Cosmology and Astrophysics with Intensity Mapping

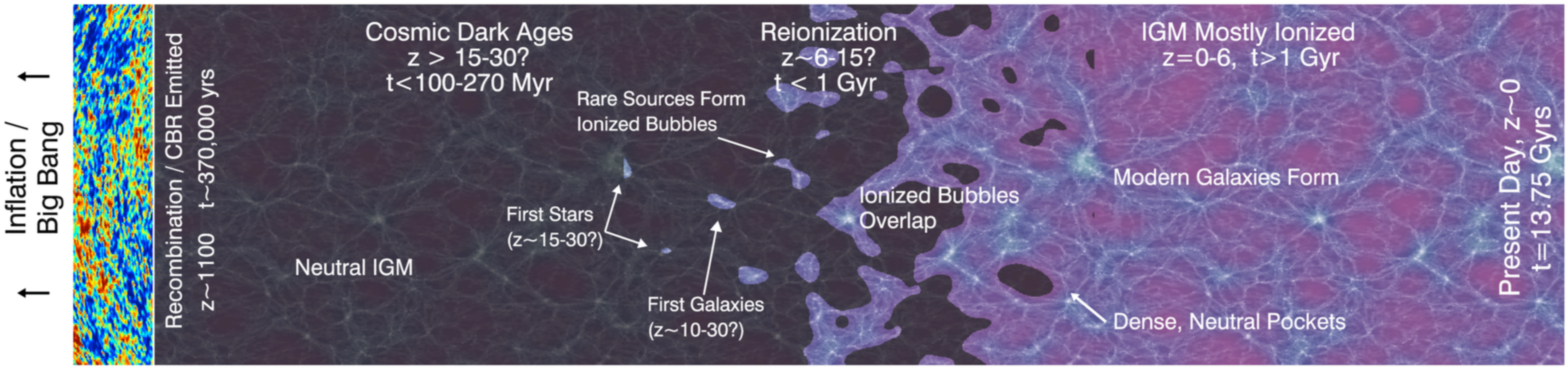
Yun-Ting Cheng (Caltech)

in collaboration with
Jamie Bock, Tzu-Ching Chang, Olivier Dore (Caltech/JPL),
TIME collaboration and **CIBER** collaboration

Berkeley BCCP Seminar, Dec 01, 2020

Cosmology and Large-Scale Structure Probes

Robertson et al. 2010



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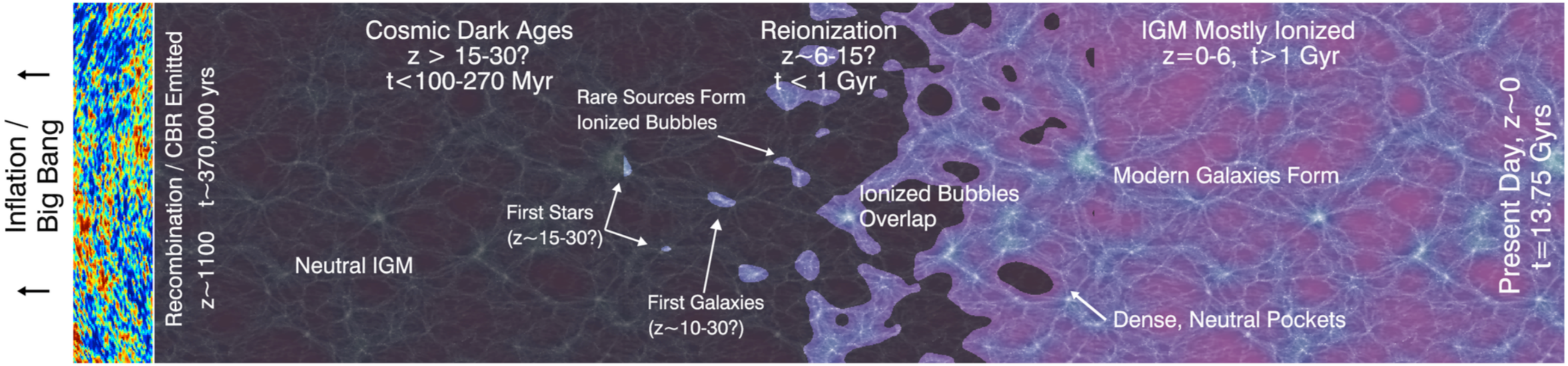
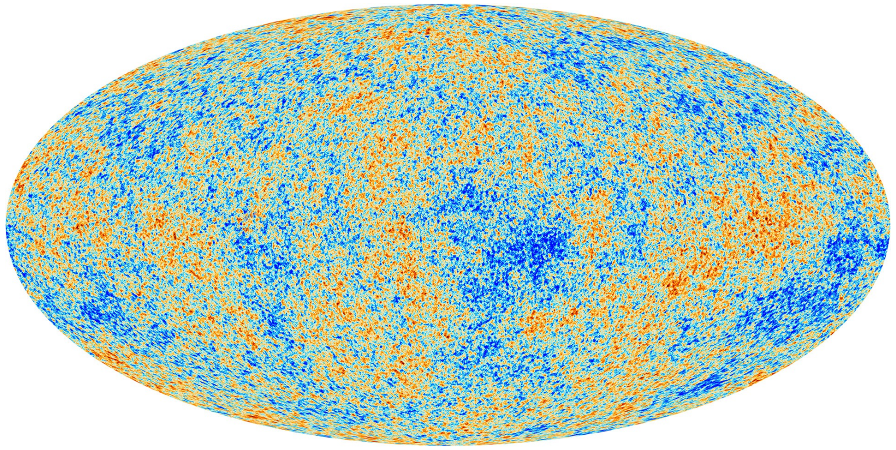


CMB z ~ 1100



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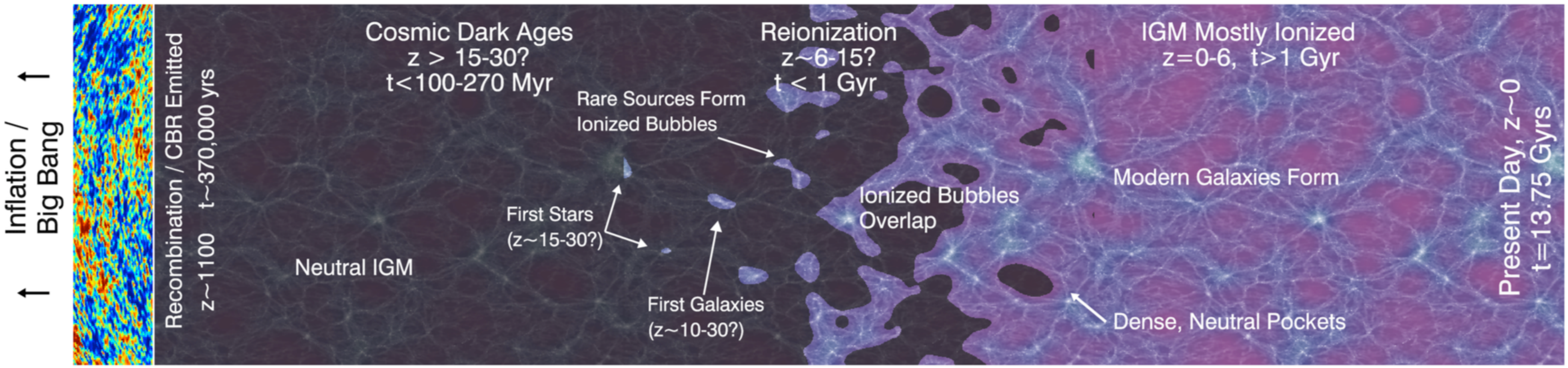
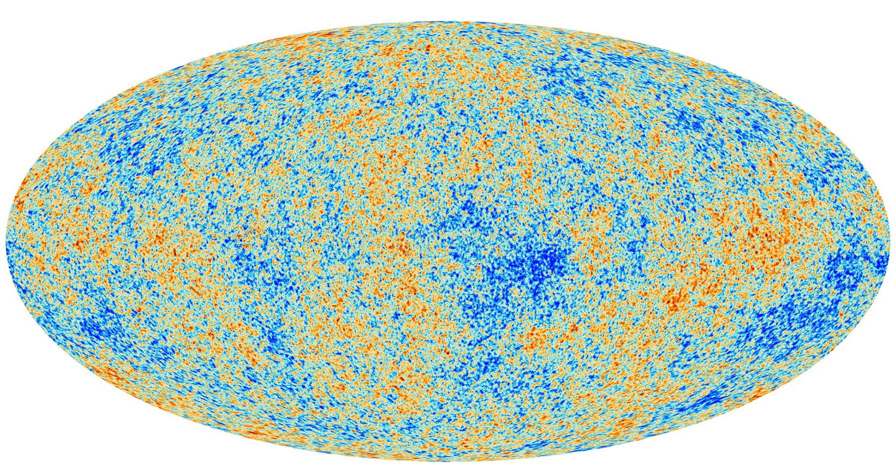
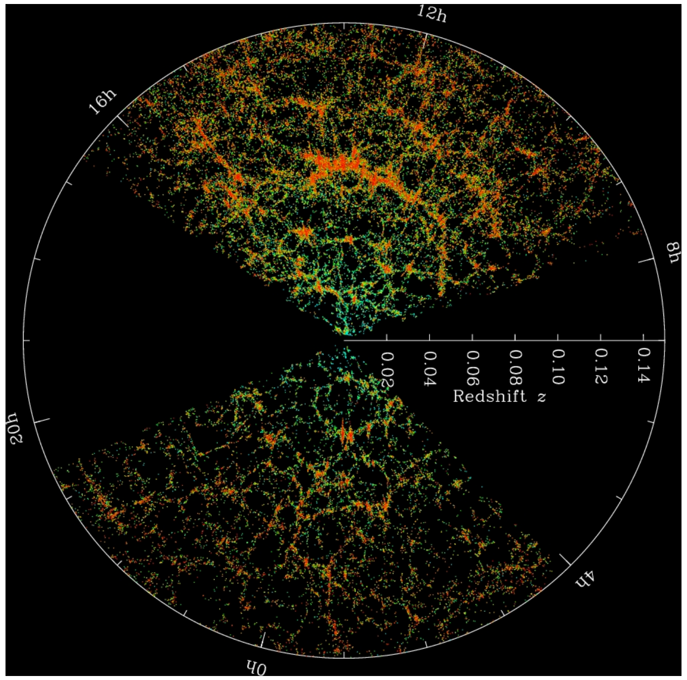


galaxy surveys z < 2.5

CMB z ~ 1100





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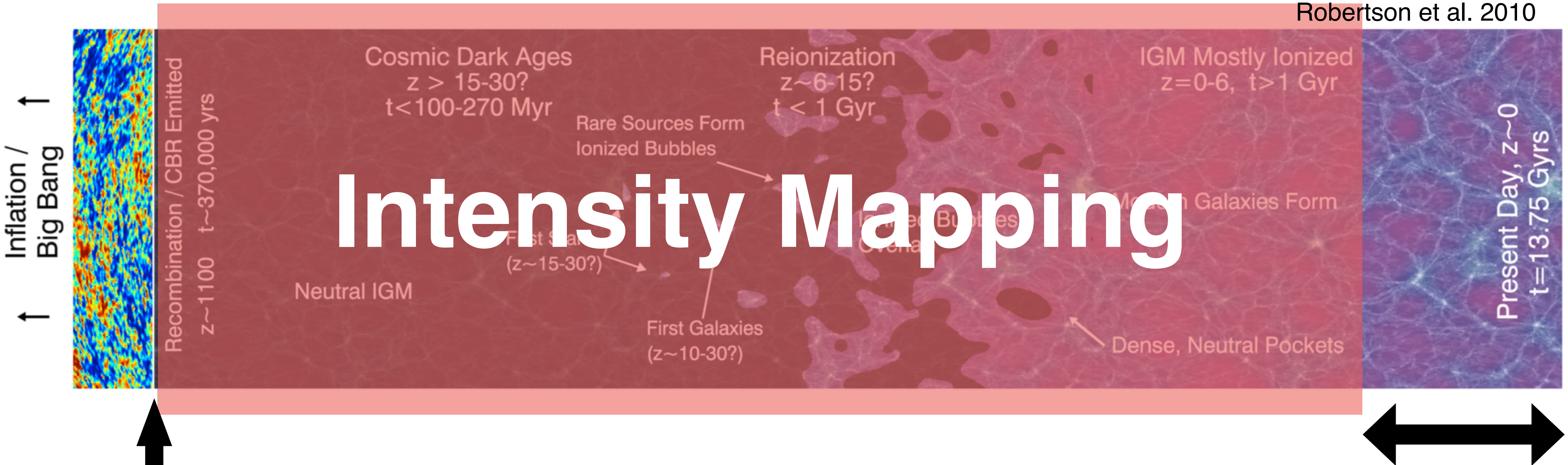

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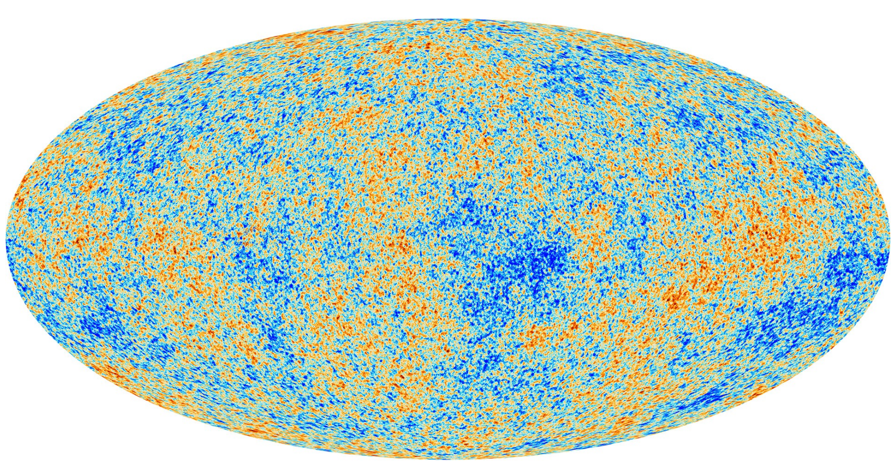
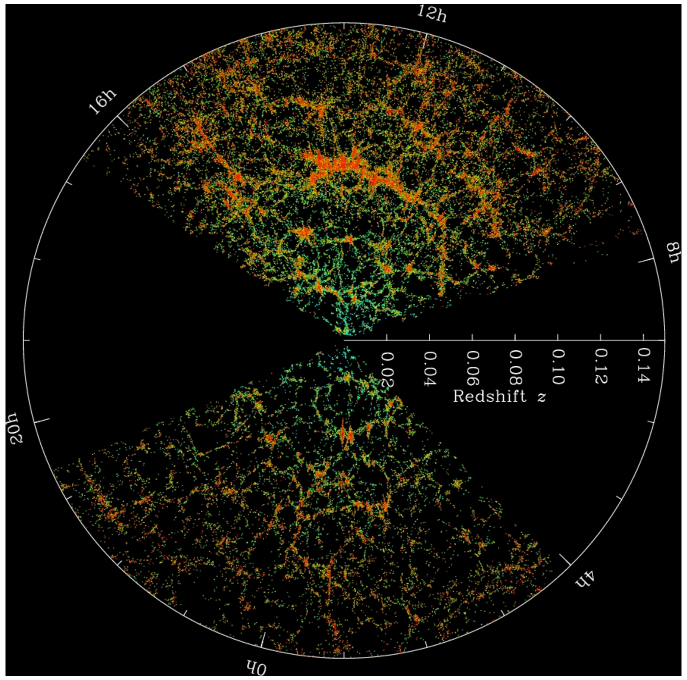
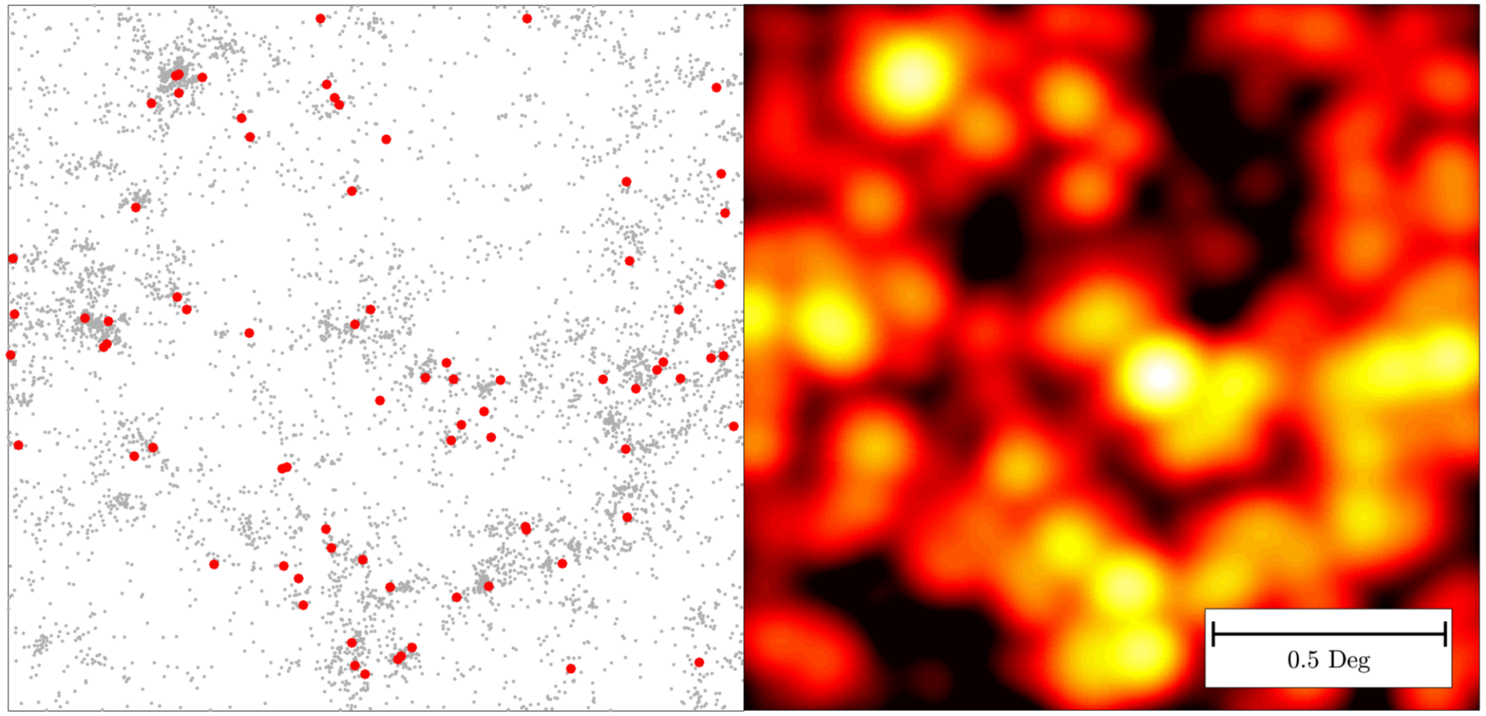




What is Intensity Mapping (IM)?

Credit: Patrick Breysse, Kovetz et al. 2017



IM measures collective emission from a large region containing multiple sources, without spatially resolving down to galaxy scales.

- Measure the intensity fluctuation (like CMB)
- Can learn about large-scale structure, average emission properties
- Low resolution (large telescope not required)

—> can efficiently scan a large volume

Cosmology & Astrophysics With Intensity Mapping

Intensity Mapping for EoR Science

Line Intensity Mapping with TIME

Y.T. Cheng, T.C. Chang, J.J. Bock, C.M. Bradford, A. Cooray 2016 arXiv:1604.07833

Y.T. Cheng, T.C. Chang, J.J. Bock 2020 arXiv:2005.05341

Intensity Mapping for Galaxy Evolution

Probing Intra-Halo Light with CIBER

Y.T. Cheng + CIBER collaboration 2020a in prep.

Intensity Mapping for Cosmology & Astrophysics

Constraining Extra-galactic Background Light with SPHEREx

Y.T. Cheng & T.C. Chang 2020b in prep.

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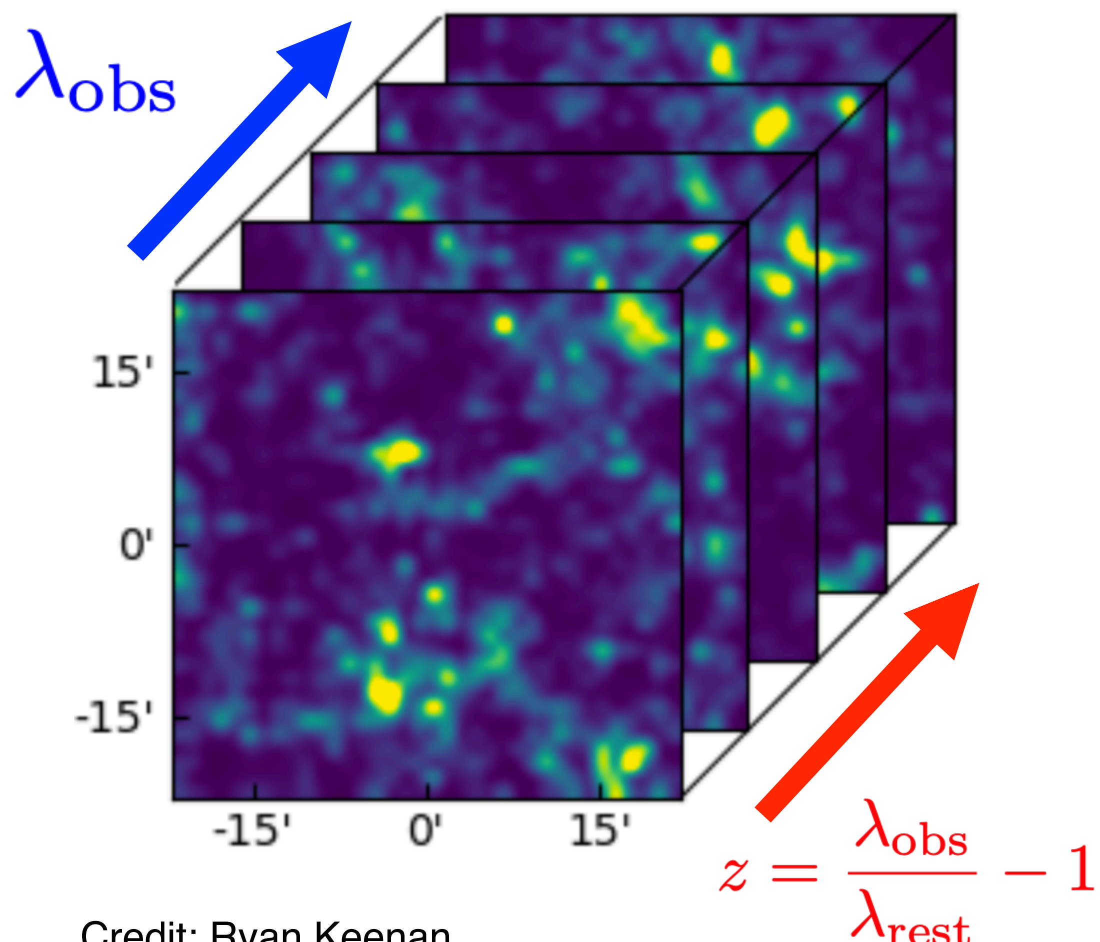
Line Intensity Mapping (LIM)

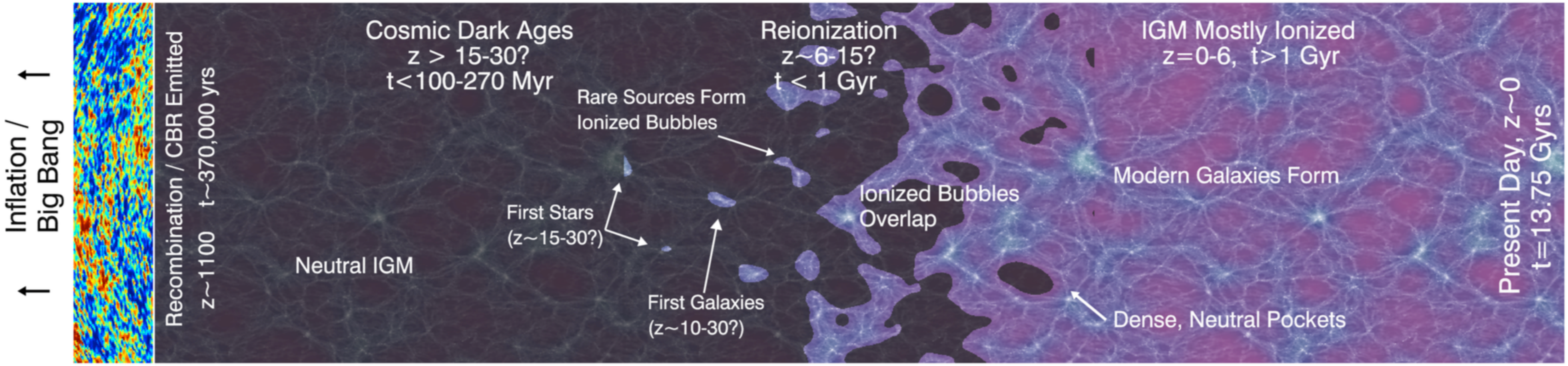
- Intensity mapping with spectral line emission
- Trace the 3D structure of the universe by redshift-frequency relation



Credit: Ryan Keenan

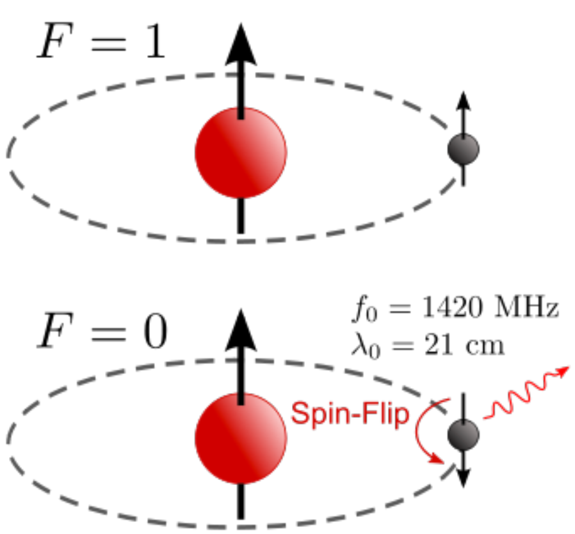
Which Lines?

Robertson et al. 2010



Dark Ages

21 cm



EoR

21 cm, CII, CO, Lyα, …

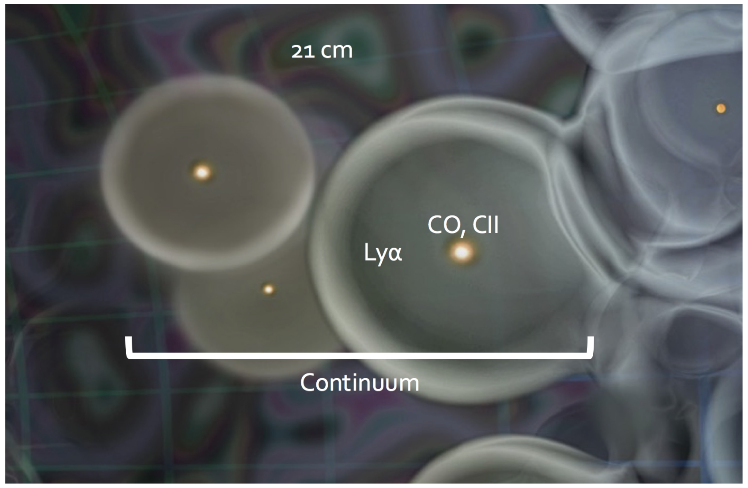


Image Credit:
Loeb 2006, Scientific American
Courtesy of Patrick Breysse

Post Reionization

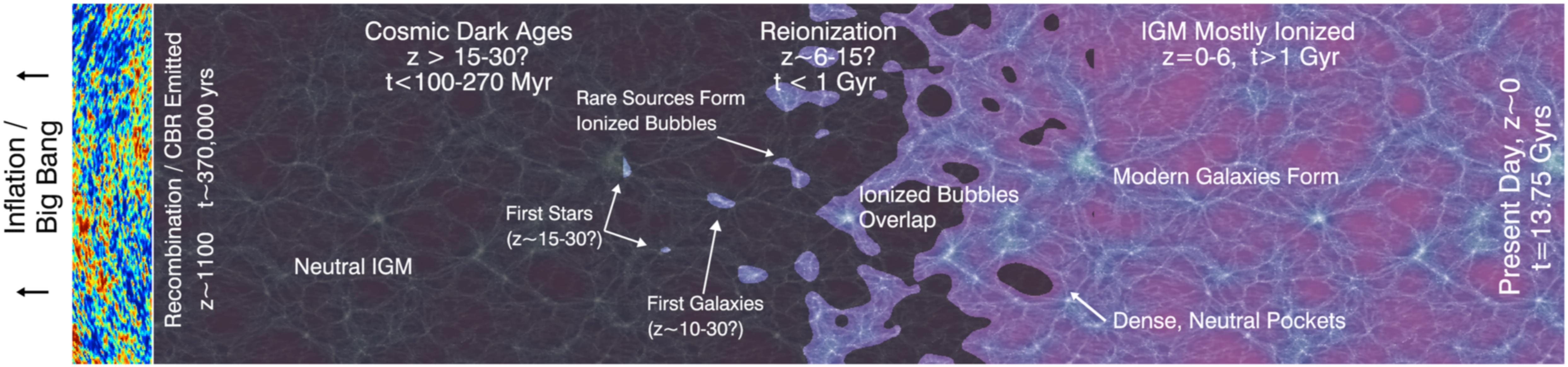
21 cm — HI

CII — PDR

CO — H_2

Which Lines?

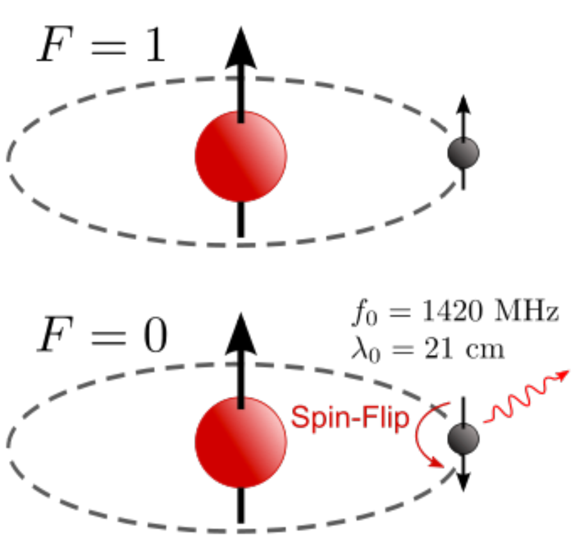
Robertson et al. 2010



TIME

Dark Ages

21 cm



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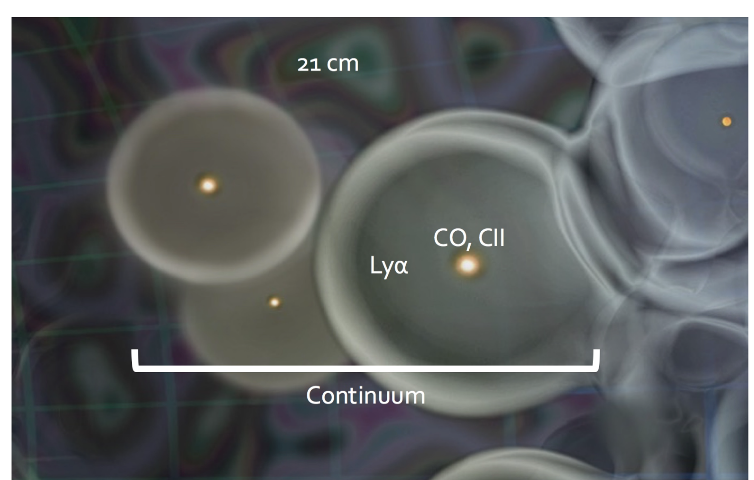

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Loeb 2006, Scientific American
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Post Reionization

21 cm — HI

CII — PDR

CO — H_2

TIME

(Tomographic Ionized carbon intensity Mapping Experiment)

Caltech/JPL
Jamie Bock
Matt Bradford
Tzu-Ching Chang
Steve Halley-Dunsheath
Lorenzo Moncelsi
Roger O'Brient
Jonathan Hunacek
Yun-Ting Cheng
Guochao Jason Son

Toronto
Abigail Crites

RIT
Mike Zemcov
Victoria Butler

Arizona
Dan Marrone
Issac Trumper
Ryan Keenan

ASIAA
Chao-Te Li
Da-Shun Wei

UCI
Asantha Cooray

NRAO
Bade Uzgil

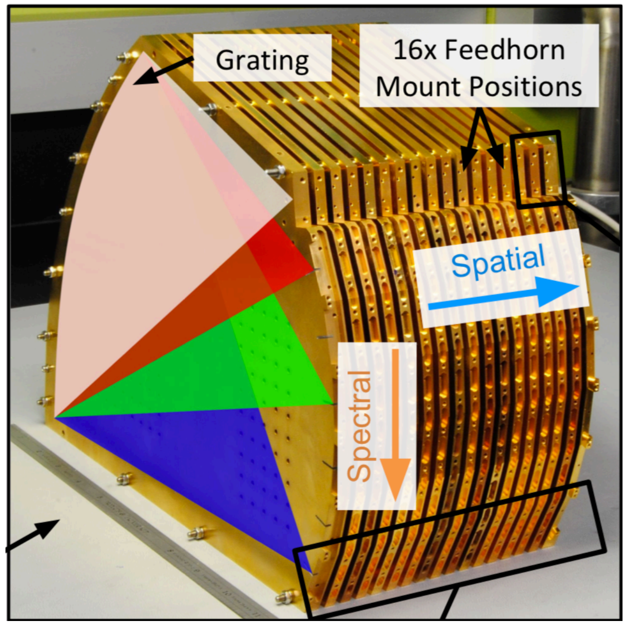
TIME

(Tomographic Ionized carbon intensity Mapping Experiment)

- CII @ z= 5.3 ~ 8.5 (~ 200-300 GHz)

- **Why [C II] 158 um?**
  - Major coolant in ISM (brightest FIR line)
  - Good tracer of star formation, complementary to 21 cm
  - EoR [C II] redshifts into atmospheric window

- **TIME**
  - grating spectrometer
  - ALMA prototype antenna (Kitt Peak Arizona)
  - 1D line scan ~ 1 deg



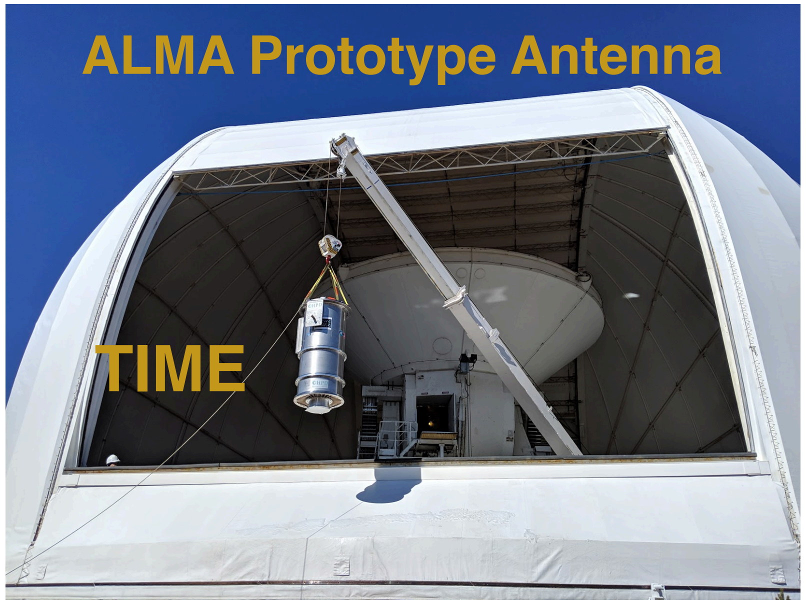
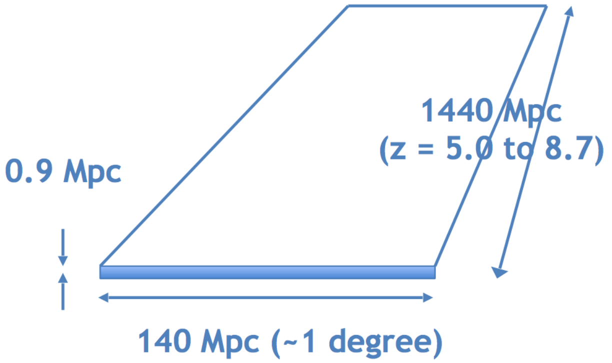
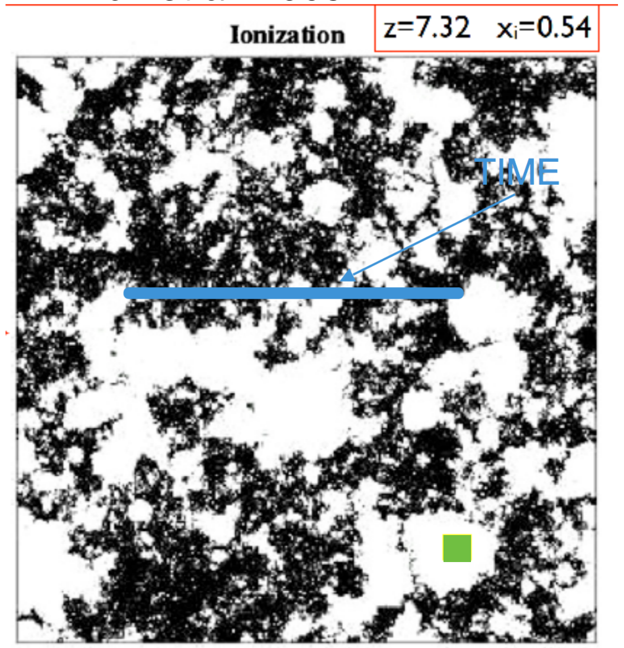


Photo credit: Jonathon Hunacek



1.3 deg x 0.43' line scan

Lidz et al. 2009



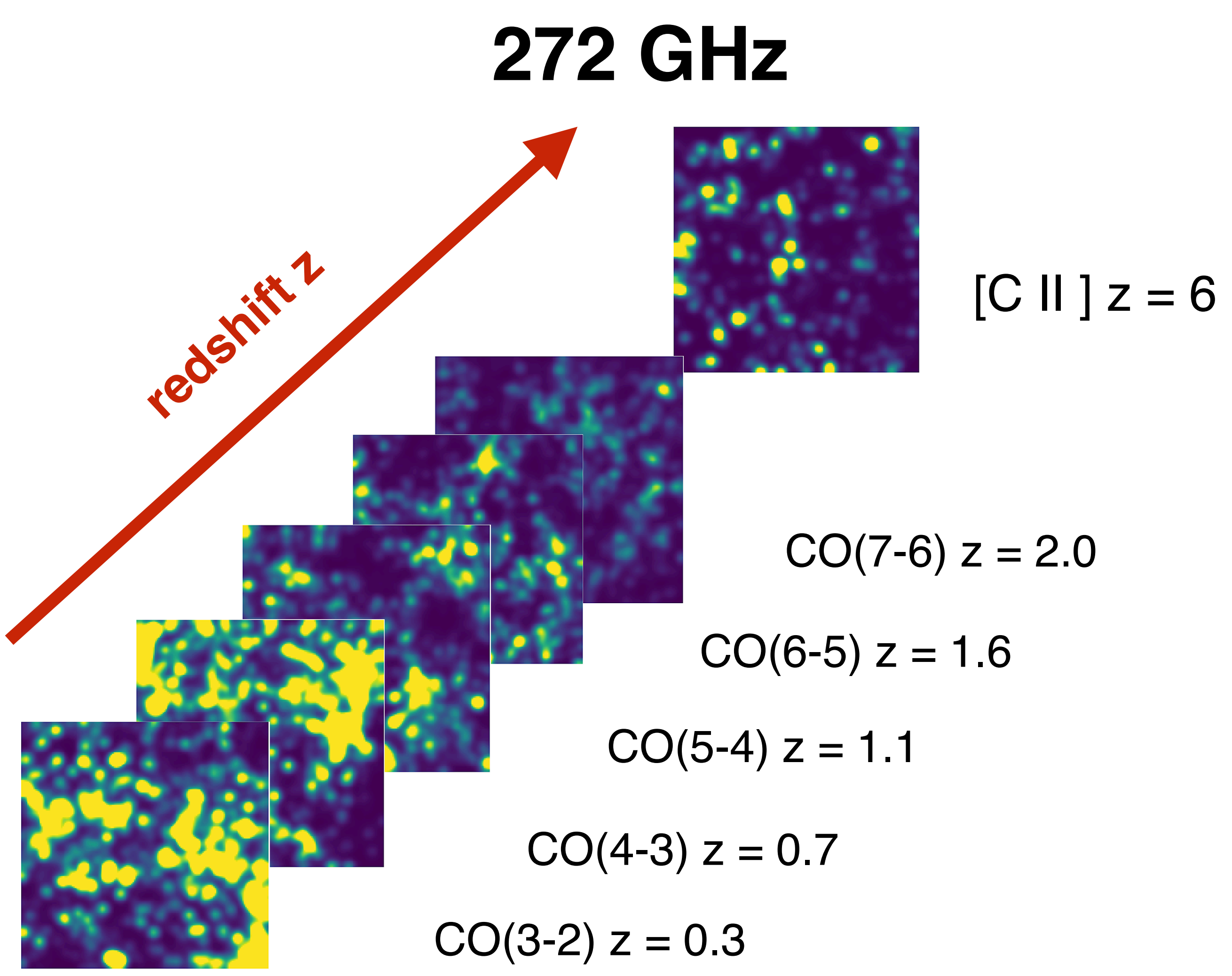
Hubble UDF 11'x11'

Foregrounds in Intensity Mapping

21 cm — **continuum foreground** ~ 10^5x signal
[C II] / CO / Lyα — **line blending**

Line de-blending methods:
- masking
- cross correlation

=> need external catalogs



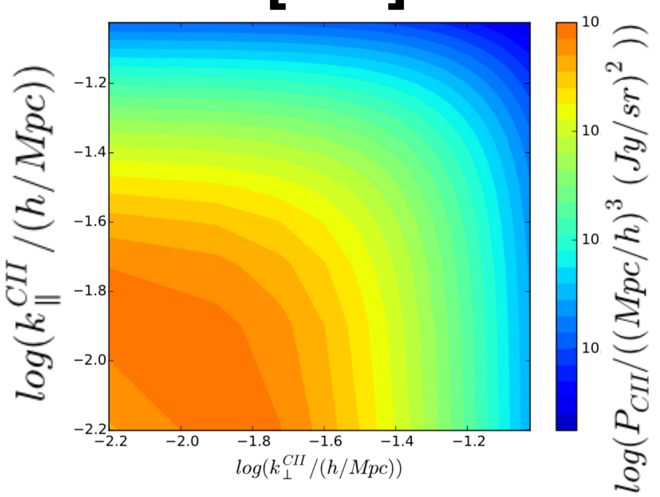
Line de-Blending With External Information

2D power spectrum anisotropy

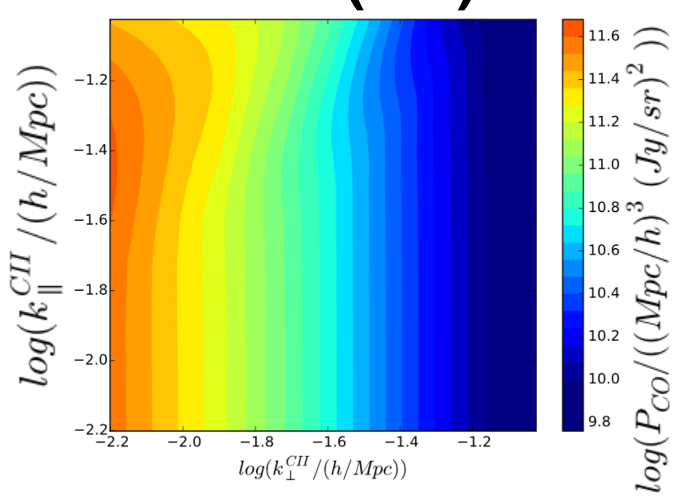
Y.T. Cheng, T.C. Chang, J.J. Bock, C.M. Bradford, A. Cooray 2016 arXiv:1604.07833
Lidz & Taylor 2016

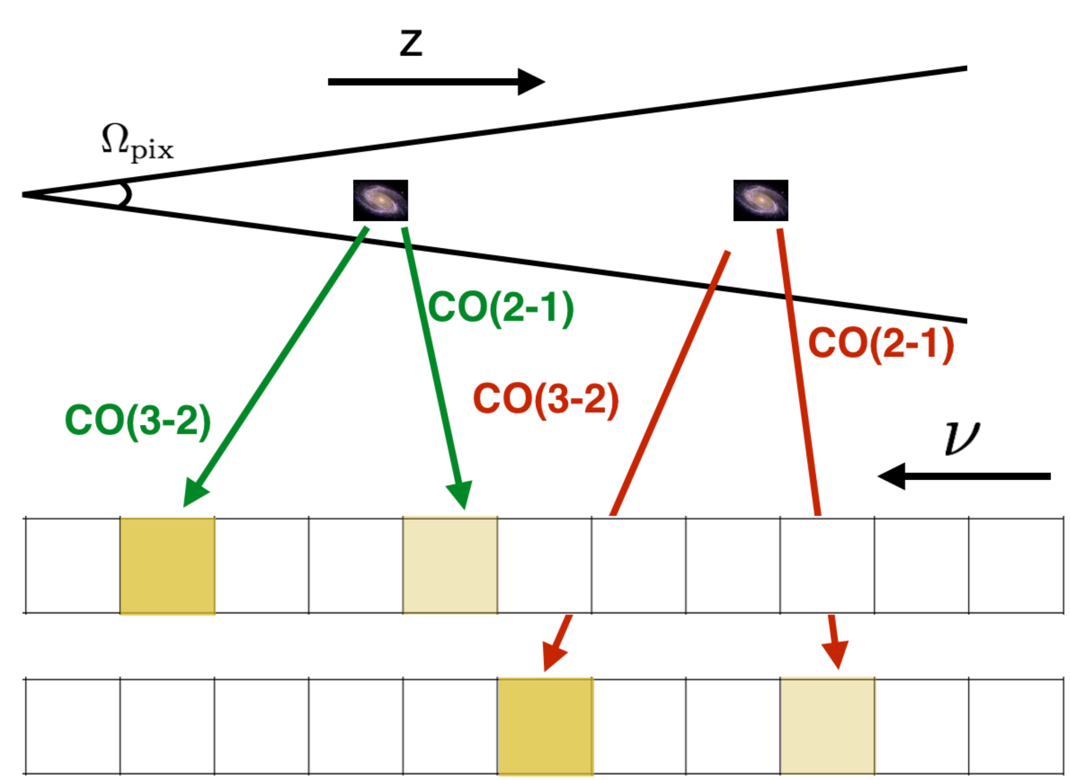
- 2D power spectrum of interloper lines become anisotropic upon projection
- Use 2D power spectrum shape to distinguish the lines

[C II]



CO (3-2)





map-space de-blending

Y.T. Cheng, T.C. Chang, J.J. Bock 2020 arXiv:2005.05341

- Spectrum template with multi-line emission
- Fit observed spectrum (per pixel) to the template with sparse reconstruction

Cosmology & Astrophysics With Intensity Mapping

Intensity Mapping for EoR Science

Line Intensity Mapping with TIME

Y.T. Cheng, T.C. Chang, J.J. Bock, C.M. Bradford, A. Cooray 2016 arXiv:1604.07833

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Constraining Extra-galactic Background Light with SPHEREx

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Broadband Intensity Mapping (2D)

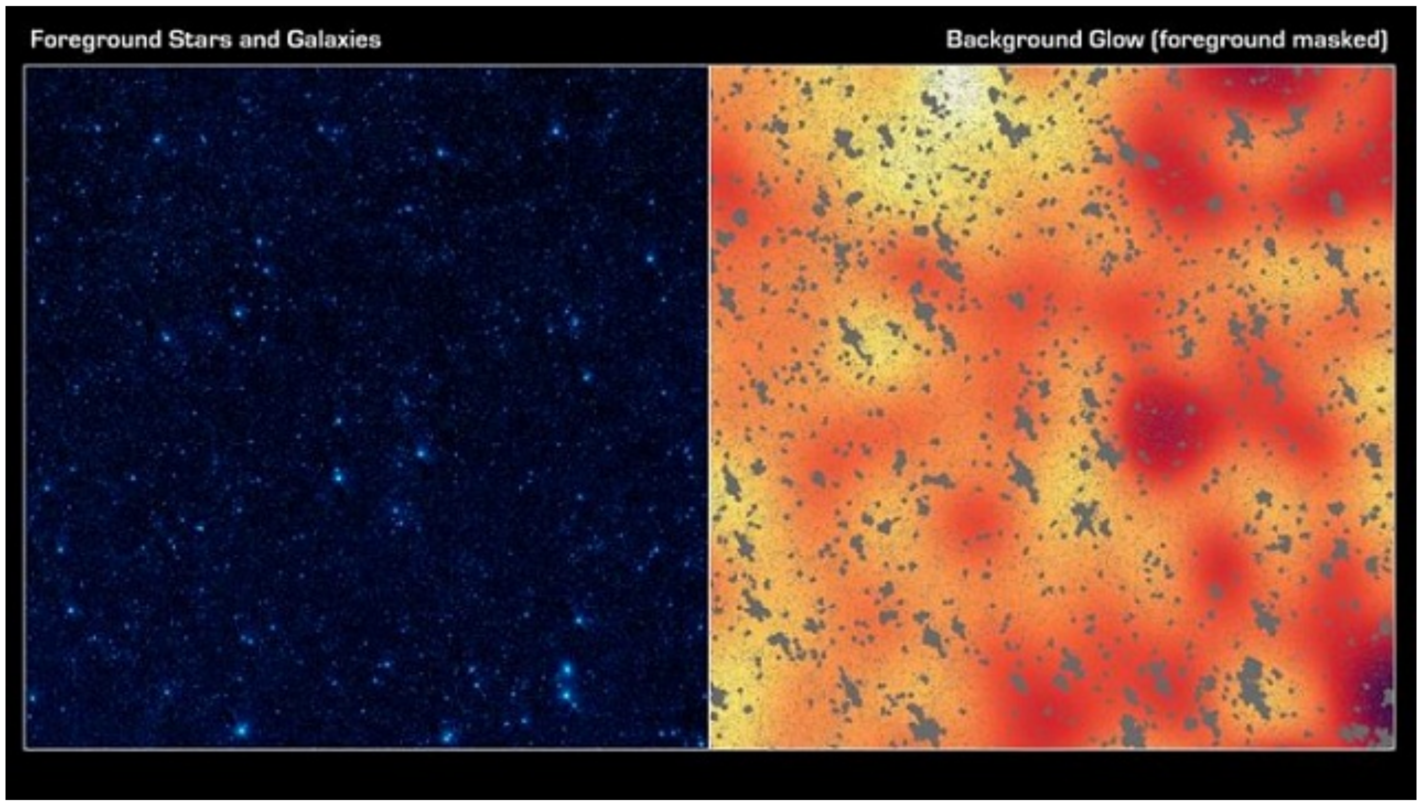
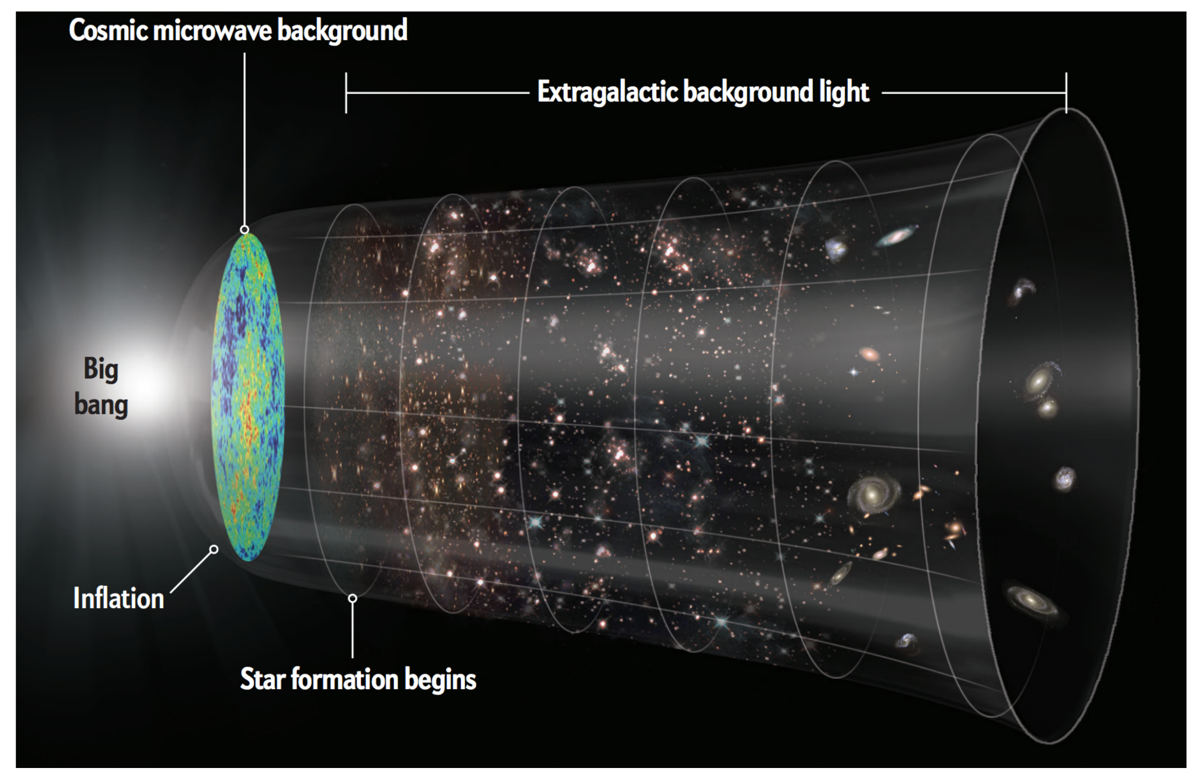


Image Credit: NASA/JPL-Caltech



Dominguez, 2015

Extragalactic Background Light (EBL)

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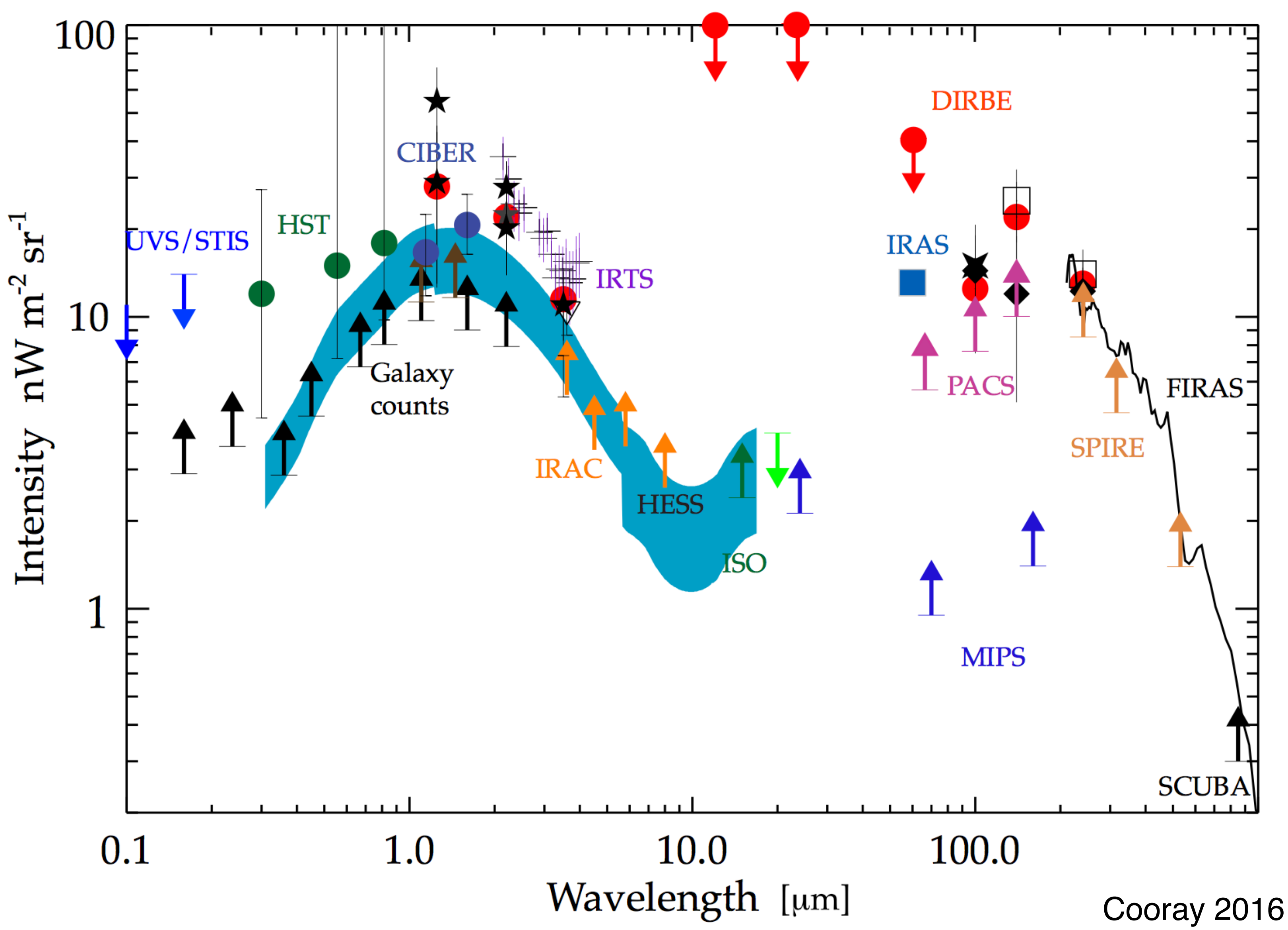
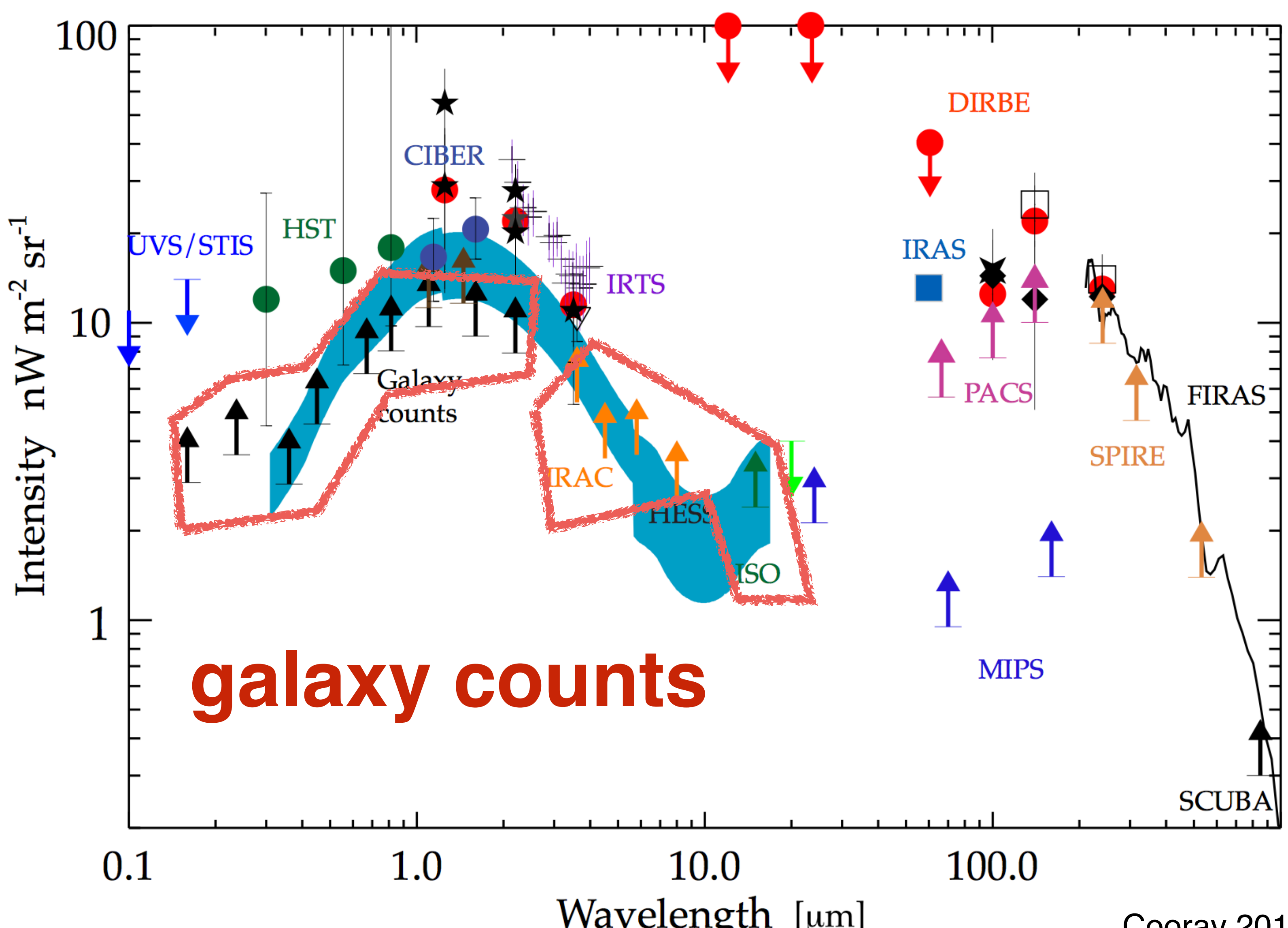


Cooray 2016

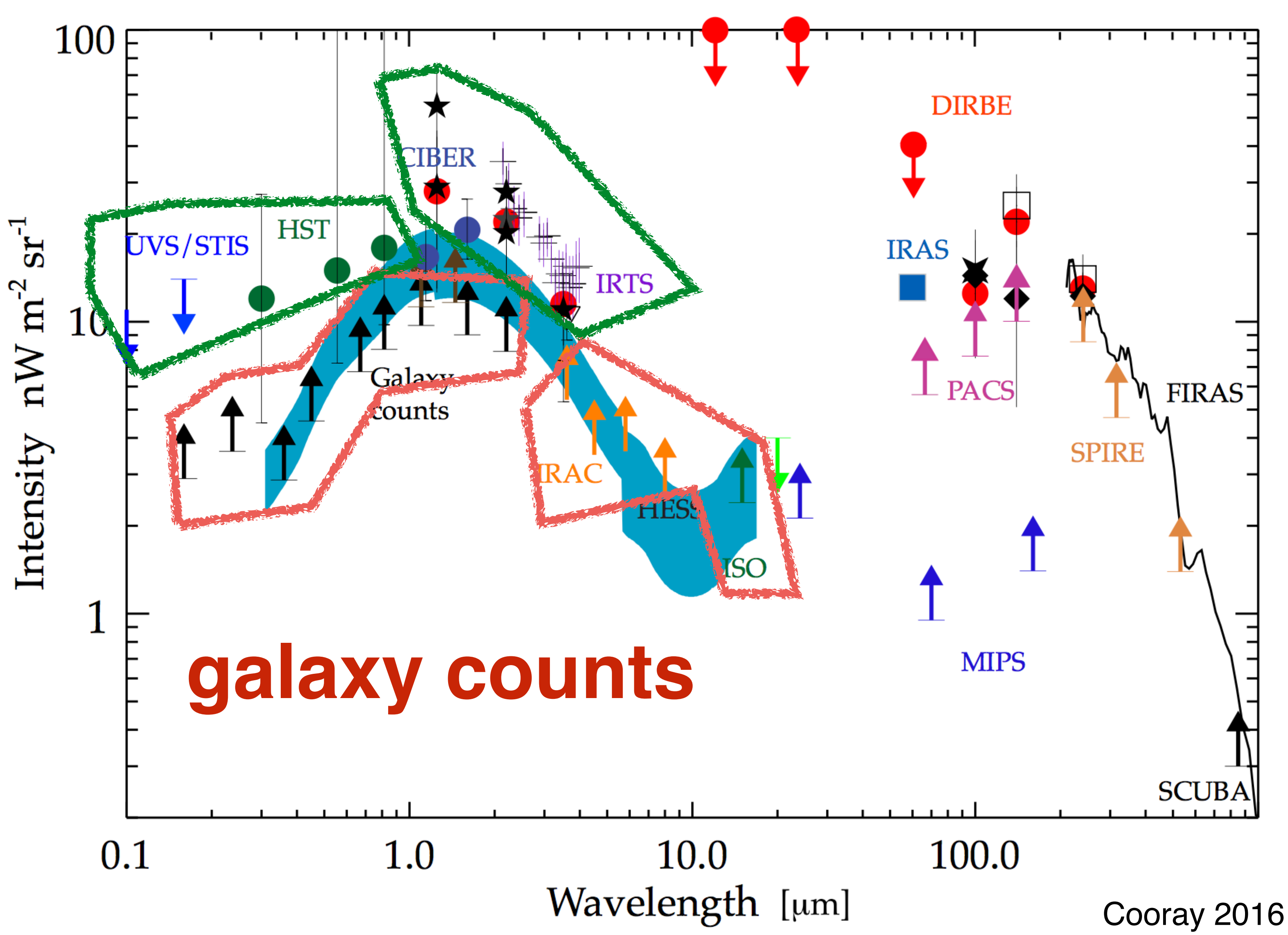
Extragalactic Background Light (EBL)



Cooray 2016

Extragalactic Background Light (EBL)

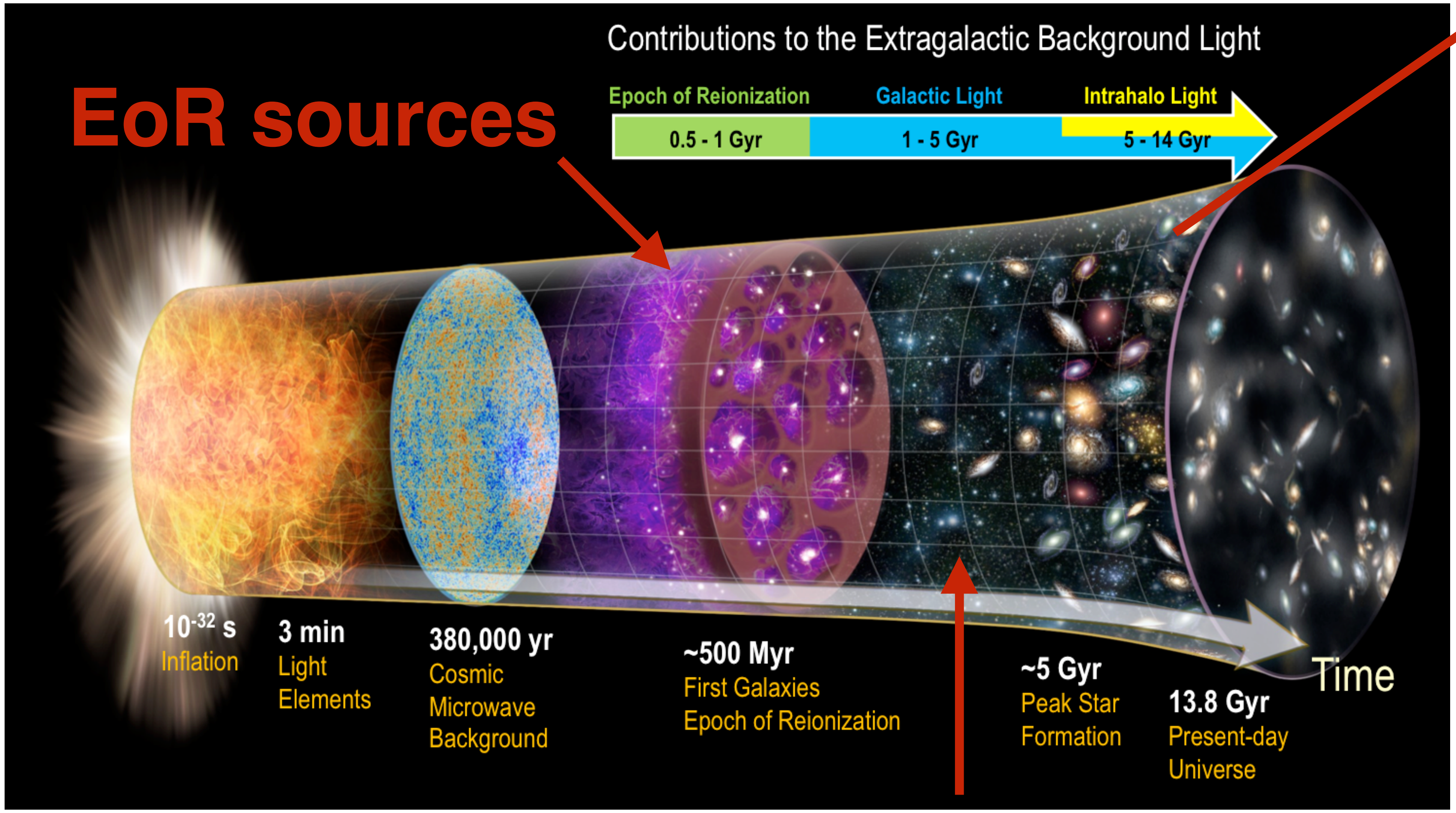
absolute photometry / fluctuation



Cooray 2016

Diffuse Components in Near-IR EBL

image credit: Jamie Bock, SPHEREx Collaboration



EoR sources

intra-halo light (IHL)

Stars being tidally stripped out from galaxy into dark matter halo

unresolved low-z galaxies

CIBER

(Cosmic Infrared Background ExpeRiment)

Caltech/Jet Propulsion Lab (USA)

Jamie Bock
Phillip Korngut
Viktor Hristov
Yun Ting Chen
Richard Feder-Staehle

University of California Irvine (USA)

Asantha Cooray
Amy Ralston
Derek Wilson

Rochester Institute of Technology (USA)

Michael Zemcov
Dorin Patru
Priyadarshini Bangale
Chi Nguyen
Kevin Gates
James Parkus
Chris Pape

Institute of Astronomy and Astrophysics Academia Sinica (Taiwan R.O.C)

Shiang-Yu Wang

Kwansei Gakuin University (Japan)

Shuji Matsuura
Ryo Hashimoto
Kohji Takimoto
Masaki Furutani
Hiroko Suzuki
Arisa Kida
Shota Sakai

Japan Aerospace Exploration Agency (Japan)

Takehiko Wada
Toshio Matsumoto

Kanazawa University (Japan)

Kei Sano (Research fellow of Kwansei Gakuin University)

Astrobiology Center (Japan)

Aoi Takahashi

Tokyo City University(Japan)

Kohji Tsumura

Korean Astronomy and Space Science Institute (South Korea)

Dae-Hee Lee
Won-Kee Park
Seung-Cheol Bang

CIBER

(Cosmic Infrared Background ExpeRiment)

Zemcov et al. 2013

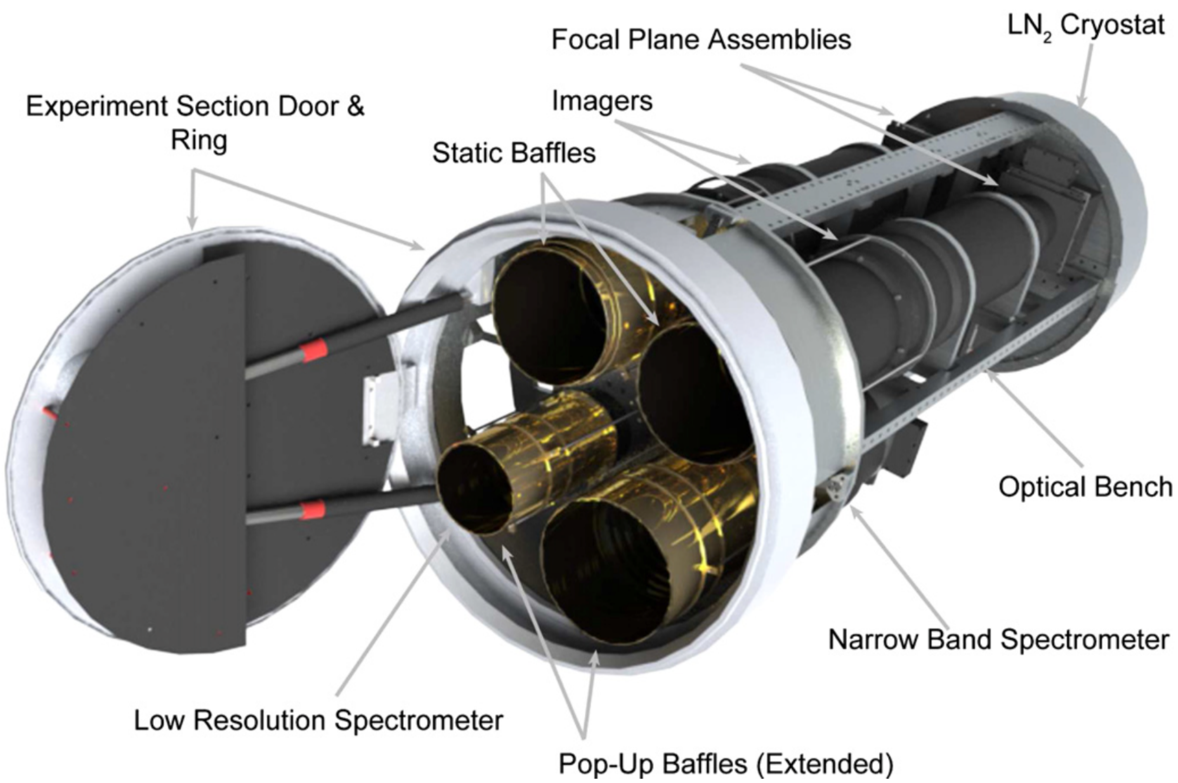


Image Credit: T. Arai

Two **Imagers** (1.1 & 1.6 um) : measure power spectrum

FOV 2x2 deg, pixel size 7”x7”, 1024x1024 pixels, R~2

(2nd / 3rd flight analysis: Zemcov et al. 2014)

Low Resolution Spectrometer (Matsuura et al. 2017)

Narrow Band Spectrometer (Korngut et al. in prep.)

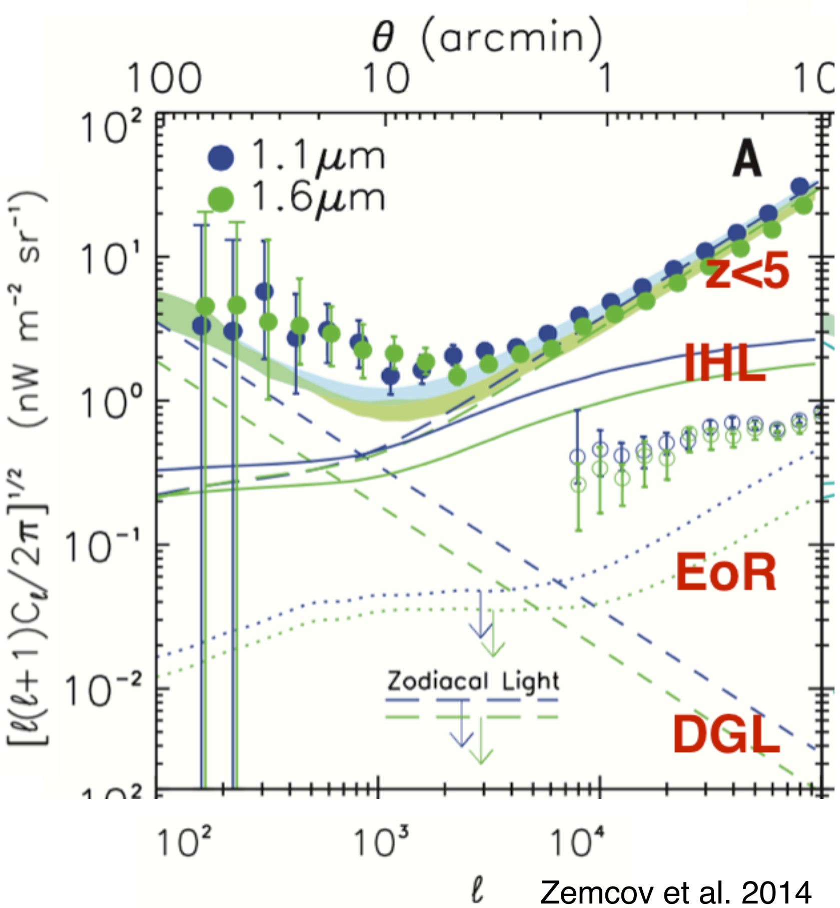
4 flights:

02/2009, 07/2010,

03/2012, 06/2013

Intra-Halo Light (IHL)

Imager power spectrum (2nd / 3rd flight)



Zemcov et al. 2014

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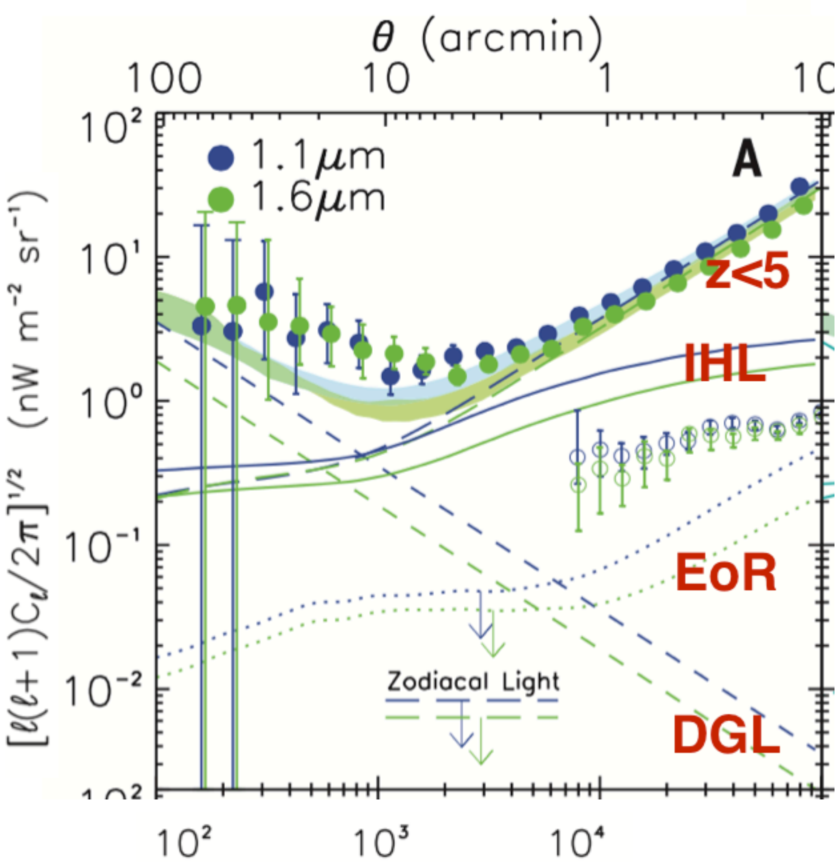

Zemcov et al. 2014

Intra-Halo Light (IHL)

contributes ~ half of
total light in DM halos!

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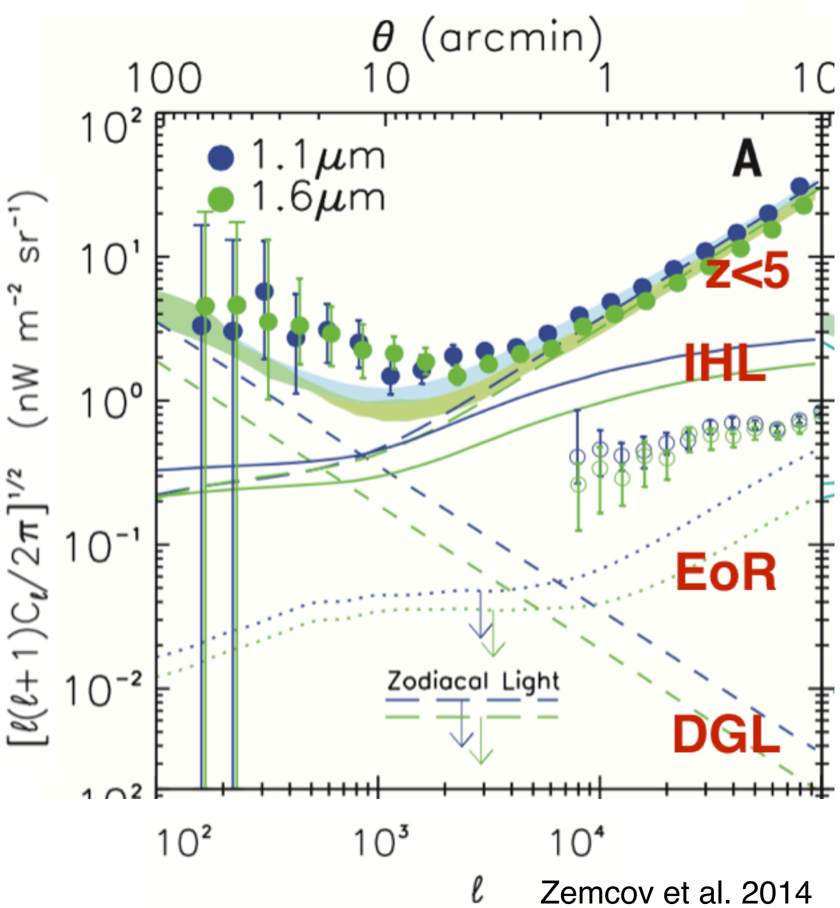

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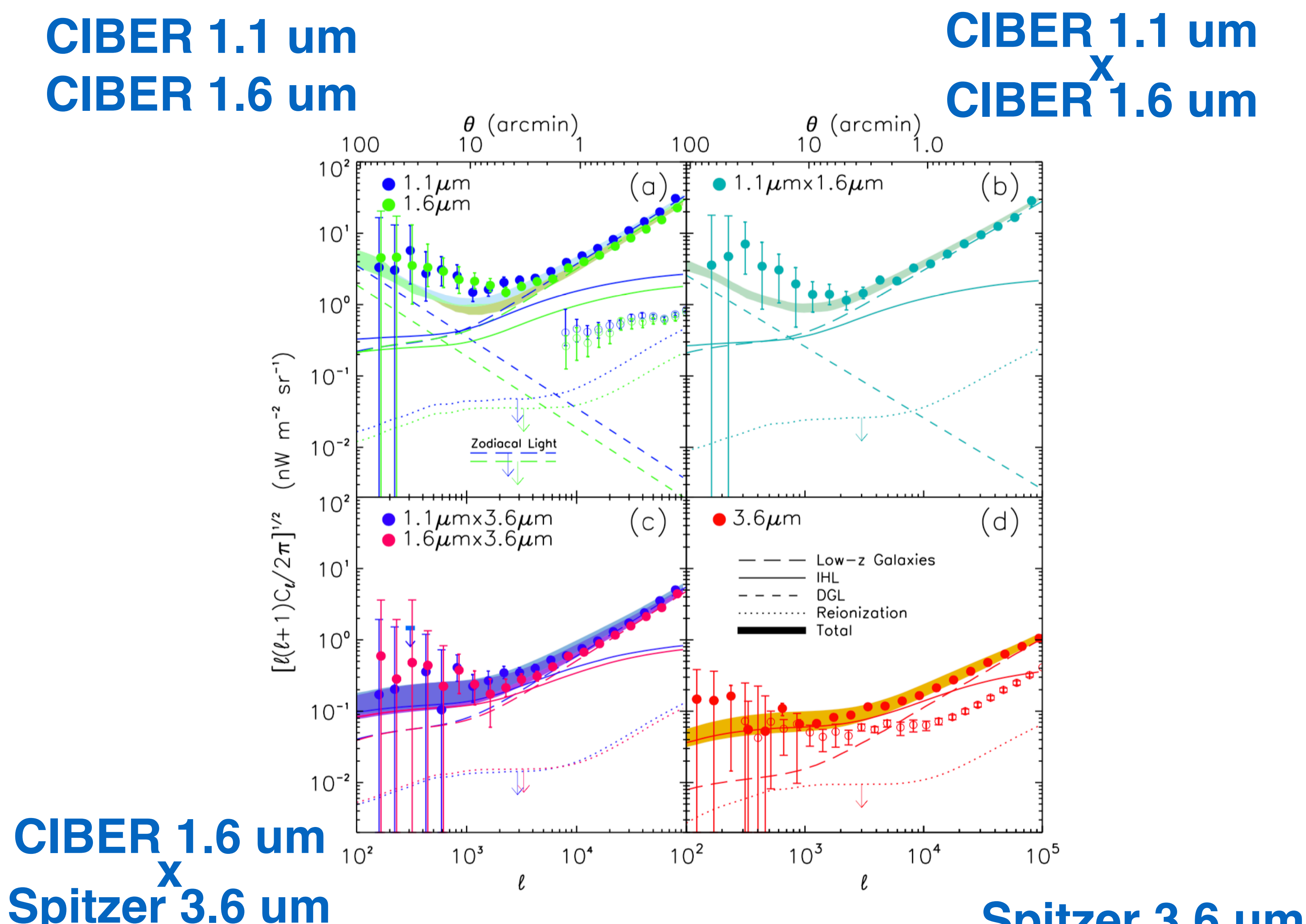
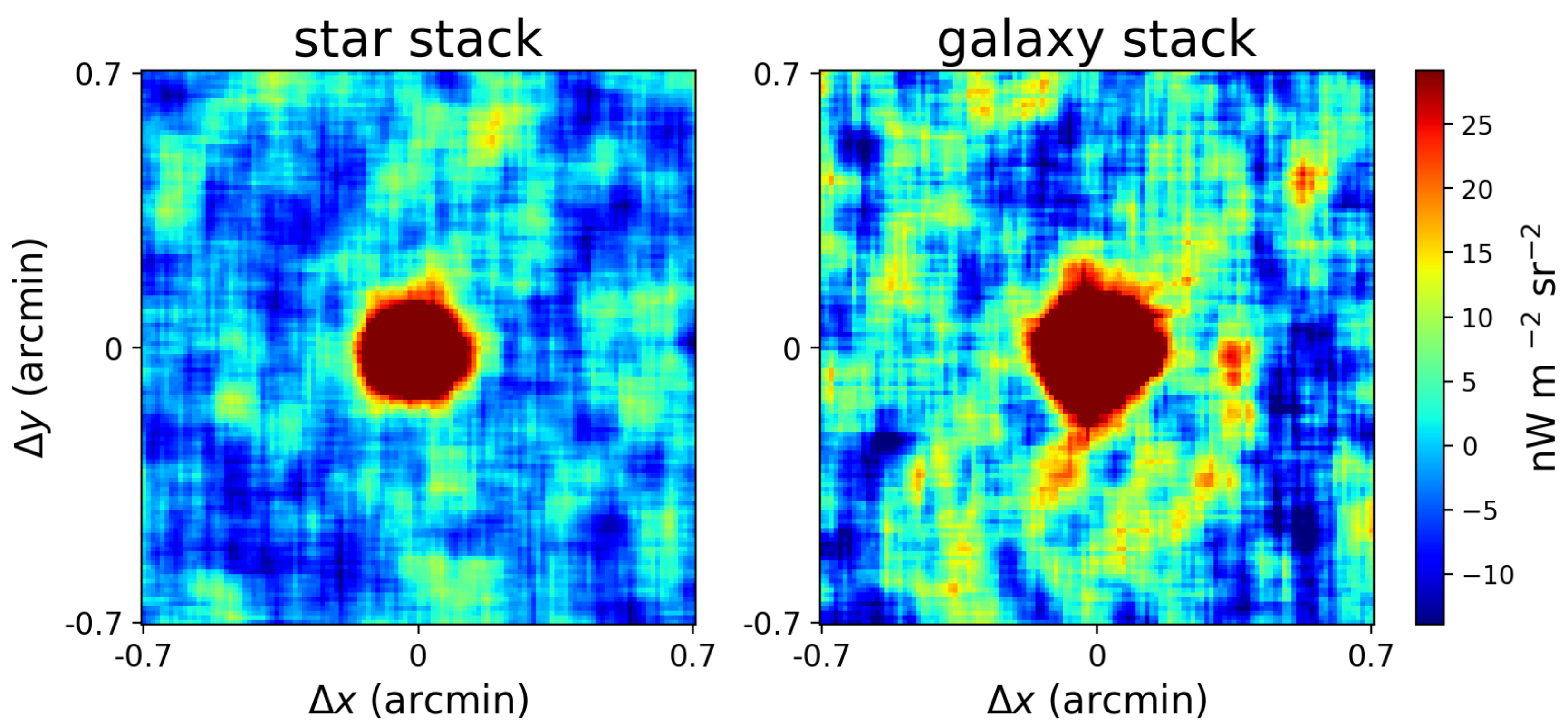


Probing IHL with Stacking Analysis

CIBER 4th flight - more fields

Probing IHL with Stacking Analysis

CIBER 4th flight - more fields



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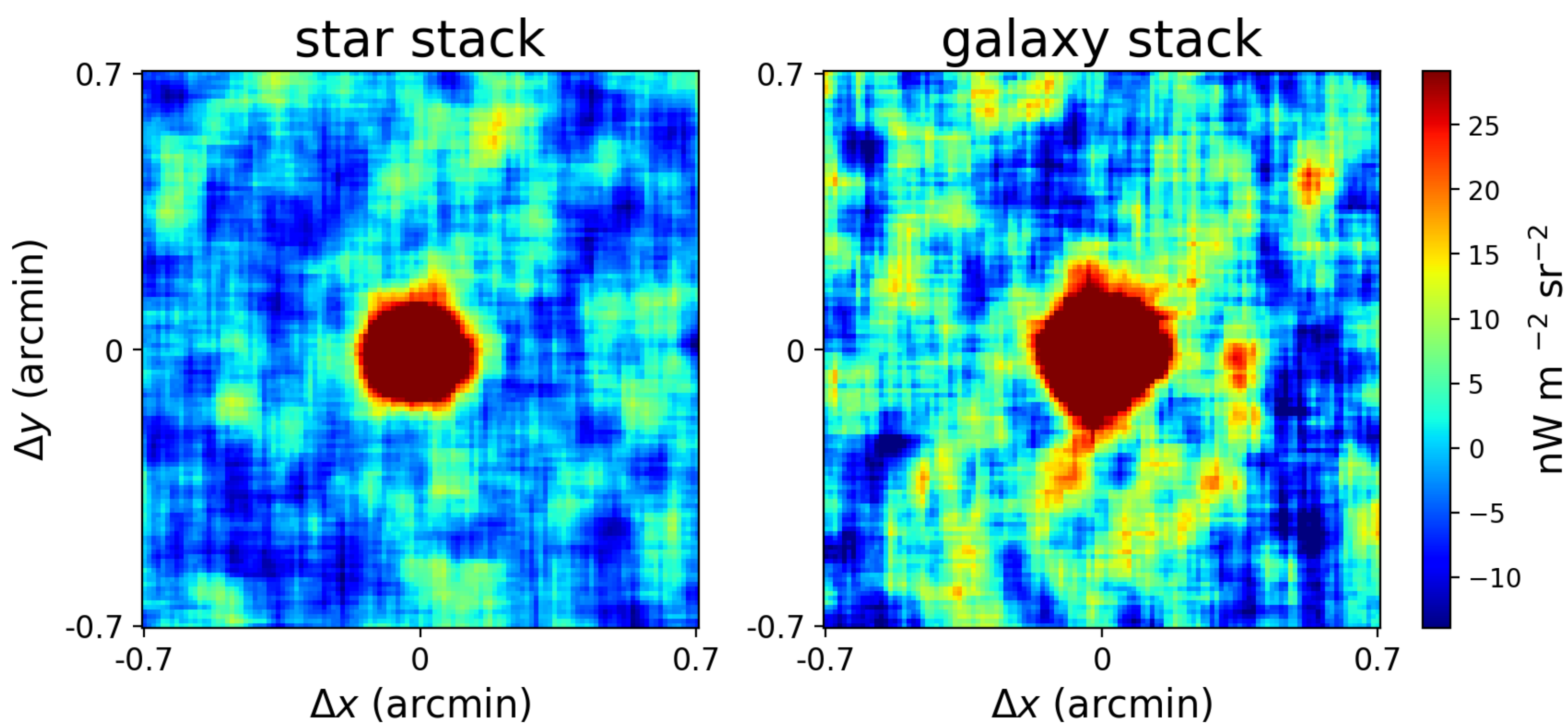

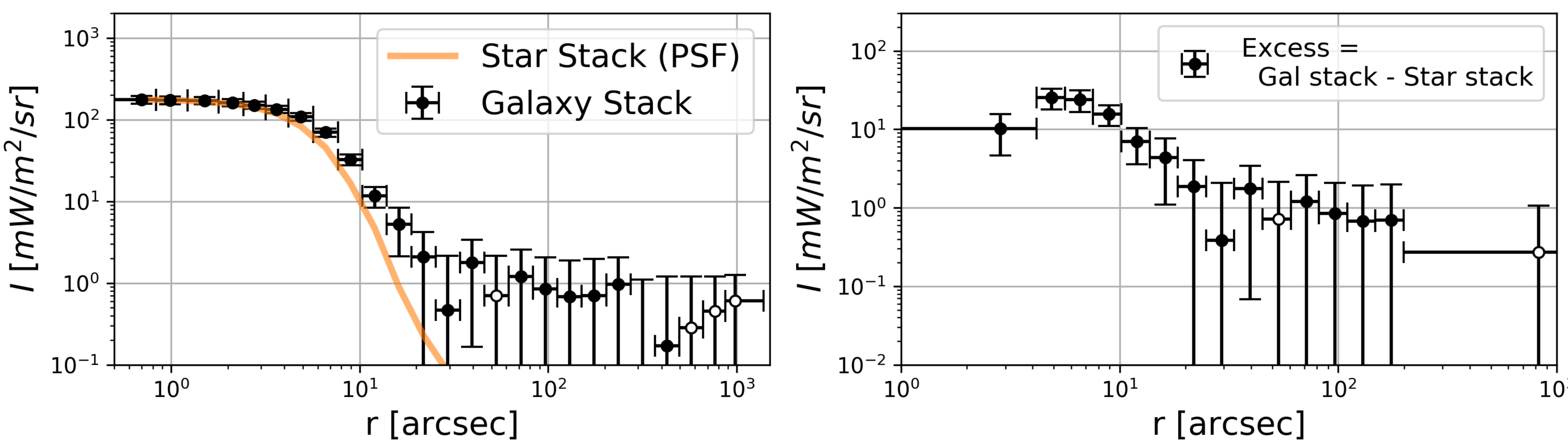

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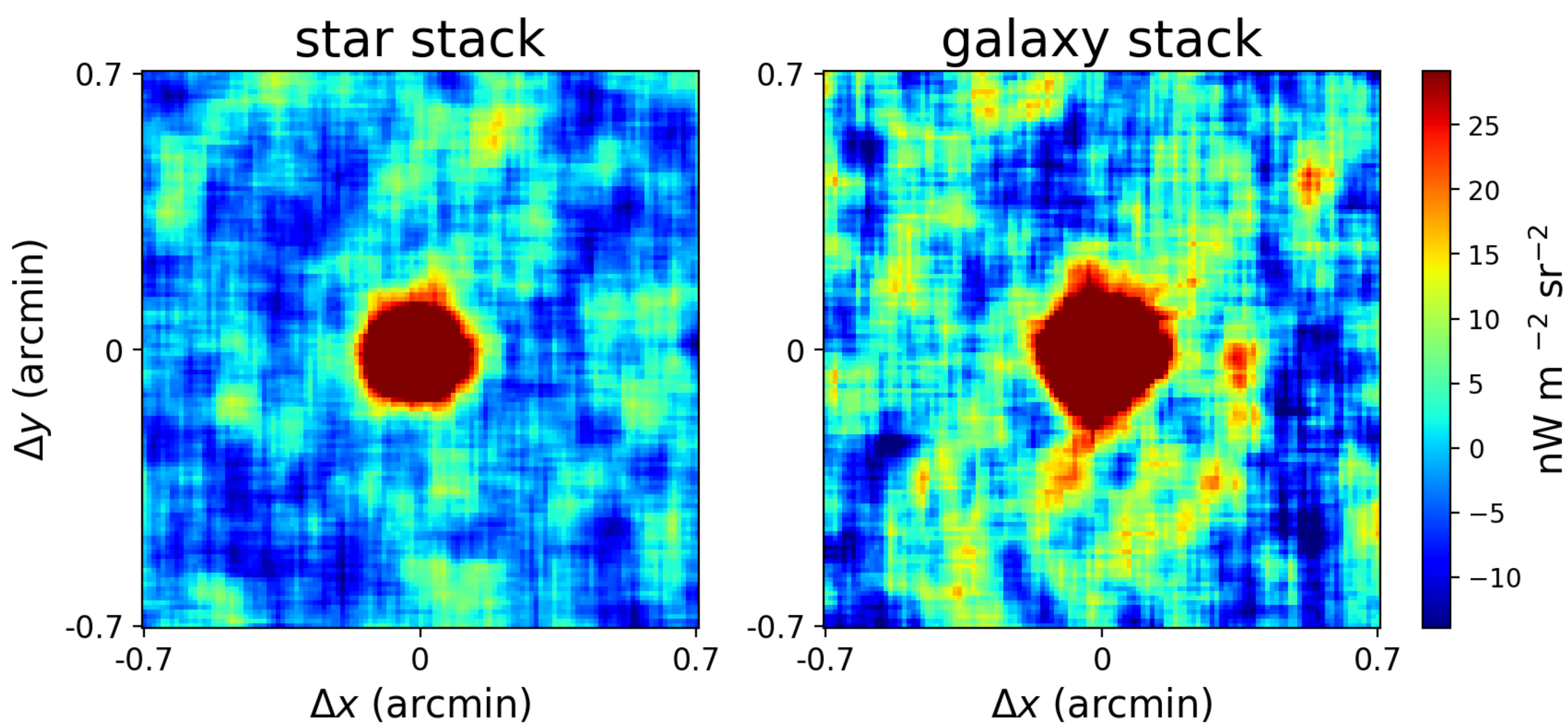
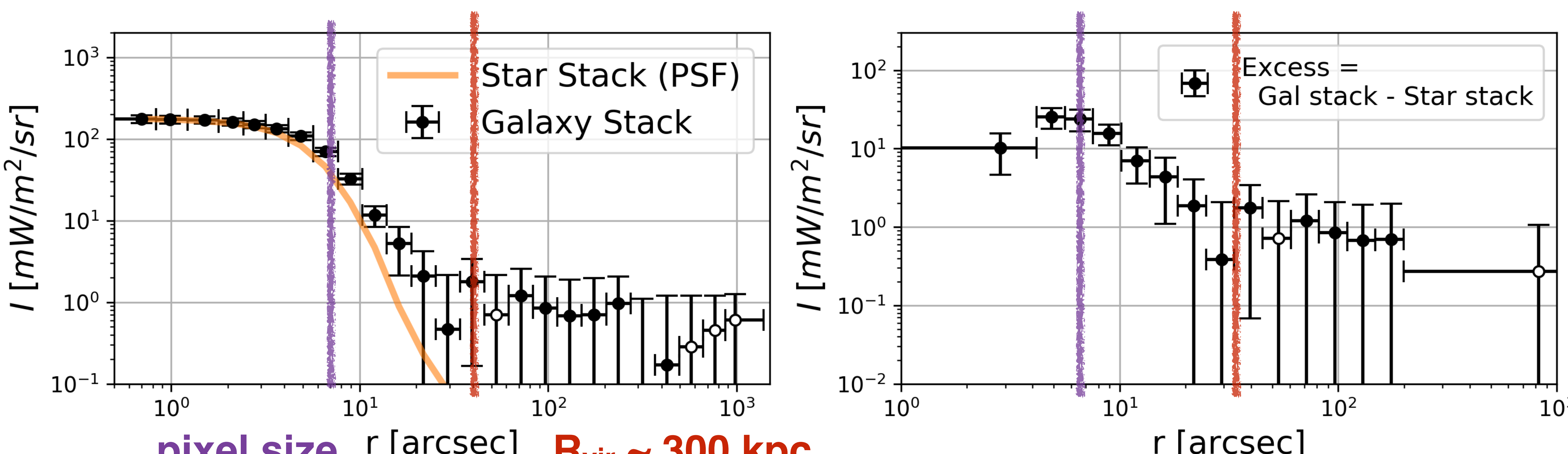
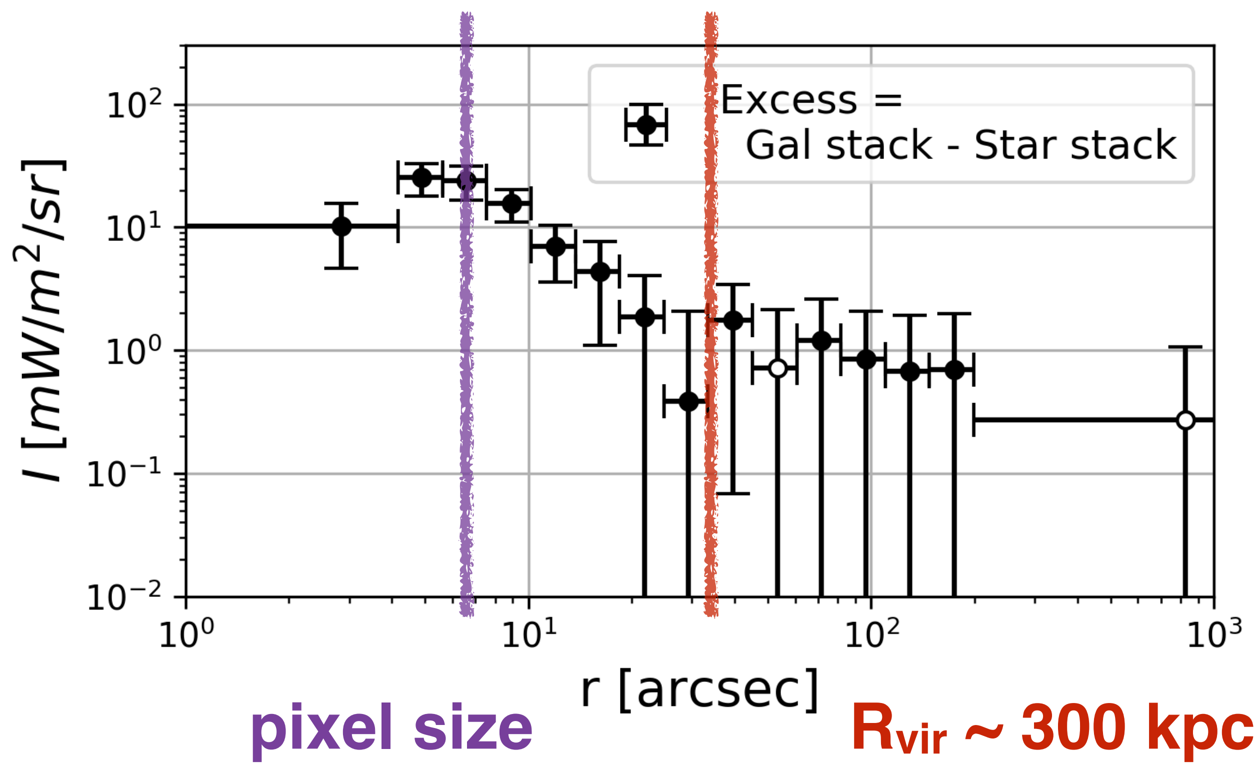




pixel size

R_{vir} ~ 300 kpc

Modeling the Excess Profile

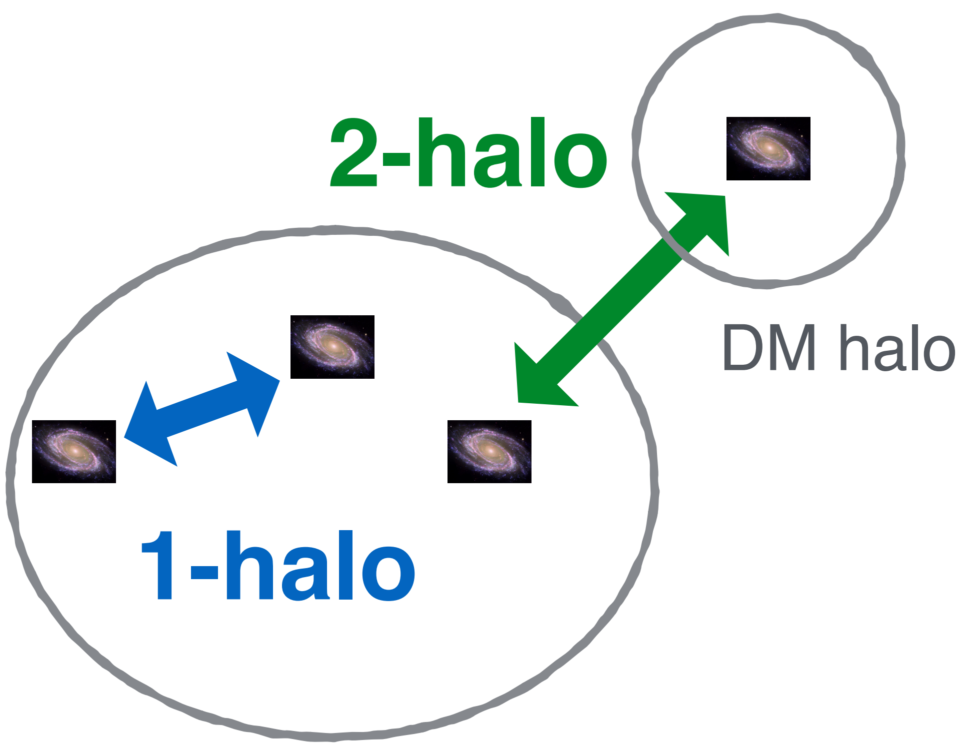


galaxy profile

- galaxy shape + IHL
- double Sersic profile

clustering: 1-halo , 2-halo

- halo model
- model from MICECAT sims
- fit a free amplitude to 1-h & 2-h template



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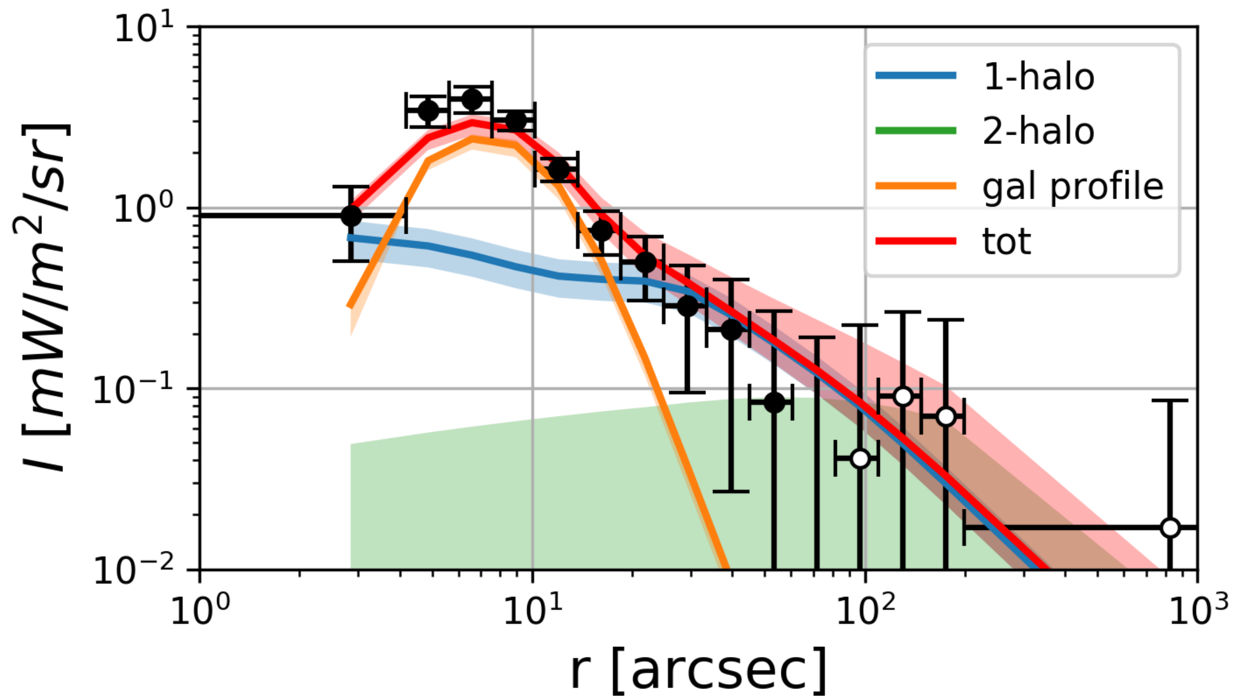

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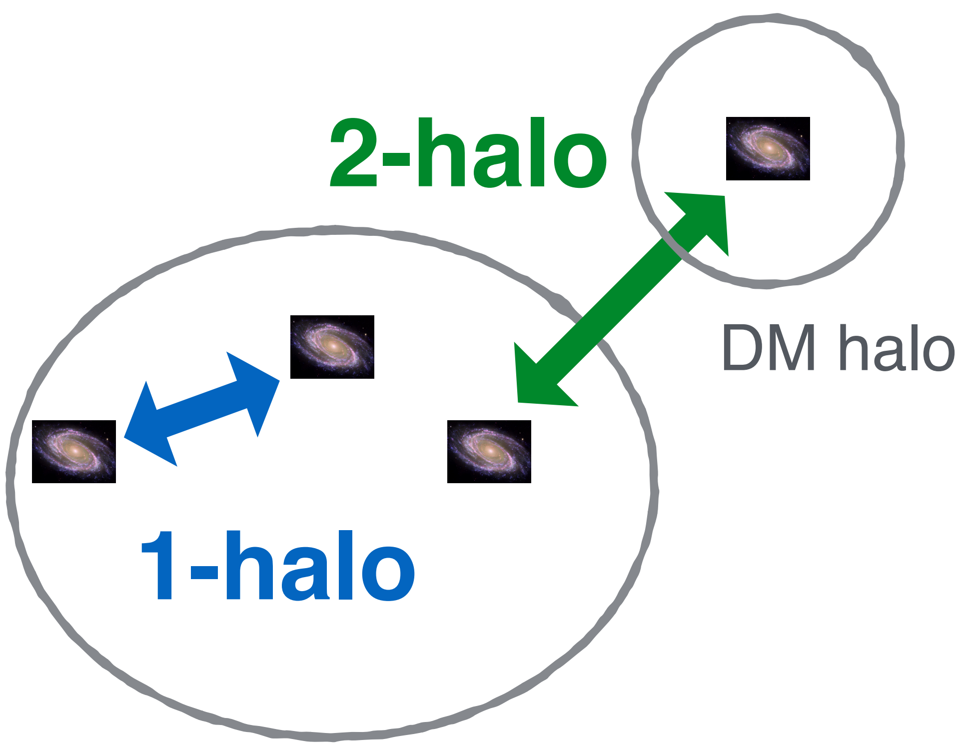
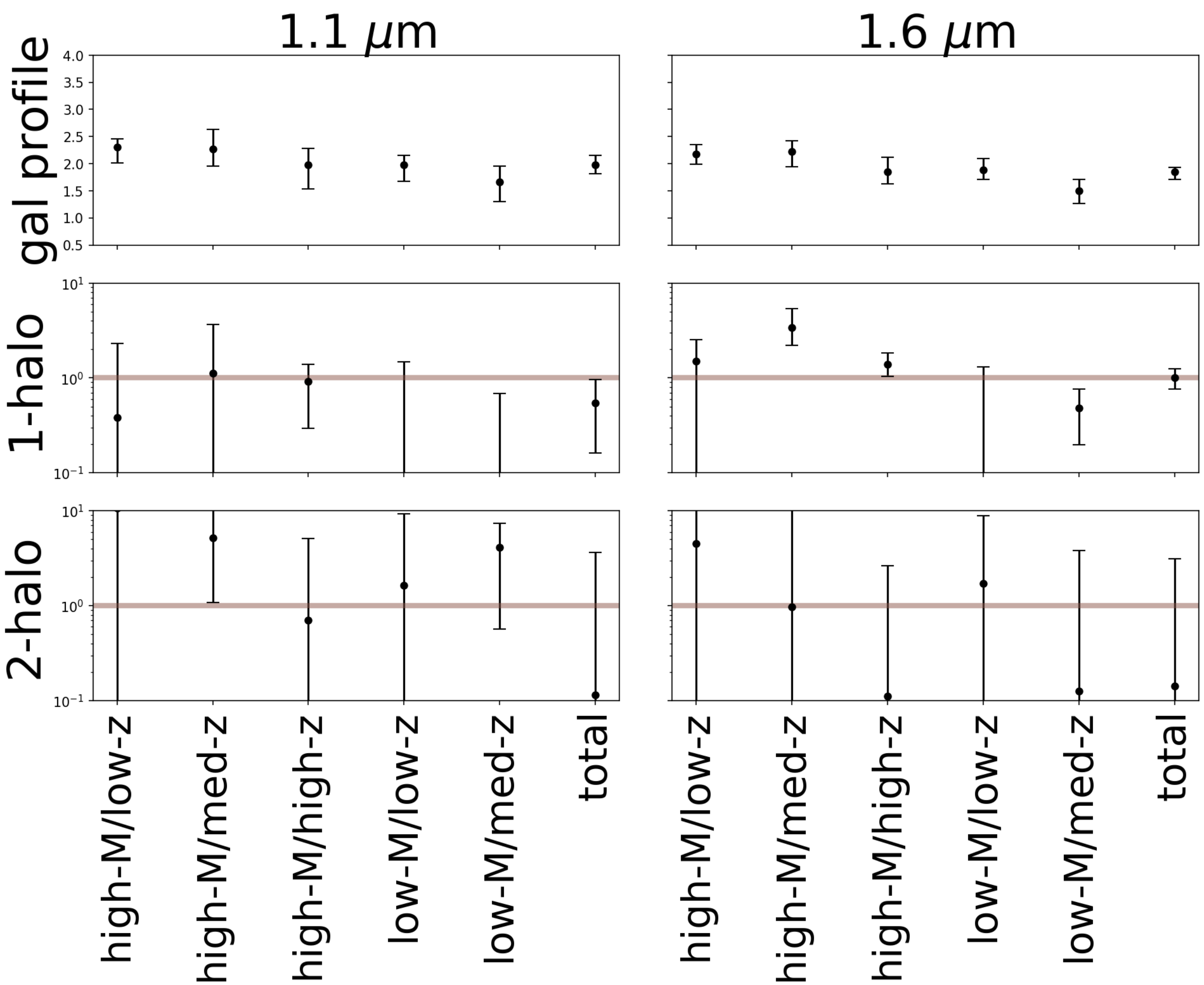


Stacking Samples

- 5 fields (2 deg x 2 deg)
- 1.1 um & 1.6 um bands

Name	$N_{\rm gal}$	$\langle z \rangle$	$\log\ \langle M_* \rangle\ [M_\odot]$	$\log\ \langle M_h \rangle\ [\mathrm{M}_\odot]$
high-M/low-z	743	0.22	11.6	12.5
high-M/med-z	1274	0.34	11.4	12.6
high-M/high-z	10916	0.54	11.3	12.6
low-M/low-z	1645	0.24	11.1	12.0
low-M/med-z	14730	0.38	11.0	12.1
total	35795	0.40	11.1	12.3

Parameter Fit



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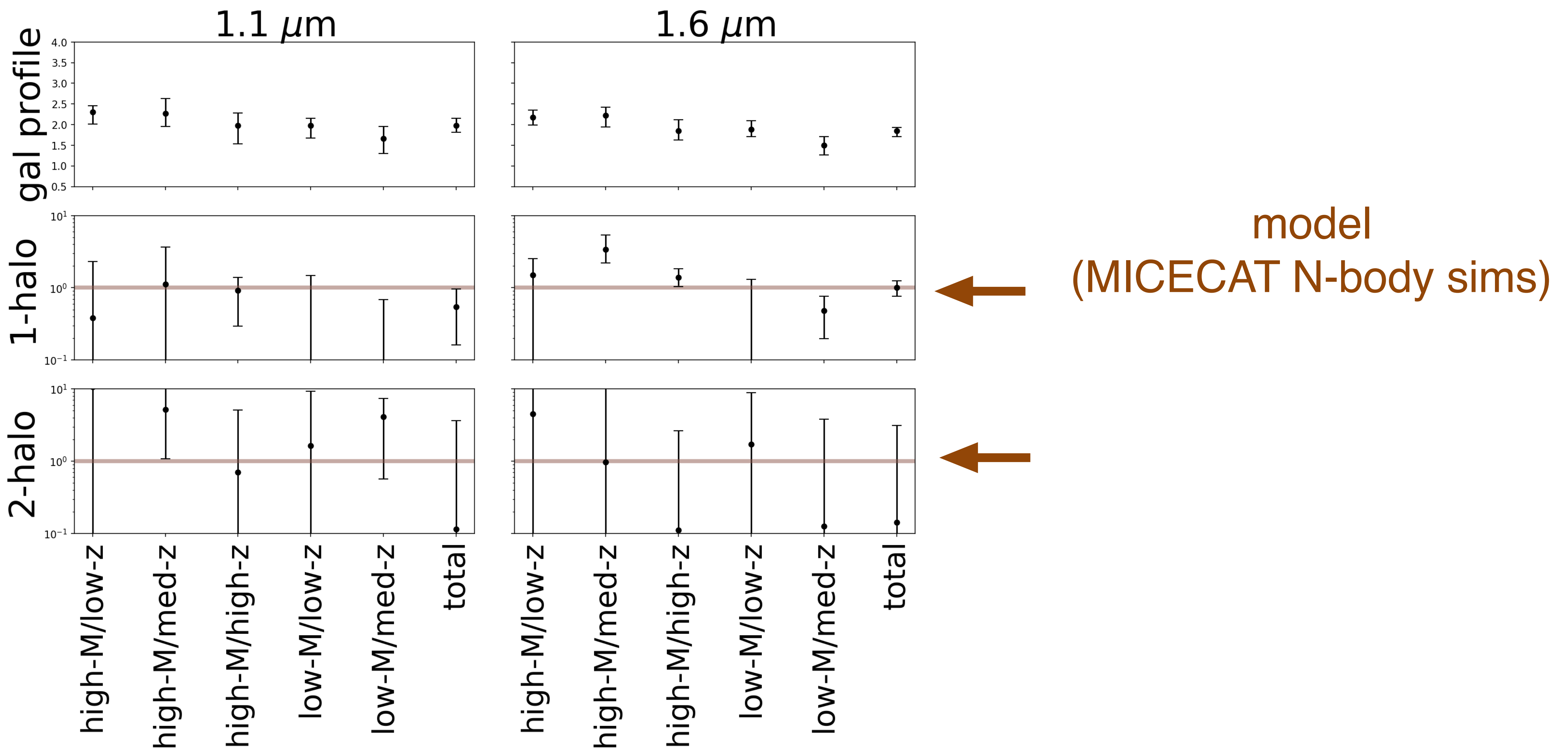

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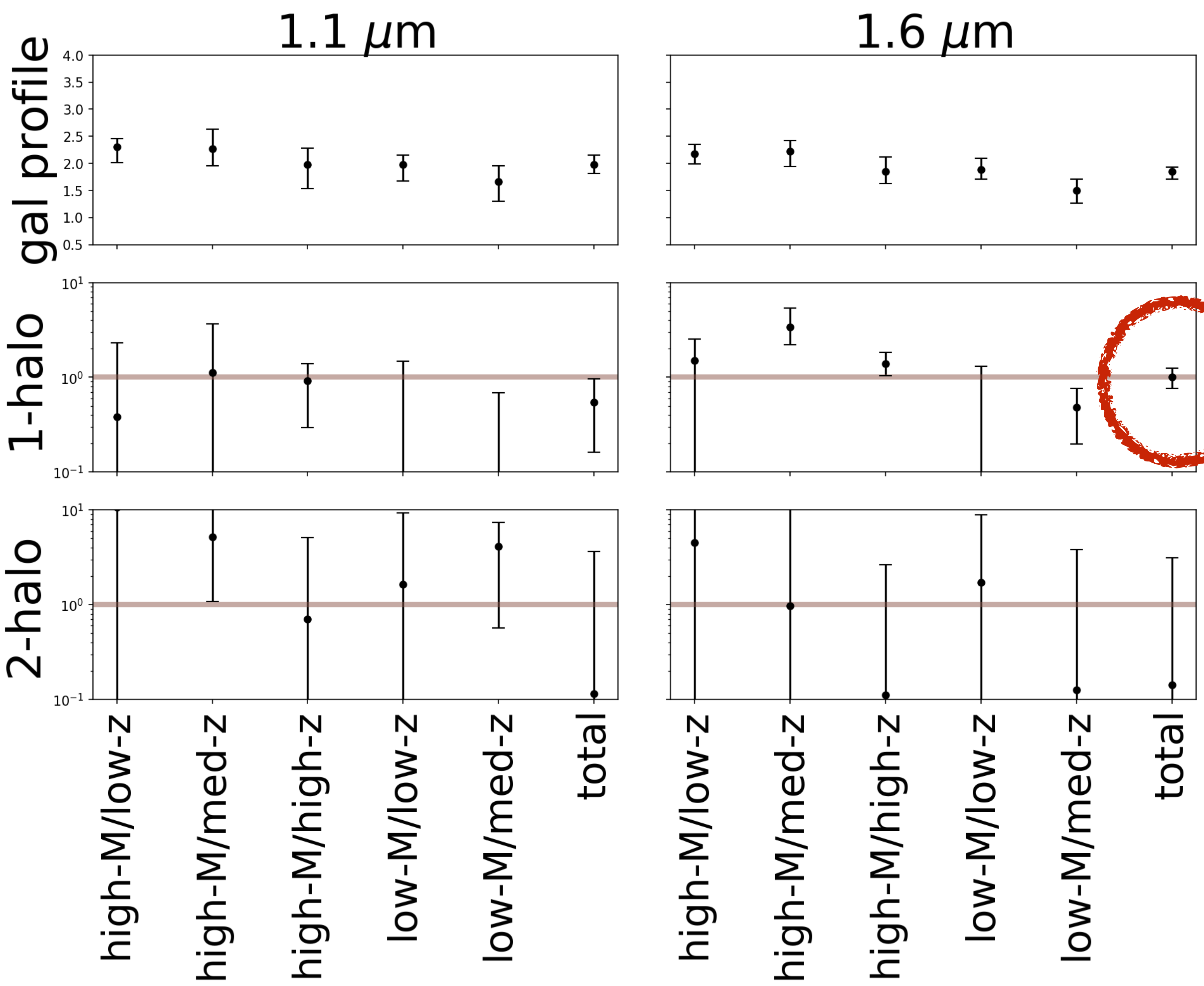
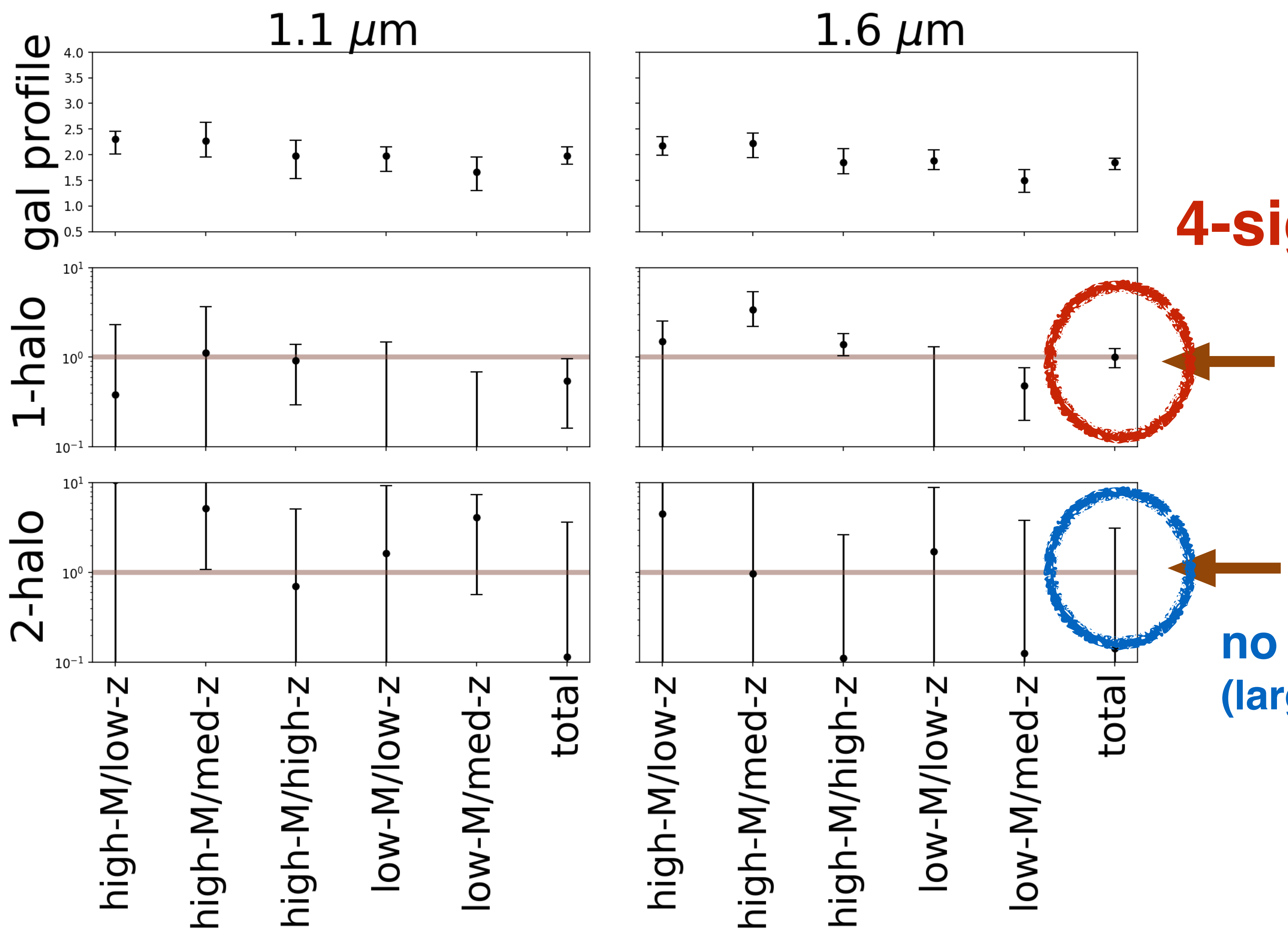


4-sigma

model
(MICECAT N-body sims)

Parameter Fit

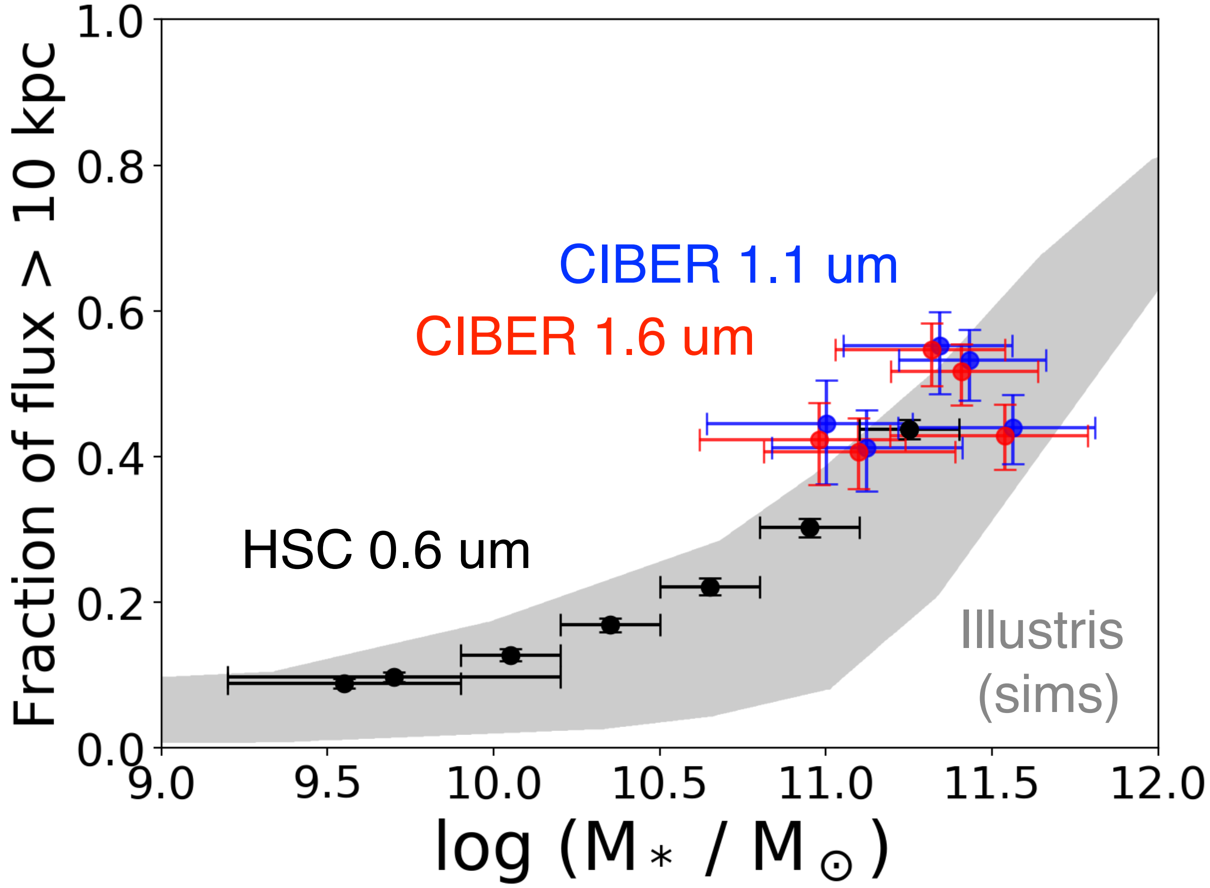


4-sigma

model
(MICECAT N-body sims)

no detection
(large-scale foreground fluctuations)

Extended Stellar Halo



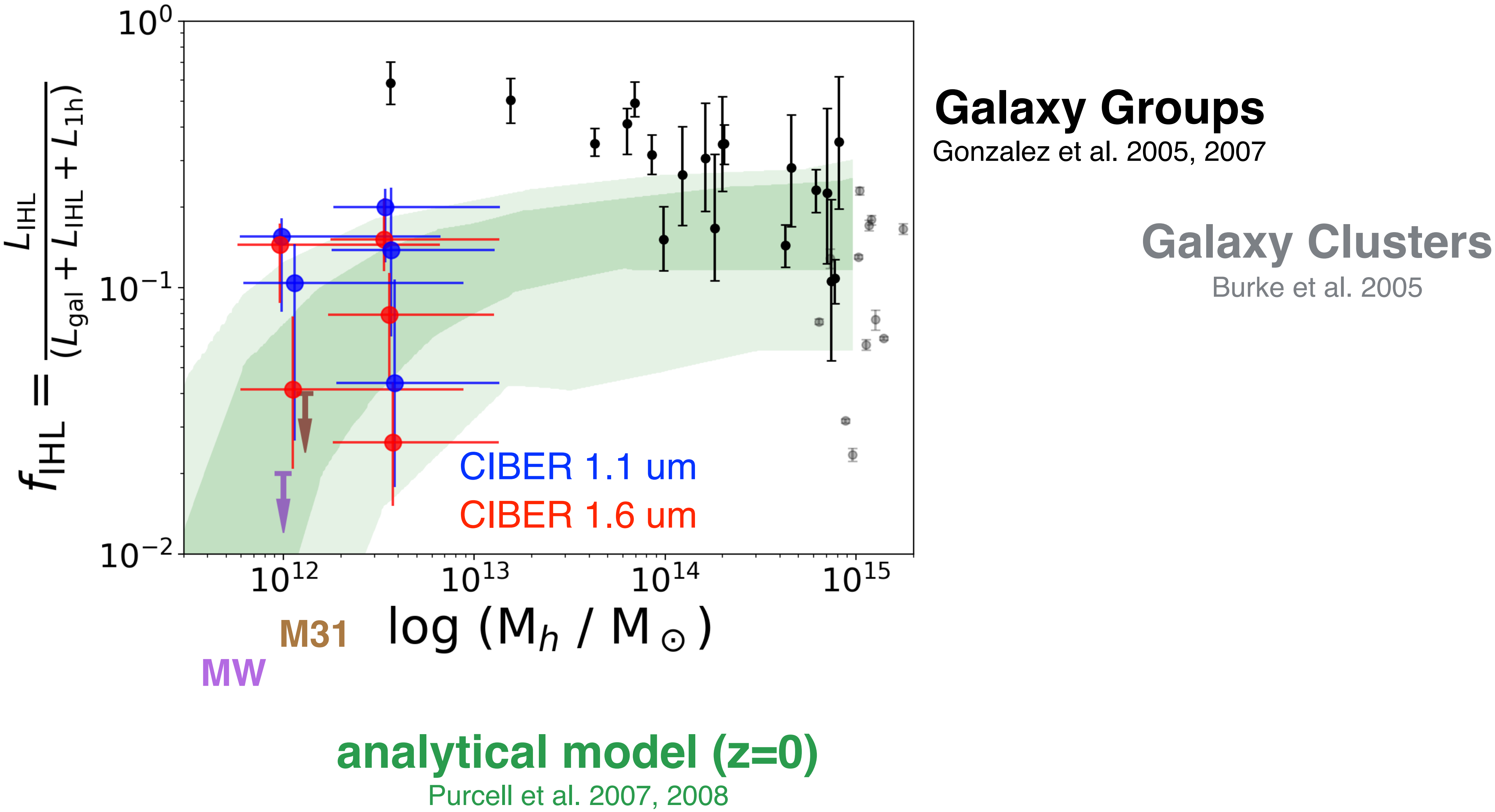
CIBER (this work)**:**
- Near-IR: 1.1 um, 1.6 um
- z ~ 0.2–0.5
- space-based

HSC (Wang et al. 2019)**:**
- Optical: 0.6 um (r band)
- z ~ 0–0.2
- ground-based

Illustris (Rodriguz-Gomez et al. 2016)**:**
- Hydrodynamic simulations

Y.T. Cheng + CIBER collaboration 2020a in prep.

Intra-Halo Light (IHL)



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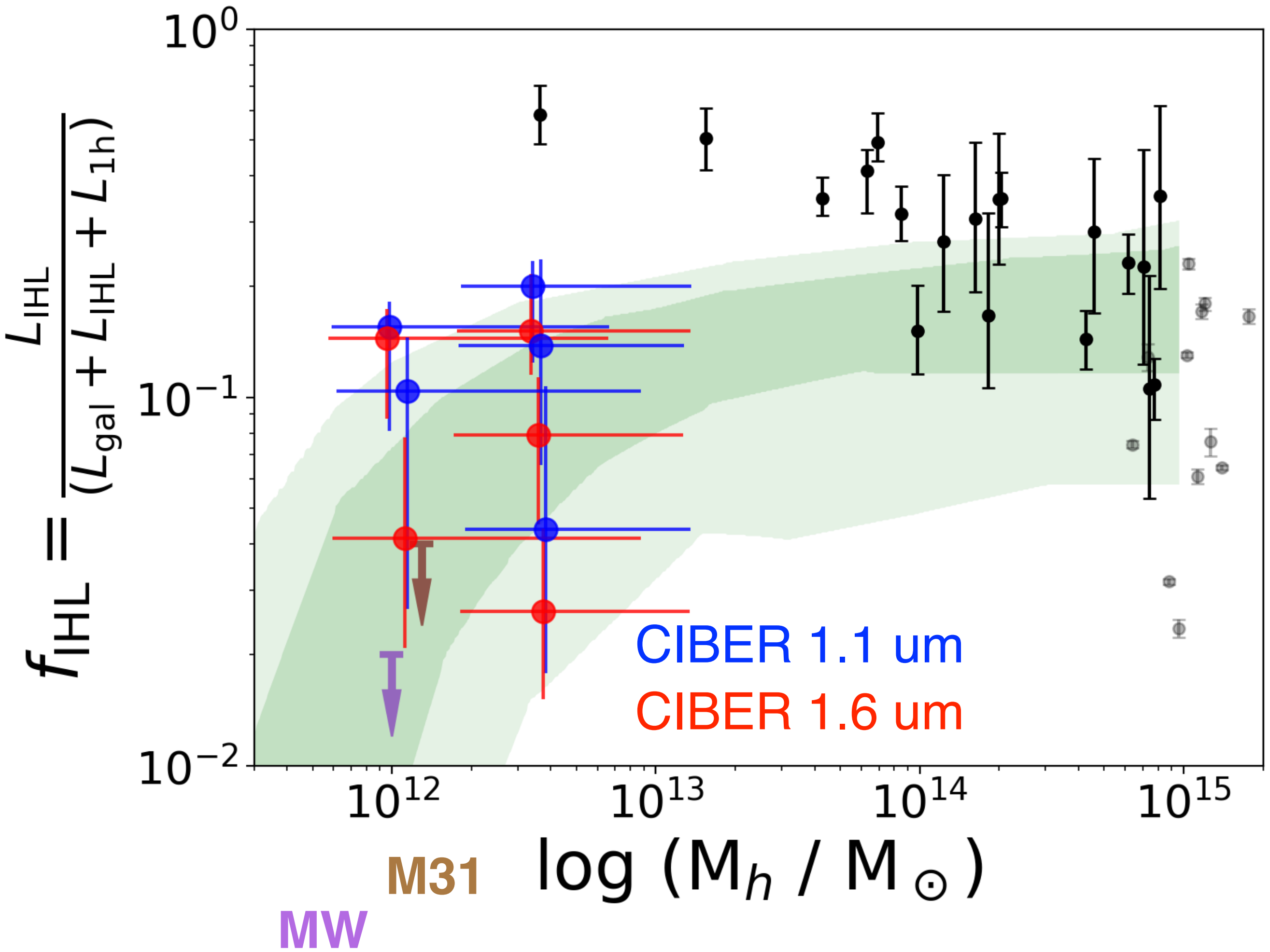
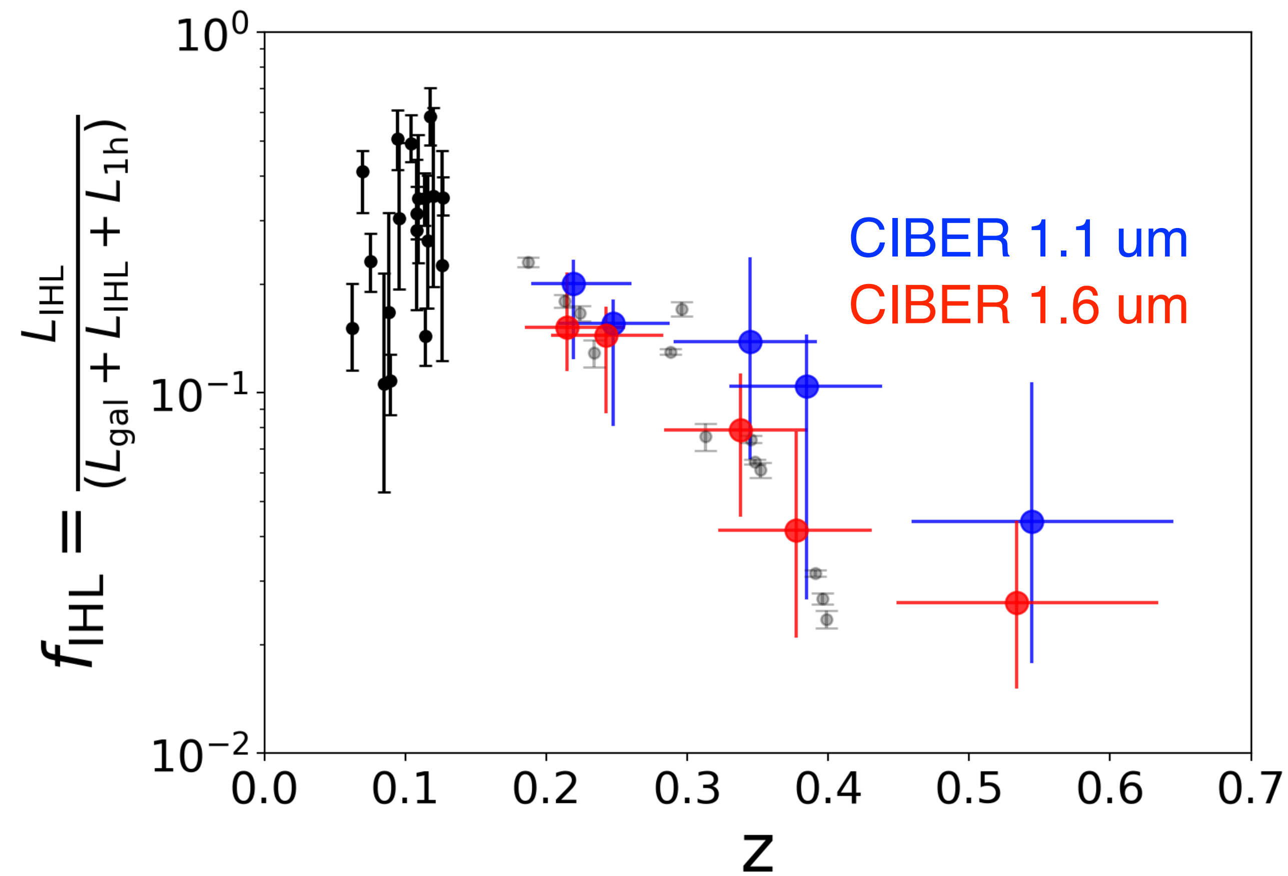
Intra-Halo Light (IHL)



Galaxy Groups
Gonzalez et al. 2005, 2007

Galaxy Clusters
Burke et al. 2005

analytical model (z=0)
Purcell et al. 2007, 2008



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Cosmology & Astrophysics With Intensity Mapping

Intensity Mapping for EoR Science

Line Intensity Mapping with TIME

Y.T. Cheng, T.C. Chang, J.J. Bock, C.M. Bradford, A. Cooray 2016 arXiv:1604.07833

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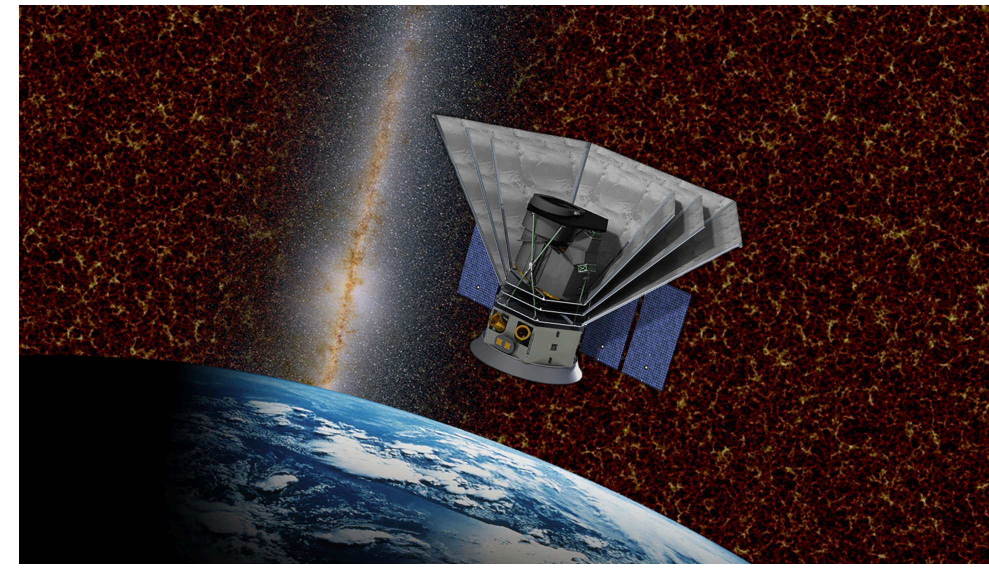
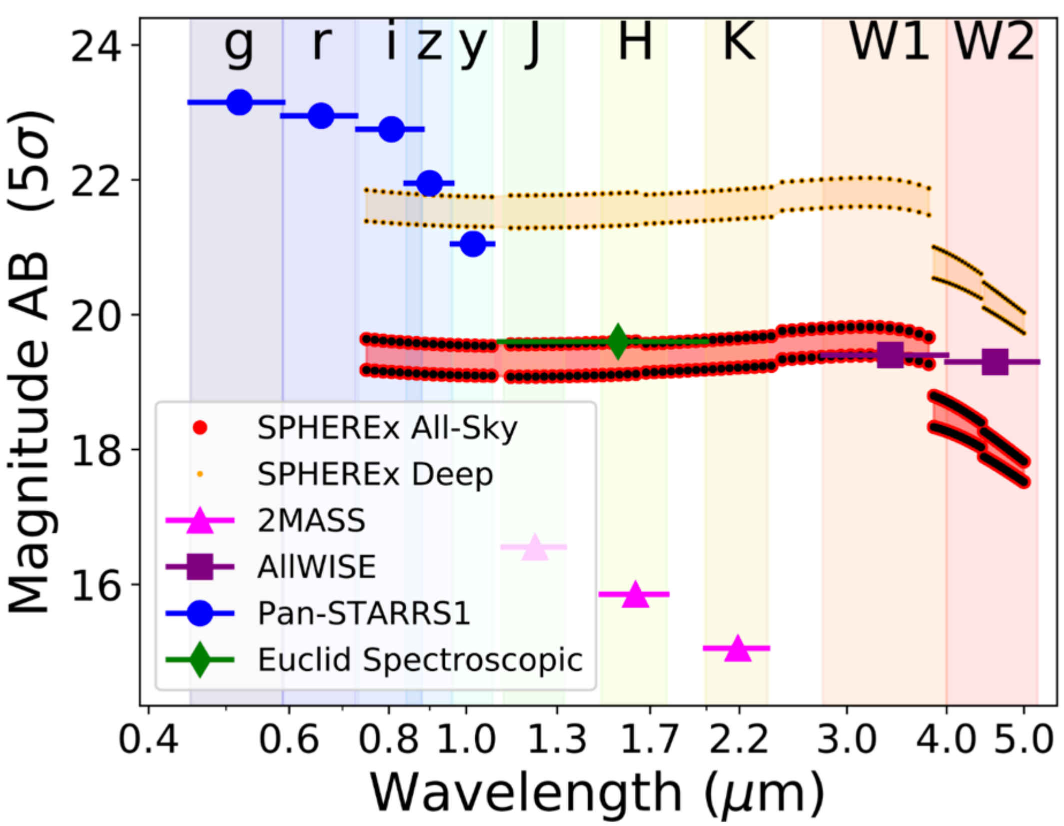
SPHEREx

https://spherex.caltech.edu/

The first all-sky near-IR spectral survey

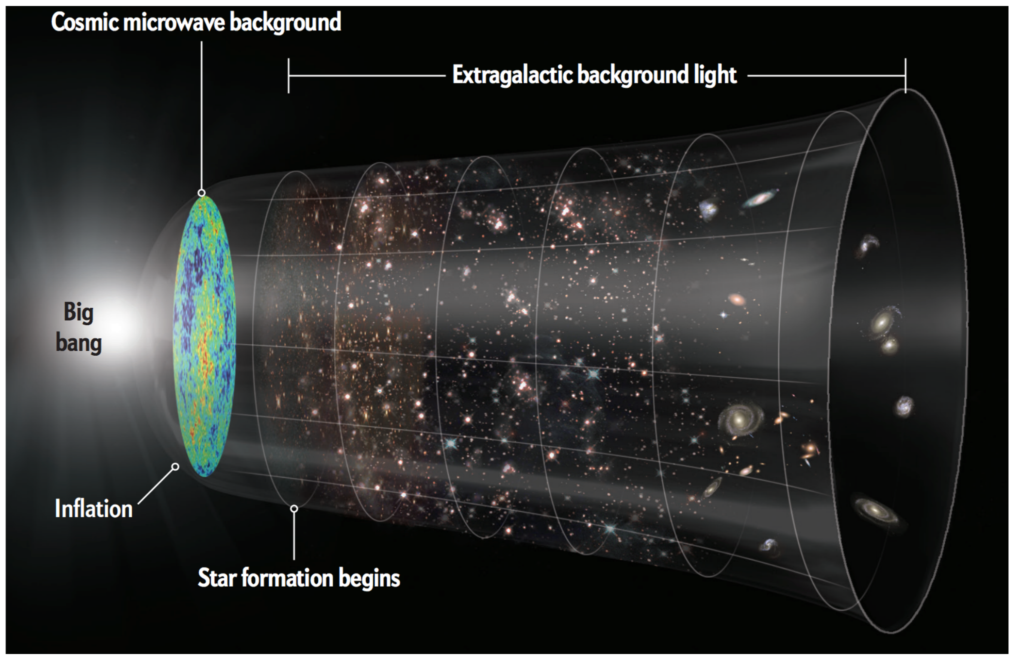
- 2024 launch
- 0.75 - 5 um
- R ~ 40 (0.75 — 3.8 um), R~110 (3.8 — 5 um)



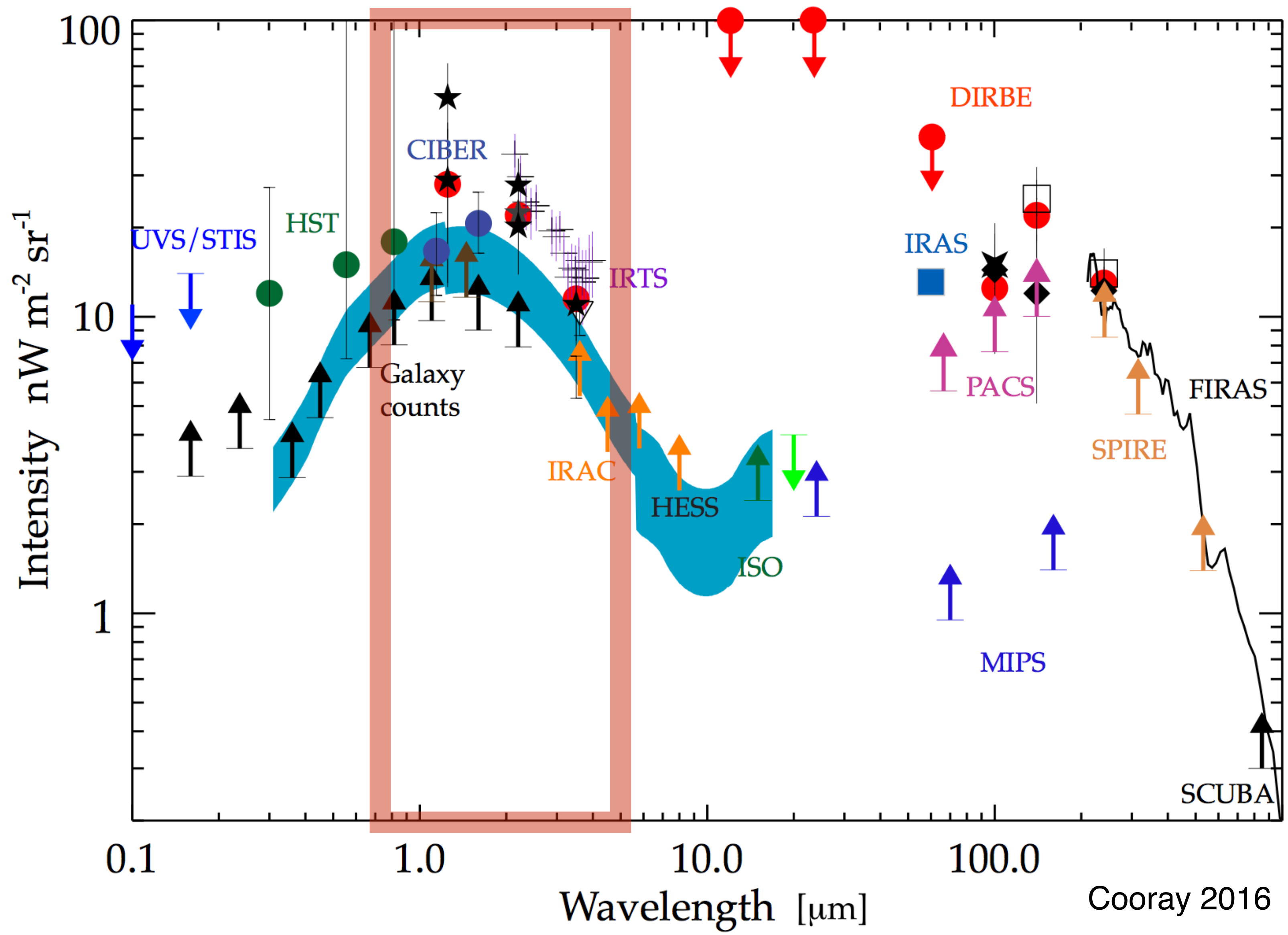


- **Cosmology**
  f_{NL}, inflation
- **Galaxy formation and evolution**
  extragalactic background light (EBL)
- **Water ice and biogenic molecules**
  ice absorption features in stellar spectra

Extragalactic Background Light (EBL)

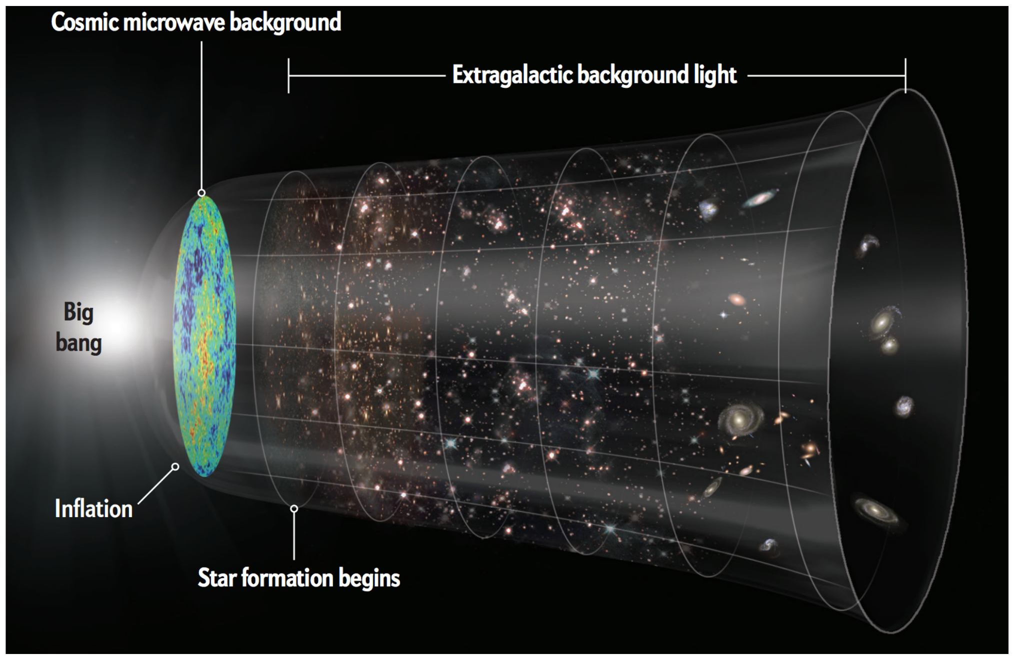


Dominguez, 2015

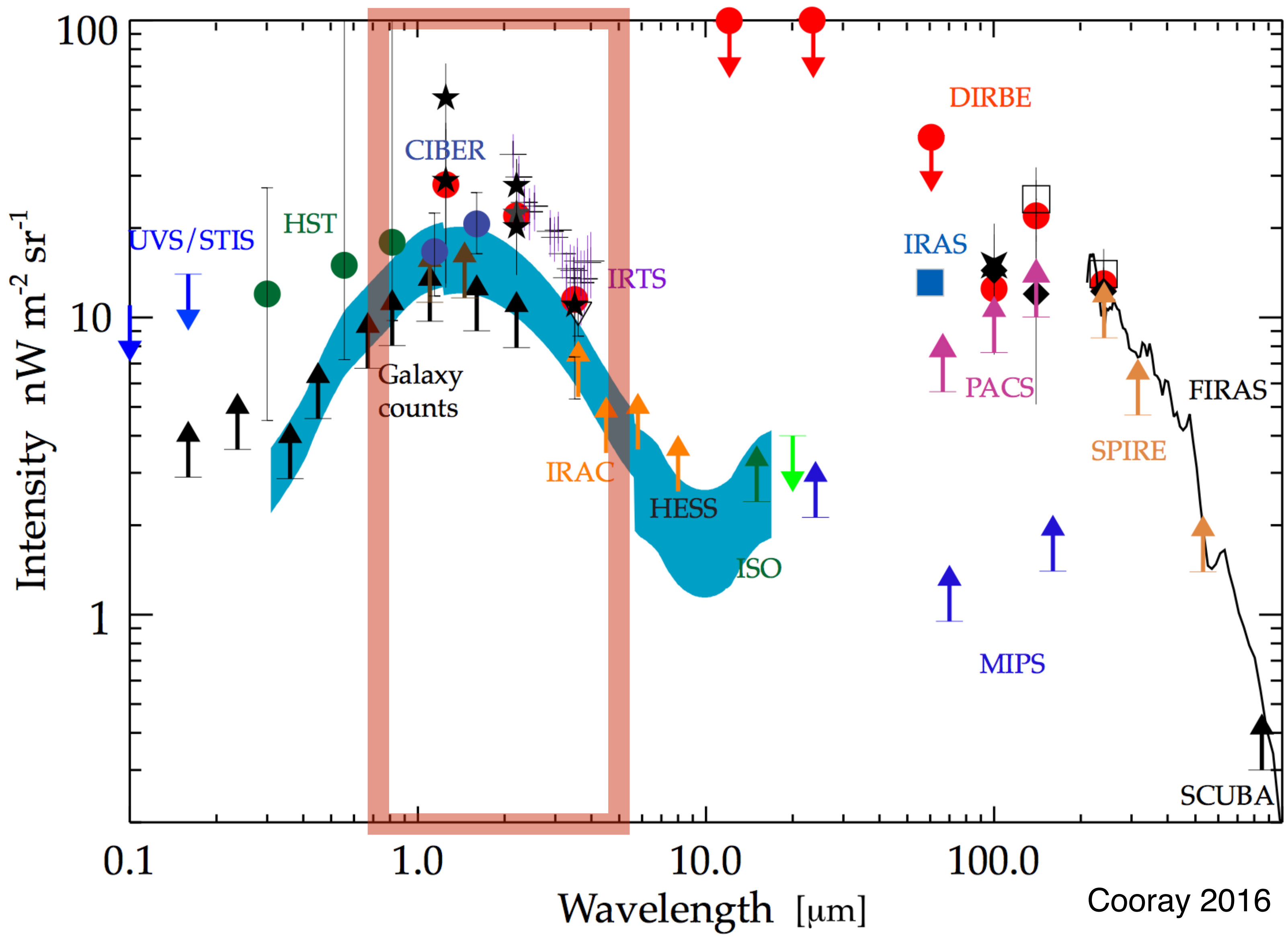


Cooray 2016

Extragalactic Background Light (EBL)



Dominguez, 2015

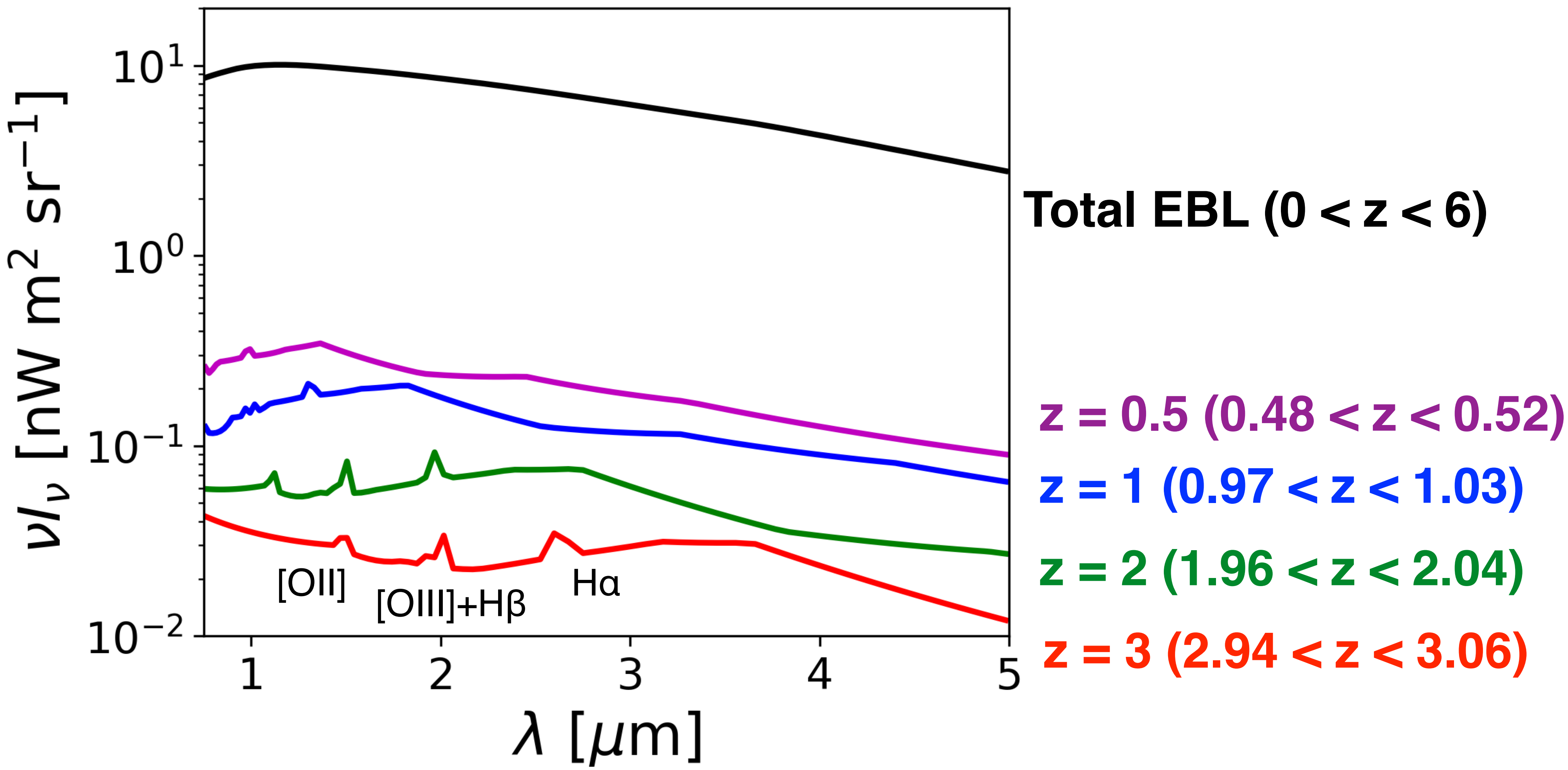


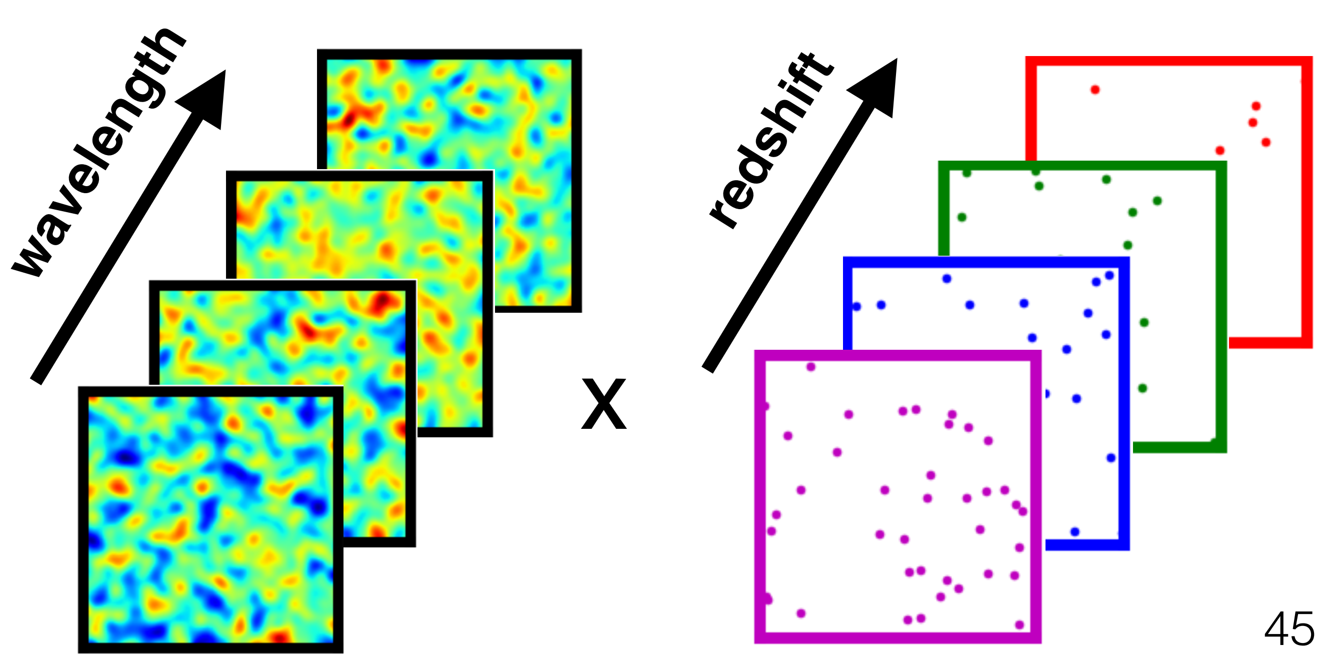
Cooray 2016

Challenges:

- Foregrounds
- **Line-of-sight Projection**

EBL Tomography With Cross-Correlation

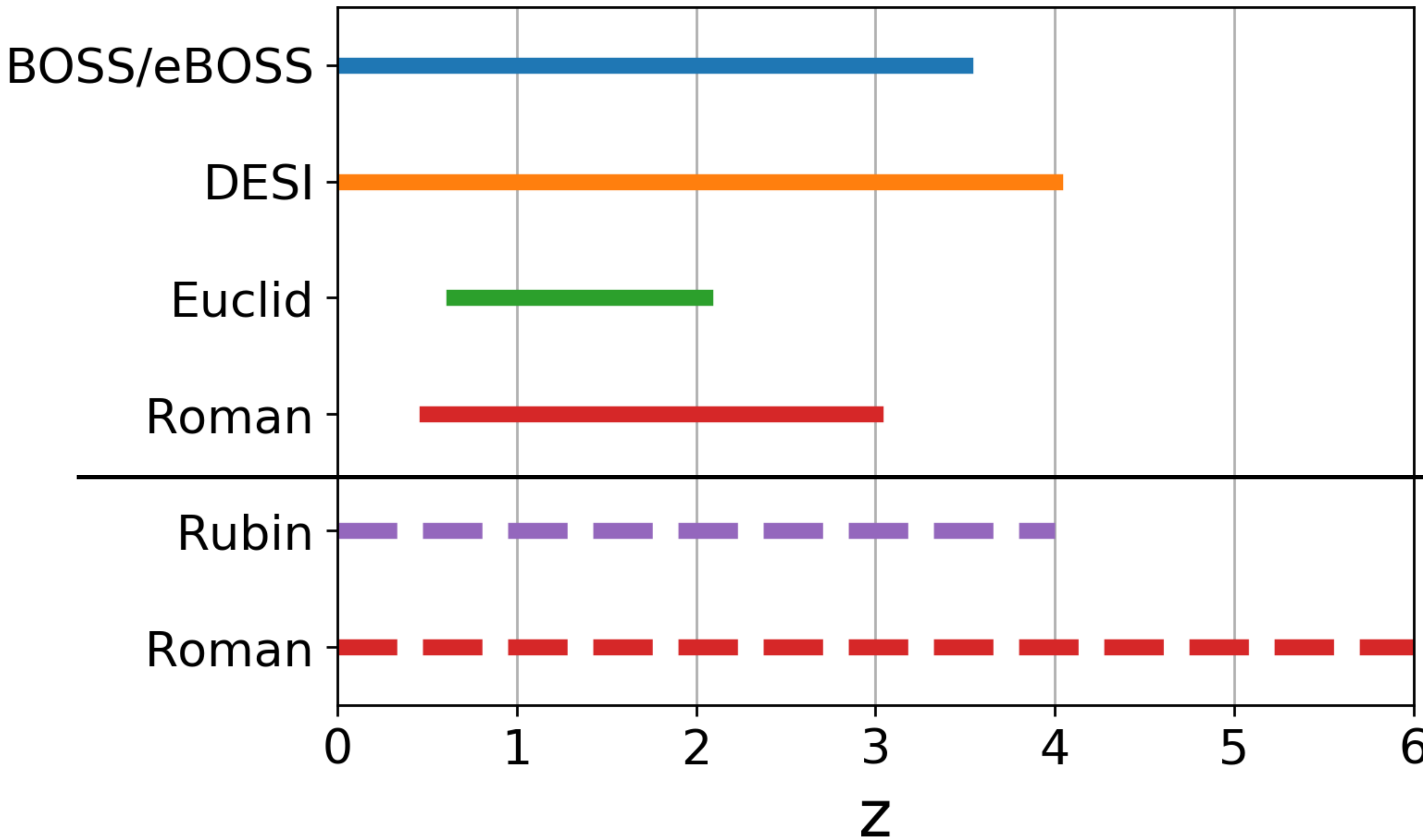




clustering redshift estimation

Newman08, Menard+13, Chiang+19

Galaxy Catalogs



Spectroscopic

$\delta z = \sigma_z/(1+z)$: 10^{-4}-10^{-3}

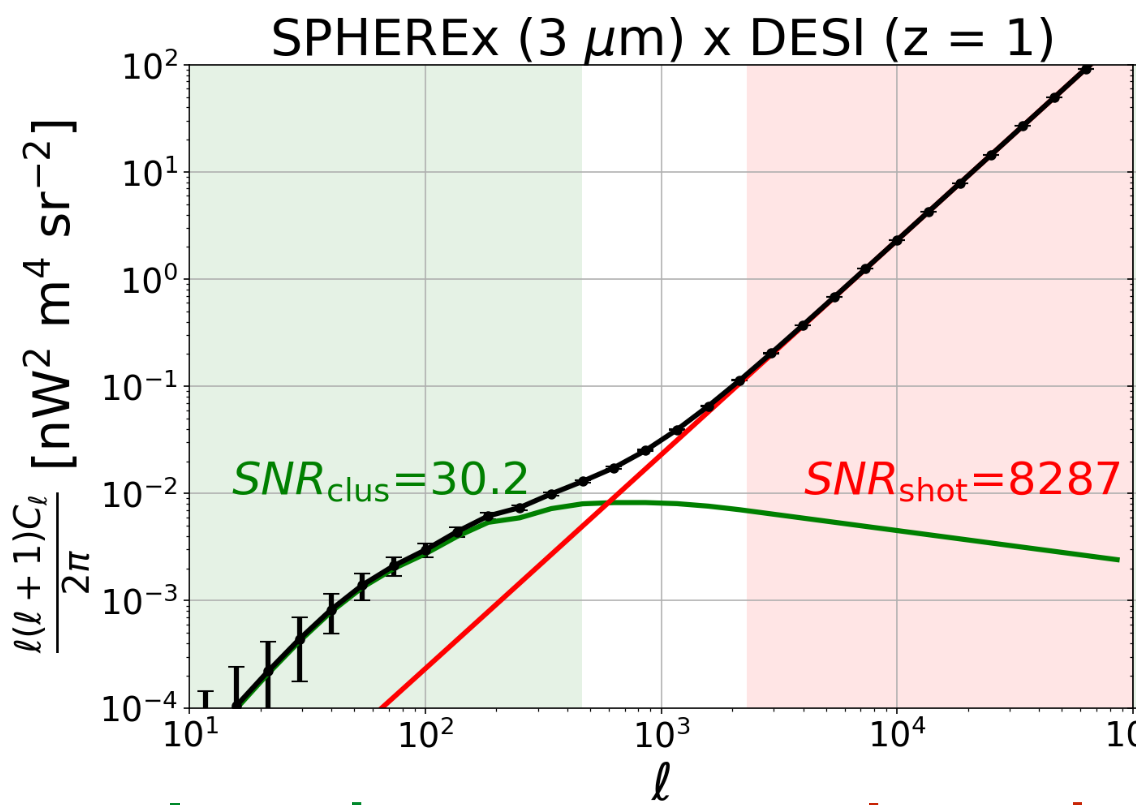
$\Delta z = 0.03$

Photometric

$\delta z = \sigma_z/(1+z)$: 0.02-0.05

$\Delta z = 0.1$

Cross Power Spectrum



clustering
k < 0.2 [h / Mpc]

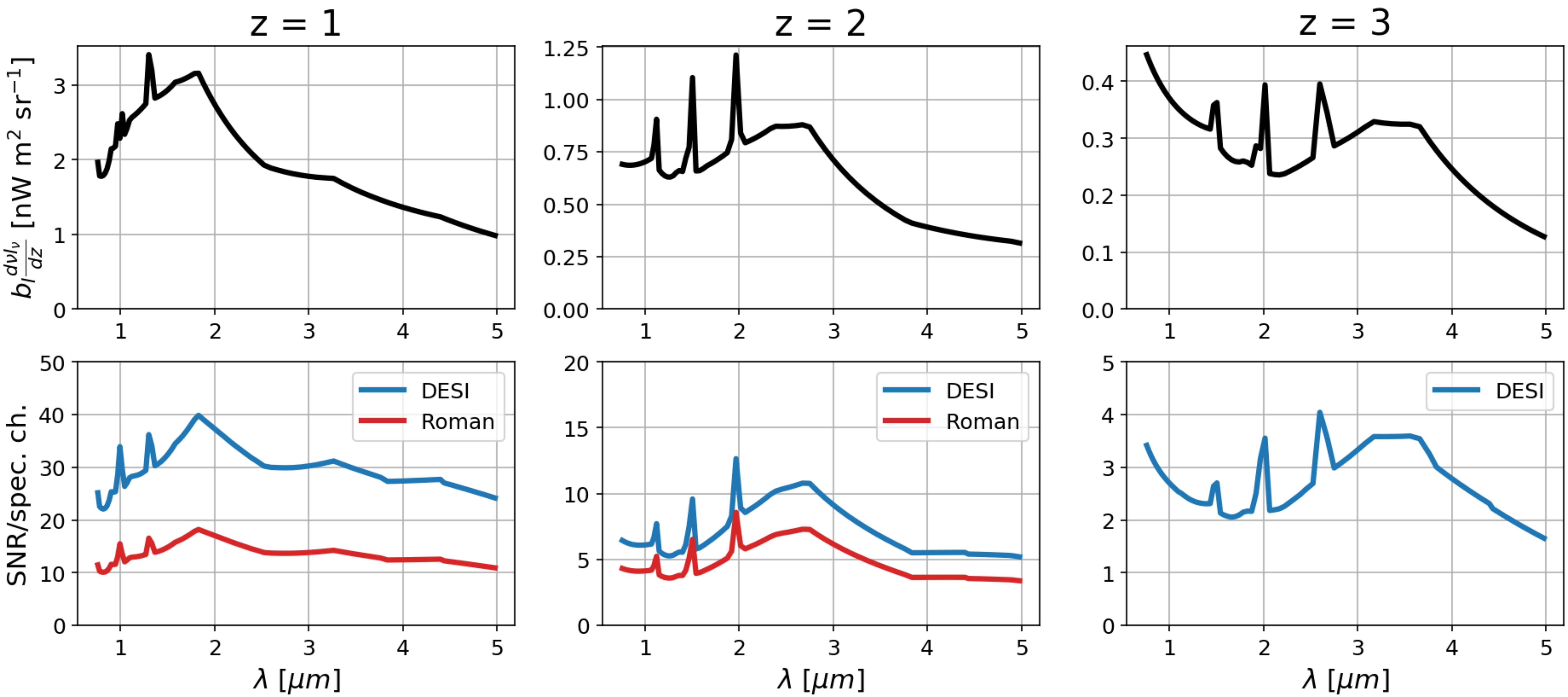
shot noise
k > 1 [h / Mpc]

$$C_{\ell,\mathrm{clus}}(z) \propto b_I(z)\frac{d\nu I_\nu}{dz}(z)P_m(k = \frac{\ell+\frac{1}{2}}{\chi(z)}, z)$$

$$C_{\ell,\mathrm{shot}}(z) \propto \left.\frac{d\nu I_\nu}{dz}(z)\right|_g$$

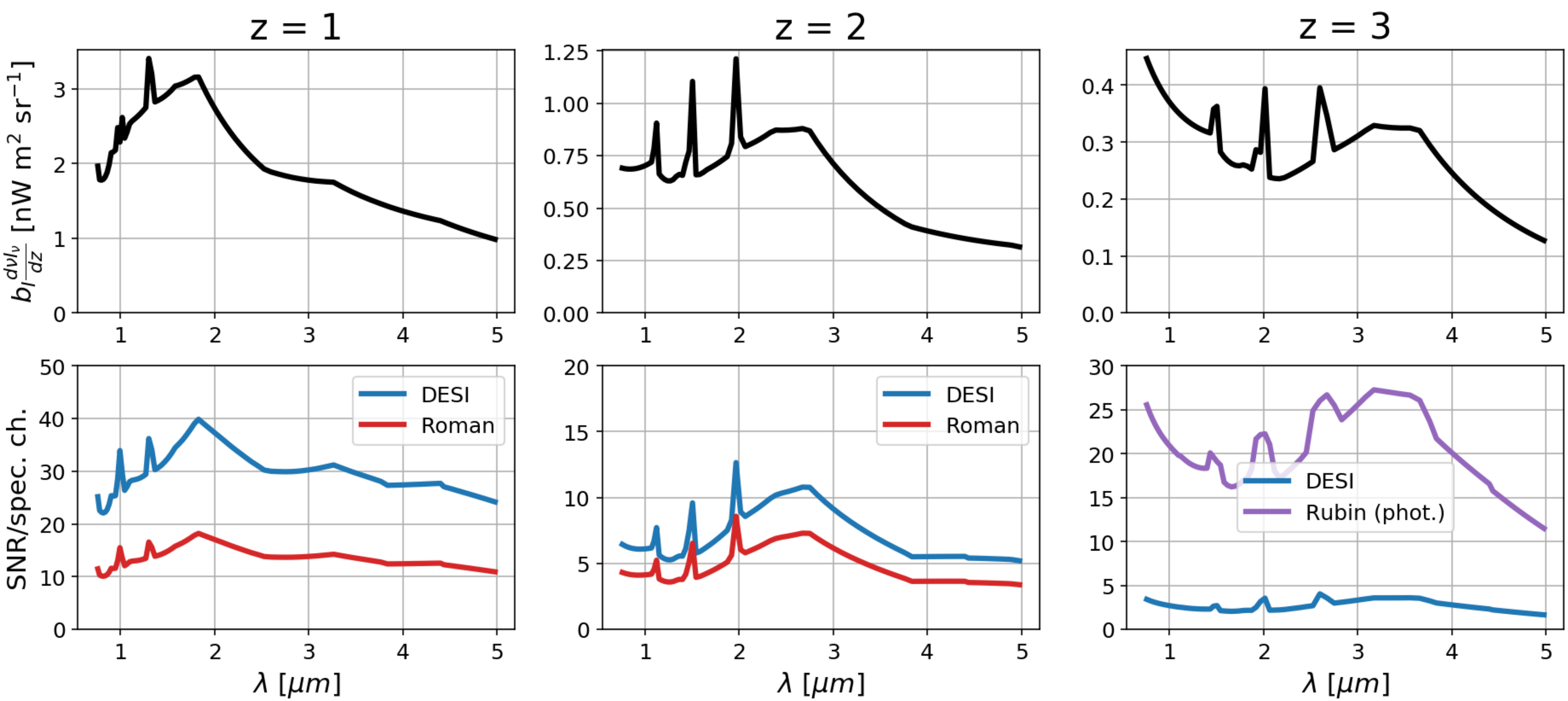
SNR on Clustering Amplitude

SPHEREx x spectroscopic samples



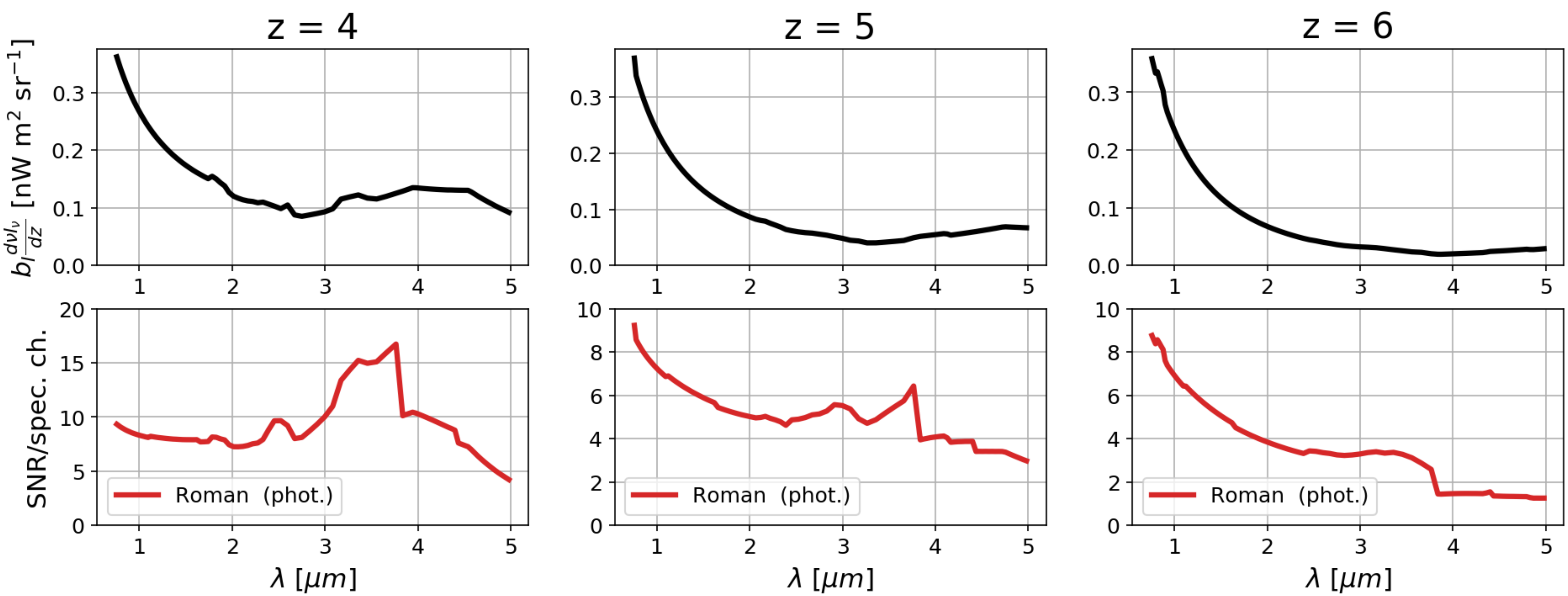
SNR on Clustering Amplitude

SPHEREx x spectroscopic samples



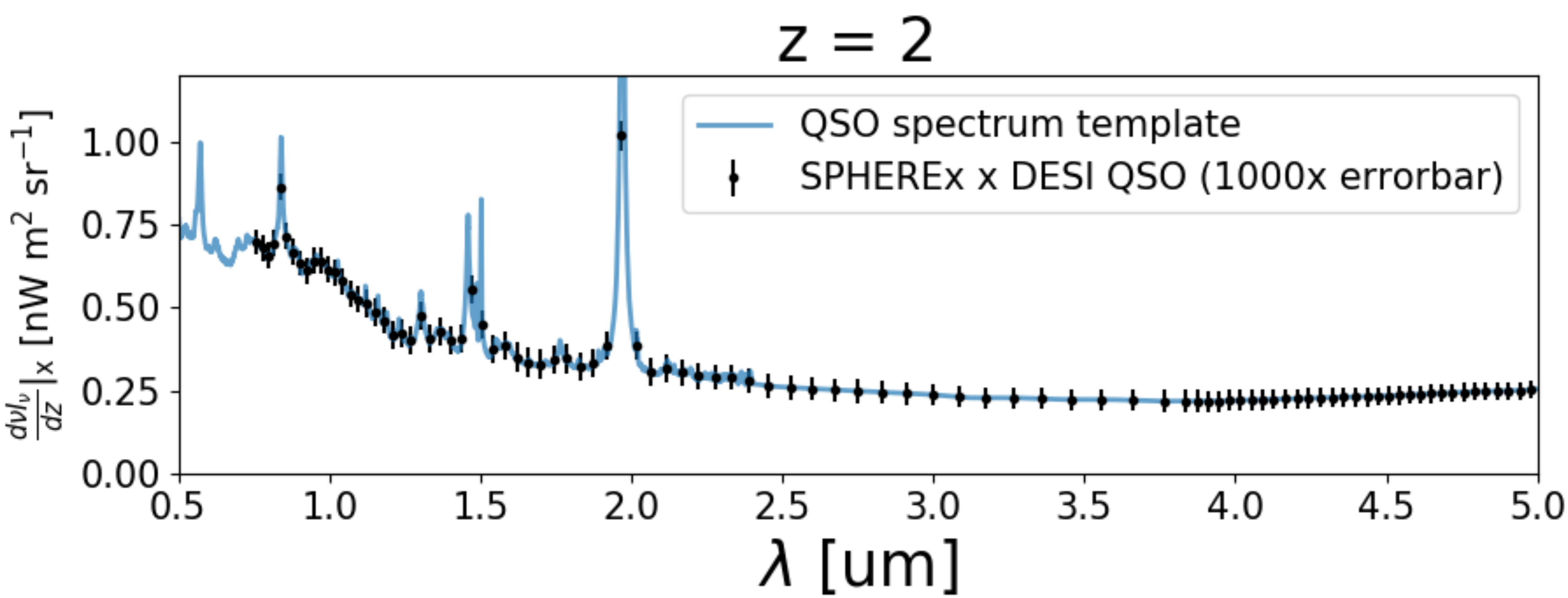
SNR on Clustering Amplitude

SPHEREx x photometric samples



Shot Noise

shot noise — averaged spectrum of stacked sources



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ycheng3@caltech.edu

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