface mass density. Each panel shows the CC region when a population of microlenses with $\Sigma = f\Sigma_o$ is present. The case $f = 1$ corresponds to the model of Spera et al. (2015) at the position of Icarus. The yellow lines show the approximation in Equation (15). The last panel at bottom does not show the yellow line since it extends beyond the boundaries of the plot. The total surface mass density (i.e., smooth plus microlens) is the same in all panels.



Diego$^+$ 2018 (ApJ, 857, 25): caustic transits in the presence of microlensing. See also Miralda-Escudé (1991), Venumadhav et al. (2017, ApJ, 850, 49).

(2a) Limits to the SKY-SB of Pop III objects: First Stars





Two Reionization/First Light constraints remain seemingly at odds:

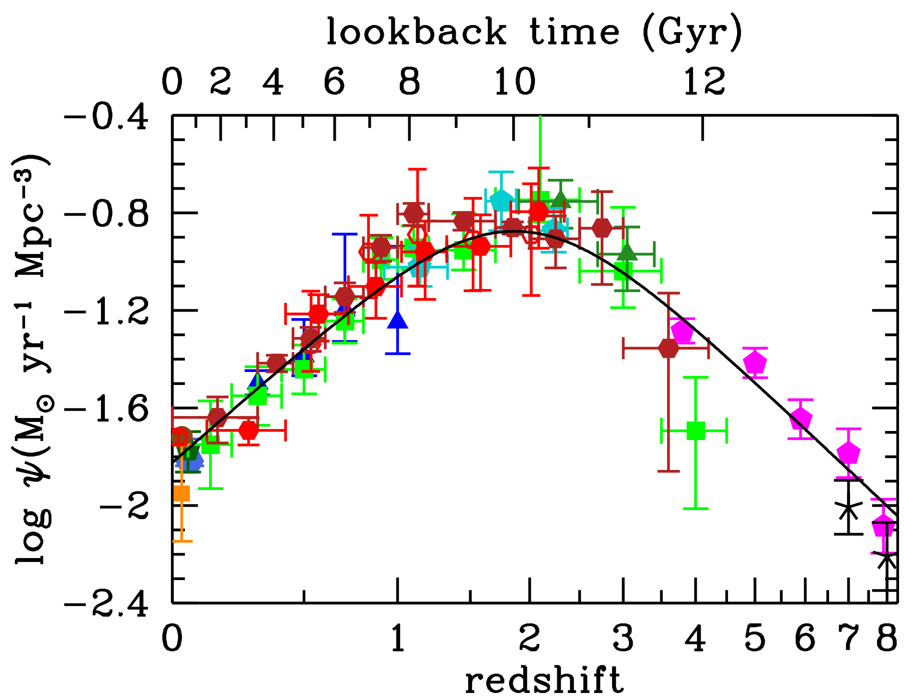
[LEFT 2]: Planck 2018 VI (astro-ph/1807.06209v1): • Cosmic Background polarization $\tau \simeq 0.054 \pm 0.007 \Rightarrow z_{reion} \simeq 7.7 \pm 0.7$ (age 670 Myr).

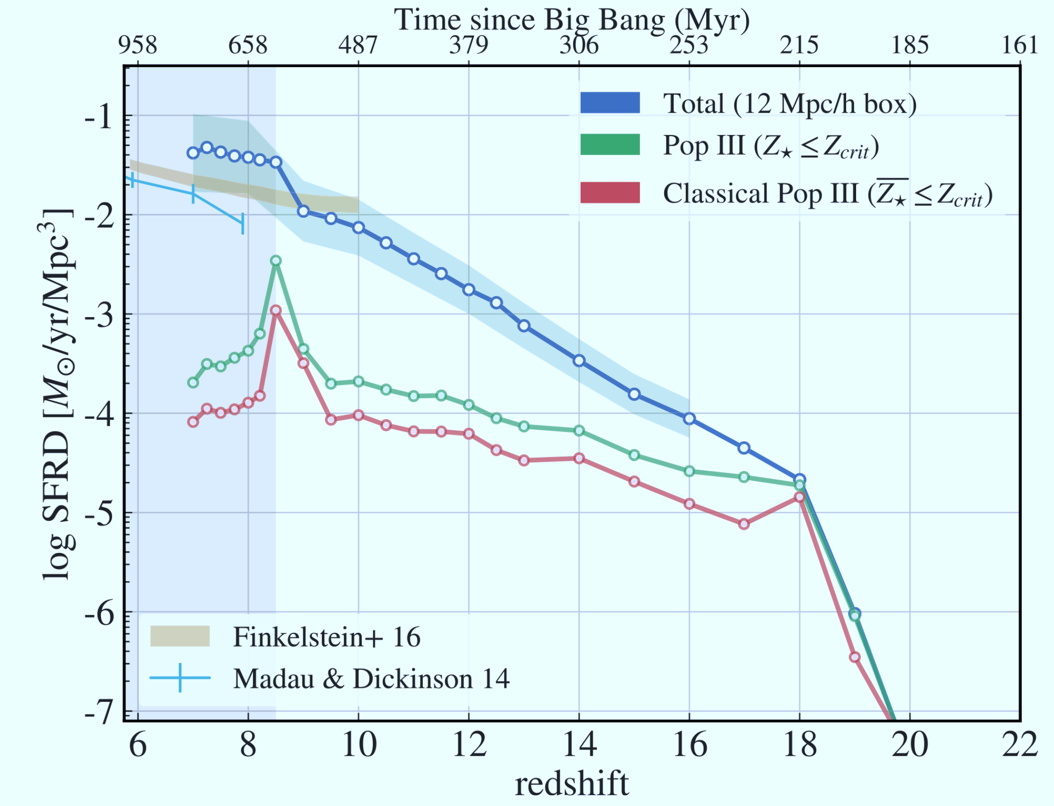
[RIGHT]: Bowman et al. EDGES result (2018, Nature, 555, 67):

• Possible global 78 MHz HI-signal at $z \simeq 17 \pm 2$ (age 225 Myr).

• How can we reconcile this in context of the First Stars?

• What does this mean for First Dust, and the first (BH) binary stars?





Anticipated cosmic star-formation rate (SFR) at z$\gtrsim$7:

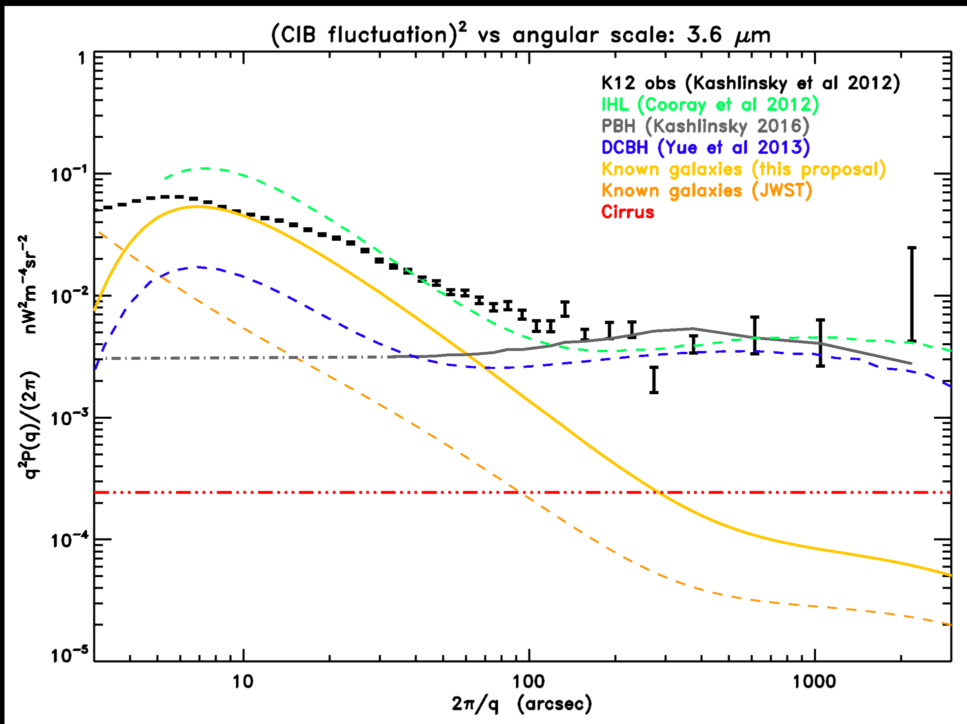
[LEFT] Observed (*e.g.*, Madau & Dickinson; 2014, ARAA, 52, 415);

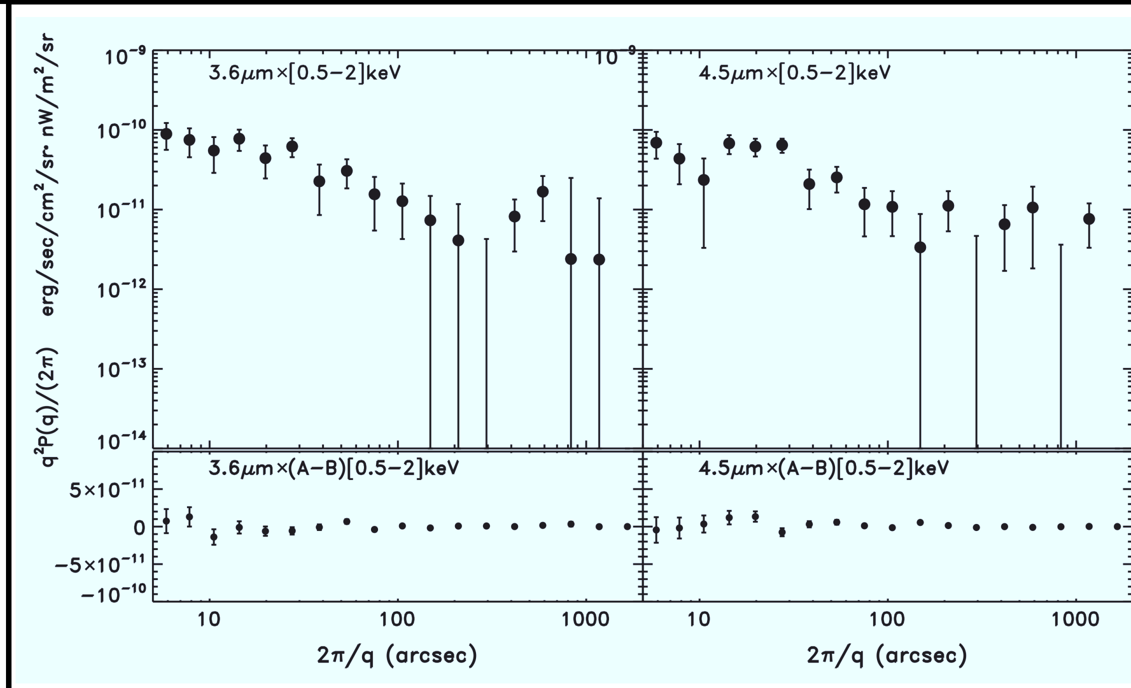
[RIGHT] RAMSES models (*e.g.*, Sarmento et al. 2018, ApJ, 854 75).

$\Rightarrow$ Adopt this SFR from z$\simeq$17 to z$\simeq$7, implying at the lowest masses:

- Metallicity increases from ∼0 at z$\simeq$18 to $\lesssim 10^{-3}$ solar at z$\simeq$7.
- $\Rightarrow$ First Stars may go quickly form forming singly (at z$\simeq$17) to forming in binaries (at z$\lesssim$7) $\Rightarrow$ Integrated sky-SB(SFR z$\gtrsim$7)$\gtrsim$31 mag/arcsec^2.

(2b) Limits to the SKY-SB of Pop III objects: Stellar Mass Black Holes



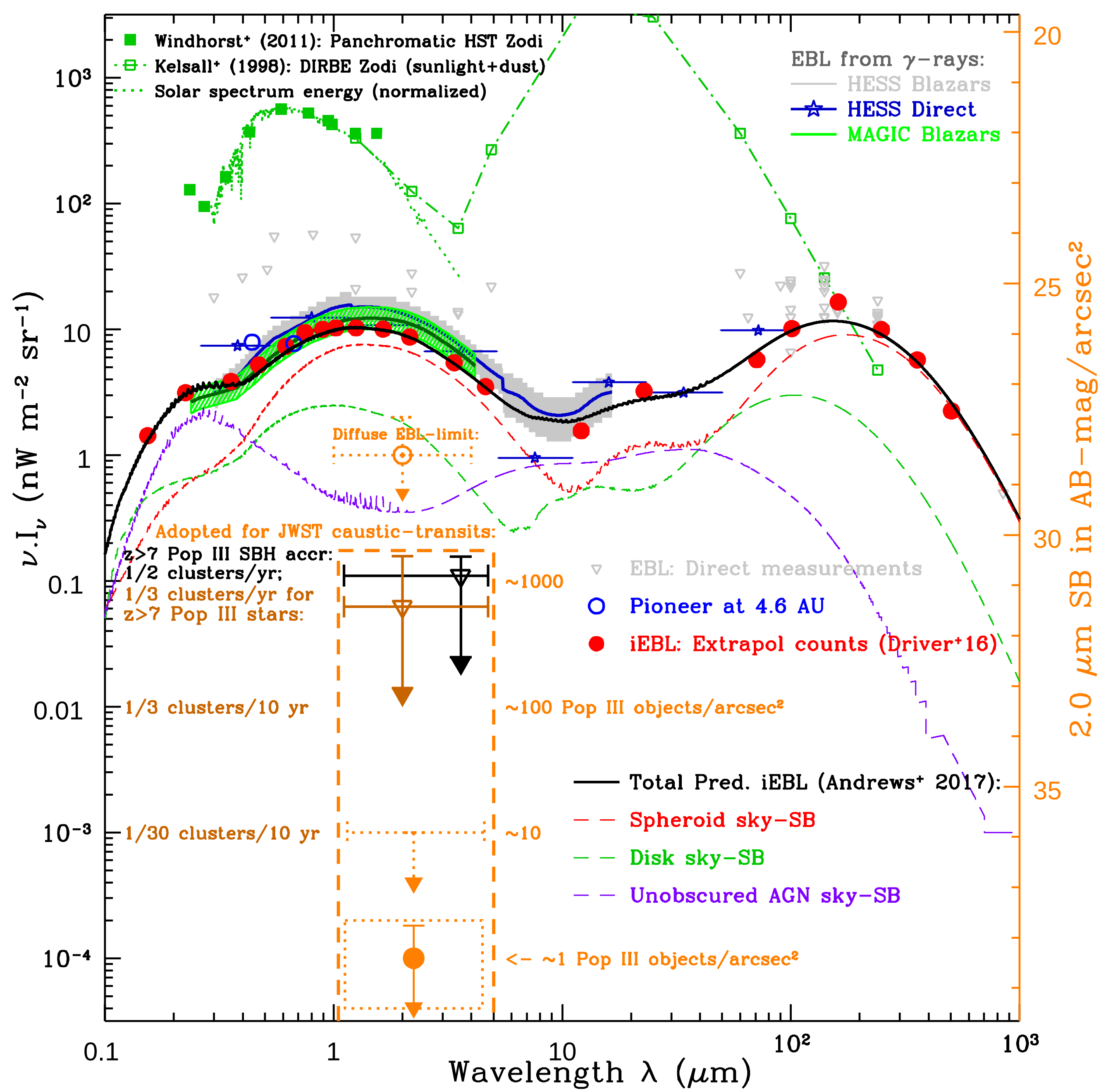


[LEFT] Object-free Spitzer 3.6 μm power-spectrum constrains noise fluctuation models (Cappelluti et al. 2017; Kashlinsky et al. 2012, 2015, 2018):

Explainable by: Primordial black hole or Direct-collapse black hole models.

[RIGHT] Spitzer–Chandra cross-corr spectrum (Mitchell-Wynne et al. 2016):

- Objects at $z \gtrsim 7$ have sky-SB$\simeq$31 mag/arcs^2, plus likely a (stellar mass) black hole X-ray component. (Kashlinsky$^+$ 2018; Windhorst$^+$ 2018, ApJ, 234, 41).



Extragalactic Background Light (Driver+ 16; Windhorst+ 18):

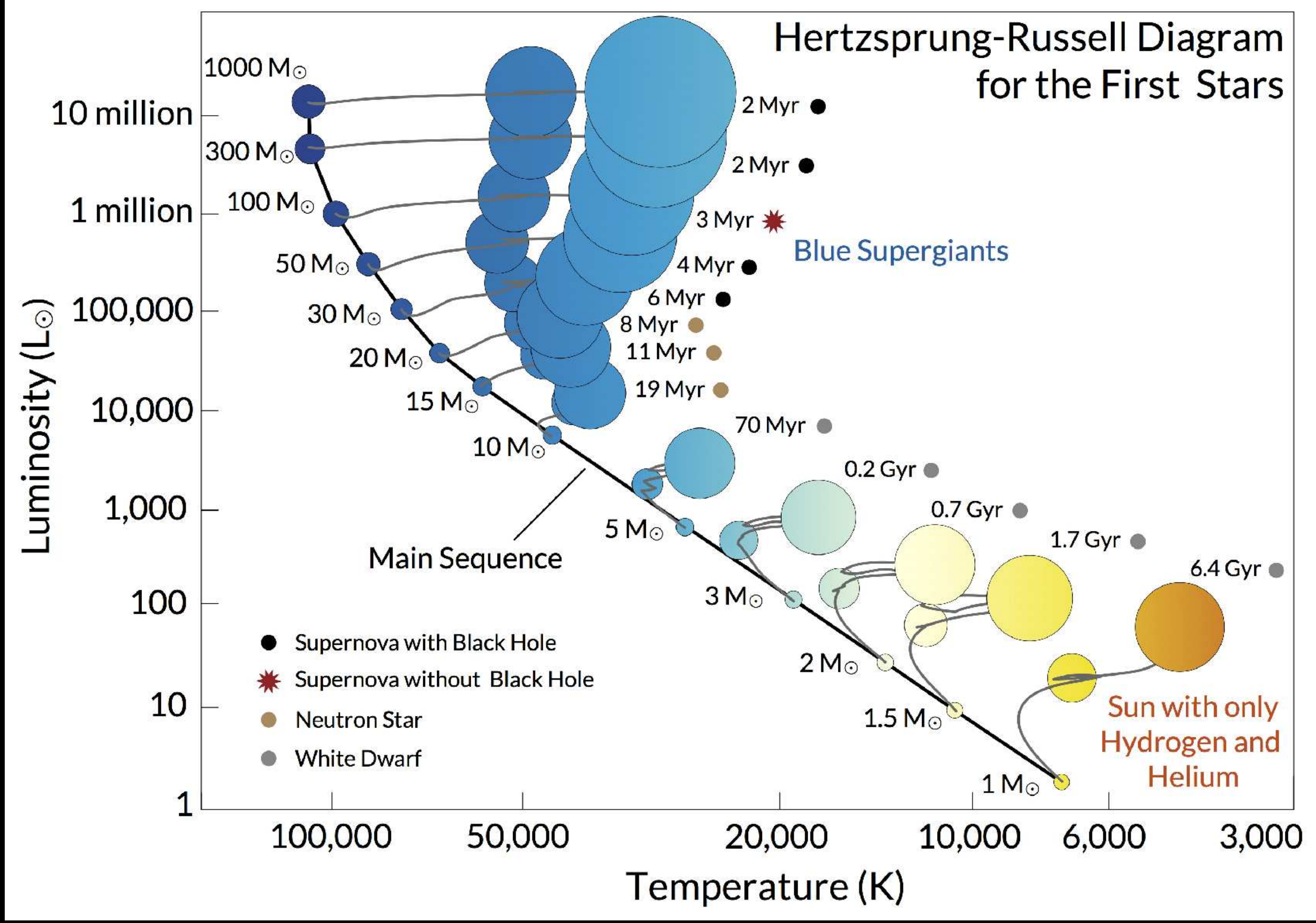
Energy(dust) $\simeq$ 52% & energy(cosmic SF)$\simeq$48% of EBL $\Rightarrow$ dust wins!

Diffuse 1–4μm sky $\lesssim$0.1 nW/m^2/sr or SB(K)$\gtrsim$31 mag/arcsec^2:

- 1) possibly from Pop III stars at z$\simeq$7–17, and/or
- 2) their stellar-mass BH accretion disks (z$\simeq$7–8).

This can make Pop III stars or their BH accretion disks visible to JWST at AB$\lesssim$28–29 mag.

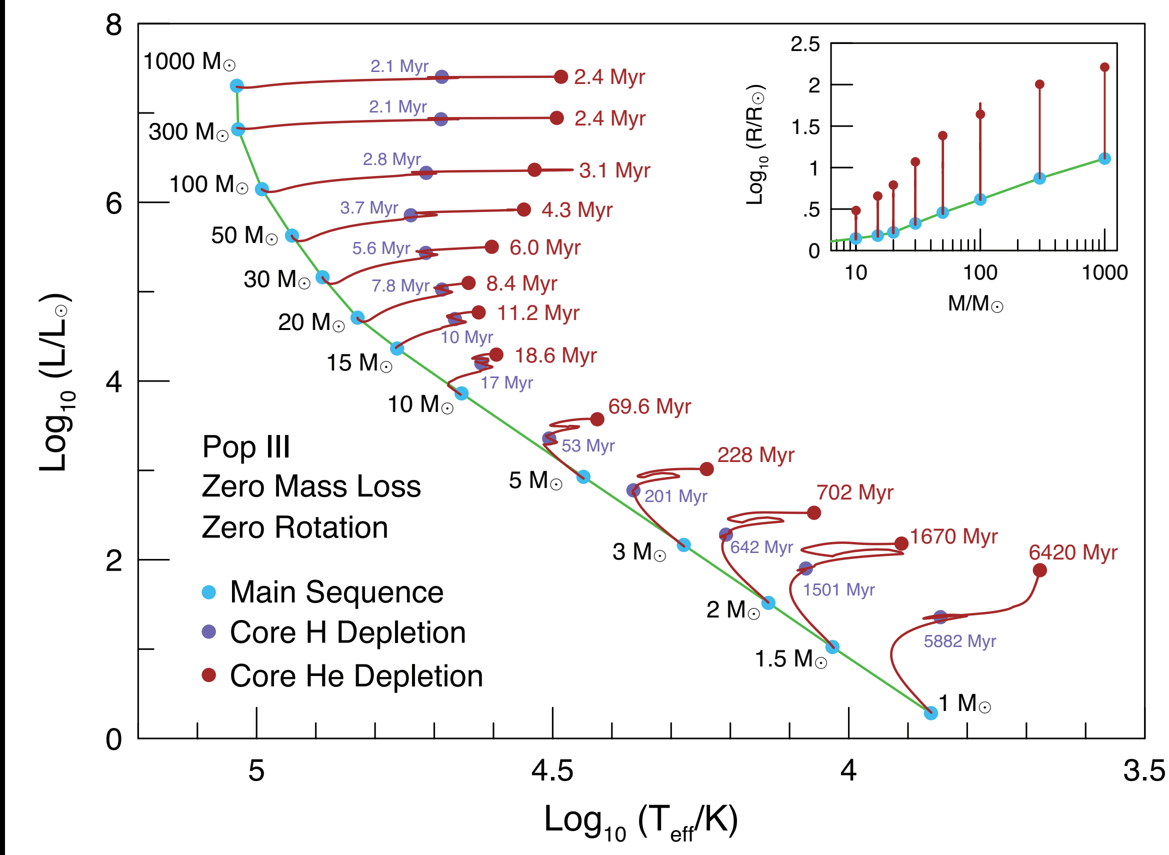
- Requires using the best lensing clusters and monitoring caustic transits.
- JWST must monitor best lensing clusters throughout its lifetime.



First Stars ("Pop III") HR-diagram: MESA stellar evolution models for zero metallicity (Windhorst, Timmes, Wyithe et al. 2018, ApJS, 234, 41):

- 30–1000 $M_{\odot}$ Pop III ZAMS stars live ∼10× shorter than 2–5 $M_{\odot}$ Pop III stars in their Giant Branch stage.

- Hence, 2–5 $M_{\odot}$ AGB companion stars can feed the LIGO-mass BHs left over from M≳30 $M_{\odot}$ Pop III stars (assuming binaries in 2nd generation).



Windhorst+ (2018, ApJS, 234, 41):

- Multicolor accretion-disk models for stellar-mass black holes [RIGHT]: For $M_{BH} \simeq$5–700 $M_{\odot}$, accretion disks radii and luminosities are similar to those of Pop III AGB stars, when the BH is fed by a Roche lobe-filling lower-mass companion star on the AGB (which live $\gtrsim$10$\times$ longer).

- Assumes 2nd generation O-stars have high enough Fe/H ($\gtrsim 10^{-4}$ $Z_{\odot}$) that 2–5 $M_{\odot}$ AGB companion stars exist and feed these LIGO-mass BHs.

- This may make stellar-mass black hole accretion disks at z$\gtrsim$7 at least as likely to be seen via caustic transits as the Pop III stars themselves.

(3) Conclusions for Pop III Star/BH Accretion Disk caustic transits

- If M$\gtrsim$30 $M_\odot$ Pop III ZAMS stars (AB$\sim$37–42 mag at z$\gtrsim$7) have $\mu\gtrsim 10^4$–10^5 during caustic transits, they could be detectable for a few months to AB$\lesssim$29 mag with JWST. Rise times of a few hours.

- Pop III stellar mass black hole (M$\gtrsim$20 $M_\odot$) accretion disks could be similarly detectable, *and* live $\sim$10$\times$ longer than their ZAMS stars.

- JWST can detect individual Pop III objects at AB$\lesssim$28-29 mag via cluster caustic transits if magnifications $\mu\simeq 10^4$–10^5 (*i.e.*, ICL microlensing doesn't dominate cluster caustics).

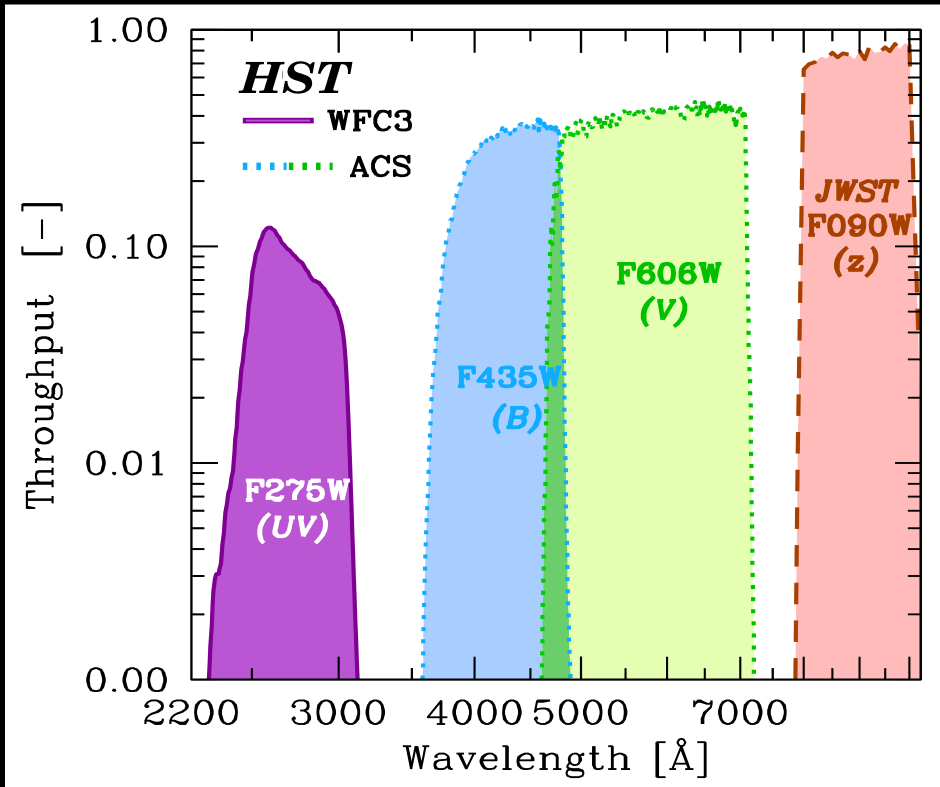
- In the case of significant micro-lensing by ICL objects, 30 m telescopes + MCAO can follow this up for decades, but only at $\lambda\simeq$ at 1–2 μm.

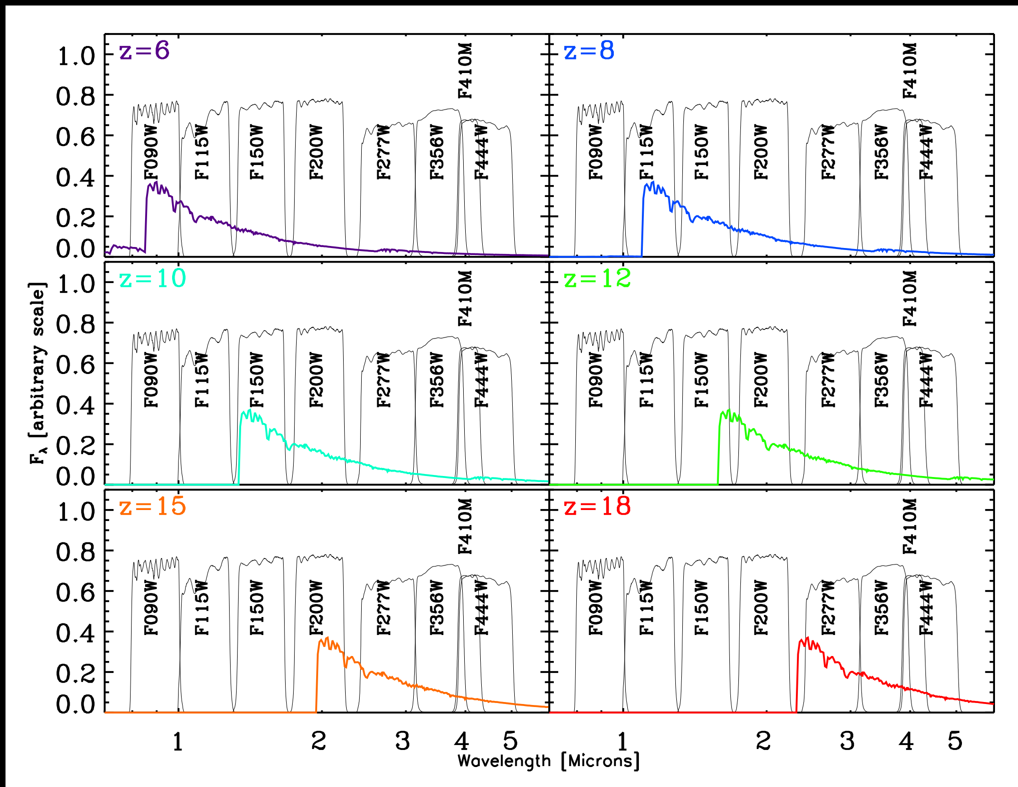
- Expect $\lesssim$1 caustic transit/yr at z$\gtrsim$7 when JWST monitors $\gtrsim$3 clusters.

- Stellar-mass BH accretion disks may dominate caustic transits at z$\gtrsim$7.

- JWST GO community should anticipate this, and plan for it.

SPARE CHARTS



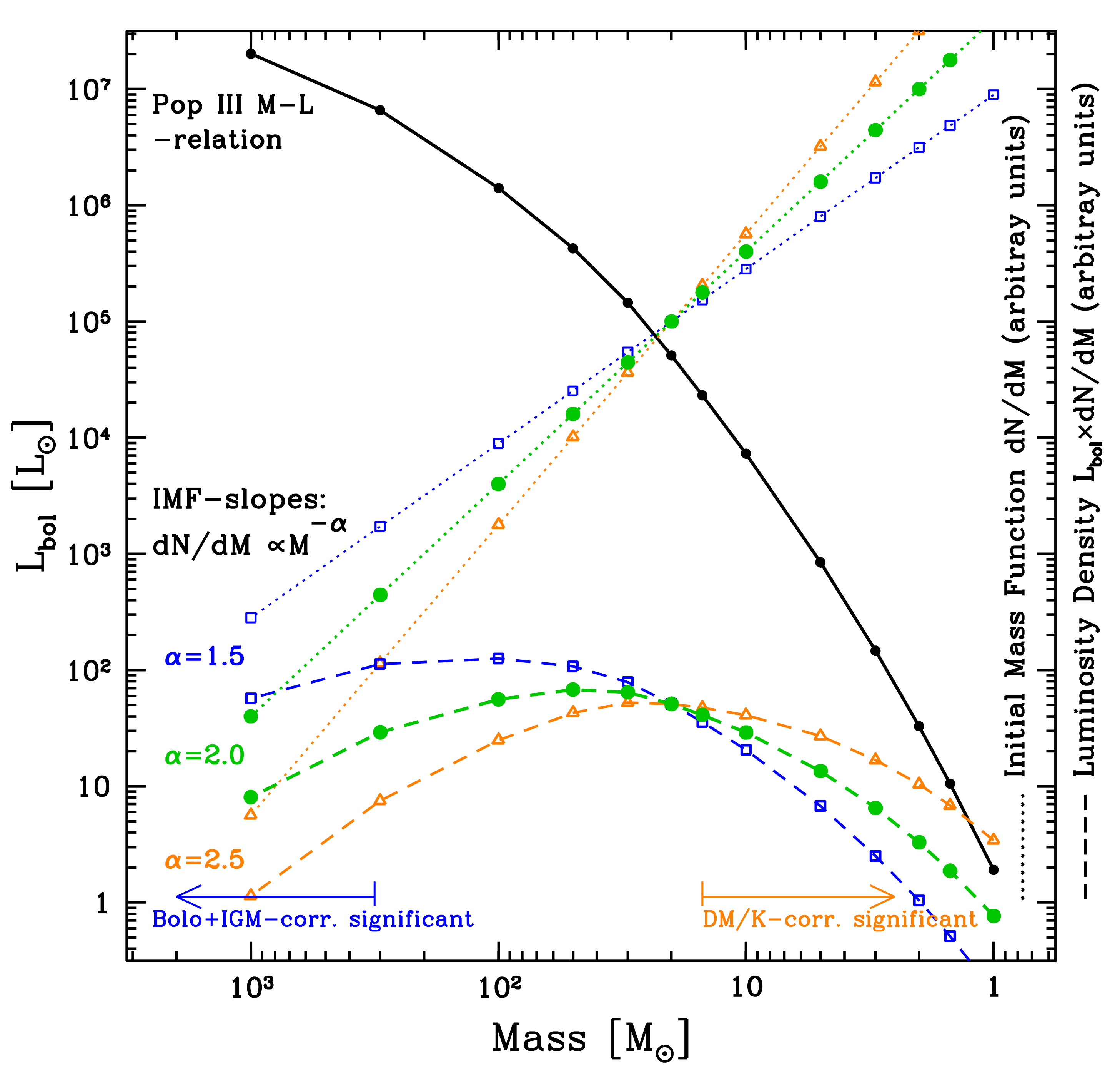


[LEFT] HST UV-vis filters complement the JWST NEP community field:

- HST adds λ's inaccessible to JWST, or where HST has better PSF.

[RIGHT] Standard 8-band 0.8–5 μm filter set for JWST NIRCam.

- These are what GTO's will use as standard NIRCam filters.



Mass–Luminosity relation for zero metallicity Pop III MESA models:

For a range of IMF slopes, most Pop III star sky-SB comes from 20–300 $M_{\odot}$.

Table 1. Adopted Pop III Star Physical Parameters from `MESA` models[a]

Mass	Age	T_{eff}	$\log R$	$\log L_{\rm bol}$	T_{eff}	$\log R$	$\log L_{\rm bol}$	Age	$T_{\rm eff}$	$\log R$	$\log L_{\rm bol}$	Age	Time[b]
	Pre-MS	— at ZAMS —			— at Hydrogen-depletion —				— at Helium-depletion —				AGB-MS
($M_\odot$)	(Myr)	(K)	($R_\odot$)	($L_\odot$)	(K)	($R_\odot$)	($L_\odot$)	Myr	(K)	($R_\odot$)	($L_\odot$)	Myr	(Myr)
1.0	9.28	7.266e3	−0.0581	0.2825	6.999e3	0.5119	1.3576	5882	—[c]	—	—	6420	538
1.5	6.11	1.065e4	−0.0203	1.0227	1.181e4	0.3292	1.9015	1501	8.149e3	0.7913	2.1804	1670	169
2.0	3.02	1.367e4	0.0108	1.5177	1.611e4	0.2498	2.2815	642	1.145e4	0.6685	2.5249	702	60
3.0	1.38	1.899e4	0.0487	2.1654	2.311e4	0.1843	2.7770	201	1.736e4	0.5510	3.0138	228	27
5.0	0.56	2.805e4	0.0911	2.9274	3.206e4	0.1903	3.3581	53	2.658e4	0.4608	3.5732	70	17
10	0.23	4.508e4	0.1462	3.8618	4.174e4	0.3807	4.1972	17	3.938e4	0.4811	4.2968	19	1.6
15	0.13	5.789e4	0.1803	4.3647	4.624e4	0.5401	4.6937	10	4.215e4	0.6581	4.7691	11	0.8
20	0.09	6.754e4	0.2183	4.7082	4.864e4	0.6612	5.0240	7.8	4.386e4	0.7879	5.0975	8.4	0.6
30	0.05	7.737e4	0.3270	5.1619	5.180e4	0.8120	5.4347	5.6	4.006e4	1.0688	5.5016	6.0	0.5
50	0.03	8.713e4	0.4570	5.6283	5.490e4	0.9722	5.8562	3.7	3.536e4	1.3862	5.9200	4.3	0.5
100	0.02	9.796e4	0.6147	6.1470	5.173e4	1.2610	6.3303	2.8	3.392e4	1.6437	6.3627	3.1	0.3
300	0.02	1.074e5	0.8697	6.8172	4.882e4	1.6111	6.9301	2.1	3.165e4	2.0041	6.9631	2.4	0.3
1000	0.02	1.080e5	1.1090	7.3047	4.807e4	1.8740	7.4288	2.1	3.122e4	2.2119	7.3549	2.4	0.3

Windhorst, Timmes, Wyithe et al. (2018, ApJS, 234, 41):

- 30–1000 $M_\odot$ Pop III stars (Z=0.0 $Z_\odot$) live ∼10× shorter than 2–5 $M_\odot$ Pop III stars in their AGB stage.
- Hence, 2–5 $M_\odot$ AGB companion stars can feed the LIGO-mass BHs left over from M$\gtrsim$30 $M_\odot$ Pop III stars (assuming binaries in 2nd generation).

Table 2. Implied ZAMS Pop III Star Observational Parameters Relevant to Caustic Transit Calculations

Mass[a] ZAMS ($M_\odot$)	$T_{\rm eff}$[b] (K)	Radius[c] at ZAMS ($R_\odot$)	$L_{\rm bol}$[d] at ZAMS ($L_\odot$)	$M_{\rm bol}$[e] (AB)	Bolo+IGM+K-corr[f] z=7 (AB-mag)	z=12	z=17	ZAMS m_{UV}[g] z=7 (AB-mag)	z=12	z=17	t_{rise}[h] caust (hr)	transit[i] rate (/cl/yr)
1.0	7.266e3	0.87	1.92	+4.03	+4.44	+3.13	+2.61	57.71	57.74	58.07	0.17	8×10^5
1.5	1.065e4	0.95	10.5	+2.18	+1.45	+0.42	–0.06	52.87	53.18	53.55	0.18	1.1×10^4
2.0	1.367e4	1.03	32.9	+0.95	+0.30	–0.59	–1.06	50.49	50.93	51.31	0.20	1.5×10^3
3.0	1.899e4	1.12	146.	–0.67	–0.51	–1.26	–1.72	48.06	48.64	49.03	0.22	182.
5.0	2.805e4	1.23	846.	–2.58	–0.70	–1.35	–1.80	45.96	46.65	47.04	0.24	29.1
10	4.508e4	1.40	7.28e3	–4.91	–0.22	–0.79	–1.23	44.10	44.88	45.27	0.27	5.70
15	5.789e4	1.51	2.32e4	–6.17	+0.23	–0.30	–0.75	43.30	44.10	44.50	0.29	2.78
20	6.754e4	1.65	5.11e4	–7.03	+0.56	+0.04	–0.40	42.77	43.59	43.99	0.32	1.74
30	7.737e4	2.12	1.45e5	–8.16	+0.88	+0.36	–0.08	41.95	42.78	43.17	0.41?	0.82?
50	8.713e4	2.86	4.25e5	–9.33	+1.17	+0.66	+0.22	41.08	41.91	42.31	0.55*	0.37*
100	9.796e4	4.12	1.40e6	–10.63	+1.47	+0.96	+0.52	40.08	40.91	41.31	0.80*	0.15*
300	1.074e5	7.41	6.56e6	–12.30	+1.71	+1.21	+0.77	38.64	39.48	39.88	1.43*	0.039*
1000	1.080e5	12.9	2.02e7	–13.52	+1.72	+1.22	+0.78	37.44	38.28	38.68	2.48*	0.013*

- If M$\gtrsim$30 $M_\odot$ Pop III ZAMS stars have $\mu\gtrsim10^4$–10^5 during caustic transits, they could be detectable for months to AB$\lesssim$29 mag with JWST.
- Expect $\lesssim$1 caustic transit/yr at z$\gtrsim$7 when JWST monitors $\gtrsim$3 clusters.

Table 3. Implied Red Giant Branch Pop III Star Observational Parameters Relevant to Caustic Transit Calculations

Mass[a] GB ($M_\odot$)	$T_{\rm eff}$[b] (K)	Radius[c] ($R_\odot$)	$L_{\rm bol}$[d] ($L_\odot$)	$M_{\rm bol}$[e] (AB)	Bolo+IGM+K-corr[f] z=7 (AB-mag)	z=12	z=17	Giant Branch $m_{\rm UV}$[g] z=7 (AB-mag)	z=12	z=17	t_{rise}[h] caust (hr)	transit[i] rate (/cl/yr)
	— at Hydrogen-depletion —											
1.0	6.999e3	3.25	22.8	+1.35	+4.83	+3.48	+2.96	55.42	55.41	55.73	0.63	9×10^4
1.5	1.181e4	2.13	79.7	–0.01	+0.91	–0.06	–0.53	50.13	50.51	50.88	0.41	1.0×10^3
2.0	1.611e4	1.78	191.	–0.96	–0.19	–1.01	–1.47	48.08	48.60	48.99	0.34	175.
3.0	2.311e4	1.53	598.	–2.20	–0.69	–1.39	–1.84	46.35	46.99	47.38	0.30	39.8
5.0	3.206e4	1.55	2.28e3	–3.66	–0.63	–1.25	–1.70	44.95	45.67	46.07	0.30	11.8
10	4.174e4	2.40	1.57e4	–5.75	–0.34	–0.92	–1.36	43.15	43.91	44.31	0.46	2.33
15	4.624e4	3.47	4.94e4	–6.99	–0.18	–0.74	–1.19	42.06	42.84	43.24	0.67?	0.87?
20	4.864e4	4.58	1.06e5	–7.82	–0.10	–0.65	–1.09	41.32	42.11	42.51	0.88*	0.44*
30	5.180e4	6.49	2.72e5	–8.85	+0.02	–0.53	–0.97	40.41	41.20	41.60	1.25*	0.19*
50	5.490e4	9.38	7.18e5	–9.90	+0.13	–0.42	–0.86	39.47	40.26	40.66	1.81*	0.081*
100	5.173e4	18.2	2.14e6	–11.09	+0.02	–0.53	–0.98	38.17	38.96	39.36	3.52*	0.024*
300	4.882e4	40.8	8.51e6	–12.59	–0.09	–0.65	–1.09	36.57	37.35	37.75	7.88*	0.006*
1000	4.807e4	74.8	2.68e7	–13.83	–0.12	–0.67	–1.12	35.29	36.07	36.47	14.44*	0.002*

- If M$\gtrsim$20 $M_\odot$ Pop III RGB stars have $\mu\gtrsim10^4$–10^5 during caustic transits, they could be detectable for a few months to AB$\lesssim$29 mag with JWST.
- Note the combined Bolometric+IGM+K-corrections are more advantageous for Pop III RGB stars.

Table 4. Implied AGB Pop III Star Observational Parameters Relevant to Caustic Transit Calculations

Mass[a] AGB ($M_\odot$)	$T_{\rm eff}$[b] (K)	Radius[c] ($R_\odot$)	$L_{\rm bol}$[d] ($L_\odot$)	$M_{\rm bol}$[e] (AB)	Bolo+IGM+K-corr[f] z=7 (AB-mag)	z=12	z=17	AGB m_{UV}[g] z=7 (AB-mag)	z=12	z=17	t_{rise}[h] caust (hr)	transit[i] rate (/cl/yr)
	— at Helium-depletion —											
1.0	6.312e3[j]	5.23[j]	39.8[j]	+0.74	+6.01	+4.57	+4.03	55.99	55.89	56.19	1.01	1.4×10^5
1.5	8.149e3	6.18	151.	–0.71	+3.36	+2.14	+1.64	51.89	52.01	52.35	1.19	4.0×10^3
2.0	1.145e4	4.66	335.	–1.57	+1.06	+0.07	–0.40	48.73	49.08	49.45	0.90	273.
3.0	1.736e4	3.56	1.03e3	–2.79	–0.36	–1.15	–1.60	46.09	46.64	47.03	0.69	28.9
5.0	2.658e4	2.89	3.74e3	–4.19	–0.72	–1.38	–1.82	44.33	45.01	45.41	0.56	6.43
10	3.938e4	3.03	1.98e4	–6.00	–0.42	–1.00	–1.45	42.82	43.57	43.97	0.58	1.71
15	4.215e4	4.55	5.88e4	–7.18	–0.33	–0.90	–1.34	41.73	42.50	42.89	0.88?	0.64?
20	4.386e4	6.14	1.25e5	–8.00	–0.27	–0.84	–1.28	40.97	41.74	42.14	1.19*	0.32*
30	4.006e4	11.7	3.17e5	–9.01	–0.40	–0.98	–1.42	39.83	40.59	40.98	2.26*	0.11*
50	3.536e4	24.3	8.32e5	–10.06	–0.55	–1.15	–1.59	38.63	39.37	39.77	4.70*	0.036*
100	3.392e4	44.0	2.31e6	–11.17	–0.59	–1.19	–1.64	37.49	38.22	38.61	8.50*	0.012*
300	3.165e4	101.	9.19e6	–12.67	–0.64	–1.26	–1.71	35.93	36.65	37.04	19.49*	0.003*
1000	3.122e4	163.	2.26e7	–13.65	–0.65	–1.28	–1.72	34.94	35.66	36.05	31.45*	0.001*

- If M$\gtrsim$20 $M_\odot$ Pop III AGB stars have $\mu\gtrsim10^4$–10^5 during caustic transits, they could be detectable for a few months to AB$\lesssim$29 mag with JWST.

- Note the combined Bolometric+IGM+K-corrections are far more advantageous for Pop III AGB stars (especially at z$\gtrsim$12)!

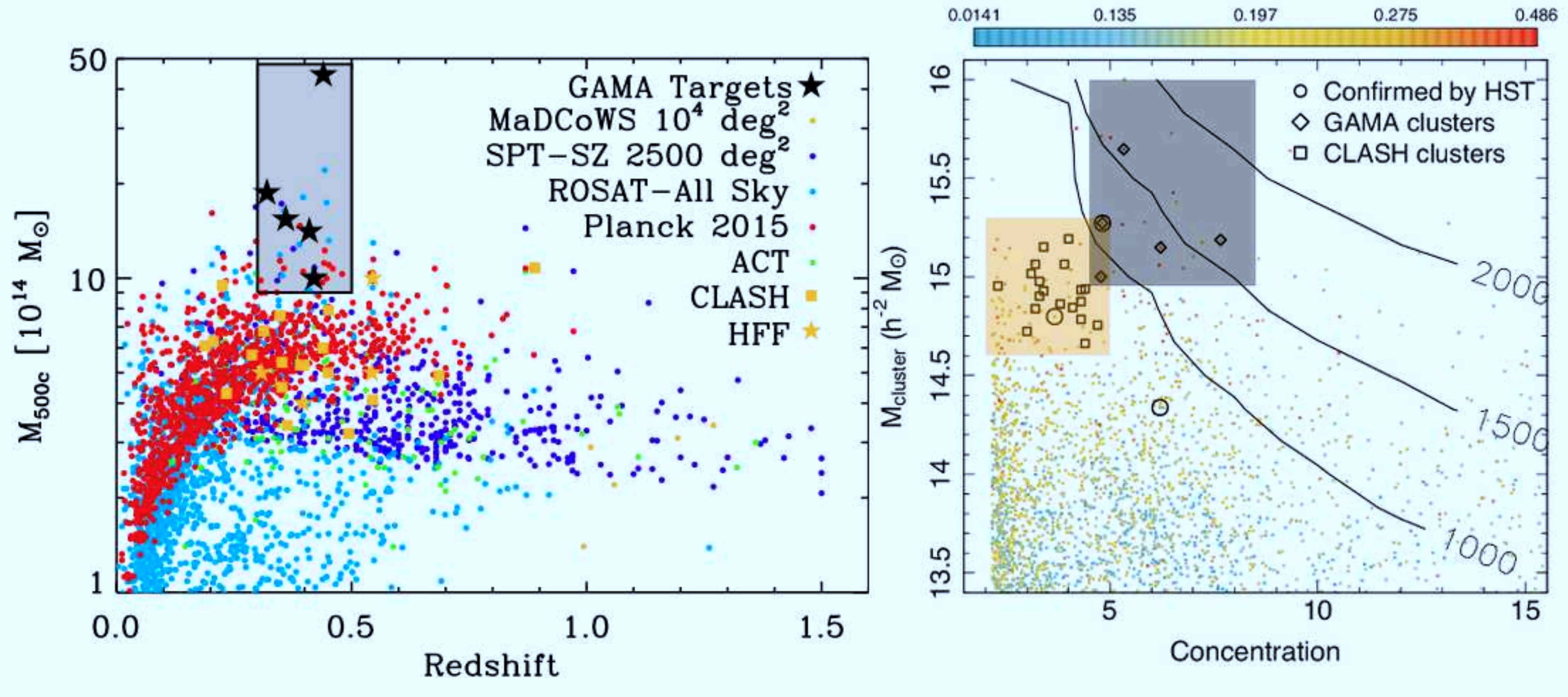
Table 5. Pop III Stellar Mass Black Hole Accretion Disk Parameters Adopted for Caustic Transit Calculations

Mass[a] ZAMS ($M_\odot$)	$M_{compact}$[b] ($M_\odot$)	R_s[c] BH (km)	Radius[d] — of the UV accretion disk — ($R_\odot$)	L_{bol}[e] ($L_\odot$)	M_{bol}[f] AB-mag	bolo+IGM+K-corr[g] z=7 (AB-mag)	z=12	z=17	m_{AB}-limits at[h] z=7 (AB-mag)	z=12	z=17	t_{rise}[i] (z=12) (hr)	Transit[j] rate (/cl/yr)
BH accretion-disk bolometric luminosities and UV half-light radii scaling from microlensed quasars (Blackburne et al. 2011)													
30	∼5.0 BH	15	1.4	$\lesssim 4.2\times10^4$	$\gtrsim$–6.8	–0.6	–1.4	–1.7	$\gtrsim$41.8	$\gtrsim$42.4	$\gtrsim$42.9	0.27?	$\gtrsim$0.58?
50	∼24 BH	72	3.0	$\lesssim 2.0\times10^5$	$\gtrsim$–8.5	–0.4	–1.2	–1.5	$\gtrsim$40.3	$\gtrsim$40.9	$\gtrsim$41.4	0.58*	$\gtrsim$0.15*
100	∼65 BH	195	4.9	$\lesssim 5.4\times10^5$	$\gtrsim$–9.6	–0.2	–0.9	–1.3	$\gtrsim$39.4	$\gtrsim$40.0	$\gtrsim$40.5	0.95*	$\gtrsim$0.06*
300	∼230 BH	690	9.2	$\lesssim 1.9\times10^6$	$\gtrsim$–11.0	–0.2	–1.0	–1.3	$\gtrsim$38.1	$\gtrsim$38.6	$\gtrsim$39.2	1.8*	$\gtrsim$0.02*
1000	∼720 BH	2160	16.3	$\lesssim 6.0\times10^6$	$\gtrsim$–12.2	–0.2	–0.9	–1.3	$\gtrsim$36.8	$\gtrsim$37.5	$\gtrsim$37.9	3.2*	$\gtrsim$0.01*
BH accretion-disk bolometric luminosities and UV half-light radii estimated from multi-color thin-disk model													
30	∼5.0 BH	15	1.9	$\lesssim 3.1\times10^4$	$\gtrsim$–6.5	–0.6	–1.4	–1.7	$\gtrsim$42.1	$\gtrsim$42.8	$\gtrsim$43.2	0.37?	$\gtrsim$0.84?
50	∼24 BH	72	4.5	$\lesssim 1.8\times10^5$	$\gtrsim$–8.4	–0.4	–1.2	–1.5	$\gtrsim$40.4	$\gtrsim$41.1	$\gtrsim$41.5	0.87*	$\gtrsim$0.18*
100	∼65 BH	195	7.8	$\lesssim 5.9\times10^5$	$\gtrsim$–9.7	–0.2	–0.9	–1.3	$\gtrsim$39.3	$\gtrsim$40.0	$\gtrsim$40.4	1.51*	$\gtrsim$0.06*
300	∼230 BH	690	15.8	$\lesssim 2.0\times10^6$	$\gtrsim$–11.0	–0.2	–1.0	–1.3	$\gtrsim$38.0	$\gtrsim$38.6	$\gtrsim$39.1	3.1*	$\gtrsim$0.02*
1000	∼720 BH	2160	29.8	$\lesssim 6.6\times10^6$	$\gtrsim$–12.3	–0.2	–0.9	–1.3	$\gtrsim$36.7	$\gtrsim$37.4	$\gtrsim$37.8	5.8*	$\gtrsim$0.01*

- If $M\gtrsim 20\ M_\odot$ Pop III stellar mass black hole accretion disks have $\mu\gtrsim 10^4$–10^5 during caustic transits, they could be detectable for a few months to AB$\lesssim$29 mag with JWST. Rise times ∼hours–1 day; Decay times $\lesssim$0.4 yr.

- Note the combined Bolometric+IGM+K-corrections are also more advantageous for Pop III stellar-mass black hole accretion disks.

Multi-λ model: $T \propto r^{-3/4}$; $T_{max} \simeq 10(\frac{M_{BH}}{100})^{-3/8}$ keV; $r_{hl} \propto M_{BH}^{1/2}$.



What are the best lensing clusters for JWST to see First Light objects?:

[LEFT] Best lensing clusters vs. ROSAT, Planck, SPT, MaDCoWS.

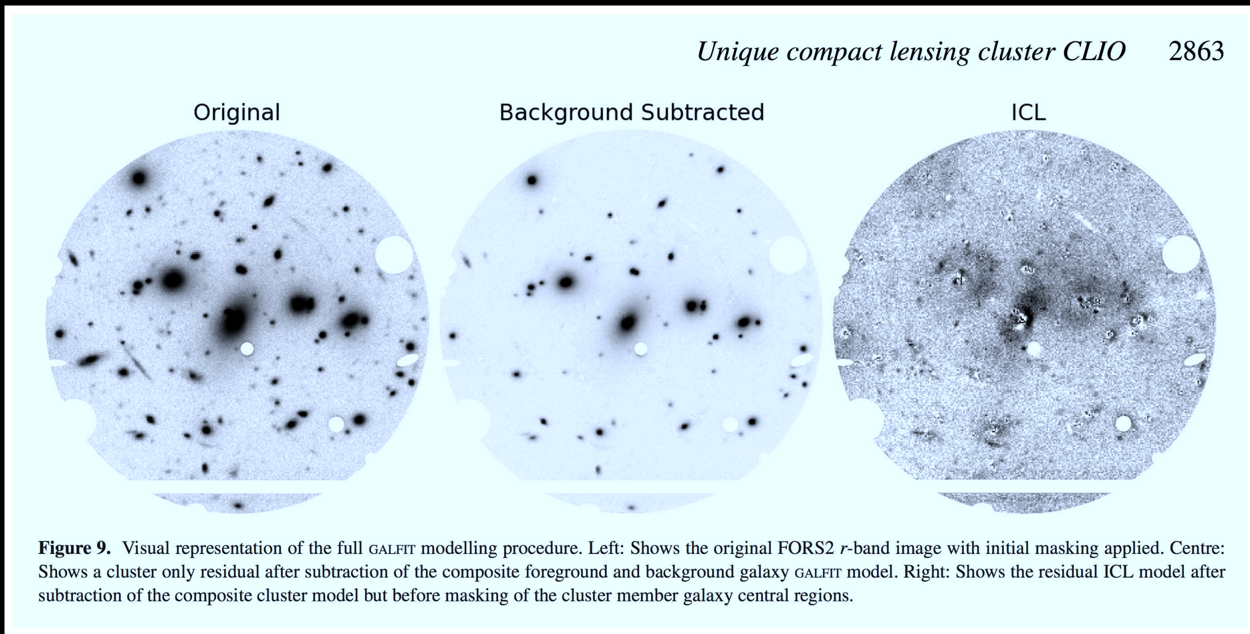
[RIGHT] Best lensing clusters compared to CLASH clusters.

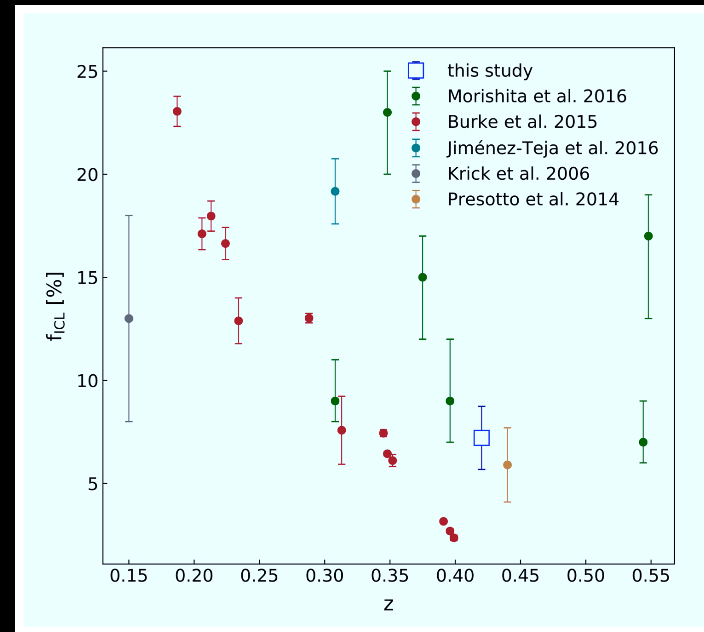
(Contours: Number of lensed JWST sources at z$\simeq$1–15 to AB$\lesssim$31 mag).

- Resulting sweet spot for JWST lensing of First Light Objects (z$\gtrsim$10):

Redshift: 0.3$\lesssim$z$\lesssim$0.5; Mass: $10^{15-15.6}$ $M_\odot$; Concentration: 4.5$\lesssim$C$\lesssim$8.5

(4) What are the best lensing clusters to monitor caustic transits?

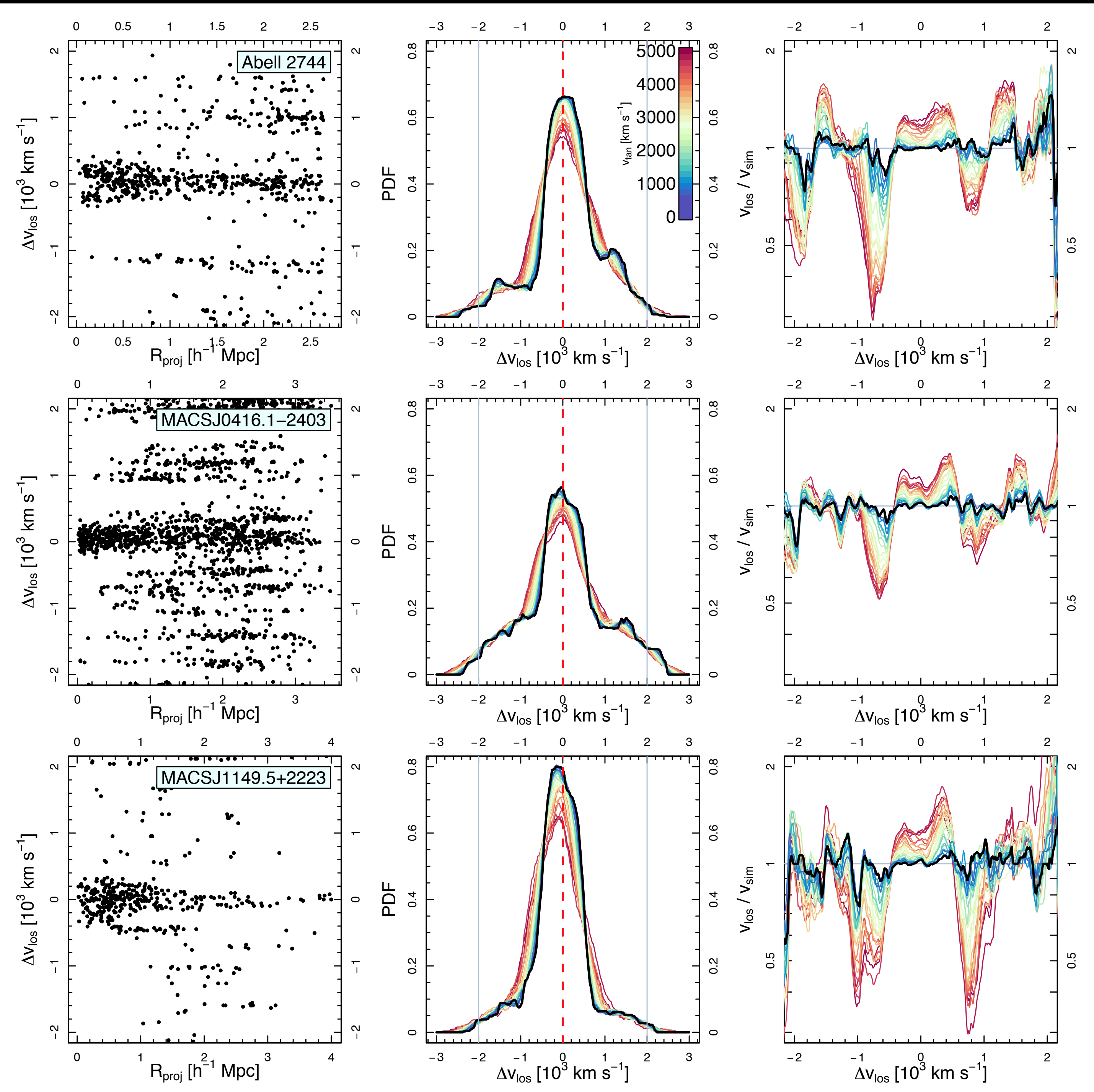




Griffiths et al. (2018 MNRAS, 475, 2853): GAMA cluster at z≃0.42 found through mass-concentration selection. Has 89 VLT MUSE members:

- Cluster has minimal ICL near the critical curves, optimal for caustic transit studies. Can see several arcs clearly in ground-based images.

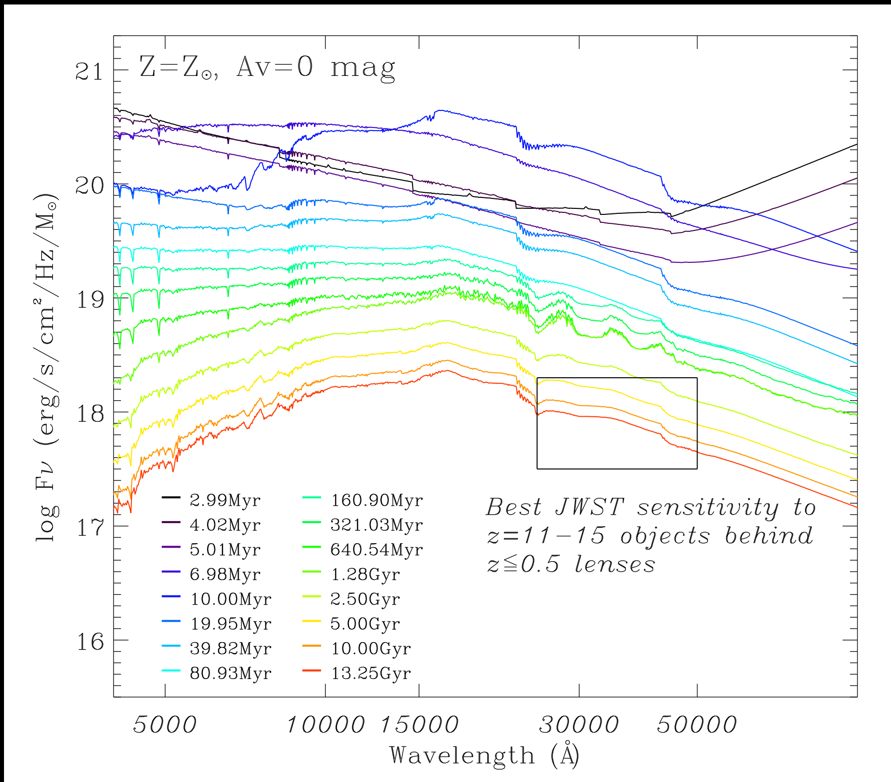
- JWST should monitor clusters with minimal ICL near the critical curves to minimize microlensing and maximize caustic transit magnifications.

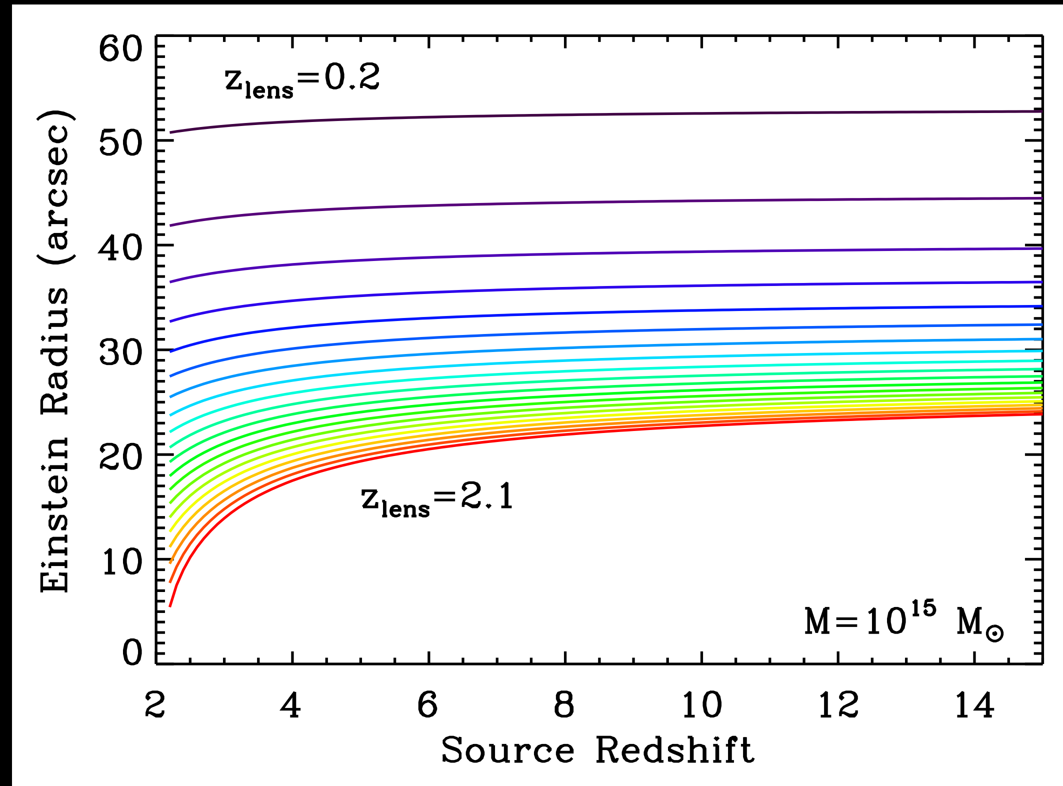


Trumpet diagrams for JWST lensing clusters from ground-based spectroscopic N(z) (Windhorst+ 2018):

- 1) Add random *space* velocity v_{sp} to clusters.
- 2) Projected v_T must be $\lesssim$1000km/s for v_{sp} not to unduly disturb radial N(z).
- 3) Best clusters (Bullet) for caustic transits can have $v_T \lesssim$2700 km s^{-1}.

- JWST should monitor such clusters during its lifetime for caustic transits.





Galaxy SEDs for different ages: peak at $\lambda_{rest}\simeq$1.6μm (Kim et al. 2017).

JWST-NIRCam peaks in sensitivity for λ=3–5μm, where Zodi is lowest.

Sweet spot for lensing cluster z$\lesssim$0.5: Zodi-gain mitigates $(1+z)^4$-dimming.

- Minimizes effects from near-IR K-correction and ambient ICL.
- Lower redshift clusters also have higher (virialized) masses and much larger Einstein radii.
- This is critical for optimizing caustic transit detections away from ICL.