Galaxy Evolution with the Far-Infrared Surveyor: Cosmic High Noon

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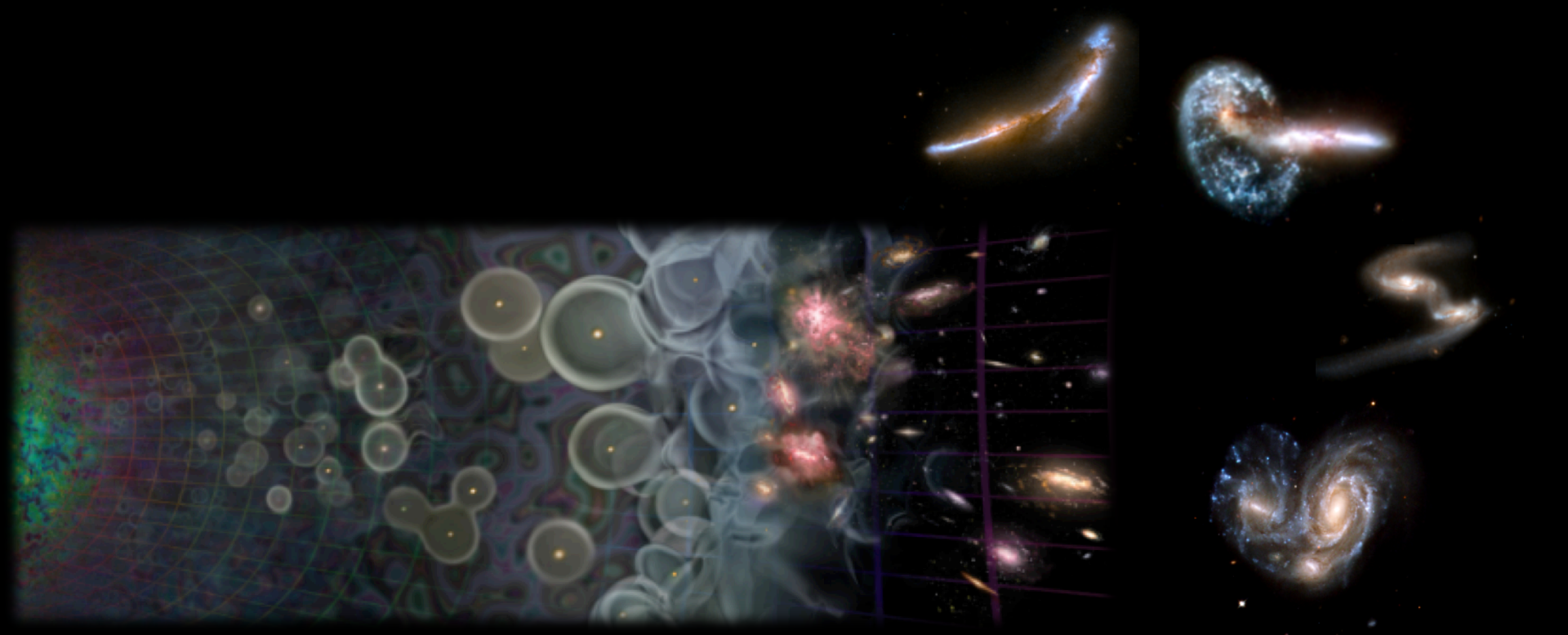
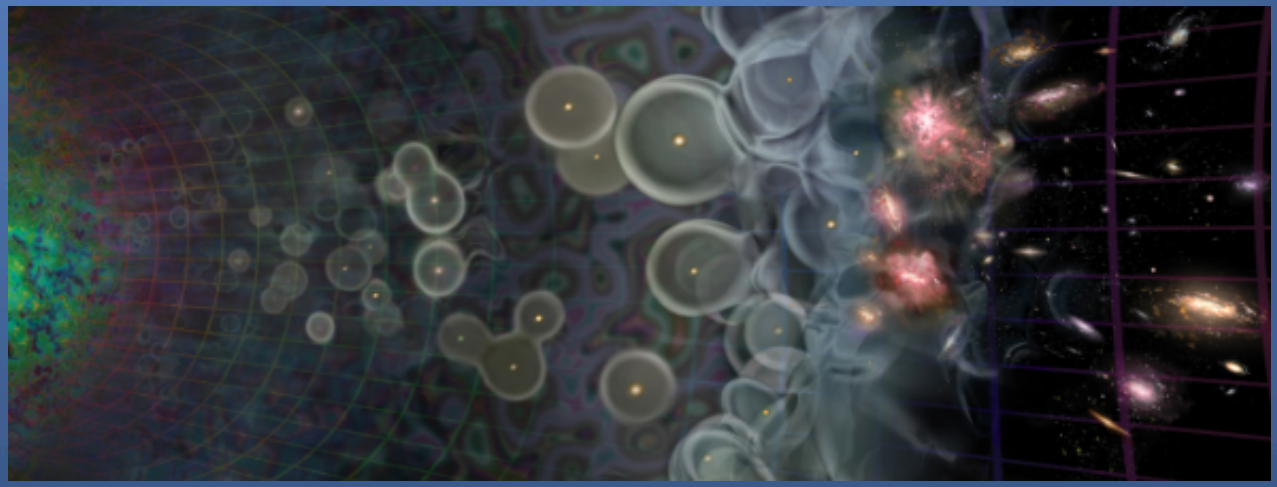


Galaxy Evolution with the FIR Surveyor

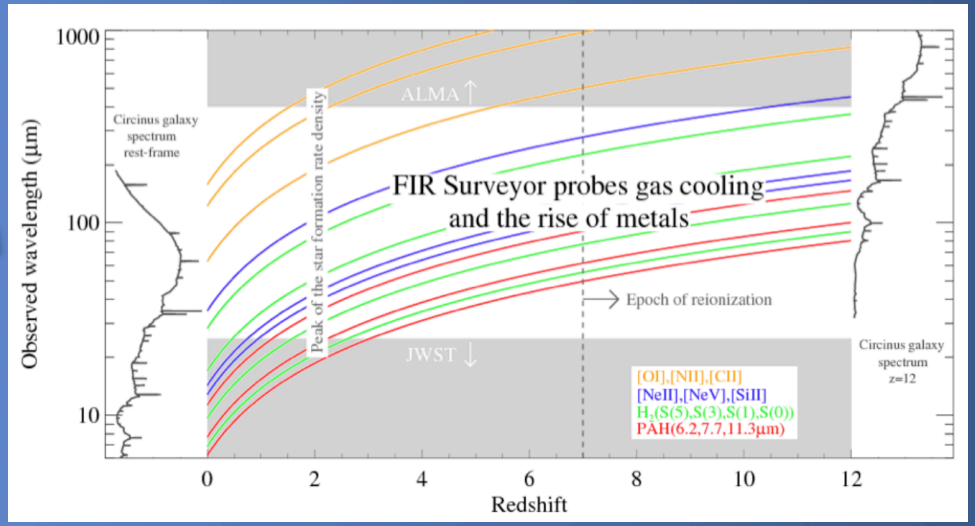
- Understanding how galaxies evolve is essential for our knowledge of how the Universe changes from a uniform state to the rich cosmic landscape we see today.
- Connects large scale structure and star formation, stellar evolution and the growth of supermassive black holes, galactic structure, starbursts, AGN and the production of metals, molecular gas and organic molecules over cosmic time.
- The FIR Surveyor will have a huge impact on our understanding of how galaxies and cosmic structure evolve from the highest redshifts to the present day.

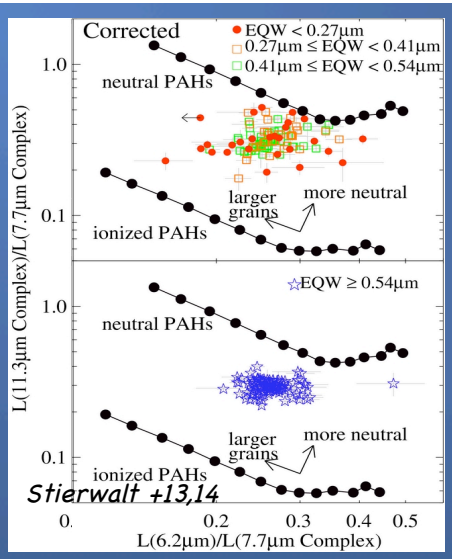


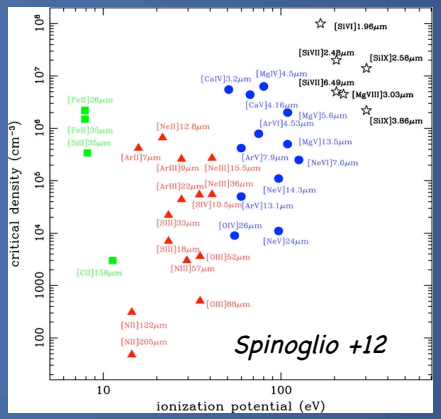
Galaxy Evolution with the FIR Surveyor

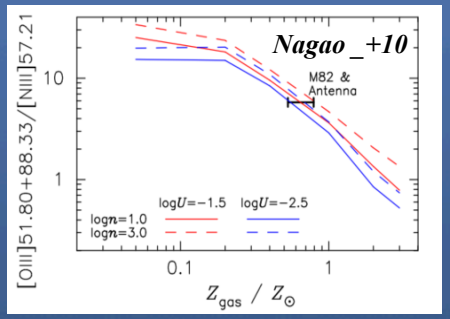
- The FIR Surveyor promises an enormous jump in sensitivity, spatial resolution, and access to a vast suite of powerful diagnostic tools covering wavelengths/ redshifts inaccessible to JWST & ALMA.

- Probe all phases of the ISM in distant and obscured galaxies: hot ionized, neutral atomic, dust, warm molecular gas, over >95% of the age of the Universe.

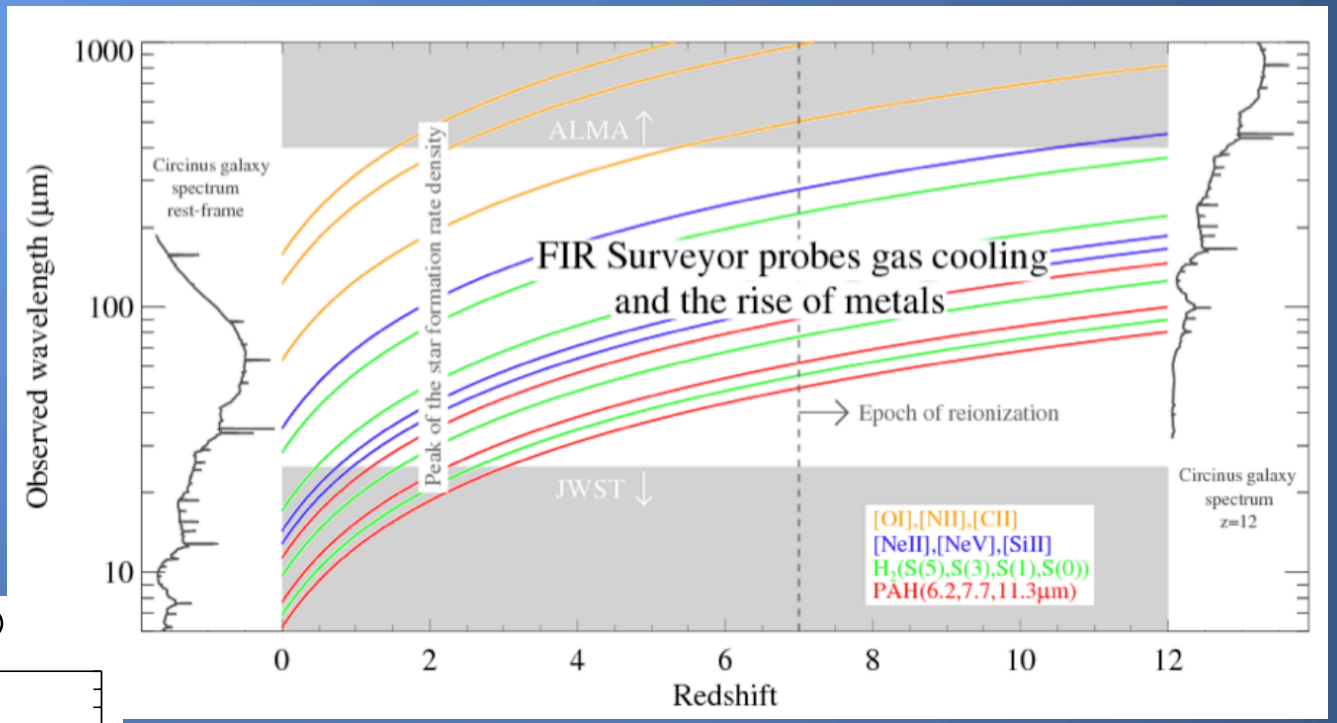


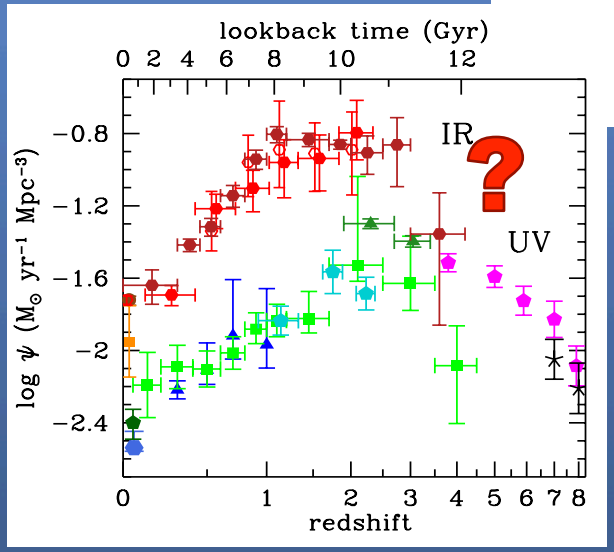






Galaxy Evolution with the FIR Surveyor





Madau & Dickinson 2014

Galaxy Evolution with the FIR Surveyor

Organizational structure and status of the group

- The Galaxy Evolution/Cosmic High Noon working group will concentrate on galaxy evolution from Re-ionization to the nearby Universe ($1 < z < 7$)
- In two telecons (11, 28 April), we solicited and discussed an initial set of key questions that could be uniquely addressed with the FIR Surveyor. *Examples:*
  - *What drives the cosmic history of star formation with redshift?*
  - *When did the first SMBH's form and what sets the SMBH-galaxy relation?*
  - *What is the role of environment in galaxy evolution over time?*
  - *How does gas and dust cycle in and out of galaxies with time?*
- We organized these questions into a set of seven science "themes" to help carry the detailed work/analysis forward.
- Questions and themes collected via a Google doc enabling all members of the group to contribute/edit.

Galaxy Evolution with the FIR Surveyor

Science Themes

- The Rise of Metals: Mapping out metal enrichment and the build up of dust over cosmic time.
- Star Formation Demographics: Understanding what controls/regulates the cosmic star formation history vs. redshift
- Large Scale Structure and Galaxy Clusters: Using IR galaxies to trace the growth of LSS and how environments shape galactic evolution
- Galaxy and BH Growth: Understanding the co-evolution of galaxies and supermassive black holes
- Star Formation Physics: Understanding the detailed properties of star formation in galaxies over cosmic time
- Galactic Ecology: Understanding the galactic baryon cycle
- The CIB and intra-halo dust: Towards a complete census of the CIB

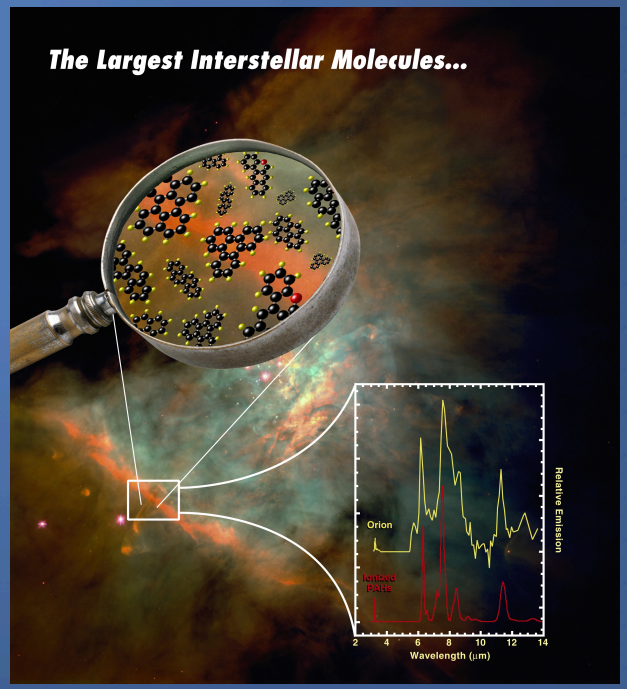
Galaxy Evolution with the FIR Surveyor

Science Theme: Star Formation Physics over Cosmic Time

- How do the star formation/ISM properties (sSFR, SFE, IMF, lum. density) of galaxies evolve with cosmic time?
- How much are these affected by environment or external triggers (e.g. mergers, satellite accretion)?

Why is this an important question now and in 2030?

- The dominant process of how star formation unfolds in galaxies changes with z, environment, mass.
- Most star formation is hidden behind dust and the FIR can uniquely probe these environments.

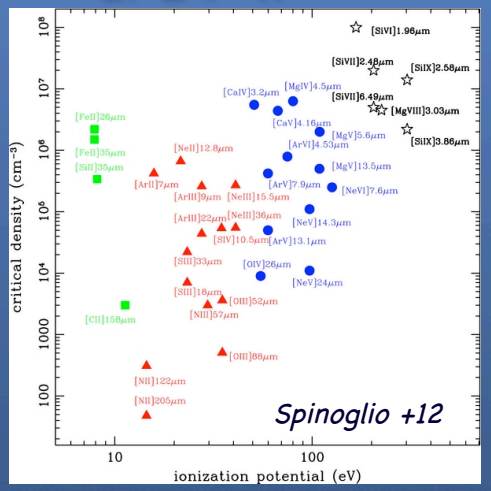


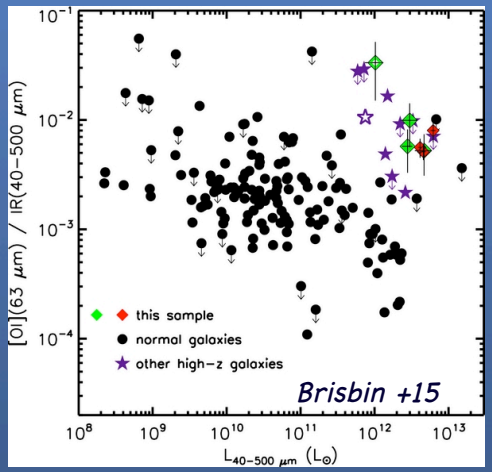
Hollenbach & Tielens 1997

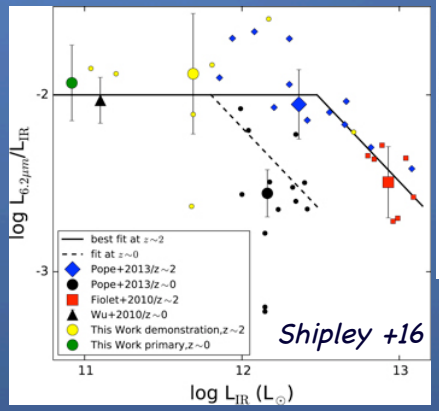
Galaxy Evolution with the FIR Surveyor

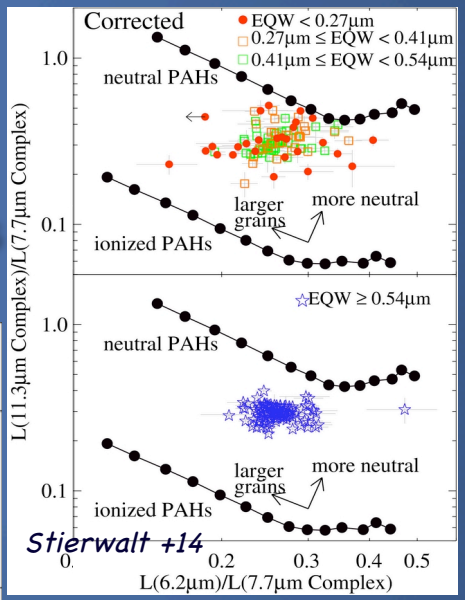
Why is the FIR uniquely suited to answer this question?

- IR fine structure lines probe PDR chemistry, radiation fields, density, ISM cooling. MIR/FIR lines cover a large range in ionization, n_{crit}.
- PAHs probe ISM and PDR heating, dust properties. These also evolve with redshift…but statistics are poor.
- Evidence that SF properties traced by gas and dust evolve with redshift but statistics are poor. We haven't detected PAHs in normal galaxies at z > 1 or in any galaxies at z > 4.

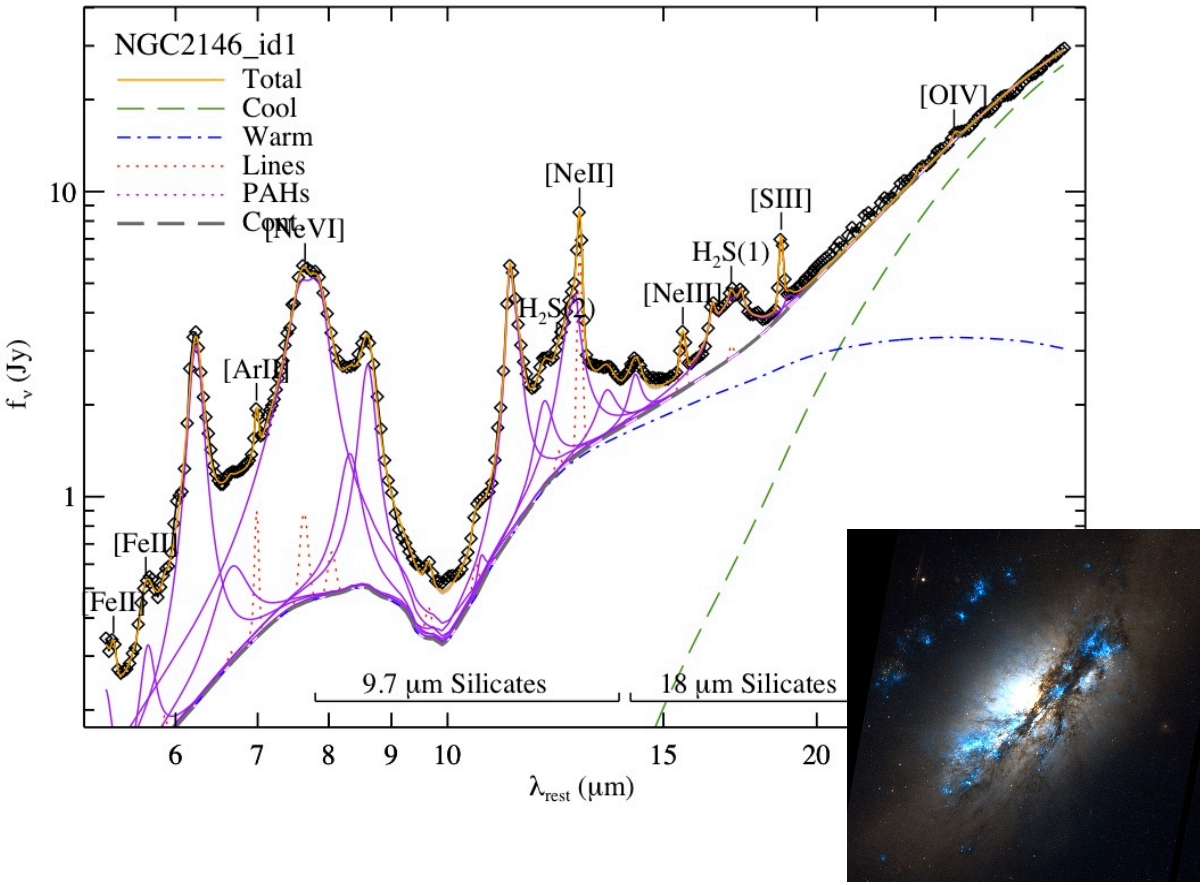


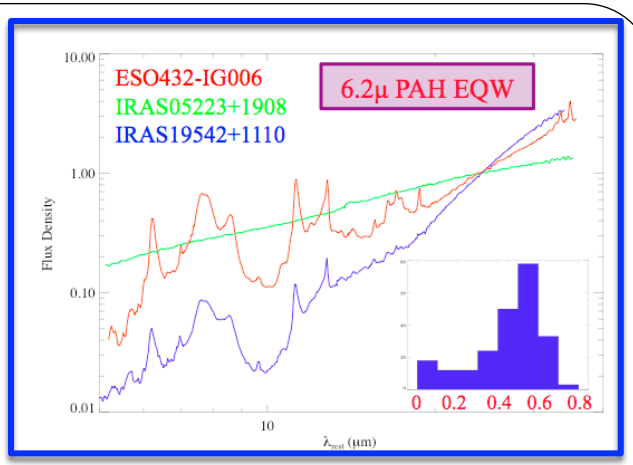


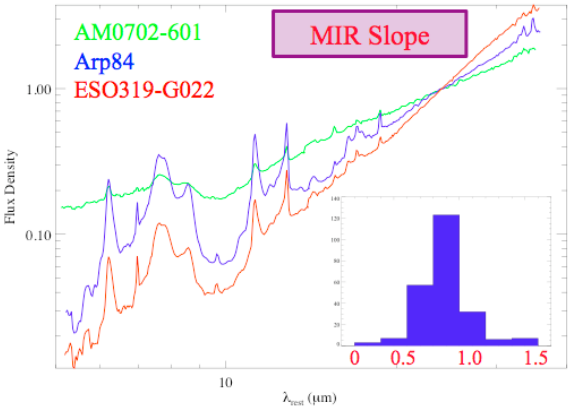


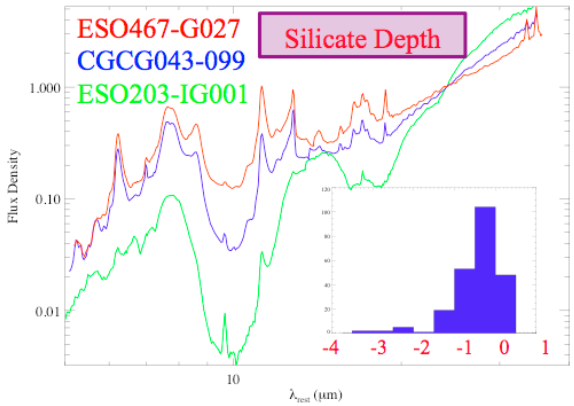


MIR Properties of LIRGs





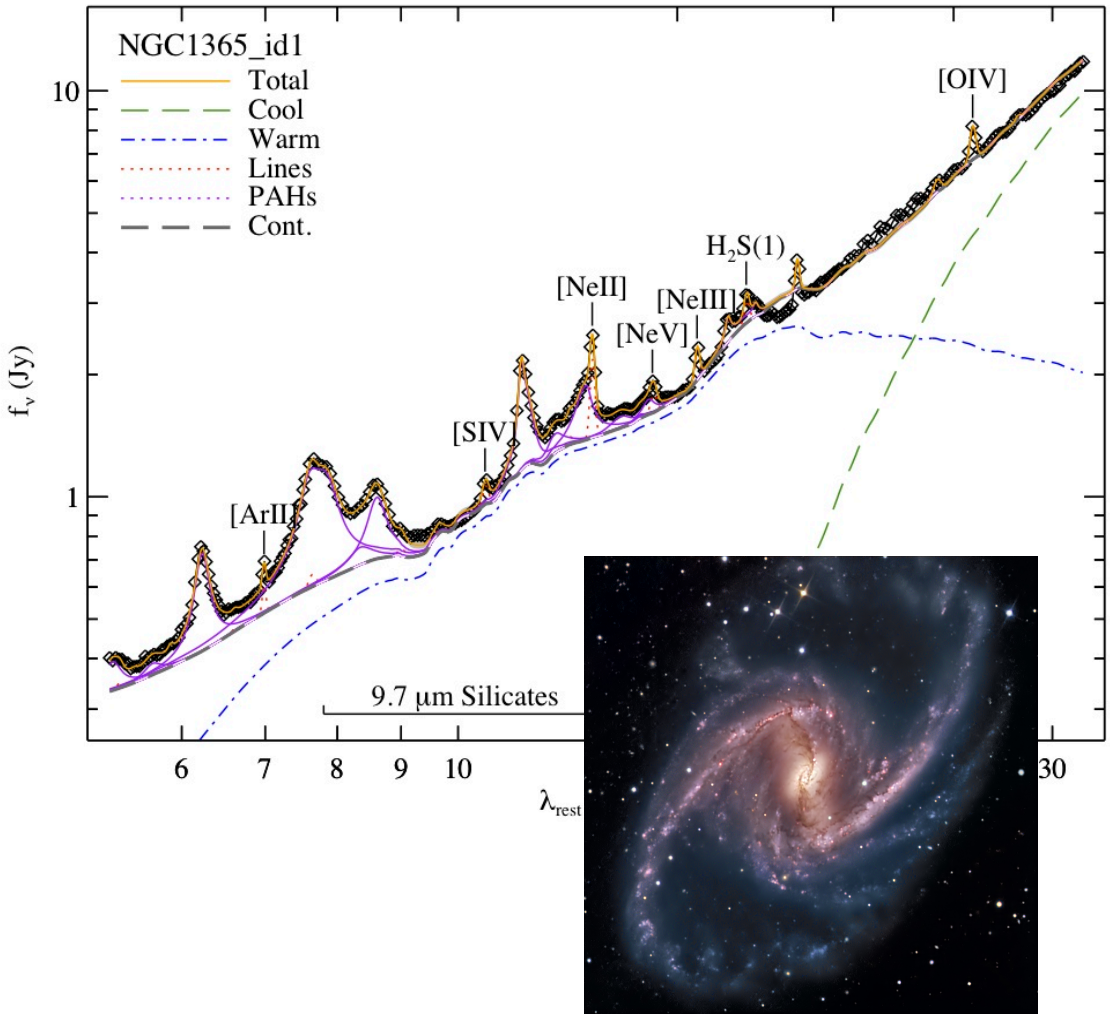


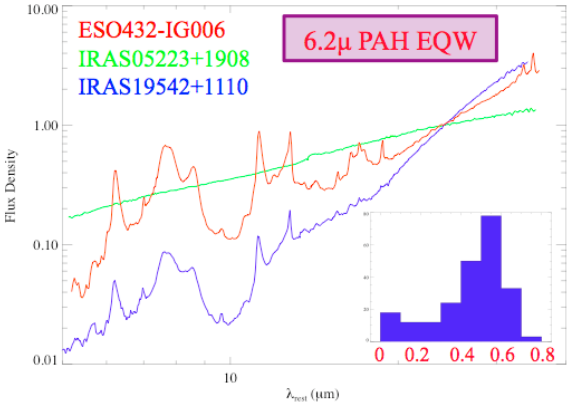


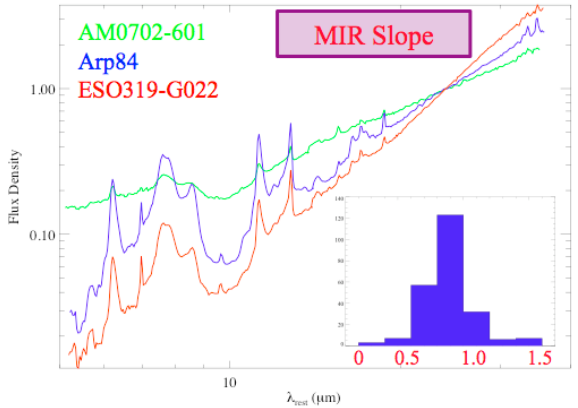
- large range in PAH EQW, silicate absorption, MIR slope

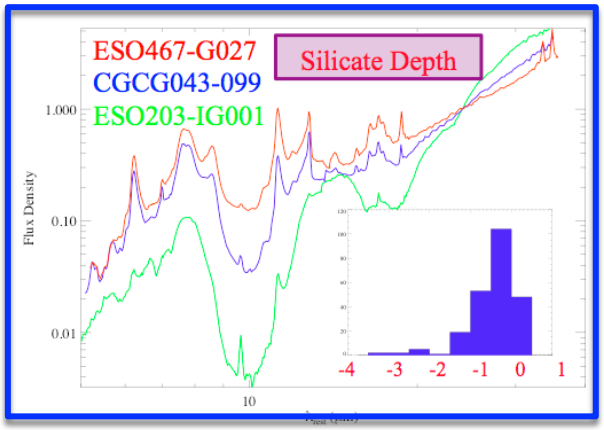
Stierwalt +13

MIR Properties of LIRGs



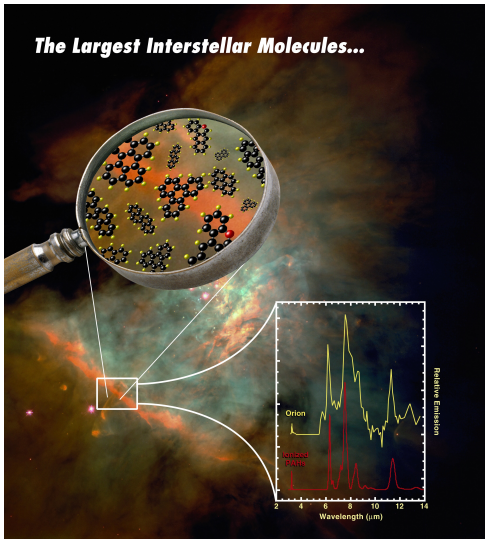


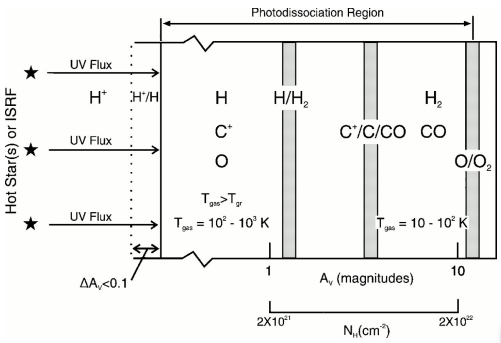


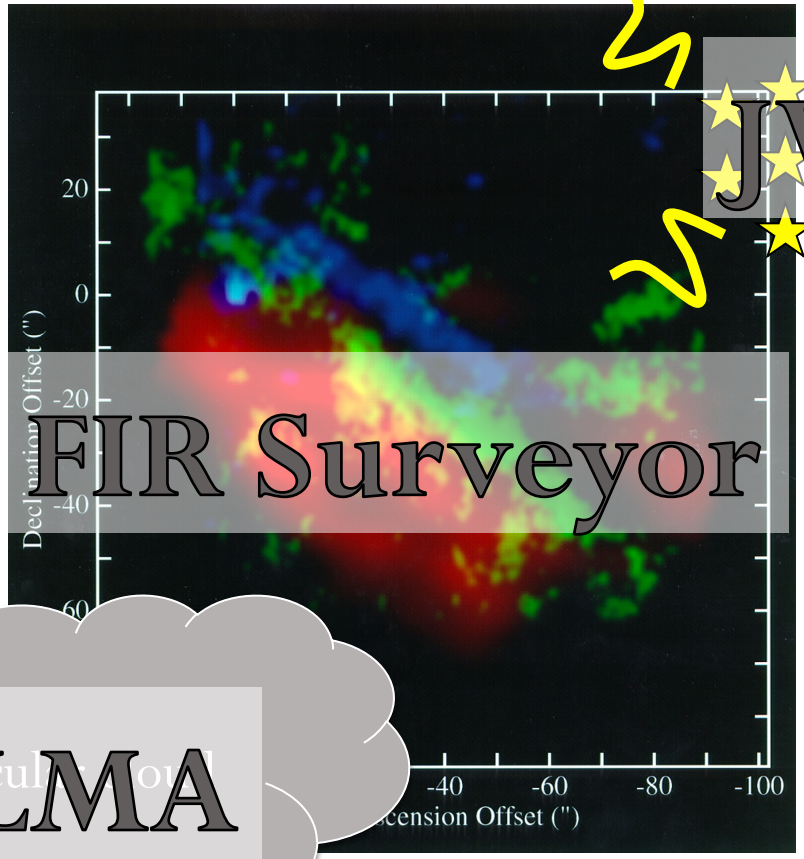


Stierwalt +13

How do we probe the interstellar medium (gas and dust where stars are forming) in high redshift galaxies?







JWST

FIR Surveyor

PAH

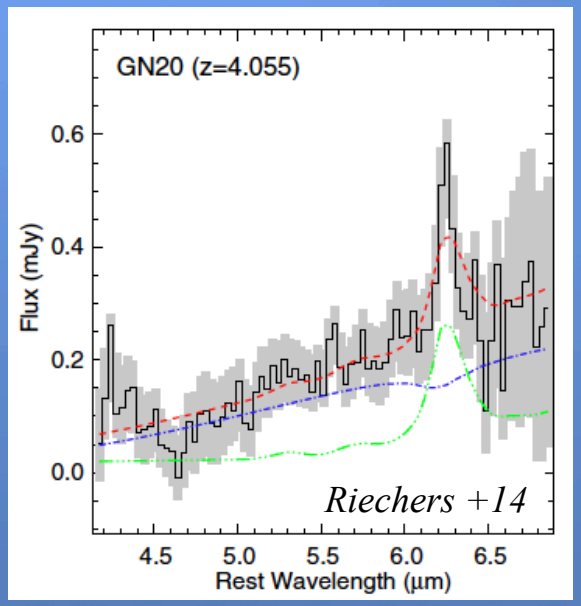
H_2

CO

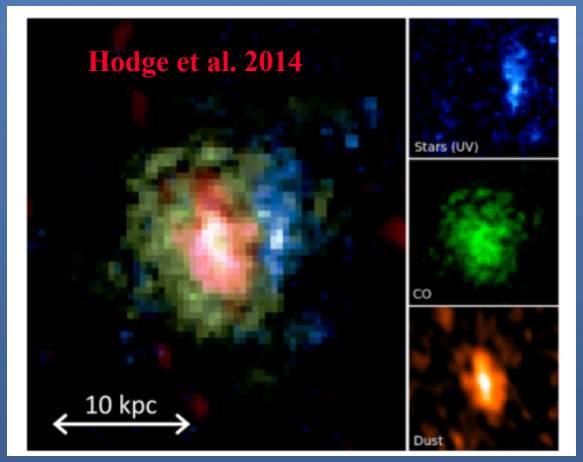
ALMA

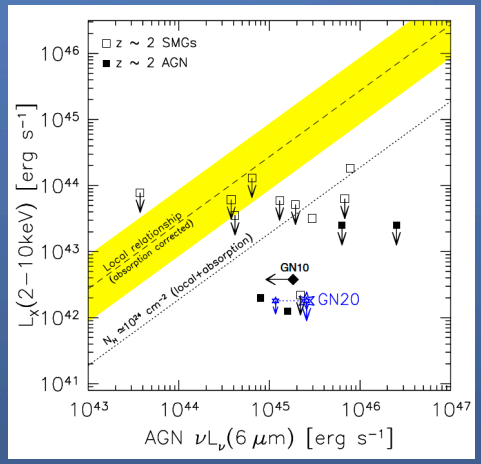
Hollenbach & Tielens 1997

IRS MIR Spectra of GN20



- GN20: One of the intrinsically brightest SMGs (S_{850} = 20.3 mJy)
- highest redshift IRS/PAH detection for Spitzer. 24hrs of integration split over 3 days!!
- Intense SB (1600-1900 $M_\odot$ yr^{-1}) dominates L_{bol} ($2x10^{13}$ Lsun) with a buried, CT AGN evident in the MIR.

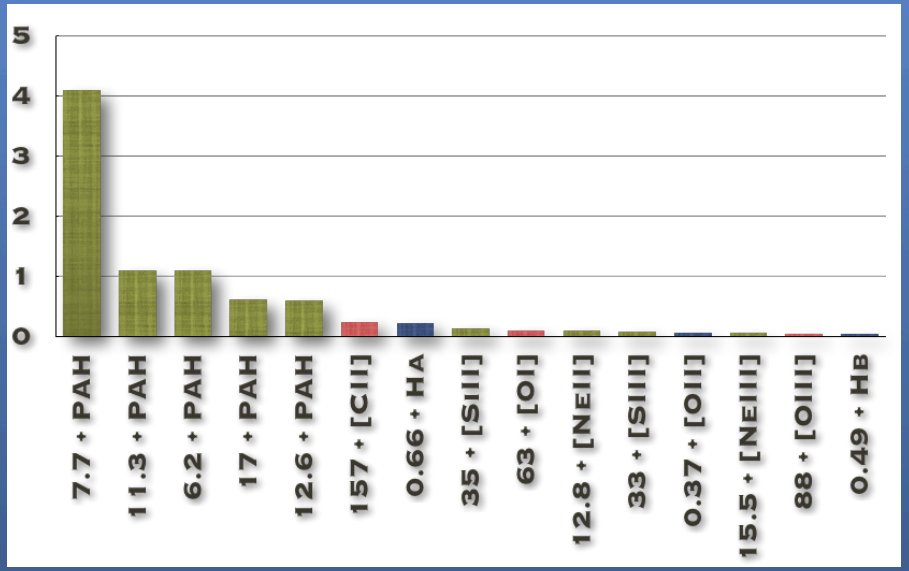


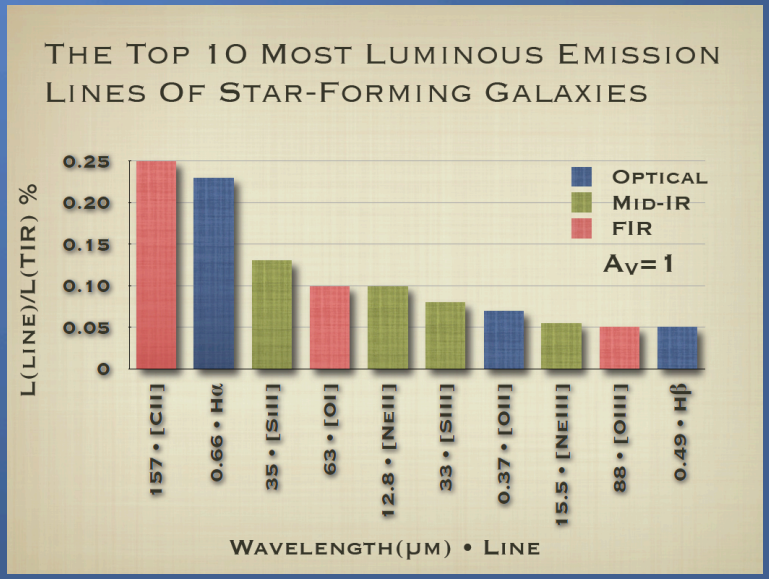


Galaxy Evolution with the FIR Surveyor

The Power PAHs:

- extremely bright/sensitive probes of PDRs and ISRF
- PAH ratios indicate the ionization, size of small grains
- when combined with continuum >> power source diagnostic





Courtesy of J.D. Smith

Galaxy Evolution with the FIR Surveyor

Science Theme: Galaxy and BH Co-evolution

- How is the SMBH – galaxy mass correlation established?
- How much of the evolution occurs in an obscured phase?
- What is the role of AGN in quenching SF?

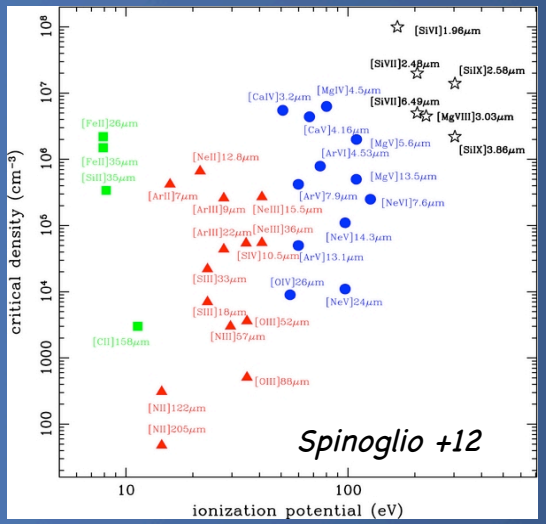
Why is this an important question now and in 2030?

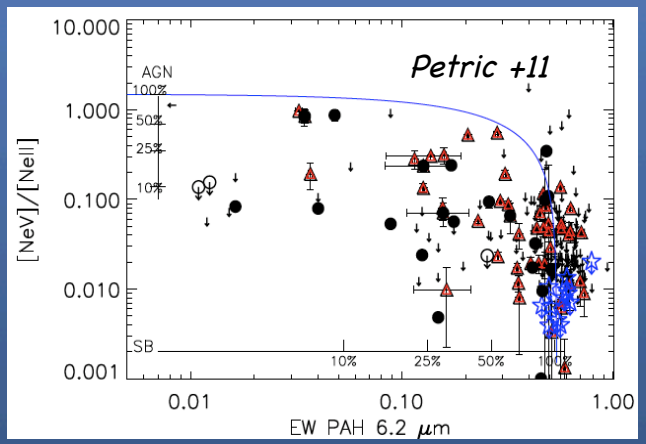
- The energetic interplay between AGN, SB and feedback regulate how high and low mass galaxies evolve. The inefficiency of SF.
- A significant fraction of SF and AGN growth occurs behind dust – need to find and quantify the power sources in dusty galaxies over a wide range in LIR, z, environment.

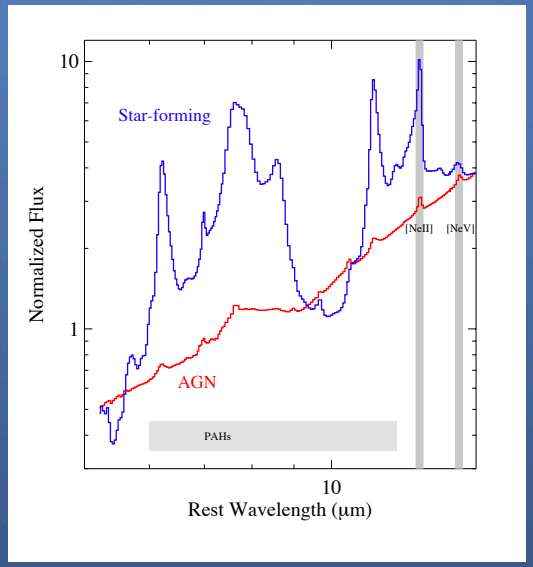
Galaxy Evolution with the FIR Surveyor

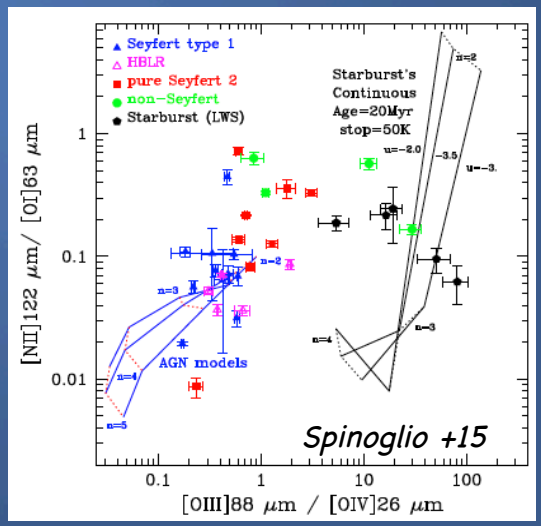
Why is the FIR uniquely suited to answer this question?

- Mid, FIR gives us probes covering a huge range in ionization potential, critical density
- F.S. lines, PAHs, and dust continuum can all be used together to quantitatively estimate the fractional contribution of SB, AGN even in the dustiest sources.
- Probe feedback via warm H2, emission and absorption line profiles



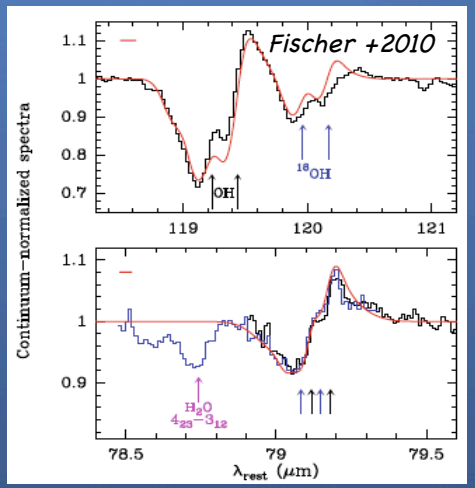


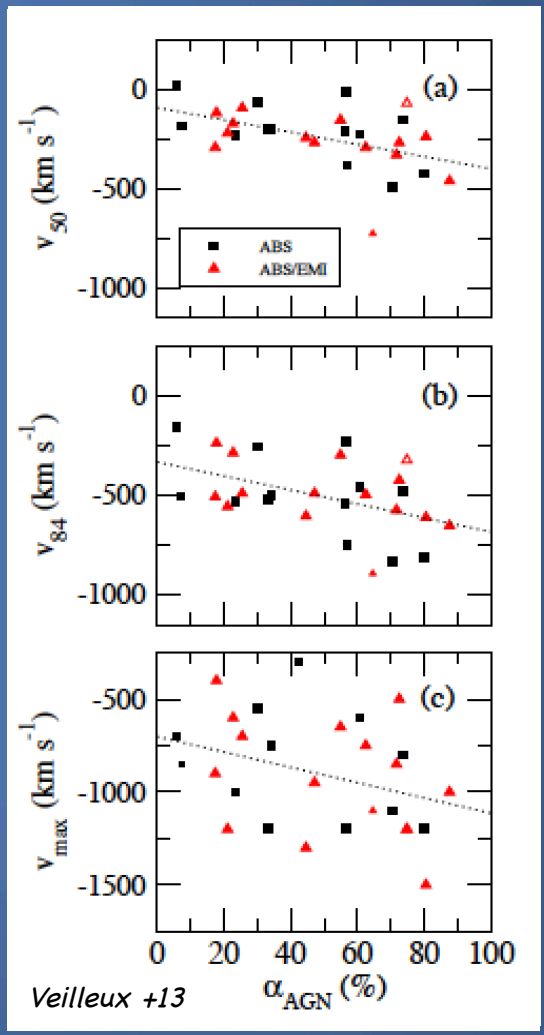




Galaxy Evolution with the FIR Surveyor

- Blue-shifted OH FIR common in local ULIRGs
- High velocity (≈1000 km/s) outflows correlated with AGN power.
- Correlation of OH EQW and silicate depth suggests early, obscured stages of feedback *(Spoon +13)*
- High mass outflow rates (500-1000 $M_\odot$ yr^{-1}) imply very short gas depletion timescales (< 10^7 yrs). Much smaller than the merger timescales. Breakout phase ?

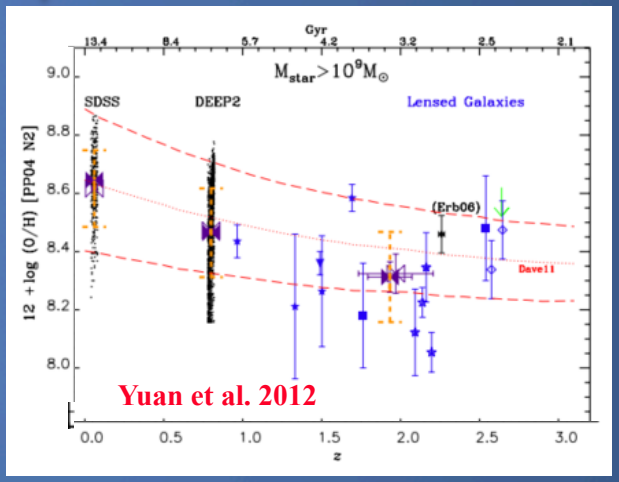




Galaxy Evolution with the FIR Surveyor

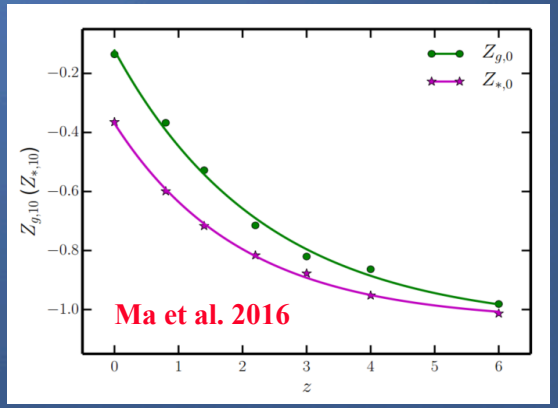
Science Theme: The Rise of Metals over Cosmic Time

- How do metals and dust build up in galaxies?
- What produces the bulk of the metals at each epoch?
- How much of the build up occurs in a dust-obscured phase? How does this affect evolution?



Why is this an important question now and 2030?

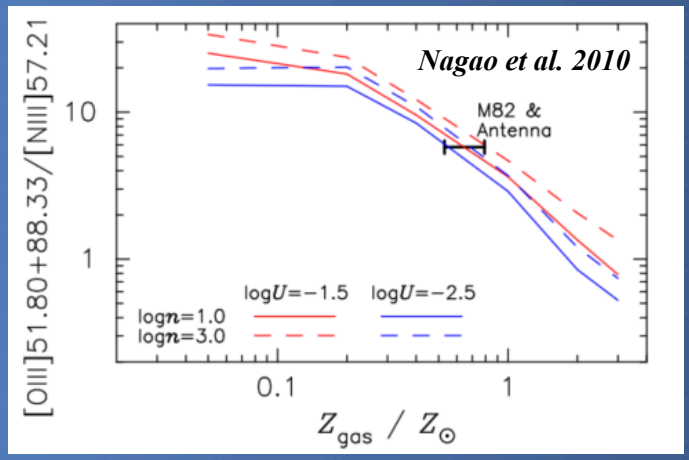
- Limited direct studies of metallicity beyond z=1-2. Simulations predict strong evolution.
- Traditional probes of gas-phase metallicities may only probe outer/dust-free regions of the ISM in IR bright galaxies >> incomplete and biased picture.

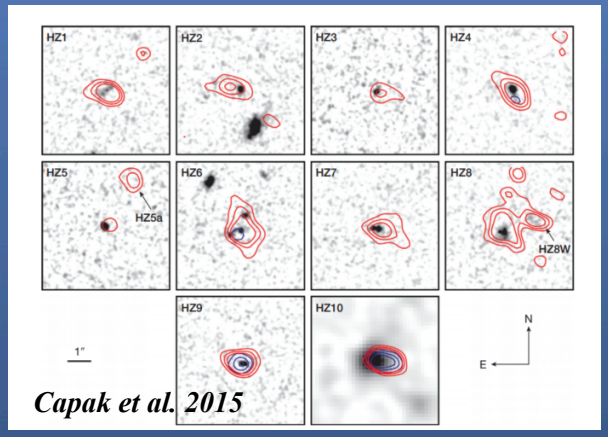


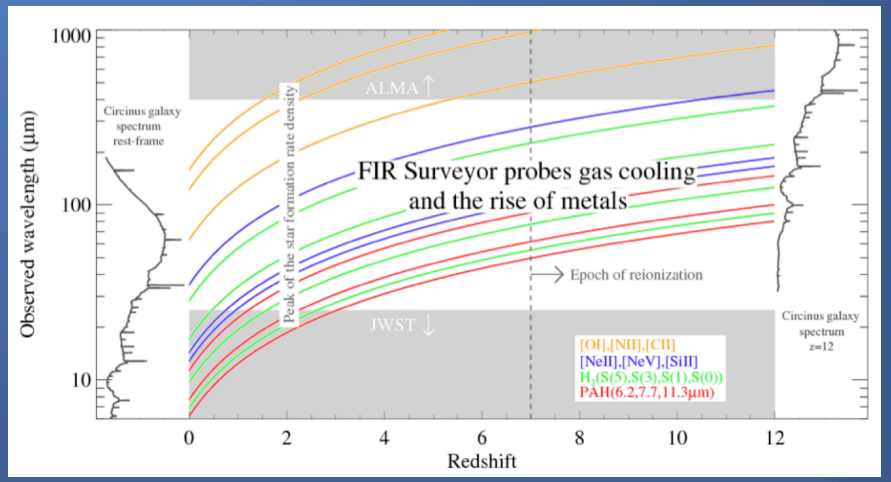
Galaxy Evolution with the FIR Surveyor

Why is the FIR uniquely suited to answer this question?

- Fine structure lines probe dense or obscured regions and dusty galaxies that are inaccessible to optical/UV tracers.
- Multiple IR transitions of O, N can be measured with the Far Infrared Surveyor over a large range in redshift/environment.



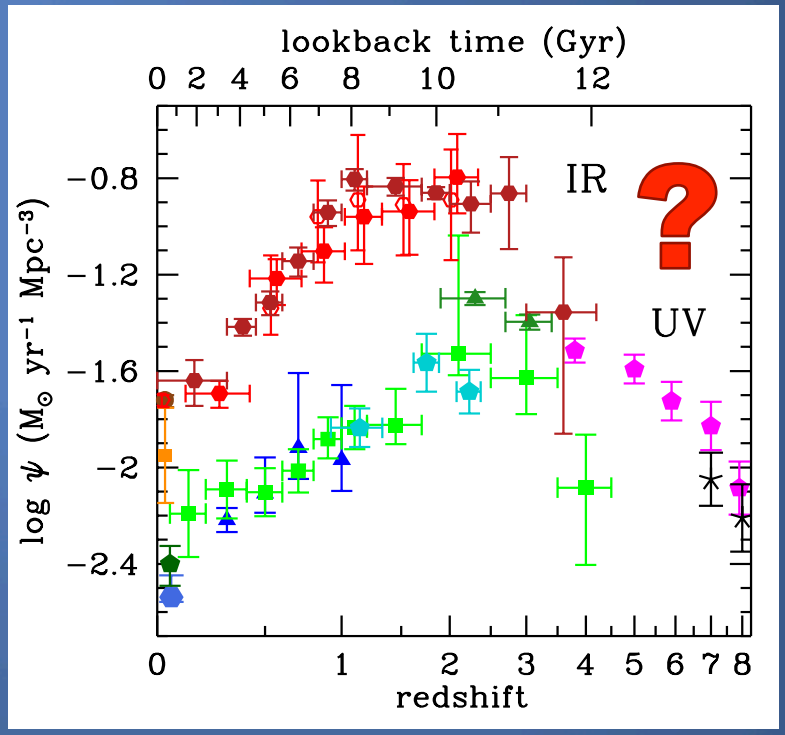




Galaxy Evolution with the FIR Surveyor

Science Theme: Star Formation (demographics) over Cosmic Time

- What is the shape of the dust-obscured cosmic SFRD for z > 4?
- What drives/regulates the shape of this curve for 1 < z < 6?
- How much of the star formation is obscured in typical LIR* galaxies at each epoch?



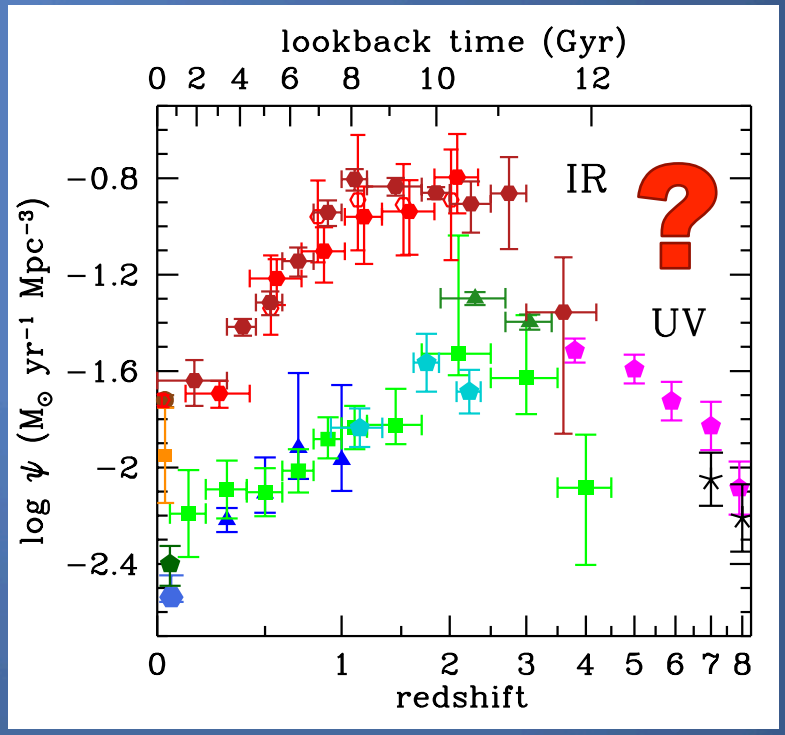
Madau & Dickinson 2014

Galaxy Evolution with the FIR Surveyor

Why is this an important question now and in 2030?

An incomplete census of cosmic SF will persist until 2030 because:

- JWST will constrain measure SF in distant galaxies but will not directly probe the highly obscured SF/AGN at z > 3
- ALMA can detect this obscured SF in typical L* galaxies at z > 3, but will not survey wide areas (cosmic variance, LSS) or have access to the vast IR MIR toolset at z < 6.

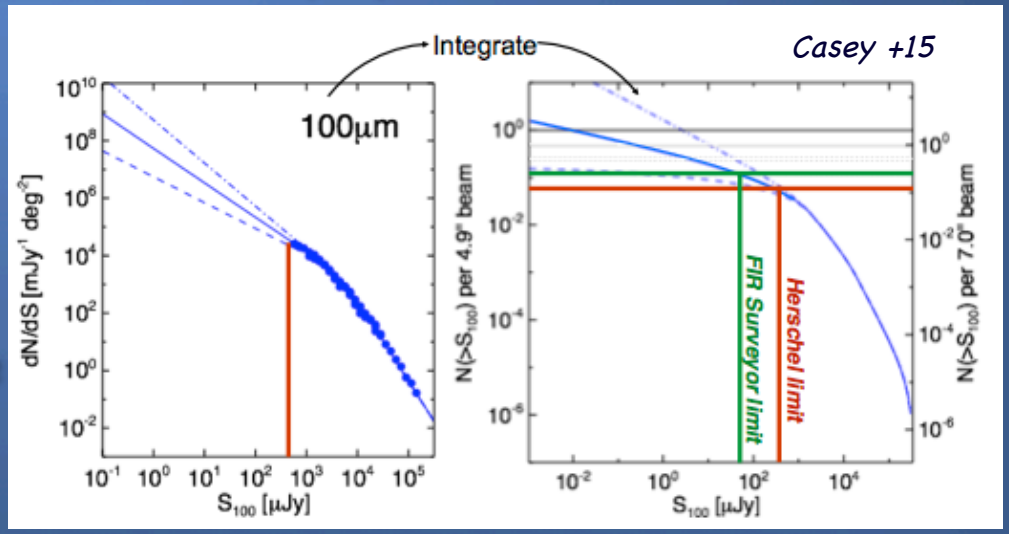


Madau & Dickinson 2014

Galaxy Evolution with the FIR Surveyor

Why is the FIR uniquely suited to answer this question?

- FIR detects the obscured SF through continuum and lines (e.g PAH and F.S. lines at z > 3)
- The FIR Surveyor can detect and sample large enough numbers of normal galaxies to trace the rise in SF from 2 < z < 6. Provides source discovery and detailed studies of SF properties.
- Because number counts turnover, we can generate huge sample gains over Herschel with even modest increase in collecting area (e.g., a 5m beam can push the confusion limit down by 10x at 100 μm compared to Herschel)



Galaxy Evolution with the FIR Surveyor

Science Theme: Tracing Large Scale Structures with FIR-luminous Galaxies

- How do galaxy assembly processes trace the evolving dark matter as a function of redshift and luminosity?
- How do different structures in the cosmic web regulate galaxy evolution?
- What and where are the progenitors of the earliest collapsed structures in the Universe?

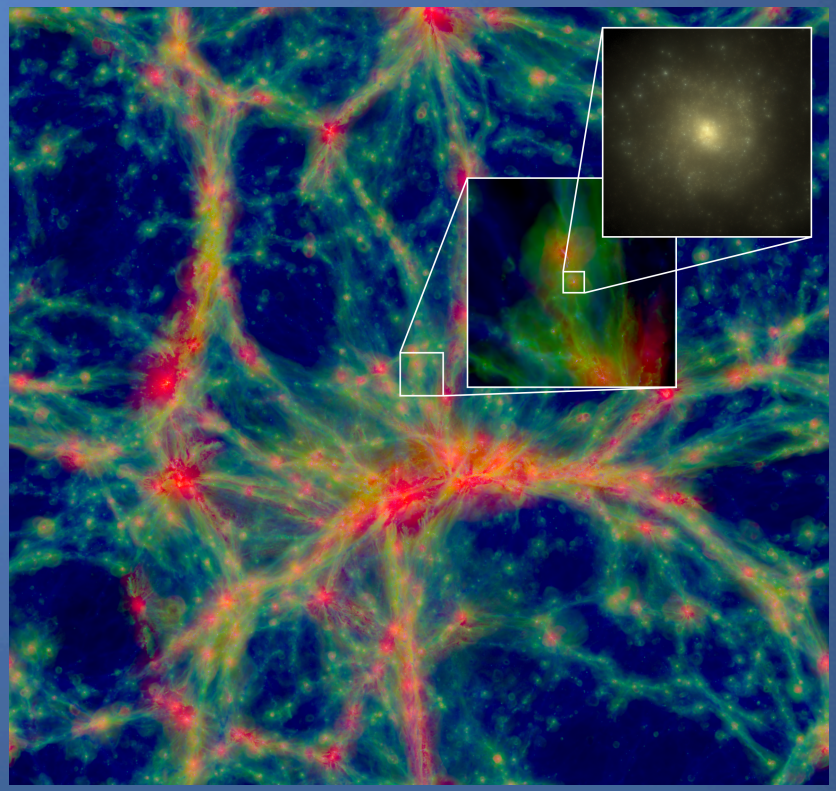
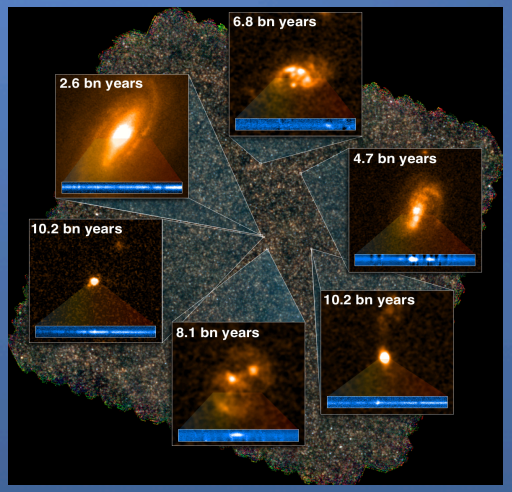


Image credit: the EAGLE project

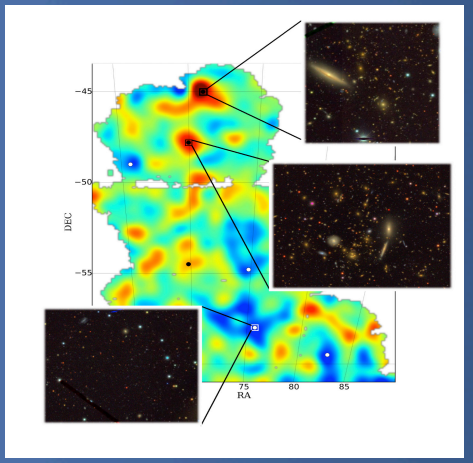
Galaxy Evolution with the FIR Surveyor

Why is this an important question now and in 2020/2030?

- Large scale structure can have a profound influence on galaxy assembly, but the scale and details are poorly understood, especially at z > 1
- Obscured SF and buried AGN activity are key galaxy assembly processes from 1 < z < 4, dominating galaxy buildup and BH growth
- The FIR is essential for tracing how galaxy assembly and evolution depends on Large Scale Structure (mergers, tidal and ram-pressure stripping, feedback)



FIR selected galaxies from Herschel H-ATLAS survey

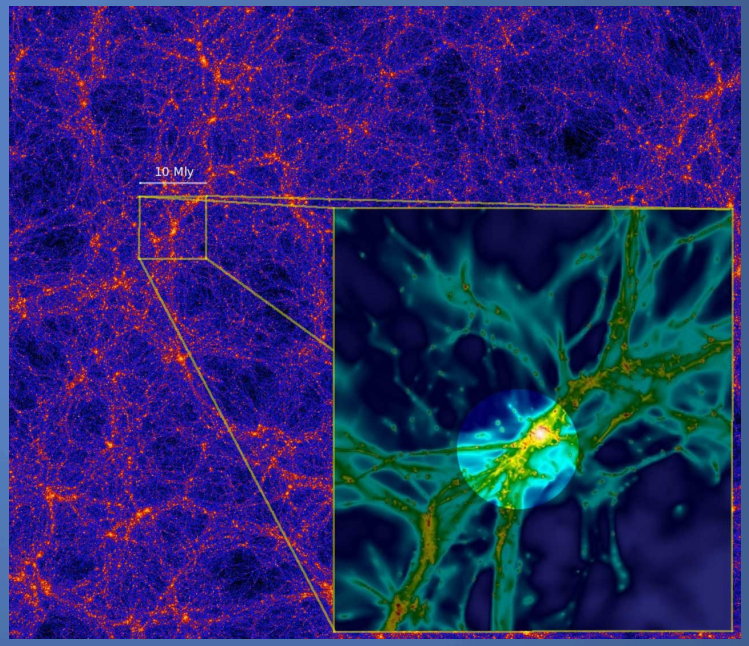


Map of the dark matter, showing clusters and voids, from the DES

Galaxy Evolution with the FIR Surveyor

Why is uniquely suited to answer this question?

- FIR luminous processes trace the cosmic web in different ways to quiescent galaxies, with, e.g. potentially different SF efficiencies and accretion modes in clusters and filaments
- The FIR Surveyor is thus a key complement to WFIRST – combining them leads to a near-complete census of the the relation between baryons and dark matter, including those in the gaseous phase



star formation in cosmic filaments is more efficient than in clusters or voids. Image Credit: Anatoly Klypin / Joel Primack / S. Cantalupo.

Galaxy Evolution with the FIR Surveyor

What are some key measurements?

- Sensitive spectra of key MIR and FIR diagnostic F.S. lines, PAHs, H2
- Well sampled SEDs and broad λ coverage (20/30-300/500μm)
- Imaging over tens of sq. degrees in survey/mapping mode (wedding cake)

What are some of the key observational requirements?

- Sensitivity: LIRG levels at $z \leq 6$ to probe SF, BH in typical galaxies -> better than 10^{-20} Wm^{-2} in short (< hr) integrations for PAHs, and 1-few x 10^{-21} Wm^{-2} for F.S. lines
- Statistics: hundreds-thousands of galaxies per redshift, luminosity environment bin -> samples of 10^{4-5} (100-1000x Spitzer, Herschel)
- Spectral resolution: low, high R (few 100 - few 1000) modes for broad feature detection, redshifts, profiles. High-res (10^4) mode a real advantage.
- Spatial resolution: 1-few arcsec to beat confusion in surveys, resolve nearby sources

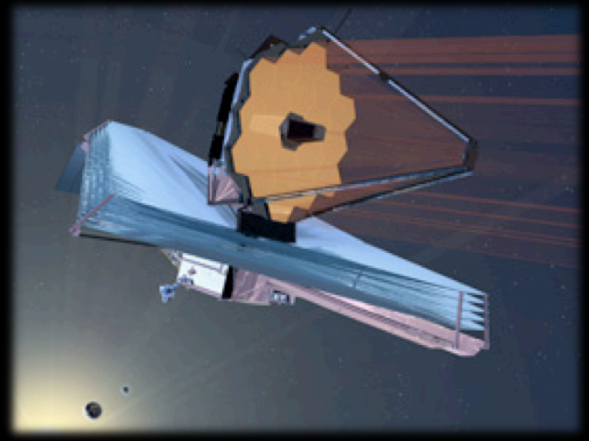
Galaxy Evolution with the FIR Surveyor

Near-term plans (Summer 2016)

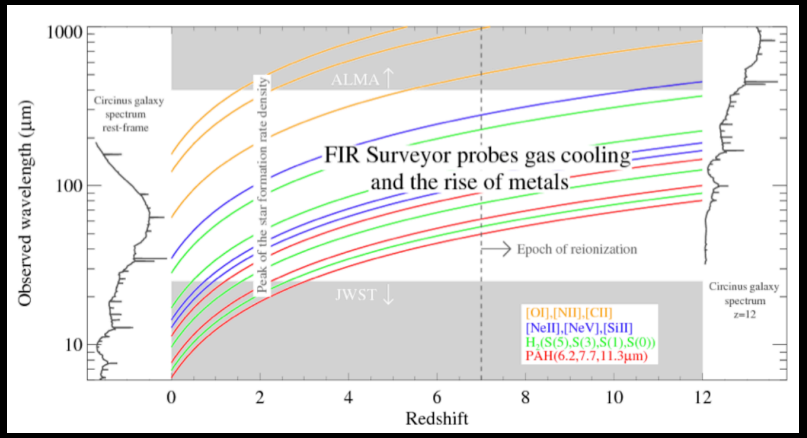
- Develop science questions/themes more fully. Rank the most important questions in terms of impact and uniqueness for the FIR Surveyor. Identify important "missing" areas, seek broader input.

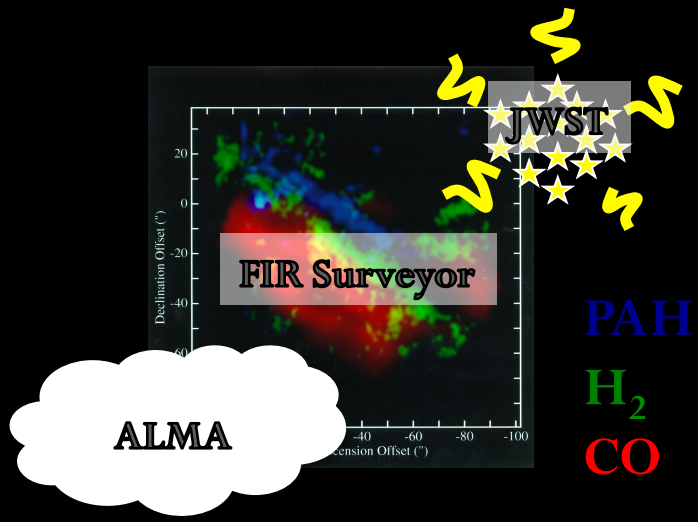
- Identify areas where more detailed calculations/simulations are needed in the short term. Assign to group or enlist additional expertise from community.

- Define key observational requirements for each science question for trade matrix study, technical requirements scoping and study team effort.



The FIR Surveyor sits squarely between JWST and ALMA in <u>wavelength</u> and <u>discovery space</u> for studies of galaxy evolution.





No matter what shape the FIR Surveyor takes it will transform our understanding of how stars, galaxies, SMBH grow over cosmic time.