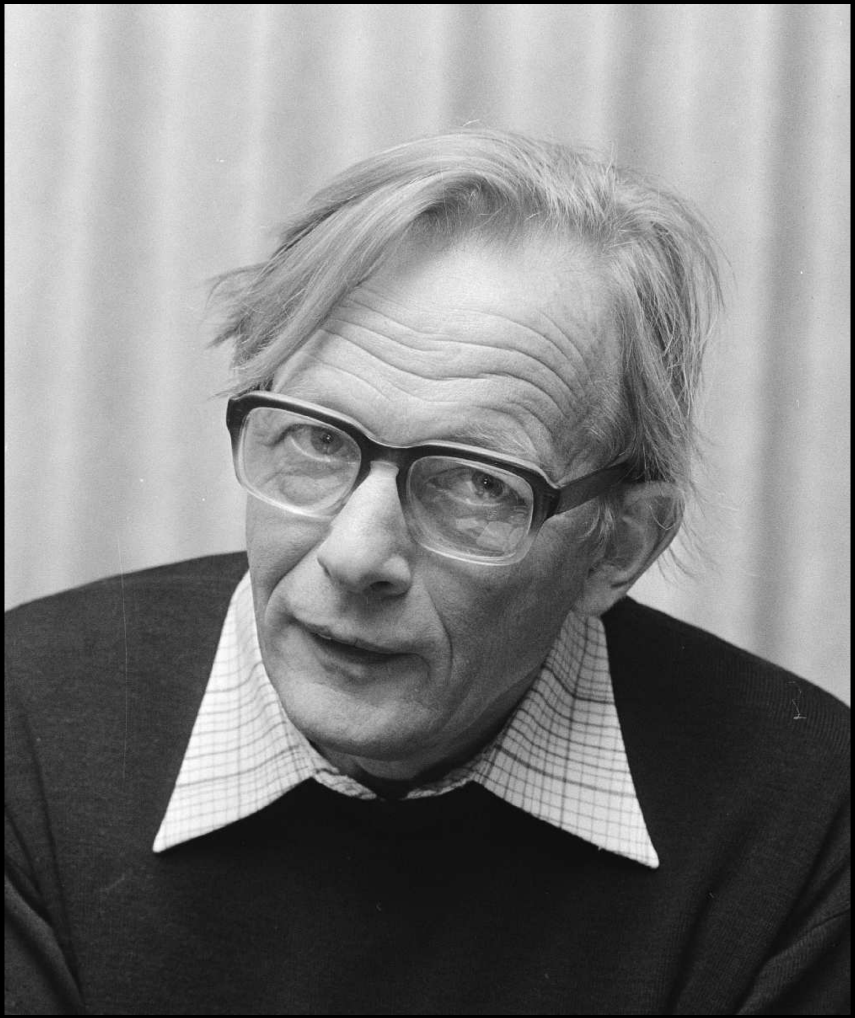
Henk, Hubble, H-I and Dust —
A quarter century of going from Gas to Dust with Hubble

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist



Talk at the Henk van de Hulst Centennial Symposium; Leiden, Wednesday Nov. 7, 2018

Talk is on: `http://www.asu.edu/clas/hst/www/jwst/jwsttalks/vandehulst100_leiden18.pdf`

Outline & Conclusions

(1) My personal observations of Prof. Henk van de Hulst.

(2) Henk and Hubble

(3) Hubble, HI, and Dust

(4) The Webb Telescope and Dust

(5) First Light, First Dust?

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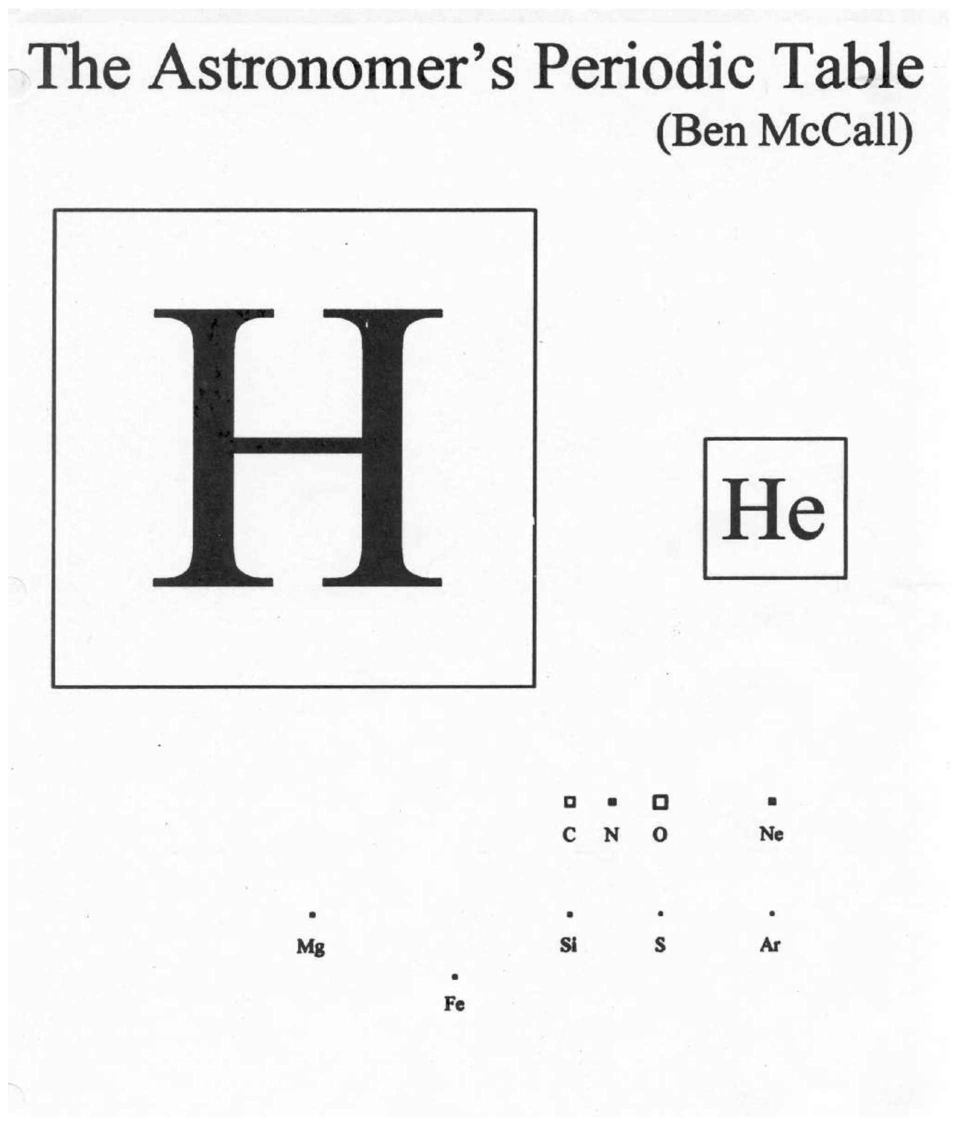

[The z≃0 periodic table with cosmic abundance included]

- In honor of Henk, I will mostly focus on Hydrogen today —
- Helium only complicates the story,
- and I wanted to ignore all other elements ("dust"), but ...

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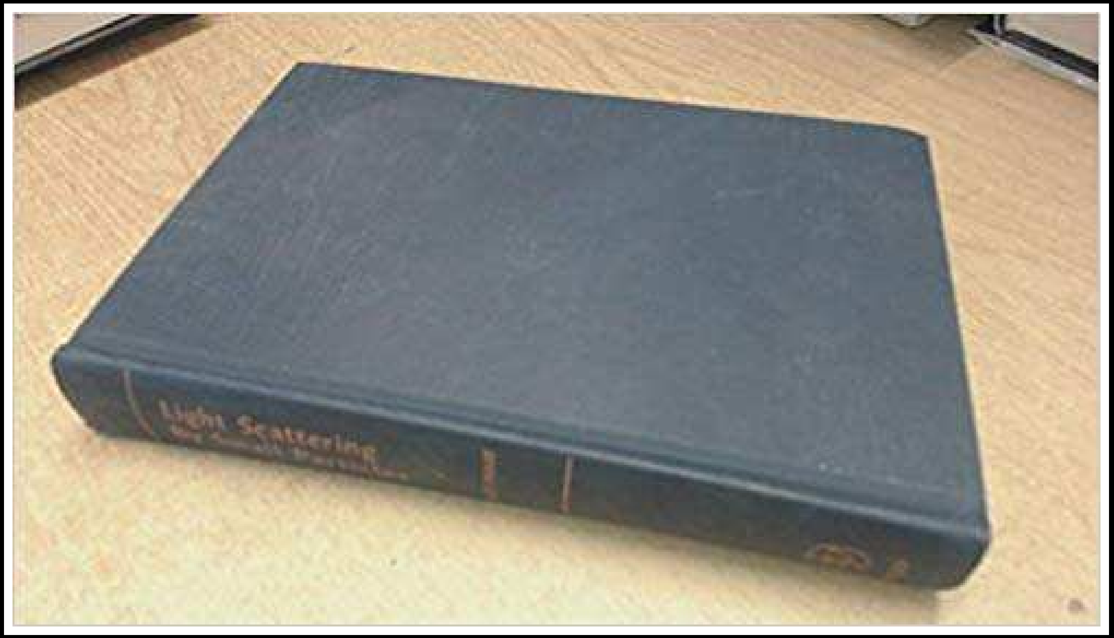
- Still, as an observer I was not allowed to brush dust under the table ...

(1) Other lessons learned about Dust from Henk van de Hulst



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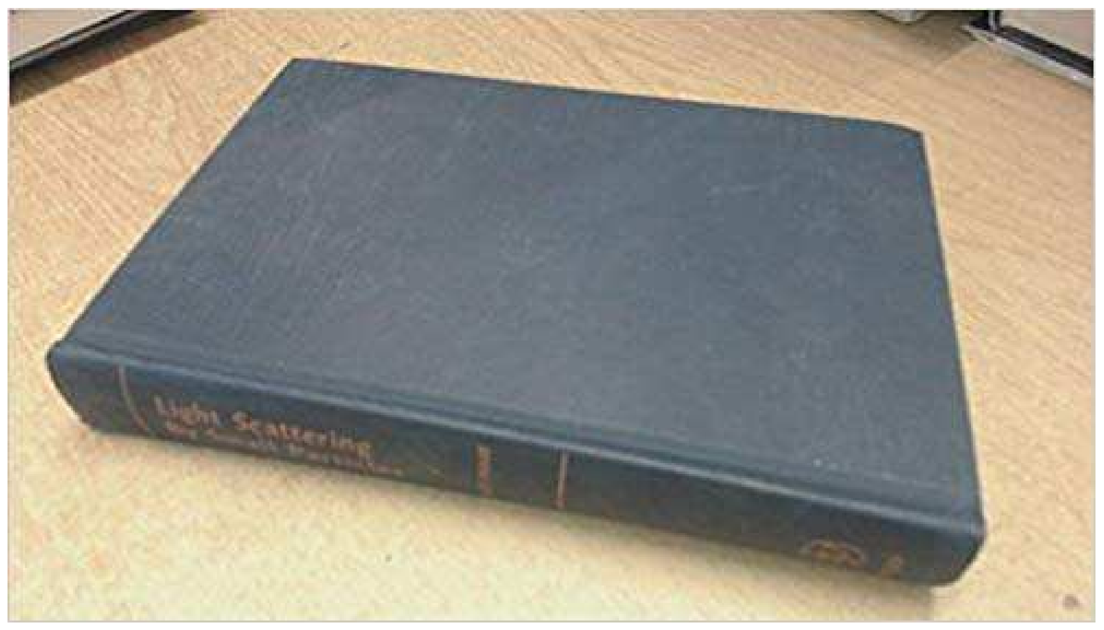

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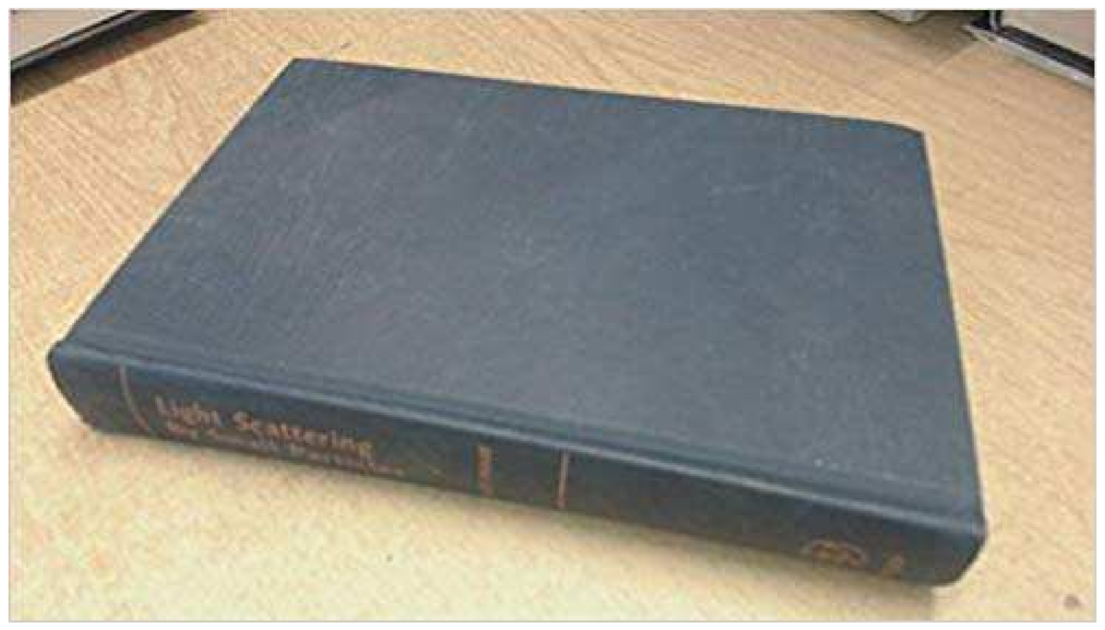

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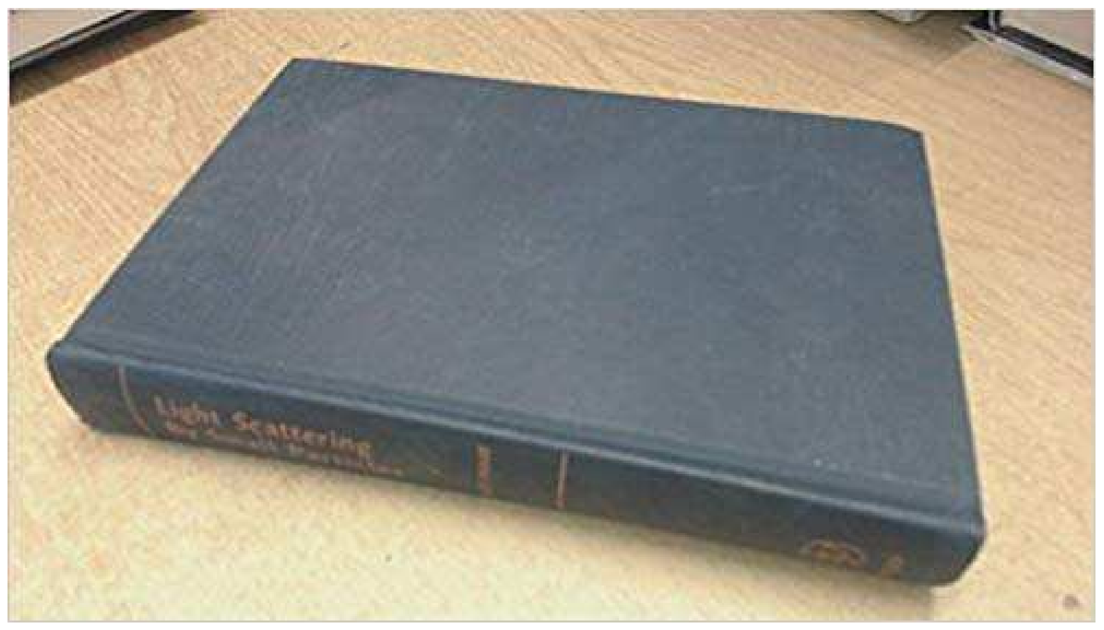

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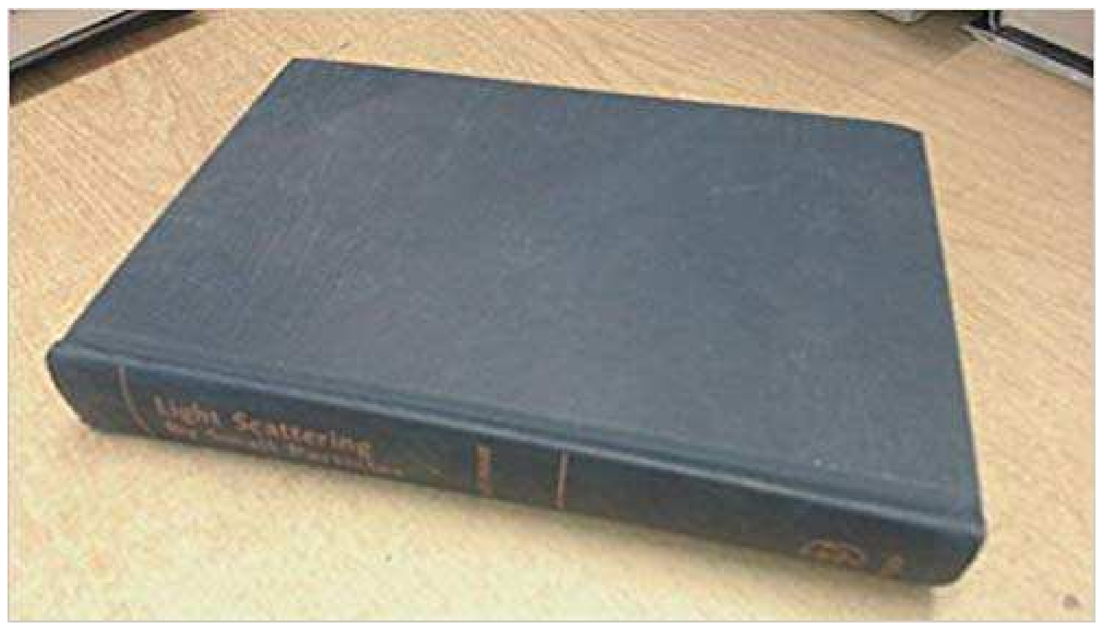

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“… for dust thou art, and unto dust shalt thou return.” [King James Version]

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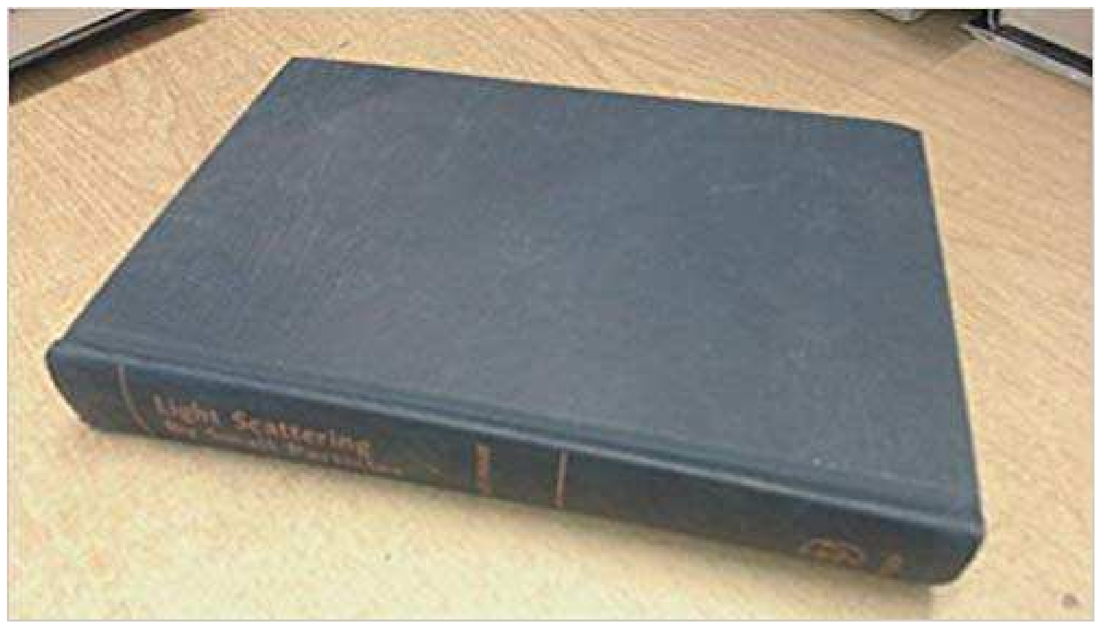

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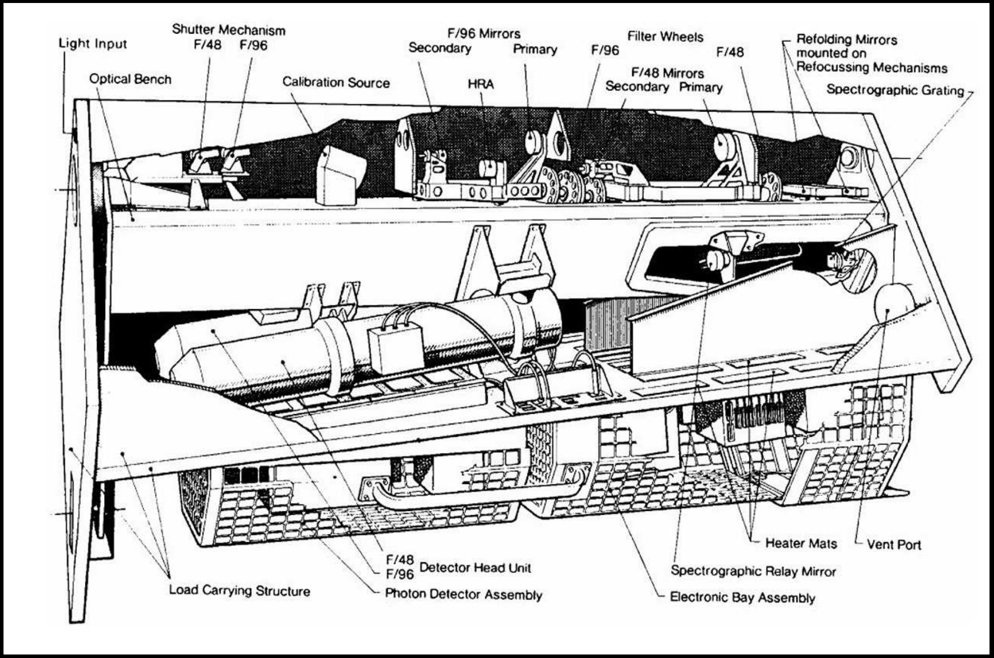
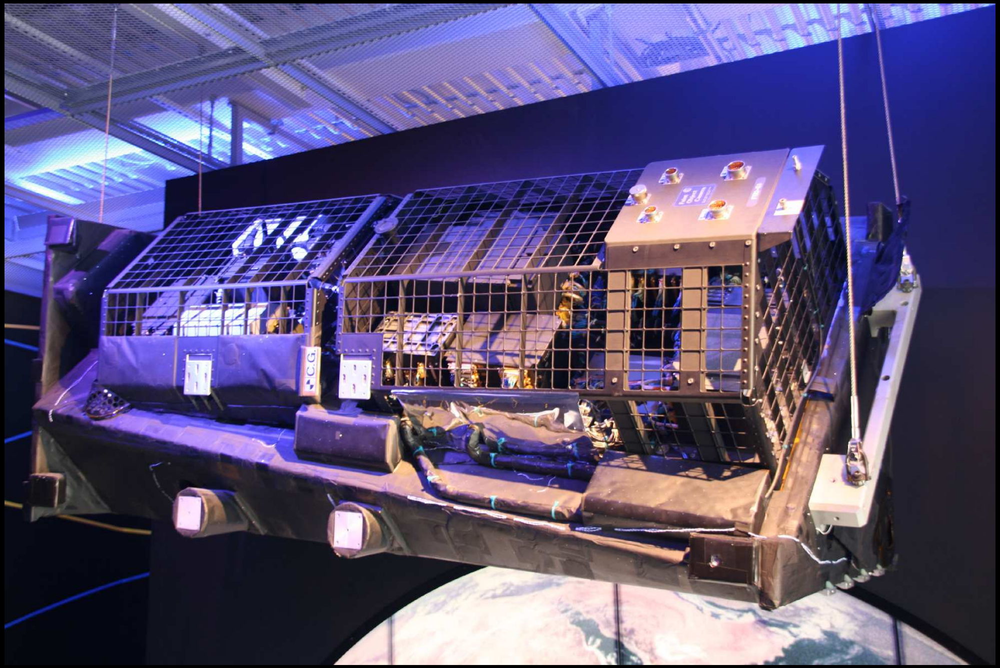
- Important lesson: While dust may be incomprehensible (to an observer), it is not ever to be treated frivolously.

(2) Henk and Hubble





- Henk was involved with the HST Faint Object Camera from the very beginning in the mid 1970's (see also Johan Bleeker's talk).

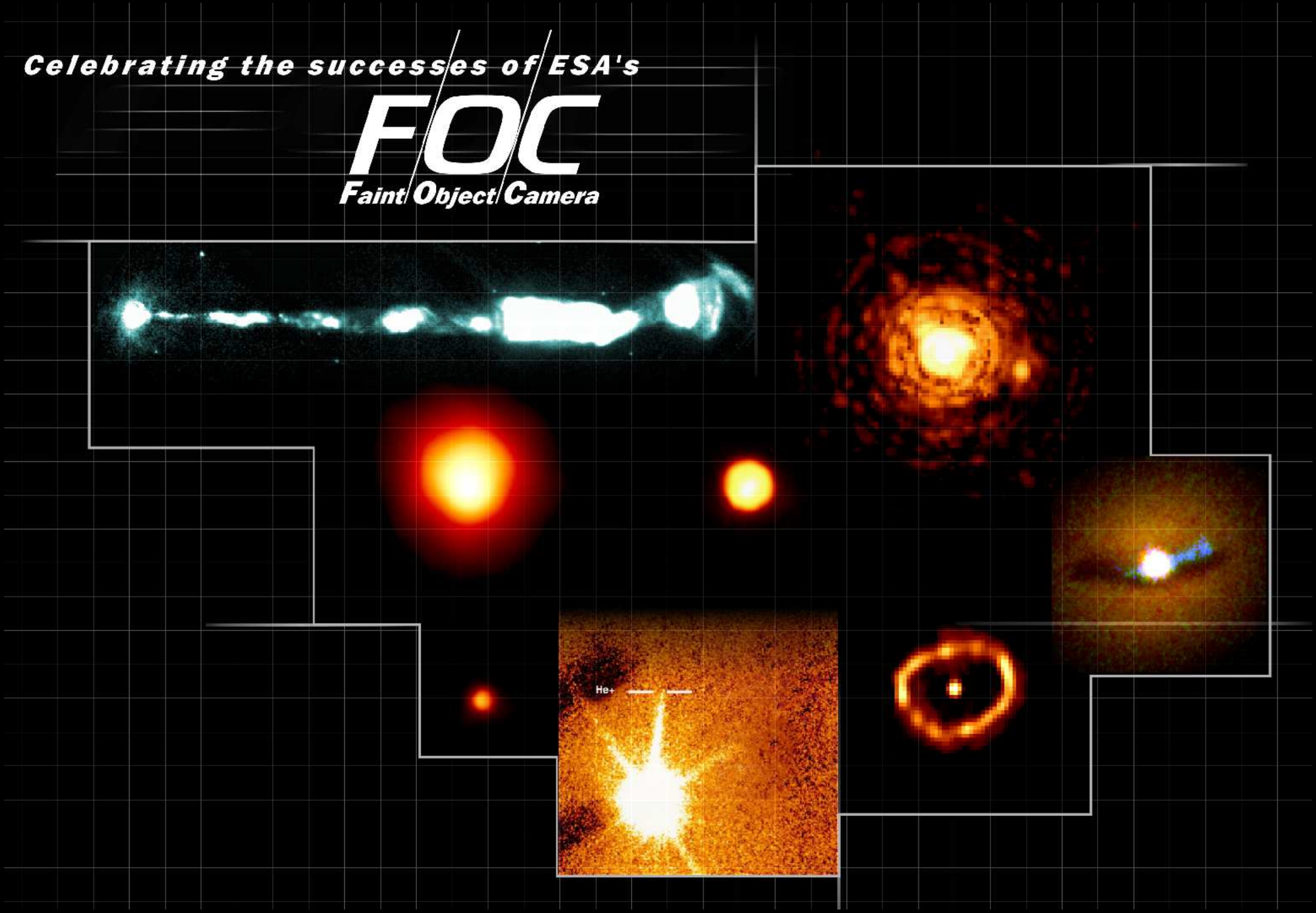
- It is due to his steady leadership that the only fully diffraction limited camera in Hubble has become such a success. The FOC has:

- f/48: $0''.043$ pix and $22''$ FOV (best pixel-size in Hubble today);

- f/96: $0''.022$ pix and $11''$ FOV;

- f/288: $0''.0072$ pix and $3''.6$ FOV.

(2) Henk and Hubble



Henk was most pleased to see the main science results from Hubble's (aberration-corrected) full-resolution FOC in January 1994.

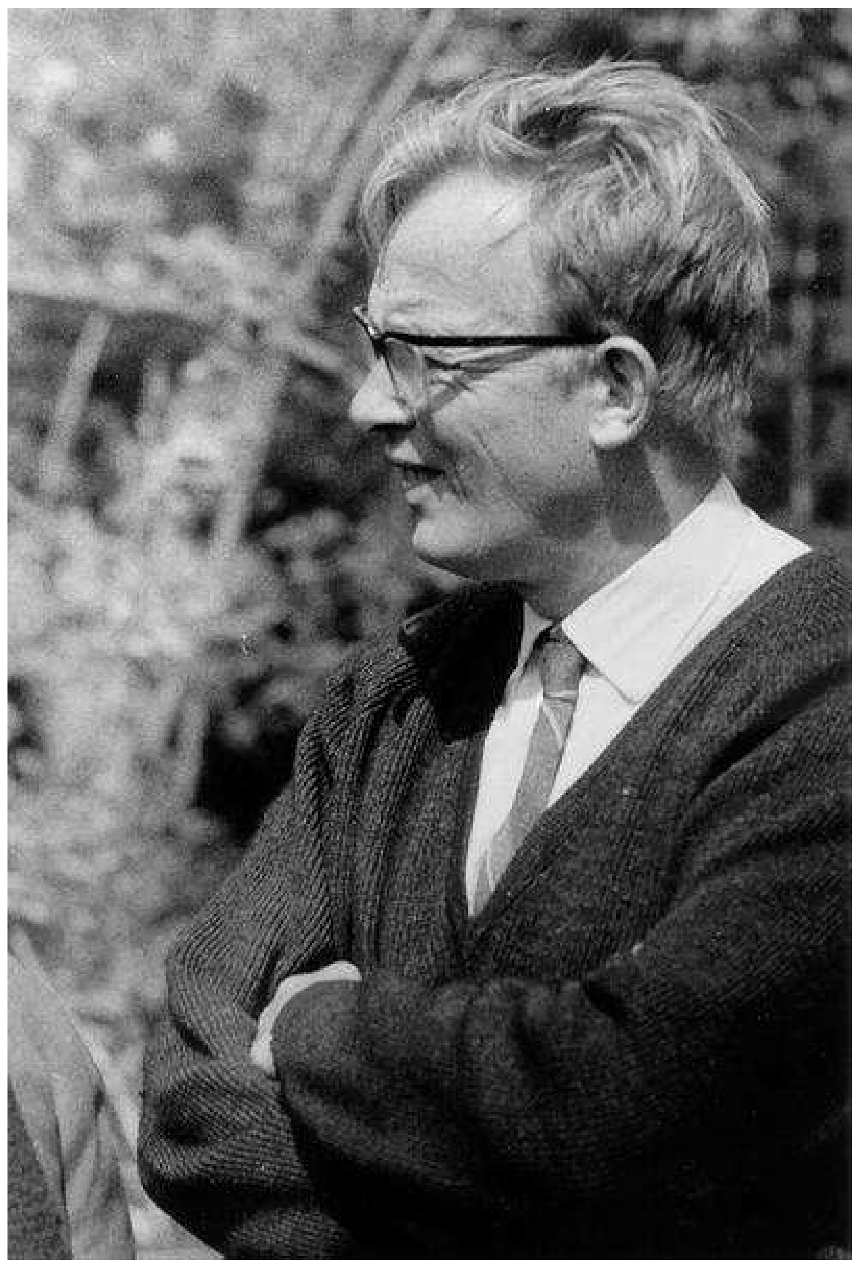
(2) Henk and Hubble

- In June 1993, the HST Project doubted that they could fund future HST instruments (NICMOS, STIS, ACS) after SM1.

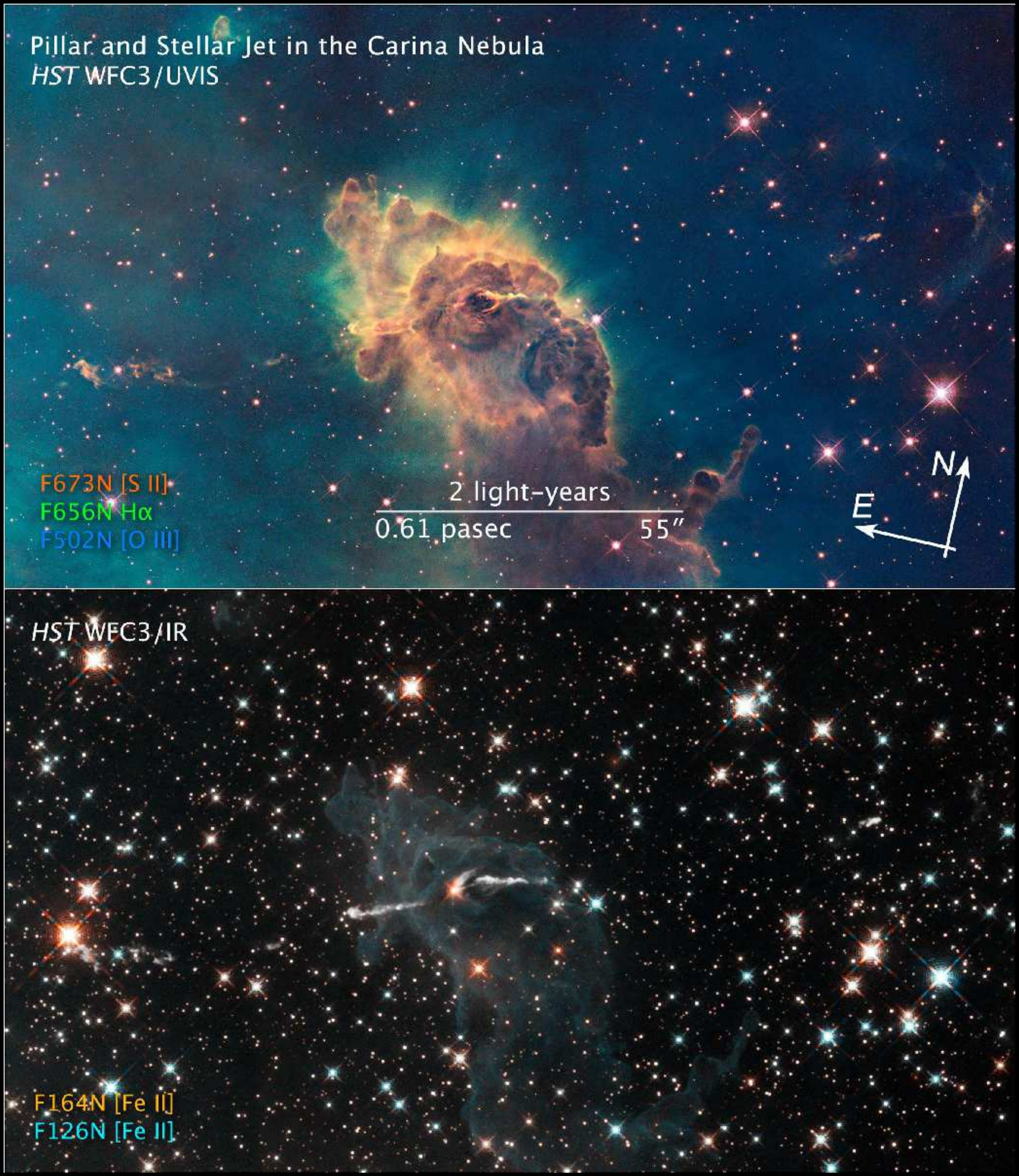
- The HST Users Committee was tasked by Ed Weiler at NASA HQ to review the HST Project budget for FY94-FY00.

- We asked Henk van de Hulst to sit on the panel, and go through 1000 (paper) PPT charts in one week in Jan. 1994.

- Henk sat through the review mostly silently, but summarized it extremely well in the end: "Hubble is the best science project mankind has ever done — it costs what it cost; one cannot argue with success. The rest is history.



(3) Hubble, HI and Dust



Made possible 15 years after Henk's 1994 HST budget review: HST WFC3's UV-optical and near-IR SF "pillar" in Carina.

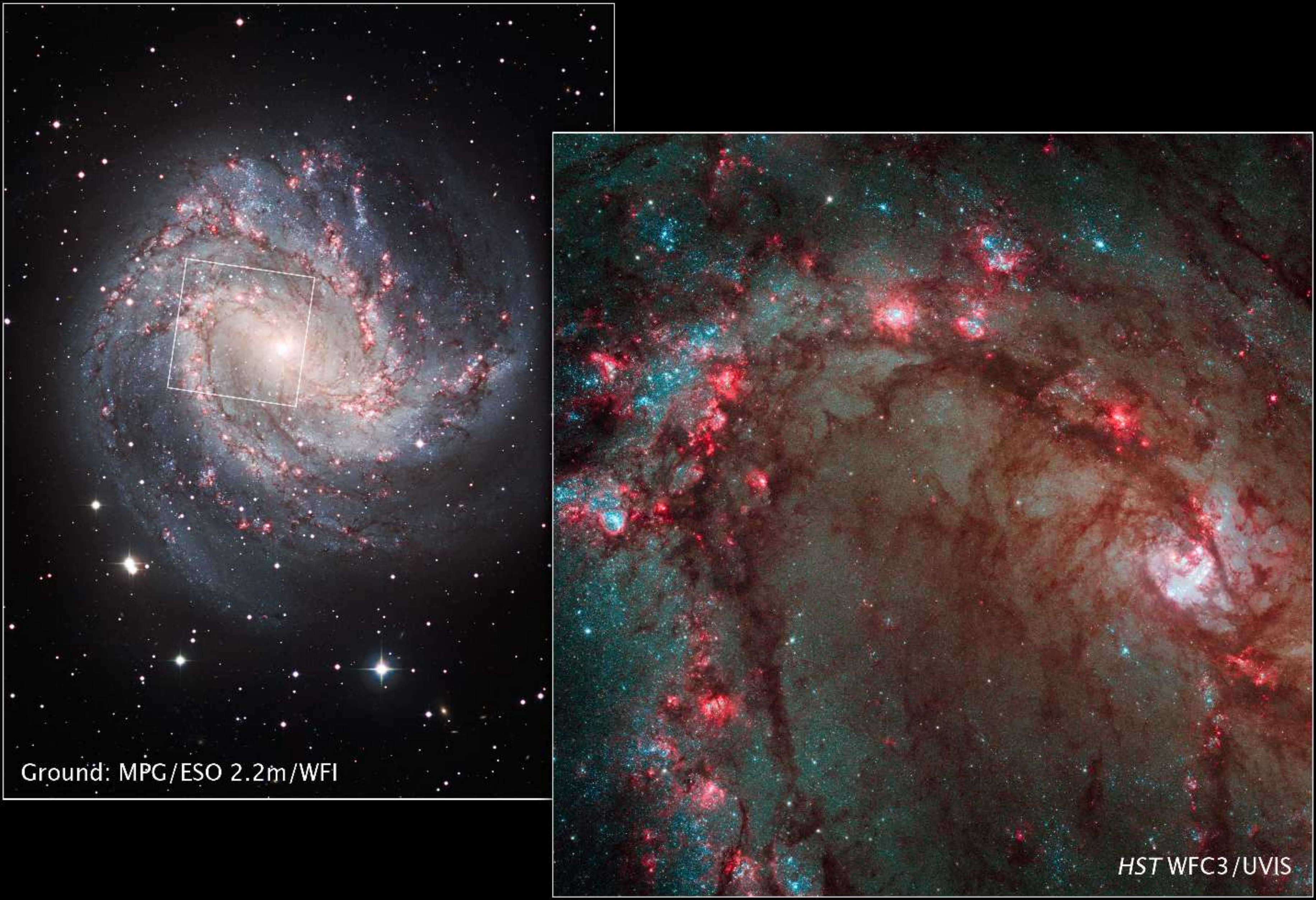
(3) Hubble, HI and Dust

30 Doradus Nebula and Star Cluster
Hubble Space Telescope ▪ WFC3/UVIS/IR

NASA, ESA, F. Paresce (INAF-IASF, Italy), and the WFC3 Science Oversight Committee

STScI-PRC09-32b

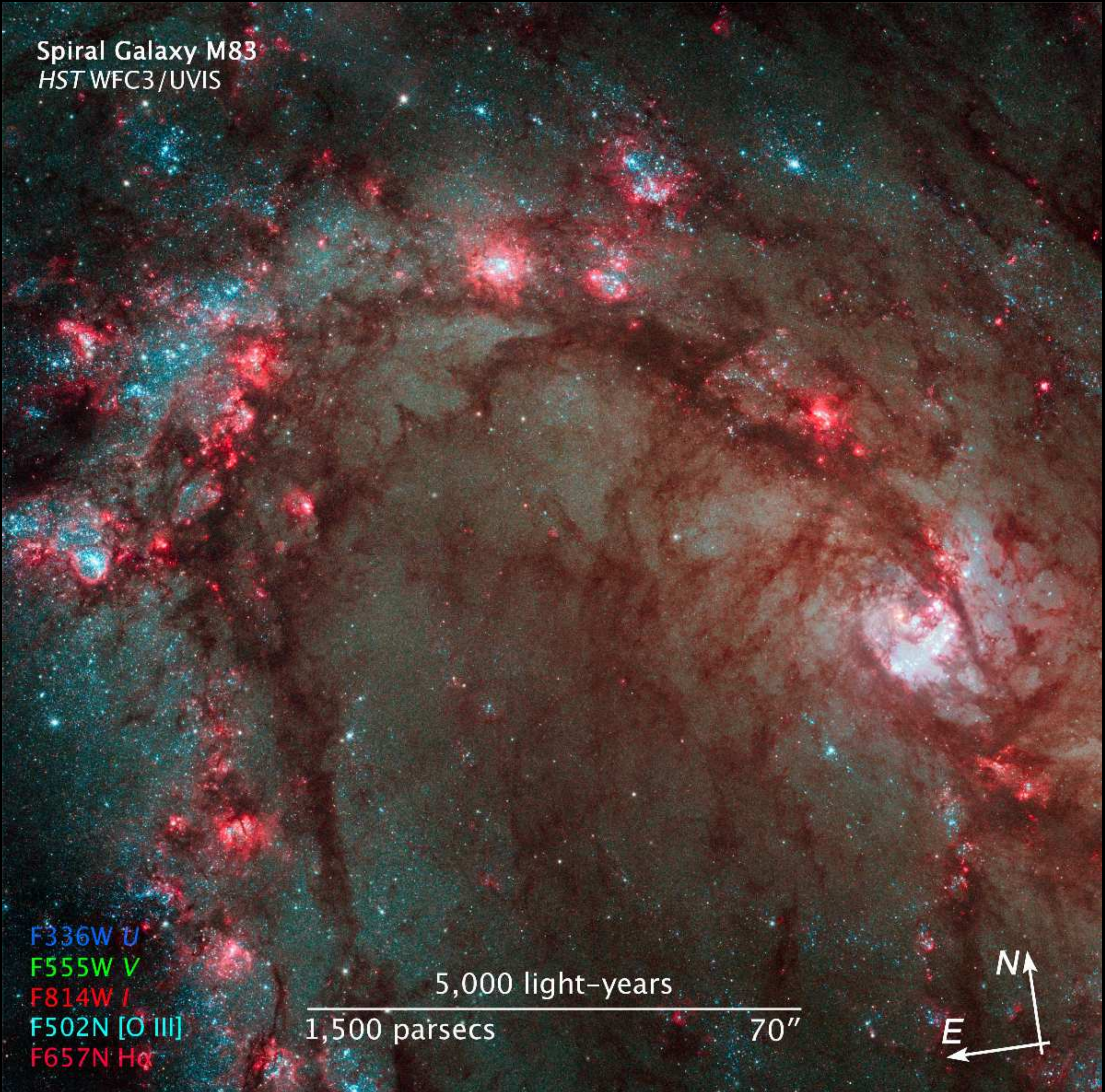
Henk would have really liked this one — light scattering in action:
30 Doradus star-cluster in LMC (150 kly), triggering birth of Sun-like stars.



Spiral Galaxy M83
Hubble Space Telescope ▪ WFC3/UVIS

NASA, ESA, R. O'Connell (University of Virginia), the WFC3 Science Oversight Committee, and ESO STScI-PRC09-29

Henk would have also liked: Eagle Nebulae like SF-regions in nearby galaxies.


Spiral Galaxy M83
HST WFC3/UVIS
F336W *U*
F555W *V*
F814W *I*
F502N [O III]
F657N Hα
5,000 light-years
1,500 parsecs
70″
N
E

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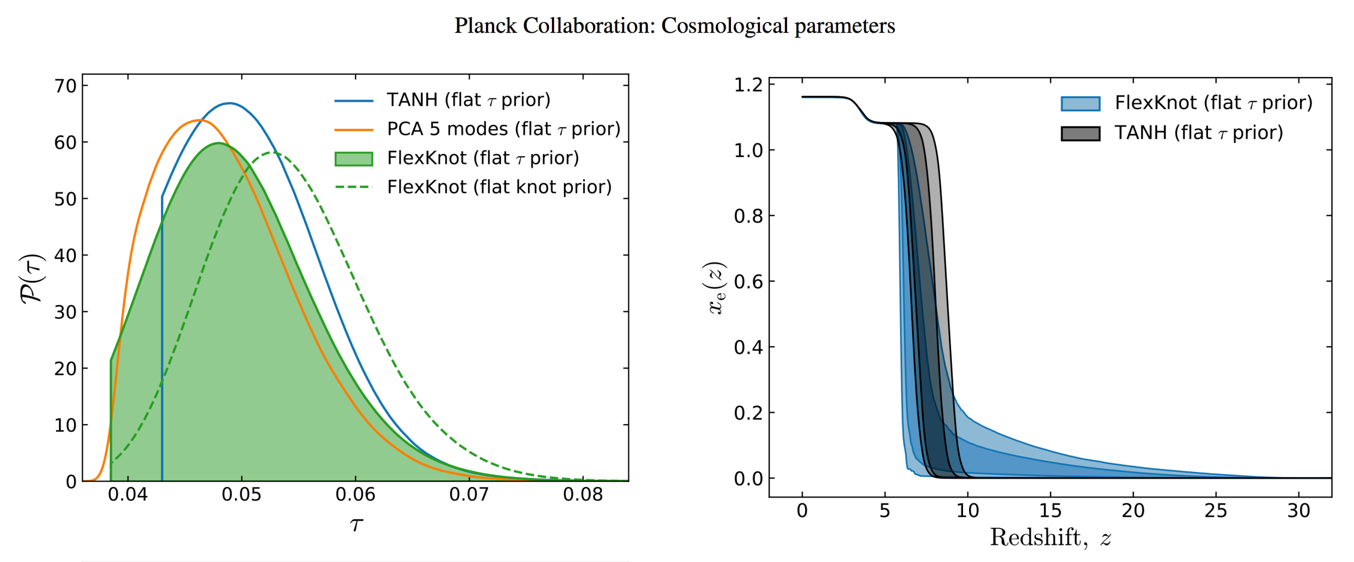
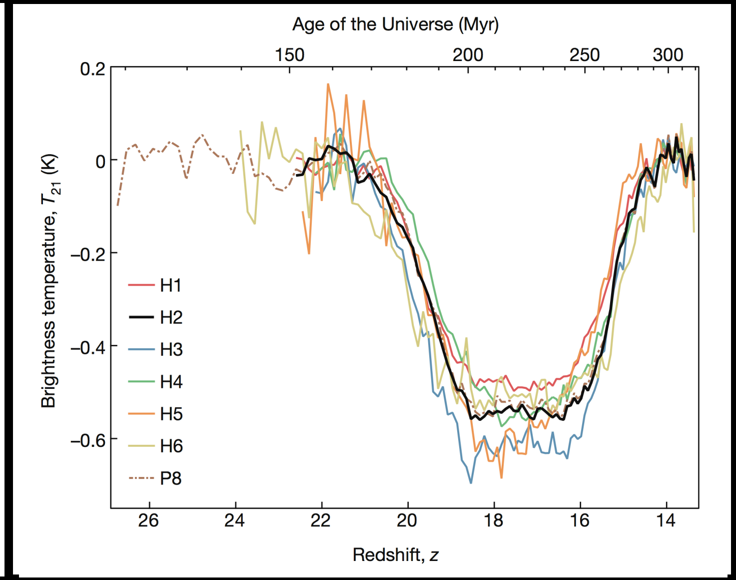
(4) The James Webb Space Telescope and Dust

Inspired by Henk: We kept JWST's mirrors free of dust! (see also M. Meixner's talk)

(5) First Light, First Dust?





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).

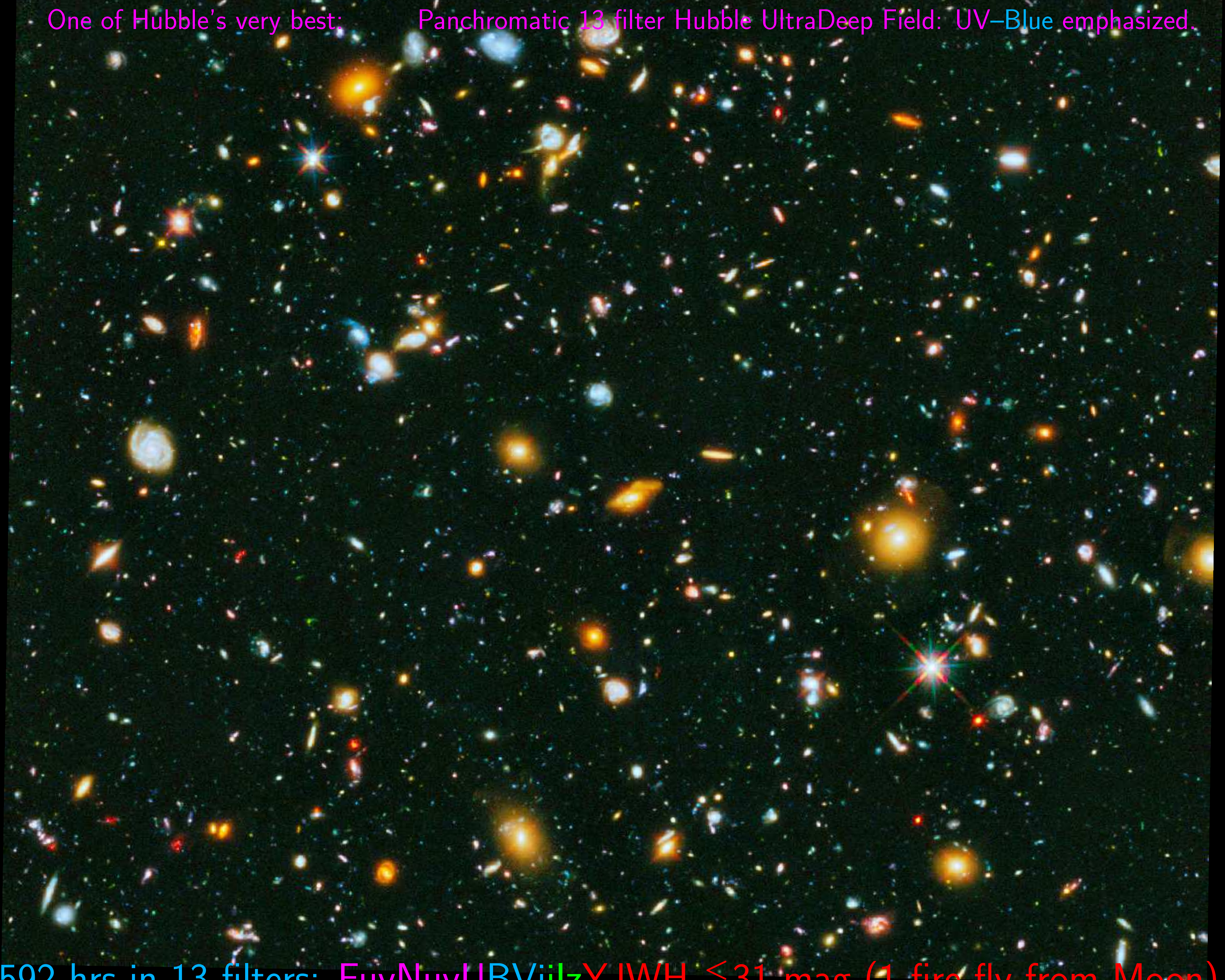
[RIGHT]: Bowman et al. EDGES result (2018, Nature, 555, 67):

- 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?

One of Hubble's very best: Panchromatic 13 filter Hubble UltraDeep Field: UV–Blue emphasized.



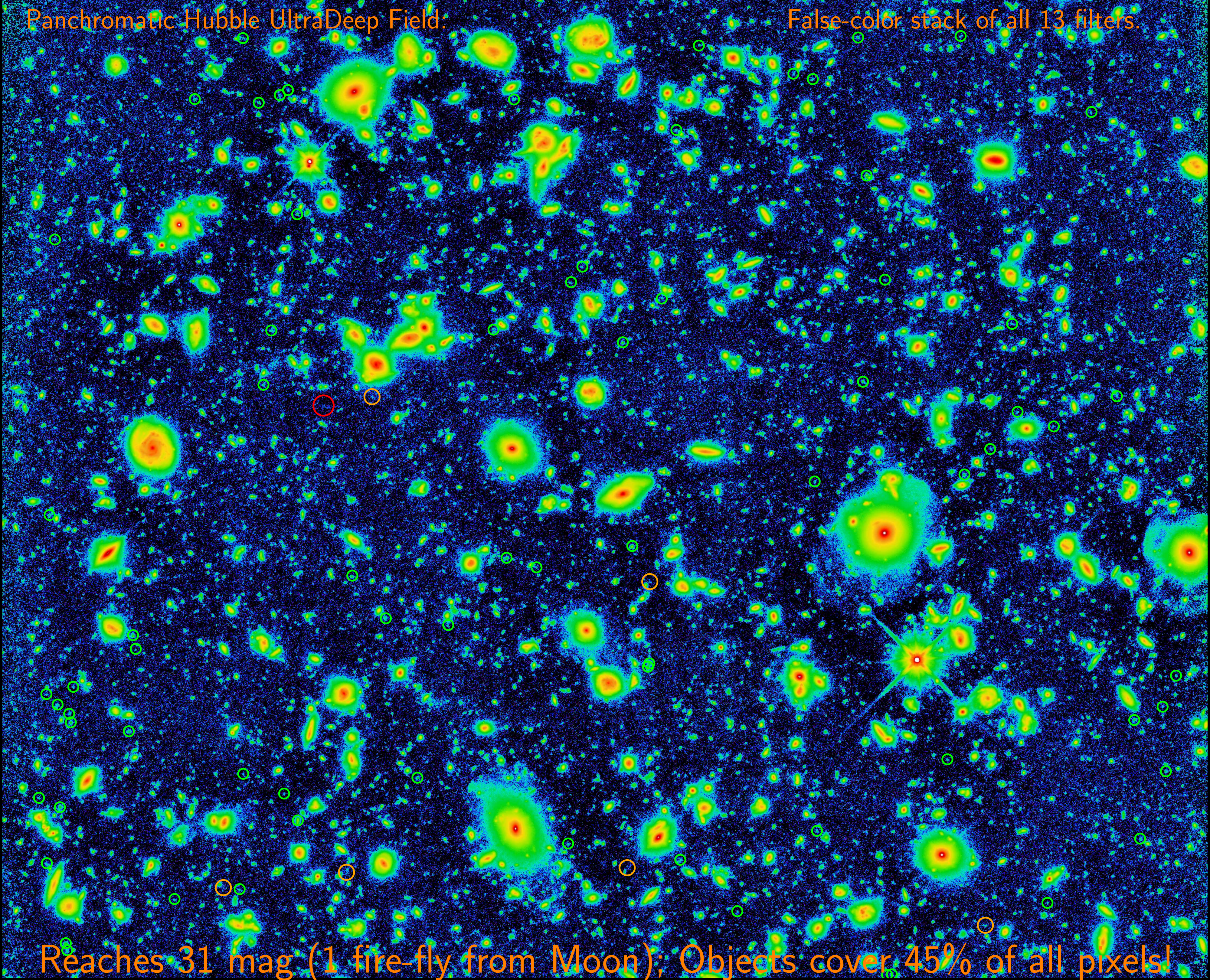
592 hrs in 13 filters: FuvNuvUBViiIzYJWH $\lesssim$31 mag (1 fire-fly from Moon).

○ z=7–8, ○ z=9, O z=10–12.

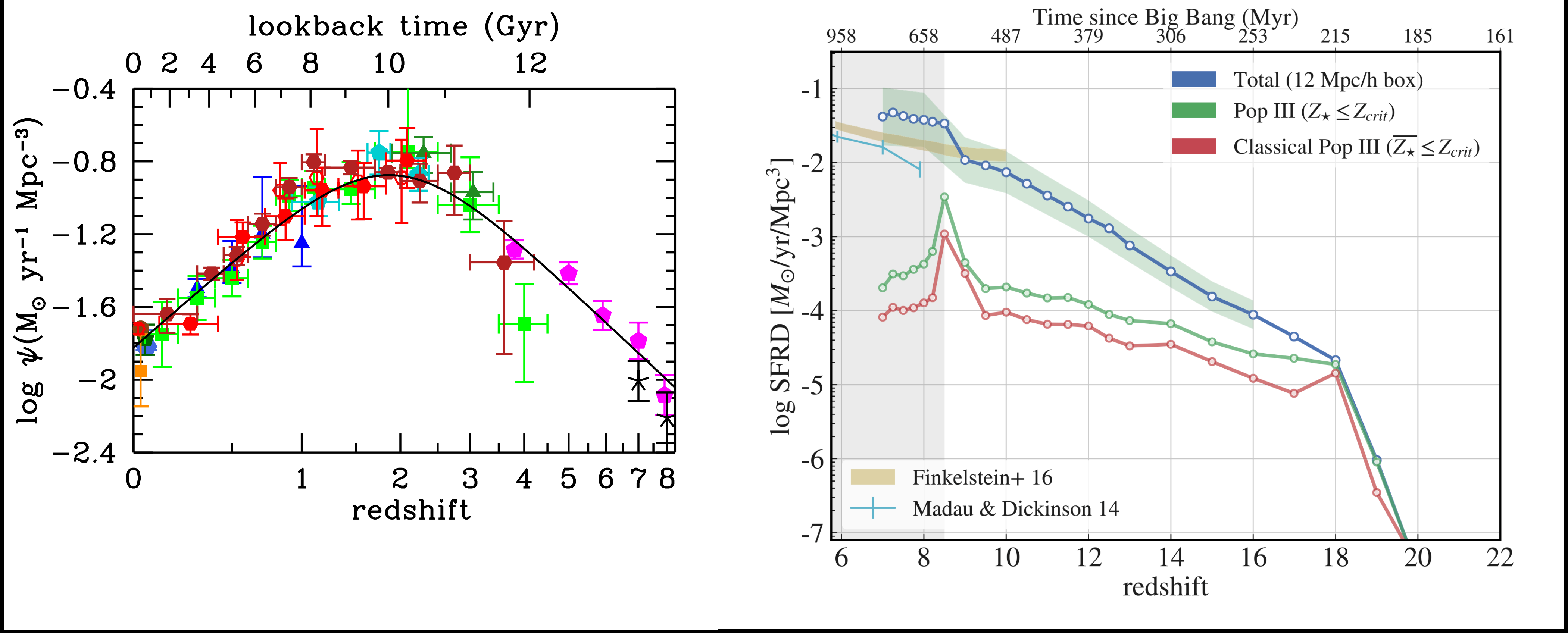
Panchromatic 13 filter Hubble UltraDeep Field: Red–IR emphasized.

592 hrs in 13 filters: FuvNuvUBViIzYJWH $\lesssim$31 mag (1 fire-fly from Moon).

Panchromatic Hubble UltraDeep Field: False-color stack of all 13 filters.



Reaches 31 mag (1 fire-fly from Moon); Objects cover 45% of all pixels!



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

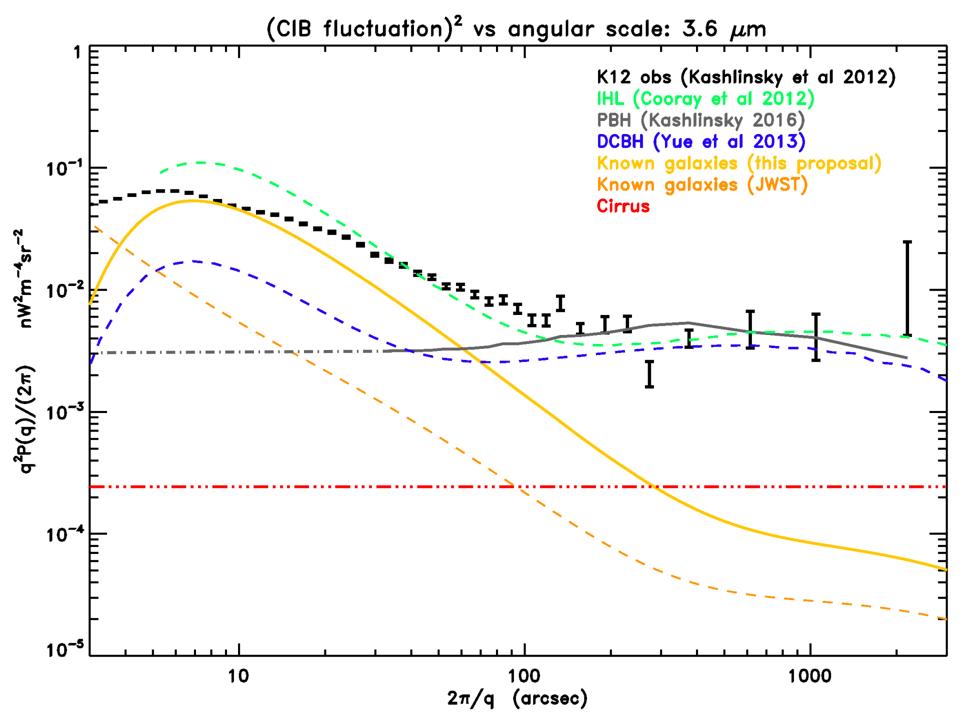
[LEFT] Observed (*e.g.*, Madau & Dickinson; 2014 ARAA, 52, 415);

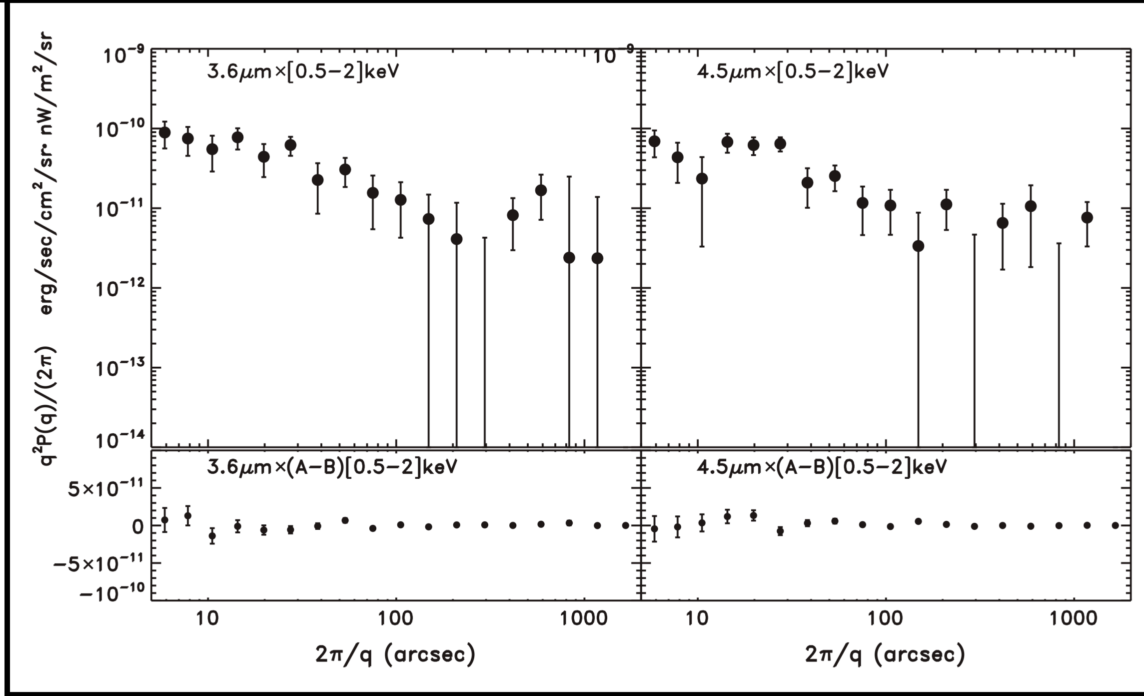
[RIGHT] RAMSES models (*e.g.*, Sarmento et al. 2018, ApJ, 854 75).

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

- Metallicity increases from $\sim$0 at z$\simeq$18 to $\lesssim 10^{-3}$ solar at z$\simeq$7.

(5) First Light, First Dust?





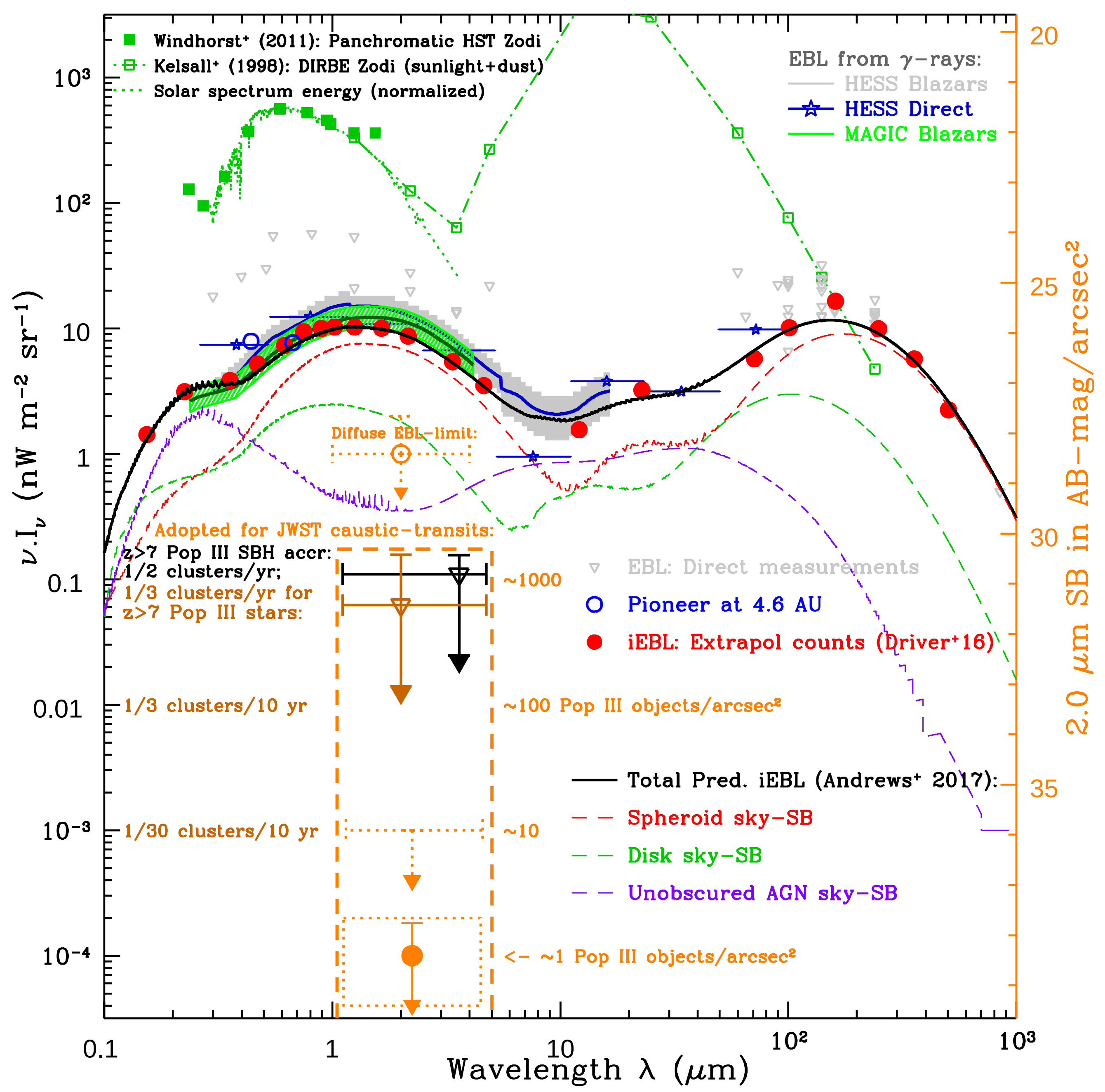
[LEFT] Object-free Spitzer 3.6 μm power-spectrum constrains noise fluctuation models (Cappelluti et al. 2017; Kashlinsky et al. 2012, 2015, 2018):

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-brightness fainter than 31 mag/arcs^2 (one firefly from Moon), 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:

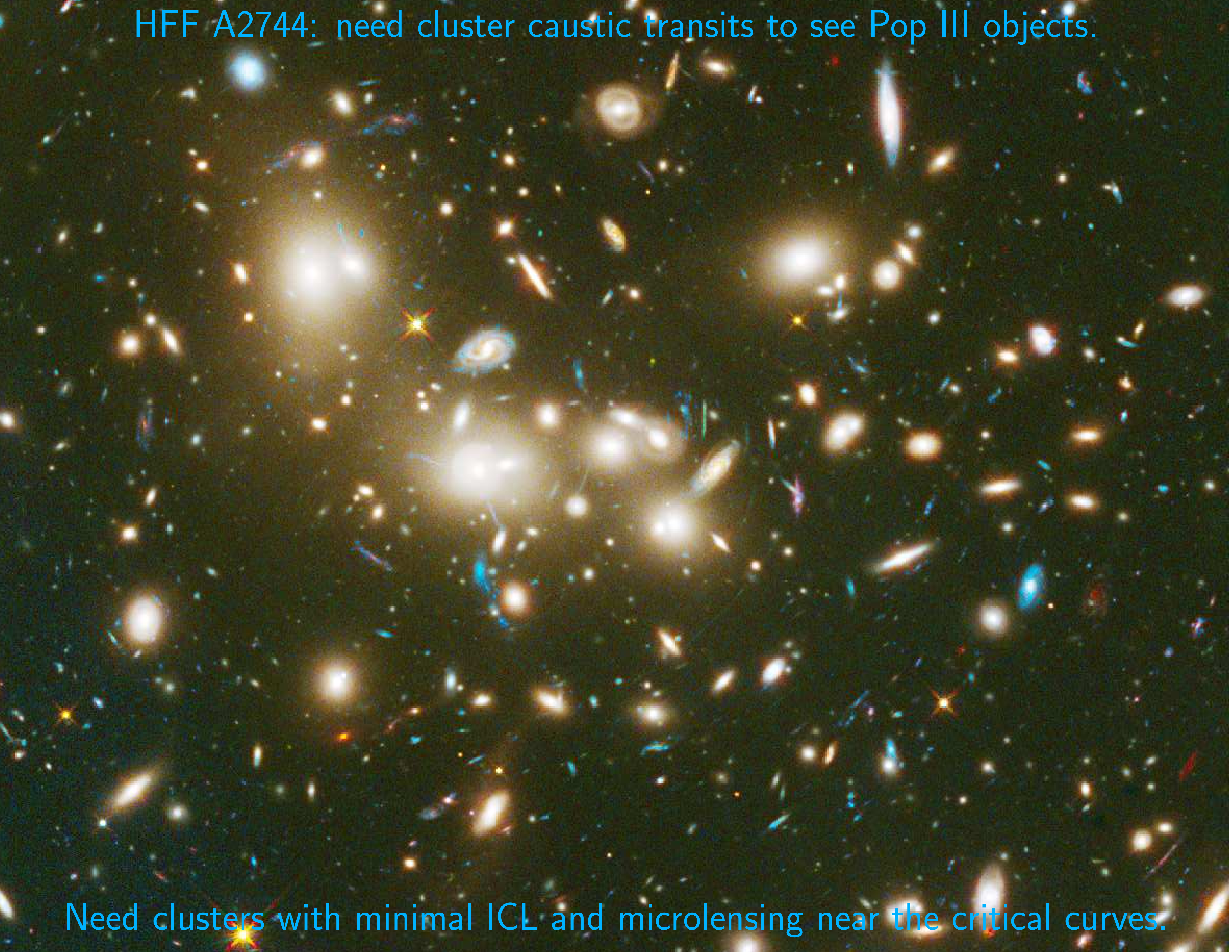
- 1) possibly from Pop III stars at z$\simeq$7–17, and/or

- 2) their stellar-mass BH accretion disks (z$\simeq$7–8).

This can make Pop III stars or their BH accretion disks temporarily visible to JWST & ground-based 30 meter telescopes at AB$\lesssim$28–29 mag.

- Requires using the best lensing clusters and monitoring caustic transits.

HFF A2744: need cluster caustic transits to see Pop III objects.



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

(5) HST observations of a B-star caustic transit at $z \simeq 1.49$

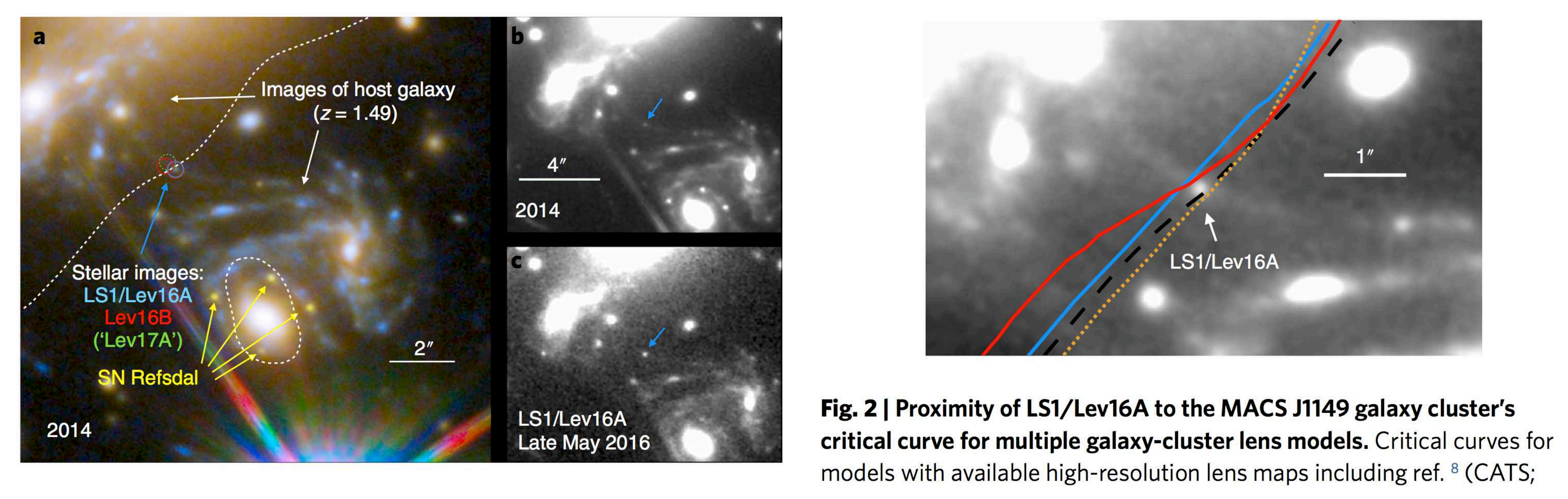


Fig. 2 | Proximity of LS1/Lev16A to the MACS J1149 galaxy cluster's critical curve for multiple galaxy-cluster lens models. Critical curves for models with available high-resolution lens maps including ref. [8] (CATS;

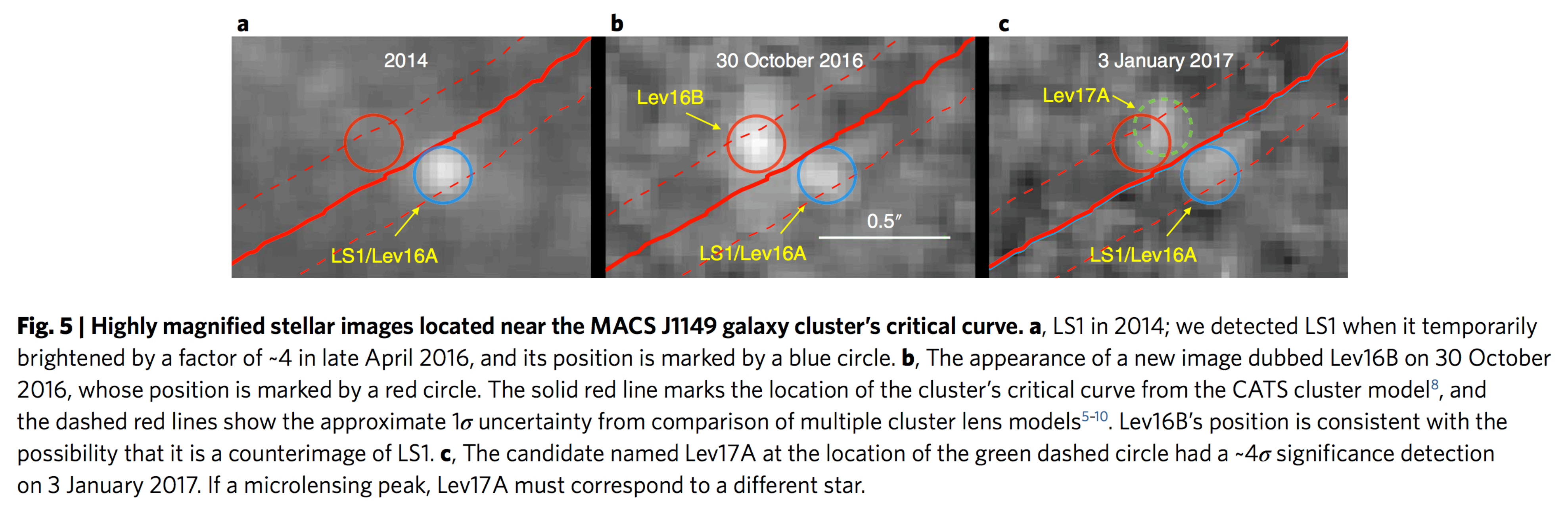
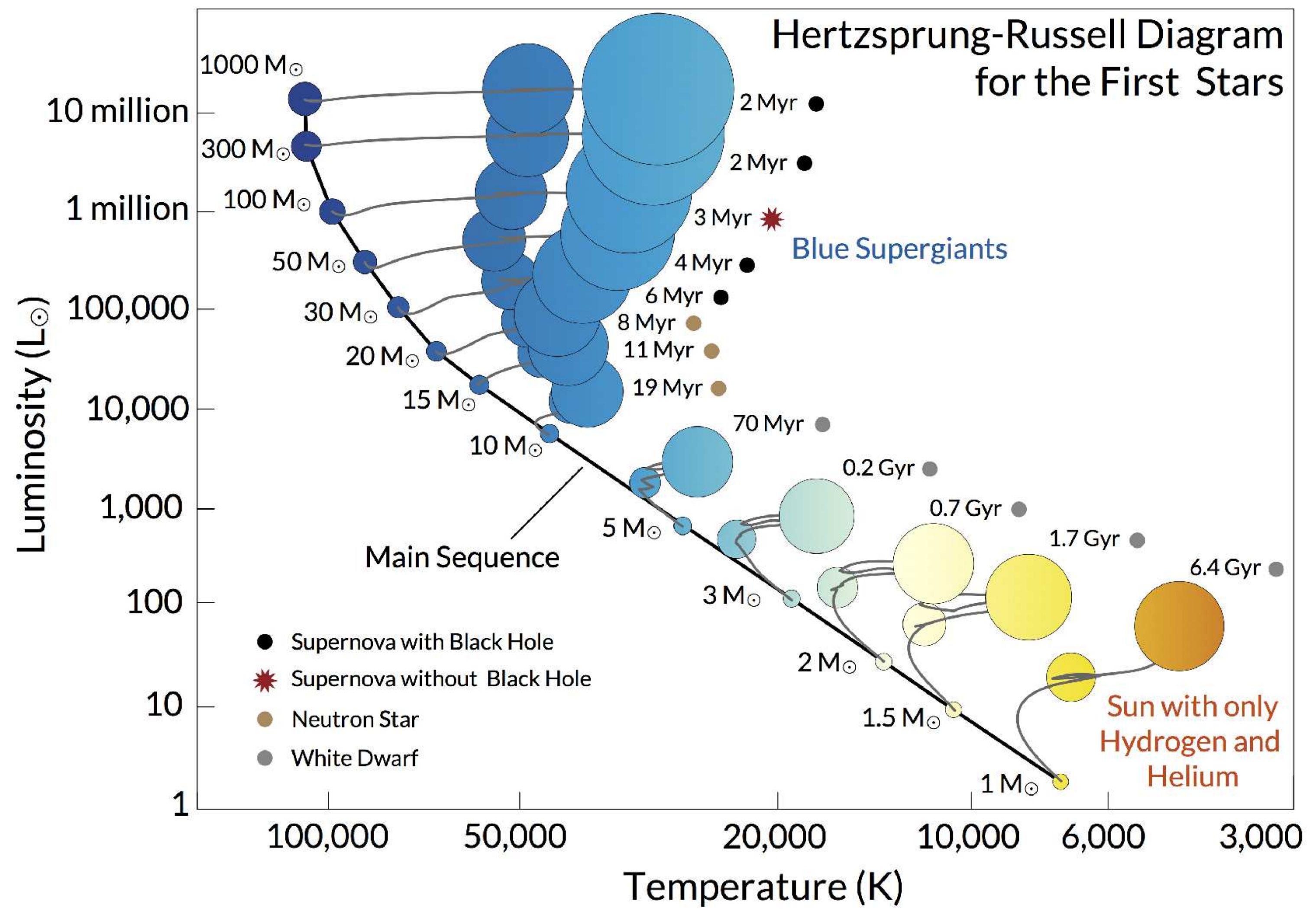


Fig. 5 | Highly magnified stellar images located near the MACS J1149 galaxy cluster's critical curve. a, LS1 in 2014; we detected LS1 when it temporarily brightened by a factor of ~4 in late April 2016, and its position is marked by a blue circle. **b**, The appearance of a new image dubbed Lev16B on 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 $z \simeq 1.49$.



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 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$\gtrsim$30 $M_\odot$ Pop III stars (assuming binaries in 2nd generation).

Conclusions — The impact of Henk van de Hulst and Hubble

- Henk was essential to get Hubble going and to keep it alive: Without Henk and the FOC, HST would not have been the miracle that it is today.

- Hubble has traced cosmic star-formation from the first Gyr until today.

- Hubble+Spitzer+Herschel's EBL: Cosmic Dust outshines Cosmic SF!

- Hubble+Spitzer+Chandra: Diffuse EBL component from BHs at z$\gtrsim$7?

- HST has seen individual B-stars through cluster caustic transits at z$\gtrsim$1.5.

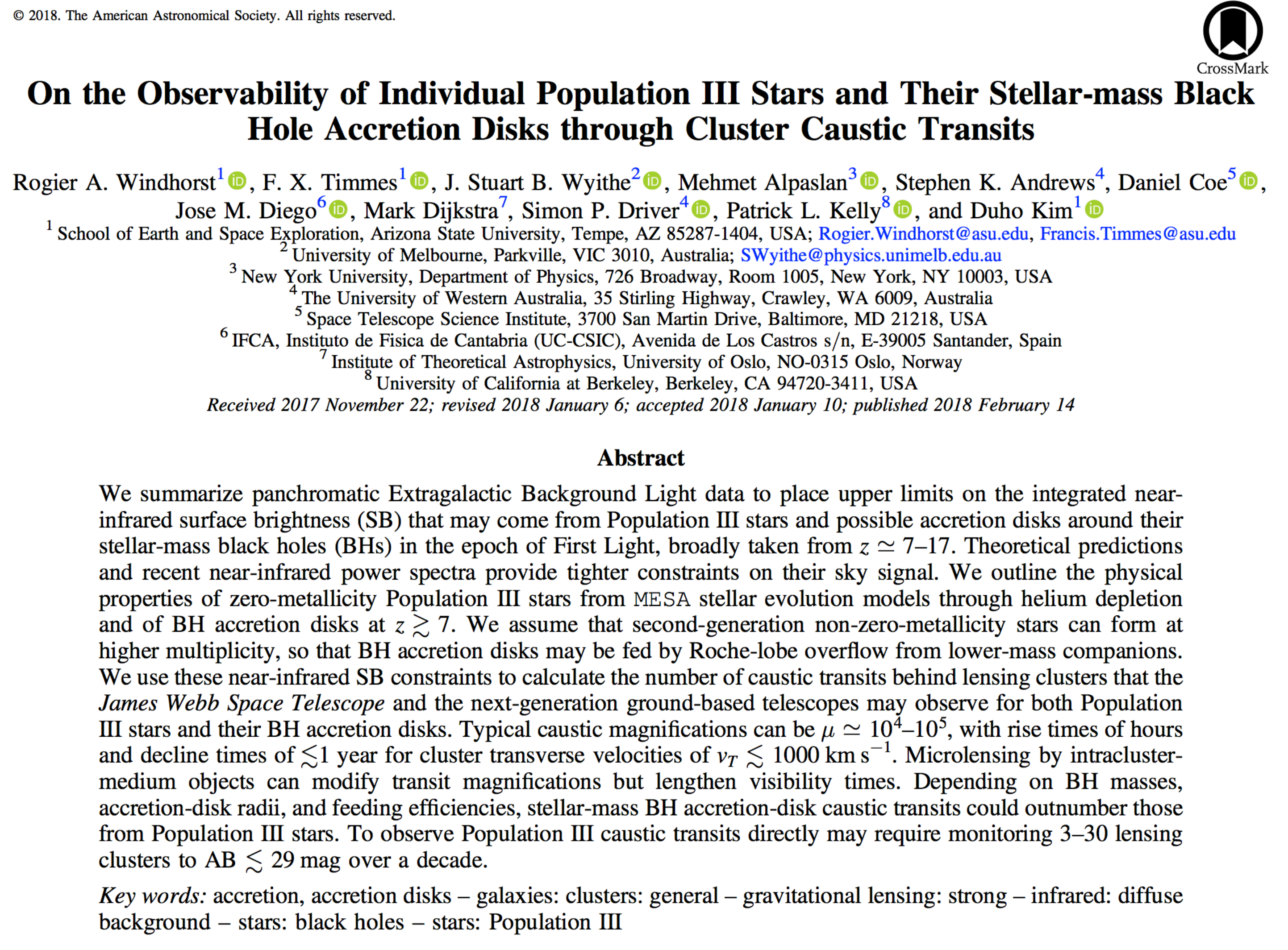
- First stars produce first dust ⇒ 2nd generation massive stars in binaries?

- JWST and ground-based 30 m telescopes can detect *both* Pop III stars and their stellar-mass BH (M$\gtrsim$20 $M_\odot$) accretion disks at AB$\lesssim$28-29 mag via caustic transits if magnifications $\mu \simeq 10^4$–10^5.

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

SPARE CHARTS

(5) Possible caustic transits from Pop III stars and their BH accretion disks.



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CrossMark

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

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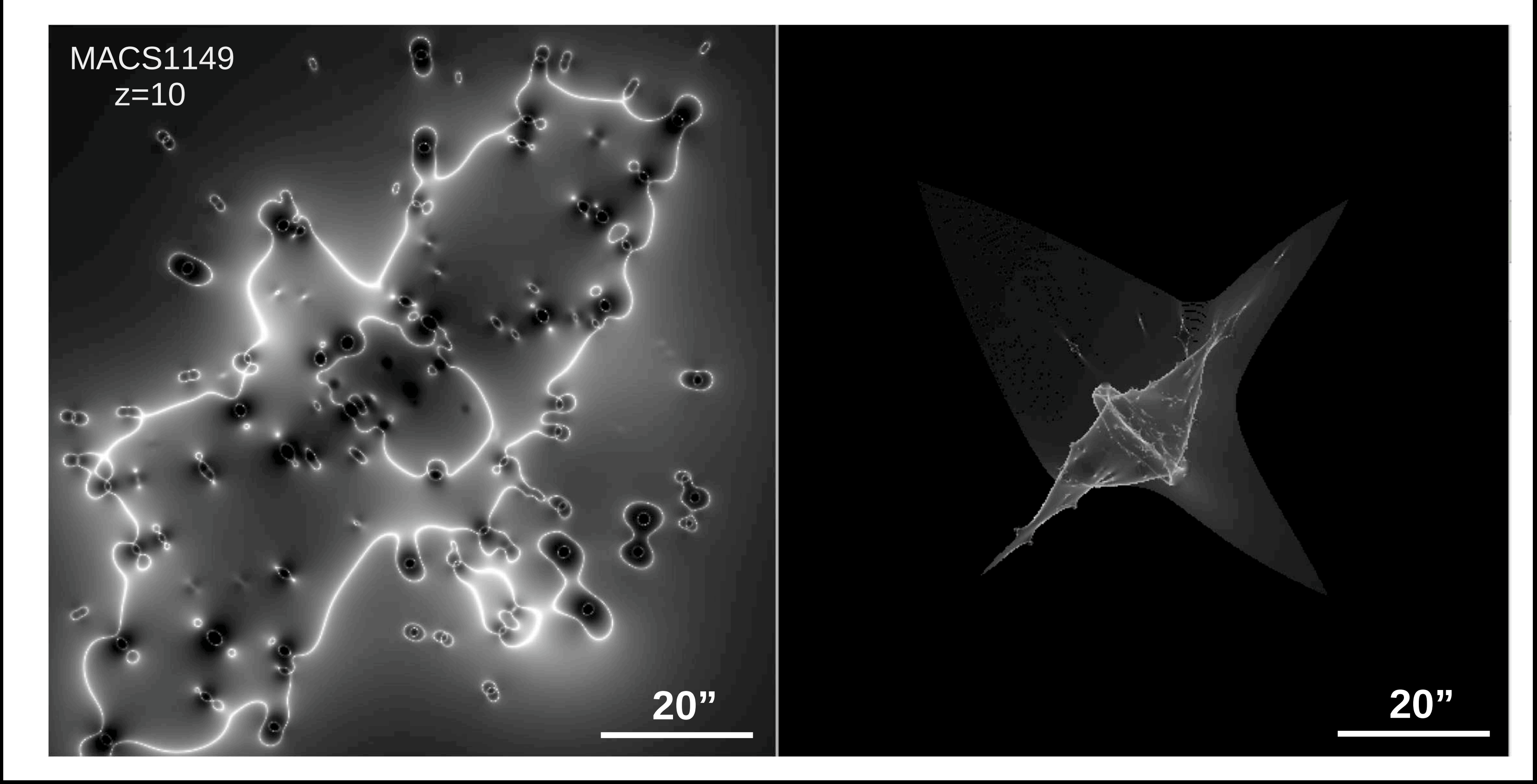
Abstract

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.



For source at z=10, critical curves for HFF cluster MACS 1149 at z$\simeq$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$10 (d$_{caustic}$/”)$^{-1/2}$. For Pop III objects at z$\gtrsim$7 with 1–30 $R_\odot$, μ can then be $\gtrsim$10^4–10^5 for $\lesssim$0.4 year.
- Must use clusters with minimal ICL near the critical curves, since ICL microlensing dilutes the main caustics (Diego$^+$ 2018, ApJ, 857, 25).

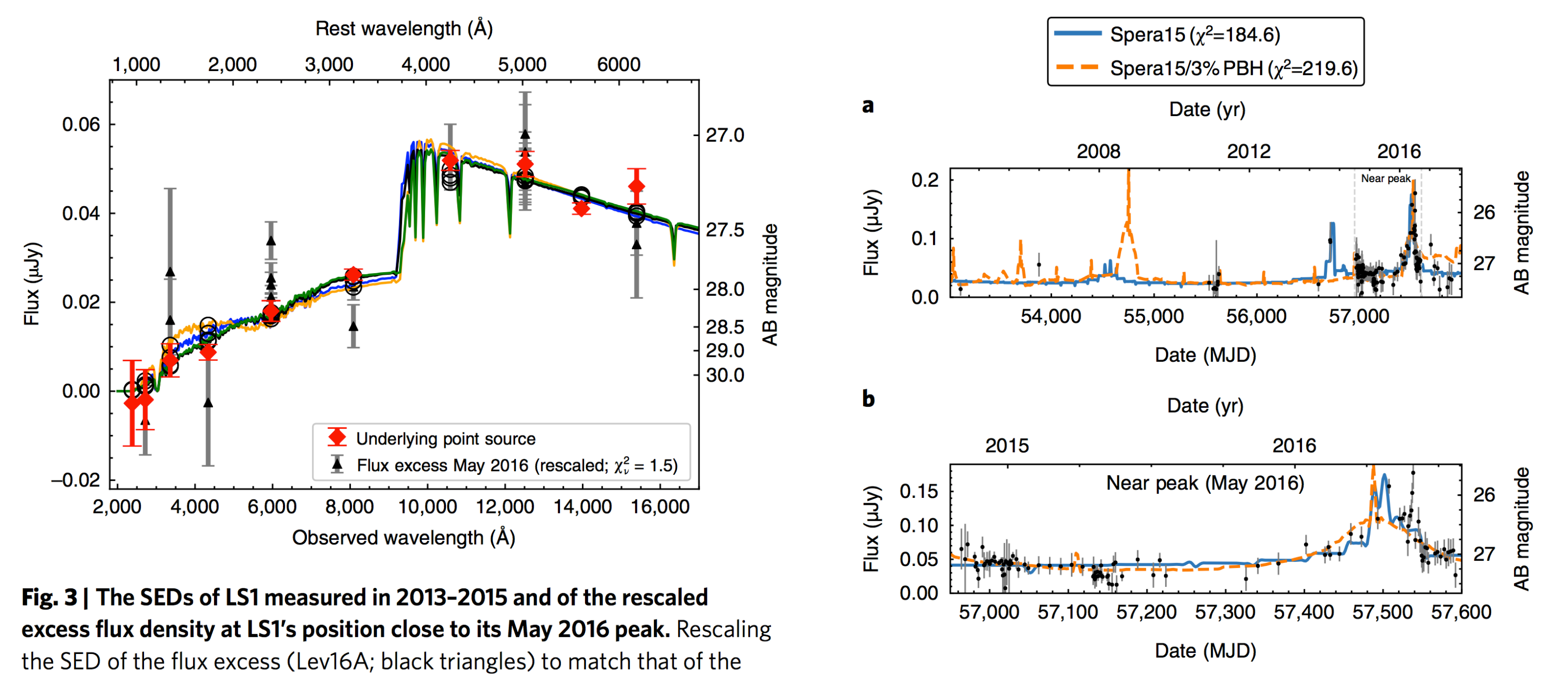
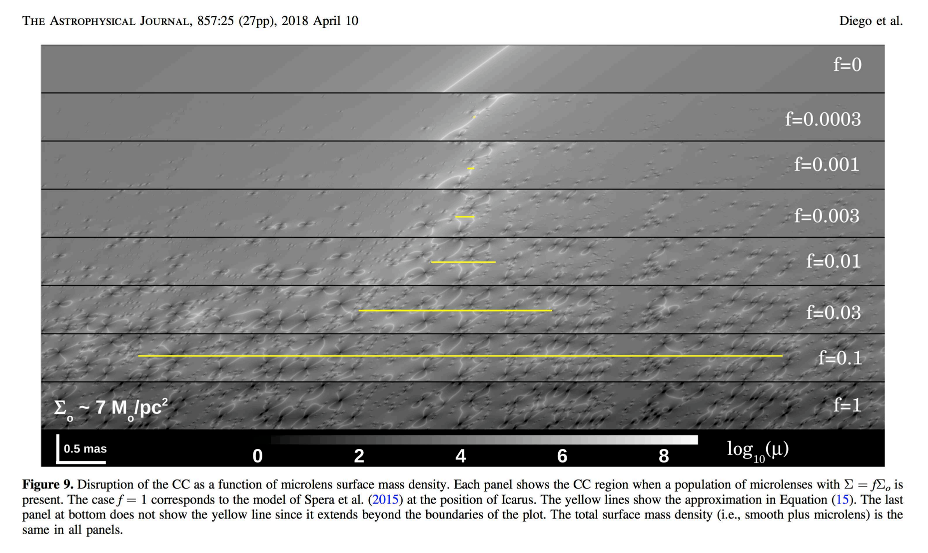


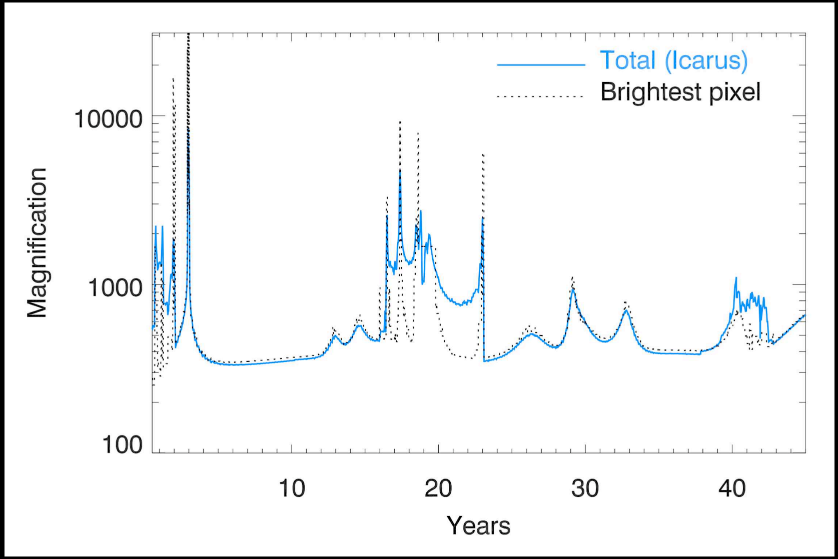
Fig. 3 | The SEDs of LS1 measured in 2013–2015 and of the rescaled excess flux density at LS1's position close to its May 2016 peak. Rescaling the SED of the flux excess (Lev16A; black triangles) to match that of the

Kelley et al. 2018 (Nat. Astr. 2, 334): caustic transit of a B-star at $z\simeq1.49$.

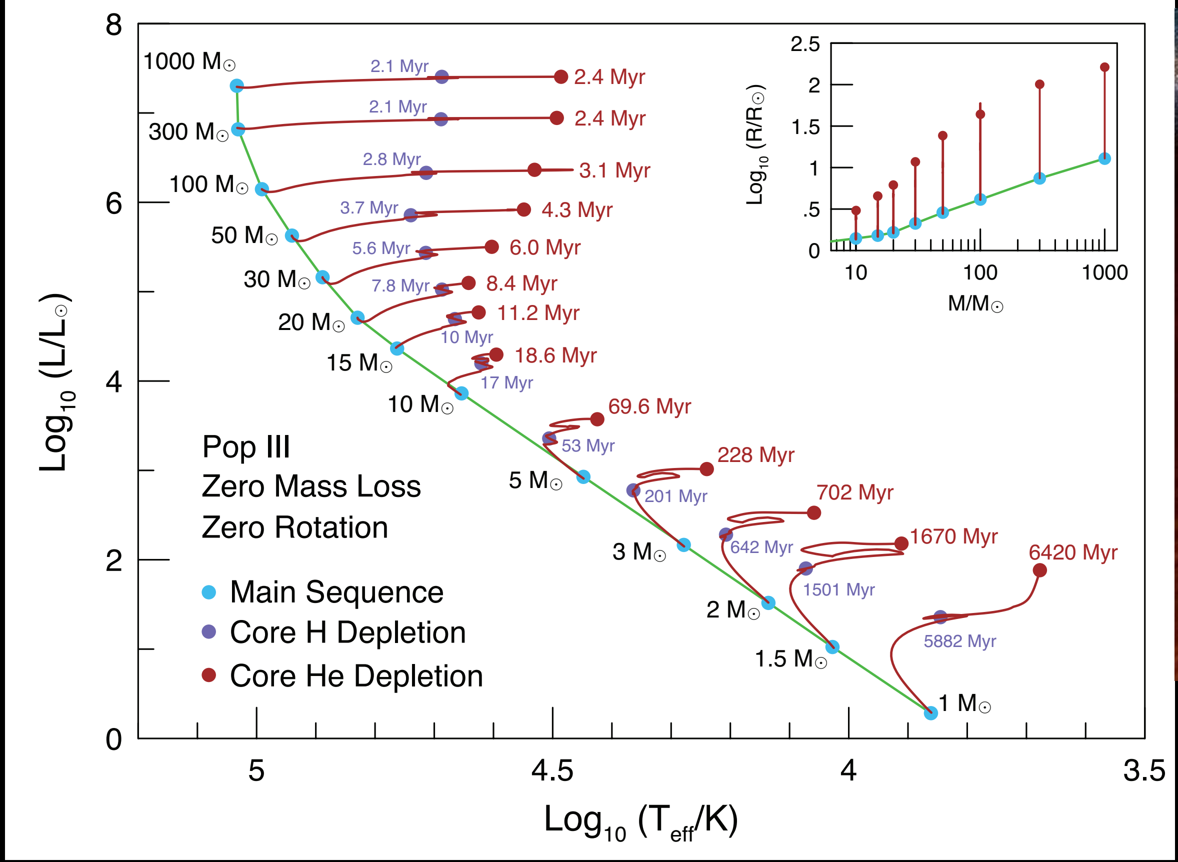


The Astrophysical Journal, 857:25 (27pp), 2018 April 10 Diego et al.

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).

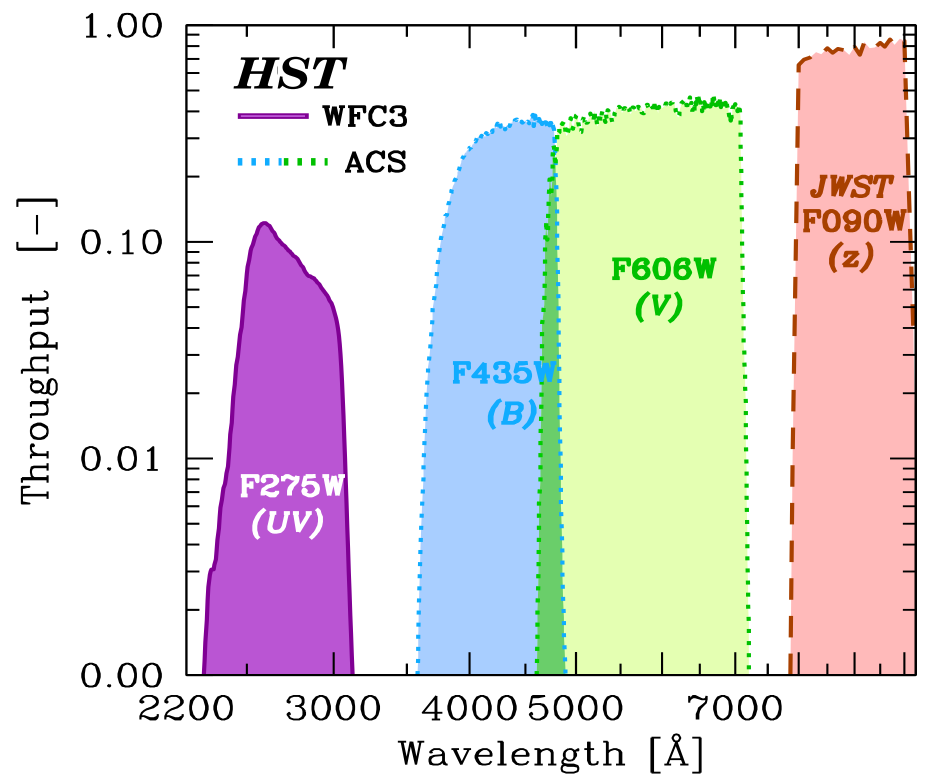


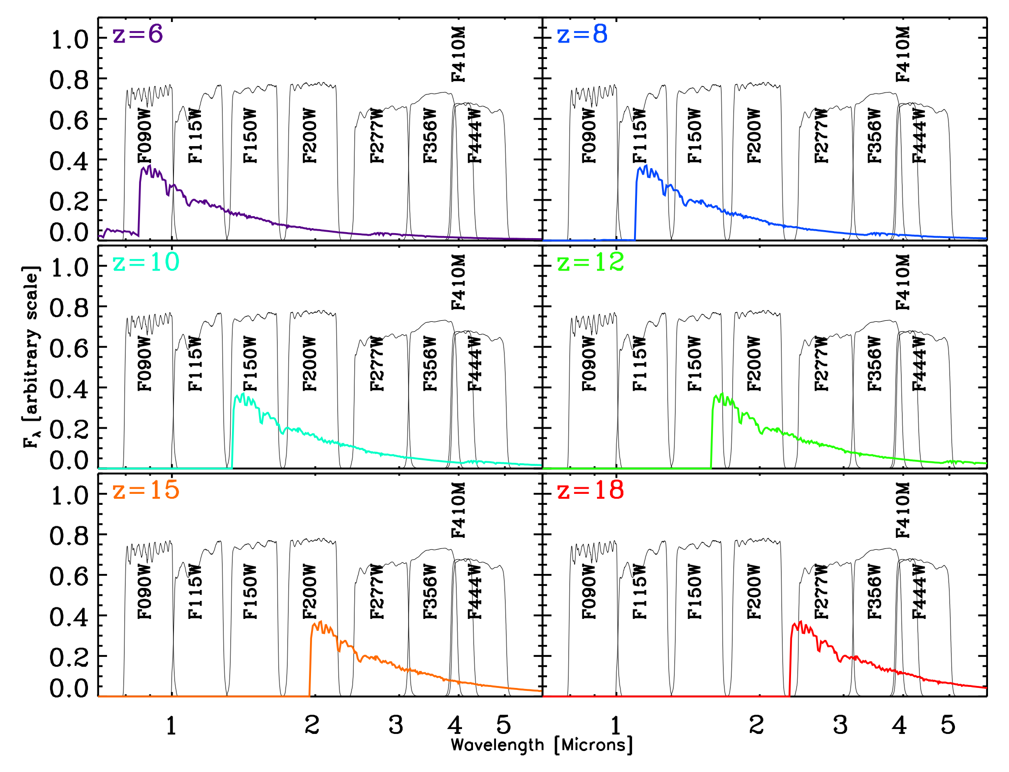
Windhorst^{+} (2018, ApJS, 234, 41):

- 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.



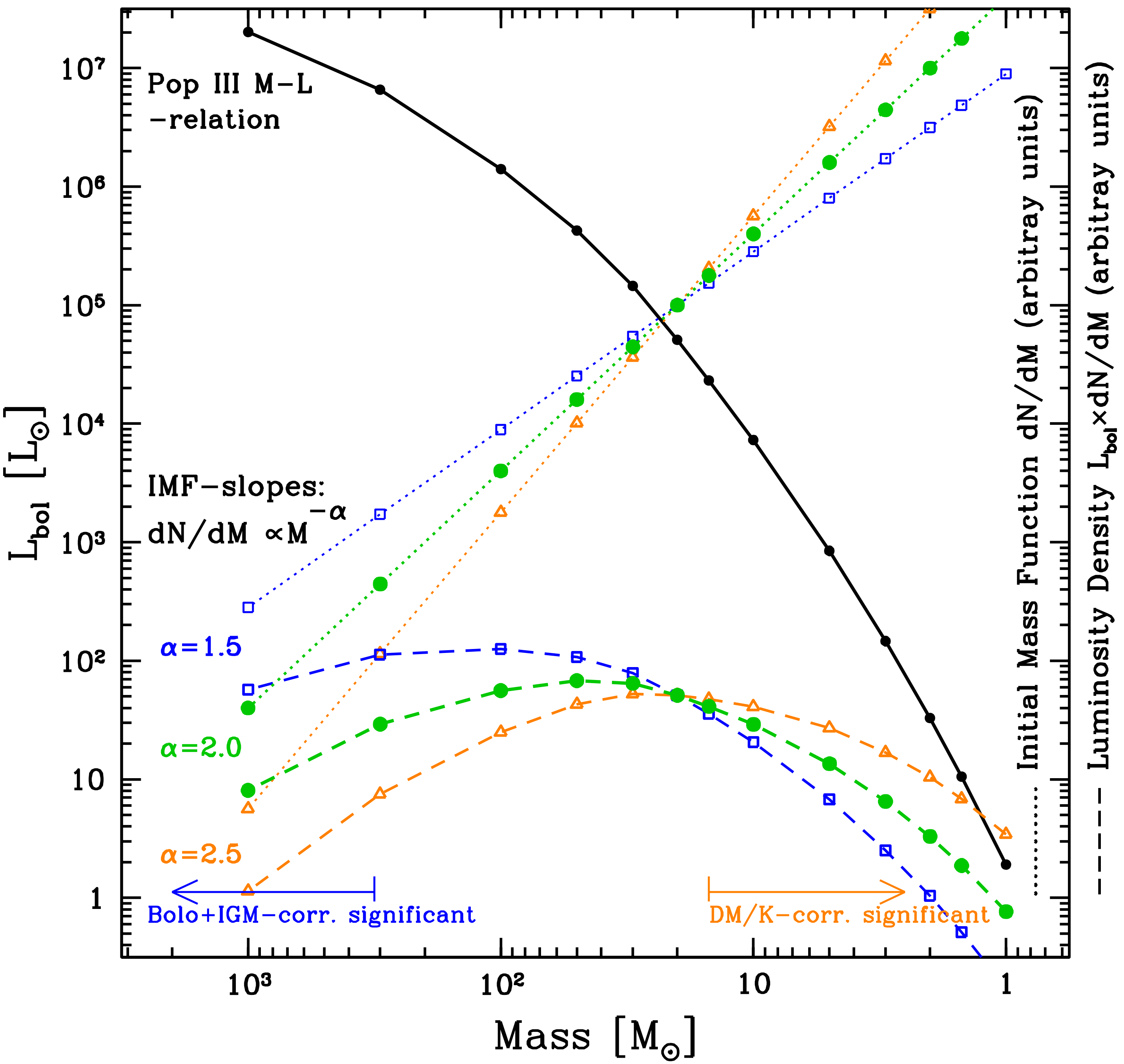


[LEFT] HST UV-vis filters complement the JWST NEP community field:

- 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 $M_{\odot}$.

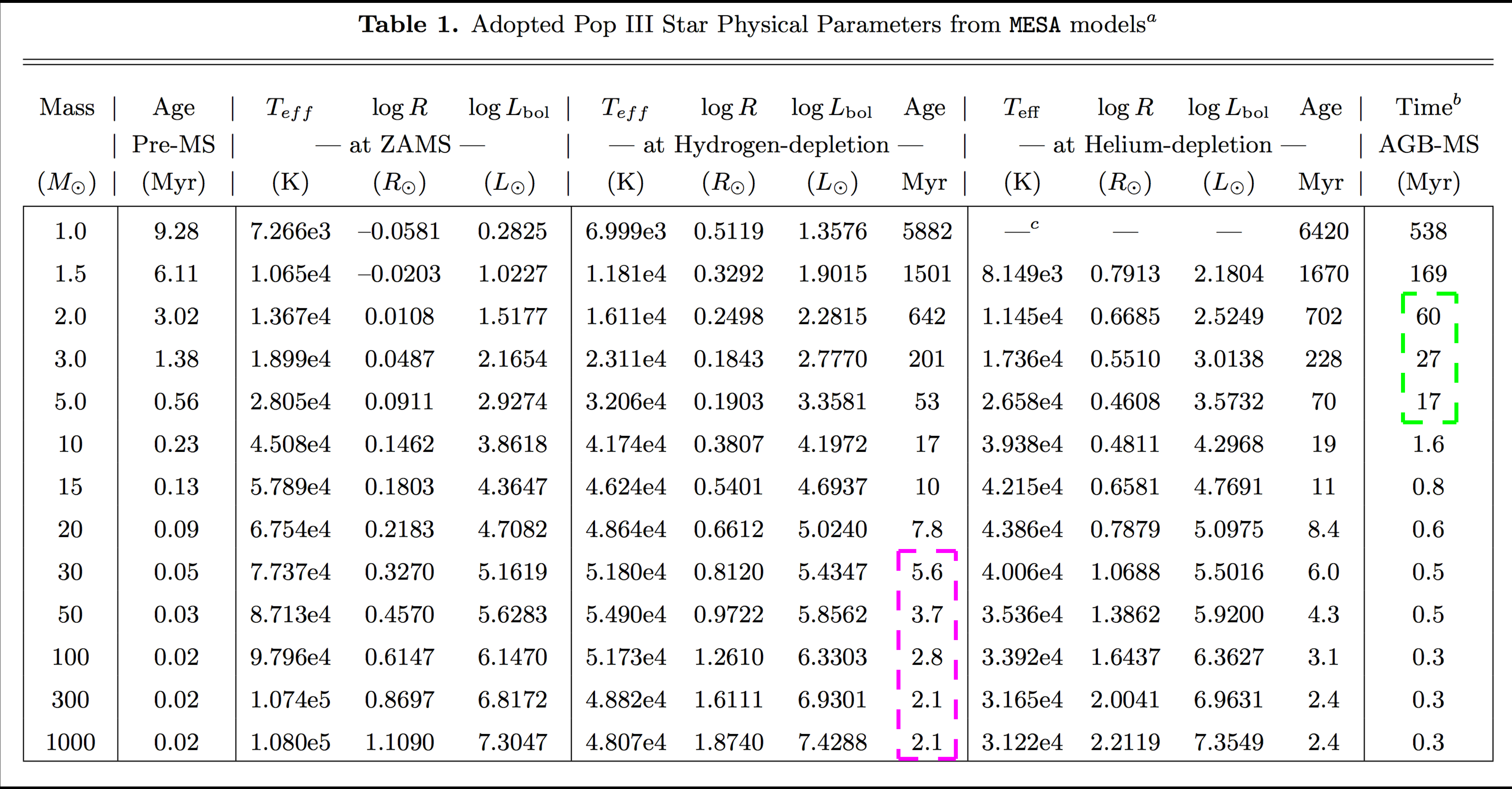


Table 1. Adopted Pop III Star Physical Parameters from MESA models[a]

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).

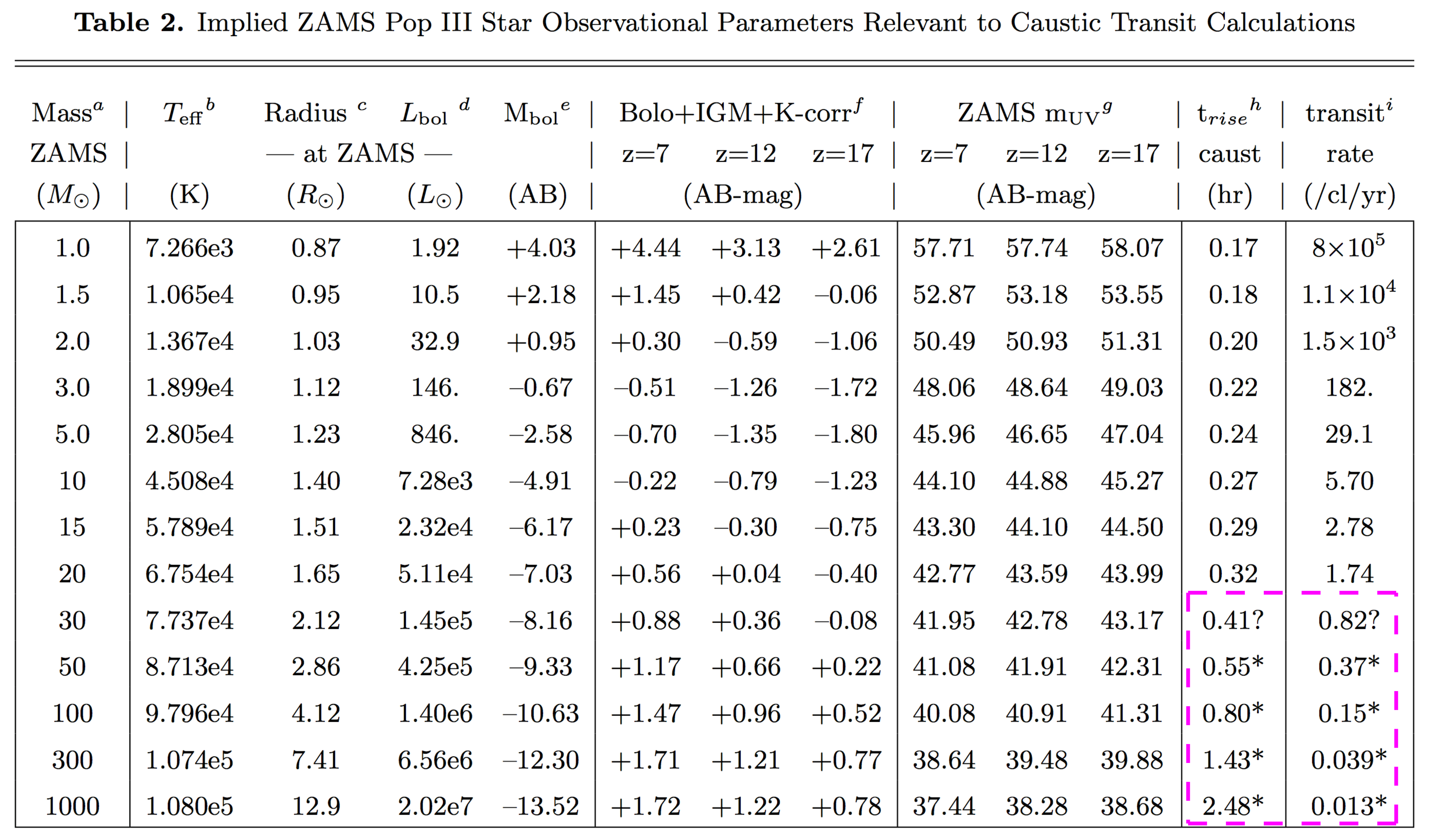


Table 2. Implied ZAMS Pop III Star Observational Parameters Relevant to Caustic Transit Calculations

Mass[a]	$T_{\rm eff}$[b]	Radius[c]	$L_{\rm bol}$[d]	$M_{\rm bol}$[e]	Bolo+IGM+K-corr[f]			ZAMS $m_{\rm UV}$[g]			t_{rise}[h]	transit[i]
ZAMS		— at ZAMS —			z=7	z=12	z=17	z=7	z=12	z=17	caust	rate
($M_\odot$)	(K)	($R_\odot$)	($L_\odot$)	(AB)	(AB-mag)			(AB-mag)			(hr)	(/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 $\mu \gtrsim 10^4$–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.

References and other sources of material shown:

`http://www.jwst.nasa.gov/` & `http://www.stsci.edu/jwst/`

`http://ircamera.as.arizona.edu/nircam/`

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