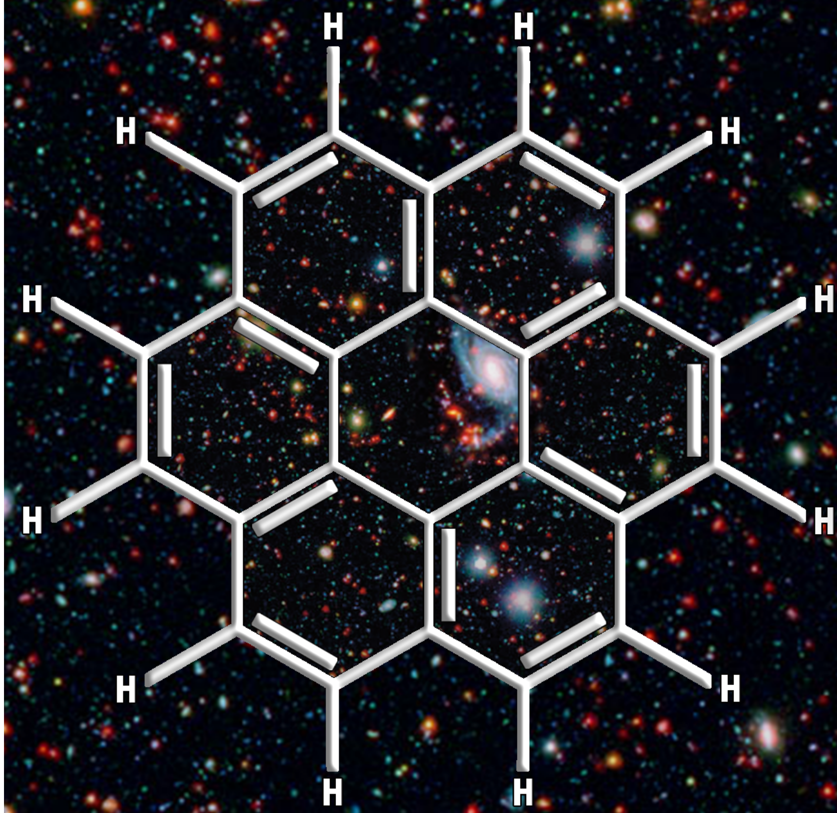


GALAXY EVOLUTION PROBE

Jason Glenn, on behalf of the GEP team

Infrared Science Interest Group, AAS, Jan. 8, 2019

University of Colorado Boulder

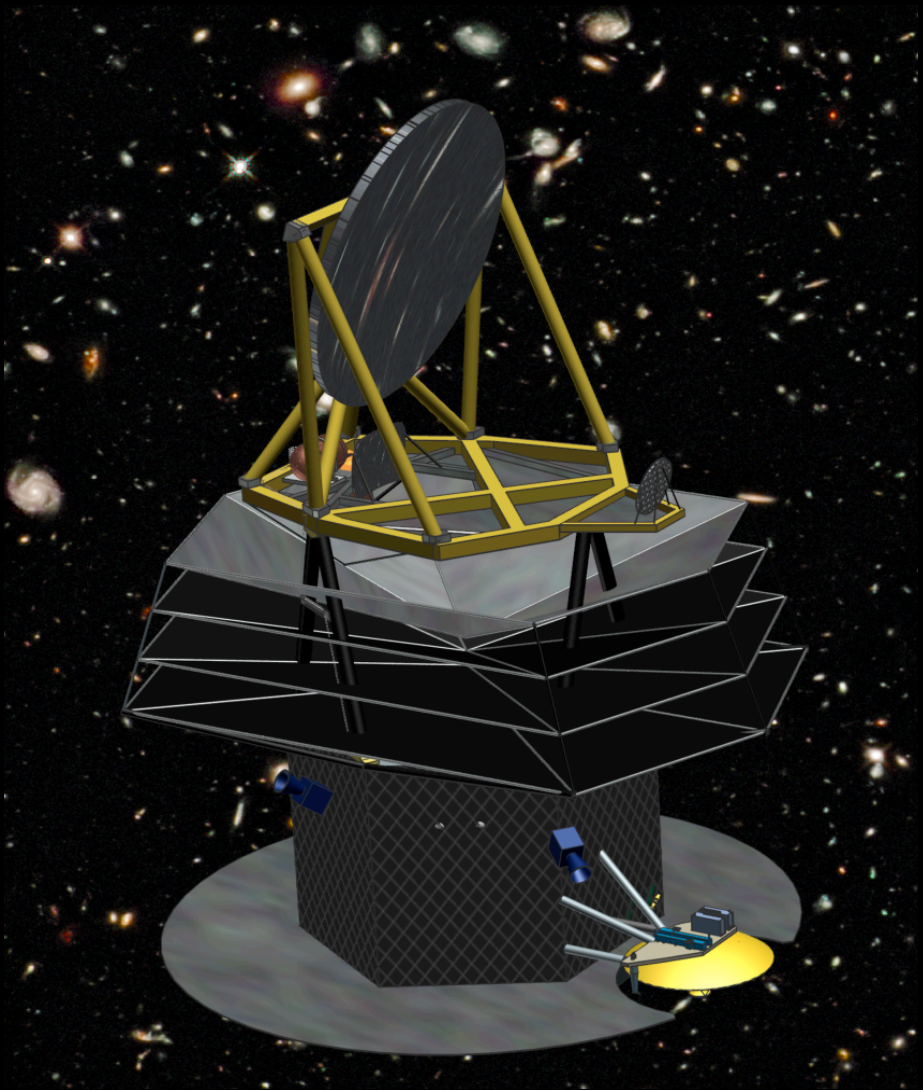
NASA

JPL

Ball Aerospace & Technologies Corp.

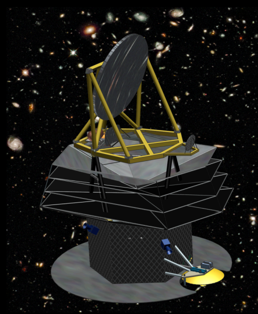
GEP Basics

- Observatory
  - 2.0 m, 4 K telescope
- Science Surveys
  - Cosmic evolution of star formation, SMBH accretion, ISM in galaxies
  - GEP-I 2 yr imaging surveys w/ photo-z's: 3, 30, & 300 sq deg, all-sky
  - GEP-S 2 yr long-slit spectroscopic surveys: targeted and 'blind'

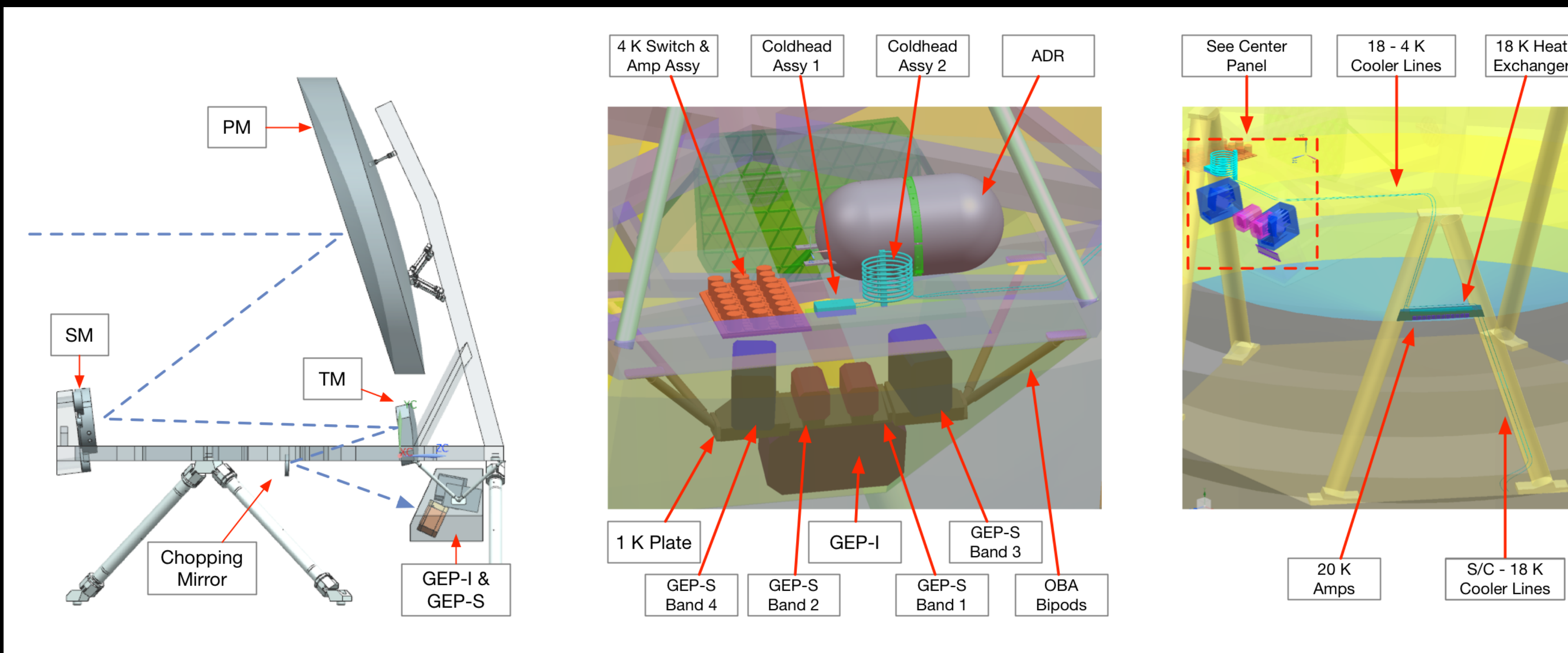


Brad Moore & JPL Team X

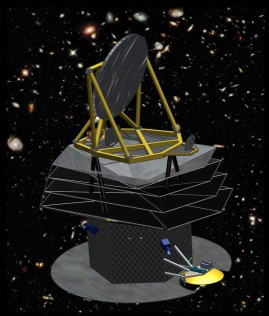
GEP Concept Study Outcome



- Design successfully closed under $1B.
- Target launch date Jan. 1, 2029.
- Look for the NASA Astrophysics Probe concept studies special issue of the *Journal for Astronomical Instrumentation* this year!



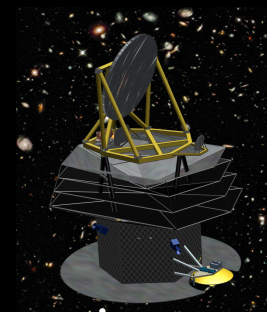
GEP Science Goals

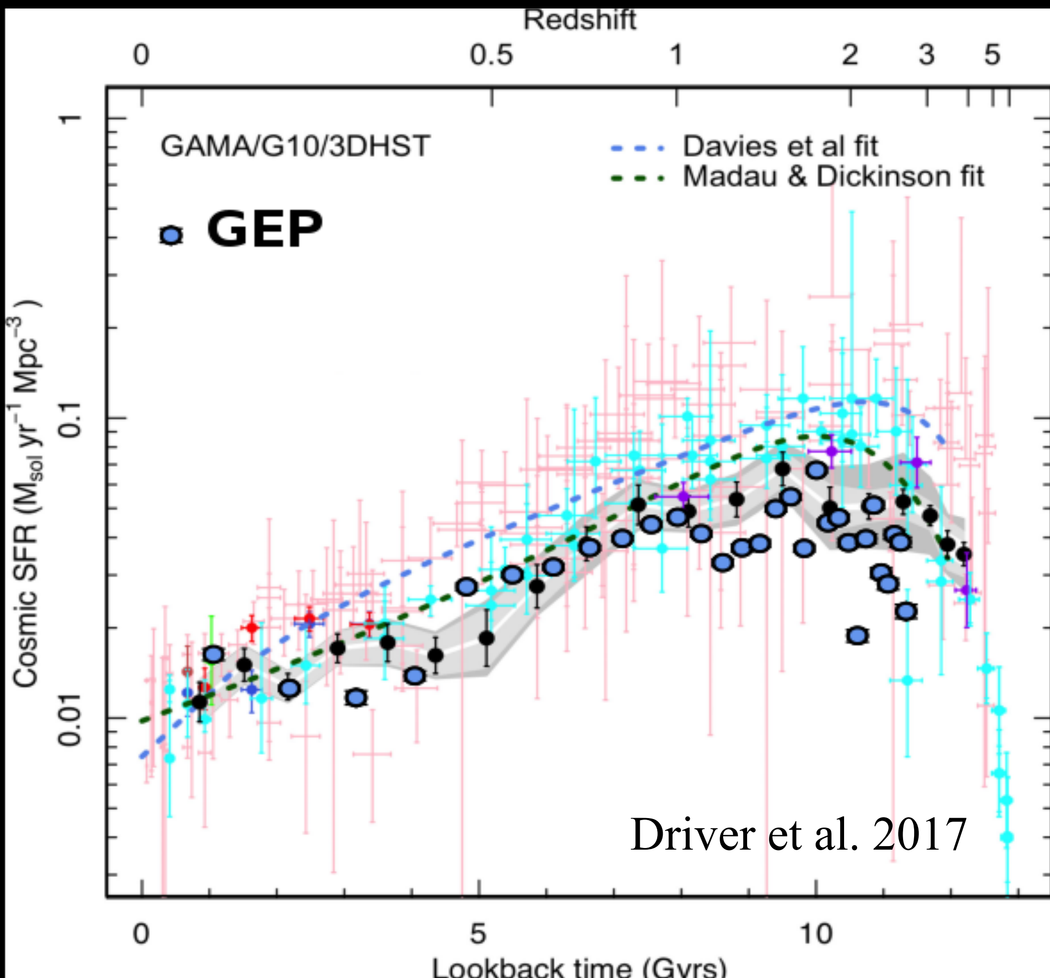


1. Map the history of galaxy growth by star formation and accretion by supermassive black holes and characterize the relation between those processes.

2. Measure the buildup of heavy elements, such as carbon, nitrogen, and oxygen, in the hearts of galaxies over cosmic time.

Cosmic Star Formation



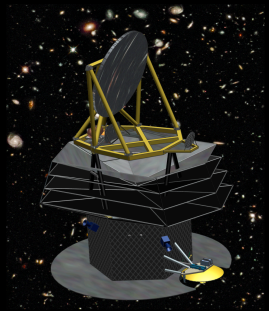


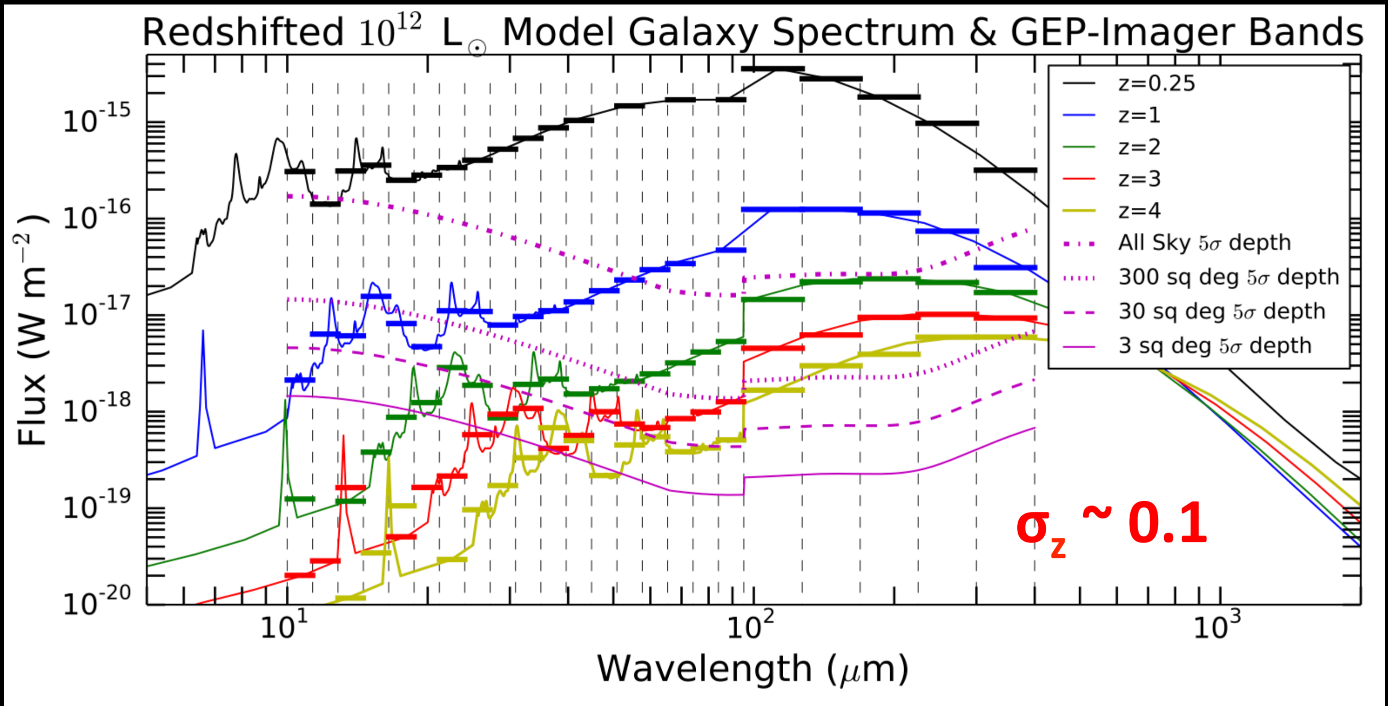
- Accurate and precise star formation rates across broad ranges of redshift and environment
- Brightening by gravitational lensing will probe to much higher redshifts.

These GEP simulations (Galacticus + Dale et al. spectra) only sample $0 < z \leq 3$.

Andrew Benson

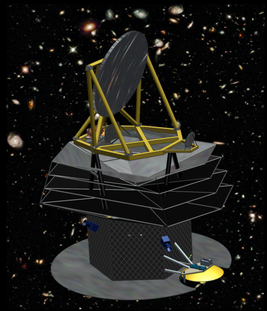
Surveys and Photometric Redshifts

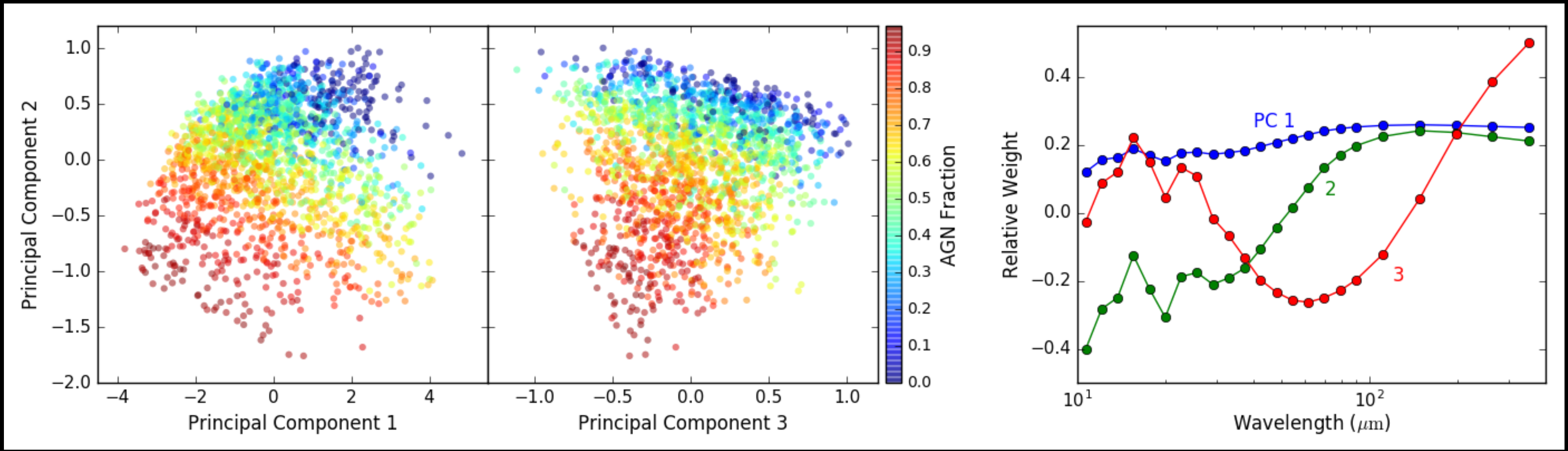




With 23 mid and far-IR spectral bands, GEP-I will measure the redshifts of millions of star-forming galaxies using the prominent PAH emission lines and silicate absorption.

Disentangling Star-Formation and SMBH Accretion Rates



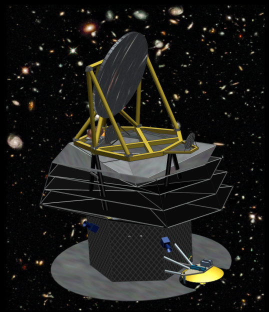


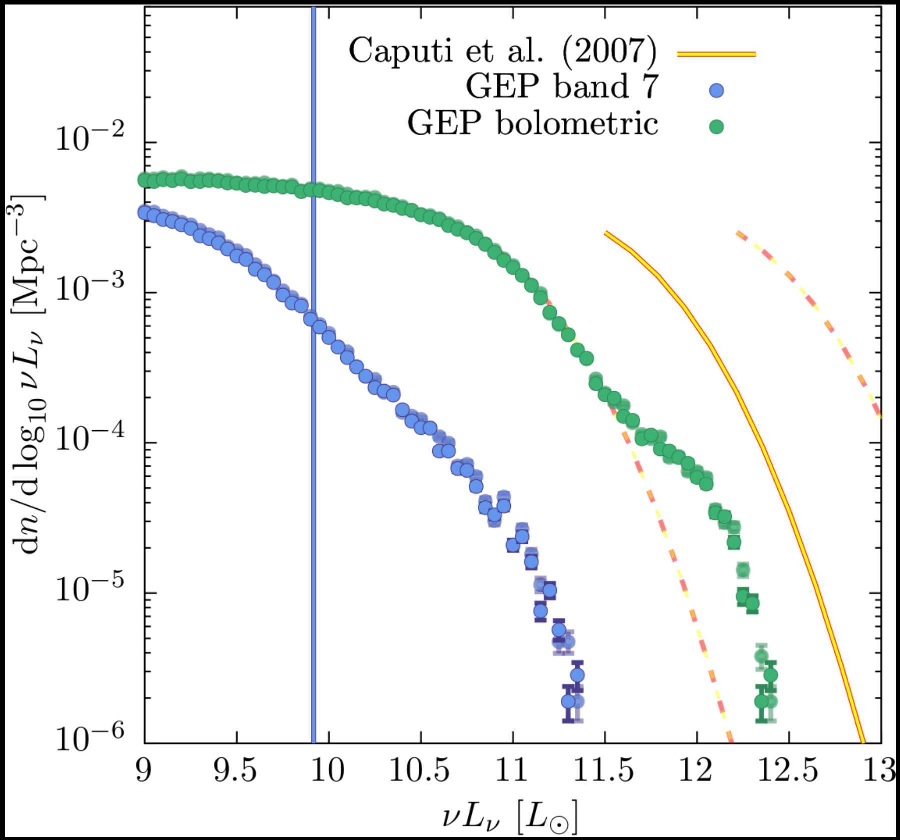
Jeremy Darling

Star formation & AGN will be separated with GEP-I's 23 IR bands. AGN indicators:

- Warm dust ('blue' mid-IR spectrum)
- Low PAH-to-continuum ratio

Going Well Beyond the State of the Art



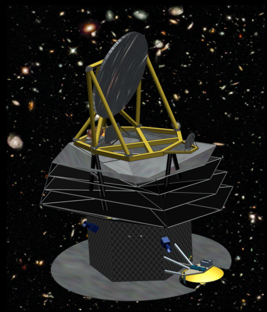


Andrew Benson

Simulated luminosity function measurements for $1.0 < z < 1.2$ compared to published measurements with 1σ error ranges (dashed lines).

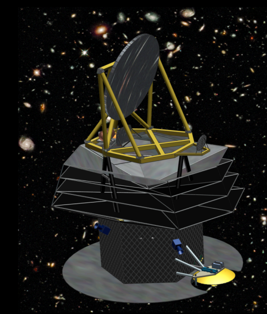
GEP will measure IR luminosity functions of galaxies with high precision, to below L* at z = 2.

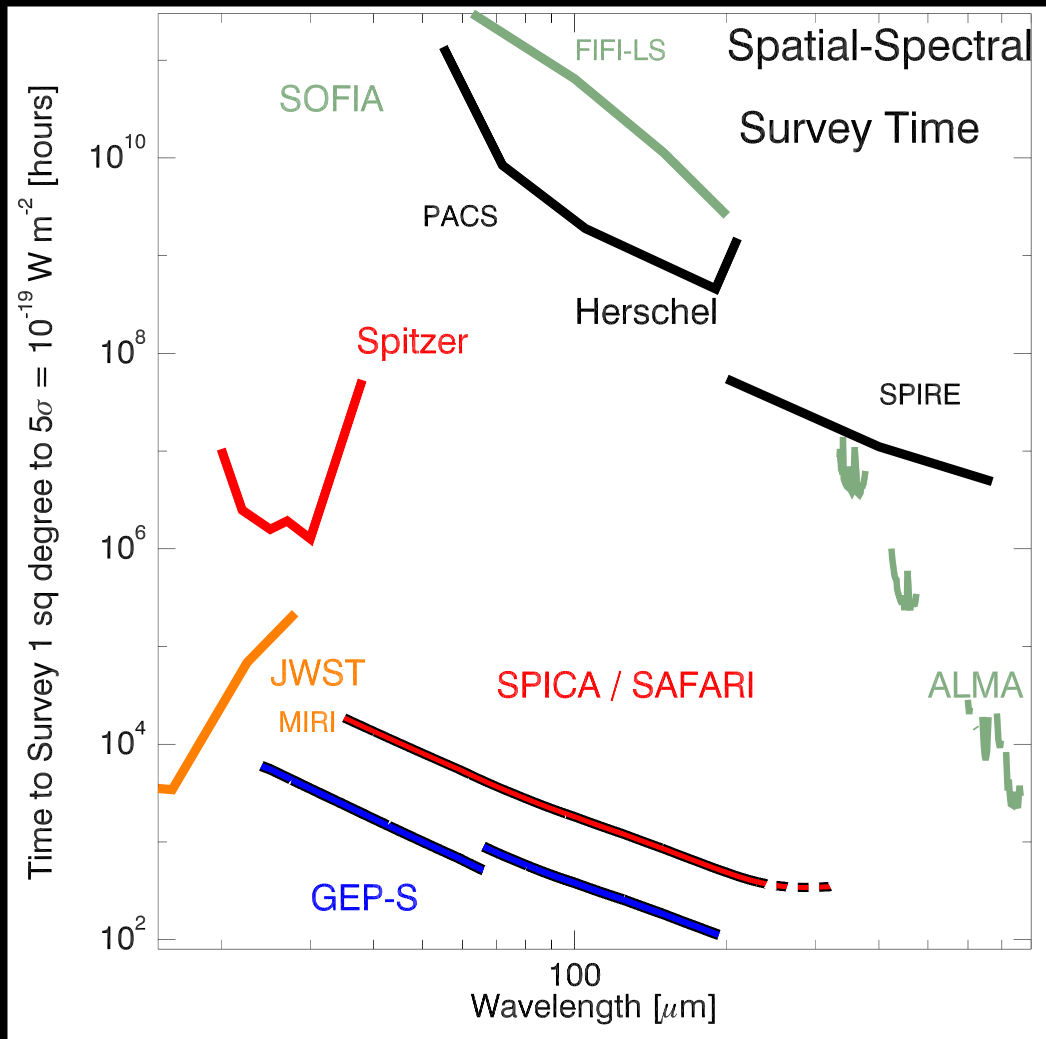
GEP-S Spectroscopic Surveys



1. Precise redshifts & AGN markers
2. ISM physical conditions: stacking on ~10^6 WFIRST grism galaxies detected in Hα to correlate with mid / far-IR tracers
   - Feedback: High-velocity outflows
   - Stellar T_{eff}: [N III] / [N II]
   - Densities around young stars: [O III] 52 μm / 88 μm
3. Metallicities in galaxy disks: extinction-free tracers, e.g. [Ne II]+[Ne III] / [S III]+[S IV]
4. Metallicity and radiation field hardness: PAH intensities
5. Integrated luminosity density and clustering: Intensity mapping – e.g., [O III] 88 μm

Spectroscopic Sensitivity





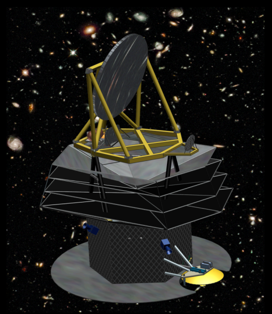
Very large sensitivity gain compared to previous, extant, and planned capabilities.

Faster spectroscopy survey capability than SPICA because of long slits.

Matt Bradford

GEP Mission Summary

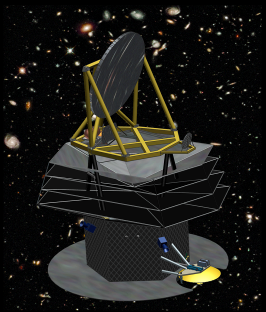
GEP Mission Parameters	
Target Launch Date	January 2029
Orbit	Sun-Earth L2
Observing Mode	Dedicated Surveys
Duration	4 Years
GEP Payload	
Telescope	2.0 m, 4 K, unobscured, SiC
Detectors	Kinetic Inductance Detectors
GEP Imager (GEP-I)	
Wavebands	23 bands covering 10-400 μm
R ($\lambda/\Delta\lambda$)	8 (10-95 μm), 3.5 (95-400 μm)
Surveys and Target Depths	All sky, ~1 mJy
	300 square degrees, ~50 μJy
	30 square degrees, ~20 μJy
	3 square degrees, ~5 μJy
GEP Spectrometer (GEP-S)	
Bands	24-42, 40-70, 66-116, 110-193 μm
R ($\lambda/\Delta\lambda$)	200
Surveys	Selected galaxies, 1.5 and 100 square degrees



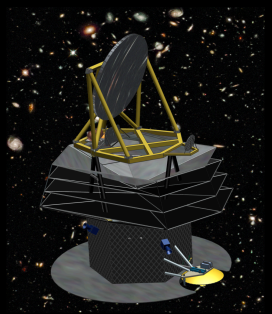
Amazing GEP Team

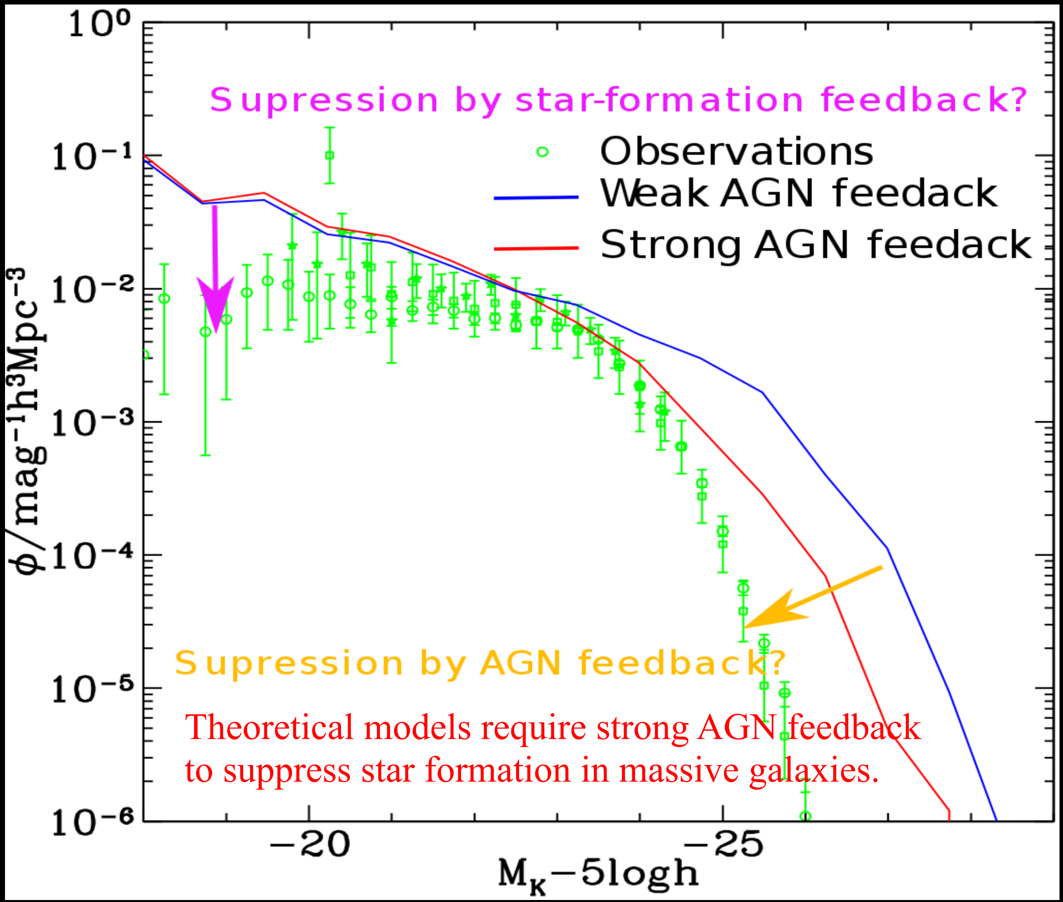
Katey Alatalo, Rashied Amini, Lee Armus, Andrew Benson, Matt Bradford, Jeremy Darling, Peter Day, Jeanette Domber, Duncan Farrah, Adalyn Fyhrie, Jason Glenn-PI, Mark Gordon, Brandon Hensley, Sarah Lipscy, Bradley Moore, Desika Narayanan, Seb Oliver, Ben Oppenheimer, Dave Redding, Michael Rodgers, Erik Rosolowsky, Mark Shannon, Raphael Shirley, John Steeves, Xander Tielens, Carole Tucker, Jonas Zmuidzinas

Extra Slides



Feedback into the ISM and Star Formation Activity



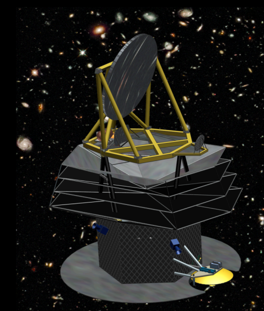


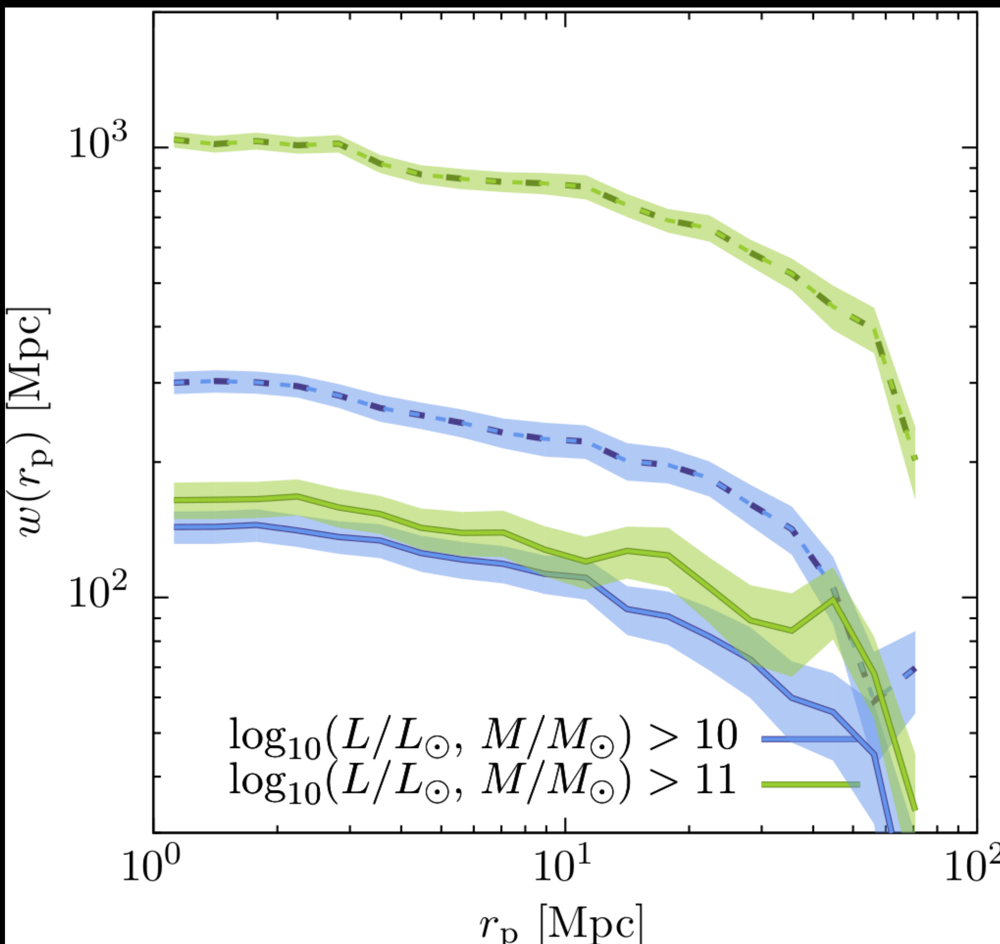
Andrew Benson

GEP offers multiple means for understanding feedback

- Concurrent star-formation and AGN accretion rates
- High-velocity outflows in stacked spectra
- Detailed spectroscopy of extra planar gas in nearby galaxies

Testing Galaxy Formation and Evolution Theory



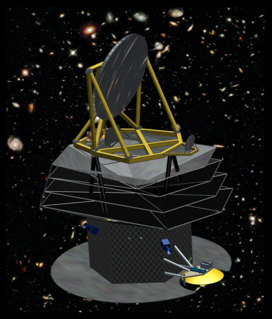


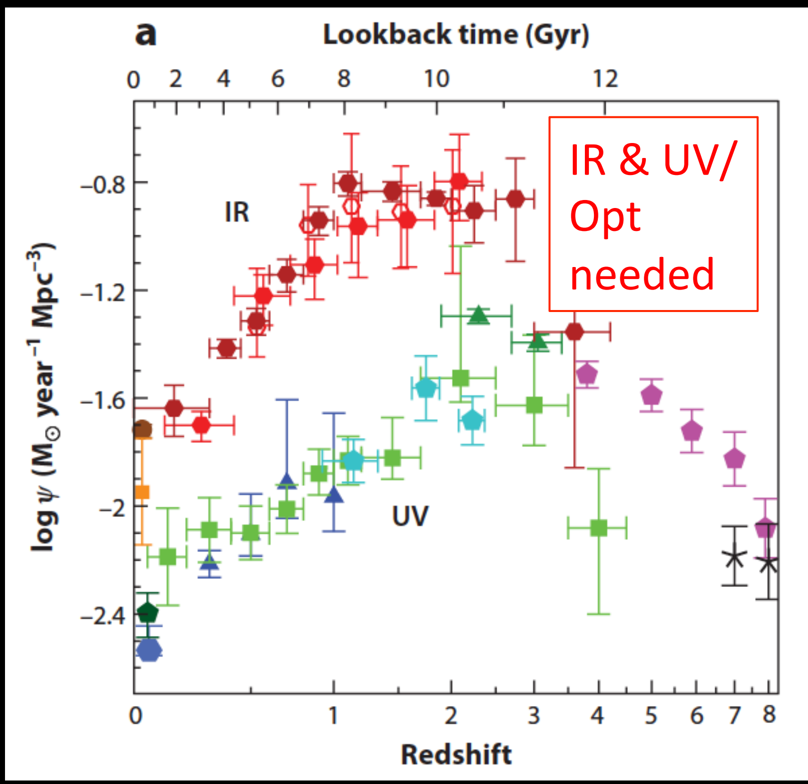
Projected correlation functions for bolometric IR luminosity (solid lines) and stellar mass (dashed lines) in a $1.0 < z < 1.2$ redshift slice (30 sq deg survey).

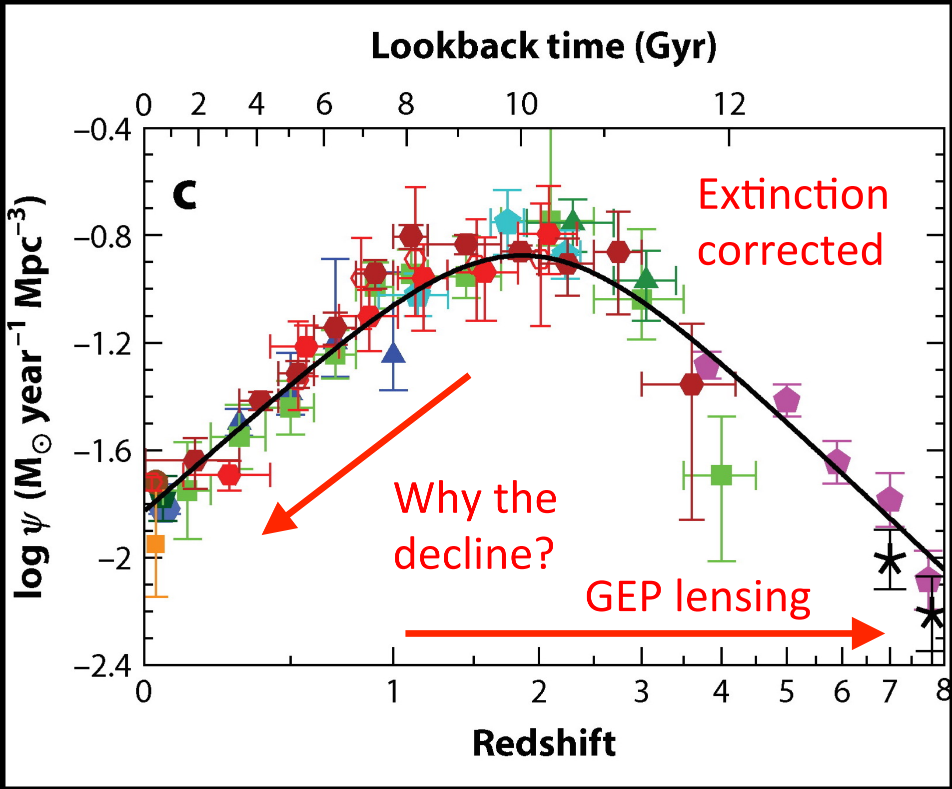
Galaxy mass correlates strongly with halo mass; bolometric IR luminosity is predicted to correlate less with halo mass *since even galaxies in low mass halos can have occasional strong starbursts.*

Andrew Benson

State of the Art: Cosmic Star Formation History

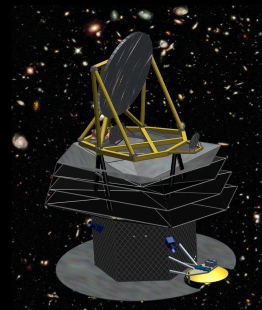


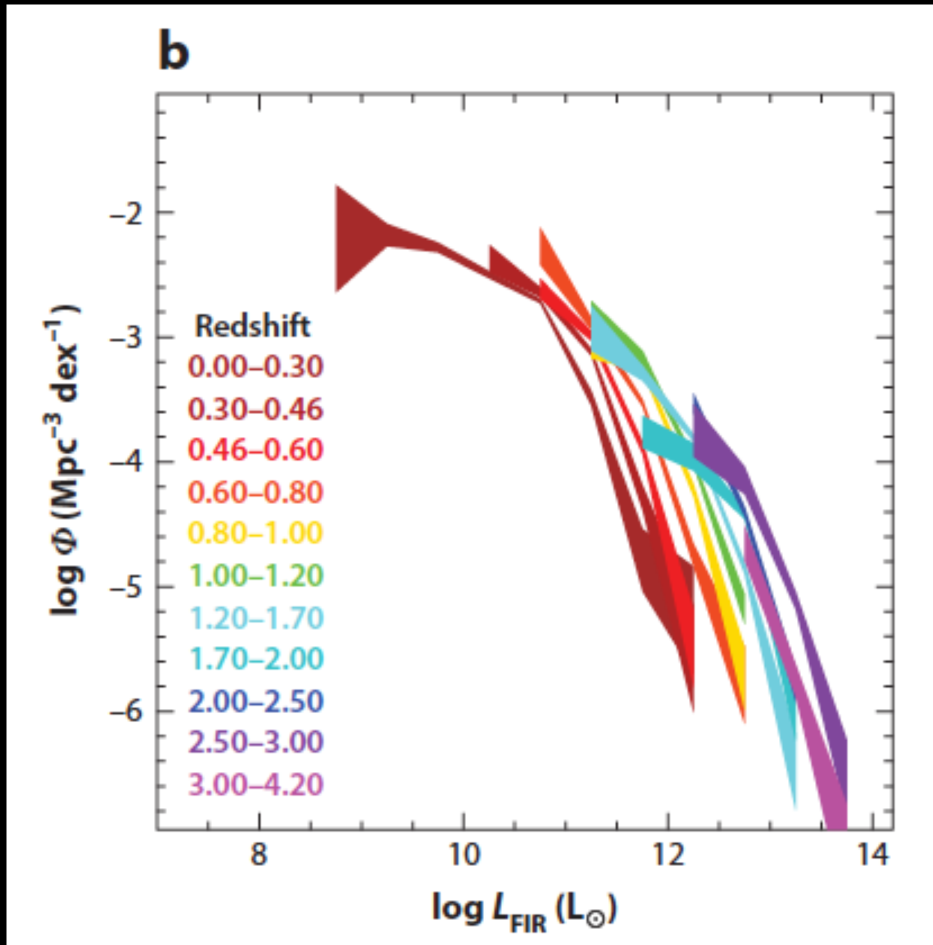




Madau & Dickinson 2014 ARAA

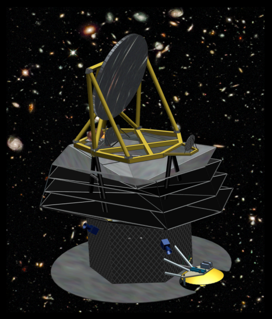
State of the Art: Far-Infrared Galaxy Luminosity Functions





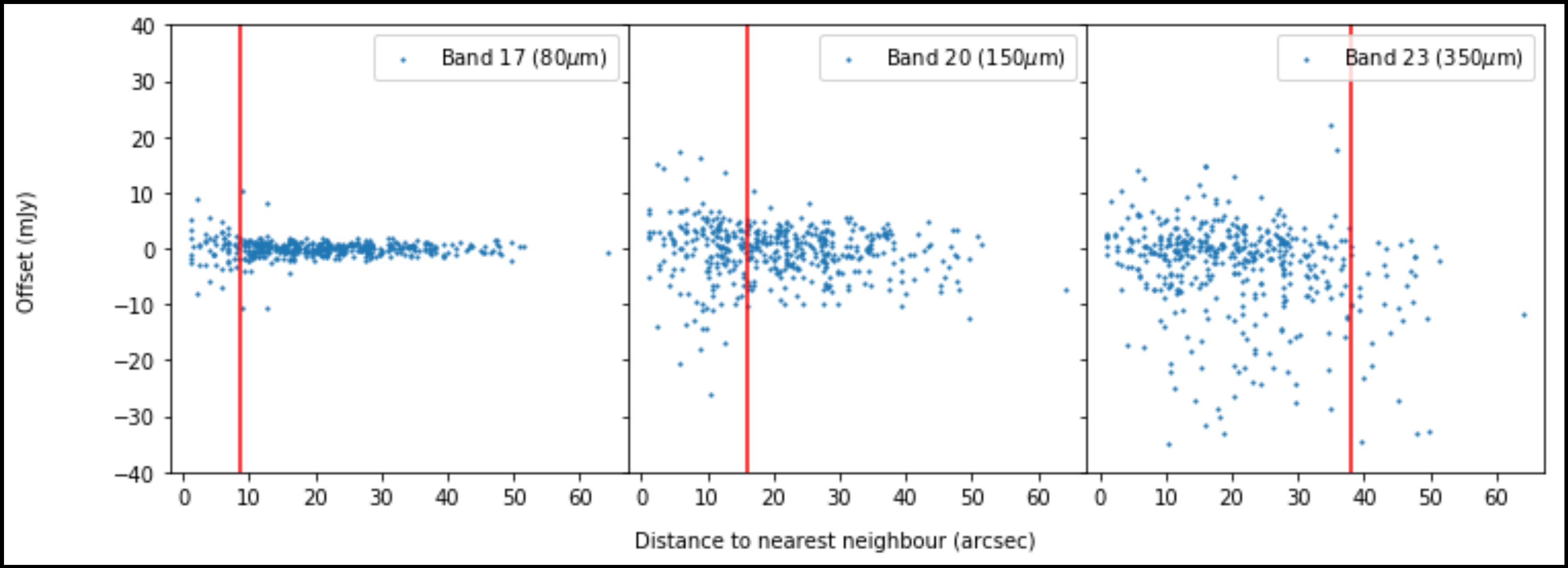
Madau and Dickinson 2014, Gruppioni et al. 2013

Extragalactic Source Confusion

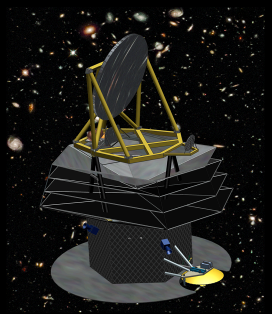


- Issue only for λ > 70 μm
- To be mitigated with, e.g., XID+ (Oliver et al.)
- λ > 100 μm important for FIR luminosities

Flux densities can be extracted with high fidelity down to the beam FWHM using shorter-wavelength positional priors (Raphael Shirley).



Some IR Lines Accessed by GEP

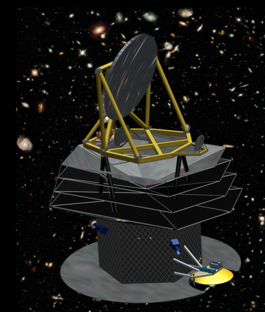


Species	Rest λ (μm)	Ionization Energy (eV)	Traces	Typical Line Luminosity $\times 10^{-4} L_{FIR}$
[Ne II]	12.8	21.6	SF	3
[Ne V]	14.3	97.1	AGN	2
[Ne V]	24.3	97.1	AGN	2
[O IV]	25.9	54.9	AGN (& SF)	5
[S III]	33.5	23.3	SF	3
[Si II]	34.8	8.2	SF	4
[O III]	51.8	35.1	SF (& AGN)	20
[O I]	63.2	N/A	SF	10
[O III]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

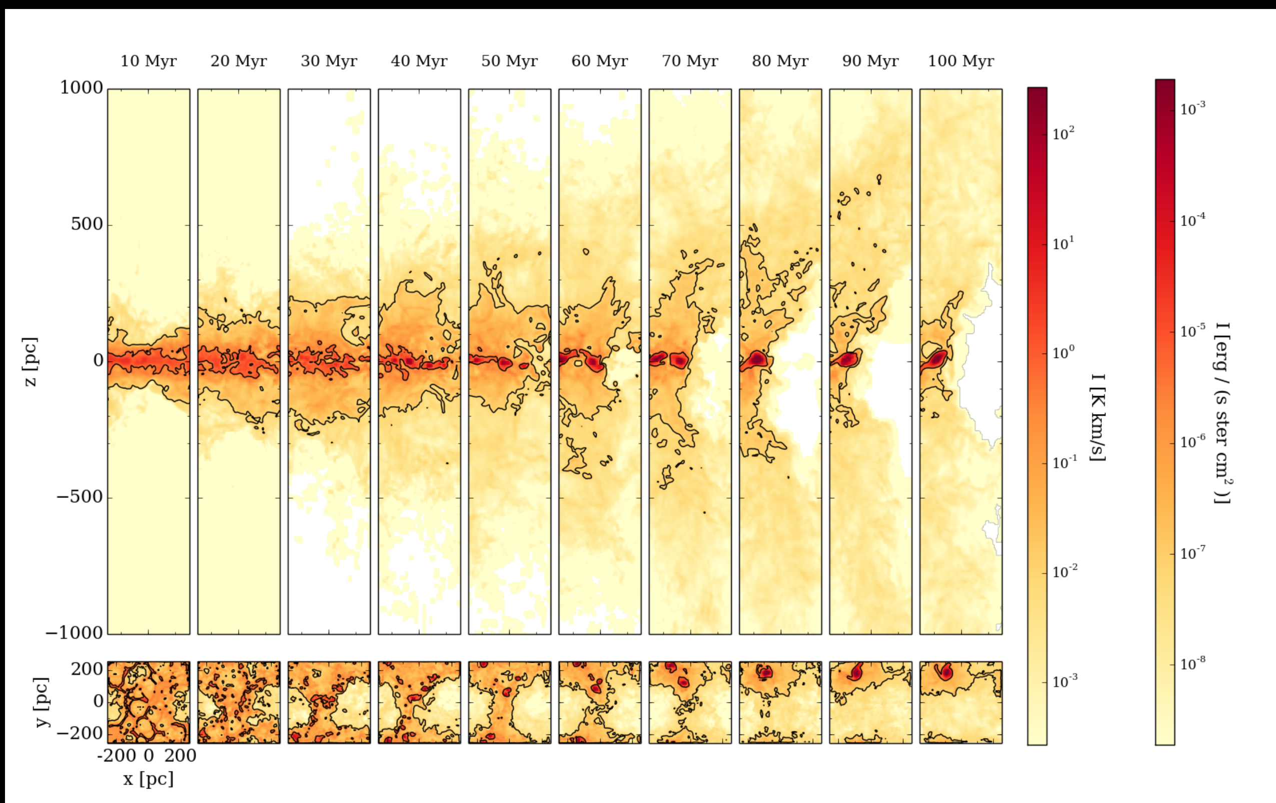
Line carrying $10^{-3} L_{FIR}$ for $10^{12} L_{\odot}$ galaxy detectable at $z = 2$, 5σ, ~1 hour

Adapted from Spinoglio 2013

Feedback: Evidence from Extraplanar Gas



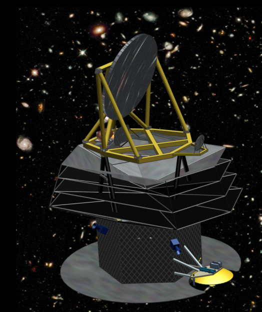
GEP-S mapping to observe stellar feedback

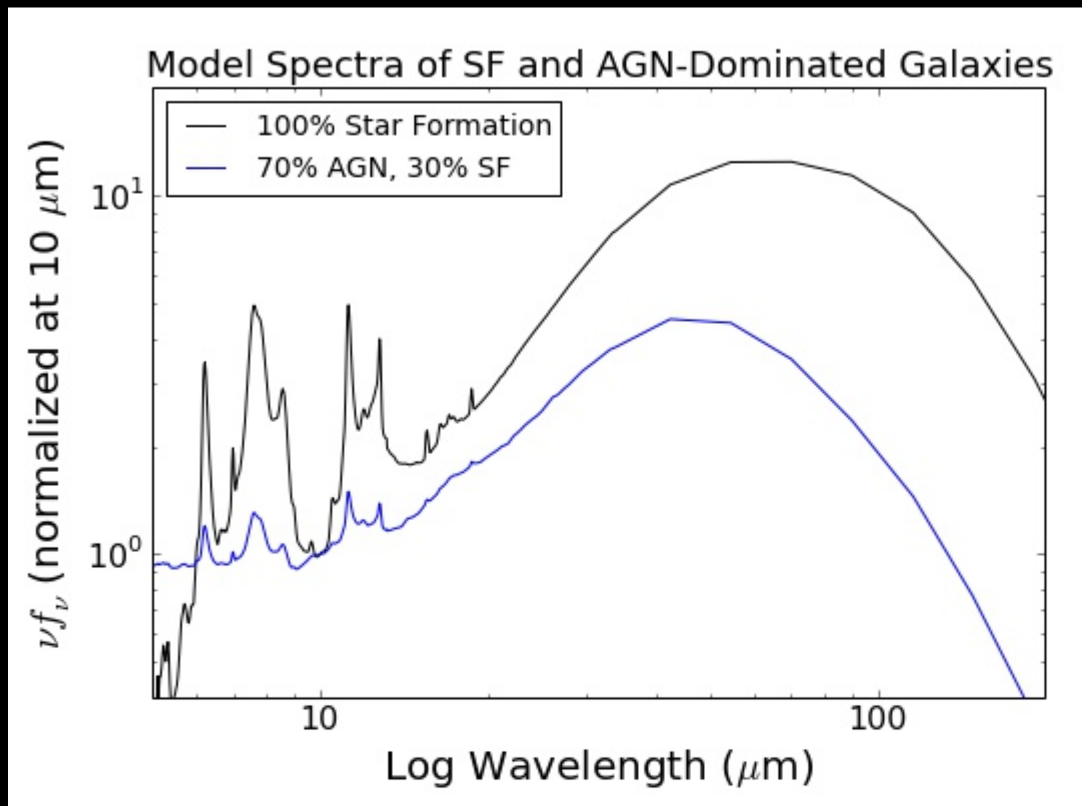


GEP-S should observe these outflows in dozens of nearby galaxies in [C II] 158 μm. This is not possible with sub-orbital platforms.

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

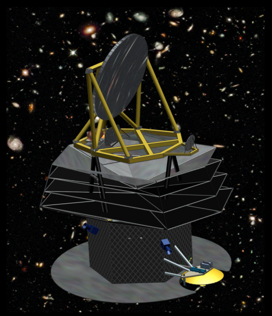
1 of 3 means for identifying obscured AGN: PAH features are weaker compared to star-formation-dominated galaxies

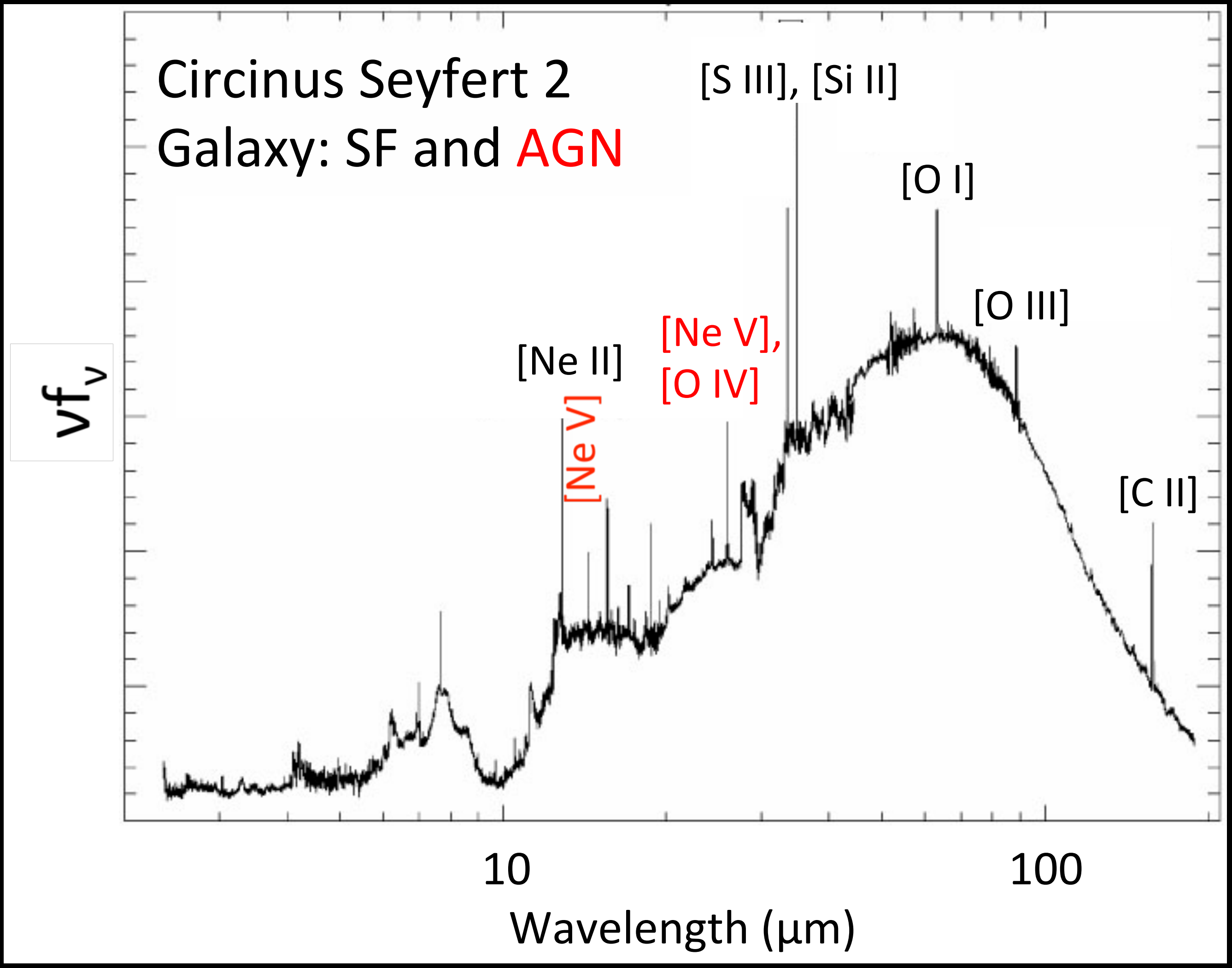




Spectral models from Dale et al. 2014 – *models do not include MIR/FIR atomic fine-structure lines*

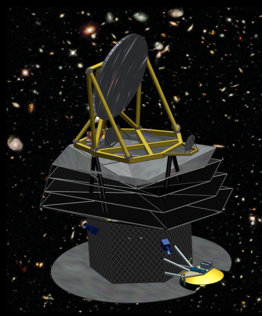
FIR Fine-Structure Lines



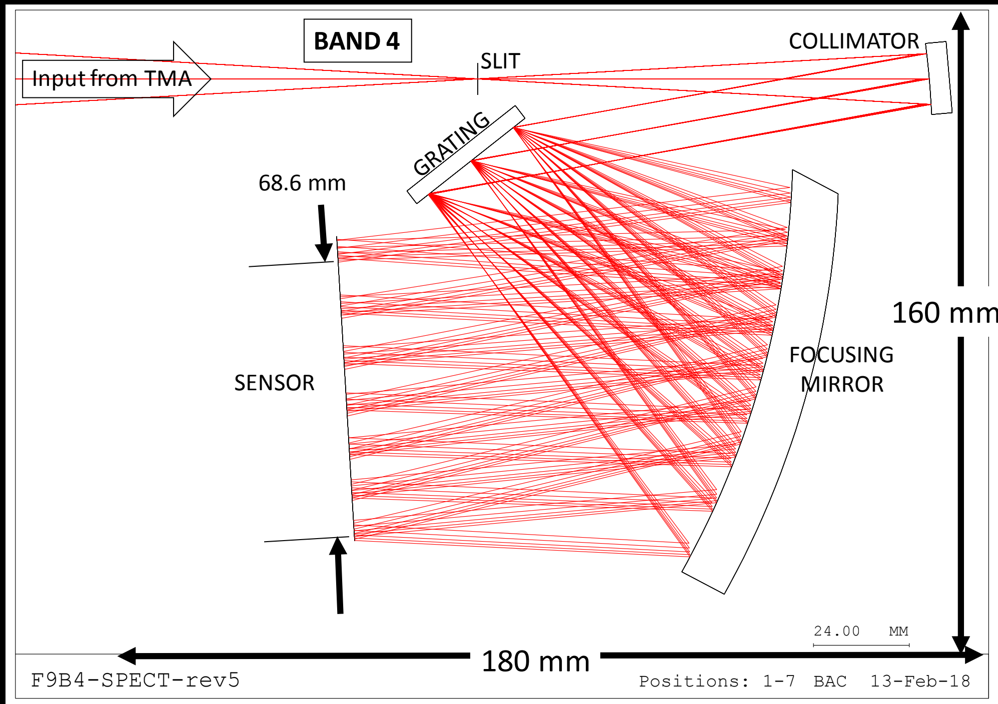


Adapted from Moorwood 1999

Spectrometer: GEP-S (KIDs)

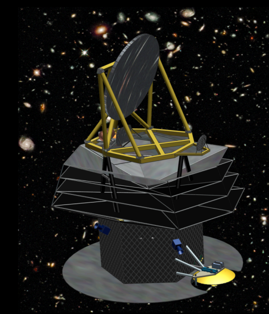


- $R = \lambda/\Delta\lambda = 200$
- Long slits (3.8’ – 10’) enable extended-object observations and ‘blind’ surveys

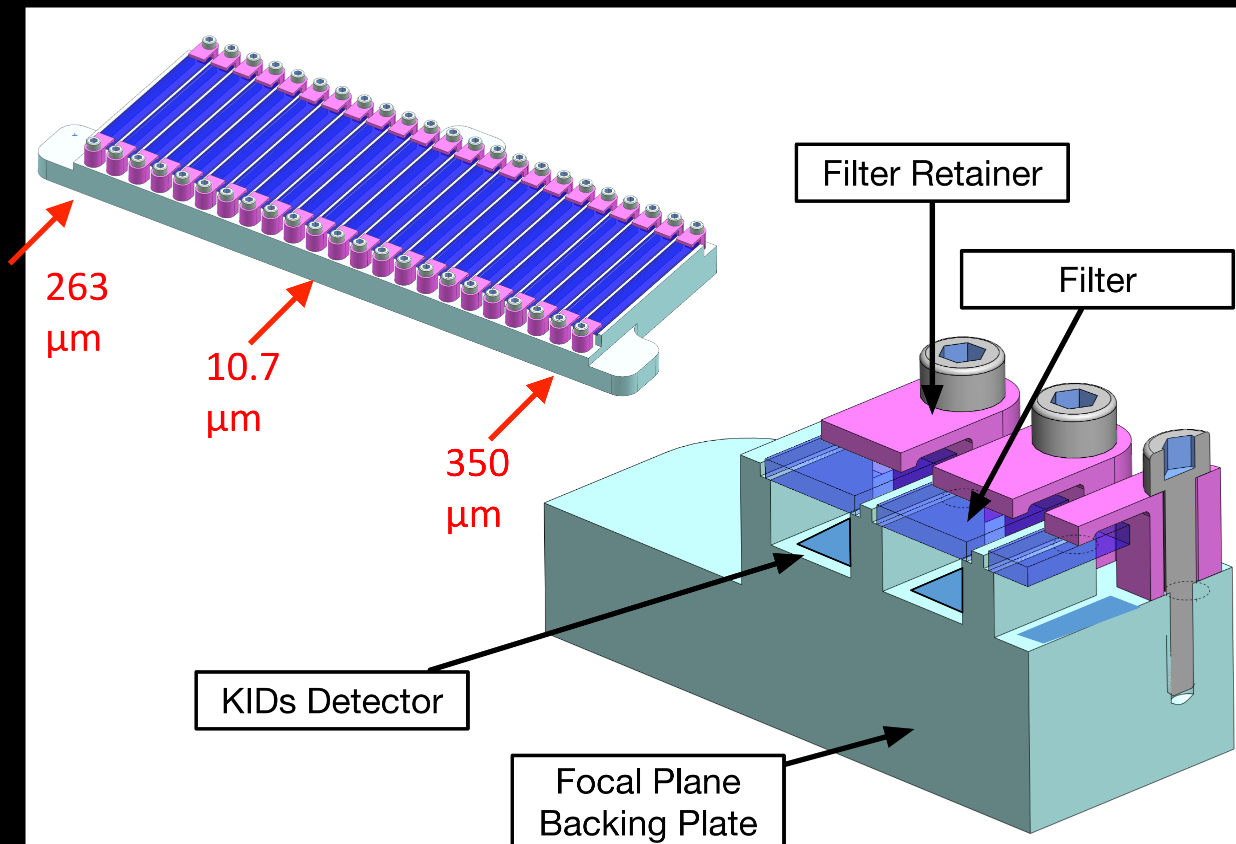


GEP-S BAND	1	2	3	4
WAVELENGTHS (μm)	24 - 42	40 - 70	66 - 116	110 - 193
SLIT LENGTH (arc min)	3.8	6.4	6.0	10.0

GEP-I Focal Plane (KIDs)



Continuous scanning for full spectral coverage



Spectral Resolution

10-95 µm:

$R = \lambda/\Delta\lambda = 8$

95-400 µm:

$R = \lambda/\Delta\lambda = 3.5$

FoV and Sampling

0.5° × 0.1°

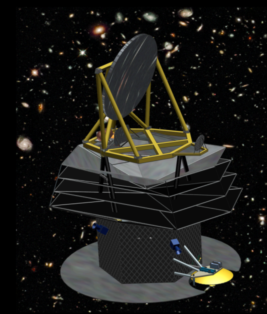
$\lambda < 70$ µm:

3.43" pixels

$\lambda > 70$ µm:

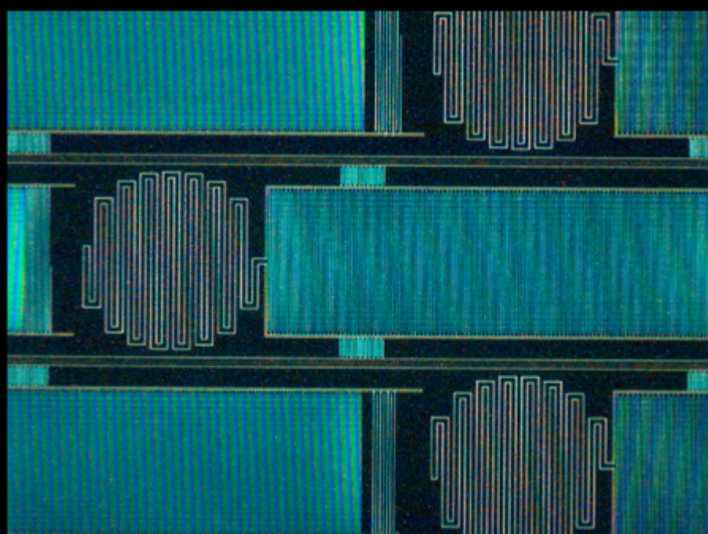
Nyquist

Galaxy Evolution Probe KIDs

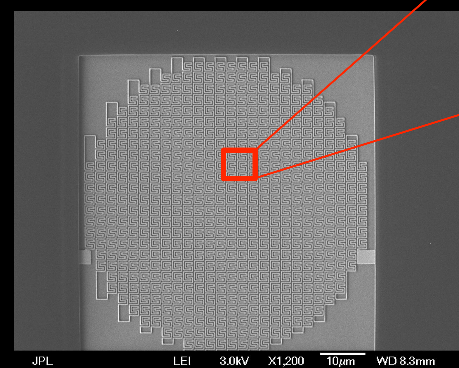


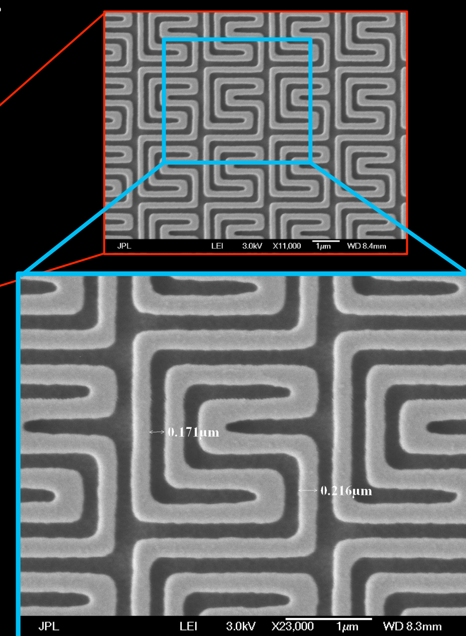
- 50,000 KIDs split evenly between imager and spectrometer
- Why baseline KIDs?
  - Simple architecture, simple cryogenic readout, one focal plane technology for all wavelengths.

100 - 400 µm: MAKO type LEKID



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

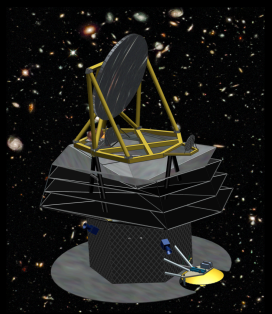


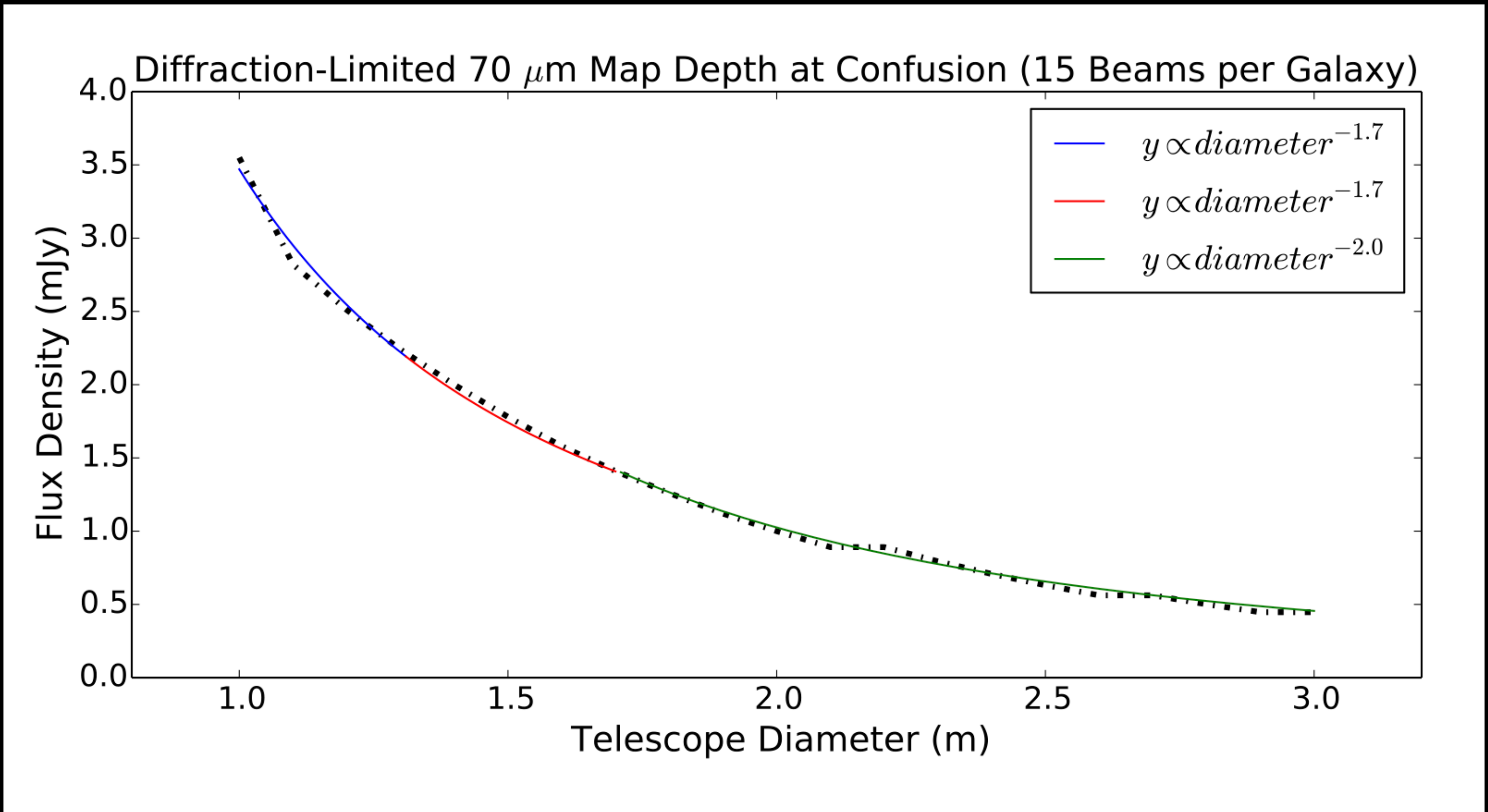


Day, LeDuc, Fyhrie, Glenn, Perido, Zmuidzinas

Technology development plan: MIR KIDs (10 – 100 µm), readout

Extragalactic Source Confusion: Why a 2.0 m aperture?





Based on Bethermin et al. 2012 models

Astrophysically Limited NEPs