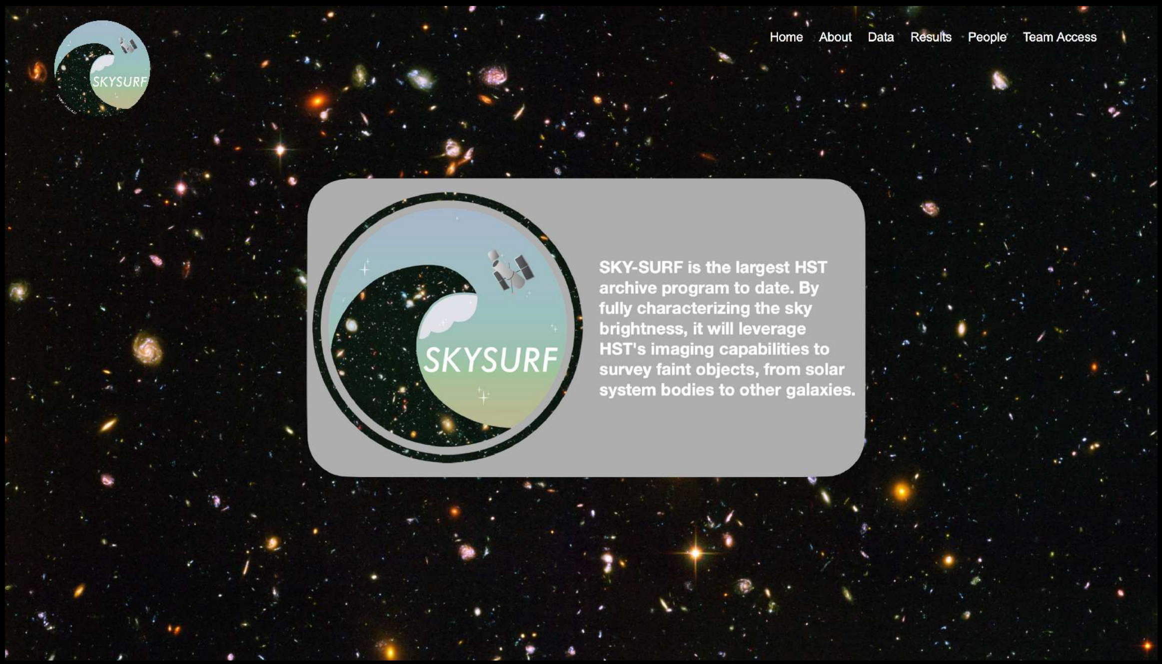
Project SKYSURF: How to hide the brightness of 10 more Jupiters (in the Solar System ?), and how to hide it well.

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

[ASU Team]: Timothy Carleton, Rosalia O'Brien, Seth H. Cohen, Delondrae Carter, Rolf Jansen, Scott Tompkins, Haley Abate, Hanga Andras-Letanovszky, Jessica Berkheimer, John Chambers, Connor Gelb, Zak Goisman, Daniel Henningsen, Isabela Huckabee, Darby Kramer, Teerthal Patel, Rushabh Pawnikar, Ewan Pringle, Ci'mone Rogers, Steven Sherman, Andi Swirbul, Kaitlin Webber (ASU), [US Team]: Norman Grogin, Anton Koekemoer, John MacKenty, Stefano Casertano, Nathan Miles, Nor Pirzkal, Russell Ryan (STScI, MD), Richard G. Arendt, Eli Dwek, Alexander Kashlinsky (GSFC, MD), Scott J. Kenyon (harvard CfA, MA), [Australia]: Sarah Caddy, Luke J. M. Davies, Simon P. Driver, Aaron Robotham.



SESE colloquium, Wednesday April 20, 2022 (Tempe, AZ; +via Zoom)

http://skysurf.asu.edu/ Talk on: http://www.asu.edu/clas/hst/www/jwst/jwsttalks/sese_skysurf22.pdf

SKYSURF-ers and HST+Webb researchers in our group (not all shown):

[Several students also in collaboration with other SESE faculty].

Outline

- (1) Diffuse Foregrounds and Backgrounds in Astronomy.
- (2) How Hubble measures sky foreground and makes object catalogs.
- (3) How SKYSURF measures sky brightness (SB) & identifies straylight
- (4) How SKYSURF measures residual sky compared to Zodiacal models
- (5) SKYSURF's first results and estimates of diffuse 1.25-1.6 μm light
- (6) Summary and Conclusions
- (7) Spare Charts: Update of JWST as of 2022

[UNITS USED]: Planck Photon Energy: E $= +$h $\boldsymbol{\nu}$;

Brightness: $\boldsymbol{F_{\nu}}$=$10^{-0.4(\mathrm{AB}-8.90\ \mathrm{mag})}$ in Jy [$\equiv 10^{-26}$ W/m^2/Hz];

Energy units: [SB or $\boldsymbol{I_{\nu}}$ in MJy/sr] . $\boldsymbol{\nu} \times 10^{-11}$ in nW/m^2/sr.

(1) Diffuse Foregrounds and Backgrounds in Astronomy.

SKYSURF: Constraints on Zodiacal Light and Extragalactic Background Light through Panchromatic HST All-Sky Surface-Brightness Measurements: I. Survey Overview, Methods, and First Results

Rogier A. Windhorst,[1] Timothy Carleton,[1] Rosalia O'Brien,[1] Seth H. Cohen,[1] Delondrae Carter,[1] Rolf Jansen,[1] Scott Tompkins,[1] Richard G. Arendt,[2] Sarah Caddy,[3] Norman Grogin,[4] Anton Koekemoer,[4] John MacKenty,[4] Stefano Casertano,[4] Luke J. M. Davies,[5] Simon P. Driver,[6] Eli Dwek,[2] Alexander Kashlinsky,[2] Scott J. Kenyon,[7] Nathan Miles,[4] Nor Pirzkal,[4] Aaron Robotham,[6] Russell Ryan,[4] Haley Abate,[1] Hanga Andras-Letanovszky,[8] Jessica Berkheimer,[1] John Chambers,[1] Connor Gelb,[1] Zak Goisman,[1] Daniel Henningsen,[1] Isabela Huckabee,[1] Darby Kramer,[1] Teerthal Patel,[1] Rushabh Pawnikar,[1] Ewan Pringle,[1] Ci'mone Rogers,[1] Steven Sherman,[1] Andi Swirbul,[1] and Kaitlin Webber[1]

[1]*School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-1404*

[2]*NASA Goddard Space Flight Center, Greenbelt, MD 21771*

[3]*Macquarie University, Sydney, NSW 2109, Australia*

[4]*Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21210*

[5]*The University of Western Australia, M468, 35 Stirling Highway, Crawley, WA 6009, Australia*

[6]*International Centre for Radio Astronomy Research (ICRAR) and the International Space Centre (ISC), The University of Western Australia, M468, 35 Stirling Highway, Crawley, WA 6009, Australia*

[7]*Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138*

[8]*Steward Observatory, University of Arizona, Tucson, AZ 85721-0065*

Abstract

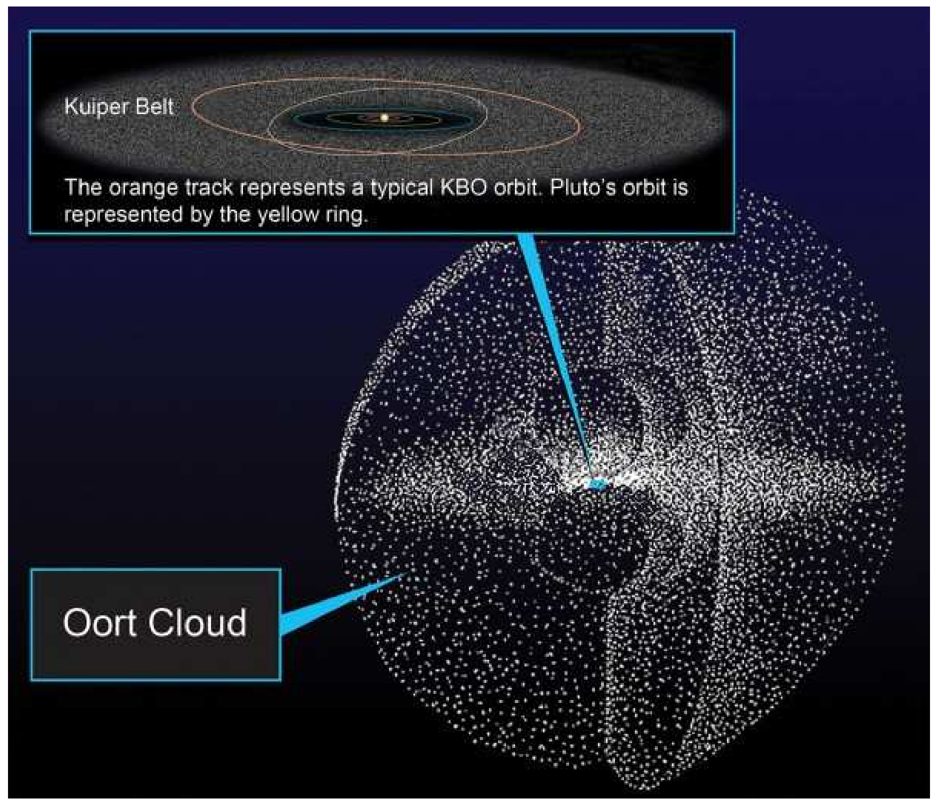
We give an overview and describe the rationale, methods, and first results from Hubble Space Telescope (HST) Archival Legacy project "SKYSURF". SKYSURF uses HST's unique capability as an *absolute photometer* to measure the $\sim$0.2–1.7 μm sky surface brightness (SB) from 249,861 WFPC2, ACS, and WFC3 exposures in $\sim$1400 independent HST fields. SKYSURF's panchromatic dataset is designed to constrain the diffuse UV to near-IR sky-SB components: Zodiacal Light (ZL; inner Solar System), Kuiper Belt Objects (KBOs; outer Solar System), Diffuse Galactic Light (DGL), and the discrete plus diffuse Extragalactic Background Light (EBL). We outline SKYSURF's methods to: (1) construct object catalogs optimized for our goals; (2) estimate the *integrated discrete* EBL, most of which comes from AB$\simeq$17–22 mag galaxies; and (3) estimate how much *diffuse light* may exist in addition to the extrapolated discrete galaxy counts. Simulations of HST WFC3/IR images with

Windhorst et al. 2022, Carleton et al. 2022 (AJ).

Excuse the provocative title of the talk ...

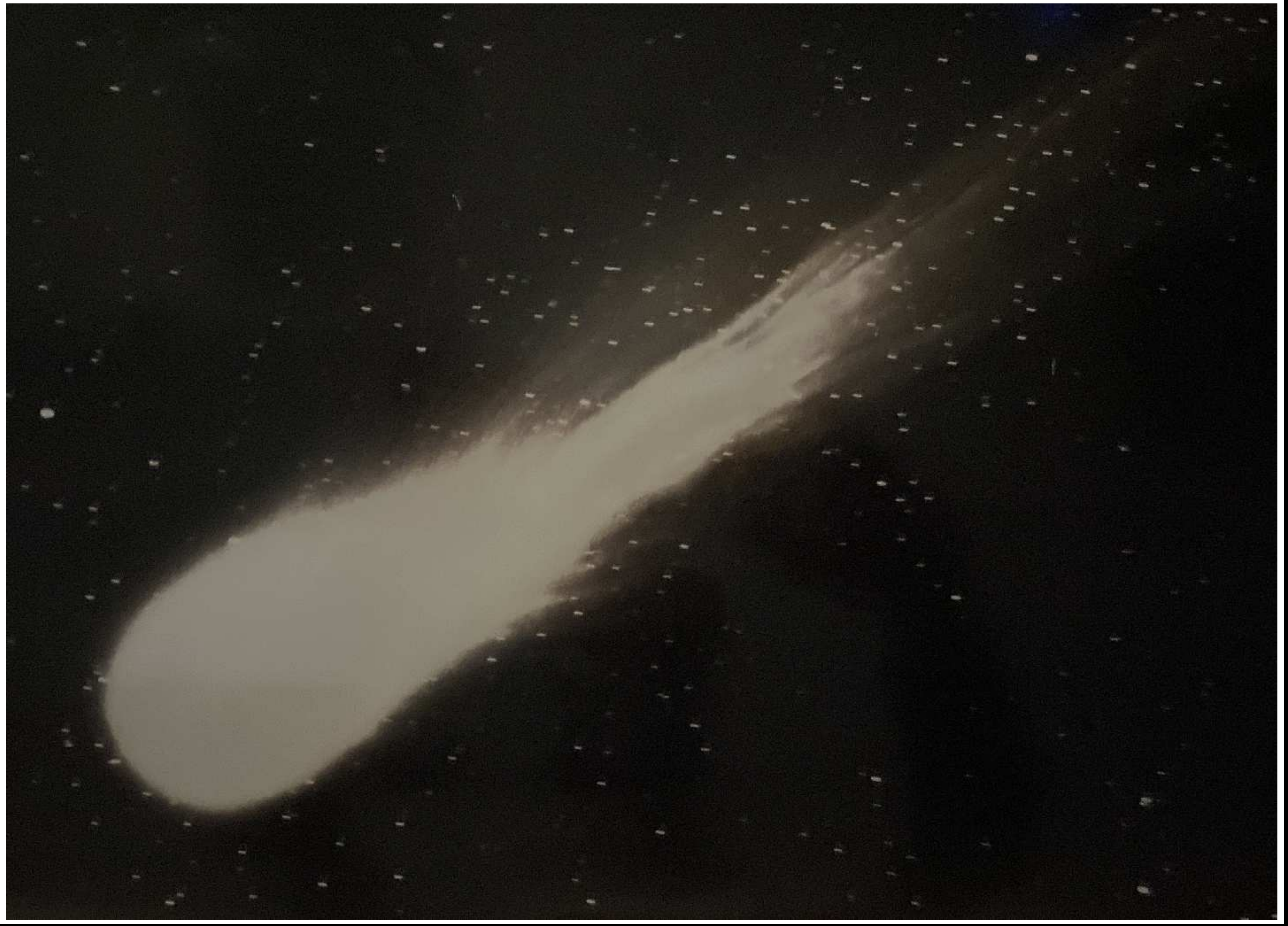
I did not mean get you in the door, and sell you a vacuum cleaner ...

but I promise that I will talk about (shiny) dust ...



I dedicate this talk to Prof. Jan Hendrik Oort (1900–1992), who during his very productive career predicted the Oort Cloud in 1950. He sometimes doubted that the Oort Cloud could be observed (Dr. M. J. A. Oort).

Acknowledgements: • NASA/STScI for their superb Archival support.
• NASA Space Grant at ASU, Prof. Tom Sharp and Desiree Crawl to enable so many students to work on Hubble & SKYSURF during the pandemic.
• Javier Colunga, Mark Stevens, & Matt Wiser for expert server help.



Halley's Comet as seen with the 100 inch du Pont telescope from Las Campanas (Chile) — Dressler and Windhorst, March 1986.

Questions to ask: does (icy) cometary dust in the outer solar system have higher albedo than meteoritic dust? How abundant is such dust?

The ASU Buseck Center for Meteorite Studies

https://meteorites.asu.edu/collection/collection-highlights

- SKYSURF looks for the light from (meteoritic) dust that doesn't make it to Earth.

Galactic plane and the Zodiacal disk at night:

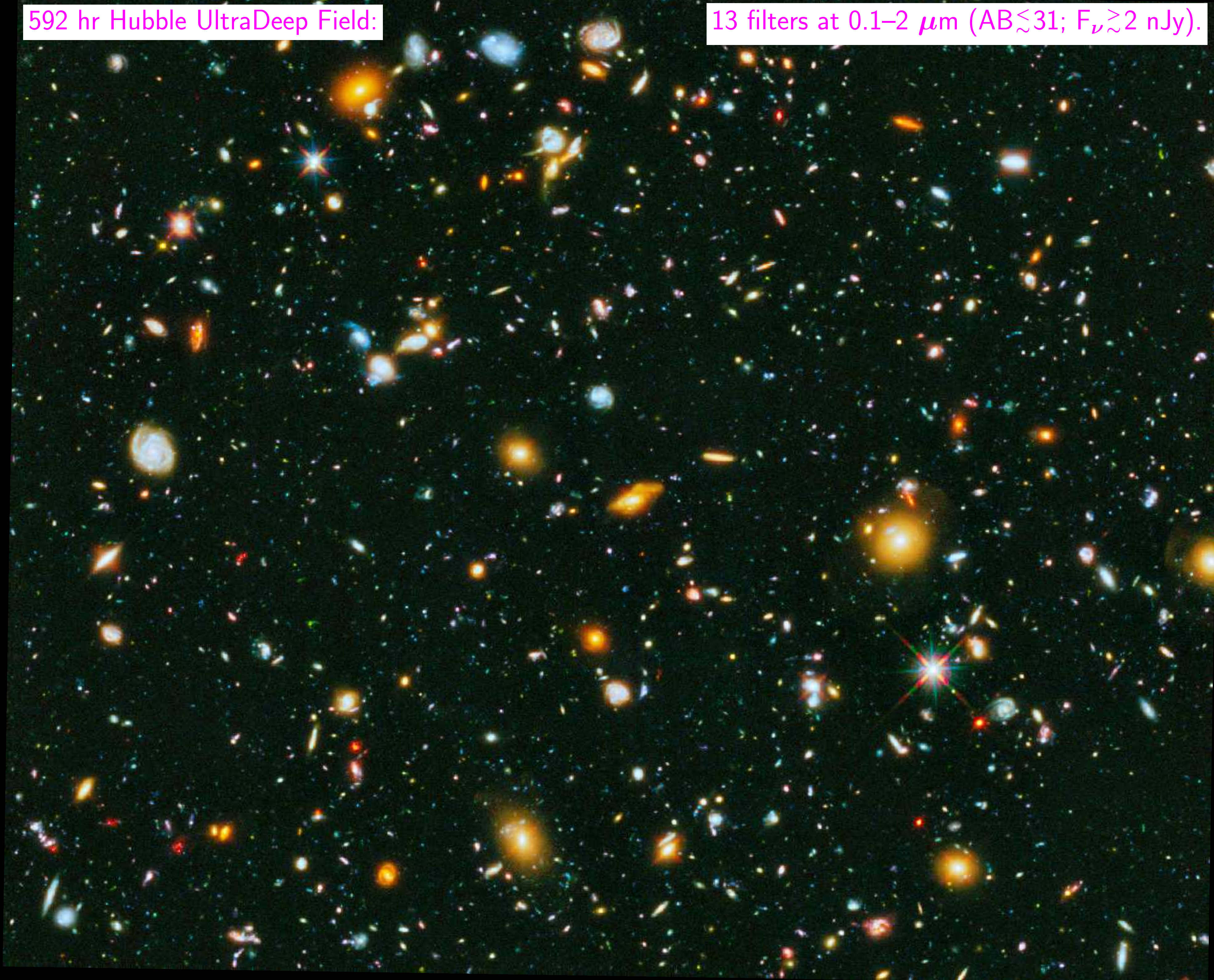
They are inclined by 60°.

SKYSURF aims to map both their diffuse light across the sky.

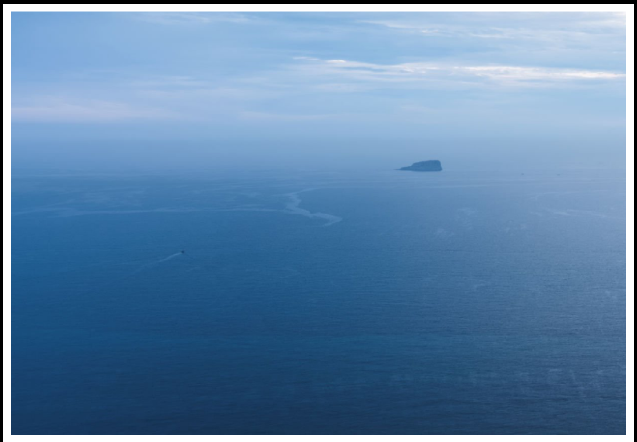
More than 95% of photons in HST Archive (outside the Galactic plane at $|b^{II}| \gtrsim 25°$) come from distances $D \lesssim 3$–5 AU [a]

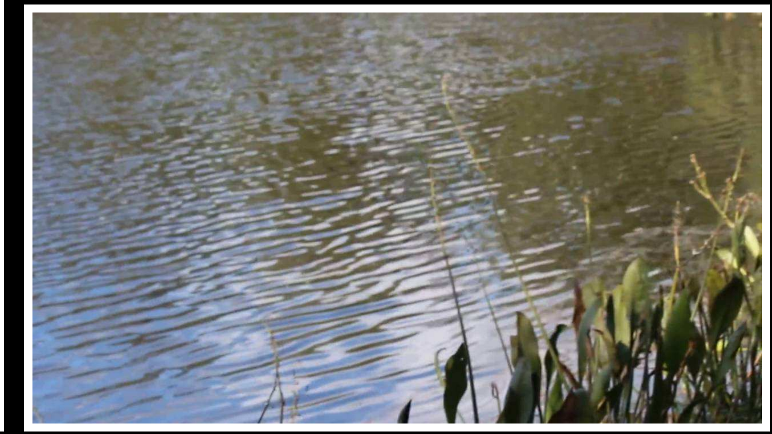
[a] 1 Astronomical Unit = 1.5×10^{8} km.

592 hr Hubble UltraDeep Field: 13 filters at 0.1–2 μm (AB$\lesssim$31; $F_{\nu}\gtrsim$2 nJy).




HUDF as JWST would see it in 20 hrs.
What is the sky?: <55% of pixels between objects!





How we detect stars+galaxies: think of finding waves on (deep) water:

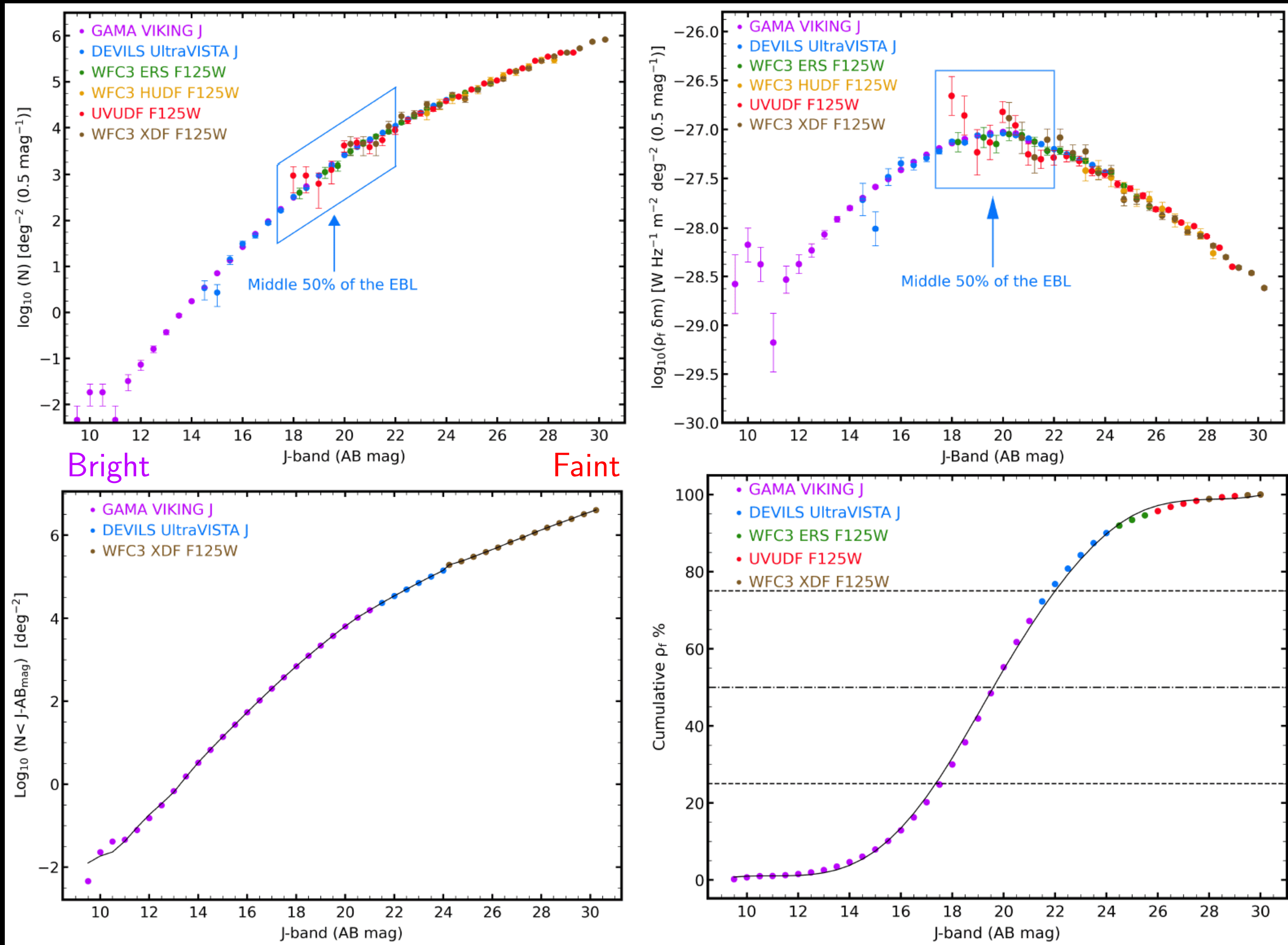
- Ground images: objects are ∼1 m waves on a 10 km deep ocean.
- Hubble images: objects are ∼10 cm waves on a 100 m deep lake.
- Webb images: objects are ∼1 cm waves on top of a 10 m deep pond.

Astronomers removed the sky (=water depth) from images for 30 years.

SKYSURF does NOT remove the sky, but measures it to constrain:

Zodiacal dust in the solar system and Extragalactic Background Light.

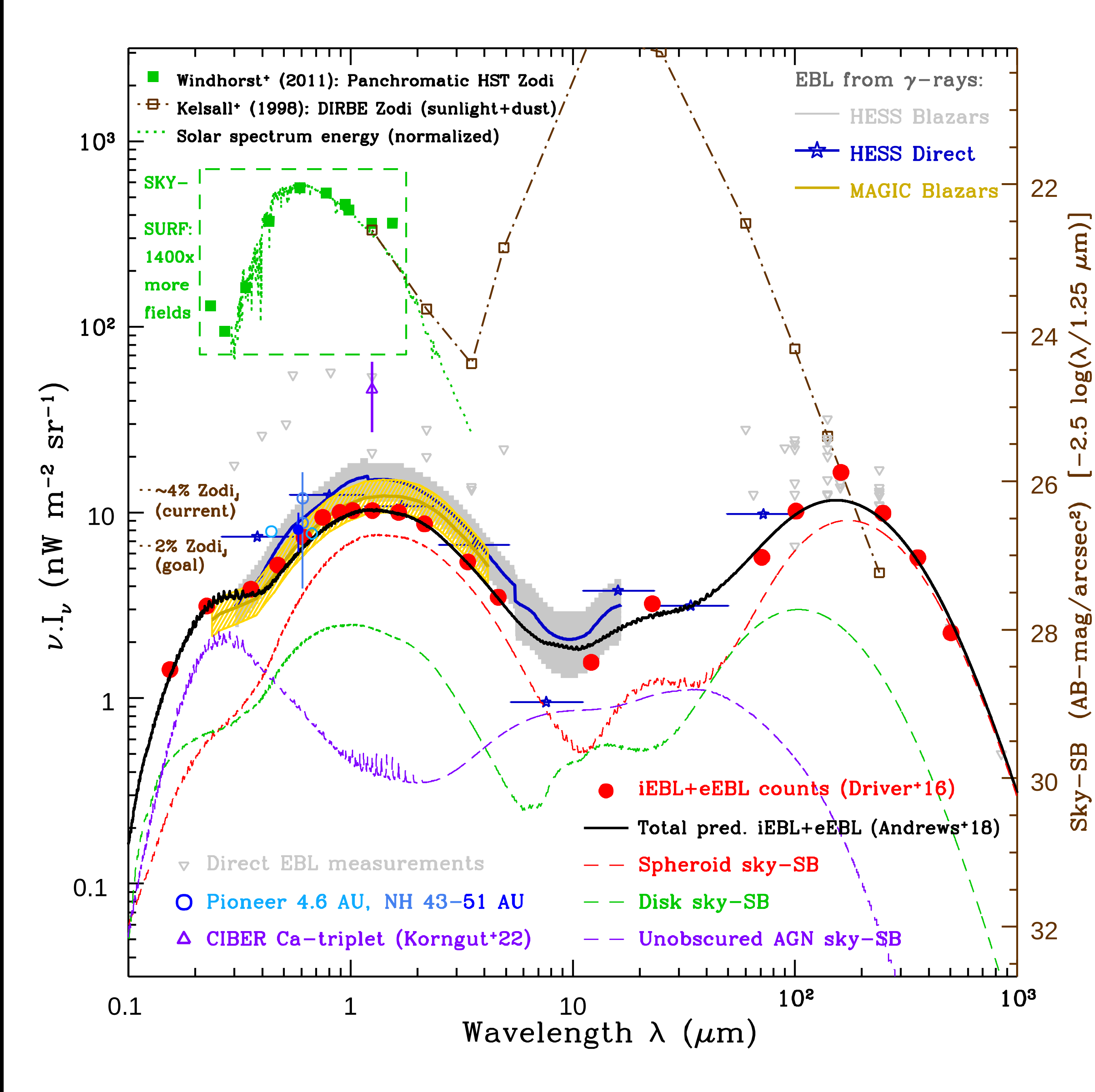
EBL comes in 3 kinds: detected, extrapolated discrete, and diffuse.



Scott Tompkins: Galaxy number counts vs. AB-mag: nearby–HUDF.

Top: counts, Bottom: integrals; Left: Number-, Right: Energy-counts.

$\Longrightarrow$ Box: Middle 50% of EBL from brighter galaxies $(17 \lesssim AB \lesssim 22)$!



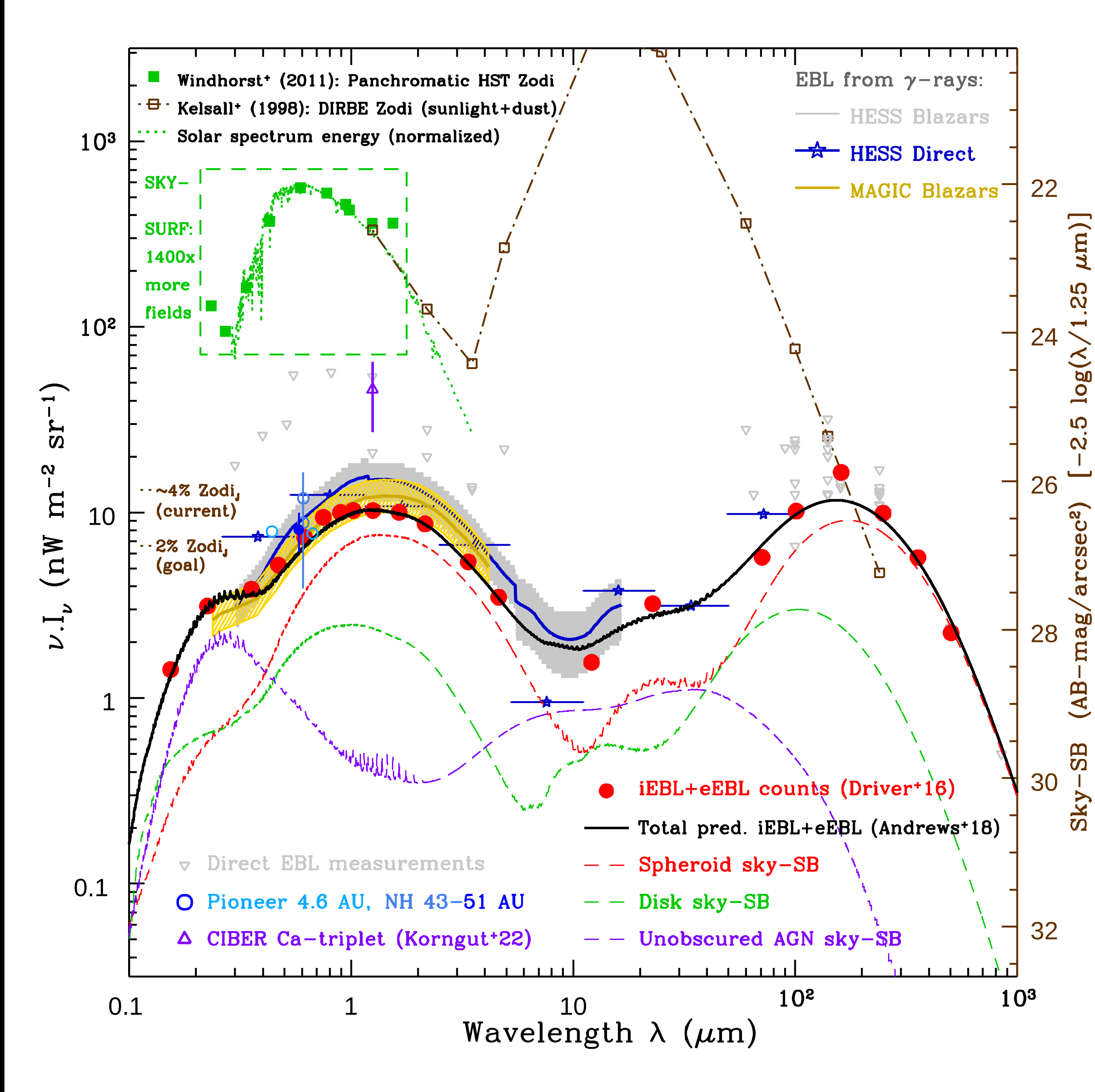
Total Energy vs. λ:

(Driver[+] 16; Windhorst[+] 18, 21):

Sunlight scattered off the Zodiacal dust.

Thermal radiation from $\gtrsim$240 K Zodiacal dust [b].

[b] The Wright (1998) model completely subtracts out the thermal Zodi at 20μm.



Total Energy vs. λ:

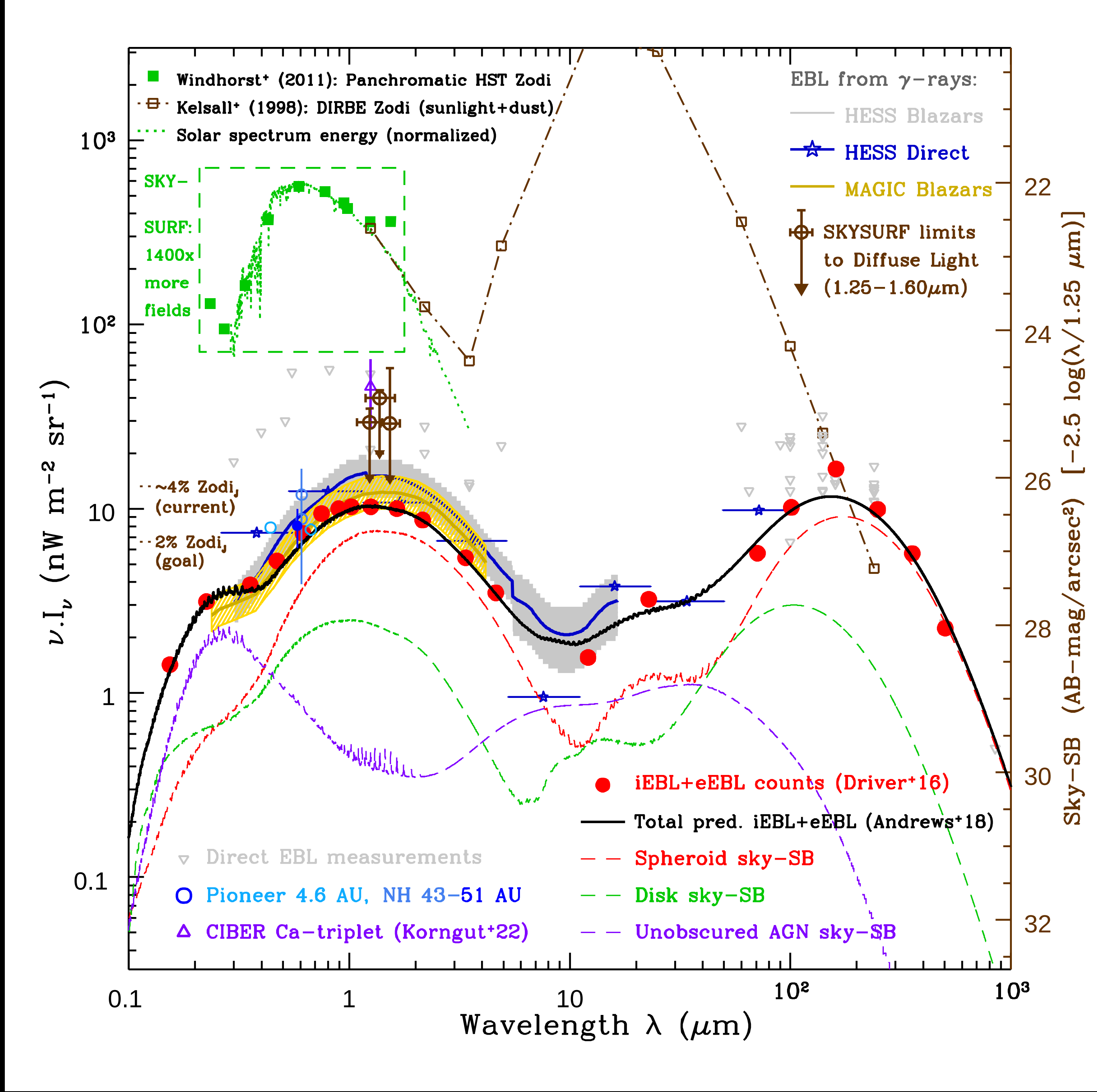
(Driver+ 16; Windhorst+ 18, 21):

Sunlight scattered off the Zodiacal dust.

Thermal radiation from $\gtrsim$240 K Zodiacal dust.

Grey dots: Diffuse EBL from direct experiments.

Dots: Discrete EBL from galaxy counts (+models).



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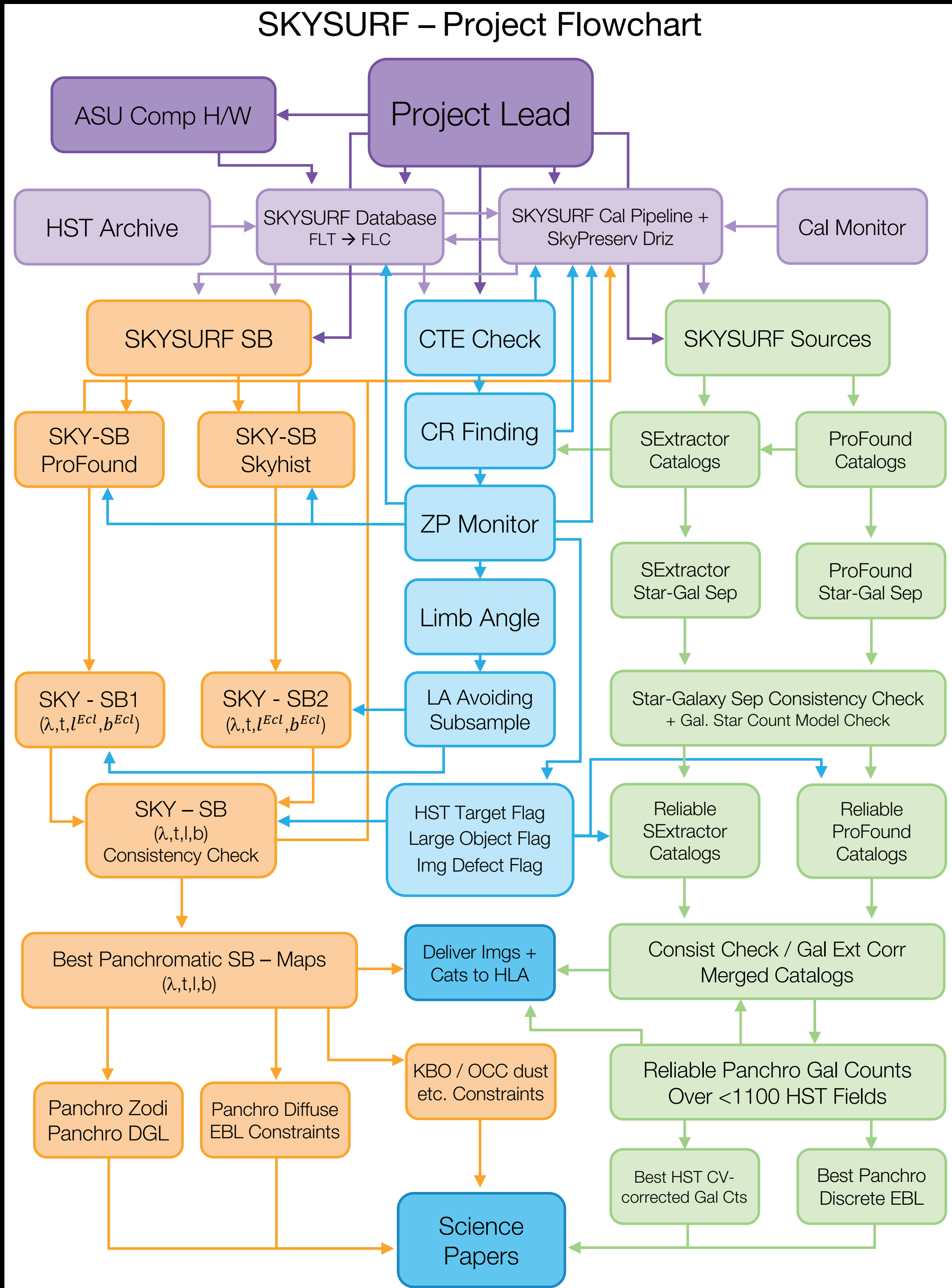
Dots: Discrete EBL from galaxy counts (+models).

Lauer (2021, 2022) NH at 43-51 AU. SKYSURF 1.25–1.6 μm limits.

At 1 AU, SKYSURF sees ~29–40 nW/m^2/sr of diffuse 1.25–1.6 μm light!



(2) Measure sky foreground & make object catalogs.

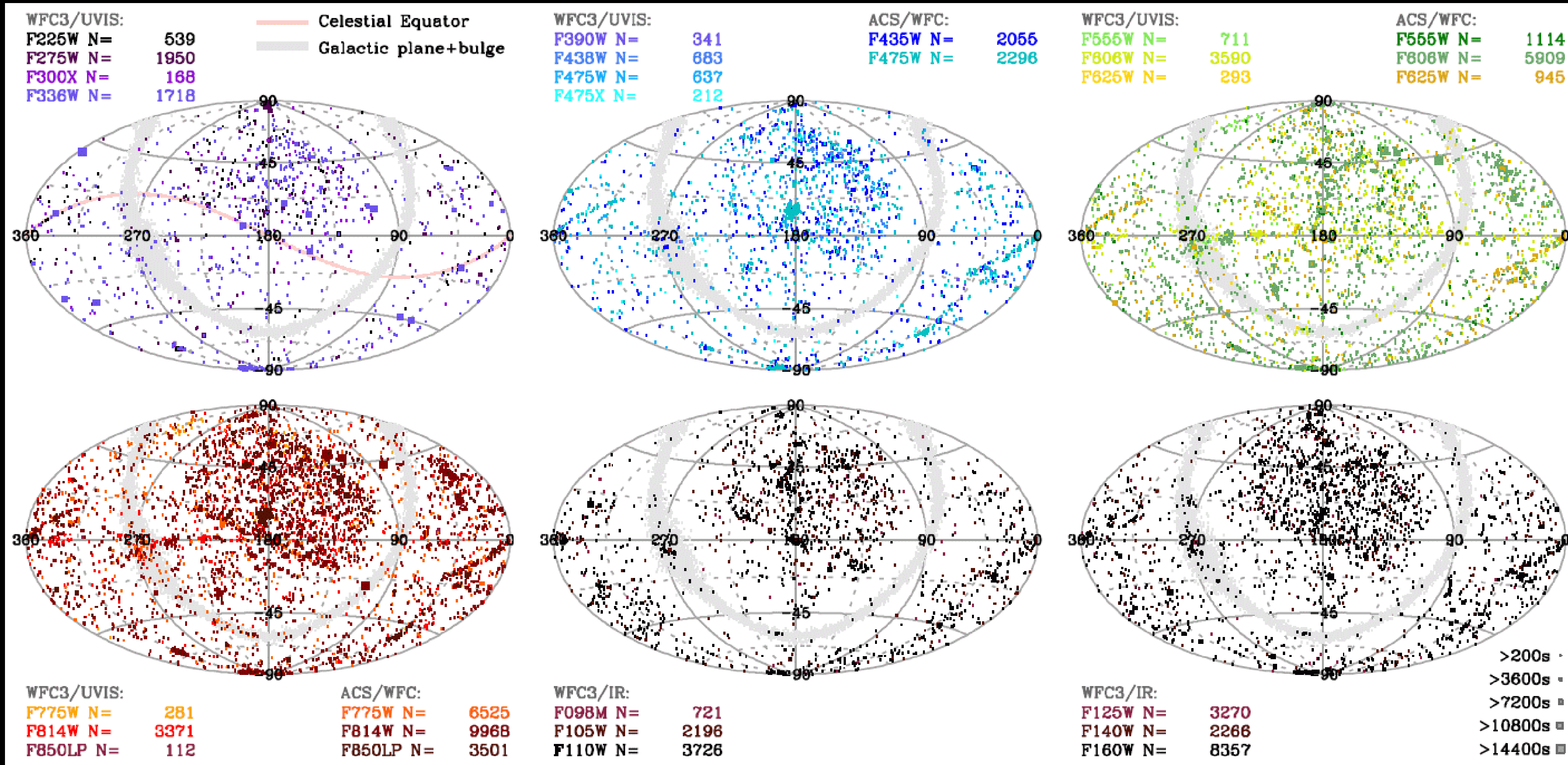
SKYSURF's project plan:

Database building and standard pipeline

Monitor systematics: Cosmic Ray filter, CTE-correction, Zeropoints, orbital straylight, artifact flagging & removal.

sky-SB estimates with two independent algorithms.

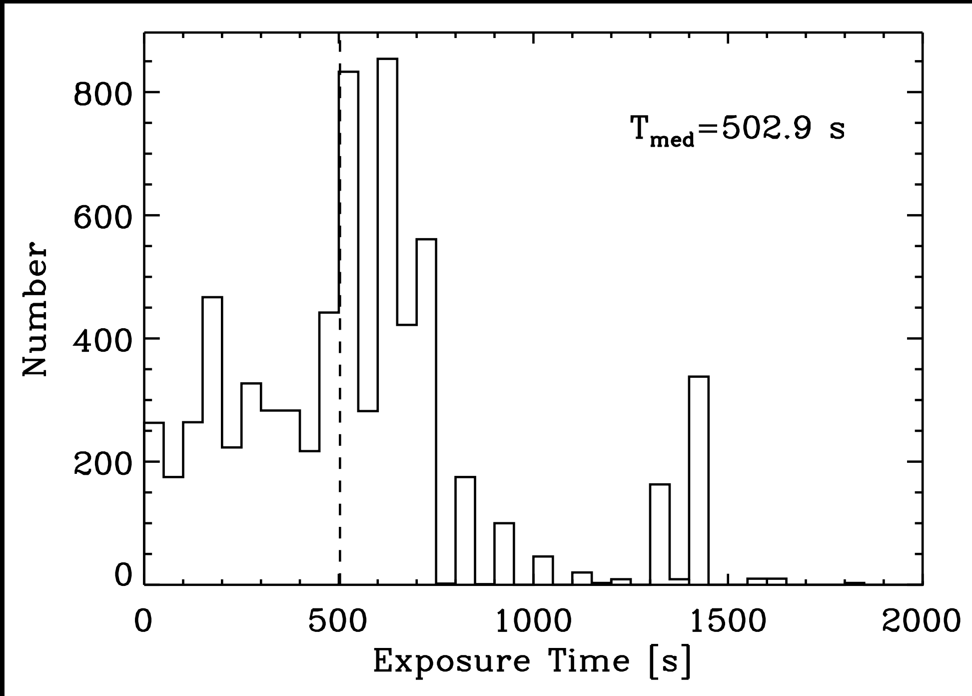
Object finding/catalogs with two independent algorithms.

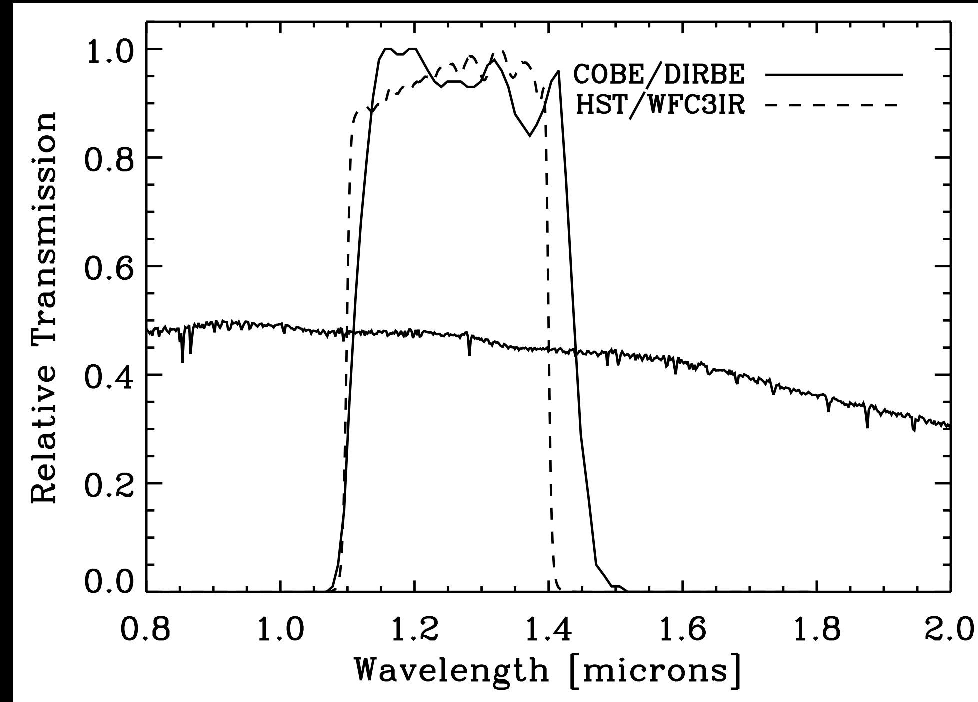


SKYSURF's database: 249,861 exposures (878,000 readouts) in 16,822 HST field-of-views (FOVs).

28 filters from 0.2-1.6 μm; with 12 main broad-band filters in ∼1400 independent HST fields.

Rolf Jansen, Tim Carleton: database lead. UGs built the database in 2020.



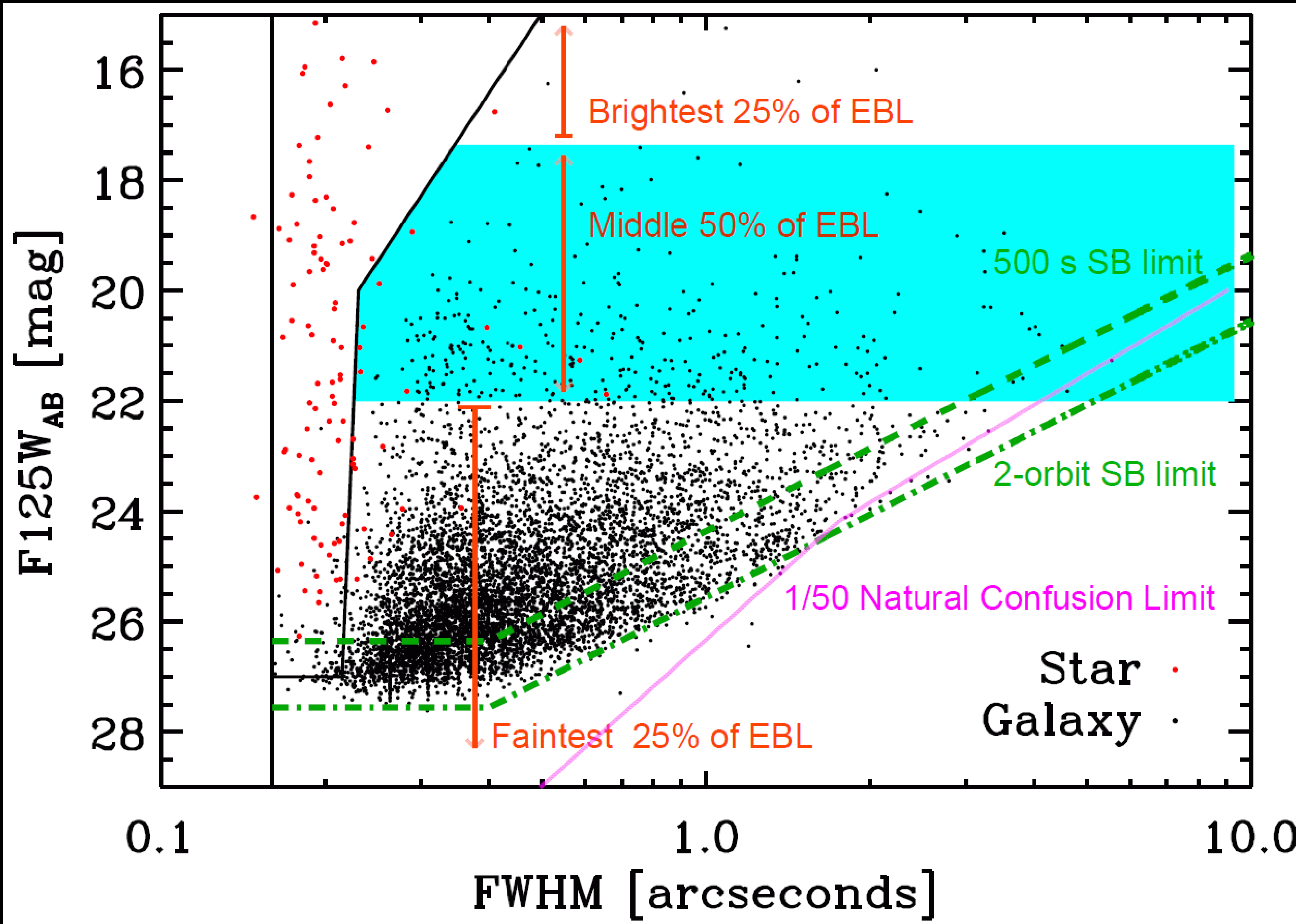


[Left]: Exposure time distribution with median $t_{exp} \simeq 500$ sec (Goisman).

- Typical HST exposure depth reaches AB∼26 mag, *i.e.*, already detects $\gtrsim$95% of the discrete EBL!

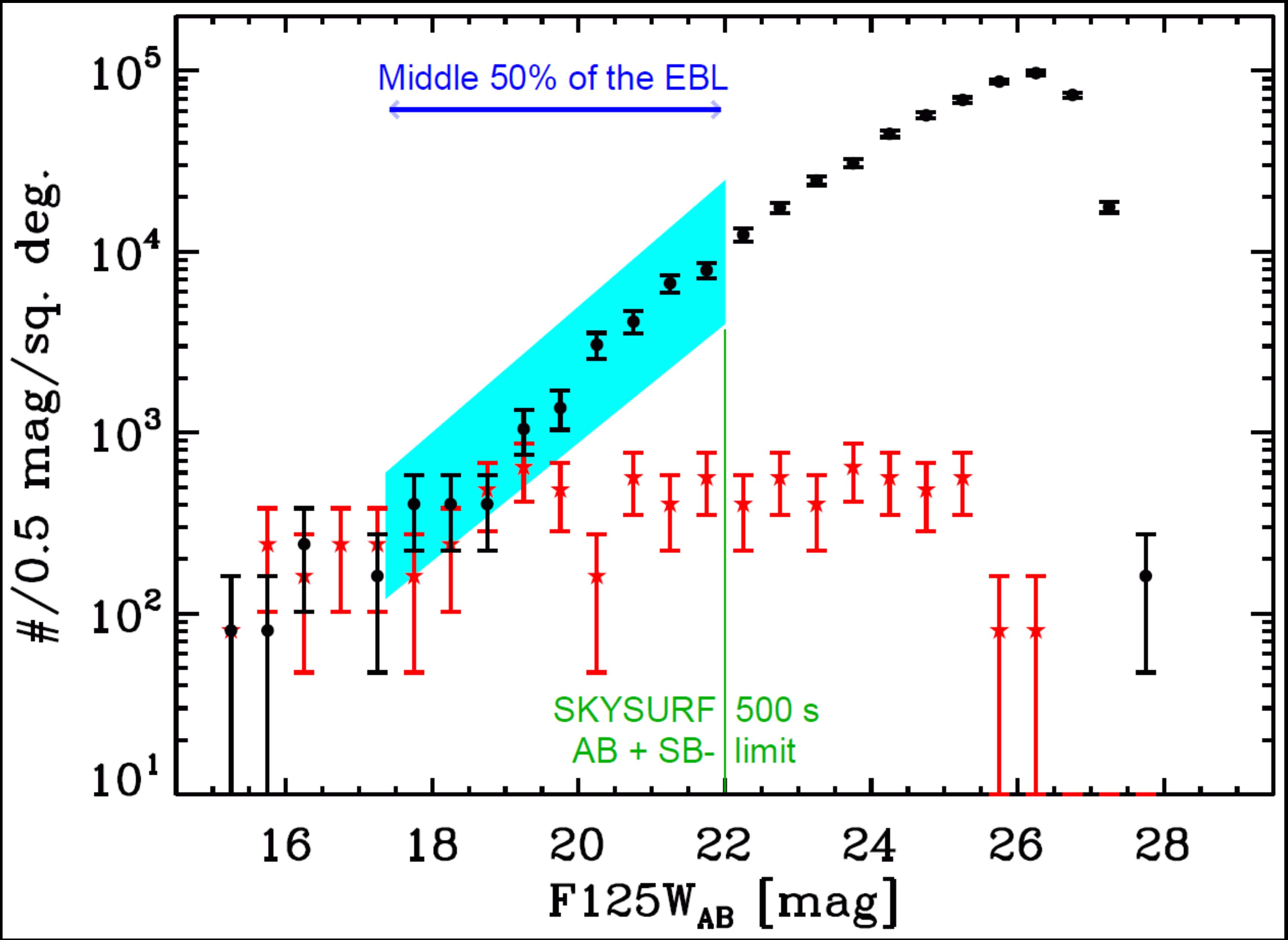
[Right]: Two main filters used for SKYSURF HST–COBE comparison: needed for precision differences in sky-SB (Seth Cohen).

- For the Zodiacal spectrum shown, 1.25 μm filter difference is only 0.56%.



Cohen: star-galaxy separation, with SB- and natural confusion limits.

- Subset of deeper exposures yield accurate completeness corrections.



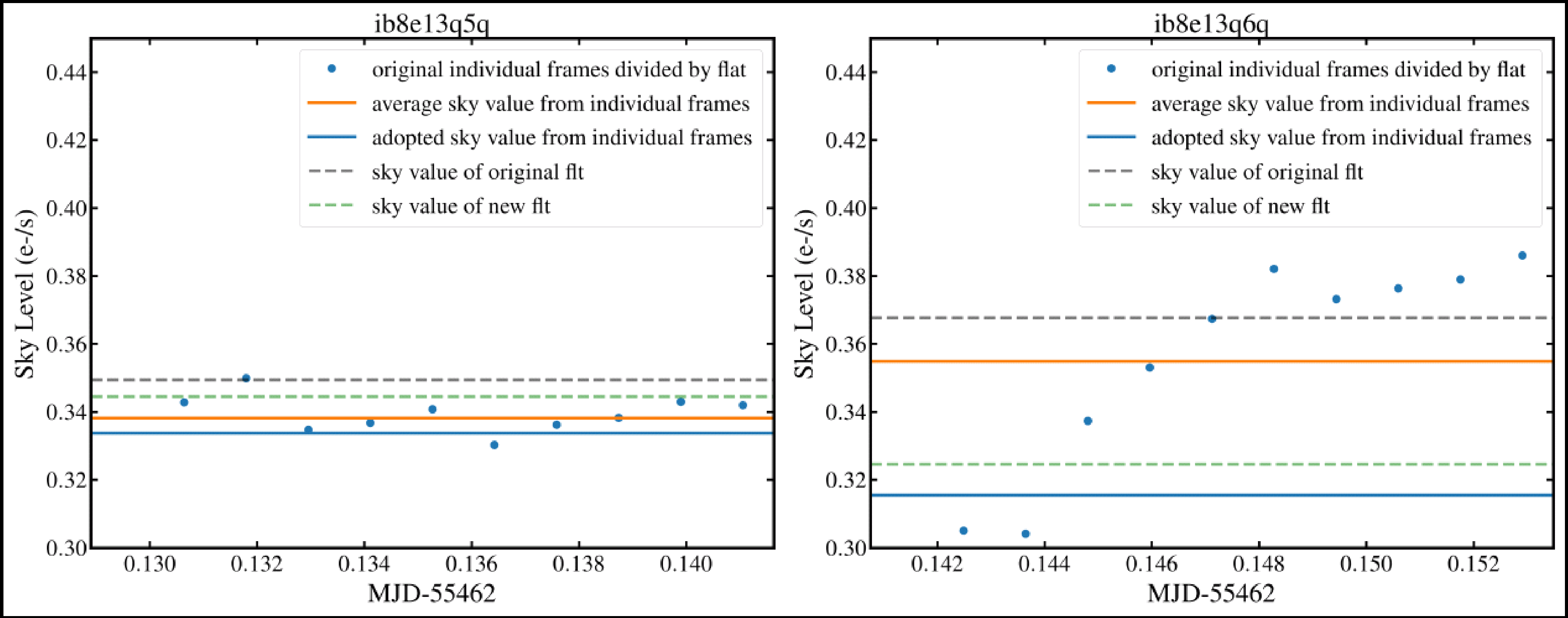
Star+Galaxy counts 100% complete to AB≲22 [where 75% of EBL is seen], and 74% complete to AB≲26 mag [where 95% of discrete EBL is seen]. (Seth Cohen)

(3) How SKYSURF measures sky brightness (SB) & identifies straylight

In all SKYSURF images we need to identify straylight from:

1) Earthshine [Limb Angle]; 2) Sunlight [Sun Angle and Sun Altitude above Earth]; 3) Moonlight [Moon Angle] (Sarah Caddy).

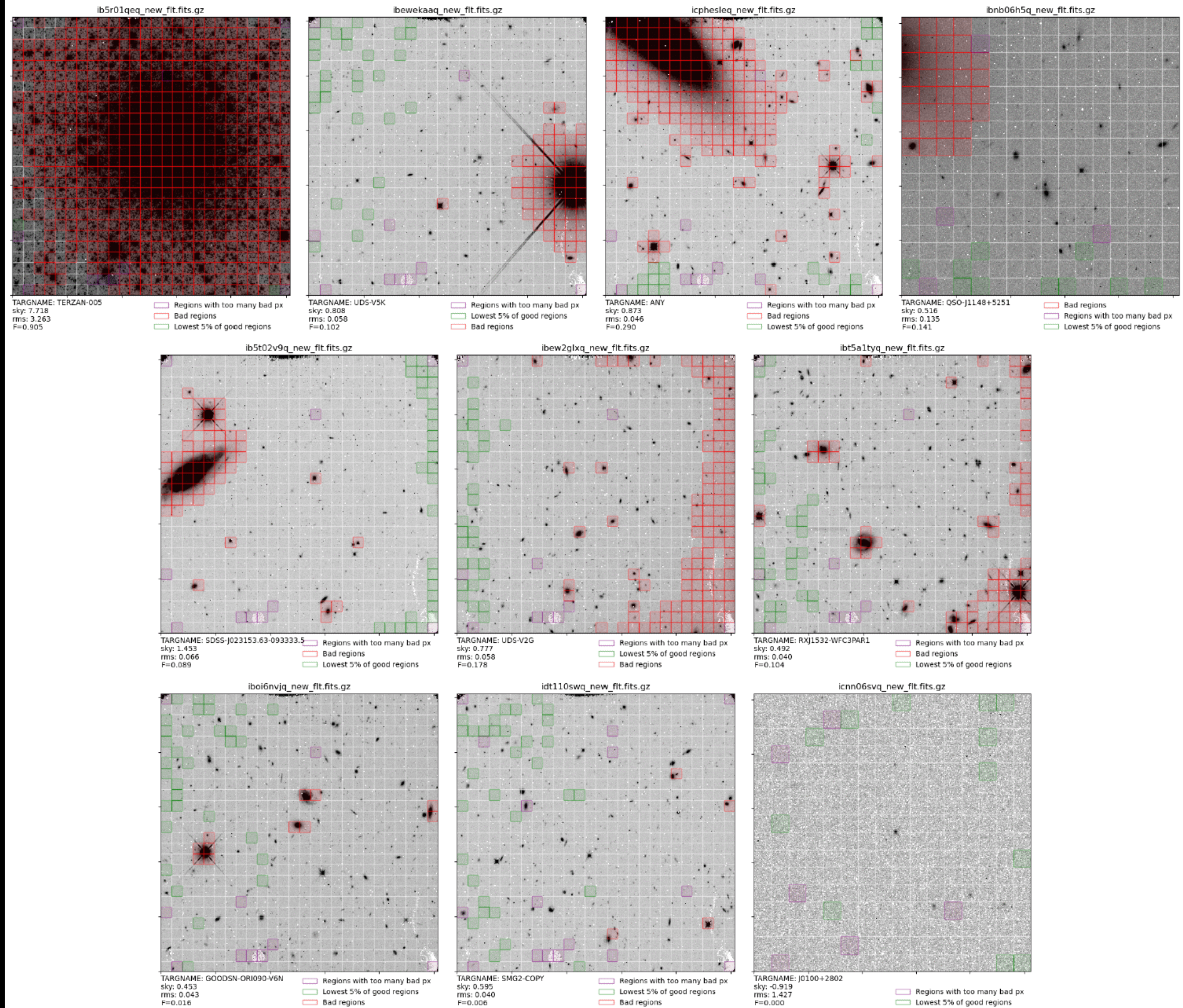
(Earth's Limb is down 24° from LEO orbital vector due to Earth curvature).



• SKYSURF's 50,073 WFC3/IR exposures are split into $\gtrsim$400,000 on-the-ramp sub-exposures (Tim Carleton) — we are not lacking statistics.

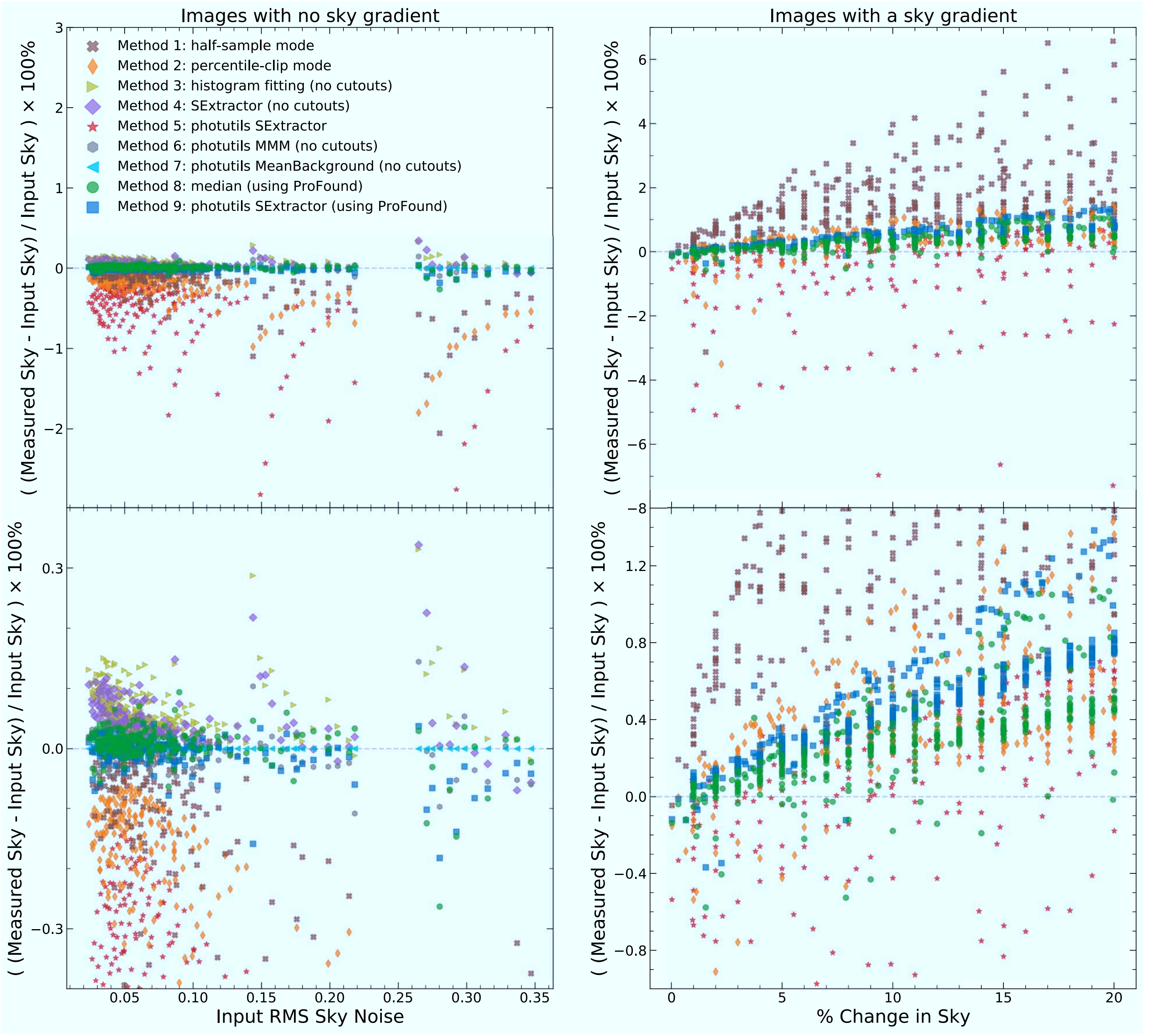
• These (+all 210,000 sub-orbital CCD exposures) allow us to monitor sky-SB vs. HST's orbital phase [Left: Start; Right: End of orbit].

• Critical for flagging & removing SKYSURF exposures with straylight.



First, identify all sub-grid regions with objects or defects (R. O'Brien).

5% of object-free boxes give best match with simulated sky-SB (D. Carter).



Top: Relative error in Measured / Simulated sky-SB in %;

Bottom: same but enlarged;

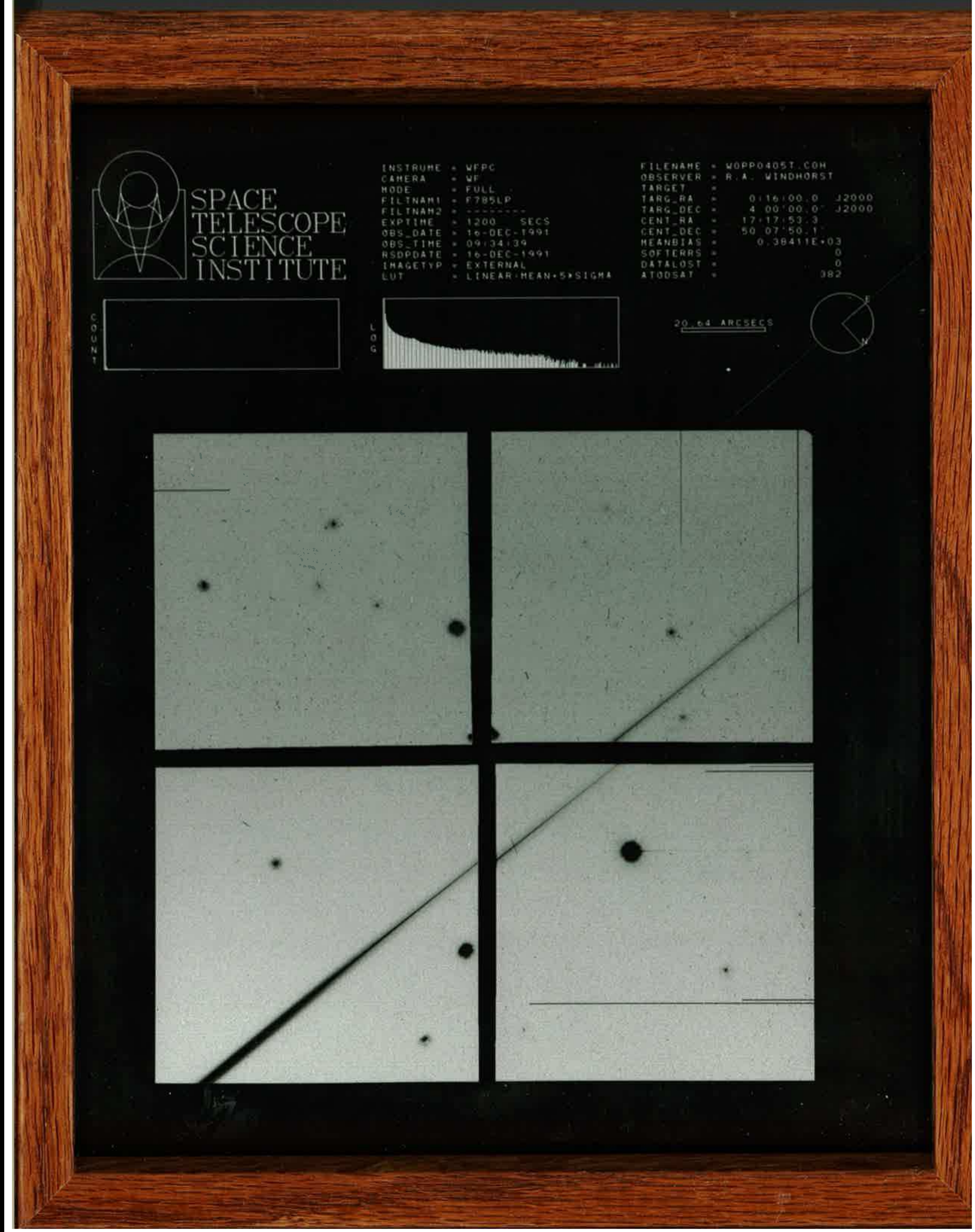
Left: simulated without gradients;

Right: images with 5–20% (straylight) gradients.

(Real Zodiacal gradients are always less across HST FOVs).

W/O gradients: Best 3 out of 9 algorithms recover sky-SB $\lesssim$0.1-0.2%.

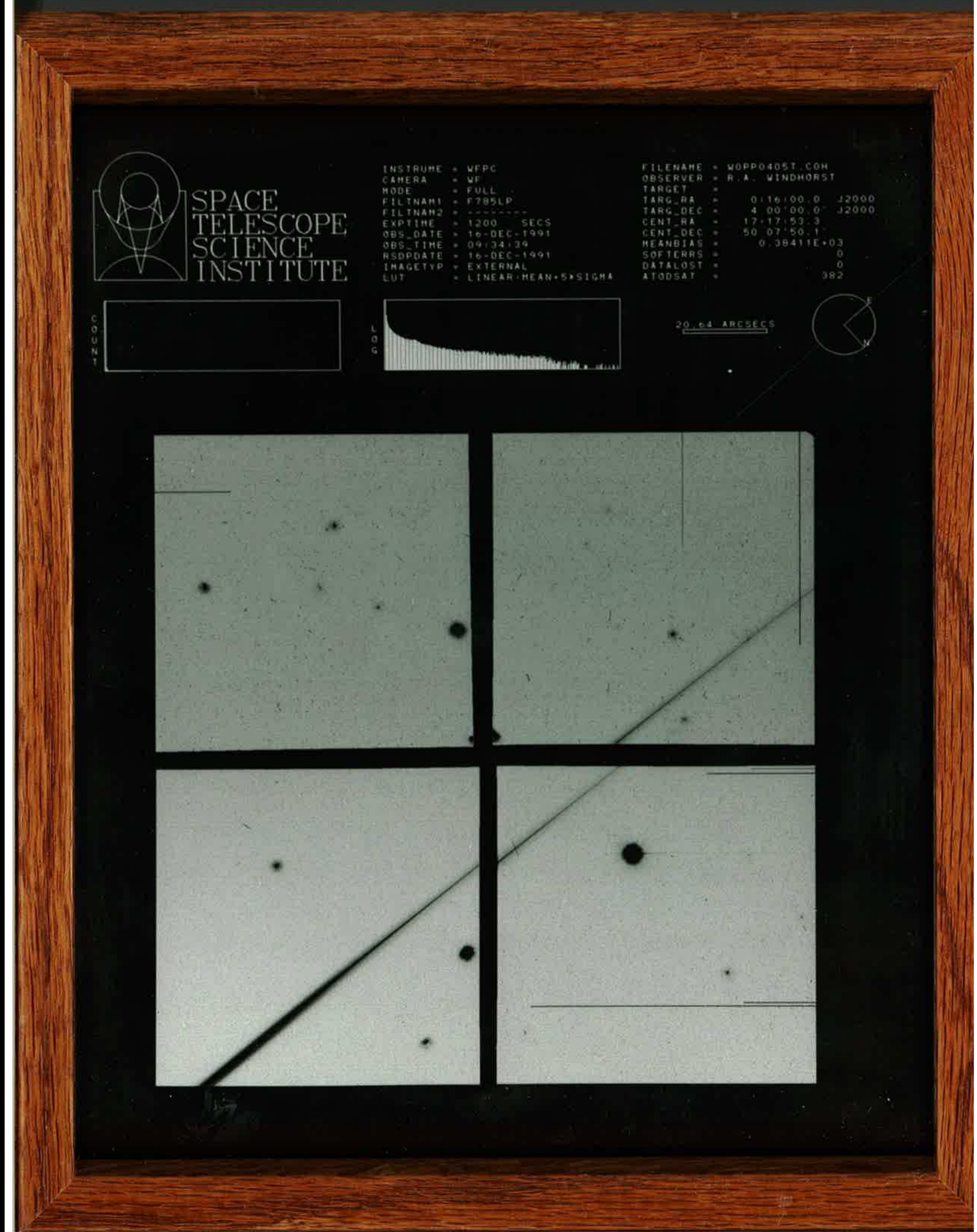
With 5–10% gradients: recover sky-SB $\lesssim$0.4% (Carter, O'Brien).



Our team also removes artifacts from the HST images ...

Dec. 1991: One of my first HST WF/PC images had bright trail !?

Next day: JPL and NRO called to get my image, and find its nature.



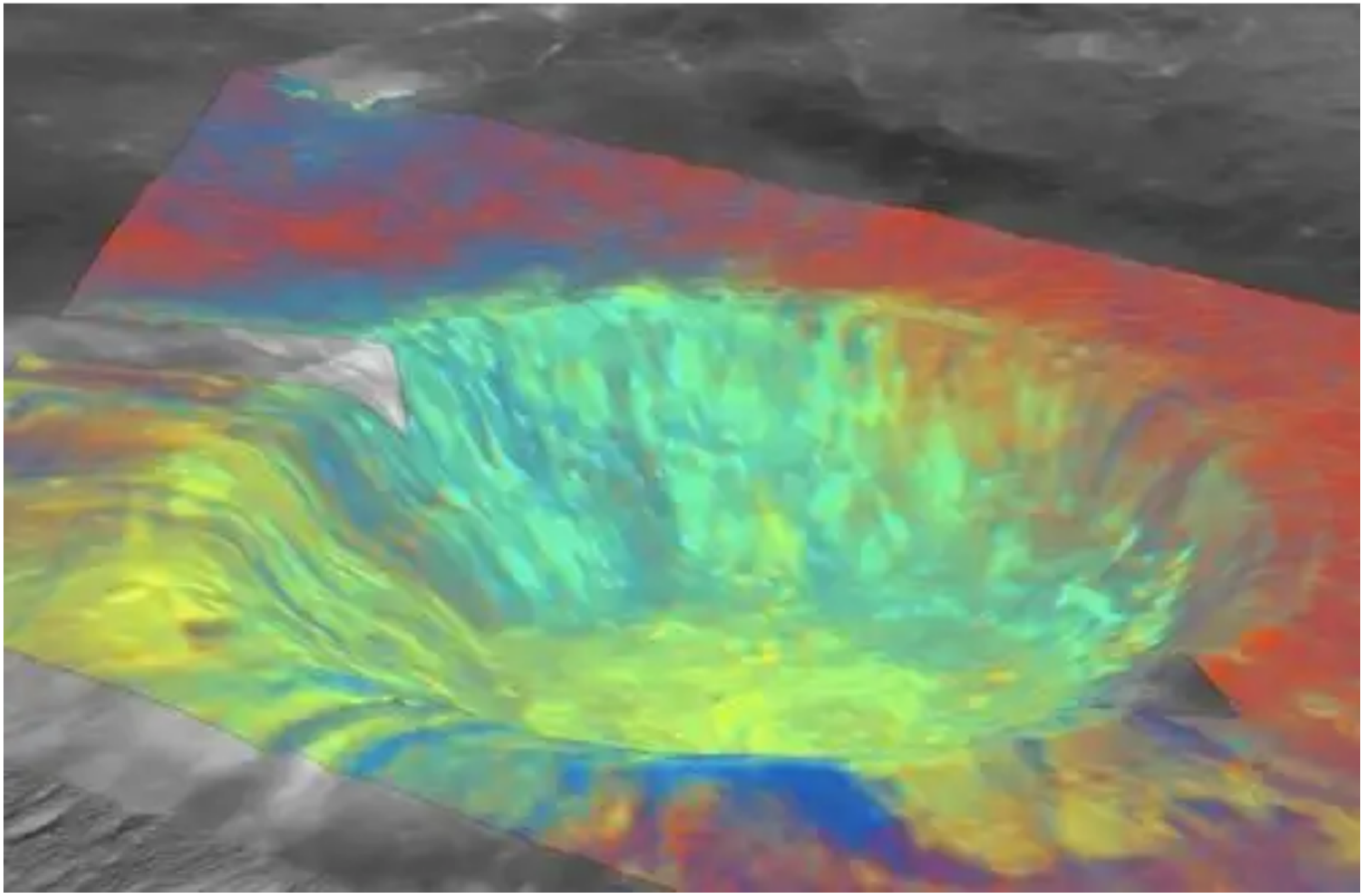
Our team also removes artifacts from the HST images ...

Dec. 1991: One of my first HST WF/PC images had bright trail !?

Next day: JPL and NRO called to get my image, and find its nature.

This 3rd stage of a Russian Proton rocket is out of focus! ...

SKYSURF's sky-finder code soundly rejects such artifacts (R. O'Brien).

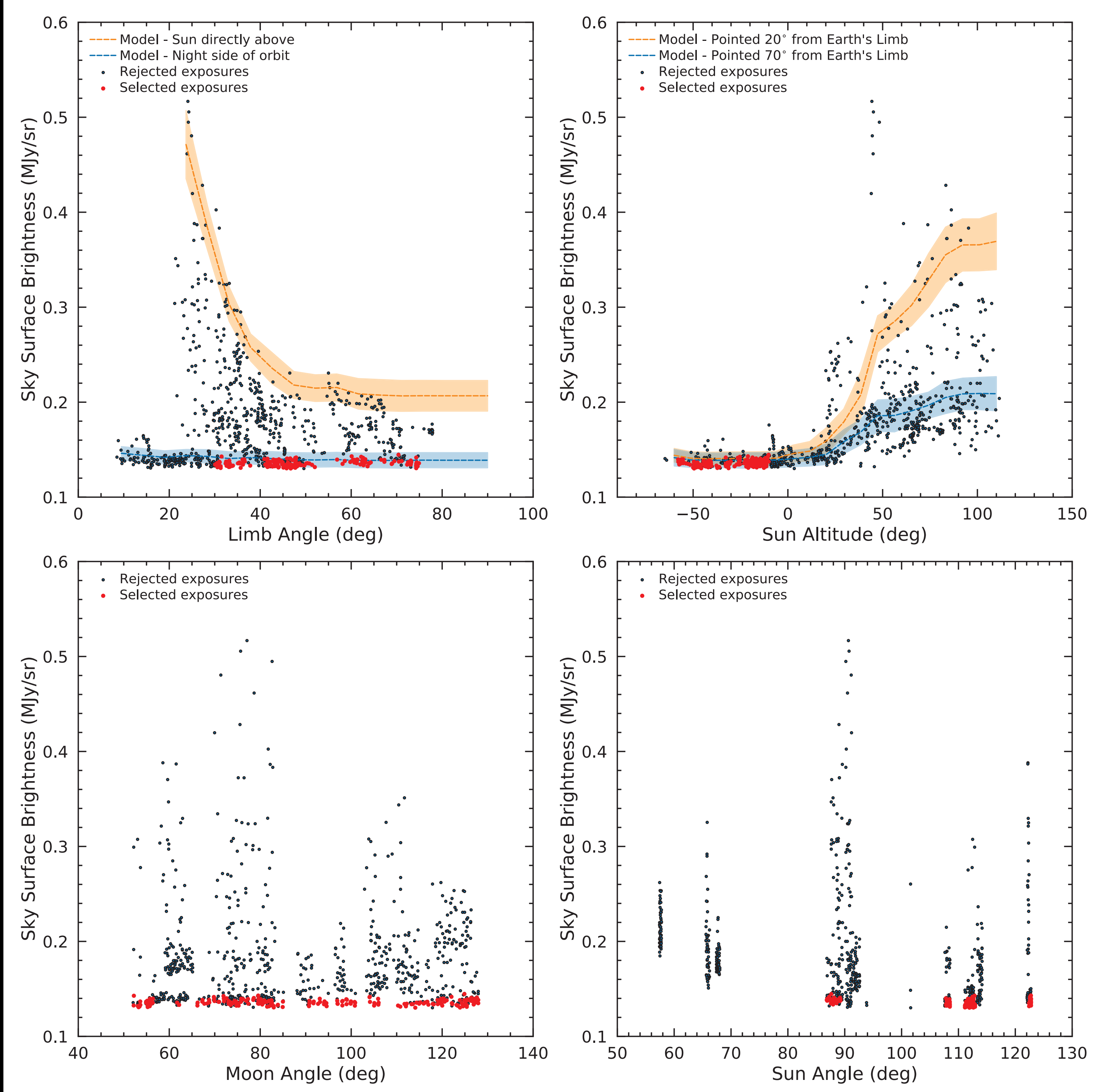


Enhancing the ratio of ultraviolet to visible light will help estimate how much ilmenite and volcanic glass exist at the Aristarchus crater
(Image: NASA/ESA/HST Moon Team)

SKYSURF also ignores images that got too close to the Moon:

including M. Robinson/J. Garvin's beautiful HST ACS/HRC Lunar UV image!

https://www.newscientist.com/article/dn8185-hubble-hints-at-sites-for-lunar-bases/



Sarah Caddy's study to minimize straylight:

(a) Earth Limb Angle LA$\gtrsim$30–40° to avoid Earthshine; and

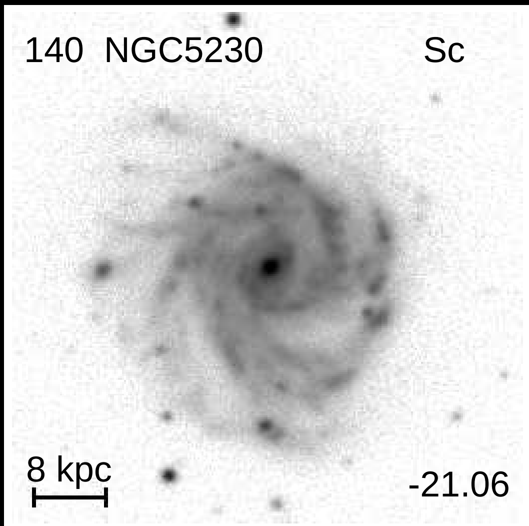
(b) Sun Alt. above Earth $\alpha_{\odot}\lesssim$–10° (orbital night side) minimizes Sunlight scattered off the bright Earth; and

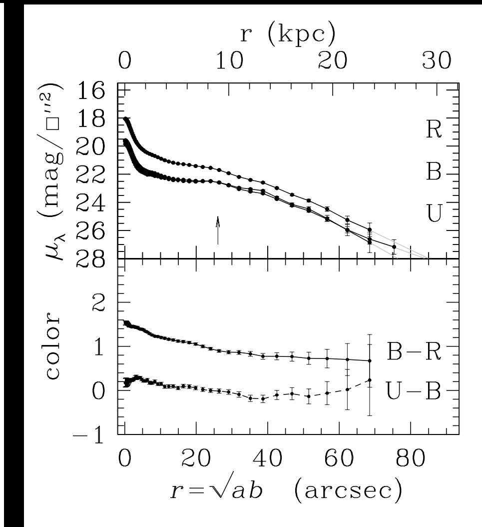
(c) The Moon Angle MA$\gtrsim$50 °; and

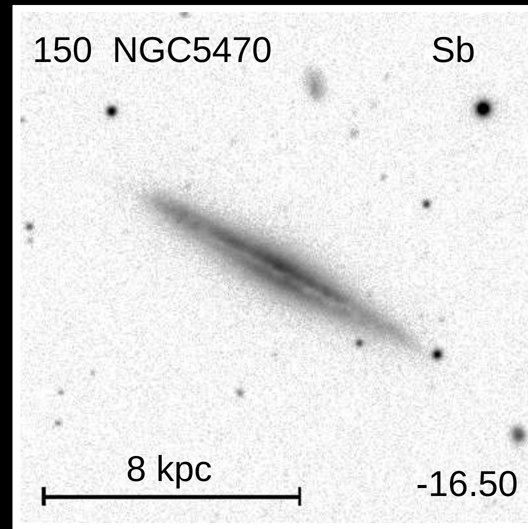
(d) Sun Ang. SA$\gtrsim$80° avoids straylight into the HST optics.

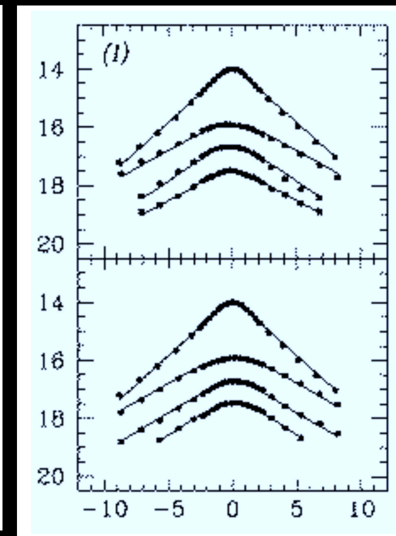
SKYSURF's high-fidelity sample will apply all these constraints (R. O'Brien).

(4) How SKYSURF measures residual sky compared to Zodiacal models









[Left]: Face-on disks: *exponential radial* light-profiles (Jansen$^+$ 2000).

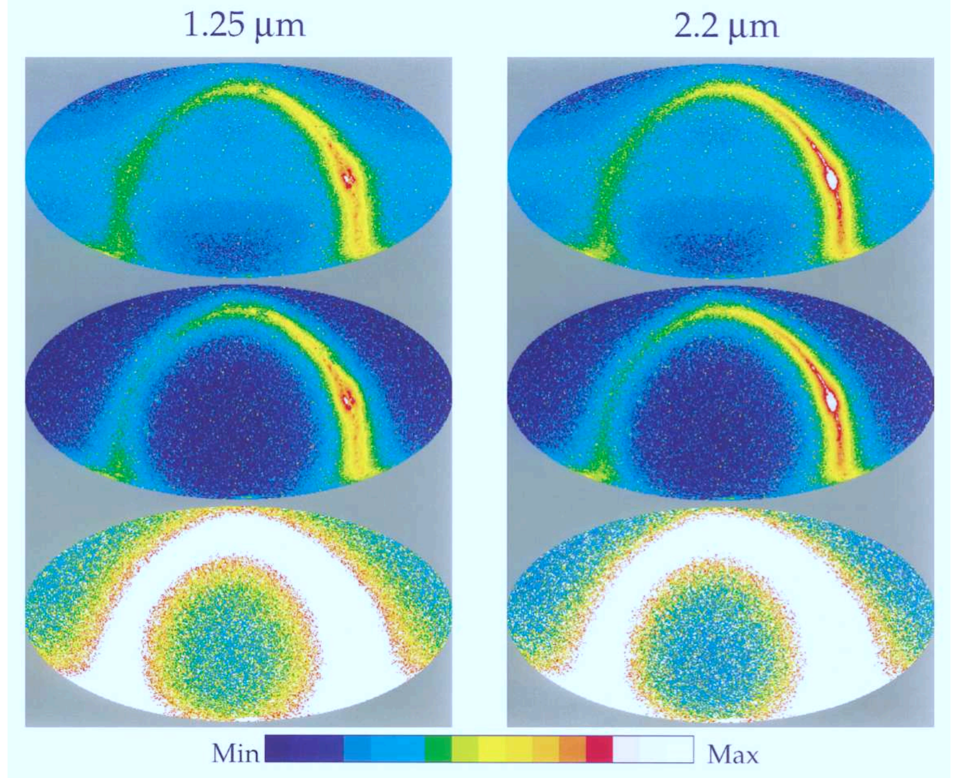
[Right]: Edge-on disks: *vertical sech* light-profiles (de Grijs$^+$ 1997).

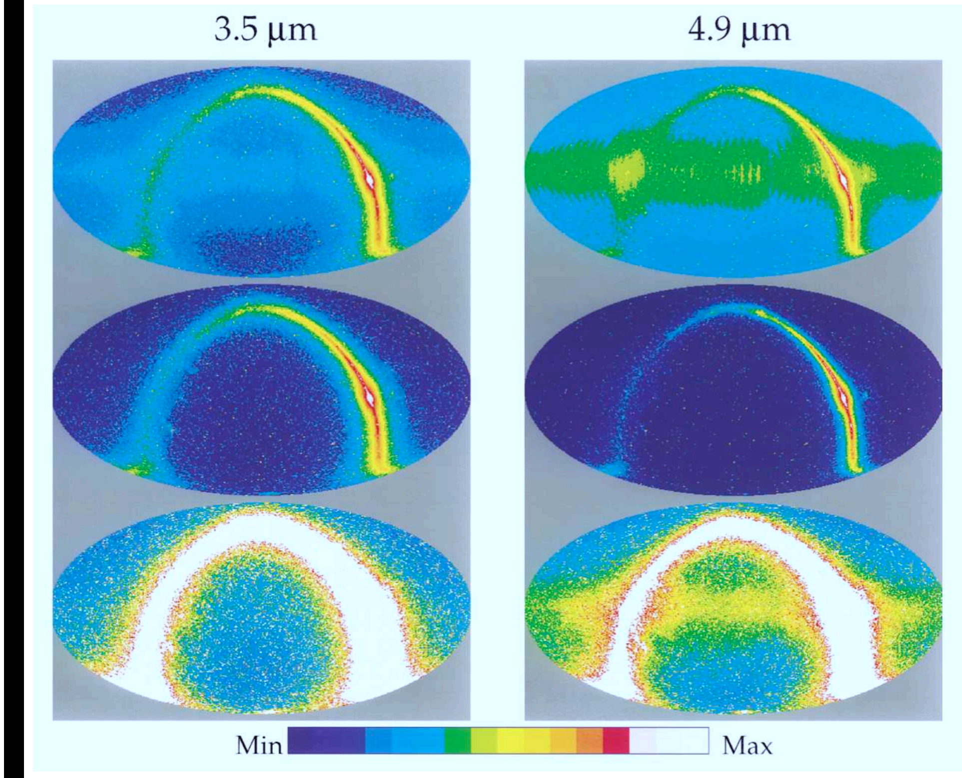
For Zodiacal disk-SB we use: sech(z) = [exp(z) + exp(-z)] / 2, which provide remarkable good fits to both dimmest HST data and Zodi models!

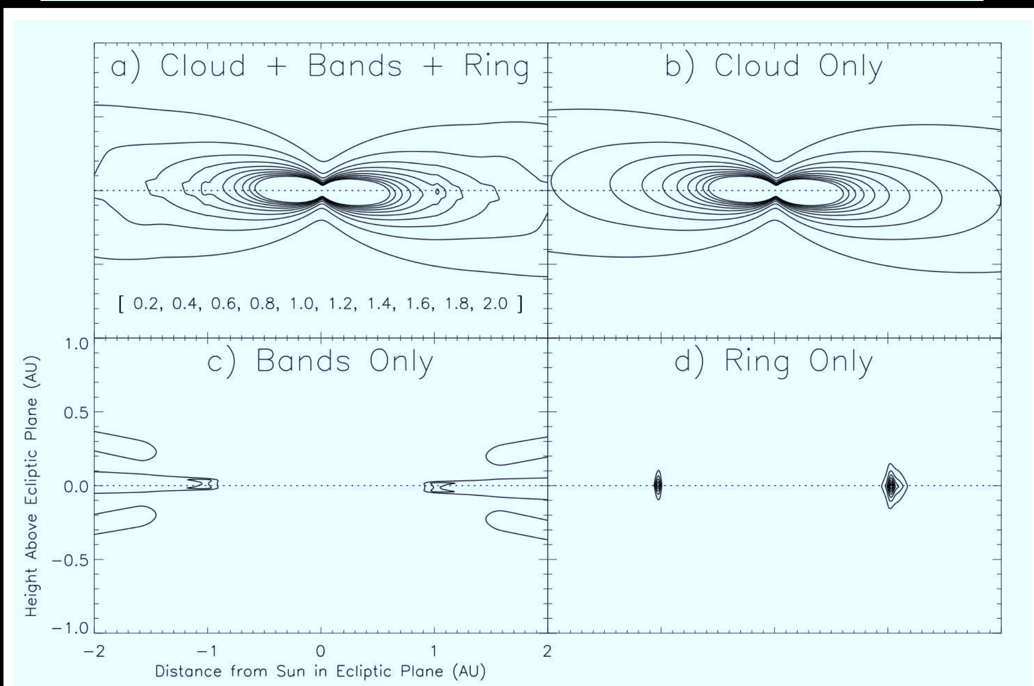
The (observed–model) sky-SB lets SKYSURF identify diffuse light sources:

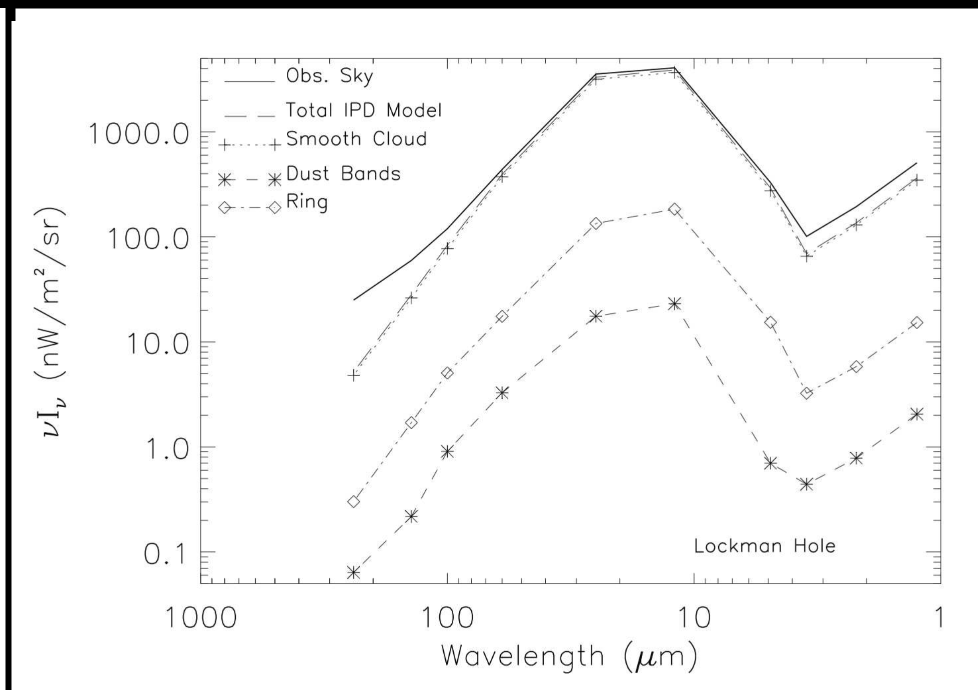
1) Residual instrumental effects; 2) Diffuse ZL component not in the model;

3) Diffuse Galactic Light (DGL); 4) Diffuse EBL between discrete galaxies.



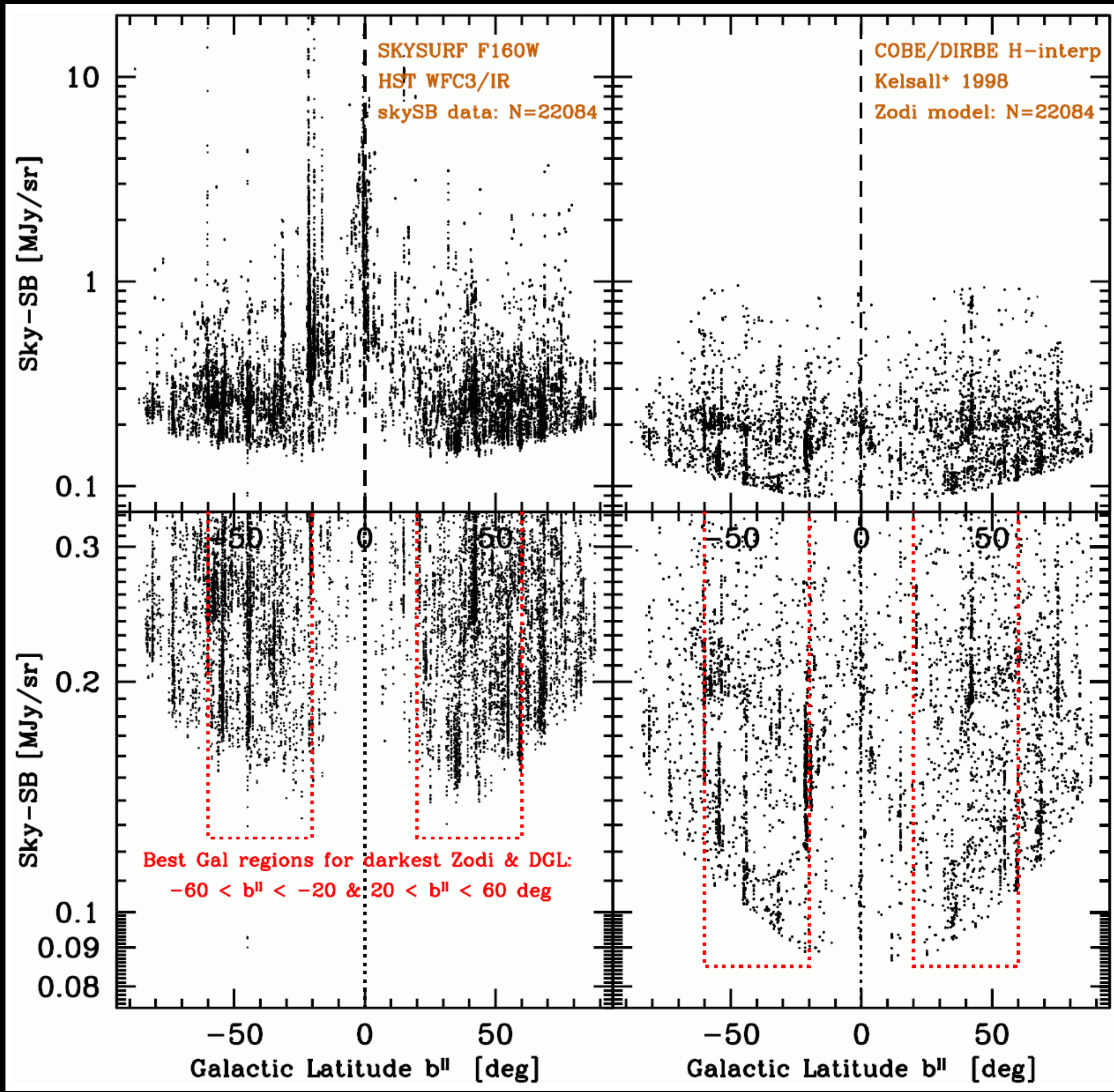






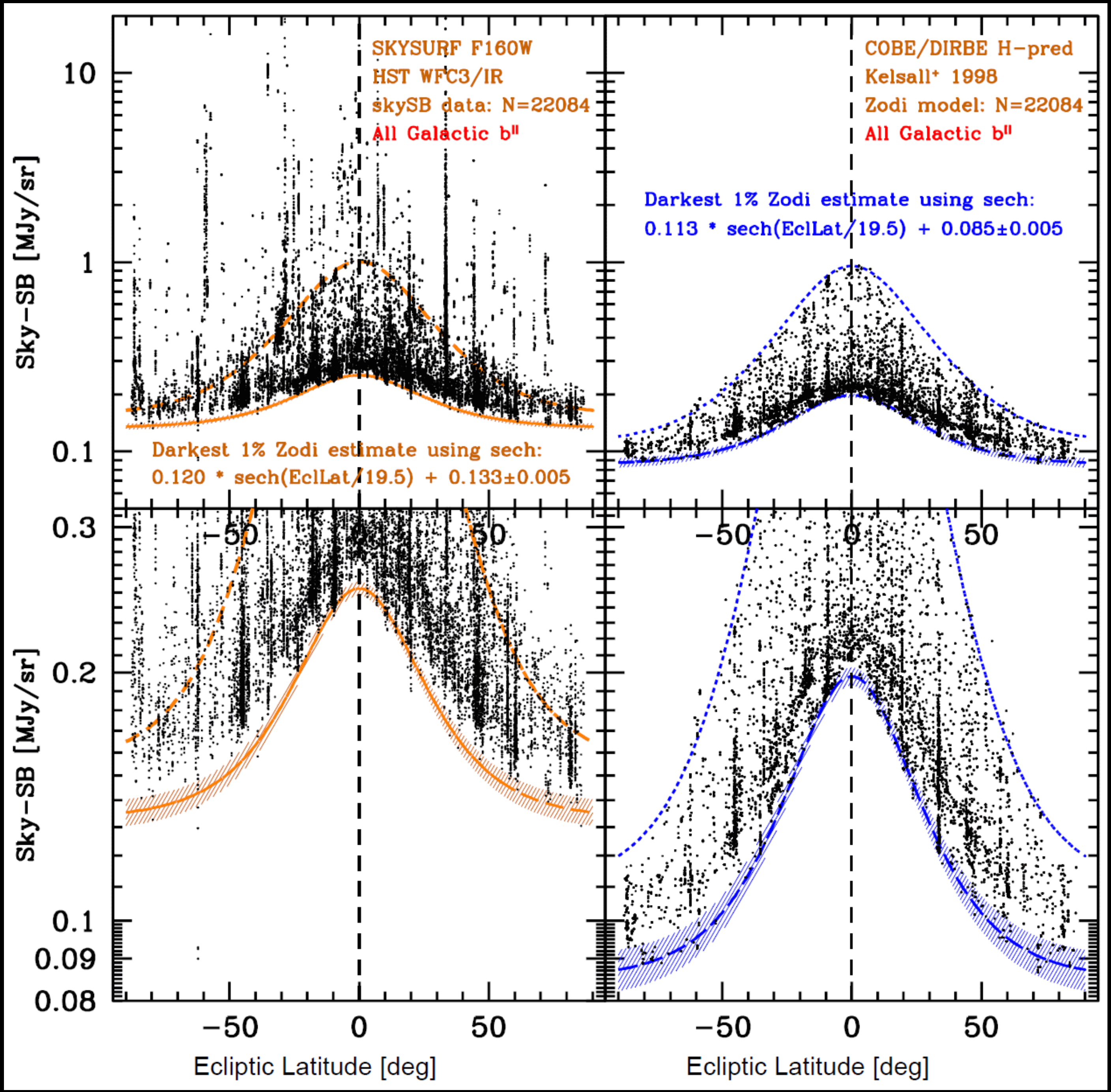
Kelsall (1998) Zodi model based on Cosmic Background Explorer data.

(5) SKYSURF's first results and estimates of diffuse 1.25-1.6 μm light



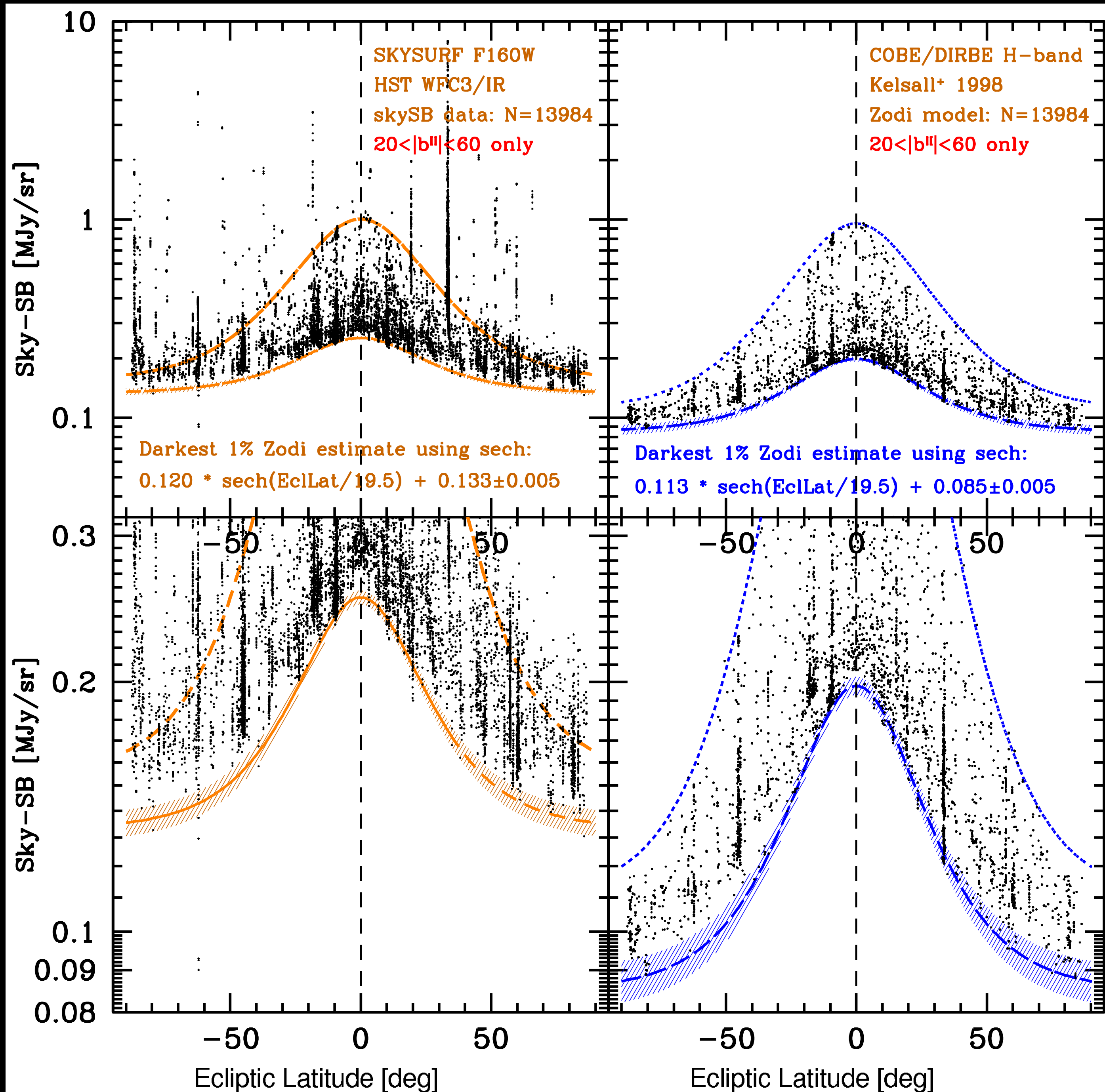
[Left]: 1.60 μm HST sky-SB; [Right]: Kelsall model for *same* (RA, Dec, t).

First, identify *darkest* regions in Galactic coordinates ($20° \lesssim |b^{II}| \lesssim 60°$).



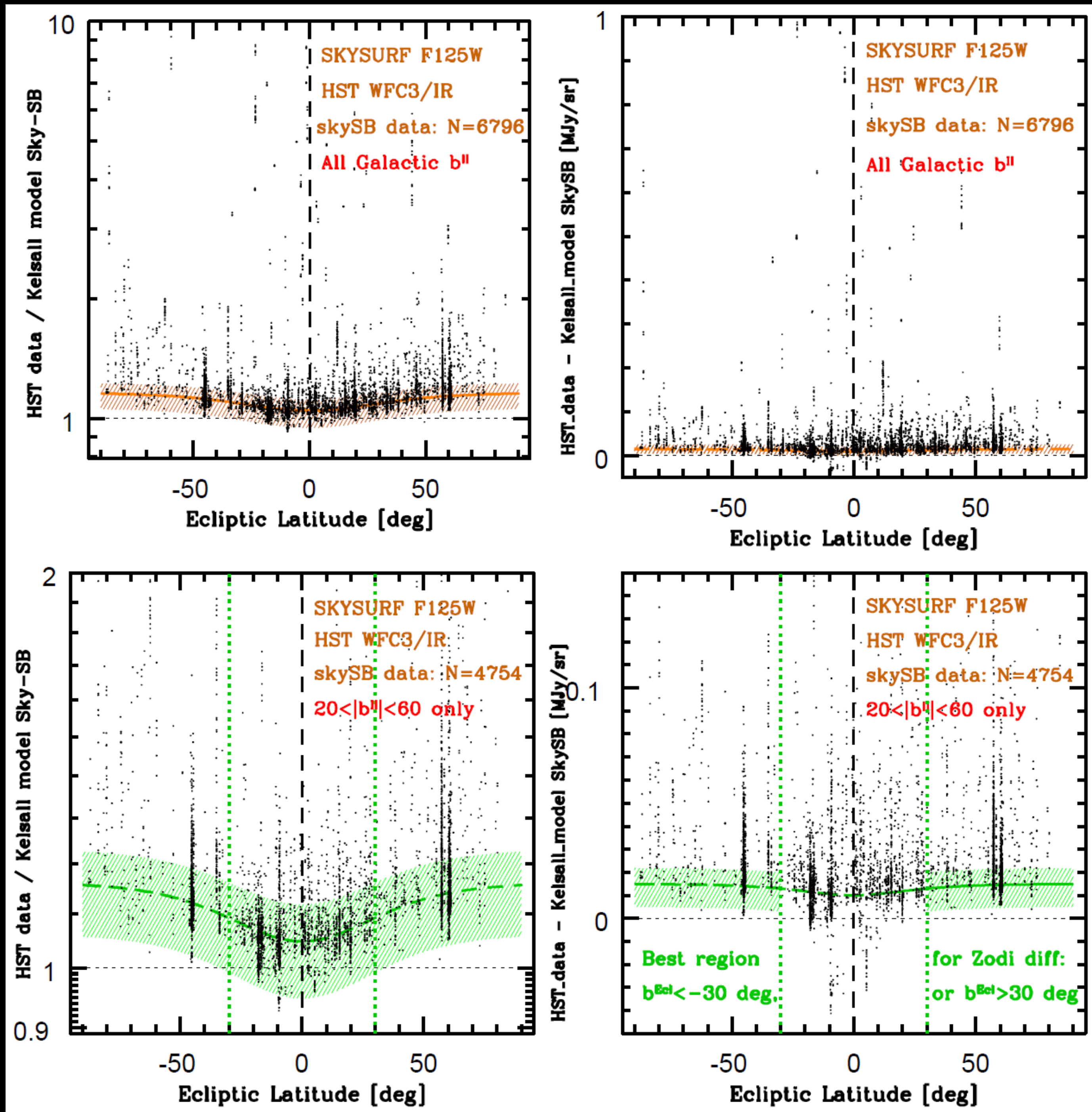
1.60 μm HST+Kelsall vs. b^{Ecl}: $sech$+error = lowest 1% of sky-SB.

Lowest data–model 1% yields Δ(HST–Kelsall) $\simeq$ 0.048±0.009 MJy/sr.



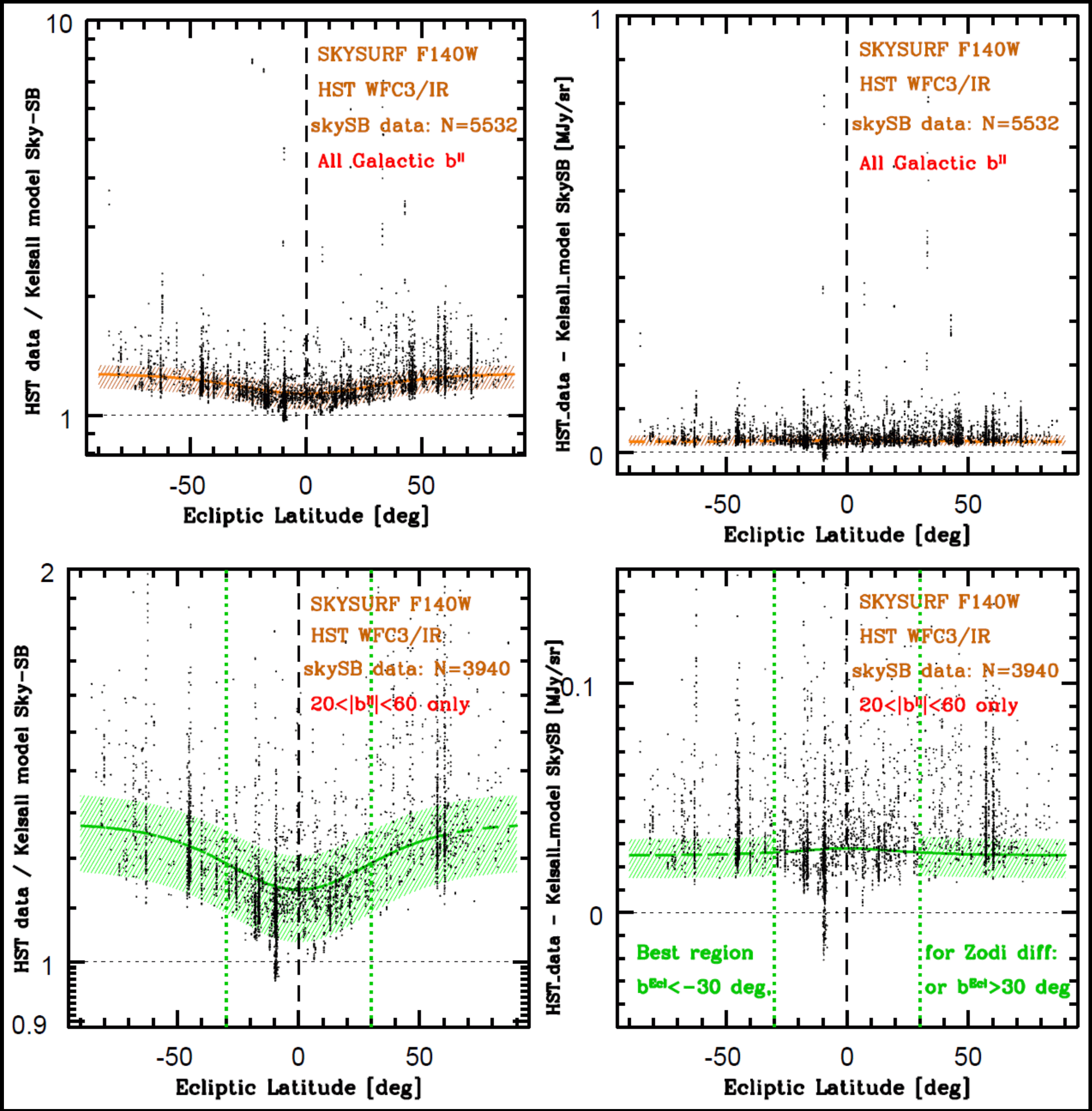
1.60 μm HST+Kelsall vs. b^{Ecl}: $sech$+error = lowest 1% of sky-SB.

Lowest 1% Δ(HST–Kelsall)$\simeq$0.048±0.009 MJy/sr at darkest Galactic.



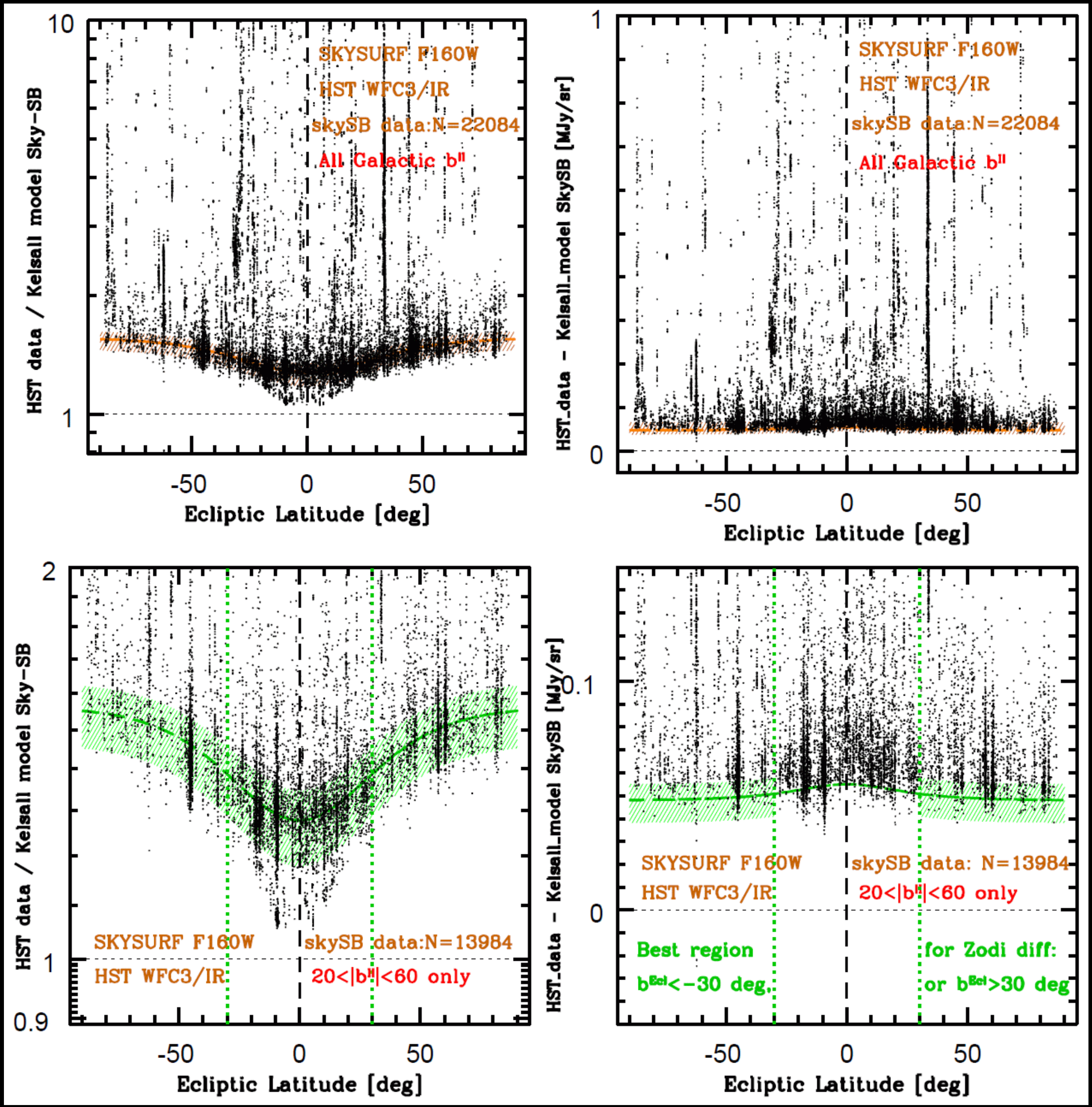
1.25 μm [Left]: HST/Kelsall ratio vs. b^{Ecl}; [Right] HST–Kelsall difference.

Linear offset Δ(HST–Kelsall)$\simeq$0.015$\pm$0.008 MJy/sr remains best fit.



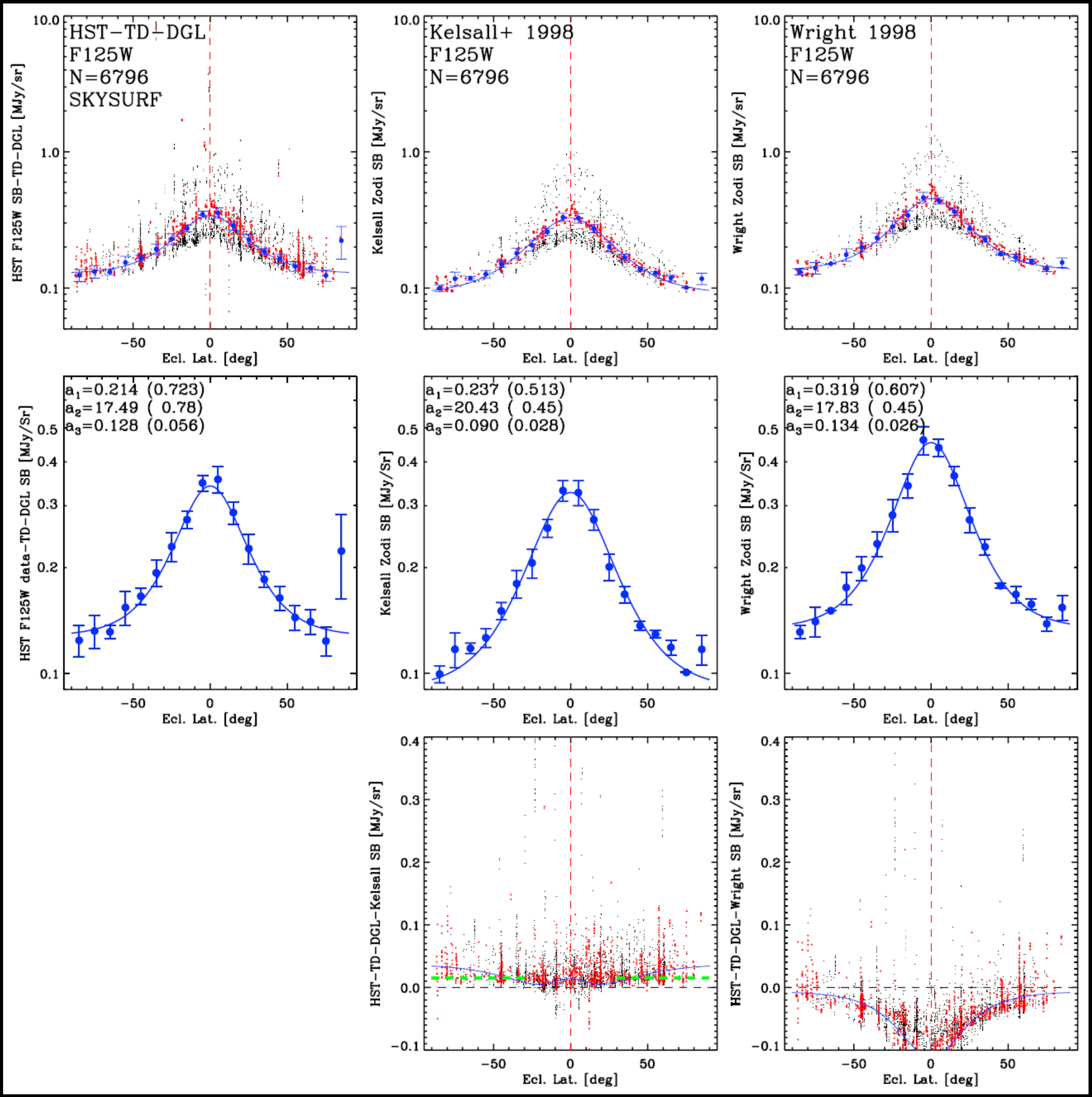
1.40 μm [Left]: HST/Kelsall ratio vs. b^{Ecl}; [Right] HST–Kelsall difference.

Linear offset Δ(HST–Kelsall)$\simeq$0.025$\pm$0.009 MJy/sr remains best fit.



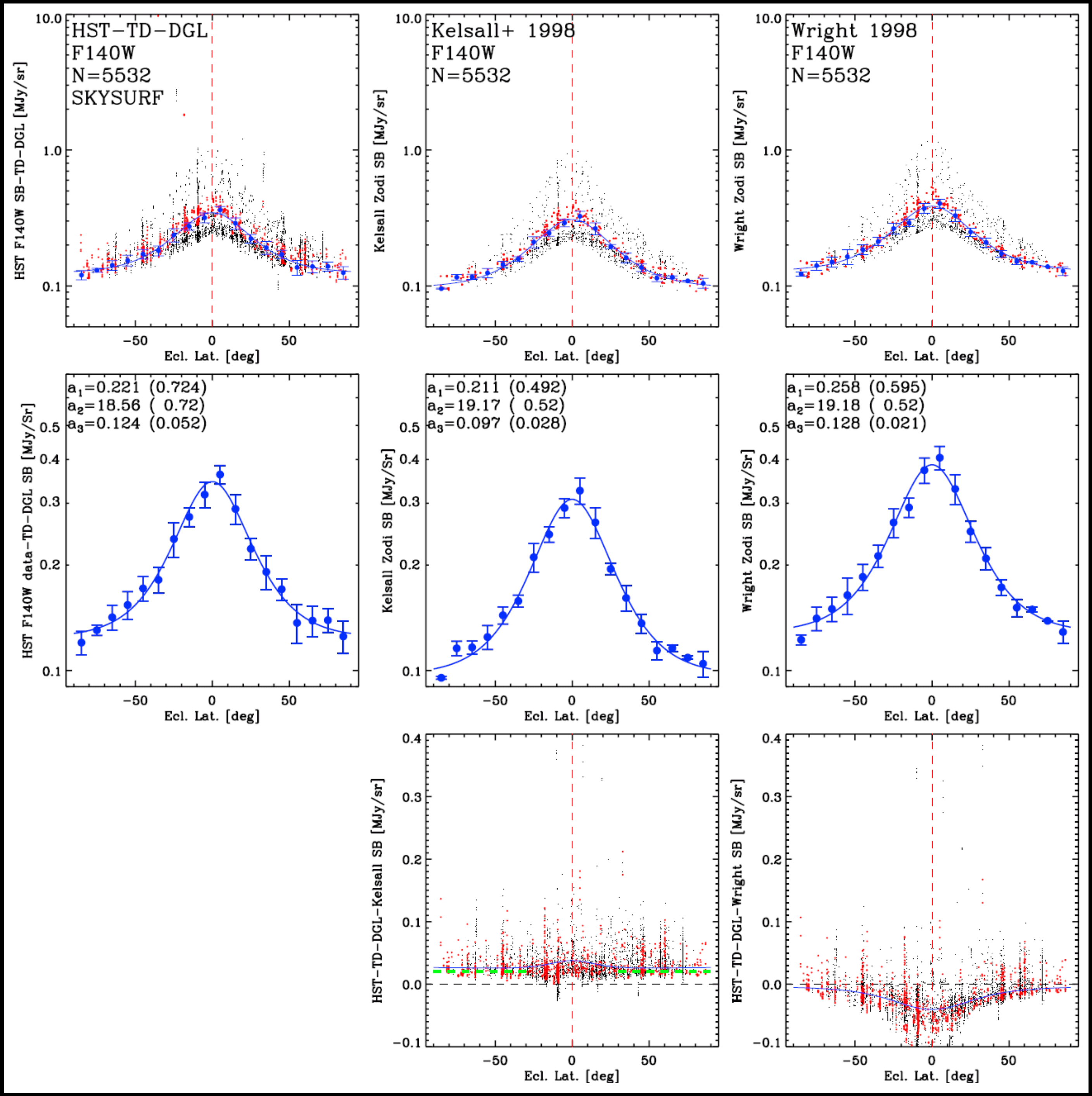
1.60 μm [Left]: HST/Kelsall ratio vs. b^{Ecl}; [Right] HST–Kelsall difference.

Linear offset Δ(HST–Kelsall)$\simeq$0.048$\pm$0.009 MJy/sr remains best fit.



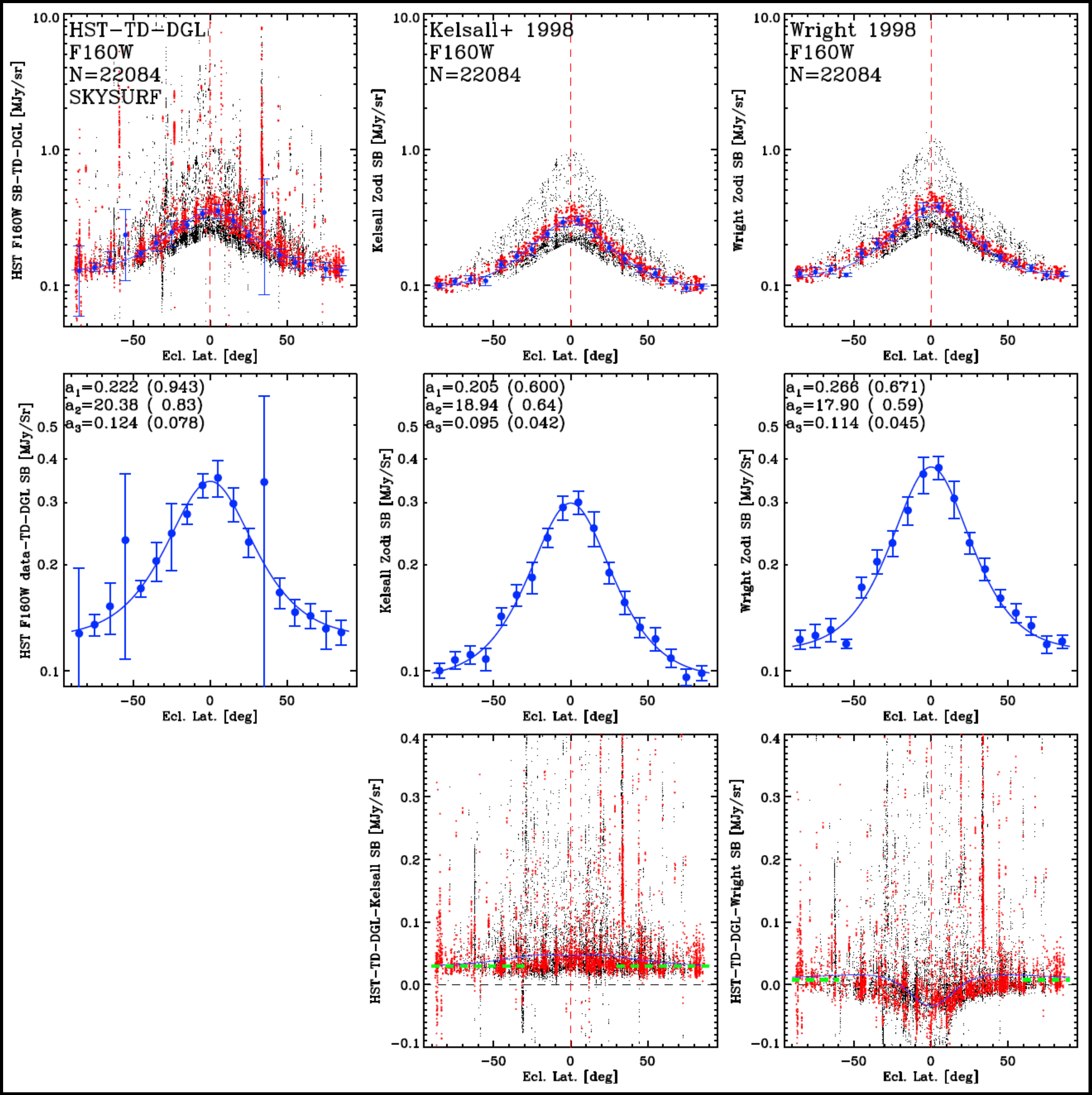
1.25 μm [Left]: HST; [Middle] Kelsall; [Right] Wright model vs. b^{Ecl}.

HST(TD+DGL-subtracted): Kelsall linear offset stays; Wright shows none.



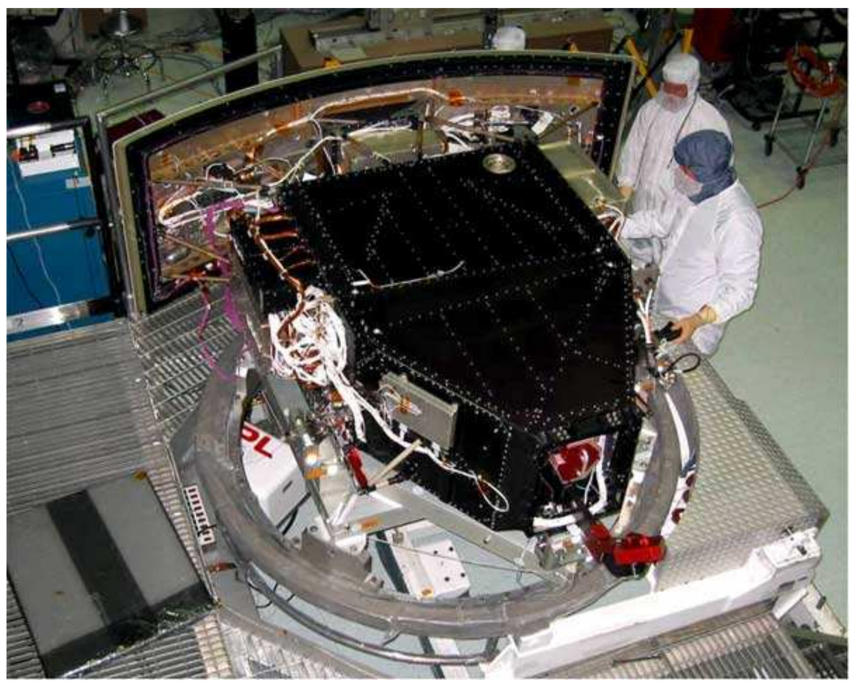
1.40 μm [Left]: HST; [Middle] Kelsall; [Right] Wright model vs. b^{Ecl}.

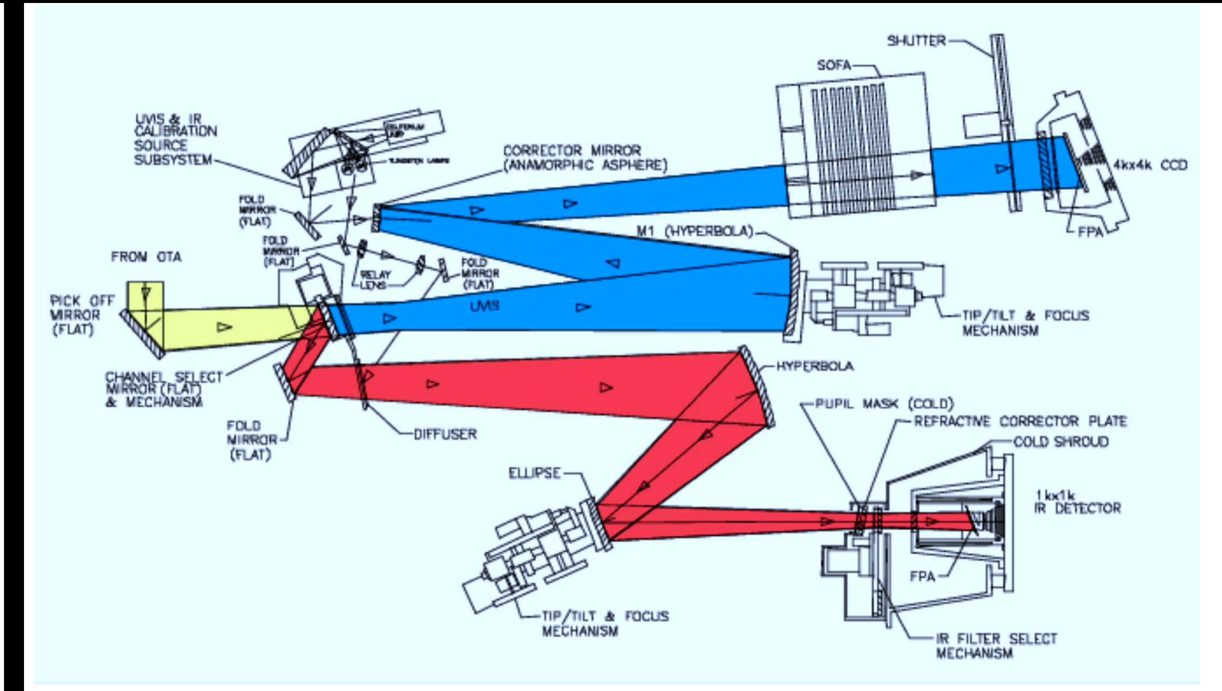
HST(TD+DGL-subtracted): Kelsall linear offset stays; Wright shows none.



1.60 μm [Left]: HST; [Middle] Kelsall; [Right] Wright model vs. b^{Ecl}.

HST(TD+DGL-subtracted): Kelsall linear offset stays; Wright has marginal.





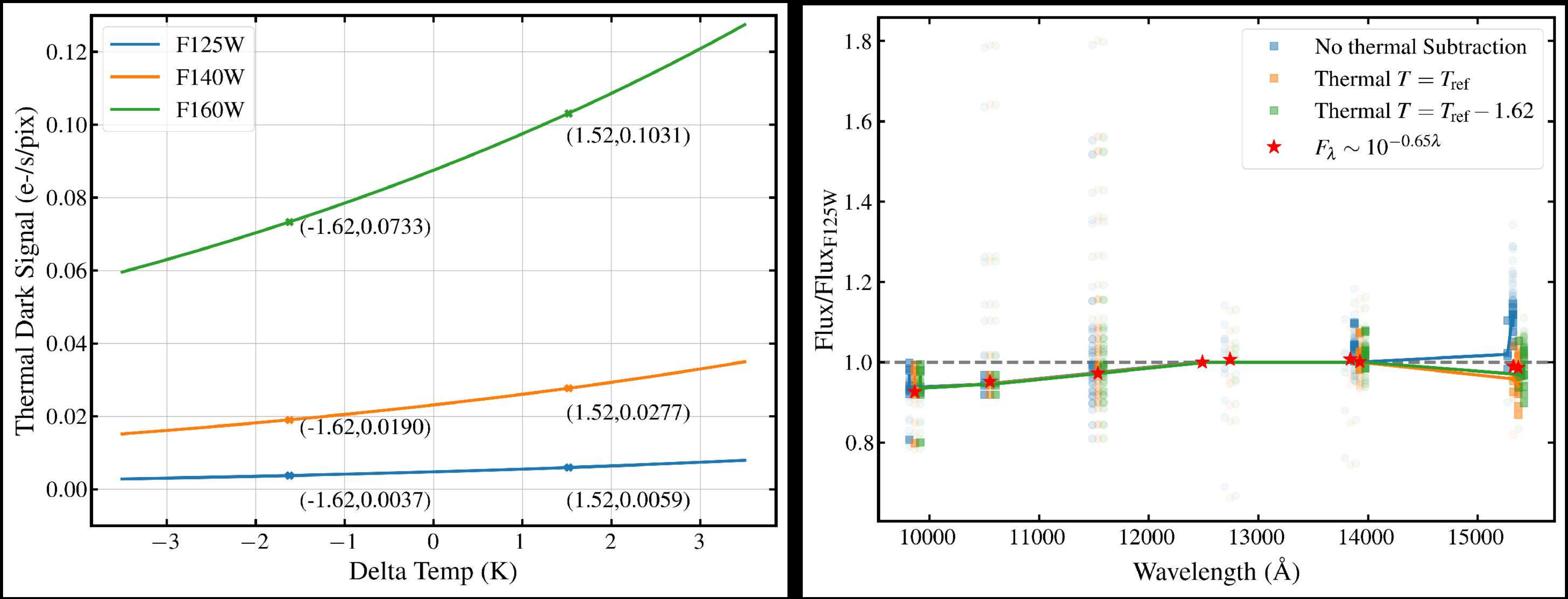
[Left] WFC3 at NASA GSFC before May 2009 Shuttle launch.

[Right] WFC3 model: optical train Temp ranges from T=287–173 K.

• Several dozen temperature sensors monitor temperature T across orbit within 1–2 K, enabling predictions of Thermal Dark (TD) signal vs. T.

• The *synphot* package predicts Planck-BB/solid-angle contribution from each optical component vs. T as seen by the WFC3/IR-detector.

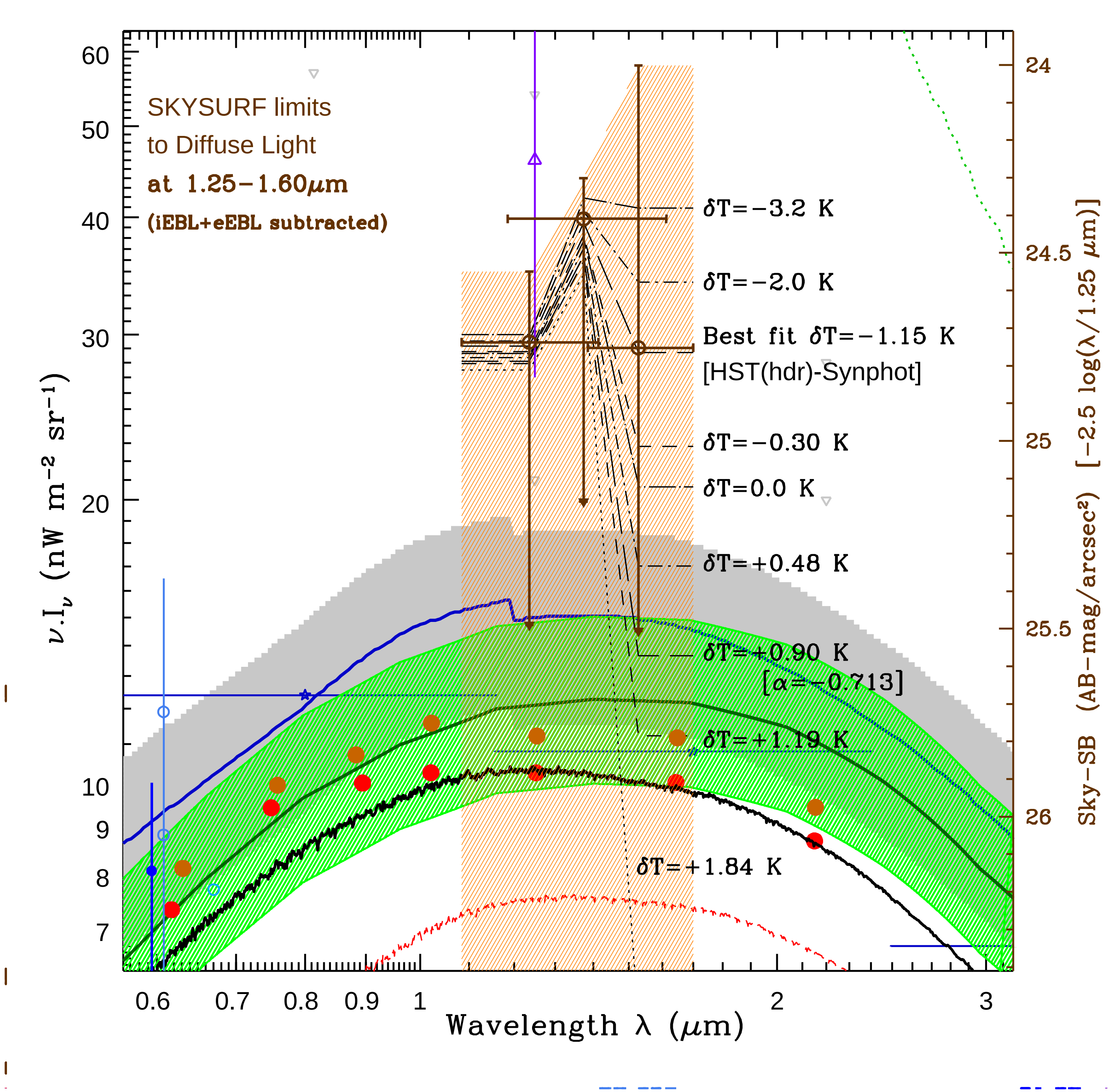
Details in Carleton et al. (2022a, 2022b).



[Left]: ***synphot*** WFC3/IR Thermal Dark (TD) signal modeling.

[Right]: TD for <T(HST)>≃–1.62 K (compared to nominal T).

- Thermal Dark signal largest at 1.6 μm, but well determined and small at 1.25–1.40 μm (Carleton et al. 2022).

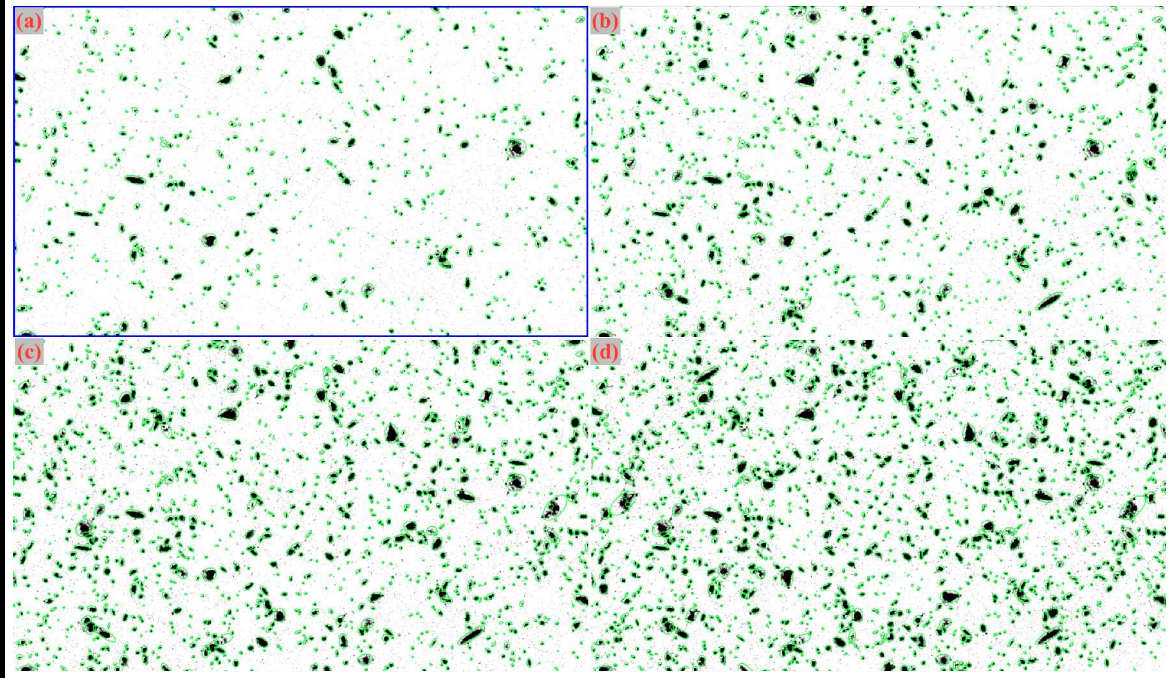


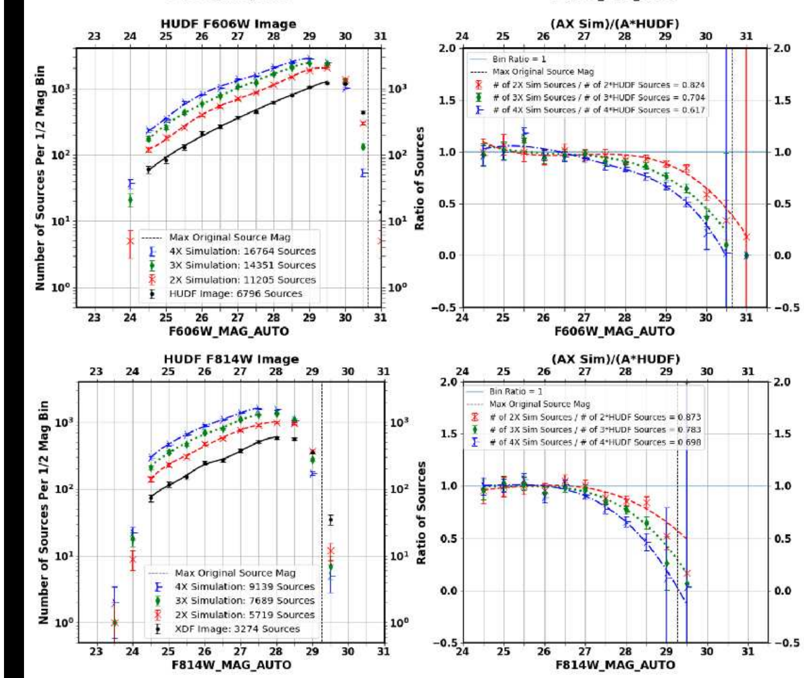
HST shows 29-40 $nW/m^2/sr$ of diffuse light at 1.25-1.6 μm compared to Kelsall's Zodiacal model.

- HST sees no significant signal compared to the Wright model.

- HST diffuse light at 1 AU larger than New Horizon's 8–10 $nW/m^2/sr$ at 43–51 AU (Lauer+ 20, 21).

Next step: Refine Zodiacal models to explain (most or all) of the diffuse light. May need to include higher-albedo Oort Cloud Comet dust at D$\gtrsim$3-10 AU.





(Darby Kramer): Can we really hide a factor ∼4 of faint galaxies?

[Left]: Add HUDF image to itself 2×, 3×, 4× after n×90° rotation.
[Right]: HUDF counts become ∼50% incomplete for AB≳28.5–29 mag.

- Crowding not enough to explain factor 3–5 missing flux at AB≳24 mag.

⟹ Cannot explain diffuse light through missing ordinary galaxies!

- Missing diffuse light caused by very dim (low-SB) galaxies?

(6) Summary and Conclusions

(1) HST built to measure faint objects & sky over decades at 0.2-1.6 μm.

(2) More than 95% of photons in HST Archive come from D$\lesssim$3–5 AU.

Traditional HST imaging techniques ignored sky-foreground for 27 years.

(3) SKYSURF can measure sky-SB to $\lesssim$3–4% & identify orbital straylight.

(4) Compared to Kelsall et al.'s (1998) Zodiacal model, SKYSURF finds $\lesssim$29–40 nW/m^2/sr of diffuse light at 1.25–1.6 μm.

- This amounts to the *brightness* of ∼10 Jupiters over 4π steradian!

- Compared to Wright's (1998) Zodiacal model, HST finds no significant diffuse light at 1.25–1.6 μm.

(5) Zodiacal models need updates to explain (most?) of the diffuse light.

- Need to include higher-albedo Oort Cloud Comet dust at D$\gtrsim$3-10 AU?

(6) Soon in a theater near you: the Webb-Surf sequel to SKYSURF.

SPARE CHARTS

Table 5. Error Estimates[a] in Calibration, Zeropoints, Sky-SB Measurements, and Thermal Dark Signals

Source of Error	WFPC2	ACS/WFC	WFC3/UVIS	— WFC3/IR —			(§§)
				F125W	F140W	F160W	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Bias/Darkframe subtraction	∼1.0%	∼1.5%	∼1.5%	∼1.0%	∼1.0%	∼1.0%	4.1
Dark glow subtraction	∼2%	—	—	—	—	—	4.1.1
Postflash subtraction	—	∼1%	∼1%	—	—	—	4.1
Global flat-field quality[b]	∼1–3%	0.6–2.2%	∼2–3%	∼0.5–2%	∼0.5–2%	∼0.5–2%	4.1
Numerical accuracy of LES[c]	$\lesssim$0.1–0.4%	$\lesssim$0.1–0.4%	$\lesssim$0.1–0.4%	$\lesssim$0.1–0.4%	$\lesssim$0.1–0.4%	$\lesssim$0.1–0.4%	4.2.3
Photometric zeropoints[d]	∼2%	0.5–1%	0.5–1%	∼1.5%	∼1.5%	∼1.5%	4.1.5
Thermal Dark signal[e]	—	—	—	∼1%	∼1%	∼3%	4.1.4, 5.2
Total Error[f]	∼4.3%	∼3.0%	∼3.7%	∼2.9%	∼2.9%	∼4.1%	

[a] *All relative errors* in this table are expressed as a percentage of the typical Zodiacal sky-SB in the F125W, F140W, and F160W filters, which are ∼331, ∼282, ∼240 nW m^{-2} sr^{-1}, respectively (*e.g.*, Fig. 1).

[b] For WFPC2, the large-scale flat-field errors in the filters F439W and redwards are $\lesssim$1%, but the upper bound includes the 1% error in the contamination correction and the ∼3% error in the residual CTE correction. For the less frequently used WFPC2 UV filters, these errors can be larger.

[c] Numerical accuracy of Lowest Estimated Sky values away from detected objects (§ 4.2). The LES algorithms also avoid areas of significant persistence or cross-talk when estimating the sky-SB, so these effects are not included as an extra term in the error budget.

[d] For WFC3/IR, this includes the ∼0.5% uncertainty in the applied detector count-rate non-linearity correction (§ 4.1.4).

[e] The errors in the estimated Thermal Dark signal values are given for the F125W and F140W filters as a percentage of the typical Zodiacal sky-SB, and are larger for the F160W filter (§ 5.2).

Absolute HST sky-SB photometry errors $\lesssim$3–4% (as fraction of Zodi).

Windhorst et al. 2022, Carleton et al. 2022 (AJ).

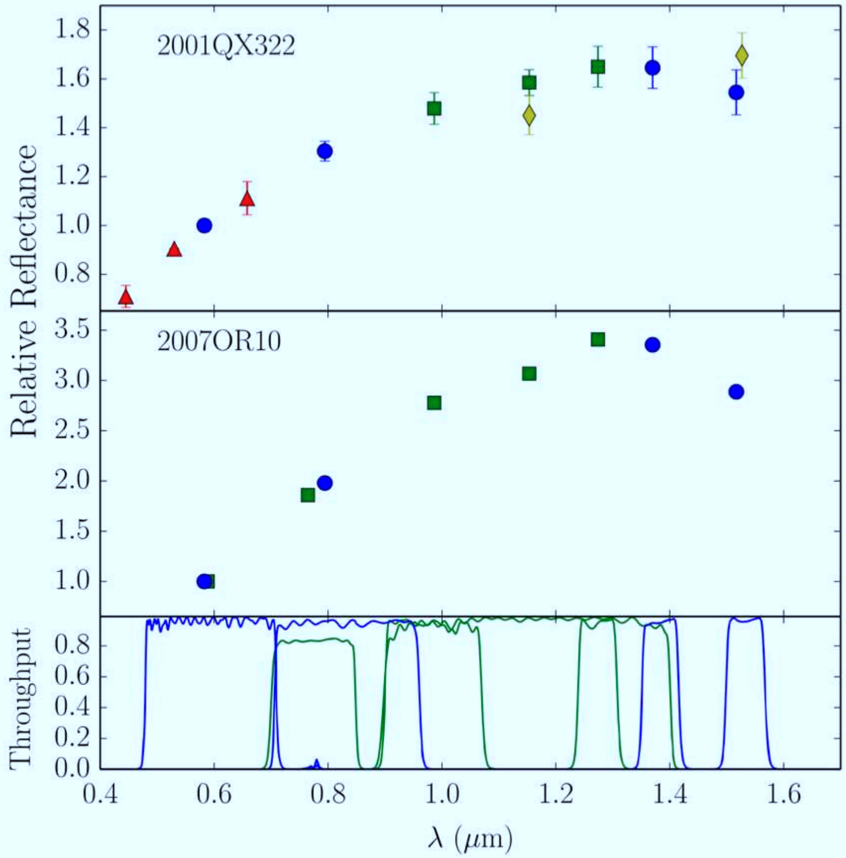


Figure 8. As in Figure 6. The yellow diamonds mark the spectra obtained for 2001 QX322 from the data presented by Benecchi et al. (2011). The F098m, F110w, and F127m photometry of 2001 QX322 have been vertically scaled for visible representation to match the F139m photometry and the photometry of Benecchi.

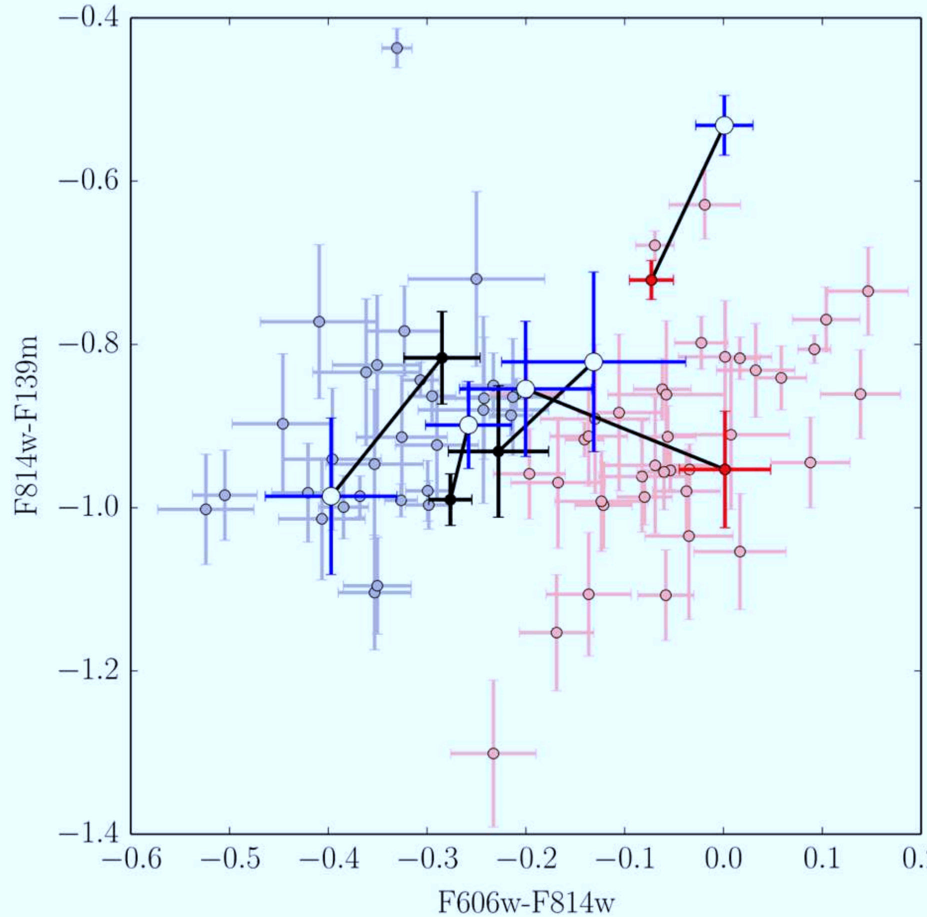
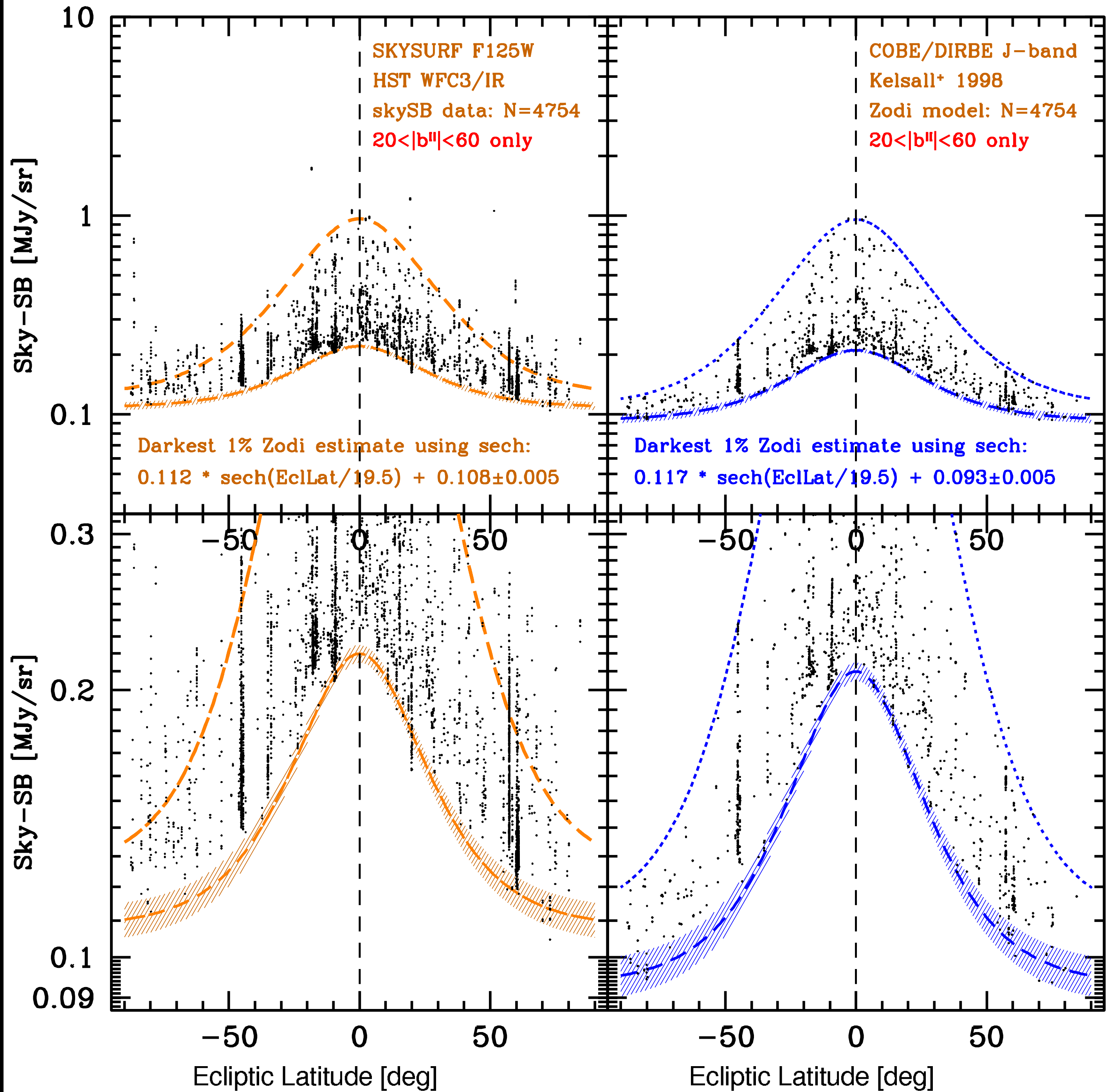


Figure 10. Observed and model optical and infrared colors of the five spectrally variable objects. The model cycle 18 colors are shown in blue points, while the observed cycle 17 colors are shown as solid red or black points according to their cycle 17 classification. Black lines connect the observed and model colors for each source. Gray and light red points show the full cycle 17 colors for comparison.

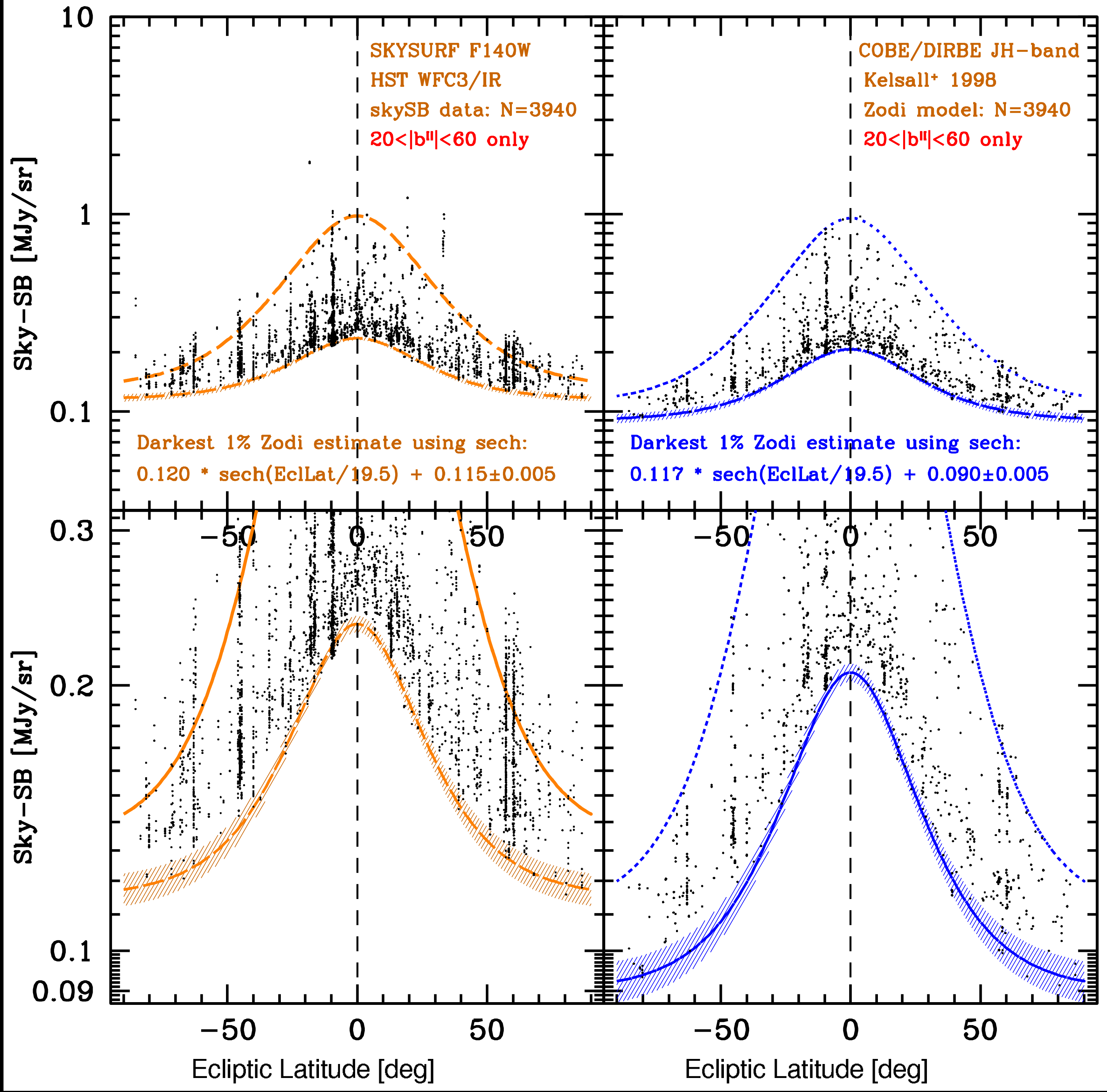
HST work on KBOs at 10–1000 AU show some remarkably blue IR colors.

Does OCC cometary dust in the inner solar system have similar albedos?



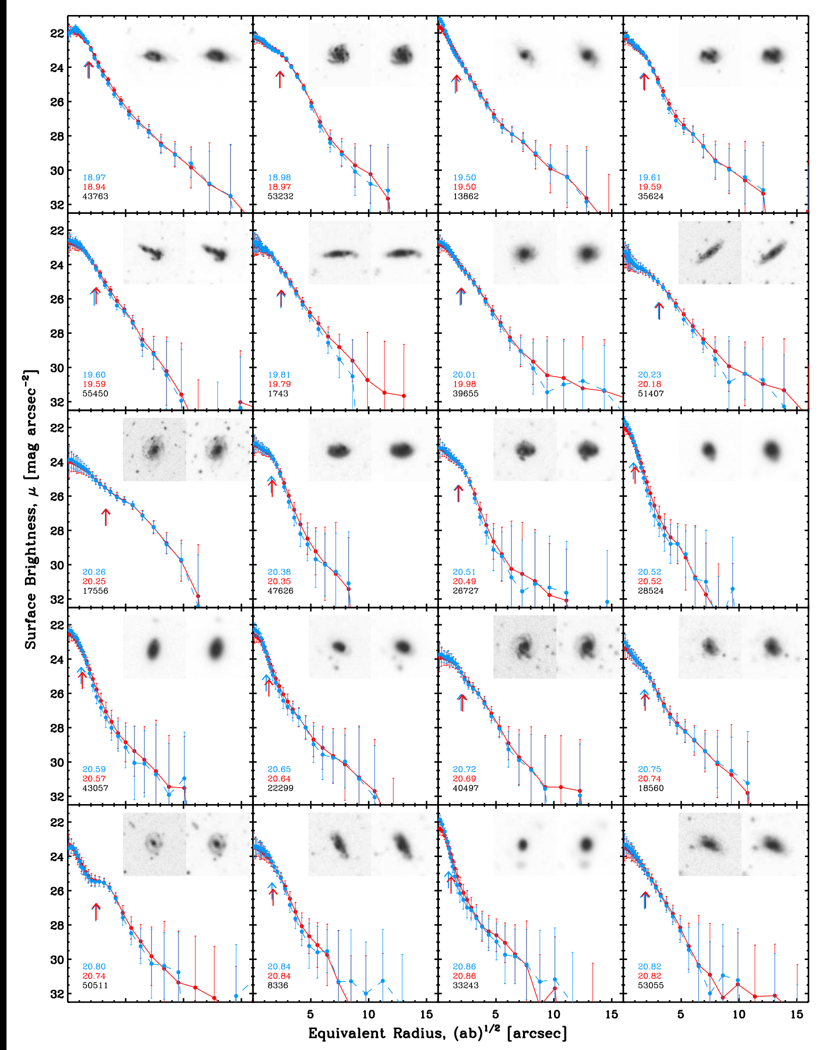
1.25 μm HST+Kelsall vs. b^{Ecl}: $sech$+error = lowest 1% of sky-SB.

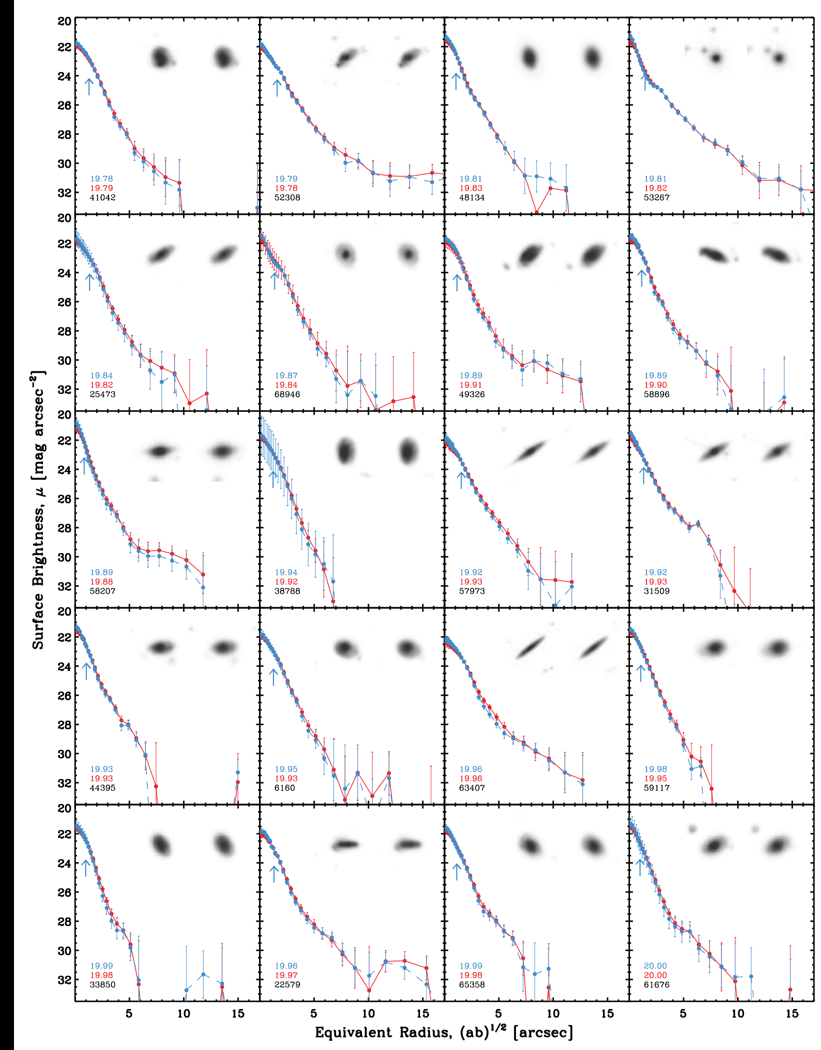
Lowest 1% Δ(HST–Kelsall)$\simeq$0.015$\pm$0.008 MJy/sr at darkest Galactic.



1.40 μm HST+Kelsall vs. b^{Ecl}: $sech$+error = lowest 1% of sky-SB.

Lowest 1% Δ(HST–Kelsall)$\simeq$0.025$\pm$0.009 MJy/sr at darkest Galactic.

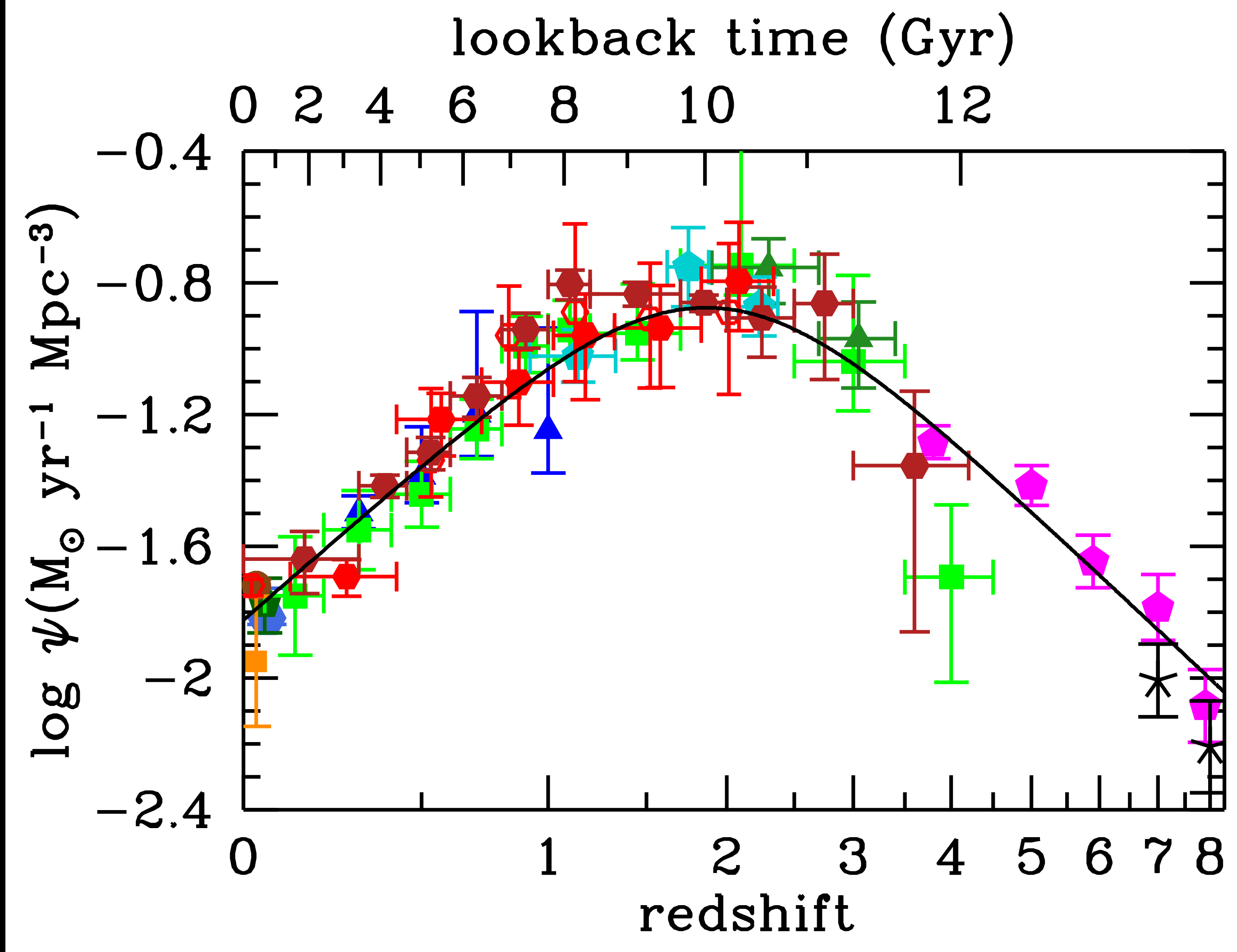




[Left]: LBT U-band, [Right] r-band: 20 of ∼300 galaxies with $17 \lesssim AB \lesssim 22$ ($i.e.$, comprising *middle 50%* of EBL; Ashcraft+ 2018, 2022).

- 27-hr LBT stack to $\lesssim$32 mag/arcsec^2 shows on average $\lesssim$10-20% extra flux in galaxy outskirts compared to 6-hr best-seeing LBT stack.

$\Longrightarrow$ Factor of 3–5 diffuse light not likely hiding in dim galaxy outskirts!



Cosmic star-formation rate (SFR) in last 13.2 Gyr (Madau & Dickinson, 2014):

- SFR peaks at redshift z≃1.9 (cosmic age≃3.8 Gyr).

A factor 3–5 excess diffuse EBL is problematic if caused by stars:

- That should have produced 3–5× as many metals and planets today ...

(beautiful)
The ^ James Webb Space Telescope

Stowed for Launch

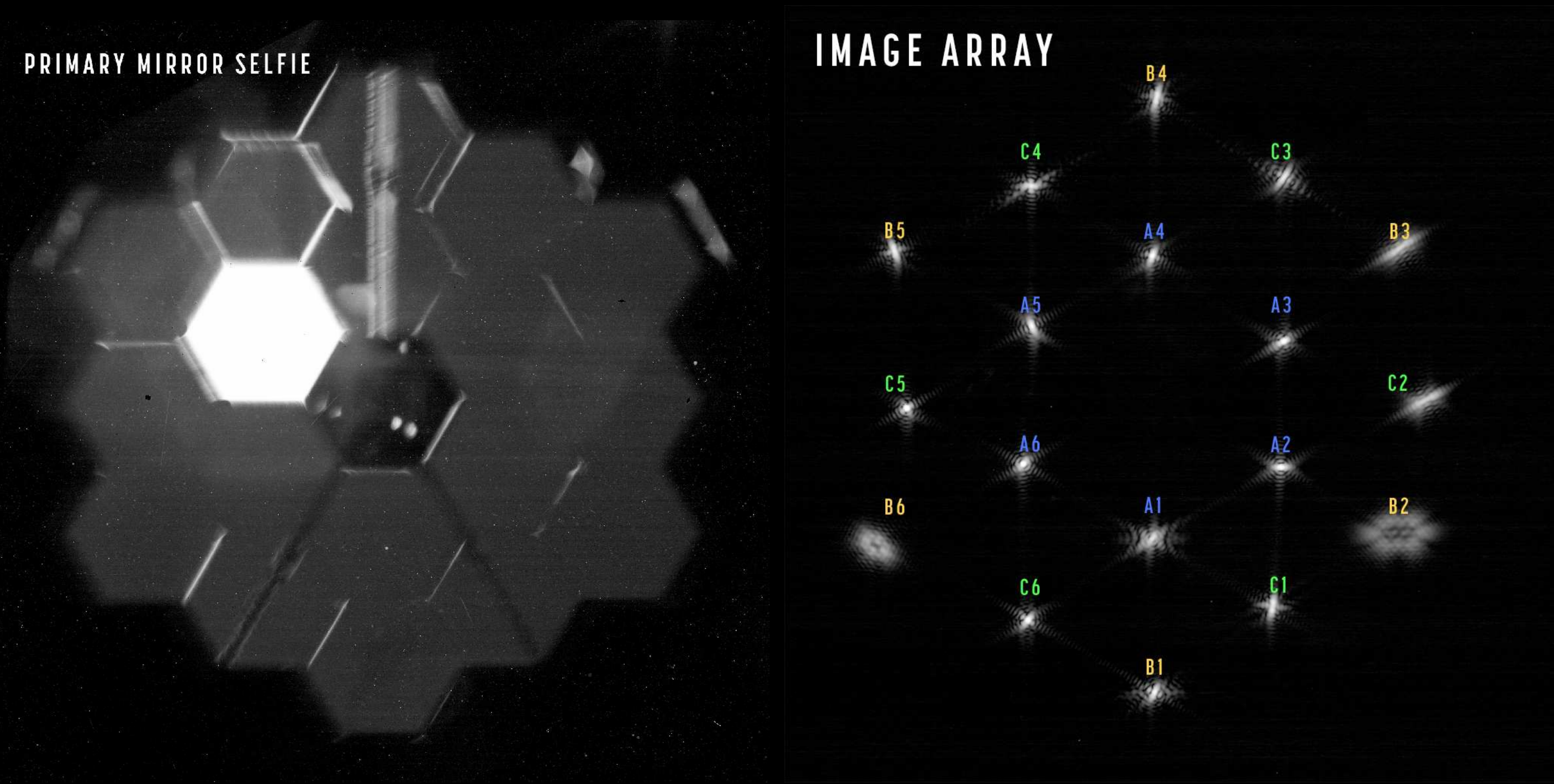
210913 JWST Monthly Telecon 18

Sept. 2021: JWST ready and stowed for shipping to Kourou

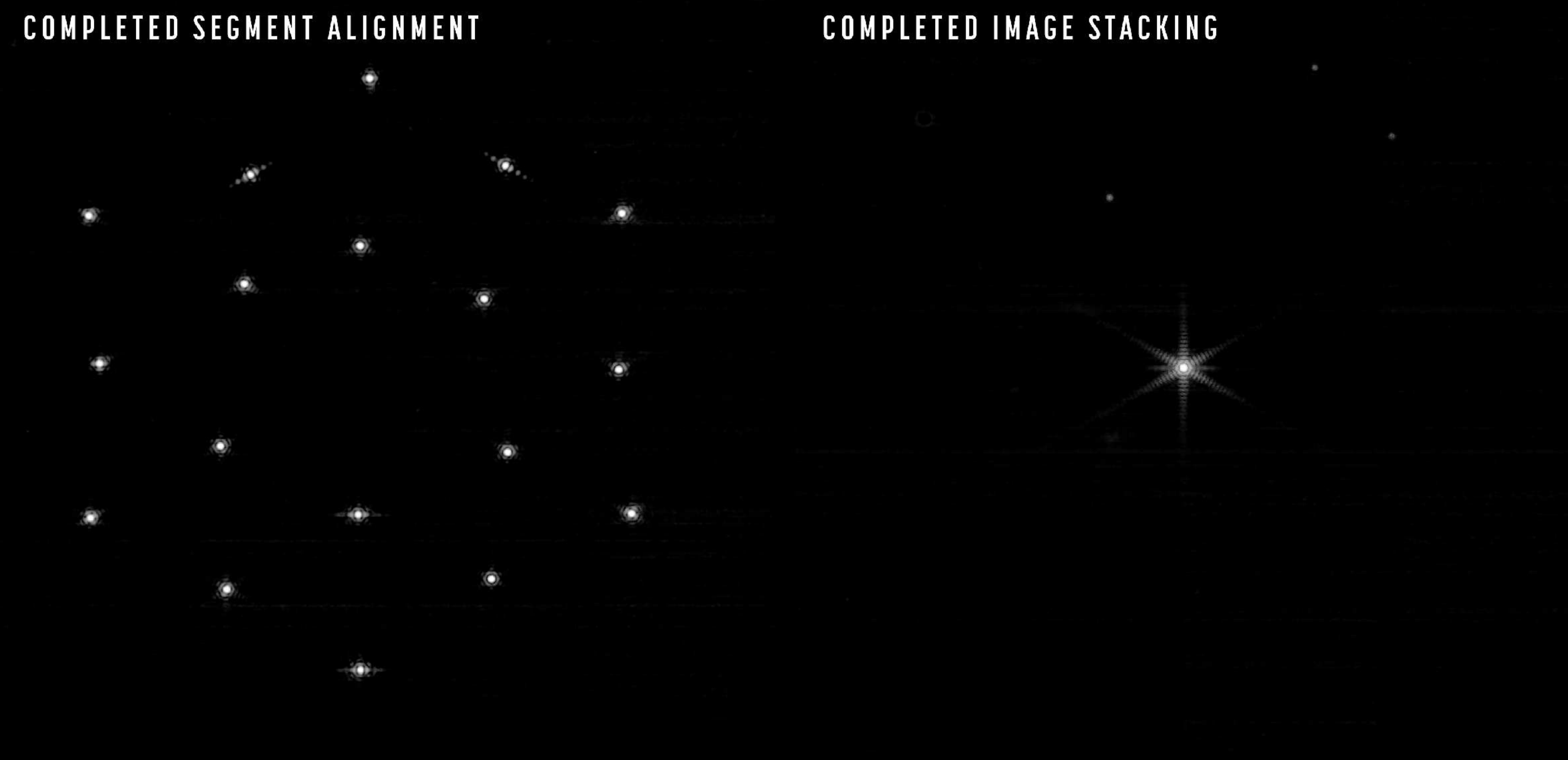
(7) Update of JWST as of 2022

Webb is finally launched from Kourou on December 25, 2021!

Feb. 2022: Webb seen shortly after launch over Africa using the Ariane V camera.



Feb. 2022: Webb's first selfie (left) and First Light raw image (right).



Webb's first segment alignment (left) and first image stack (right).

March 16, 2022: Webb's first fully focused image publicly released !!
Note the plethora of faint galaxies — Webb's looking back in time!

https://www.nasa.gov/press-release/nasa-s-webb-reaches-alignment-milestone-optics-working-successfully

• References and other sources of material shown:

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https://webb.nasa.gov/

https://blogs.nasa.gov/webb/

http://www.asu.edu/clas/hst/www/jwst/

http://ahah.asu.edu/ [Appreciating Hubble at Hyperspeed]

http://ahah.asu.edu/download.html [Download Java–tool]

http://ahah.asu.edu/clickonHUDF/index.html [Clickable map]

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