ICRAR

International Centre for Radio Astronomy Research

Everything everywhere

Sabine Bellstedt | Aaron Robotham | Luke Davies

Simon Driver and many co-conspirators

GAMA

DEVILS
DEEP EXTRAGALACTIC VISIBLE LEGACY SURVEY

WAVES
wide area vista extragalactic survey

SKYSURF

Prime Extragalactic Areas for Reionization and Lensing Science
PEARLS

Overview and key UWA references

Integrated Galaxy Light (IGL; methodology and data):

- Driver et al 2011, MNRAS, 413, 971 – Galaxy And Mass Assembly Survey (GAMA)
- Windhorst et al 2011, ApJS, 193,27 – WFC3 panchromatic early-release science dara
- Driver et al 2016, MNRAS, 455, 391 – GAMA Panchromatic data release
- Wright et al 2016, MNRAS, 460, 765 – GAMA Panchromatic photometry
- Driver et al 2016, ApJ, 827, 108 – *Compendium* of integrated galaxy light from far-UV to far-IR
- Andrews et al 2017, MNRAS, 464, 1569 – Reanalysis of all COSMOS data (38 bands)
- Robotham et al 2018, MNRAS, 476, 3137 – ProFound: Source extraction and application to modern survey data
- Koushan et al 2021, MNRAS, 503, 2033 – IGL update and calibration of the Cosmic Star-Formation History
- Bellstedt et al 2020, MNRAS, 498, 5581- GAMA: bright-magnitude galaxy counts from VST and VISTA
- Davies et al 2021, MNRAS, 506, 256 – DEVILS: deep panchromatic galaxy counts in COSMOS, XMMLSS and ECDFS
- Tompkins et al 2025, in prep – SKYSURF: Revised IGL across HST ACS and WFC3 filters
- Bellstedt et al 2025, in prep – WAVES: revised bright-magnitude galaxy counts

Modelling the EBL (everything everywhere all at once):

- Driver et al 2013, MNRAS, 430, 2622 – Two-component phenomenological model
- Andrews et al 2018, MNRAS, 474, 898 – Improved modelling of the EBL and CSED
- Robotham et al 2020, MNRAS, 495, 905 – ProSpect: SED modelling
- Robotham et al 2024, MNRAS, submitted – ProGeny: SSP generator

The CSFH and CAGNH (critical model ingredients):

- Driver et al 2018, MNRAS, 475, 2891 – CSFH to z=5 from MAGPHYS SED fitting
- Bellstedt et al 2020, MNRAS, 498, 5581 – CSFH to z=5 from forensic reconstruction with ProSpect
- D'Silva et al 2023, MNRAS, 524, 1448 – The CSFH and CAGNH from ProSpect SED fitting: 0 – 5Gyrs ago
- D'Silva et al 2025, in prep – The CSFH and CAGNH from ProSpect SED fitting of JWST NIRcam data: 5-12Gyrs ago

The Cosmic Spectral Energy Distribution (CSED):

- Driver et al 2008, ApJ, 678, 101 – Energy production at z<0.1
- Hill et al 2010, MNRAS, 404, 1215 – Luminosity densities at z<0.1
- Driver et al 2012, MNRAS, 427, 3244 – First Cosmic spectral energy distribution
- Andrews et al 2017, MNRAS, 470, 1342 – Evolution of the cosmic spectral energy distribution since z=1

Radio Source Counts (towards the SKA):

- Tompkins et al 2023, MNRAS, 521, 332 – The cosmic radio background and its division into star-formers and AGN

Next steps, and future prospects:

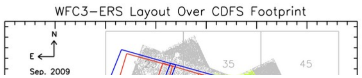
- Towards 1% EBL errors from UV to radio: JWST MIRI, ASKAP, SphereX, LSST, Euclid, Roman and the SKA (Data Fusion)
- Building the CSED from UV to radio out to z=10
- Separating the energy produced from star-formation and energy produced from SMBH accretion
- Improved EBL/CSED modelling with ProSpect and ProGeny: a full CSFH reconstruction, Z(z), IMF(z) ?

Part I: Integrated Galaxy Light (IGL) data and methodology

Why the IGL

THE HUBBLE SPACE TELESCOPE WIDE FIELD CAMERA 3 EARLY RELEASE SCIENCE DATA: PANCHROMATIC FAINT OBJECT COUNTS FOR 0.2–2 MICRONS WAVELENGTH *

ROGIER A. WINDHORST [1], SETH H. COHEN [1], NI
JR. [4], HAOJING YAN [5], IVAN K. BALDRY [6], SIM
KELVIN [7], ANTON M. KOEKEMOER [9], MAT
ROBOTHAM [7], MICHAEL J. RUTKOWSKI [1], MAR
BRUCE BALICK [13], HOWARD E. BOND [9], HOWAR
MICHAEL J. DISNEY [16], MICHAEL A. DOPITA
KAVIRAJ [15], RANDY A. KIMBLE [11], JOHN W. MA
SAHA [21], JOSEPH I. SILK [14], JOHN T. TRAUGER [2

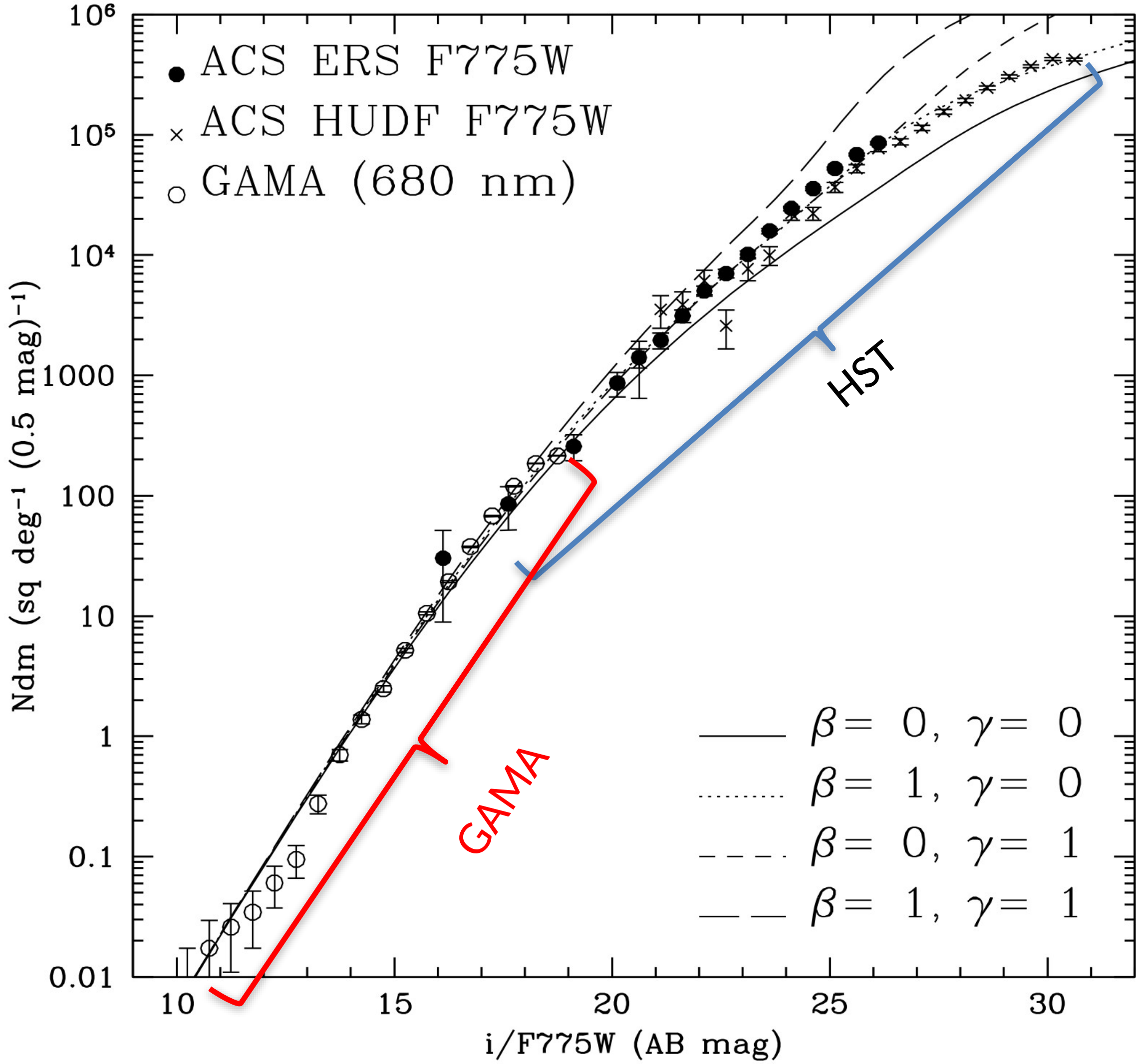


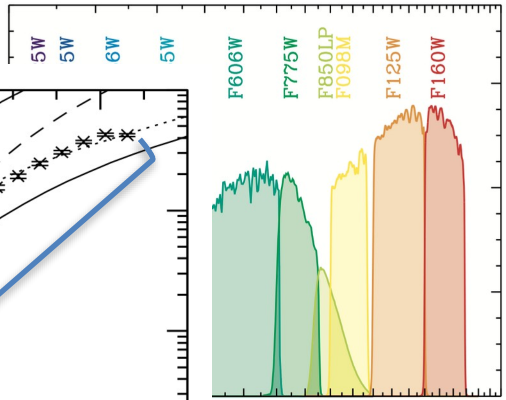
Galaxy and Mass Asseml
and core data release

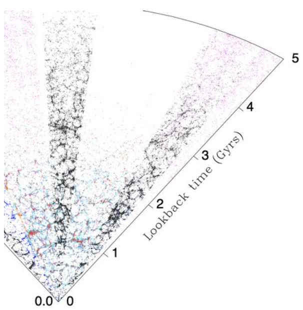
S.P.Driver[1⋆], D.T.Hill[1], L.S.Kelvin[1], A
S.P.Bamford[5], A.M.Hopkins[6], J.Loved
S.Brough[6], M.J.I.Brown[10], E.Cameron
S.M.Croom[9], N.J.G.Cross[3], R.De Prop
Alister W.Graham[15], M.W.Grootes[15],
C.Maraston[12], R.C.Nichol[16], H.R.Park
M.Prescott[4], I.G.Roseboom[7], E.M.Sad
E.Taylor[8,20], D.Thomas[16], R.J.Tuffs[8],
B.F.Madore[24], M.J.Meyer[25], M.Seiber

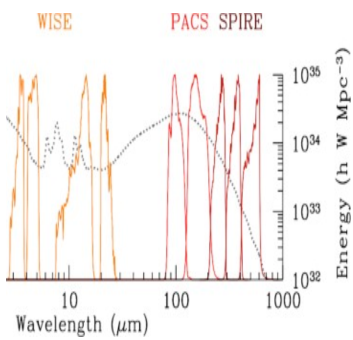
Galaxy And Mass Assembl
Release (far-UV—far-IR) a

Simon P. Driver,[1,2⋆†], Angus H. Wrig
Prajwal R. Kafle[1], Rebecca Lange[1], A
Aaron S. G. Robotham[1], Kevin Vinse
Ivan K. Baldry[5], Amanda E. Bauer[6],
Nathan Bourne[9], Sarah Brough[6], Mic
Scott Croom[8], Matthew Colless[12], Ch
Roberto De Propris[14], Michael Drinkv
Alastair Edge[17], Carlos Frenk[18], Alist
Benne W. Holwerda[19], Andrew M. Ho
Lee S. Kelvin[5], Tom Jarrett[22], D. Hea
Jochen Liske[25], Angel R. Lopez-Sanch
Barry Madore[27], Smriti Mahajan[28], M
Samantha J. Penny[29], Steven Phillipp
John A. Peacock[9], Kevin A. Pimbblet
Anne E. Sansom[31], Mark Seibert[27], Matthew W.L. Smith[15], Will J. Sutherland[33],
Edward N. Taylor[34], Elisabetta Valiante[16] J. Antonio Vazquez-Mata[26], Lingyu Wang[18,35]
Stephen M. Wilkins[26], Richard Williams[5]









IGL compendium

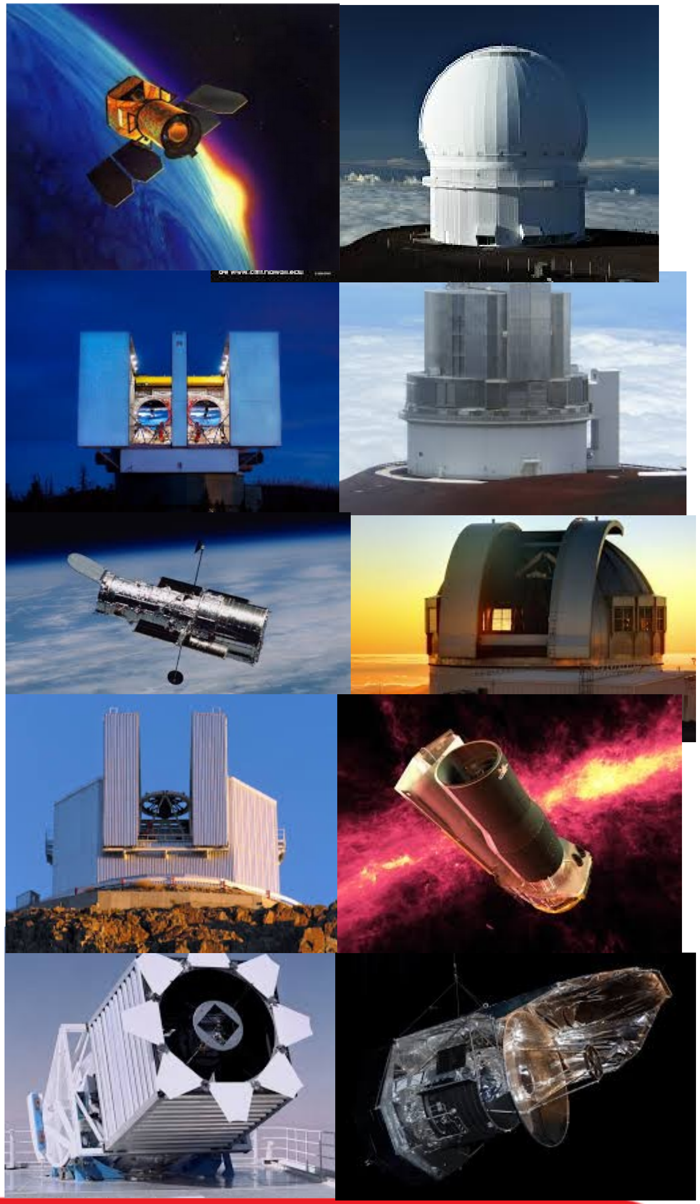
EXTRA-GALACTIC BACKGROUND LIGHT MEASUREMENTS FROM THE FAR-UV TO THE FAR-IR FROM DEEP GROUND AND SPACE-BASED GALAXY COUNTS

Simon P. Driver[12], Stephen K. Andrews, Luke J. Davies, Aaron S.G. Robotham, Angus H. Wright
International Centre for Radio Astronomy Research (ICRAR), The University of Western Australia, M468, 35 Stirling Highway, Crawley, Australia, WA 6009

Rogier A. Windhorst, Seth Cohen, Kim Emig, Rolf A. Jansen
School of Earth & Space Exploration, Arizona State University, Tempe, AZ85287-1404, USA

and

Loretta Dunne
School of Physics and Astronomy, Cardiff University, Queen's Buildings, Cardiff, CF24 3AA, UK and Institute for Astronomy, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UK
Accepted for Astrophysical Journal



Compendium of count data from multiple authors:

GAMA FUV-FIR - Wright et al (2016)
COSMOS FUV-FIR - Andrews et al (2017)
HST UV-NIR - Windhorst et al (2011)
HST UV-NIR - Rafelski et al (2015)
HST FUV SBC - Voyer et al (2011)
HST NUV STIS - Gardner et al (2000)
u LBT - Grazian et al (2009)
K NTT - Fontana et al (2014)
Spitzer - Ashby et al (2015)
Spitzer - Barmby et al (2008)
Spitzer - Papovich et al (2004)
Spitzer/PACS - Bethermin et al (2010)
PACS - Berta et al (2011)
PACS - Magnelli et al (2013)
SPIRE - Valiante et al (2016)

A massive multi-facility effort

Driver et al (2016)

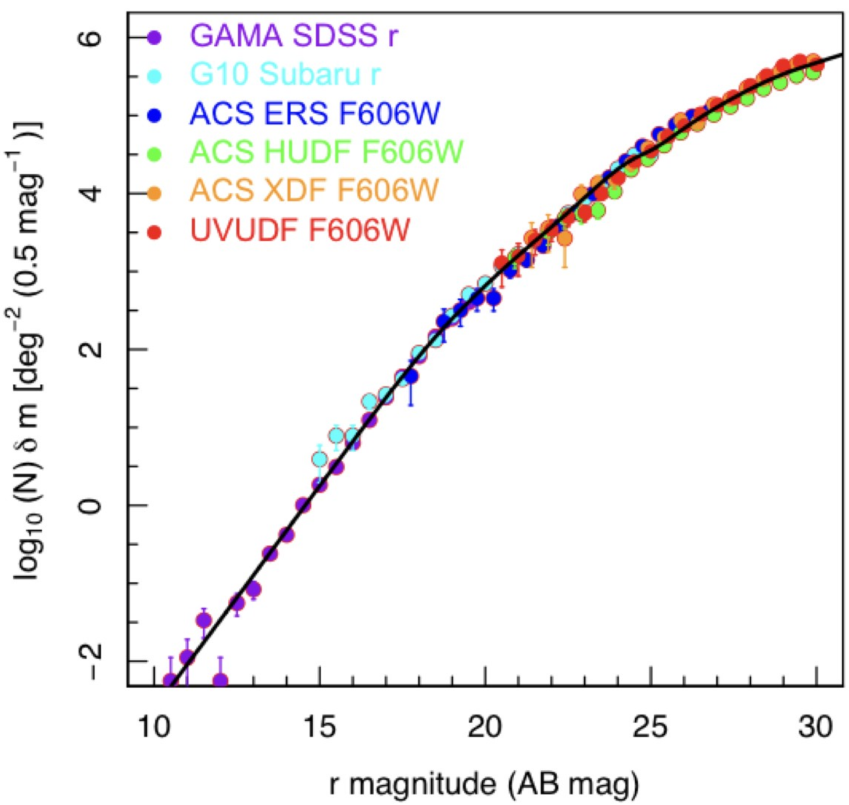
IGL methodology

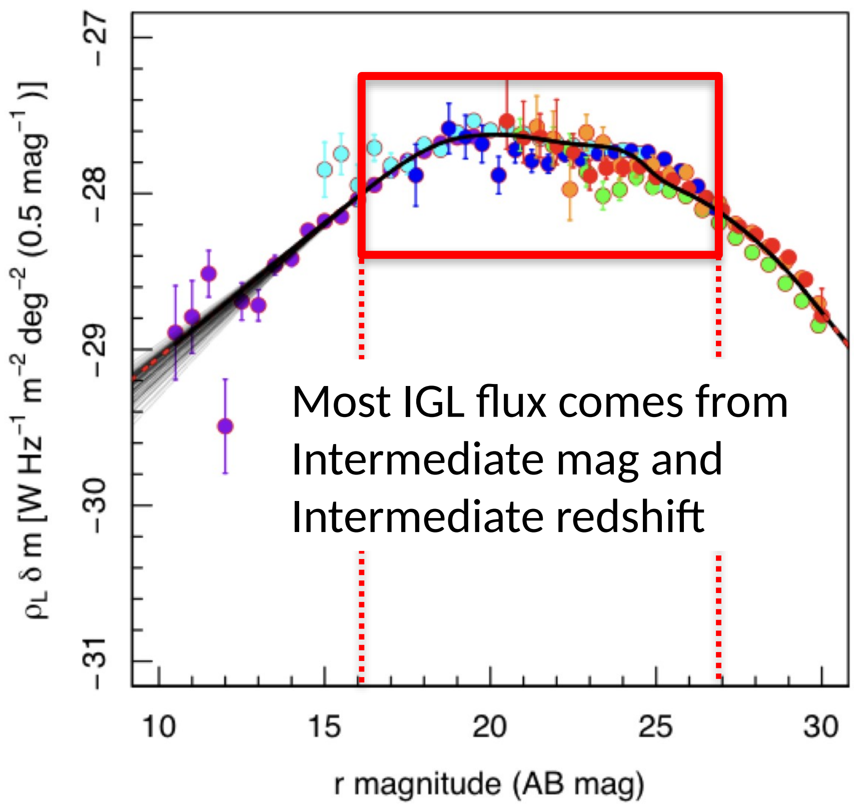
EBL Value:

- Construct counts: dlogN/dm
- Filter correct counts
- Subtract a slope of 0.4
- Spline fit the data ($1/\sigma^2$)
- Integrate spline to limits

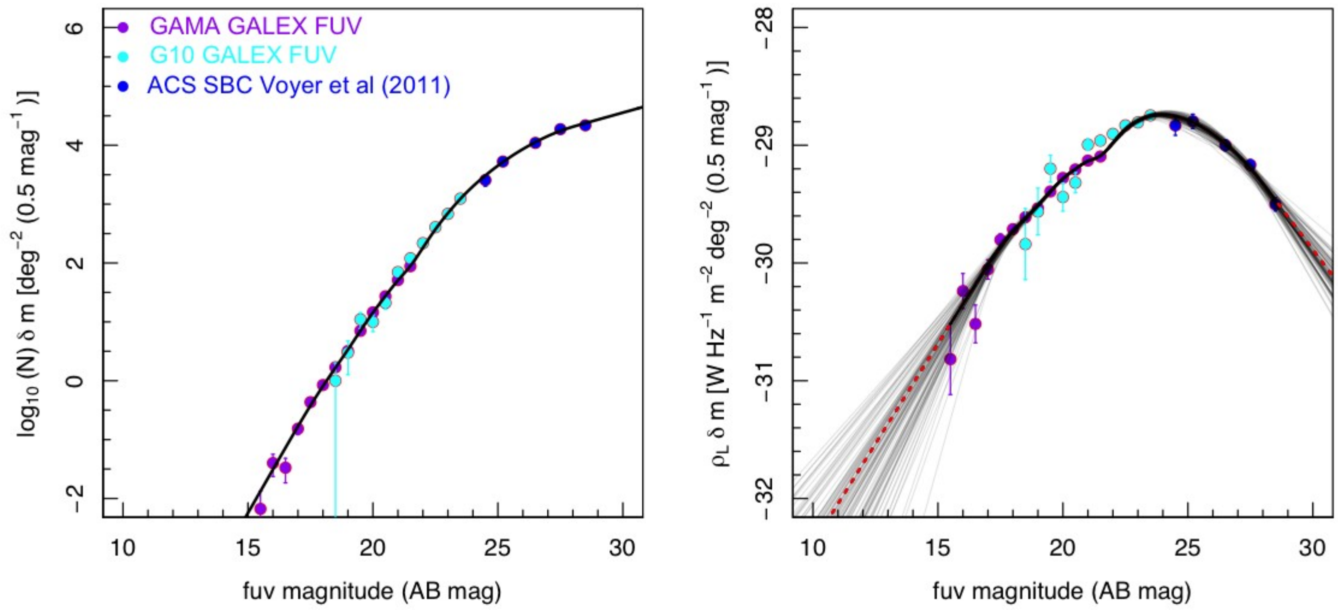
EBL errors:

- Perturb data points and refit
- Perturb datasets by CV and refit
- Perturb datasets by ZP errors
- Refit with varying spline orders
- Fit to range only
- MC all errors together



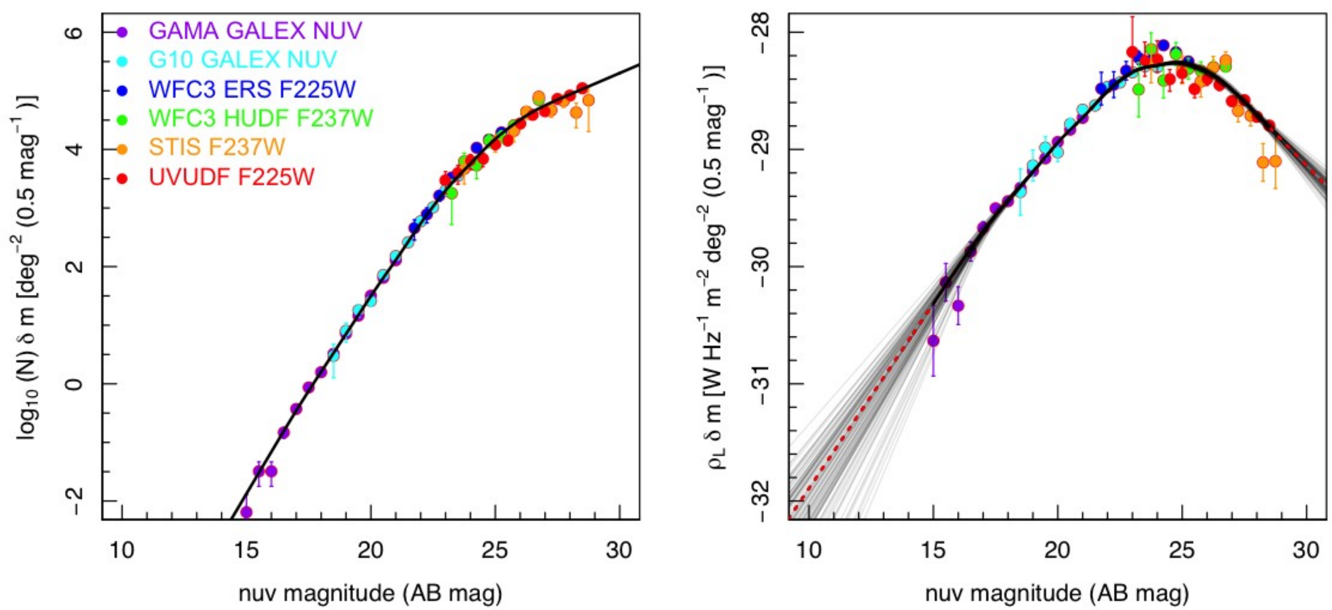


FUV



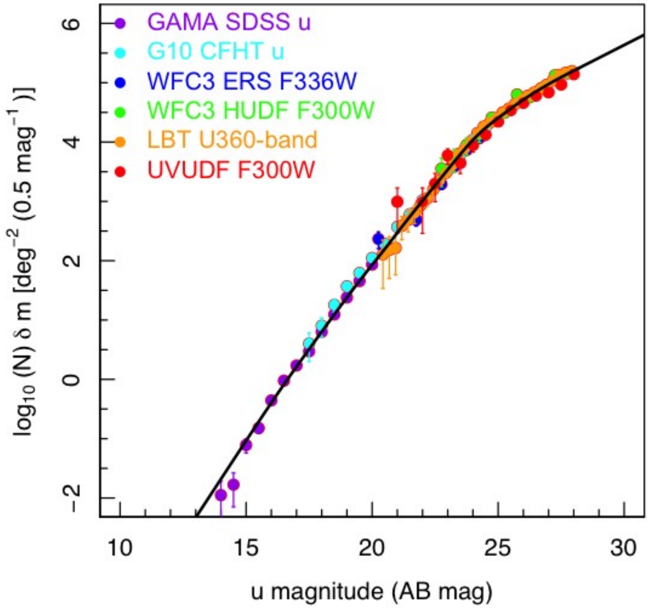
GAMA GALEX FUV
G10 GALEX FUV
ACS SBC Voyer et al (2011)
log10 (N) δ m [deg^-2 (0.5 mag^-1)]
fuv magnitude (AB mag)
ρL δ m [W Hz^-1 m^-2 deg^-2 (0.5 mag^-1)]
fuv magnitude (AB mag)

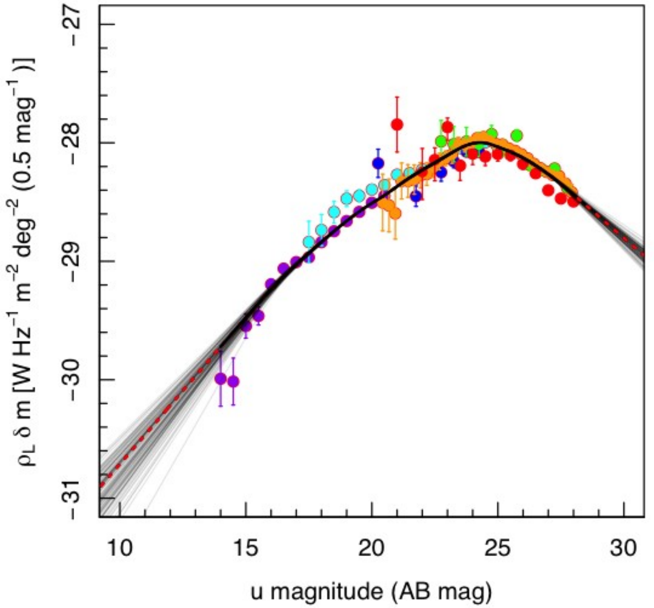
NUV



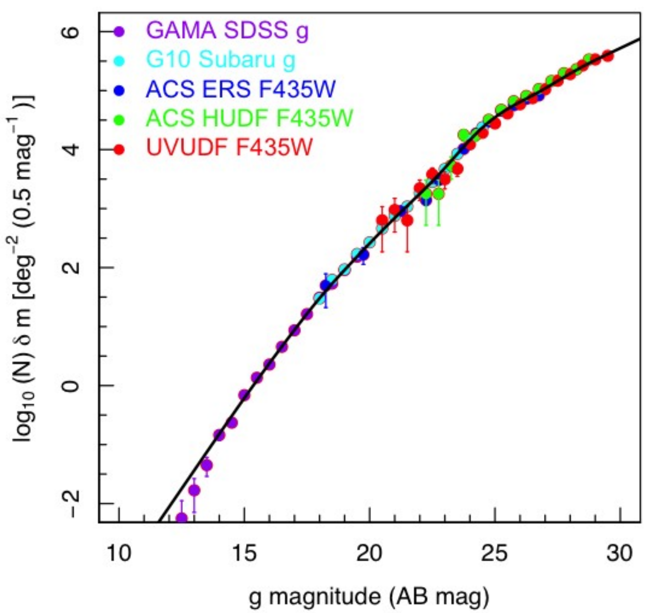
GAMA GALEX NUV
G10 GALEX NUV
WFC3 ERS F225W
WFC3 HUDF F237W
STIS F237W
UVUDF F225W
log10 (N) δ m [deg^-2 (0.5 mag^-1)]
nuv magnitude (AB mag)
ρL δ m [W Hz^-1 m^-2 deg^-2 (0.5 mag^-1)]
nuv magnitude (AB mag)

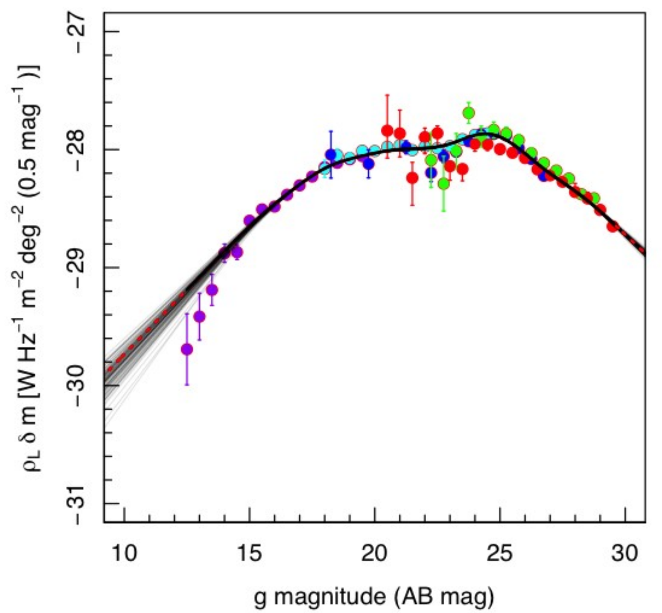
u


GAMA SDSS u
G10 CFHT u
WFC3 ERS F336W
WFC3 HUDF F300W
LBT U360-band
UVUDF F300W
$\log_{10}$(N) δ m [deg^{-2} (0.5 mag^{-1})]
u magnitude (AB mag)

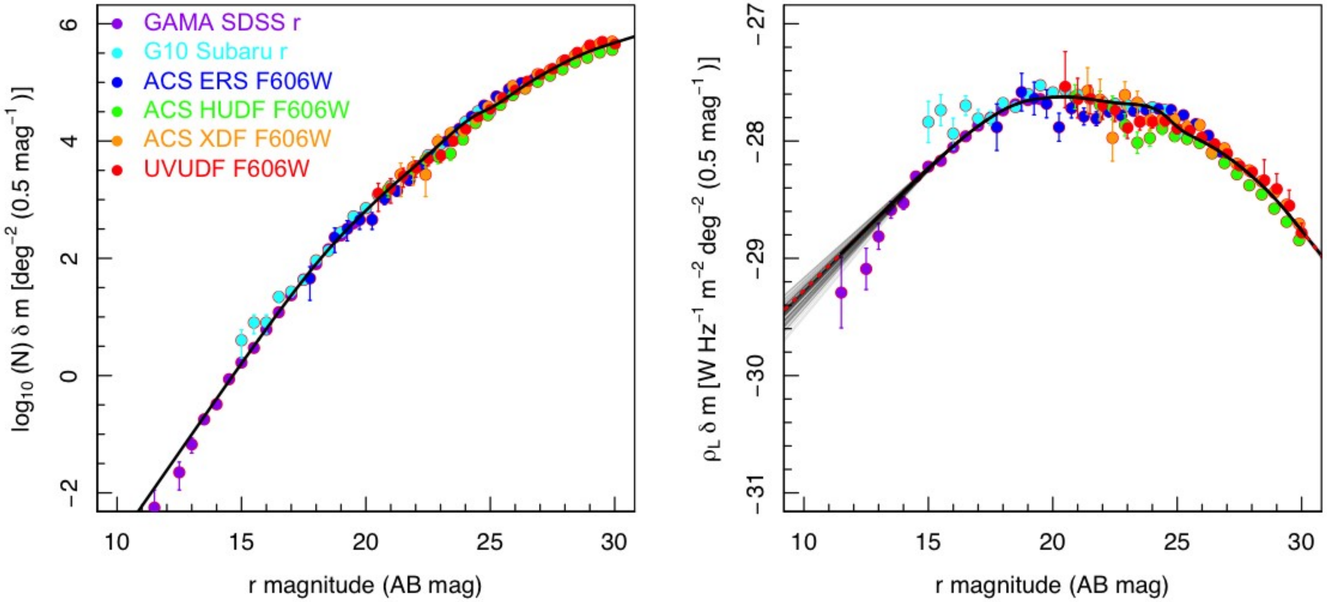

ρ_L δ m [W Hz^{-1} m^{-2} deg^{-2} (0.5 mag^{-1})]
u magnitude (AB mag)

g

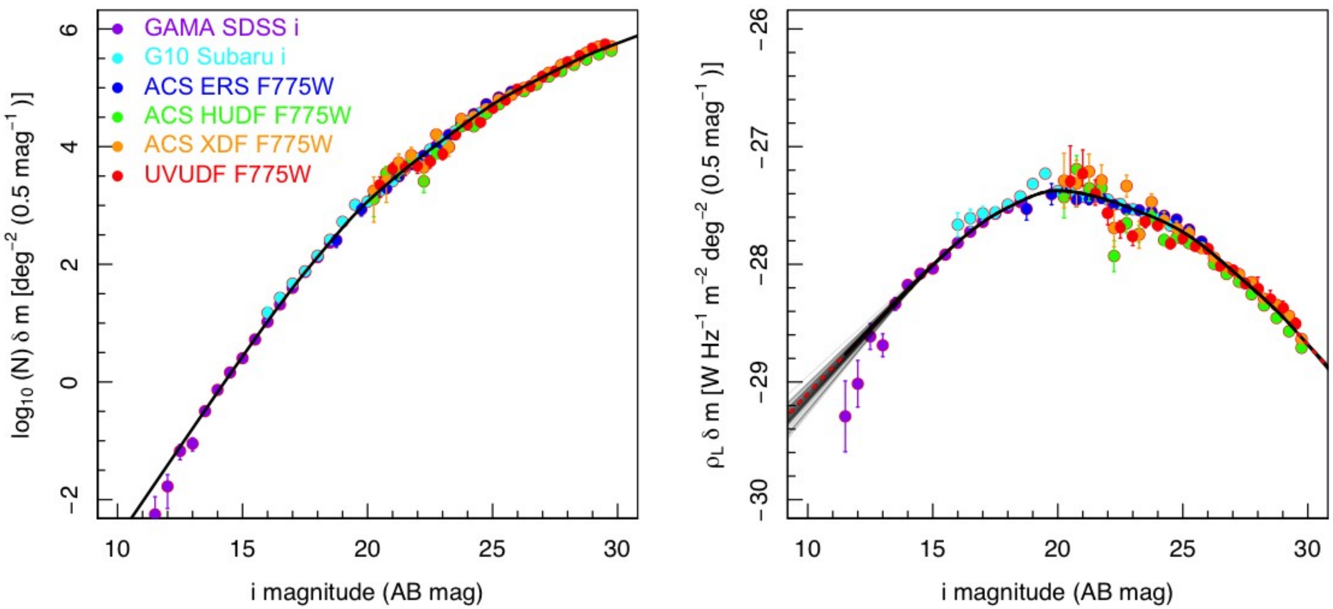

GAMA SDSS g
G10 Subaru g
ACS ERS F435W
ACS HUDF F435W
UVUDF F435W
$\log_{10}$(N) δ m [deg^{-2} (0.5 mag^{-1})]
g magnitude (AB mag)


ρ_L δ m [W Hz^{-1} m^{-2} deg^{-2} (0.5 mag^{-1})]
g magnitude (AB mag)

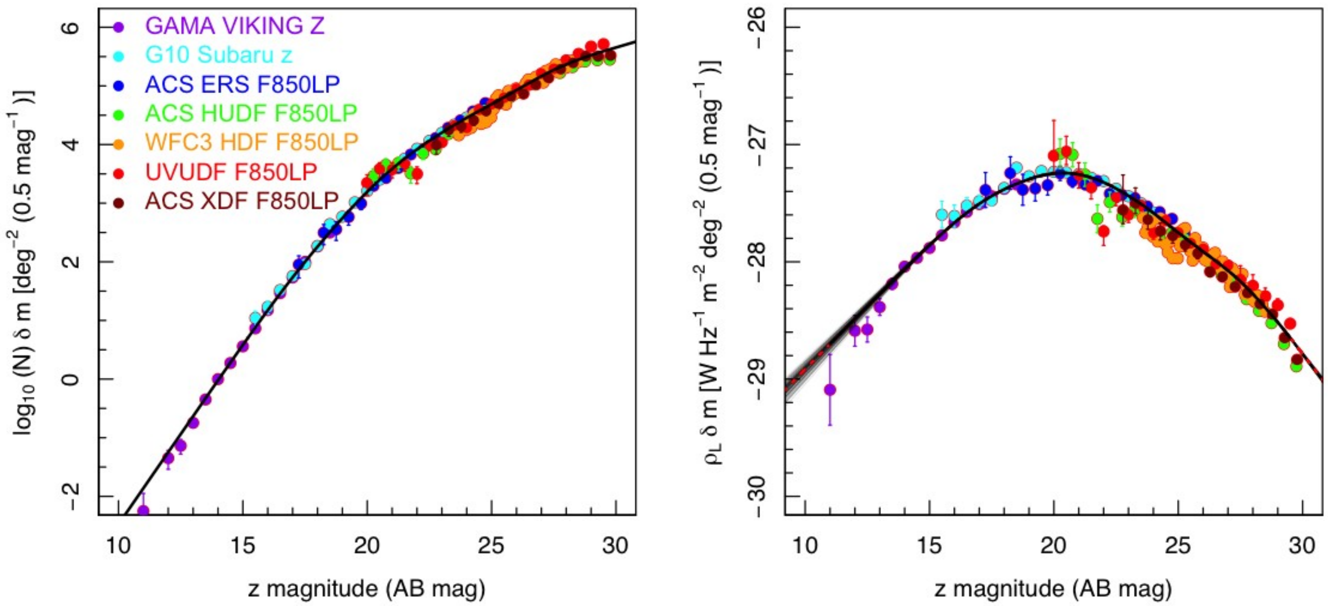
r


GAMA SDSS r
G10 Subaru r
ACS ERS F606W
ACS HUDF F606W
ACS XDF F606W
UVUDF F606W
log10 (N) δ m [deg^-2 (0.5 mag^-1)]
r magnitude (AB mag)
ρL δ m [W Hz^-1 m^-2 deg^-2 (0.5 mag^-1)]
r magnitude (AB mag)

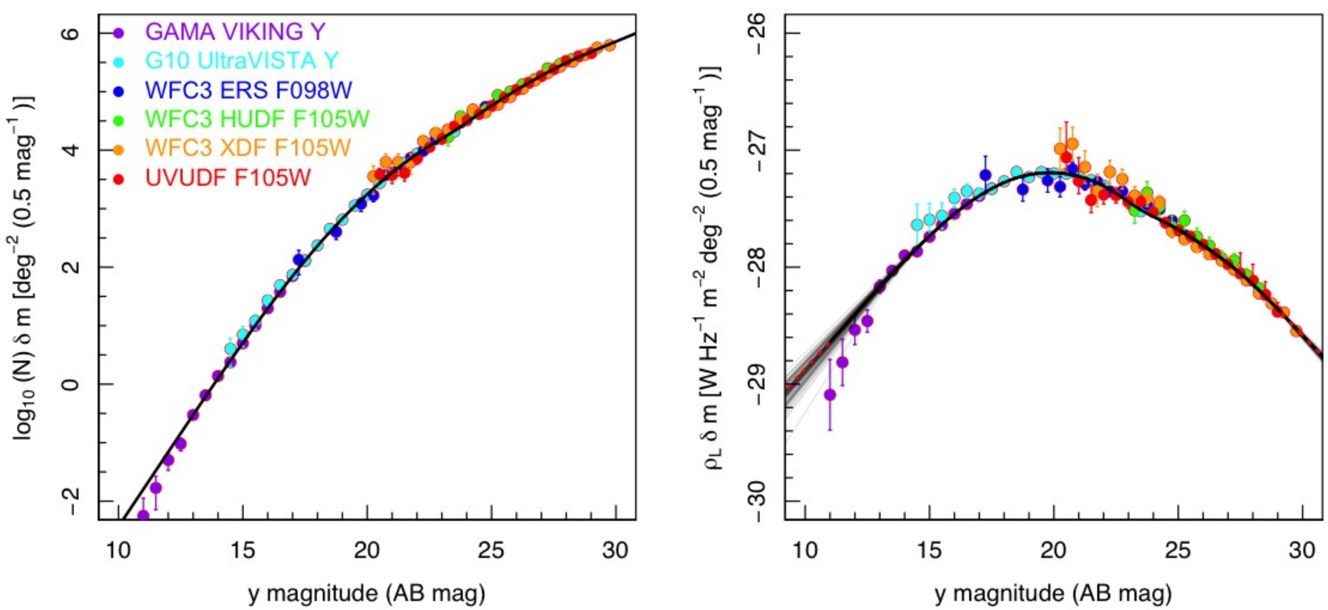
i


GAMA SDSS i
G10 Subaru i
ACS ERS F775W
ACS HUDF F775W
ACS XDF F775W
UVUDF F775W
log10 (N) δ m [deg^-2 (0.5 mag^-1)]
i magnitude (AB mag)
ρL δ m [W Hz^-1 m^-2 deg^-2 (0.5 mag^-1)]
i magnitude (AB mag)

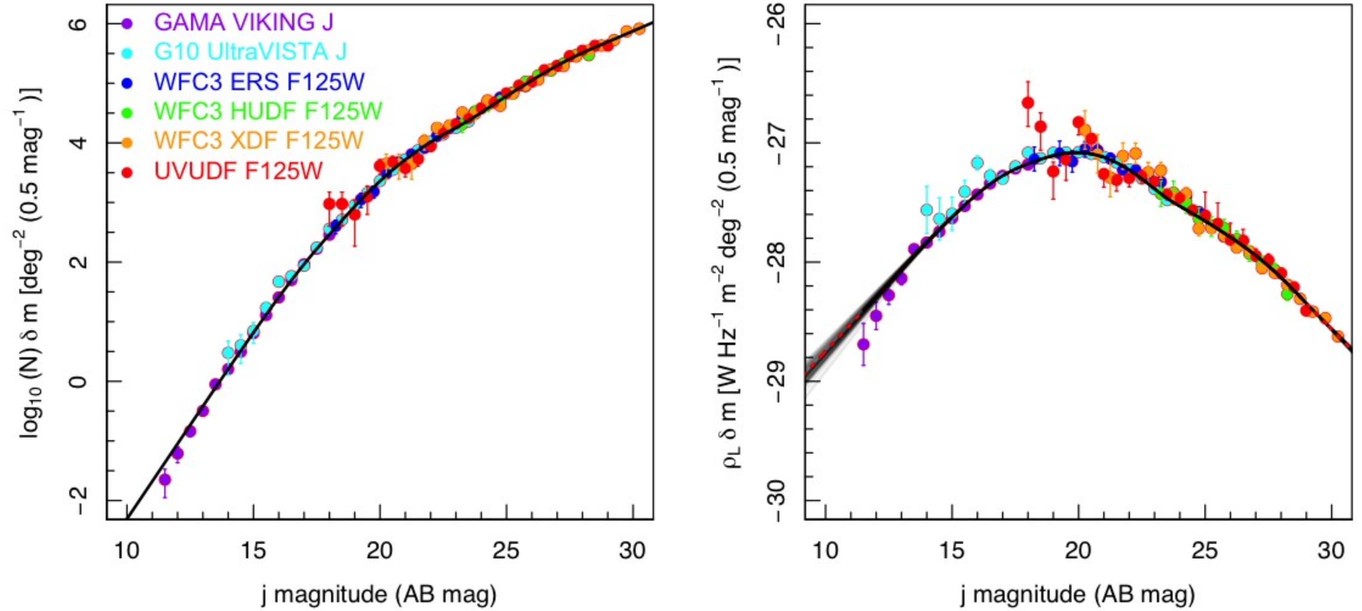
Z


GAMA VIKING Z
G10 Subaru z
ACS ERS F850LP
ACS HUDF F850LP
WFC3 HDF F850LP
UVUDF F850LP
ACS XDF F850LP
$\log_{10}(N)\ \delta m$ [deg^{-2} (0.5 mag^{-1})]
z magnitude (AB mag)
$\rho_L\ \delta m$ [W Hz^{-1} m^{-2} deg^{-2} (0.5 mag^{-1})]
z magnitude (AB mag)

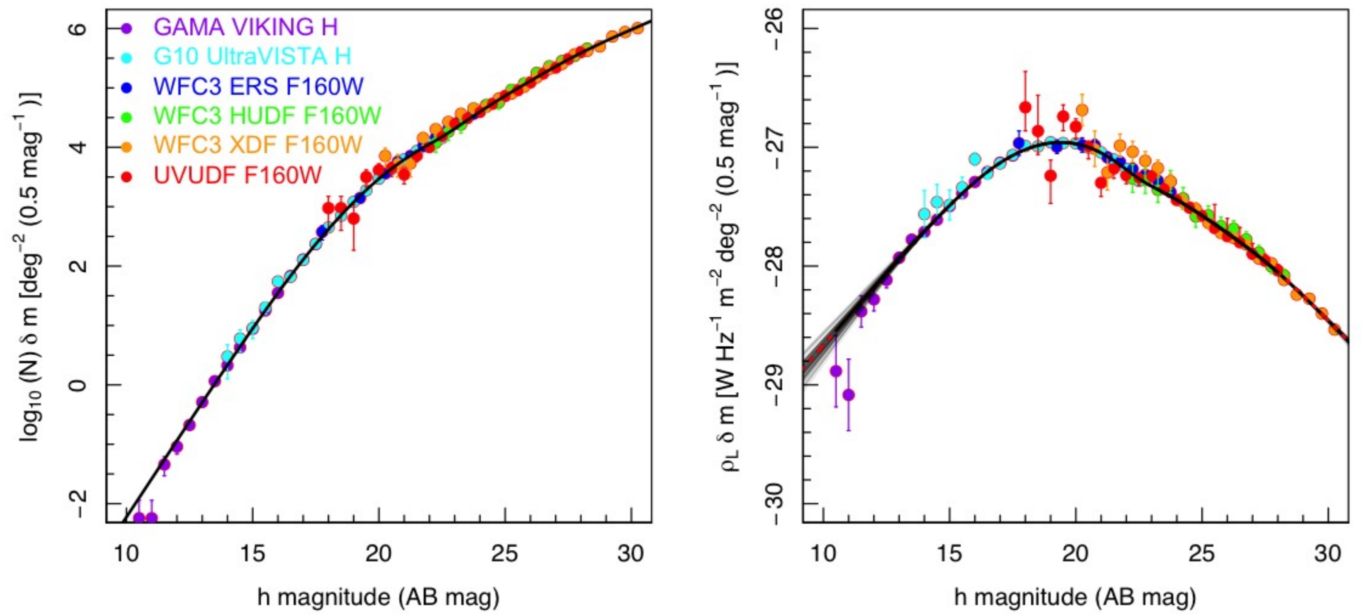
Y


GAMA VIKING Y
G10 UltraVISTA Y
WFC3 ERS F098W
WFC3 HUDF F105W
WFC3 XDF F105W
UVUDF F105W
$\log_{10}(N)\ \delta m$ [deg^{-2} (0.5 mag^{-1})]
y magnitude (AB mag)
$\rho_L\ \delta m$ [W Hz^{-1} m^{-2} deg^{-2} (0.5 mag^{-1})]
y magnitude (AB mag)

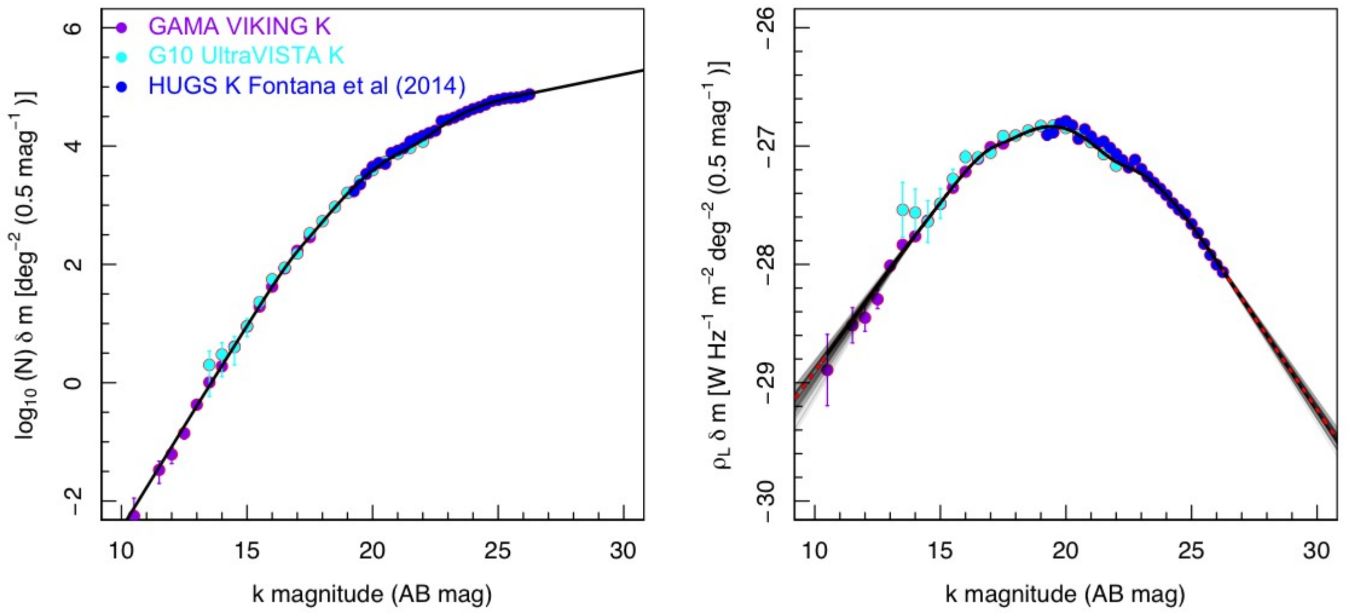
J


GAMA VIKING J
G10 UltraVISTA J
WFC3 ERS F125W
WFC3 HUDF F125W
WFC3 XDF F125W
UVUDF F125W
$\log_{10}(N)\ \delta m$ [deg^{-2} (0.5 mag^{-1})]
j magnitude (AB mag)
$\rho_L\ \delta m$ [W Hz^{-1} m^{-2} deg^{-2} (0.5 mag^{-1})]
j magnitude (AB mag)

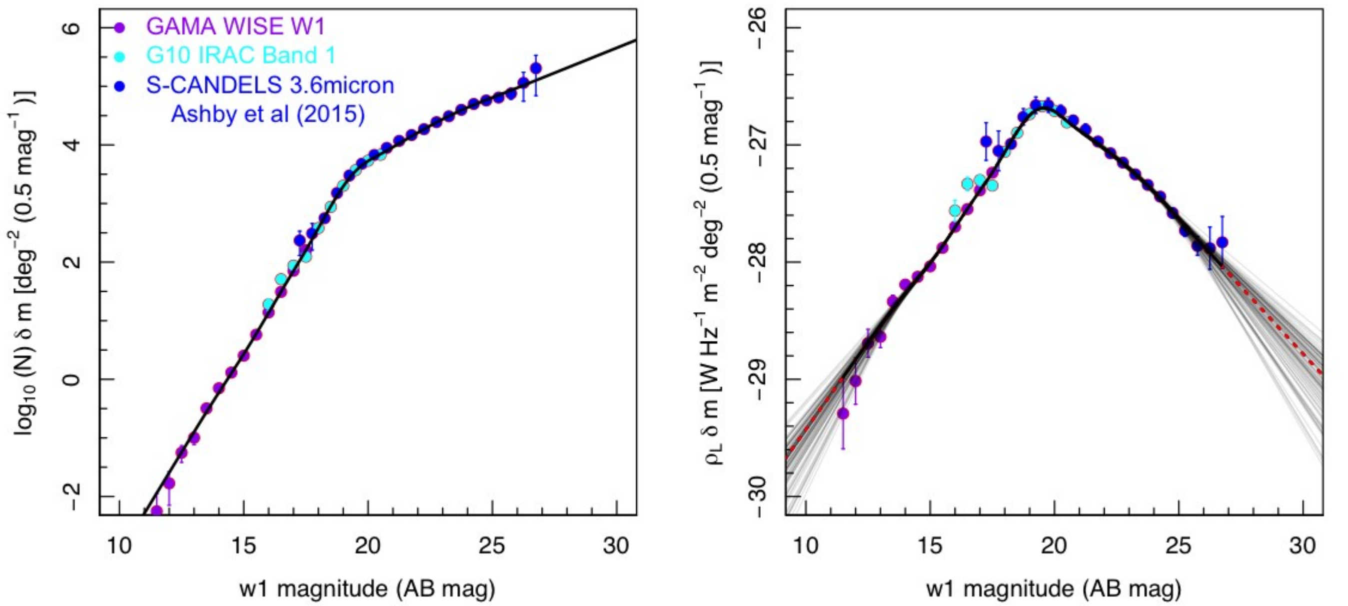
H


GAMA VIKING H
G10 UltraVISTA H
WFC3 ERS F160W
WFC3 HUDF F160W
WFC3 XDF F160W
UVUDF F160W
$\log_{10}(N)\ \delta m$ [deg^{-2} (0.5 mag^{-1})]
h magnitude (AB mag)
$\rho_L\ \delta m$ [W Hz^{-1} m^{-2} deg^{-2} (0.5 mag^{-1})]
h magnitude (AB mag)

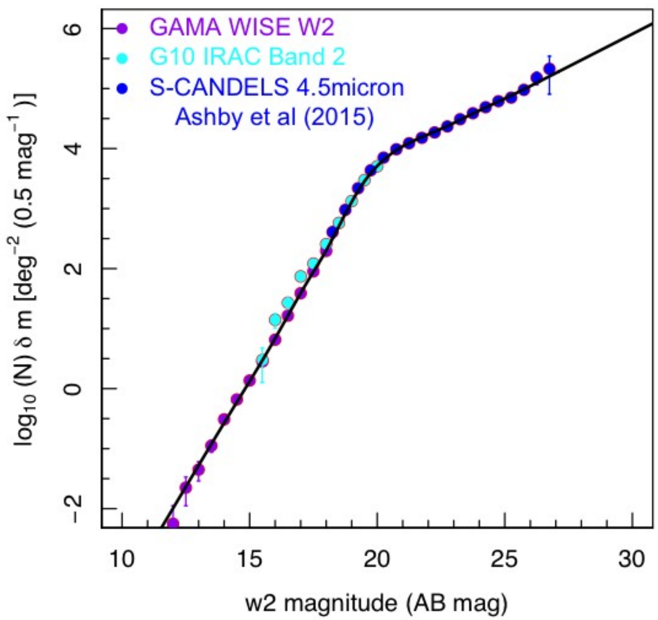
K

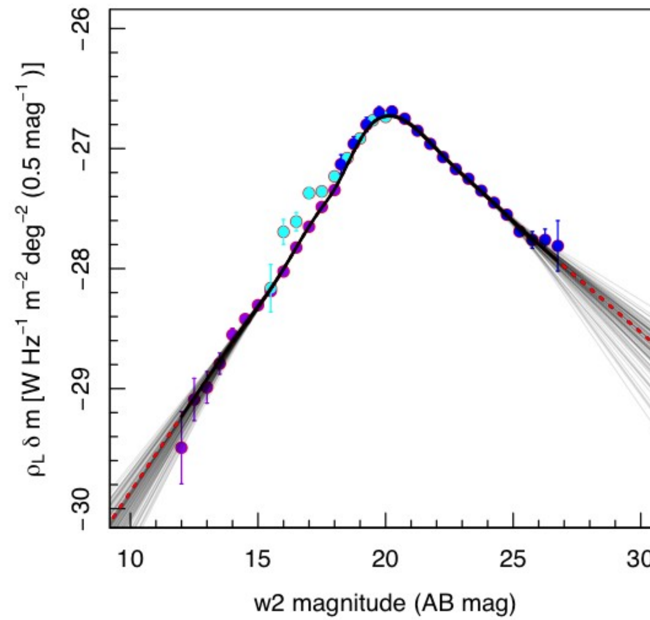

GAMA VIKING K
G10 UltraVISTA K
HUGS K Fontana et al (2014)
log10 (N) δ m [deg^-2 (0.5 mag^-1)]
k magnitude (AB mag)
ρL δ m [W Hz^-1 m^-2 deg^-2 (0.5 mag^-1)]
k magnitude (AB mag)

W1

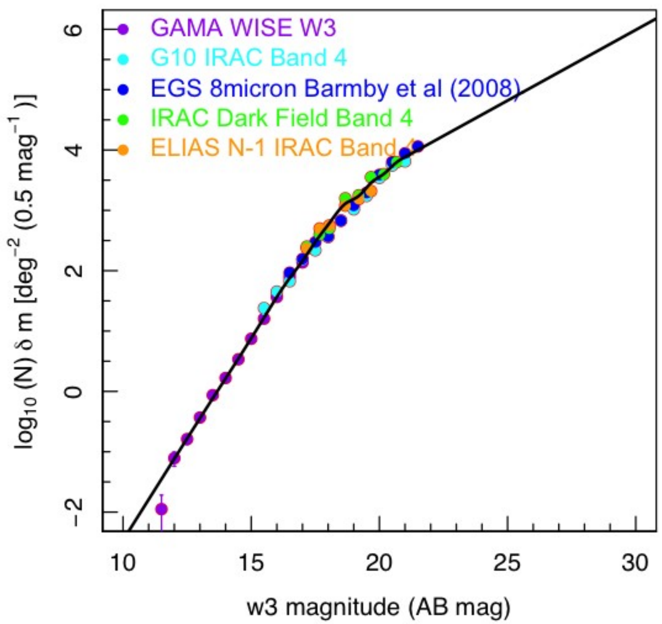

GAMA WISE W1
G10 IRAC Band 1
S-CANDELS 3.6micron
Ashby et al (2015)
log10 (N) δ m [deg^-2 (0.5 mag^-1)]
w1 magnitude (AB mag)
ρL δ m [W Hz^-1 m^-2 deg^-2 (0.5 mag^-1)]
w1 magnitude (AB mag)

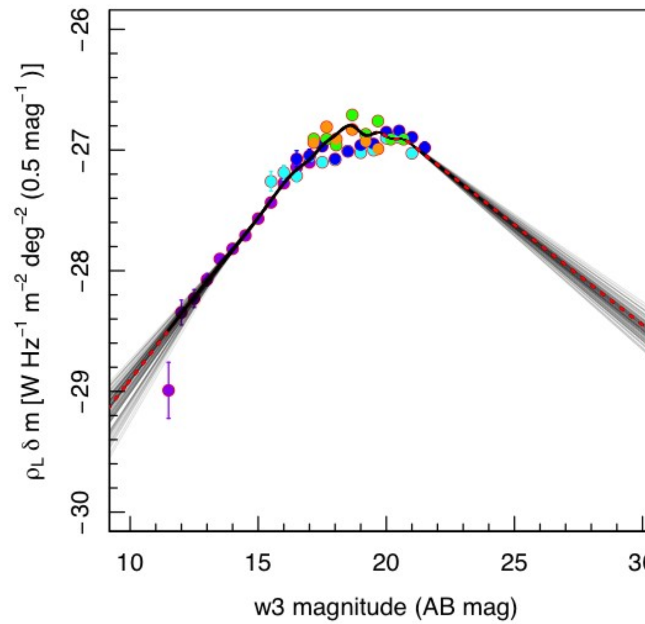
W2


GAMA WISE W2
G10 IRAC Band 2
S-CANDELS 4.5micron
Ashby et al (2015)
$\log_{10}$(N) δ m [deg^{-2} (0.5 mag^{-1})]
w2 magnitude (AB mag)

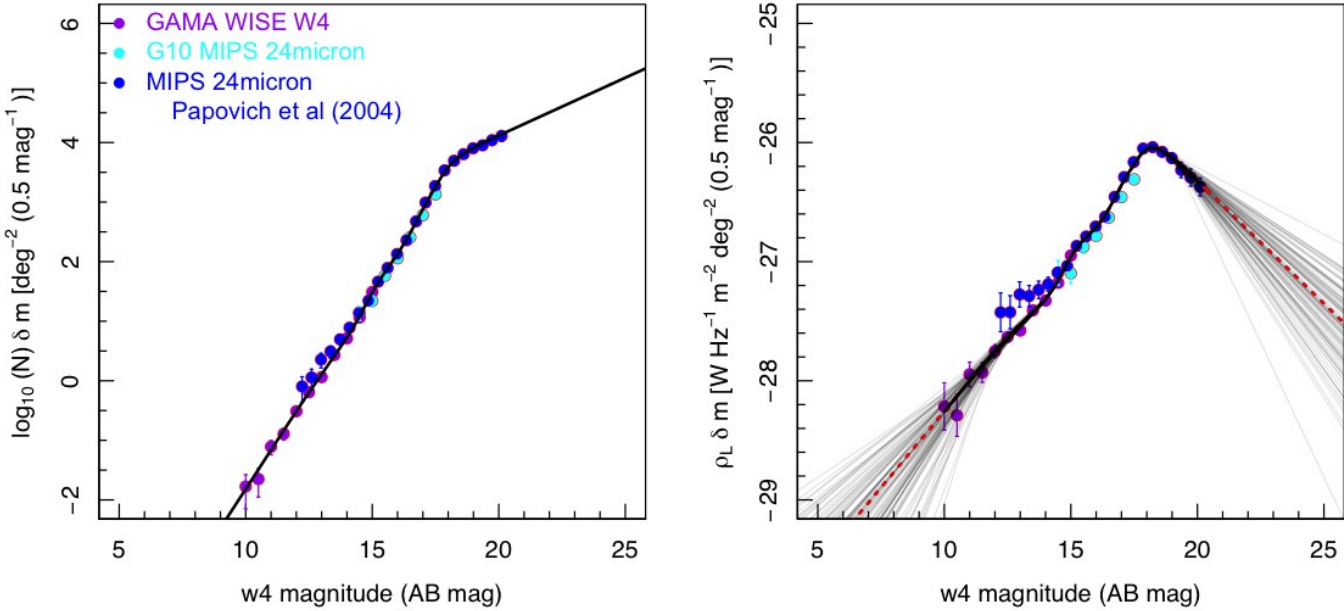

ρ_L δ m [W Hz^{-1} m^{-2} deg^{-2} (0.5 mag^{-1})]
w2 magnitude (AB mag)

W3

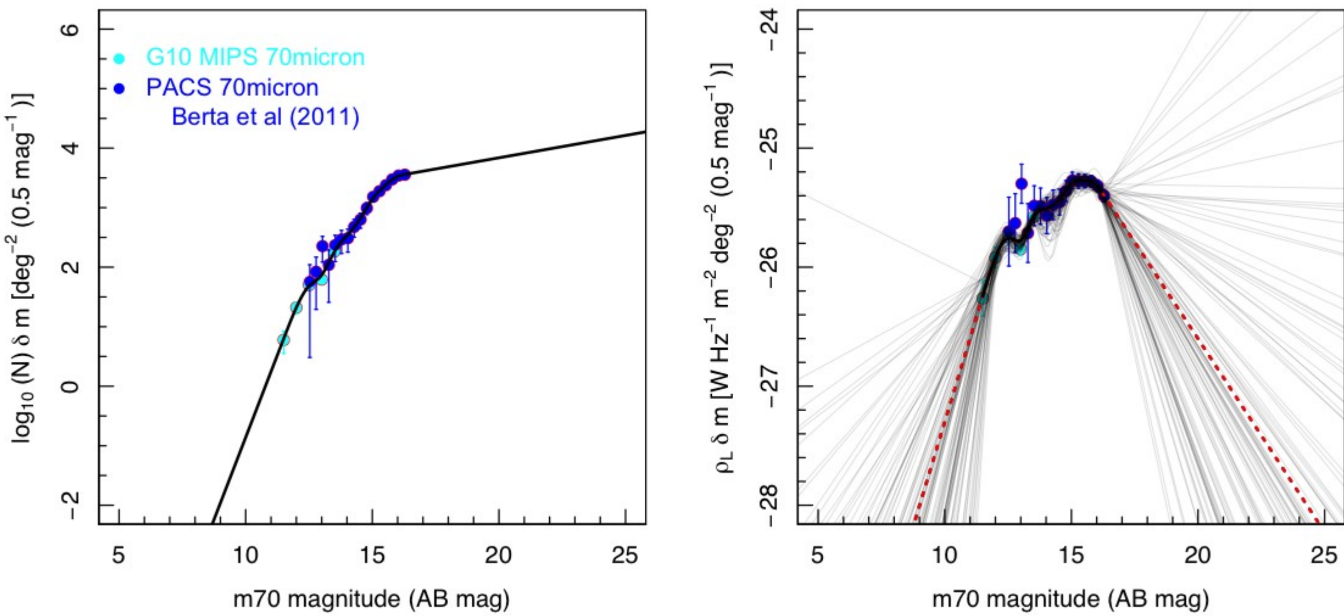

GAMA WISE W3
G10 IRAC Band 4
EGS 8micron Barmby et al (2008)
IRAC Dark Field Band 4
ELIAS N-1 IRAC Band 4
$\log_{10}$(N) δ m [deg^{-2} (0.5 mag^{-1})]
w3 magnitude (AB mag)


ρ_L δ m [W Hz^{-1} m^{-2} deg^{-2} (0.5 mag^{-1})]
w3 magnitude (AB mag)

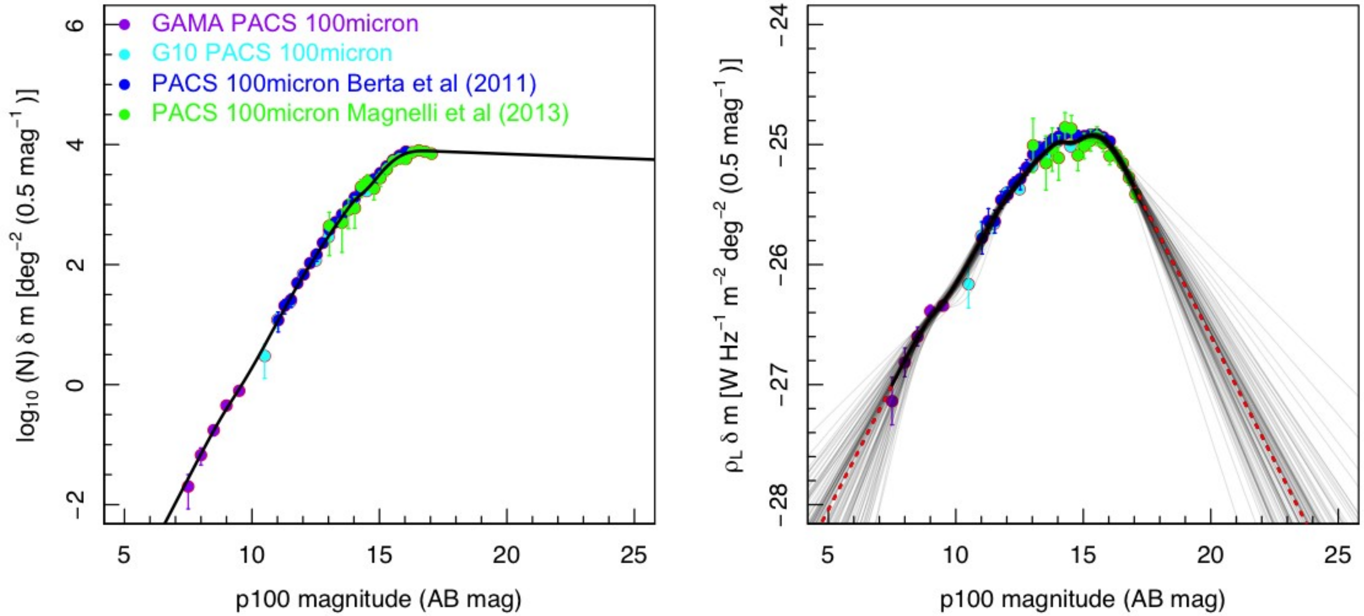
W4


GAMA WISE W4
G10 MIPS 24micron
MIPS 24micron
Papovich et al (2004)
log10 (N) δ m [deg^-2 (0.5 mag^-1)]
w4 magnitude (AB mag)
ρL δ m [W Hz^-1 m^-2 deg^-2 (0.5 mag^-1)]
w4 magnitude (AB mag)

P70

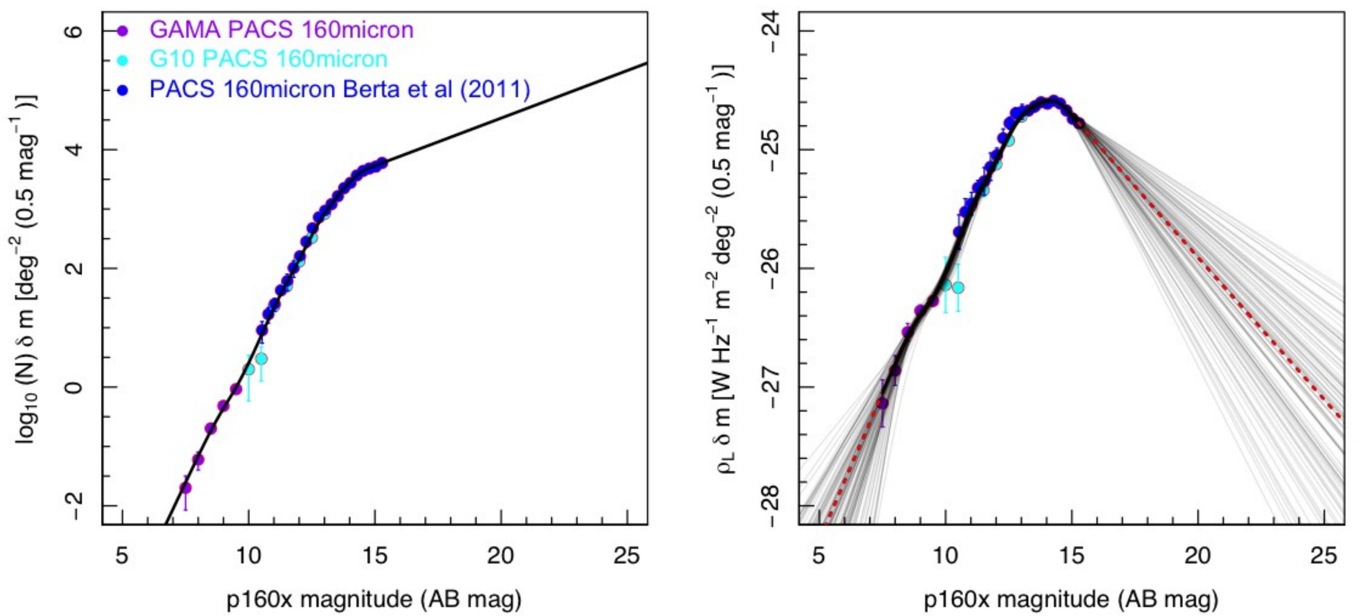

G10 MIPS 70micron
PACS 70micron
Berta et al (2011)
log10 (N) δ m [deg^-2 (0.5 mag^-1)]
m70 magnitude (AB mag)
ρL δ m [W Hz^-1 m^-2 deg^-2 (0.5 mag^-1)]
m70 magnitude (AB mag)

P100



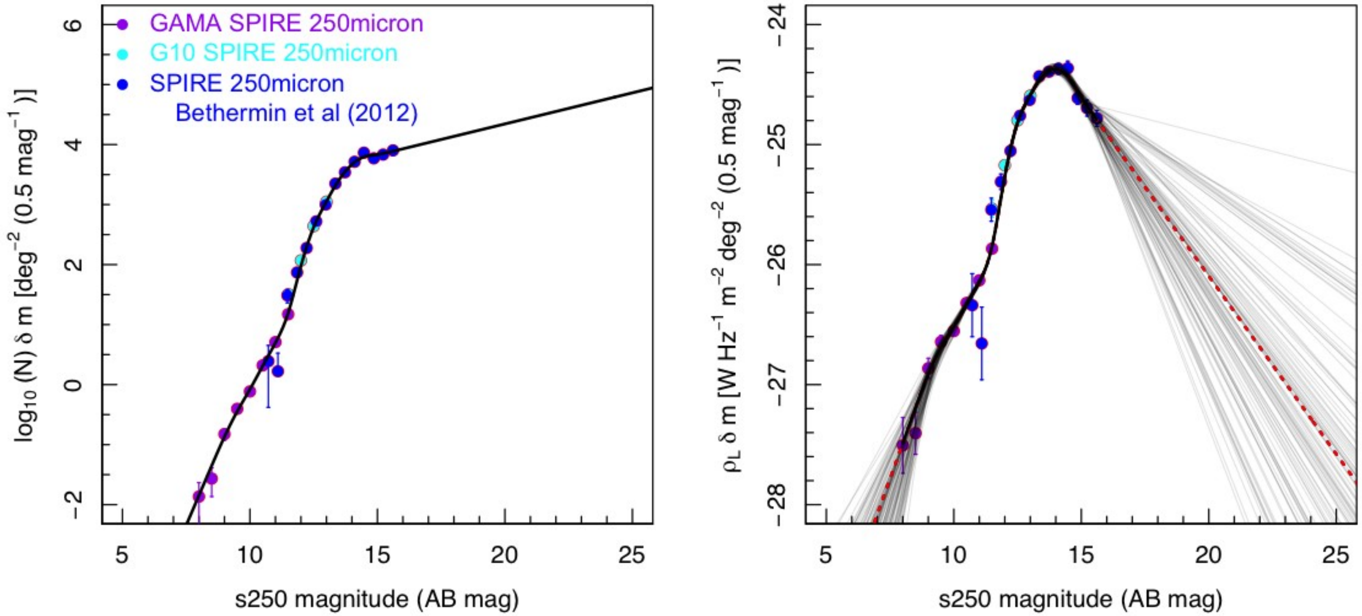
GAMA PACS 100micron
G10 PACS 100micron
PACS 100micron Berta et al (2011)
PACS 100micron Magnelli et al (2013)
$\log_{10}$ (N) δ m [deg^{-2} (0.5 mag^{-1})]
p100 magnitude (AB mag)
ρ_L δ m [W Hz^{-1} m^{-2} deg^{-2} (0.5 mag^{-1})]
p100 magnitude (AB mag)

P160

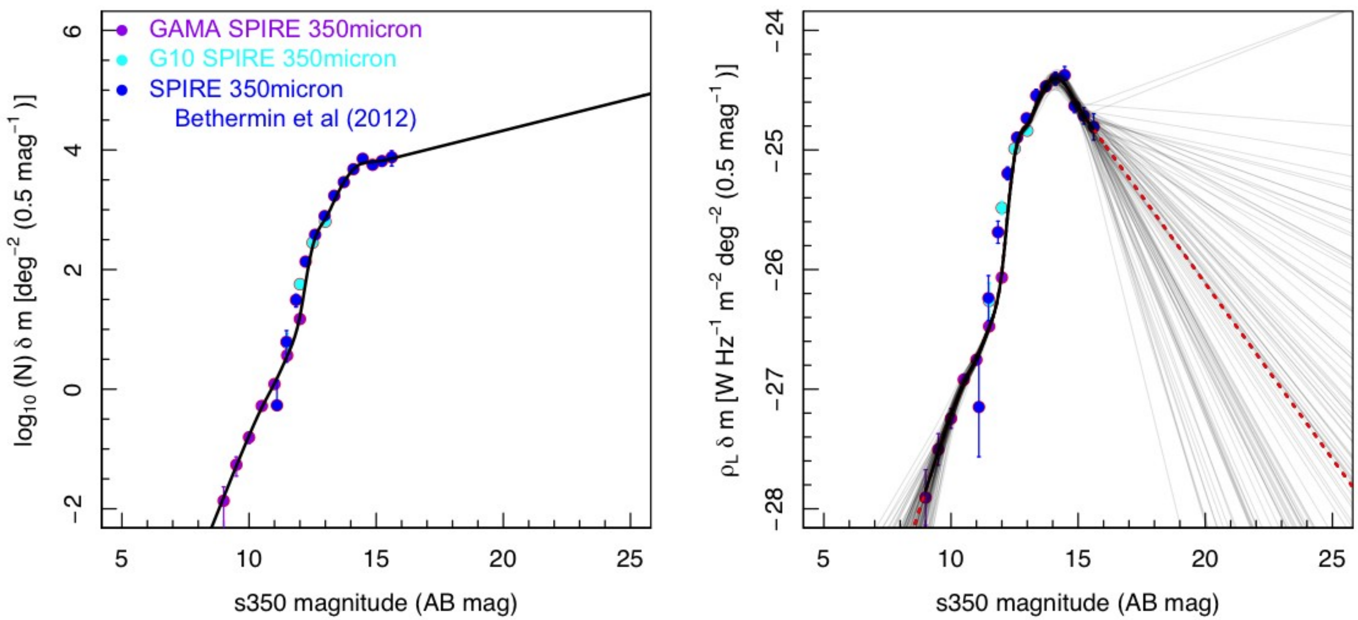


GAMA PACS 160micron
G10 PACS 160micron
PACS 160micron Berta et al (2011)
$\log_{10}$ (N) δ m [deg^{-2} (0.5 mag^{-1})]
p160x magnitude (AB mag)
ρ_L δ m [W Hz^{-1} m^{-2} deg^{-2} (0.5 mag^{-1})]
p160x magnitude (AB mag)

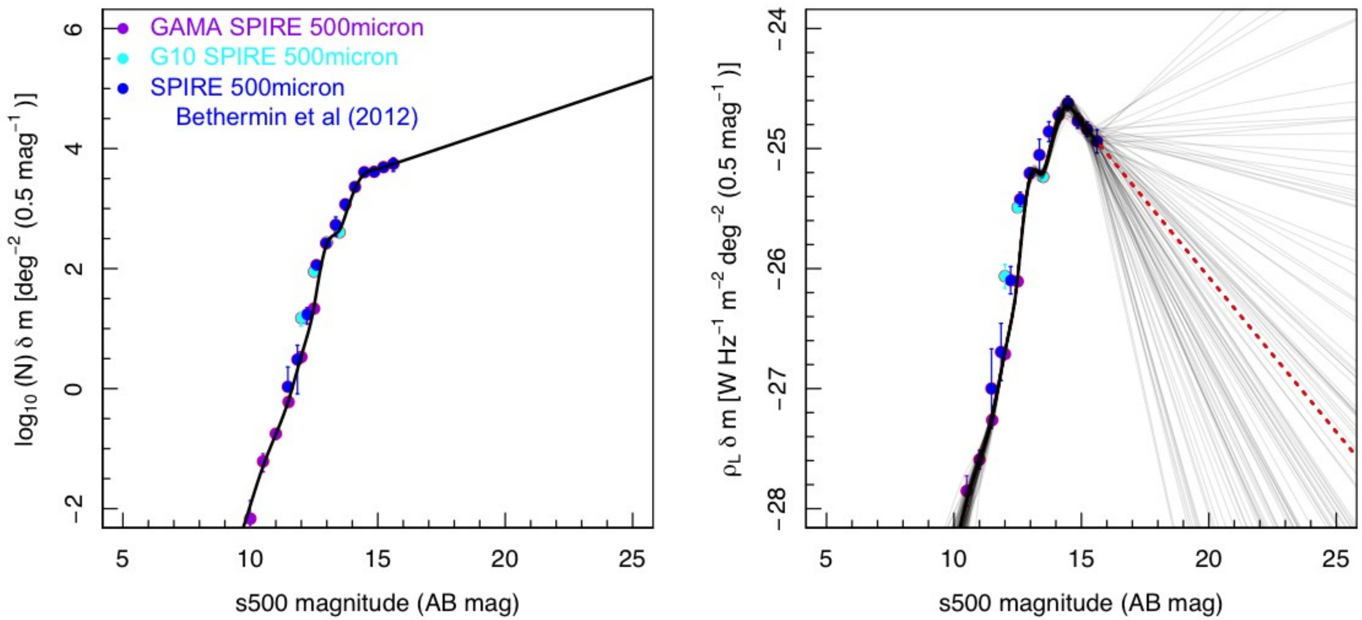
S250


GAMA SPIRE 250micron
G10 SPIRE 250micron
SPIRE 250micron
Bethermin et al (2012)
log10 (N) δ m [deg^-2 (0.5 mag^-1)]
s250 magnitude (AB mag)
ρL δ m [W Hz^-1 m^-2 deg^-2 (0.5 mag^-1)]
s250 magnitude (AB mag)

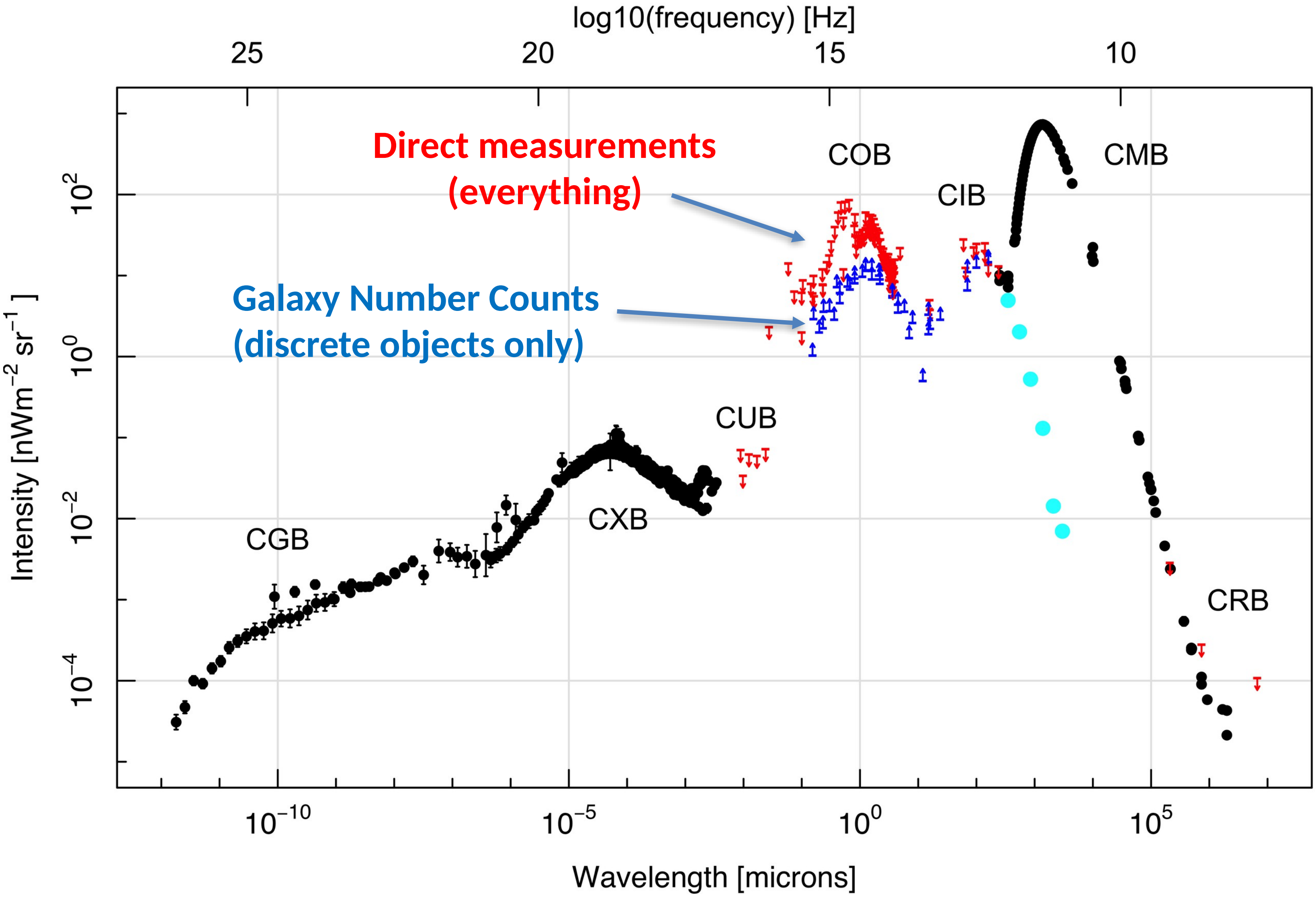
S350


GAMA SPIRE 350micron
G10 SPIRE 350micron
SPIRE 350micron
Bethermin et al (2012)
log10 (N) δ m [deg^-2 (0.5 mag^-1)]
s350 magnitude (AB mag)
ρL δ m [W Hz^-1 m^-2 deg^-2 (0.5 mag^-1)]
s350 magnitude (AB mag)

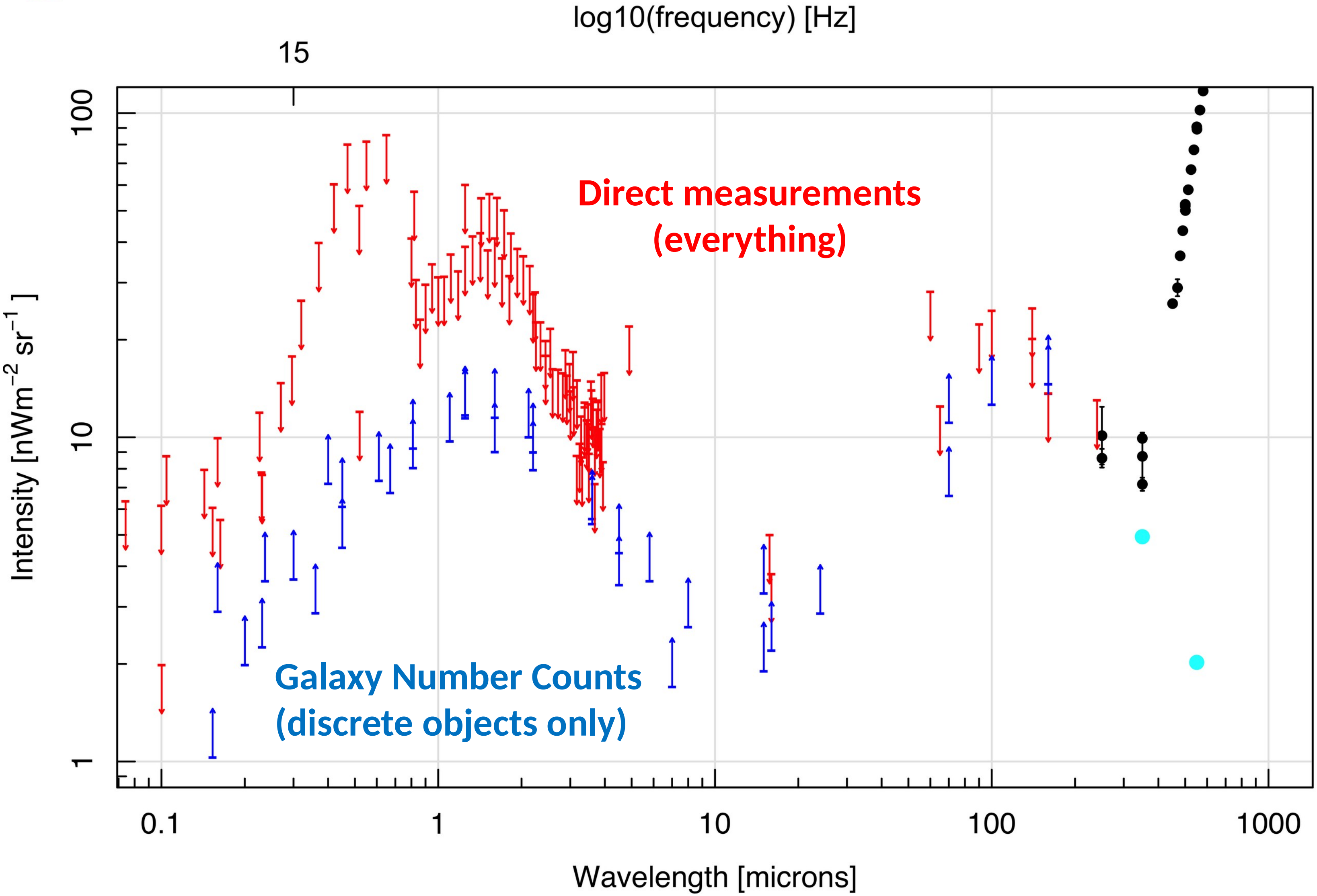
S500


GAMA SPIRE 500micron
G10 SPIRE 500micron
SPIRE 500micron
Bethermin et al (2012)
log10 (N) δ m [deg^-2 (0.5 mag^-1)]
s500 magnitude (AB mag)
ρL δ m [W Hz^-1 m^-2 deg^-2 (0.5 mag^-1)]
s500 magnitude (AB mag)

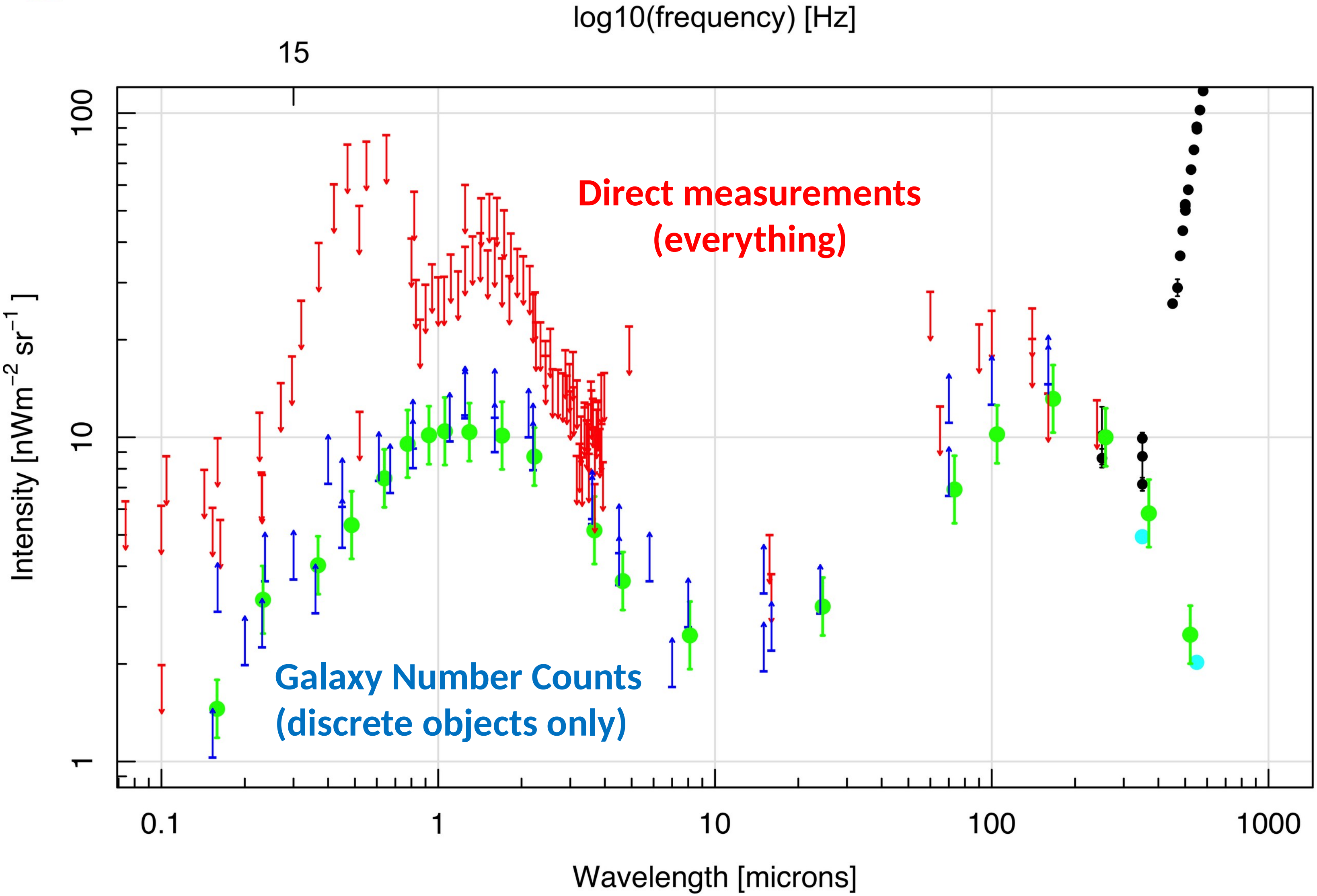
The Panchromatic EBL: ~2010



The Panchromatic EBL: ~2010

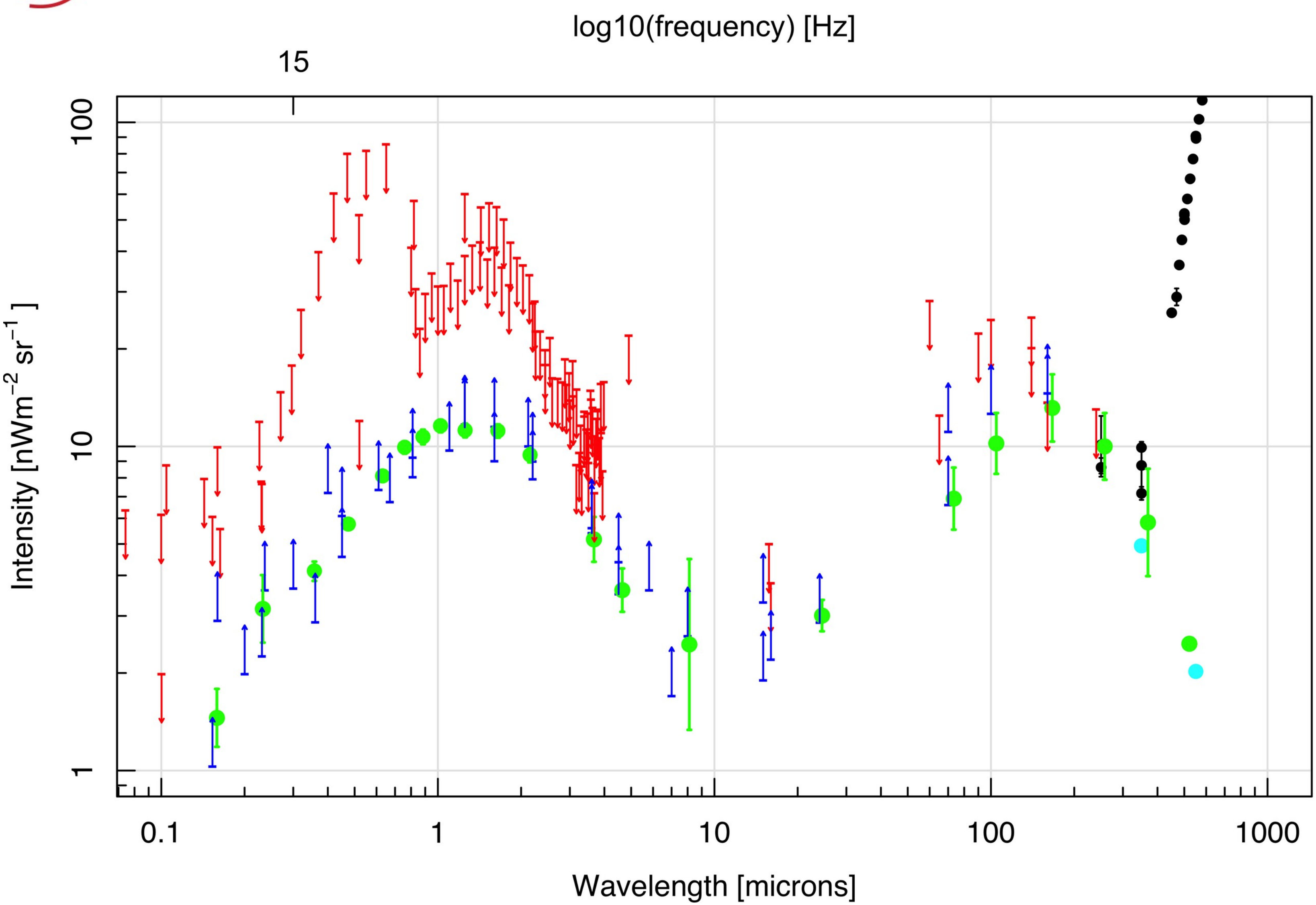


The Panchromatic EBL: ~2016



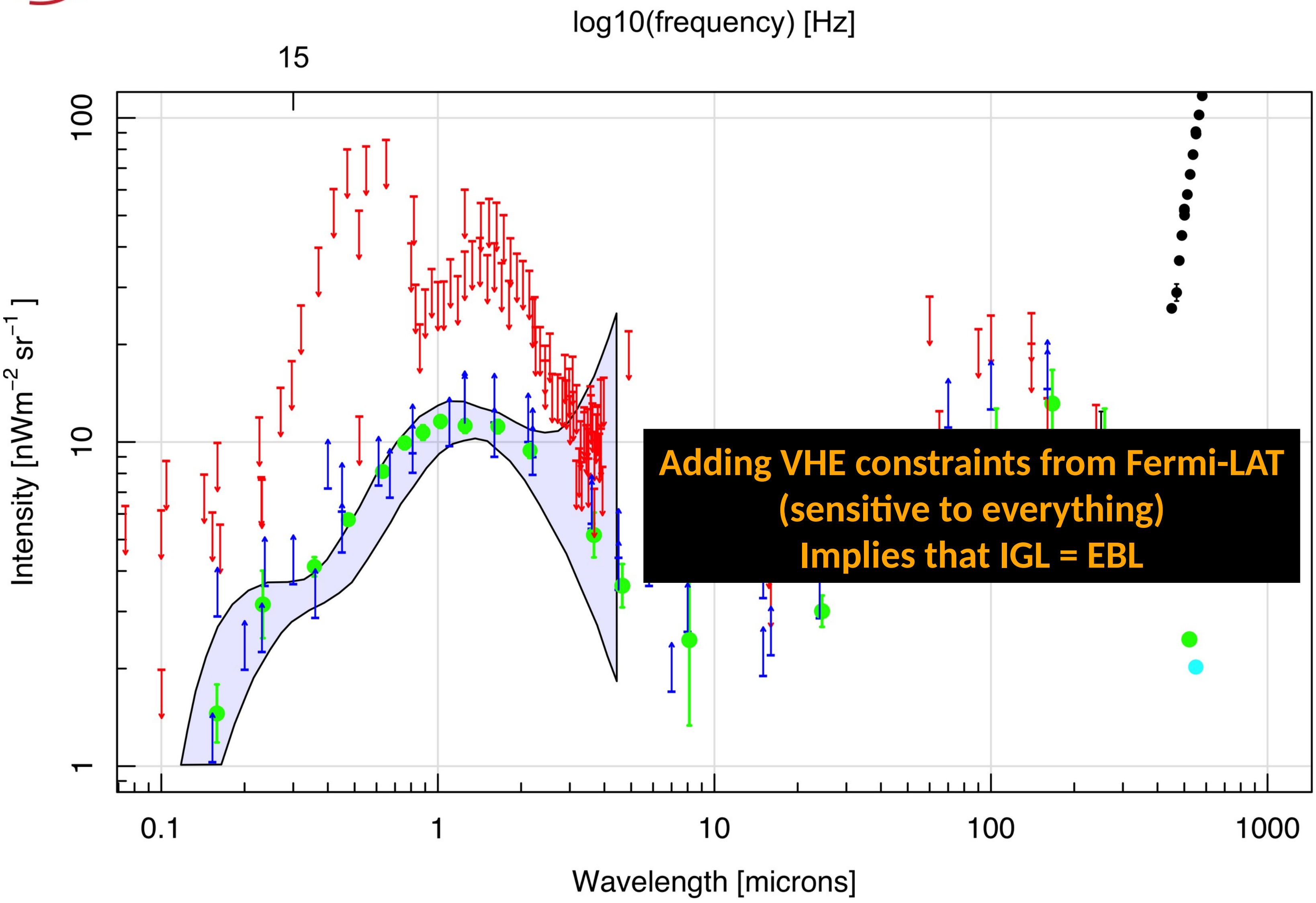
Driver et al (2016)

The Panchromatic EBL: ~2021



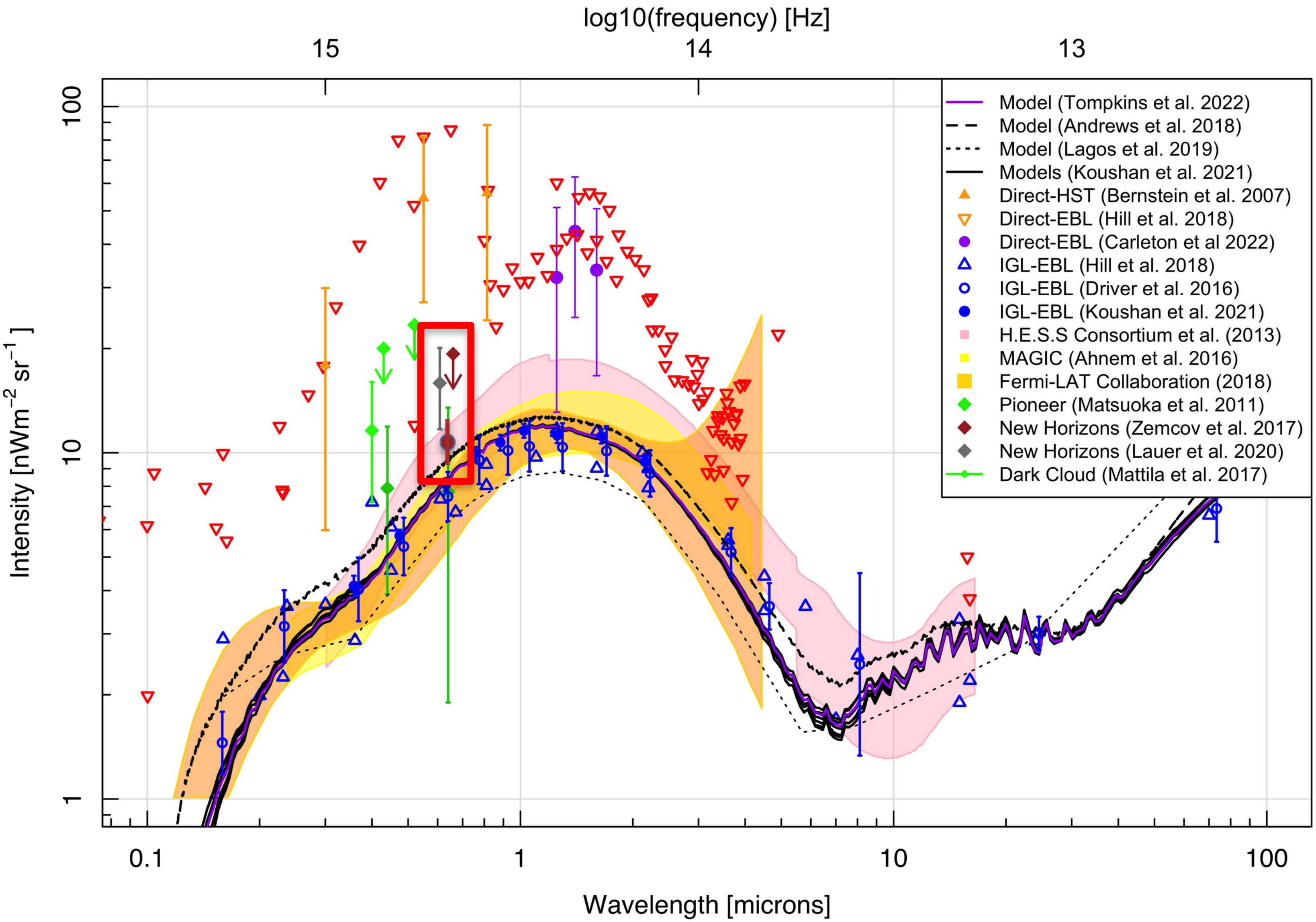
Koushan et al (2021)

The Panchromatic EBL: 2022+VHE



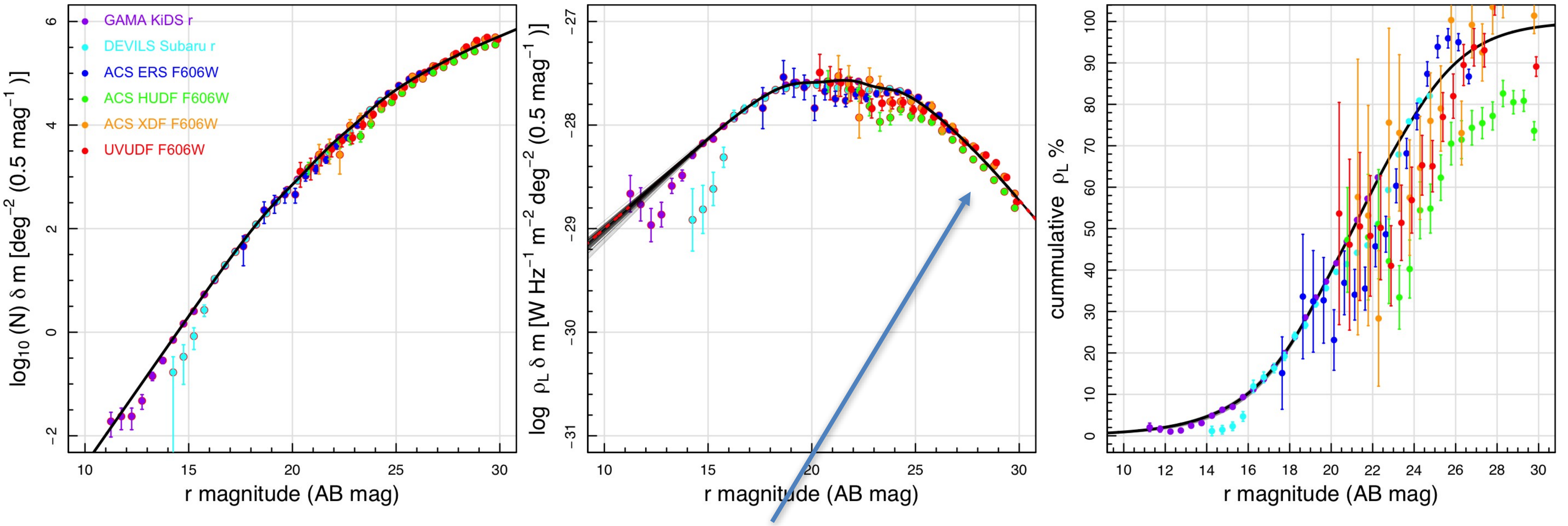
Fermi-LAT Collaboration: Abdollahi et al (2018, Sci)

The EBL: COB controversy



The EBL: Counts at 0.6micron?

Counts are very well defined, bounded, with little scope for more than 5% adjustment



Adding a very faint high-z population, has only a minor impact.

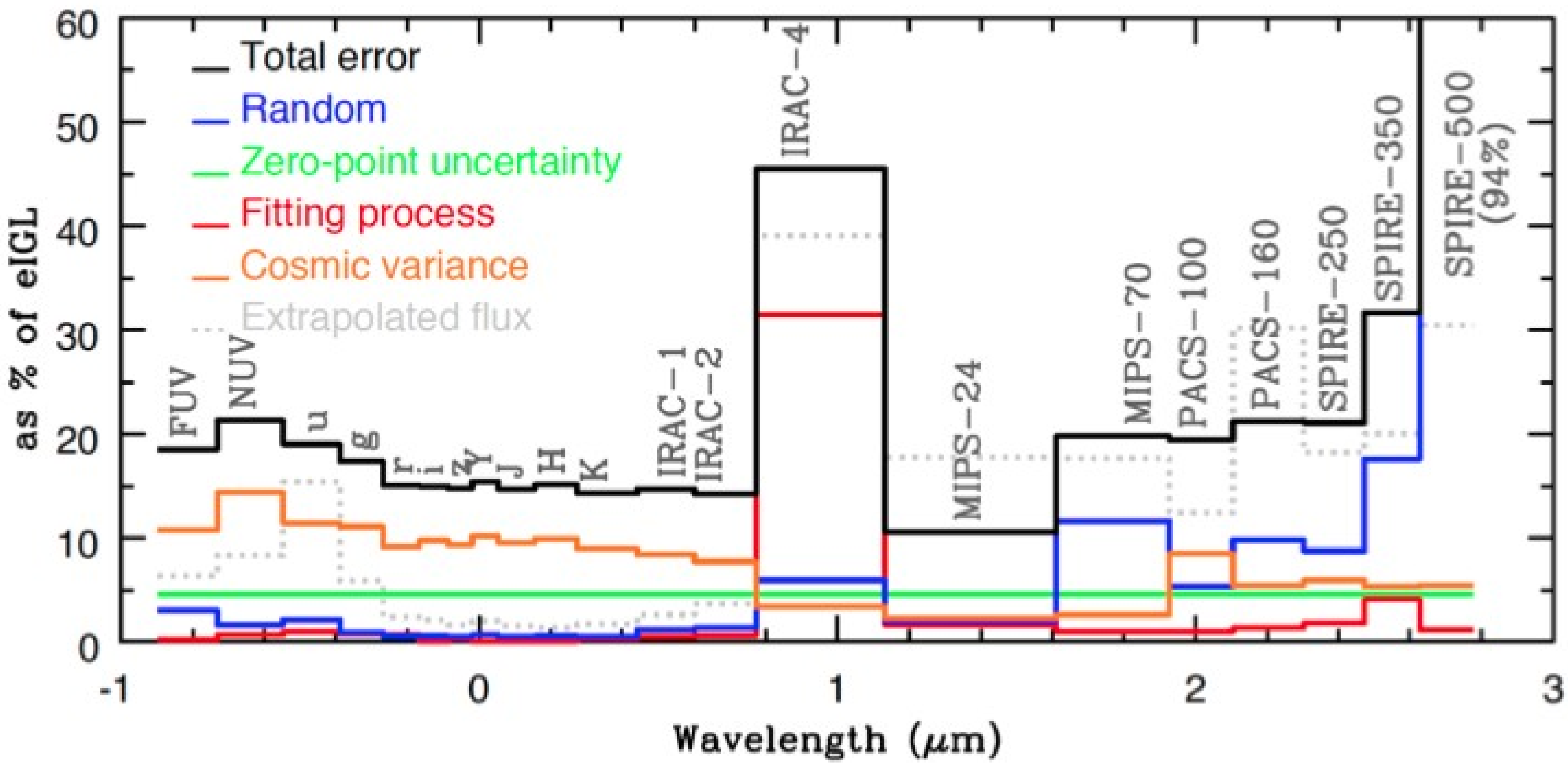
SkySURF and NH results must be local, but how local: Outer SS or DGL?

The IGL: Uncertainties

Driver et al (2016): 200% → 20%

Dominant error is Cosmic Variance, can we do better?

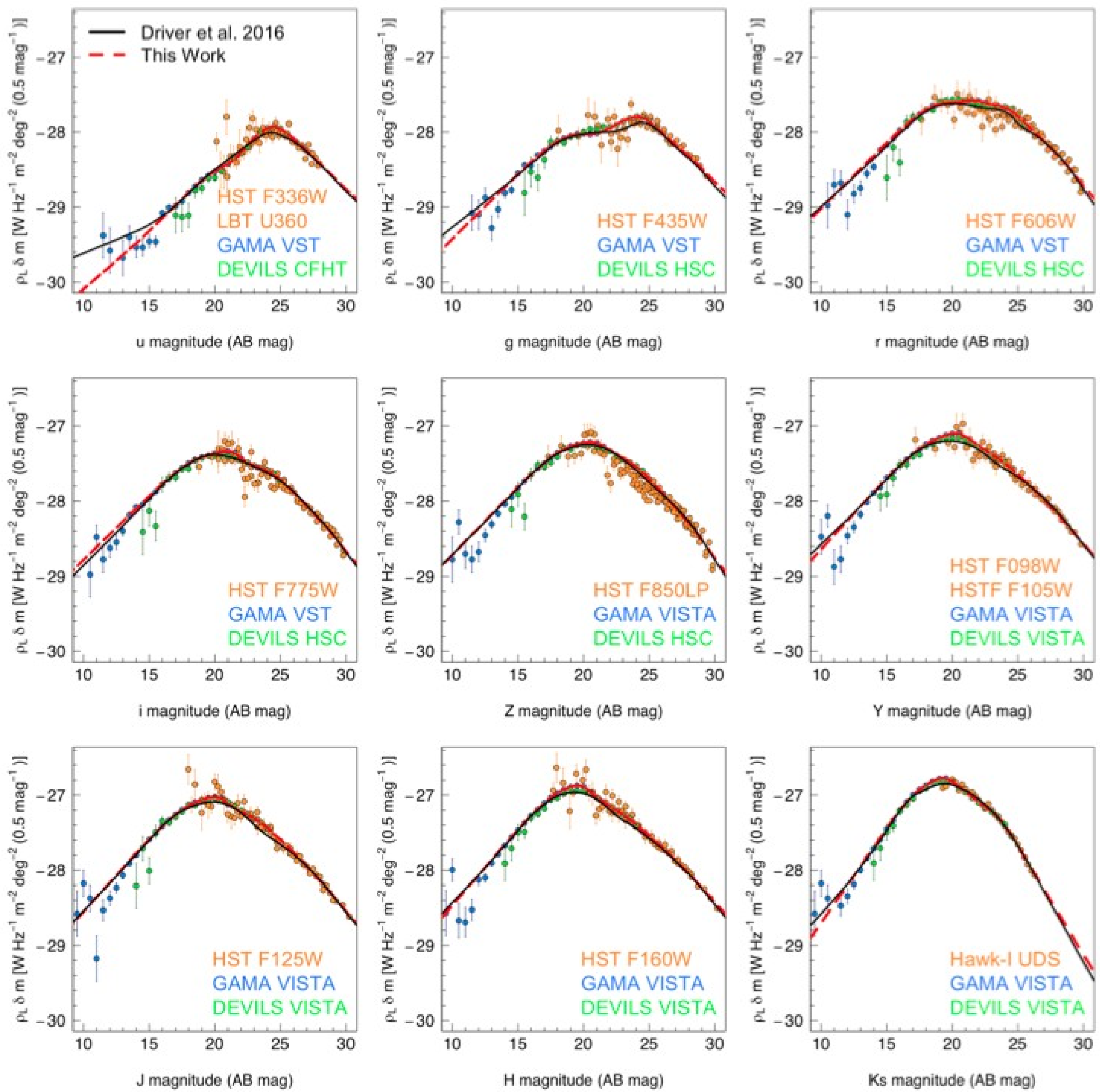
THE EBL FROM THE FAR-UV TO THE FAR-IR



Recent IGL improvements

GAMA/DEVILS: Constraining the cosmic star-formation history from improved measurements of the 0. Extragalactic Background Light

Soheil Koushan[1*], Simon P. Driver[1], Sabine Bellstedt[1], Luke J. Aaron S. G. Robotham[1], Claudia del P Lagos[1,2], Abdolhosein H Danail Obreschkow[1], Jessica E. Thorne[1], Malcolm Bremer[3], B.V Andrew M. Hopkins[5], Matt J. Jarvis[6], Malgorzata Siudek[7,8], an Rogier A. Windhorst[9]



SDSS → VST

UKIRT → VISTA

Sextractor → ProFound

COSMOS → DEVILS (COSMOS+XMM+ECDFS)

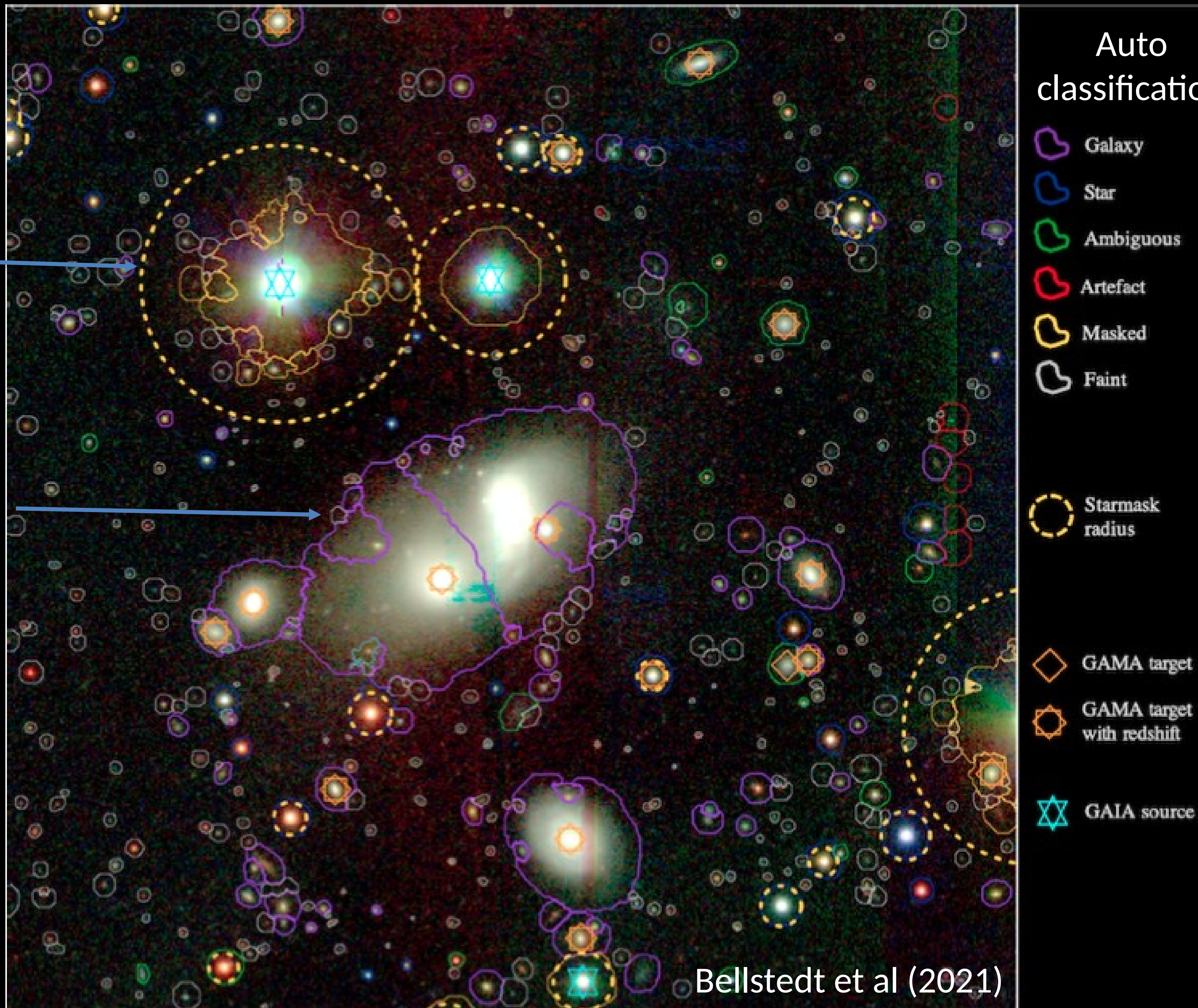
New source finding code developed; ProFound (Robotham et al 2016) [on Github

GAIA star masking

Defragmentation

Dilated segments

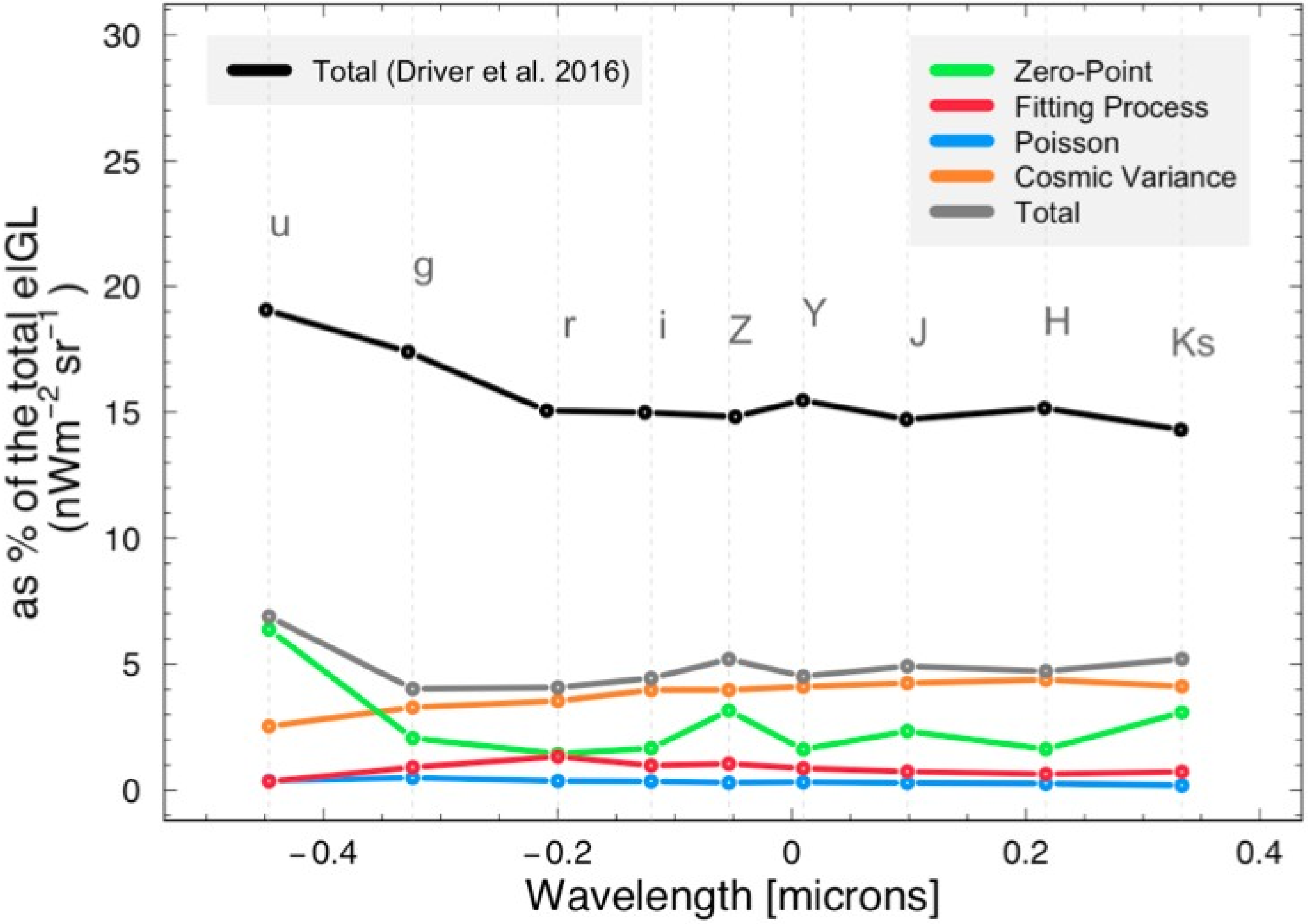
Matched Segment Photometry over 21 bands



The EBL: Uncertainties

Koushan et al (2022): 20% ⊟ 5%

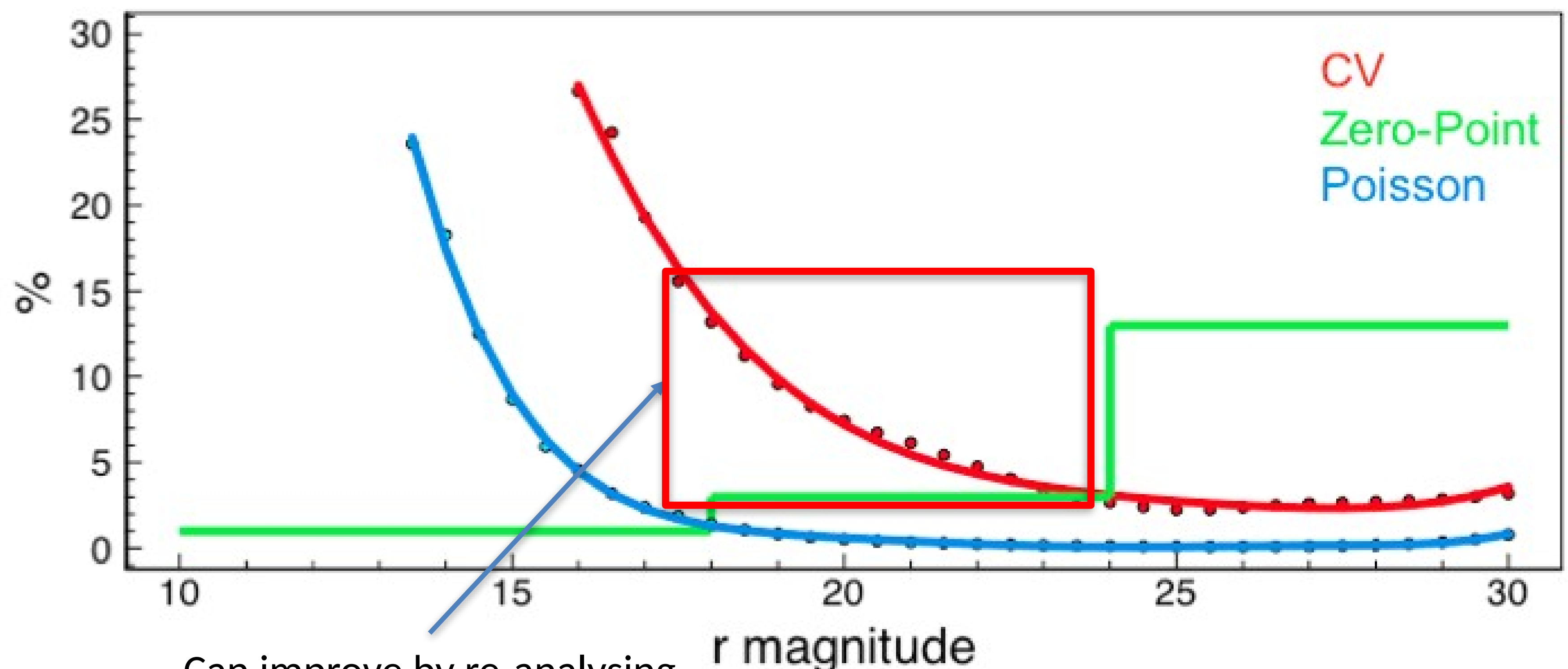
- GAMA (230sq deg) ▭ WAVES (1350sq deg in ugriZYJHK)



The EBL: Uncertainties

Koushan et al (2022): 20% → 5%

- GAMA (230sq deg) → WAVES (1350sq deg in ugriZYJHK)
- Main errors are now Cosmic Variance and zero-point uncertainties (HST & JWST).



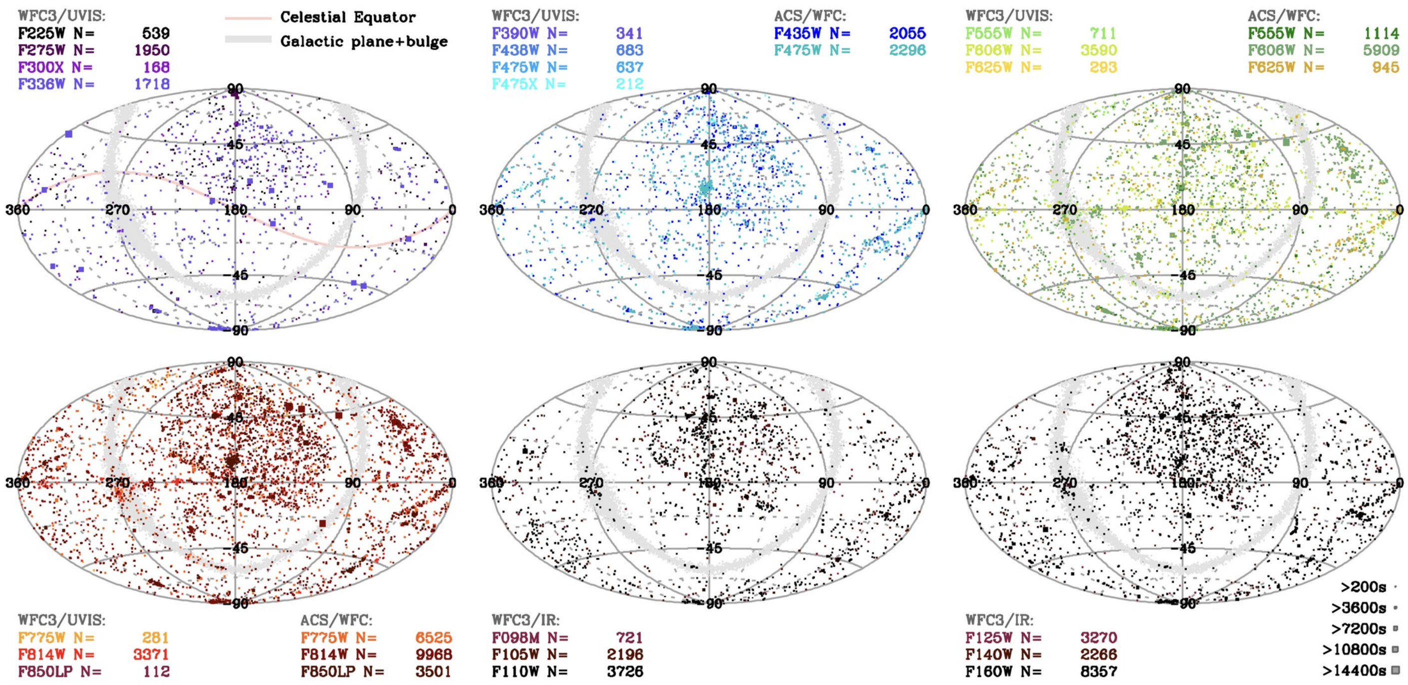
Can improve by re-analysing
HST archive = SkySURF

Koushan et al (2021)

SkySURF: HST reanalysis

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

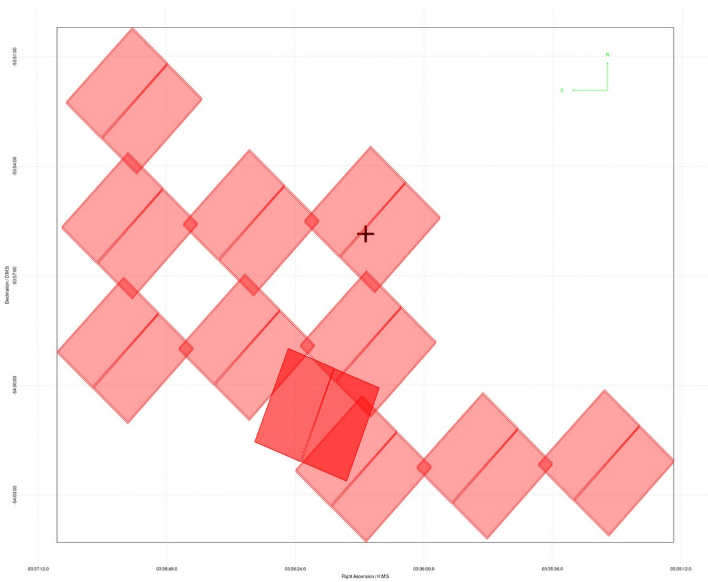
Rogier A. Windhorst,[1] Timothy Carleton,[1] Rosalia O'Brien,[1] Seth H. Cohen,[1] Delondrae Carter,[1] Rolf Jansen,[1] Scott Tompkins,[1] Richard G. Arendt,[2] Sarah Caddy,[3] Norman Grogin,[4] Anton Koekemoer,[4] John MacKenty,[4] Stefano Casertano,[4] Luke J. M. Davies,[5] Simon P. Driver,[6] Eli 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]

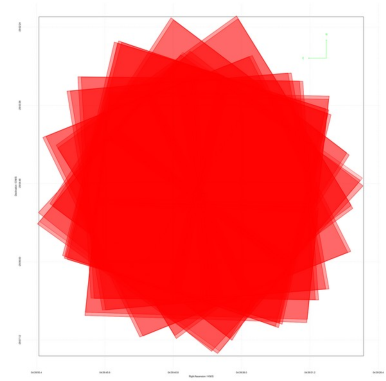


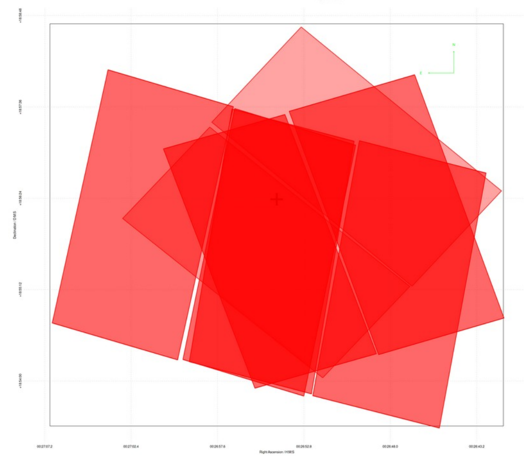
SkySURF: HST reanalysis

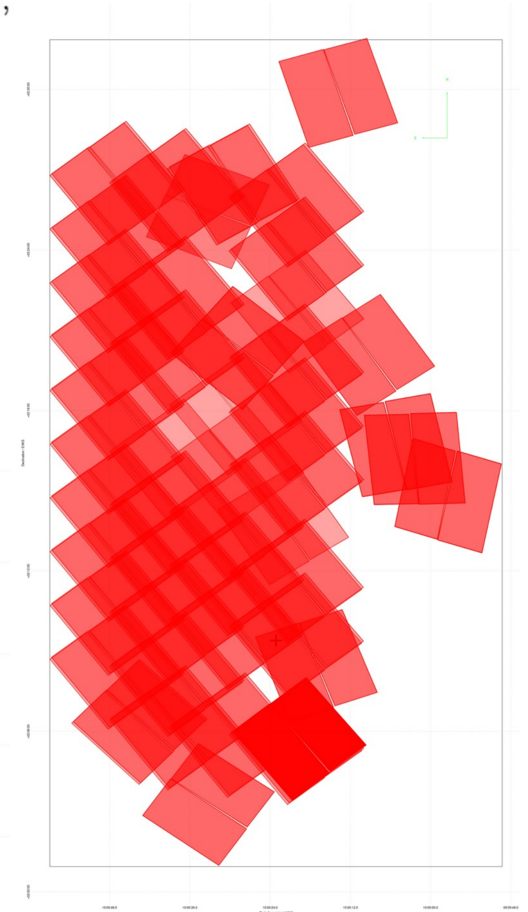
SKYSURF VII - ProFound Galaxy Catalog Construction and Measurements of the Ultraviolet to Near-Infrared Extragalactic Background Light

Scott A. Tompkins[2], Simon P. Driver[2], Aaron S. G. Robotham[2], Rogier A. Windhorst[1], Delondrae Carter[1], Timothy Carleton[1], Zak Goisman[1], Daniel Henningsen[1], Luke J. Davies[2], Sabine Bellstedt[2]
Jordan C. J. D'Silva[2] Juno Li[2]

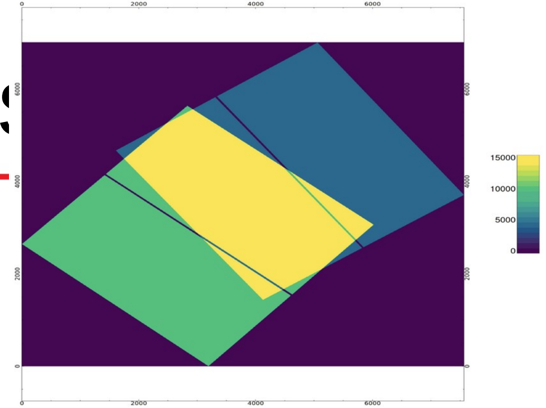






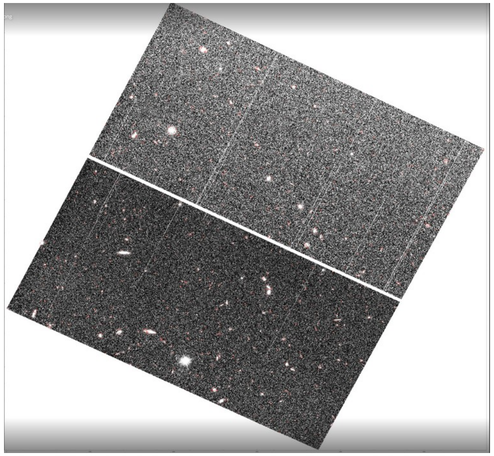


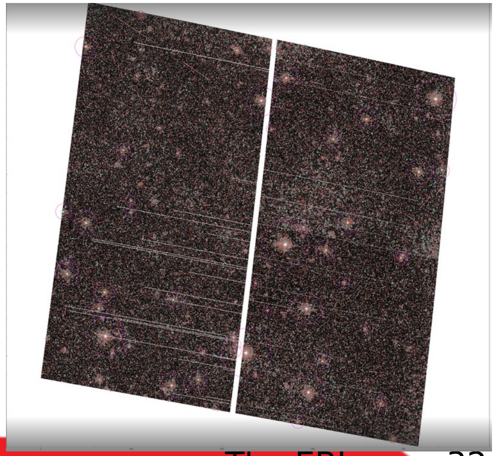
SkySURF: HST reanalysis

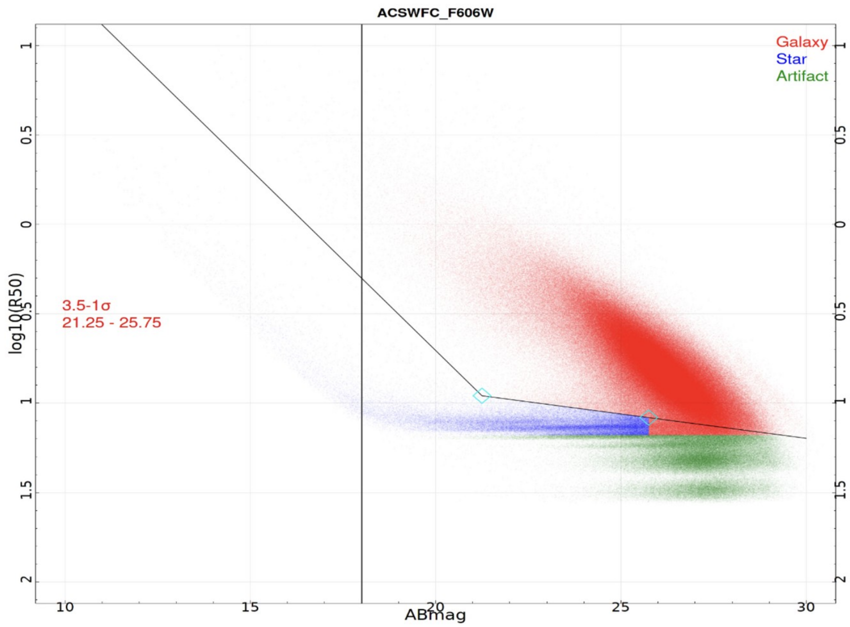


A lot harder than expected because:

- Highly irregular mosaics
- Variable exposure times
- Pointing bias (cluster science bias)
- HST anomalies (CTE, SAA, Chip drops)
- Star-gal intractable without colour info





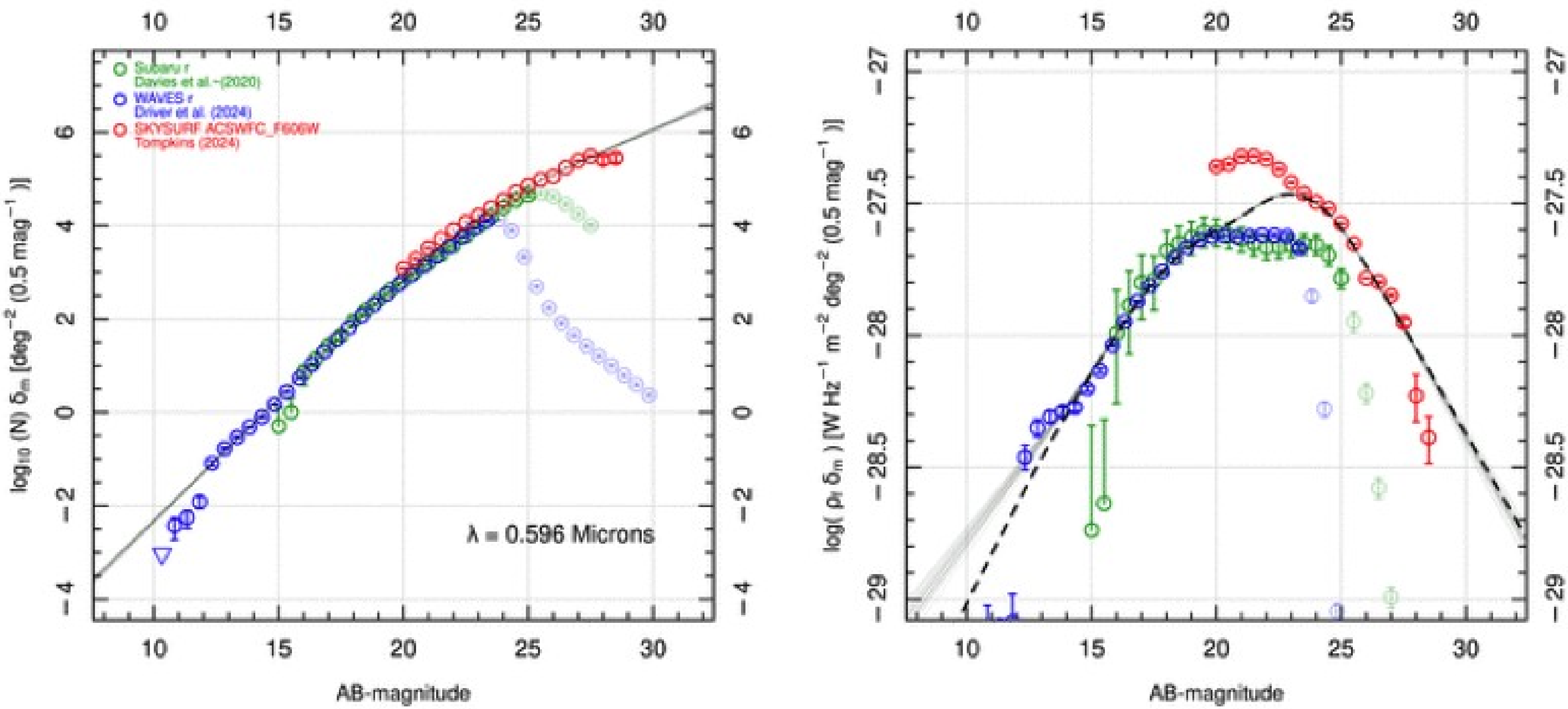


SkySURF: HST reanalysis

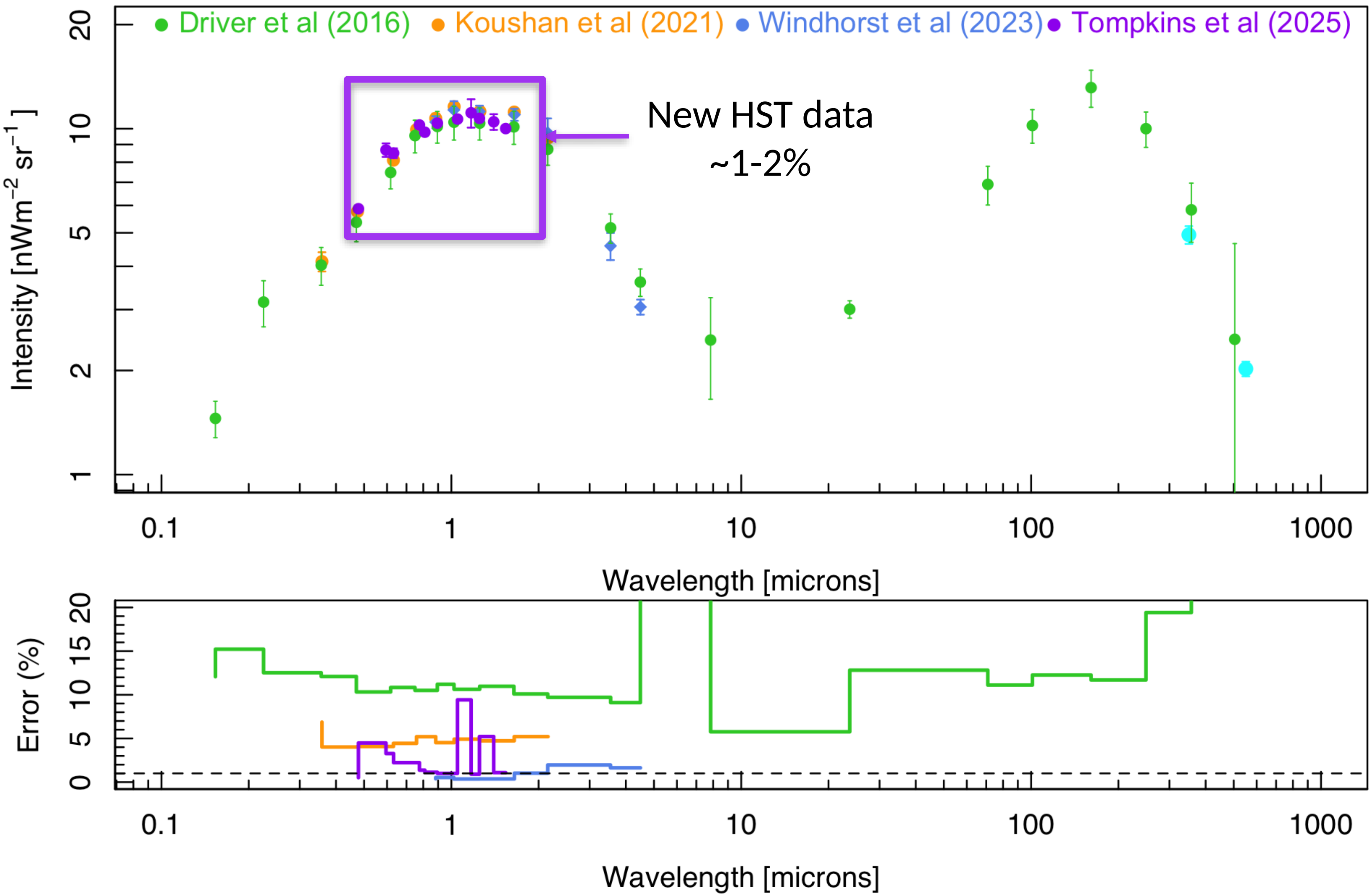
Strategy needed to remove cluster fields and dead chip fields.

Identify and reject anomalous frames from count excess or defeceit.

Uses a strategy to progressively reject outlier fields.



Current state of the IGL



Data and surveys used for IGL

GAMA:

- 240sq deg
- **GALEX+VST+VISTA+WISE+Herschel**
- 20 million galaxies

COSMOS/DEVILS:

- 3sq deg
- **GALEX+CFHT+Subaru+VISTA+WISE+Spitzer+Herschel**
- 1 million glaxies

WAVES

- 1200sq deg
- **GALEX+VST+VISTA+WISE+Herschel (300 sq deg)**
- 100 million galaxies

HST SkySURF

- 1-10sq deg
- **ACS, WFC2 and WFC3**
- 1million galaxies

JWST Pearls

- 400 sq arcmin
- **NIRCam (MIRI coming)**
- 300,000 galaxies

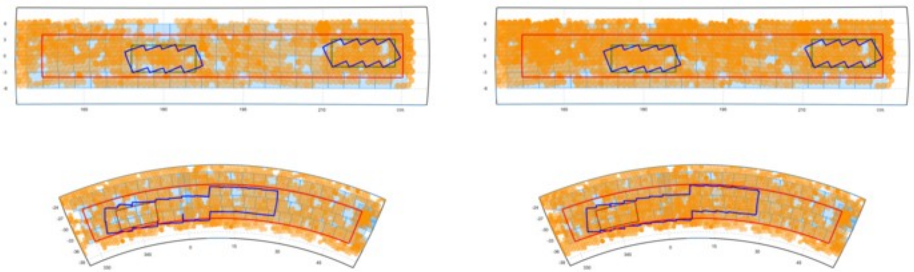
UWA DATA Fusion Centre

Critical Tools (UWA):

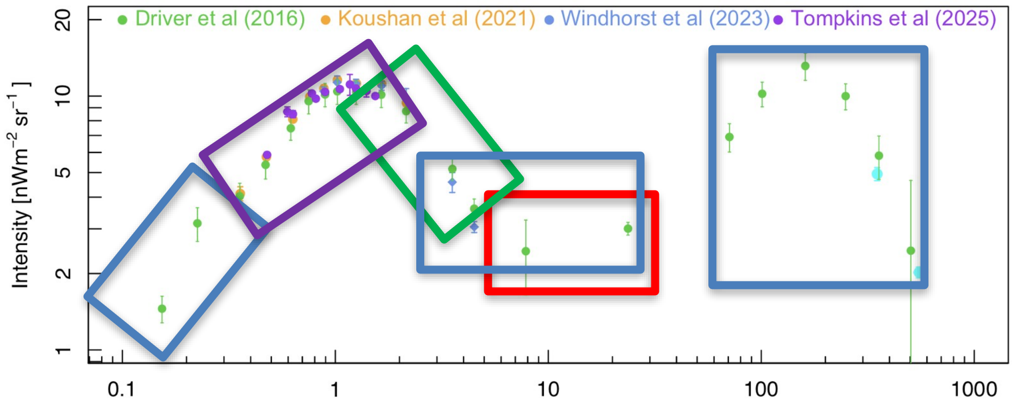
- ProFound
- ProPane
- ProSpect
- ProGeny

Efforts to improve in far-IR and far-UV IGL

- **Currently processing GALEX, WISE and Herschel in WAVES, expect ~x2 improvement in IGL errors.**



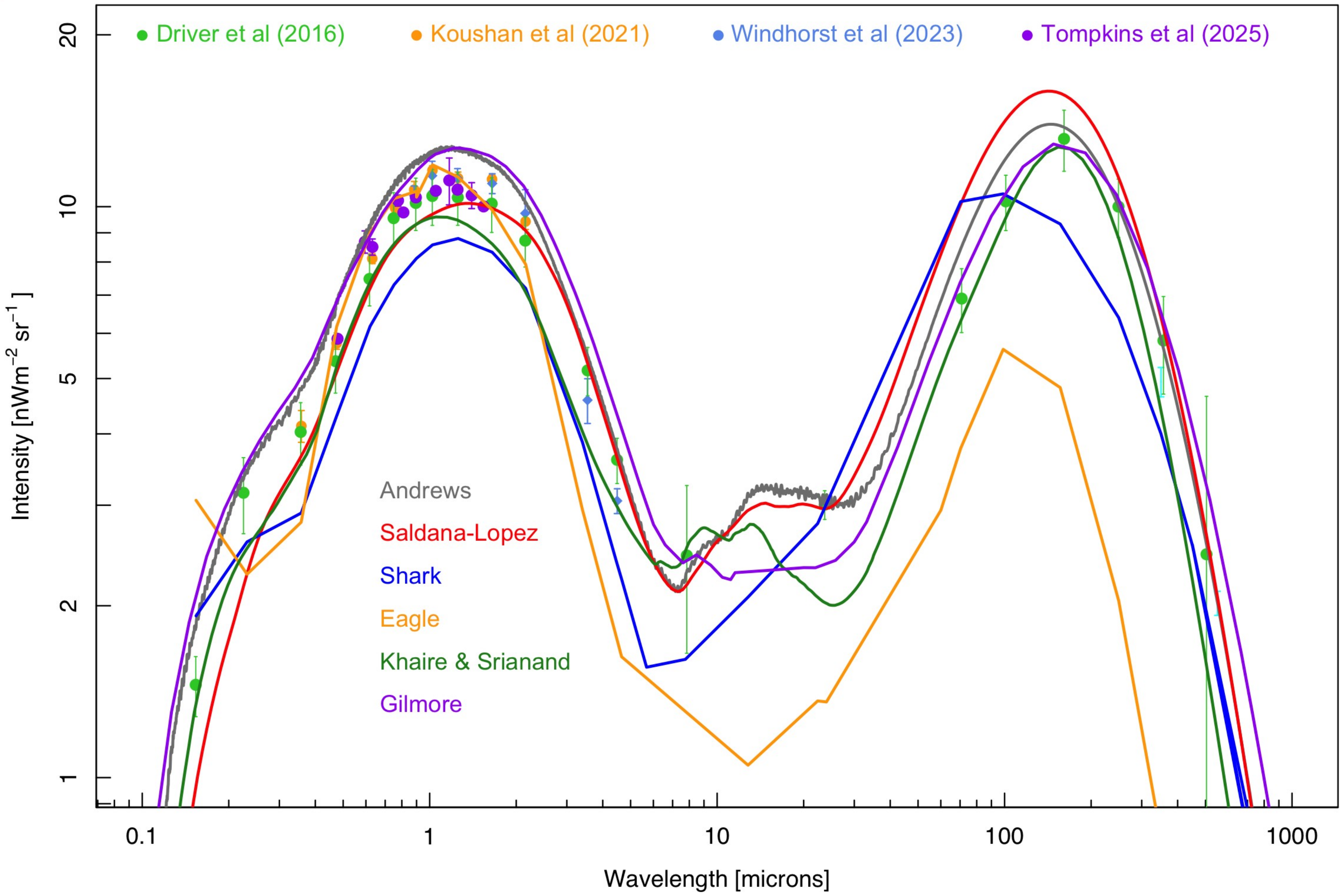
- **JWST DarkSky (Windhorst et al): 0.6 to 4 micron**
- **JWST MIRI (Tompkins et al): 4.9 to 28.8 micron**
- **SphereX: 60 filters from 0.75-5micron**
- **LSST/Euclid/Roman: Deep and wide from 0.3micron to 1.8micron**



Expecting <5% from far-UV to far-IR and <1% from u-H ~3-5years

Part II: Modelling the EBL
(everything everywhere all at once)

The EBL: Current models (incomplete)



The UWA phenomenological IGL/EBL models

Basic concept:

Generate stars with a volume agnostic to their distribution (no clustering info)

For Star-formation:

Adopt a Cosmic Star-Formation History (Madau & Dickinson 2014)

Adopt a standard stellar population synthesis model (Pegace2 or BC03 etc)

Adopt a fixed IMF (Chabrier or Kroupa etc)

Link Z evolution to CSFH (Closed box esque)

Adopt a standard dust processing model (Dale & Helou 2008, Charlot & Fall)

Adding AGN:

Adopt a Cosmic AGN History

Add in obscured and unobscured AGN templates by scaling to AGN history.

> No tuning only choices <

First model: Pegace2, variable Z, Salpeter-lite IMF

- Driver et al 2013, MNRAS, 430, 2622 – Two-component phenomenological model

Second model: BC03, AGN template (dust free & dust obscured), Chabrier IMF

- Andrews et al 2018, MNRAS, 474, 898 – Improved modelling of the EBL and CSED

Third model: ProSpect (BC03, Chabrier IMF, Chabrier & Fall Dust, Fritz AGN)

- Robotham et al 2020, MNRAS, 495, 905 – ProSpect: SED modelling

In development: ProSpect+ProGeny (Any SSP, any IMF, SKIRTOR AGN)

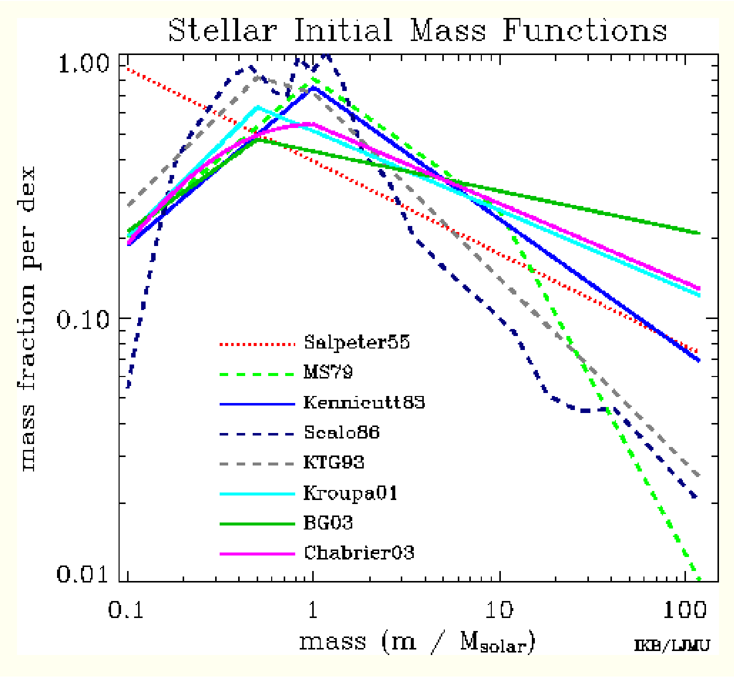
- Robotham et al 2024, MNRAS, submitted – ProGeny: SSP generator

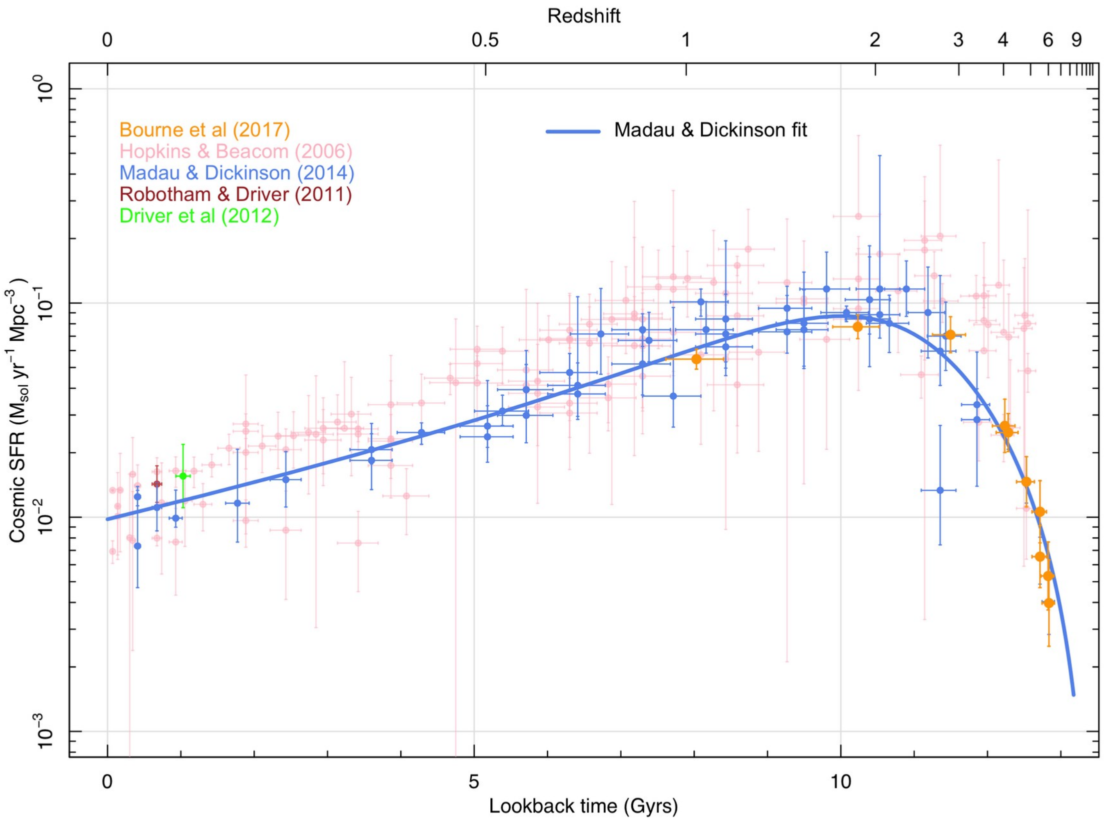
ICRAR

Key ingredients: IMF and CSFH

Universality of IMF unknown

CSFH reconstructed from multiple tracers

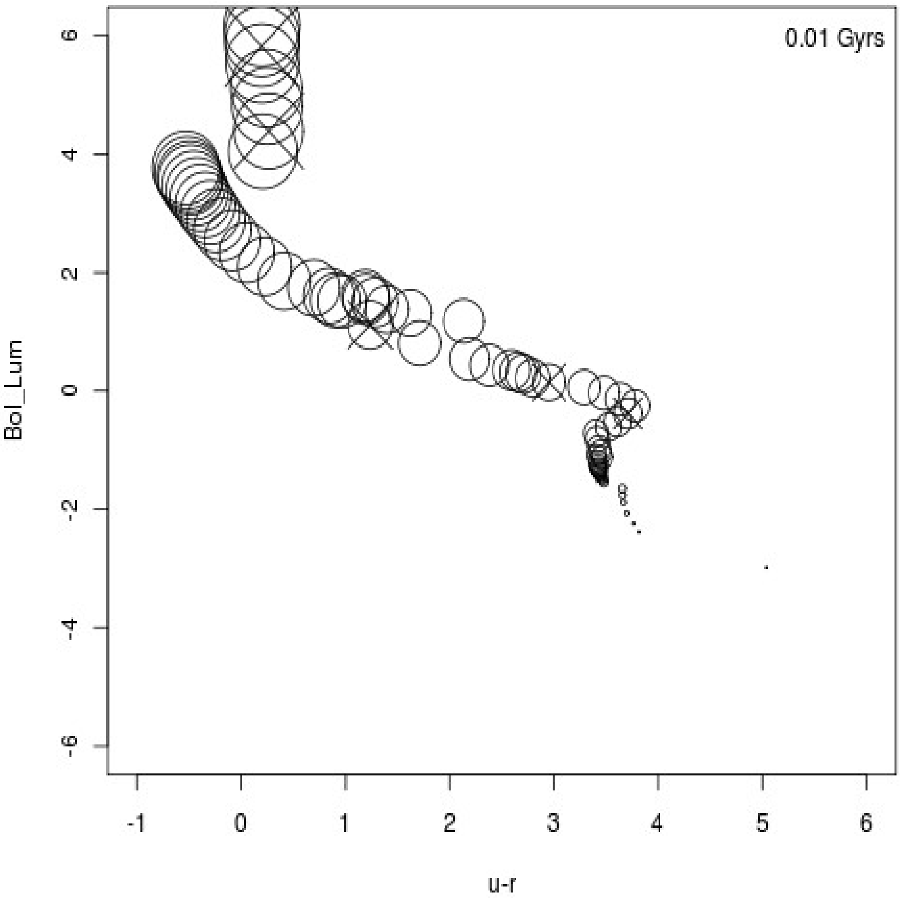




Single stellar population evolution

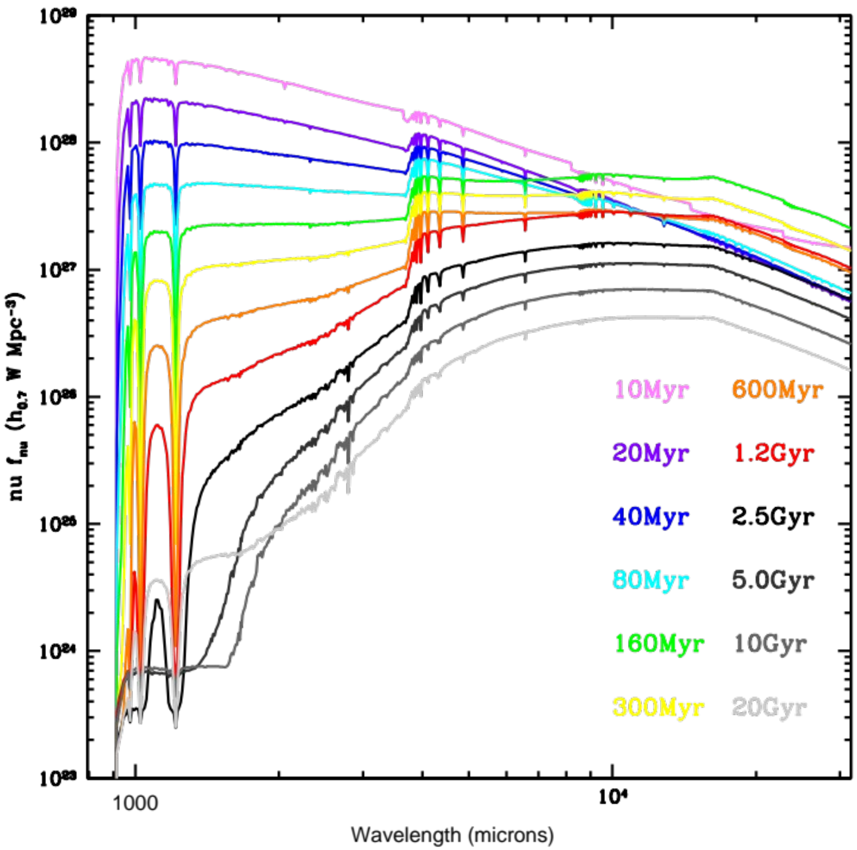
Stellar components incorporated:

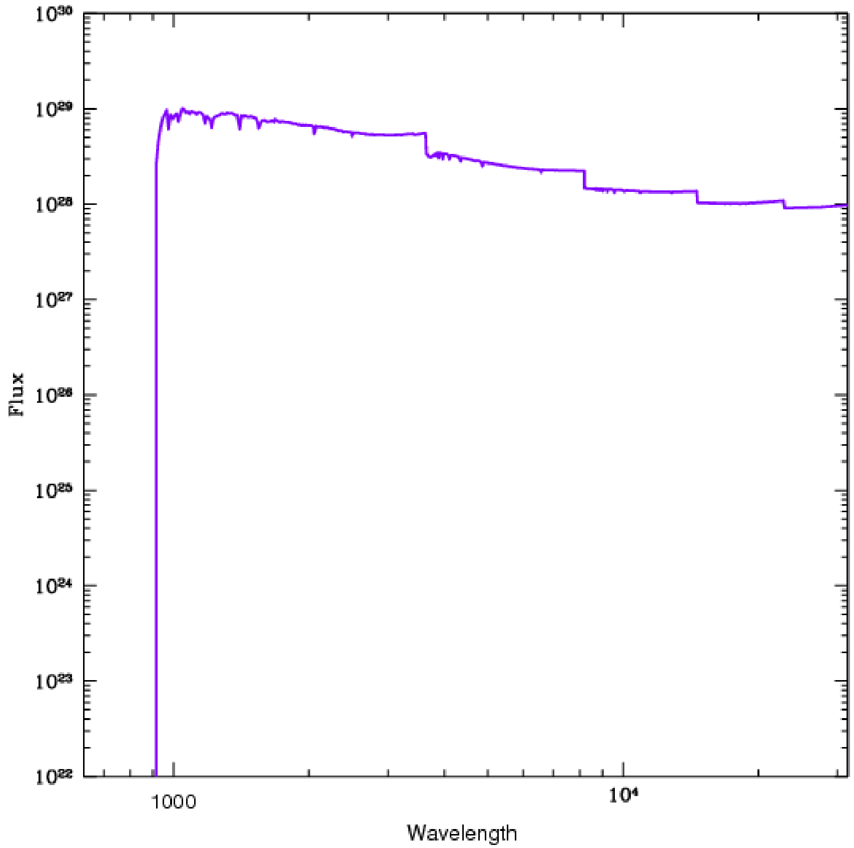
- -1 PMS / Pre main sequence
- 0 MS < 0.7Msol / low-mass main sequence
- 1 MS > 0.7Msol / high-mass main sequence
- 2 SGB / sub-giant branch
- 3 RGB / red giant branch
- 4 HZB / horizontal branch
- 5 EAGB / early asymptotic giant branch // WN / Wolf-Rayet - H rich
- 6 TPAGB / thermal-pulse asymptotic giant branch // LBV - Luminous Blue Variable
- 7 HeMS / Helium main sequence // WN / Wolf-Rayet - He and N dominated
- 8 HeSG / Helium sub-giant // WC / Wolf-Rayet - He, C and O dominated
- 9 HeRG / Helium red giant // proto-planetary nebulae
- 10 HeWD / Helium white dwarf
- 11 COWD / Carbon - Oxygen white dwarf
- 12 ONeW / Oxygen - Neon white dwarf
- 13 NS / neutron star
- 14 BH / black hole
- 15 NR / no remnant



Weidner, Robotham & Wilkins (2011)

SSP isochorones -> time dependent SED

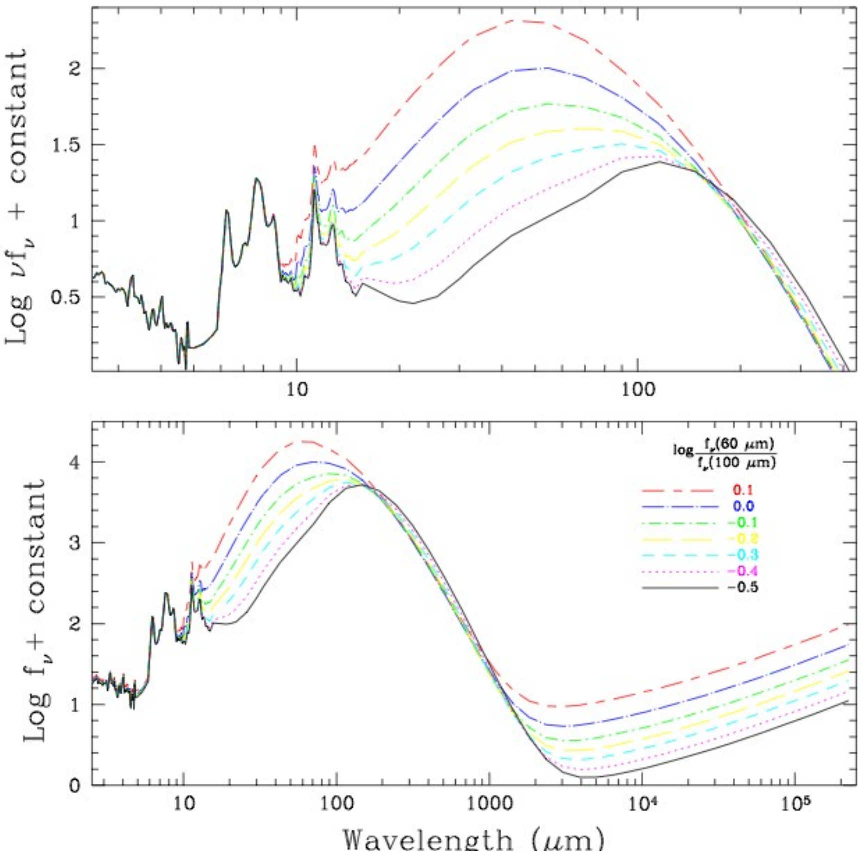




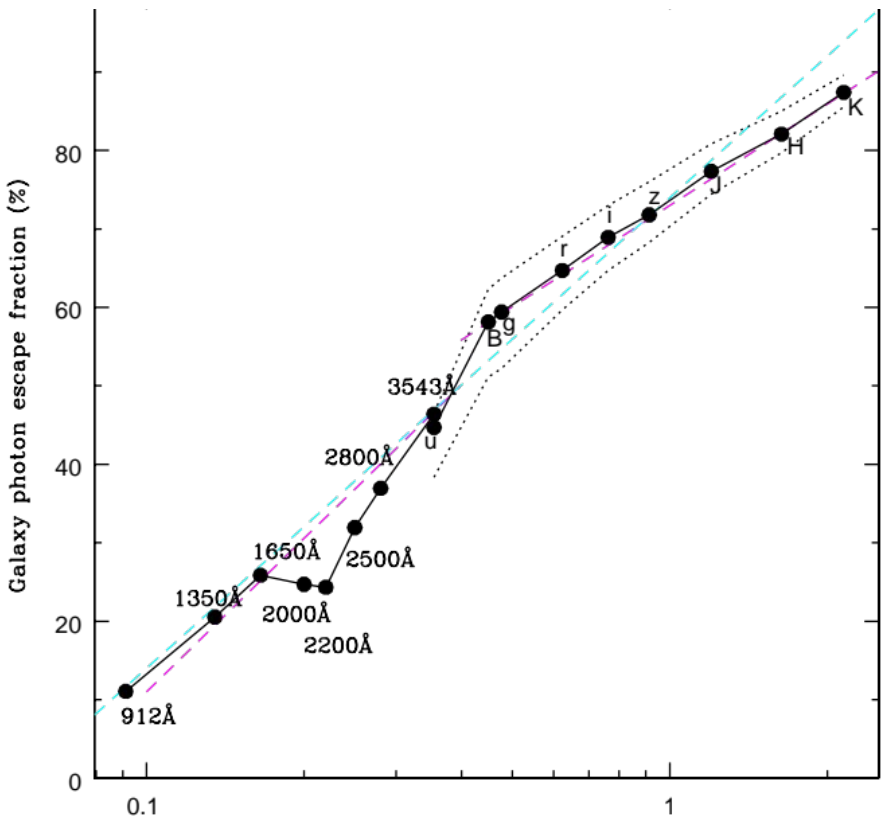
PEGASE: SSP code (Fioc & Rocca-Volmerange 1999)

Adding in the dust attenuation

Charlot & Fall dust attenuation (2000)
Dale & Helou dust templates (2002)

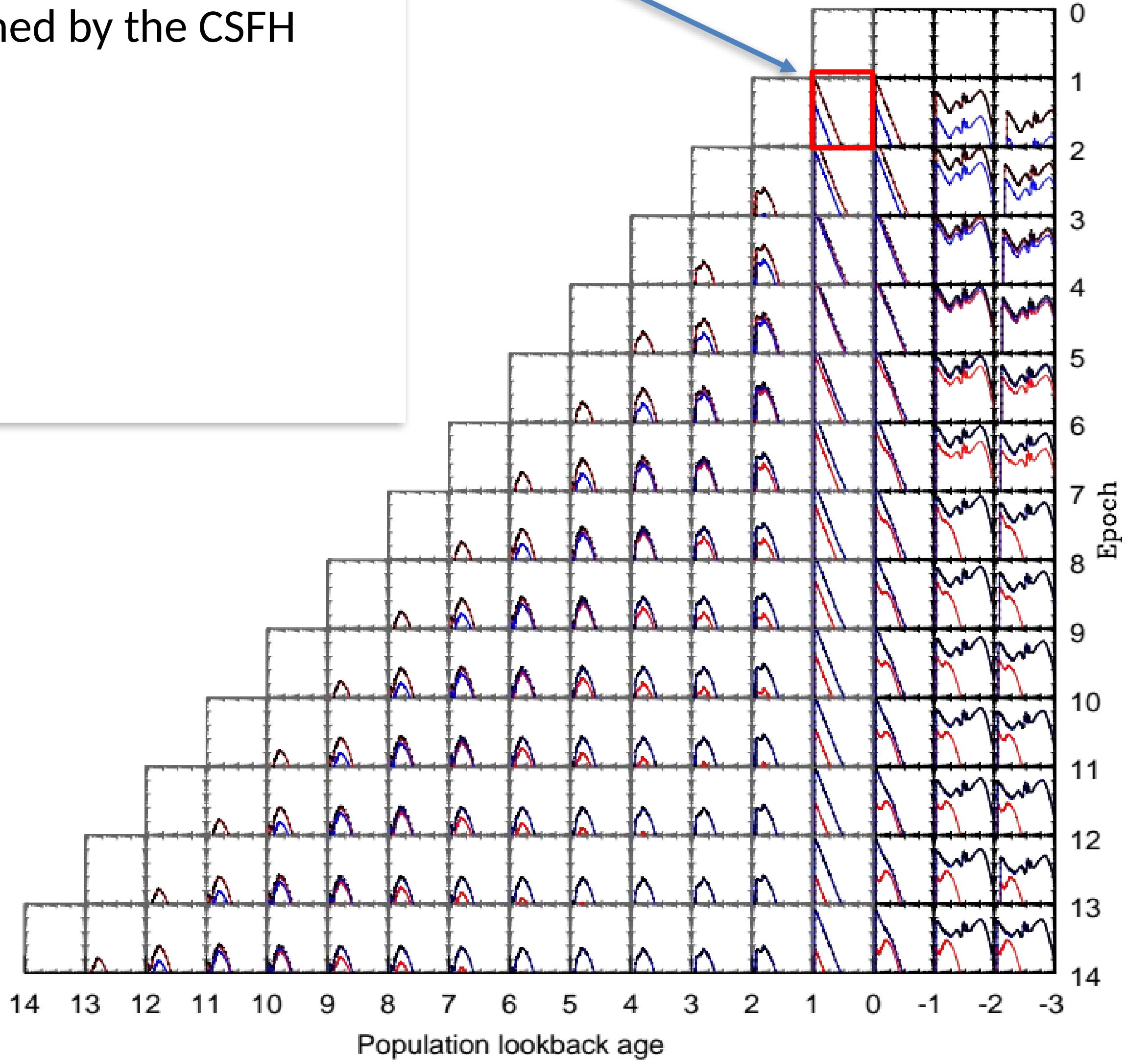


which implies the photon escape fraction



SSP SEDs to EBL construction

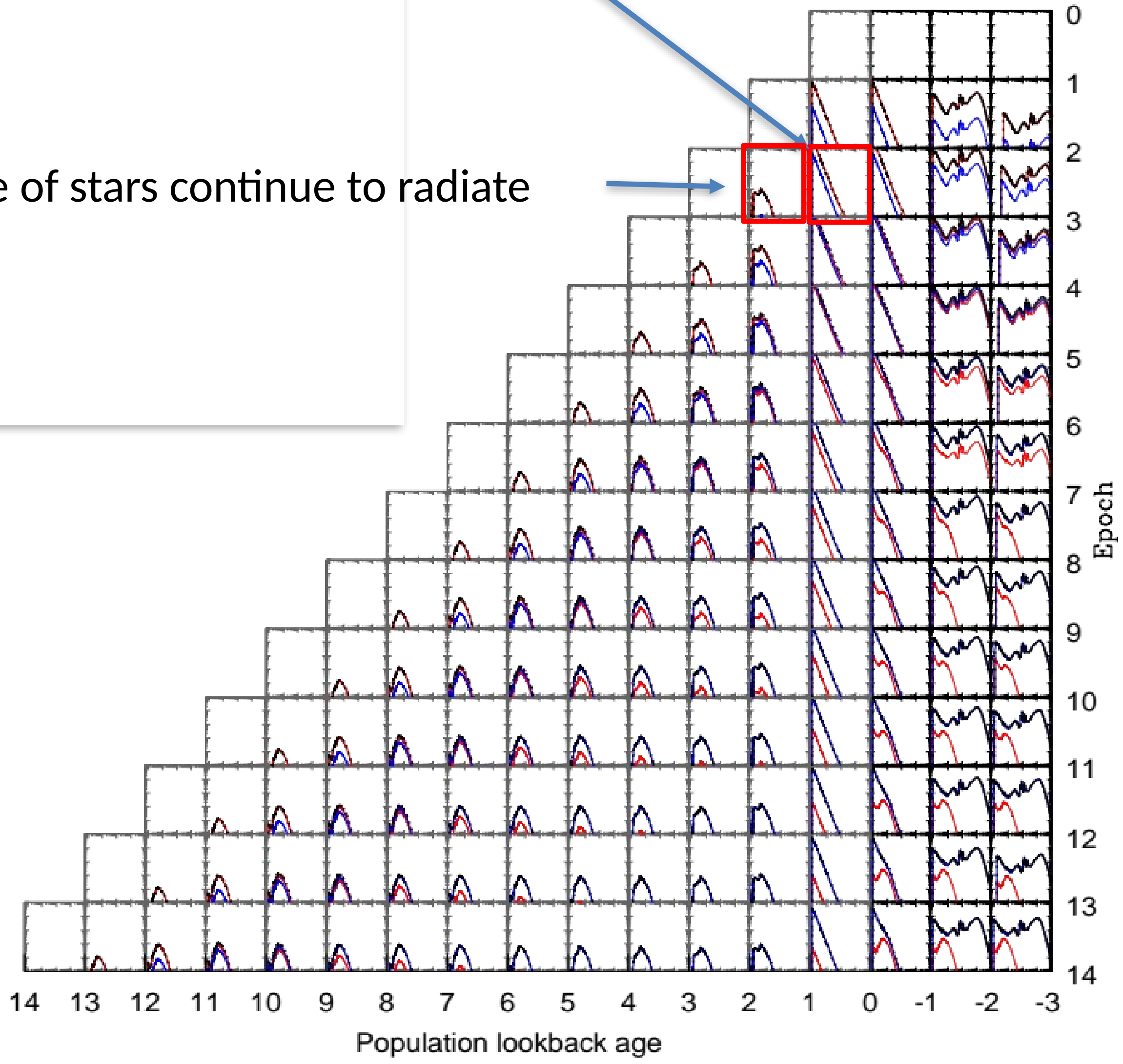
First wave of stars form at high-z
Informed by the CSFH



SSP SEDs to EBL construction

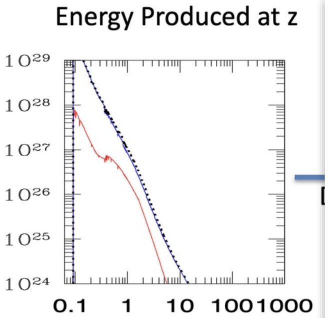
Second wave of stars form at next time step

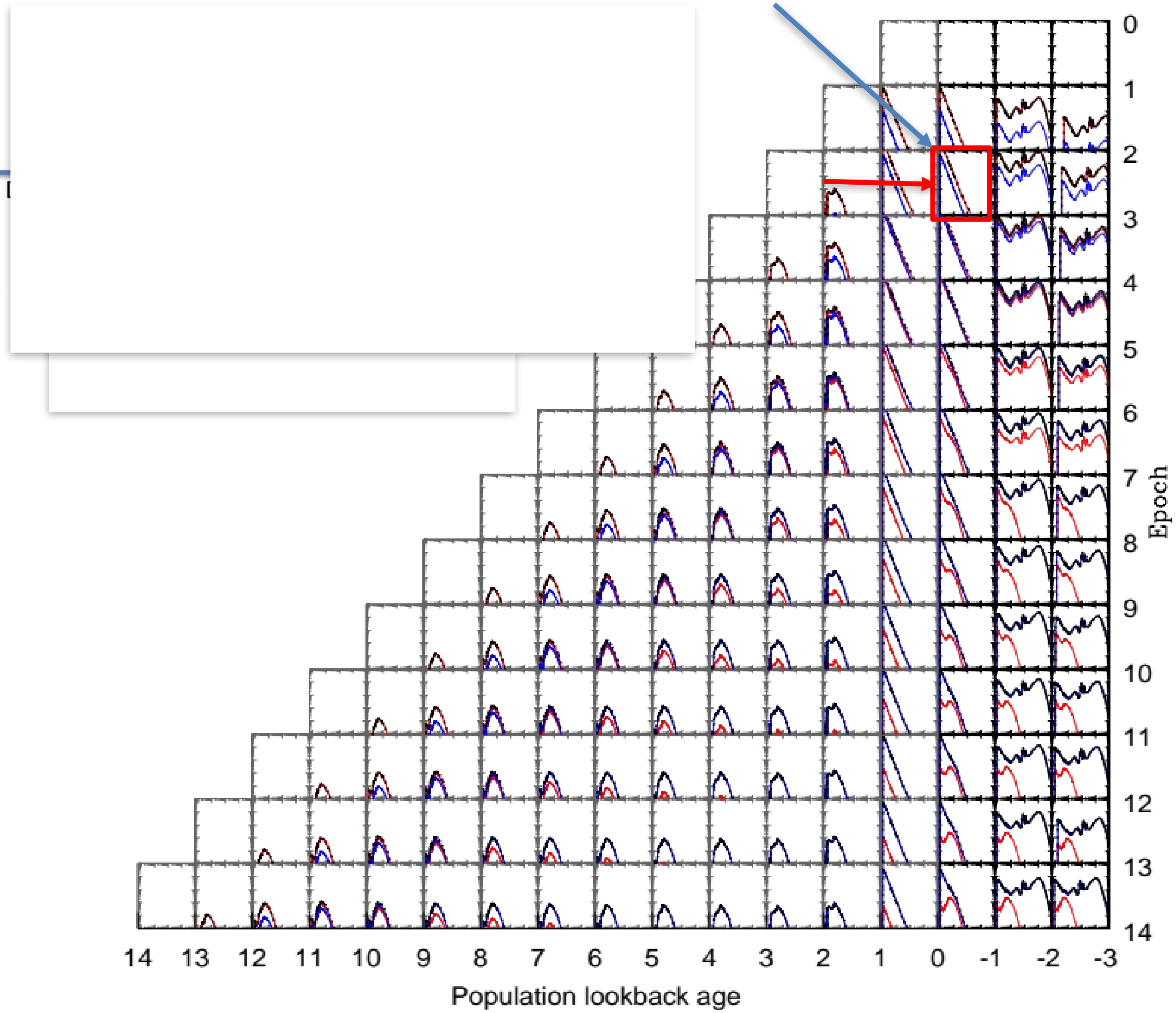
First wave of stars continue to radiate



SSP SEDs to EBL construction

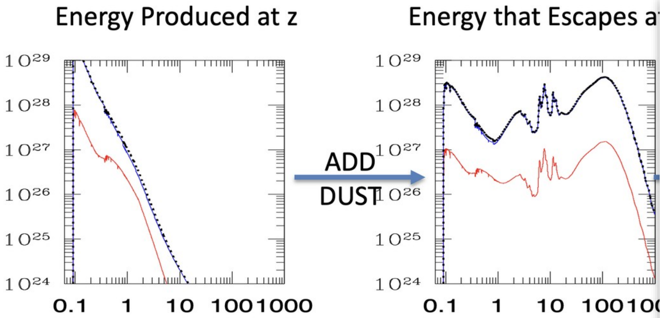
Generated energy in second time step = sum of new and aging SP

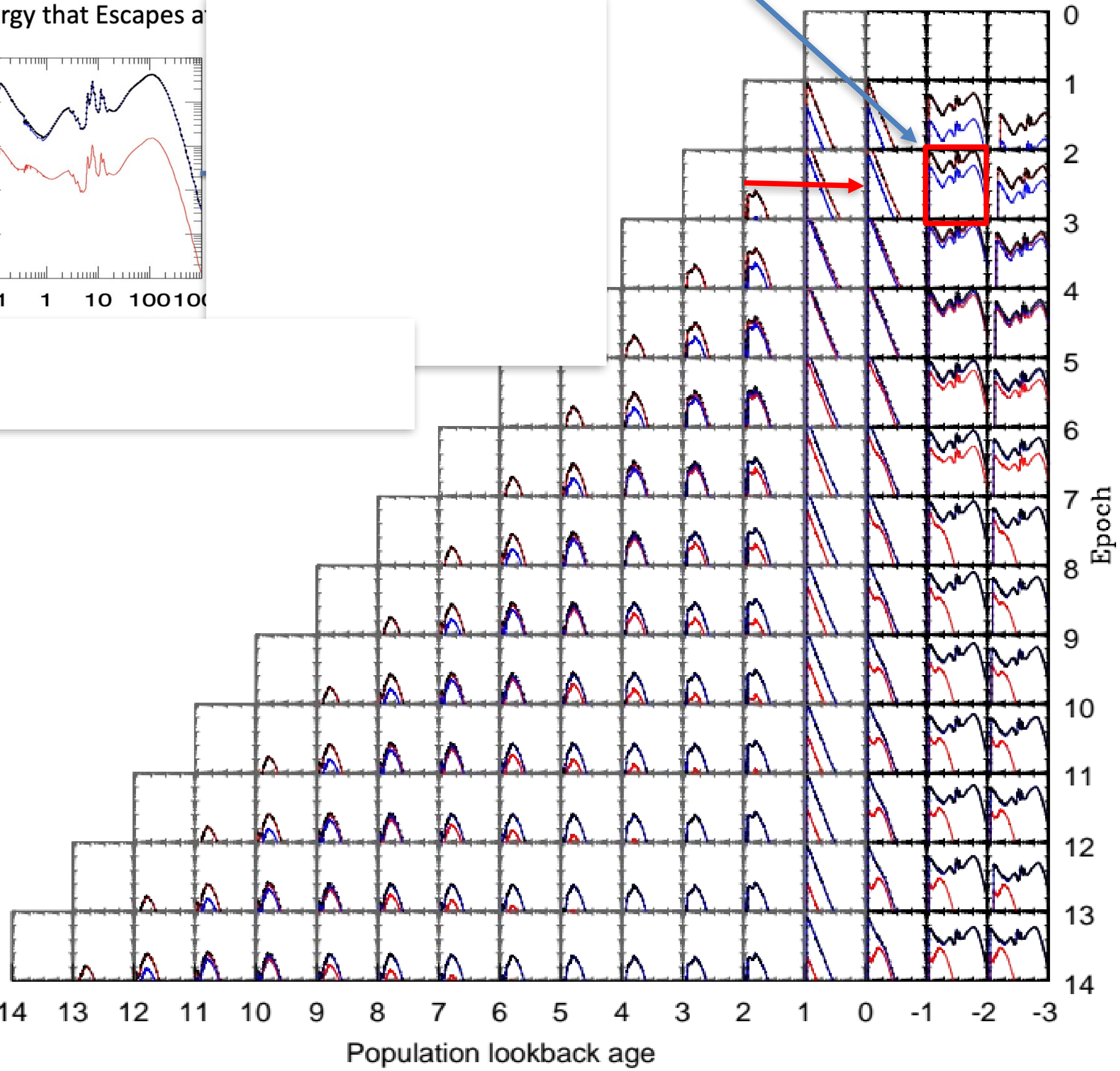




SSP SEDs to EBL construction

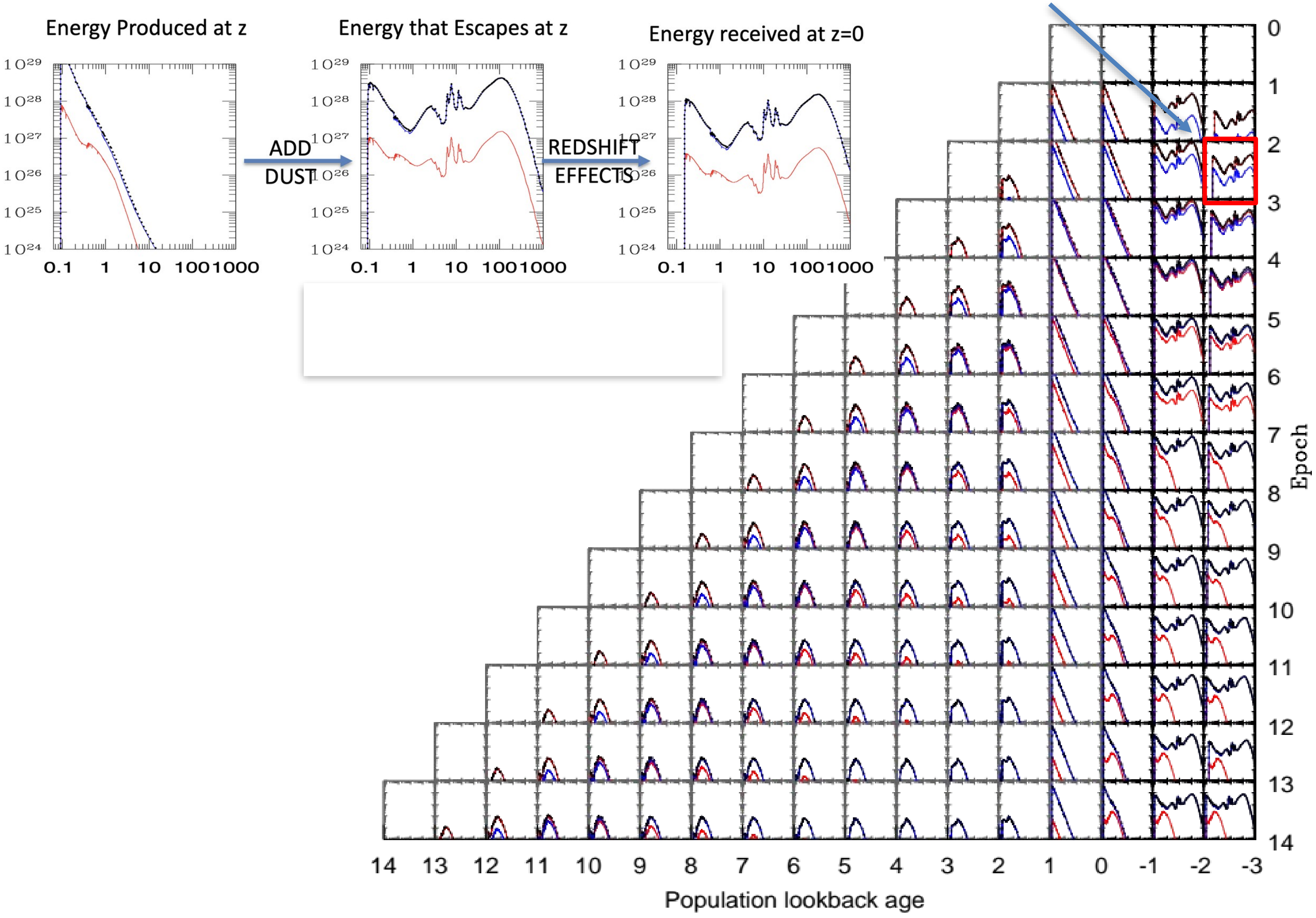
Energy is attenuated by dust redistributing into far-IR



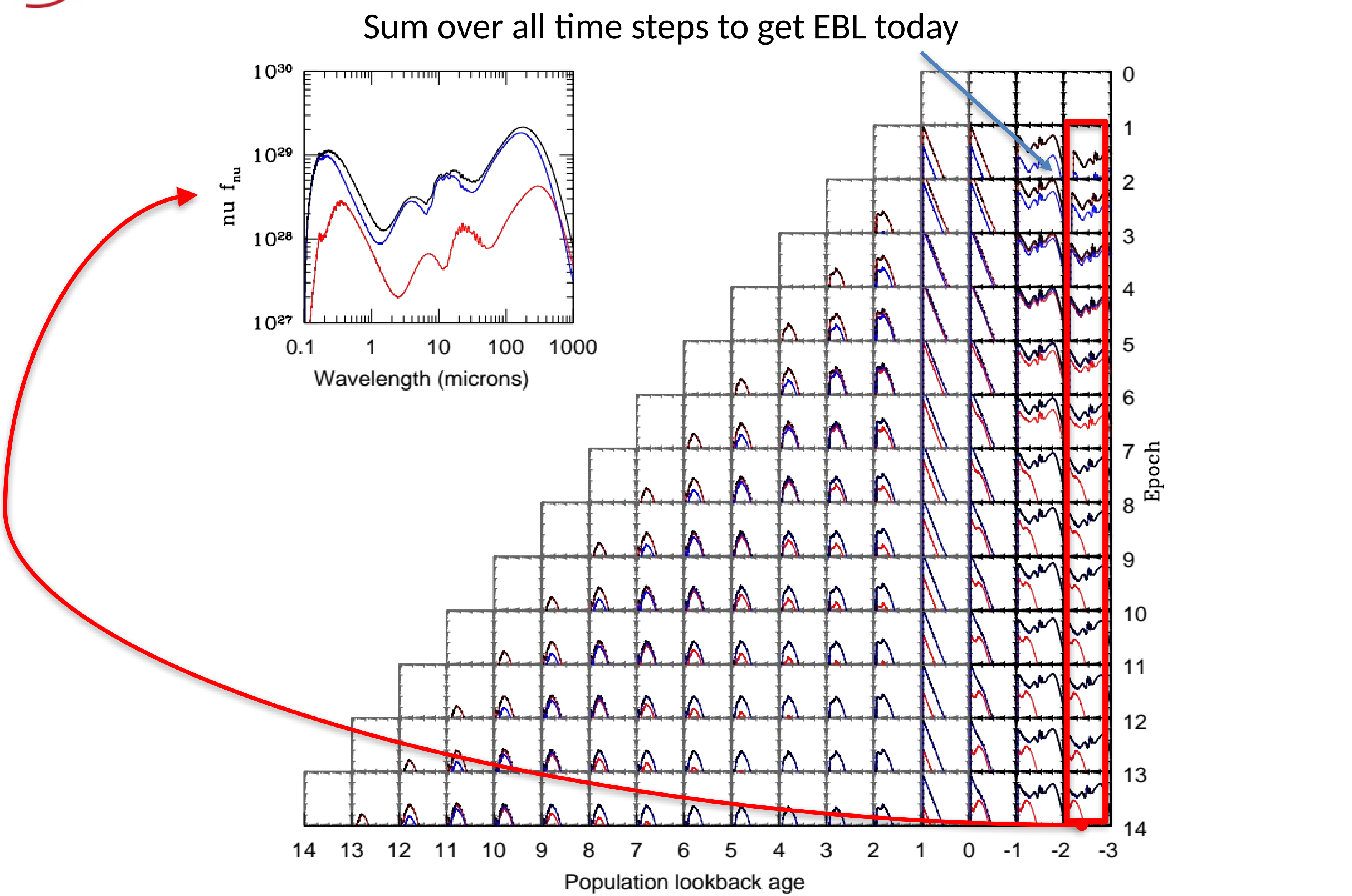


SSP SEDs to EBL construction

Energy we receive from this distant volume is redshift and diminished

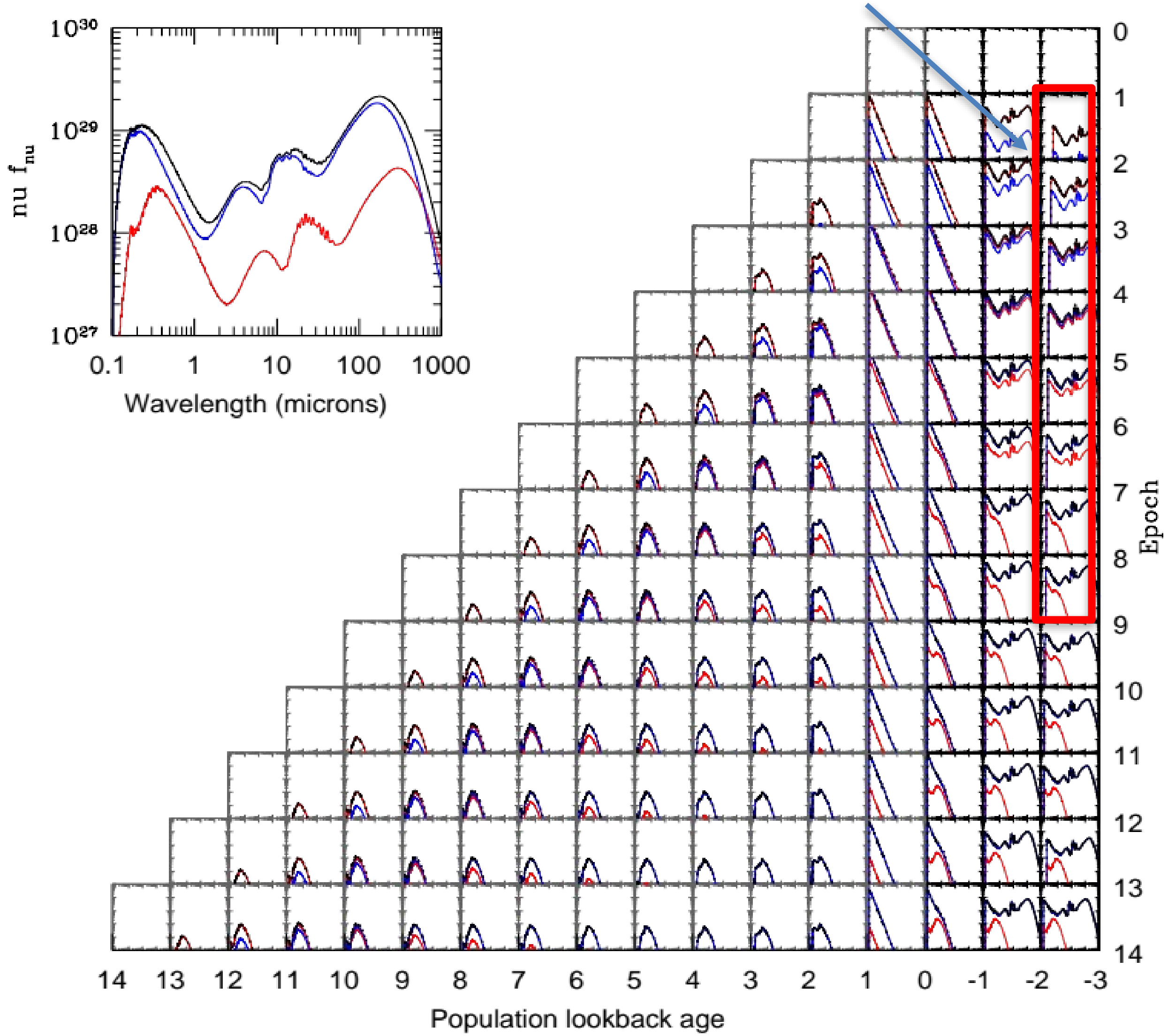


SSP SEDs to EBL construction



SSP SEDs to EBL(z) construction

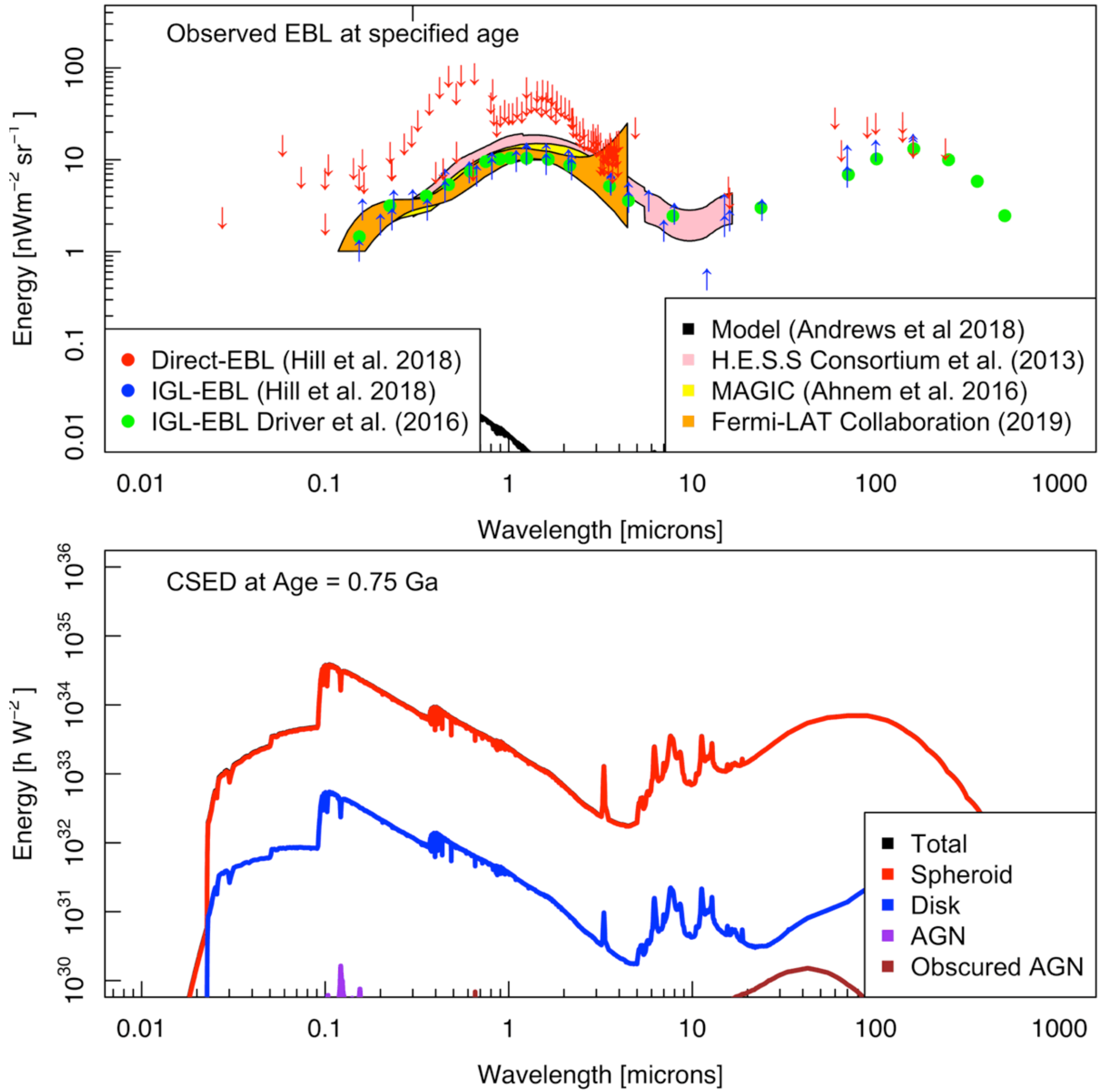
Sum over all time steps to get EBL today (or to any epoch)



Putting it together

Cumulative EBL as a function of redshift

Instantaneous energy production with redshift



Andrews et al (2018)

New EBL model based on *ProSpect* and *Progeny*

ProGeny I: a new simple stellar population generator and impact of isochrones / stellar atmospheres / initial mass functions

A. S. G. Robotham[1]* & S. Bellstedt[1]

Capacity to add/modify SSPs:

- Stellar atmosphere libraries

Library	log(Age / Myr)	N (Age)	log(Z/Z$_\odot$)	N (Z)	N (All)
MIST	5 – 10.3	107	-4 – 0.5	15	1,494,453
PARSEC	6.6 – 10.1	36	-2 – 0.5	27	340,909
BaSTI	7.3 – 10.3	30	-3.2 – 0.45	21	1,299,900

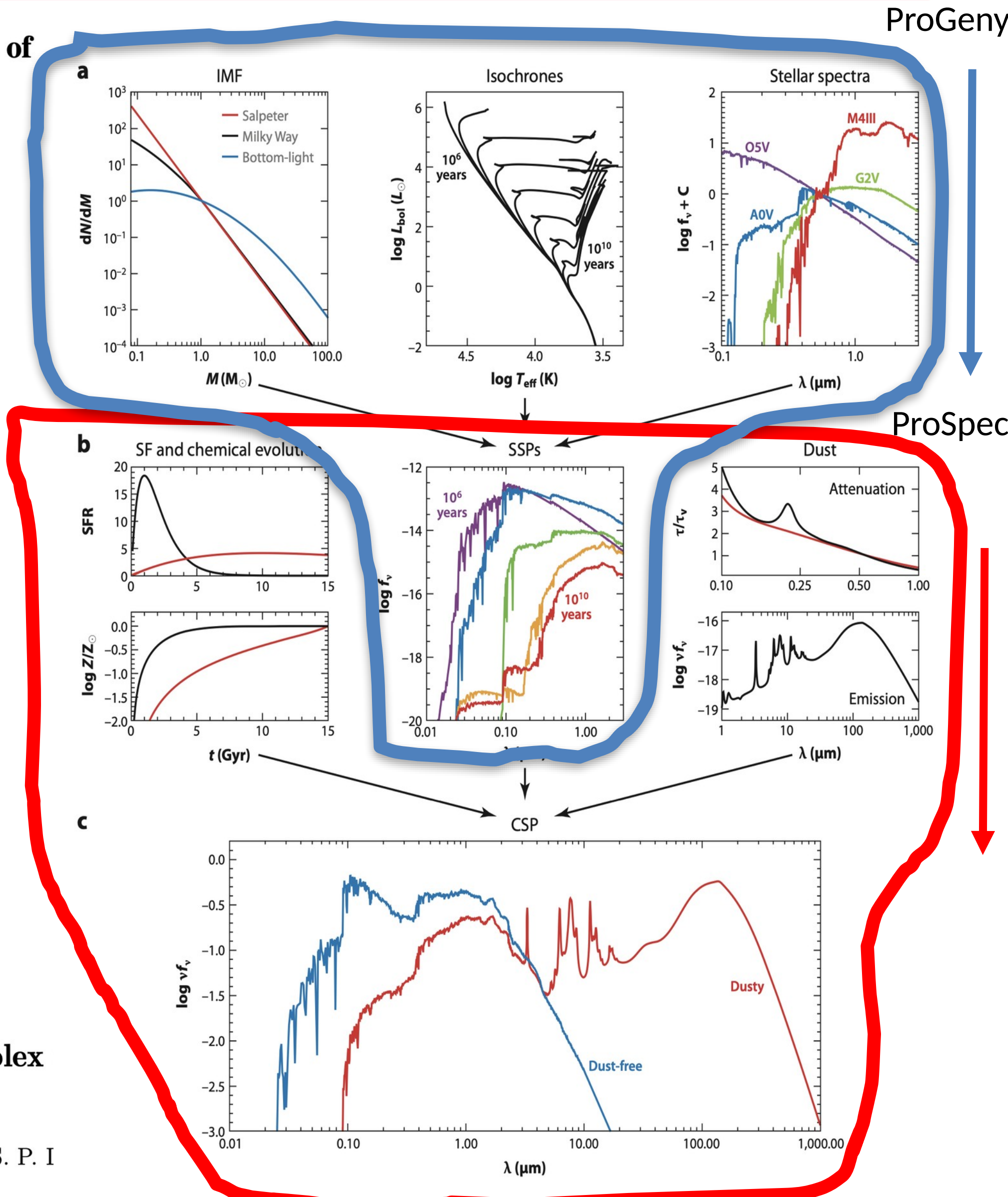
- Isochrones

Library	Type Teff (K)	logG	logZ	N	Reference	
C3K (Conroy)	Base	2,000 – 50,000	-1 – 5.5	-2.1 – 0.5	8,602	Conroy et al. (2018)
PHOENIX (Husser)	Base	2,300 – 12,000	0 – 6	-4 – 1	7,559	Husser et al. (2013)
PHOENIX (Allard)	Extend	2,000 – 70,000	0 – 5.5	-4 – 0.5	12,045	Allard et al. (2012)
MILES (Vazdekis)	Alternative	2,000 – 50,000	-1 – 5.5	-1.4 – 0.2	3,915	Vazdekis et al. (2010)
BaSeL (WLBC)	Alternative	2,000 – 50,000	-1 – 5.5	-2 – 0.5	4,649	Westera et al. (2002)
ATLAS9 (Castelli)	Alternative	2,000 – 50,000	-1 – 5.5	-1 – 0.5	2,735	Castelli & Kurucz (2003)
AGB (Lacon)	AGB	2,000 – 4,000	NA	NA	14	Lançon & Mouhcine (2002)
TMAP (Werner)	Hot (inc. white dwarfs)	20,000 – 190,000	5 – 9	NA	124	Werner et al. (2003)

- IMFs

Name	Isochrones	Spectra	IMF	log(Age/Myr)	N (Age)	log(Z/Z$_\odot$)	N (Z)	Reference
BC03	Padova	STELIB	Chabrier	0 – 10.3	221	-2.3 – 0.4	6	Bruzual & Charlot (2003)
CB19	PARSEC	MILES	Chabrier	0 – 10.15	221	-2.3 – 0.5	15	Plat et al. (2019)
BPASS	STARS	BaSeL	Chabrier	6 – 11	51	-3.3 – 0.3	13	Stanway & Eldridge (2018)
M05	Maraston	Mixture	Kroupa	3 – 10.18	67	-1.3 – 0.3	4	Maraston (2005)
FSPS	MIST	Padova	Chabrier	5.5 – 10.15	94	-2 – 0.2	22	Conroy et al. (2009)
EMILES	BaSTI / Padova	MILES	Chabrier	7.48 – 10.15	53	2.3 – 0.3	12	Vazdekis et al. (2016)

- Generate SEDs given a CSFH
- Measure M*, SFH, Z, M_{DUST} etc
- Reconstruct CSFH from SED

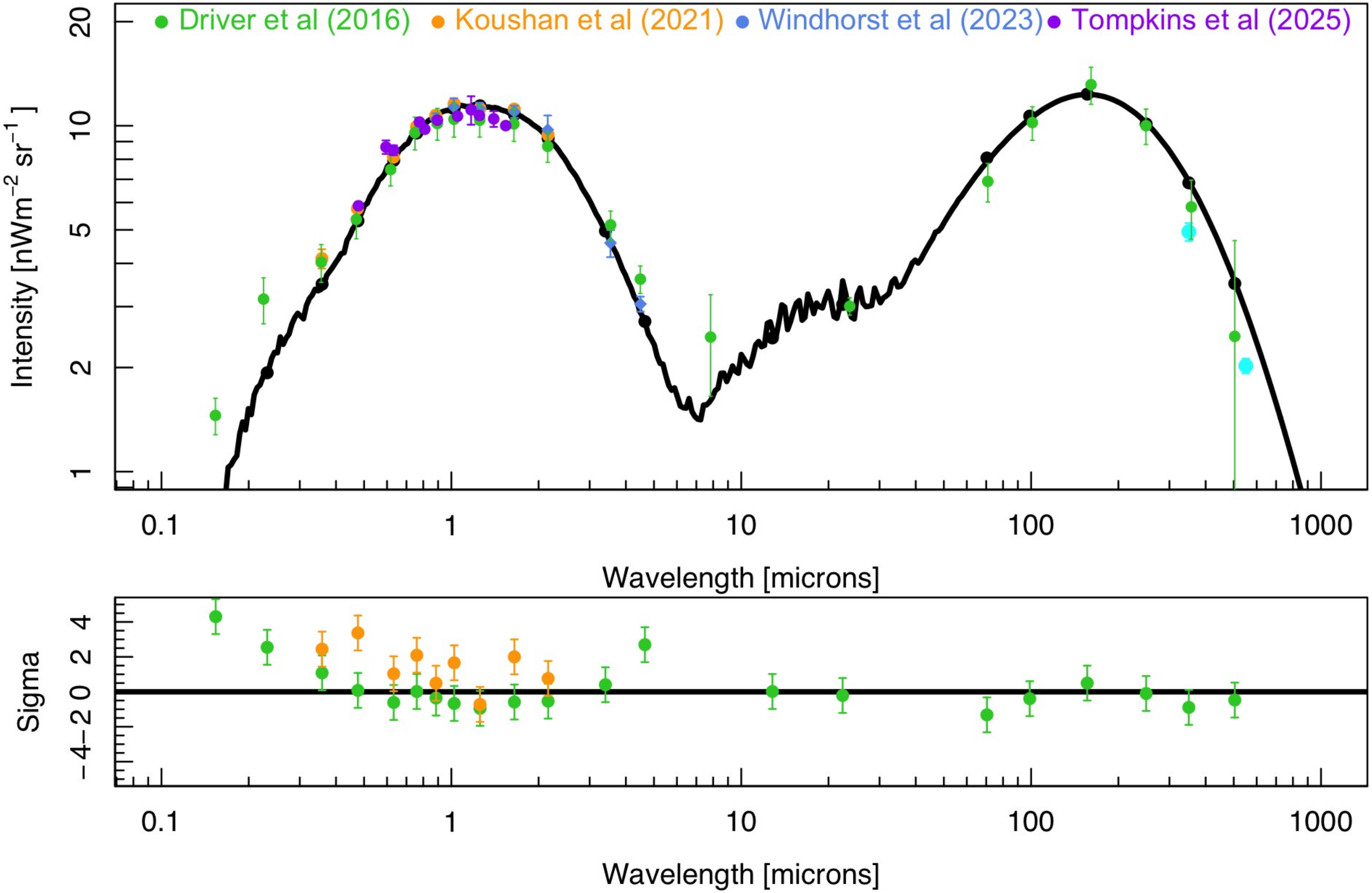


ProSpect: Generating Spectral Energy Distributions with Complex Formation and Metallicity Histories

A. S. G. Robotham,[1,2]* S. Bellstedt,[1] C. del P. Lagos,[1,2] J. E. Thorne,[1] L. J. Davies,[1] S. P. I M. Bravo[1]

ProSpect model: No free parameters!

MD14 + Chabrier IMF + Evolving Z + Charlot & Fall



Part III: The CSFH and CAGNH (critical model ingredients and dependencies)

Review of the CSFH from multiple methods

MD14 based on combination of indicators?

GAMA/G10-COSMOS/3D-HST: The $0 < z < 5$ cosmic star-formation history, stellar- and dust-mass densities

Simon P. Driver[1,2*], Stephen K. Andrews[1], Elisabete da Cunha[3], Luke J. Davies[1], Claudia Lagos[1], Aaron S.G. Robotham[1,2], Kevin Vinsen[1], Angus H. Wright[1], Mehmet Alpaslan[4], Joss Bland-Hawthorn[5], Nathan Bourne[6], Sarah Brough[7], Malcolm N. Bremer[8], Michelle Cluver[9], Matthew Colless[3], Christopher J. Conselice[9] Loretta Dunne[6,10], Steve A. Eales[10], Haley Gomez[10] Benne Holwerda[11], Andrew M. Hopkins[12], Prajwal R. Kafle[1], Lee S. Kelvin[13], Jon Loveday[14], Jochen Liske[15], Steve J. Maddox[6,10], Steven Phillipps[8], Kevin Pimbblet[16], Kate Rowlands[17], Anne E. Sansom[18], Edward Taylor[19], Lingyu Wang[20], Stephen M. Wilkins[14]

MagPhys analysis (SED fitting) of 600,000 galaxies from GAMA/COSMOS and 3DHST

Galaxy And Mass Assembly (GAMA): A forensic SED reconstruction of the cosmic star formation history and metallicity evolution by galaxy type

Sabine Bellstedt,[1*] Aaron S. G. Robotham,[1,2] Simon P. Driver,[1,3] Jessica E. Thorne,[1] Luke J. M. Davies,[1] Claudia del P. Lagos,[1,2] Adam R. H. Stevens,[1,2] Edward N. Taylor,[4] Ivan K. Baldry,[5] Amanda J. Moffett,[6] Andrew M. Hopkins,[7] Steven Phillipps[8]

Forensic reconstruction of full CSFH from 6000 z<0.06 galaxies

GAMA/DEVILS: Cosmic star formation and AGN activity over 12.5 billion years

Jordan C. J. D'Silva,[1,2*] Simon P. Driver,[1] Claudia D. P. Lagos,[1,2] Aaron S. G. Robotham,[1,2] Sabine Bellstedt,[1] Luke J. M. Davies,[1] Jessica E. Thorne,[1] Joss Bland-Hawthorn,[3,2] Matias Bravo,[4] Benne Holwerda,[5] Steven Phillipps,[6] Nick Seymour,[7] Malgorzata Siudek,[8,9] Rogier A. Windhorst,[10]

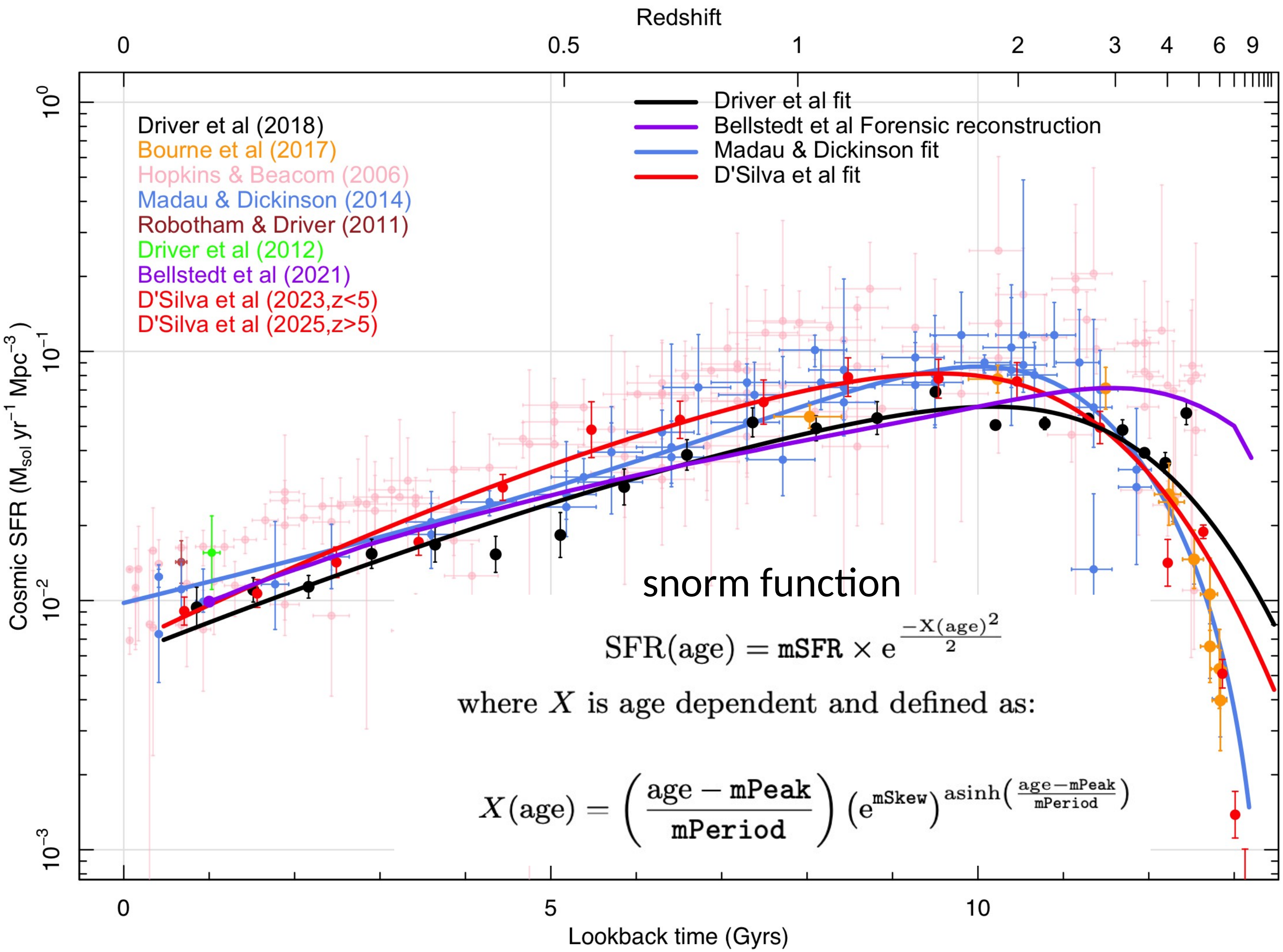
ProSpect analysis of 400,000 galaxies from GAMA and DEVILS

Self-Consistent JWST Census of Star Formation and AGN activity at $z = 5.5 - 13.5$

Jordan C. J. D'Silva,[1,2] Simon P. Driver,[1] Claudia D. P. Lagos,[1,2] Aaron S. G. Robotham,[1] Nathan J. Adams,[3] Christopher J. Conselice,[3] Nimish P. Hathi,[4] Thomas Harvey,[3] Rafael Ortiz III,[5] Clayton Robertson,[6] Ross M. Silver,[7] Stephen M. Wilkins,[8] Christopher N. A. Willmer,[9] Rogier A. Windhorst,[5] Seth H. Cohen,[5] Rolf A. Jansen,[5] Jake Summers,[5] Anton M. Koekemoer,[10] Dan Coe,[10,11,12] Brenda Frye,[13] Norman A. Grogin,[10] Madeline A. Marshall,[14] Mario Nonino,[15] Nor Pirzkal,[10] Russell E. Ryan, Jr.,[10] and Haojing Yan[16]

SED fitting of over 100,000 galaxies in JWST PEARLS+CEERS+JADES+PRIMER+NGDEEP 400sq arcmin, 100k galaxies

CSFH is the primary ingredient



snorm function

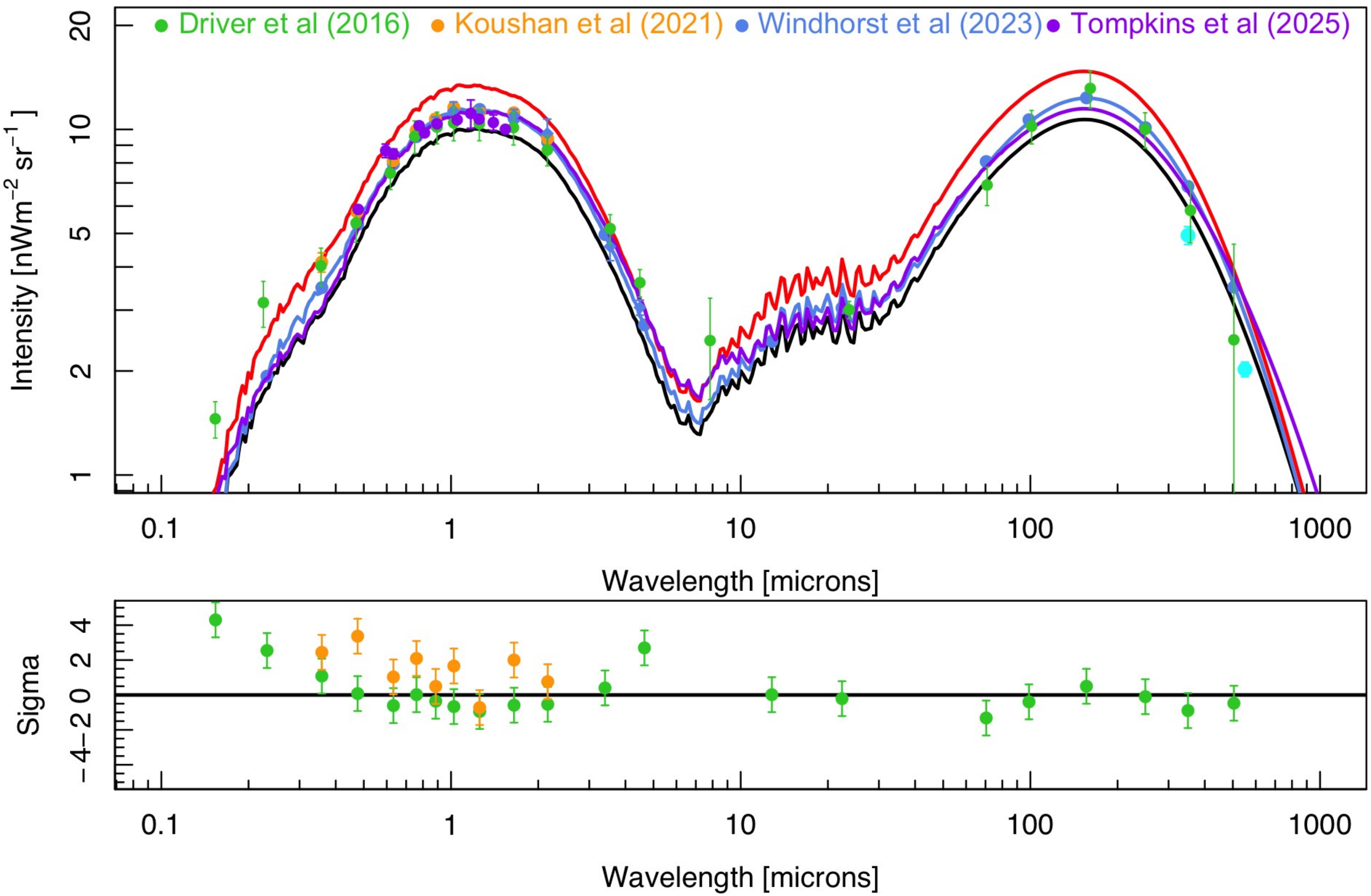
$$\mathrm{SFR(age)} = \mathtt{mSFR} \times e^{\frac{-X(\mathrm{age})^2}{2}}$$

where X is age dependent and defined as:

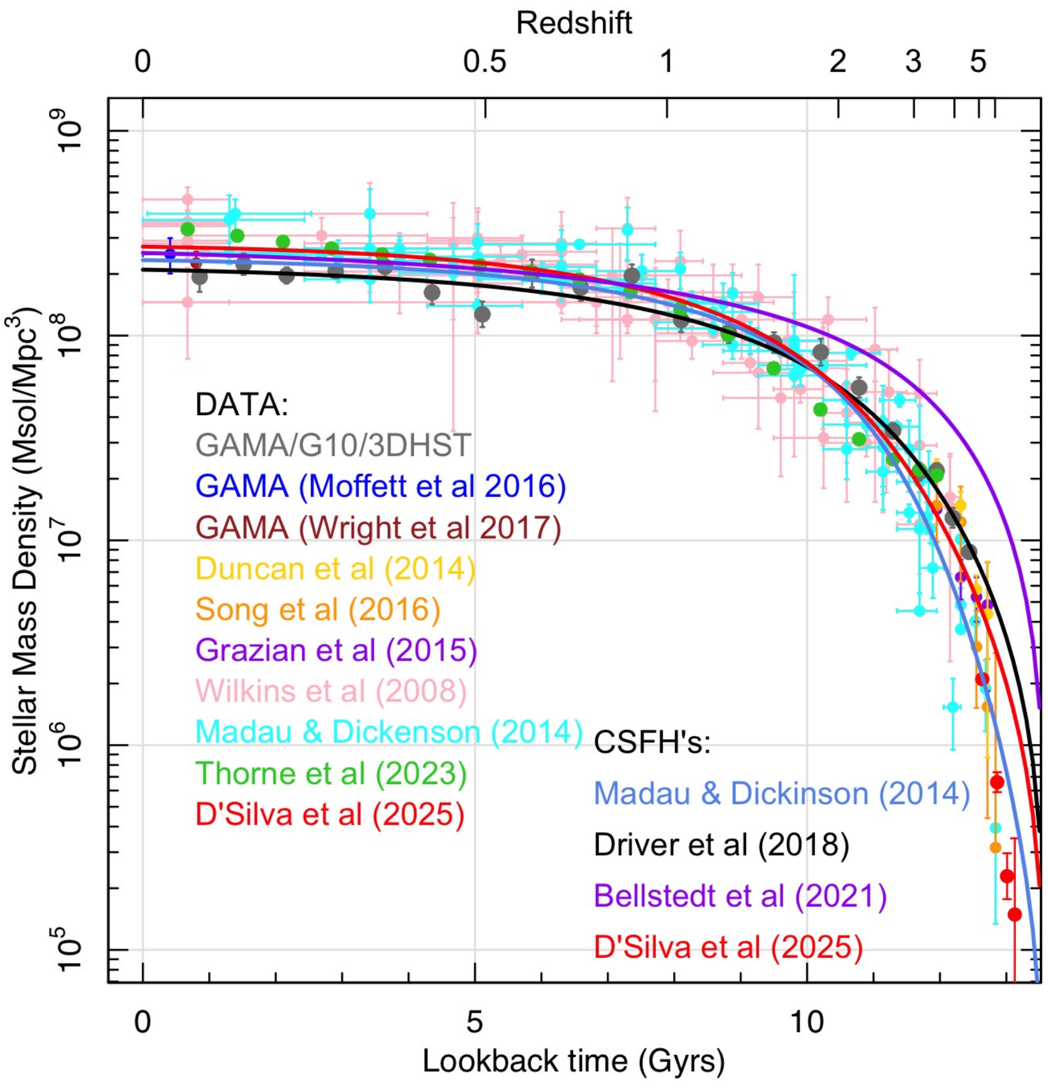
$$X(\mathrm{age}) = \left(\frac{\mathrm{age} - \mathtt{mPeak}}{\mathtt{mPeriod}}\right) \left(e^{\mathtt{mSkew}}\right)^{\mathrm{asinh}\left(\frac{\mathrm{age}-\mathtt{mPeak}}{\mathtt{mPeriod}}\right)}$$

ProSpect model:

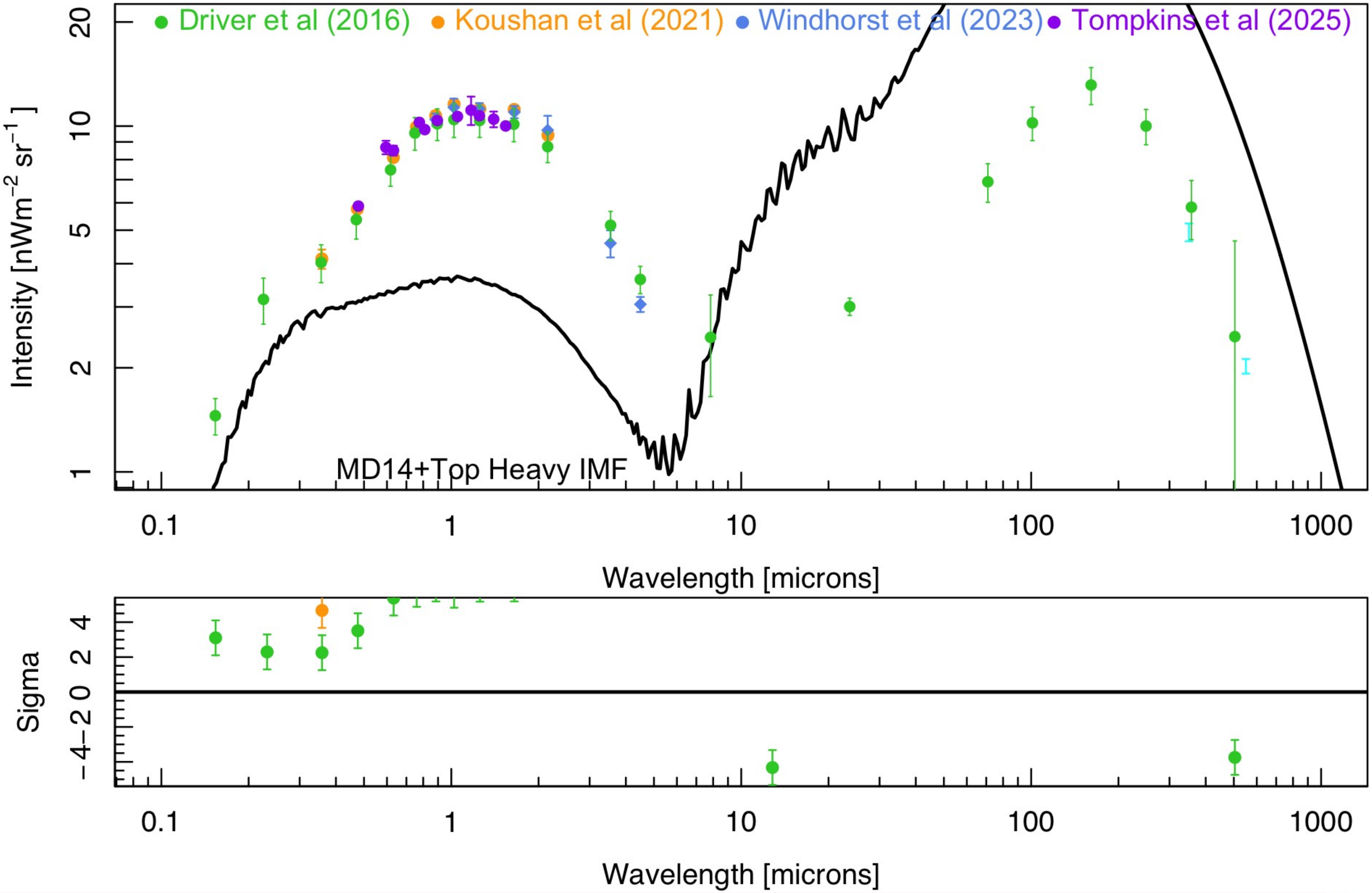
MD14 + Chabrier IMF + Evolving Z + Charlot & Fall



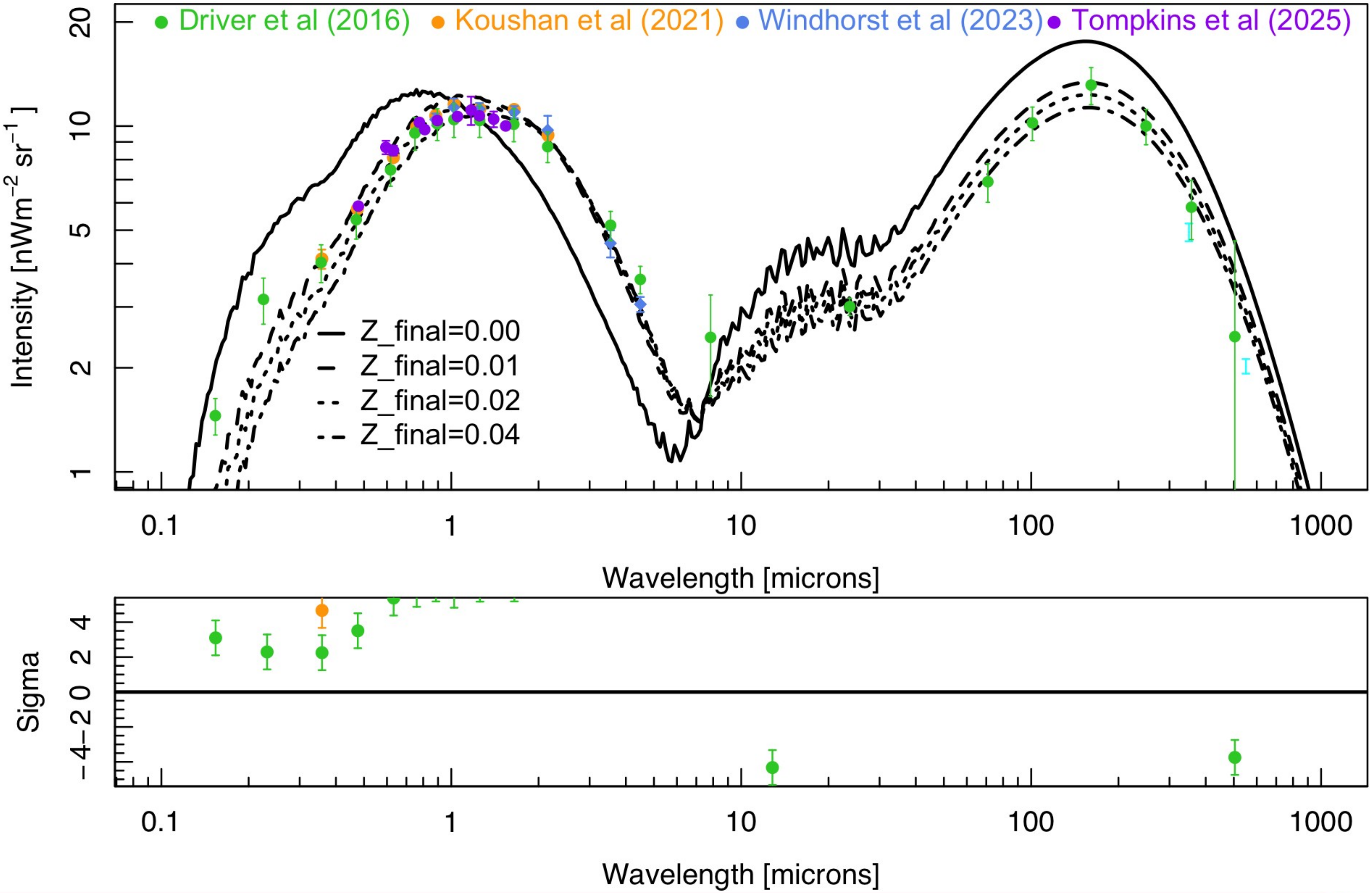
ProSpect stellar mass build-up



MD14 and varying the IMF

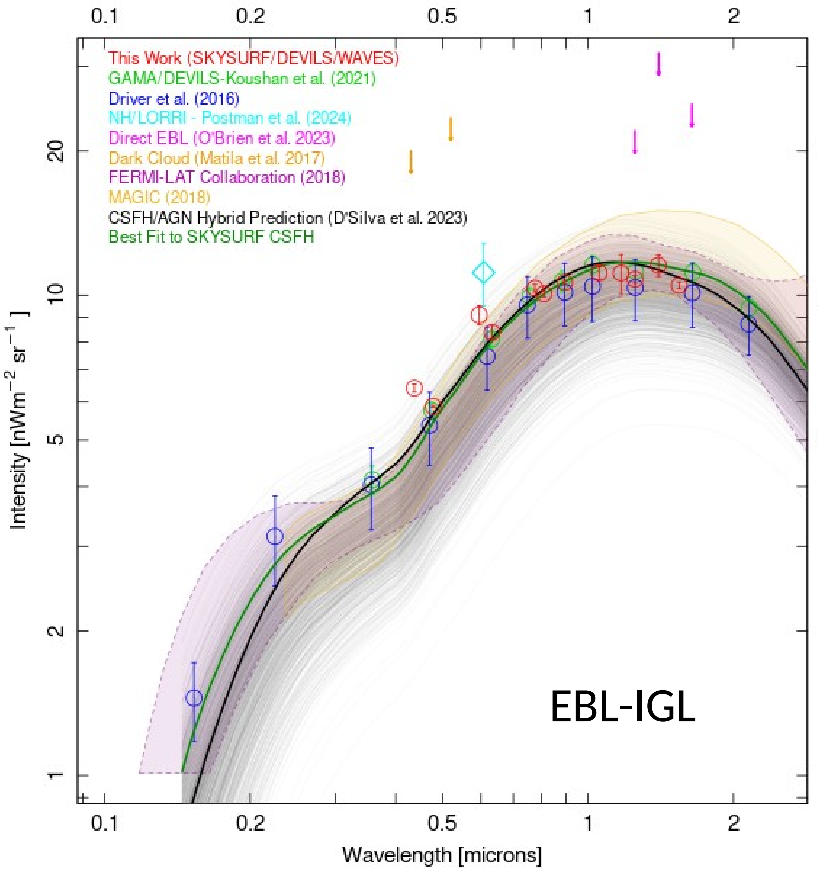


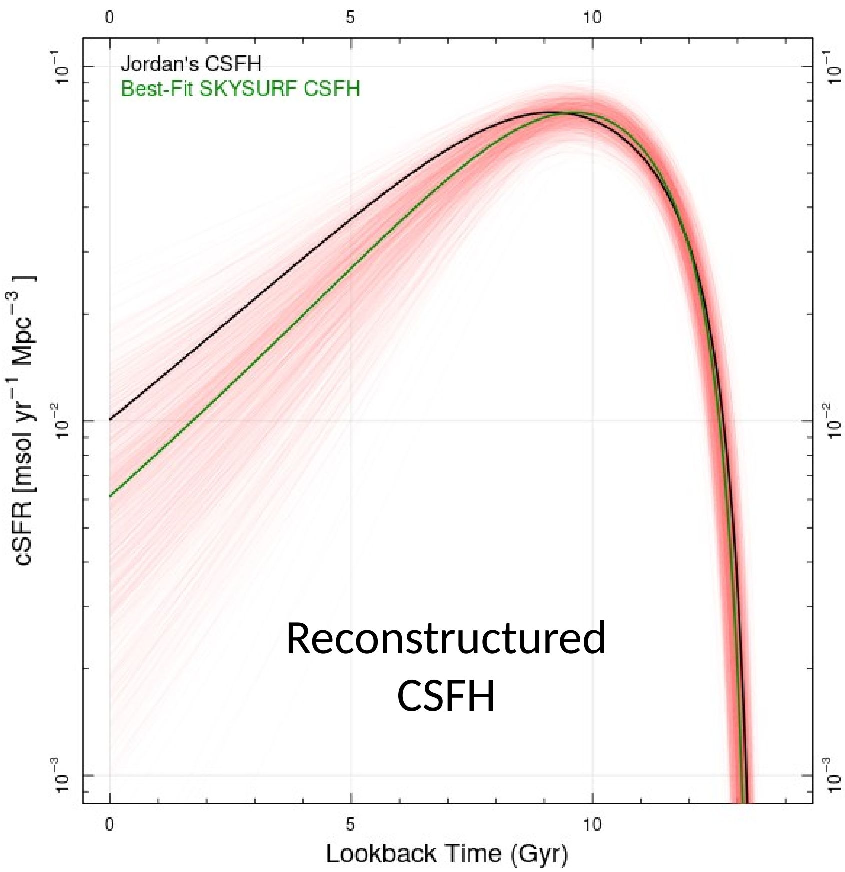
MD14 and varying final Z



Can we reconstruct the CSFH from the EBL

Work in progress (Tompkins et al) but promising



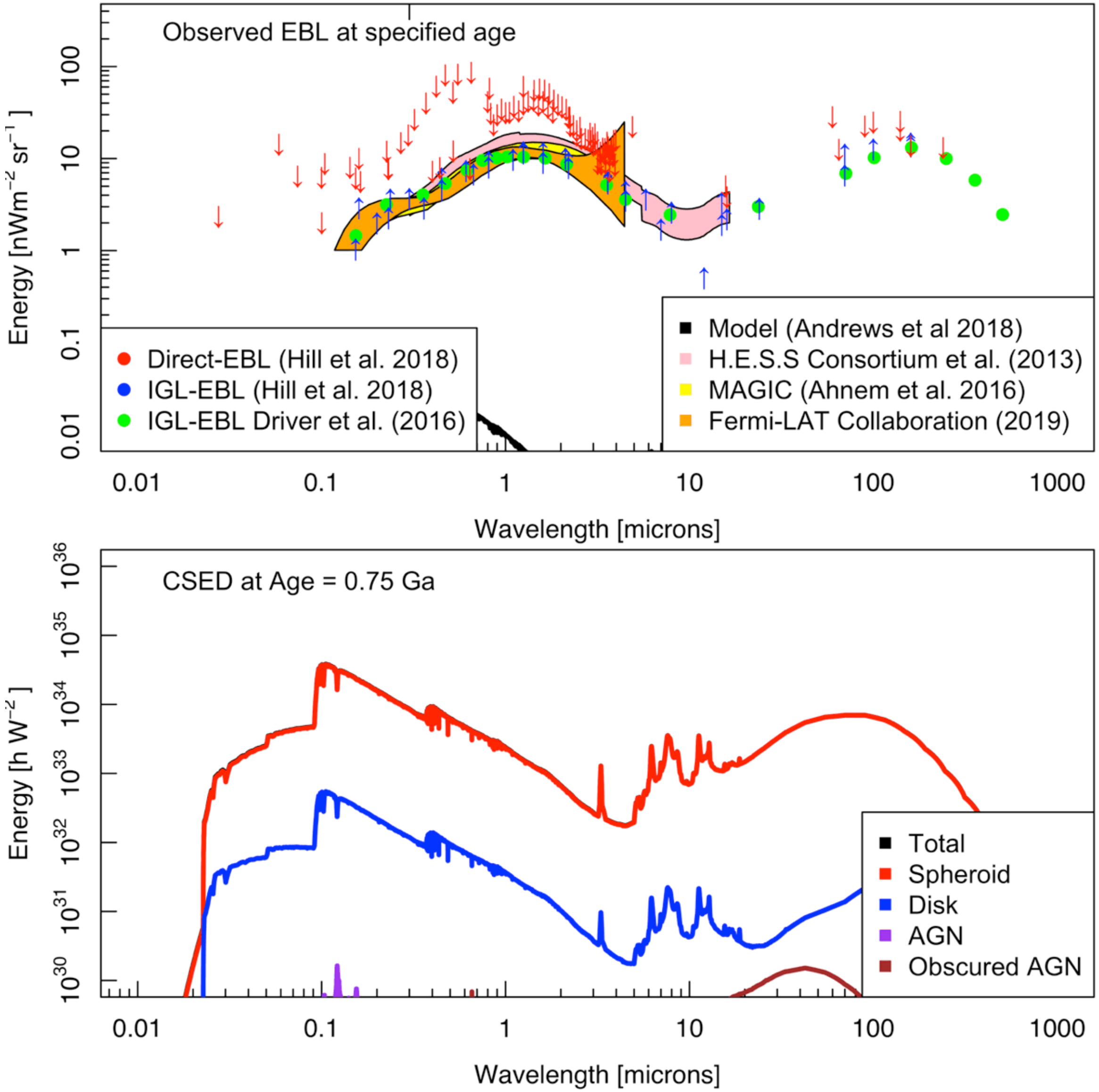


Part IV: The Cosmic Spectral Energy Distribution (CSED):

The EBL and the CSED

Cumulative EBL as a function of redshift

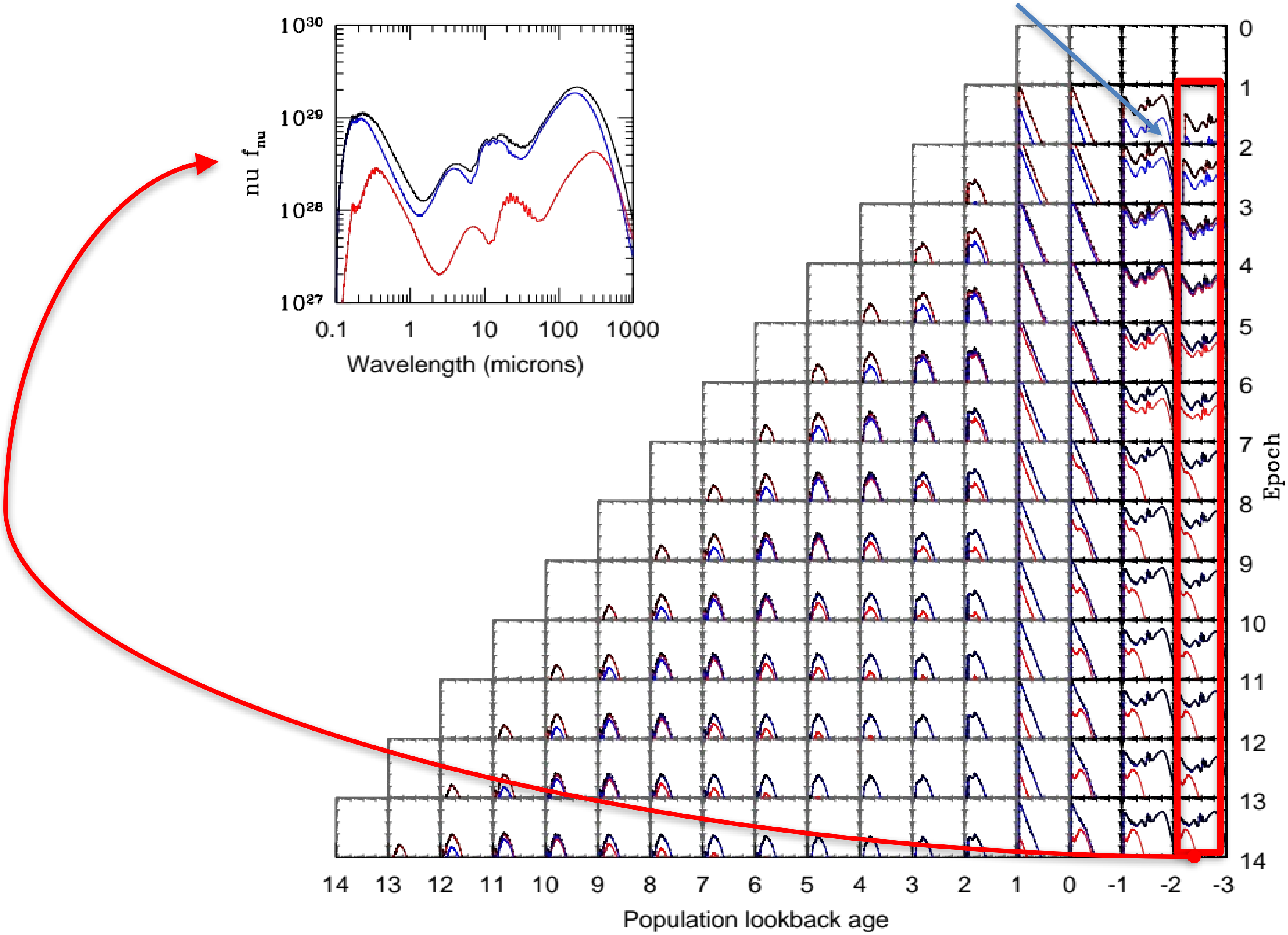
Instantaneous energy production with redshift



Andrews et al (2018)

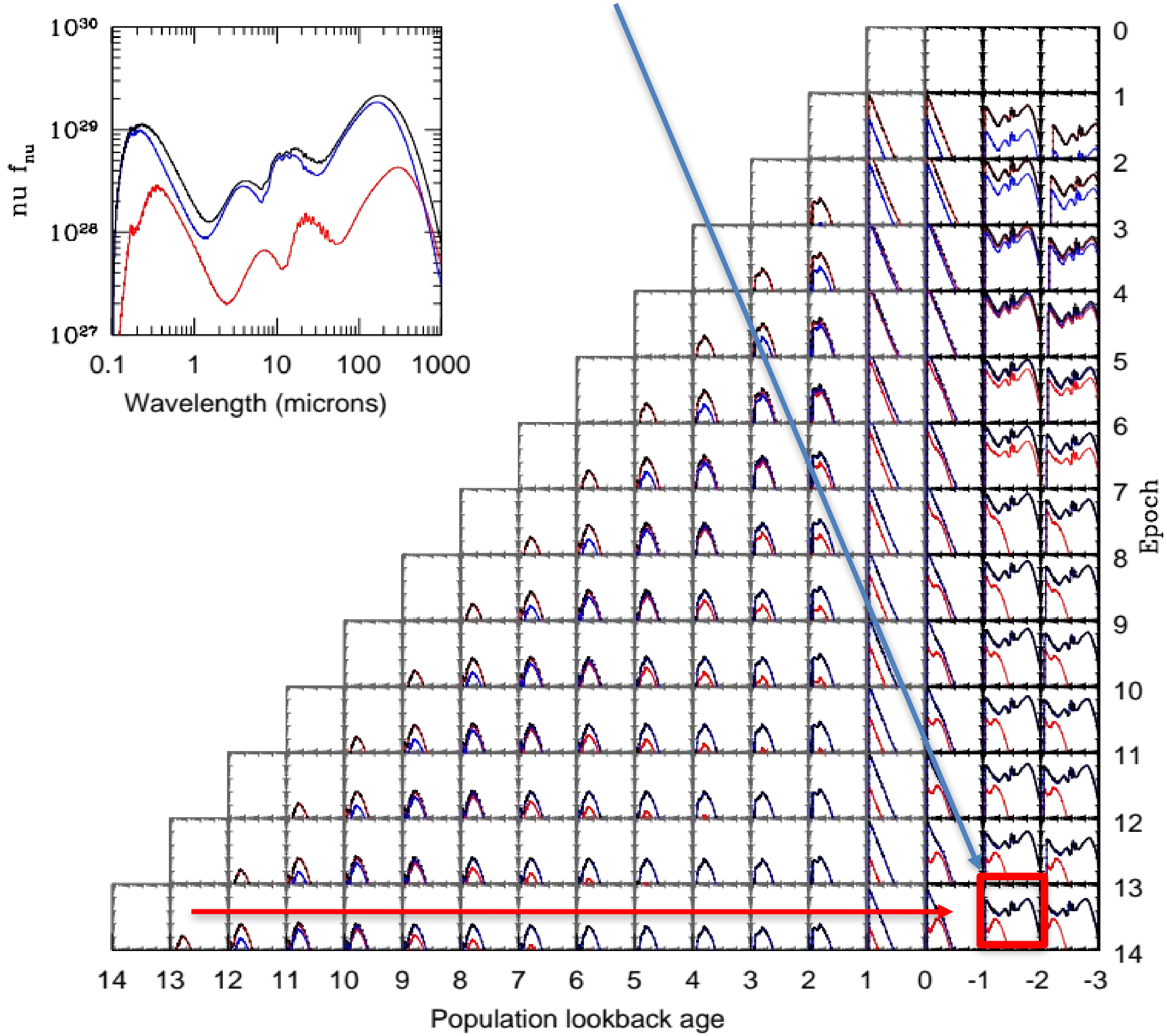
EBL construction

Sum over all time steps to get EBL today



CSED construction

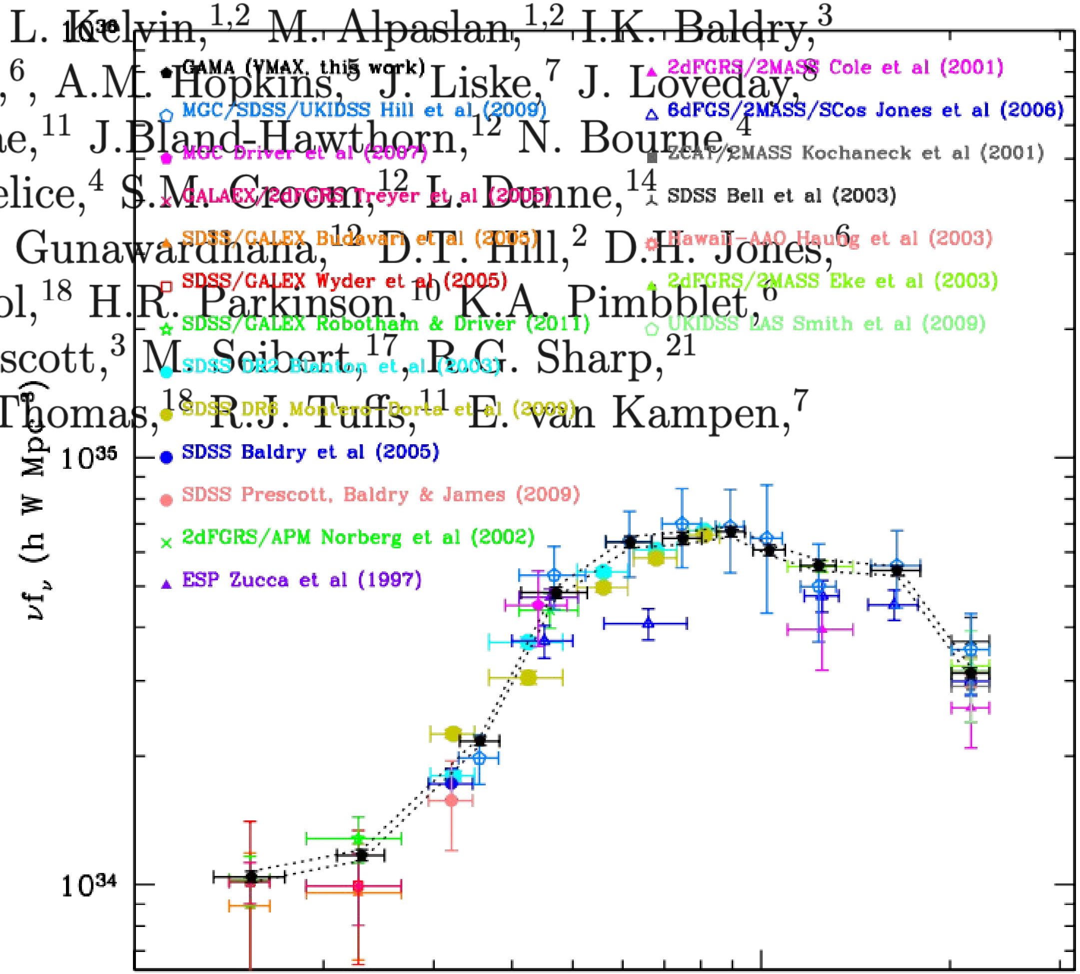
Sum over all panels from one epoch to getvCSED



CSED at z=0: LFs at various λ

Galaxy And Mass Assembly (GAMA): The $0.013 < z < 0.1$ cosmic spectral energy distribution from 0.1 μm to 1 mm

S.P. Driver,[1,2⋆†], A.S.G. Robotham,[1,2] L. Kelvin,[1,2] M. Alpaslan,[1,2] I.K. Baldry,[3] S.P. Bamford,[4] S. Brough,[5] M. Brown,[6], A.M. Hopkins,[5] J. Liske,[7] J. Loveday,[8] P. Norberg,[9] J.A. Peacock,[10] E. Andrae,[11] J.Bland-Hawthorn,[12] N. Bourne,[4] E. Cameron,[13] M. Colless,[5] C.J. Conselice,[4] S.M. Croom,[12] L. Dunne,[14] C.S. Frenk,[9] Alister W. Graham,[15] M. Gunawardhana,[12] D.T. Hill,[2] D.H. Jones,[6] K. Kuijken,[16] B. Madore,[17] R.C. Nichol,[18] H.R. Parkinson,[10] K.A. Pimbblet,[6] S. Phillipps,[19] C.C. Popescu,[20] M. Prescott,[3] M. Seibert,[17] R.G. Sharp,[21] W.J. Sutherland,[22] E.N. Taylor,[12] D. Thomas,[18] R.J. Tuffs,[11] E. van Kampen,[7] D. Wijesinghe,[12] S. Wilkins[23]



GAMA CSED compared
to previous measurements

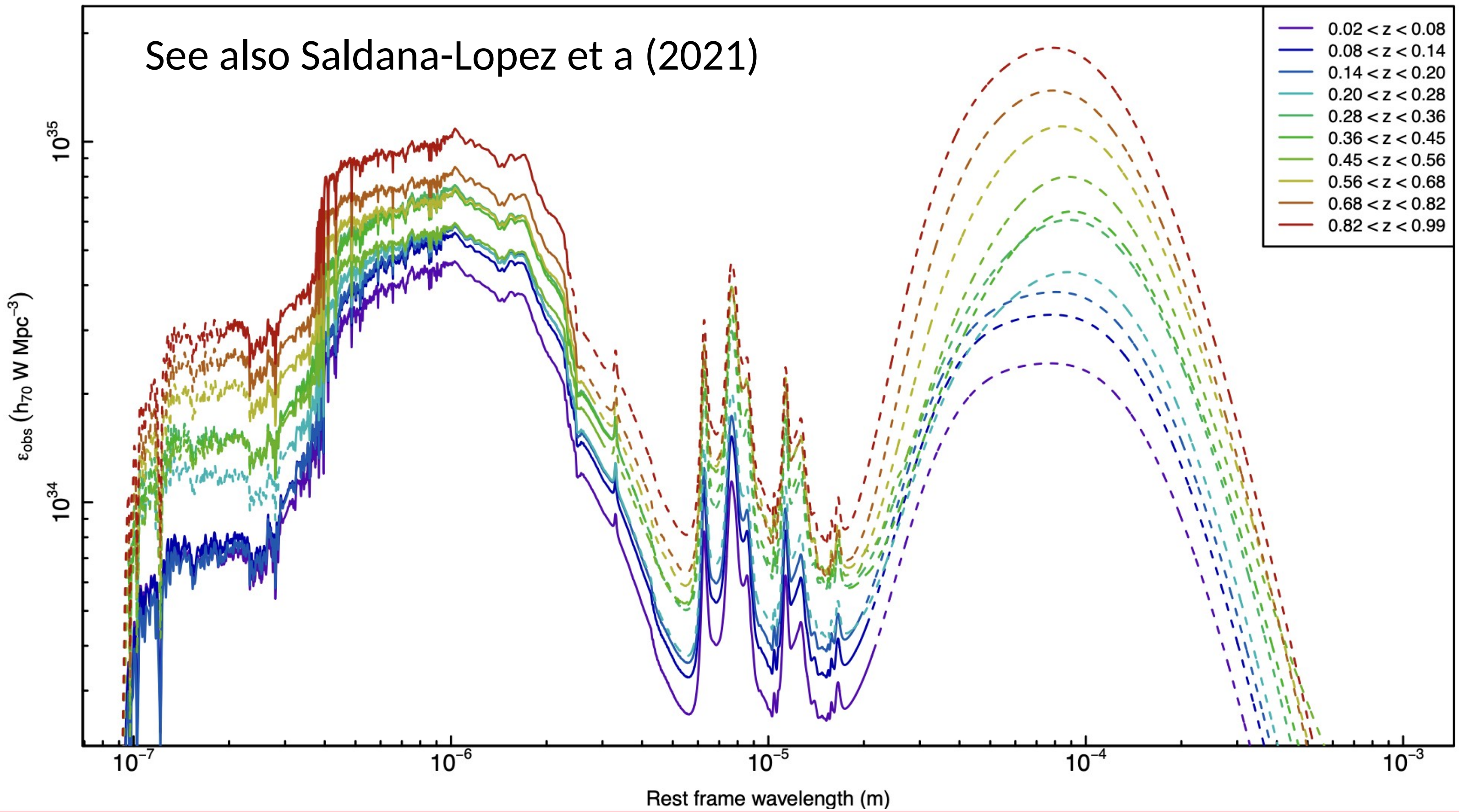
CSED at z < 1: SED stacking

Only(?!) measurement of the CSED to date from z=1 to 0

Far more power to constrain models with extra redshift constraint

Photo-z probably OK for construction of broad z-bin CSEDs

Easily doable to z=5 over the next 5-10 years

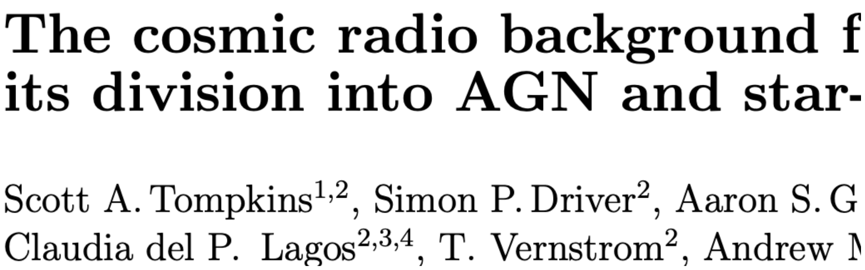


Andrews et al (2018)

Part V: Radio Source Counts

(towards the SKA)

The CRB

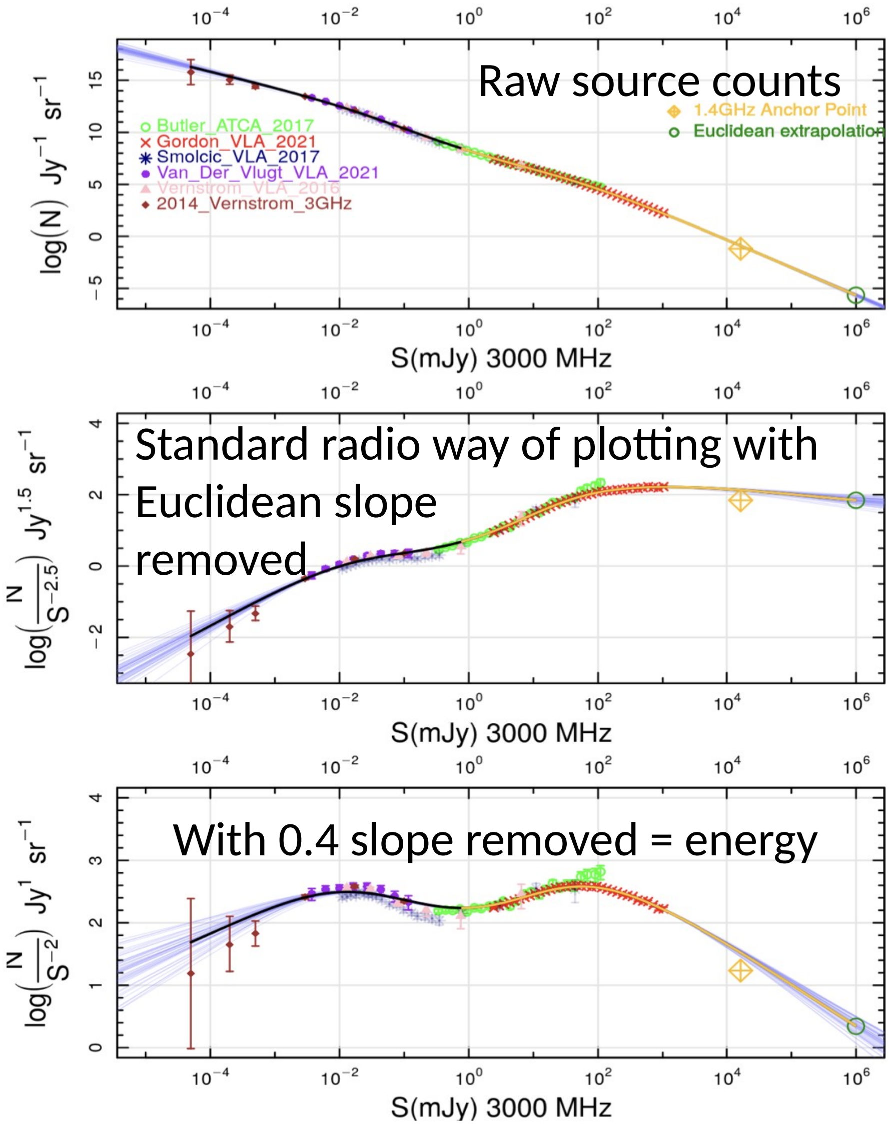

The cosmic radio background f
its division into AGN and star-

Scott A. Tompkins[1,2], Simon P. Driver[2], Aaron S. G
Claudia del P. Lagos[2,3,4], T. Vernstrom[2], Andrew M

Compendium of radio source counts at 7 frequencies as prep for SKA

- 150MHz, 325MHz, 610Mhz, 1.4GHz, 3GHz, 5GHz, 8.4GHz

Controversy between direct measurements from ARCADE2 and IGL (x5 offset)!



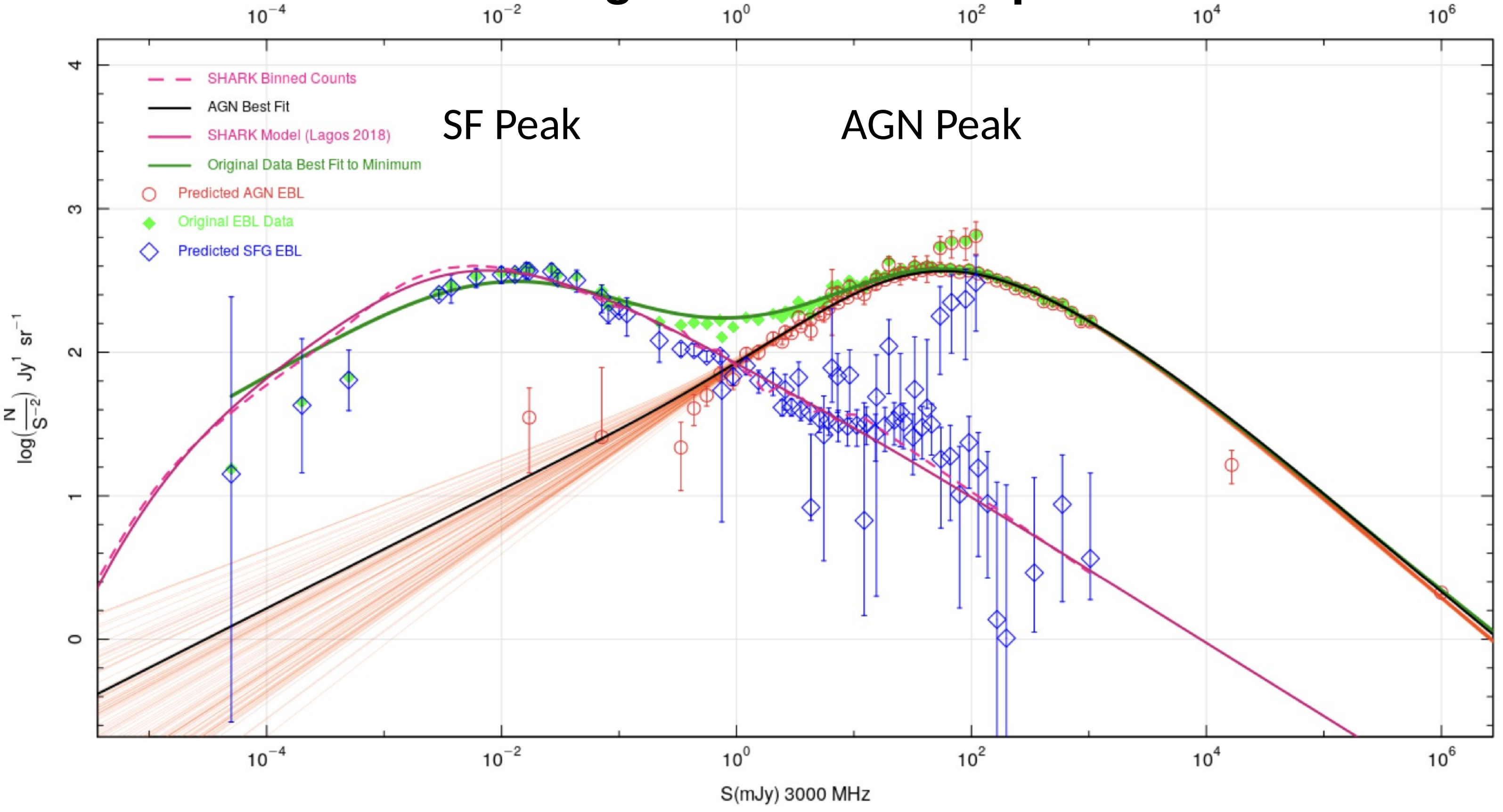
The CRB: Separation of AGN and SF flux

Radio counts typical show double hump. Typically not bounded

But can fit and subtract bright SF counts

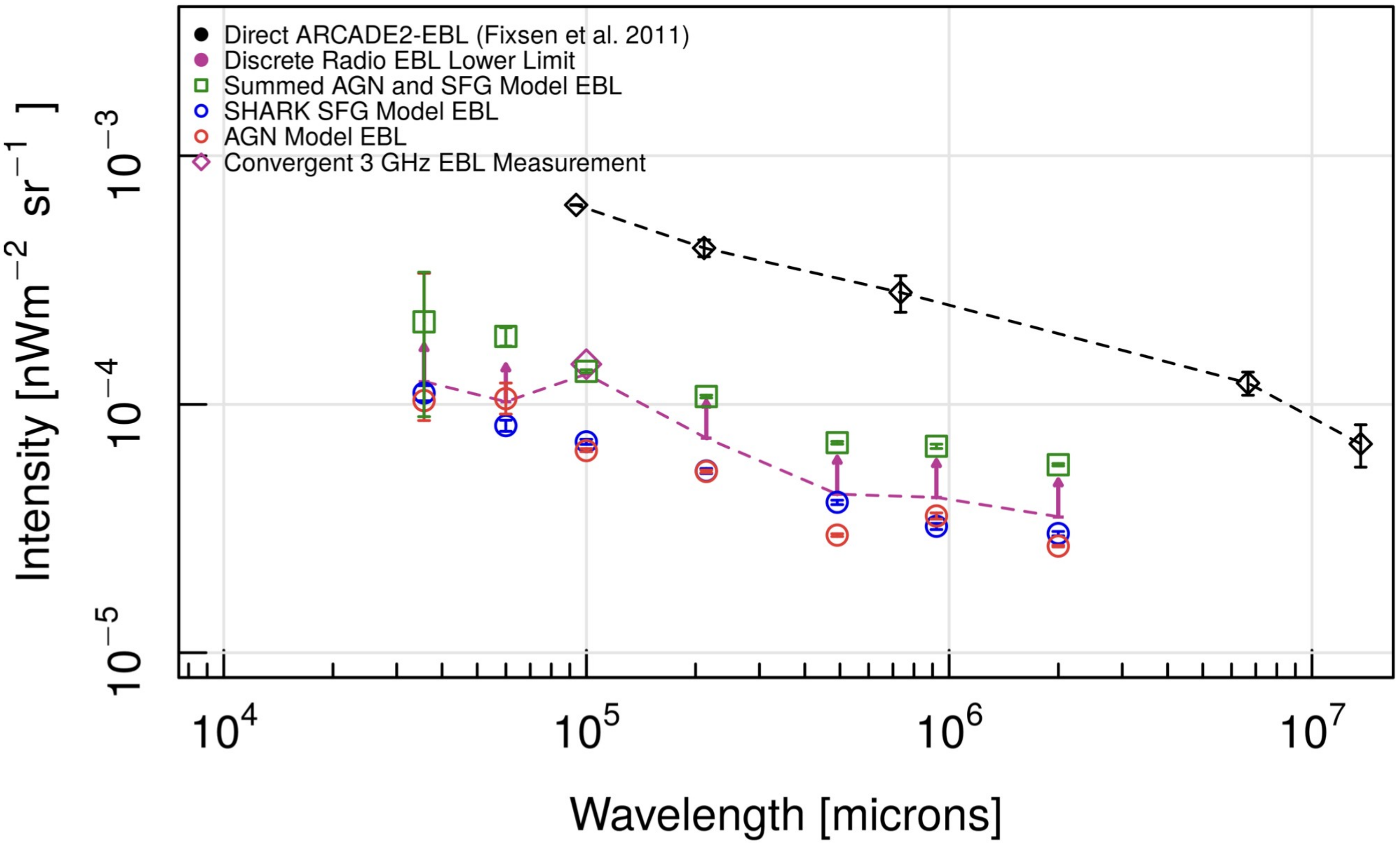
To recover bound AGN flux and use numerical simulations

To integrate the SF component



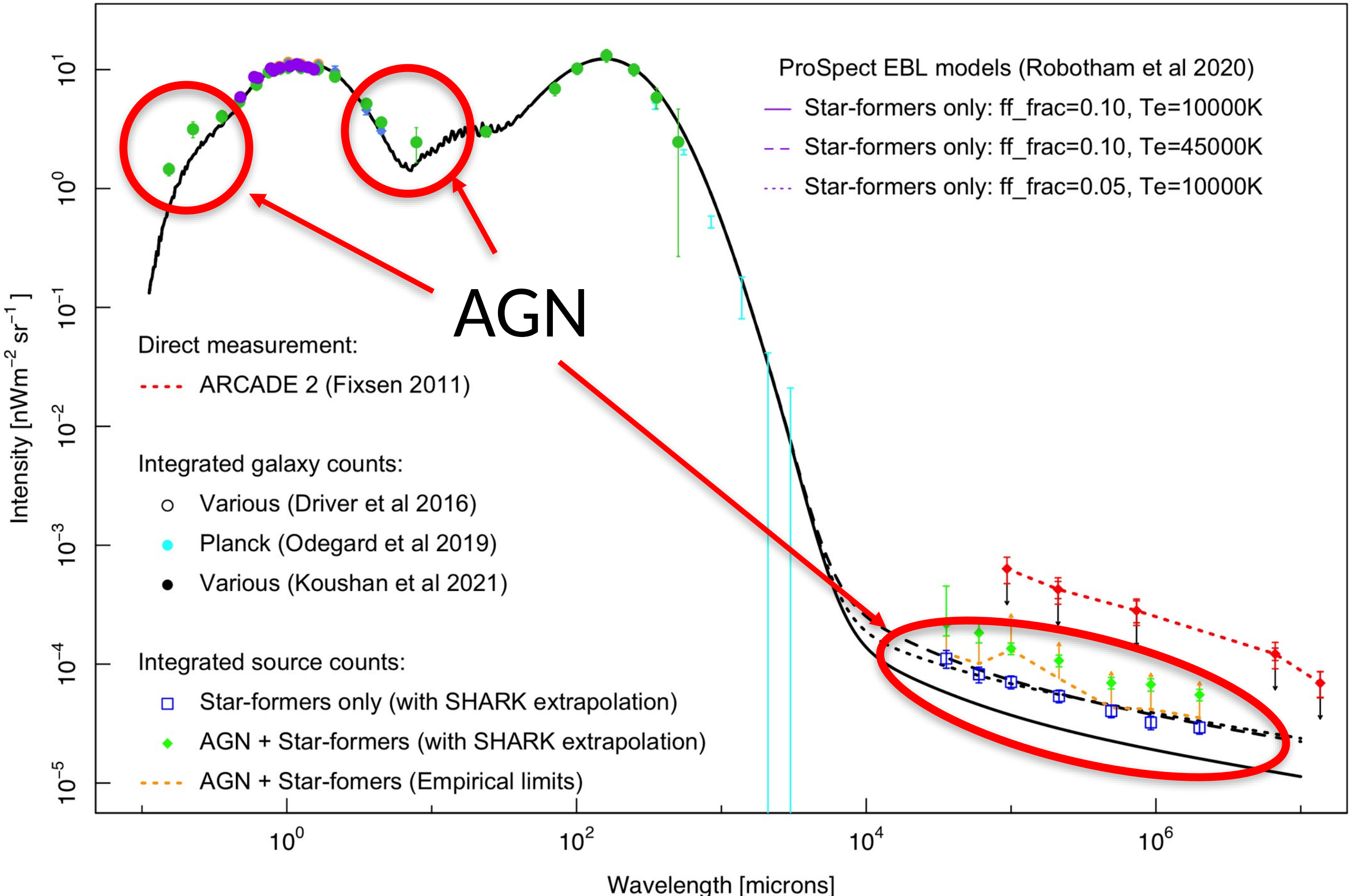
The CRB: Separation of AGN and SF flux

Integrated **AGN** and **SF** flux almost identical.
Sum is one fifth of the ARCADE2 direct flux



The CRB: ProSpect prediction

- Marvil, Owen, Eilek (2015) for SF continuum emission built into ProSpect
- Need to either increase free-free emission or plasma temperature to fit SF data. .
- AGN need as well as better mid-IR sampling: SphereX and JWST

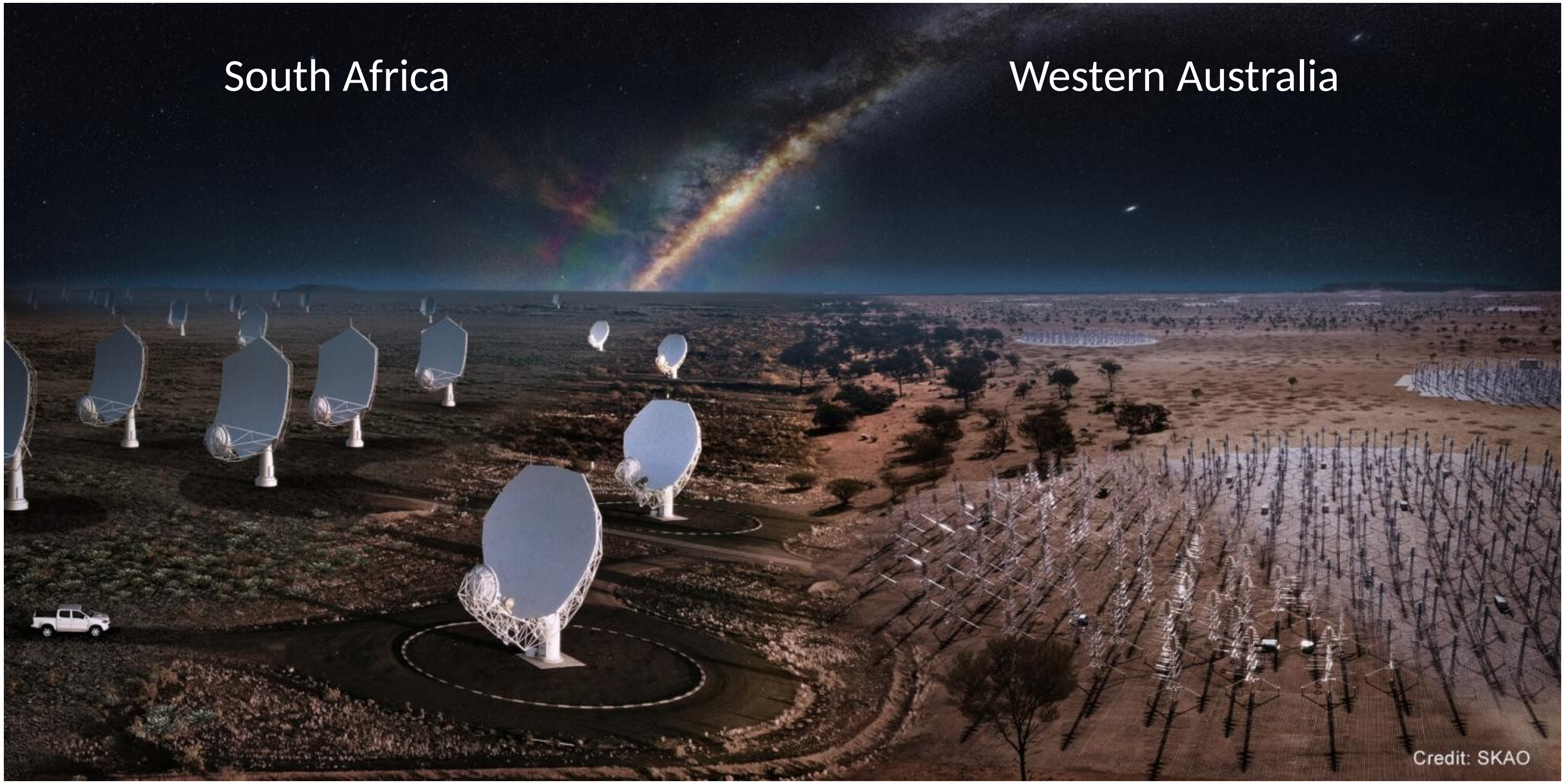


Square Kilometer Array

SKA-Low: 50-300MHz
SKA-Mid: 350MHz – 15.4 GHz

Early operations from 2029

Expect all radio source counts to be fully bounded for AGN and star-formers



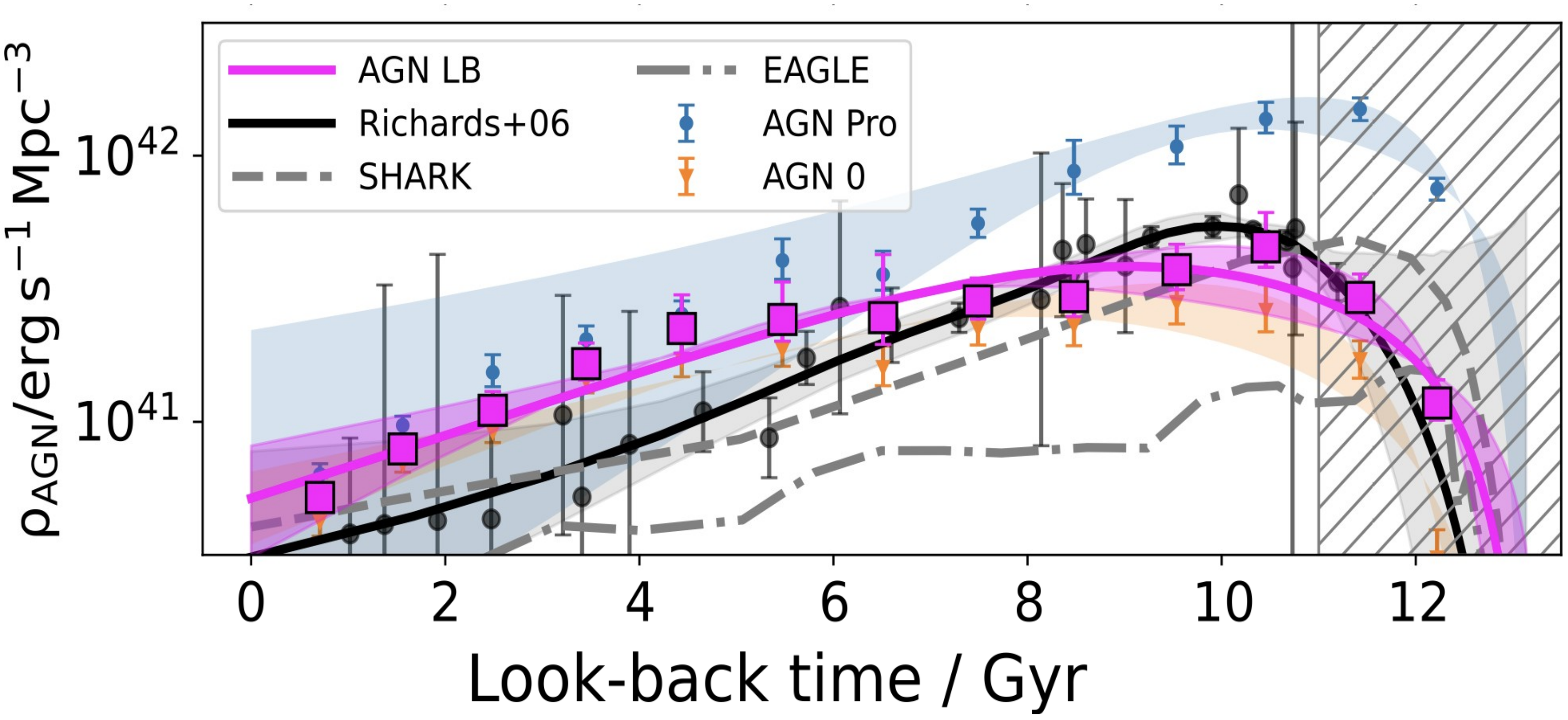
Part VI: Next steps, and future prospects

The EBL: Summary

- **Count measurements have improved dramatically: x10 to ~1% (u-K)**
  - Dominant errors all systematic: CV, ZP, Galaxy photometry
  - Agree with VHE constraints extremely well. NH now close. Concordance.
- **Models show consistency with VHE & counts to within 1%:**
  - Models able to predict EBL/CSED from UV to radio to within a few percent
  - EBL can now be used to refine model parameters: IMF, Z or predict CSFH
- **Improved accuracy now demands inclusion of AGN into optical/IR model:**
  - For the moment need to split AGN into three distinct regimes: x-ray, O/IR, radio
- **Potential for further improvements soon:**
  - mid-IR 20% to <5% SphereX & JWST MIRI
  - O/IR to sub-1% LSST and Euclid

The CAGNH

Very similar in shape and form as CSFH
Will use to inform the AGN modelling



Adding in the AGN to ProSpect

AGN dominant in three regimes

Unable to physical link them at current time

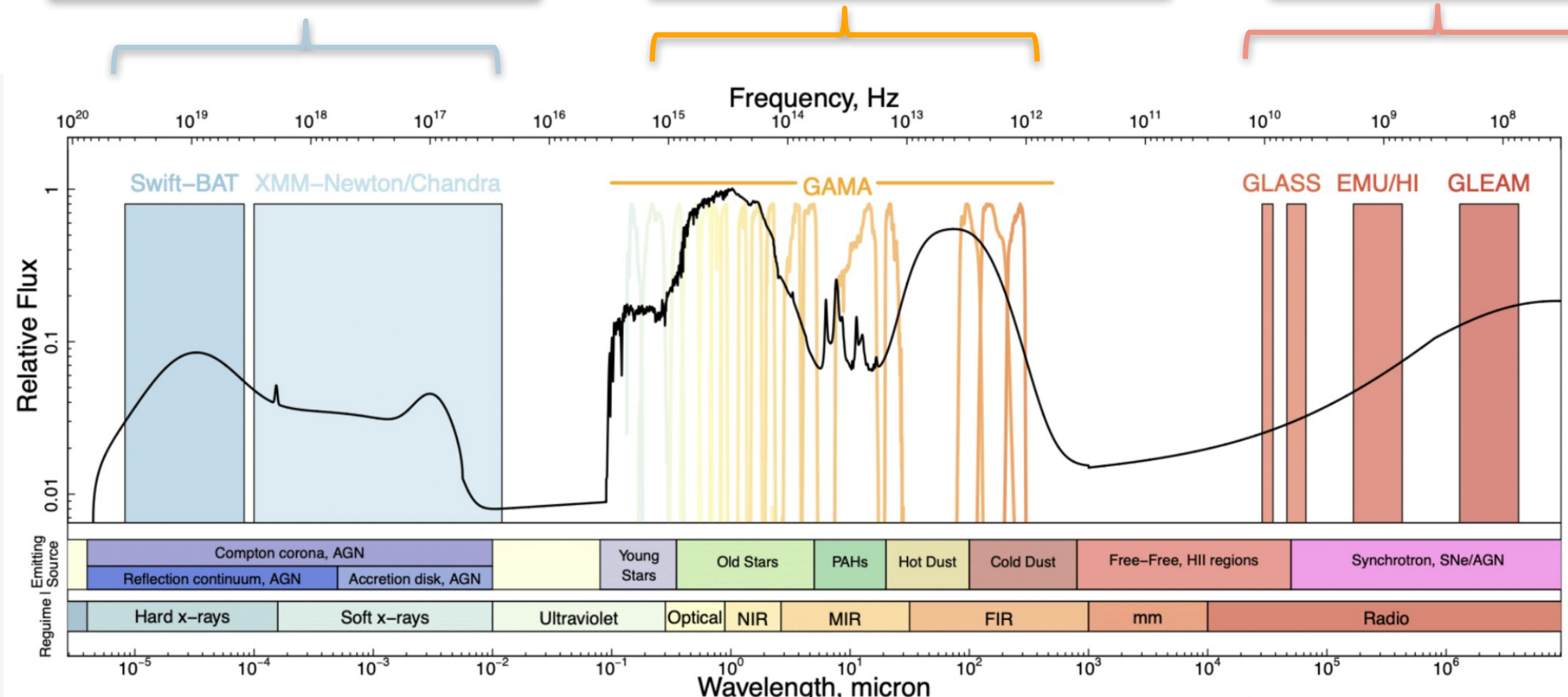
Adopt **<u>three independent AGN model components</u>**

Aim to constrain relative duty cycles and frequency links to environment

Template fitting in X-ray

SKIRTOR in optical/near-IR

Power law in Radio



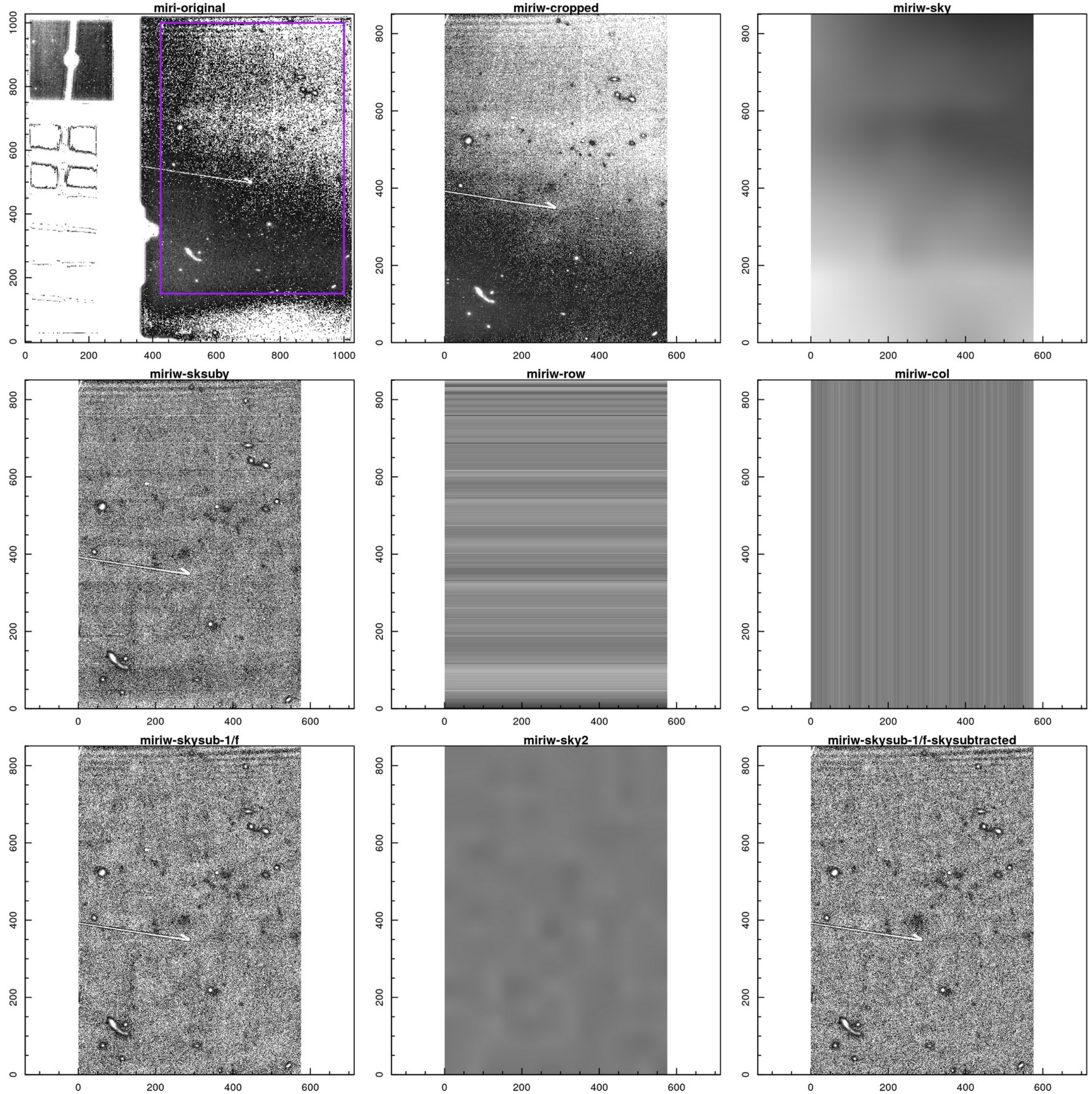
Credit: Luke Davies

The EBL: JWST MIRI

Currently only a few bands and fields but MIRI wavelengths extremely important for mid-IR.

Tools developed as part of JWST PEARLS collaboration to remove 1/f noise and remove sky

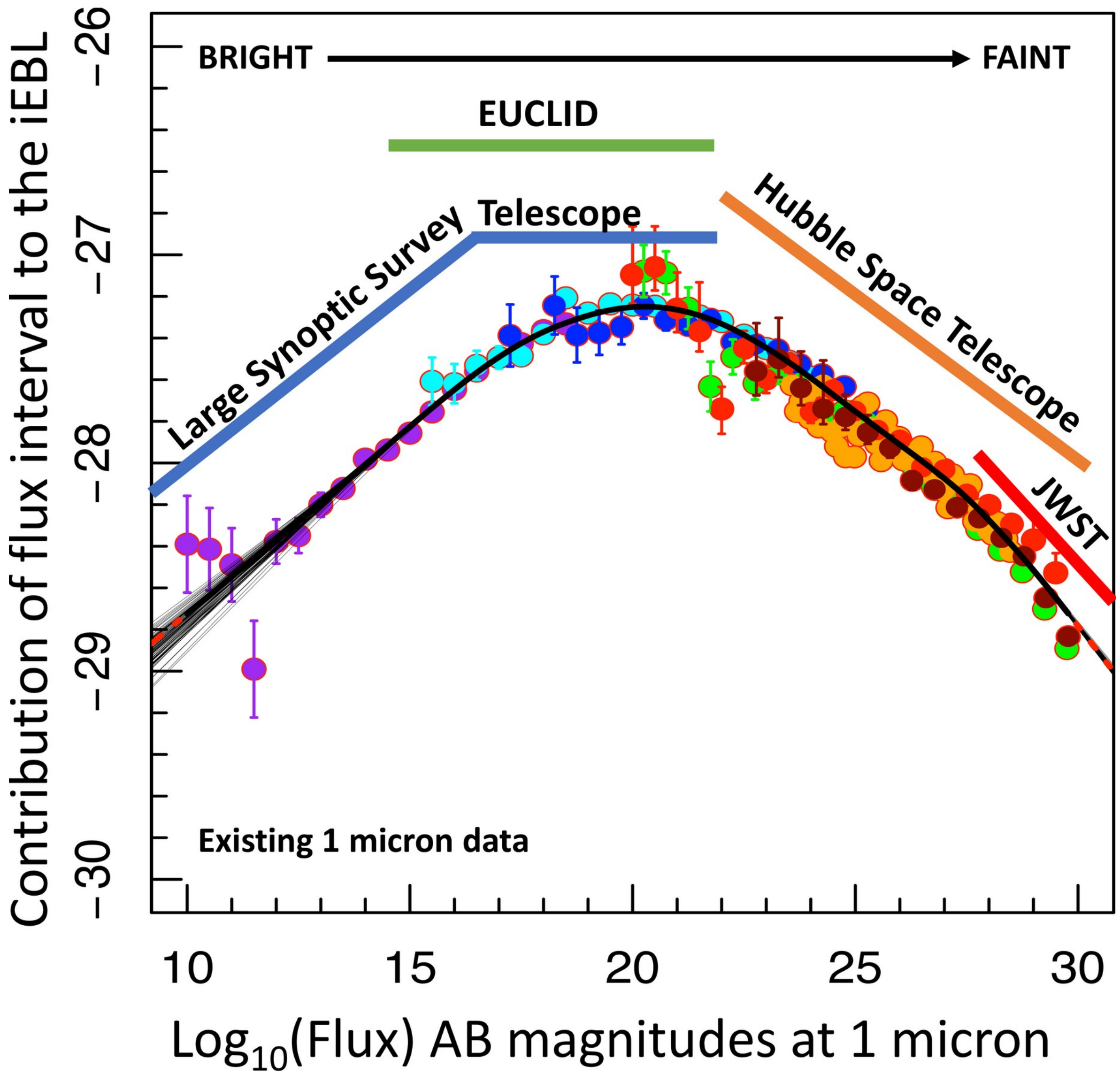
First results expected in 2023 (Tompkins et al 2023b)



The EBL: Next steps

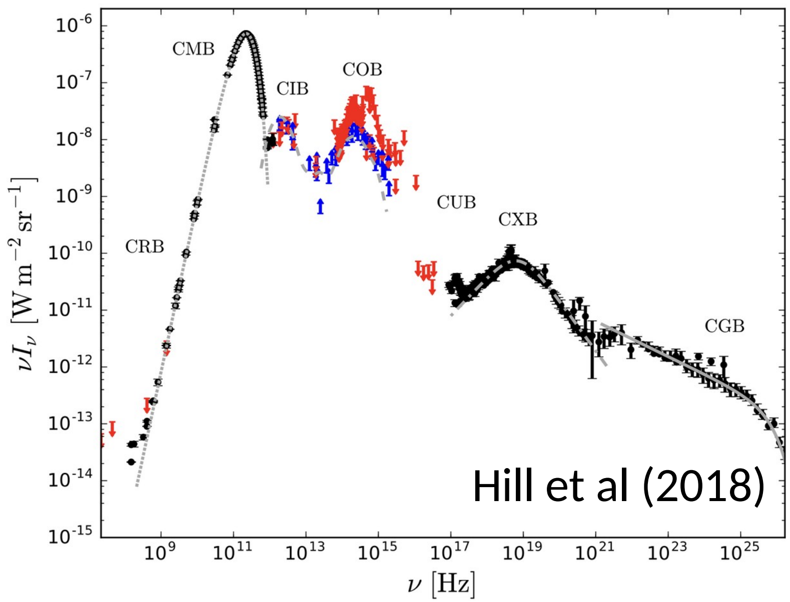
Towards <1% uncertainty
u-Ks

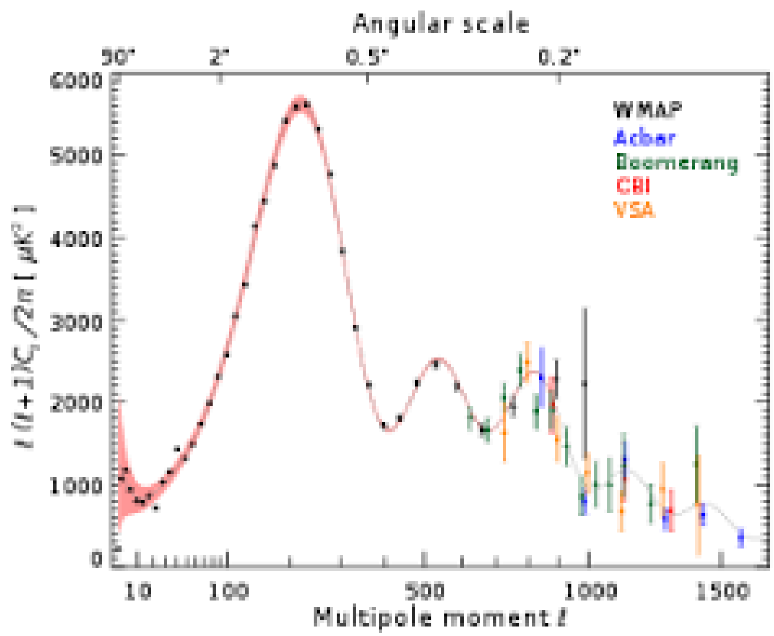
(SkySURF)



The Extragalactic Background Light or EBL

Everything everywhere all the time!





The EBL encodes the entire history of photon production since recombination:

Star-formation, AGN, intra-halo light, low surface brightness, reionisation (e.g., Pop III)

Potentially as powerful for galaxy/AGN evolution studies as CMB anisotropies are to Cosmology