Extragalactic Background Light: Measurements, Opportunities, And Challenges

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Outline

- Introduction to EBL
- EBL measurement opportunities and challenges
- EBL anisotropies or spatial fluctuation measurements
  - Near-IR with Spitzer, Hubble, CIBER etc
- Brief introduction to intensity mapping of spectral lines
  - Lyman-α has lots of information
  - Plans with SPHEREx, Euclid etc

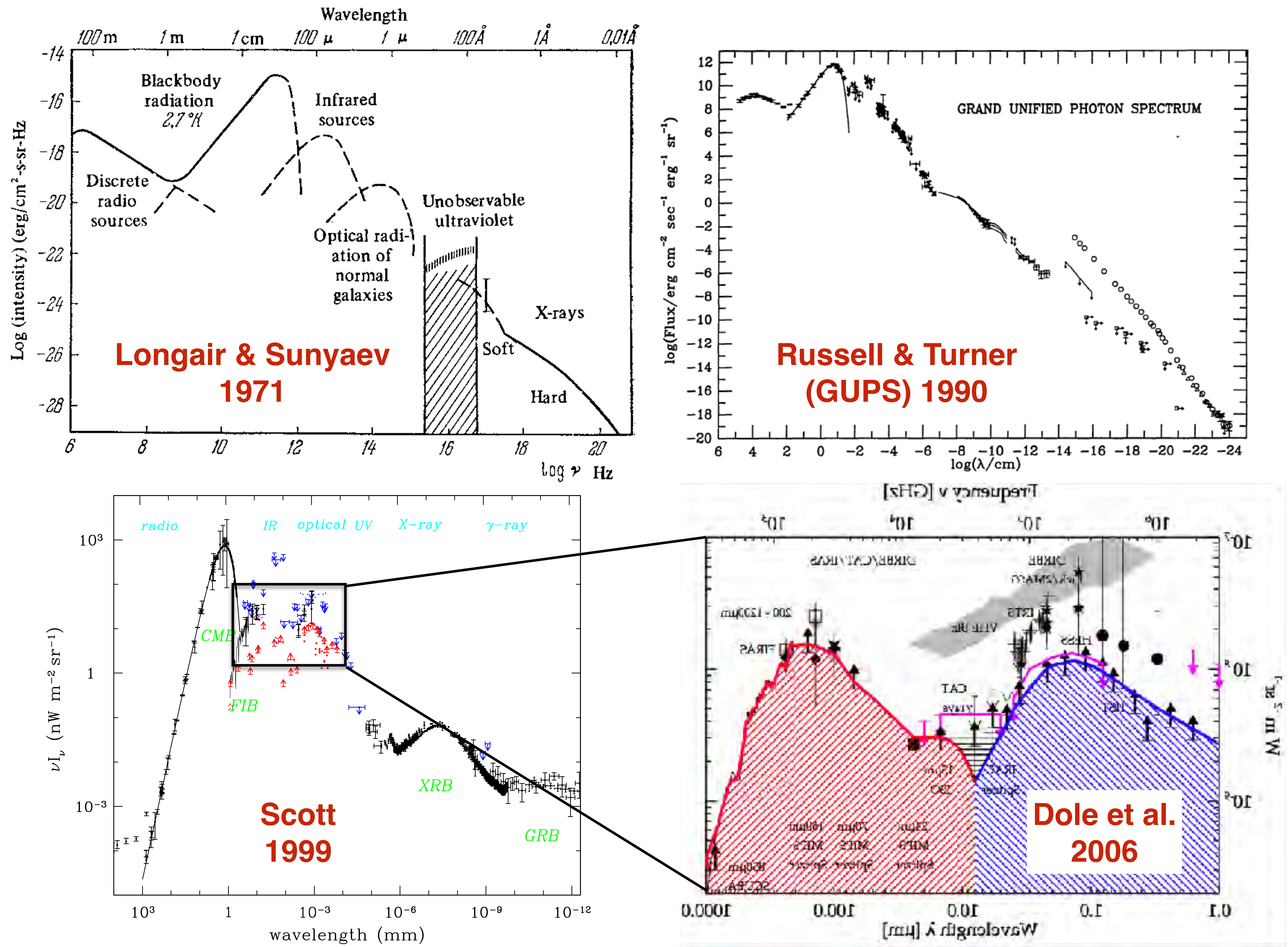
Heinrich Olbers
1758-1840

"Why is the night sky dark?"

21st century version:

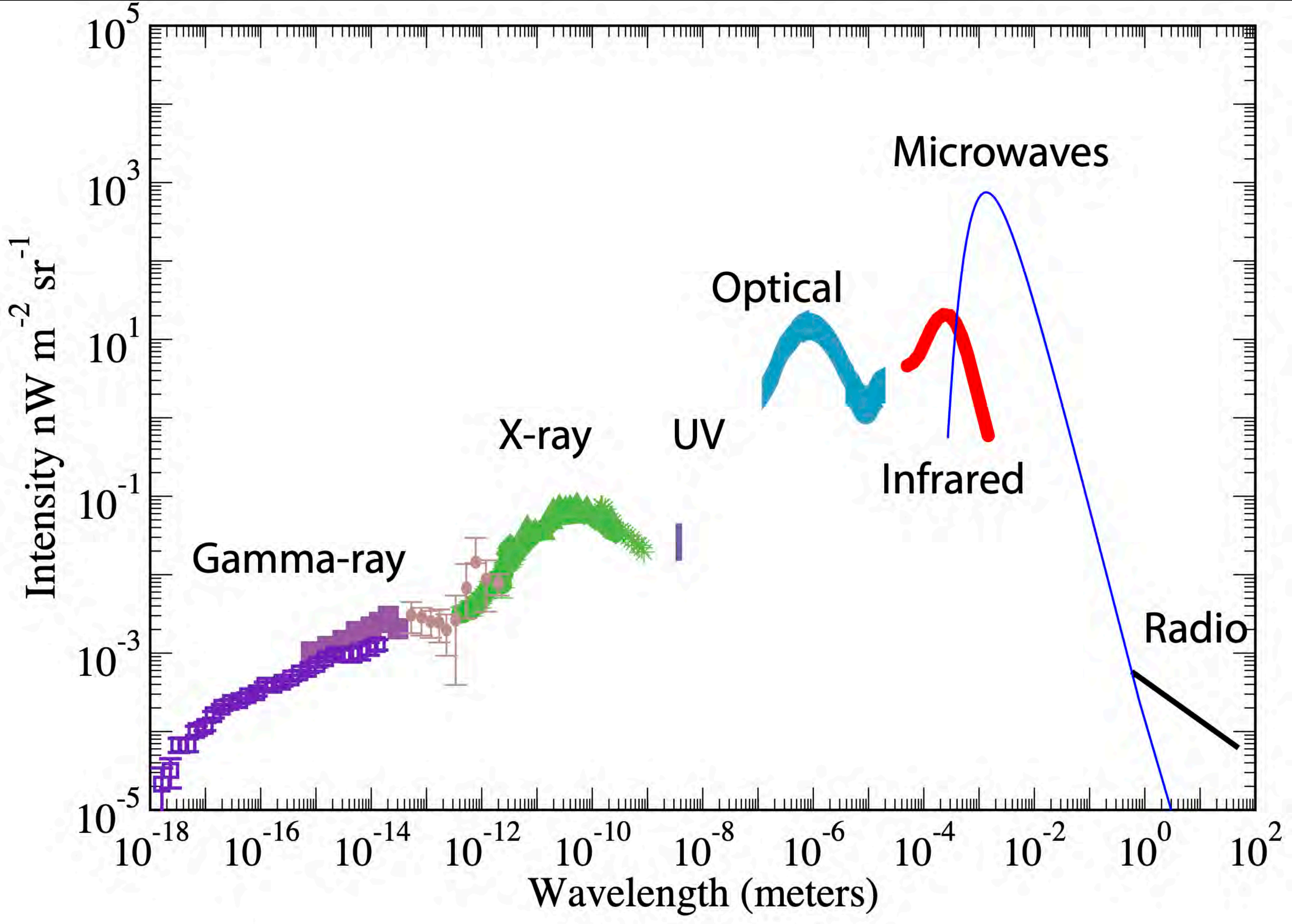
What is the spectrum of the background light in the Universe?

The extragalactic background spectrum

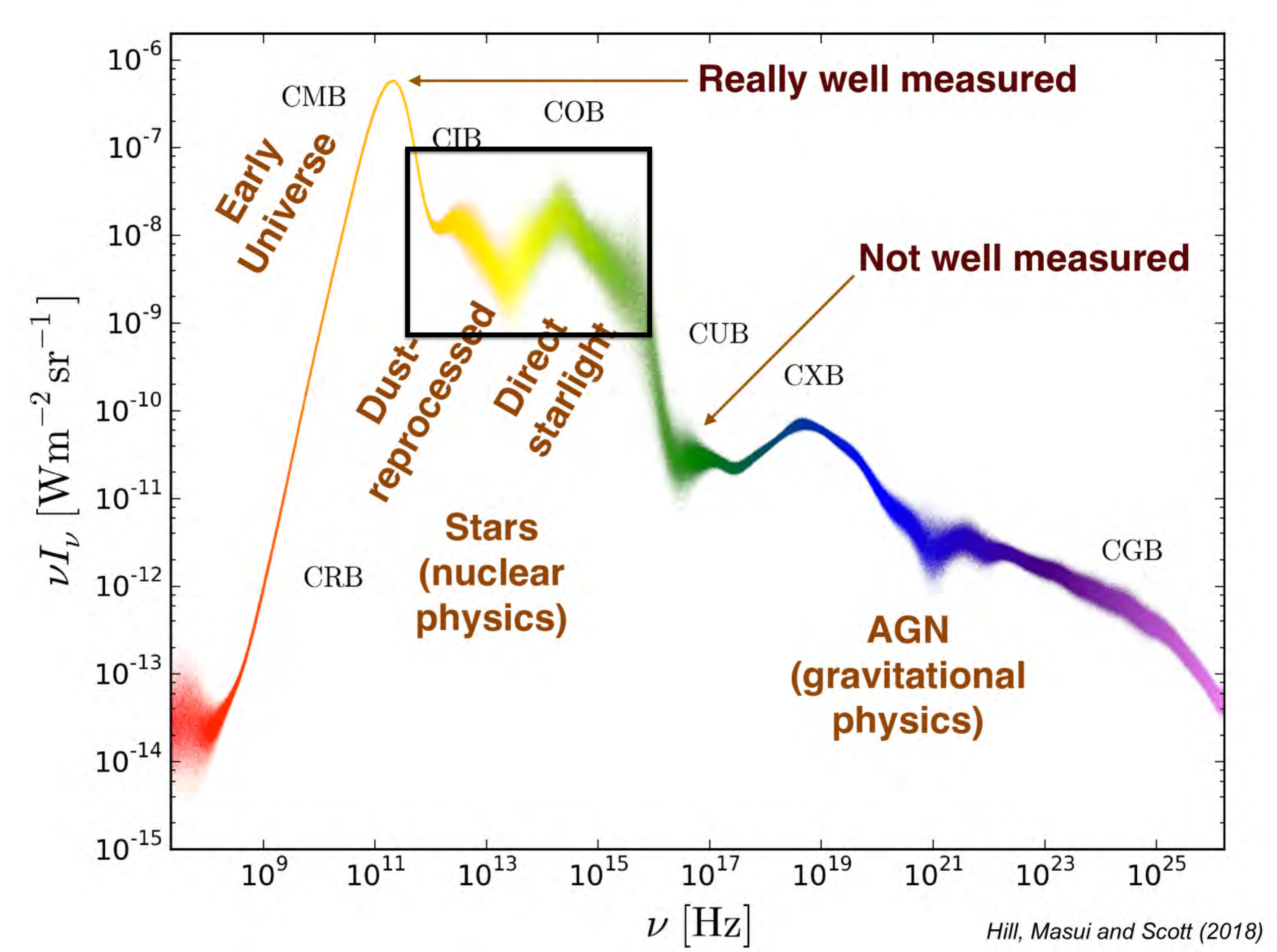


Scott, D. 2018

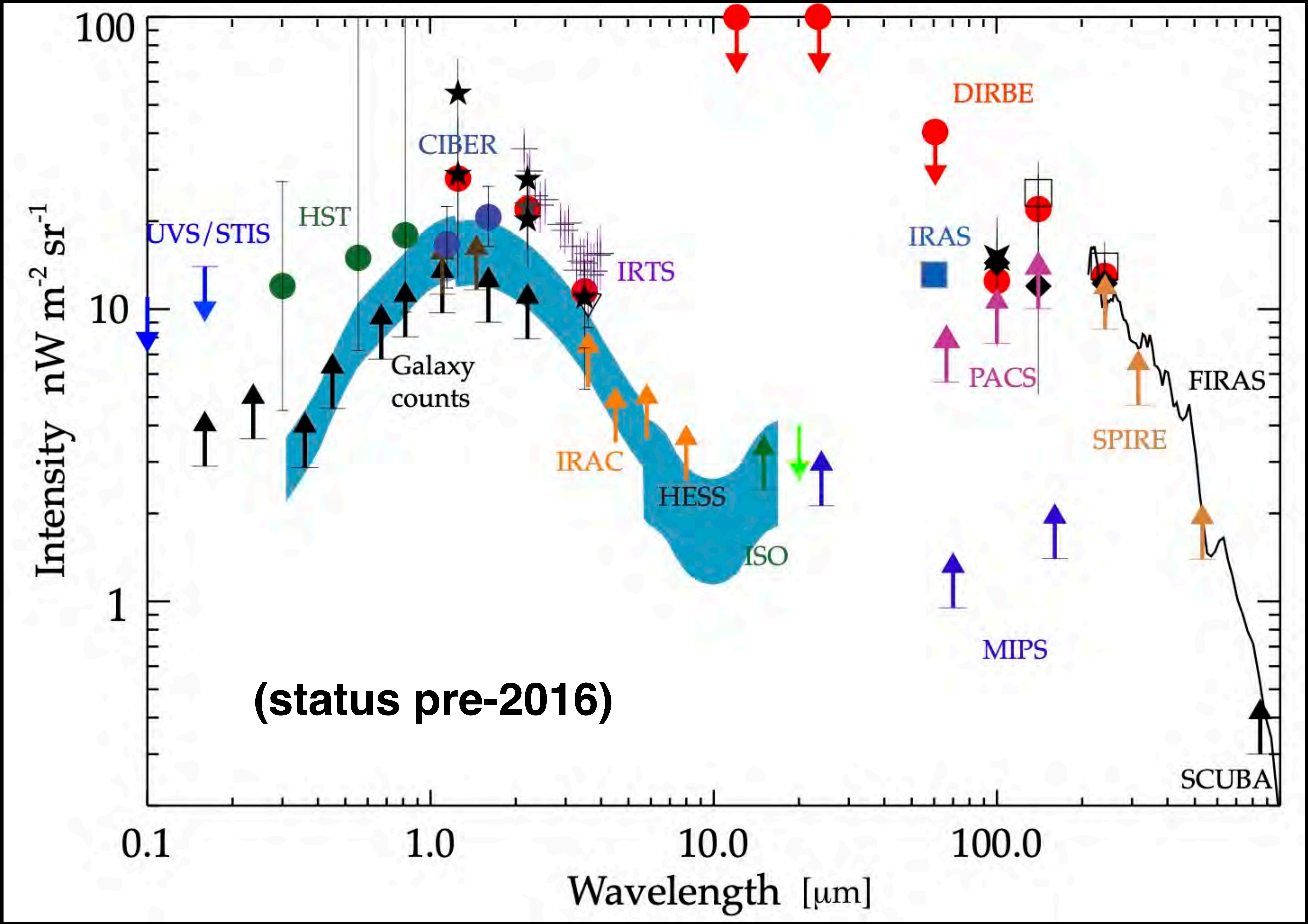
The extragalactic background spectrum



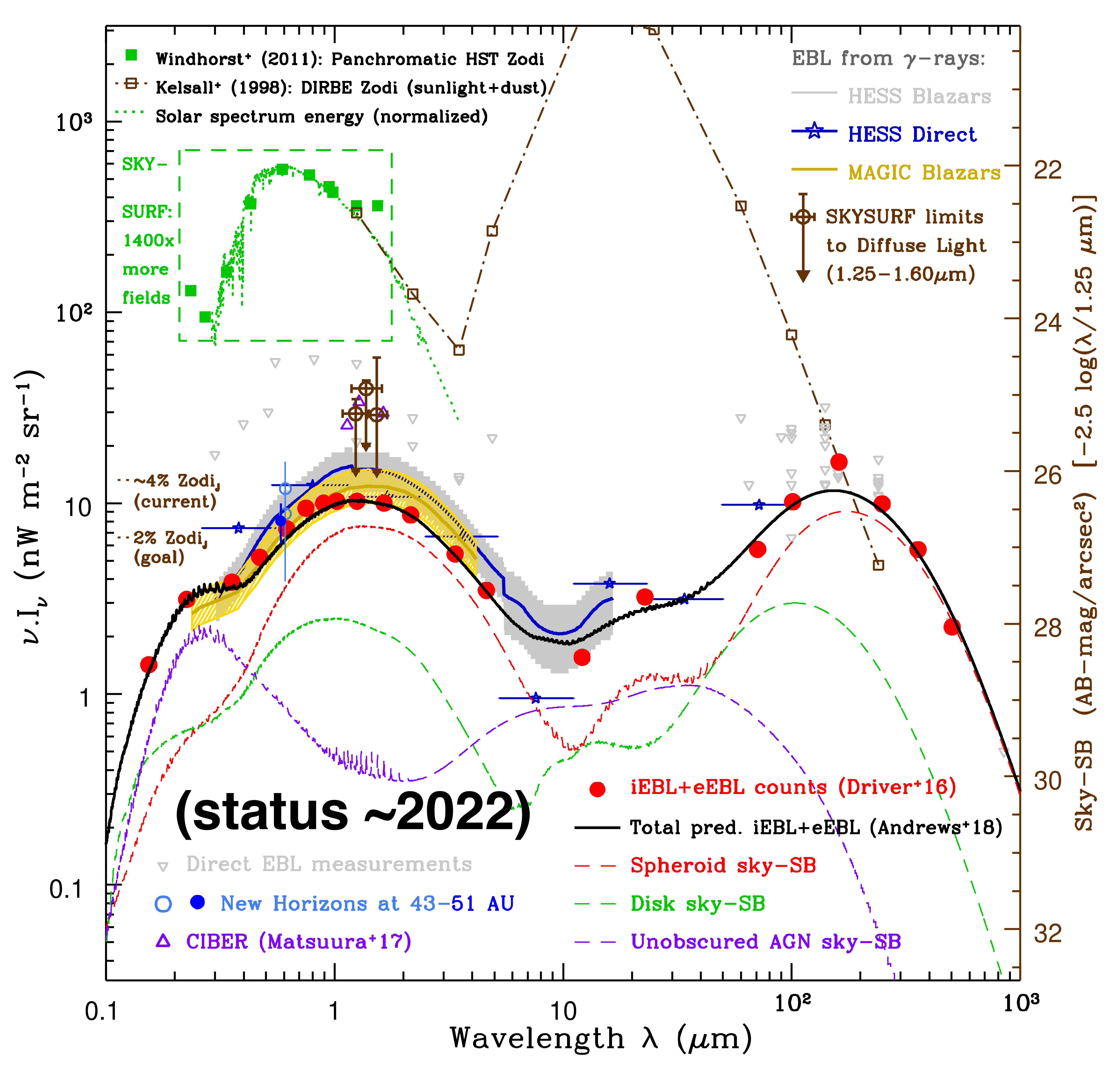
The extragalactic background spectrum



The extragalactic background spectrum



The extragalactic background spectrum

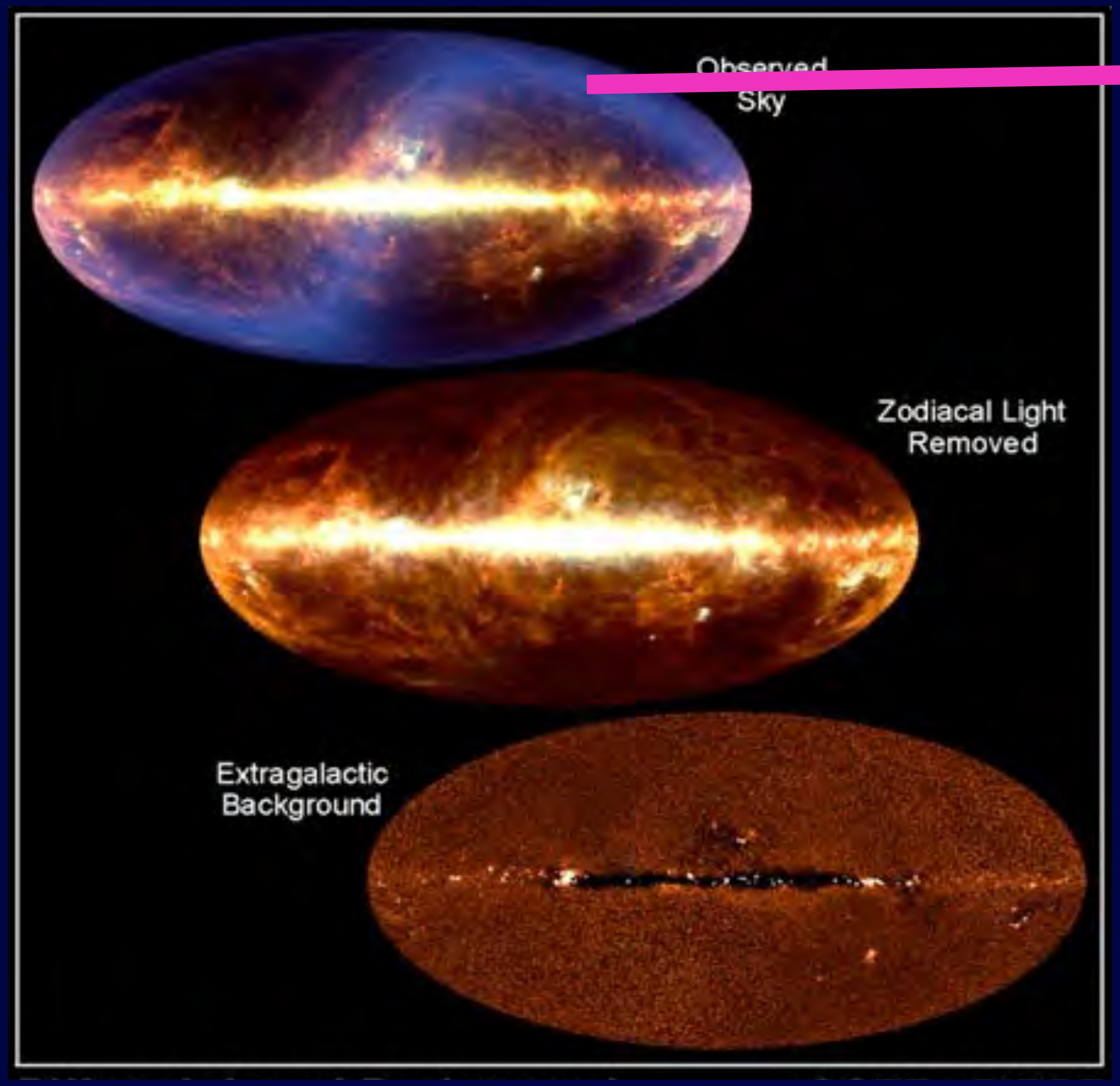


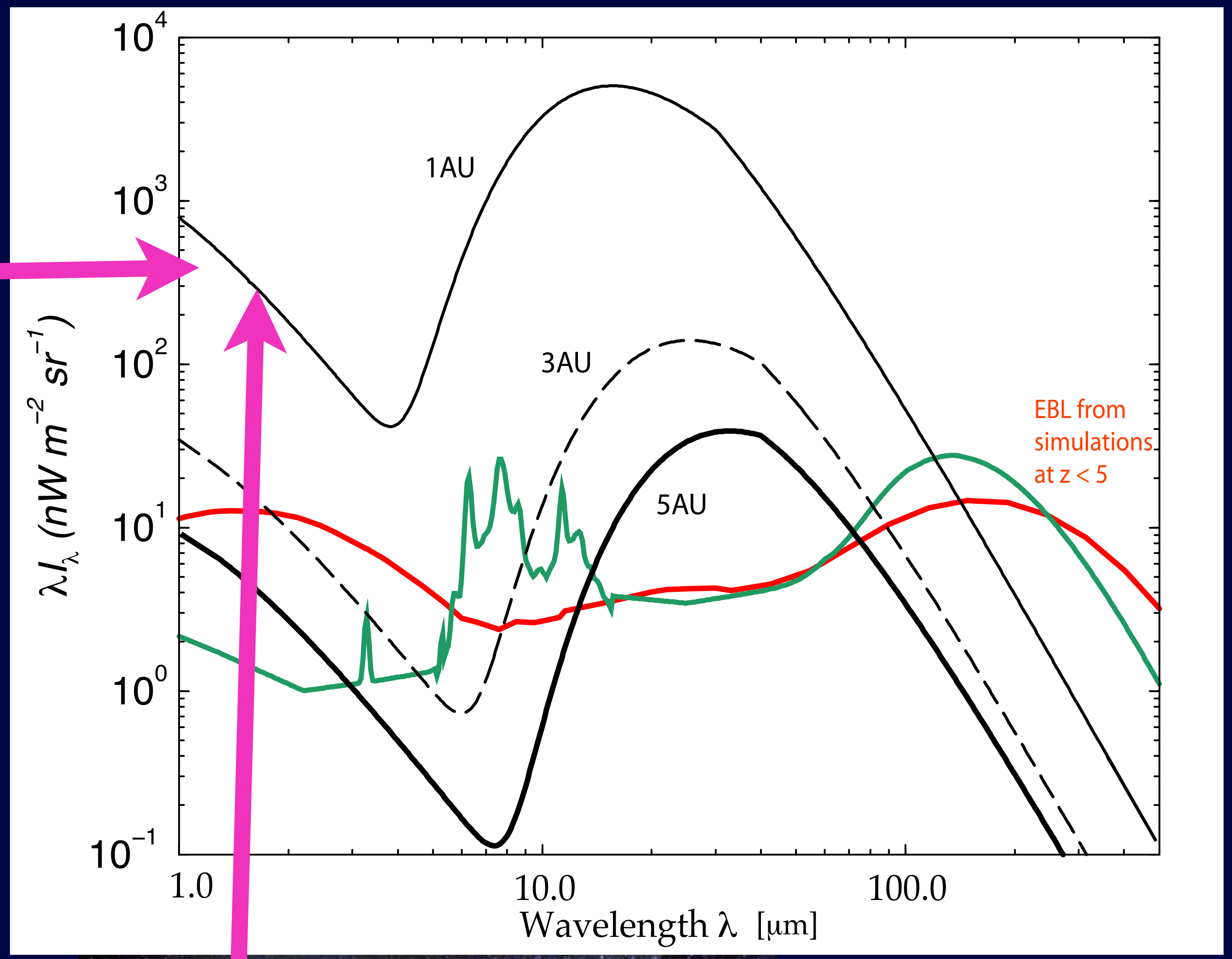
SKYSURF team;
Windhorst et al. 2022

2022+
CosmoGlobe effort
to reanalyze all of DIRBE
to improve Zodi models
and EBL/CIB

San et al. 2022
Watts et al. 2024
San et al. 2024

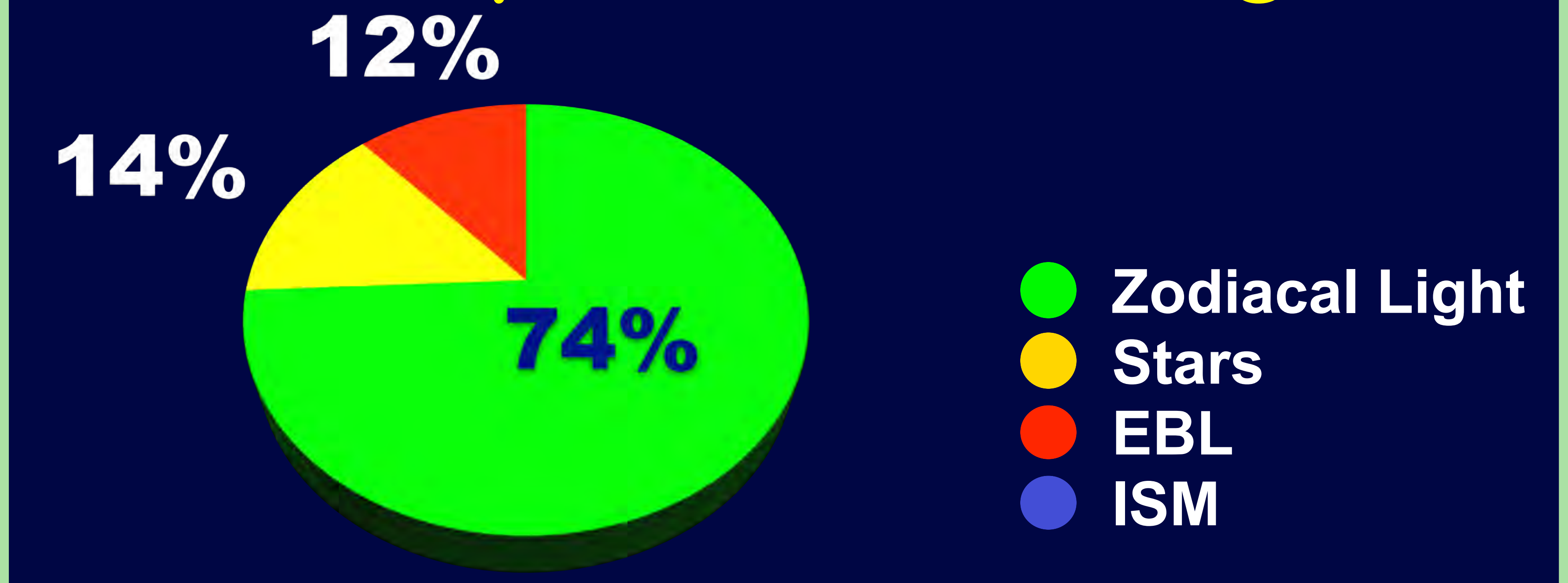
Why is the UV to IR EBL is hard to measure?



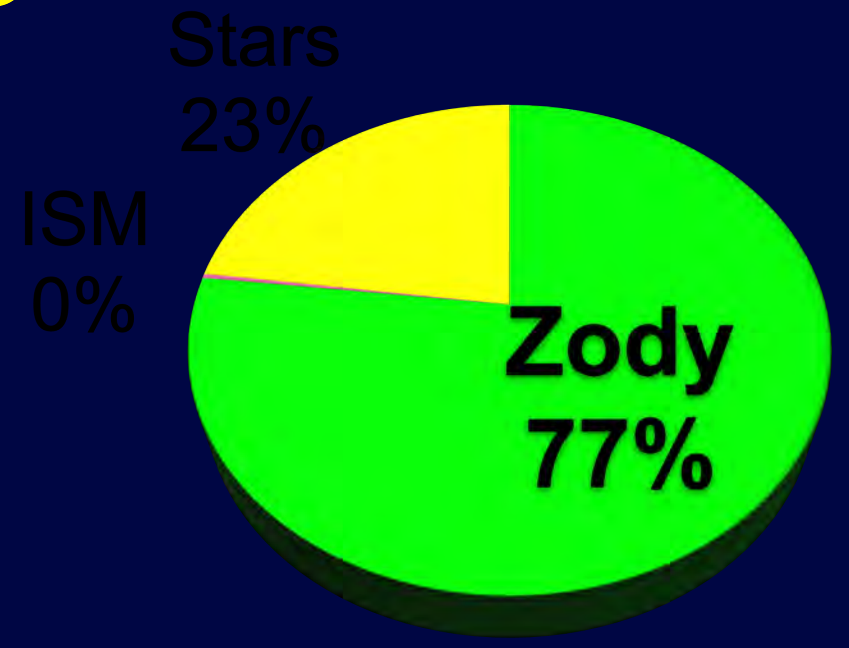


Extragalactic Background Light =
Total sky brightness – Stars – Zodiacal light – ISM

74% of the sky brightness at 2.2μm is zodiacal light

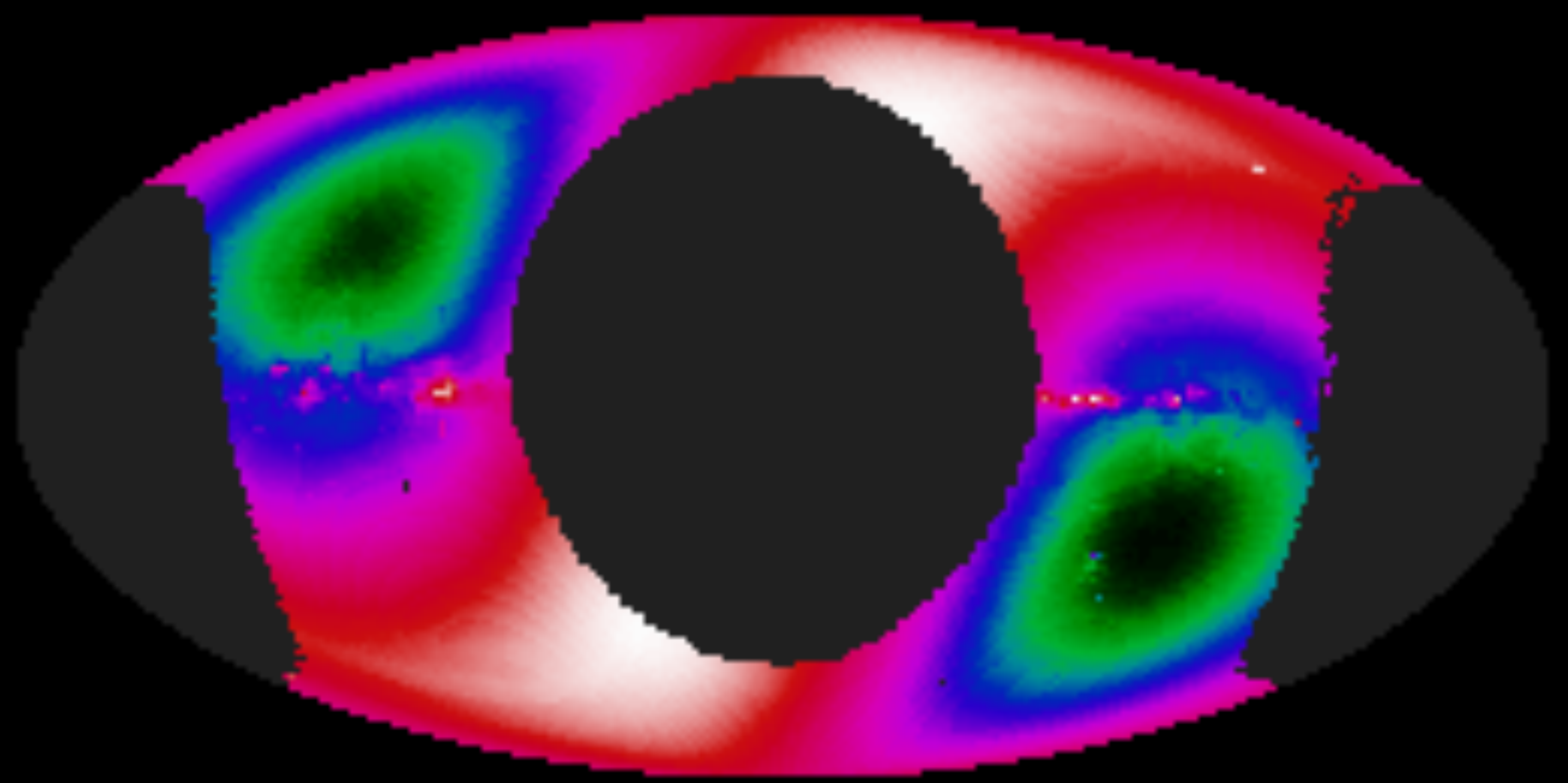


77% of the 2.2 μm EBL error budget is from zodiacal light



What do we know about Zodiacal Light?

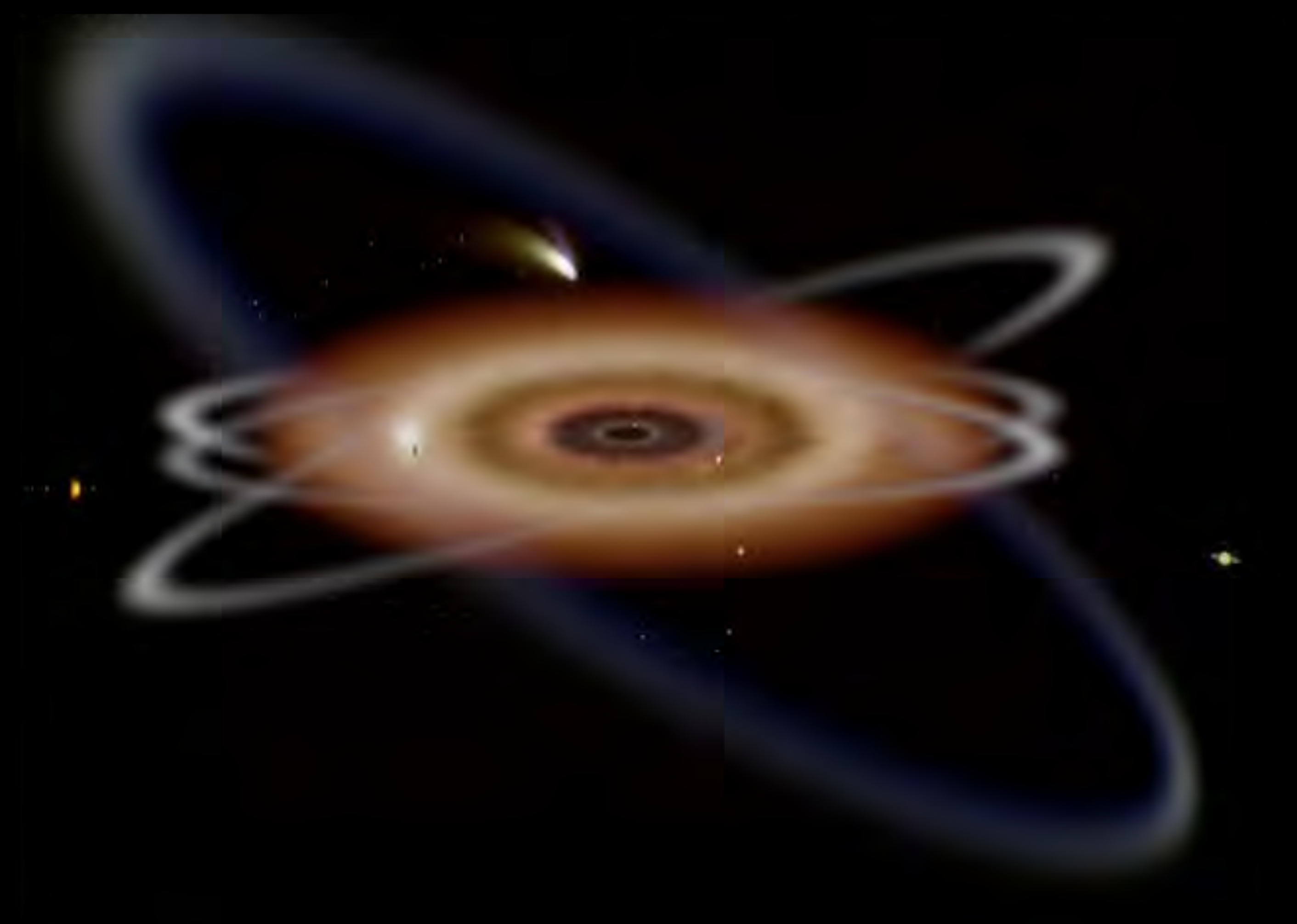
DIRBE Annual Modulation 25um

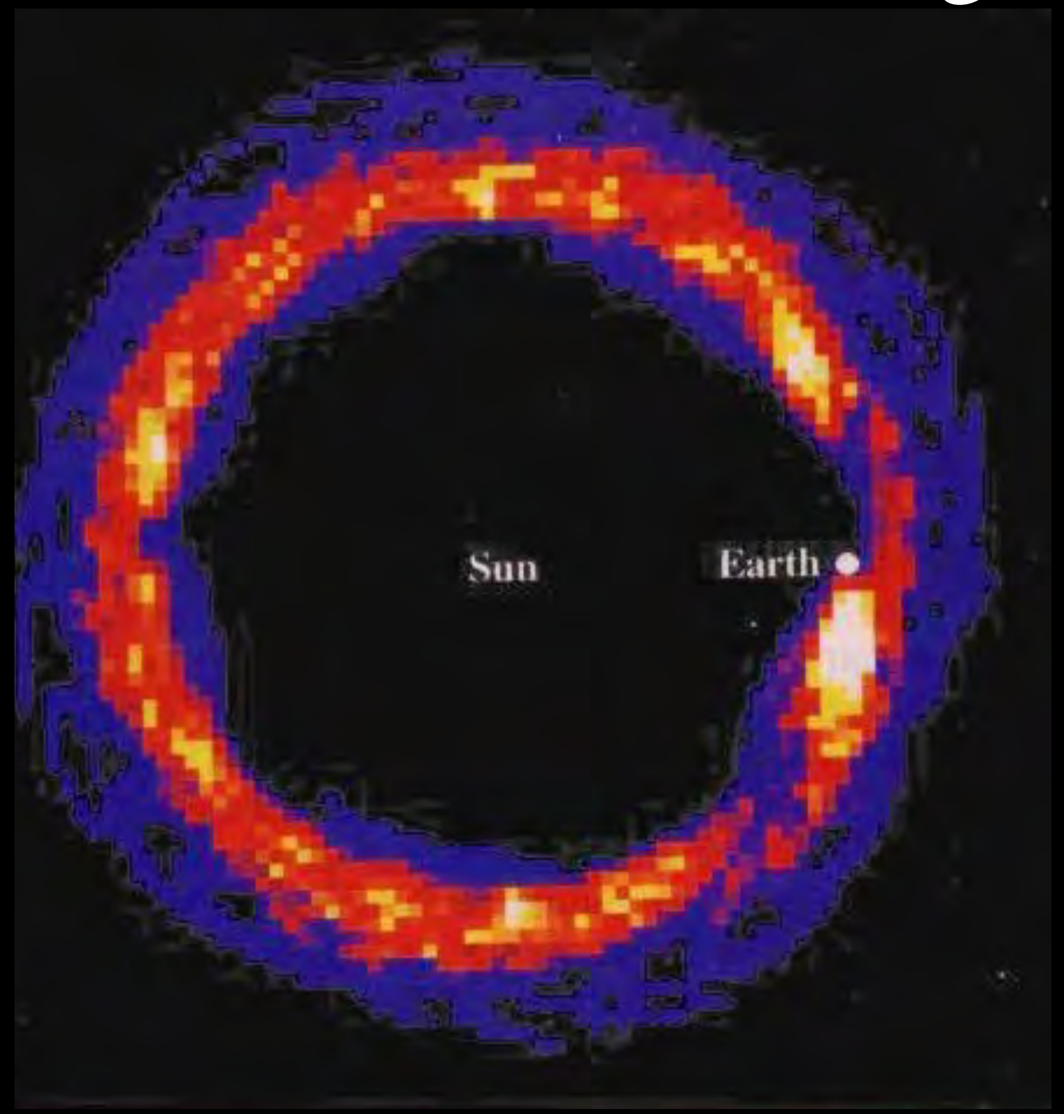


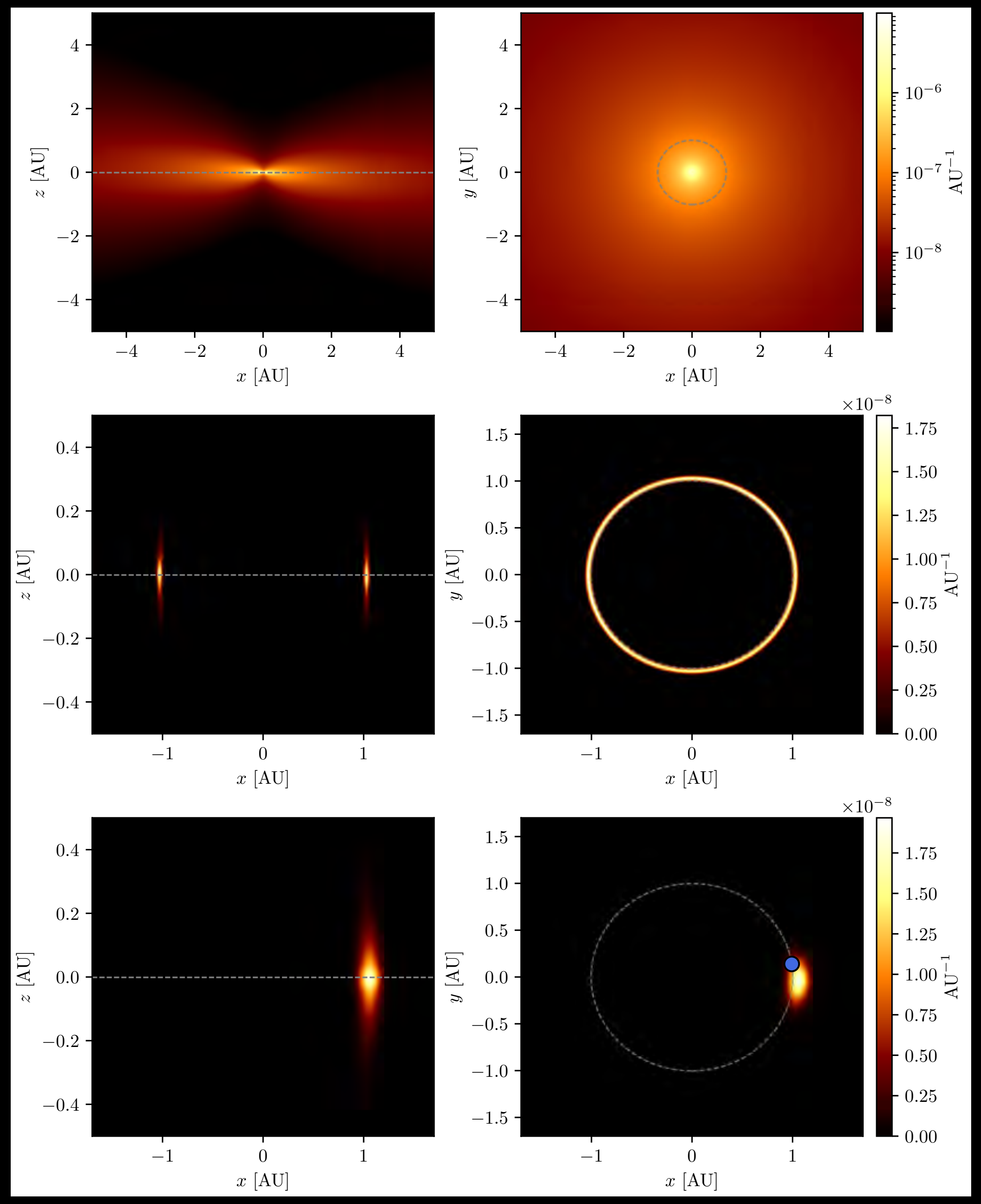
Two models with similar 3D structure (Kelsall et al. 1998; Wright 1998)

- *both position- and time-dependent.*
- *~90 free parameters!*
- *Wright (1998) assumes all of DIRBE 25 micron brightness is Zodi with no extragalactic monopole.*

1. Diffuse cloud
2. 3 dust bands (in COBE/DIRBE) at +/- 1.4, +/- 10 and +/-15 degrees identified with asteroid families. *[IRAS found a total of 5 bands.]*
3. Circumsolar ring in resonance with Earth and a trailing clump.







Diffuse cloud

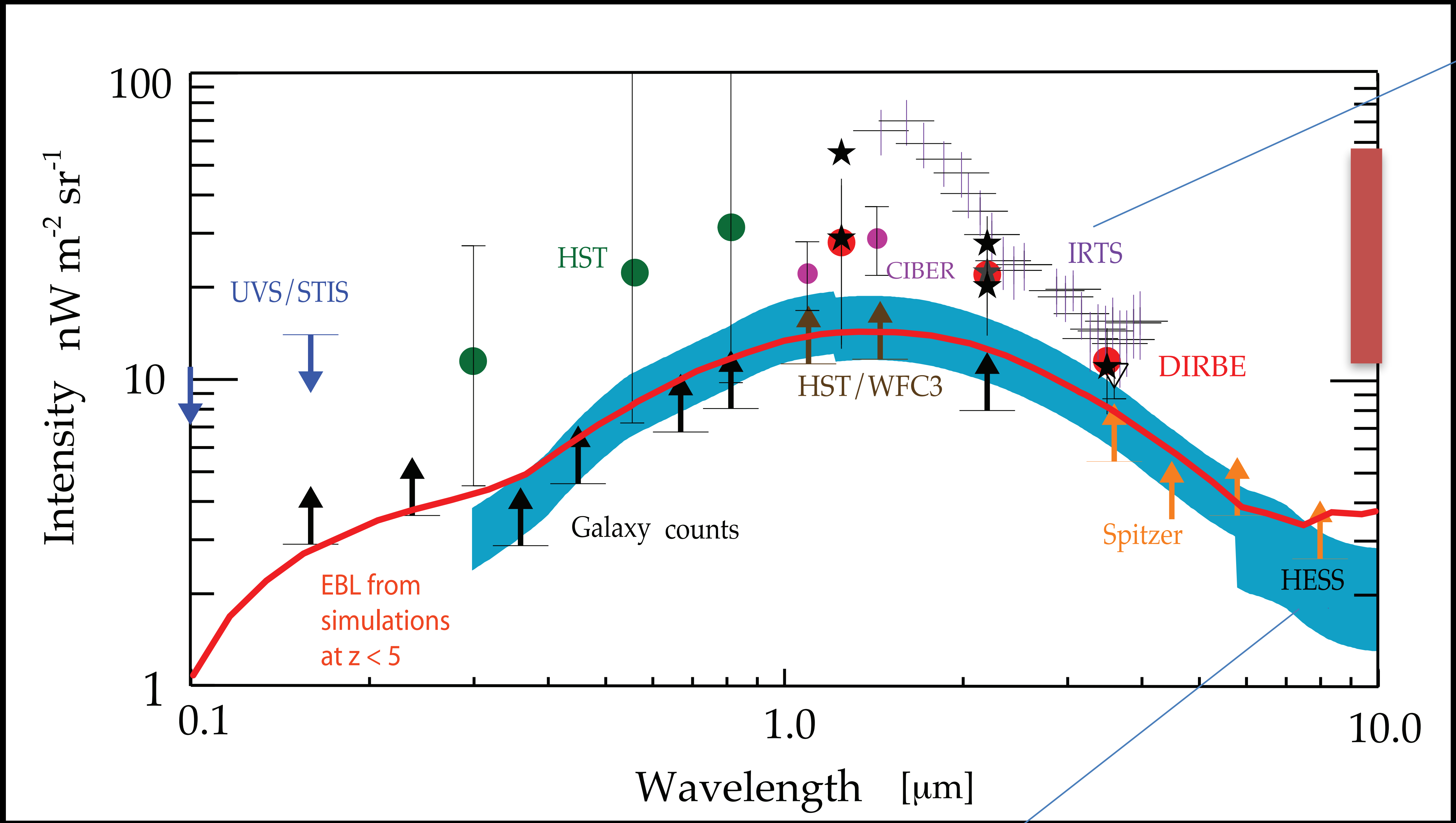
Circumsolar ring

Earth trailing blob.

San et al. 2022

From Measurements to EBL

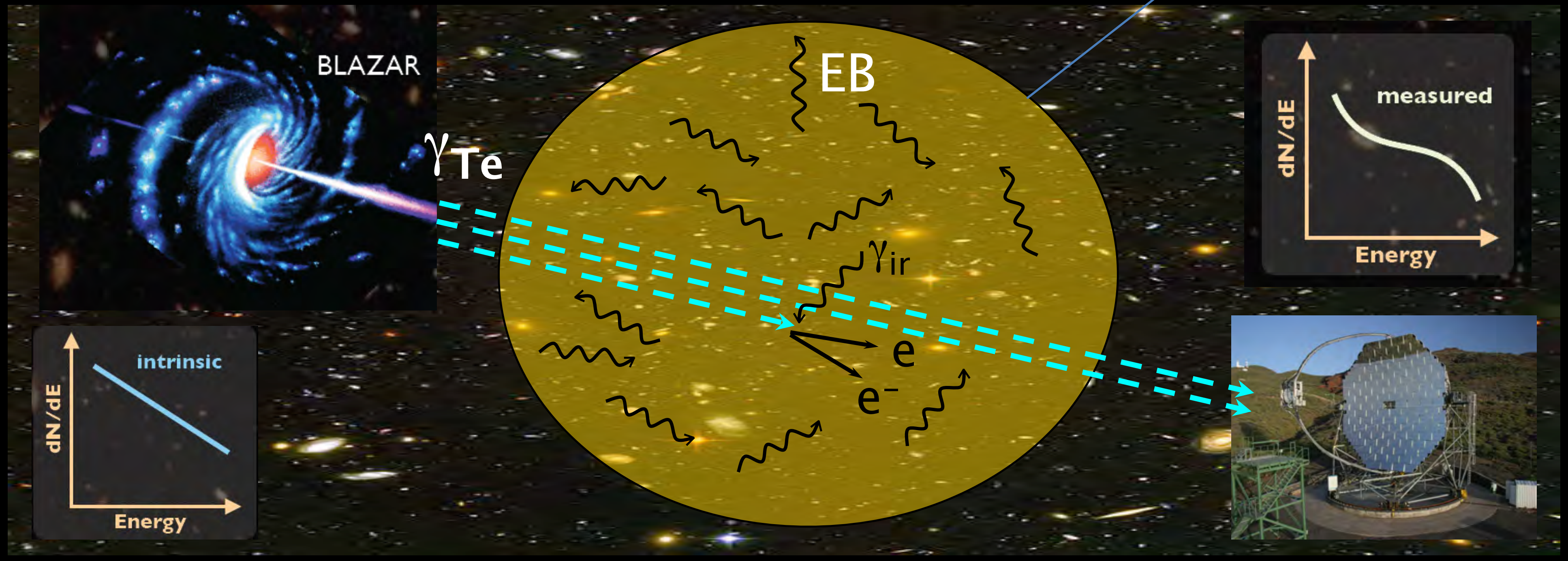
Extragalactic Background Light =
Total sky brightness – Zodiacal light – Stars – ISM



Difference in absolute photometry measurements is predominantly foreground model

Component	3.5 μm (kJy sr^{-1})
Total	105.3 ± 0.3
Zodi	80.4 ± 3.3
ISM	1.1 ± 0.2
Stars, m < 9 mag......	5.3 ± 1.8
Stars, m > 9 mag......	5.7 ± 0.3
CIRB	12.8 ± 3.8

Hard to quantify a systematic error to the ZL model



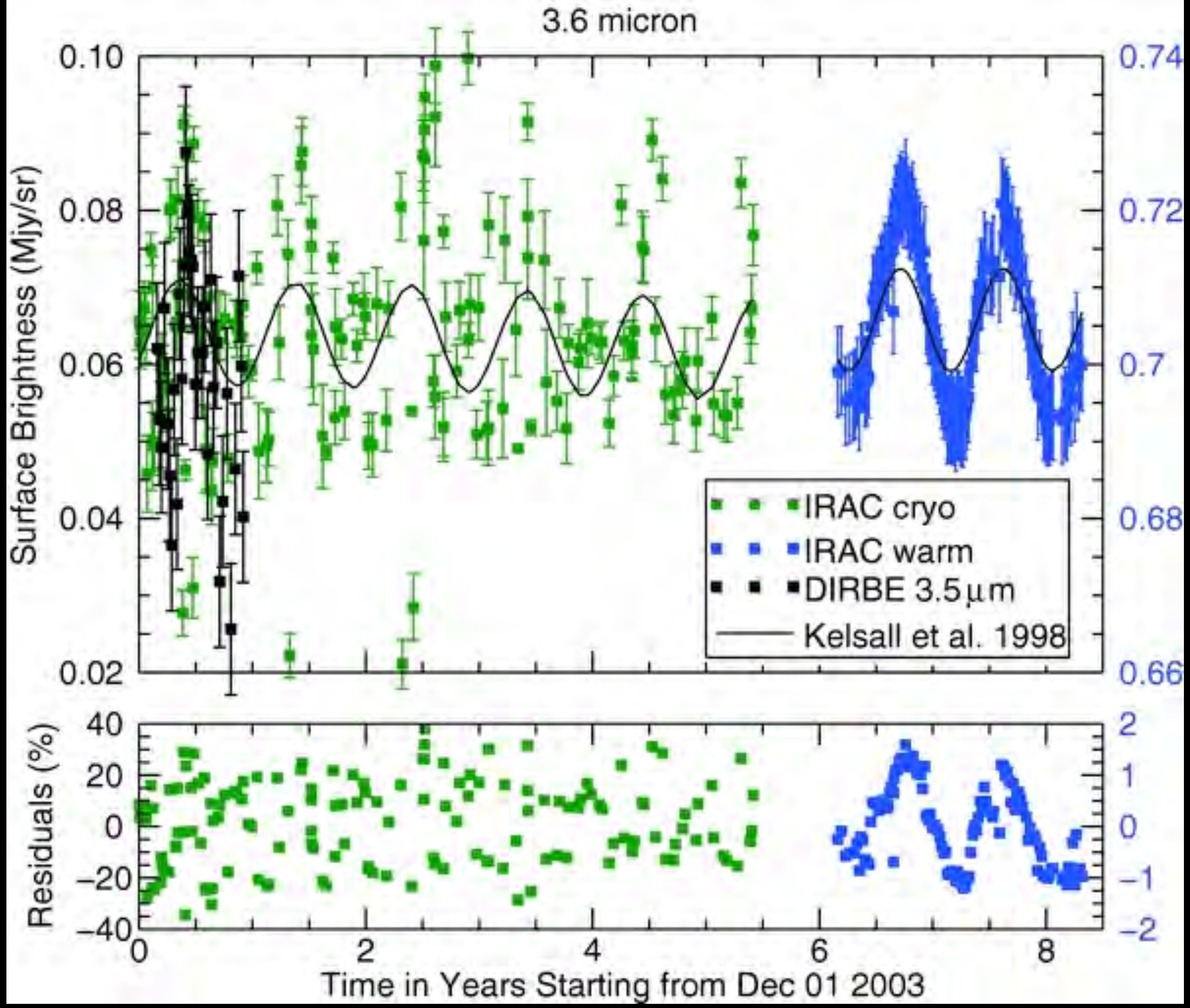
TeV absorption

From TeV data 1.4 um EBL known to
+/- 15% statistical

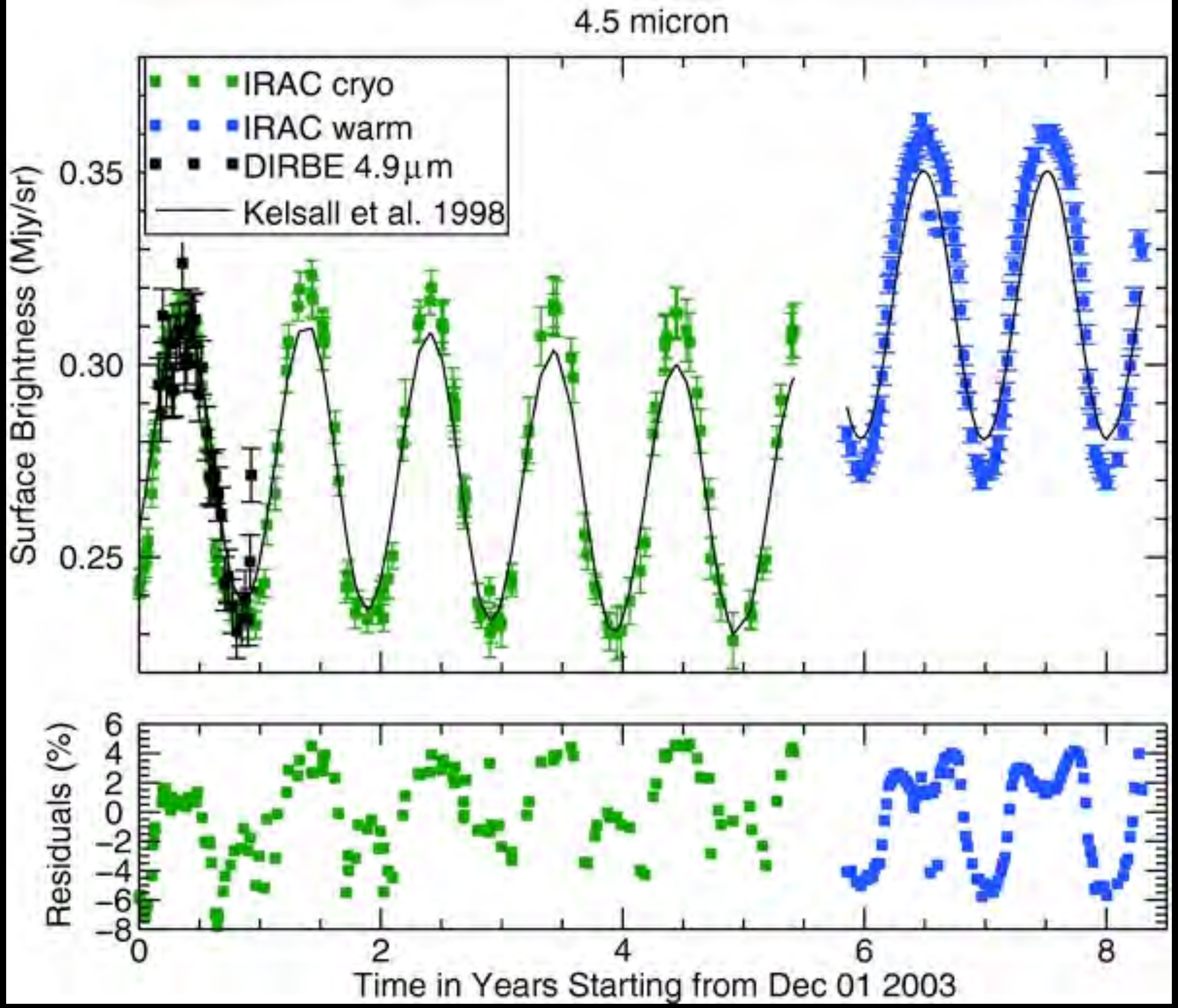
From Measurements to EBL

Extragalactic Background Light =
Total sky brightness – Zodiacal light – Stars – ISM

3.6 micron: dust scatted light



4.5 micron: direct dust emission



Existence of large differences relative to model already clear from Krick+ 2012, especially for scattered component.

CIBER

Cosmic Infrared Background ExpeRiment

NASA

June 20, 2013 launch Wallops, VA

The CIBER Collaboration

California Institute of Technology / Jet Propulsion Laboratory, California Institute of Technology:

John Battle
Jamie Bock
Viktor Hristov
Alicia Lanz
Phil Korngut
Peter Mason
Gael Roudier
Michael Zemcov

UC Irvine (University of California, Irvine):

Asantha Cooray
Yan Gong
Ketron Wynne
Chang Feng
Joseph Smidt

JAXA:

Toshiaki Arai
Shuji Matsuura
Yosuki Onishi
Takehiko Wada

Tohoku University:

Kohji Tsumura

ASIAA:

Toshio Matsumoto

NAOJ (National Astronomical Observatory of Japan):

Mai Shirahata

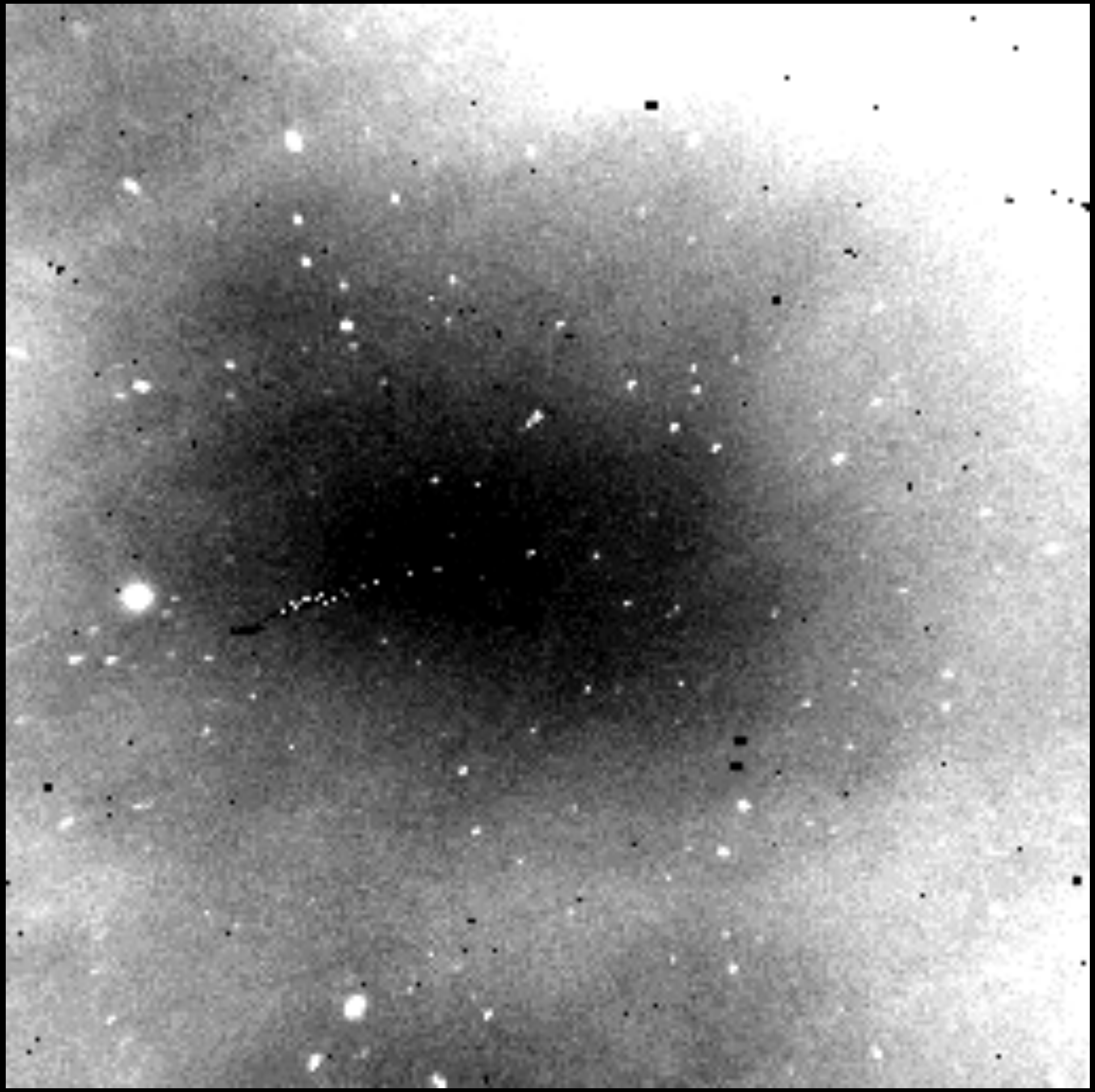
Seoul National University:

Min Gyu Kim

KASI:

Dae Hee Lee

THE CASE FOR SPACE



H-BAND 9º X 9º IMAGE OVER 45 MINUTES FROM KITT PEAK

WIDE-FIELD AIRGLOW EXPERIMENT: HTTP://PEGASUS.PHAST.UMASS.EDU/2MASS/TEAMINFO/AIRGLOW.HTML

Airglow Emission

- Atmosphere is **500 – 2500** times brighter than the astrophysical sky at 1-2 μm
- Airglow fluctuations in a **1-degree** patch are **10^6** times brighter than CIBER's sensitivity in 50 s
- Brightest airglow layer at an altitude of **100 km**… can't even use a balloon

CIBER
Cosmic Infrared Background ExpeRiment

CIBER-1: before third flight

CIBER
Cosmic Infrared Background ExpeRiment

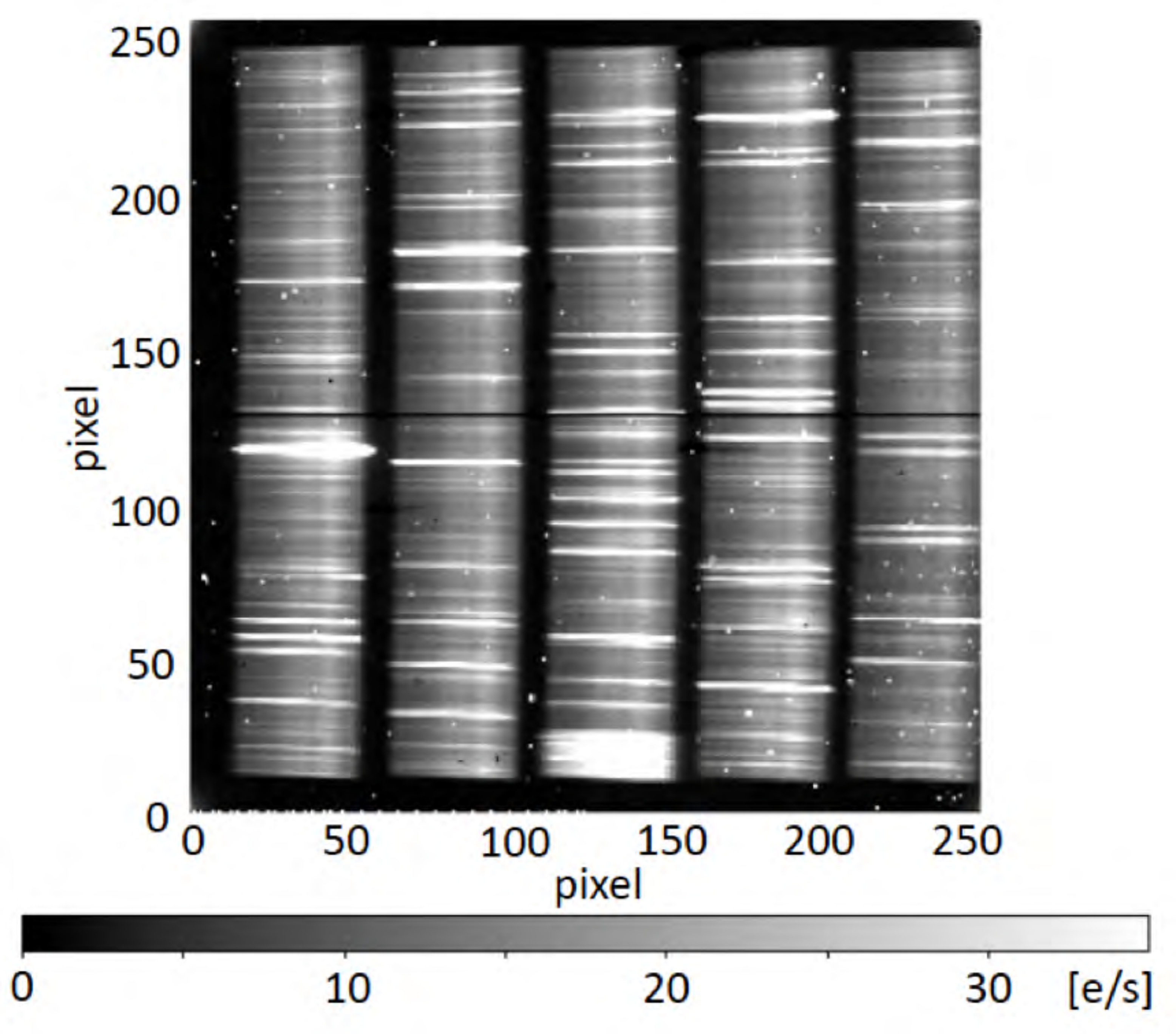
EBL measurement with CIBER/Low Resolution Spectrometer

<u>Low-Resolution Spectrometer</u>

λ = 0.8 – 2.0 μm $\lambda/\Delta\lambda$ ~ 20

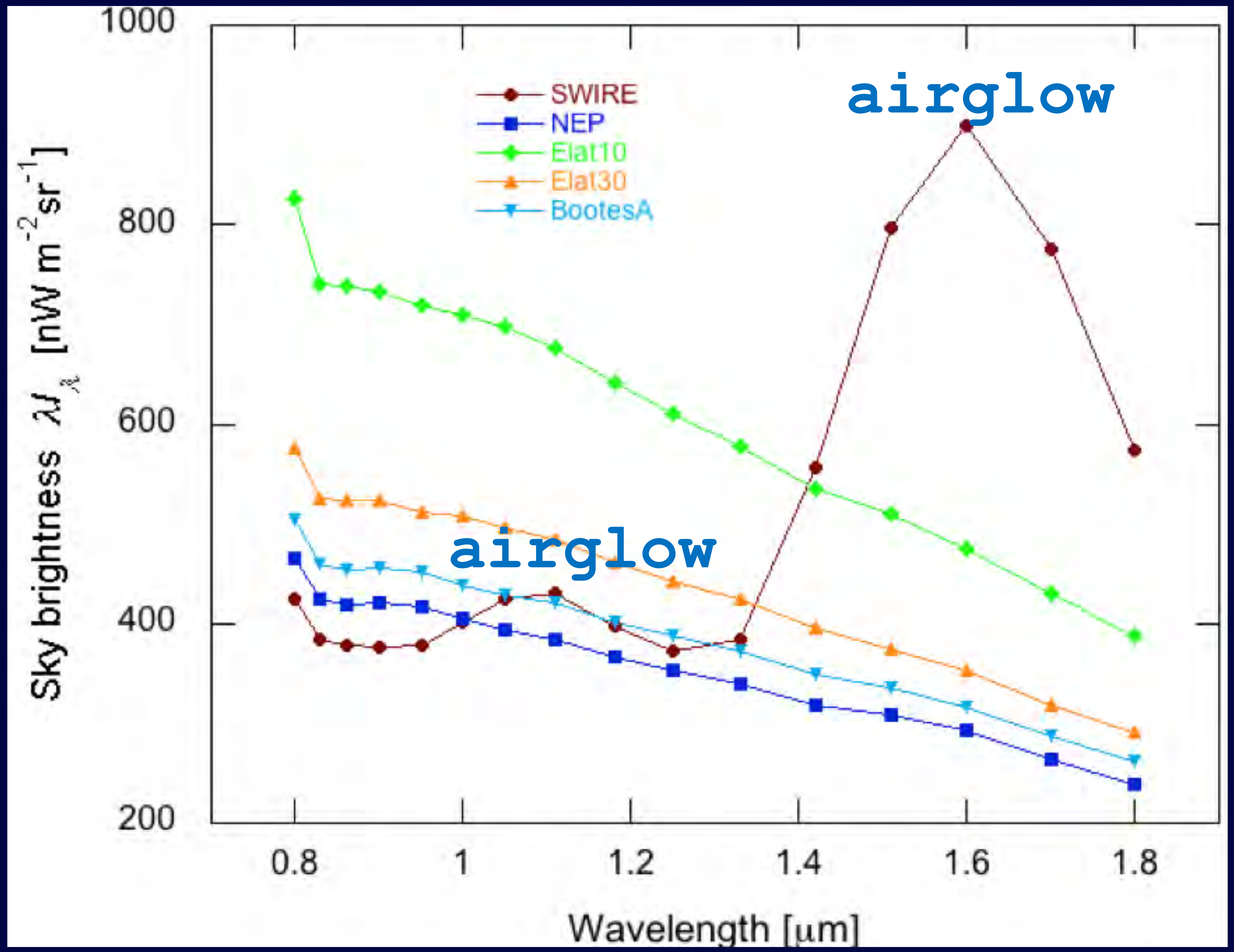
4° x 4° FOV   60" pixels

- Dispersed with a prism
- Laboratory calibrated
- Uses NIST-calibrated LEDs on the focal plane (that are turned on between sky observations)



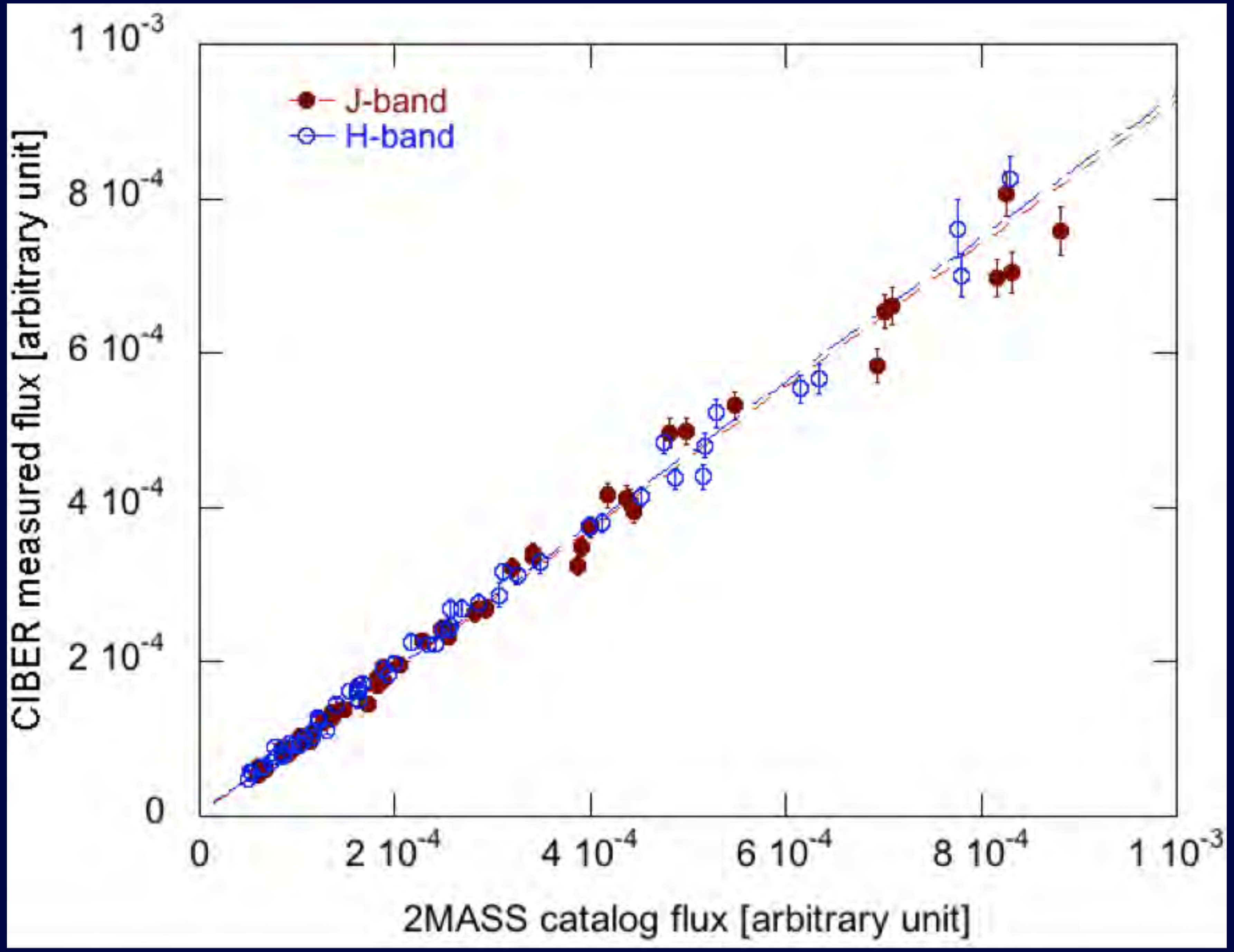
Measured intensities are a x10-20 larger than the expected EBL

Thermal emission from rocket skin, scattered via optics, dominates above 1.8 microns.

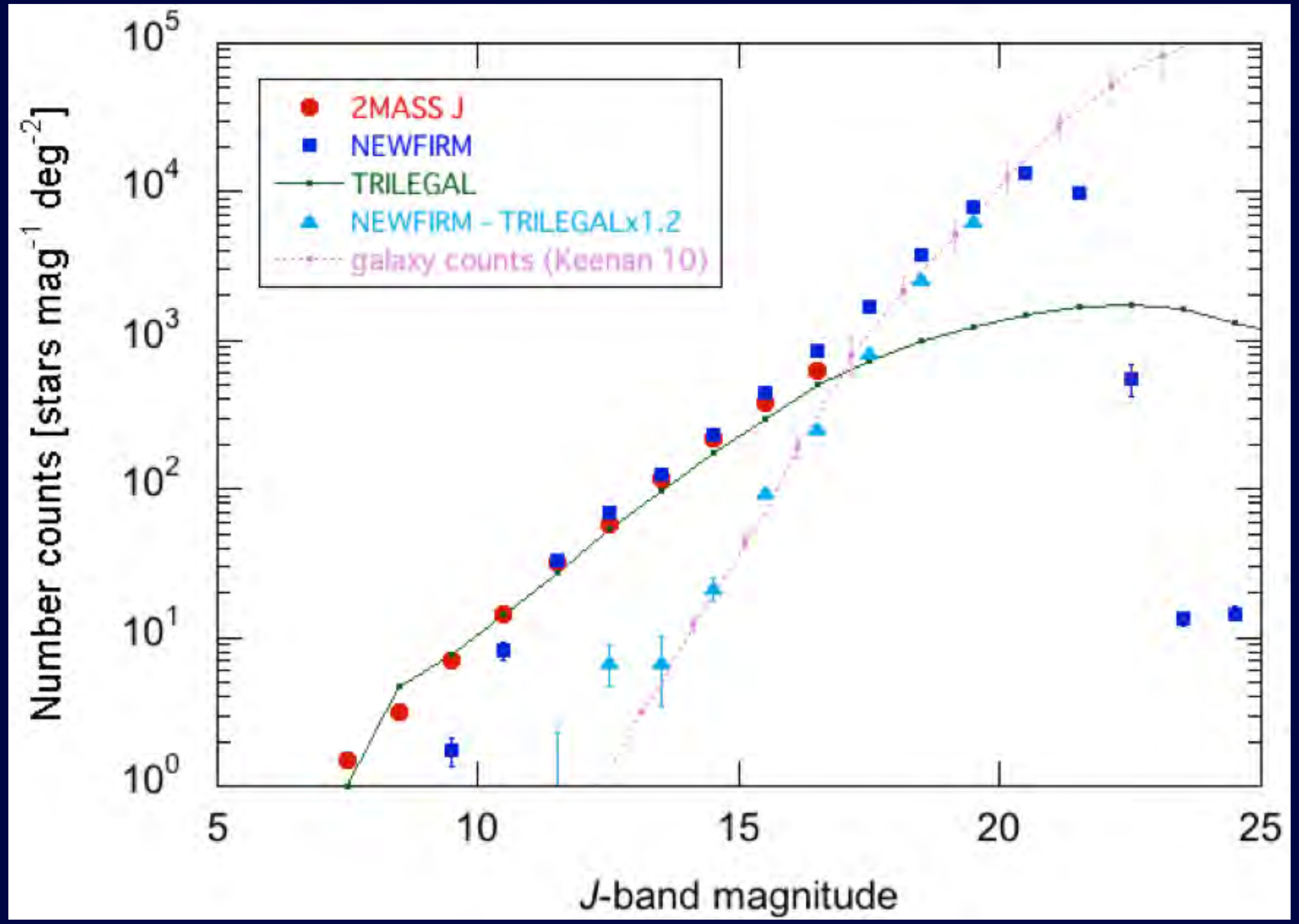


Matsuura et al. ApJ

Extragalactic Background Light =
Total sky brightness – Zodiacal light – Stars – ISM - Instrumental Systematics

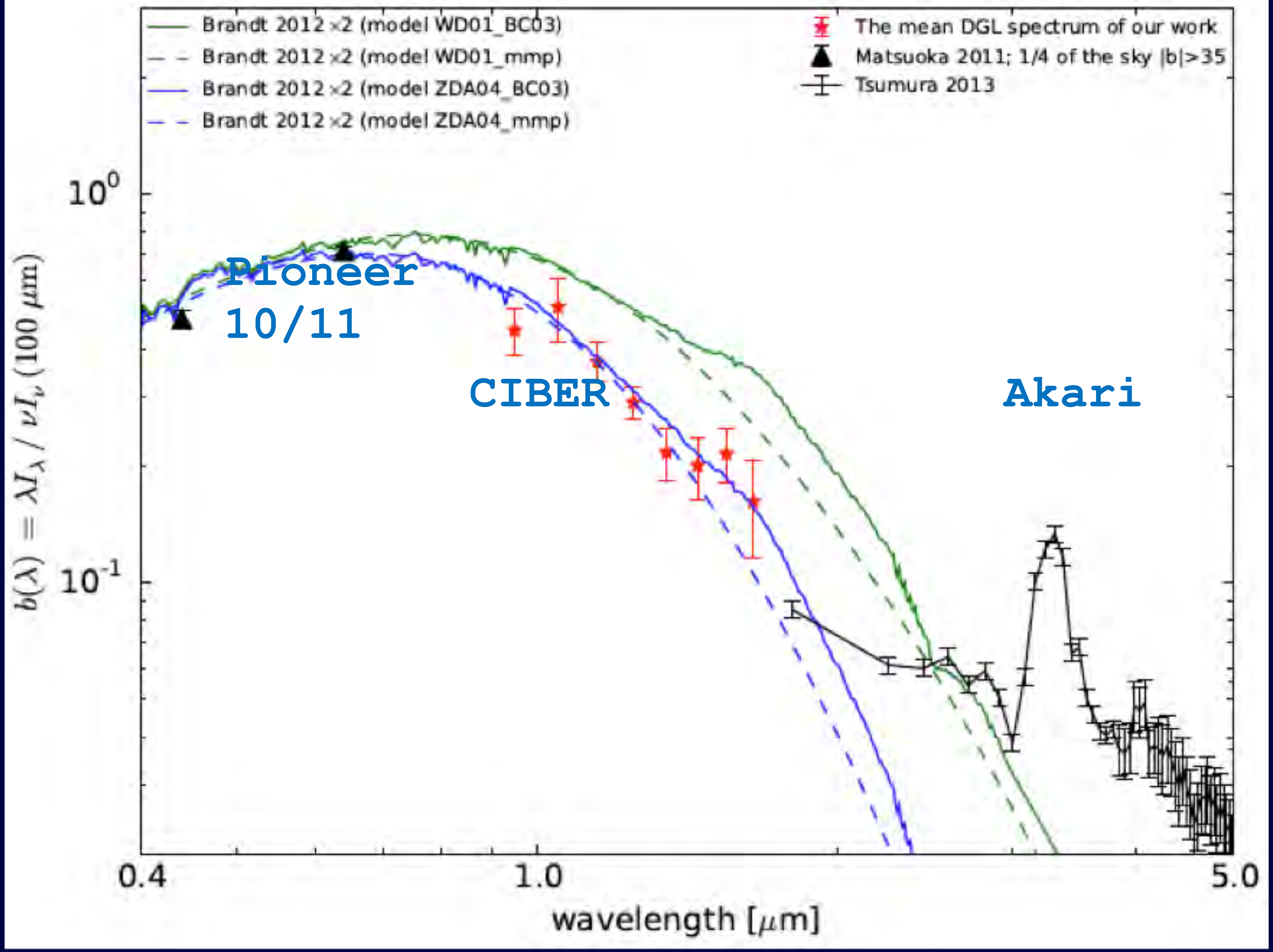


Detected star counts



Extrapolated down based on
models/known counts
in each of the Legacy fields

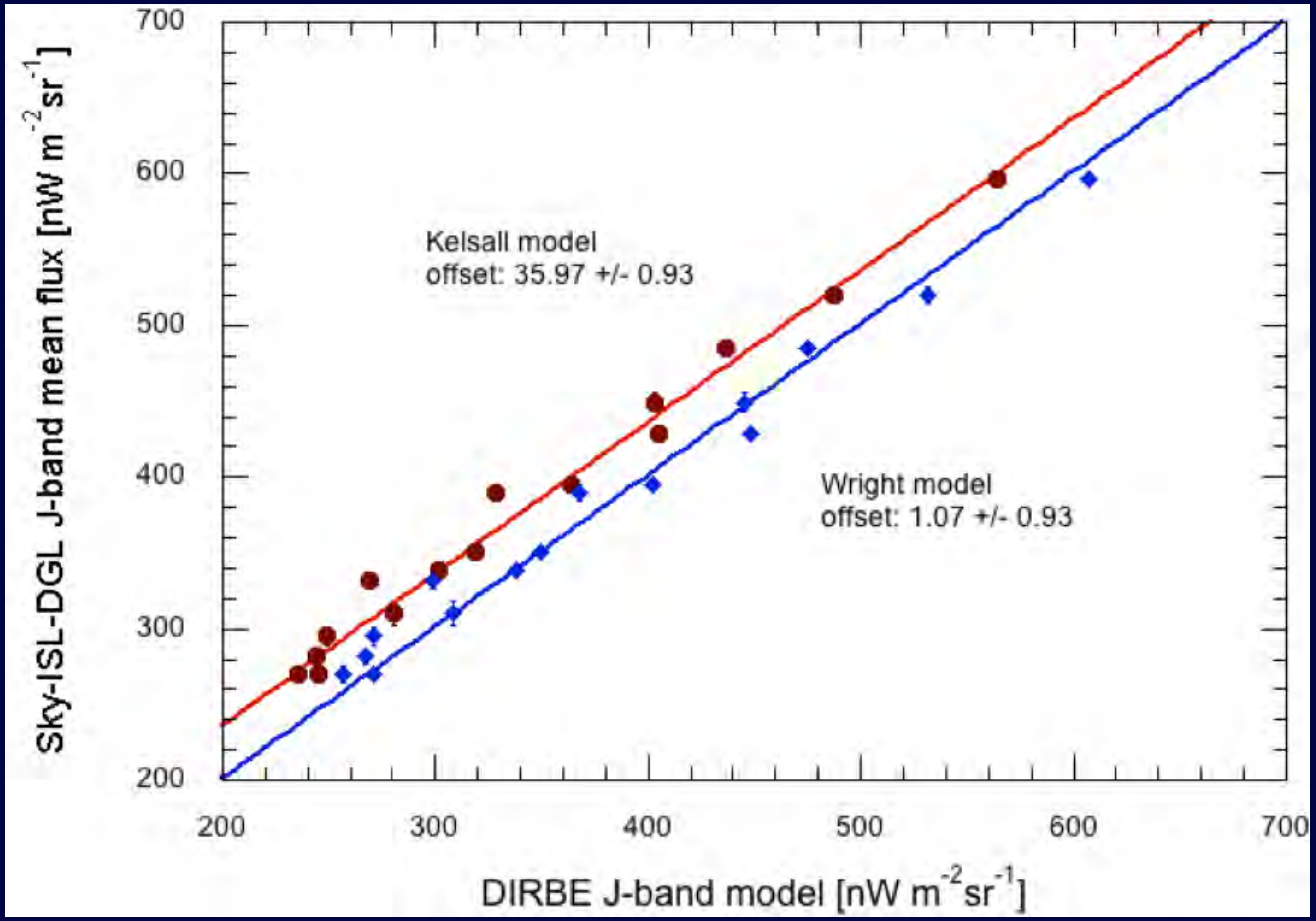
Extragalactic Background Light =
Total sky brightness – Zodiacal light – Stars – ISM - Instrumental Systematics



Tsumura et al. 2013

ISM (Diffuse Galactic Light) constructed from CIBER/LRS (assumes a Zodi model)

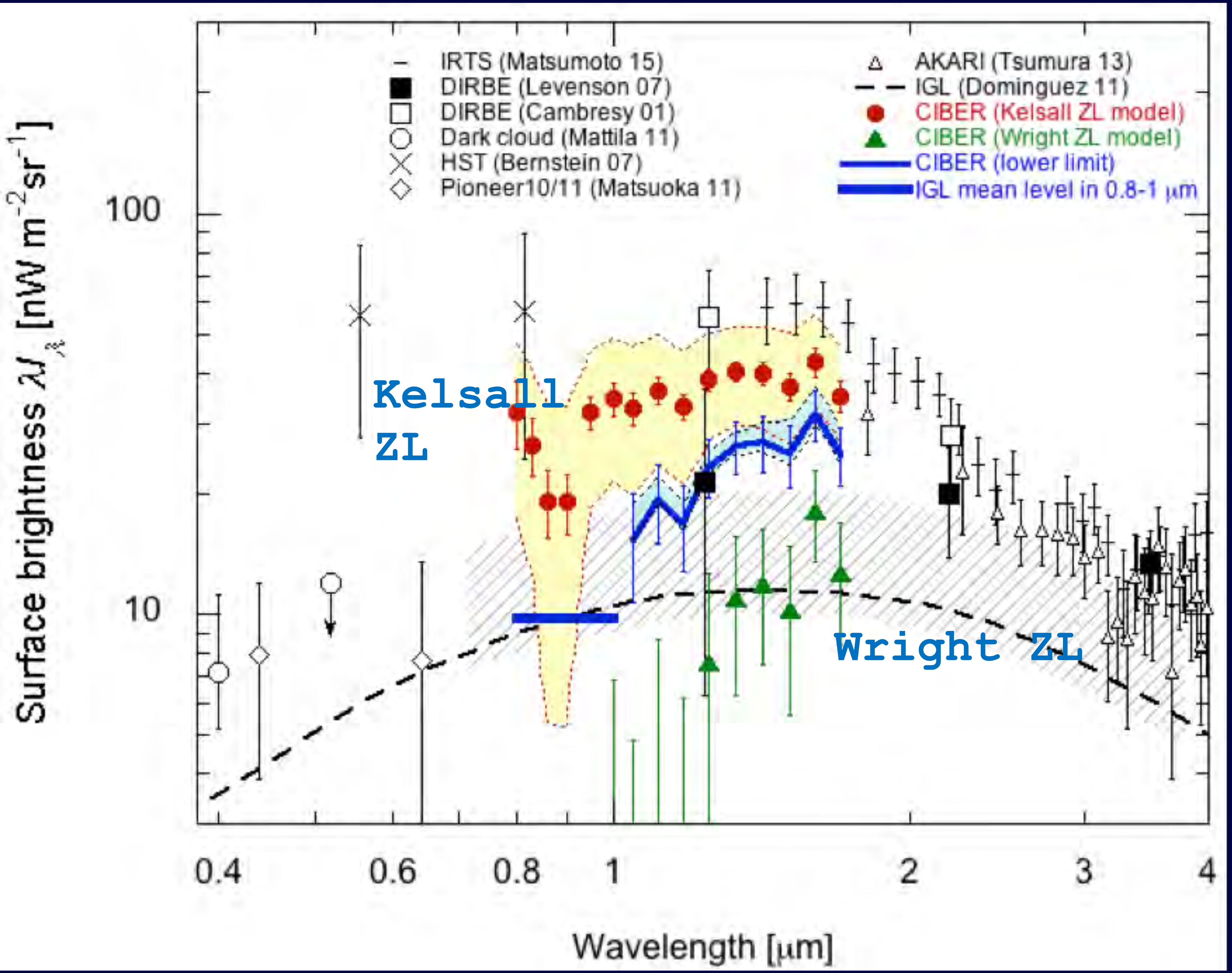
Extragalactic Background Light =
Total sky brightness – Zodiacal light – Stars – ISM - Instrumental Systematics



Assuming Kelsall+ 98 or Wright 01 Zodiacal light normalization.
Intercept should be the absolute EBL. *Wright's model leads to effectively no EBL.*

LRS Zodiacal light intensity absolute level can be calibrated with NBS ZL measurement.

Extragalactic Background Light =
Total sky brightness – Zodiacal light – Stars – ISM - Instrumental Systematics

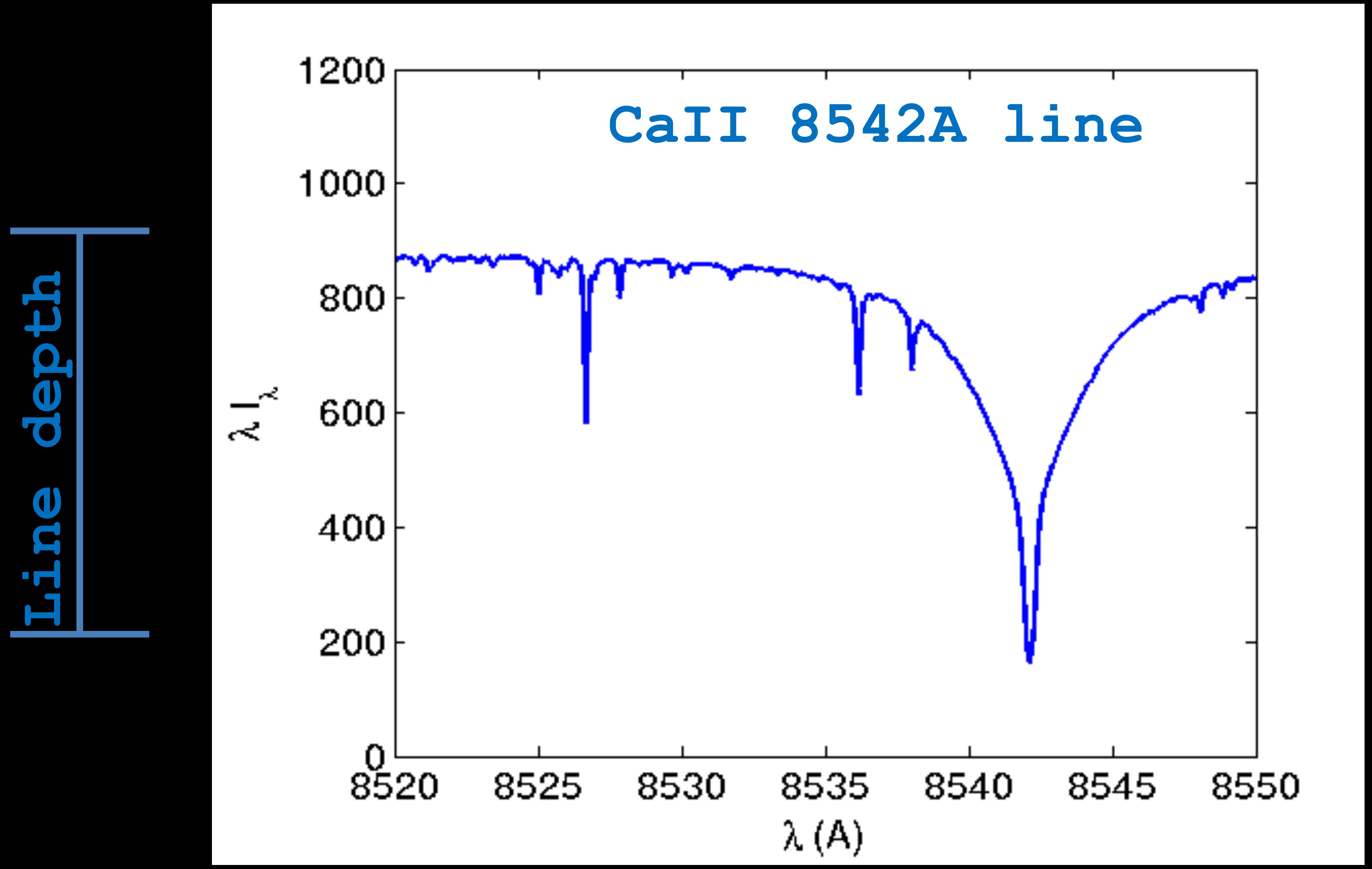


CIBER finds Wright model is not a good description of ZL at < 3.5 microns - for the scattered component.

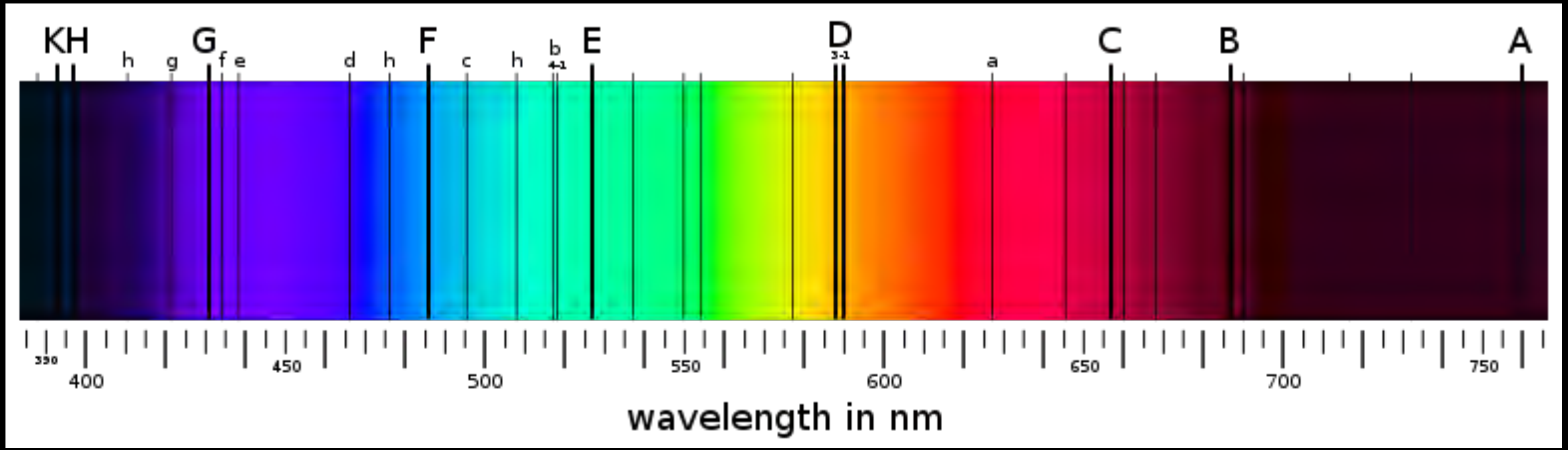
Matsuura et al. ApJ

How can we improve?

Joseph von Fraunhofer
(1787 – 1826)



Short of ~3.5 microns, the ZL is reflected Solar spectrum with well characterized absorption features.



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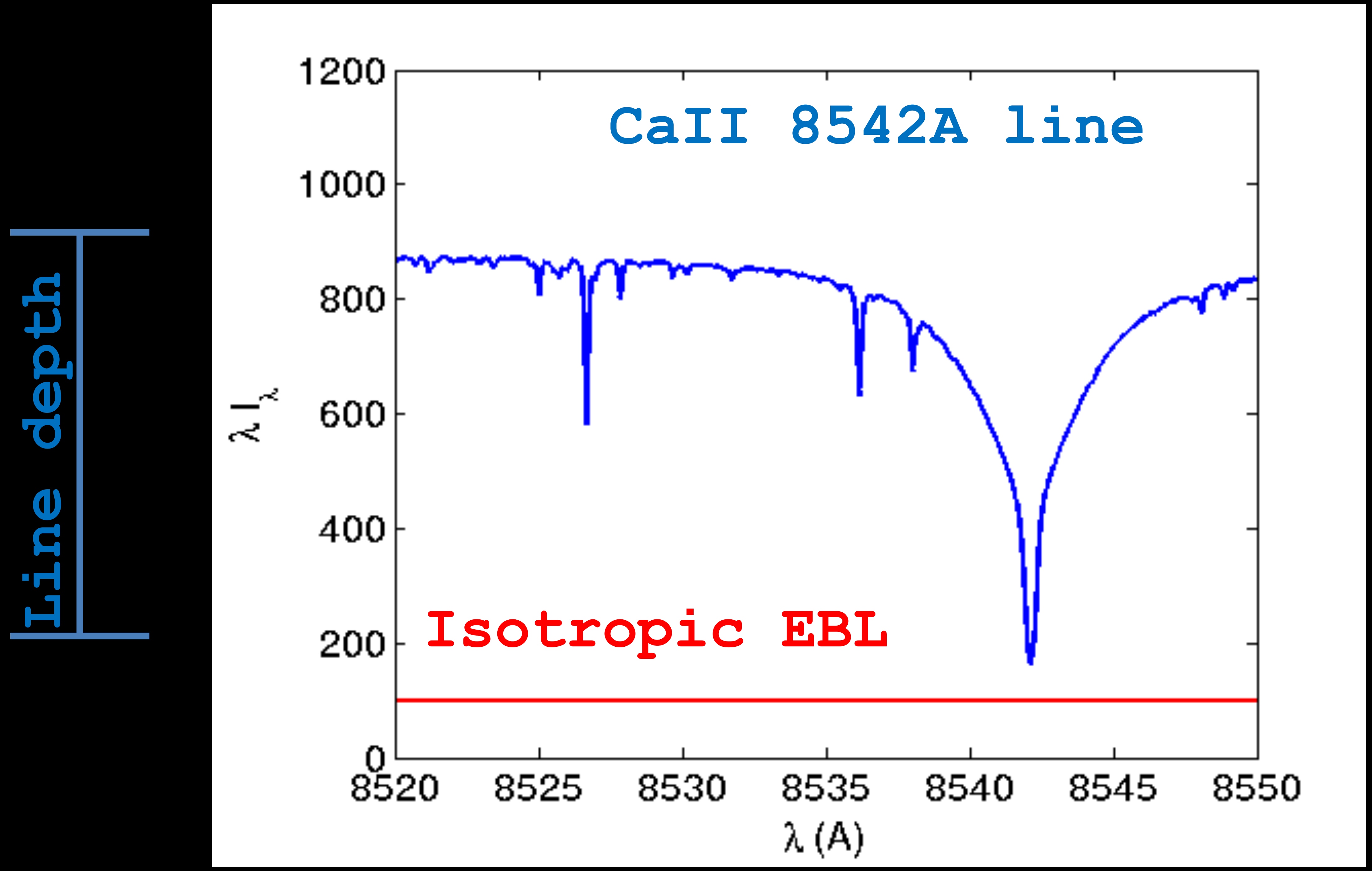

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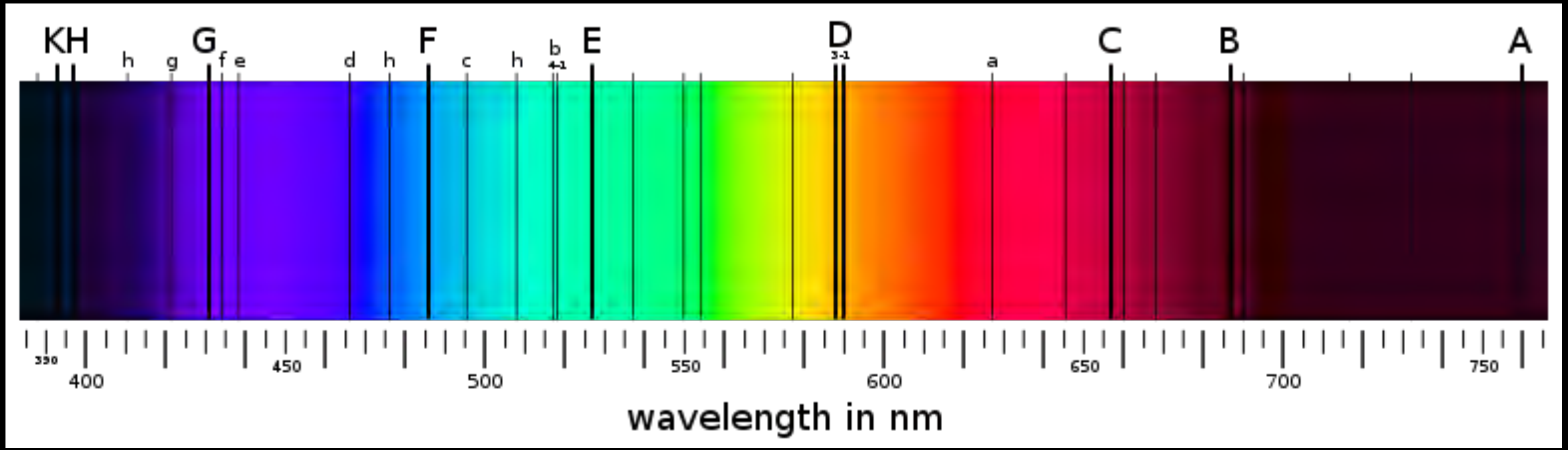

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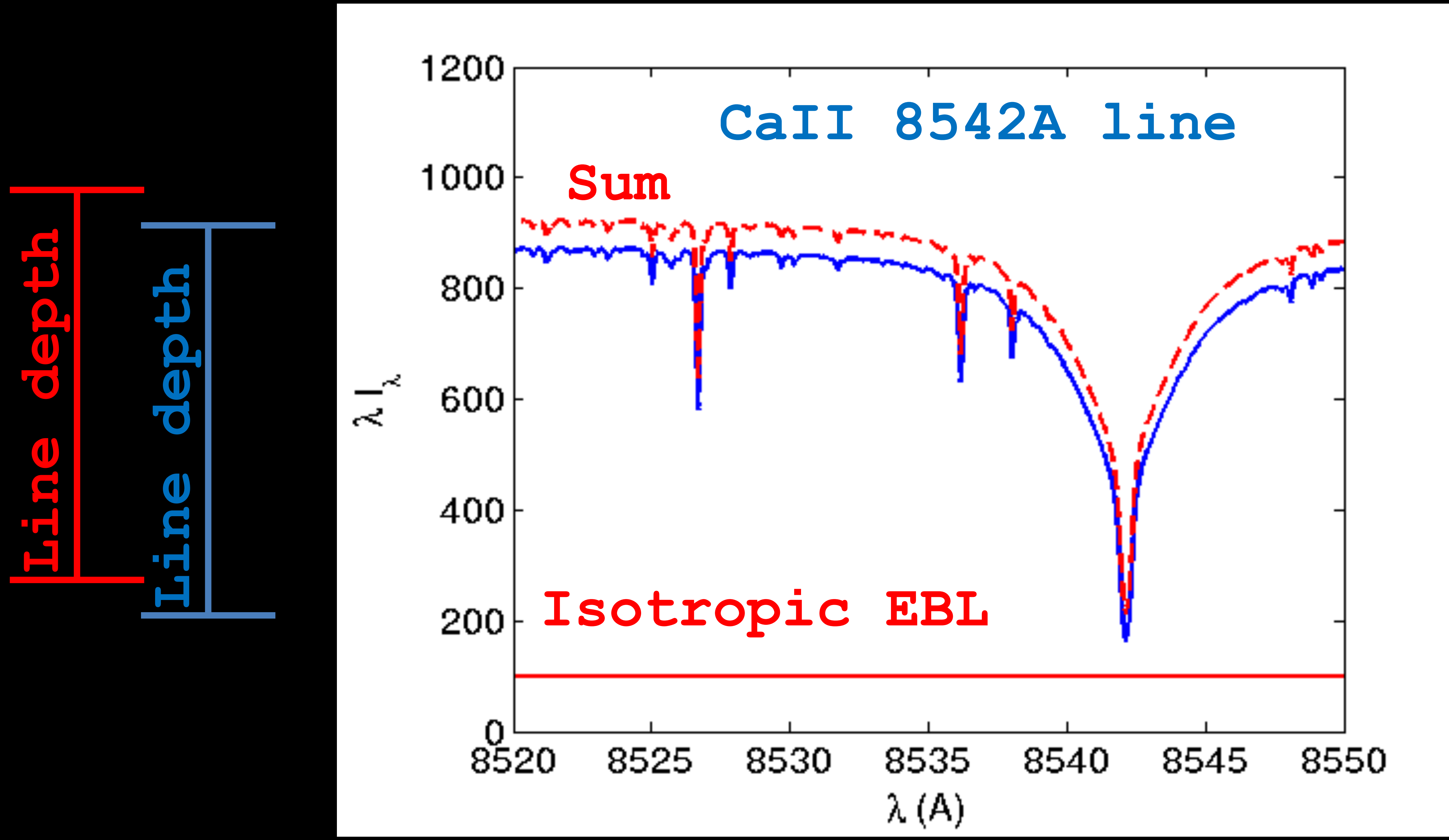

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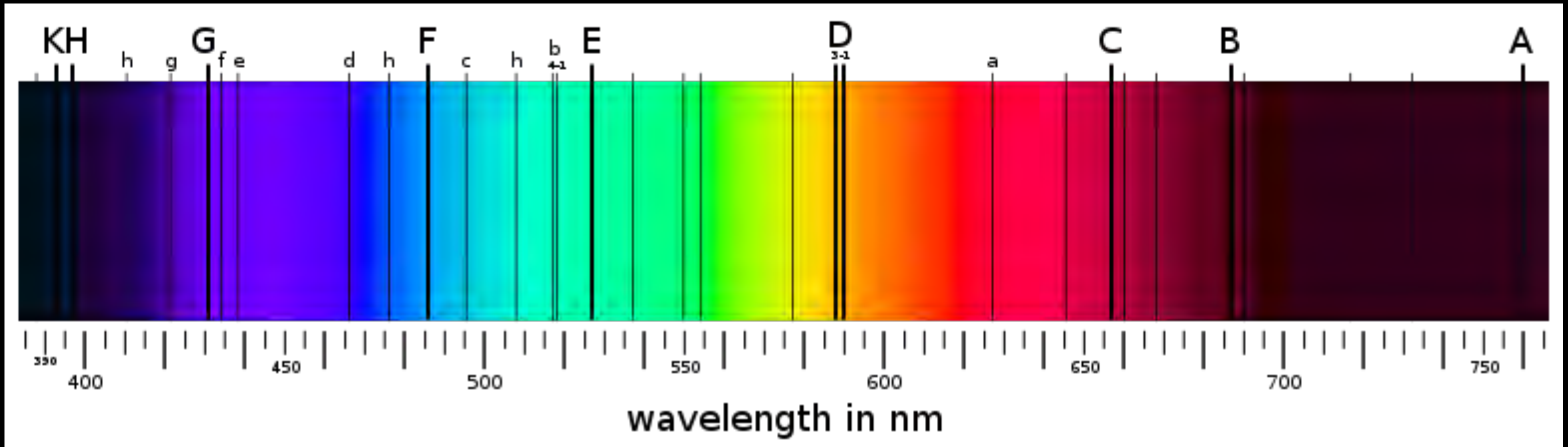
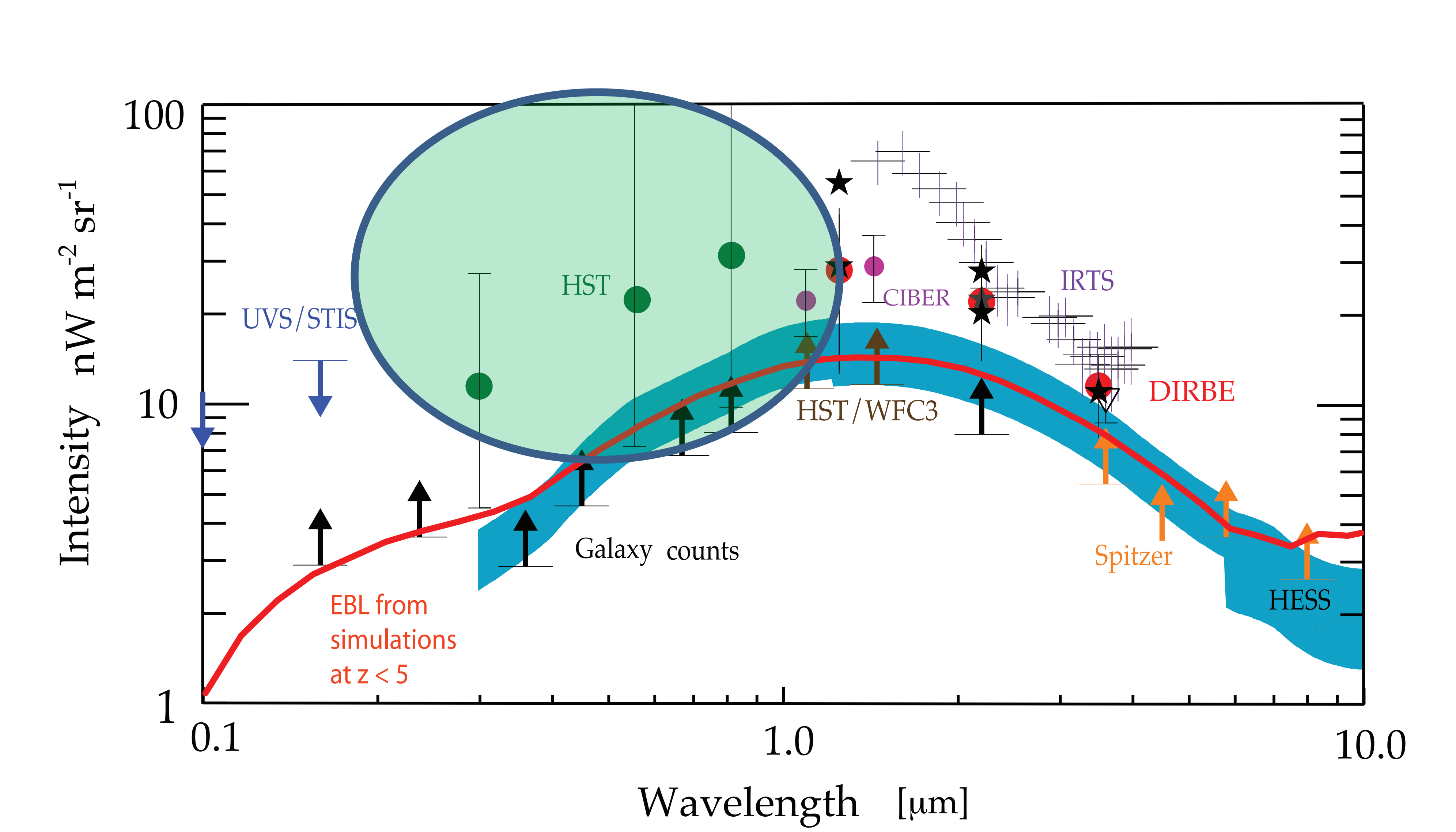


Previous Application of Fraunhofer Line Measurements to EBL

Bernstein et al 2002
Measurements From HST + the Ground
Systematics in Matilla 2003; Revision in Bernstein 2003

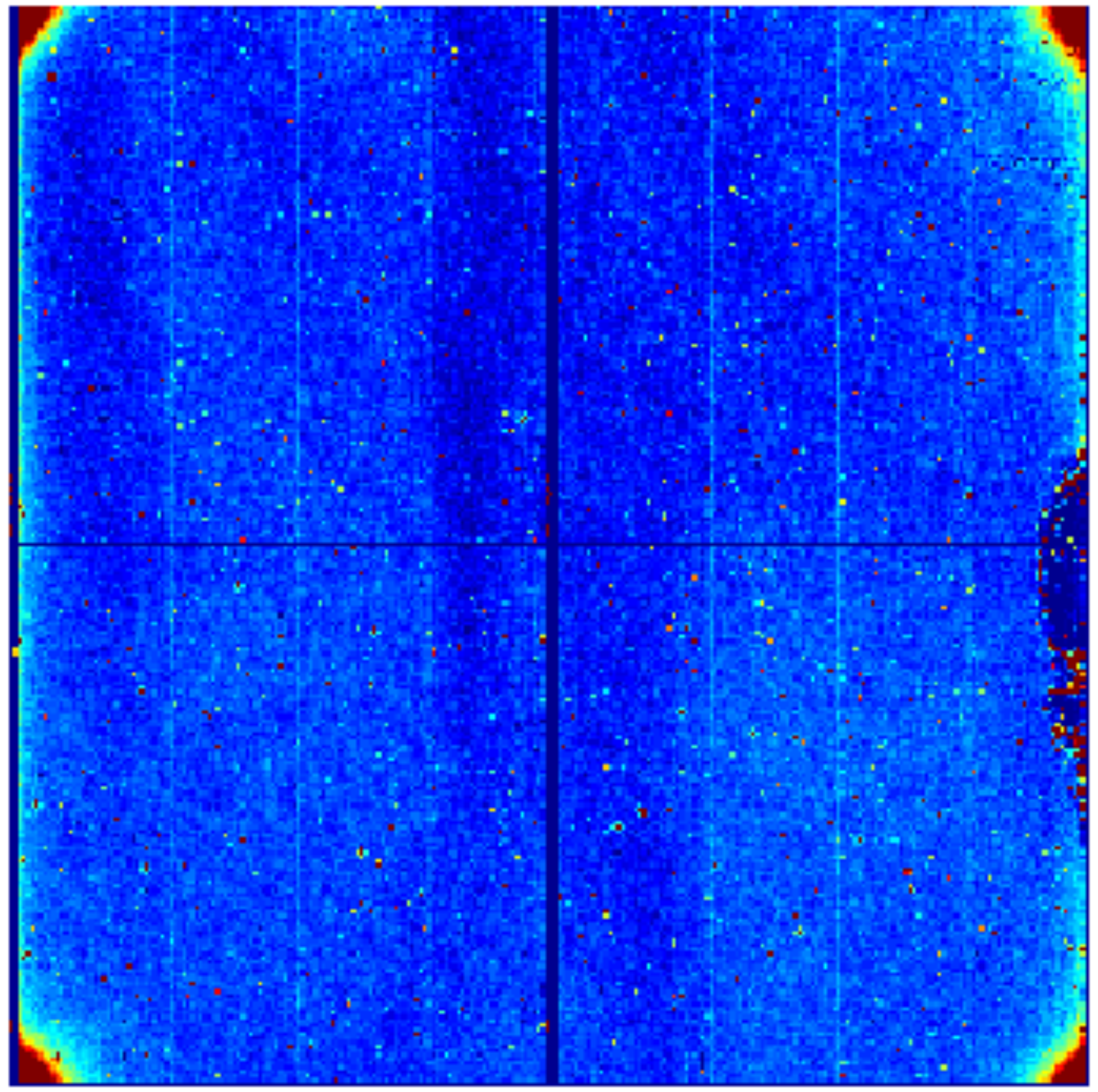


Systematic limitation: Atmospheric Extinction & Atmospheric scattering

Lesson: ground to space transfer of Fraunhofer line is subject to large uncertainties
Many systematics can be avoided by doing this measurement from Space!

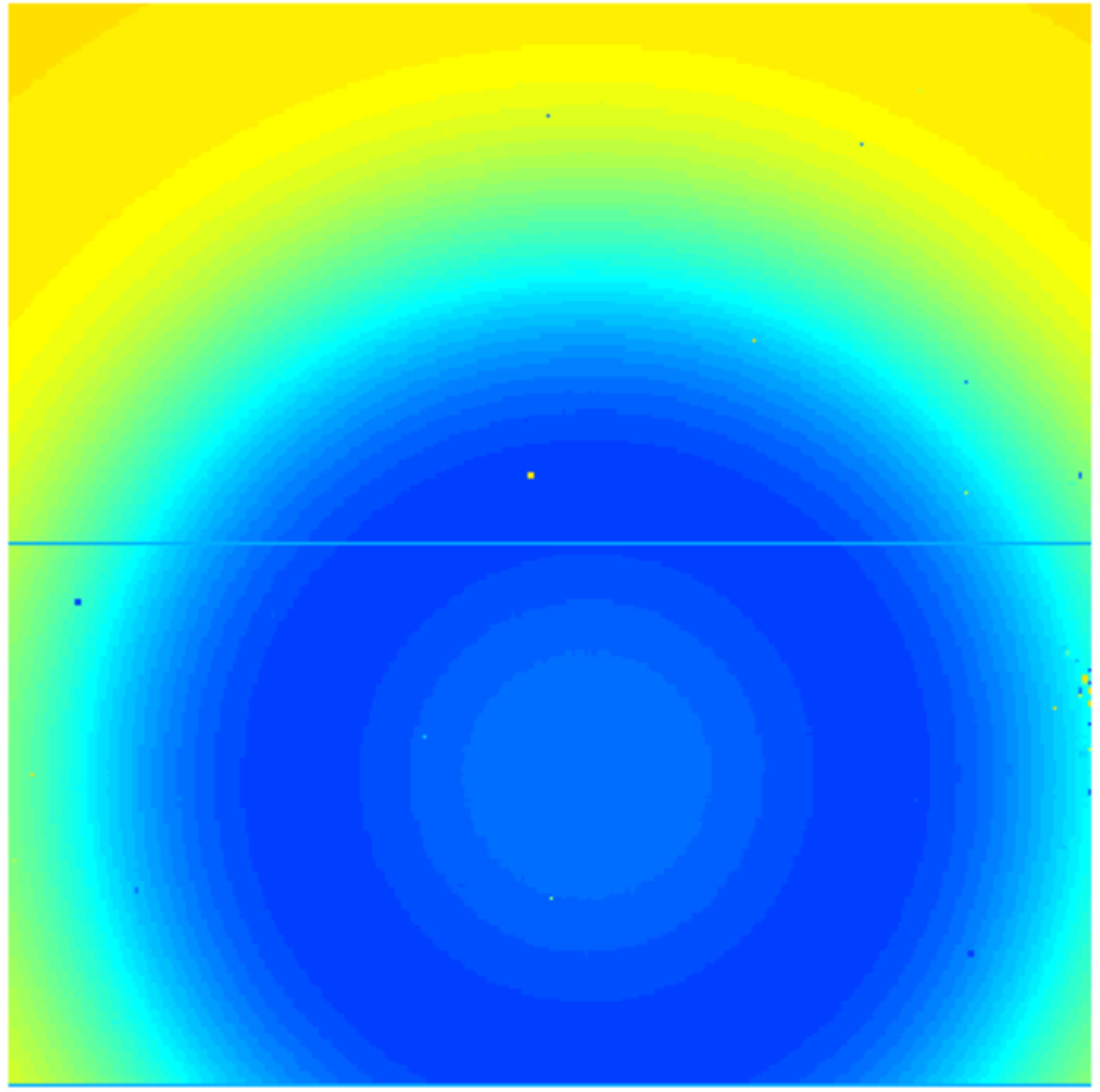
Narrow Band Spectrometer Data Reduction

Raw Single field NBS Image



Subtract Dark Current and mask outlier regions.

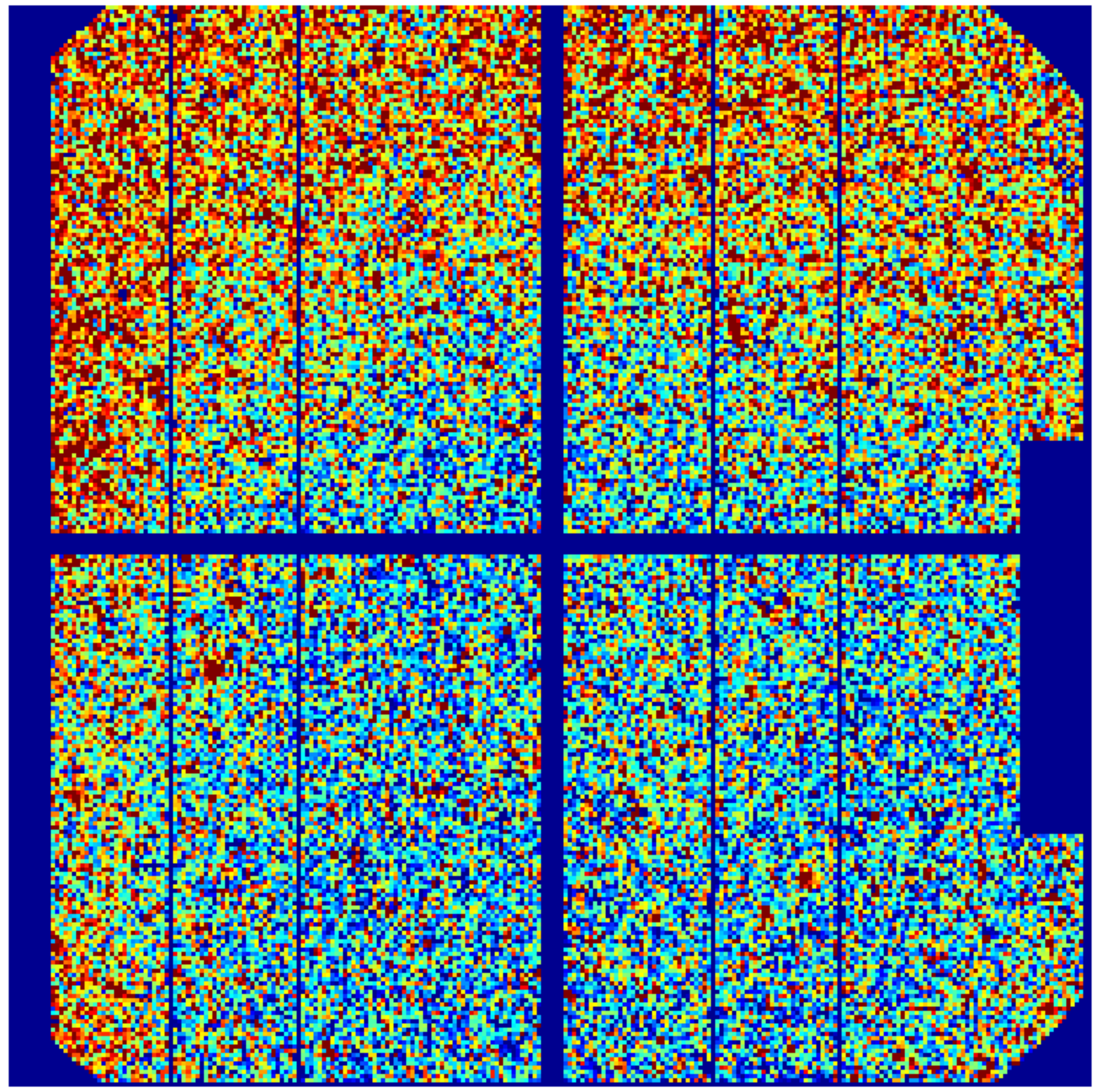
Ideal ZL CaII image



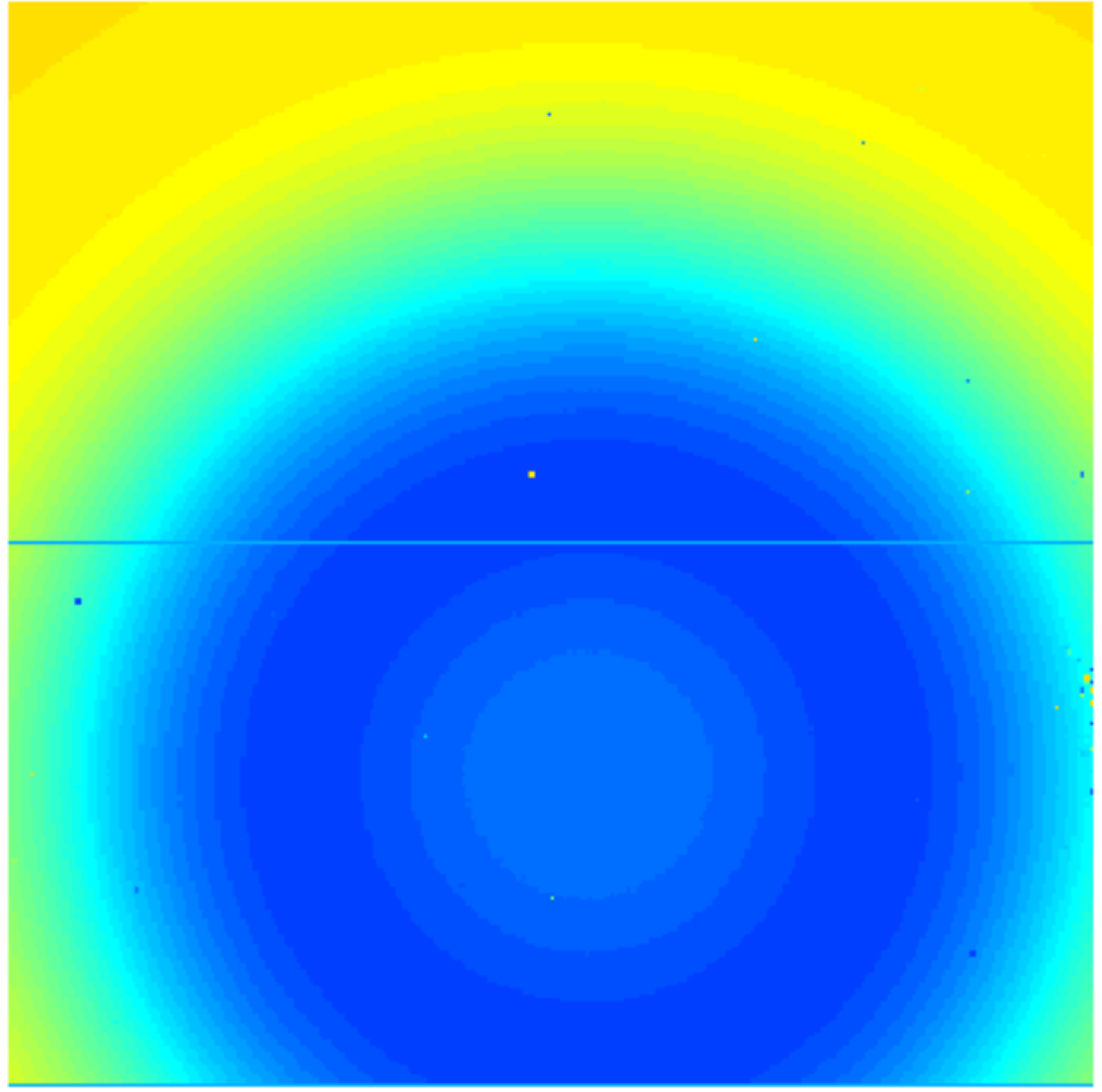
Korngut et al. 2023

Narrow Band Spectrometer Data Reduction

Single field NBS Image
Dark Current, Flat field, Bad pixels masked



Ideal ZL CaII image



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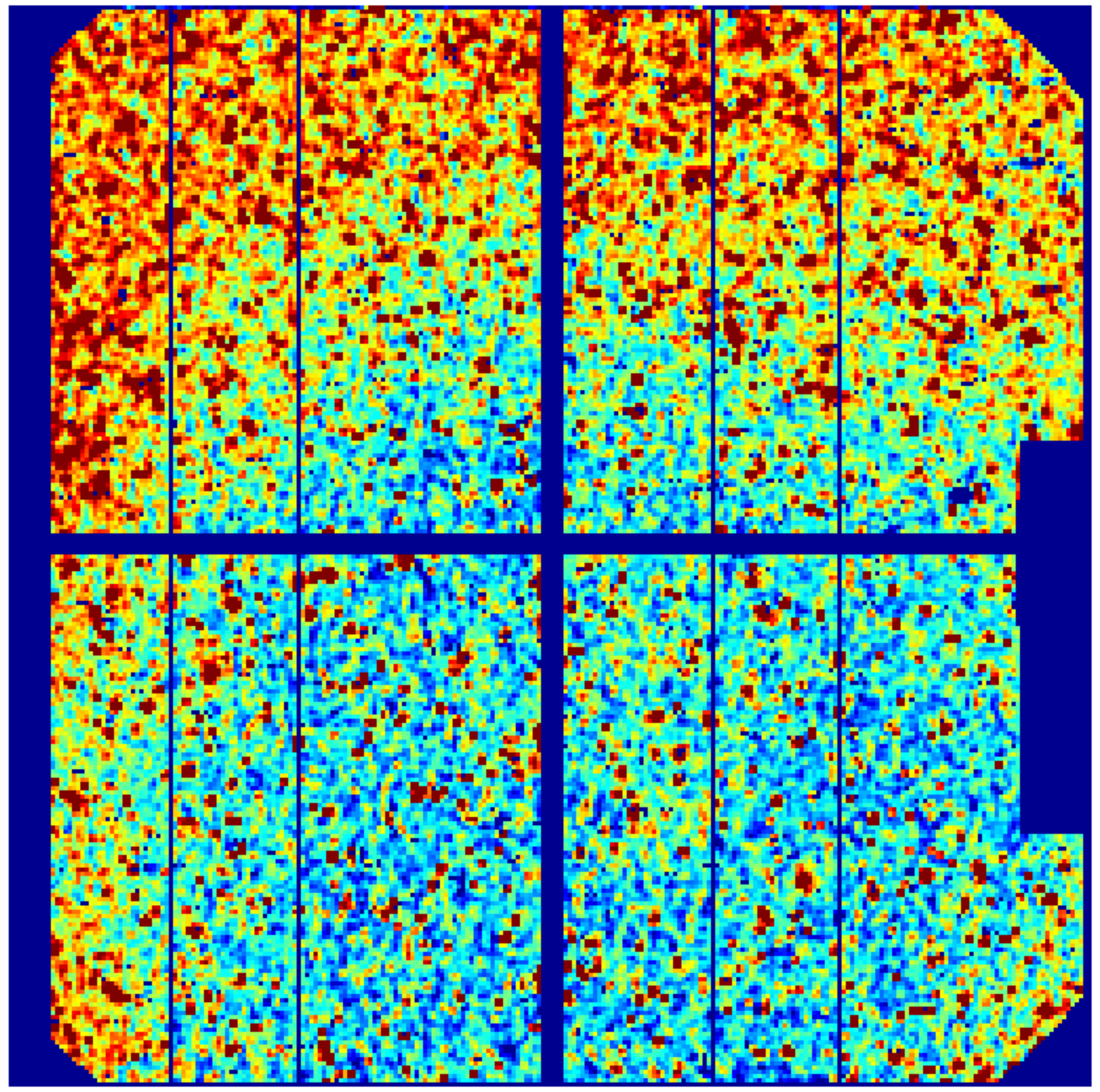
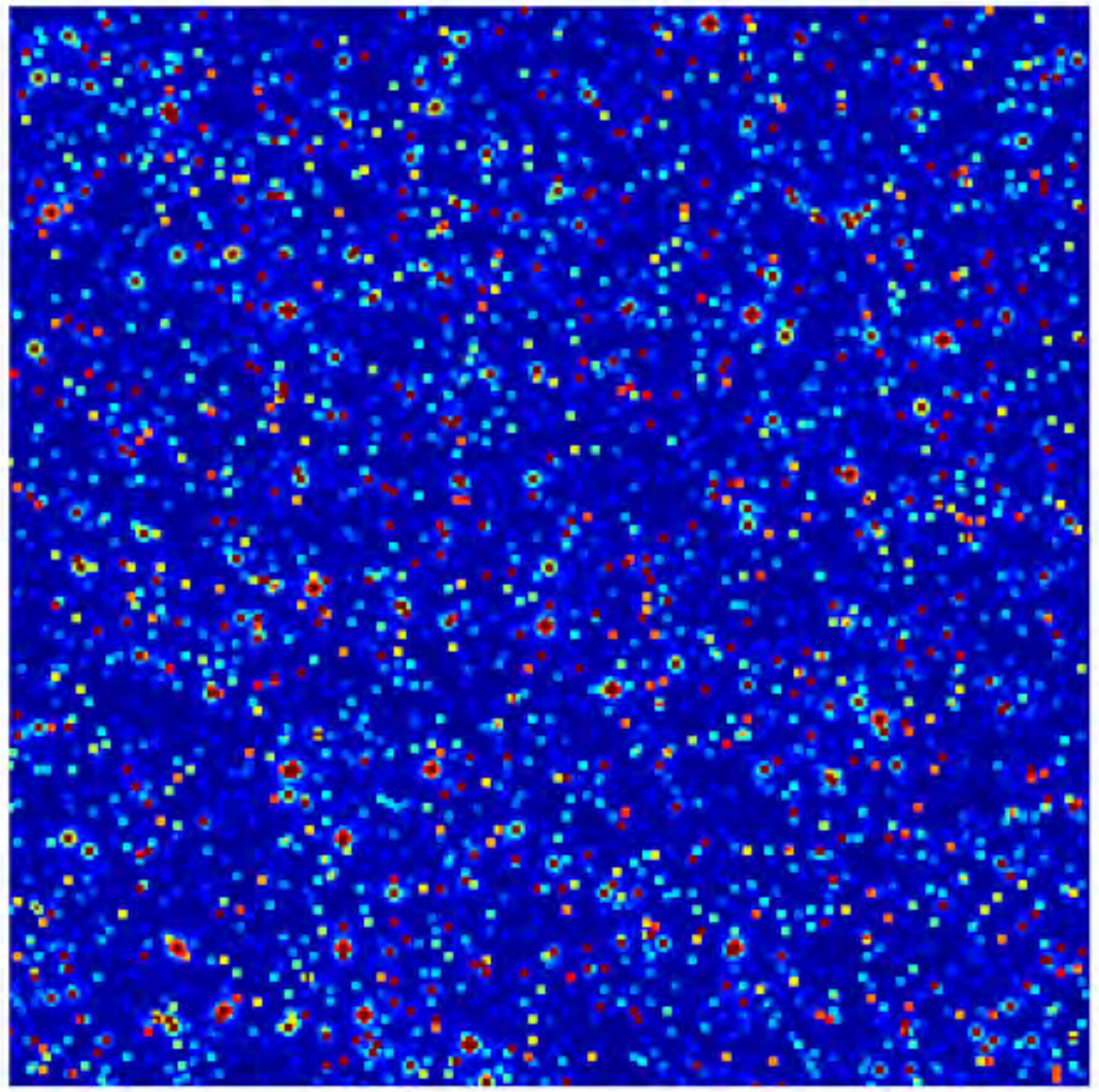
Narrow Band Spectrometer Data Reduction

Single field NBS Image
Dark Current, Flat field, Bad pixels masked



Smoothed for Ease of Viewing only

Ideal ZL CaII image

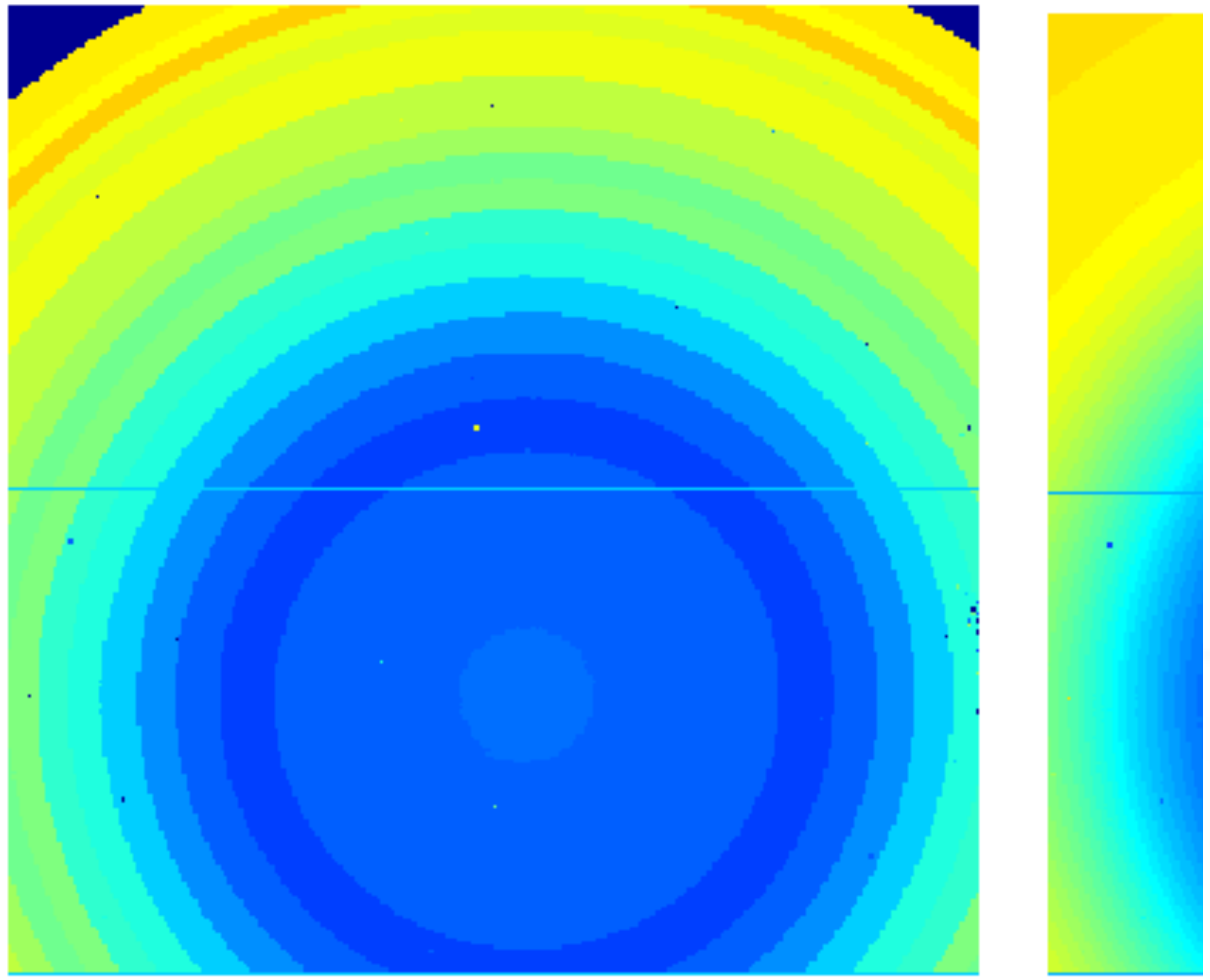


Register Astrometry & Create synthetic image based on 2MASS stars

Korngut et al. 2023

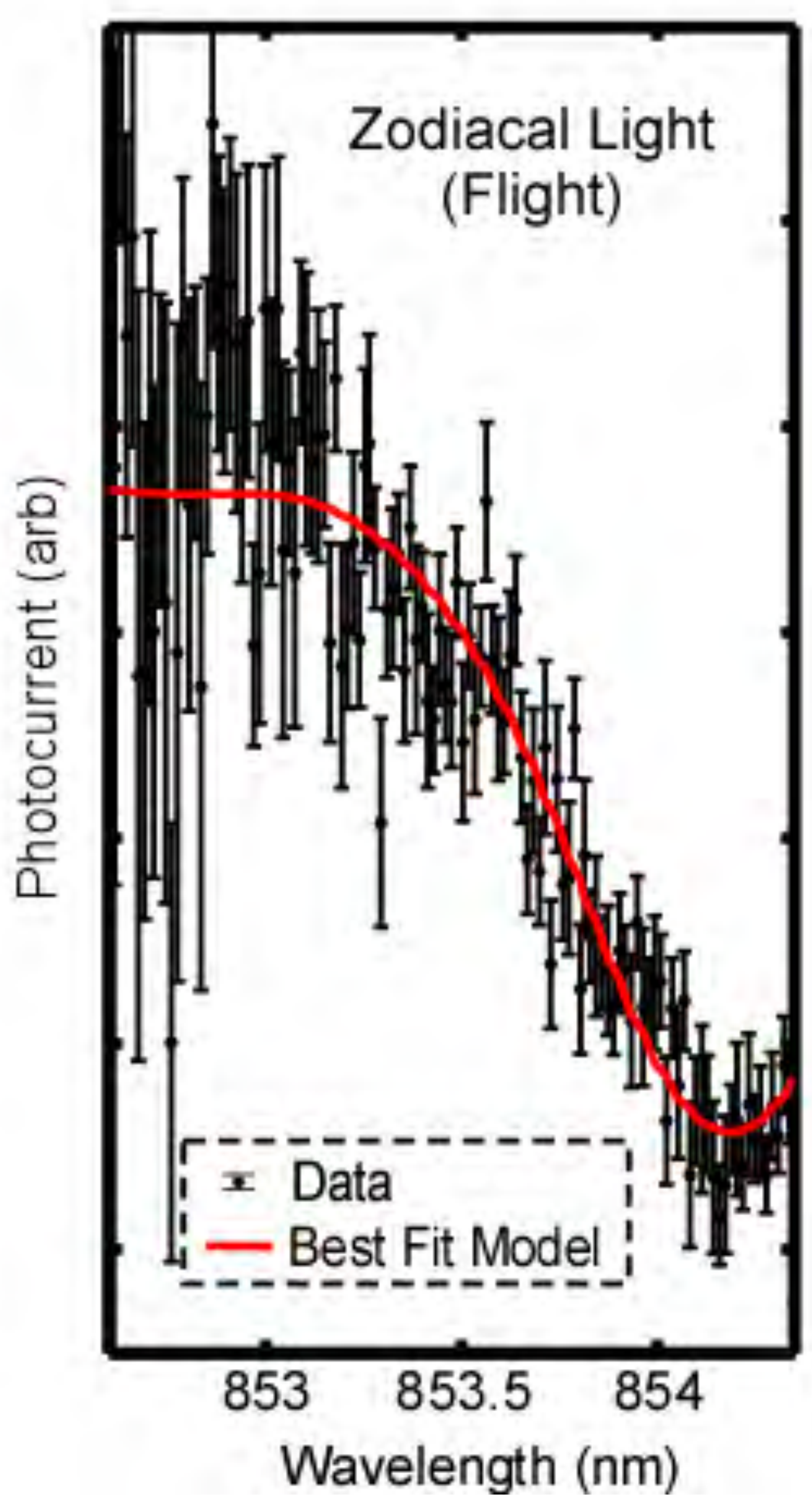
Narrow Band Spectrometer Data Reduction

Single field NBS Image
Dark Current, Flat field, Bad pixels masked



Binned By Wavelength

Ideal ZL CaII image



Korngut et al. 2023

Modeling all of the components required for Accurate ZL Estimates

What we measure | What we want

$$
\begin{aligned}
\lambda I_{\lambda,total,x,y} = {} & A_{ZL} G_{ZL,x,y} \int d\lambda \Lambda_{x,y}(\lambda) F_{\lambda,ZL}(\lambda) \\
& + \\
& A_{DGL} G_{DGL,x,y} \int d\lambda \Lambda_{x,y}(\lambda) F_{\lambda,DGL}(\lambda) \\
& + \\
& A_{BISL} G_{BISL,x,y} \int d\lambda \Lambda_{x,y}(\lambda) F_{\lambda,BISL}(\lambda) \\
& + \\
& A_{FISL} \int d\lambda \Lambda_{x,y}(\lambda) F_{\lambda,FISL}(\lambda) \\
& + \\
& C,
\end{aligned}
$$

Zodiacal Light

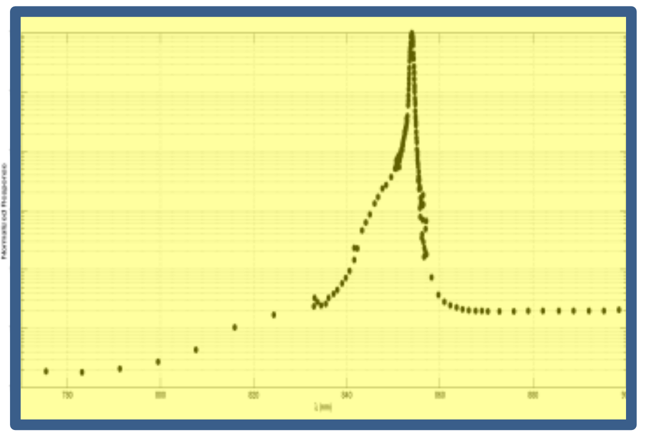
Diffuse Galactic Light (ISM)

Stellar Light

EBL, Airglow resid, Dark Current Resid etc.

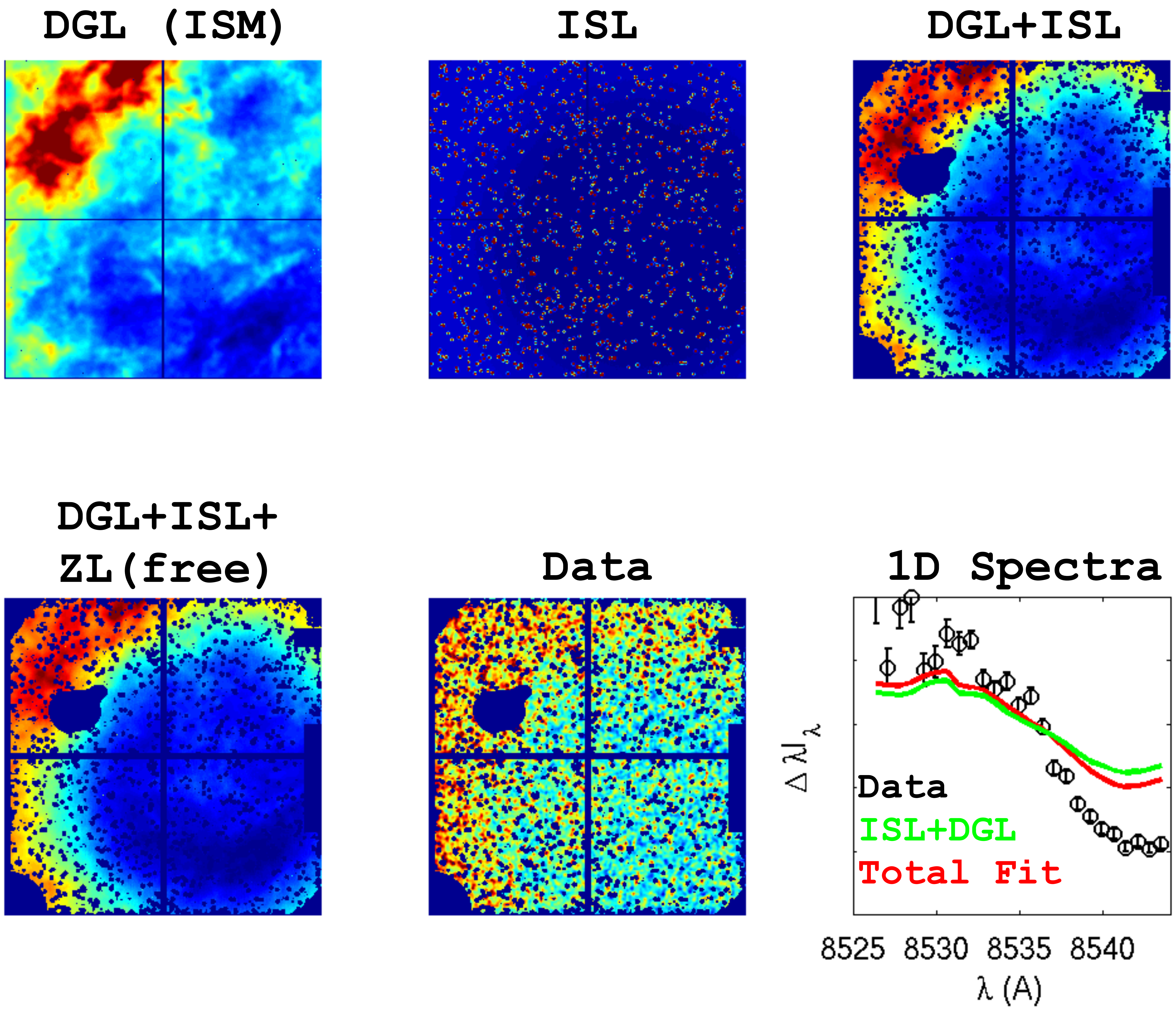
amplitude

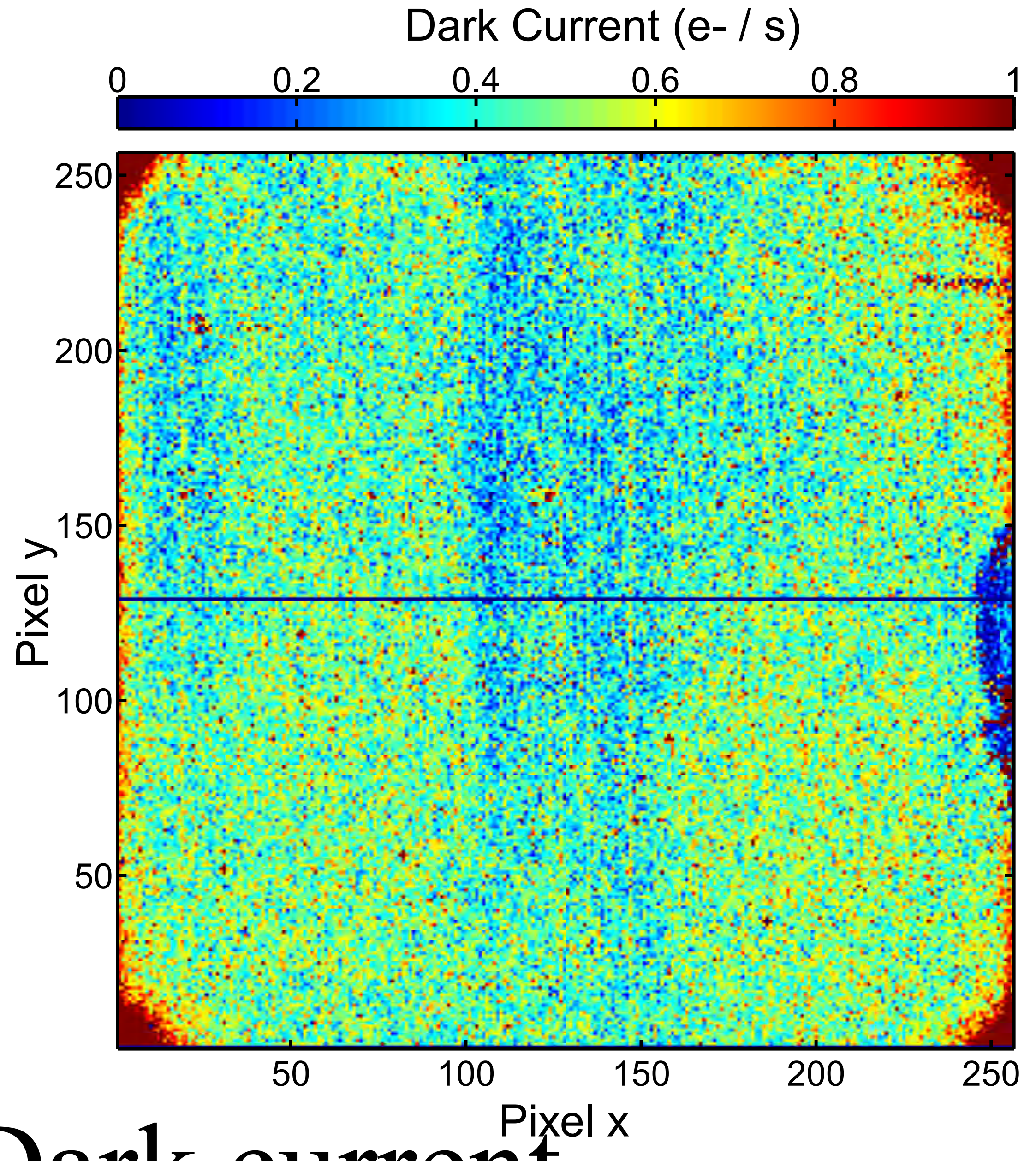
Spatial Distribution



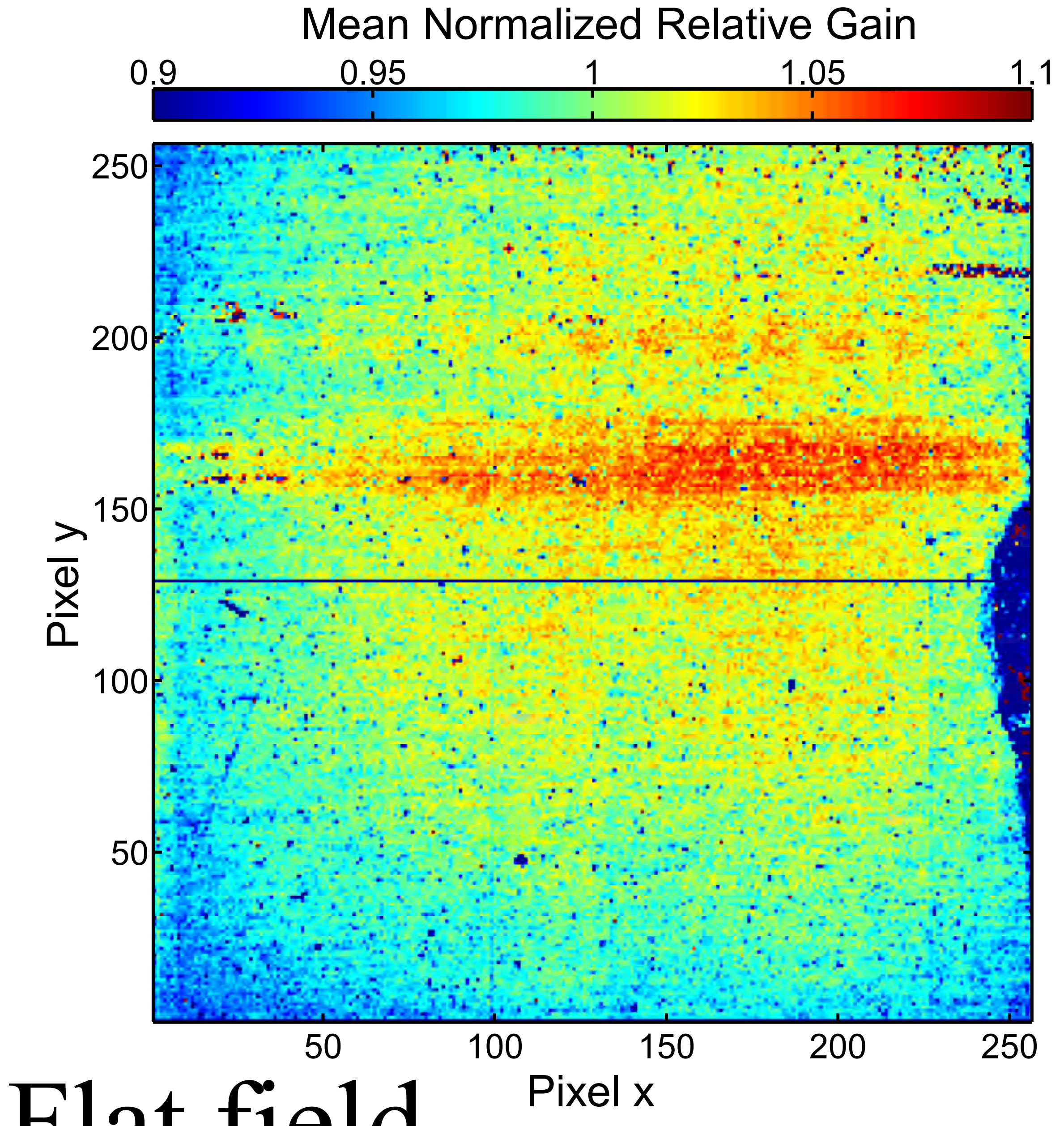
Effective CaII absorption profile of the component

Fit For the ZL amplitude Large Relative Contamination

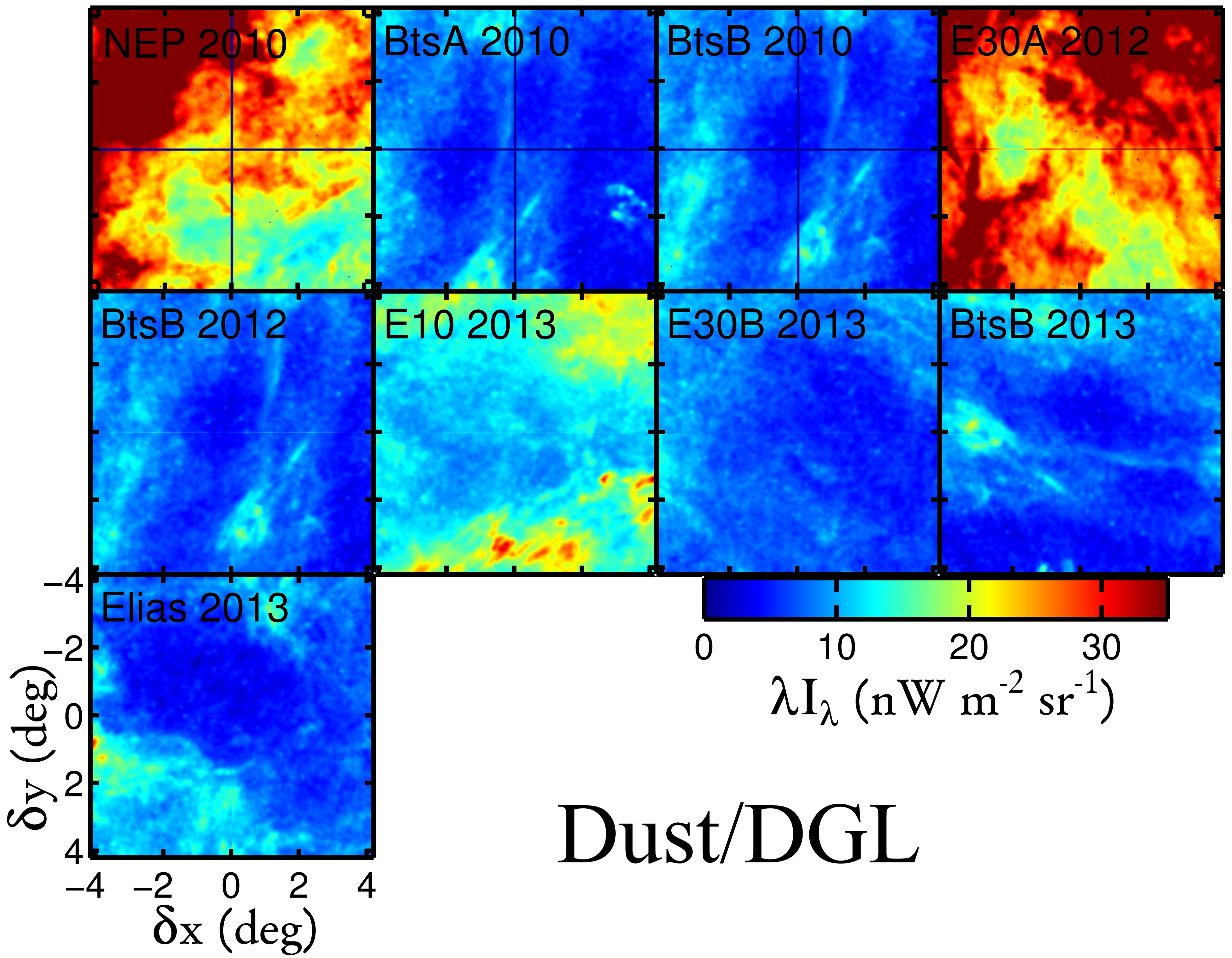




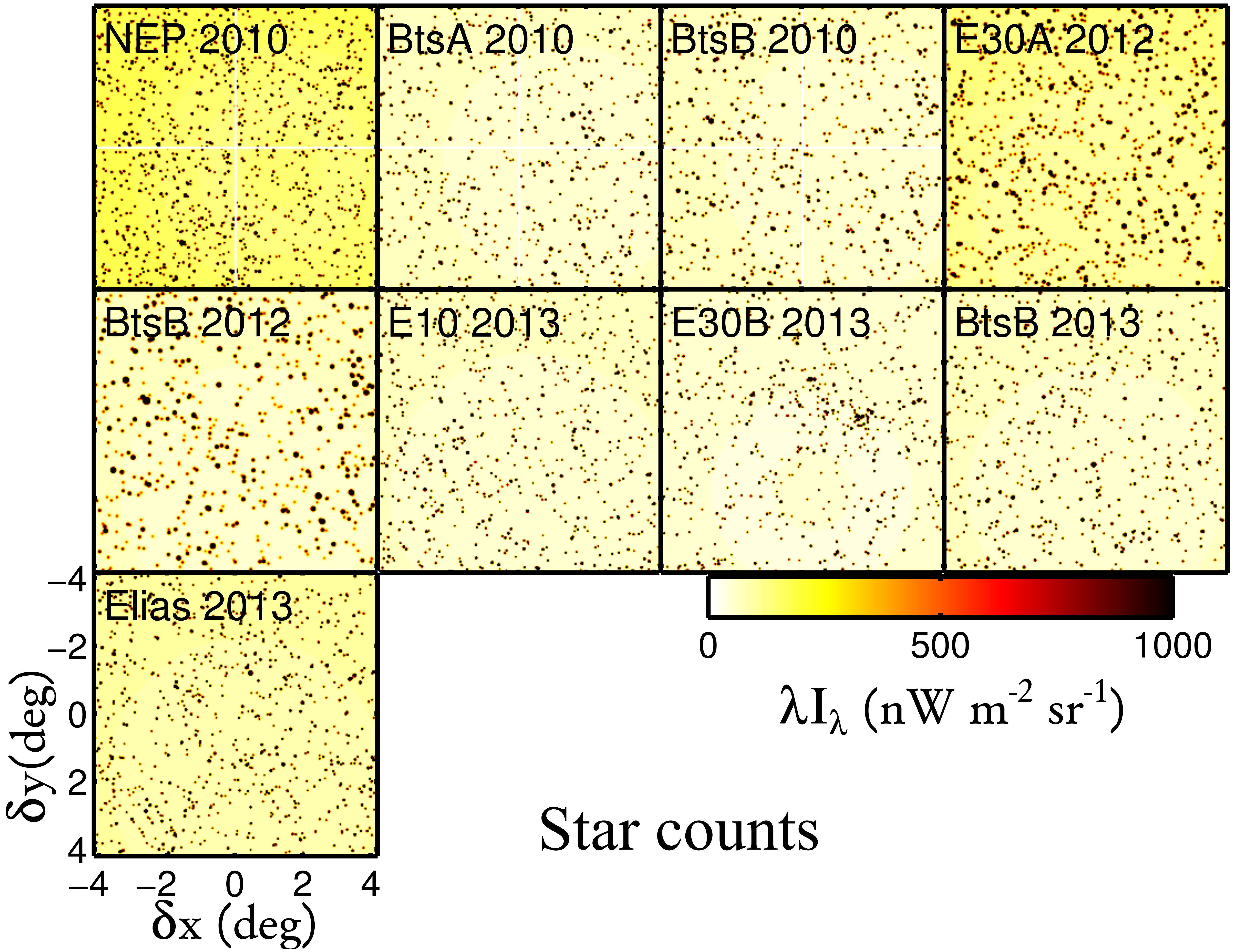
Dark current



Flat field



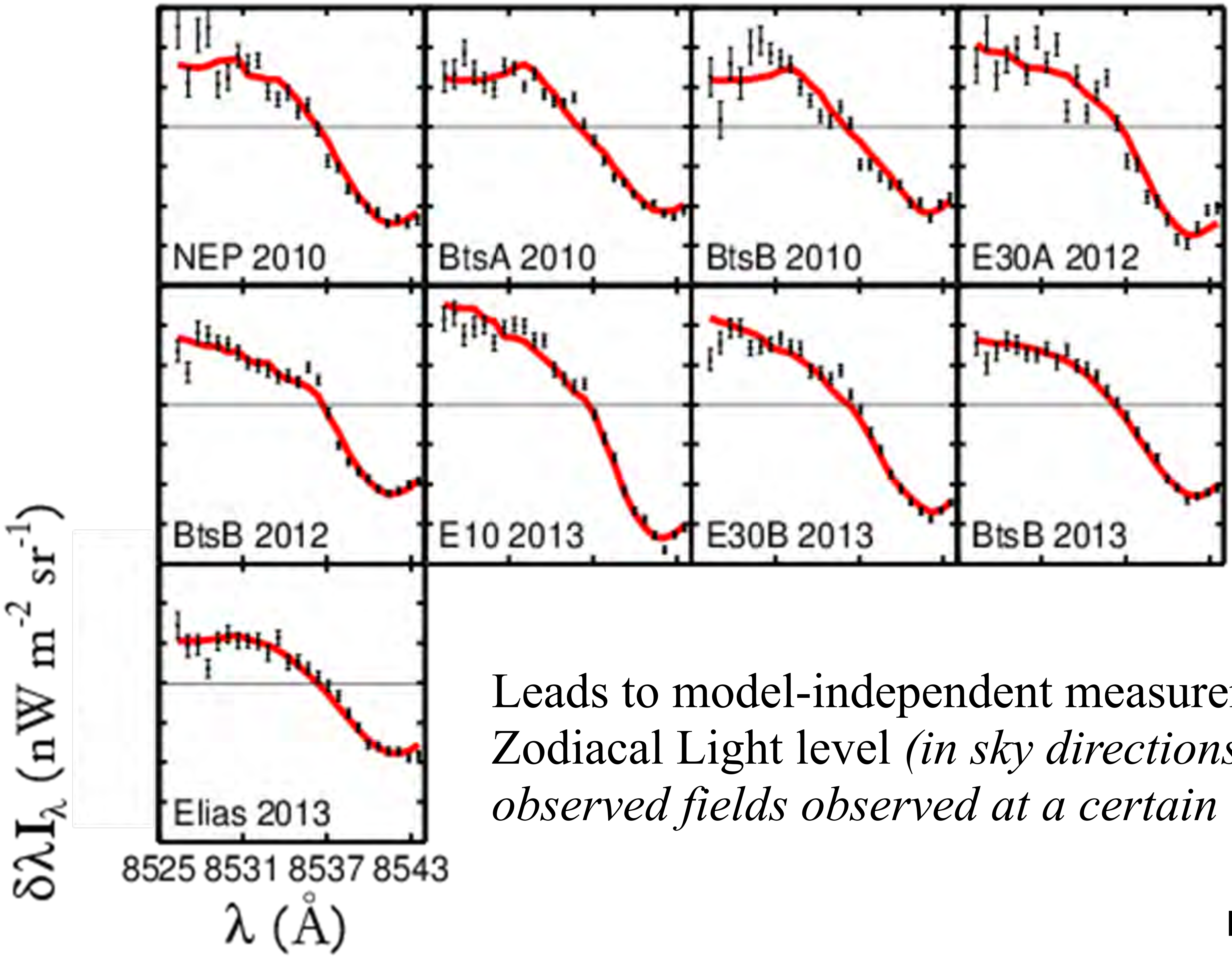
Dust/DGL



Star counts

Korngut et al. 2023

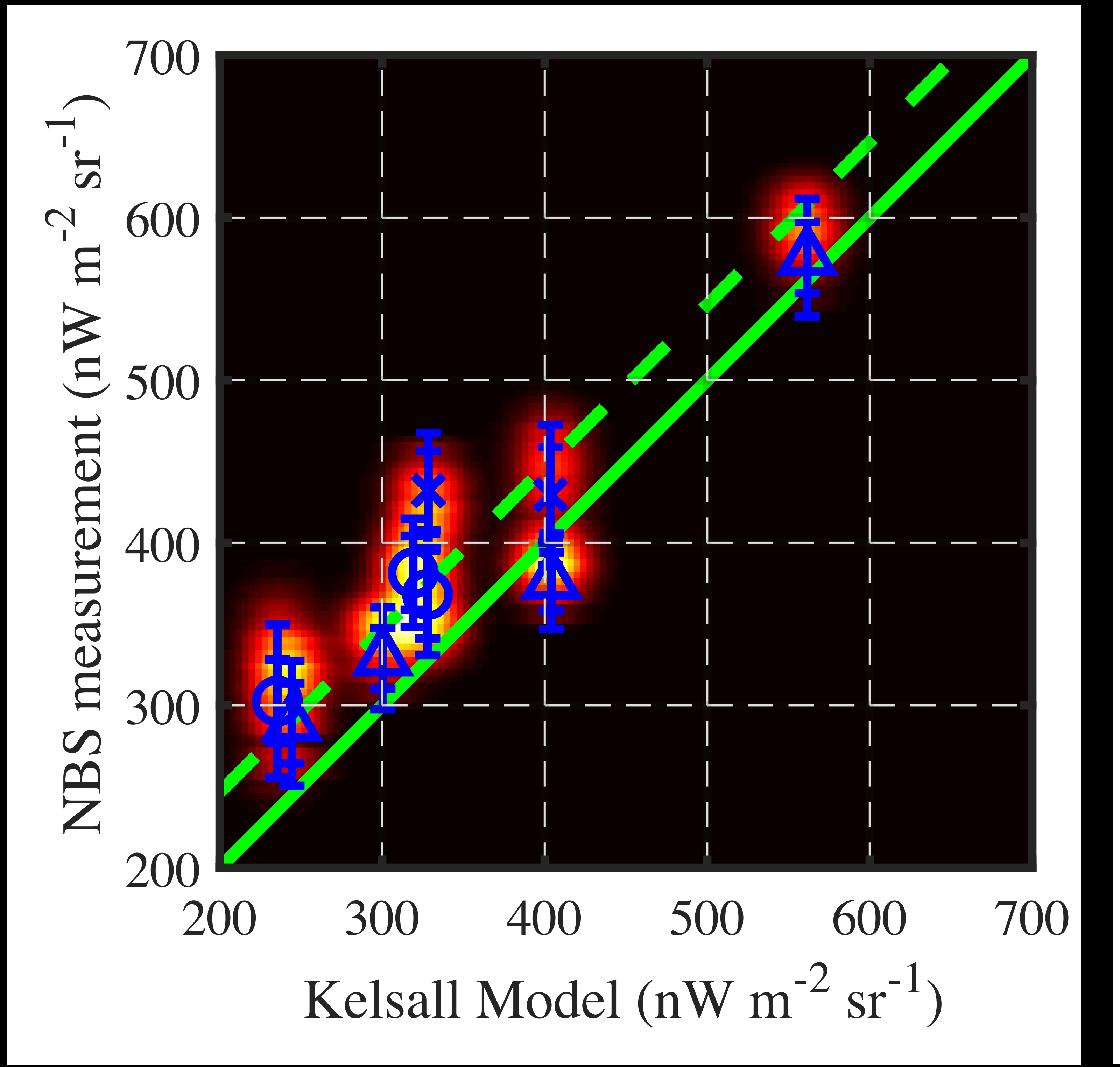
Best Fit Spectra For the Whole Sample

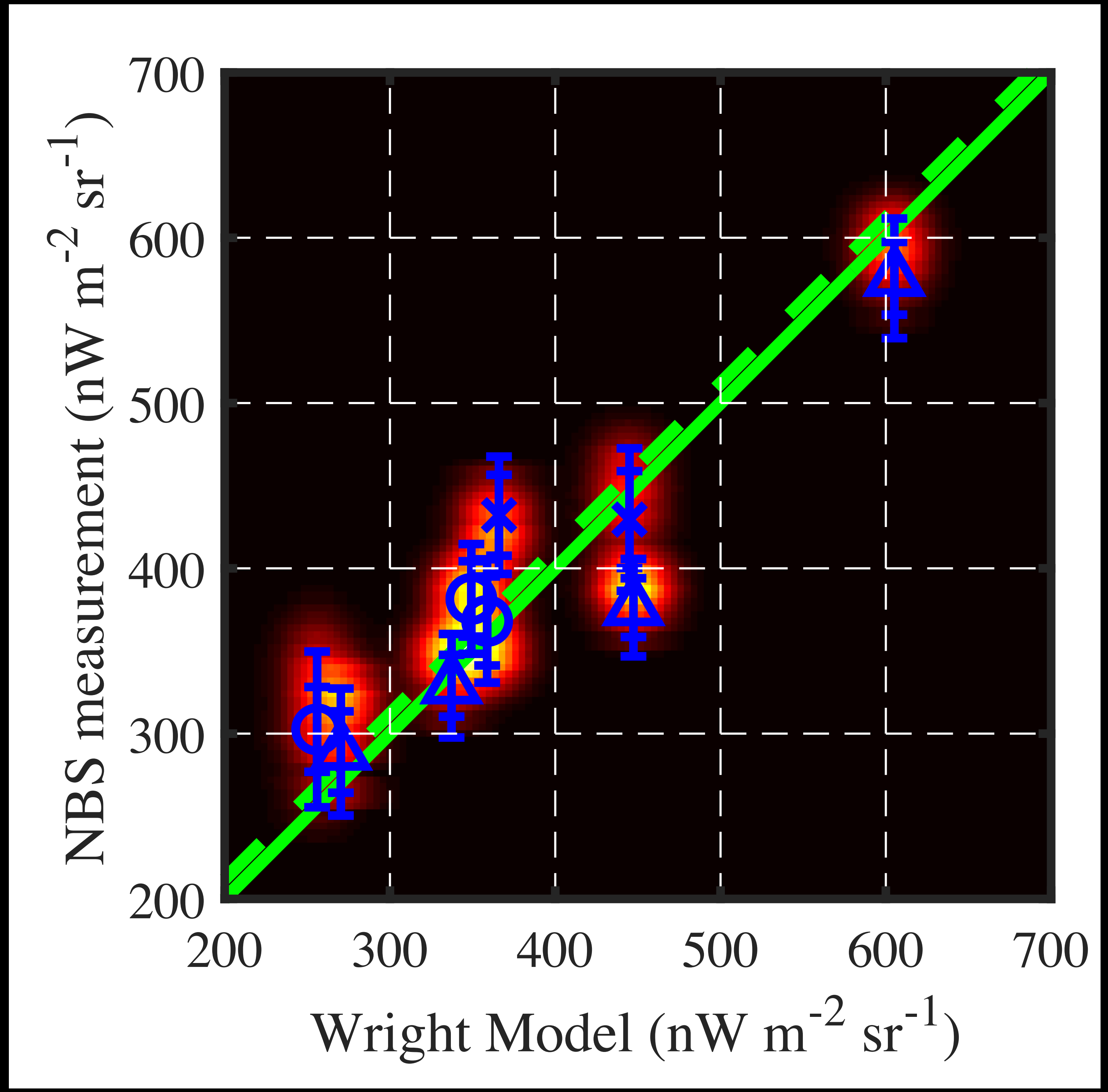


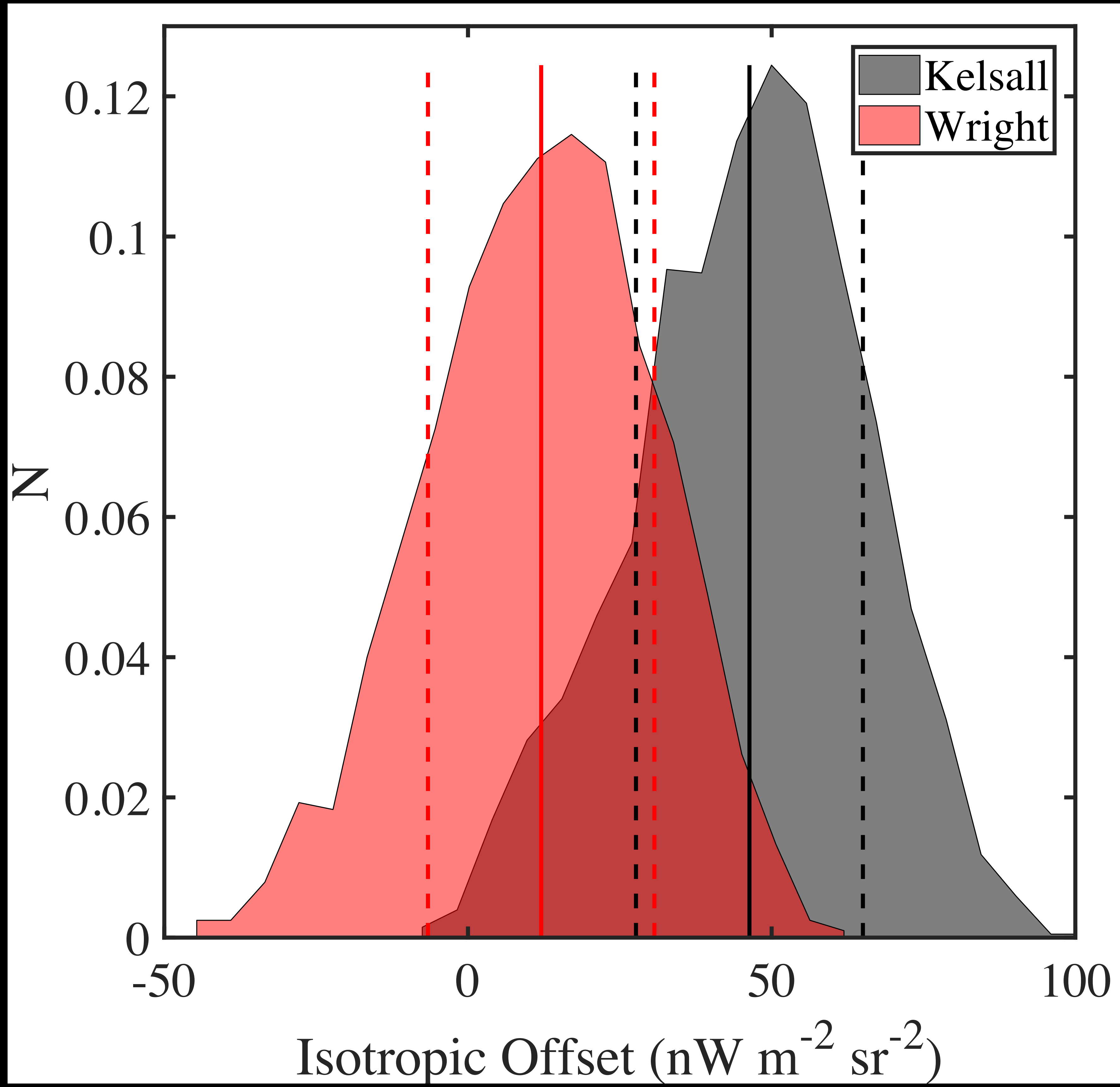
Leads to model-independent measurement of Zodiacal Light level *(in sky directions of the observed fields observed at a certain time).*

Korngut et al. 2023

Is there a missing component in Zodi models?







CIBER/NBS zodi measurement show an "isotropic" excess above Kelsall zodi models. 46 ± 19 nW m^{-2} sr^{-1} at 1.25 μm. An isotropic component is not in Kelsall model.

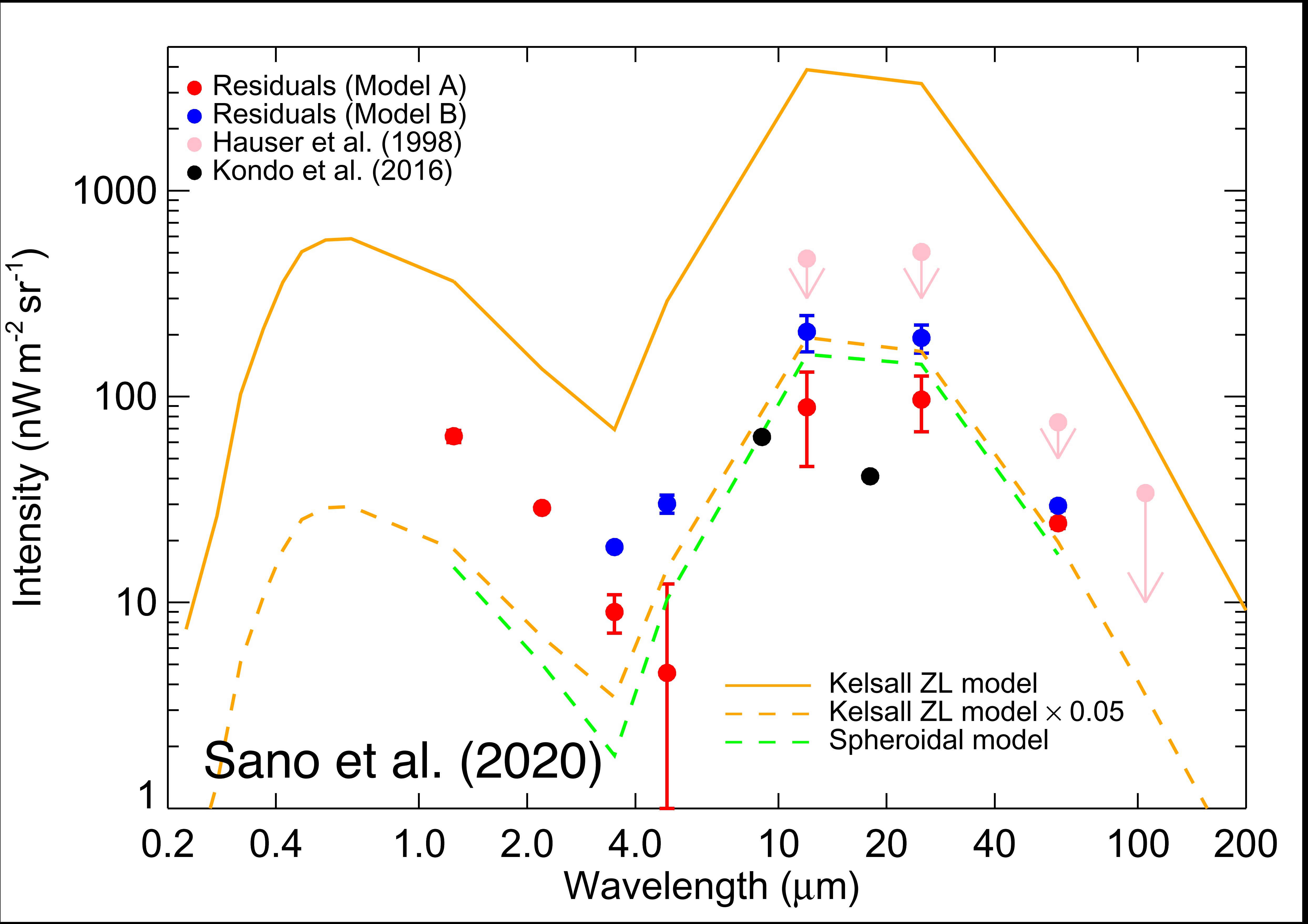
This excess is not seen in Wright (1988) zodi model - Wright re-normalization include flux from an isotropic component through 25 μm EBL assigned to zodiacal light.

Is there a missing component in Zodi models?

Origin of Zodiacal dust (Inter-Planetary Dust): Nesvorny et al. (2010): ~85-90% Jupiter family comets, ~10% Oort cloud comets, <10% asteroids. *(exact fraction depends on the size of the dust particle). Oort cloud comets (OCCs) produce an isotropic dust distribution, isotropic zodi.*

Also in models of Poppe et al. (2016)

Sano et al. (2022)
DIRBE reanalysis finds 5% of the zodiacal light intensity is isotropic.
19 ± 2 nW m^{-2} sr^{-1} at 1.25 μm.



Not all dust are equal: Dust responsible for scattering may not be the same dust seeing in emission at longer wavelengths.
Or, asteroidal dust may scatter more than cometary dust!

EBL Opportunity: Spitzer

Extragalactic Background Light =

Total sky brightness – Zodiacal light – Stars – ISM – Instrumental Bias

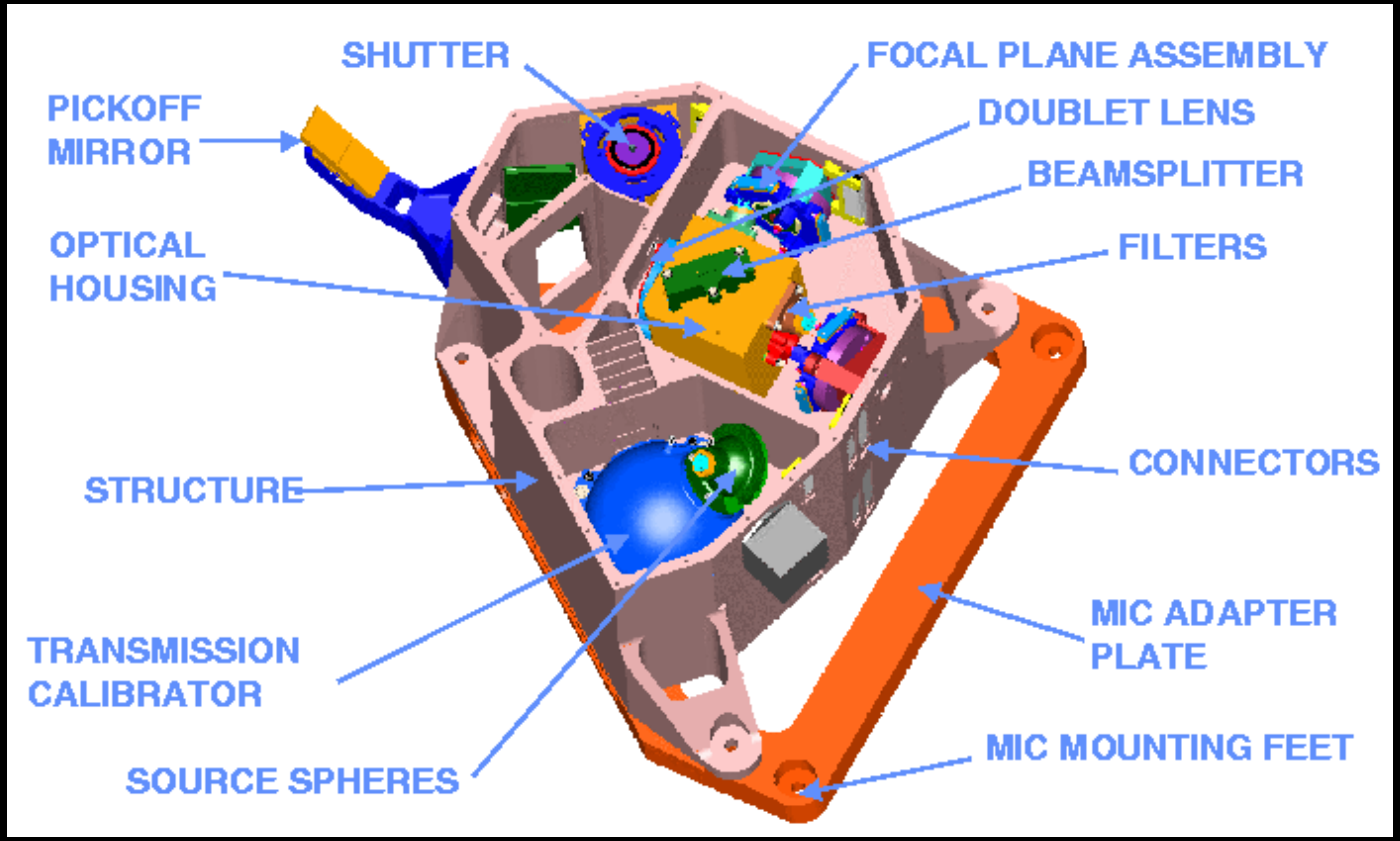
Measure Model/Measure Model/Measure Shutter

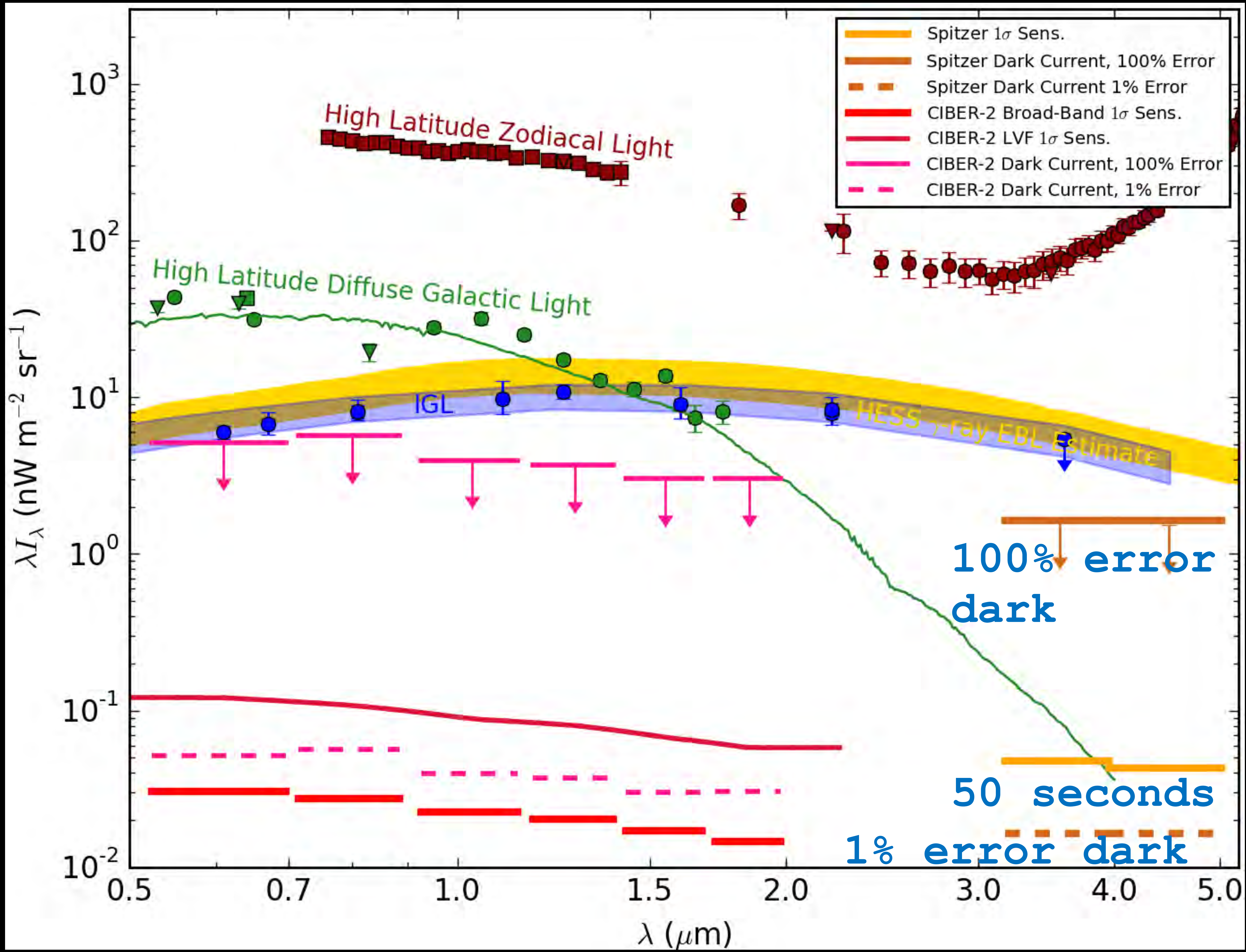
Spitzer/IRAC had a shutter but never used (soon after launch in instrument verification shutter did not behave properly and it was decided to leave shutter open for all of IRAC operations.

Spitzer can absolute calibrate time-dependence in NEP or other fields, with multiple observations separated at ~ 1 month, as a way to improve Zodiacal light models at 3.6 and 4.5 μm

Proposal was to do a new measurement of EBL with an improved ZL model.
Spitzer operations thought it was risky using the shutter even during the last few months of the mission.
Spitzer shutter was only used during the last 24 hours of observations. Shutter had no mechanical issues!

EBL Opportunity: Spitzer

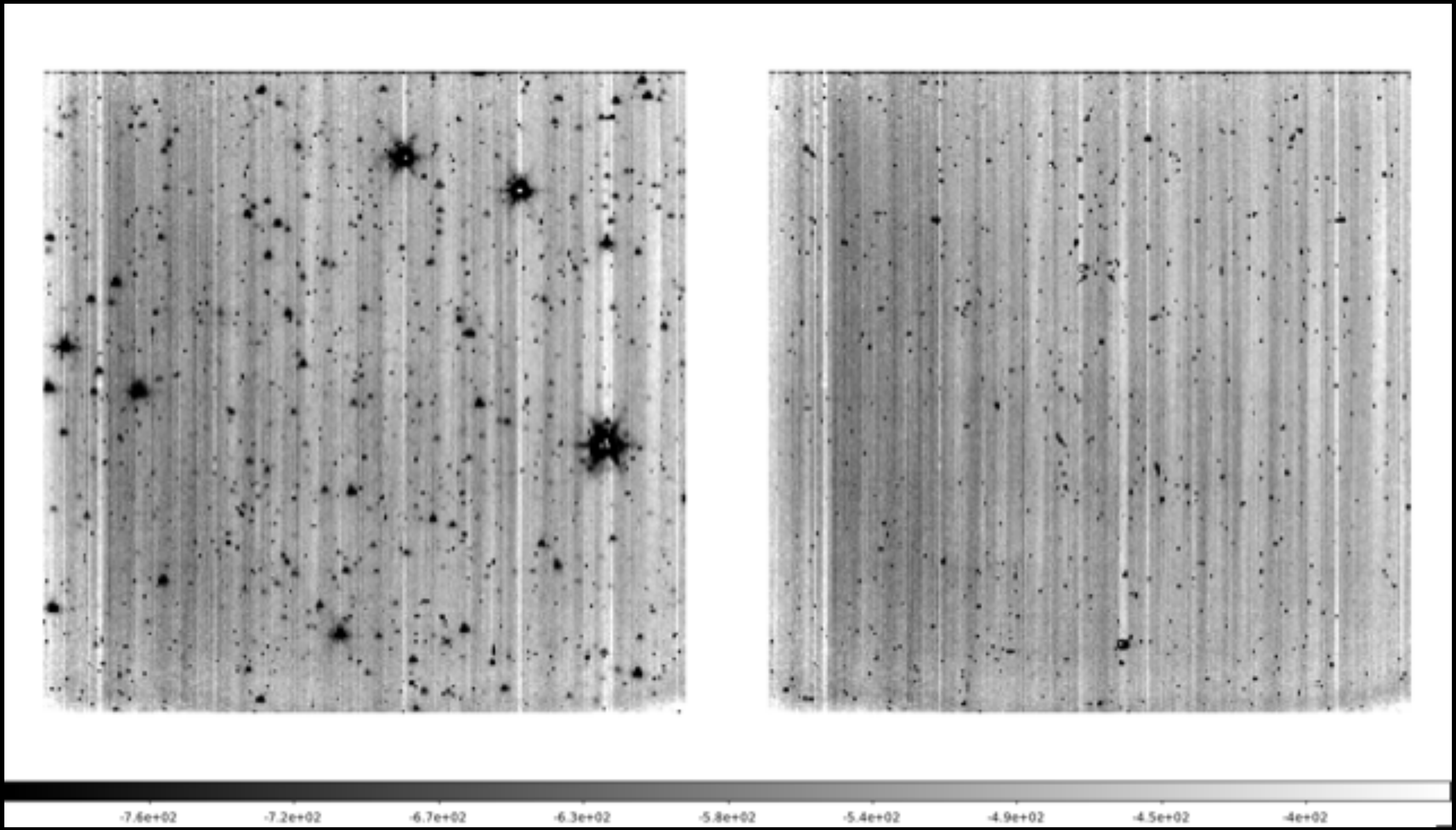




Proposed a proper zodi/EBL program over 1600 hours during the last six months, allocated 24 hours of DDT observations during the last day of Spitzer operations.

EBL Opportunity: Spitzer

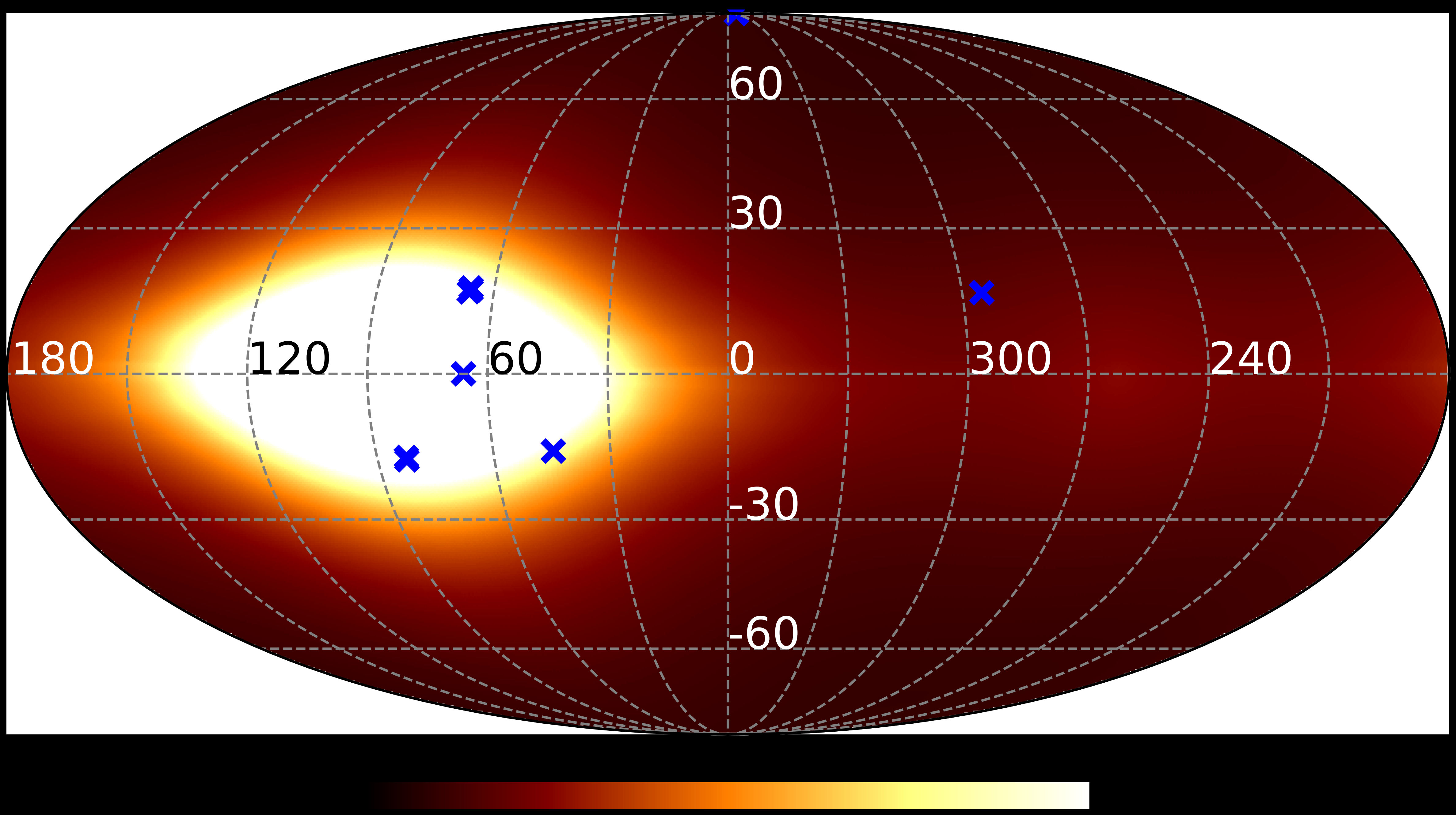
Raw frames - first ever shutter closed IRAC image (Jan 28 2020), 17 years after launch.
Spitzer powered down: Jan 29 2020

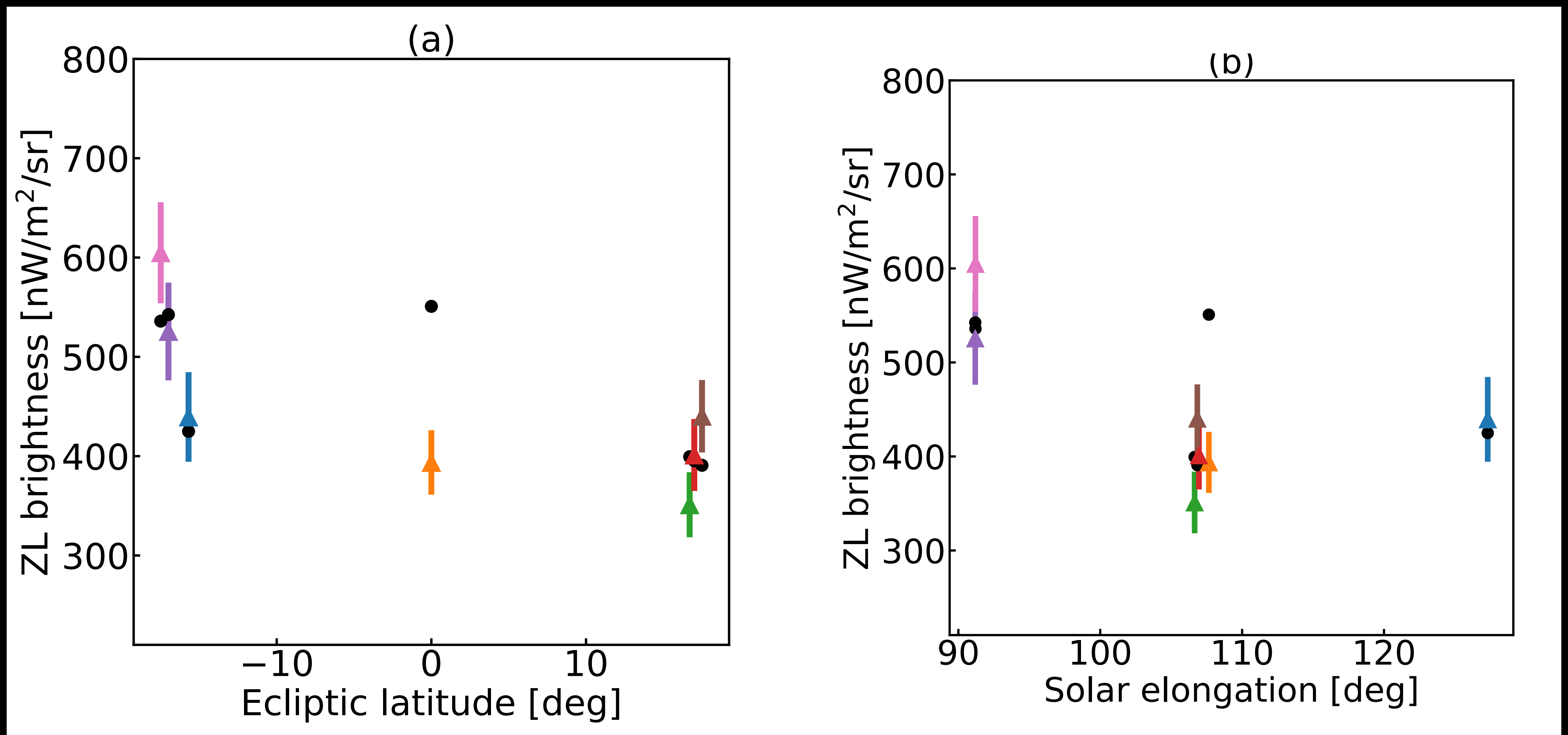


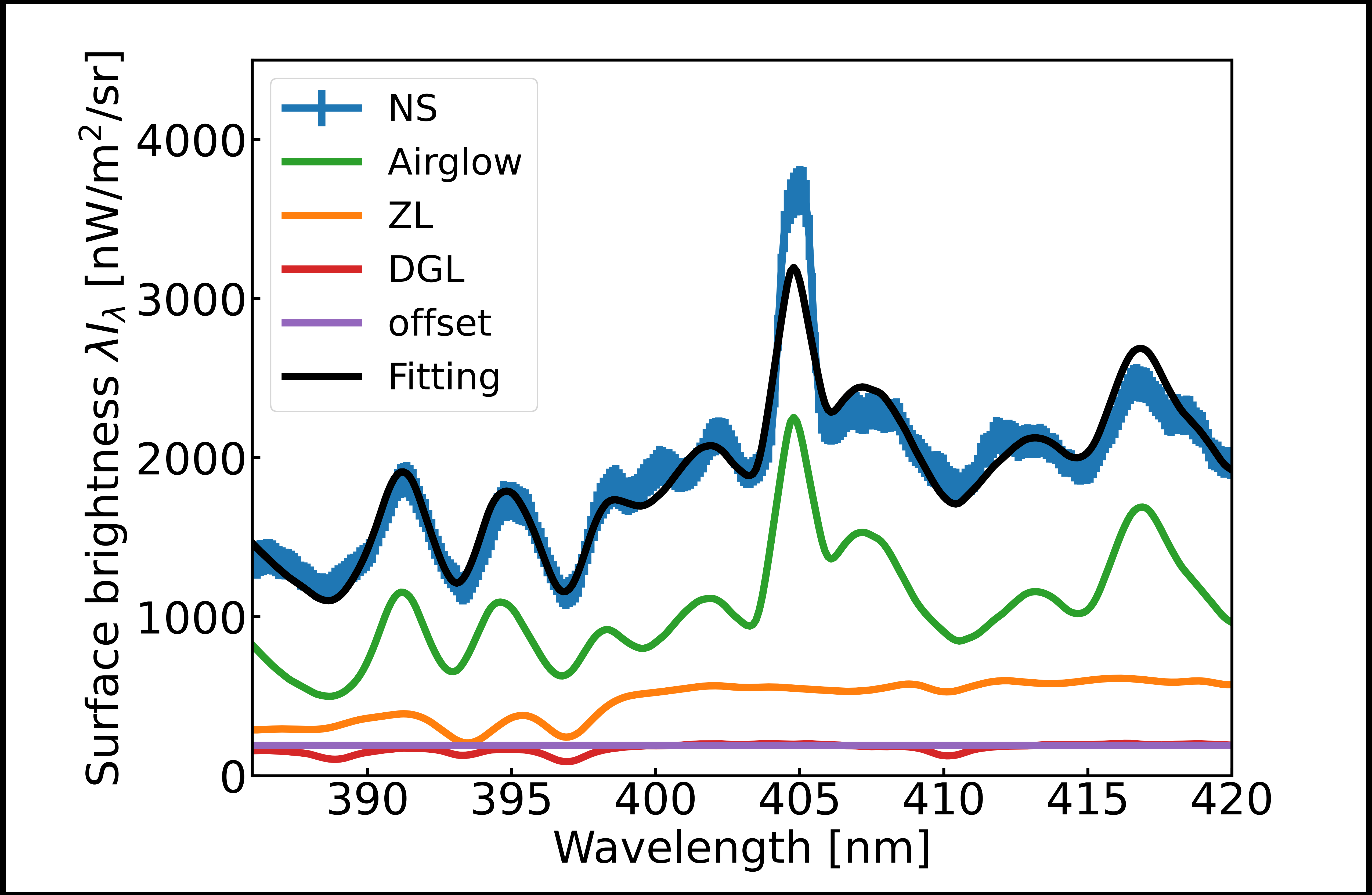
Shutter open

Shutter closed

Spitzert + Ground Palomar observations of Fraunhofer lines of IRAC shutter fields

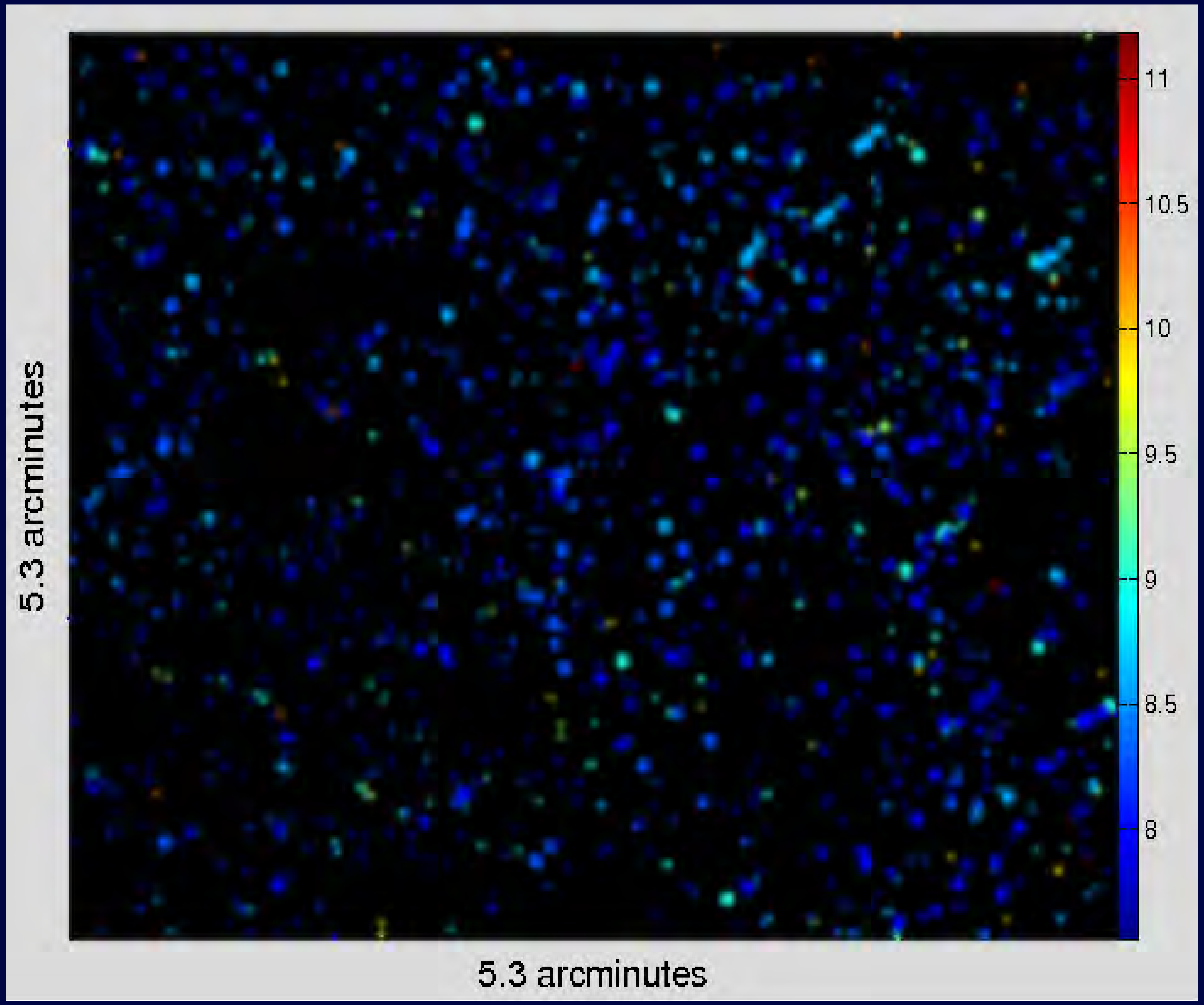


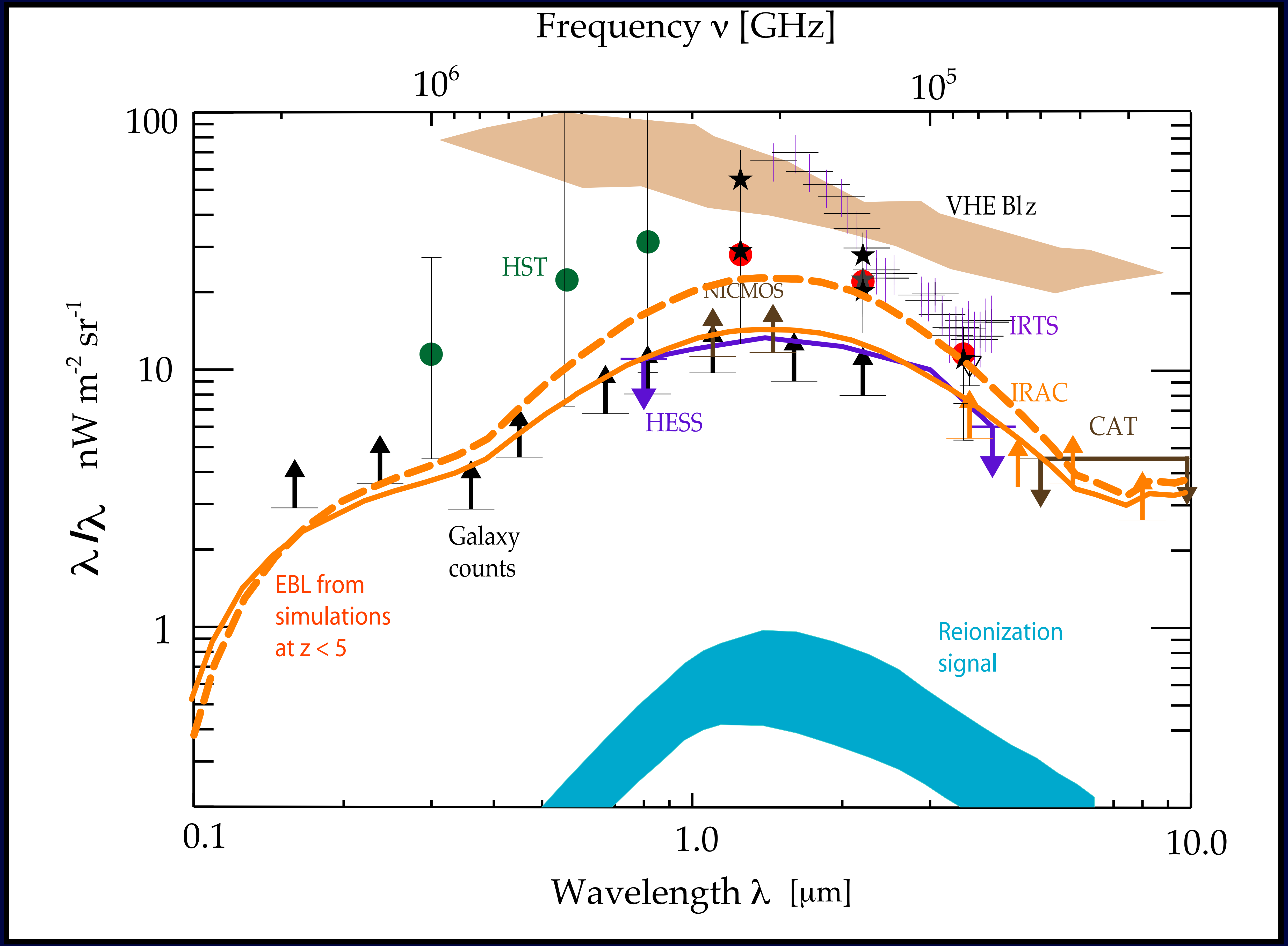




Hanzawa et al. 2023

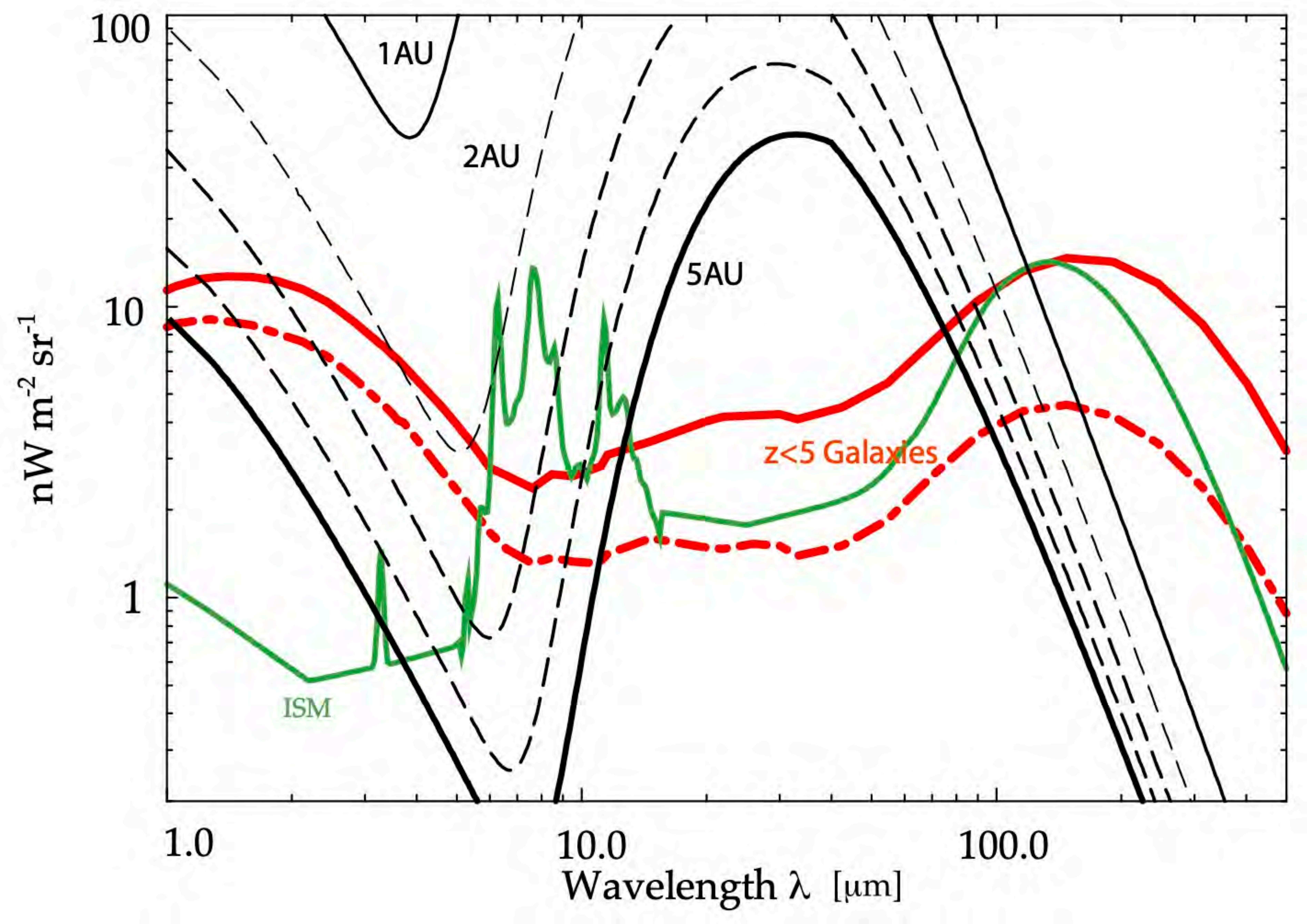
Can we ever measure EBL to sub-1% accuracy?



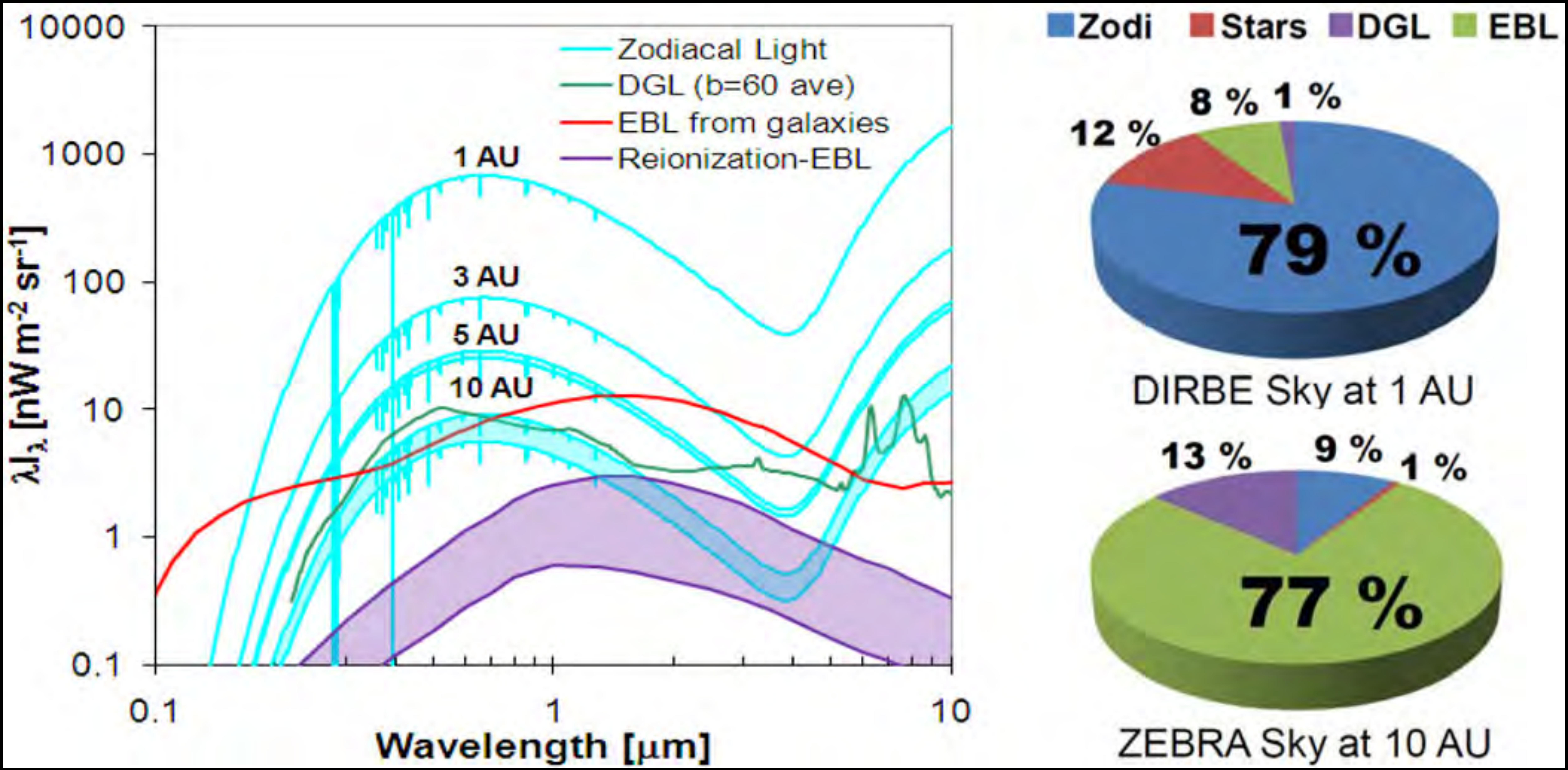


What do we need:

A small aperture telescope with multi-wavelength coverage observing outside of 5-10 AU



100
10
1
1.0
10.0
100.0
nW m^-2 sr^-1
Wavelength λ [μm]
1AU
2AU
5AU
z<5 Galaxies
ISM



Zodiacal Light
DGL (b=60 ave)
EBL from galaxies
Reionization-EBL
1 AU
3 AU
5 AU
10 AU
λIλ [nW m-2 sr-1]
Wavelength [μm]
10000
1000
100
10
1
0.1
0.1
1
10
Zodi
Stars
DGL
EBL
12 %
8 %
1 %
79 %
DIRBE Sky at 1 AU
13 %
9 %
1 %
77 %
ZEBRA Sky at 10 AU

ZEBRA Mission Concept Study

Concept Study for Strategic Space Flight Science Missions

ZODIACAL DUST, EXTRAGALACTIC BACKGROUND AND REIONIZATION APPARATUS

A Science Enhancement Option for an Outer Planet Discovery Mission

ZEBRA Mission Concept Study

Concept Study for Strategic Space Flight Science Missions

ZEBRA

ZODIACAL DUST, EXTRAGALACTIC BACKGROUND AND REIONIZATION APPARATUS

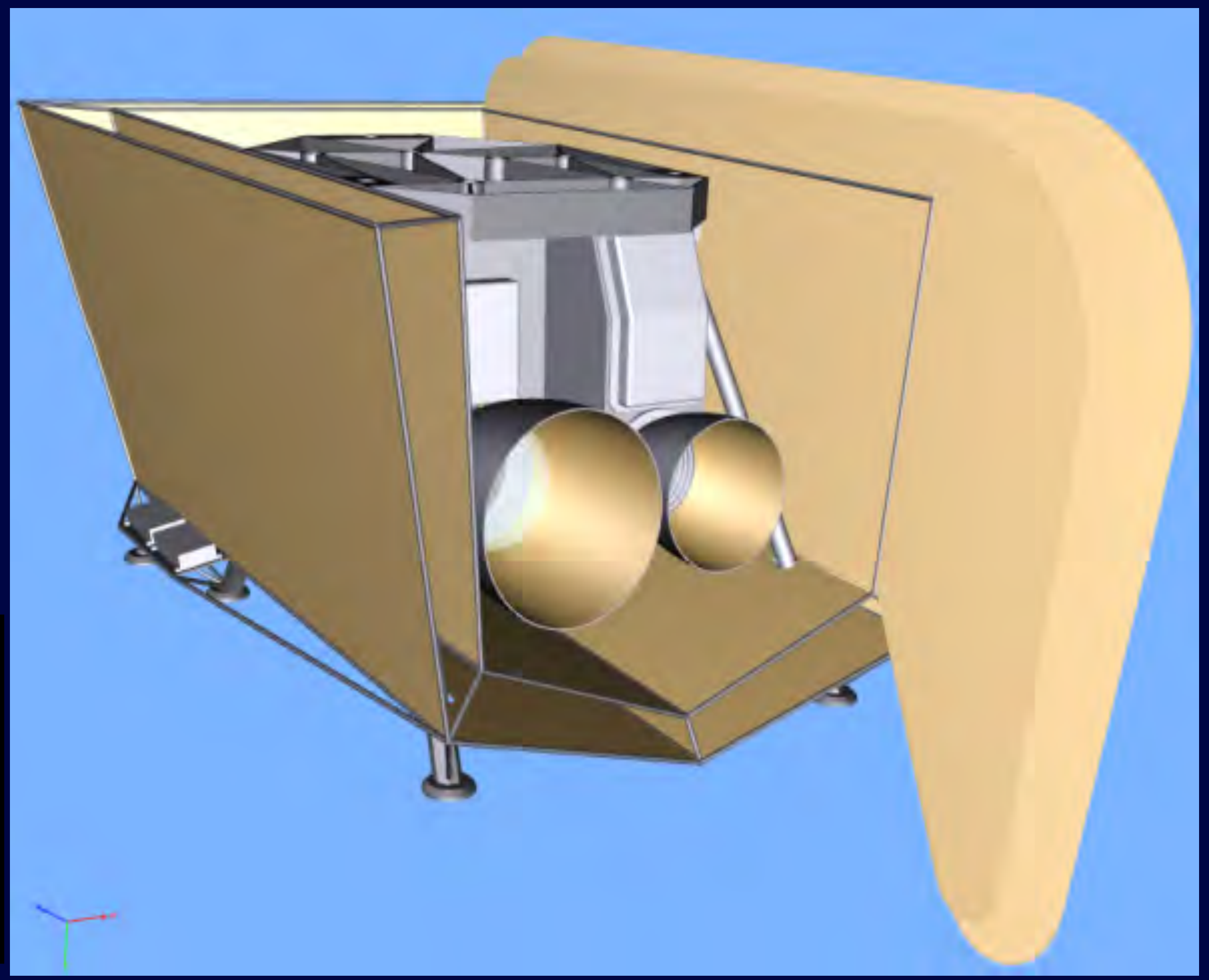
Two Fundamental Science Goals in One Instrument to the Outer Planets

- **Extragalactic Background Light**
  - Measures galaxy history
  - Epoch of reionization galaxies
- **Zodiacal Dust**
  - Structure and origin of solar system dust
  - Detect and map Kuiper belt dust

Bock, Cooray et al. 2012
Mission of Opportunity proposal to NASA for an instrument for EBL as part of a mission to Saturn

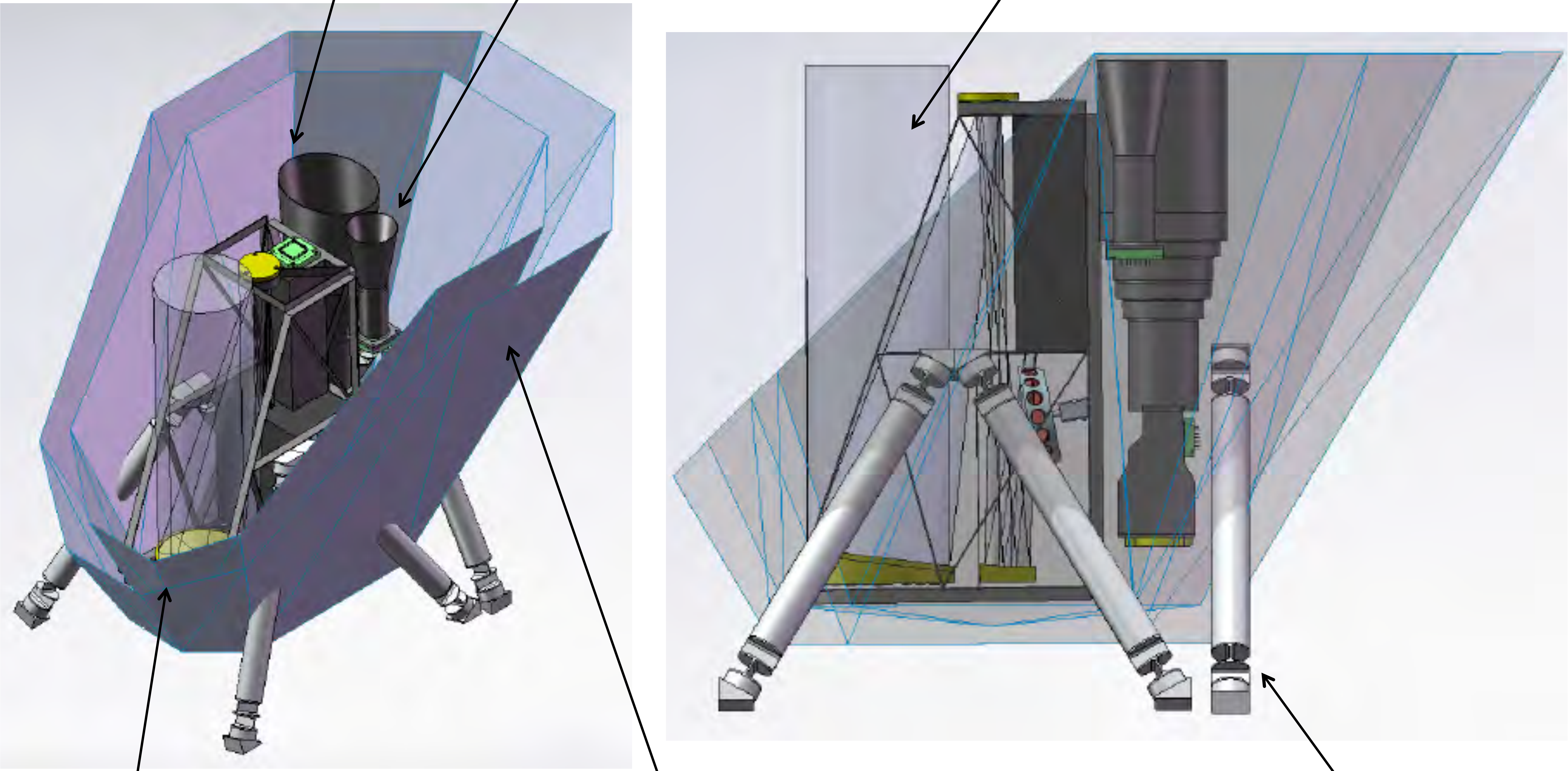
- Platform: Outer planets mission to Saturn
- Description of payload instrumentation: Optical to near-infrared absolute photometer with 15 cm telescope; Wide field optical camera with 3 cm telescope
- Mission duration: 5-year outer planets cruise-phase
- Temperature: 50 K
- Pointing requirements: 0.5″ stability over 500 s.
- Data rate to ground (kbits/day): 0.5 Mbpd

ZEBRA is a high-TRL instrument with minimum impact to host mission
- All key technologies demonstrated
- Well-defined interfaces
- ZEBRA engineers offset to net mass



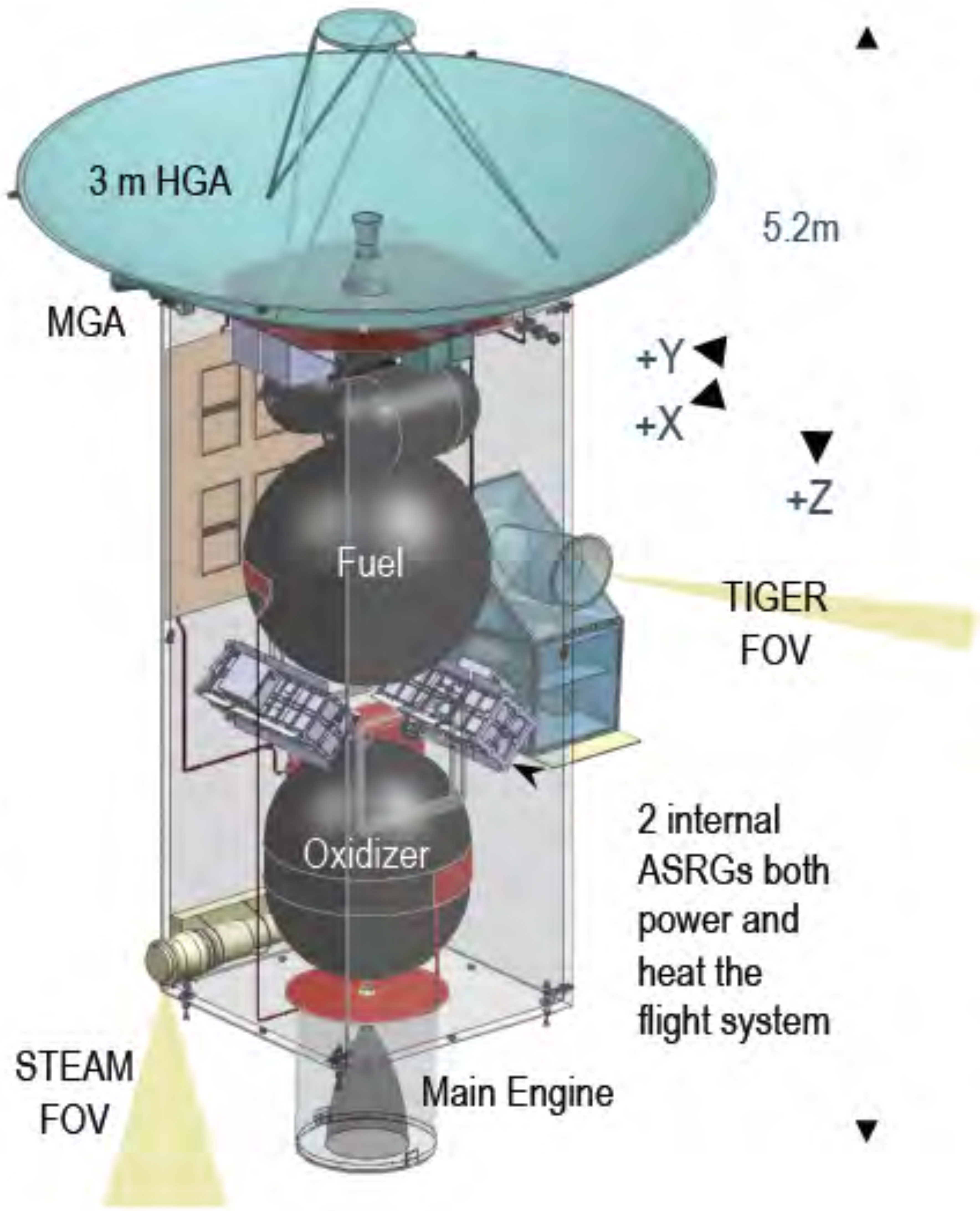
Optics: 15 cm & 3 cm off-axis
Wavelengths: 0.4 – 5 μm
Cooling: Passive to 50 K

Instrument Overview



We need a host craft

e.g a mission to Enceladus

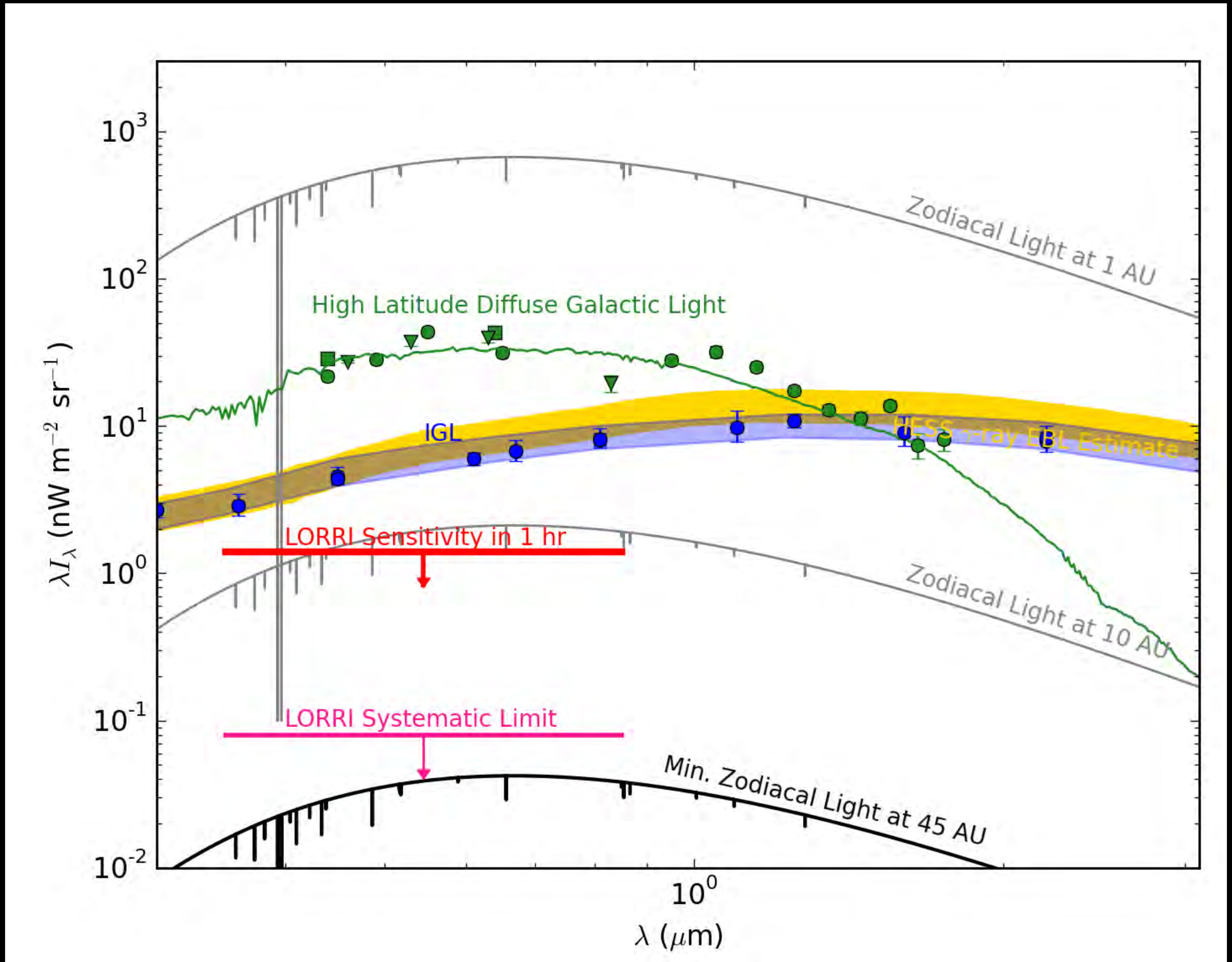


- 3-axis stabilized, redundant RWA
- Two 30-A-hr Li-ion batteries for peak load
- X-Band comm: HGA, MGA, 2 LGA
- 2 NASA ASRGs also heat subsystems
- 1-axis TIGER gimbal, S/C roll for 2nd DOF
- 652.7 kg dry, 1786 kg wet, 25.2% margin
- 32 Gb storage, 4 flyby capacity
- Flight-qualified solar system avionics
- Dual-mode biprop with 2.45 km/s ΔV
- Standard intermediate LV from CCAFS

Use the small instrument during
cruise phase between Jupiter and Saturn

ZEBRA was not selected in 2012. And we have yet to re-propose (hard to put an astrophysics instrument to a planetary S/C - at least with NASA)

Since 2018 or so, EBL with New Horizons/LORRI instrument

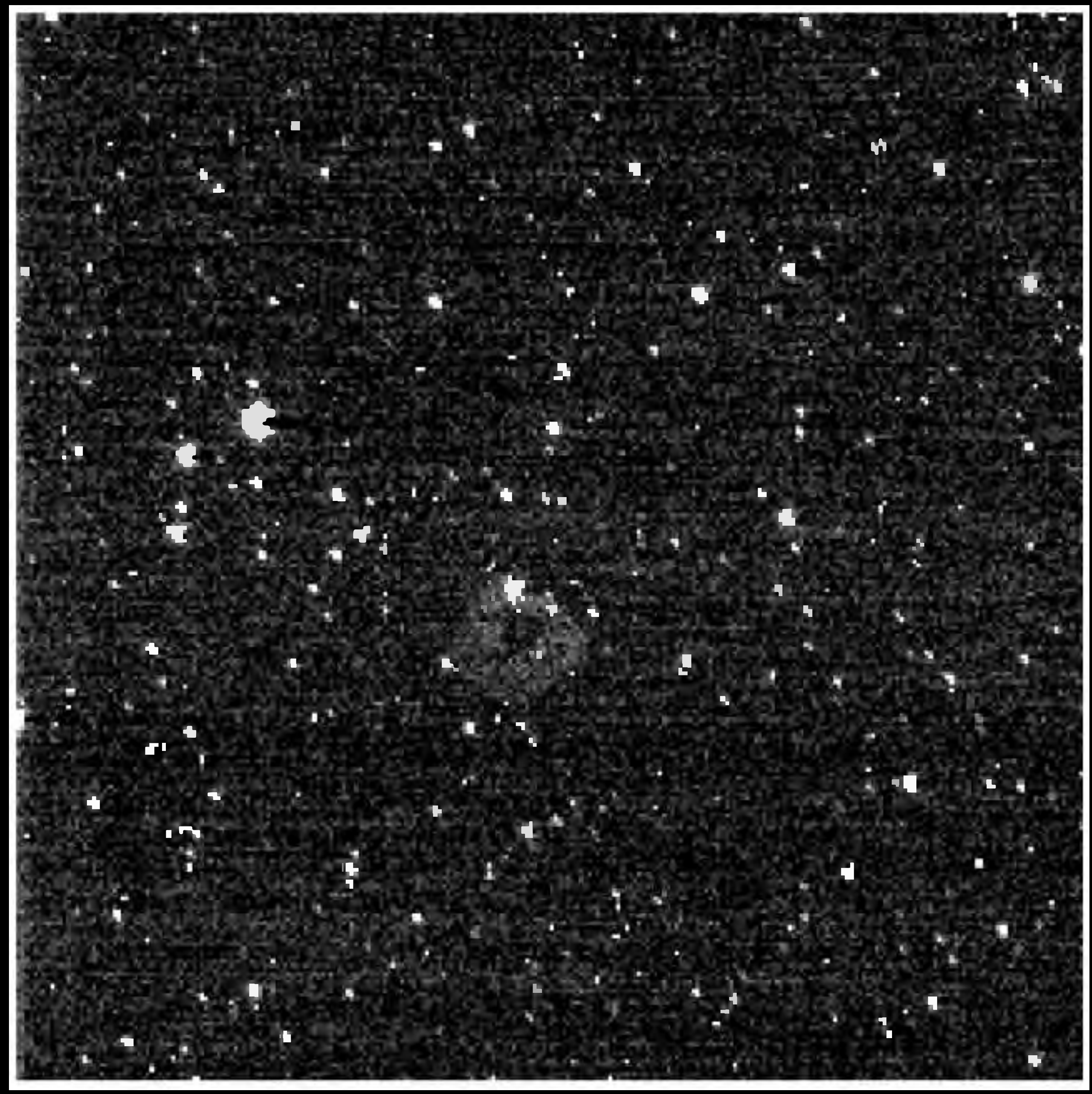


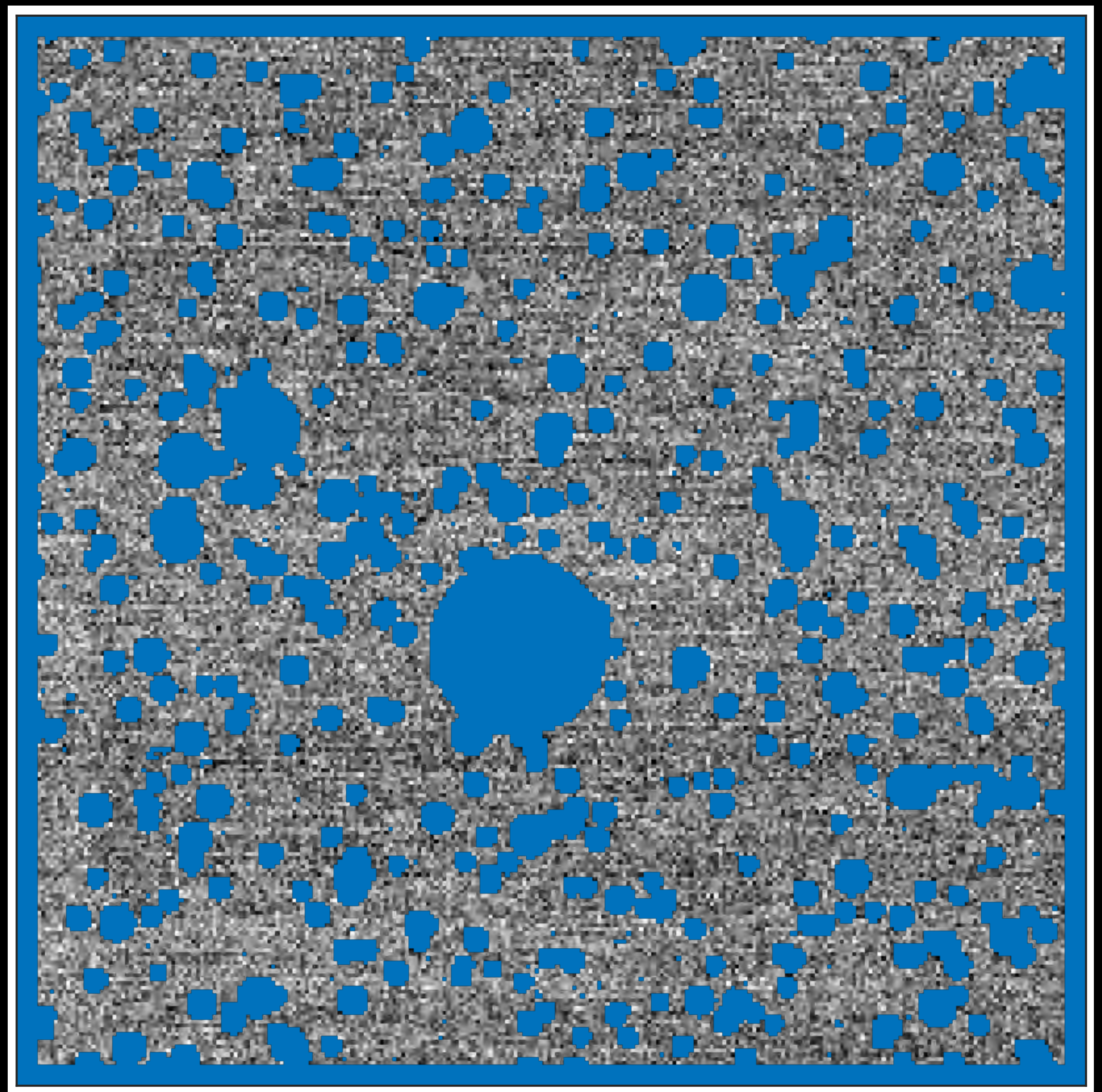
Teresa Symons RIT PhD/UCI Postdoc

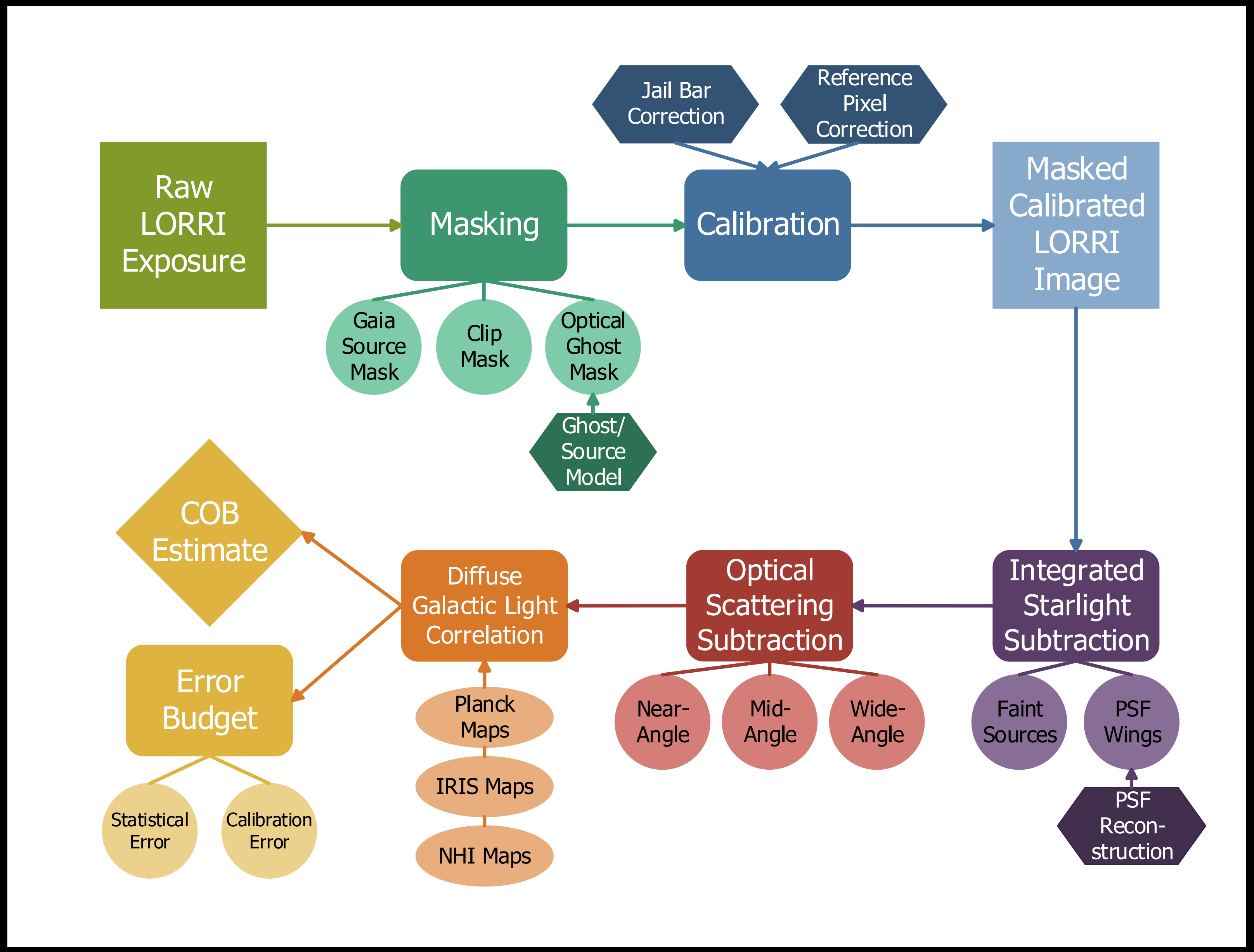
Symons et al. 2023

Parameter	LORRI	Ralph/MVIC	Ralph/LEISA
Wavelength Range	350-850 nm, single band.	400-975 nm 400-550 nm 540-700 nm 780-975 nm 860-910 nm	1.25 – 2.5 mm, LVF
Spectral Resolution	1.2	1.2, 3.2, 3.9, 4.5, 17.7	240
PixelResolution	1.0x1.0 arcsec^2	4.1x4.1 arcsec^2	12.8x12.8 arcsec^2
FOV (smallest w/ complete spectral sampling).	0.29 deg x 0.29 deg	5.7 deg x 0.037 deg	0.9 deg x 0.9 deg
N_{pix}	1024x1024	Wide-band 2x5000x32 pix; all others 5000x32 pix	256x256 (~1 pix/spectral band)
Telescope Aperture	20.8 cm	7.5 cm	7.5 cm
Diffraction Limited Performance	0.5 arcsec	2.0 arcsec	5.3 arcsec
Temperature	200 K	200 K	100 K
Nominal Spectral Scan Speed	-	? (32x row transfer time)	25.7 arcsec/s
Data Size (@ 16 bits/pixel)	16.8 Mb/frame (1.0 Mb/frame in 4x4 pixel means).	17.9 Mb/frame	1.0 Mb/frame
Max Integration Time	30 s	4 s (?)	4 s
Point Source Sensitivity	V=19.3 1σ in 4x4 pixel bins in 30s	V=10 14σ in 0.25 s	?
Surface Brightness Sensitivity	4.06x10^3 nW m^{-2} sr^{-1} pixel rms in 30 s	9.51x10^4 nW m^{-2} sr^{-1} pixel rms in 4 s	6x10^4 nW m^{-2} sr^{-1} pixel rms in 4 s
Total Surface Brightness Sensitivity	16 nW m^{-2} sr^{-1} at 1σ in 30 s	170 nW m^{-2} sr^{-1} at 1σ in 4 s	750 nW m^{-2} sr^{-1} at 1σ in 4 s at R~10

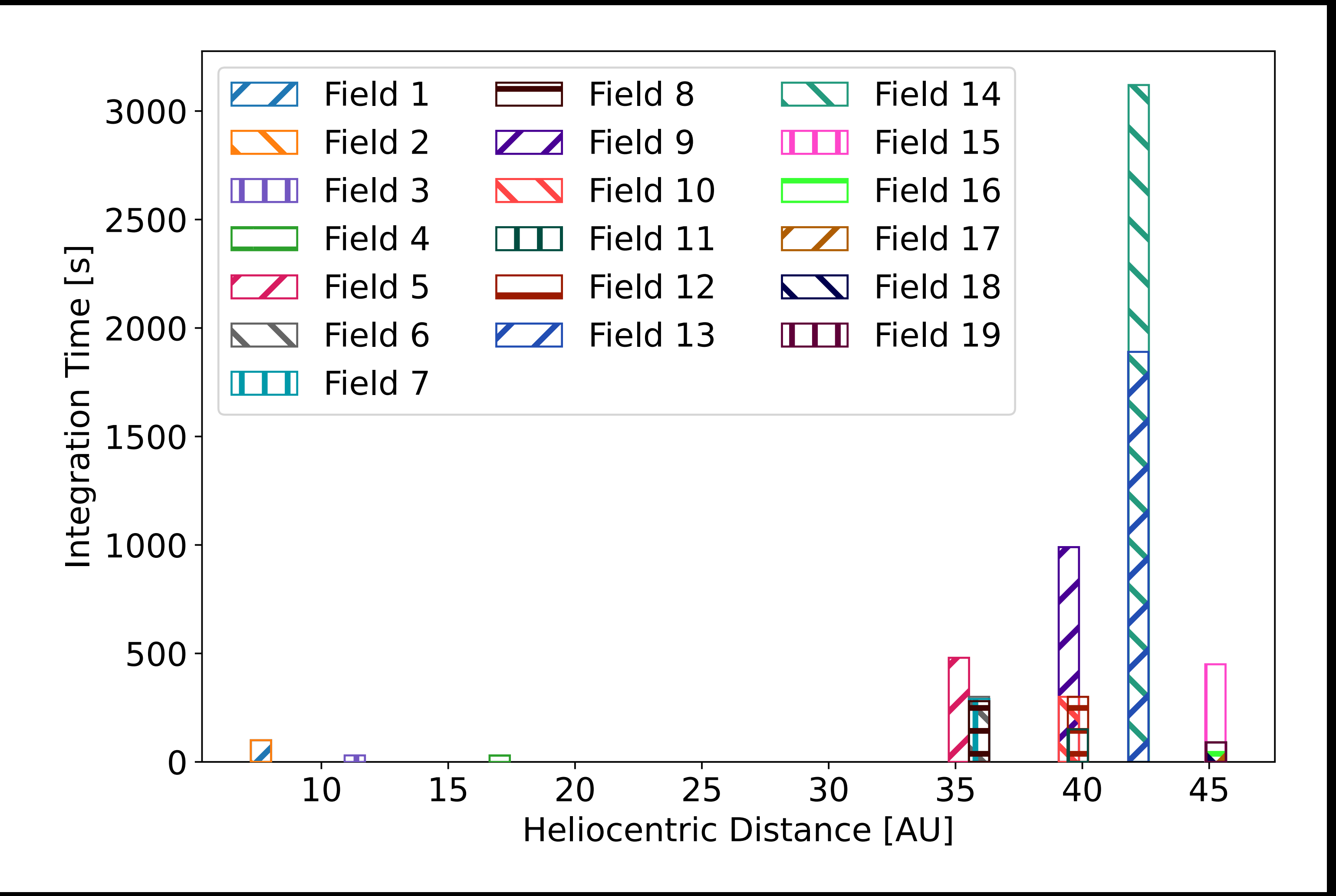
Since 2018 or so, EBL with New Horizons/LORRI instrument



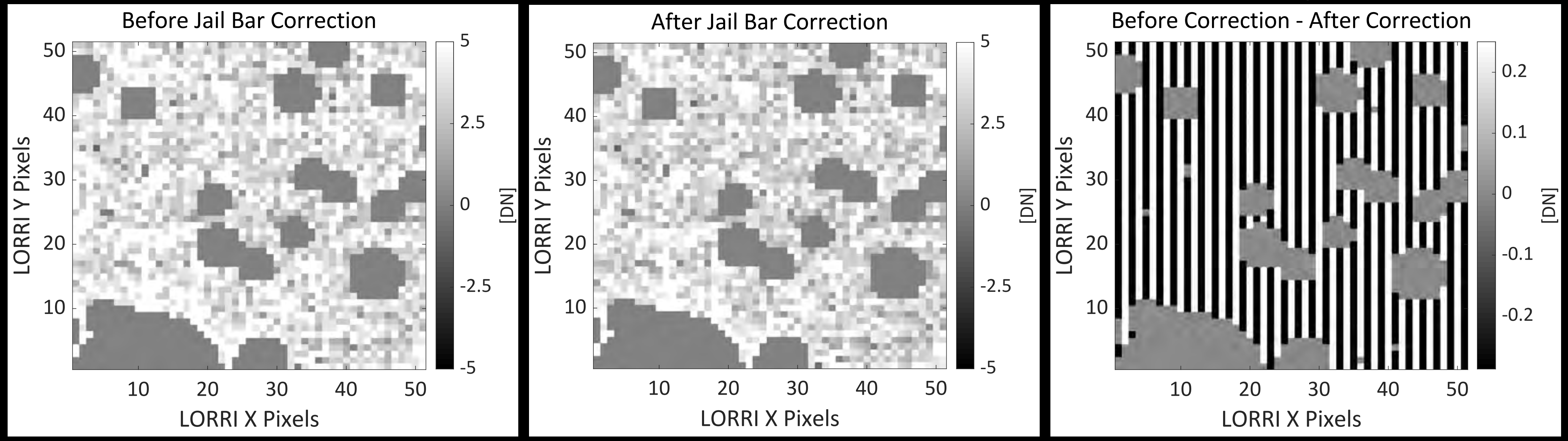




LORRI was not designed for EBL measurements - straylight/ghosts (donut)

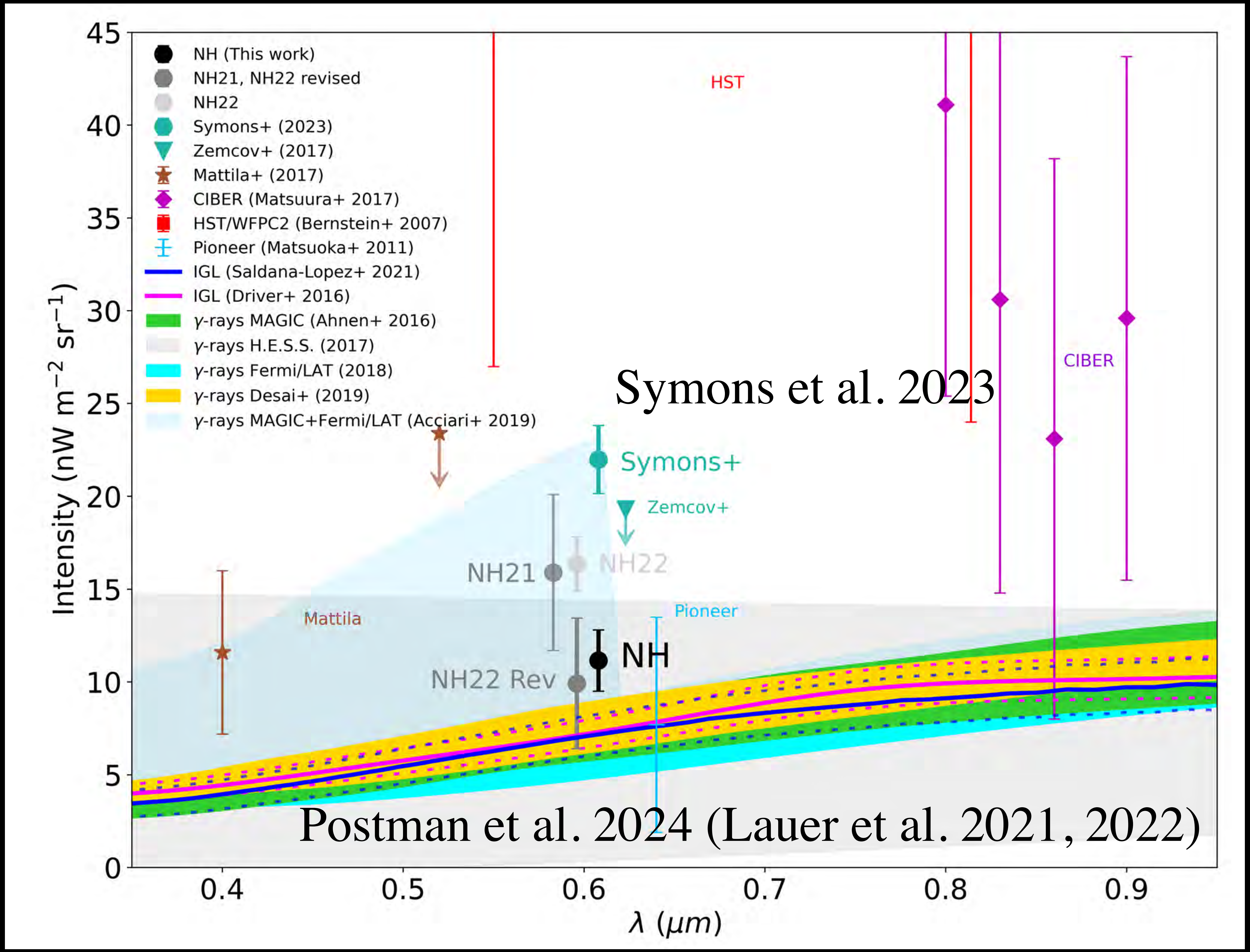


LORRI readout electronics amplifier bias (jail bar)



each readout column has a different bias due to small voltage offsets.

Since 2018 or so, EBL with New Horizons/LORRI instrument

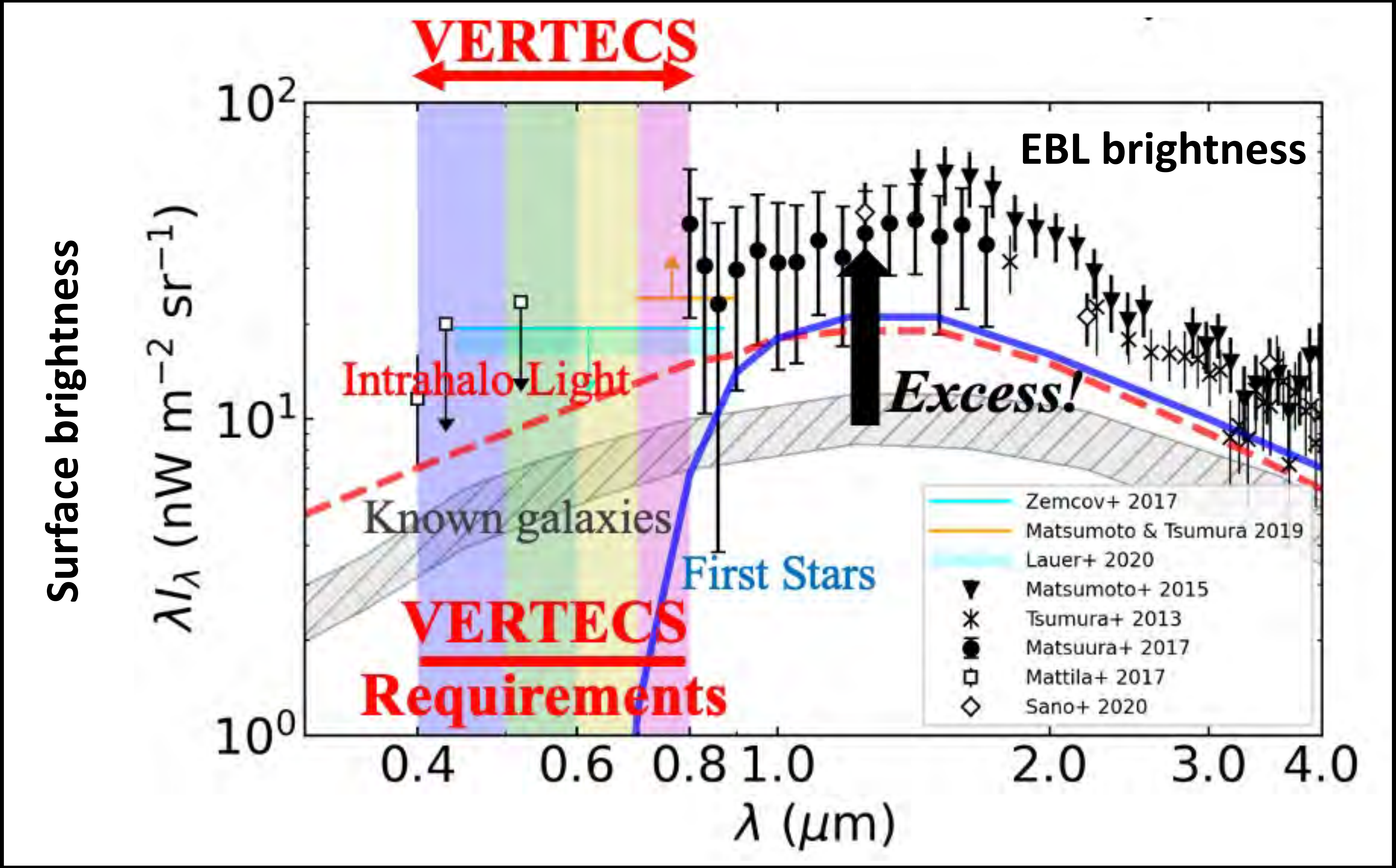


Is there an isotropic zodi component at 1 AU? - answer seems yes (from CIBER NBS; Sano et al.)

Is there an isotropic zodi-like component at 50 AU? - likely not according to latest New Horizons/LORRI team analysis (Postman et al. 24):
2.99 ± 2.03 nW m^{-2} sr^{-1} excess (~1.5σ)

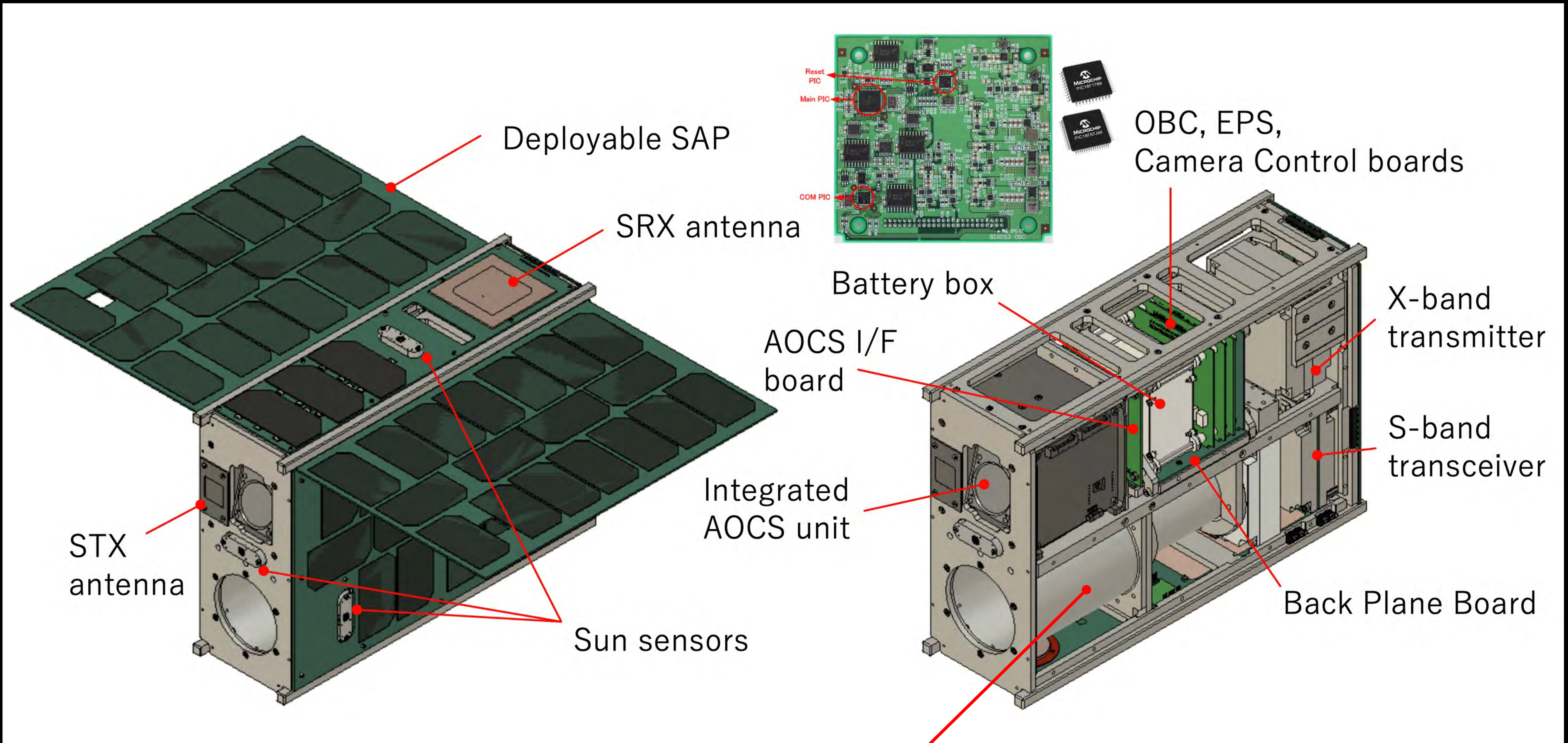
Leaves a very small contribution above IGL and EBL inferred from TeV absorption spectra.

EBL Opportunity: VERTECS



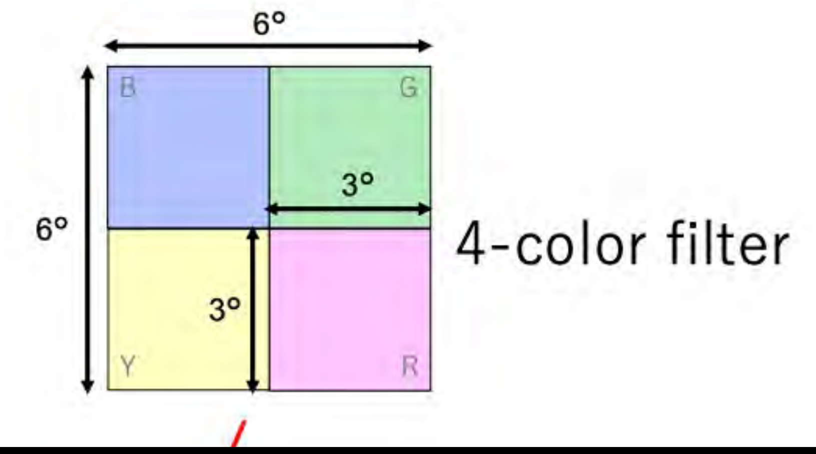
Matsuura et al.

VERTECS - JAXA Small Sat Rush Program Selected 2022 and launching 2025



Telescope

- **2U size wide-field optics and baffle structure**



Matsuura et al.

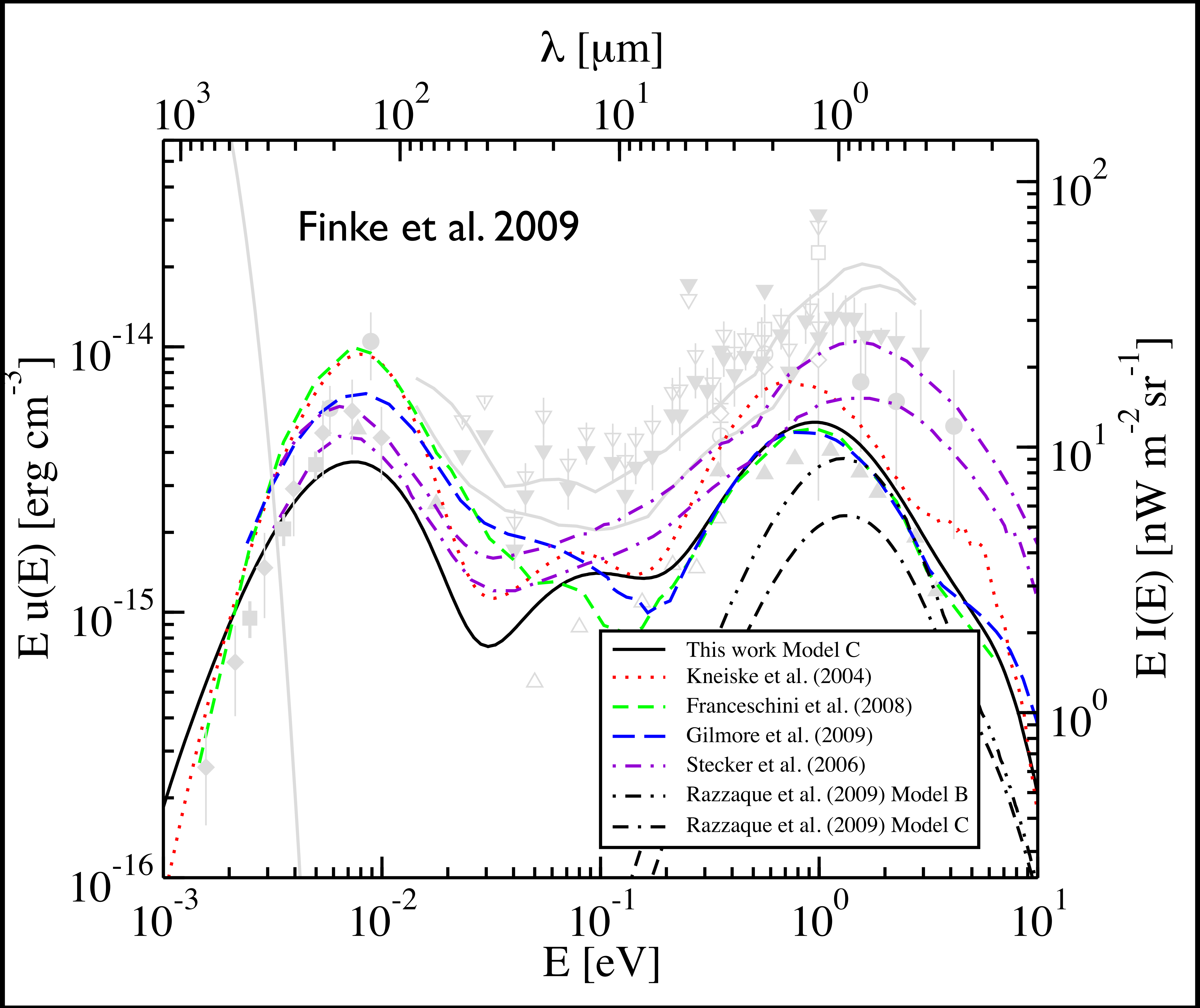
VERTECS - JAXA Small Sat Rush Program Selected 2022 and launching 2025

Why measure EBL?

I. Improve our models of galaxy evolution model

EBL provides an anchor that all theories of galaxy formation and evolution must satisfy.

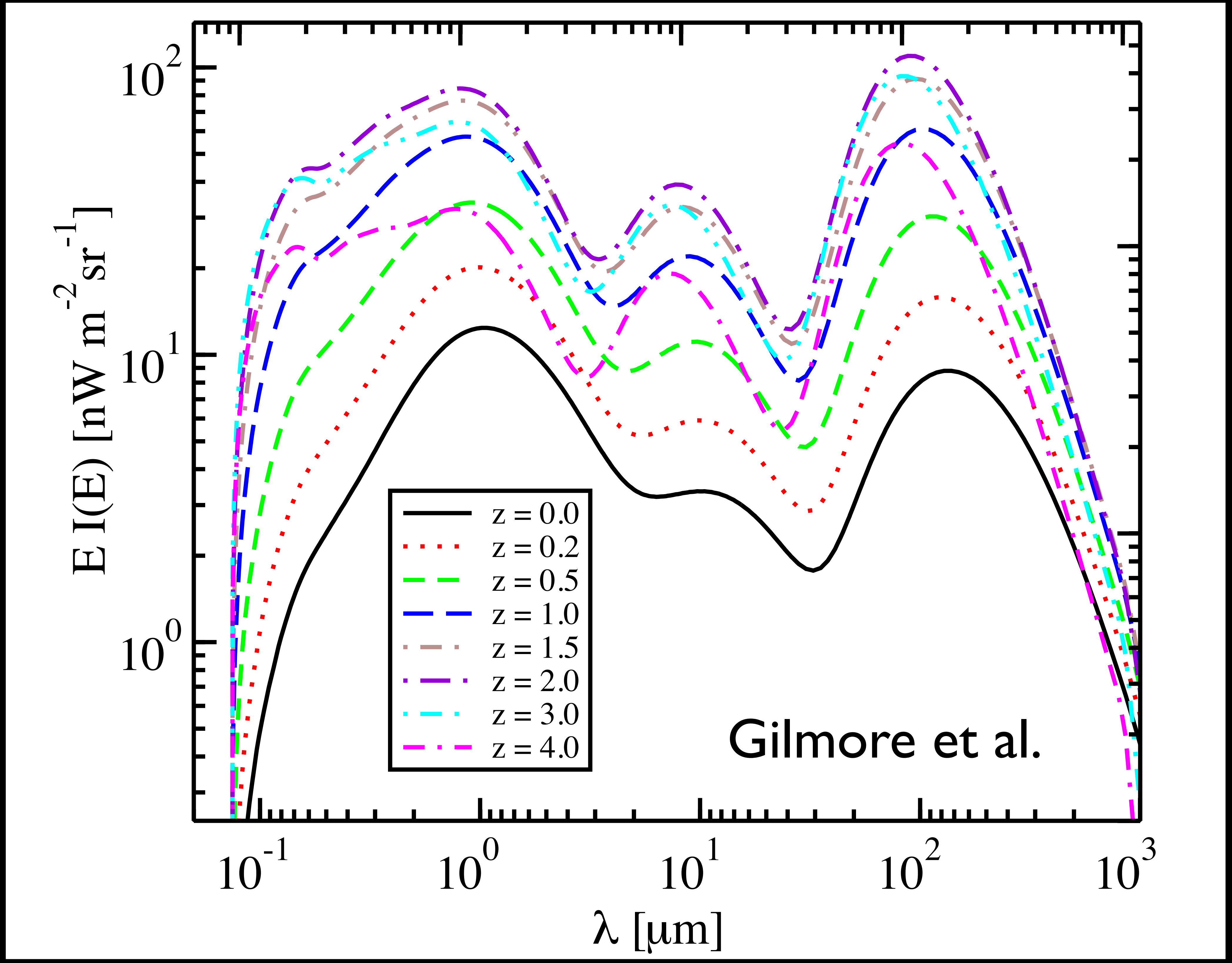
EBL can distinguish between different models of galaxy formation and evolution

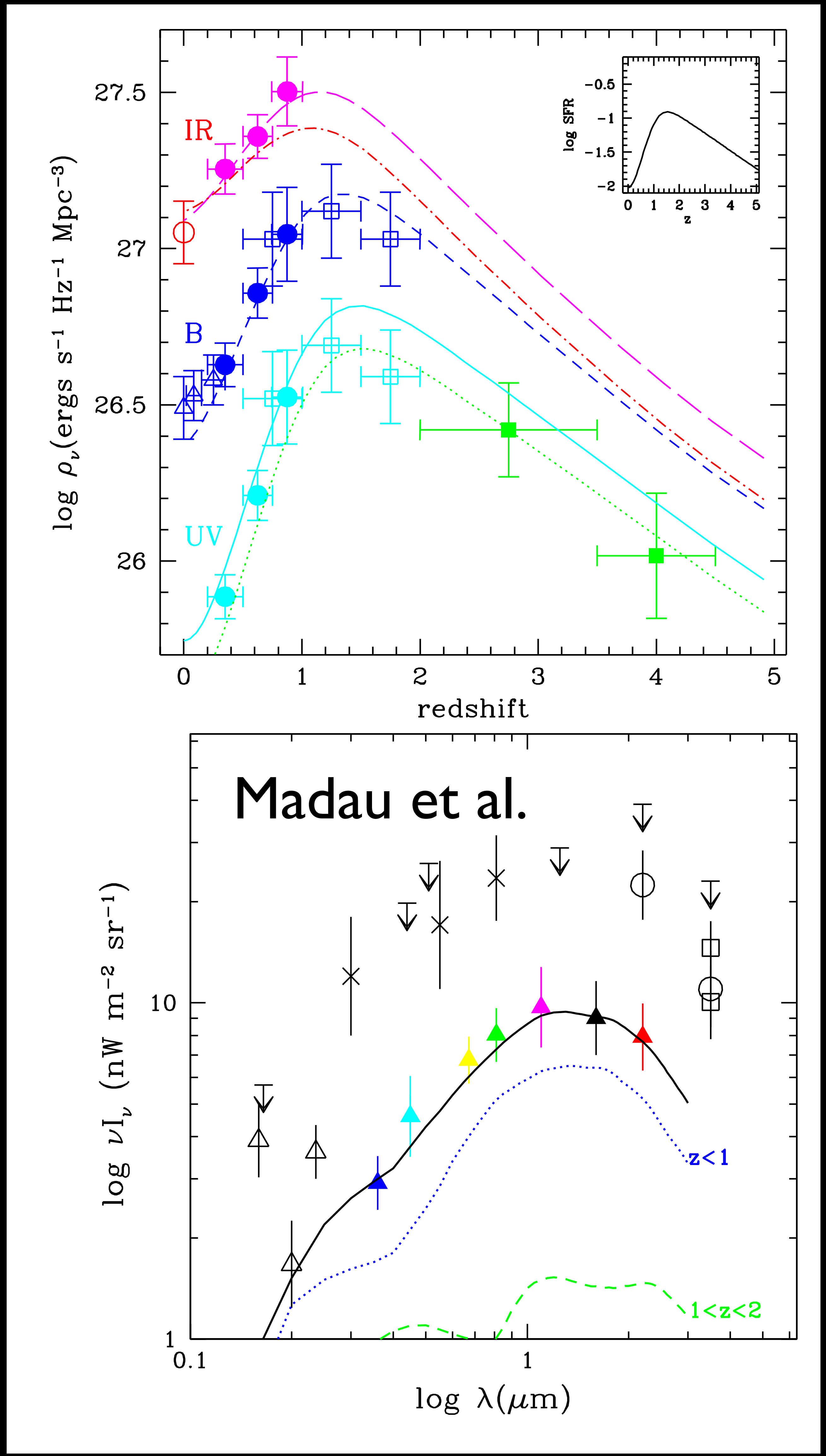


Why measure EBL?

II. EBL provides an independent probe of star-formation history of the Universe

What is the fraction of EBL as a function of the redshift when combined with deep galaxy surveys?

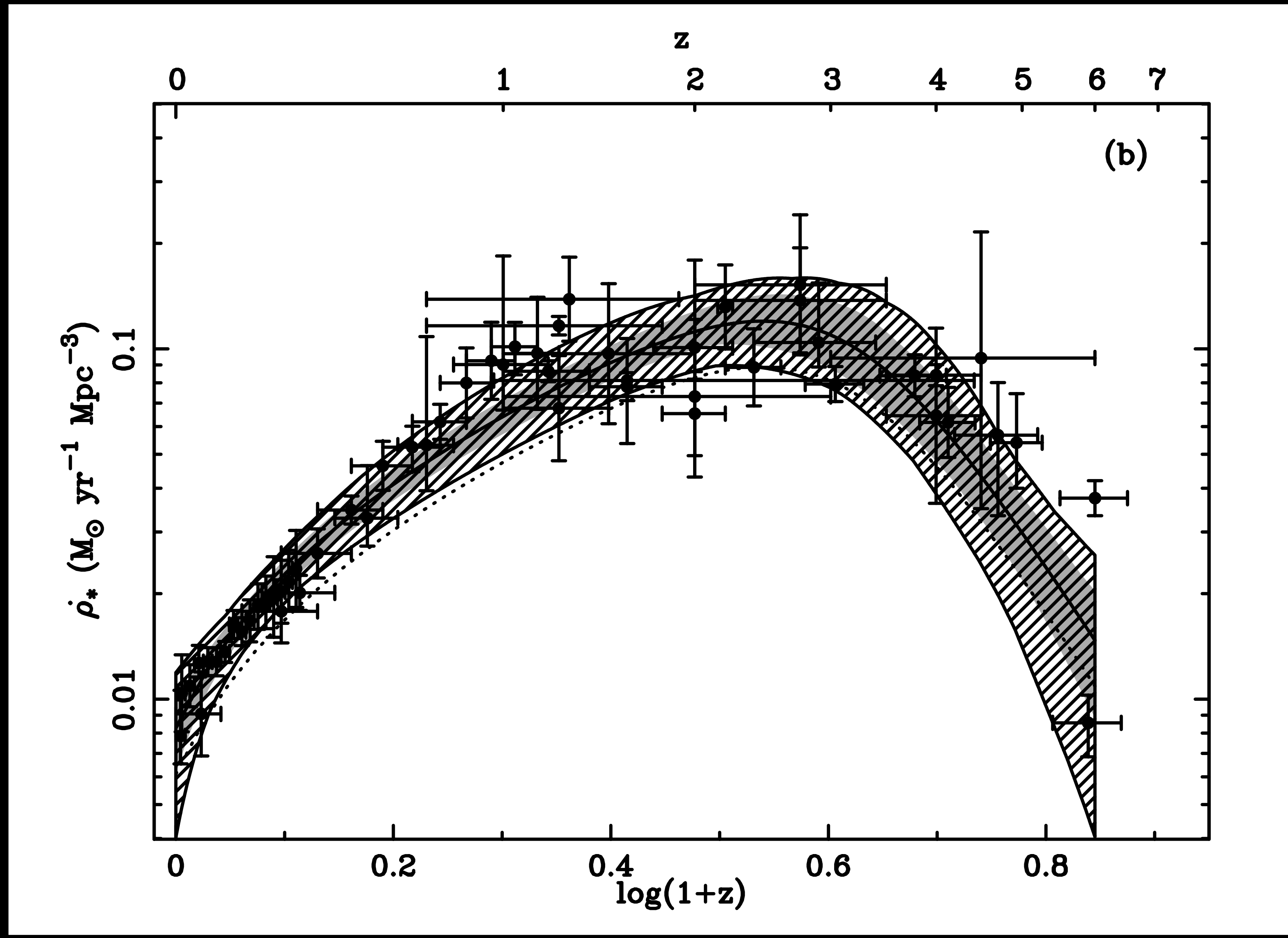


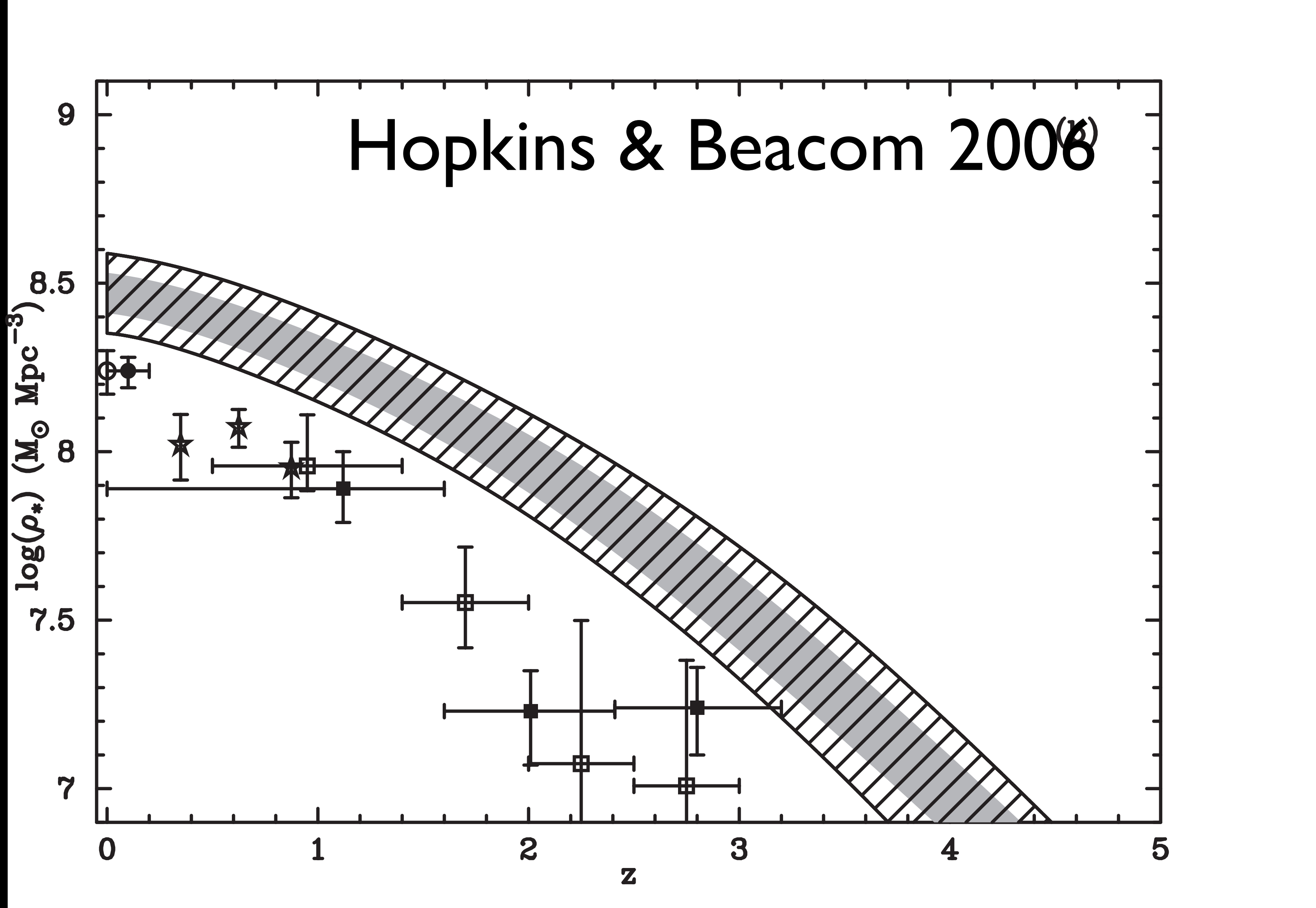


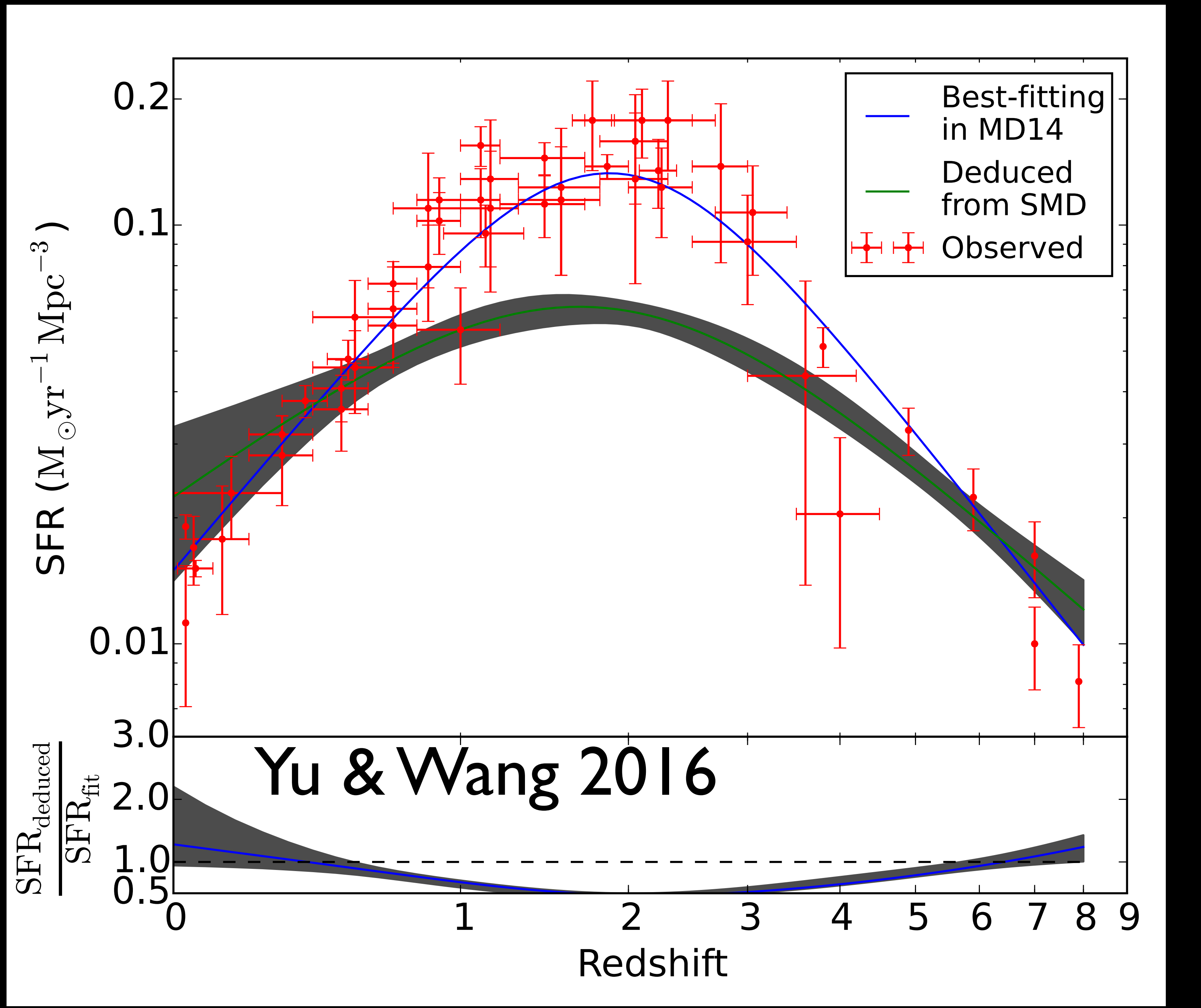
Why measure EBL?

III. EBL could untangle the missing stellar mass problem

Too much star-formation or not enough stellar mass density - Star-formation history is inconsistent with stellar mass density at all redshifts.





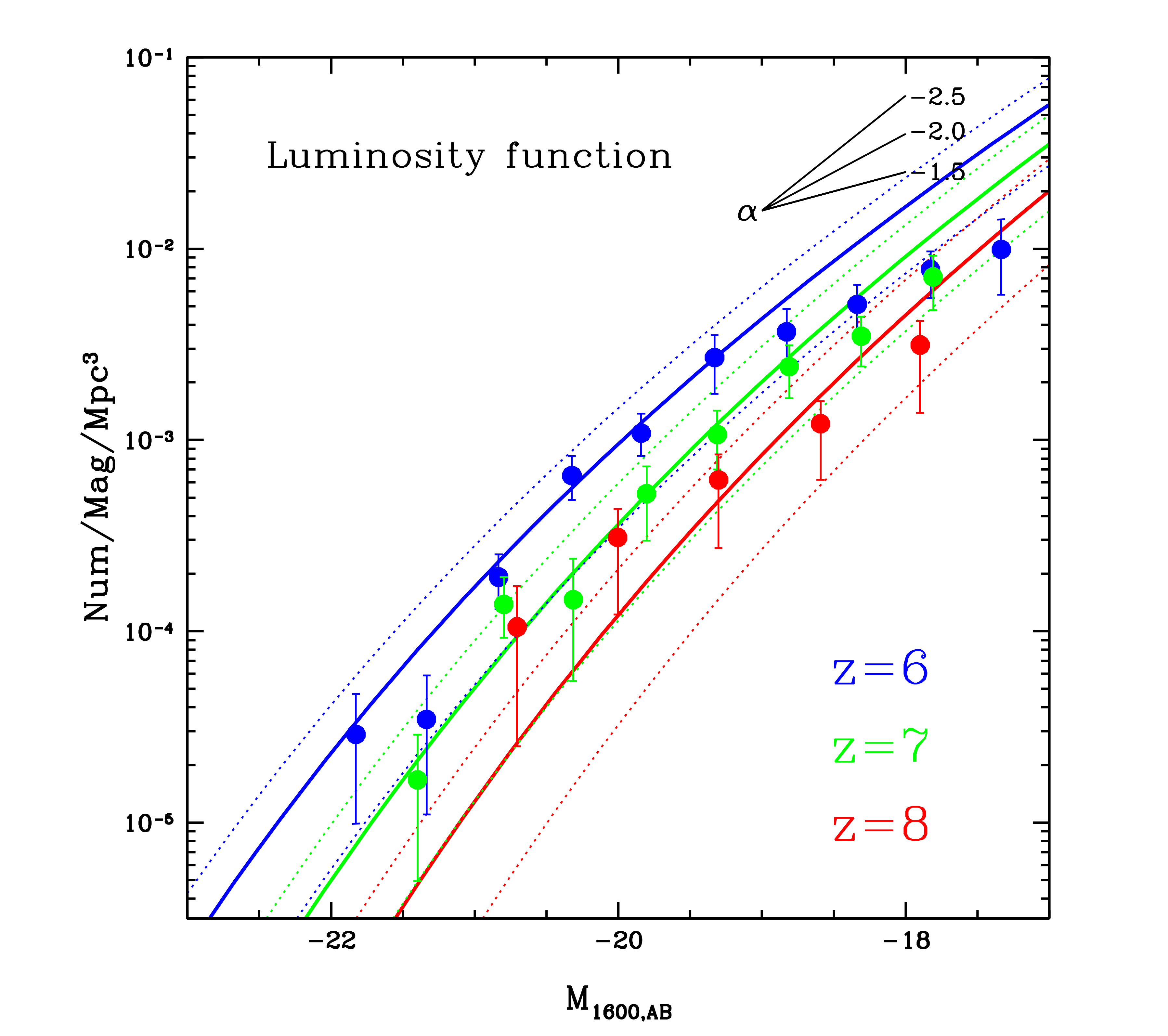


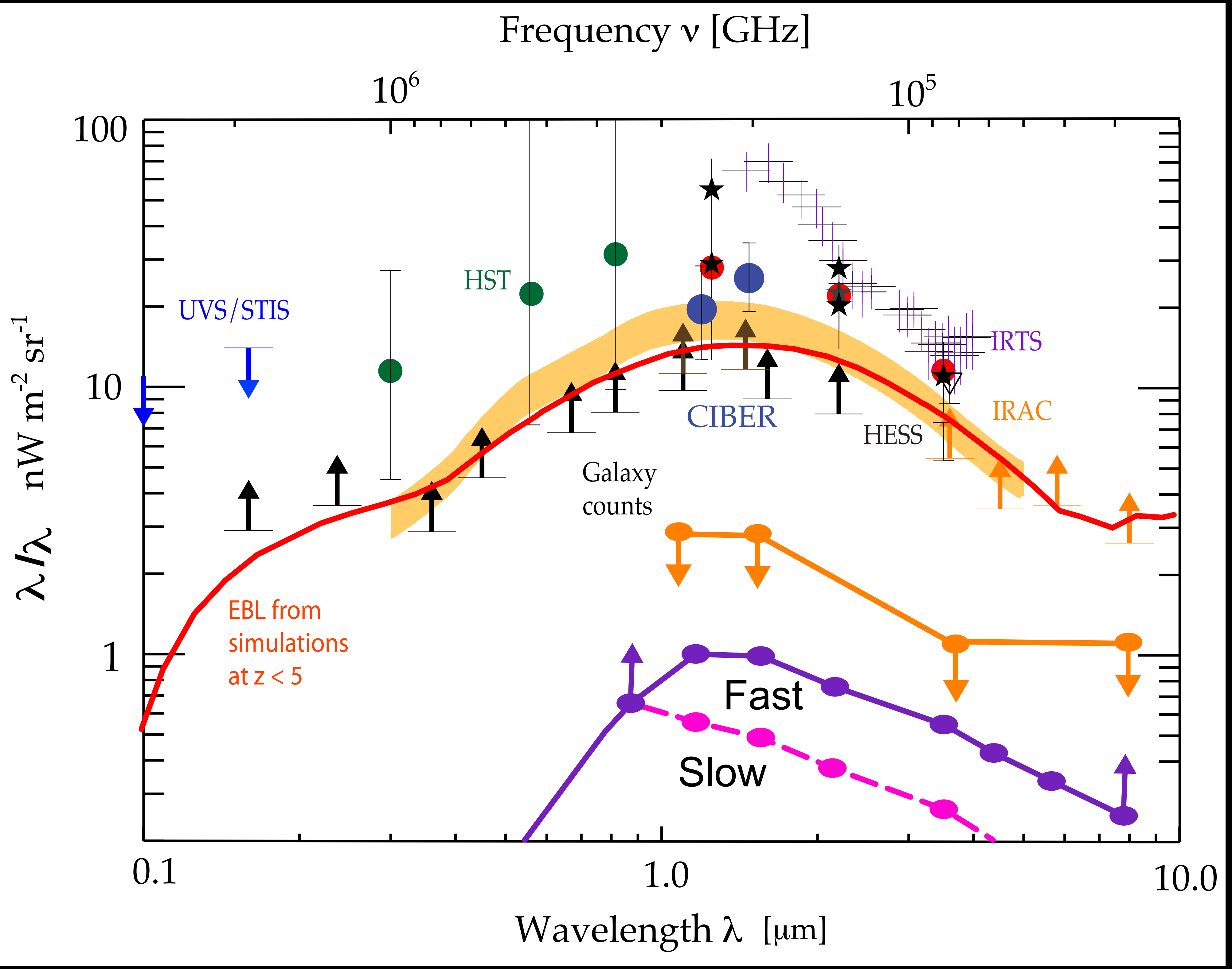
Solutions: IMF of stars top heavy (Chabrier or heavier), metallicity, mass loss from galaxies (~50%), tidally stripped stars (IHL) etc.

also Driver et al. 2018 from GAMA

IV. EBL as a probe of reionization

Detect the collective emission from faint galaxies/quasars etc responsible for realization.



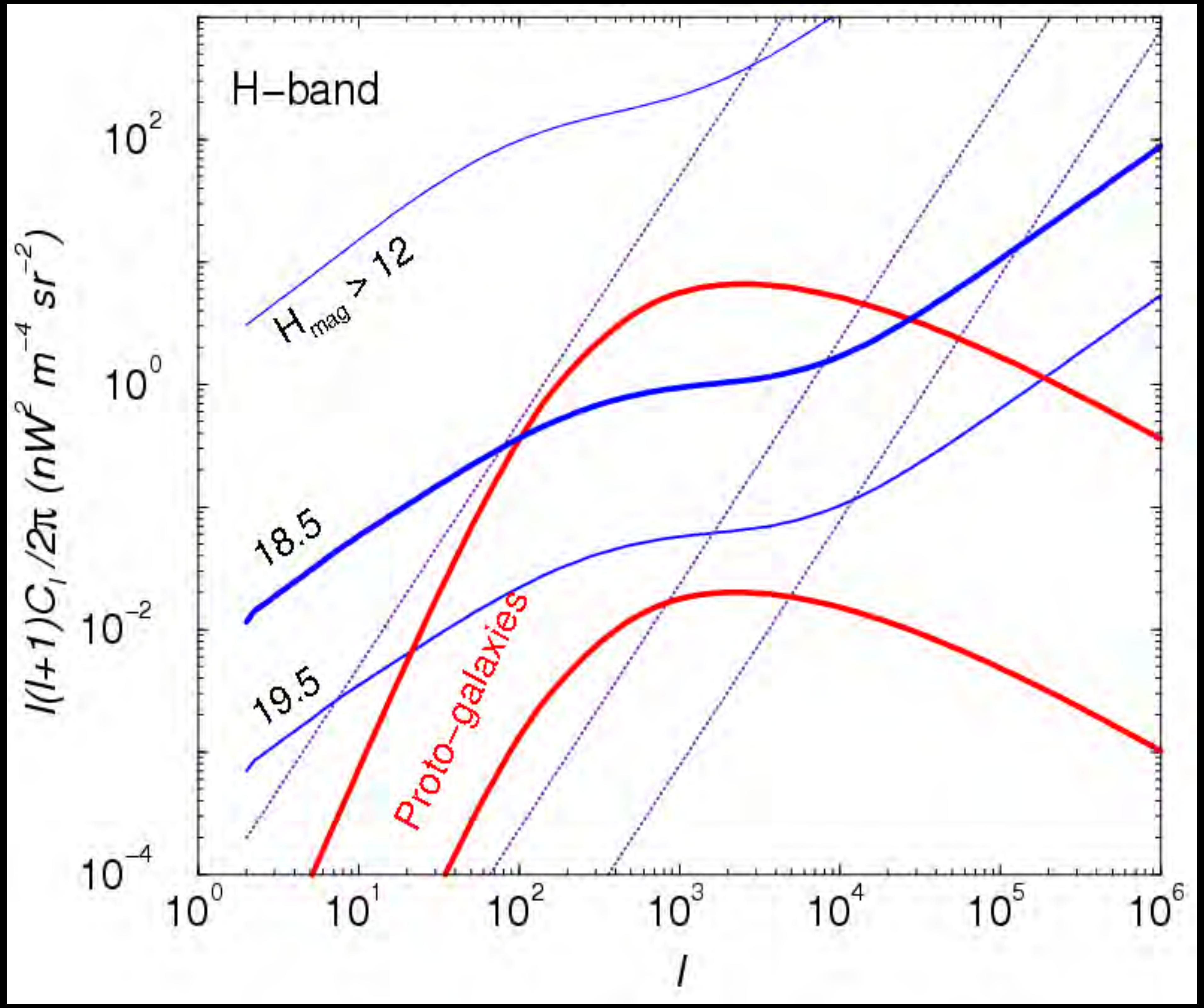


- *The predicted z > 8 background intensity ~ 0.1 to 0.8 nW/m2/sr between 1 to 3 microns.*
- *Could we search for this signal? SPHEREx will attempt.*

IR Background Fluctuations Measurements

Missing emission components

Study EBL anisotropies.

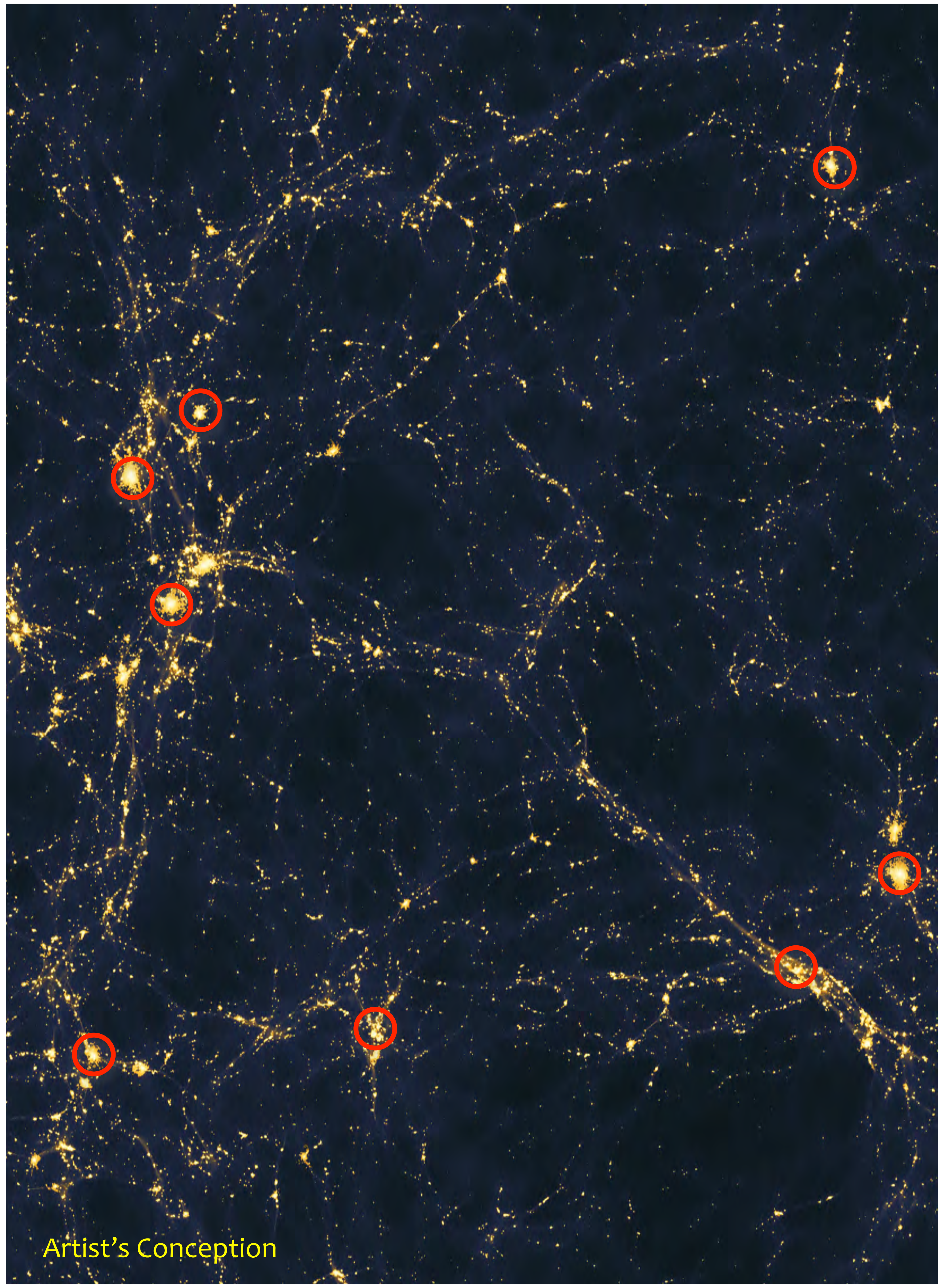


Instead of the absolute total IRB intensity, measure anisotropies or fluctuations of the intensity (just like in CMB).

IRB anisotropies probe substantially below 0.1 nW/m2/sr intensity.

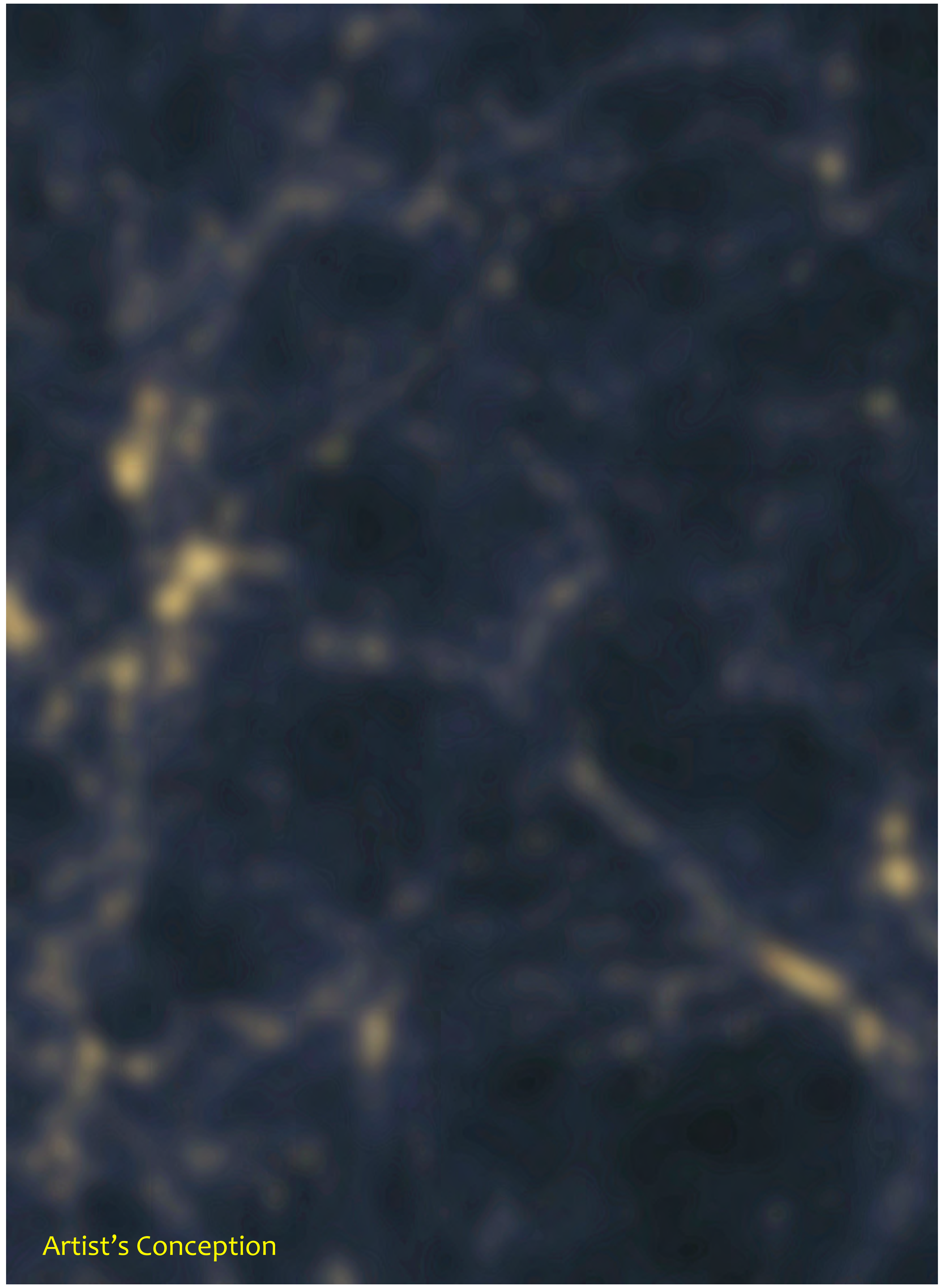
(Cooray, Bock, Keating, Lange & Matsumoto 2004, ApJ)

An Introduction to Fluctuations



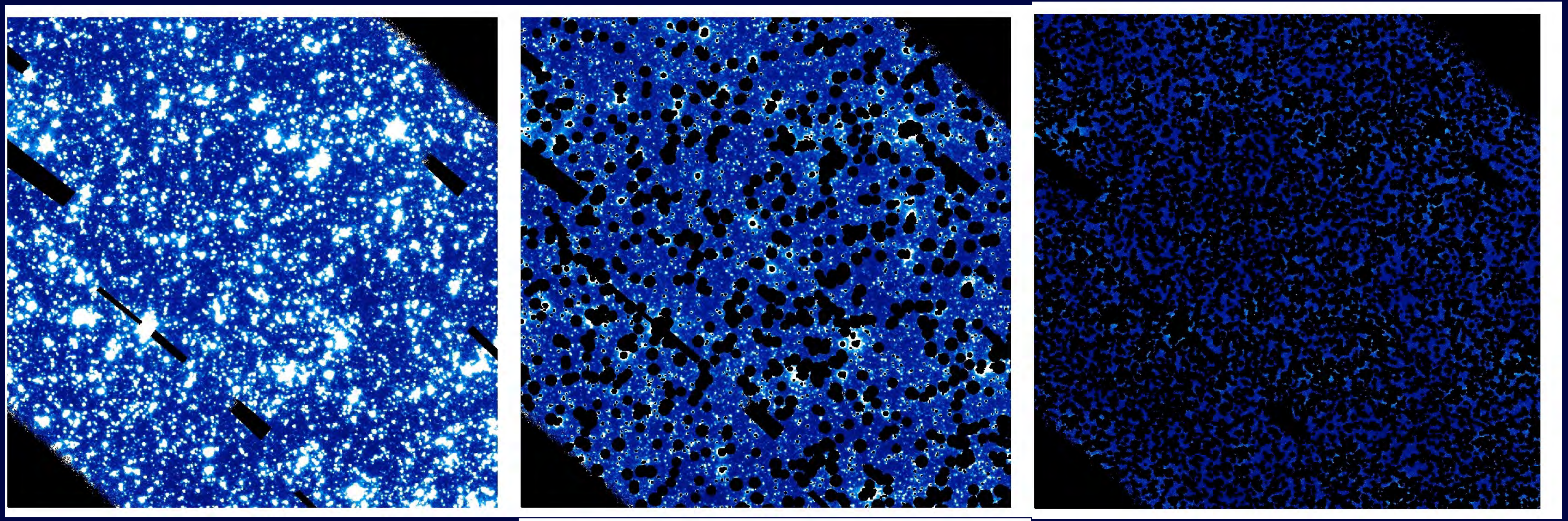
- What is the large scale structure of the universe?
- To find out, we could identify individual sources of emission.

An Introduction to Fluctuations

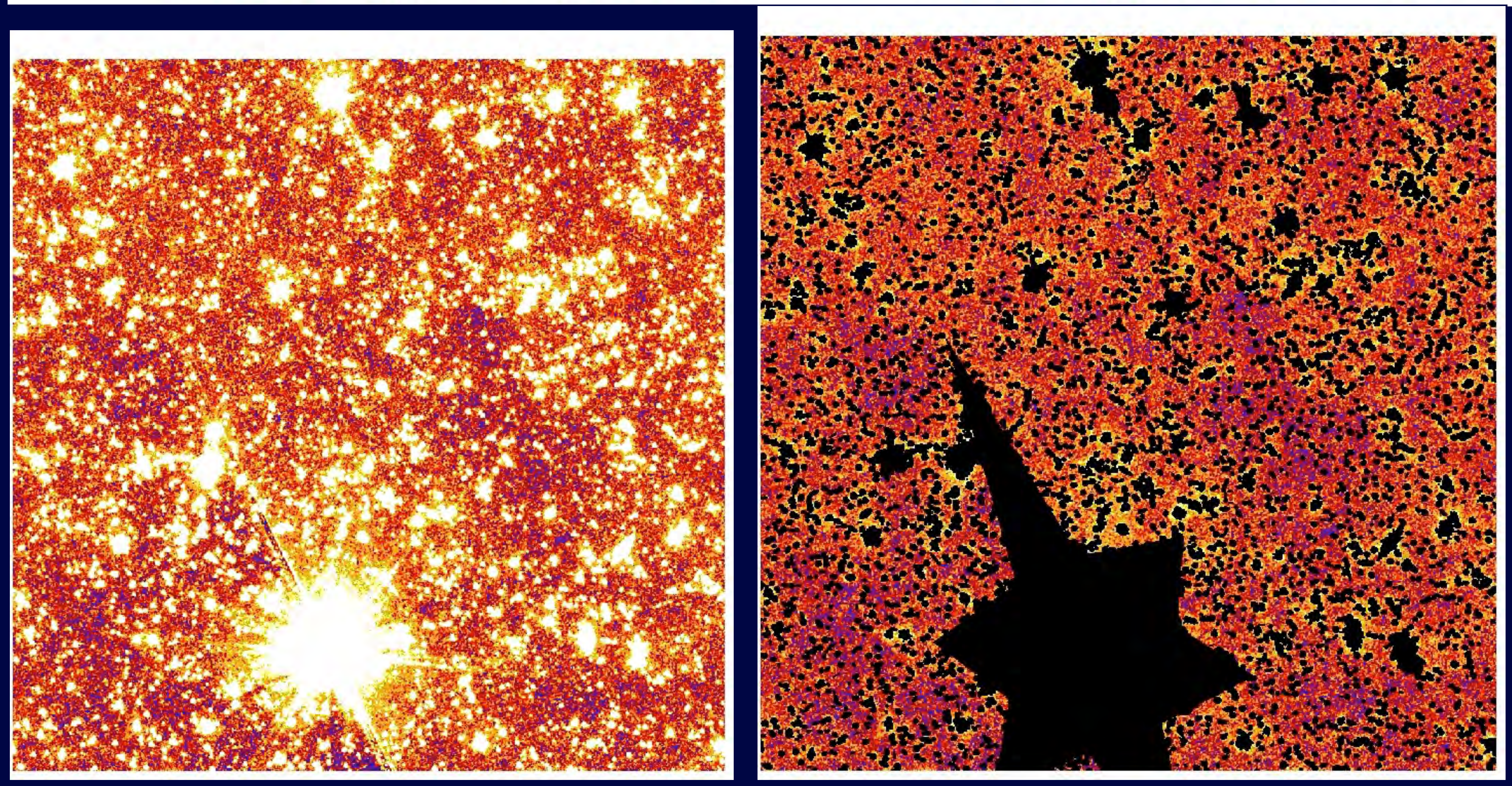


- What is the large scale structure of the universe?
- To find out, we could identify individual sources of emission.
- Alternatively, we could sum all the emission in large areas and measure fluctuations.
- This is called "Intensity Mapping".

IR Background Fluctuations Measurements



GOODS
CDF-S



COSMOS

What do we do?

Measure statistics of “empty” pixels.

If unresolved faint galaxies are hidden in noise, then there is a clustering excess above noise

Challenges: > 10 million of pixels (higher complexity than analyzing CMB data.)

We also mask > 50% of pixels (GOODS we masked 70% of pixels).

Techniques to handle mask - borrowed from CMB analyses.

Foregrounds – Zodiacal Light

» Sunlight scattered off dust in the solar system.

» Intensity at some point in the sky is a function of time, so observing same area at different times give different overall offset.

» Effectively a fictitious anisotropy.

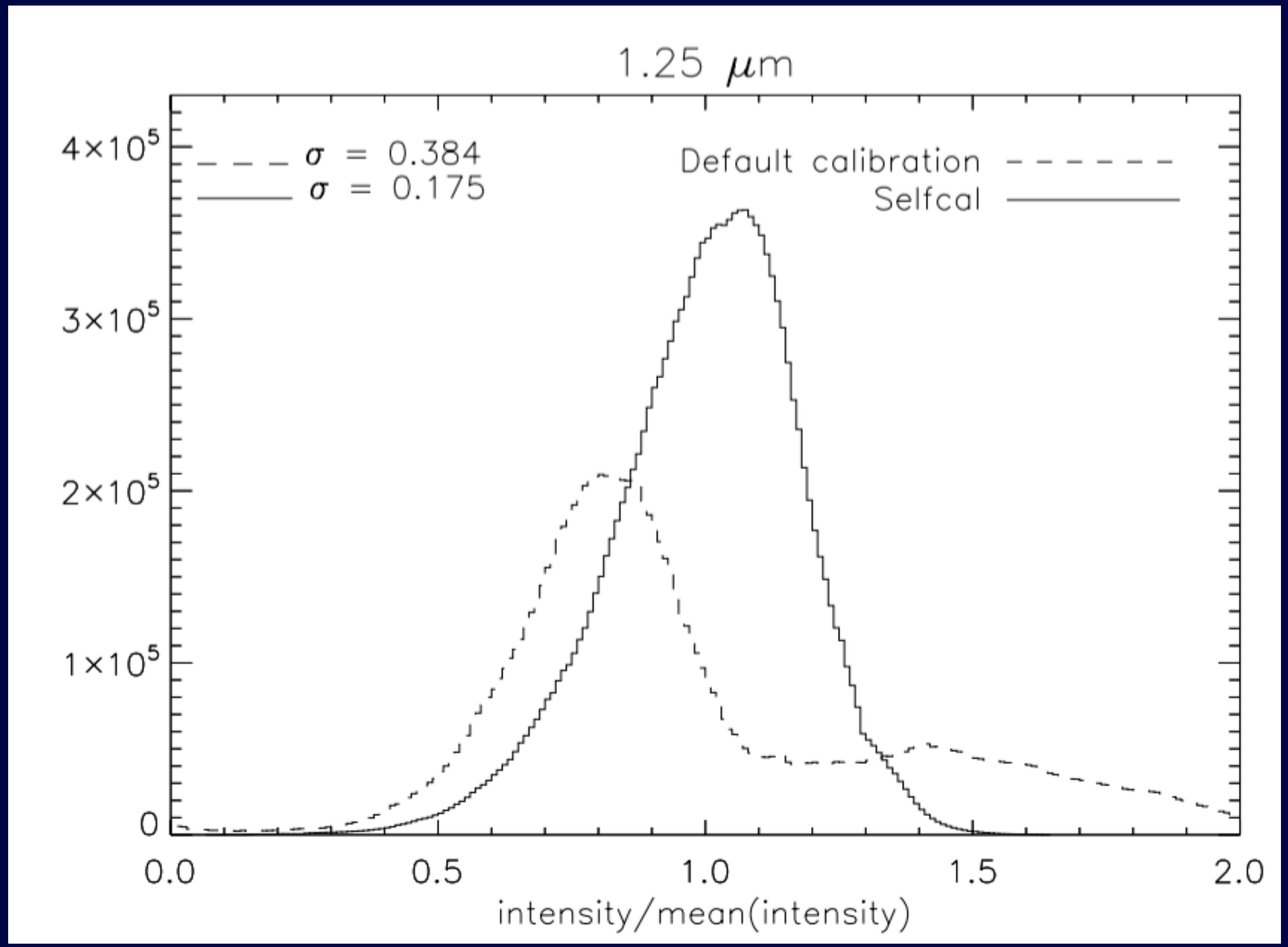
Mitchell-Wynne et al. 2015
Nature Communications

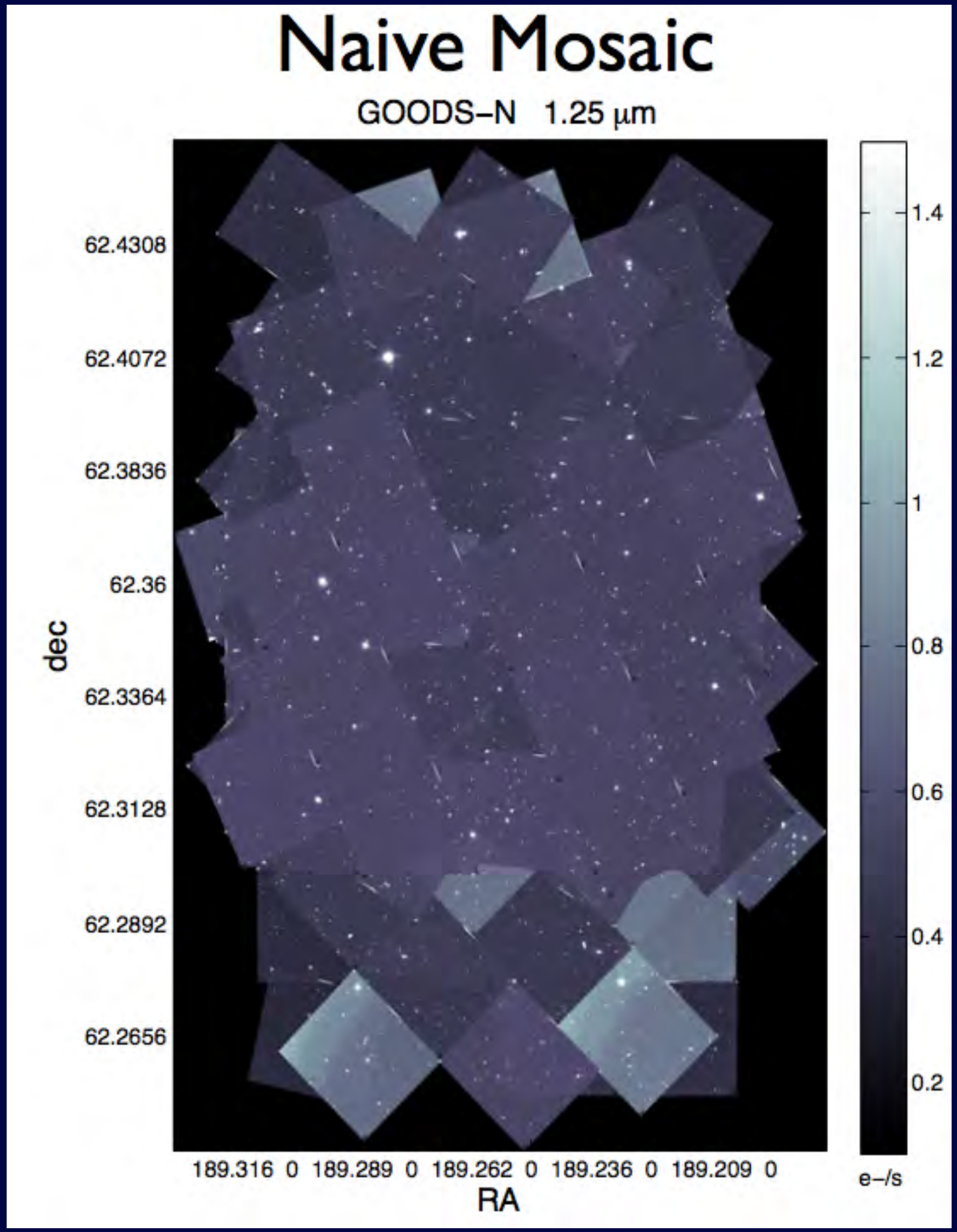
Self-Calibration vs. Default Calibration

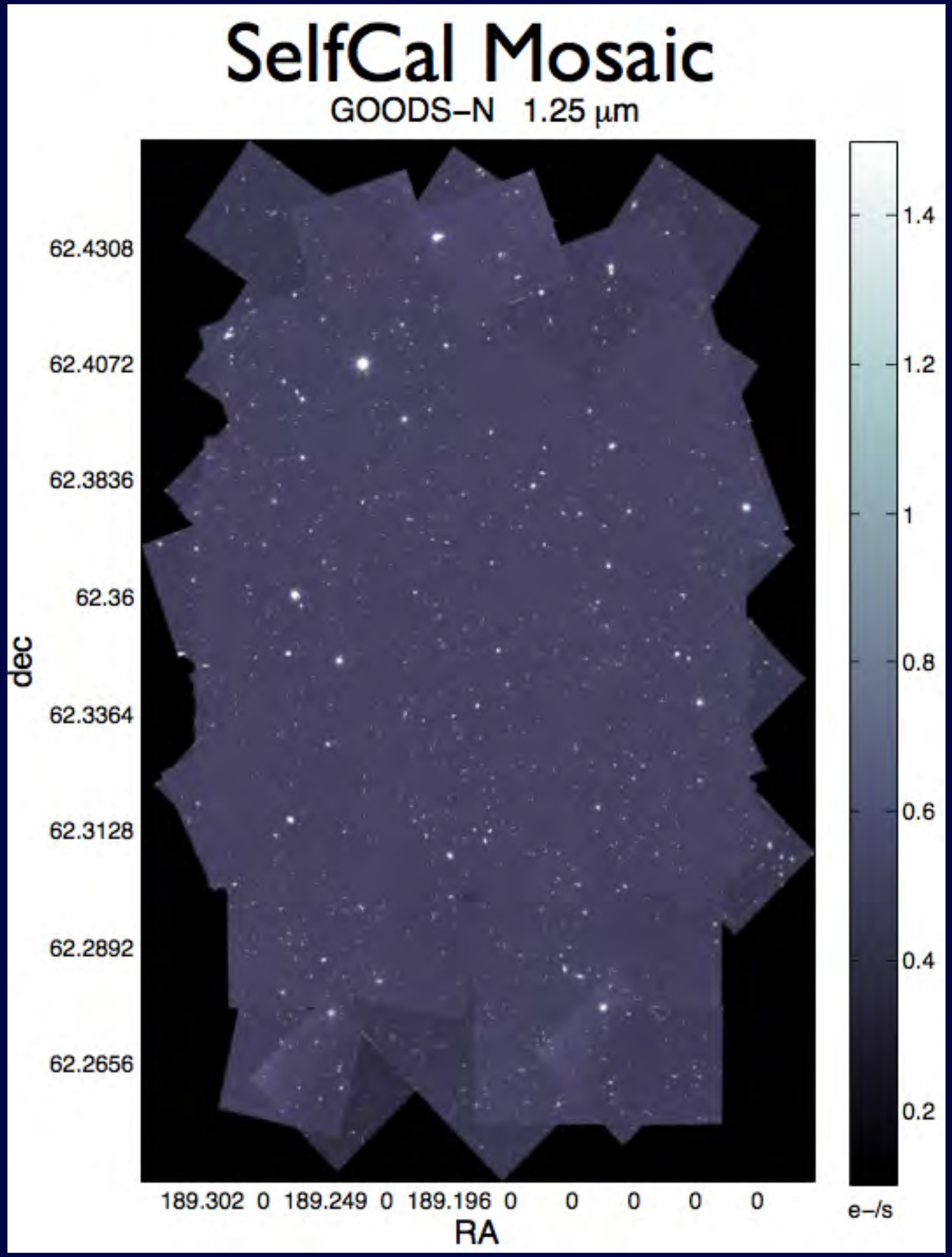
Use multiple pointings of the same sky area with different pixels to simultaneously solve for sky brightness and detector properties (non-constant gain and offset parameters) via Self-Calibration algorithm

(Fixsen, Moseley & Arendt, 2000, ApJS)

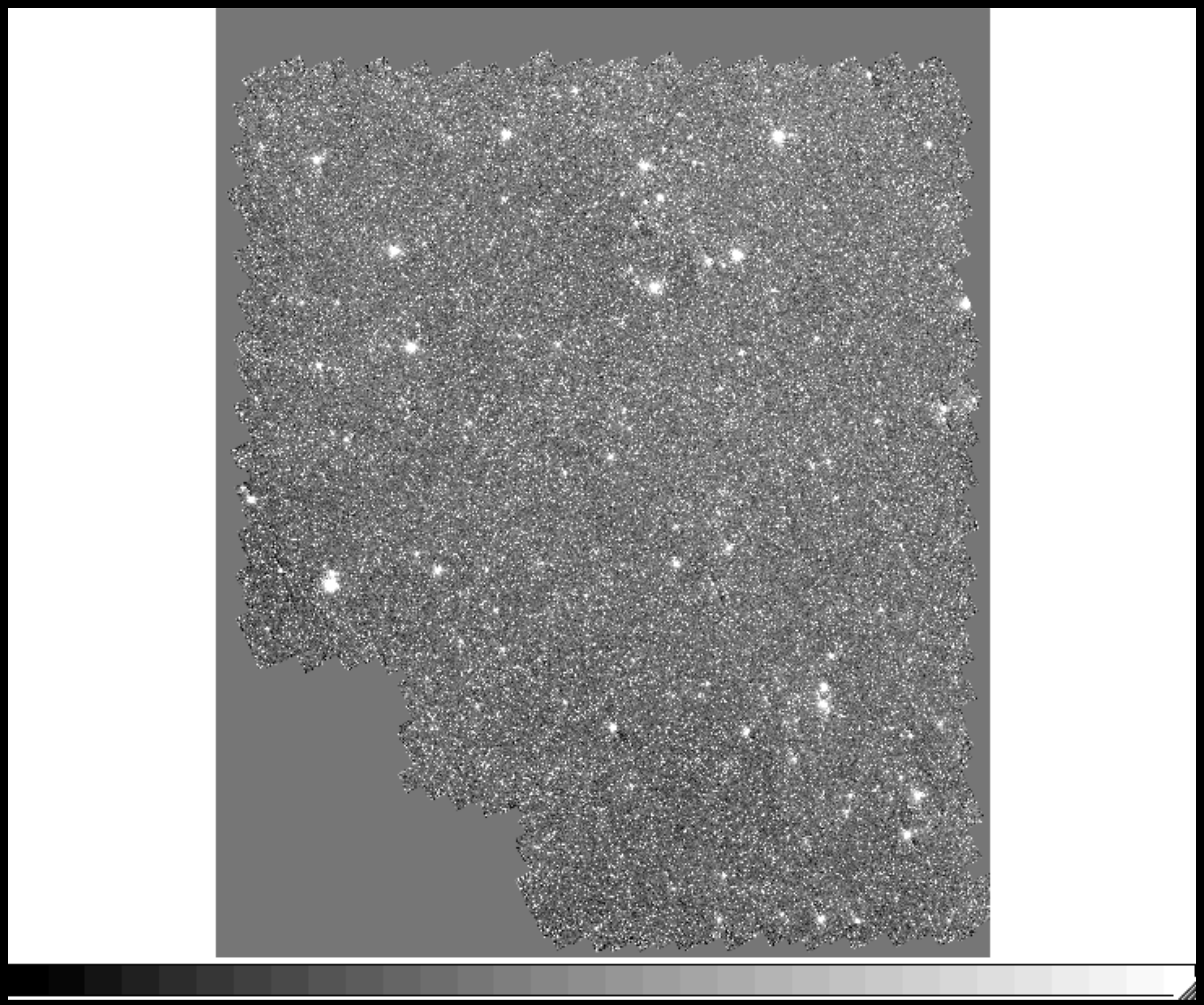
Must have sufficient pixel overlap for Self-Cal to work!



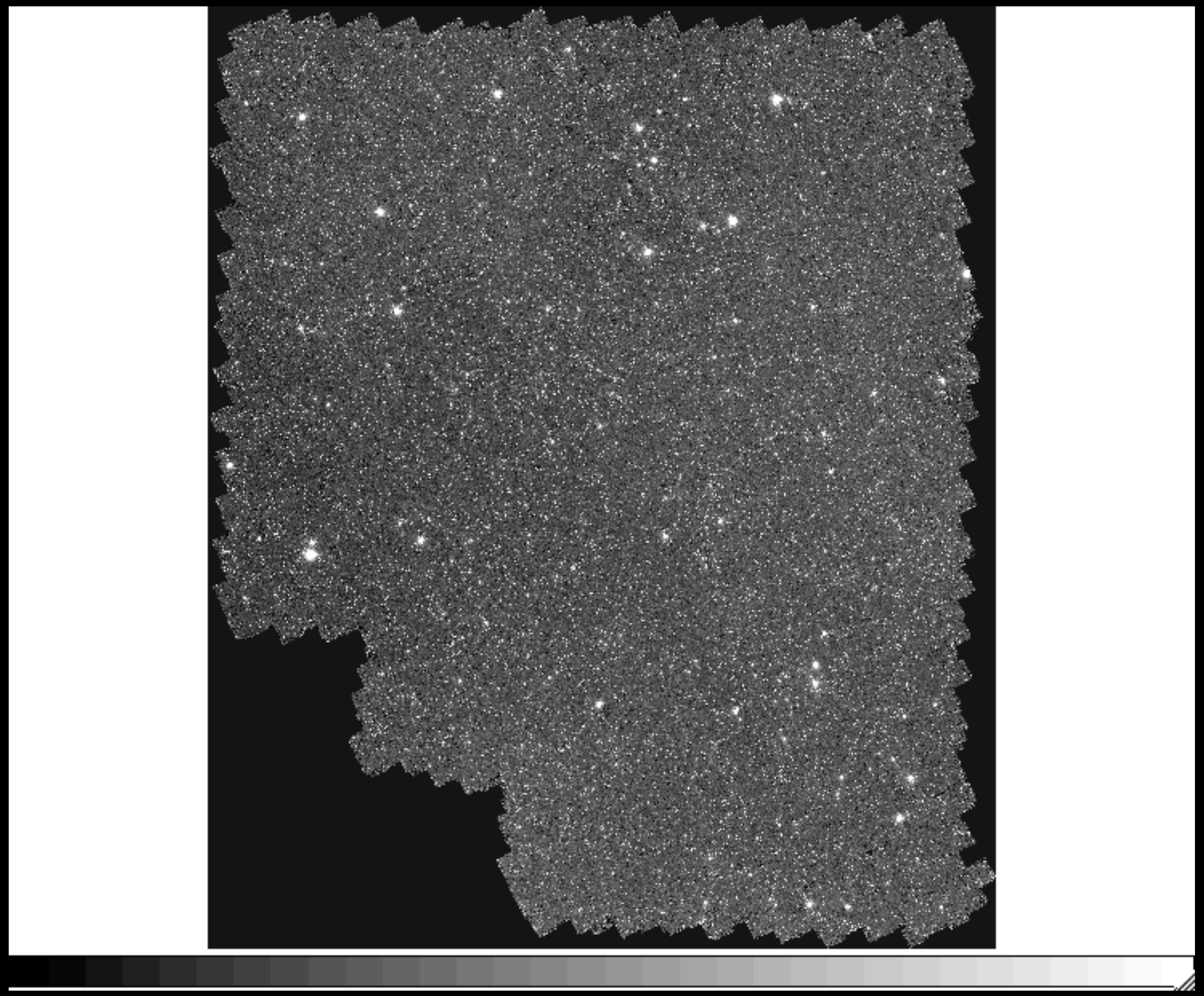




Self-calibrate data to remove background offsets



Standard *Spitzer* software, MOPEX

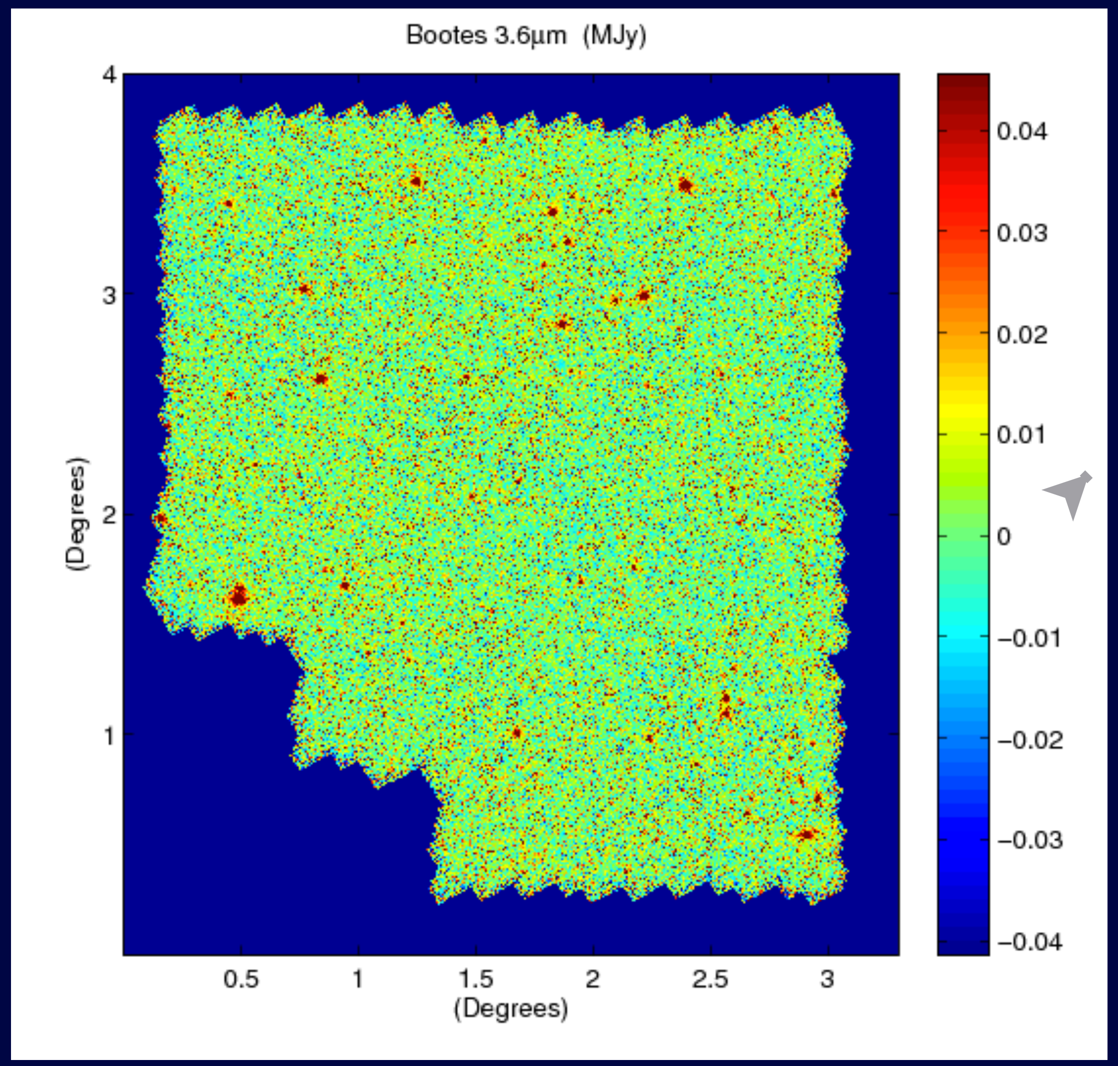


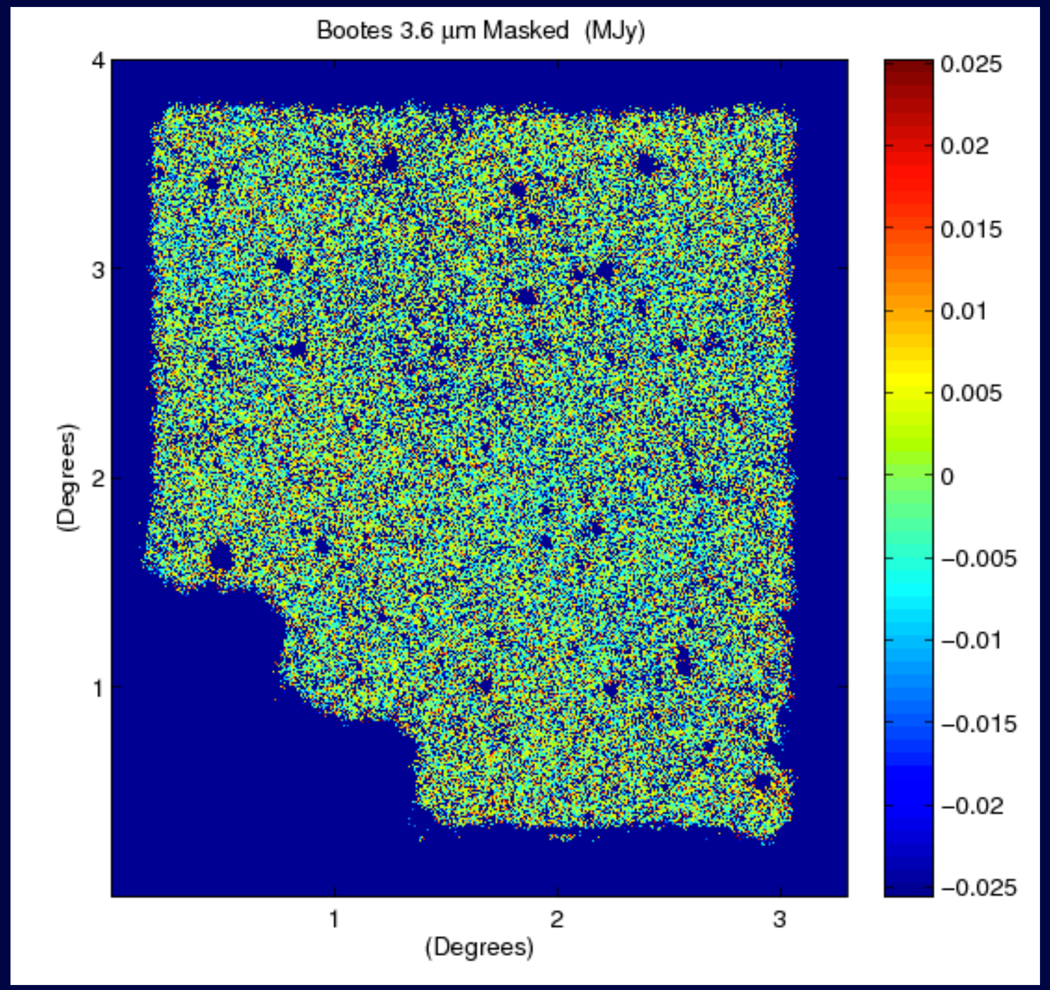
Our self-calibrated mosaic

Self-calibrated mosaics are aimed at preserving the background, unlike MOPEX and HST multi-drizzle for WFC3. Based on works by Fixsen et al. 1998 & Arendt et al. 2010 (Our internal code is cross-checked against Rick Arendt's routines).

Spitzer Background Fluctuations in SDWFS

Cooray et al. 2012, Nature, 490, 514





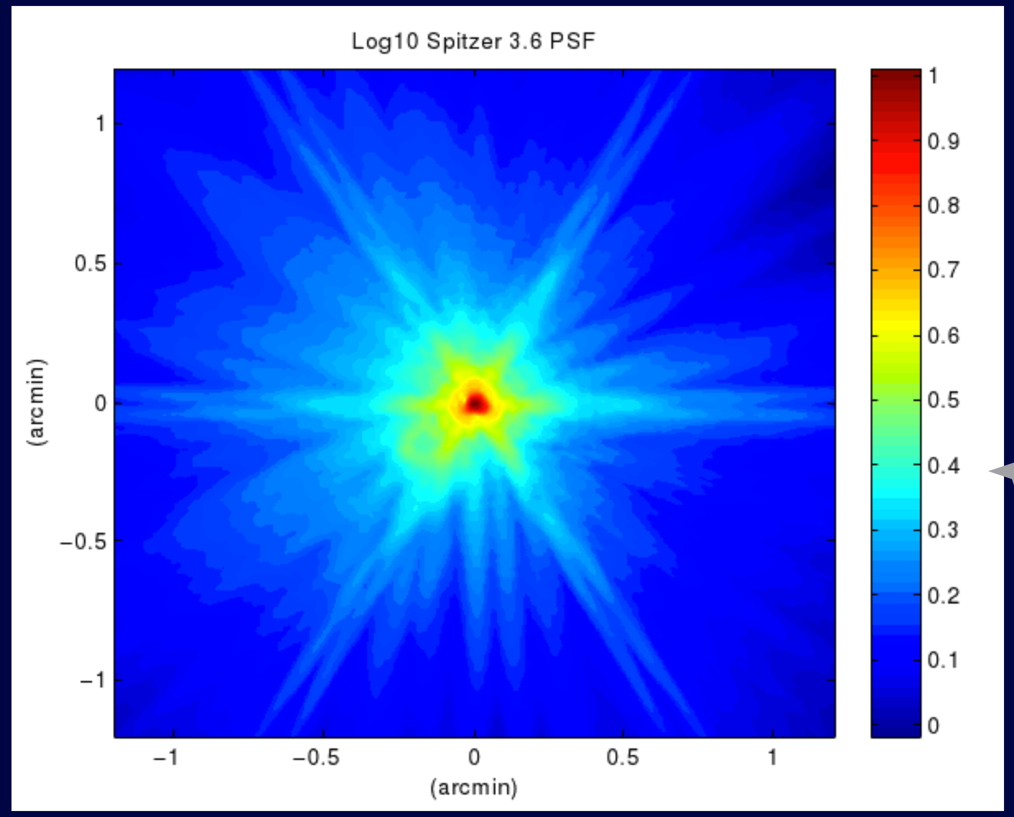
Mask map. (Sextractor)

Epoch 1 + Epoch 2

X

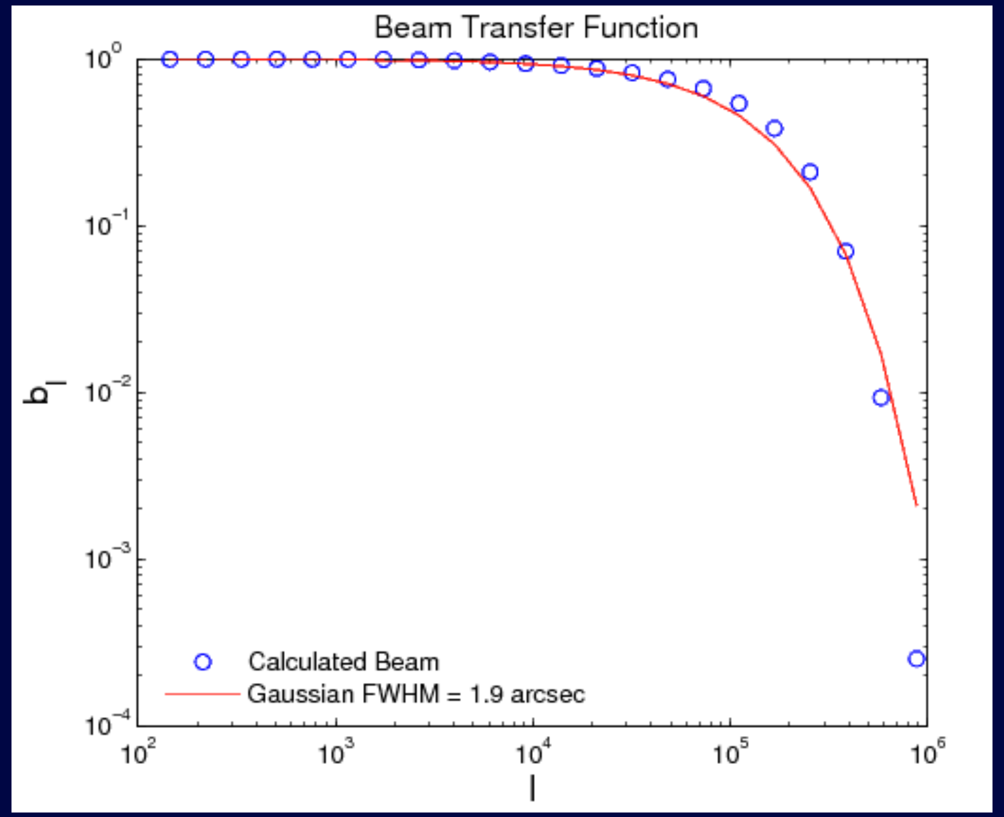
Epoch 3 + Epoch 4

Cross-Correlate Coadded Epochs



PSF

Fourier Transform



BEAM TRANSFER FUNCTION

Epoch 1 - Epoch 2

X

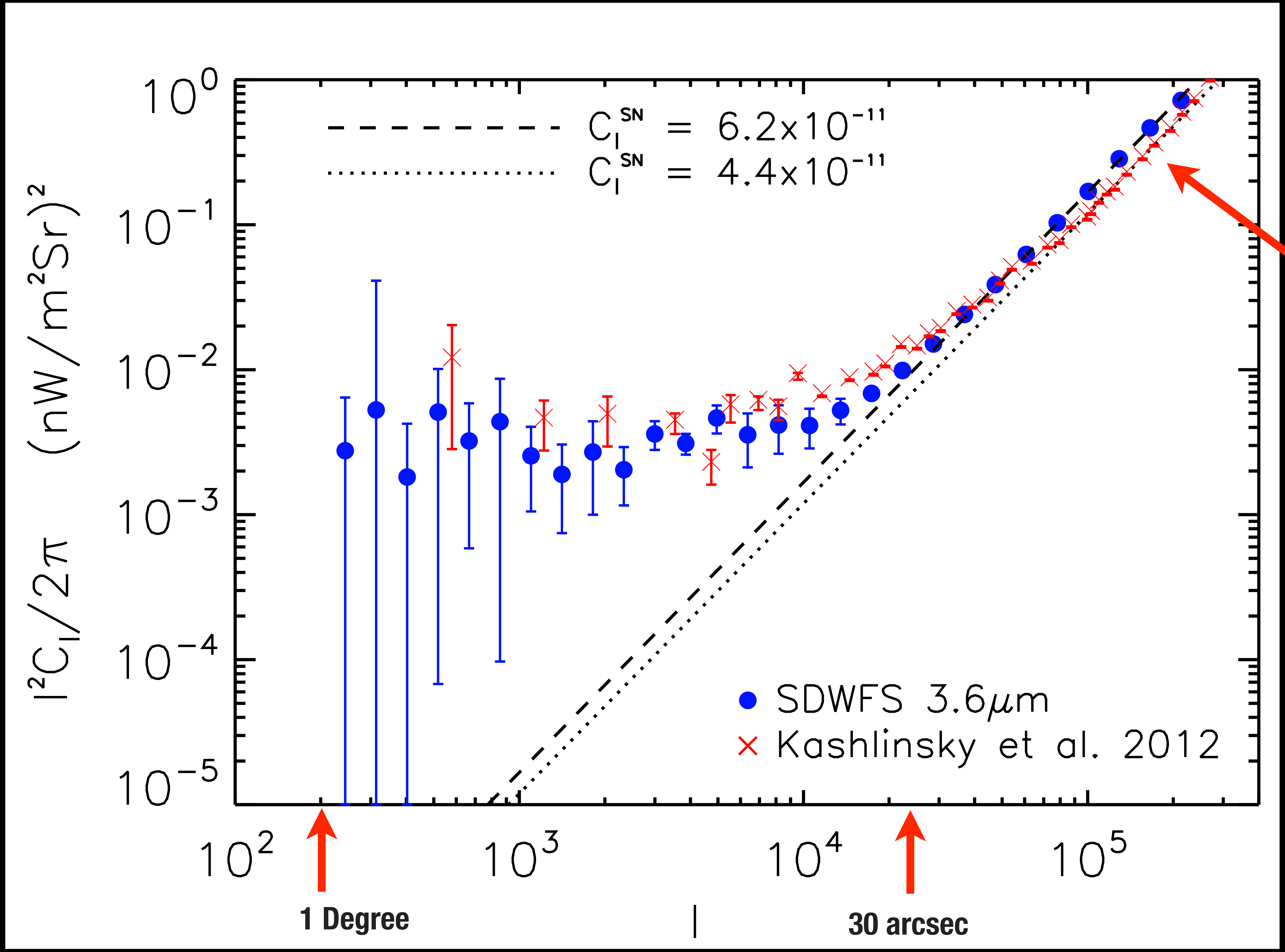
Epoch 3 - Epoch 4

Jackknife For Noise Errors

Spitzer Background Fluctuations in SDWFS

Cooray et al. 2012, Nature, 490, 514

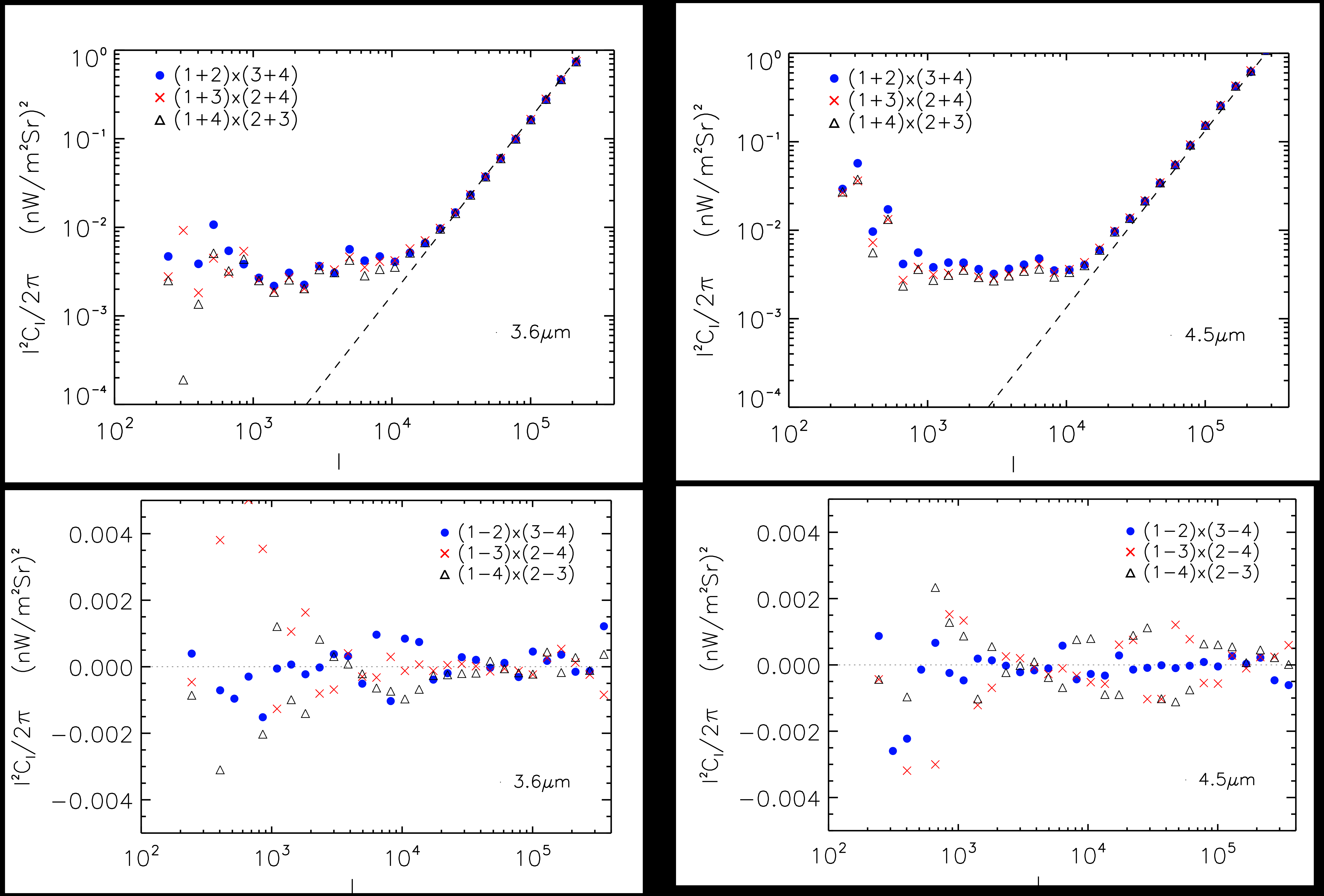
Spitzer fluctuations are real! *Not an instrumental systematic nor zodiacal light.*
Its extragalactic, repeatable, time-independent.



Kashlinsky et al. SEDS data are deeper than SDWFS (so more point sources are masked)

Spitzer Background Fluctuations in SDWFS

Cooray et al. 2012, Nature, 490, 514



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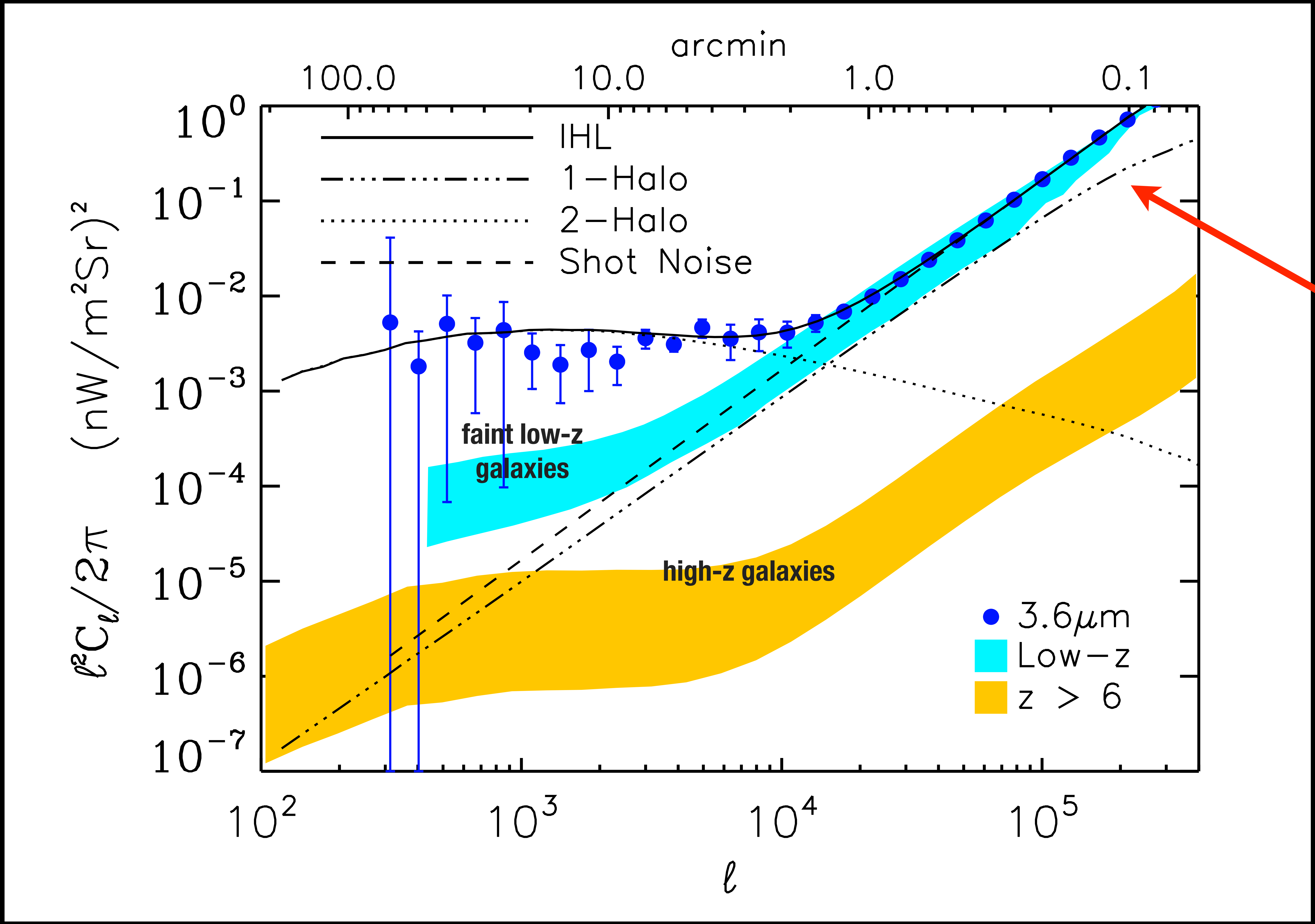
Spitzer Background Fluctuations



Measured shot-noise agrees with prediction for faint galaxies below the detection threshold (Helgason et al. 2012)

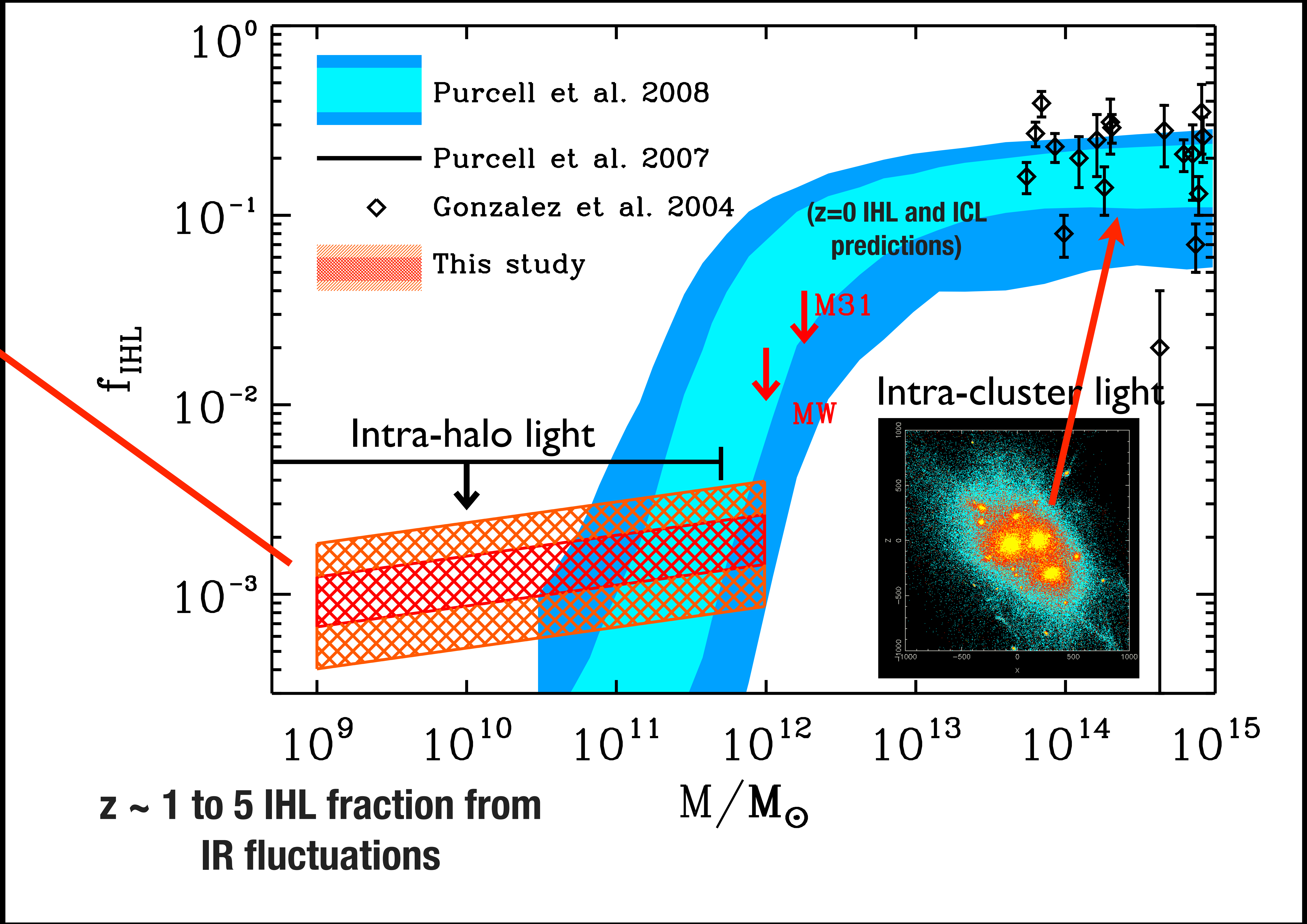
Argues against a new source population to explain the observations

Cooray et al. 2012, Nature, 490, 514

Intra-halo light in galaxy-scale dark matter halos

Intrahalo light:
stars outside of the galactic disks and in the outskirts of dark matter halos due to tidal stripping and galaxy mergers.

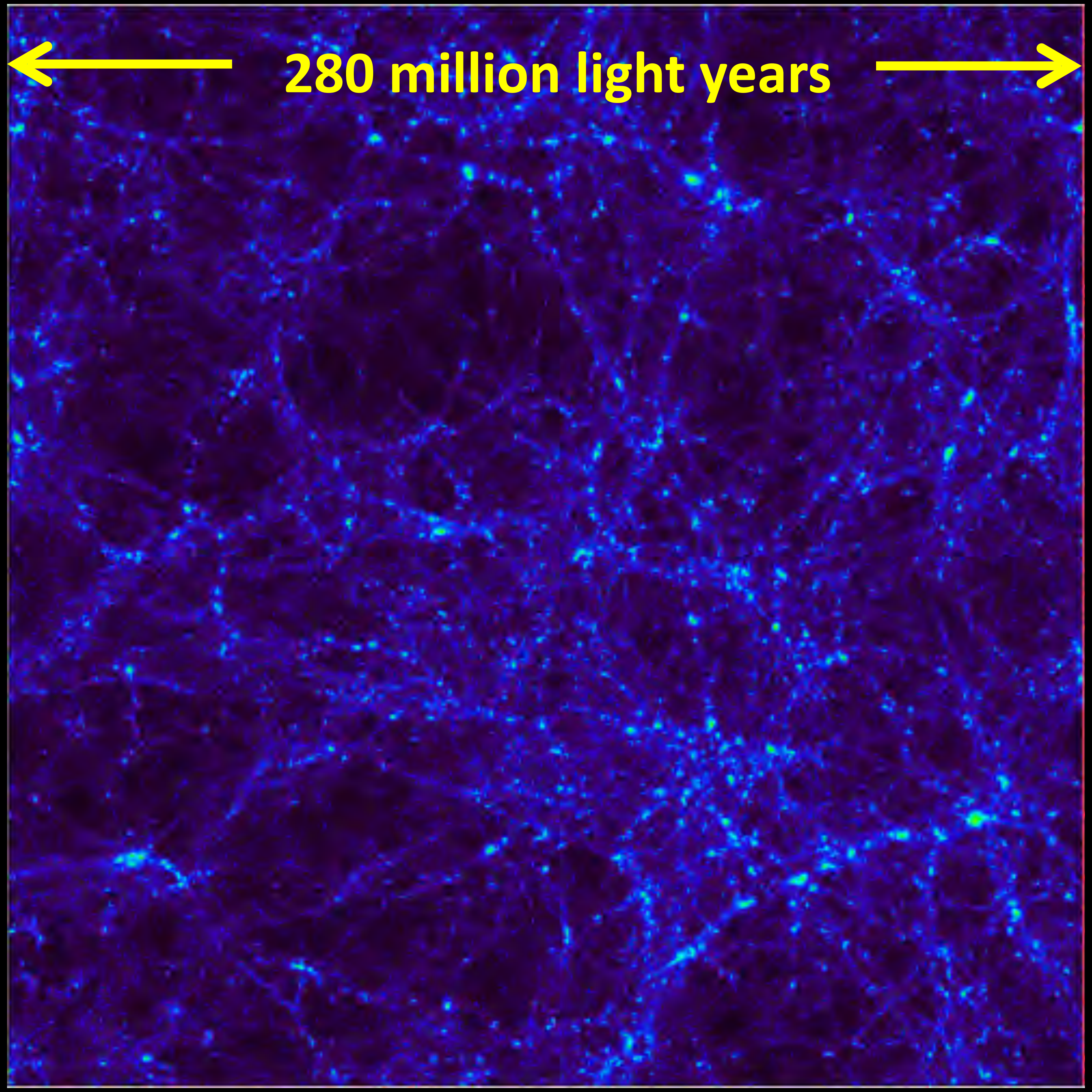
Simulation/theory predictions:
Purcell et al. 2007
Watson et al. 2012



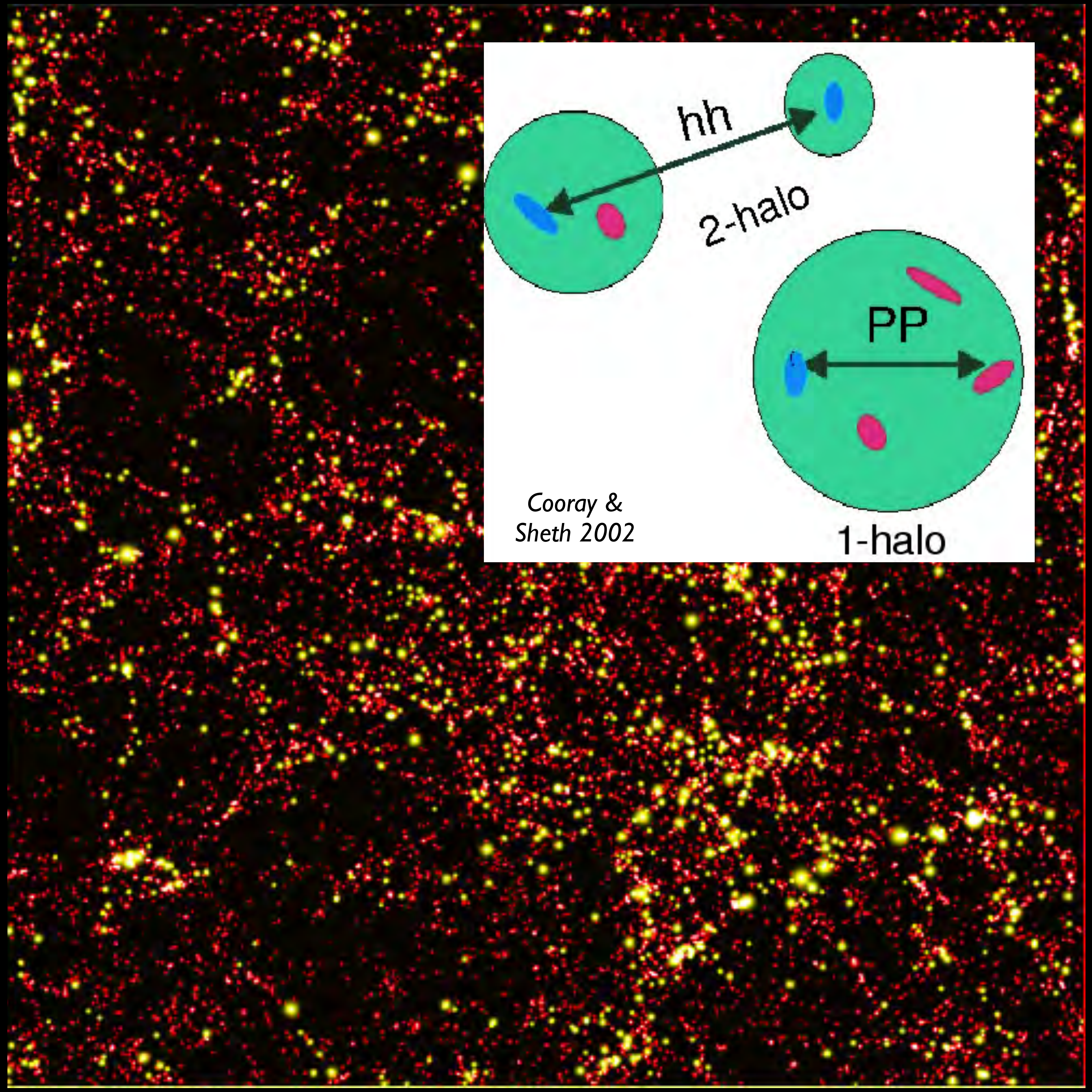
Cooray et al. 2012, Nature, 490, 514

Relating Galaxies to Dark Matter

Dark Matter from Numerical Simulation (z = 2)



Dark Matter Clumps Color-Coded by Mass



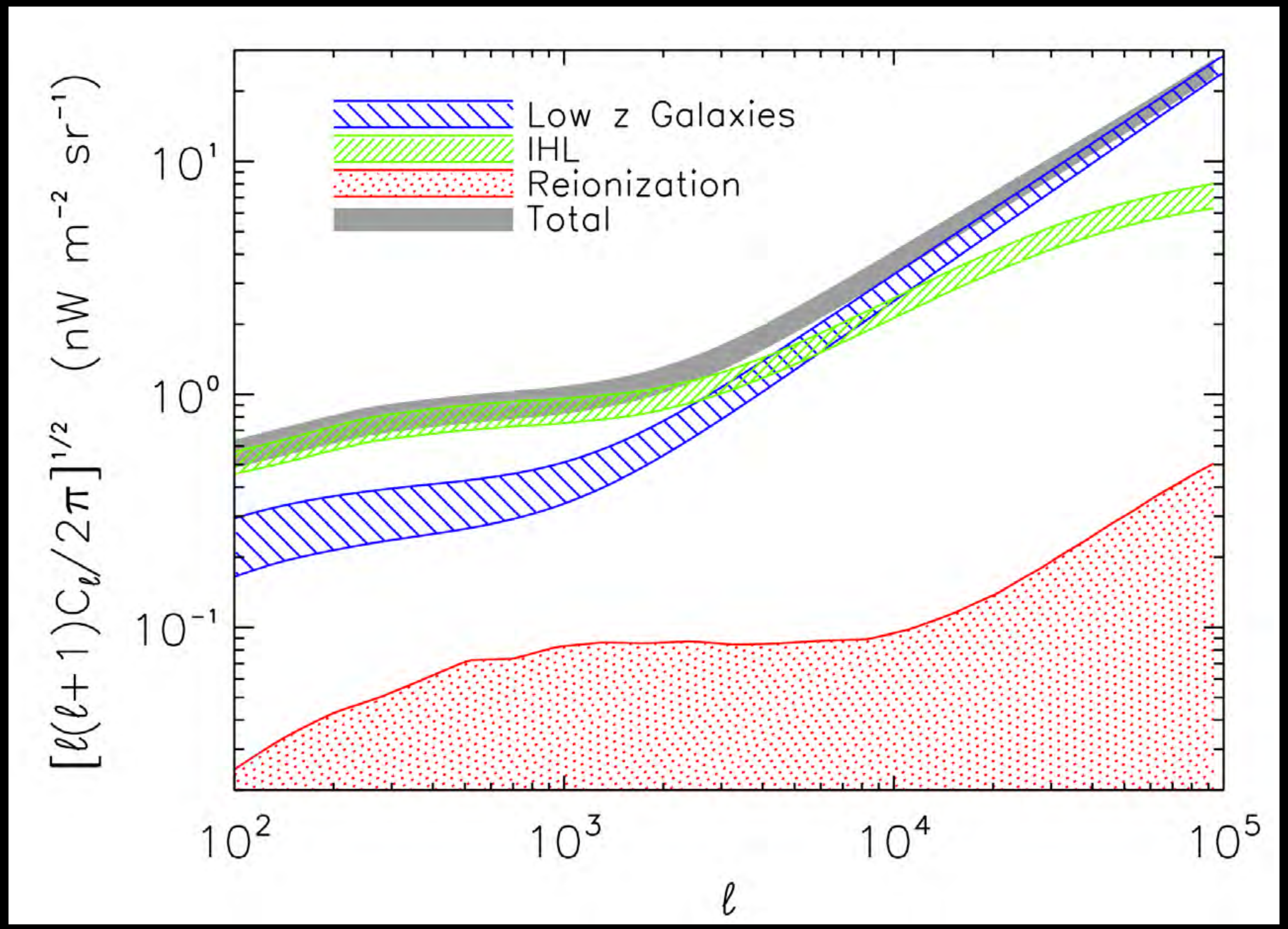
Large scales: **Light traces dark matter** -------------------> **Integrated luminosity**

Med scales: **Non-linear clustering** -----------------------> **Galaxy formation within a halo**

Small scales: **Poisson fluctuations** ------------------------> **Galaxy luminosity function**

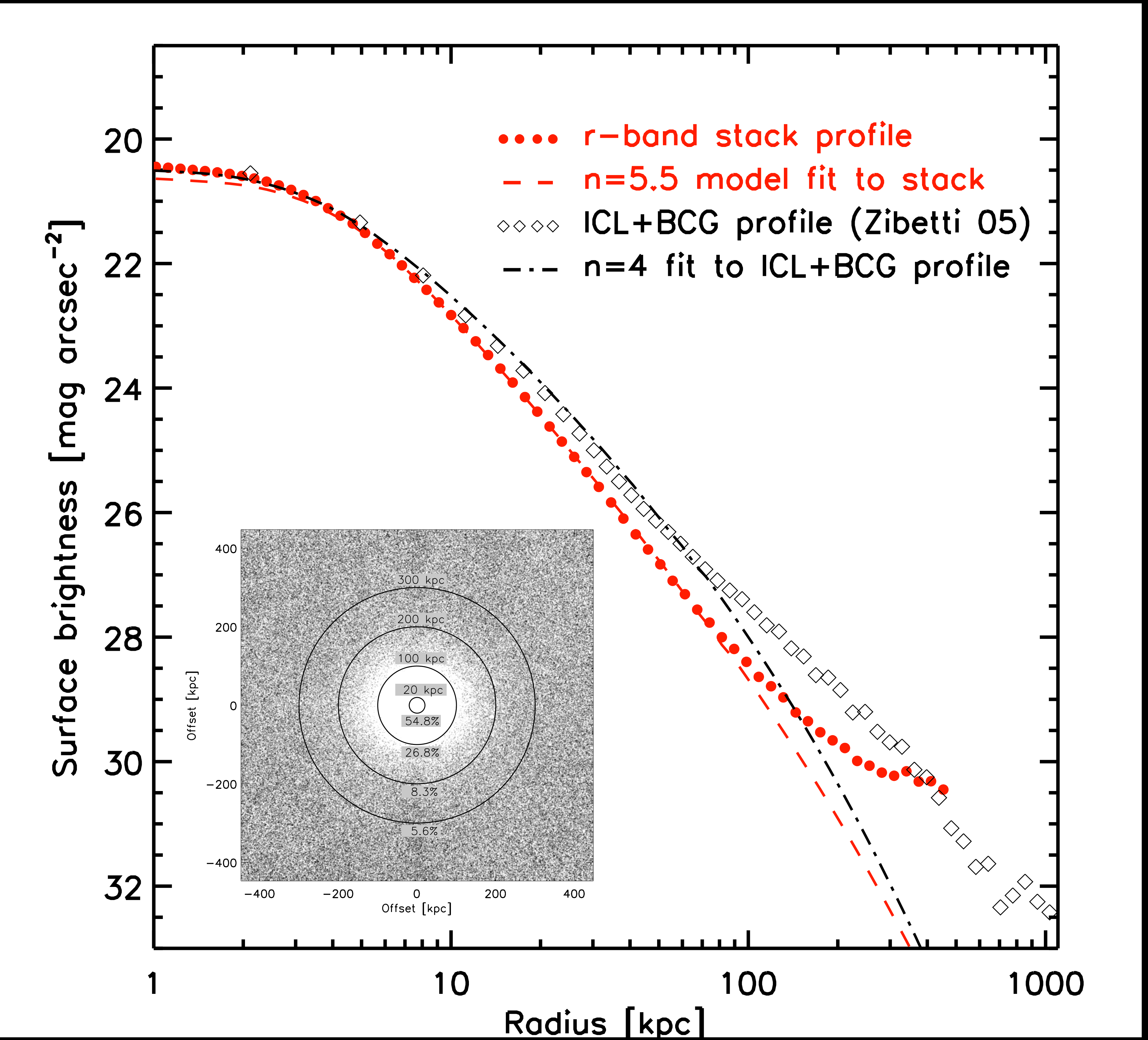
Intra-halo light

Intra-halo light (IHL): stars which have been tidally stripped from their parent galaxies during galaxy mergers and go onto form an extended diffuse sea of stars in dark matter halos.

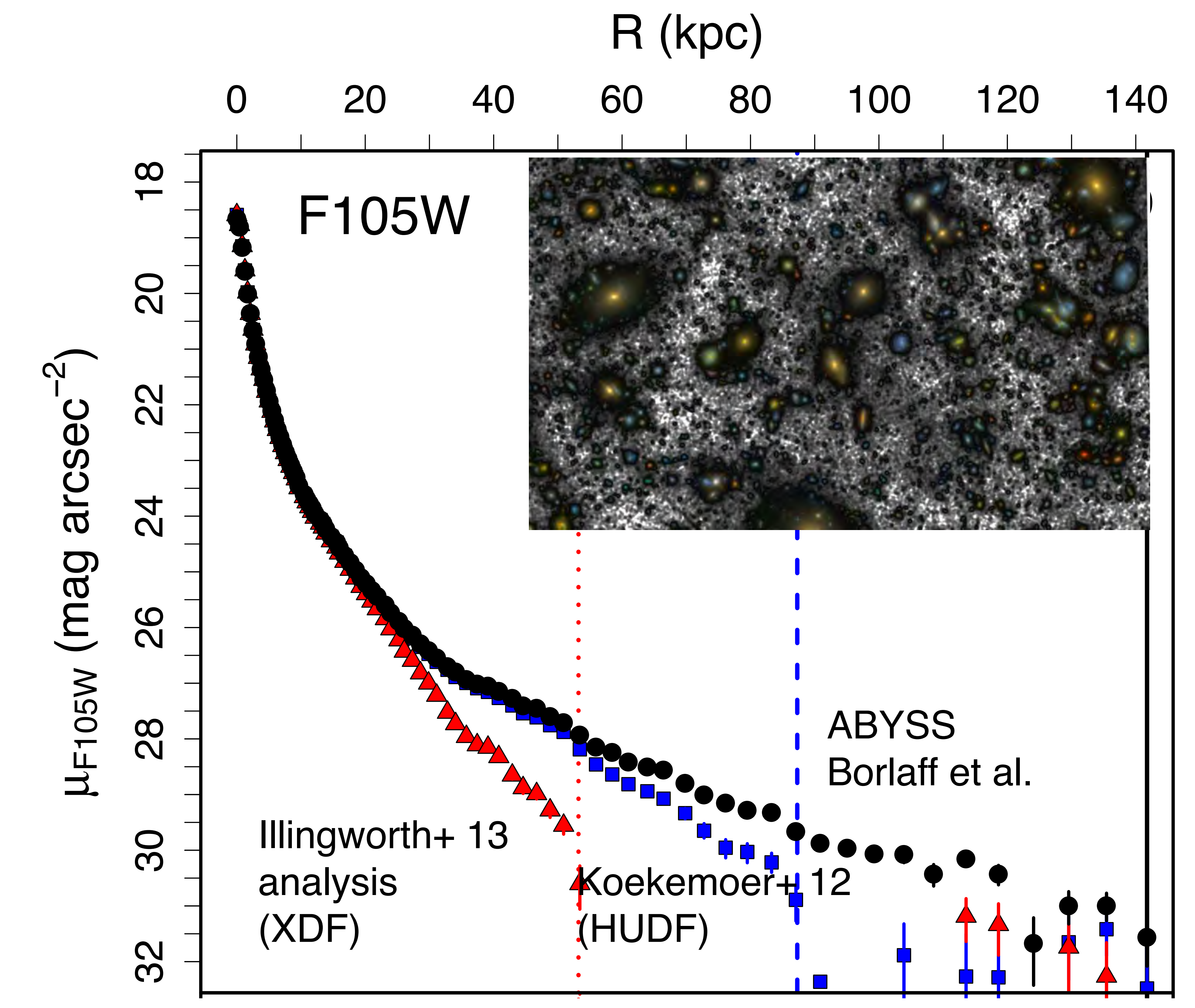


Is IHL Real? extended light profiles of galaxies

400k galaxies SDSS stack (Tal & van Dokkum 12)

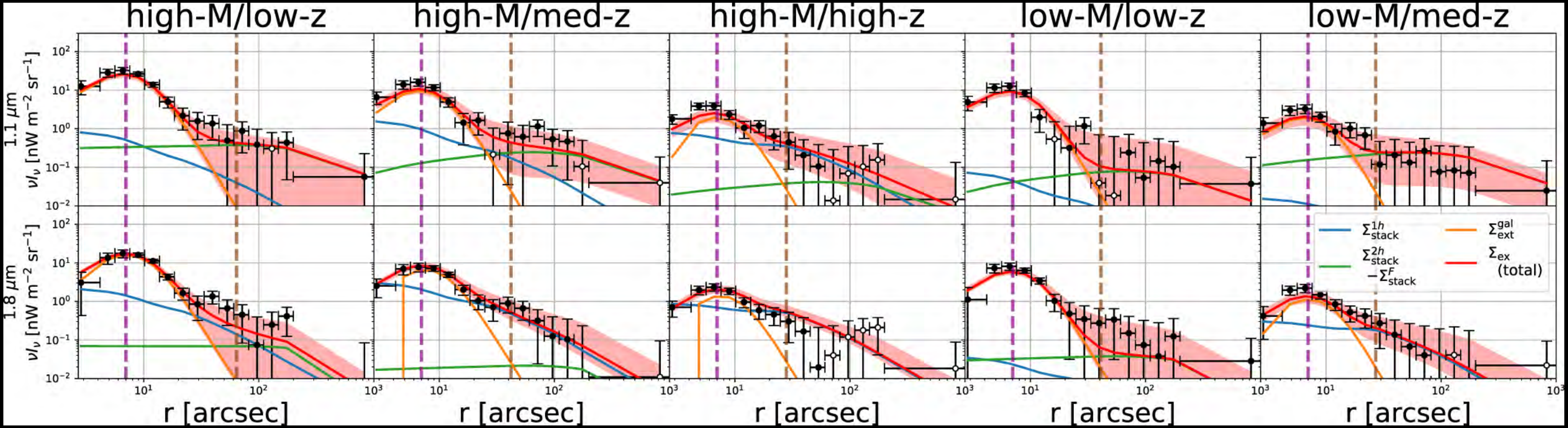


The missing light of the HUDF (Borlaff et al. 2019)



- If IHL should see extended light profiles - more in early-type galaxies (likely merger products) than late types (evidences starting to show up slowly)
- There should be clear color differences, not demonstrated yet.
- When does the galactic disk end? when does IHL start? no clear definitions of IHL/ICL yet.

Is IHL Real? extended light profiles of galaxies



CIBER-detected galaxy stacks (Cheng et al. 2022)

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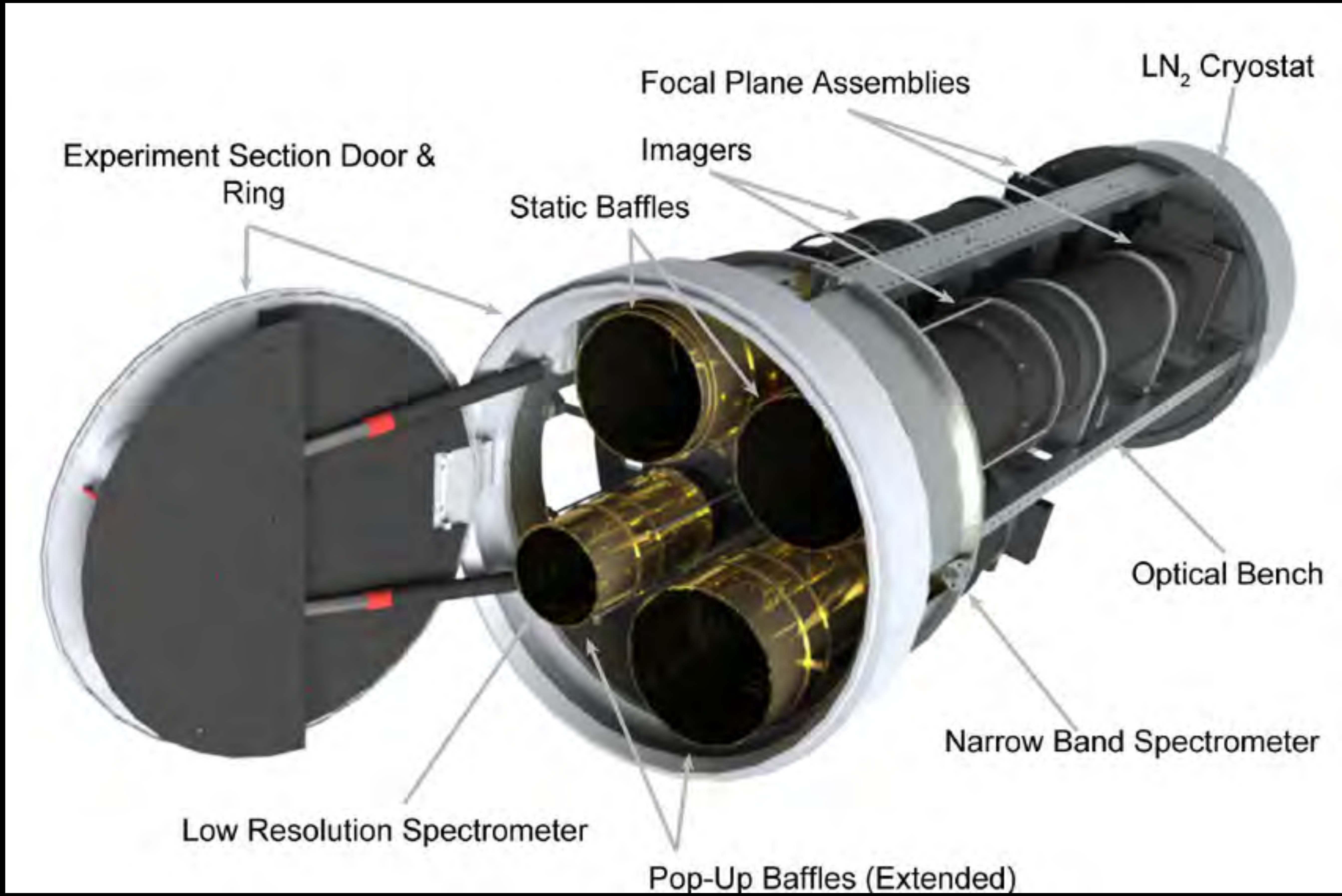
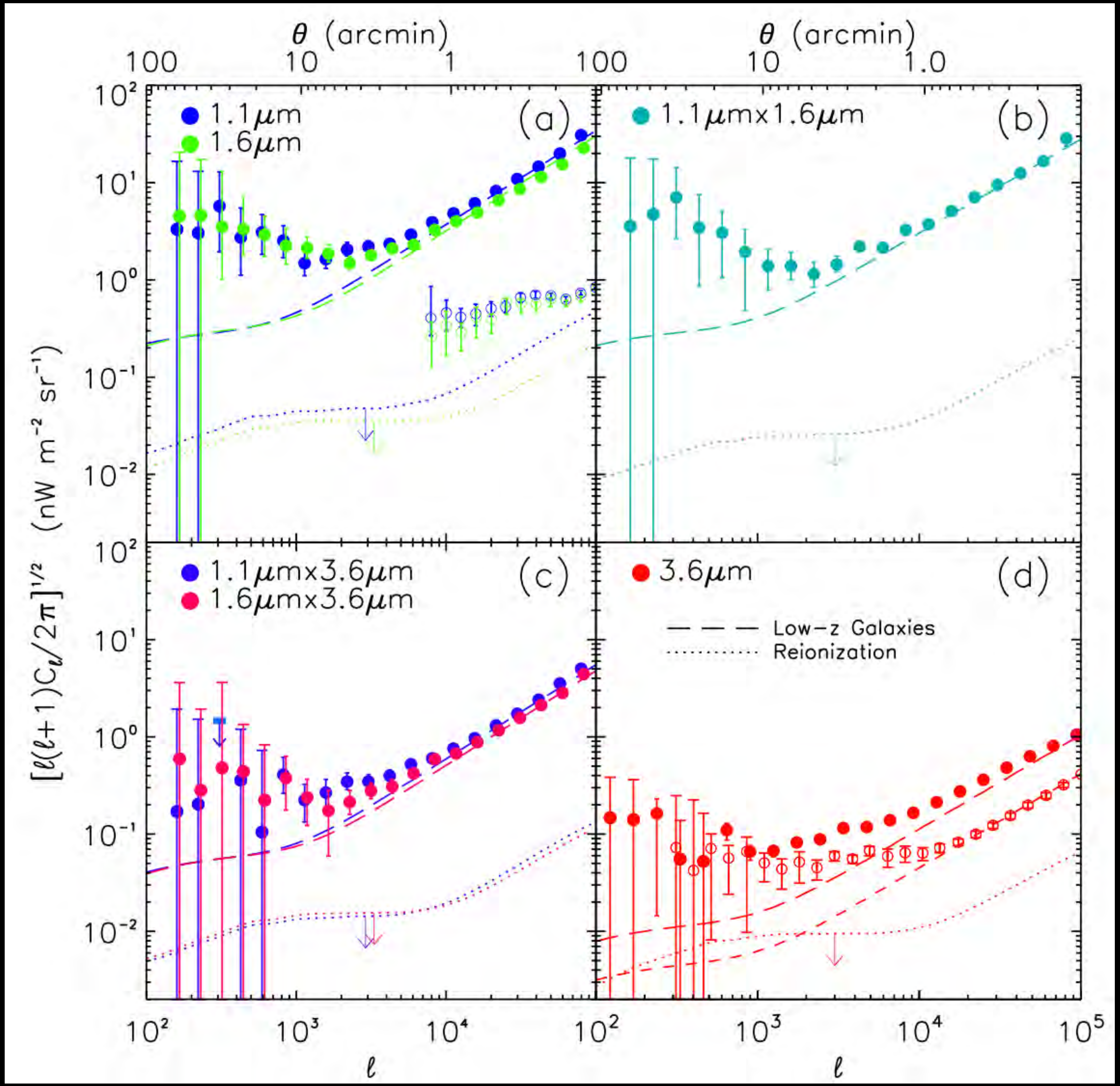


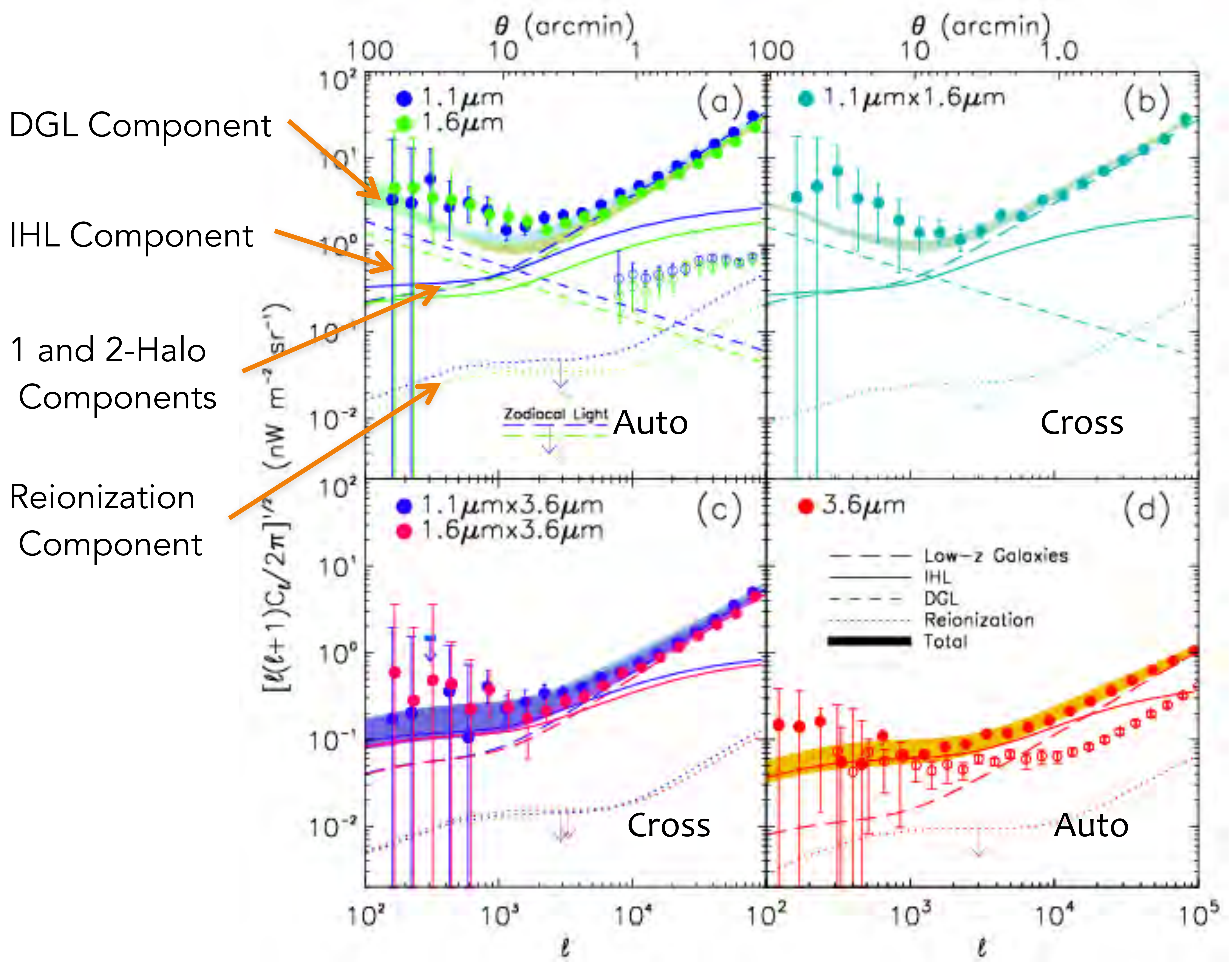
Uses the two imaging cameras



CIBER Fluctuations

Zemcov et al. 2014, Science, 490, 514

CIBER Fluctuation Results



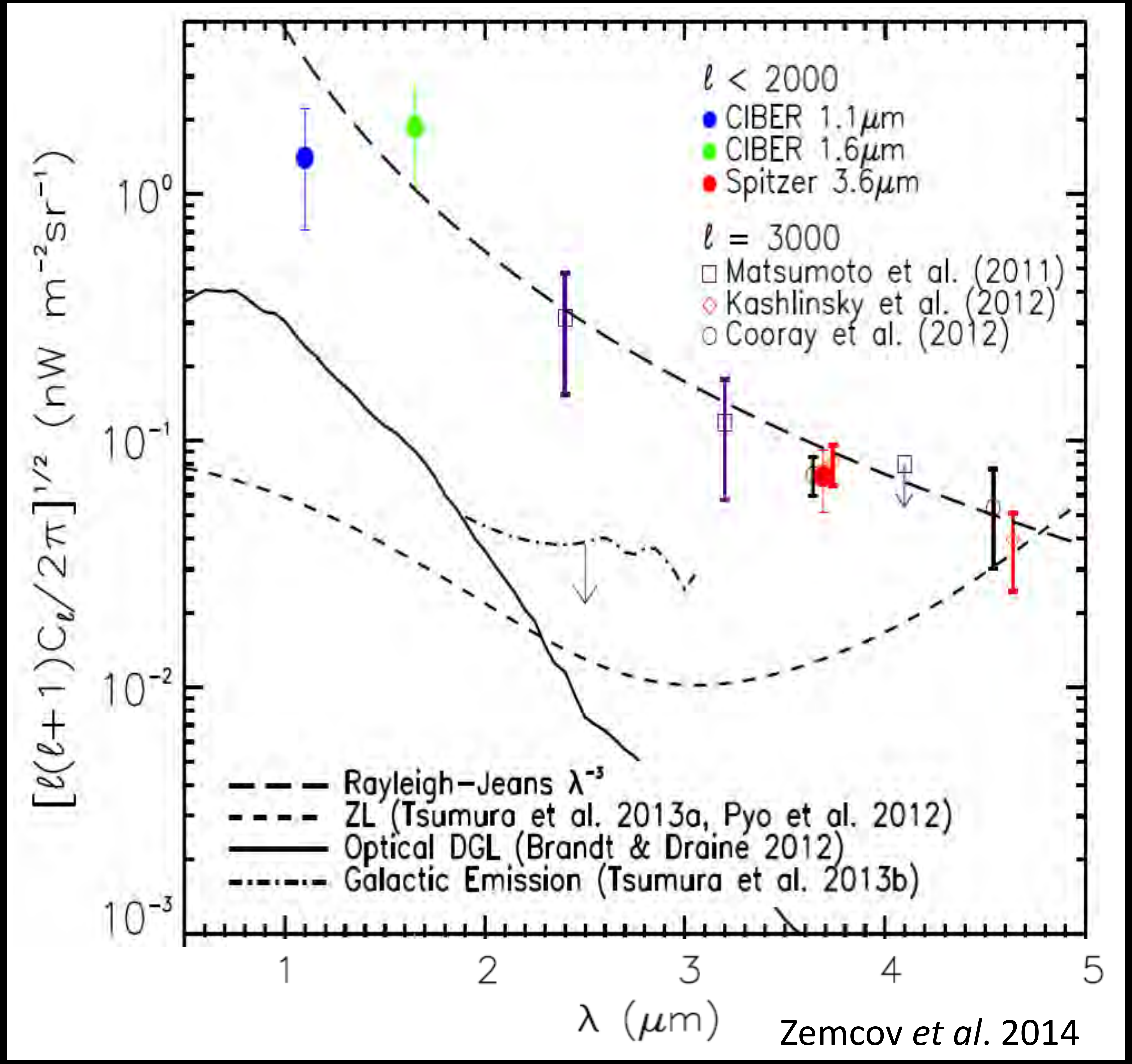
- CIBER power spectra follow galaxies to scales of a few arcmin, and then strongly deviate.
- Behavior is well matched by Spitzer data at longer wavelengths.

Zemcov et al. 2014, CIBER results, Science

Near-Infrared Clustering Fluctuations

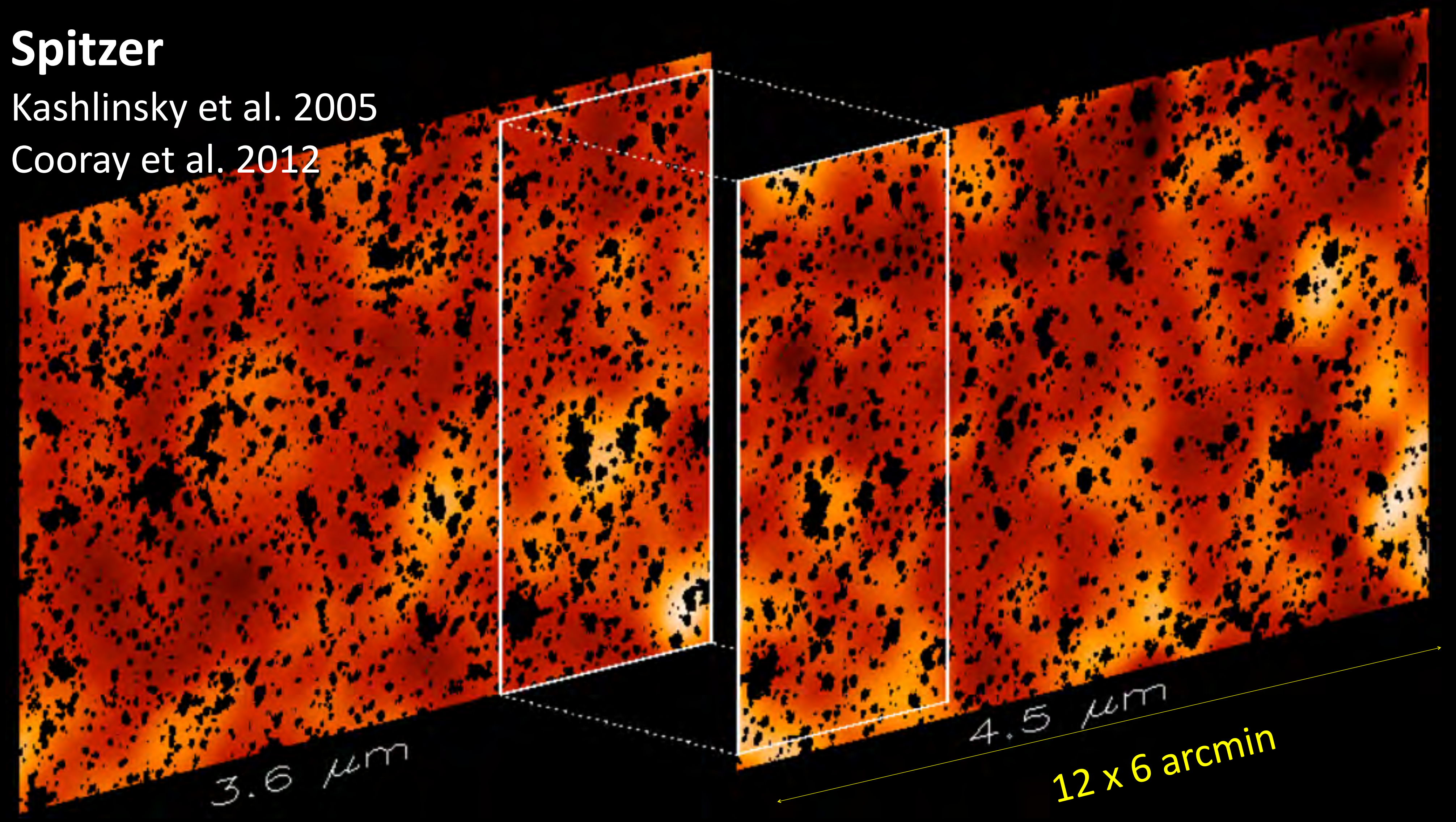
IHL (at redshift 0-2) or EOR (at redshift 6-8)?

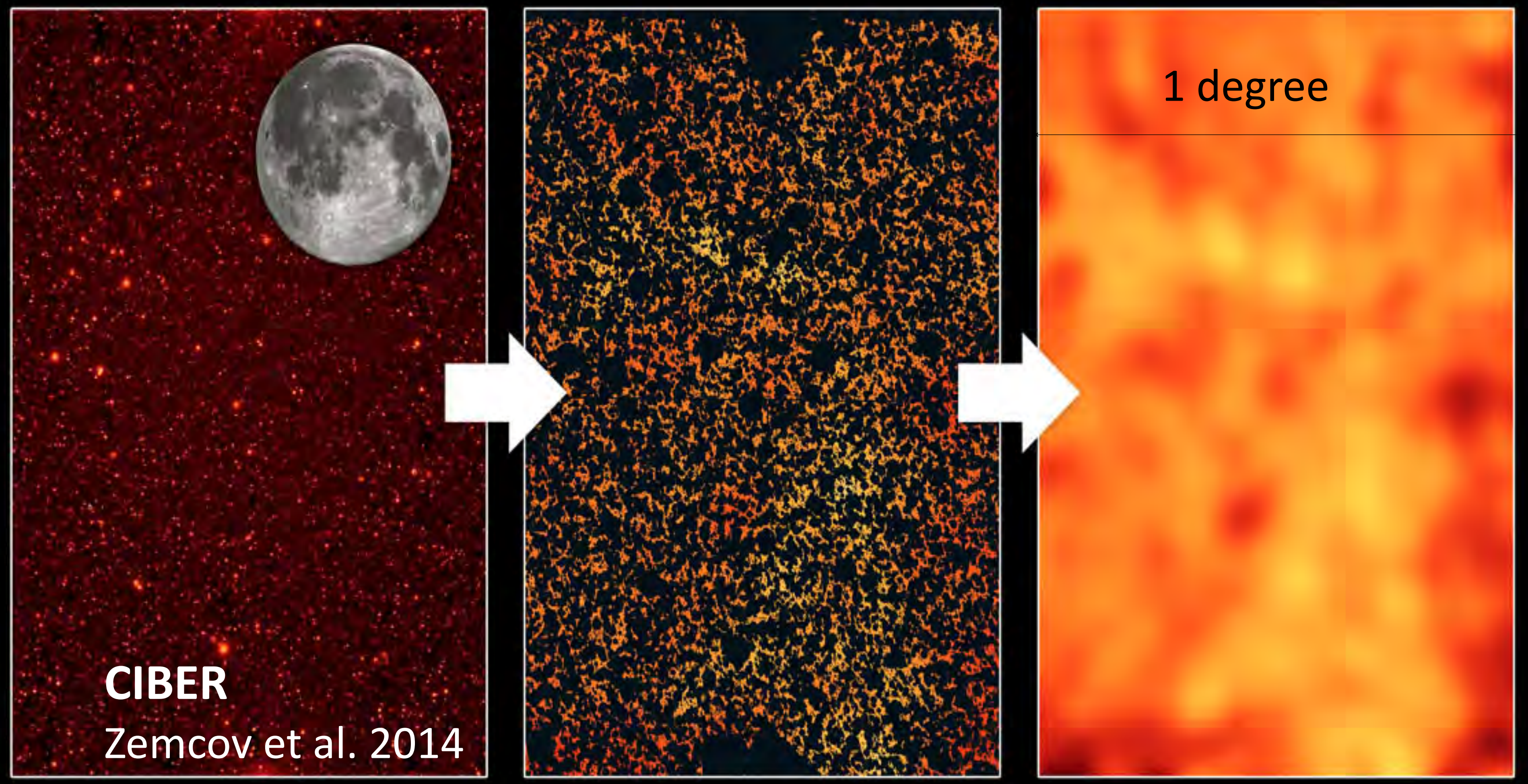
Amplitude of clustering power spectrum



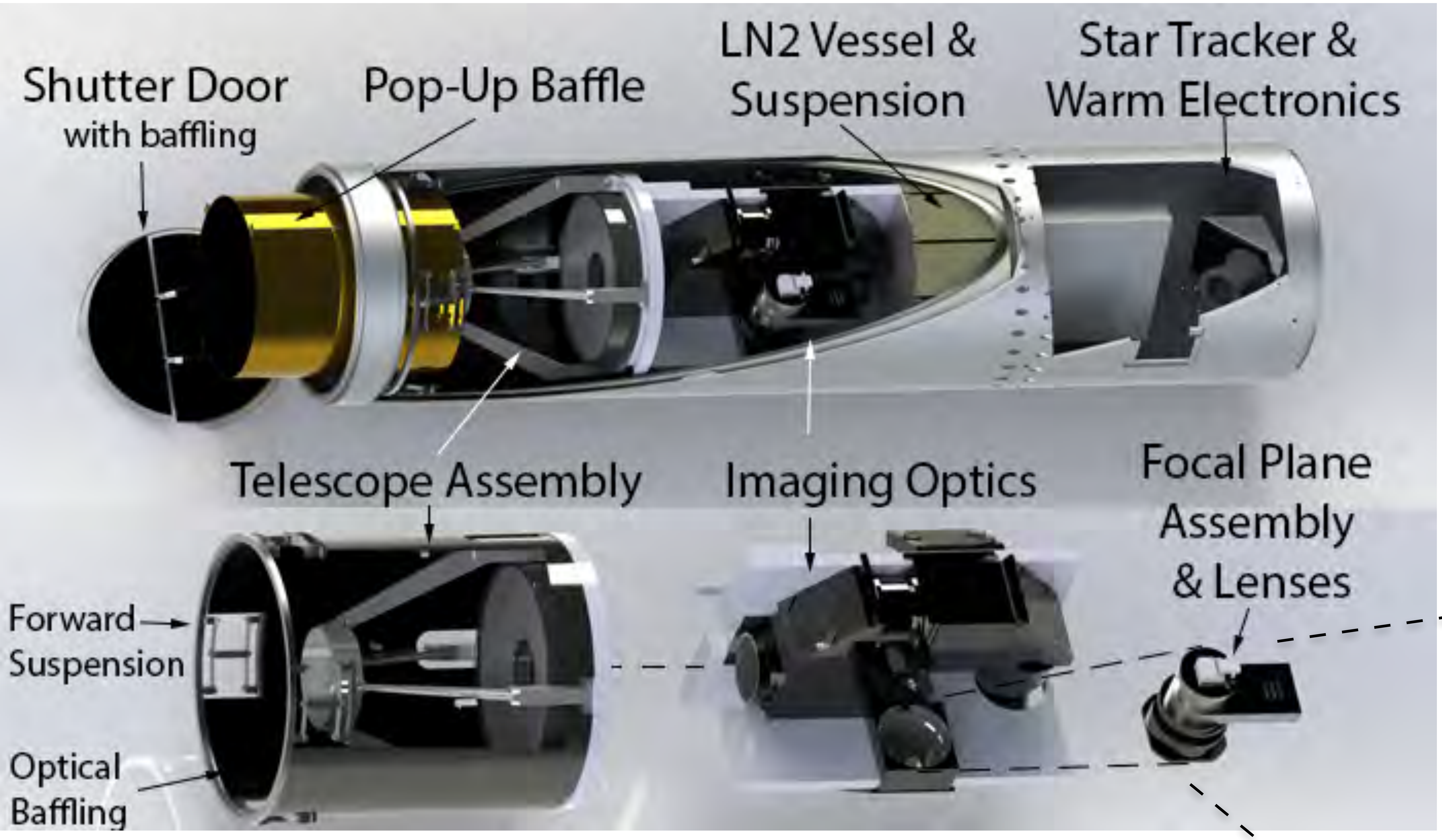
Inferred Extragalactic Background

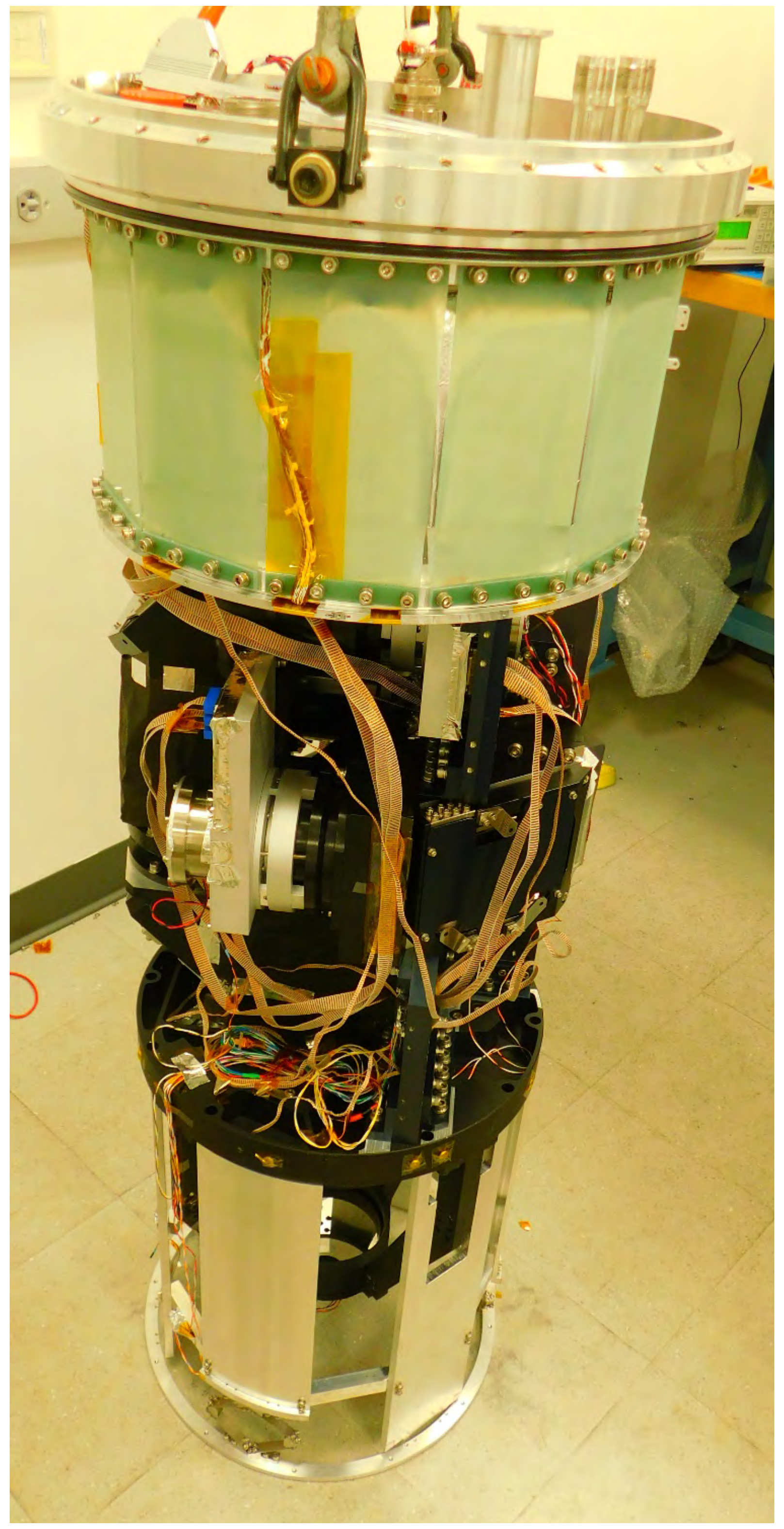
λ (μm)	Measured $\delta\lambda I_\lambda^a$ (nW m^{-2} sr^{-1})	$\frac{\lambda I_{\lambda,\mathrm{IHL}}}{\delta\lambda I_\lambda}$	$\lambda I^b_{\lambda,\mathrm{IHL}}$ (nW m^{-2} sr^{-1})	$\lambda I^c_{\lambda,\mathrm{IGL}}$ (nW m^{-2} sr^{-1})
1.1	$1.4^{+0.8}_{-0.7}$	5	$7.0^{+4.0}_{-3.5}$	$9.7^{+3.0}_{-1.9}$
1.6	$1.9^{+0.9}_{-0.8}$	6	$11.4^{+5.4}_{-4.8}$	$9.0^{+2.6}_{-1.7}$
2.4	$0.32 \pm 0.05^*$	7	2.2 ± 0.4	$7.8^{+2.0\ e}_{-1.2}$
3.6	$0.072^{+0.019}_{-0.021}$	9	$0.65^{+0.17}_{-0.19}$	5.2 ± 1.0
3.6^f	$0.049^{+0.021}_{-0.007}$	9	$0.44^{+0.19}_{-0.06}$	5.2 ± 1.0
4.5	$0.053 \pm 0.023^*$	7	0.37 ± 0.16	3.9 ± 0.8

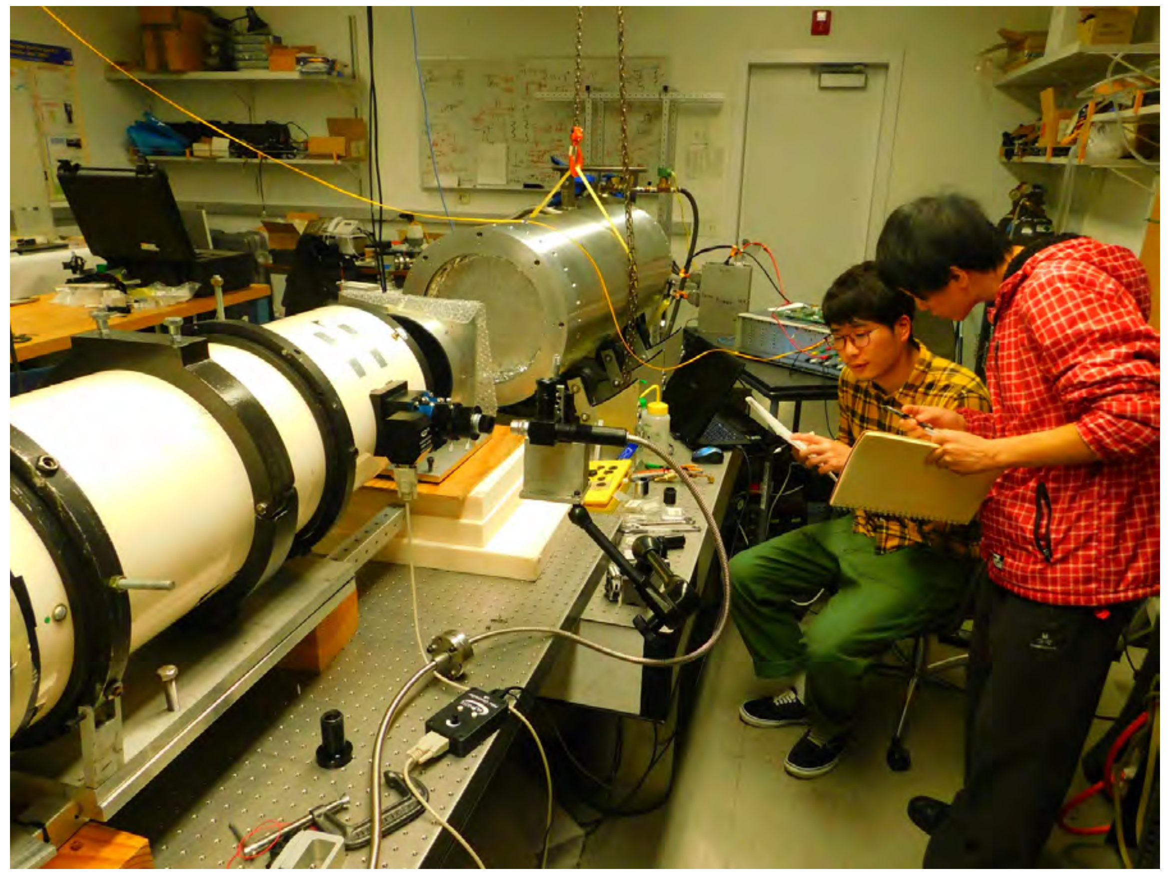


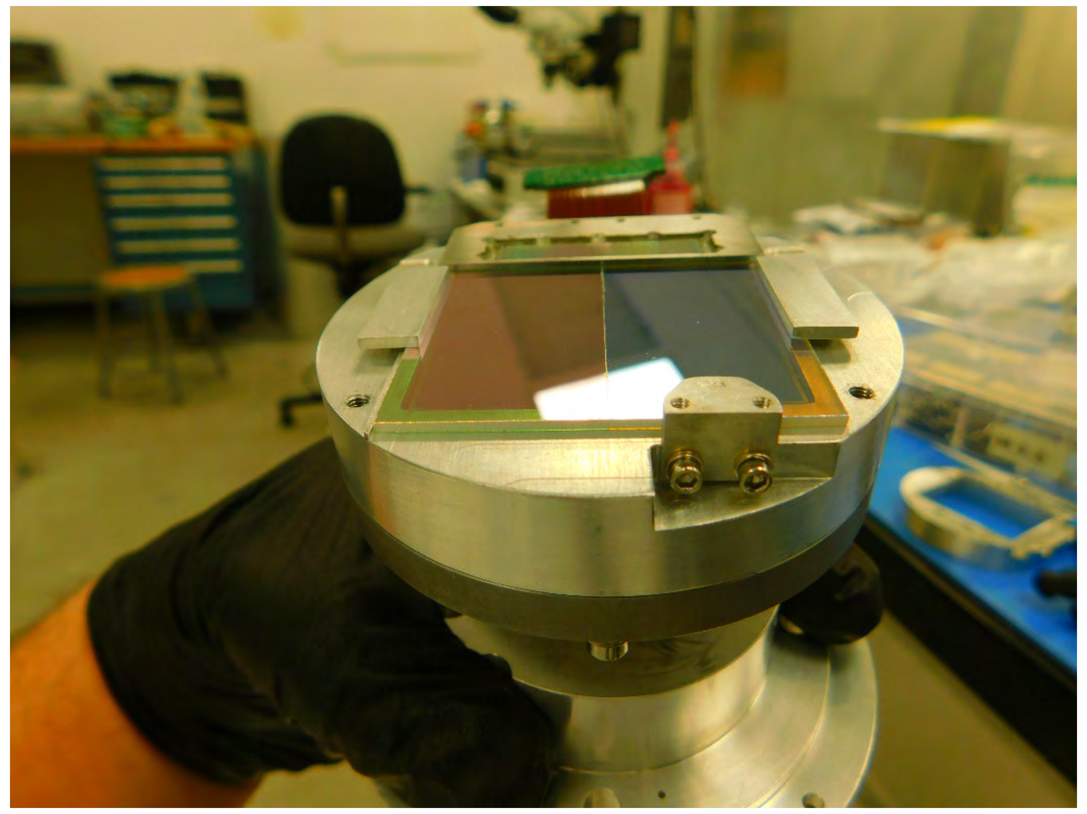


CIBER-2 (2 flights 2022-2024)







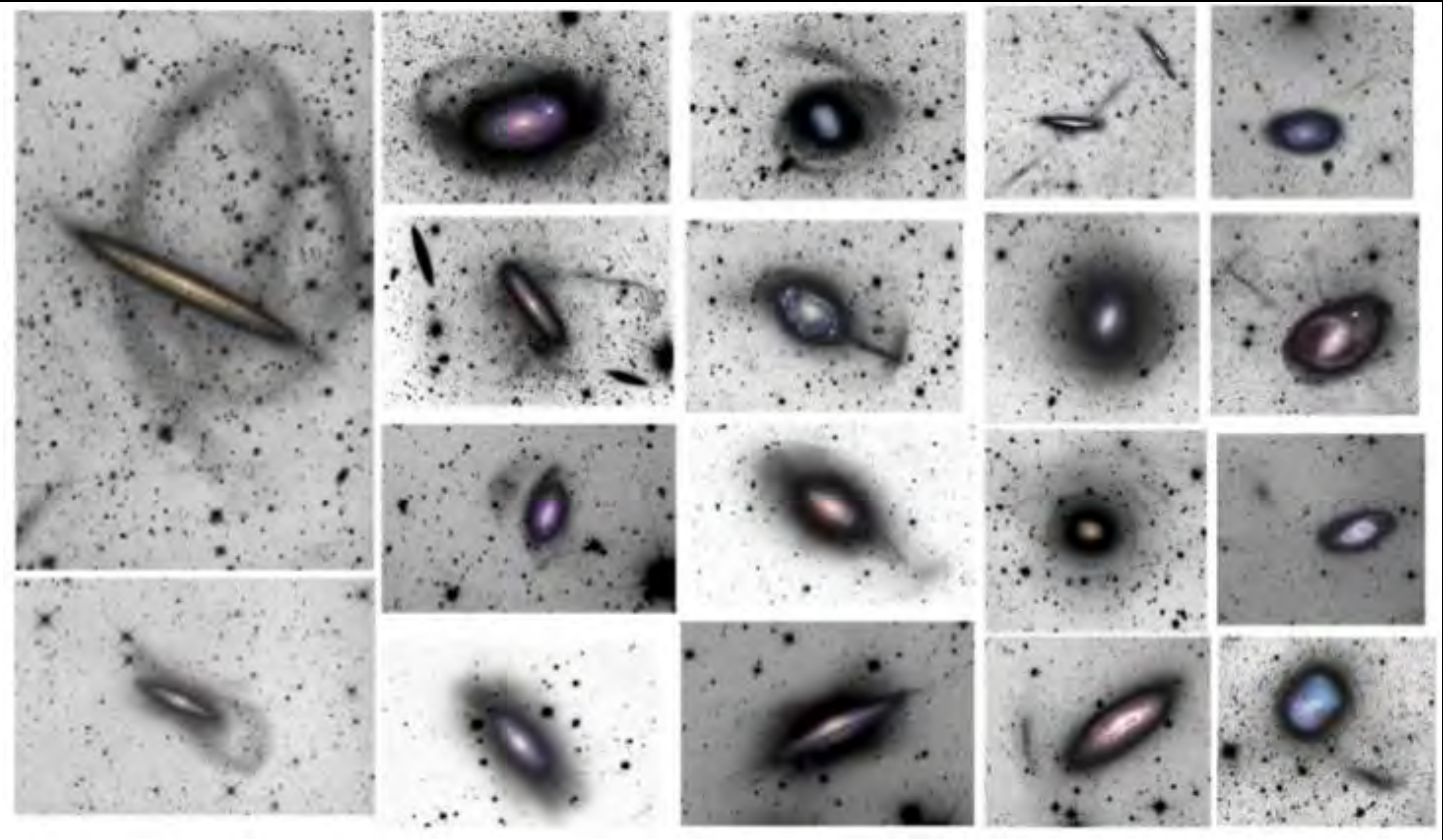


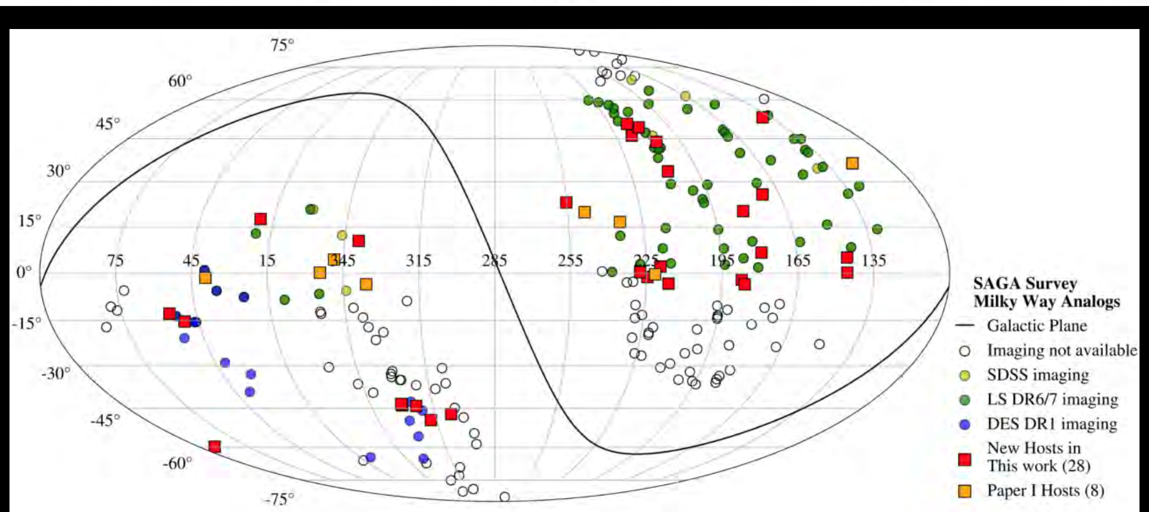
- NASA-APRA funded
- Hardware integrated at Caltech
- Two launches completed; papers now in preparation

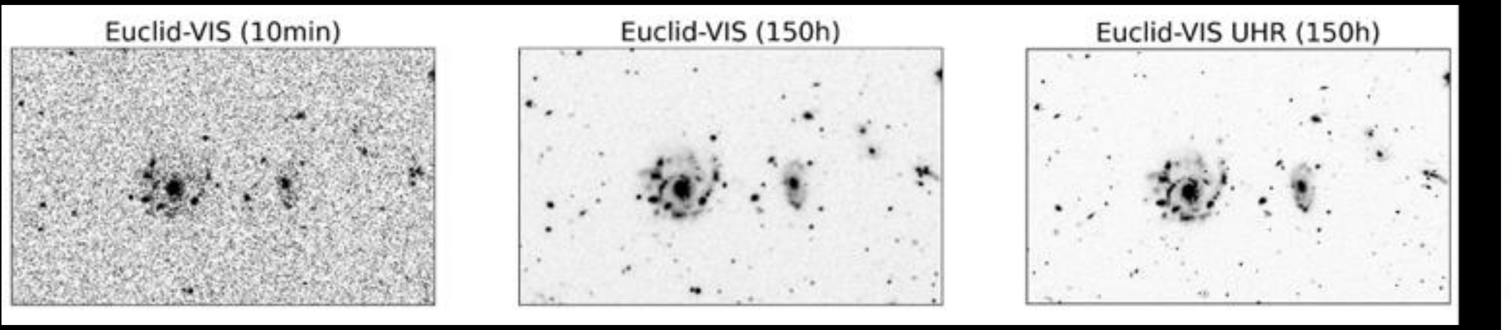
Mike Zemcov and CIBER Collaboration

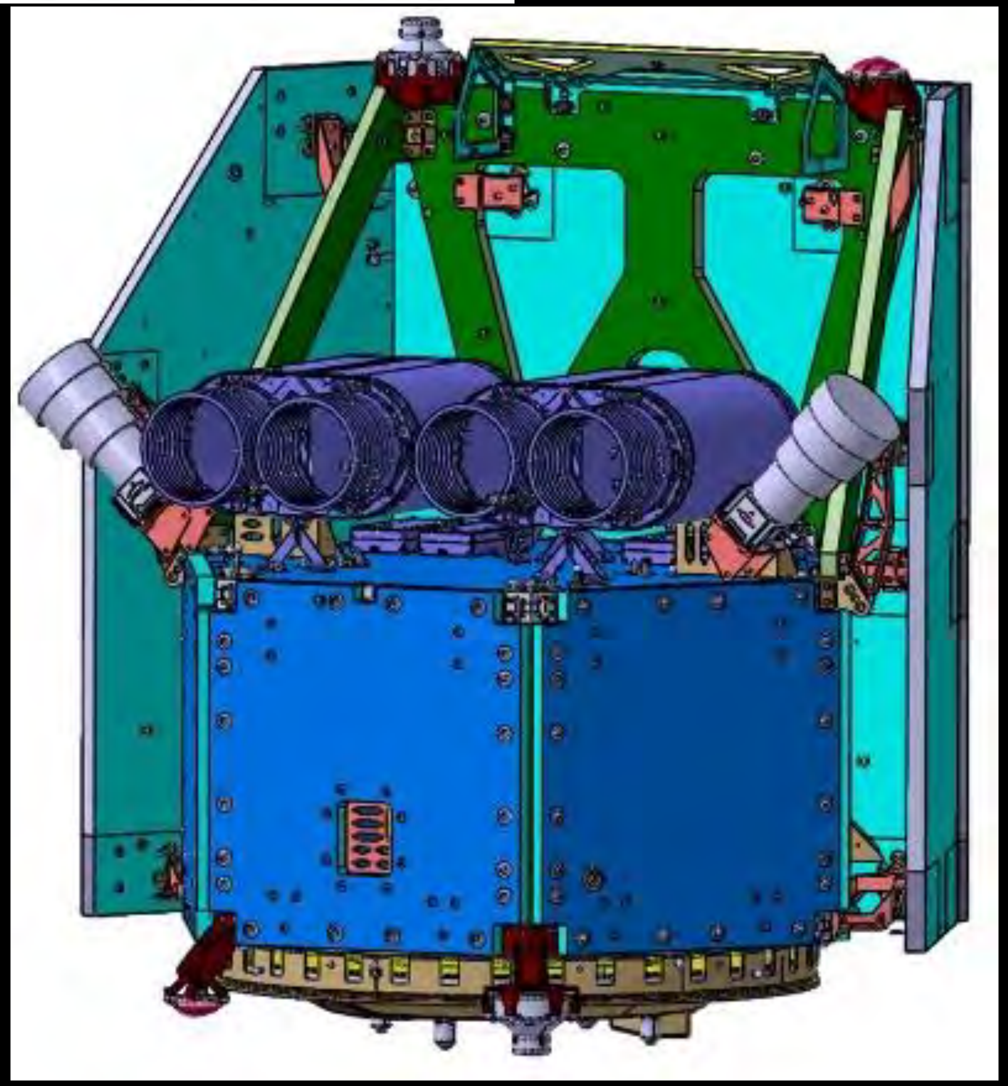
ARRAKIHS

IHL imager





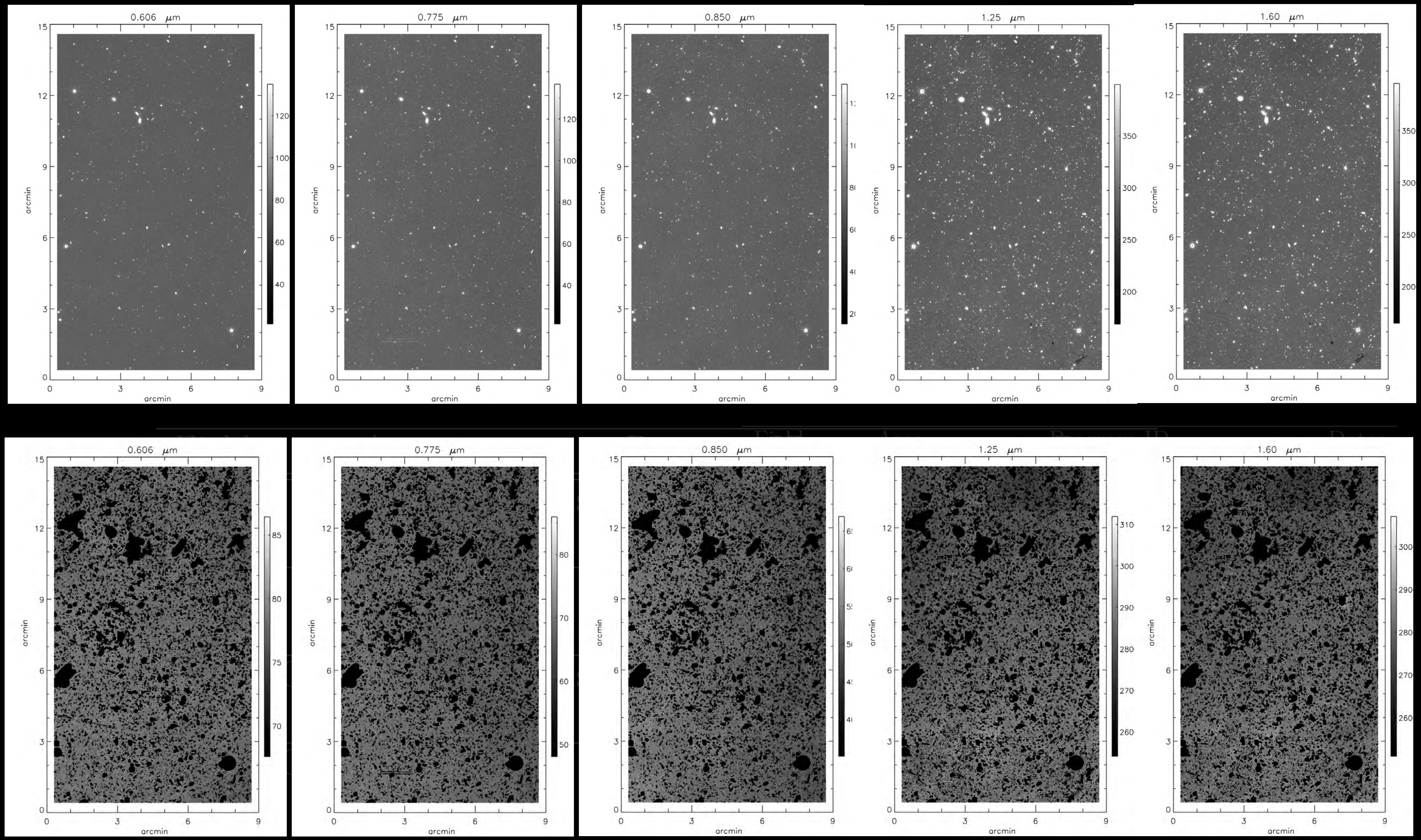




MAIN SCIENCE GOALS				
• Test the predictions of the Cold Dark Matter model with unprecedented ultra-low surface brightness observations of a magnitude-limited and volume-limited sample of Milky Way-type galaxies in the local universe. • Determine the statistics and distribution of satellite galaxies down to Mv<-6 in the haloes of Milky Way-type galaxies • Determine the statistics and geometry of the stellar streams and diffuse extended light in these galaxy haloes				
SURVEY				
Sample Selection	115 MW-type galaxies from the SAGA survey between 25Mpc and 40Mpc			
	Targets	*Area*	*Dithers / Target*	*Total Integration time*
Main Sample	100 galaxy systems	160 deg2	900	150h
Duration	2 years (nominal) - 3 years (goal)			
PAYLOAD				
Telescope	Design	4x modified Maksutov-Cassegrain		
	Aperture	150 mm		
	Field-of-View	1.4 deg diameter		
Instrument Type	Visible and Infrared Imager			
Weight	50-60 kg			
Filters	HST-F475X	Euclid VIS	Euclid Y	Euclid J
Wavelengths	380 - 630 nm	550 – 900 nm	920 -1230 nm	1169 - 1590 nm
Pixel scale	1.37 arcsec		2.3 arcsec	
Coadd resolution	0.8 arcsec		1.25 arcsec	
Detector	2x Teledyne e2v 4k x 4k CCD		2x Teledyne 2k x 2k H2RG	
Operating temp	150 K		140 K	
Sensitivity	~ 31 mag/arcsec^2		~ 30 mag/arcsec^2	
SPACECRAFT				
Launcher	Vega C dedicated or Rideshare			
Orbit	Sun Synchronous Orbit LTAN 6AM/6PM from 600 to 1000 km			
Pointing	0.5 arcsec RMS over 10 minutes			
Cooling	Passive radiators and heat pipes			
Communications	Bands	S and X		
	Downlink Rate	15 Mbps		
	Daily data volume	11,1 GB		
AOCS & Propulsion	Micro Propulsion Subsystem, Reaction Wheels, Gyro Payload Fine Guidance System			
Total Wet Mass	< 300 kg			
SCHEDULE				
Mission Kick Off	*Mission Adoption*	*Launch*	*End of Observations*	
2023 Q1	2025 Q2	2029 Q3	2032 Q1	

ESA F (fast) mission, selected in 2020; final adoption decision in 2025-2026; launch in 2029 with M-class ARIEL (ride share for ARIEL)

Reionization signal in IR fluctuations?



Mitchell-Wynne et al. 2015 Nature Comm using archival Hubble CANDELS deep fields

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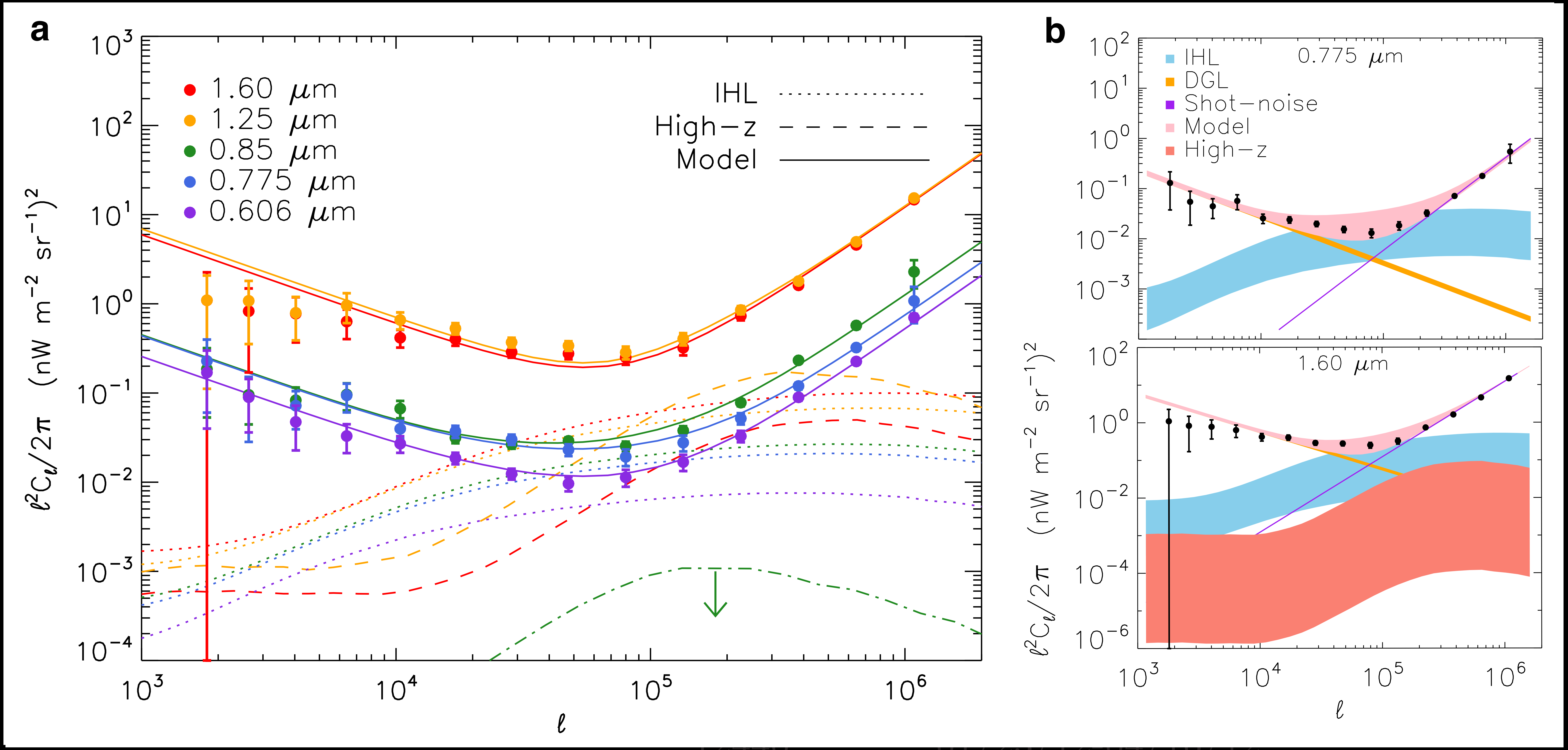
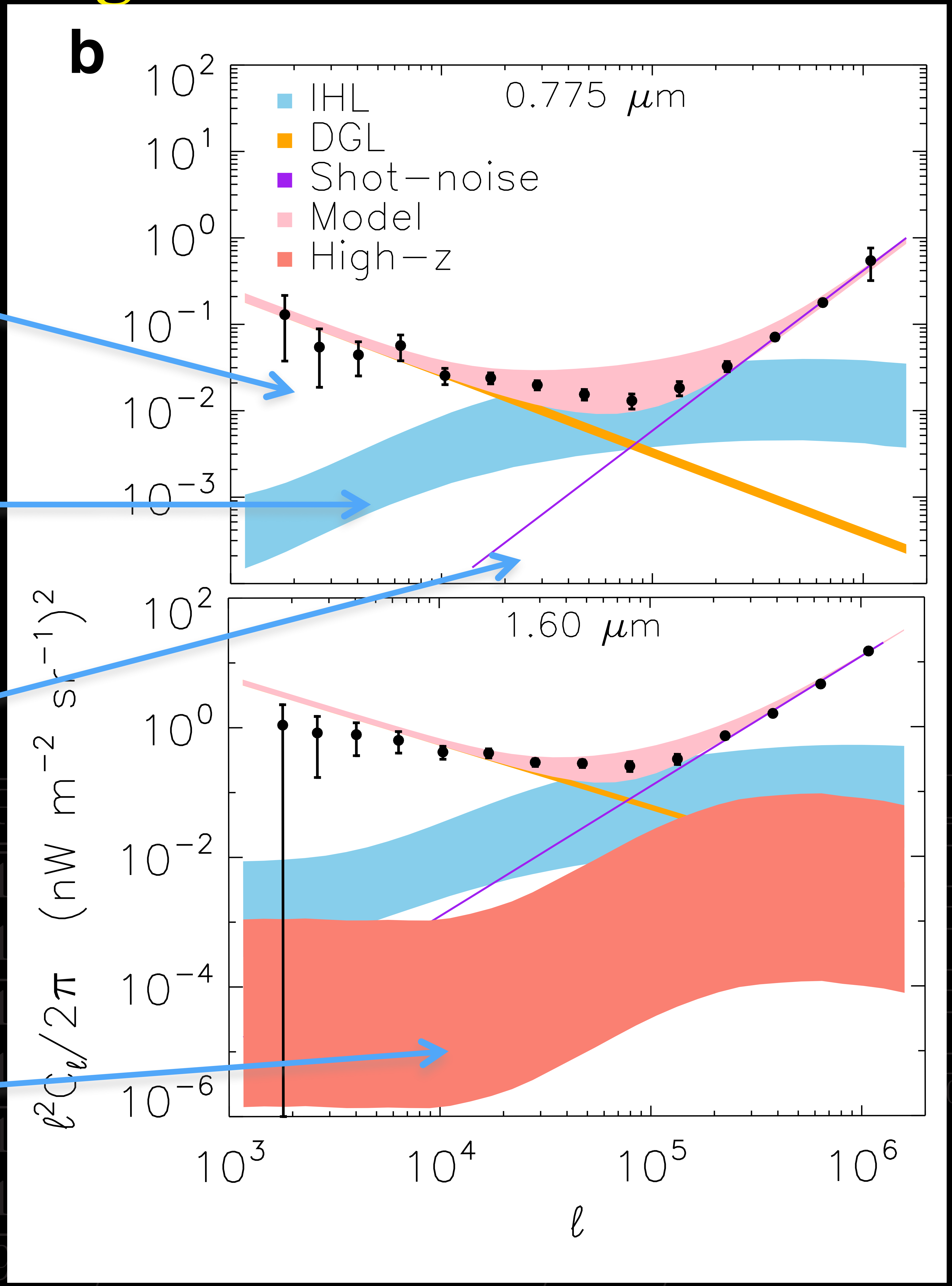


COSMOS 1.8 sq degrees 9822/10092 10/03-5/04

Mitchell-Wynne et al. 2015 Nature Comm
using archival Hubble CANDELS deep fields

Reionization signal in IR fluctuations?



Mitchell-Wynne et al. 2015 Nature Comm using archival Hubble CANDELS deep fields

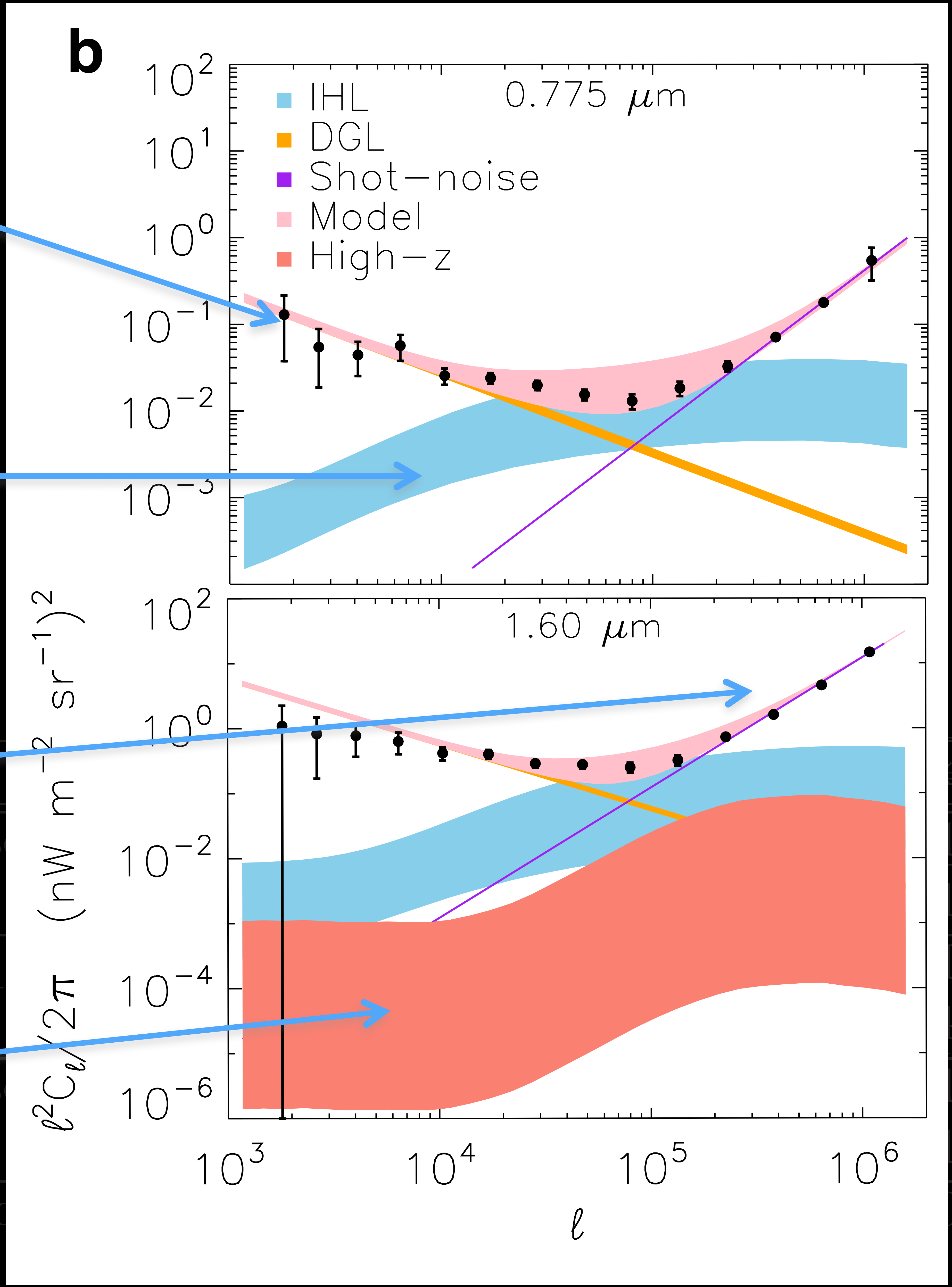
Reionization signal in IR fluctuations (CIBER-II/SPHEREx)

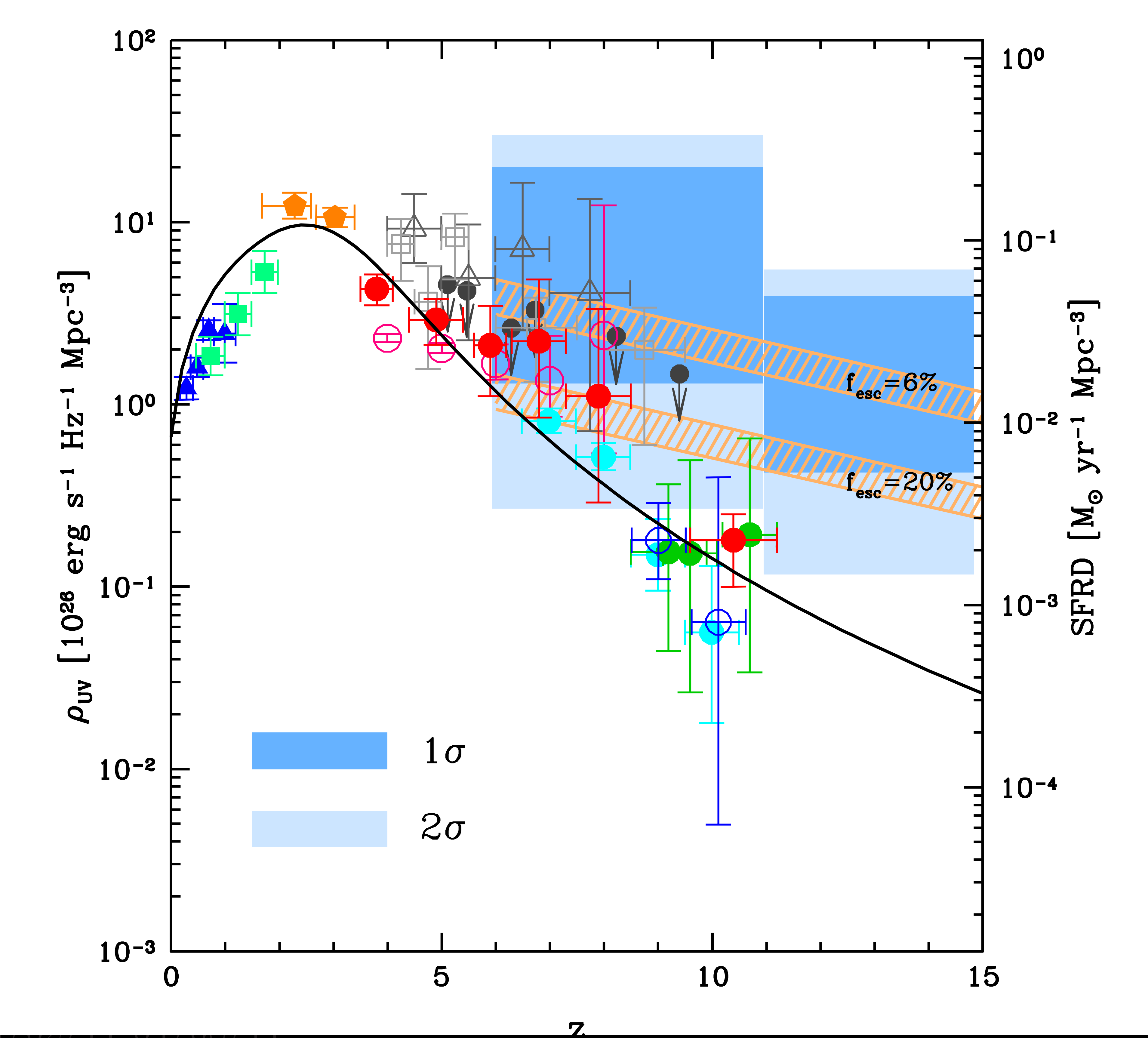
DGL

IHL

Shot-noise from low-z galaxies

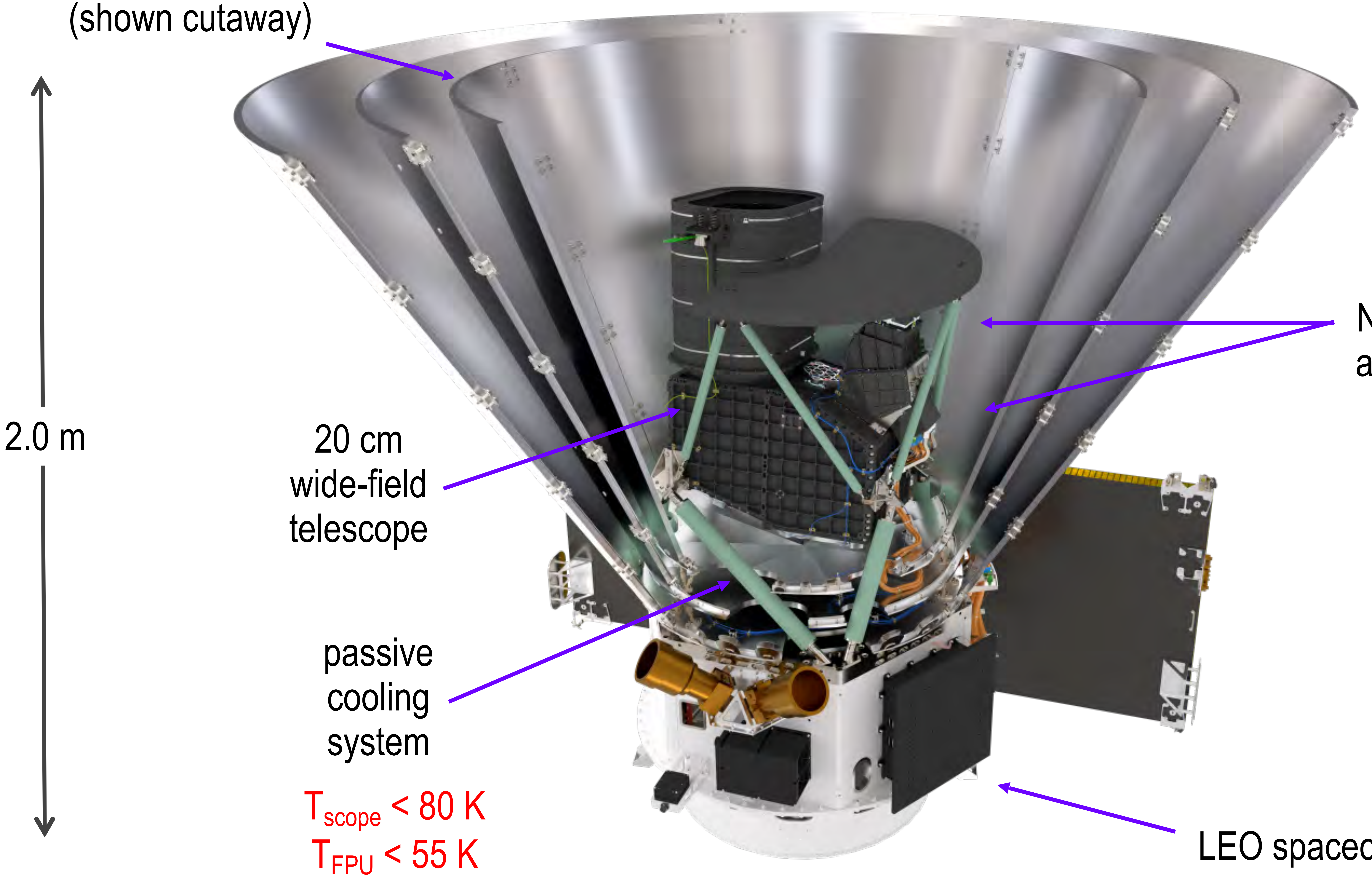
High-redshift galaxies





Mitchell-Wynne et al. 2015 Nature Comm using archival Hubble CANDELS deep fields

SPHEREx IN A NUTSHELL



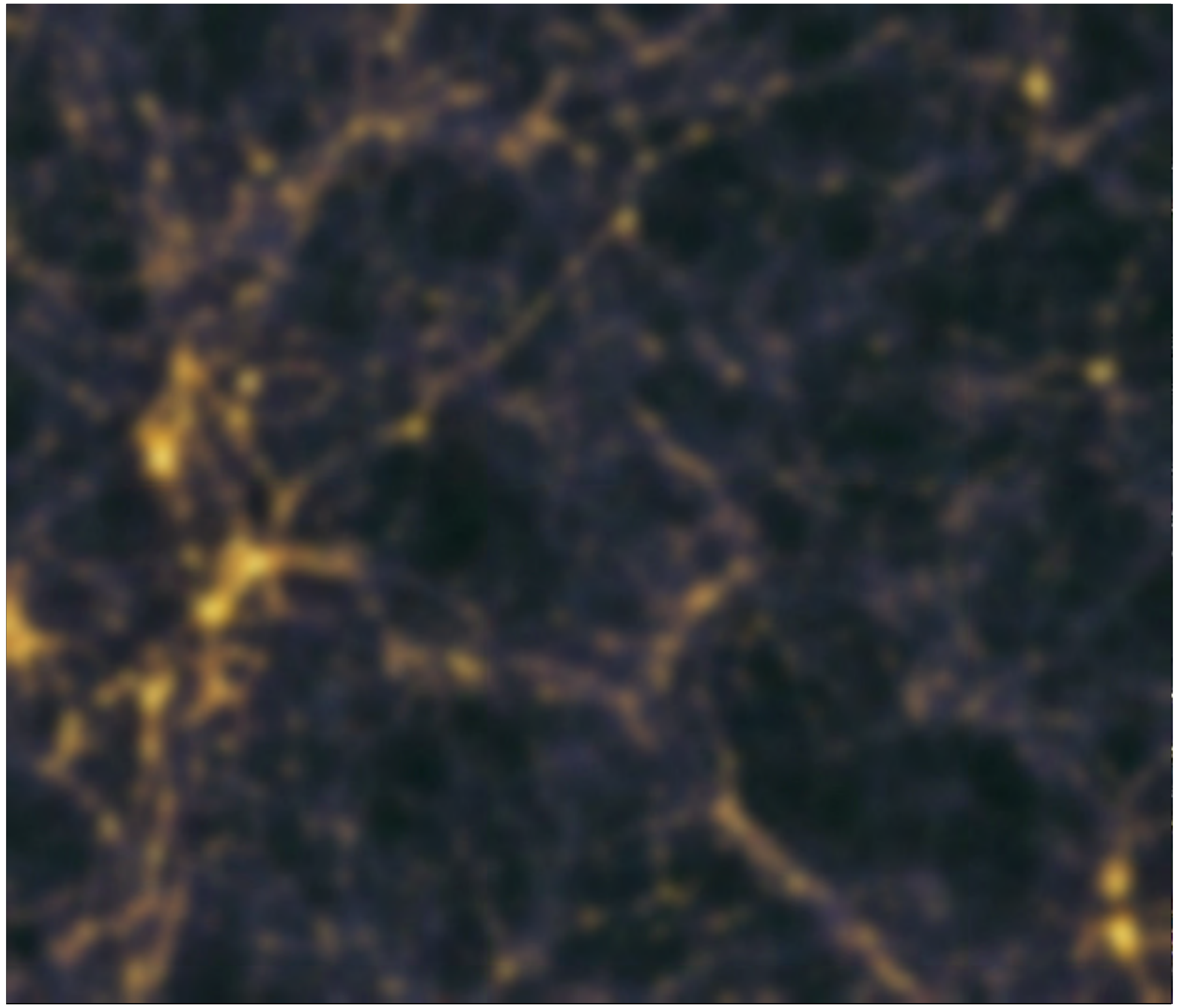
$T_{scope} < 80$ K
$T_{FPU} < 55$ K

$\lambda = 0.75 – 5\ \mu m$
$\lambda/\Delta\lambda = 35 – 130$
6.2" pixels

Launch around Feb-March 2025

Surveying Cosmic History with EBL fluctuations

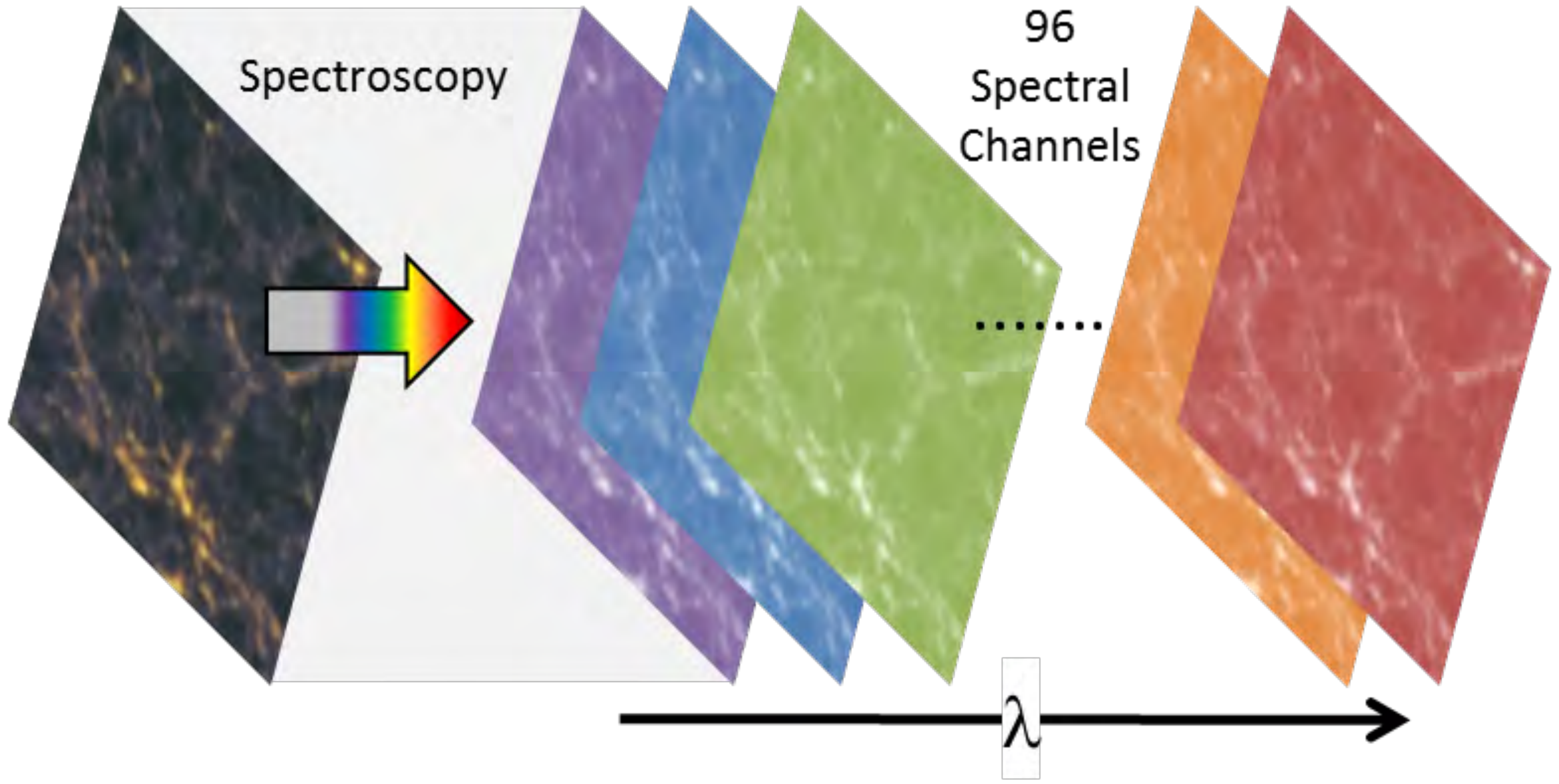
SPHEREx



EBL anisotropy measures light emitted by *everything that gravitationally clusters*

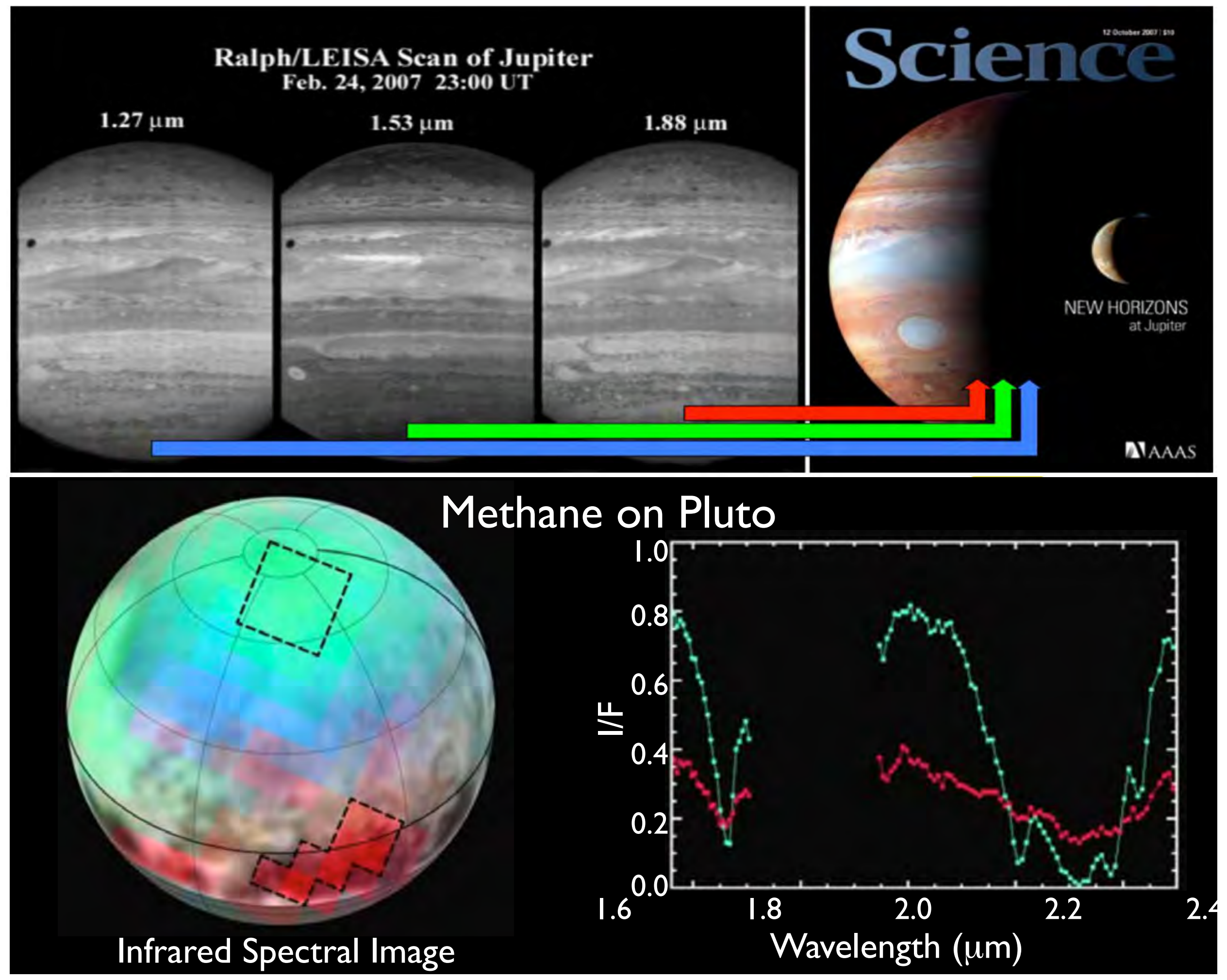
- Traces faint light associated with dark matter
  - Emission from all galaxies
  - Dwarf galaxies responsible for reionization
  - Diffuse emission from stripped stars
  - Dark matter decay (?)
- Complements galaxy-by-galaxy surveys
- Method used on CIBER, Spitzer, Herschel, Planck

Spectroscopy is key for untangling cosmic history

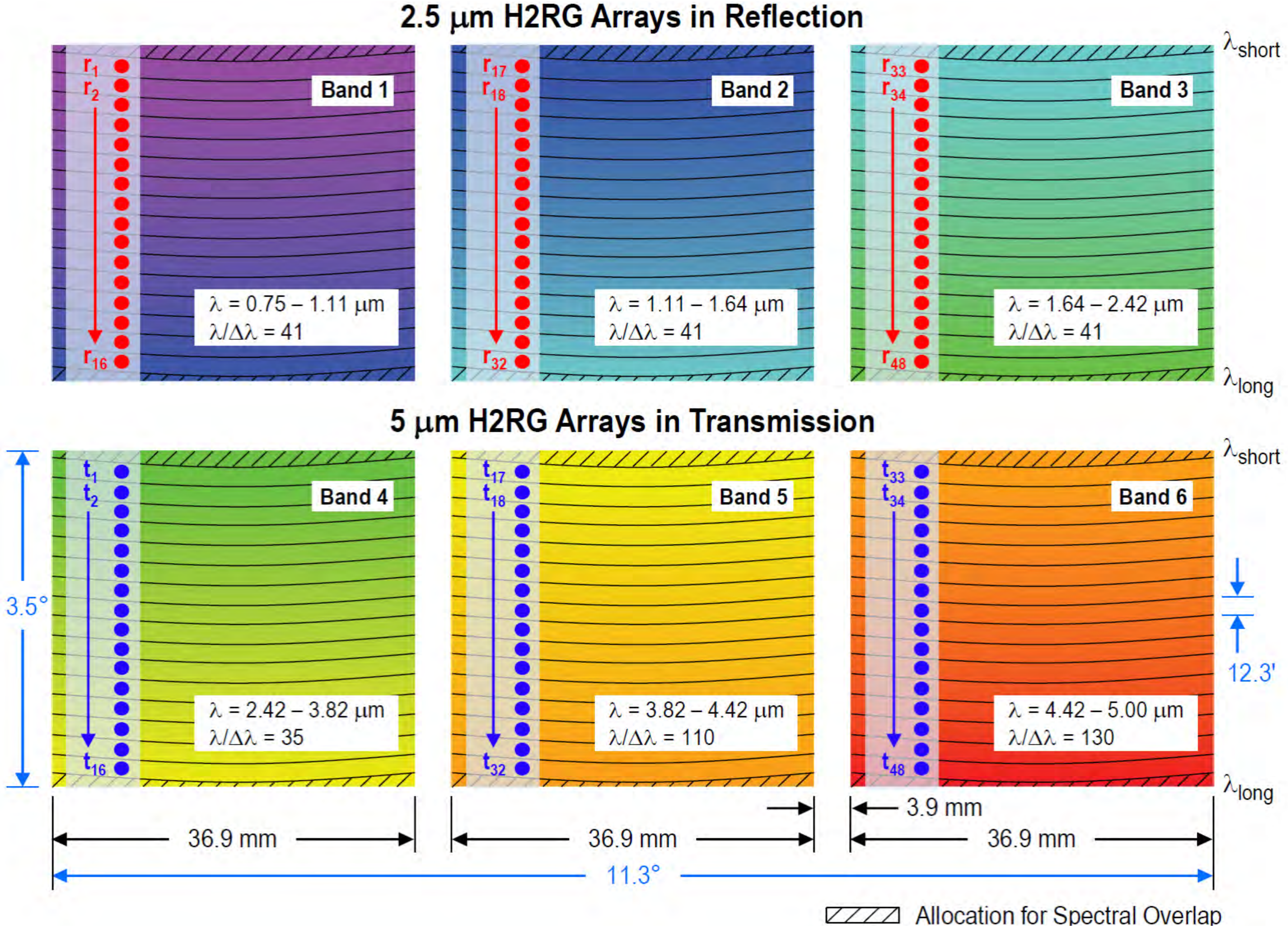


SPHEREx

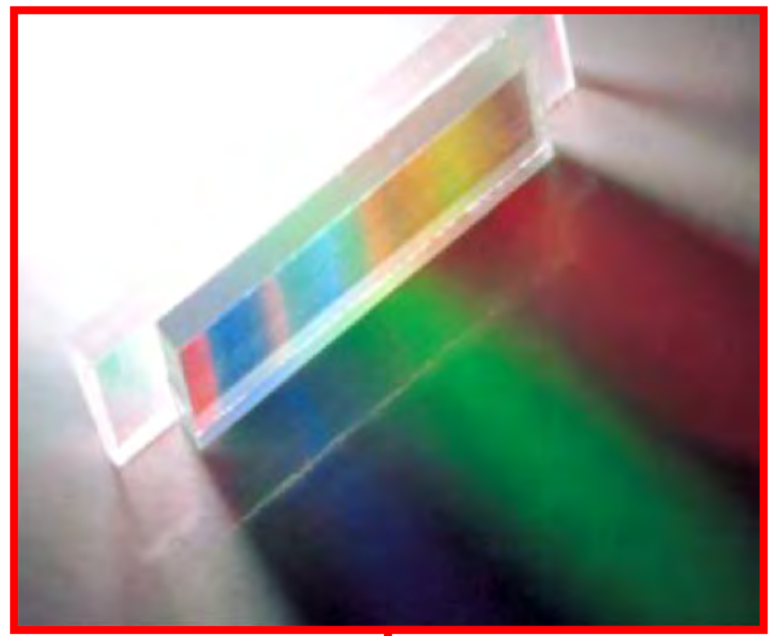
High-Throughput LVF Spectrometer



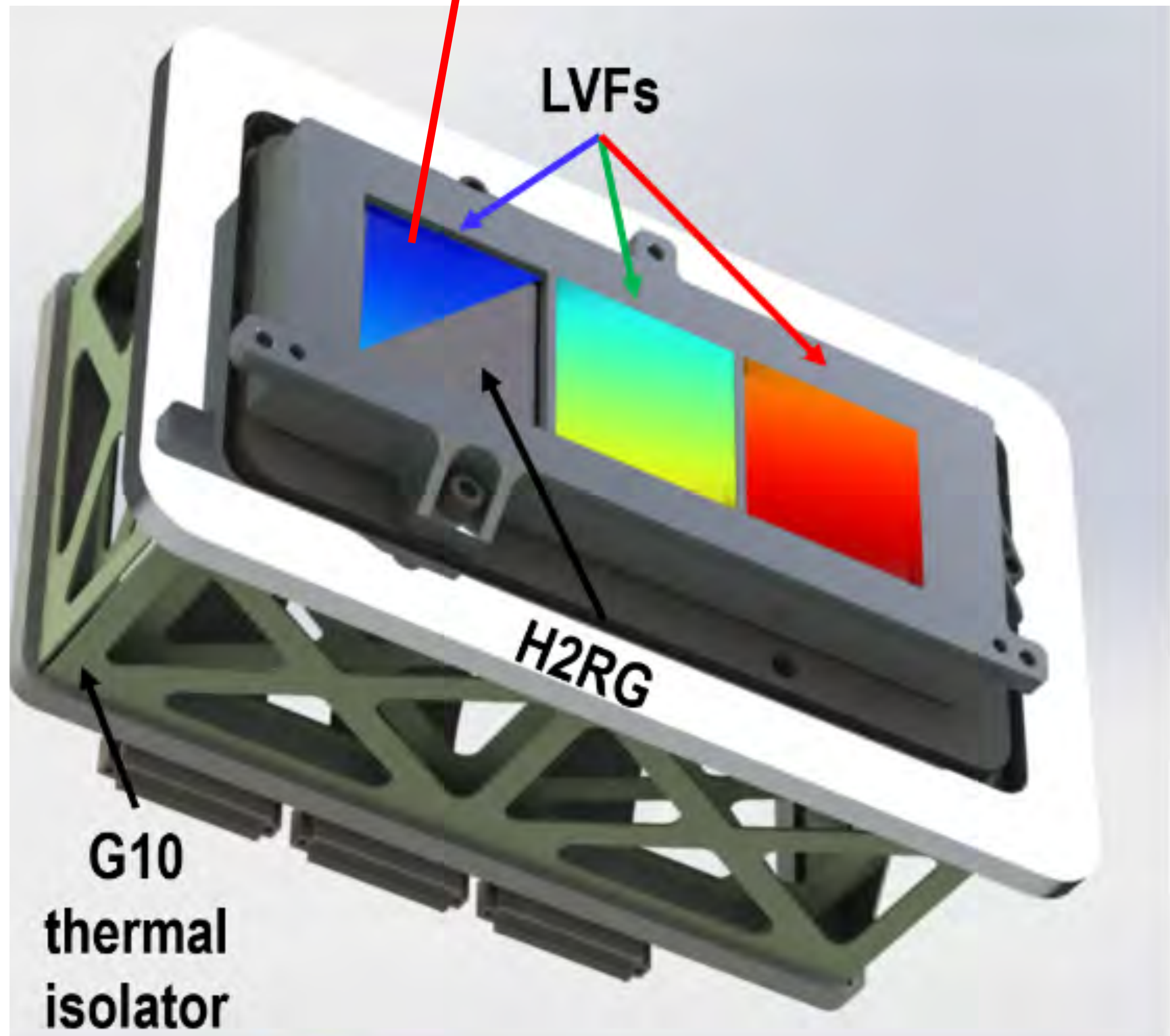
LVFs used on ISOCAM, HST-WFPC2, New Horizons LEISA, and OSIRIX-Rex



Spectra obtained by stepping source over the FOV in multiple images: **no moving parts**

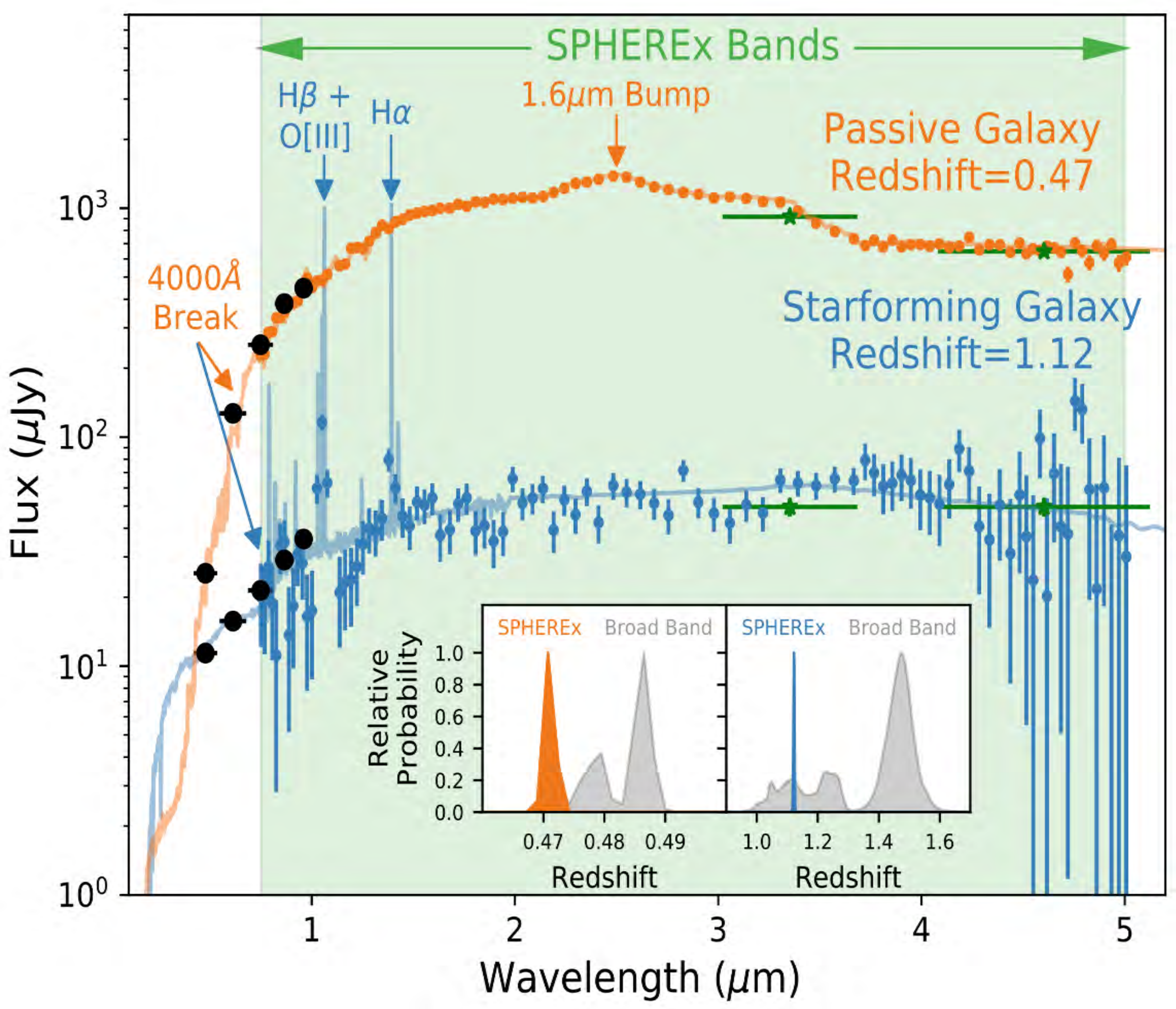


Linear Variable Filter



Focal Plane Assembly

How SPHEREx Determines z



Detected galaxies > 1 billion
Galaxies $\Delta z/1+z < 10\%$ > 450 million
Galaxies $\Delta z/1+z < 0.3\%$ > 10 million

- We extract the spectra of *known* sources using the full-sky catalogs from PanSTARRS/DES.

➡ Controls blending and confusion

- We compare this spectra to a template library (robust for $z < 1.5$ sources).

➡ For each galaxy: redshift & type

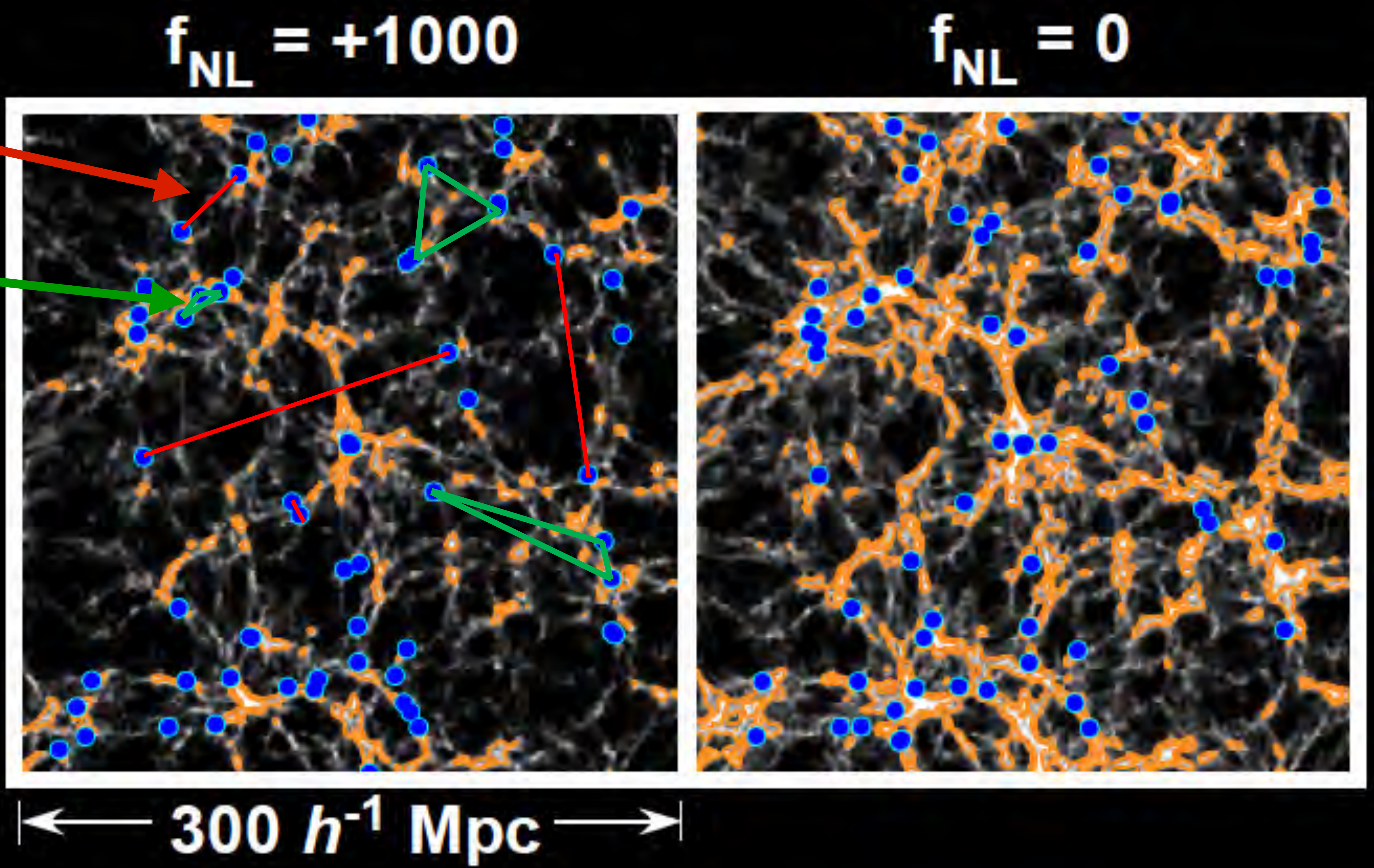
- The 1.6 μm bump is a well established universal photometric indicator, see Simpson & Eisenhardt 99.
- We simulate this process using the COSMOS data set (similar to Euclid/WFIRST assessments; Stickley et al.)

How To Measure Non-Gaussianity

f_{NL} Affects the clumpiness of galaxies.
Probes the non-gaussianity at early times.

Quantified through the Power Spectrum via 2 point correlation function

And the BiSpectrum via the 3 point correlation function



$$\phi = \phi_{linear} + f_{NL}\,\phi^2_{linear}$$

primordial potential = Gaussian random field + f_{NL} x χ^2-like field

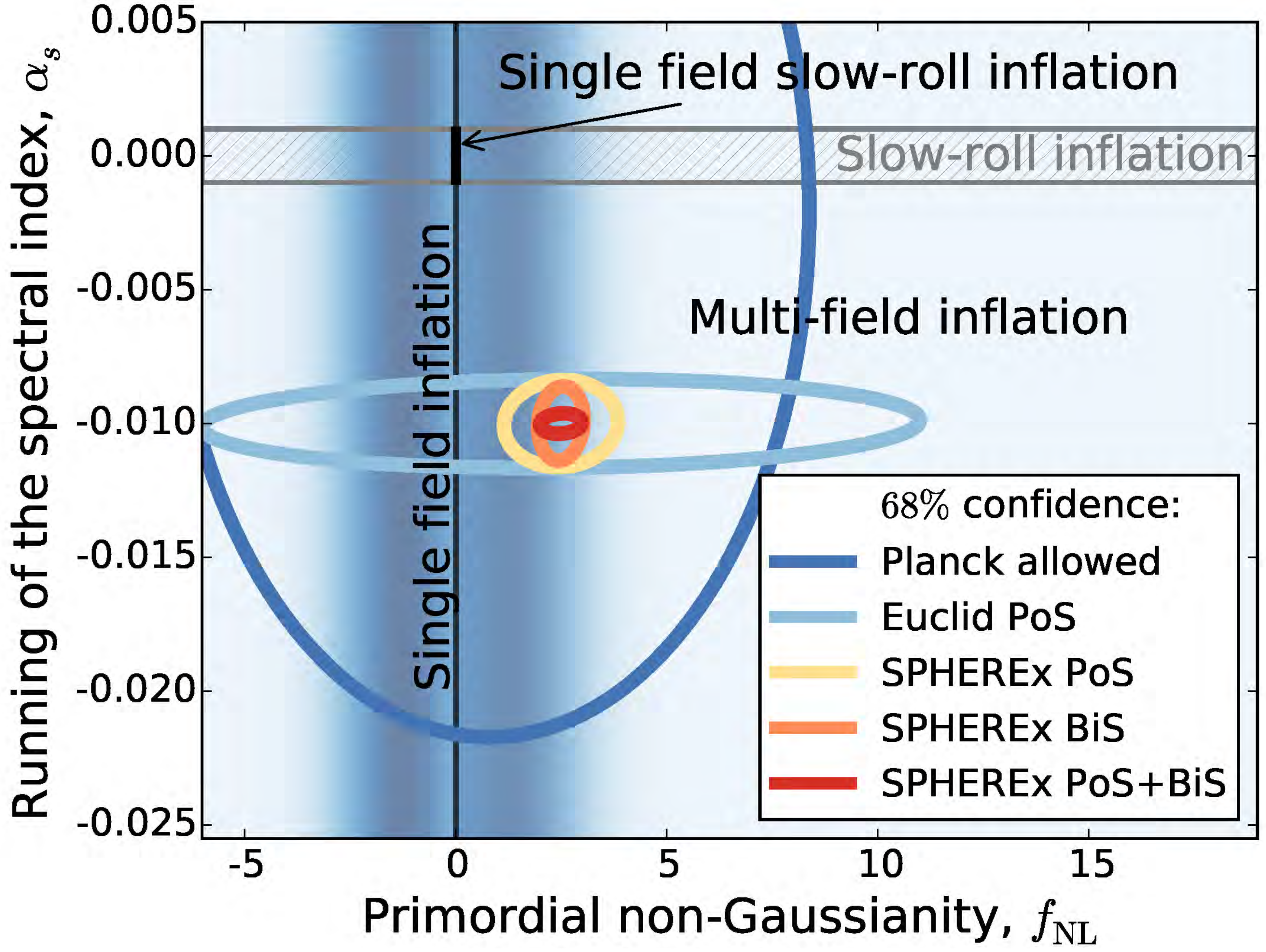
Current best
CMB: f_{NL} < 10.8 (2σ)
Cosmic Variance Limited

Non-Gaussianity appears on largest spatial scales – <u>need a large volume survey</u>

Science to Requirements: Cosmology

SPHEREx

- SPHEREx accuracy on inflationary non-Gaussianity is $\Delta f_{NL} < 0.5$ (1σ)
  - Two independent tests via power spectrum and bispectrum

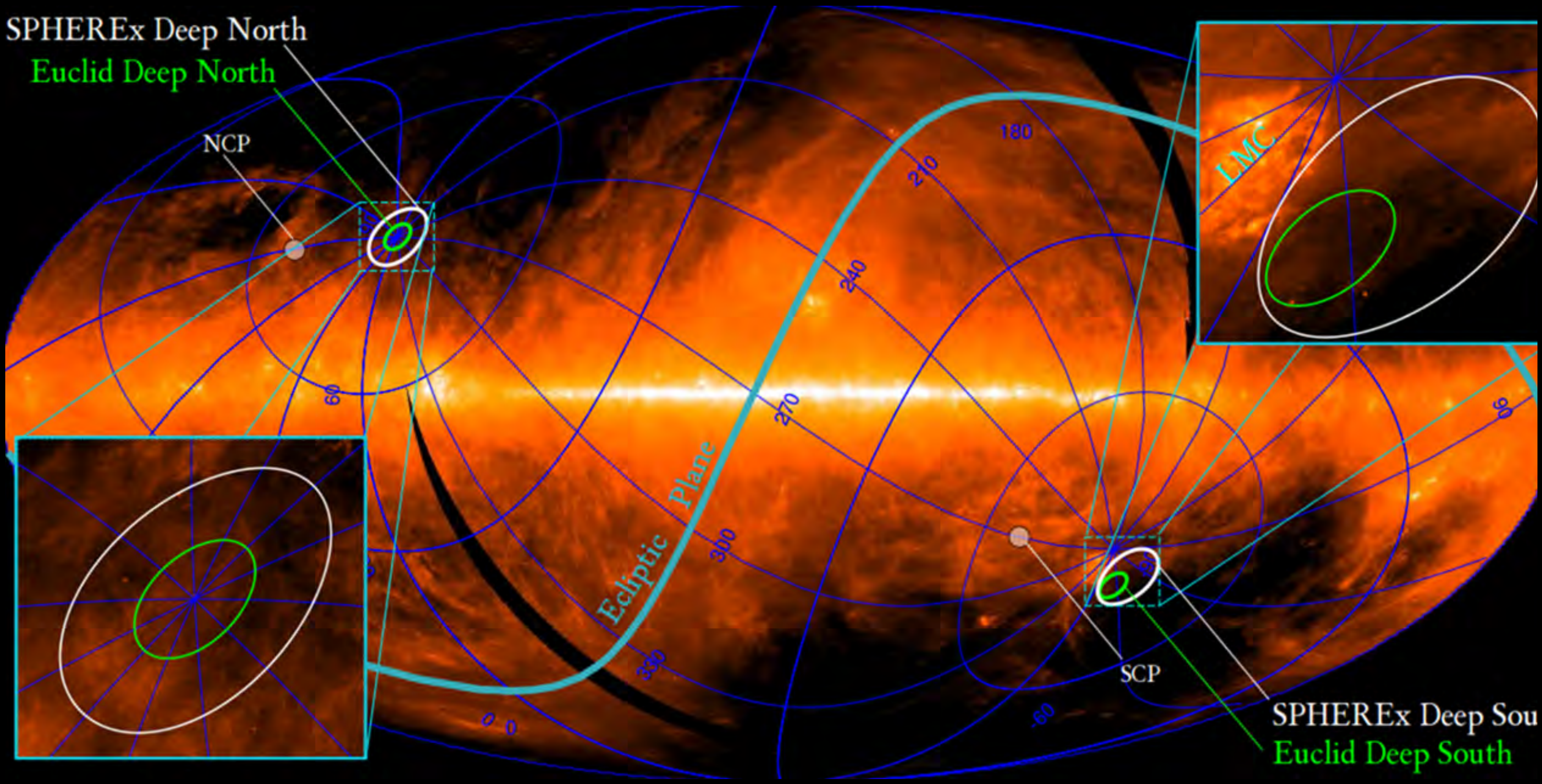


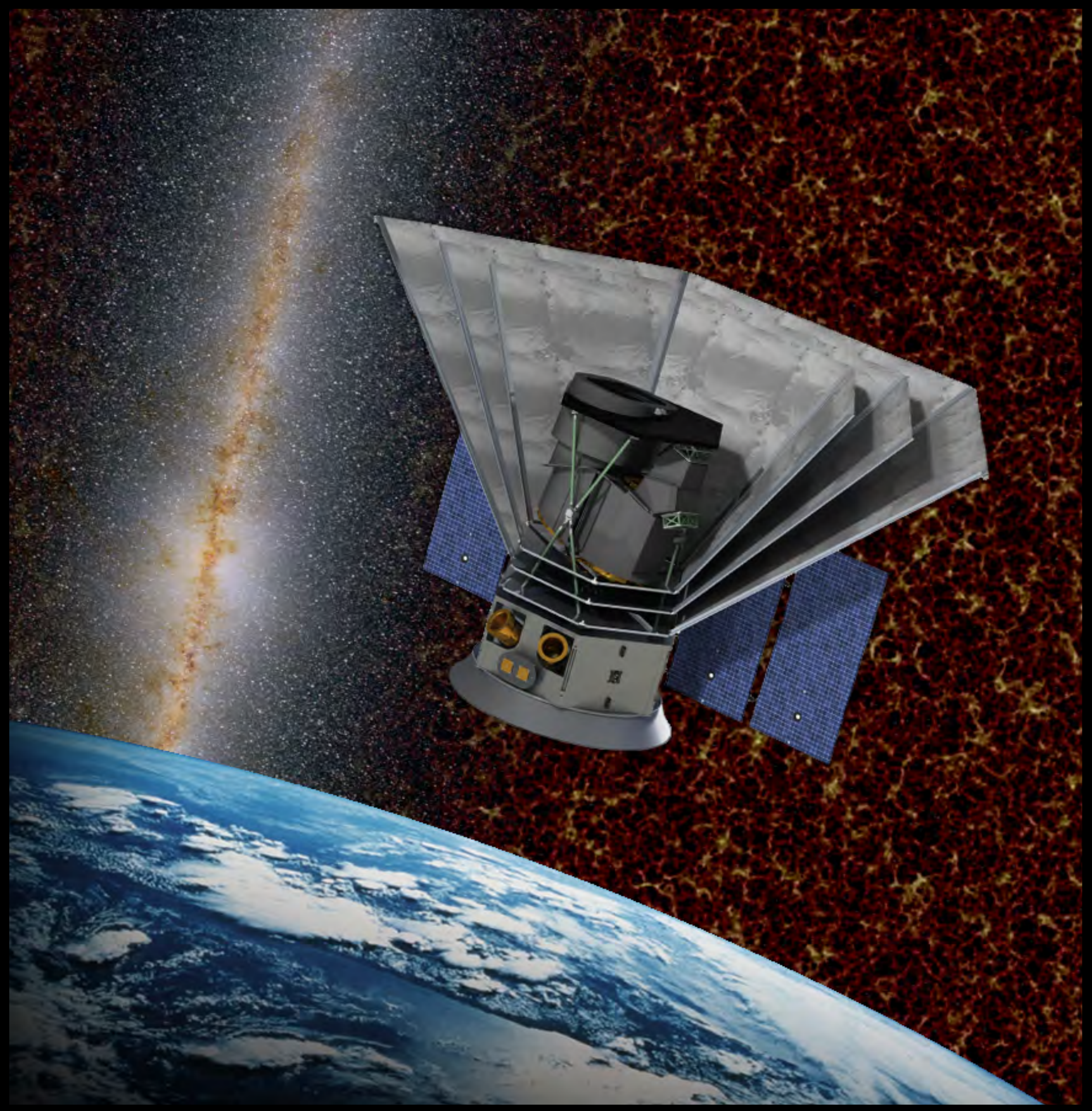
1σ errors statistical (systematics)	SPHEREx (MEV)			Euclid PoS	Planck & BOSS
	PoS	BiS	PoS+BiS		
SPHEREx f_{NL} Req't	1.15	0.55	0.5	N/A	N/A
f_{NL}	0.89 (0.53)	0.35 (0.22)	0.32 (0.21)	5.6	5.0
Spectral Index n_s ($\times 10^{-3}$)	2.7	1.9	1.1	2.6	4.0
Running α_s ($\times 10^{-3}$)	1.0	0.9	0.25	1.1	13
Curvature Ω_k ($\times 10^{-4}$)	7.7	8.1	4.4	7.0	40
Dark Energy figure of merit (bigger is better)	371			309	14

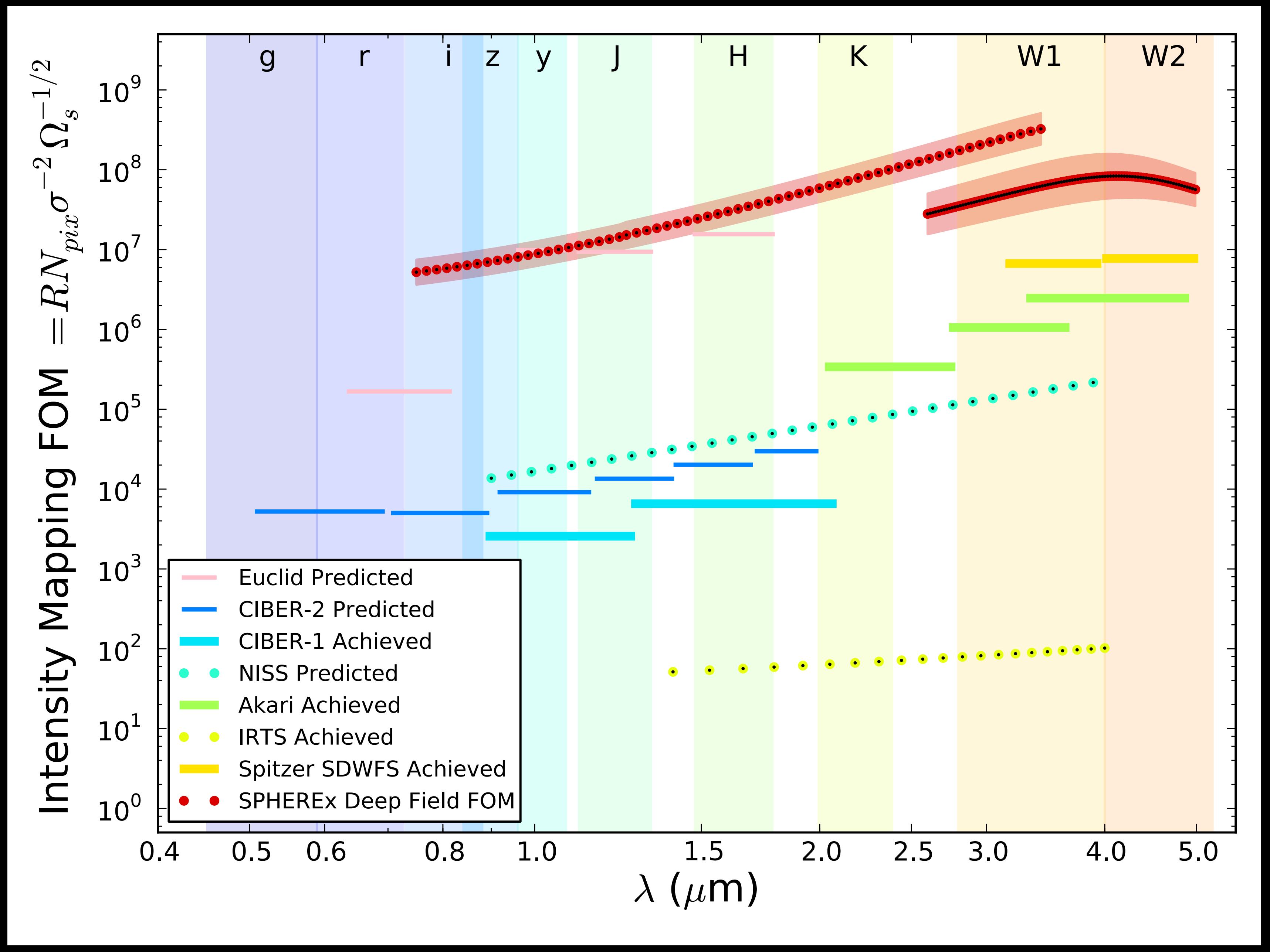
SPHEREx improves non-Gaussianity accuracy by >10x

Discriminates between models: Single-field inflation, $f_{NL} < 0.01$ and Multi-field inflation, $f_{NL} > 1$

EBL Fluctuation Measurements with SPHEREx





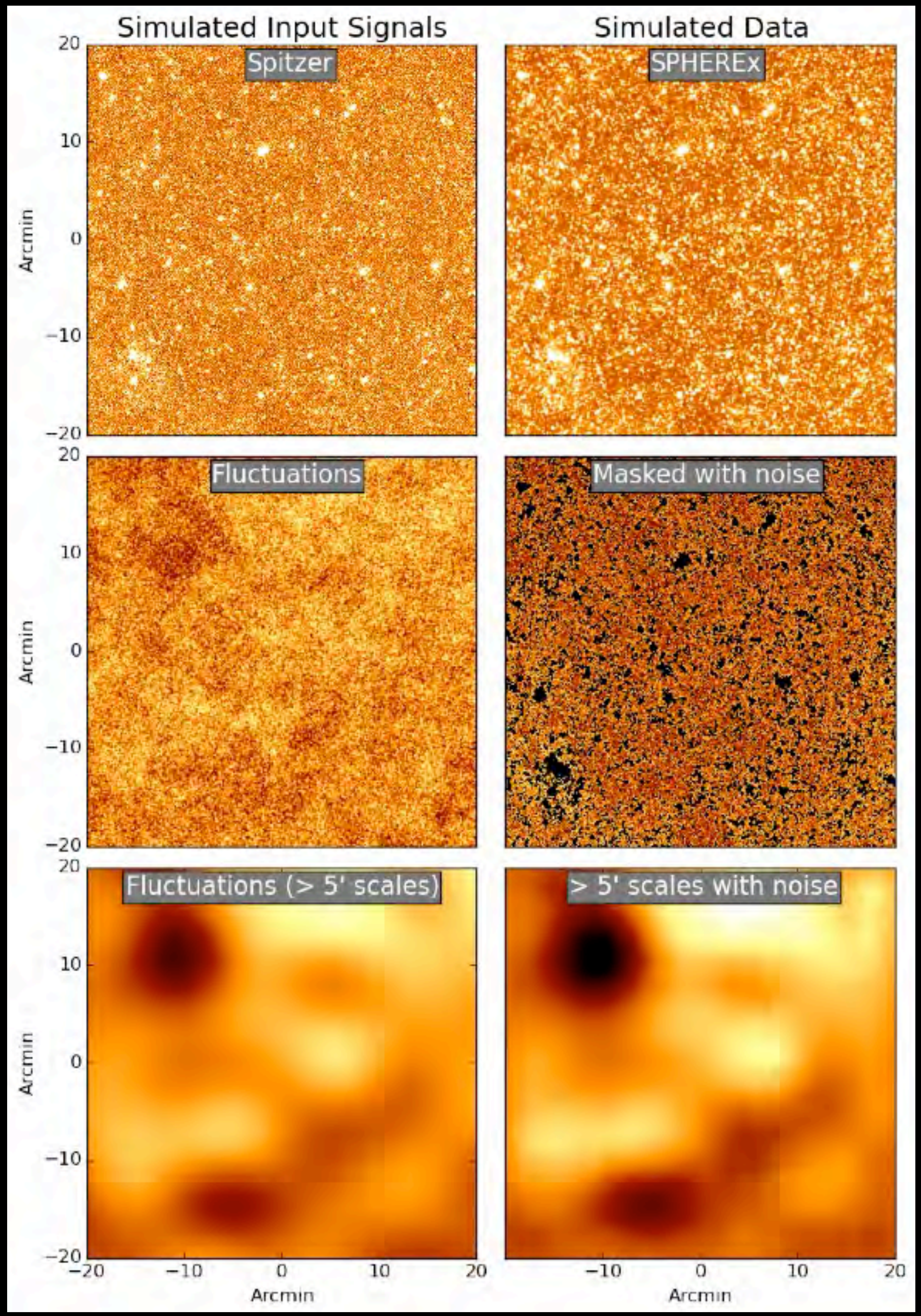


2 x 100 sq. degree regions at the poles which are ~30x deeper than the all-sky survey.

An opportunity for unique science

SPHEREx Intensity Mapping Figure of Merit

SPHEREx EBL
Continuum Fluctuations

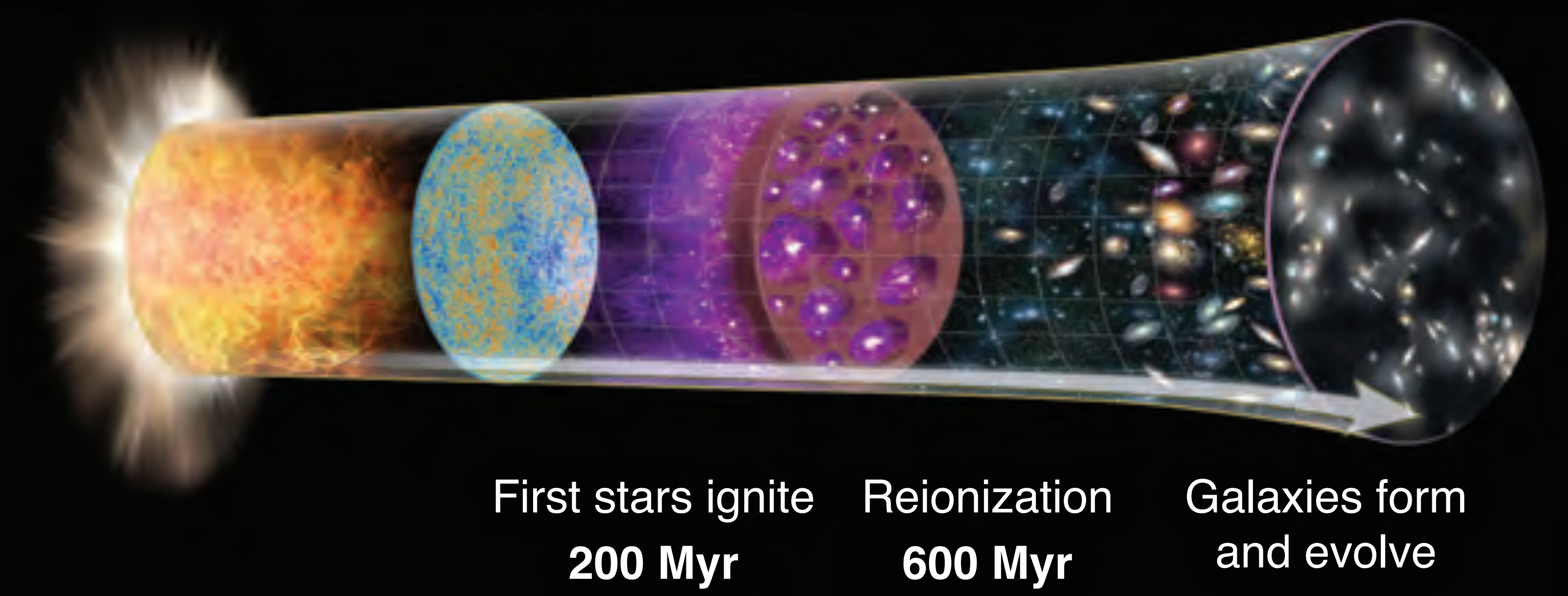


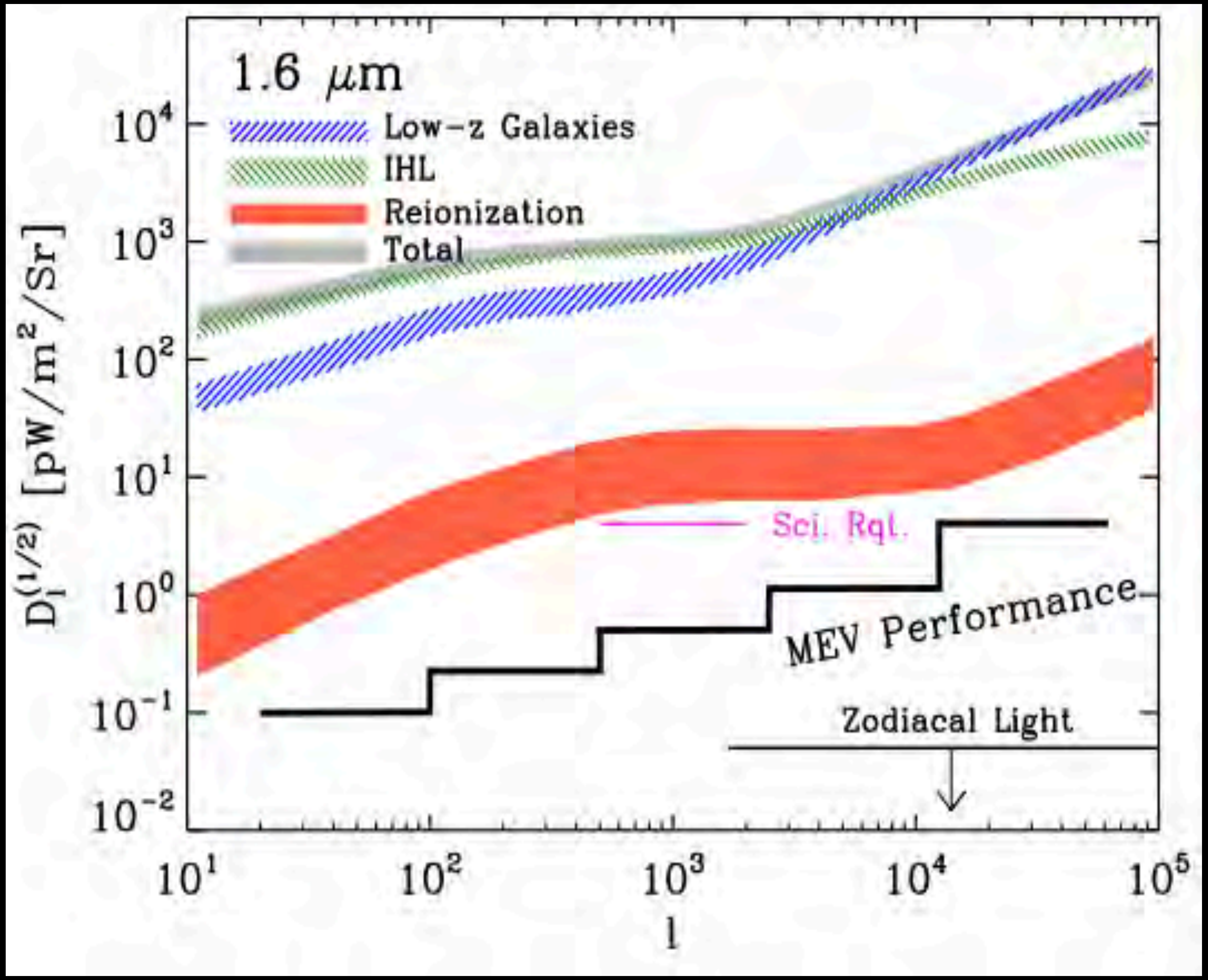
NASA GOAL

Explore the origin and evolution of galaxies

SPHEREx traces the total light emitted over cosmic time from the first stars to modern galaxies.

SPHEREx measures the cosmic history of galactic light production

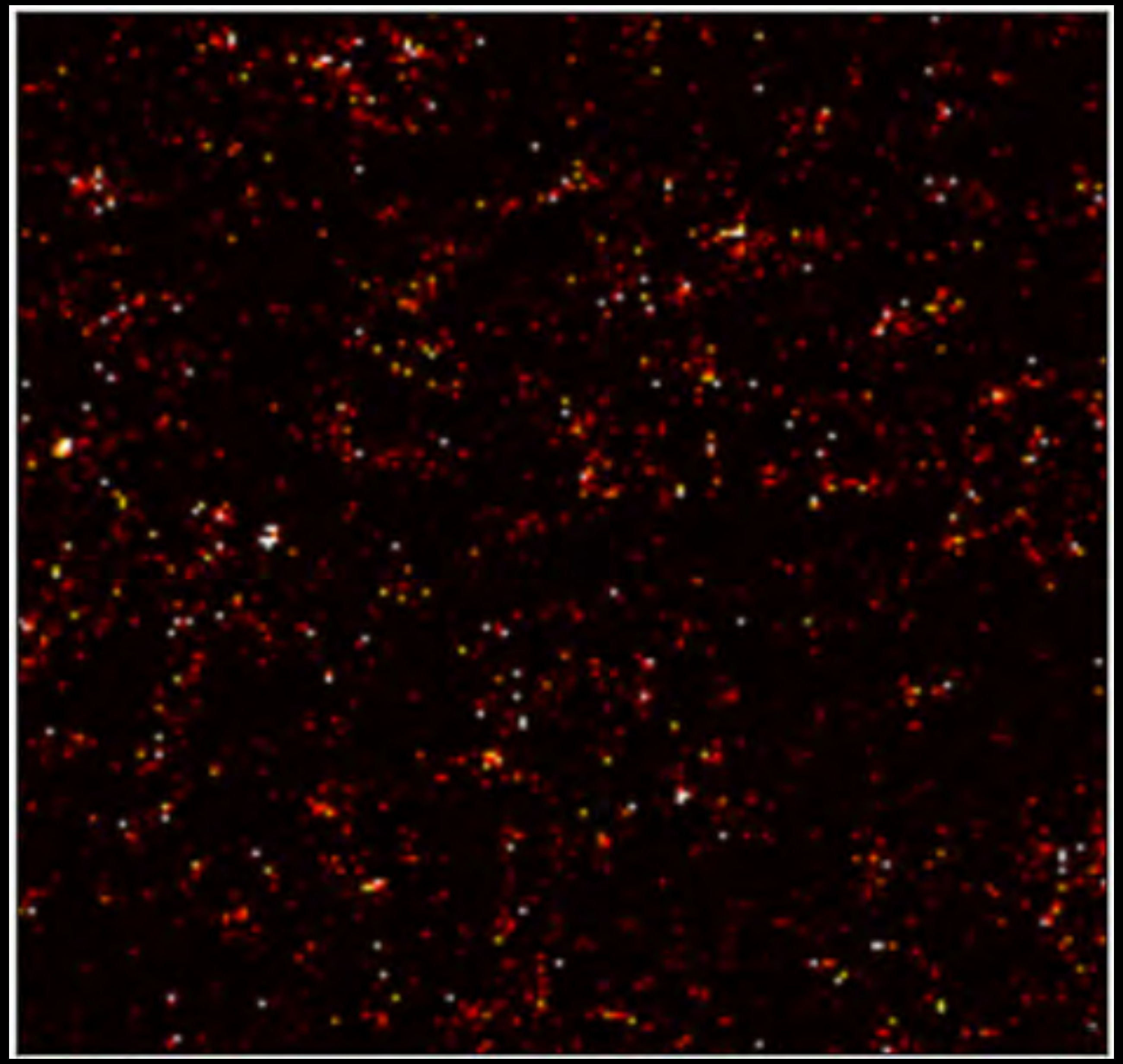




3-D Intensity Mapping

Sky map at z

Intensity map at z



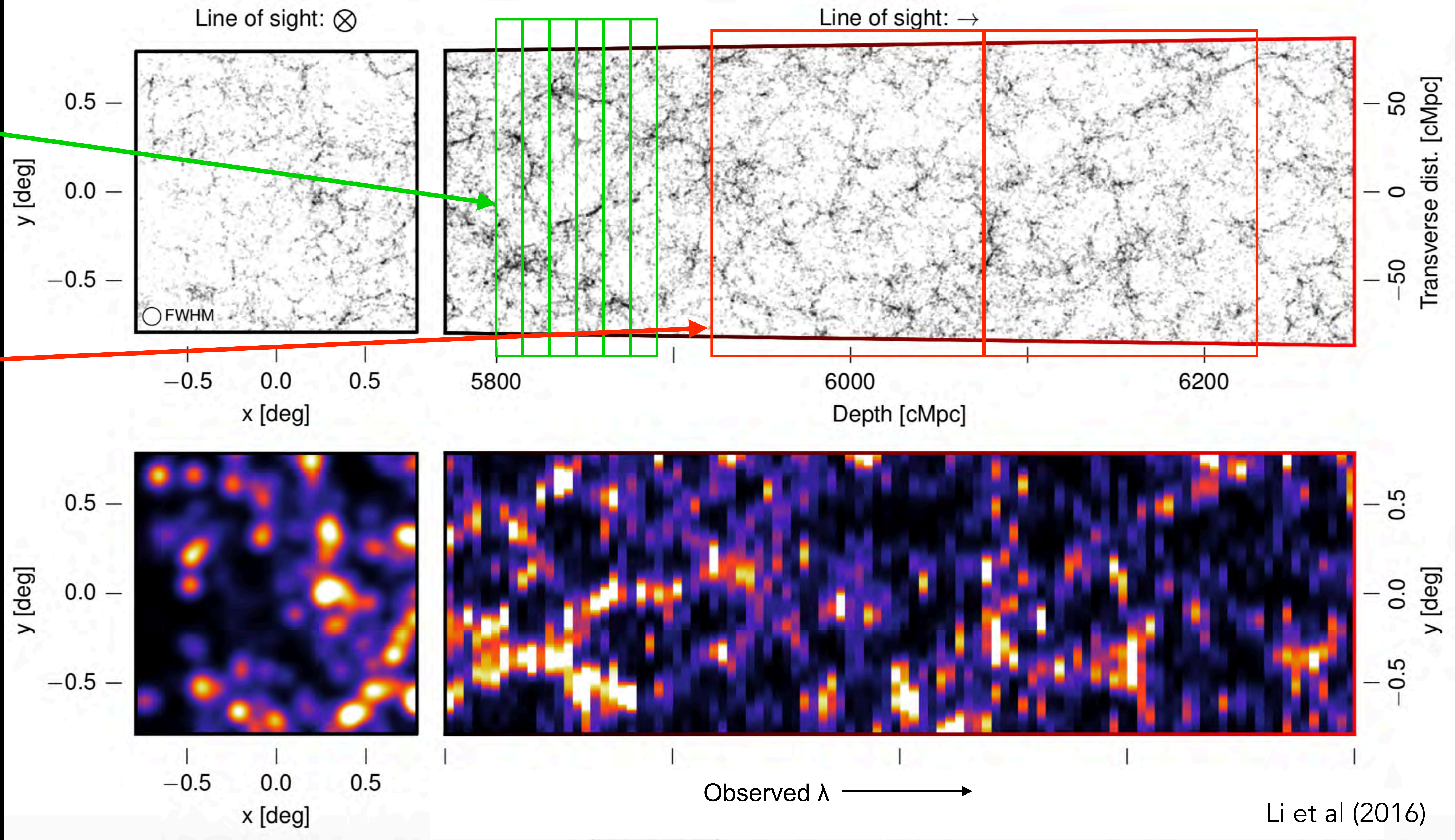
- No need to resolve individual sources
- Measure the collective emission from many sources
- Map large volume throughout cosmic history economically
- Astrophysical and cosmological applications from cosmological parameters, structure formation to galaxy formation.

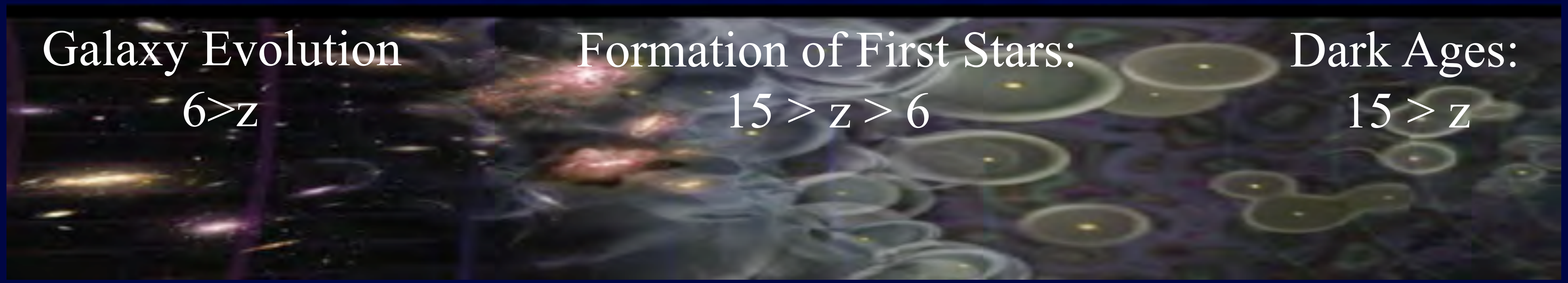
Spectral line Intensity Mapping

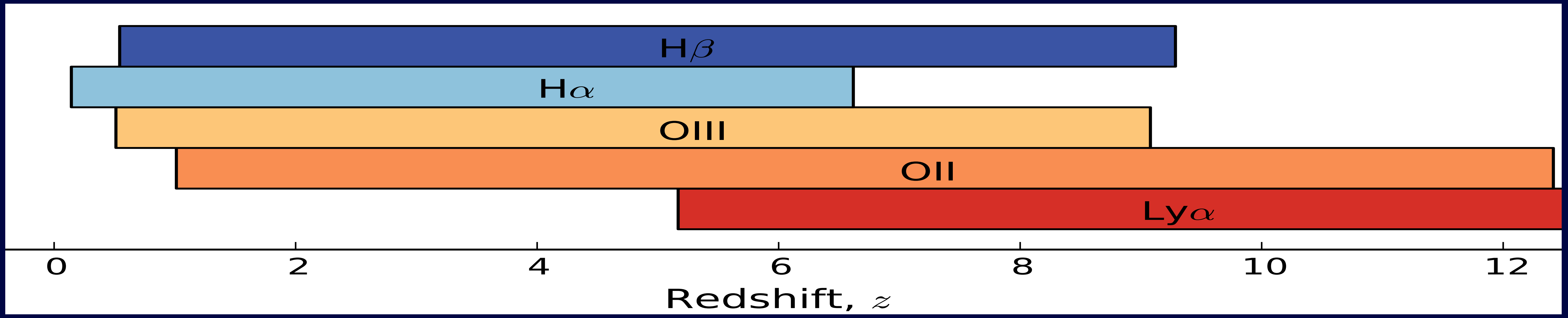
Measurements in fine bins trace line emission

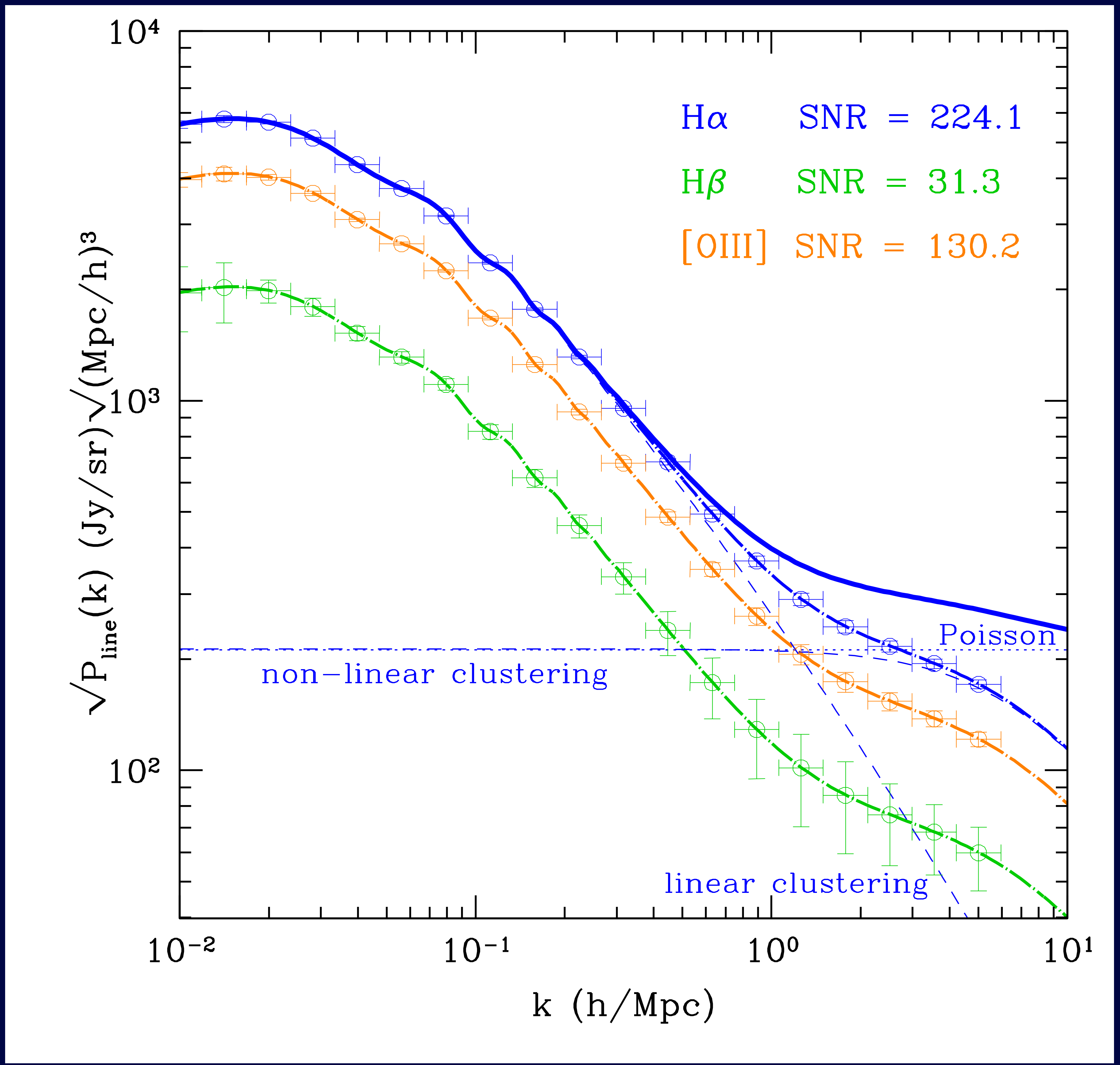
Measurements in coarse bins trace continuum emission

Power spectra allow us to quantify the measurements and compare to models







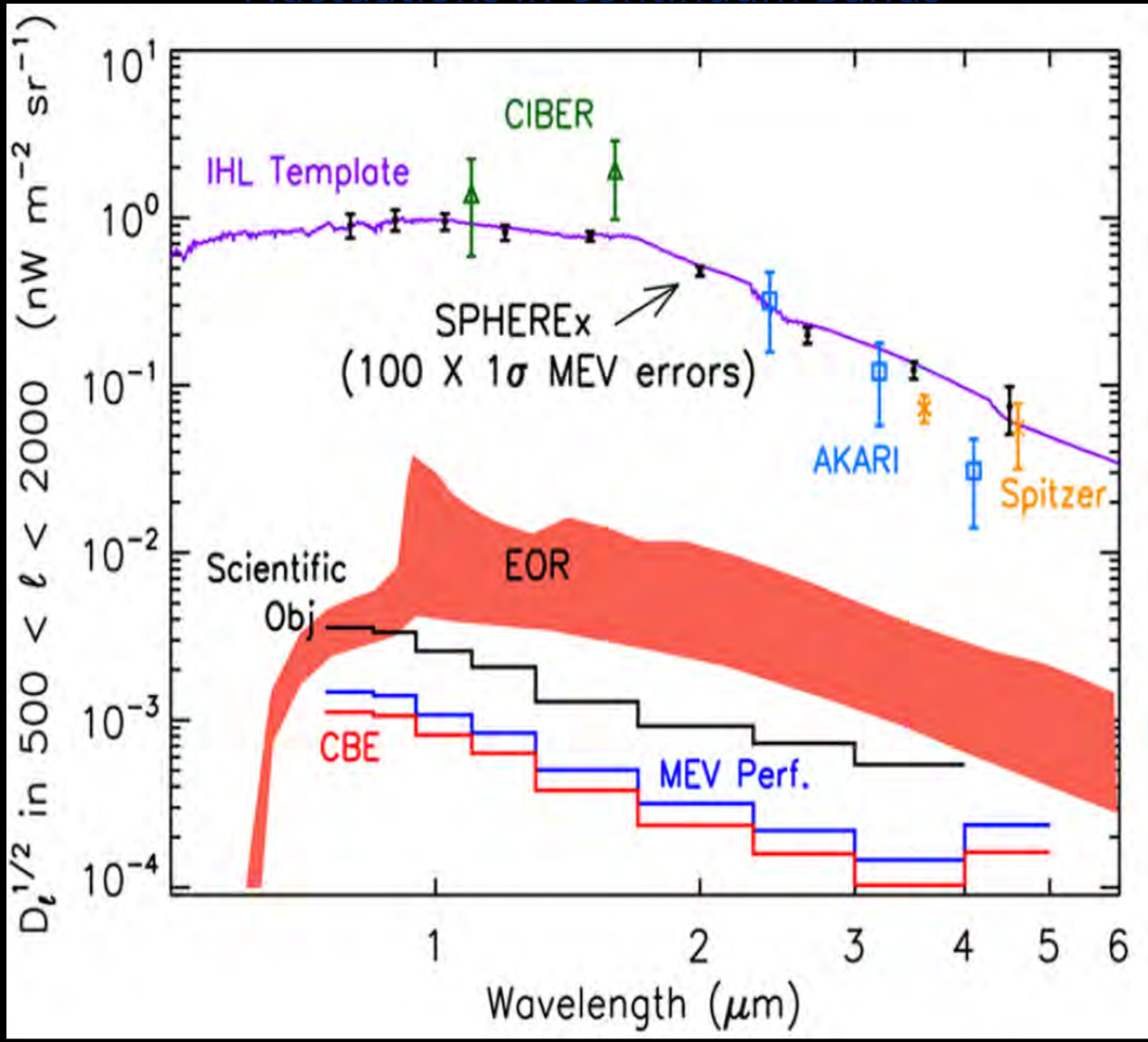


SPHEREx Spectral Line Intensity Mapping

- Our key galaxy formation science program concentrates on continuum fluctuations
- But with R~40 spectro-imaging, SPHEREx contains some spectral line information throughout the cosmic history.
- Opportunity with Hα and Hβ between 0.5 < z < 6 - combine the two to IM of dust as a function of z slices.
- Challenging to do Lyα IM at z > 6 with SPHEREx due to low S/N, but could be surprises.

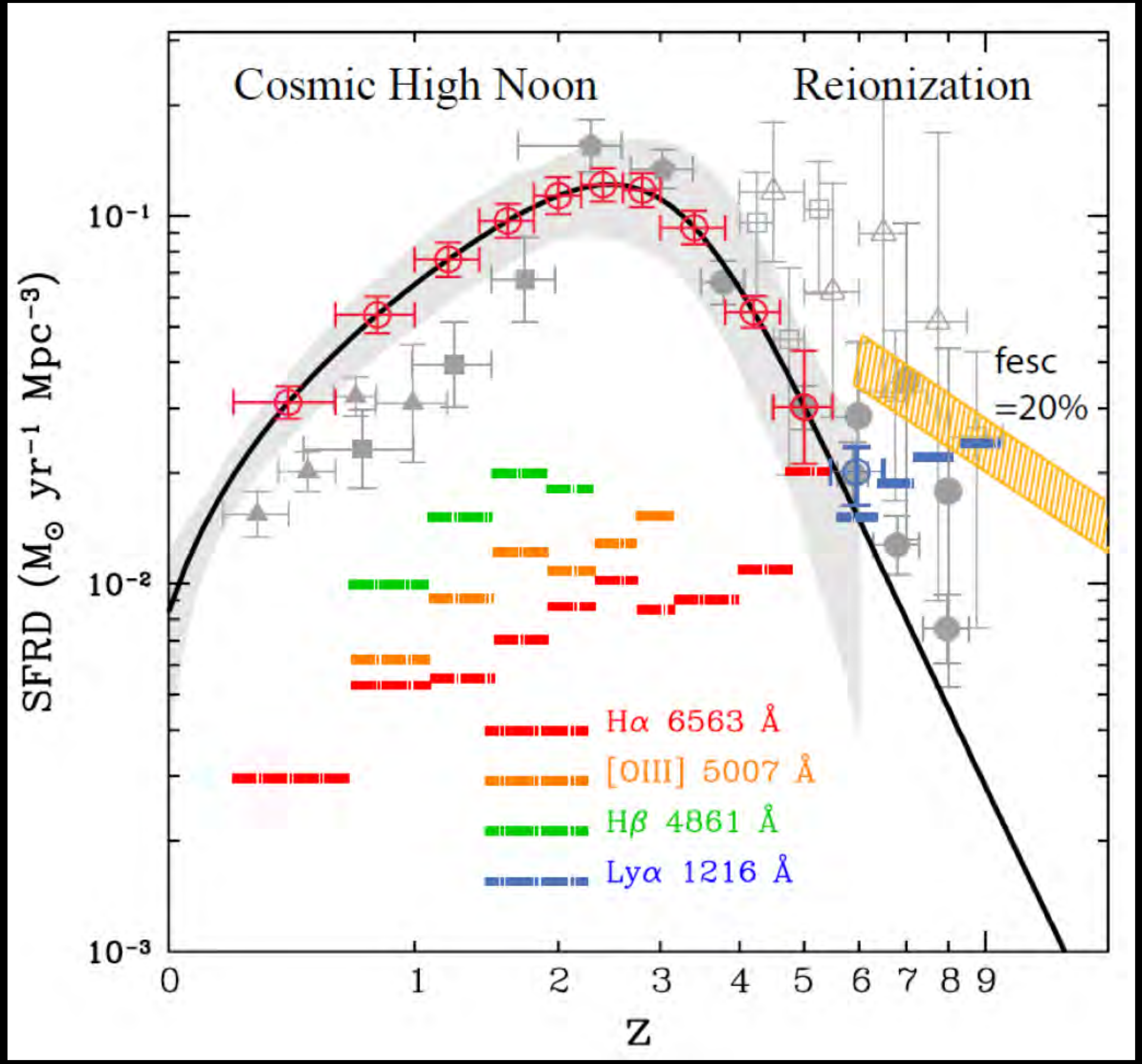
SPHEREx Measures Large-Scale Fluctuations

Fluctuations in Continuum Bands

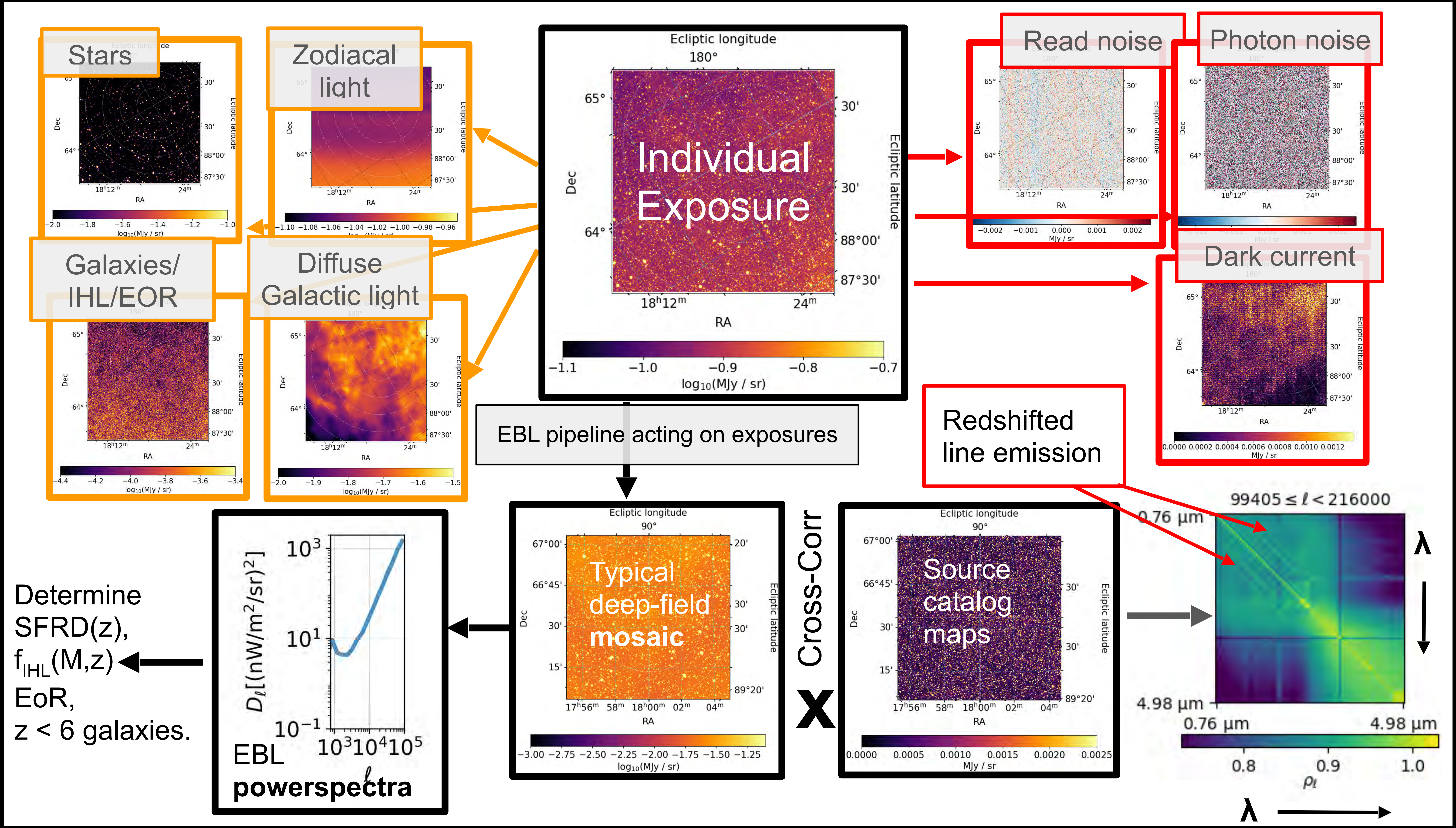


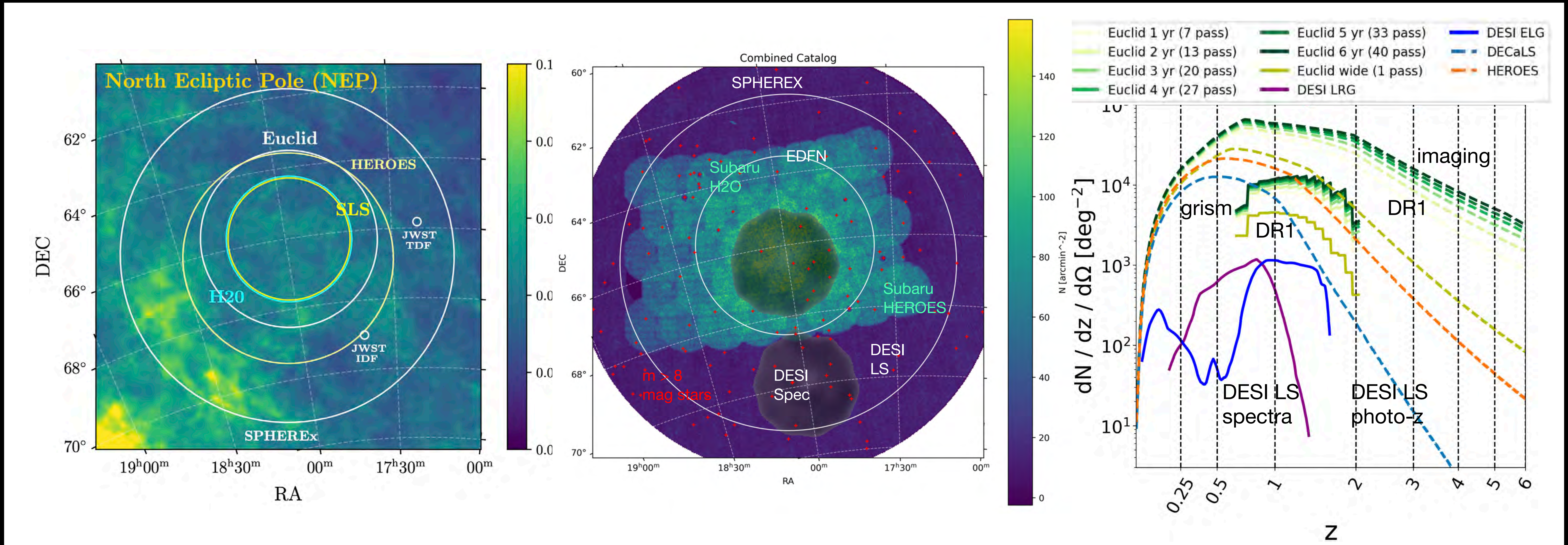
- SPHEREx has ideal wavelength coverage and high sensitivity
- Multiple bands enable correlation tests sensitive to redshift history
- Method demonstrated on Spitzer & CIBER

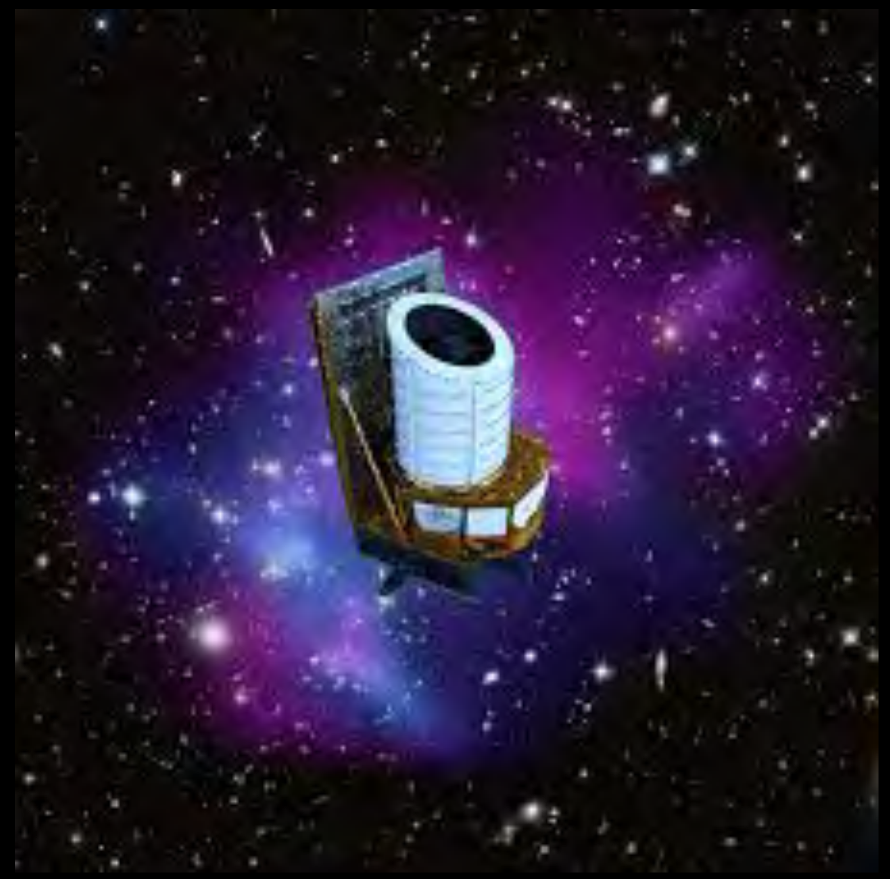
Fluctuations in Lines



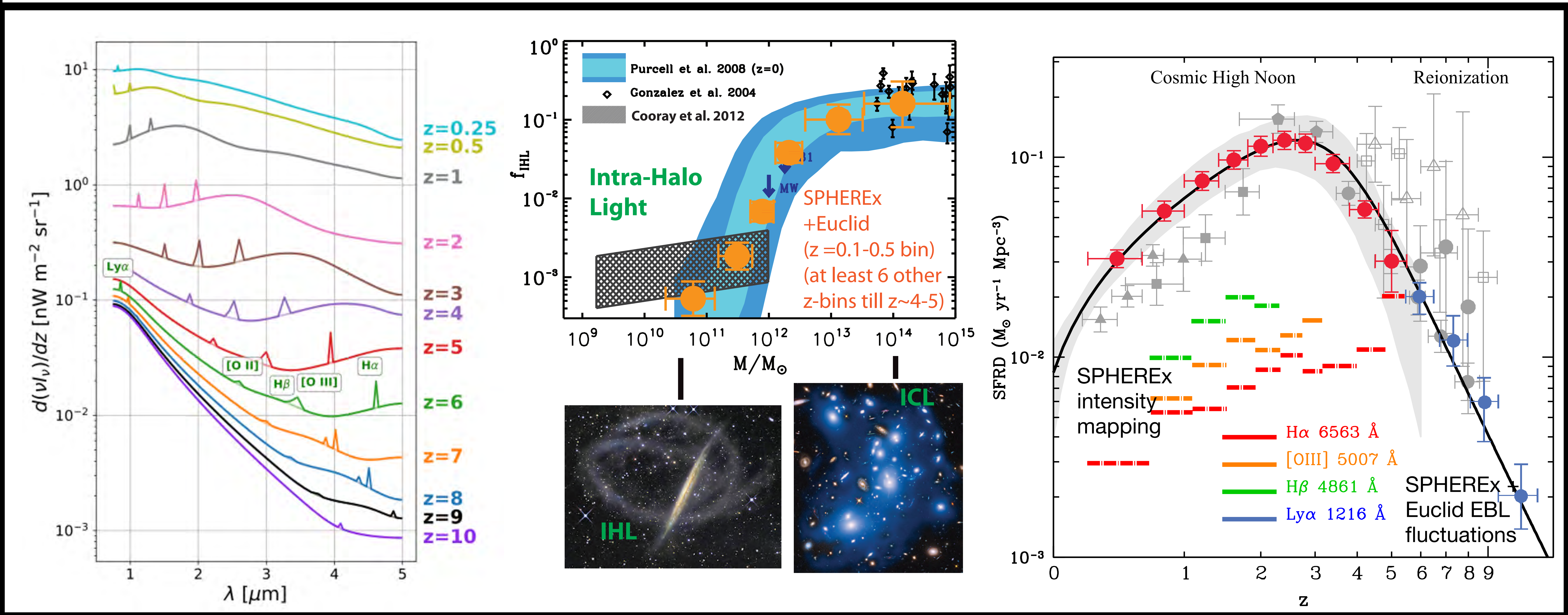
- Emission lines encode clustering signal at each redshift over cosmic history
- Amplitude gives line light production
- Multiple lines trace star formation history
  - High S/N in Hα for z < 5; OIII and Hβ for z < 3
  - Lyα probes EoR models for z > 6
  - Hα and Lyα crossover region 5 < z < 6


Stars
Zodiacal light
Galaxies/ IHL/EOR
Diffuse Galactic light
Individual Exposure
Read noise
Photon noise
Dark current
Redshifted line emission
EBL pipeline acting on exposures
Typical deep-field mosaic
Cross-Corr
X
Source catalog maps
EBL powerspectra
Determine SFRD(z), f_IHL(M,z), EoR, z < 6 galaxies.
99405 ≤ ℓ < 216000
0.76 µm
4.98 µm
λ
ρ_ℓ





Euclid DFN overlaps with SPHEREx NEP deep field



Cross-correlate SPHEREx intensity maps with Euclid-WL and galaxy catalog

Reconstruct IHL(M_{halo},z) and SRFD (z > 6)

Summary

Infrared background is a probe of high-z galaxies and low-z intra-halo light.

From Spitzer fluctuations at 3.6 microns, a 0.1 to 0.5% of IHL fraction in $z \sim 1$ to 5 Milky Way-like galaxies.

CIBERI has extended fluctuations to 1.1 microns, with strong evidence for IHL; CIBERII concluded - results forthcoming.

From Hubble/CANDELS, a measure of total UV luminosity density of the Universe at $z > 8$ with fluctuations.

SPHEREx will be the ultimate $z<0.6$ cosmology and $z > 8$ fluctuations. Launching in February 2025.

Still unresolved issues on absolute EBL, but steady progress with data on-hand. A dedicated instrtrument to the outer Solar system would be helpful.