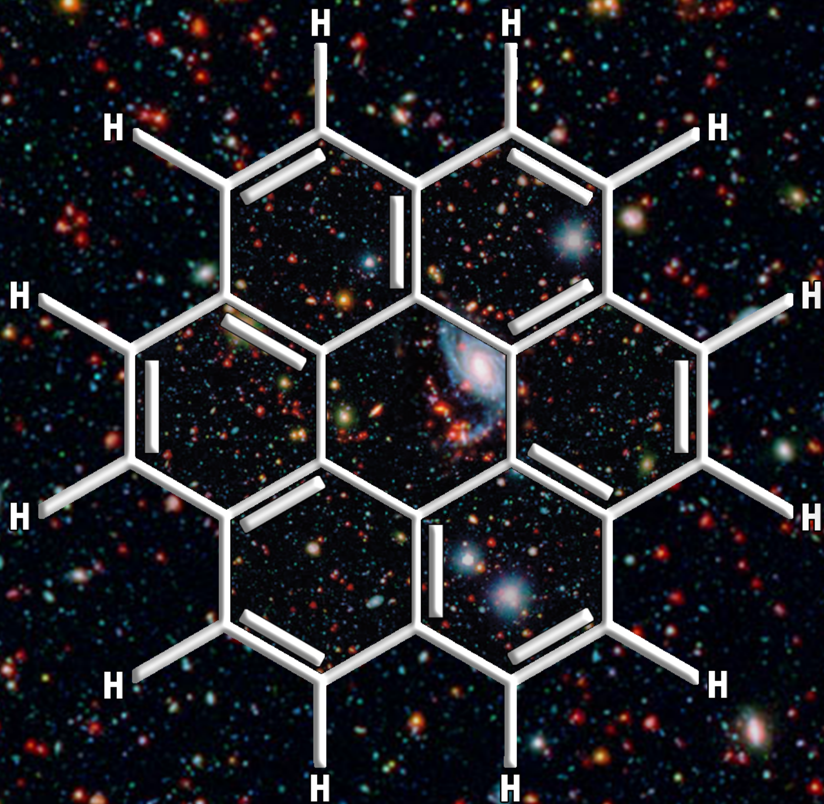

GALAXY EVOLUTION PROBE

Jason Glenn, on behalf of the GEP team

Massively Parallel, Large-Area Spectroscopy, Sept. 19, 2018

University of Colorado Boulder

NASA

JPL

Ball Aerospace & Technologies Corp.

Galaxy Evolution Probe Team

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Lee Armus – IPAC
Andrew Benson – Carnegie
Matt Bradford – JPL
Jeremy Darling – CU Boulder
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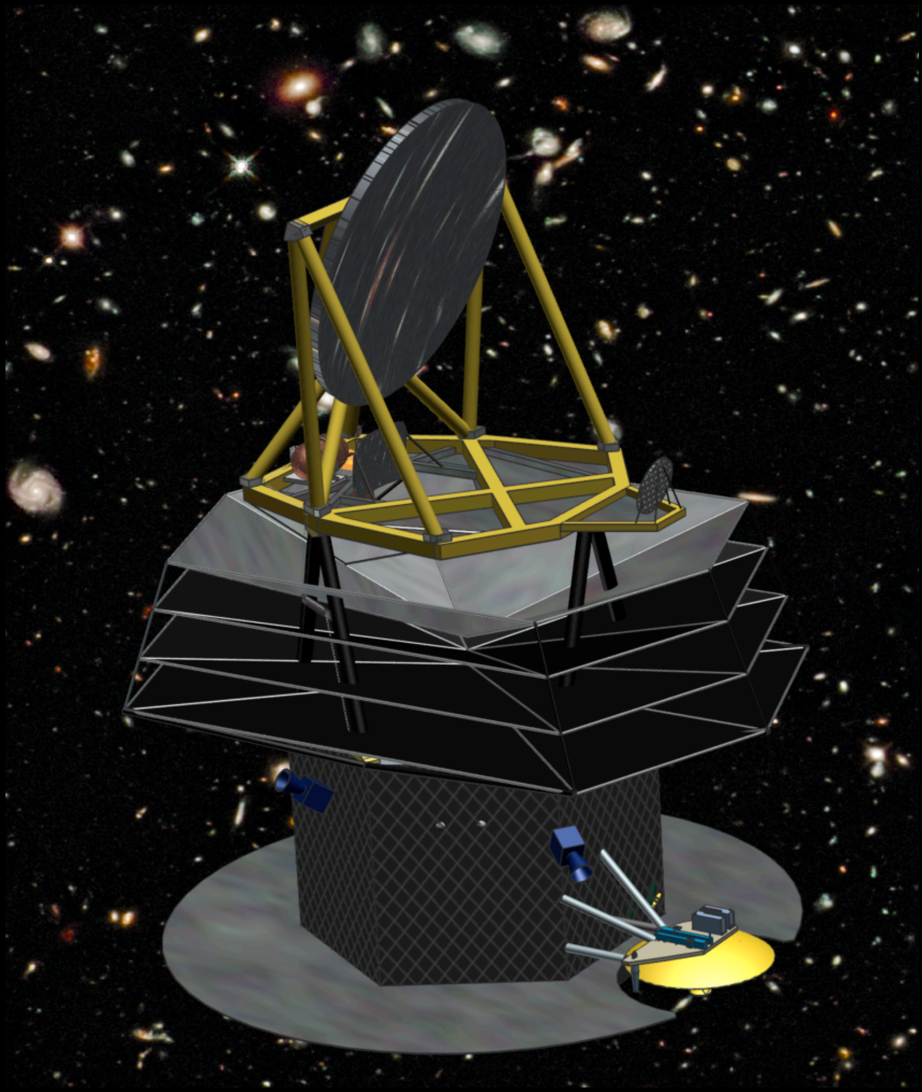
Mark Shannon – Ball
Raphael Shirley – Sussex
John Steeves – JPL
Xander Tielens – NASA Ames
Carole Tucker – Cardiff
Jonas Zmuidzinas – Caltech

GEP Take-Aways

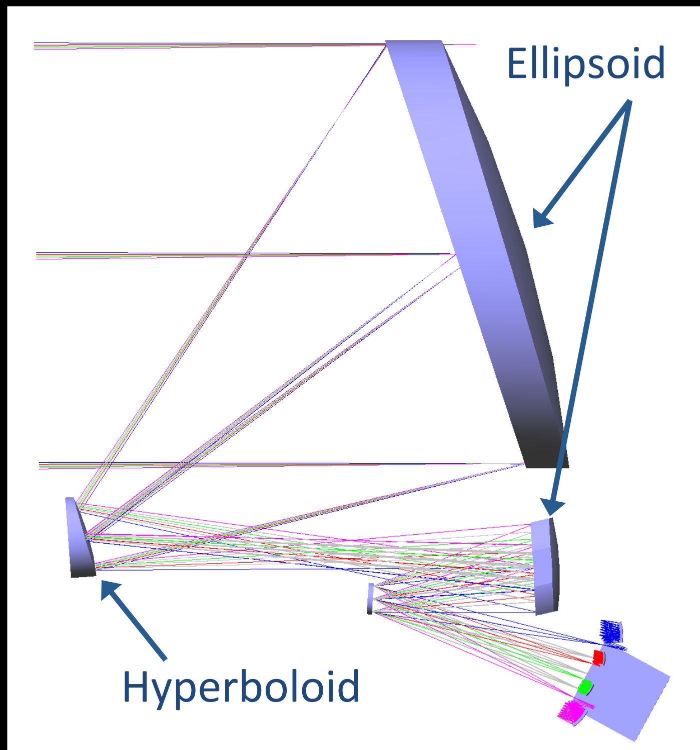
- Science
  - Cosmic evolution of star formation and SMBH accretion in galaxies
  - 2 yrs imaging surveys w/ photo-z's (3° sq, 30° sq, 300° sq, all-sky)
  - 2 yrs long-slit spectroscopic surveys
- Observatory
  - Concept design complete
  - 2.0 m, 4 K telescope
  - Jan. 2029 planned launch



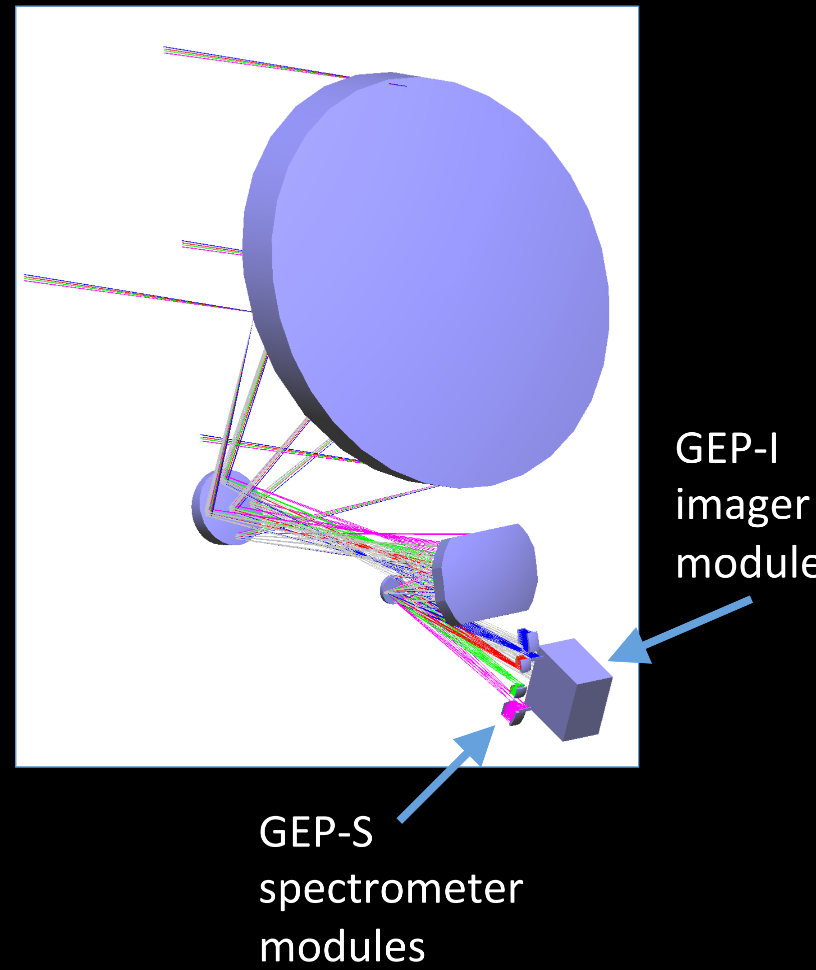
B. Moore & JPL Team-X

Optical Design – all optics < 4 K

2 m

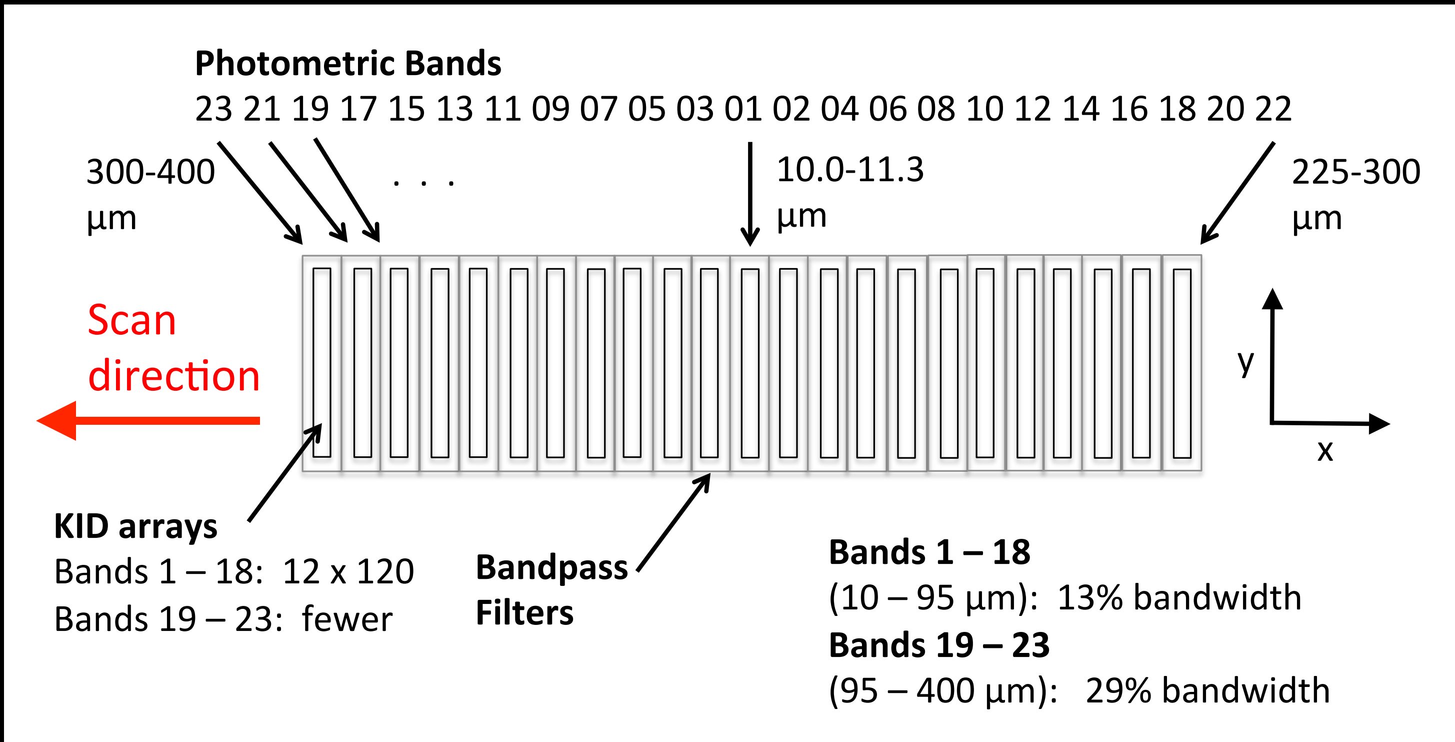


Mike Rogers



4 K telescope: sensitivities limited by astrophysical backgrounds: zodiacal light and Galactic dust emission

Imager: GEP-I (KIDs)



<u>Spectral Resolution</u>

$R = \lambda/\Delta\lambda = 8$ (10-95 µm)

$R = \lambda/\Delta\lambda = 3.5$ (95-400 µm)

<u>FoV and Sampling</u>

0.5° × 0.1°

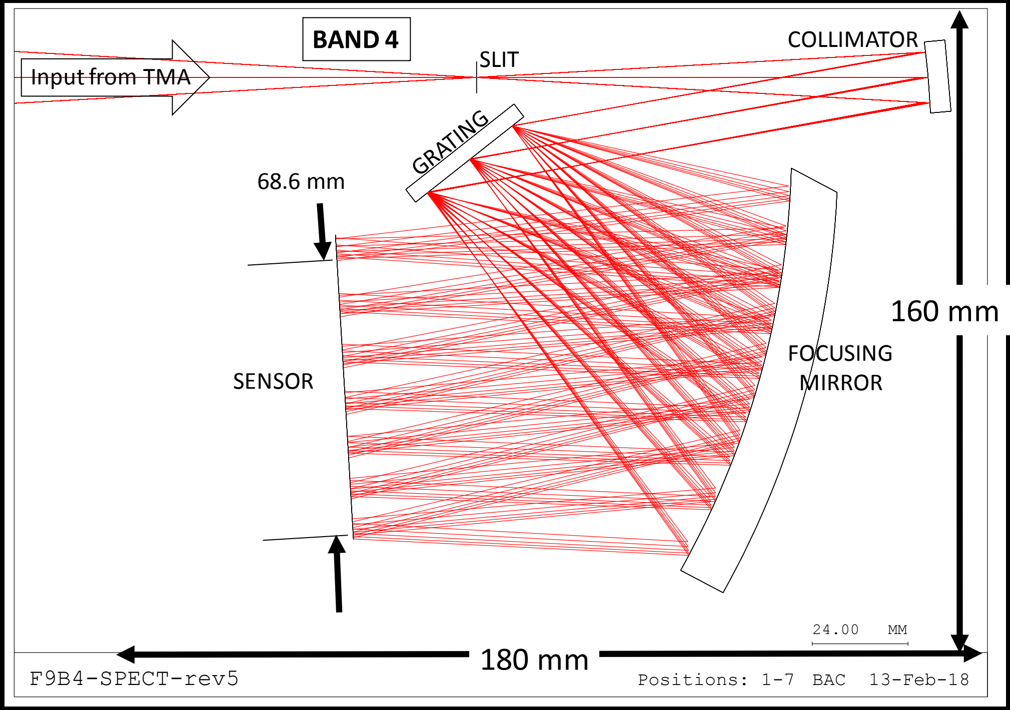
λ < 70 µm, 3.43” pixels

λ > 70 µm, Nyquist

GEP-I BAND	λ (µm)
1	10.7
2	12.1
3	13.7
4	15.5
5	17.6
6	19.9
7	22.6
8	25.6
9	29.0
10	32.9
11	37.3
12	42.3
13	47.9
14	54.3
15	61.5
16	69.7
17	79.0
18	89.6
19	111
20	148
21	197
22	263
23	350

Spectrometer: GEP-S (KIDs)

- $R = \lambda/\Delta\lambda = 200$
- Long slits (3.8’ – 10’) enable extended-object observations and ‘blind’ surveys



M. Bradford

GEP-S BAND	1	2	3	4
WAVELENGTHS (µm)	24 - 42	40 - 70	66 - 116	110 - 193
SLIT LENGTH (arc min)	3.8	6.4	6.0	10.0

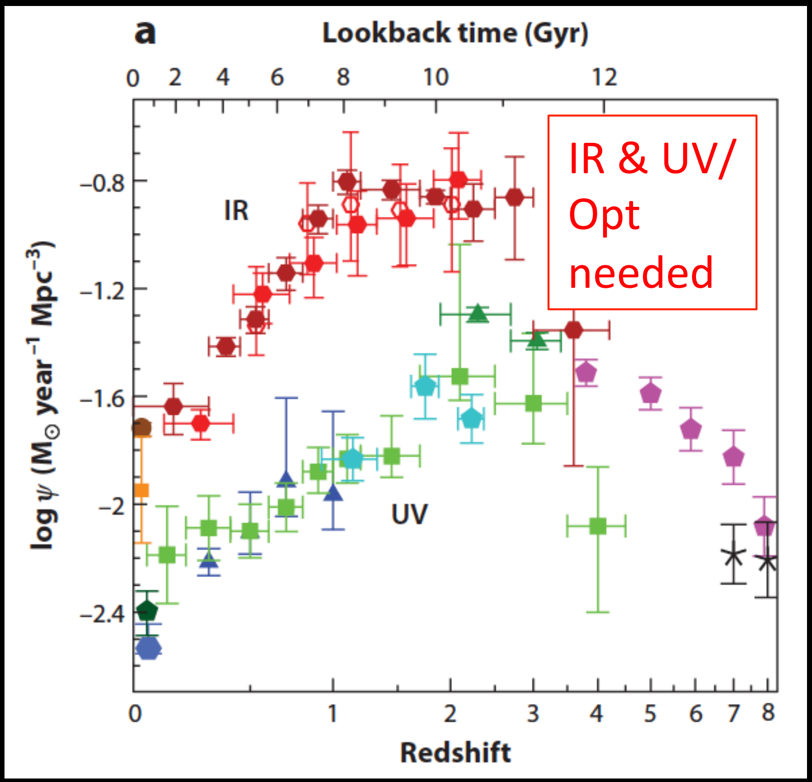
Some FIR Atomic Fine-Structure Lines Accessed by GEP

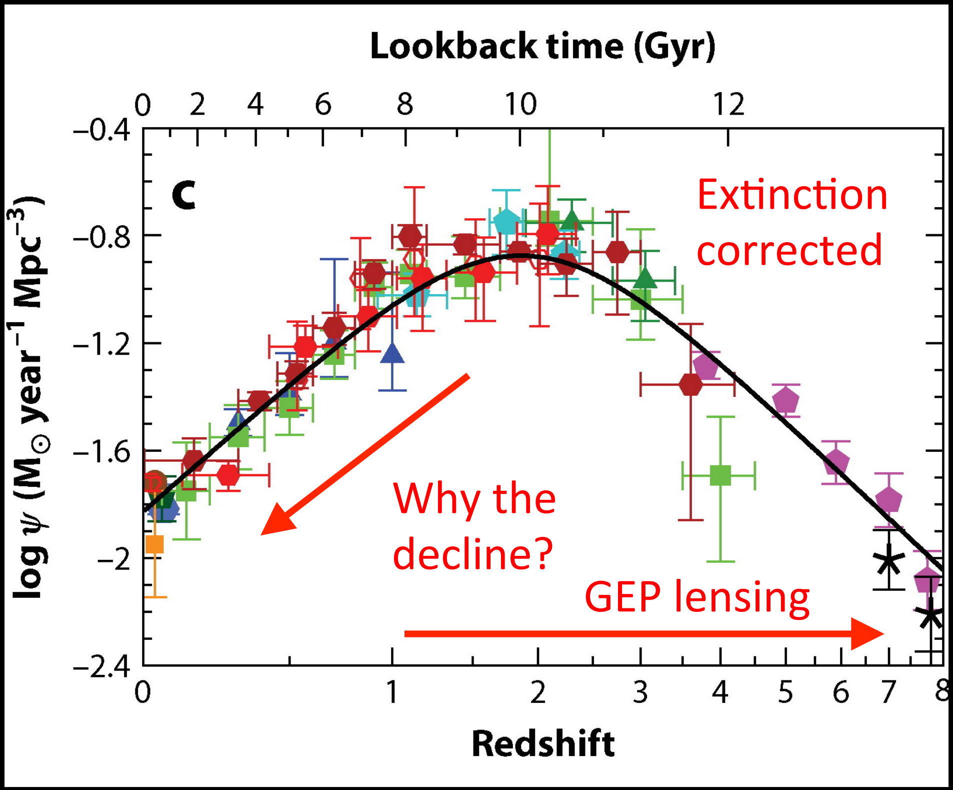
Species	Rest λ (μm)	Ionization Energy (eV)	Traces	Typical Line Luminosity × 10^{-4} L_{FIR}
[Ne II]	12.8	21.6	SF	3
[Ne V]	14.3	97.1	AGN	2
[Ne V]	24.3	97.1	AGN	2
[O IV]	25.9	54.9	AGN (& SF)	5
[S III]	33.5	23.3	SF	3
[Si II]	34.8	8.2	SF	4
[O III]	51.8	35.1	SF (& AGN)	20
[O I]	63.2	N/A	SF	10
[O III]	88.4	35.1	SF (& AGN)	8
[N II]	122	14.5	SF	2
[O I]	146	N/A	SF	3
[C II]	158	11.3	SF	20

Line carrying 10^{-3} L_{FIR} for 10^{12} $L_{\odot}$ galaxy detectable at z = 2, 5σ, ~1 hour

Adapted from Spinoglio 2013

Cosmic Star Formation History
State of the Art



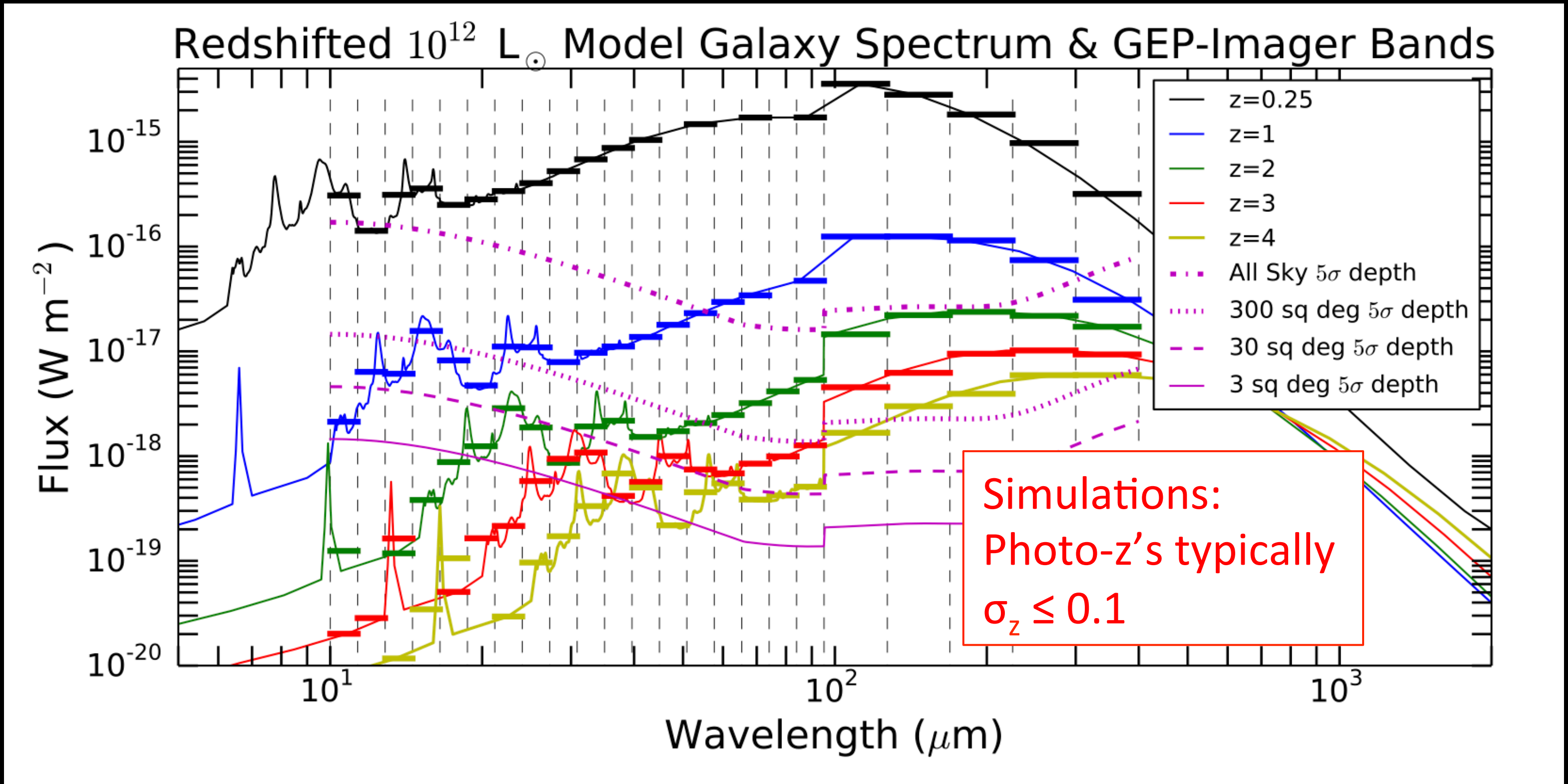


Madau & Dickinson 2014 ARAA

- How does the cosmic SFR history depend on environment (i.e., clustering)?
- What processes led to the decline in SFR (i.e., feedback)?

Large Mid/Far-IR Galaxy Surveys

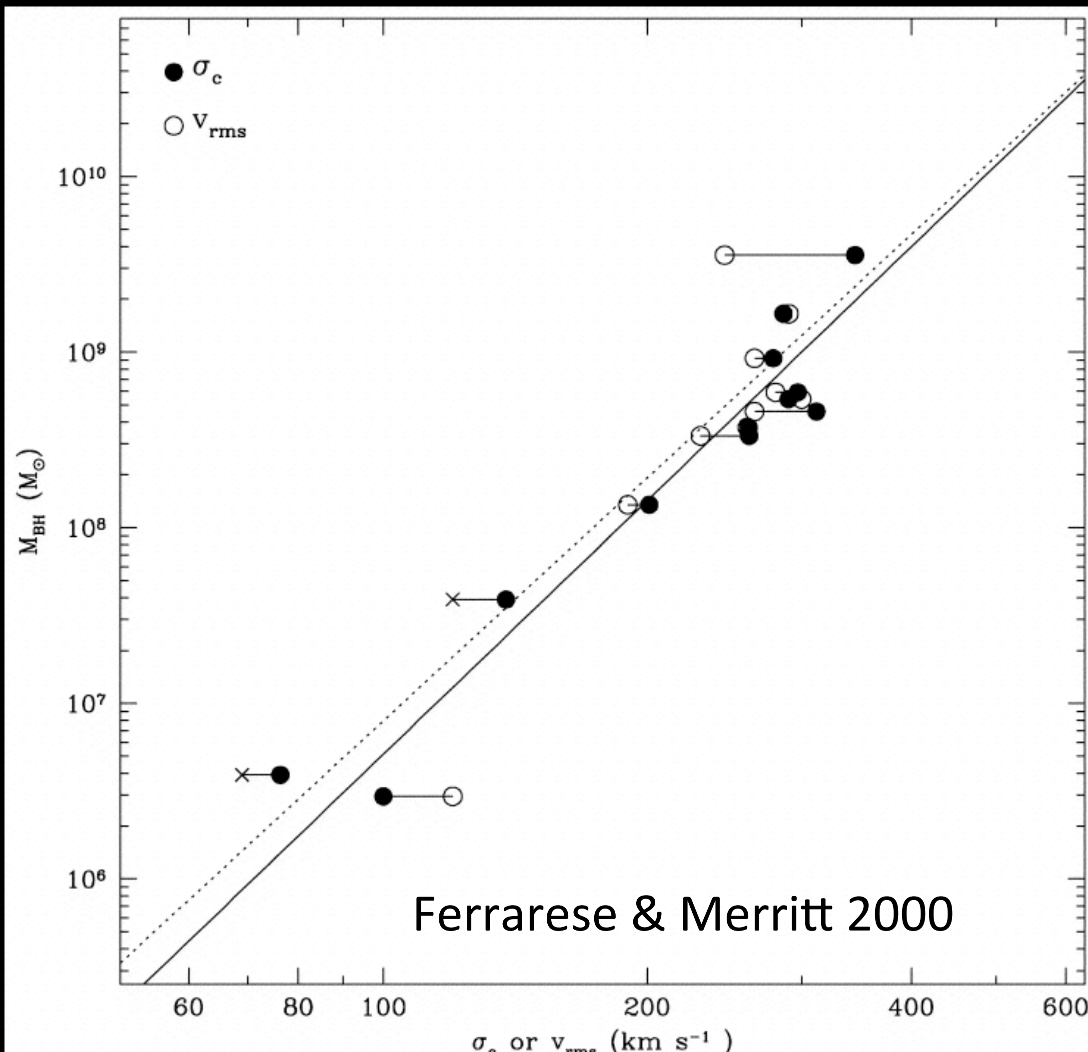
NASA Astrophysics Roadmap 2013: "Use telescopes as time machines to map the full history of galaxy formation and assembly, from the birth of the first stars through the turbulent epoch of rapid growth, to the galaxies we see today."



Models from Dale et al. 2014

Models do not include MIR/FIR atomic fine-structure lines

The Observed Correlation Between SMBH & Bulge Masses



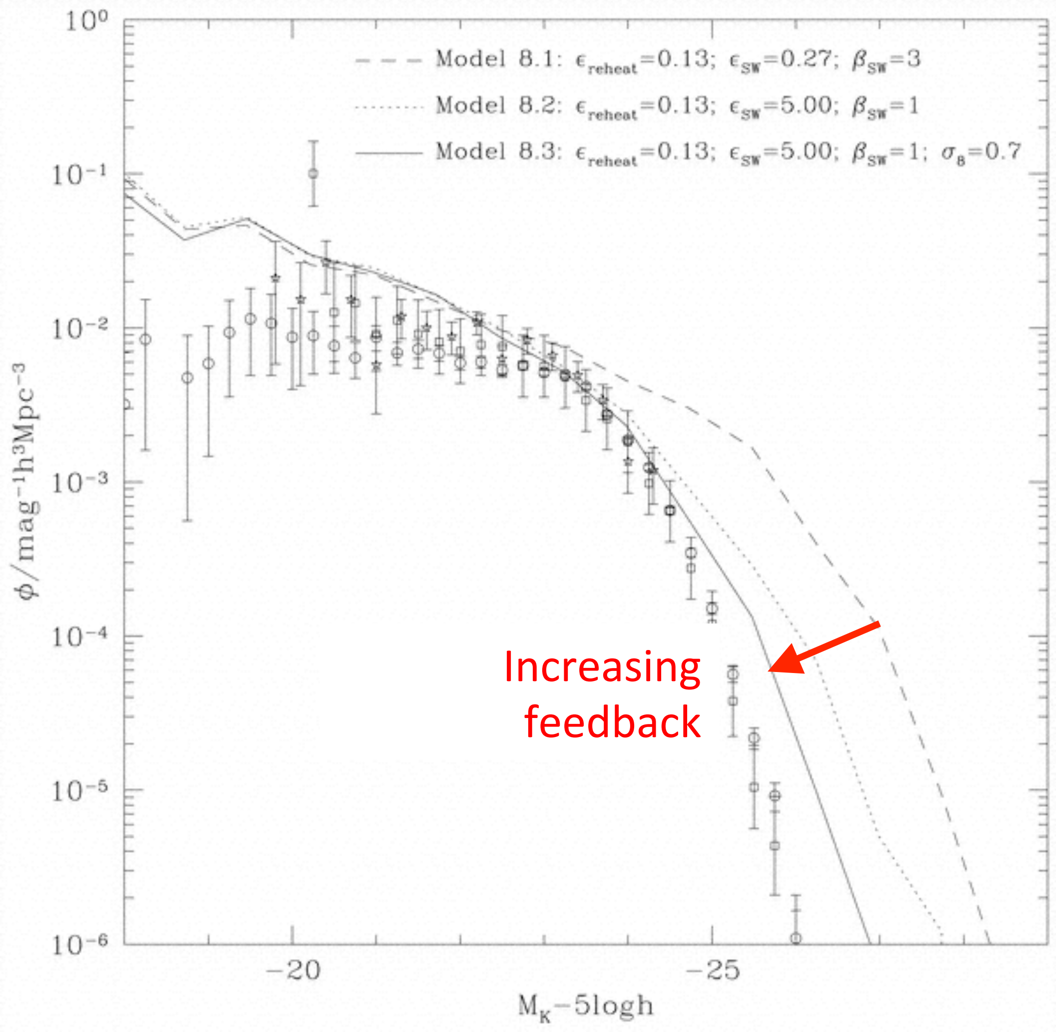
NASA Astrophysics Roadmap 2013: "Characterize … the relation between galaxy growth and black holes."

=> Measure the *growth rates* of galaxy stellar & SMBH masses

AGN feedback is invoked to suppress numbers of luminous galaxies

Investigating this with large GEP-I surveys:

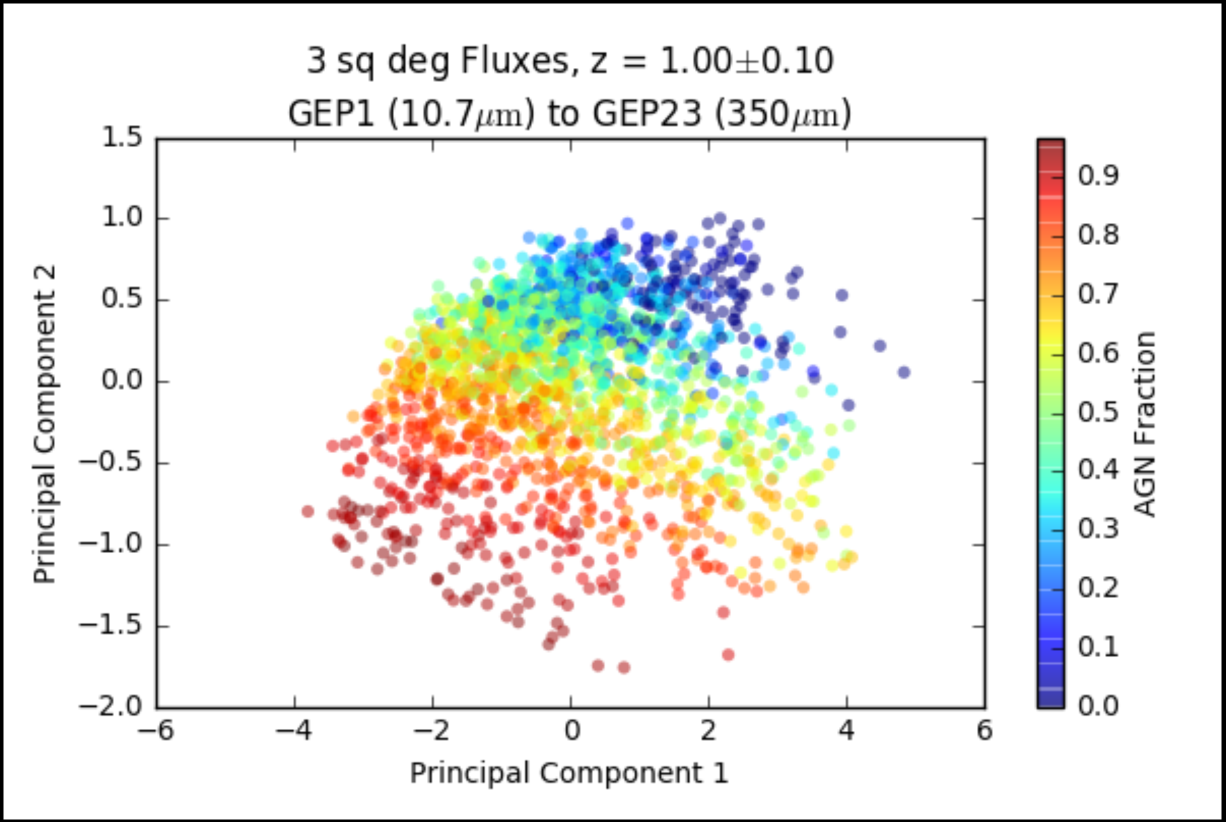
- What are the LFs of star-forming galaxies as f(z)?
- Do they differ from LFs sampled by stellar mass?
- What are the LFs of obscured AGN as f(z)?
- Do they support suppression for massive galaxies?



Benson et al. (2003).

SFRs and AGN Accretion Rates from GEP-I Surveys

AGN -> Warm dust -> 'Blue' continuum

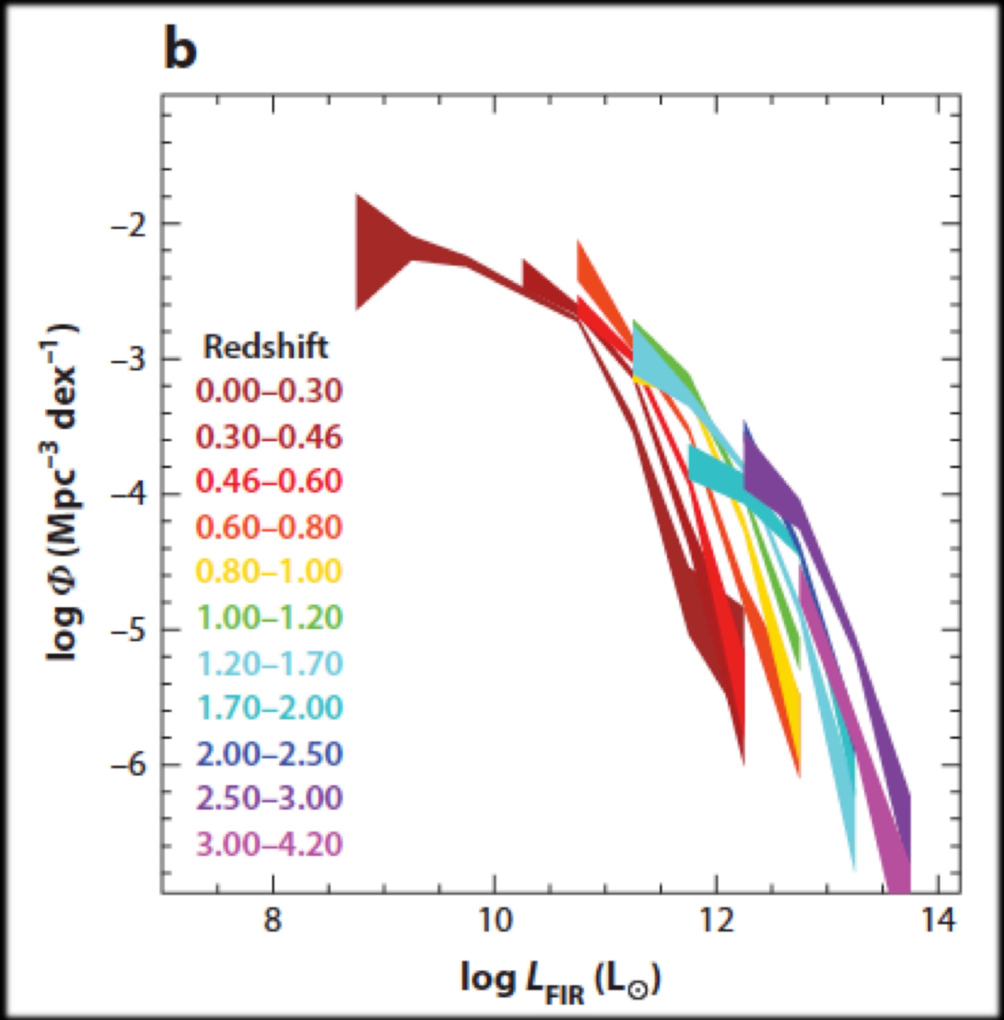


Principle-Component Analysis (*of two bands only!*)

- Ratio of two principle components yields AGN fraction
- Luminosity converts to SFR or AGN accretion rate
- Many more bands available to probe dust temperature, PAH abundance and excitation…

Darling, Lee, & Benson

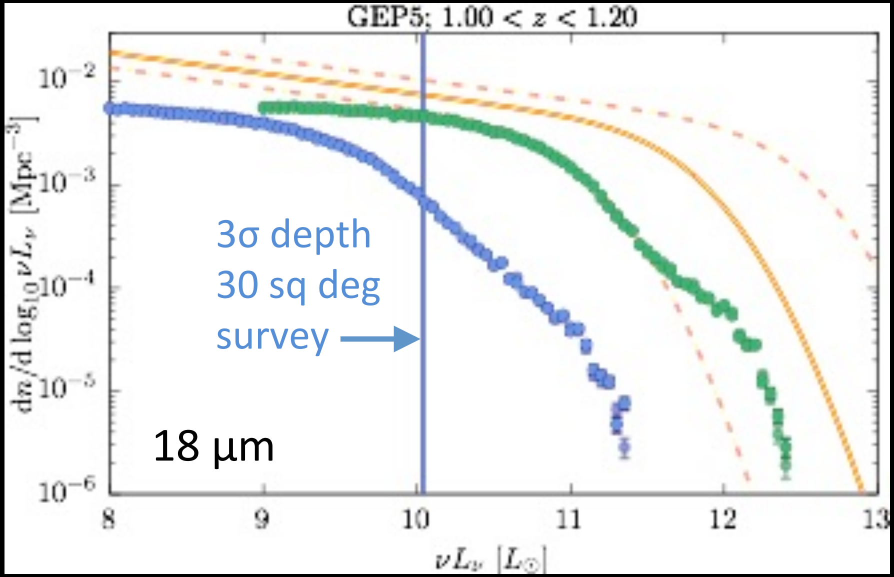
Far Infrared Galaxy Luminosity Functions State of the Art

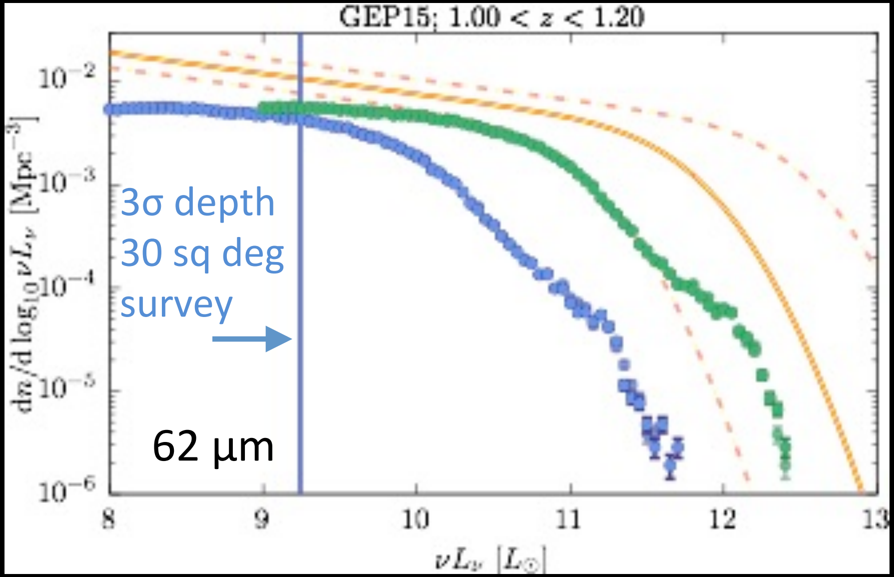


Madau and Dickinson 2014, Gruppioni et al. 2013

Simulated GEP Luminosity Functions

A. Benson: Galacticus + Dale et al. spectra & Millenium dark matter distribution





Blue points: GEP-I band LFs

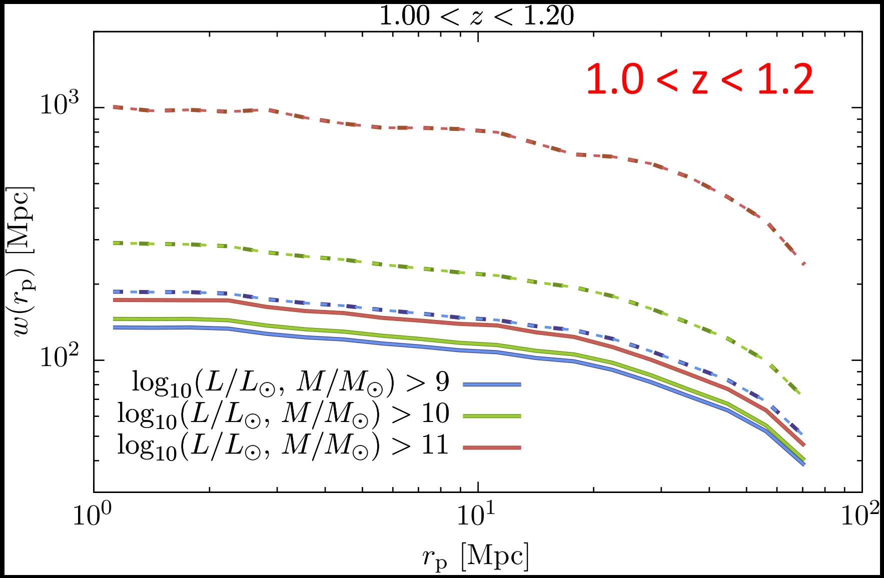
Green points: bolometric LFs

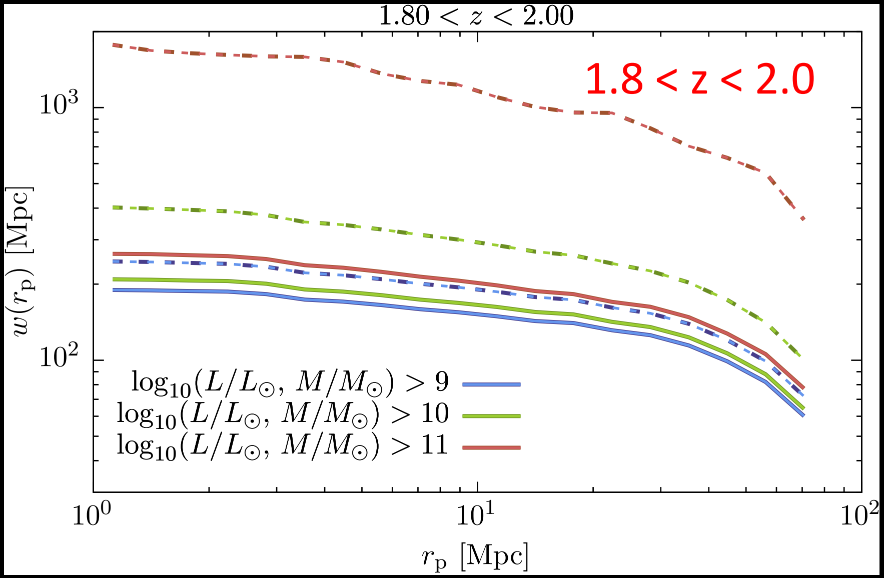
Orange lines: Caputi et al. 8 µm LFs in GOODs

➔ GEP will make a major advance in measuring mid and far-IR LFs at least to z ≈ 2, more than an order of magnitude deeper than state of the art, over a range of environments.

Simulated GEP Large-Scale Structure Measurement

NASA Astrophysics Roadmap 2013: "How do cosmic structures form and evolve? What are the connections between dark and luminous matter?"





A. Benson

Solid lines: selected by bolometric IR luminosity

Dashed lines: selected by stellar mass

In Galacticus, galaxies selected by IR luminosity correlate weakly with halo mass (because even galaxies in low-mass halos have starbursts).

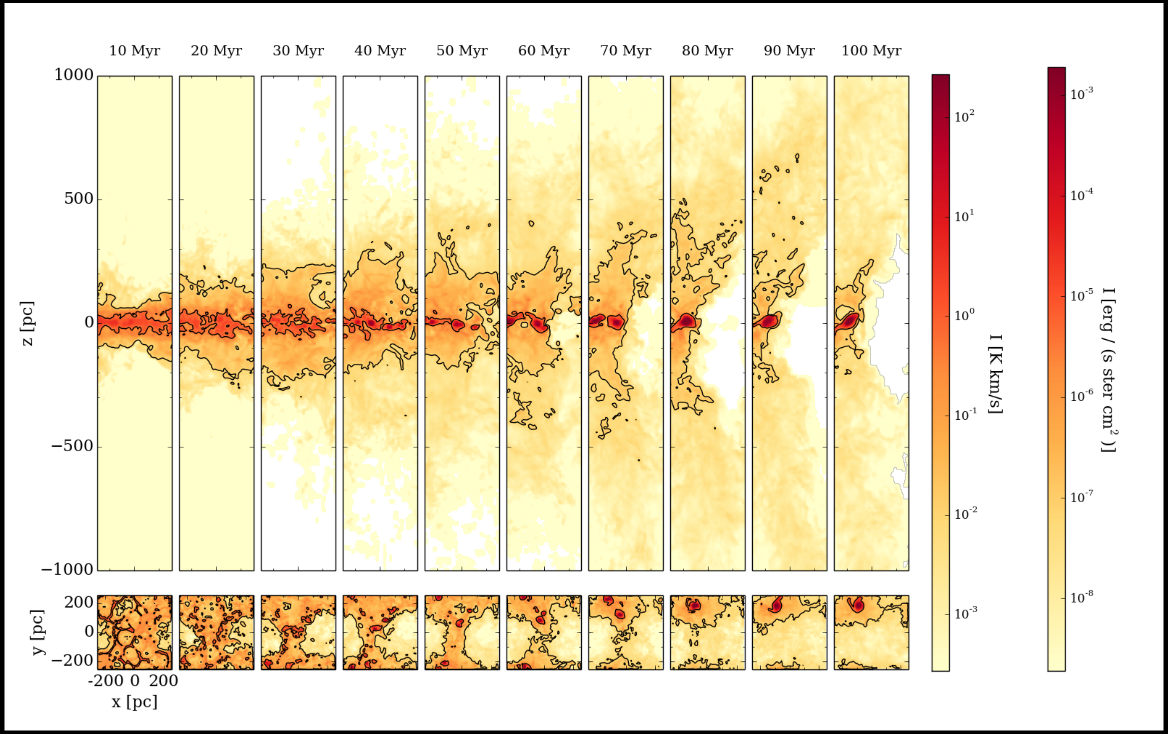
➔ GEP will test the predicted difference in clustering & may measure DM less biased.

Sample Science from GEP-S Spectroscopic Surveys

- GEP-I follow-up: precise redshifts & AGN markers
- Metallicities measured with extinction-free tracers, e.g. [Ne II] + [Ne III] / [S III] + [S IV]
- ISM physical conditions: stacking on ~10^6 WFIRST grism galaxies detected in Hα to correlate with various mid / far-IR tracers
  - [N III] / [N II] sensitive to stellar T_{eff}
  - [O III] 52 μm / 88 μm sensitive to density around young stars
- Intensity mapping – e.g., [O III] 88 μm will yield luminosity density and clustering
- PAH intensities are affected by metallicity and the line ratios probe radiation fields

How Impactful is SF Feedback?

Observing stellar feedback in nearby galaxies with long-slit GEP-I mapping



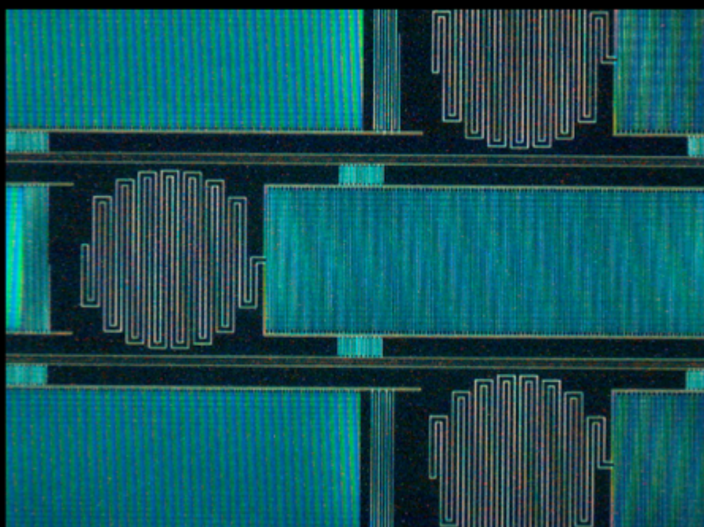
GEP-S should observe these outflows in dozens of nearby galaxies in [C II] 158 µm if they are present.
– Not possible with sub-orbital platforms

Outflows from simulations by Walch et al. 2015 (private communication to M. Bradford)

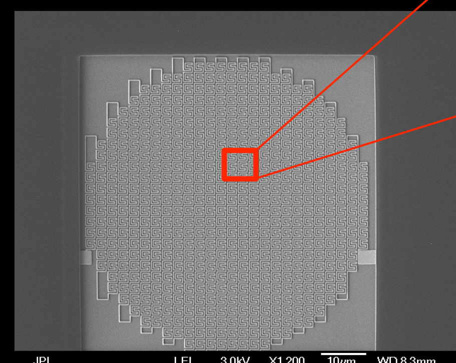
Kinetic Inductance Detectors

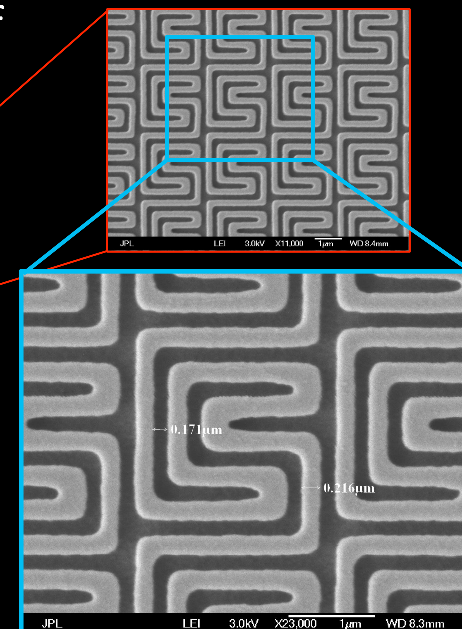
Why baseline KIDs? -> Simple architecture, simple cryogenic readout, one focal plane technology.

100 - 400 µm: MAKO type LEKID



10 - 95 µm: Unit cell of mid-IR KID absorber.





P. Day & H. LeDuc

Technology development plan: MIR KIDs, readout

Animation Here

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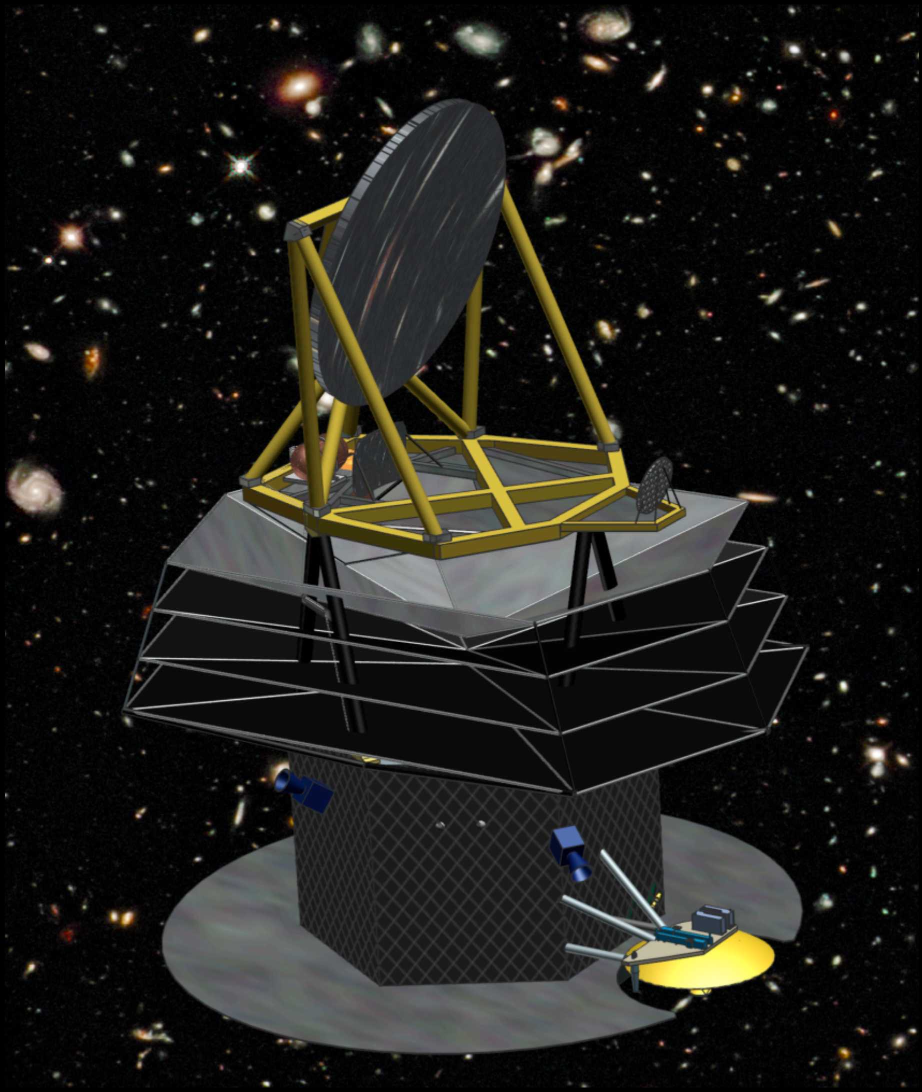
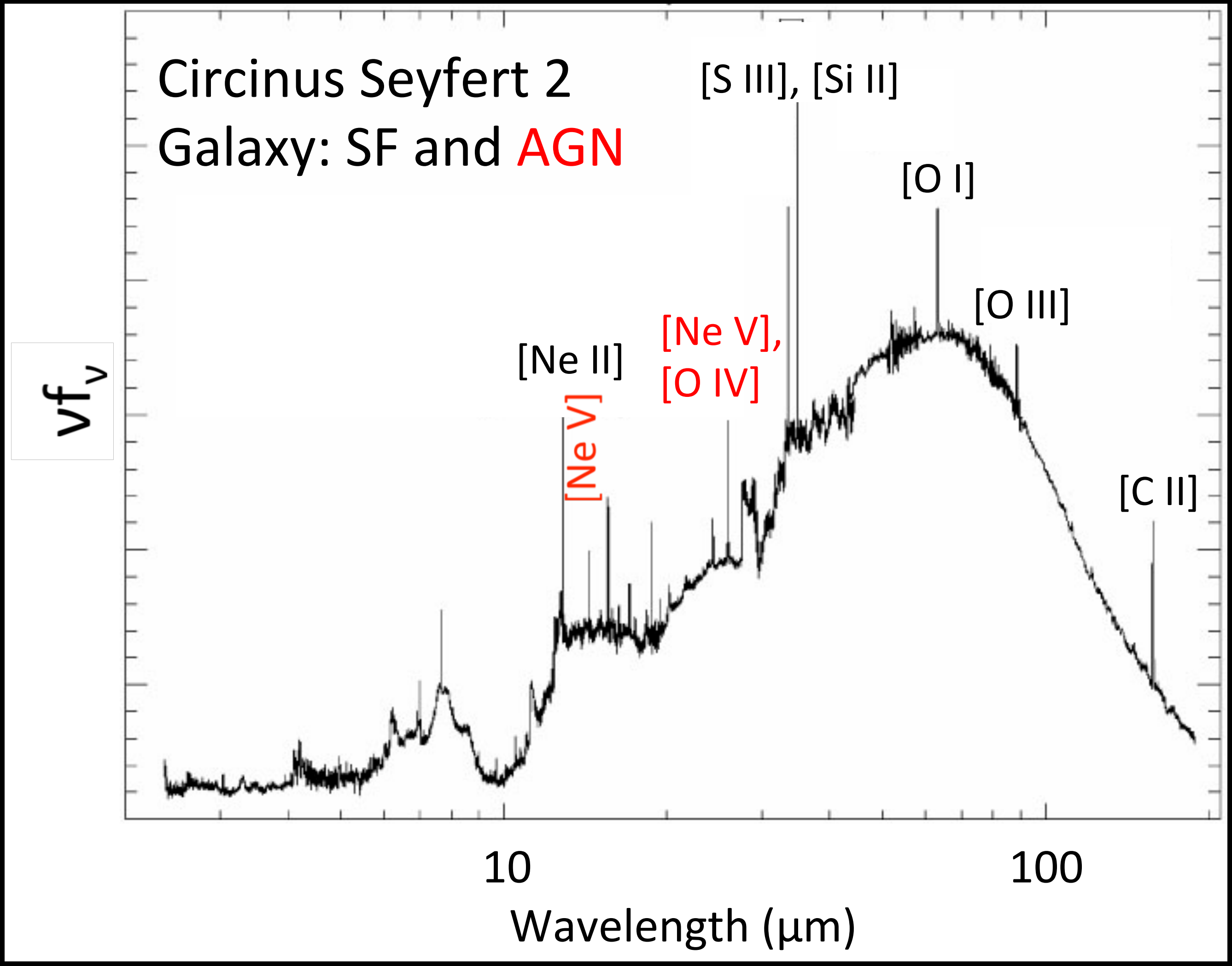


B. Moore & JPL Team-X

Galaxy Survey Yields

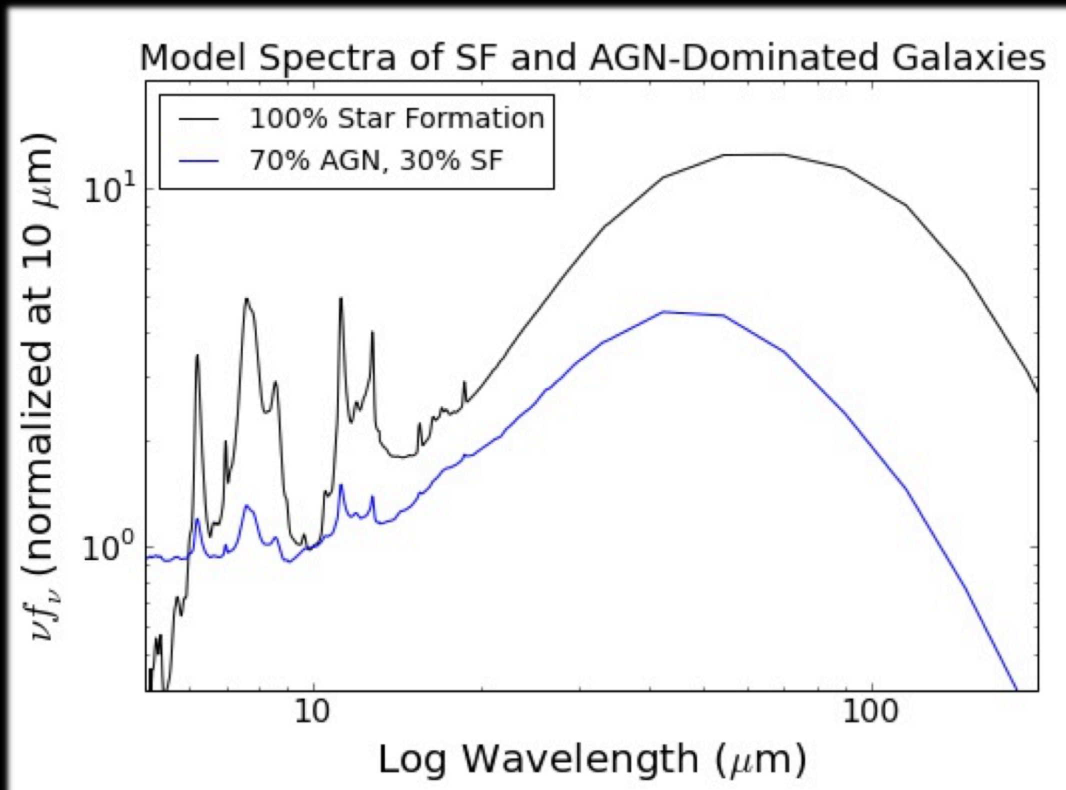
Instrument	Area or Targets	Depth	Region	Number of Galaxies	Number of Redshifts	Science Objectives
GEP-I	3 sq deg	10 μJy	Ecliptic Poles	10^6 above confusion noise	10^5	1a, 2a, 2b, 3, 4a
GEP-I	30 sq deg	30 μJy	Ecliptic Poles	10^6 above confusion noise	$2x10^5$	1a, 1b, 2a, 2b, 3, 4a
GEP-I	300 sq deg	100 μJy	Ecliptic Poles	10^7 above confusion noise	$5x10^5$	1a, 1b, 2a, 2b, 3, 4a
GEP-I	All sky	1 mJy	N/A	10^8 above confusion noise	10^6	1a, 1b, 2a, 2b, 3, 4a
GEP-S	GEP-I galaxies z=1.2-4	$4x10^{-20}$ W m^{-2}	Various, up to 6 hours / galaxy	300	20 ea. In 15 Δz bins from z = 1.2 to 4	1a, 1b, 2a, 2b, 4a
GEP-S	GEP-I galaxies z=0-1.2	$4.6x10^{-20}$ W/m^2 in the 100-193 micron band	Various, 2 hours per galaxy	500	20 ea. in 5 z and luminosity bins from z = 0 to 1.2	4a
GEP-S	3 sq deg	$7x10^{-20}$ W m^{-2} @ 100 μm	Ecliptic Poles	Expect ~20,000 galaxies between z=1 and 2	N/A	2a, 2b, 4a
	Same			Intensity mapping provides P(k) for all bright lines, multiple redshift bins.	N/A	2a, 2b, 3a, 4a, 4b
GEP-S	100 sq deg	3.5×10^{-19} W m^{-2} at 100 μm	Overlap with WFIRST /Euclid grism fields	Blind detections of tens of thousands of ULIRG-class galaxies expected between z=1-2	N/A	4a, 4b
	Same			Stack on ~400,000 to 1 million galaxy 3-D positions to provide stacked spectra in ~100 independent bins.	N/A	2a, 2b, 4a, 4b

Some FIR Atomic Fine-Structure Lines Accessed by GEP



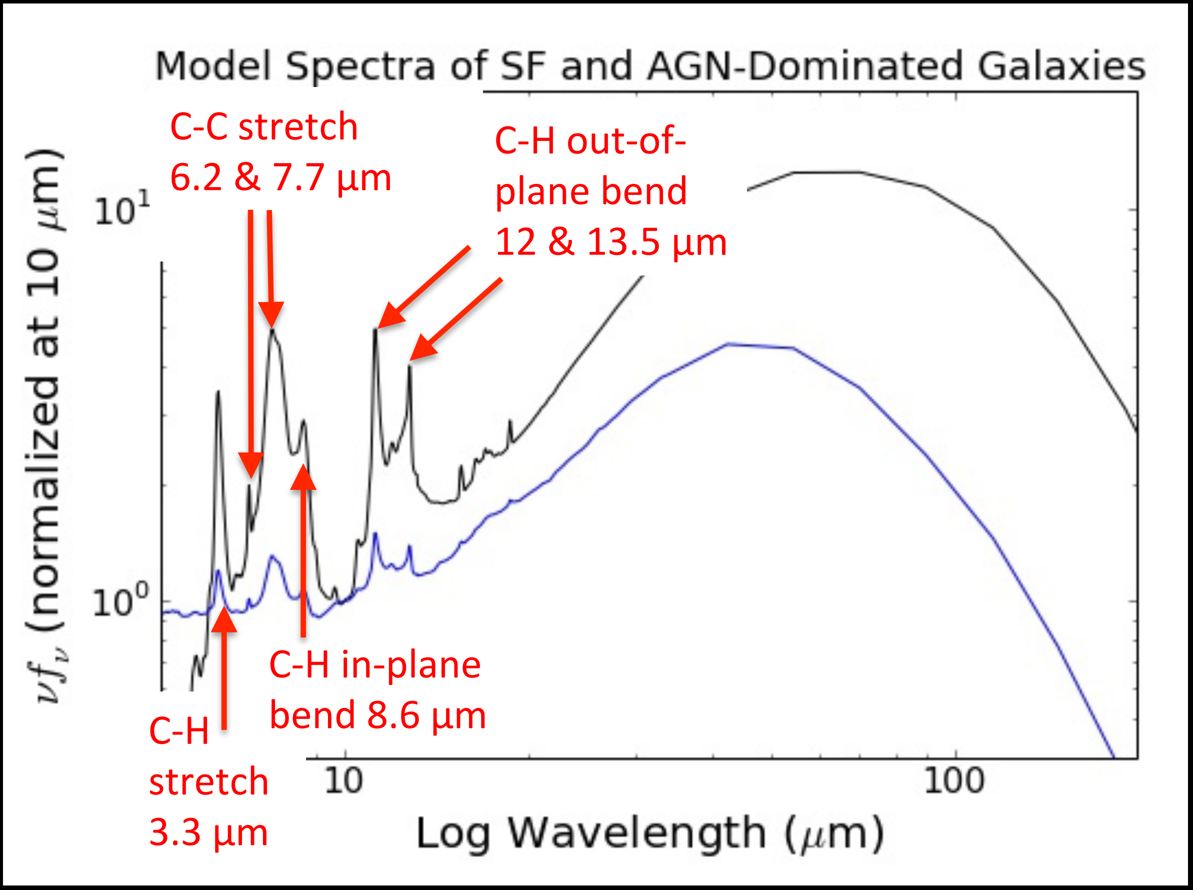
Adapted from Moorwood 1999

One of three means for identifying obscured AGN: PAH features are weaker compared to star-formation-dominated galaxies



Models from Dale et al. 2014 – *models do not include MIR/FIR atomic fine-structure lines*

Origin of PAH Emission Features



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