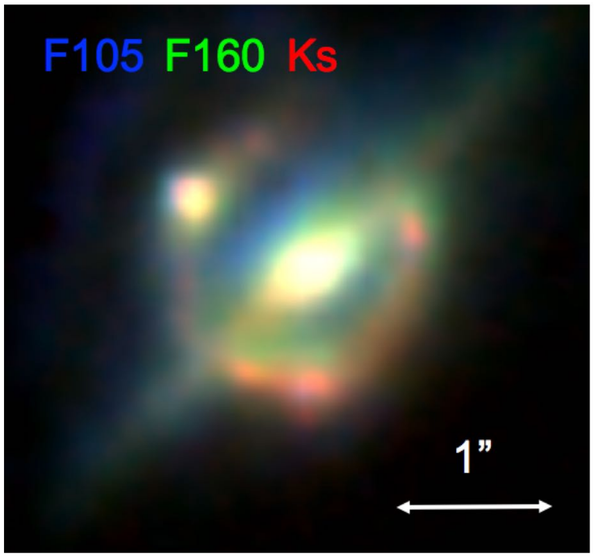
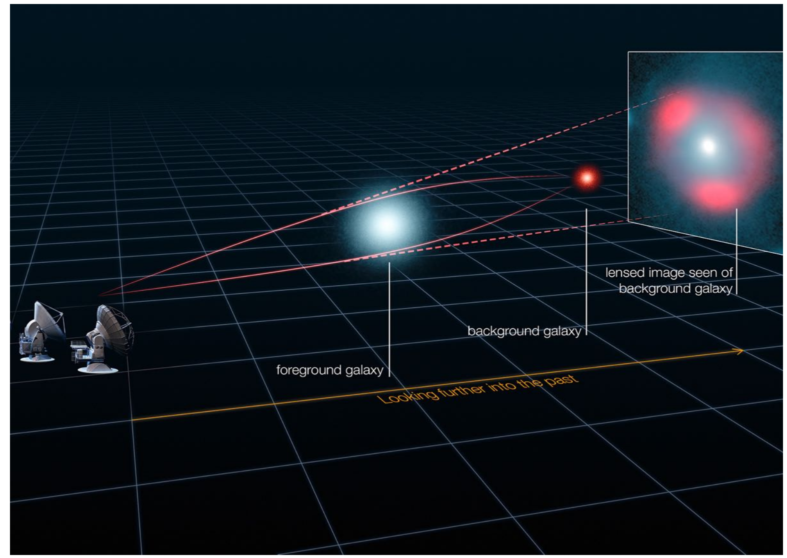
SOFIA/HAWC+ Detection of a Gravitationally Lensed Starburst Galaxy at z = 1.03





Jingzhe Ma

University of California, Irvine

Collaborators: Asantha Cooray, Arianna Brown, Hooshang Nayyeri, Hugo Messias, Nicholas Timmons, Johannes Staguhn, Pasquale Temi, C. Darren Dowell, Julie Wardlow, Dario Fadda, Attila Kovacs, Dominik Riechers, Ivan Oteo, Derek Wilson, and Ismael Perez-Fournon

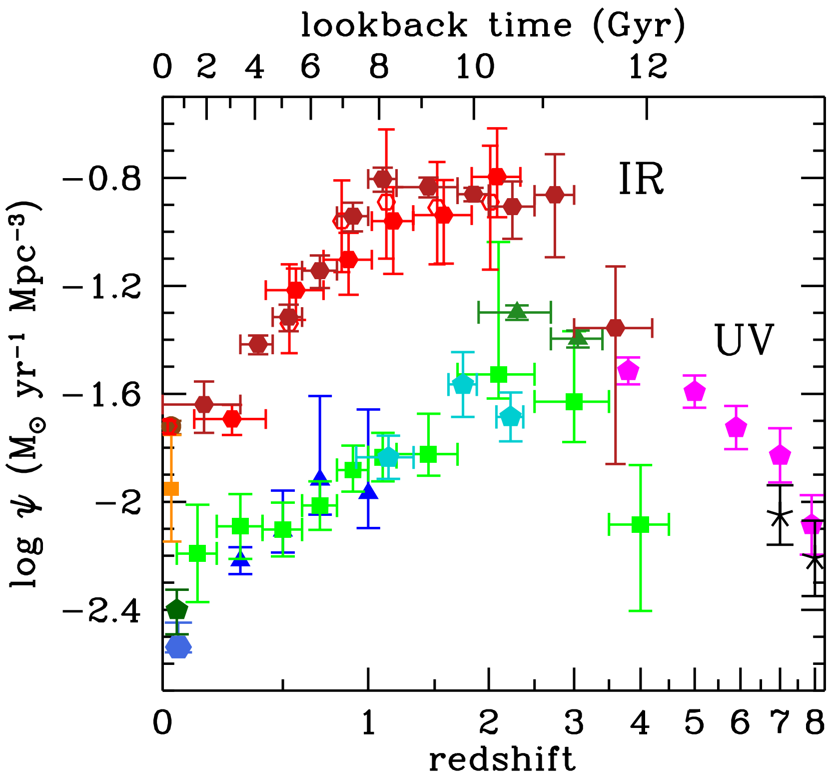
SOFIA tele-talk 11/28/2018

Dust obscured universe

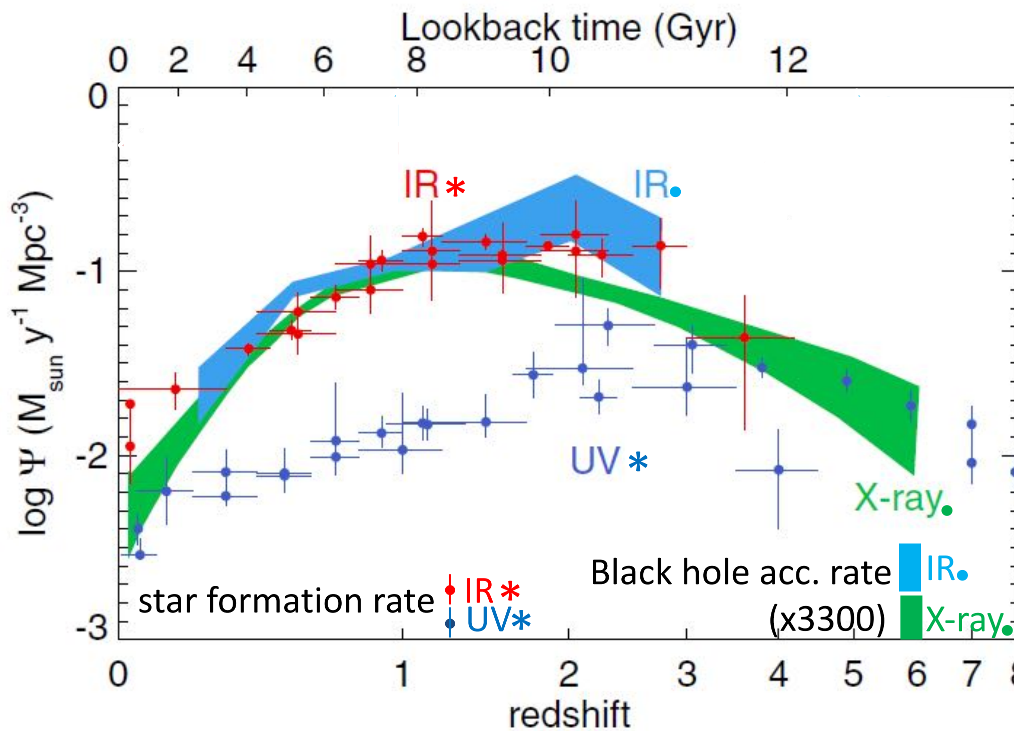
The evolution of galaxies is fueled by two major energy production processes:

Star formation

Super massive black hole accretion

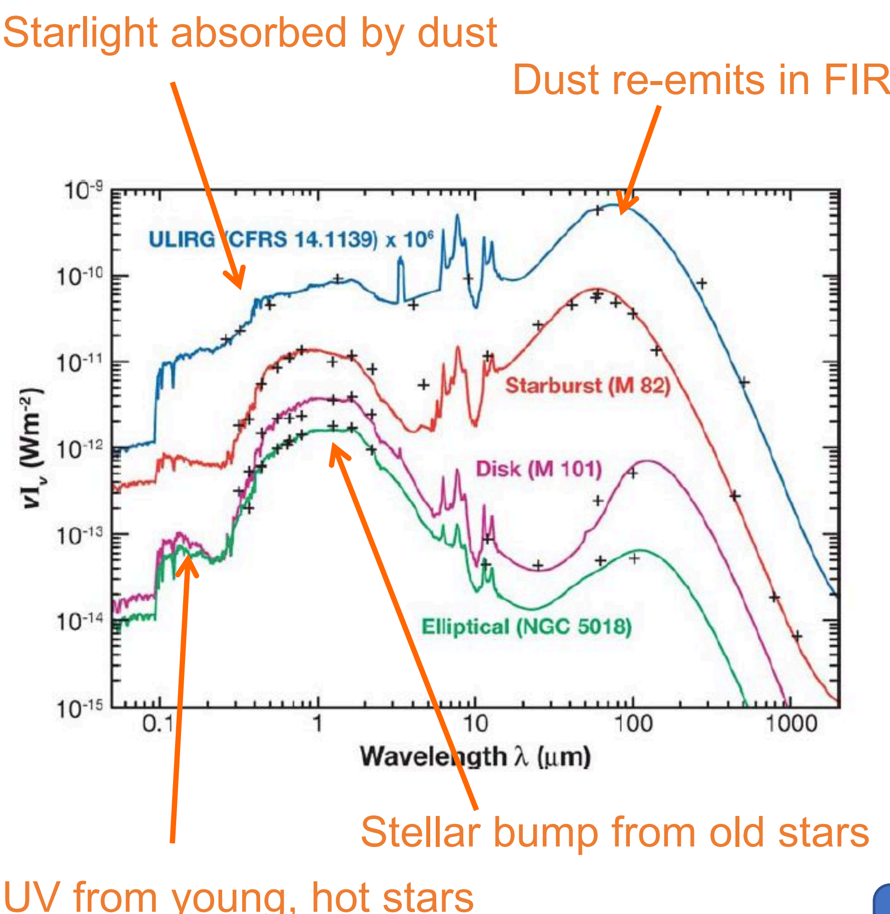


Madau & Dickinson 2014



Spinoglio et al. 2018

Dusty star-forming galaxies (DSFGs)



❖ Properties

- $L_{IR} \sim 10^{12}$ - $10^{13}\, L_\odot$
- SFR > 100~1000 $M_\odot$ /yr
- Massive and gas rich
  $M_* \sim 10^{11}\, M_\odot$; $M_{gas} \sim 10^{10}\, M_\odot$
- Progenitors of massive elliptical galaxies in the local universe

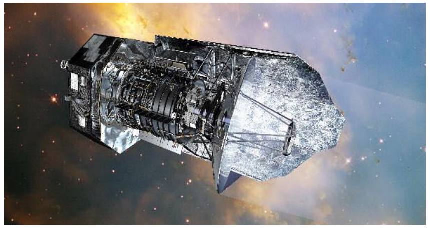
❖ Triggering mechanisms

- Large reservoirs of molecular gas through secular processes
- A gas-rich major merger leads to an intense phase of star formation

❖ Power source

- Star formation or AGN
- ~20% DSFGs appear to host an AGN

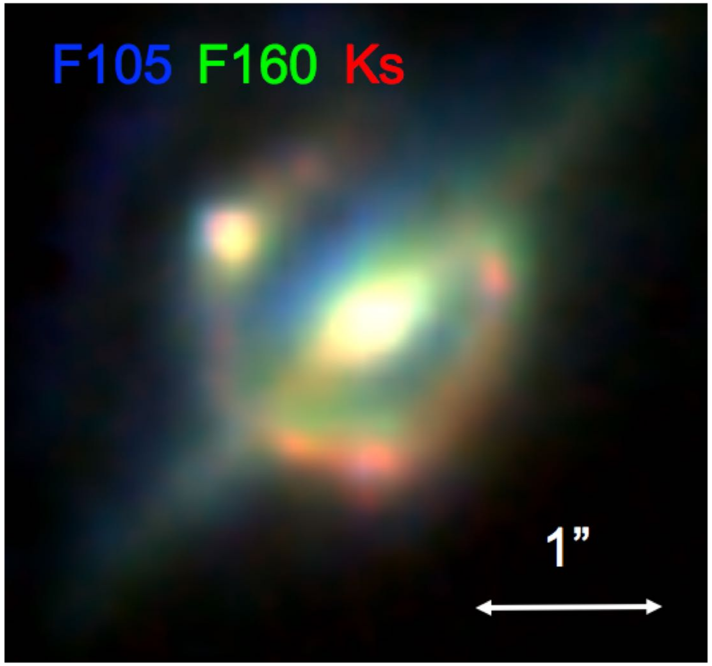
The Astrophysical Tera-Hertz Large Area Survey (PI: S. Eales)

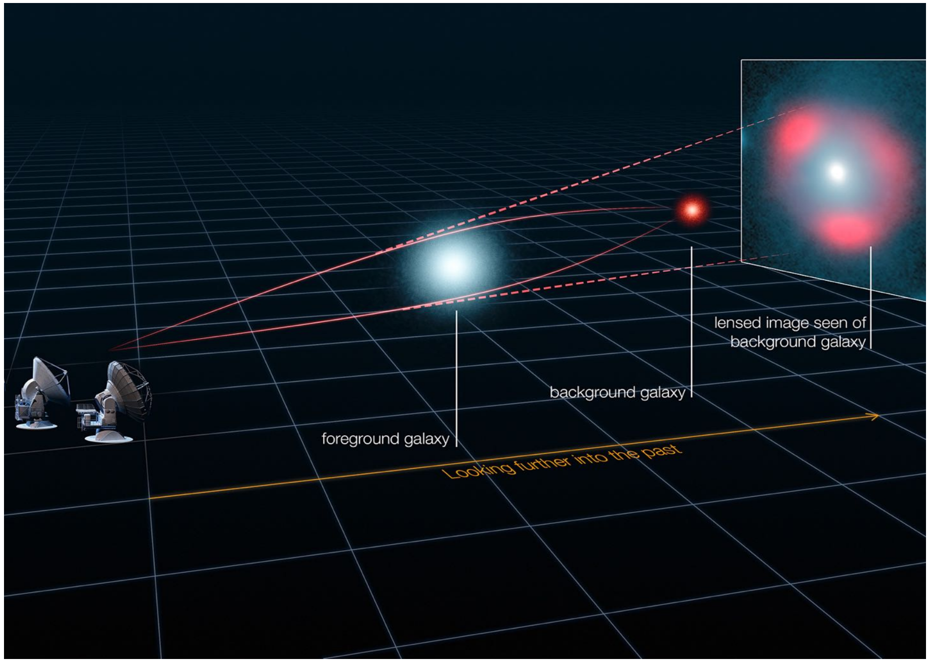


- The Herschel-ATLAS is a key legacy survey of ~570 deg^2 covering 5 bands with PACS and SPIRE (100 – 500 um)

J1429-0028 (G15v2.19): GAMA-15hr field (Messias+2014; Timmons+2015)

- Foreground: edge-on disk galaxy at z = 0.22
- Background: DSFG Einstein ring at z = 1.03 S_{160um} ~ 1 Jy
- Lensing magnification ~ 10 intrinsic L_{IR} ~$4 \times 10^{12}\, L_{\odot}$ SFR ~ 400 $M_{\odot}$ /yr





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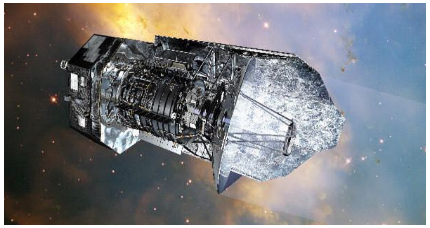

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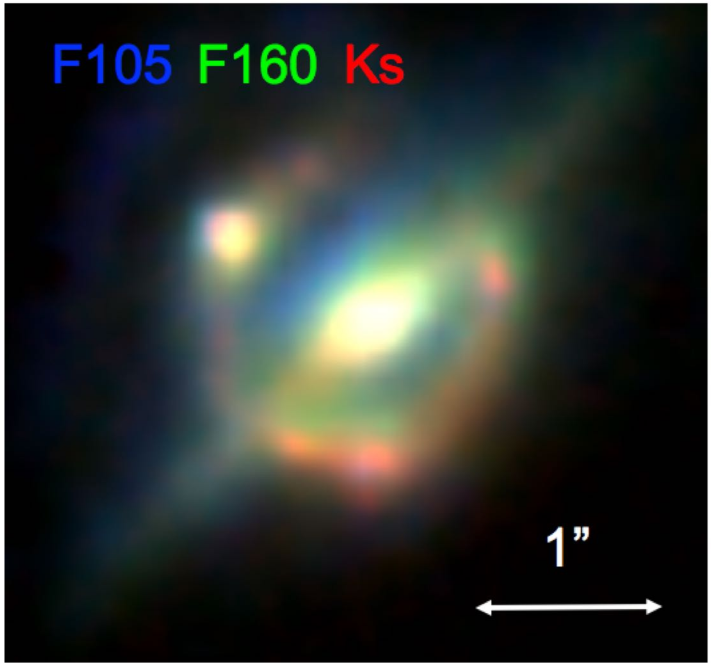

Imaging

UV ↕ radio

- SDSS
- VIKING
- HST/WFC3
- Keck/NIRC2
- Spitzer/IRAC
- WISE
- Herschel/PACS
- Herschel/SPIRE
- IRAM/MAMBO-2
- ALMA
- JVLA

Spectroscopy

redshifts

- Gemini/GMOS-S
- APEX/Z-SPEC
- CARMA
- ALMA

CO(2-1)
CO(4-3)
CI (1-0)

J1429-0028 : Gravitationally lensed DSFG at z= 1.03

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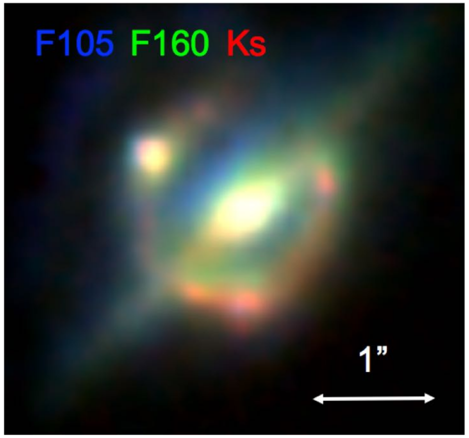

Remaining questions:

1. Is there an energetically important AGN in the system and what is the fractional contribution to the total IR luminosity, if any?

2. How did the galaxy build up the stellar mass, i.e., are we able to constrain the star formation history (SFH)?

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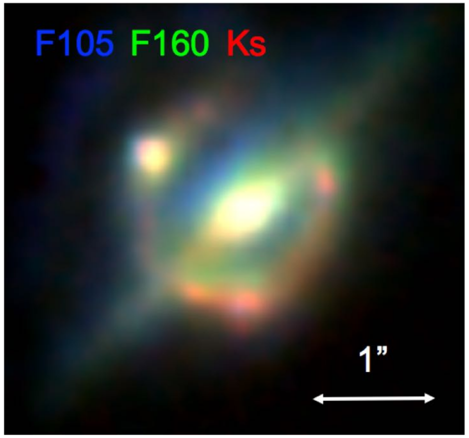

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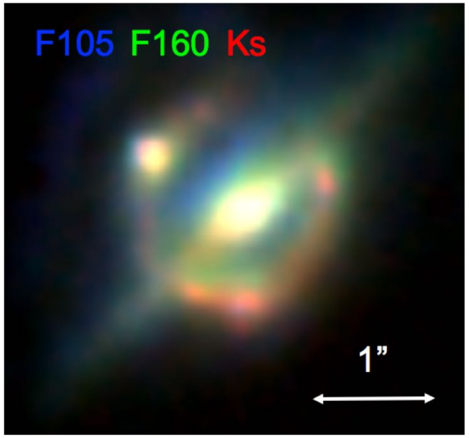
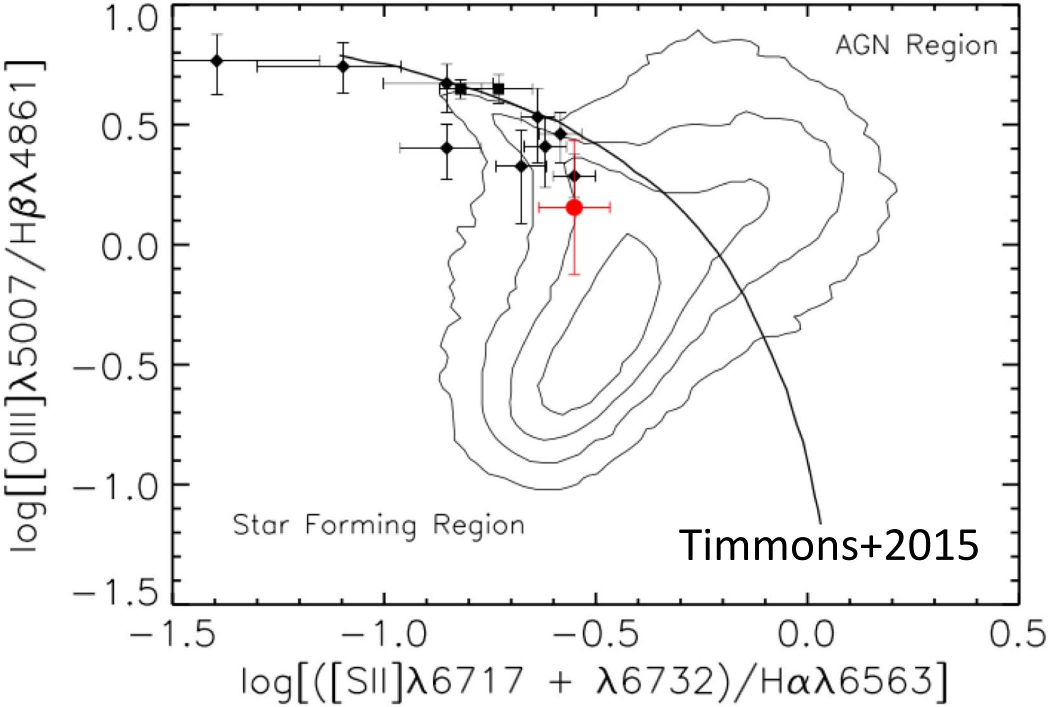


BPT diagram



HST G102 & G141 grism:

Only brightest knots detected

Dust extinction

H-alpha/NII not resolved

J1429-0028 : Gravitationally lensed DSFG at z= 1.03

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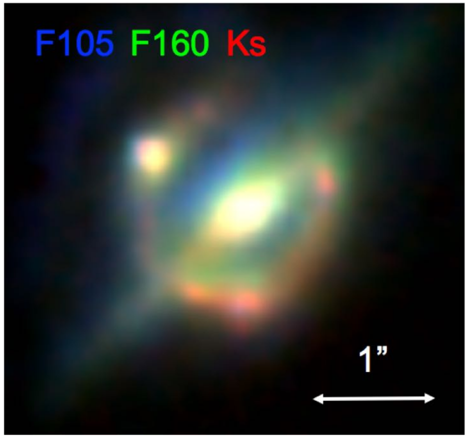

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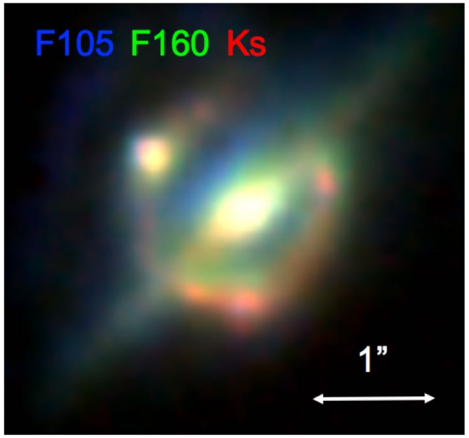

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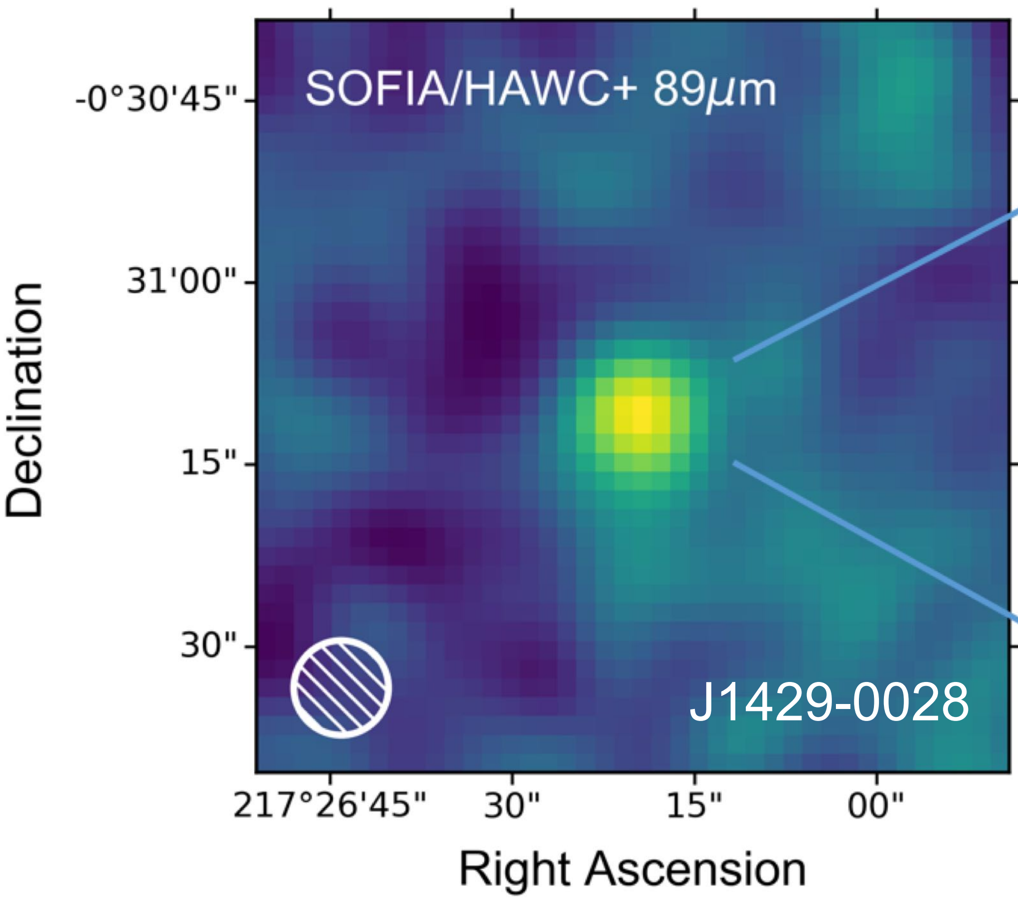
J1429-0028 can serve as a laboratory to test systematic uncertainties in deriving physical properties via panchromatic SED modeling.

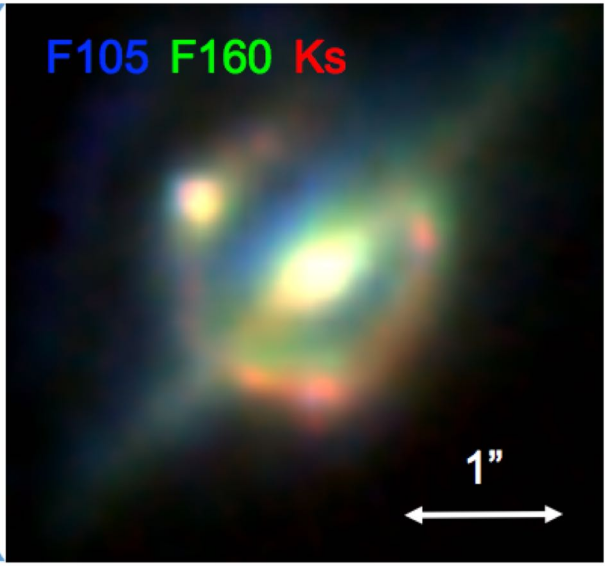
SOFIA High-resolution Airborne Wideband Camera-plus (HAWC+)

SOFIA Cycle 5 (PI: A.Cooray):

C band 89um 15 min S/N ~ 7 FWHM - 7.8” S_{89um} = 77.2 ± 11.8 mJy

HAWC+: the only current facility covering 50-100 um





Ma et al. 2018c

Spectral Energy Distribution (SED) modeling

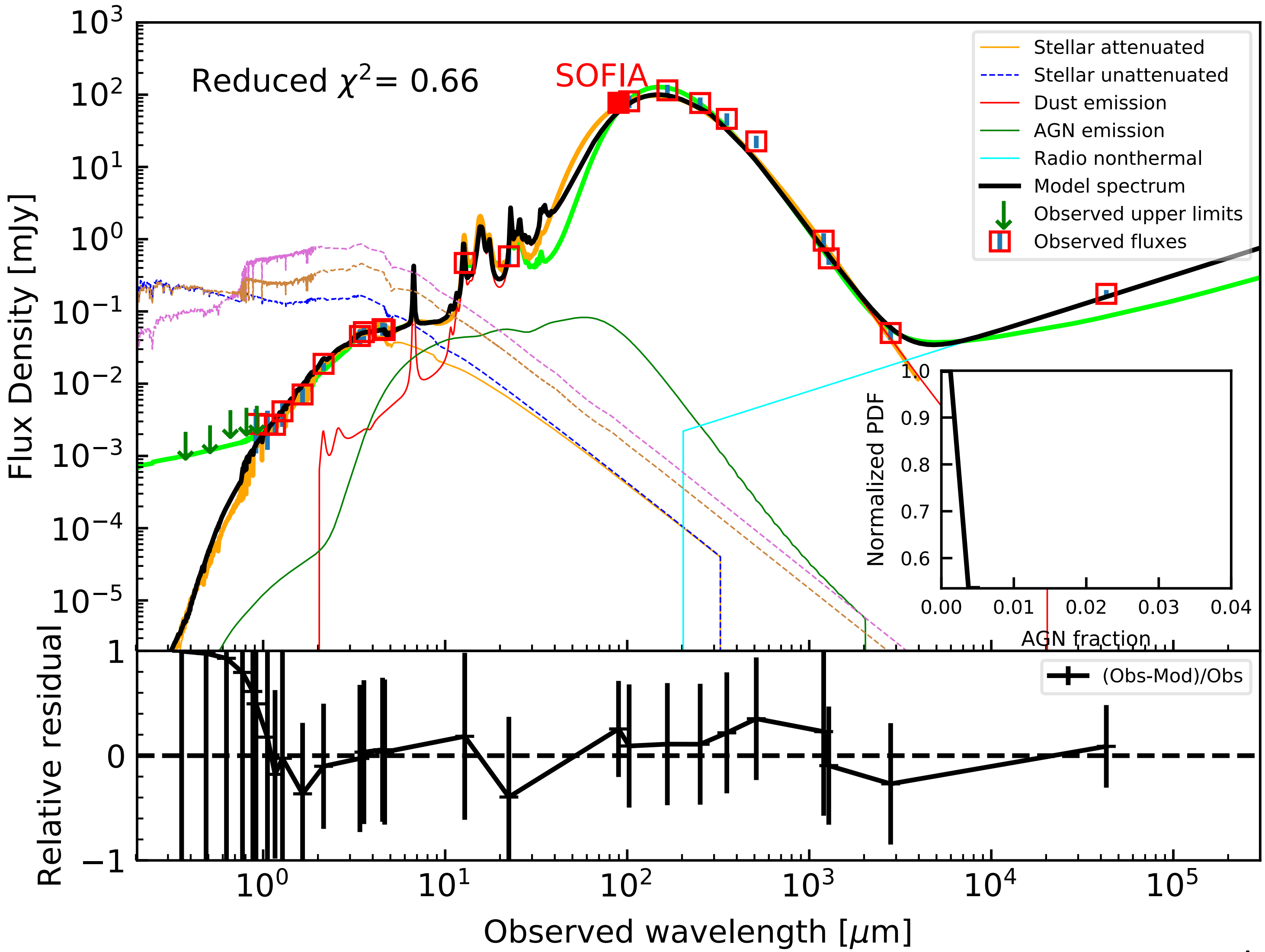
SED fitting codes: Bayesian approach

- MAGPHYS (da Cunha+2008): no AGN, no radio emission
- MAGPHYS high-z version (da Cunha+2015): extends parameter space, radio
- SED3FIT (Berta+2013): MAGPHYS + AGN templates
- CIGALE (Noll+2009): flexible SFHs, dust attenuation curves, AGN templates, radio

SED components: combined in an energy balance manner

- Stellar component: Chabrier (2003) IMF, BC03 stellar population synthesis models
  test SFHs: exponentially decreased/increased SFH (tau model)
  delayed-tau, two-component tau-SFH
  continuous SFH + random bursts
- Dust attenuation: single power-law, two-component model (differential attenuation in young and old stellar populations)
- Dust emission: cold and host dust emission, PAH templates
  derive dust luminosity, dust mass, and dust temperature
- AGN templates: Fritz+(2006) Type 1 (unobscured), Type 2 (obscured), and intermediate-type AGN $L_{\mathrm{IR,total}} = L_{SF} + L_{\mathrm{AGN}}$
- Radio: thermal (free-free) and nonthermal (synchrotron emission)

Spectral Energy Distribution (SED) modeling



Ma et al. 2018c

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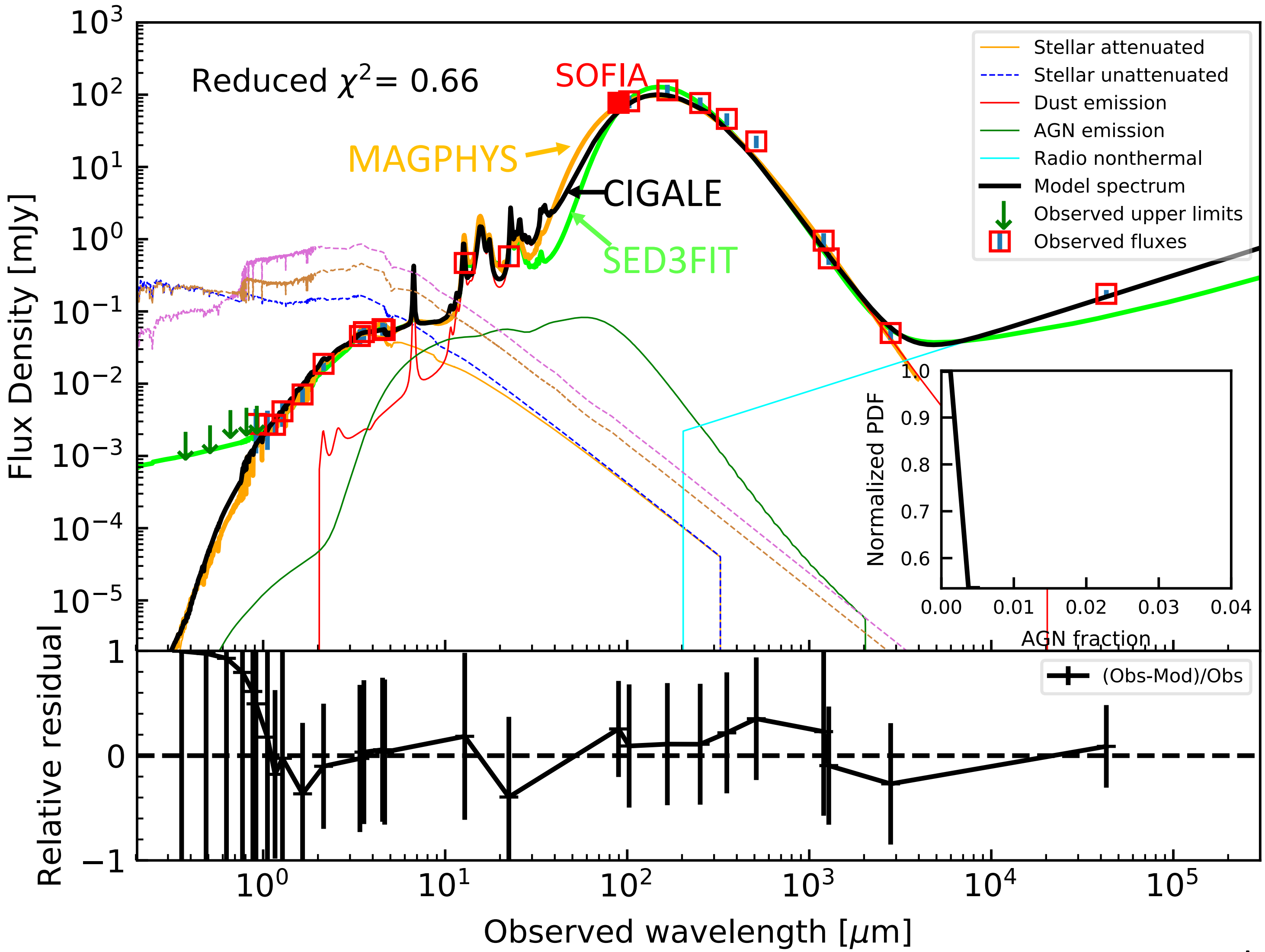

Ma et al. 2018c

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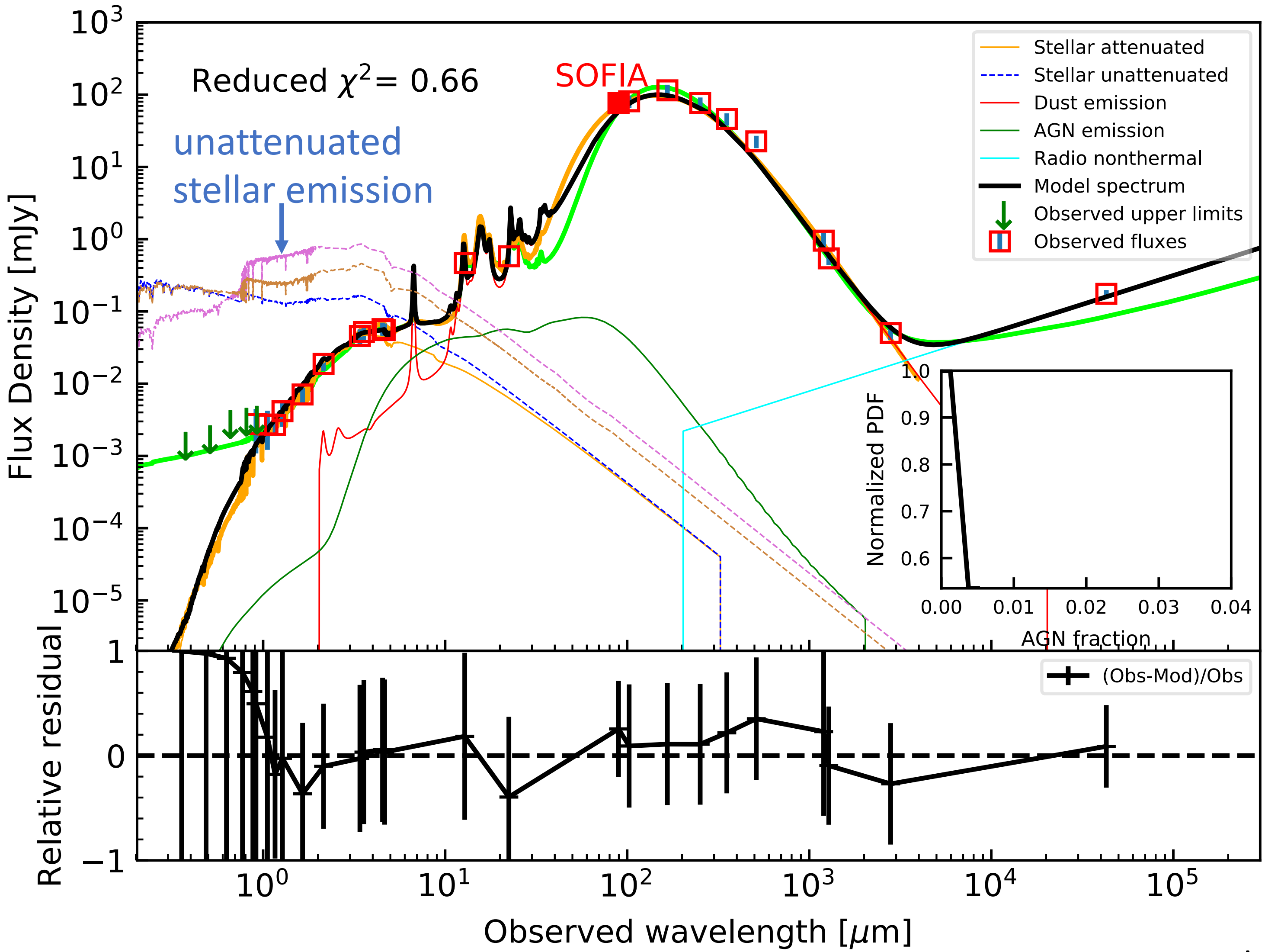

Ma et al. 2018c

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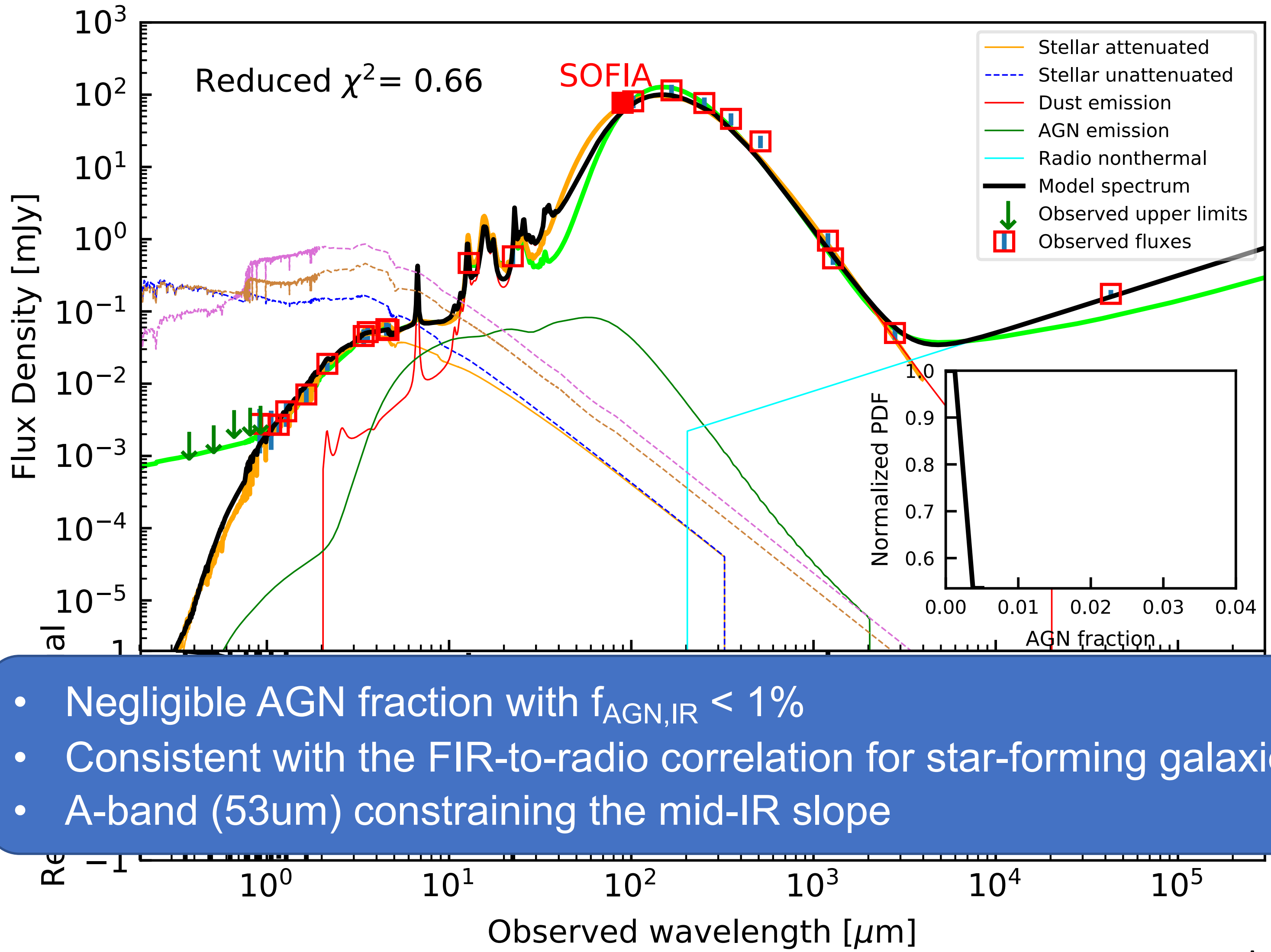

- Negligible AGN fraction with $f_{AGN,IR}$ < 1%
- Consistent with the FIR-to-radio correlation for star-forming galaxies
- A-band (53um) constraining the mid-IR slope

Ma et al. 2018c

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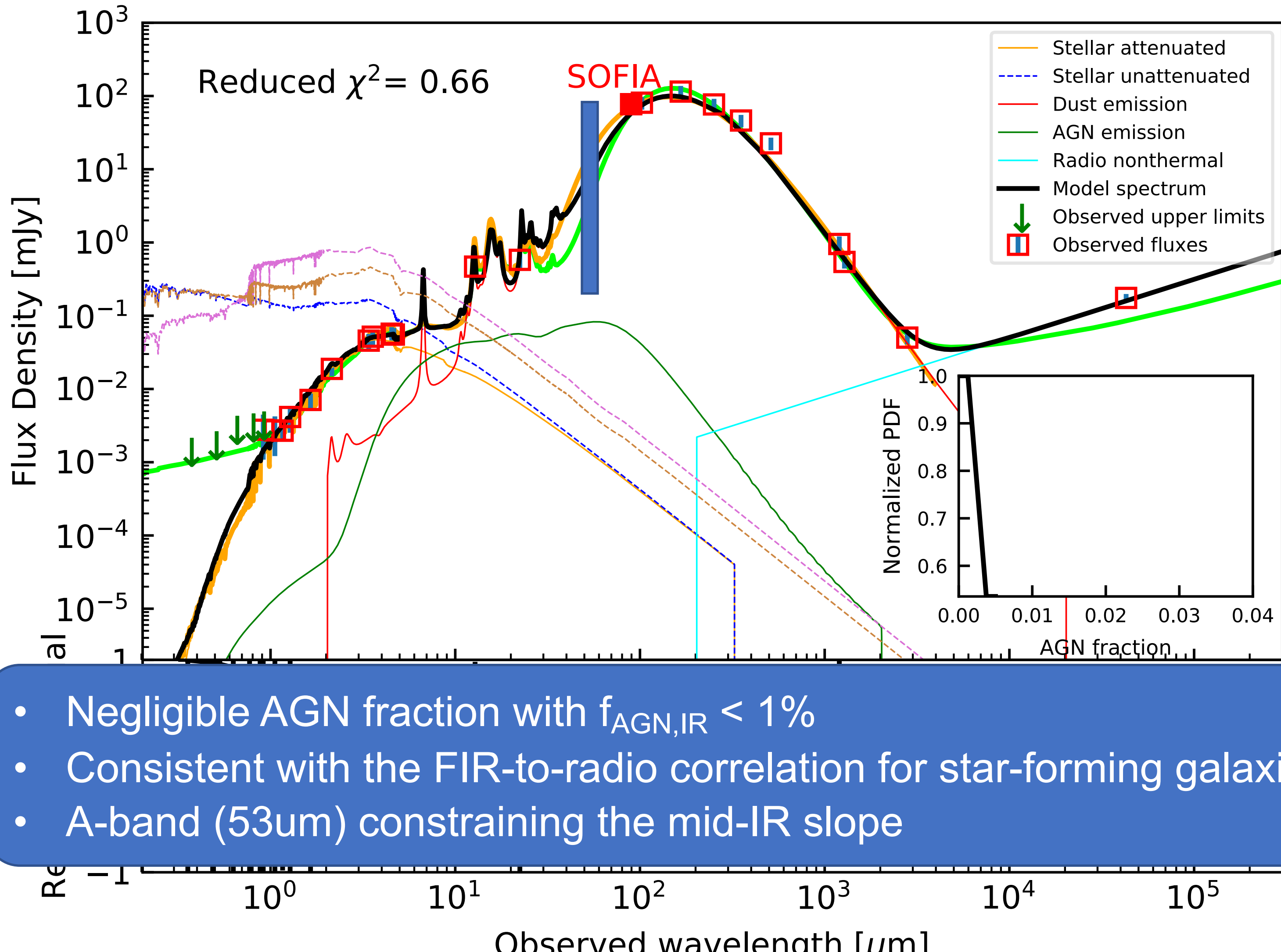

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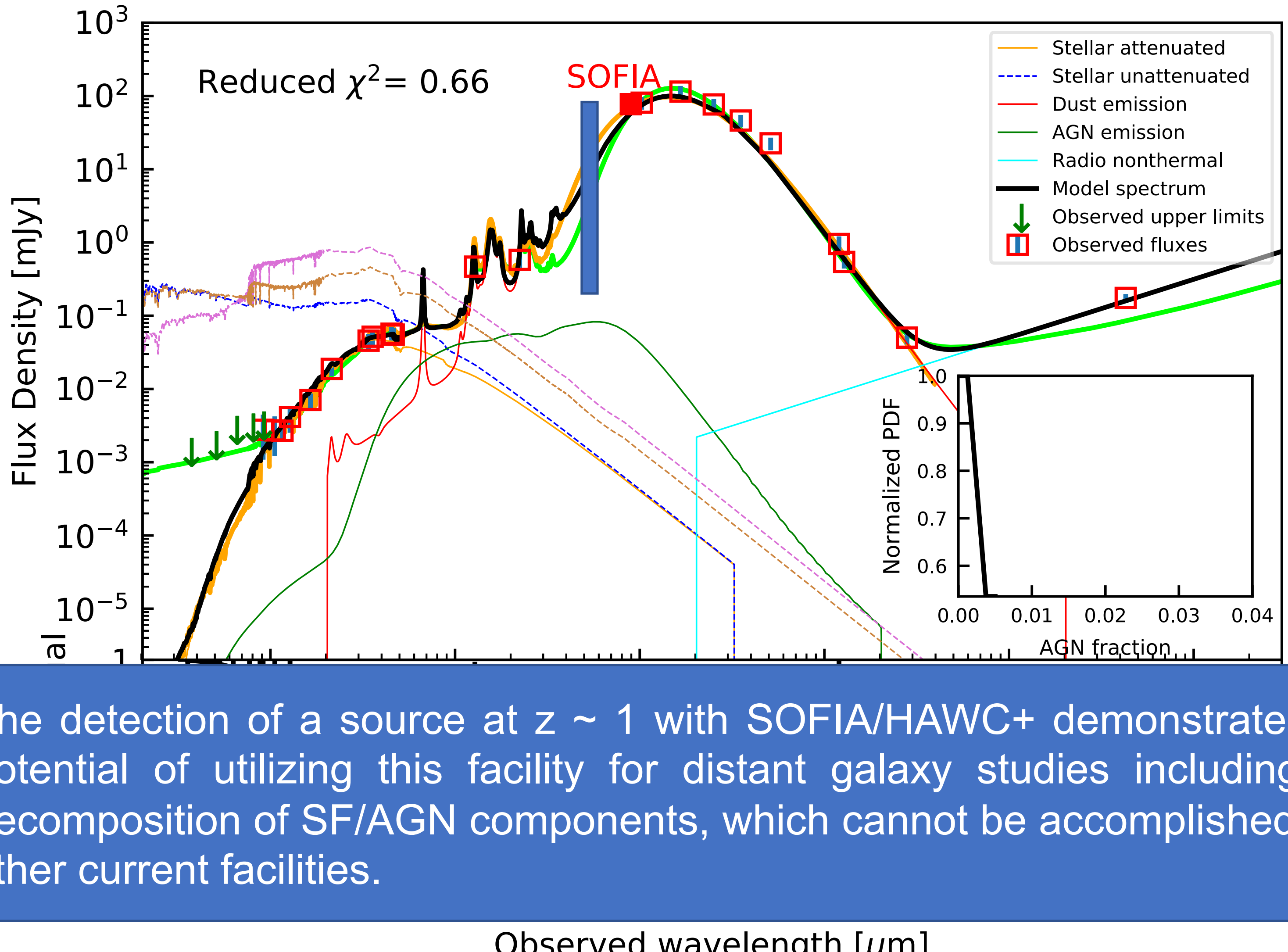
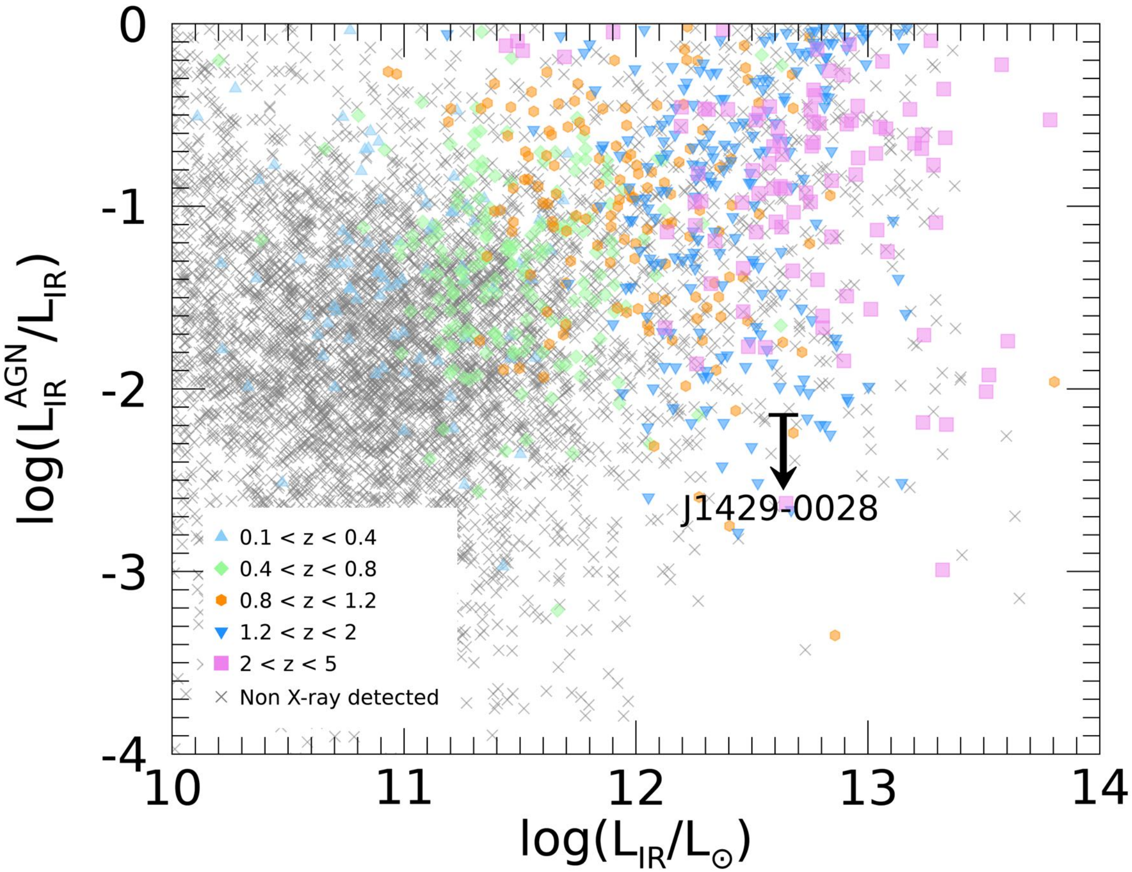


The detection of a source at z ~ 1 with SOFIA/HAWC+ demonstrates the potential of utilizing this facility for distant galaxy studies including the decomposition of SF/AGN components, which cannot be accomplished with other current facilities.

Ma et al. 2018c

AGN fraction vs. IR luminosity of Chandra X-ray selected AGN



- Boötes legacy field with MIR and FIR counterparts detected by Spitzer and Herschel
- largest AGN sample with a multi-wavelength SED fitting analysis (Brown et al. 2018)

Ma et al. 2018c

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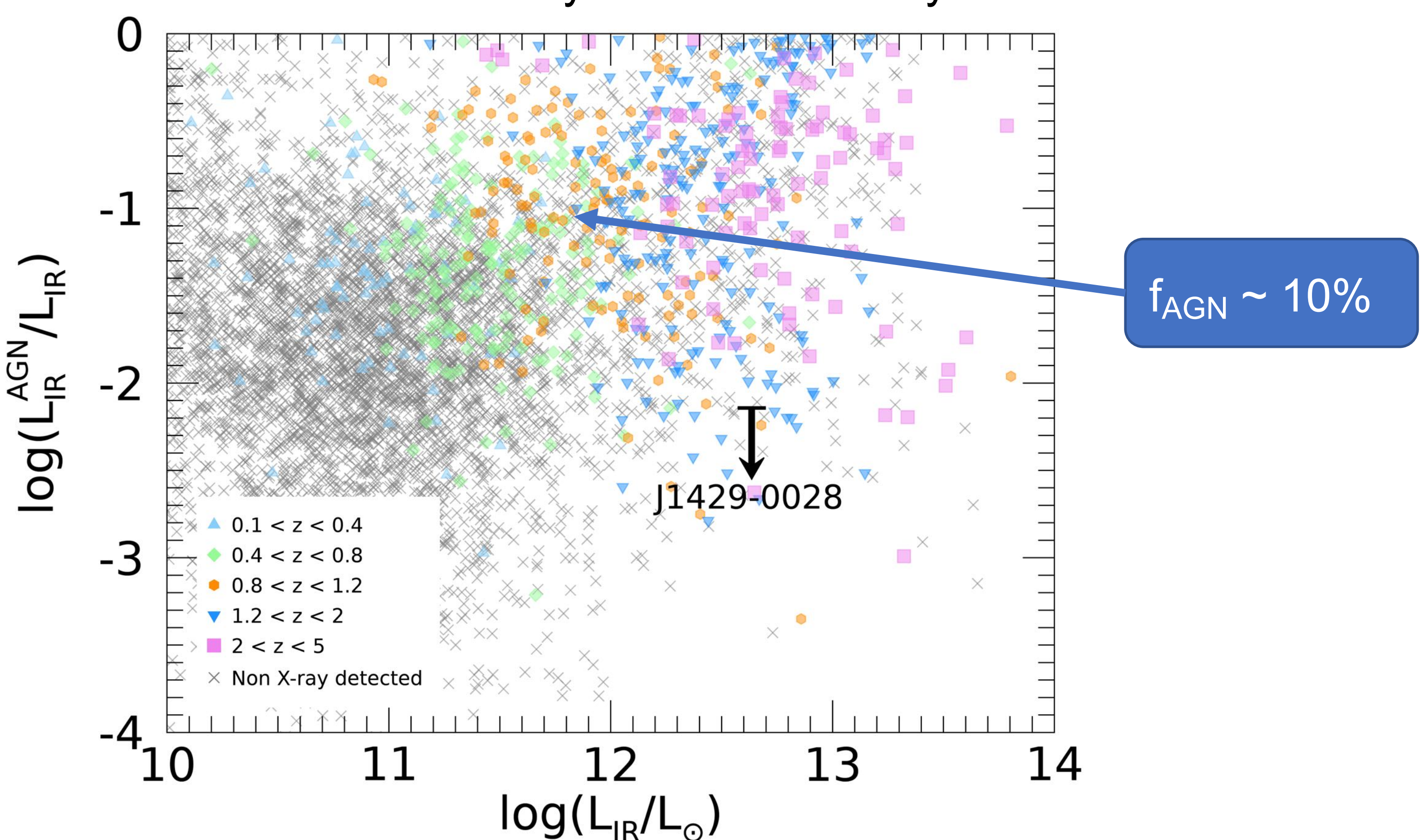

- A general trend of higher AGN fraction with increasing IR luminosity
- J1429-0028 has an intrinsic IR luminosity that is higher than most of the sources at similar redshifts.
- The 3σ upper limit of J1429-0028 is significantly below the majority of the X-ray detected AGN.

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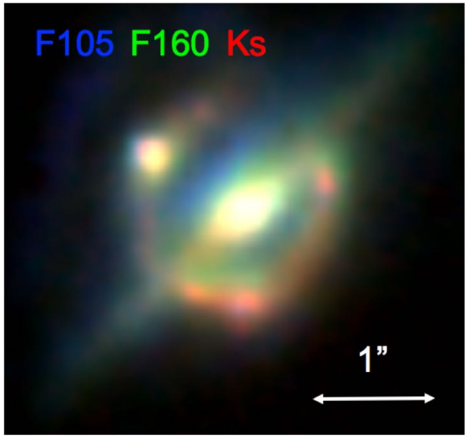
  lensing magnification ~ 10



Remaining questions:

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Negligible AGN fraction

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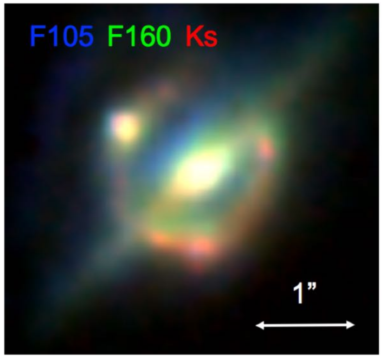

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Models and Properties	A. MAGPHYS[a]	B. High-z MAGPHYS	C. SED3FIT	D. CIGALE	E. CIGALE	F. CIGALE
Stellar population	CB07	BC03	BC03	BC03	BC03	BC03
SFH	modified τ SFH + random bursts	delayed-τ SFH + random bursts	delayed-τ SFH + random bursts	delayed-τ SFH	double-τ SFH ($f_{\rm burst}$ = 0–1)	double-τ SFH ($f_{\rm burst} \leqslant 0.1$)
Dust attenuation	Charlot+2000	Charlot+2000	Charlot+2000	power law	power law	power law
Dust emission	Rowlands+2014	daCunha+2015	daCunha+2015	Draine+2014	Draine+2014	Draine2014
AGN emission	…	…	Feltre+2012	Fritz+2006	Fritz+2006	Fritz+2006
M_* (10^{10} $M_\odot$)	$13.2^{+6.3}_{-4.1}$	44^{+26}_{-18}	83^{+43}_{-29}	2.1 ± 0.5	3.4 ± 1.1	15.1 ± 1.2

We cannot reliably distinguish the different SFHs, which introduce large uncertainties on the stellar mass with similarly good fits.

Summary and Future Work

- For J1429-0028, the AGN fraction in the IR luminosity is negligible, which confirms the starburst nature of this galaxy.

- Star formation history is the dominant source of uncertainty in the derived stellar mass (as high as a factor of ~10) even in the case of extensive photometric coverage.

- The detection of a source at z ~ 1 with SOFIA/HAWC+ demonstrates the potential of utilizing this facility for distant galaxy studies including the decomposition of SF/AGN components, which cannot be accomplished with other current facilities.

- To complete SEDs and constrain AGN fractions of the brightest lensed sources in the Herschel wide extragalactic surveys as well as mm-selected sources from the Planck all-sky survey.