FIRSST: Far-Infrared Spectroscopy Space Telescope

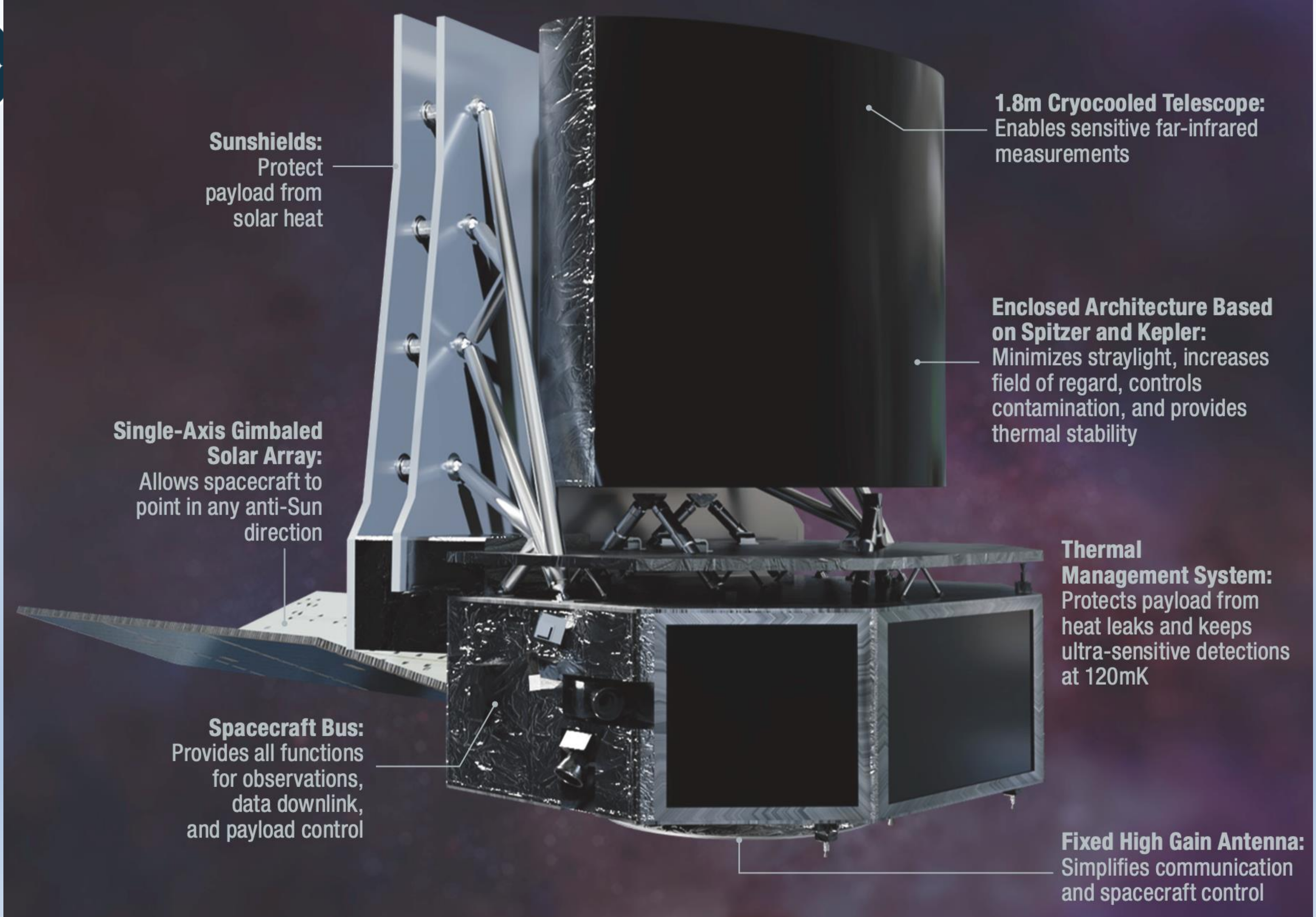
Presented by Gordon Stacey, DDSI PI
Asantha Cooray (PI)
Meredith MacGregor (Deputy PI)
on behalf of the entire FIRSST Team

1B$ Cost Cap Mission: Design Motivation

- Protostars and Protoplanetary Disks
  - Probed in uniquely important, yet widely unexplored tracers
  - e.g. HD lines, H_20 lines, [OI] – all lie in the far-IR to submm bands
  - Need to surpass Herschel in both sensitivity and resolving power
- Evolution of galaxies
  - A wide range of spectral probes of SF (intensity, luminosity, stellar populations), its evolution over cosmic time and the consequent evolution of the ISM – e.g. [OIII], [NII], [NIII], [OI], [CII] far-IR lines
  - Need to surpass Herschel in band coverage and sensitivity
- Take advantage of new technologies enable new investigations
  - MKID detectors
  - VIPA-based spectrometers

Clean sheet: Science/cost trade-offs

- Maximum sensitivity $\Rightarrow$ large, cold aperture, & direct detection
  - aperture cost grows rapidly, especially when considering cooling requirements:
  - A bottom-up/top-down cost estimates put a hard upper limit at 1.8 meters
- Maximize bandwidth in JWST to ALMA hole: 25 um to 260 um
  - Can be implemented as continuous spectrometer with RP ~ 100
  - Modest slit width since detector count drives systems and costs
- Minimal emphasis on photometry: Herschel already did this quite well and its confusion limit is much deeper than our 1.8 m telescope
  - Unfortunately, this makes us less useful for polarization studies, but could do it at RP ~ 100!
- For velocity resolved spectroscopy we implement VIPA for the higher frequencies and heterodyne receivers for the lower frequencies



Sunshields: Protect payload from solar heat
1.8m Cryocooled Telescope: Enables sensitive far-infrared measurements
Enclosed Architecture Based on Spitzer and Kepler: Minimizes straylight, increases field of regard, controls contamination, and provides thermal stability
Single-Axis Gimbaled Solar Array: Allows spacecraft to point in any anti-Sun direction
Thermal Management System: Protects payload from heat leaks and keeps ultra-sensitive detections at 120mK
Spacecraft Bus: Provides all functions for observations, data downlink, and payload control
Fixed High Gain Antenna: Simplifies communication and spacecraft control

PI: Asantha Cooray
UC Irvine
Meredith MacGregor
JHU
Deputy-PI
Fingerprinting Planetary Reservoirs Lead
Uma Gorti
SETI Institute
Tracing Water to Rocky Planets Lead
Vivian U
UC Irvine
Unveiling the Drivers of Galaxy Growth Lead
Ron Vervack
JHU APL
Project Scientist
APL
JOHNS HOPKINS
APPLIED PHYSICS LABORATORY
NASA
Goddard
Space Flight Center
NASA
Marshall Space Flight Center
Ball
ipac
CORNELL UNIVERSITY
FOUNDED A.D. 1865
DLR
l'Observatoire de Paris
UK SPACE AGENCY
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Agenzia Spaziale Italiana
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CENTRE NATIONAL D'ÉTUDES SPATIALES
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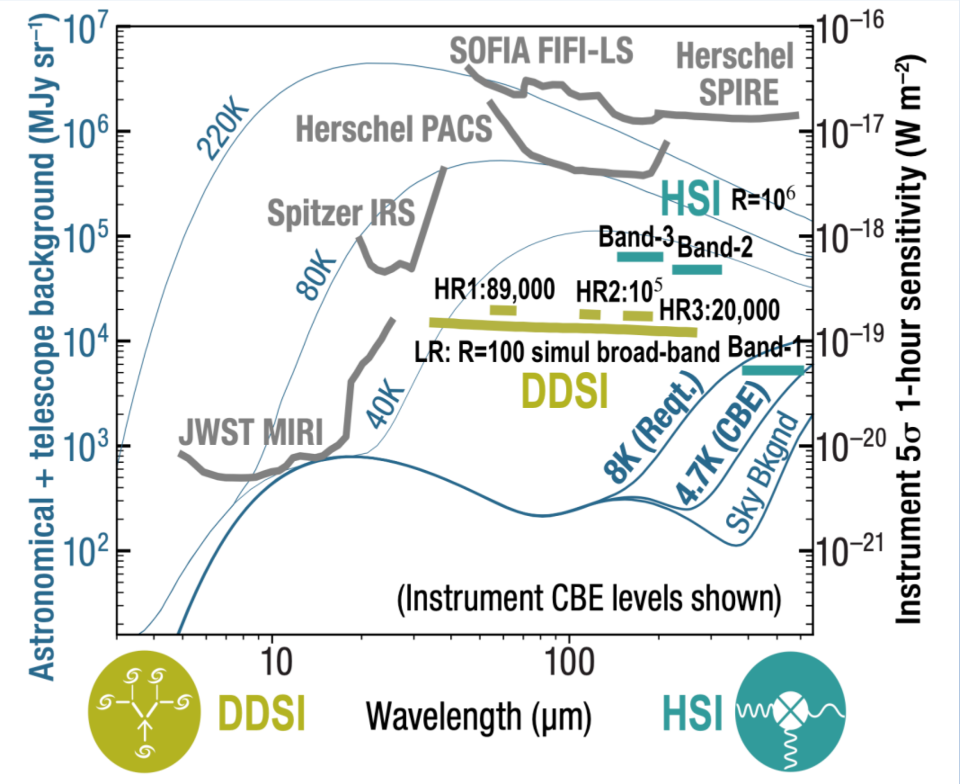
SRON
Rymdstyrelsen
Swedish National Space Agency

Two Instruments dedicated to spectroscopy

(1) Direct Detection Spectroscopy Instrument (DDSI)

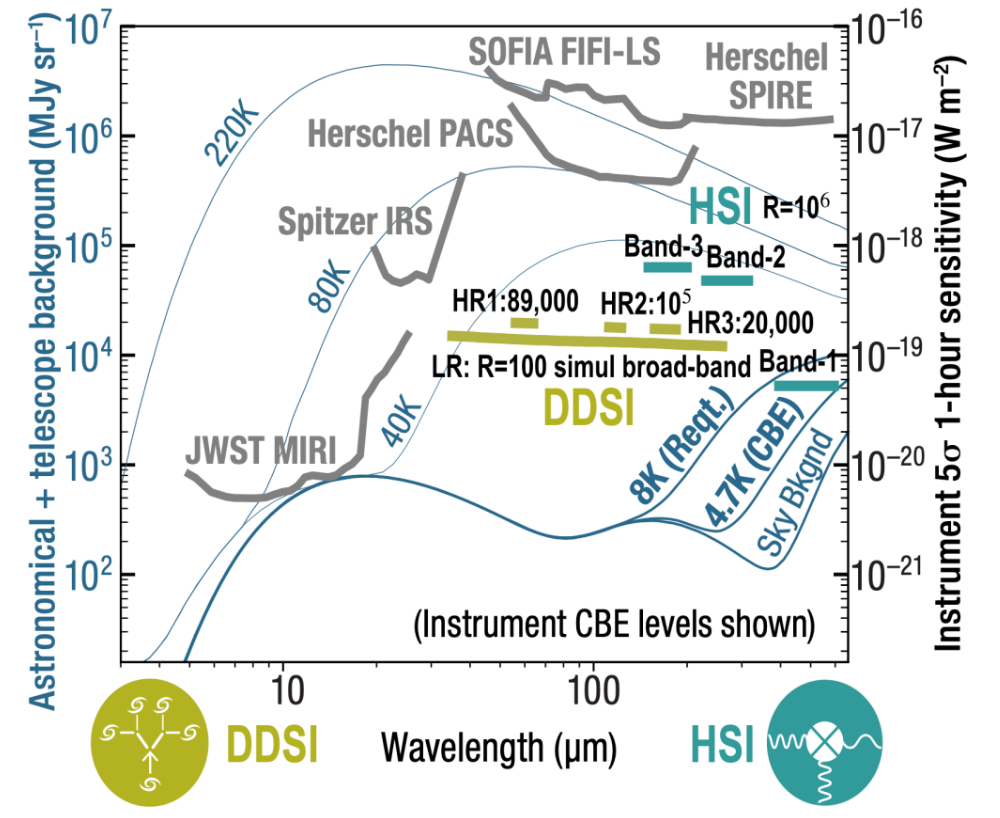
- Low resolving power (R = 100) broadband from 35 to 260 µm simultaneously in four-49 spectral element channels-8 beams
- Medium resolving power (R = 20,000) from 156 to 180 µm in 58 spectral element channel- 6 beams
- High resolving power (R = 89,000 – 100,000) in two 58-element channels covering the HD 56 and 112 µm, OH 119 µm, and OI 63 µm lines- 6 beams



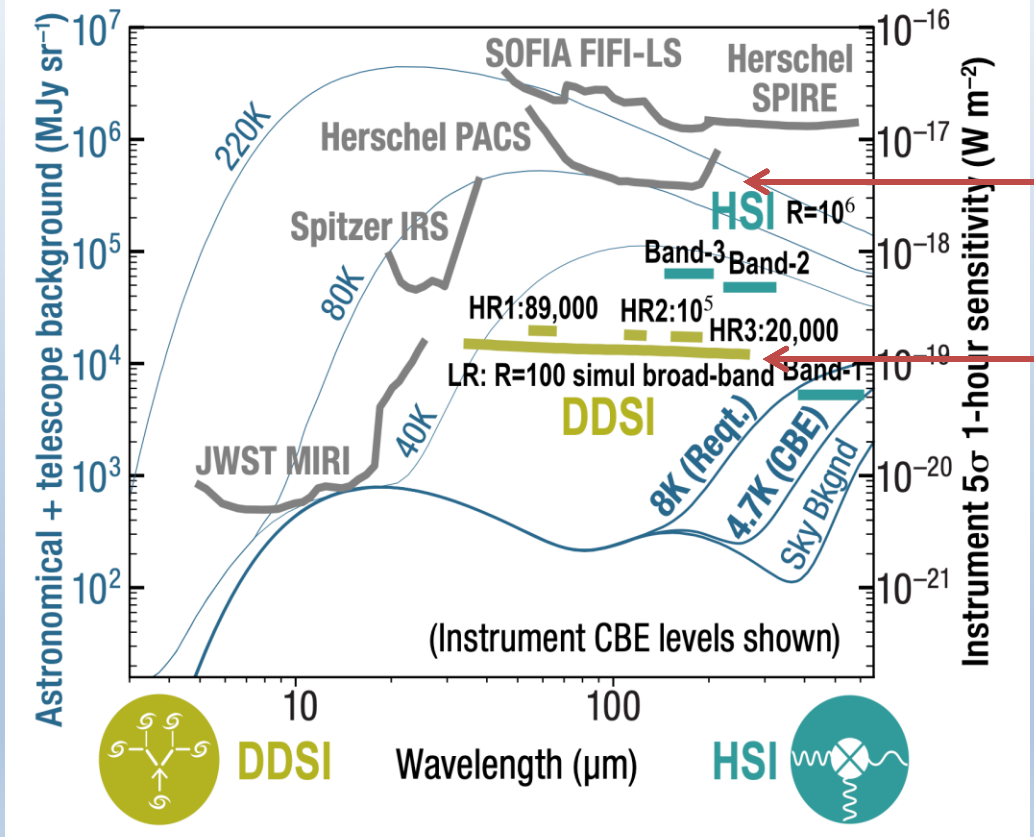
Two Instruments dedicated to spectroscopy

2) Heterodyne Spectroscopy Instrument (HSI)

- Three bands from 150 – 200, 240 – 340, and 380 – 600 µm
- Five-pixel arrays, each with dual polarization arrays for both mapping at resolving powers up to R = 10^6 – 10^7
- Optimized to cover a broad range of water lines



FIRSST DDSI and Herschel

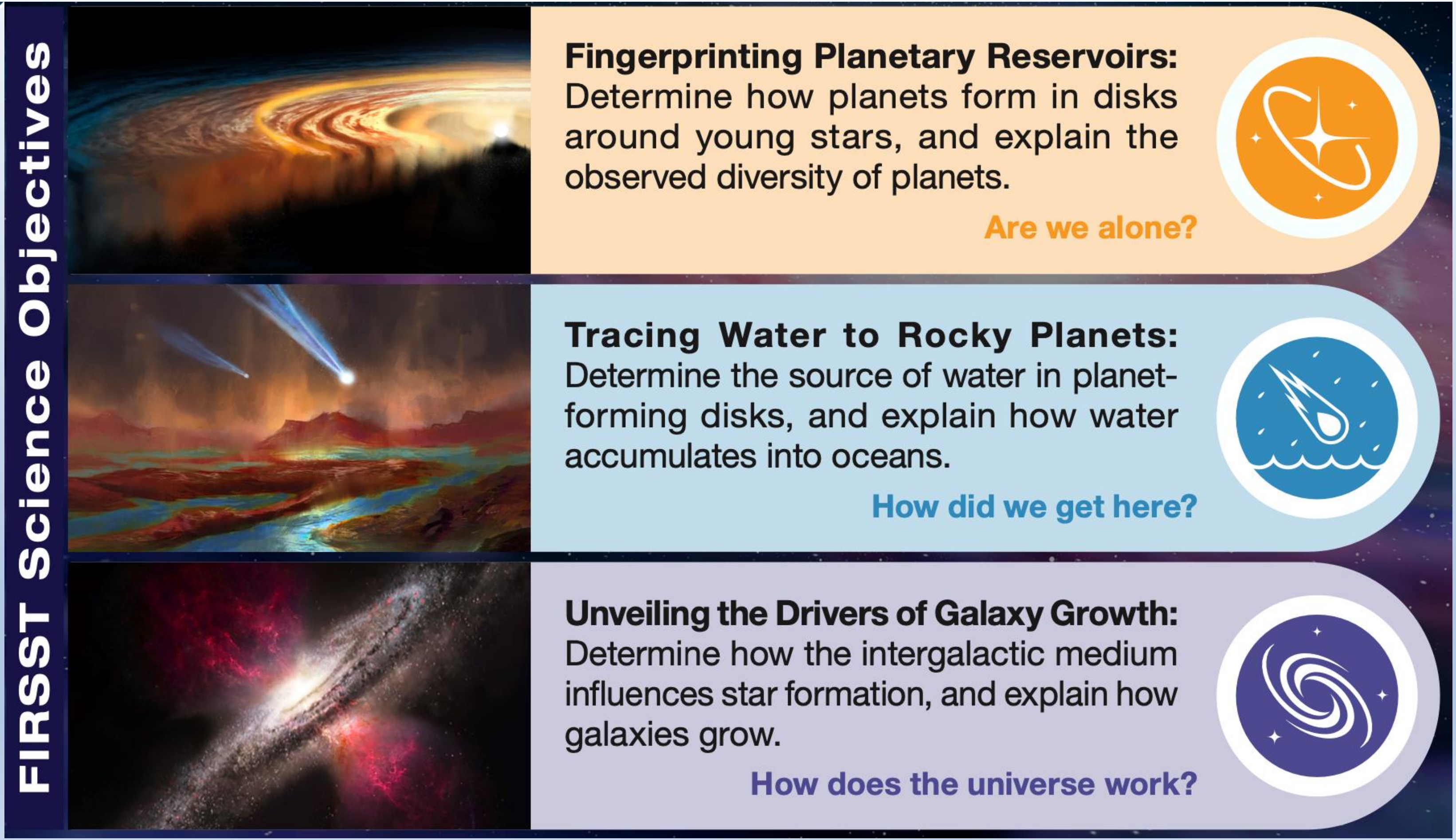


- The cold (4.7 K) telescope and state-of-the-art detectors give the 1.8m FIRSST/DDSI system a mapping speed 3600 (Current Best Estimate, CBE) times faster than Herschel/PACS instrument.
- FIRSST therefore opens a deep discovery space beyond all prior far-infrared missions.

Science Time Allocation

- PI-led Science Investigation – 25% of observatory time
  - A diverse science team with existing experience covering all aspects of the mission, from science to instrumental techniques, and technologies.
  - PI-led science data to become public without any proprietary period.
- Community-led GO Science Investigation – 75% of time
  - Unique features allowing efficient observations in the far-Infrared, for example, a very large instantaneous field of regard
- Science Implementation
  - All high TRL instrument components.
- Mission Implementation
  - Substantial heritage with successful $1B class missions at APL, delivering within budget.
  - Substantial heritage with IR mission science operations at IPAC.

The FIR uniquely addresses 2020 survey science questions



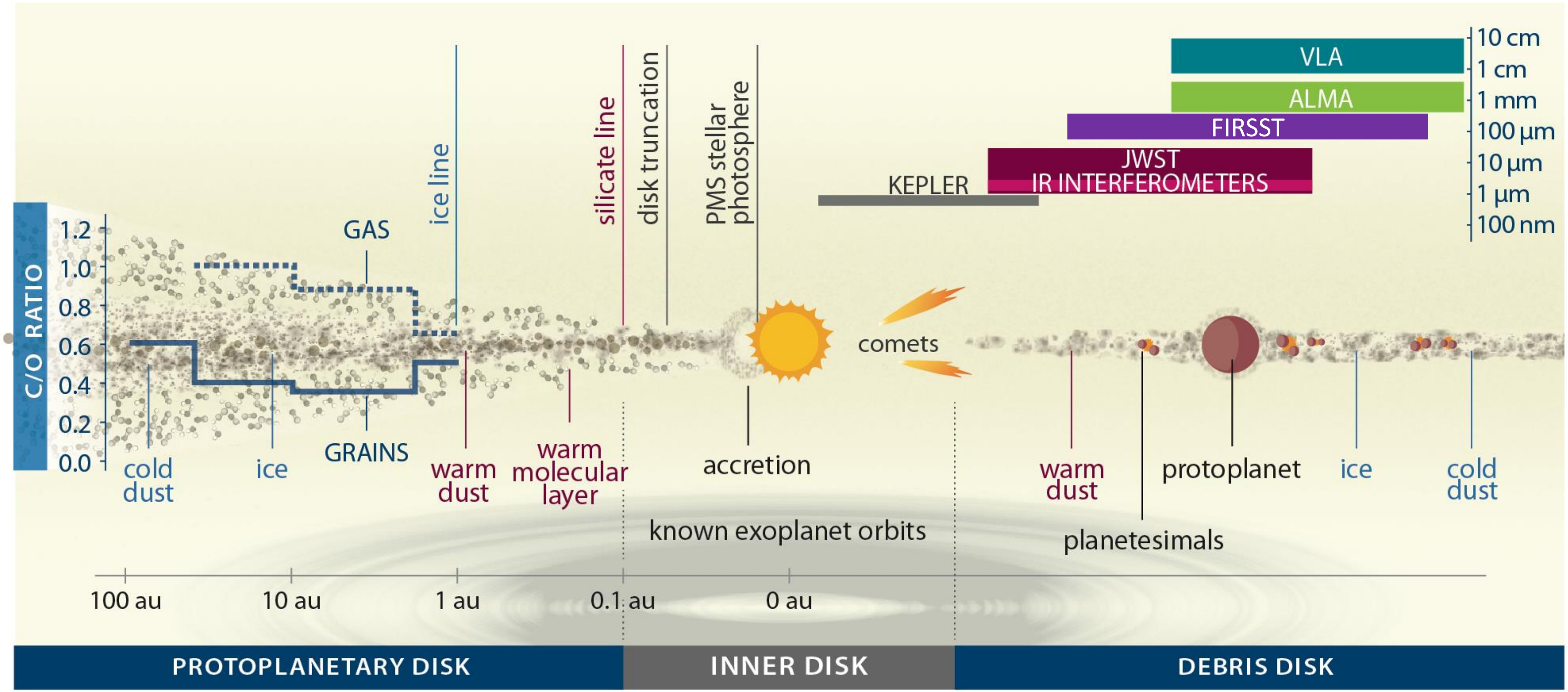
PI-Led Science Goals and Objectives

SG #1: Determine the ability of planet-forming disks to form planets with masses down to super-Earths and mini-Neptunes.
SG #2: Determine how gaseous volatiles are distributed within and removed from disks, setting the timescale for planet formation and the composition of the resulting planets.

SG #3: Determine the source of water in protoplanetary disks
SG #4: Determine the origin of water in terrestrial/rocky planets and the delivery of water to Earth's oceans by comets.

SG #5: Determine the influence of the intergalactic medium on galaxy-wide star formation.
SG #6: Determine the mass growth rate of galaxies from today to cosmic noon, across a range of galaxy properties, stellar masses, and environments.

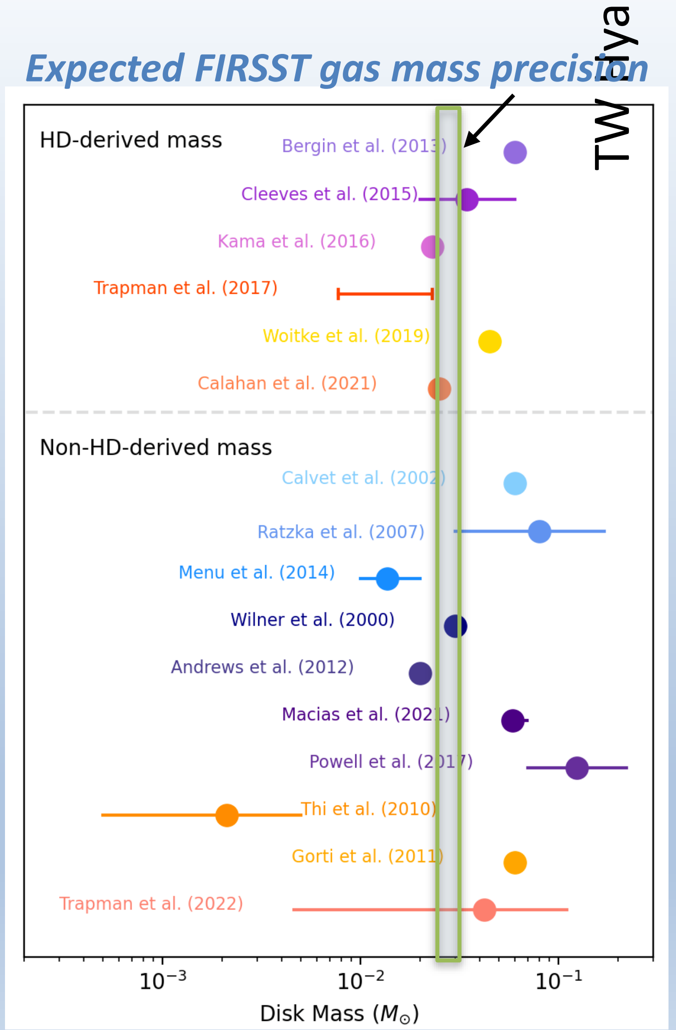
Fingerprinting Planetary Reservoirs



How much mass is available to form planets?

- ALMA CO and continuum estimates of disk masses suggest that very few disks would have enough mass to form a Jupiter-sized planet … We need a better way to measure disk masses!
- CO is often optically thick with a very uncertain conversion factor
- Other methods rely on a variety of assumptions and suffer from systematic uncertainties

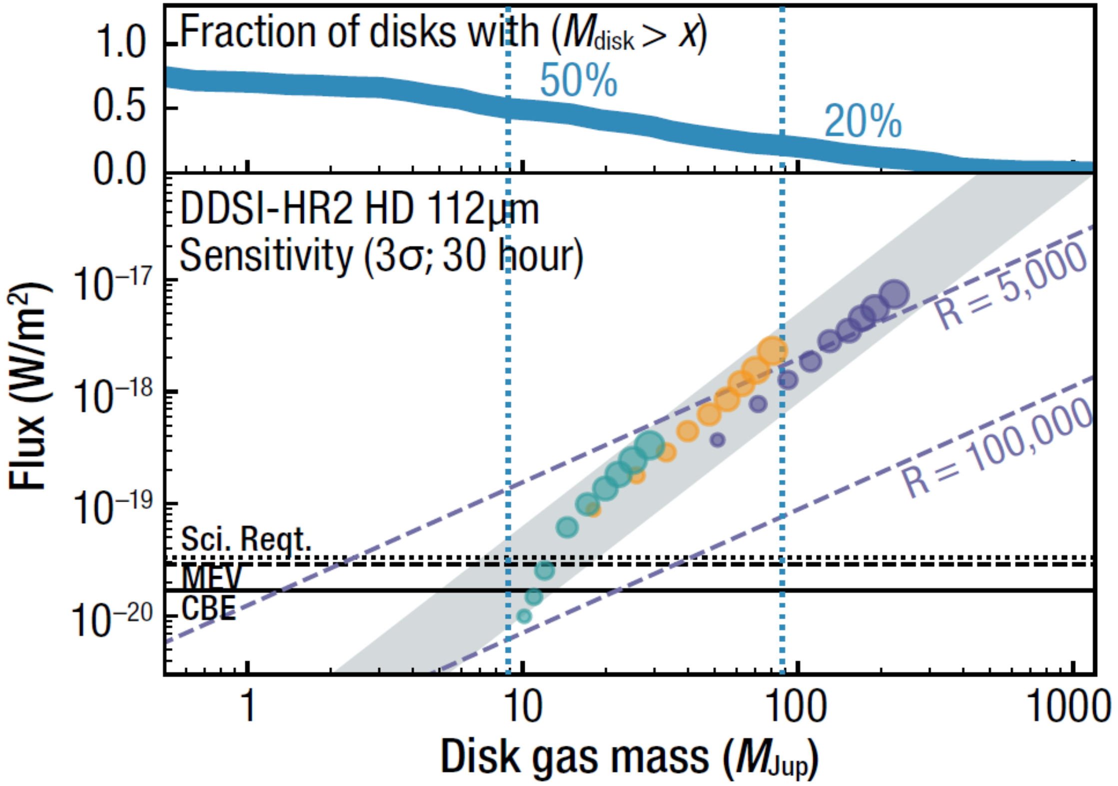
Credit: Miotello+ (2022, and references therein)



HD as a Probe of H_2 Mass

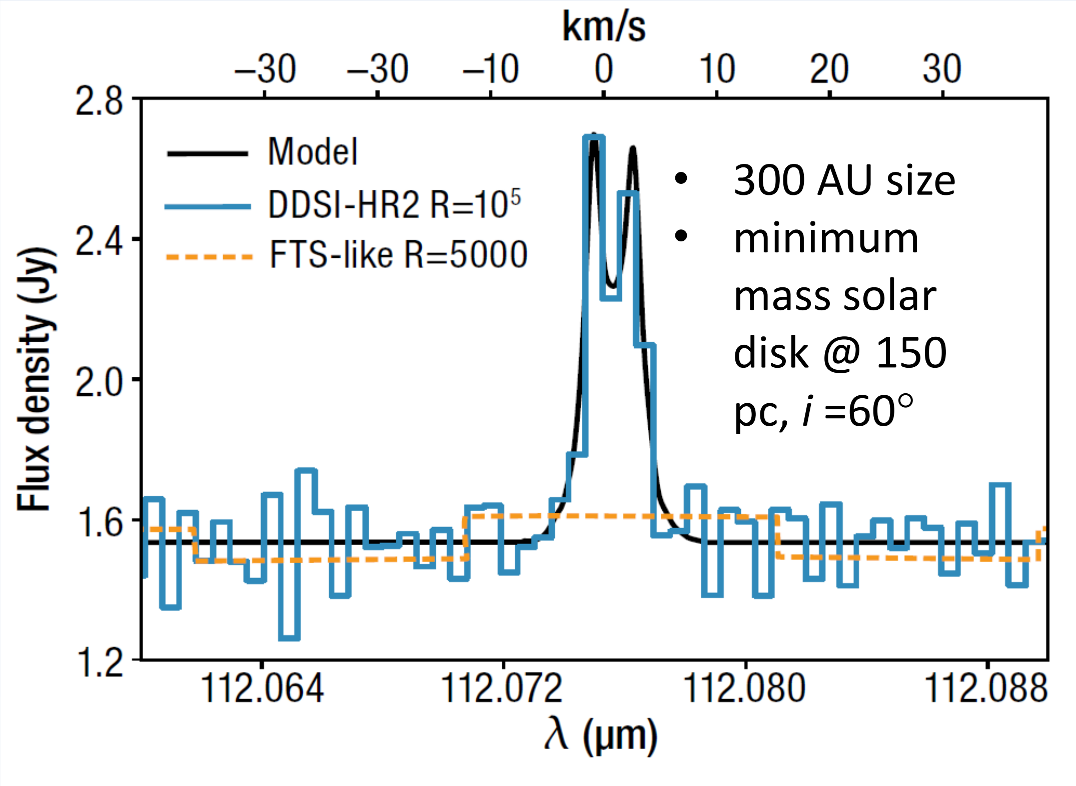
- From first principles, HD is a very good tracer for H_2
  - It has energetically accessible transitions at
    - 112 μm (J=1-0) (128 K) and 56 μm (J=2-1) (385 K)
  - Small Einstein A
    - + The lines are *optically thin and easily thermalized*
    - - The lines are optically thin and *weak ⇒ small line-to-continuum* ratios
    - - Therefore, need high resolving power for line detection
  - We therefore need exceptional sensitivity (direct detection) and exceptional resolving power (for direct detection)
  - The line ratio yields gas temperature refining gas mass estimates

Observable and Goal: Measure the distribution of mass available to form planets in protoplanetary disk gas masses down to 0.001 M, or below 1 M_{Jup} via velocity resolved HD line spectroscopy



- With RP=10^5, DDSI can measure HD for half the PPD population
- 300 AU-sized disks at 150 pc
  - Stellar masses 0.3 to 2 $M_{\odot}$
  - Disk/stellar mass from 1% -grey, 0.4% - yellow, 0.1%-green
- However, at R = 5000 the line to continuum is small ⇒ <20% of the population is detected
- Most are missed at R = 5000!

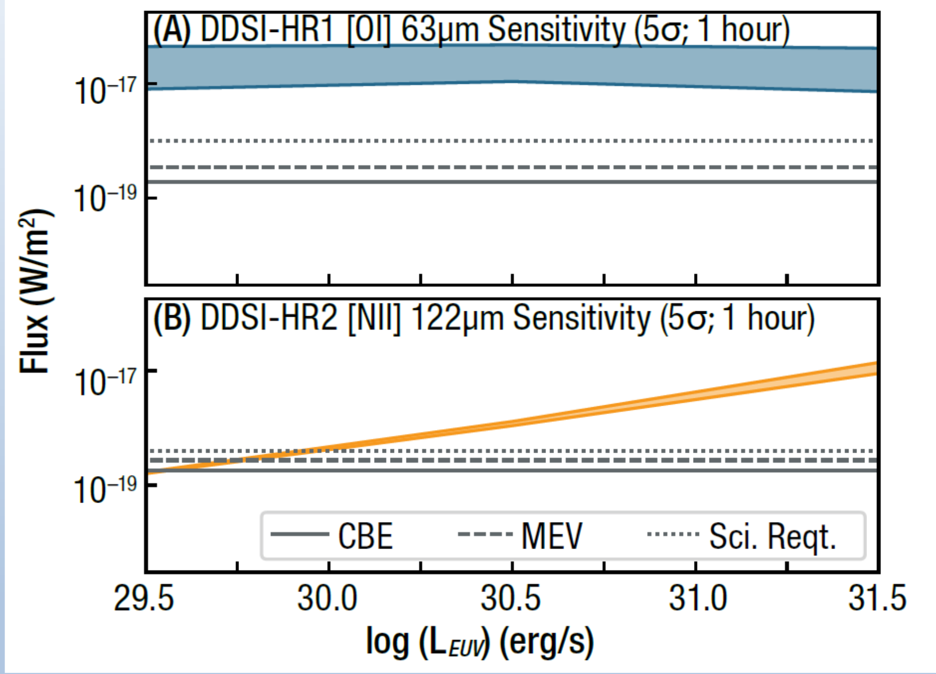
Observable and Goal: Velocity resolve the HD line in 300 protoplanetary disks in multiple bins of host star age and mass out to a distance of 200 pc for line tomography



- Extracted Nyquist-sampled spectra with **DDSI** (w/noise and deconvolved) compared with a no-noise observation with a RP ~ 5000 **FTS** instrument
- RP ~ 10^5 is necessary to measure the **line flux**, gas **excitation**, and to **radial distribution**.

Observable and Goal: Establish the time-scale for planet formation by measuring the mass loss rate with the [OI] 63 μm and [NII] 122 μm line flux

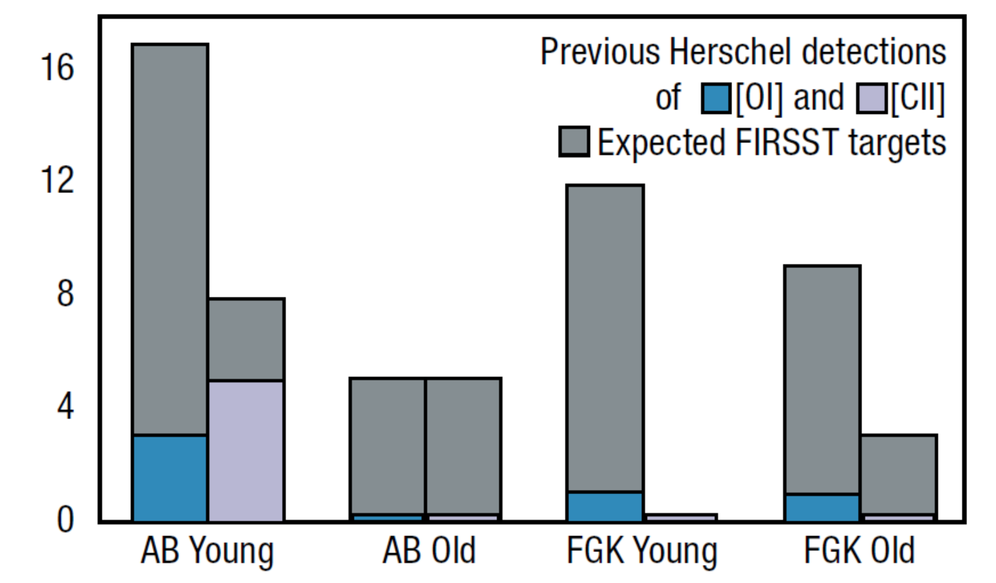
- Star approaches MS: remaining gas will photo-evaporates over time
- The [OI] and [NII] lines distinguish between EUV and X-Ray/FUV photoevaporation models
- Shown are **(blue) [OI]** and **(orange) [NII]** line fluxes in a $1M_{Jup}$ disk as a function of L_{EUV}
- The [OI] flux is insensitive to L_{EUV} while the [NII] shows a strong trend.
- Line flux translates to mass estimates down to 10^{-11} $M_{\odot}$/yr



Observations: 500 hours for [OI] 63 μm/[NII] 122 μm for 1000 planet-forming disks out to 200 pc

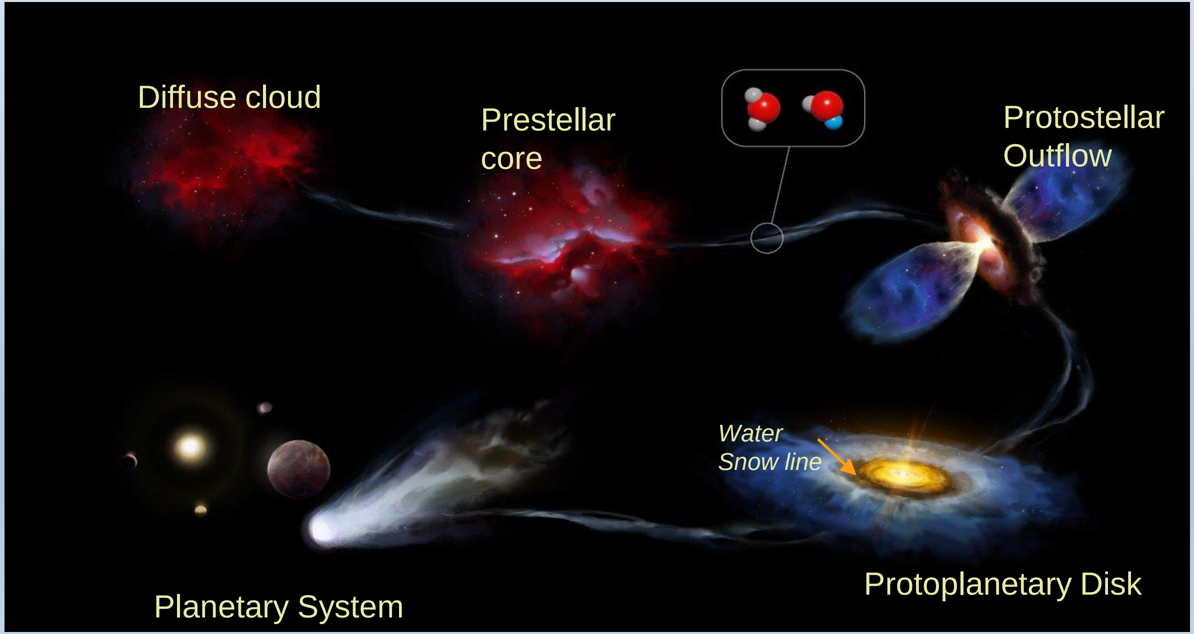
Observable and Goal: Measure the gas remaining in debris disks to connect disk chemistry with planetary compositions

- Connect disk chemistry with planet composition by measuring the C/O ratio in gas-rich debris disks down to a CO gas mass of $10^{-6}\ M_{\oplus}$.
- [OI] at 63 µm and [CII] at 158 µm for 40 gas-rich debris disks in 500 hours.



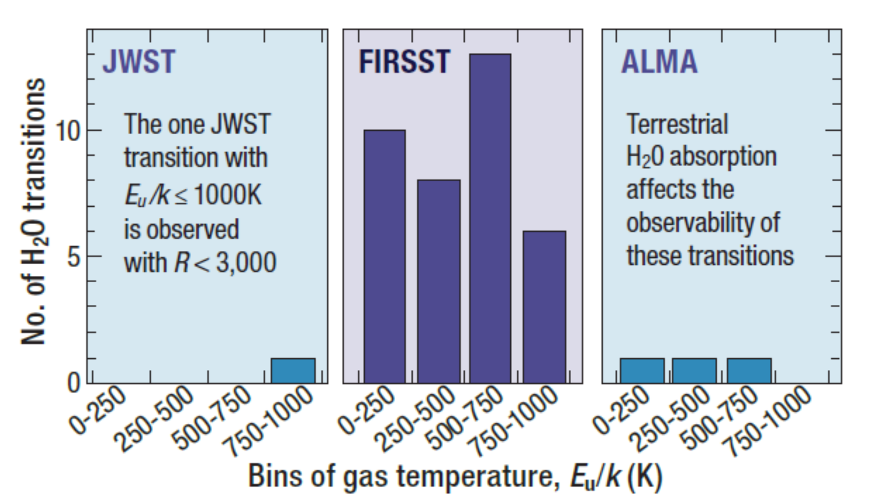
Tracing Water to Rocky Planets

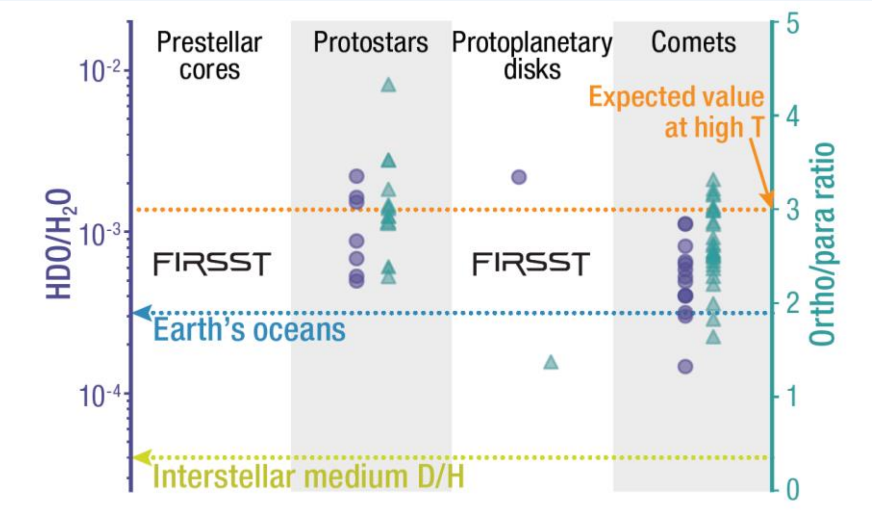
Water has to be delivered to terrestrial, habitable planets.
Is habitability determined by natal cloud core environments or disk conditions?



- Inherited water in cold pre-stellar cores.
- Water may be re-processed in disks.
- Water delivered to inner planets by comets.

Observable and Goal: Determine if water in planet-forming disks is inherited from the ISM or regenerated within disks through measurement of the ortho-to-para and HDO/H2O ratios down to $1M_\odot$ cores and $\sim 0.03M_\odot$ disks.

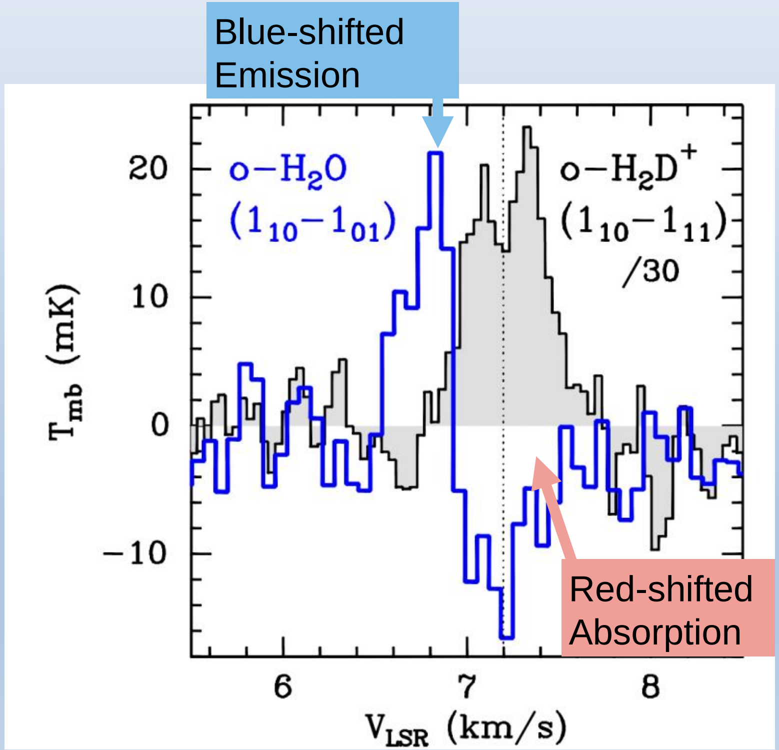


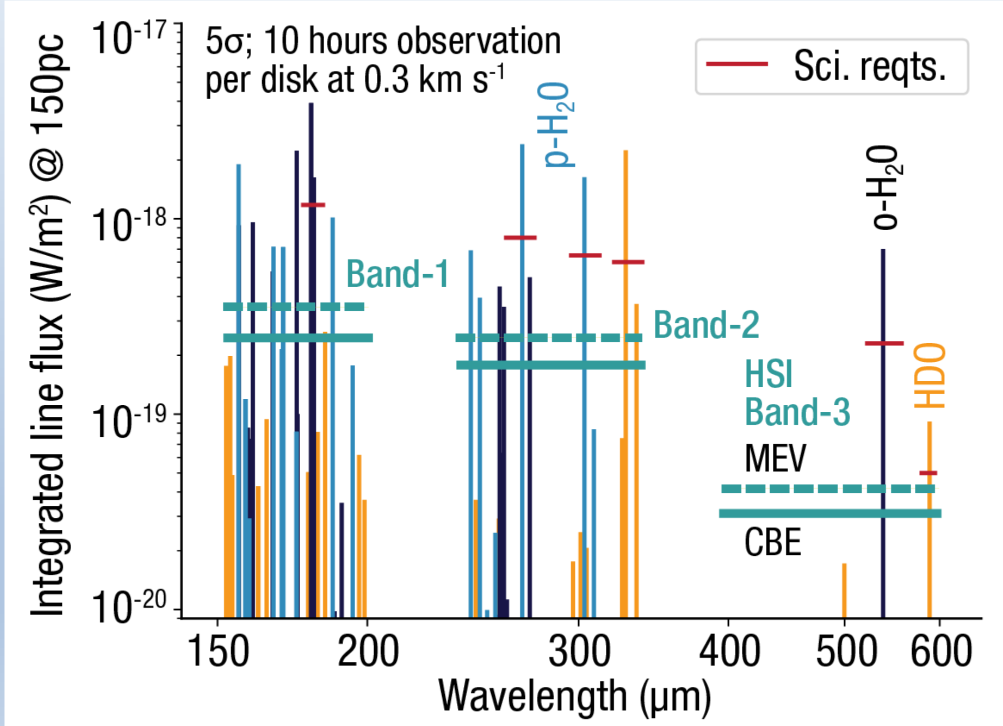


- A wide variety of water lines are available to FIRST HSI spectroscopy.
- These line and their ratios connect to formation conditions thereby constraining their origins.
- HSI will measure ortho-to-para and HDO/H2O ratios in 40 pre-stellar cores and 40 disks, thus completing the water trail.

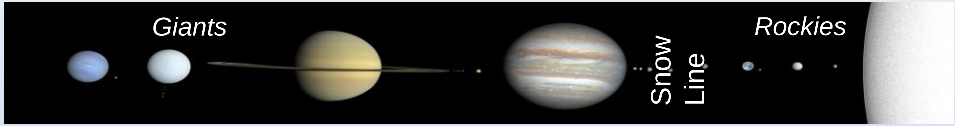
Many lines in HSI and they need to be velocity resolved

Infall in Pre-Stellar Core L1544 Herschel HIFI

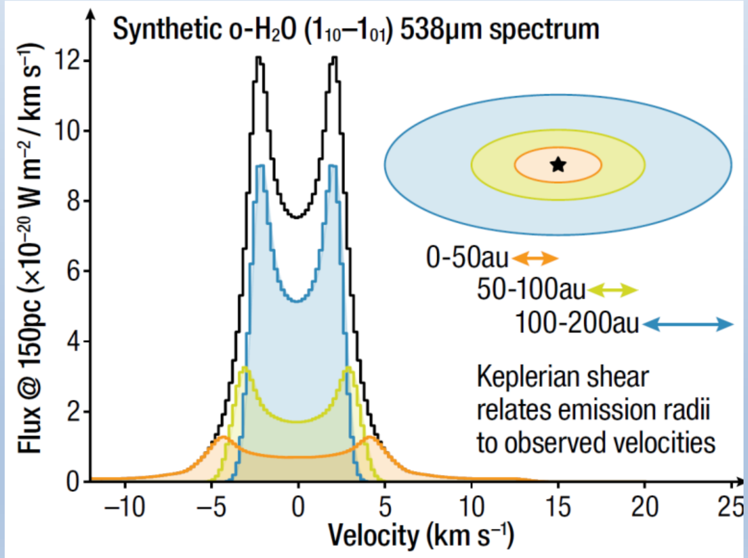


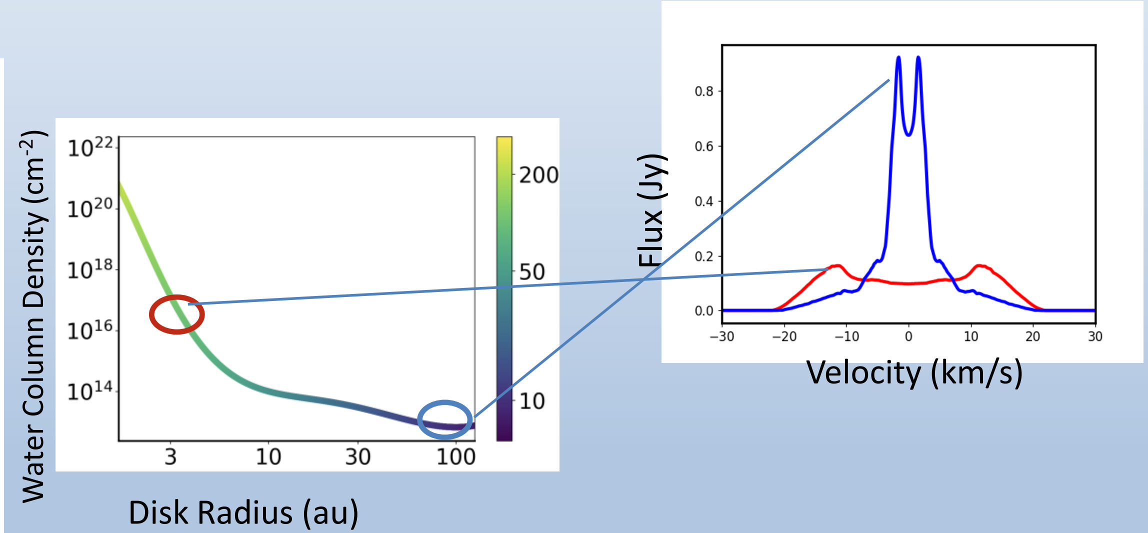


Water chemistry in pre-stellar cores and planet forming disks



FIR lines will locate radial water snowline



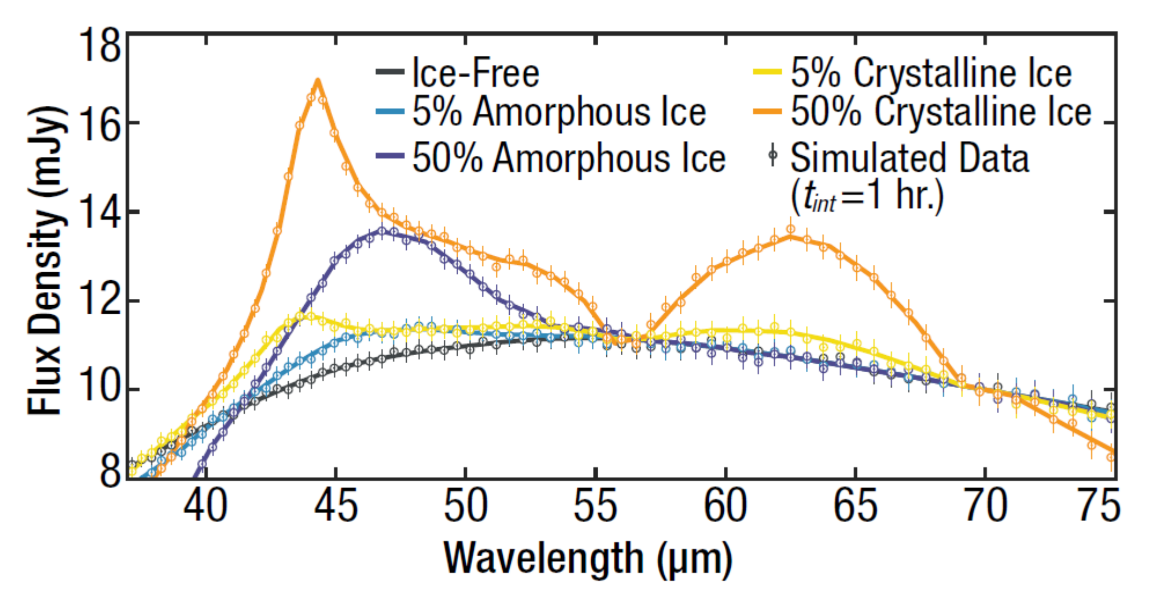


The variety of water lines map out the radial temperatures in the disk, the water mass, and the snow line

Water content for fully formed planets.

Objective: Determine the water content available for fully formed planets, measure the fraction of water ice mass to 5% in debris disks.

Measuring the water content available to (future) planets



Requirements: Spectral line sensitivity of 3×10^{-21} W m^{-2} to 43, 47 and 63 μm ice features at 5σ in 1hr at R (λ/Δλ) = 50

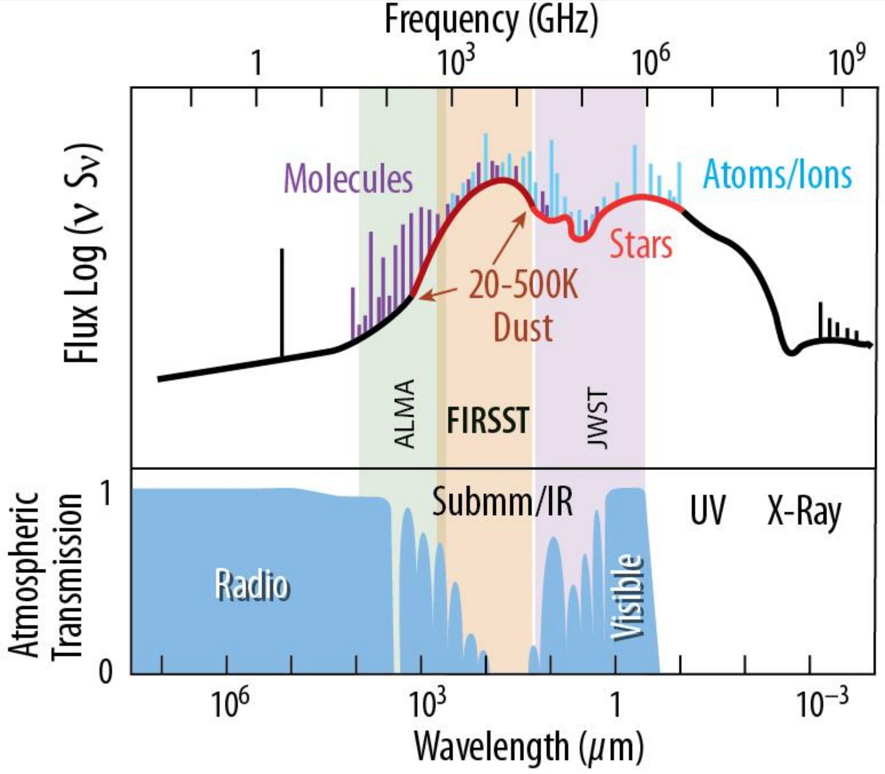
- **Objective:** To measure the water ice mass to 5% in debris disks
- **Observations:** Emission bands of amorphous and crystalline water ice in 40 debris disks around FGK (solar type) stars over 200 hours

Address how inner planets, including Earth, received water

Objective: To discover how the inner planets like the early received water by measuring the D/H ratio from comets.

Observations: Emission lines of H_2O and HDO for 10 comets over a range of heliocentric distances including both periodic and Oort cloud comets. Map D/H in the coma of 5 bright comets.

Unveiling the Drivers of Galaxy Growth

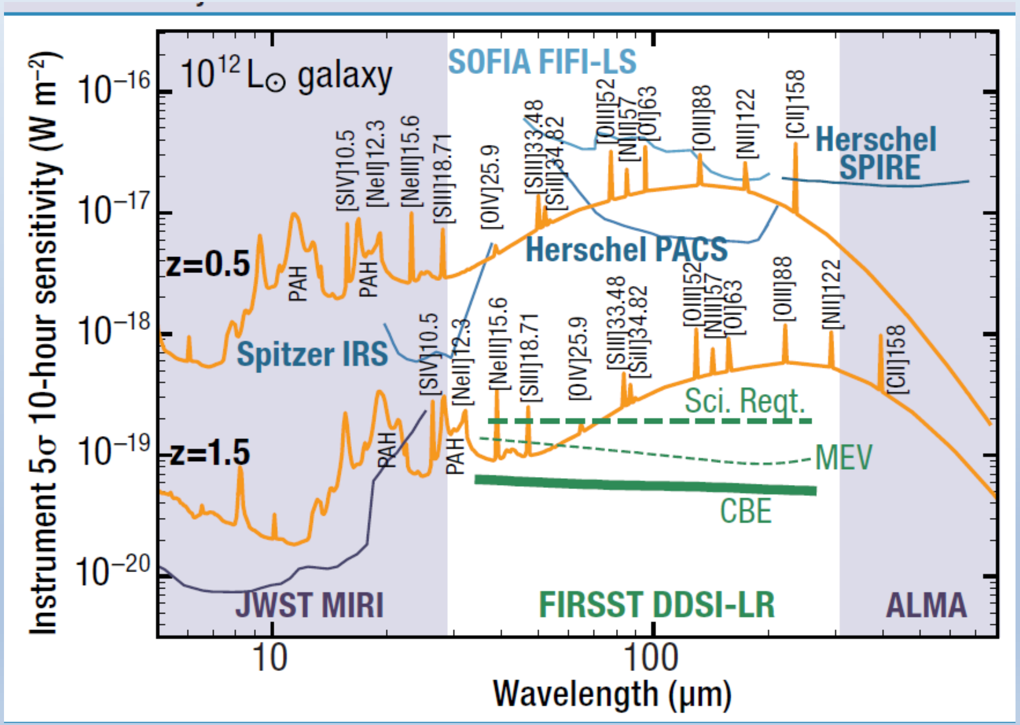


FIRSST bridges the crucial wavelength gap between ALMA and JWST.

FIRSST allows studies in the peak of the dust emission.

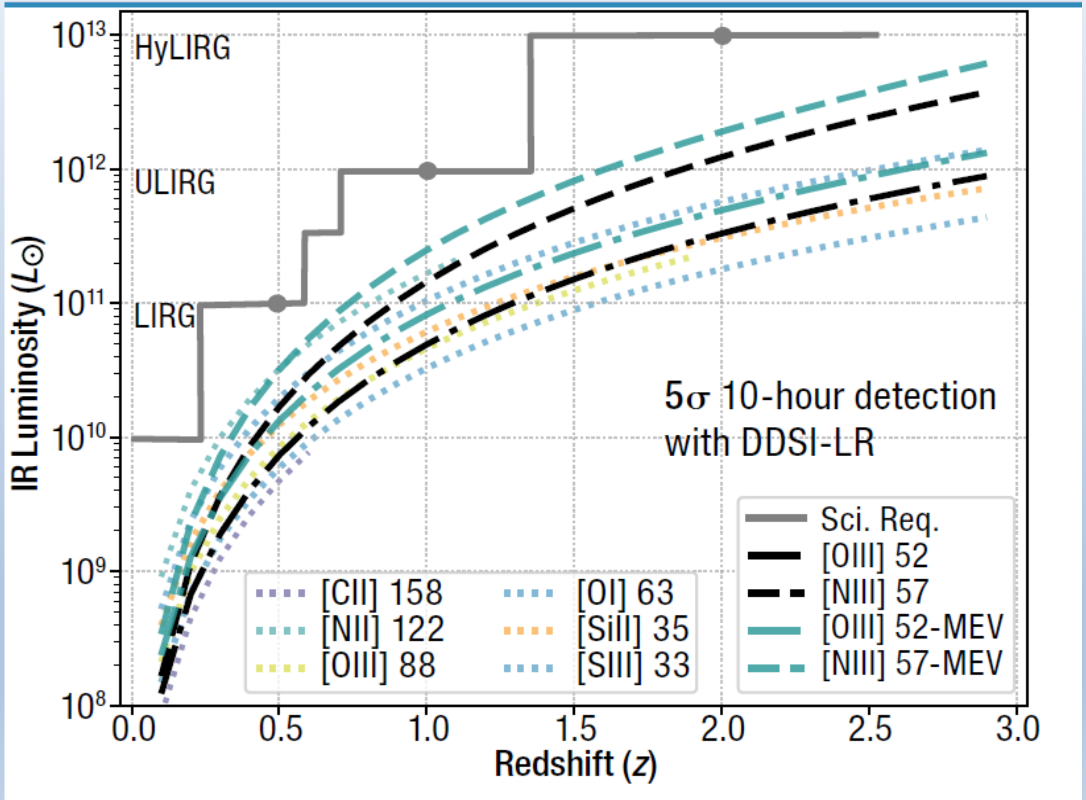
FIRSST captures emission from gas and dust heated by stars, shocks and and supermassive blackhole activity in galaxies through multiple atomic and molecular lines.

FIRSST compared with SOFIA FIFI-LS and Herschel PACS



- There are a very wide variety of lines available to the observer in the spectral regime covered by FIRRST DDSI
- They are tracers of ISM properties, which reflect the properties of the sources of heating and star formation histories

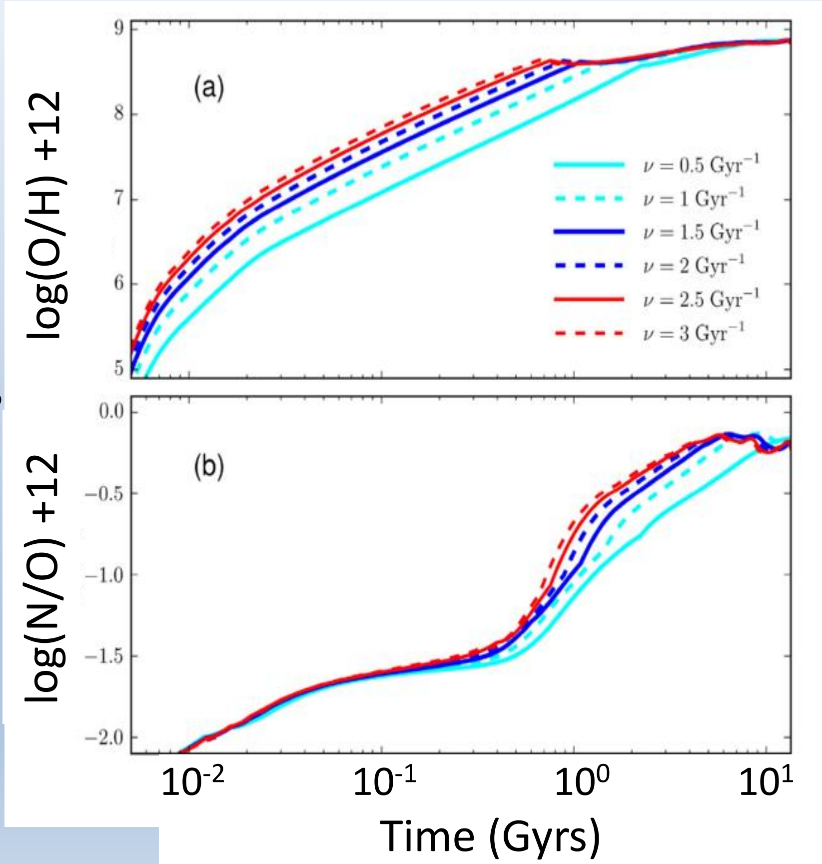
Star Formation at Cosmic Noon



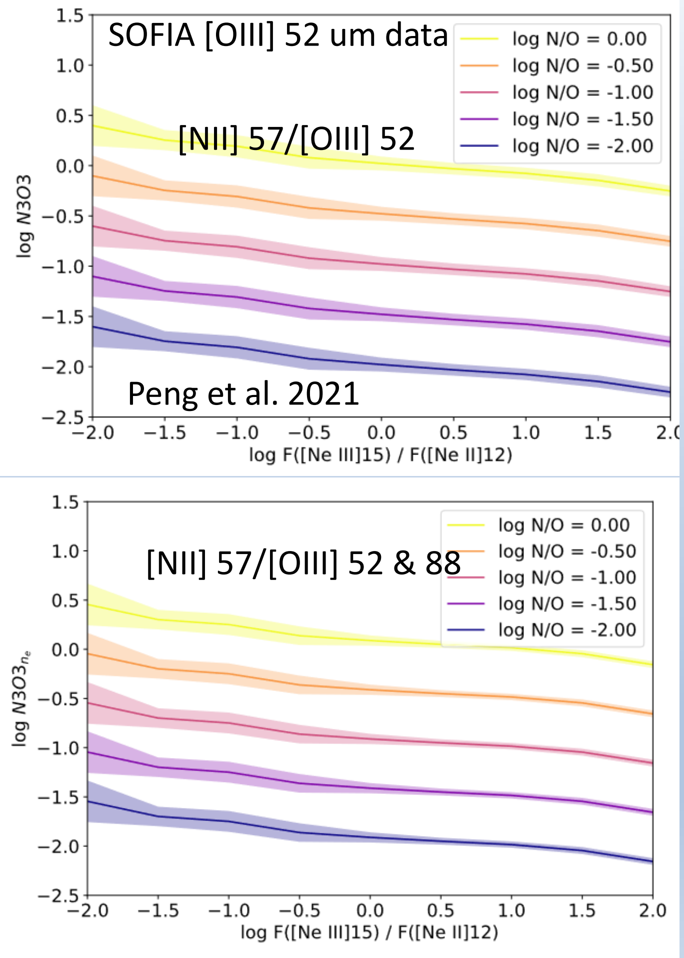
- The bread and butter will likely be the bright far-IR fine-structure lines
- All the bright fine-structure lines are detectable for reasonable luminosities up to redshifts approaching 3 and beyond

Measuring the Rise of Metals over Cosmic Noon

- Establish the numbers of generations of stars through the growth in metallicity via the steady growth of O/H
- However, one needs a hydrogen proxy, recombination lines??
- Not likely available… fortunately, N/O is also tightly coupled to O/H
- N/O grows steadily within a stellar population until the first mid-mass stars reach AGB stage
- Takes off, gives a handle on N/O hence age of stellar populations within synthesis models.

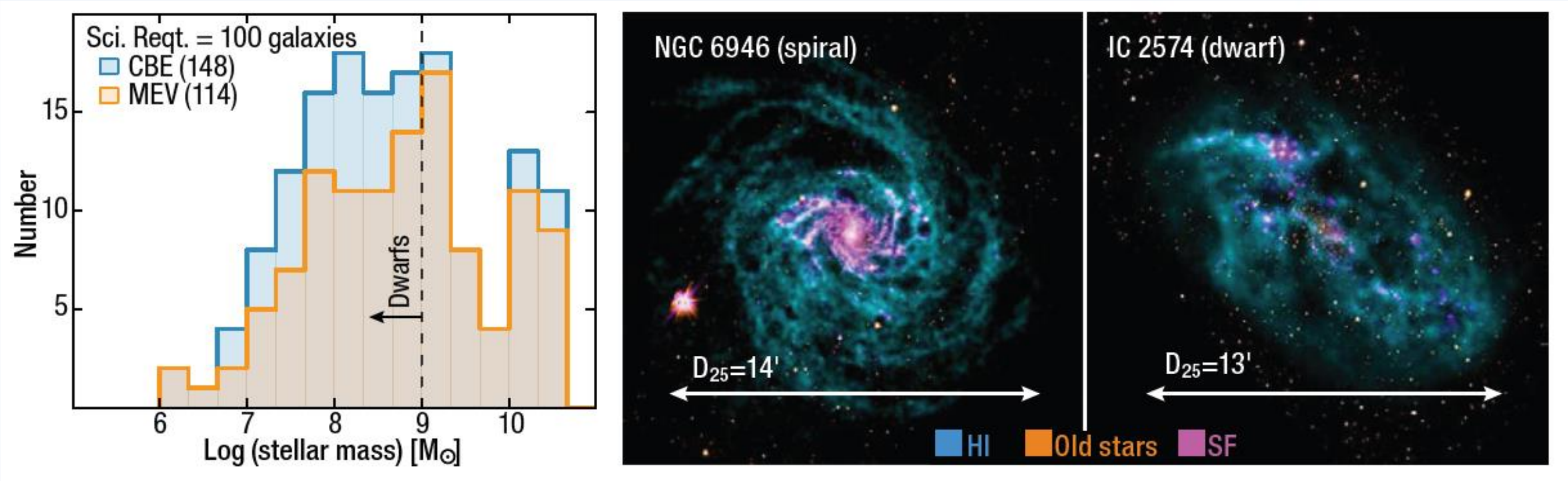


How to track the History of Star Formation in the FIR



- N/O reasonably well constrained with simple [NIII] 57/[OIII] 52 μm line ratio
- This ratio is dramatically improved by correcting for ionization [NeIII/[NeII] or [NIII] 57/[NII] 122 μm
- And improved further though addition of the [OIII] 88 μm line to correct for density
- Note that this line tool-set is available to nearly z = 4 with DDSI LR mode (35 to 260 μm)

Mapping nearby systems: CO dark gas

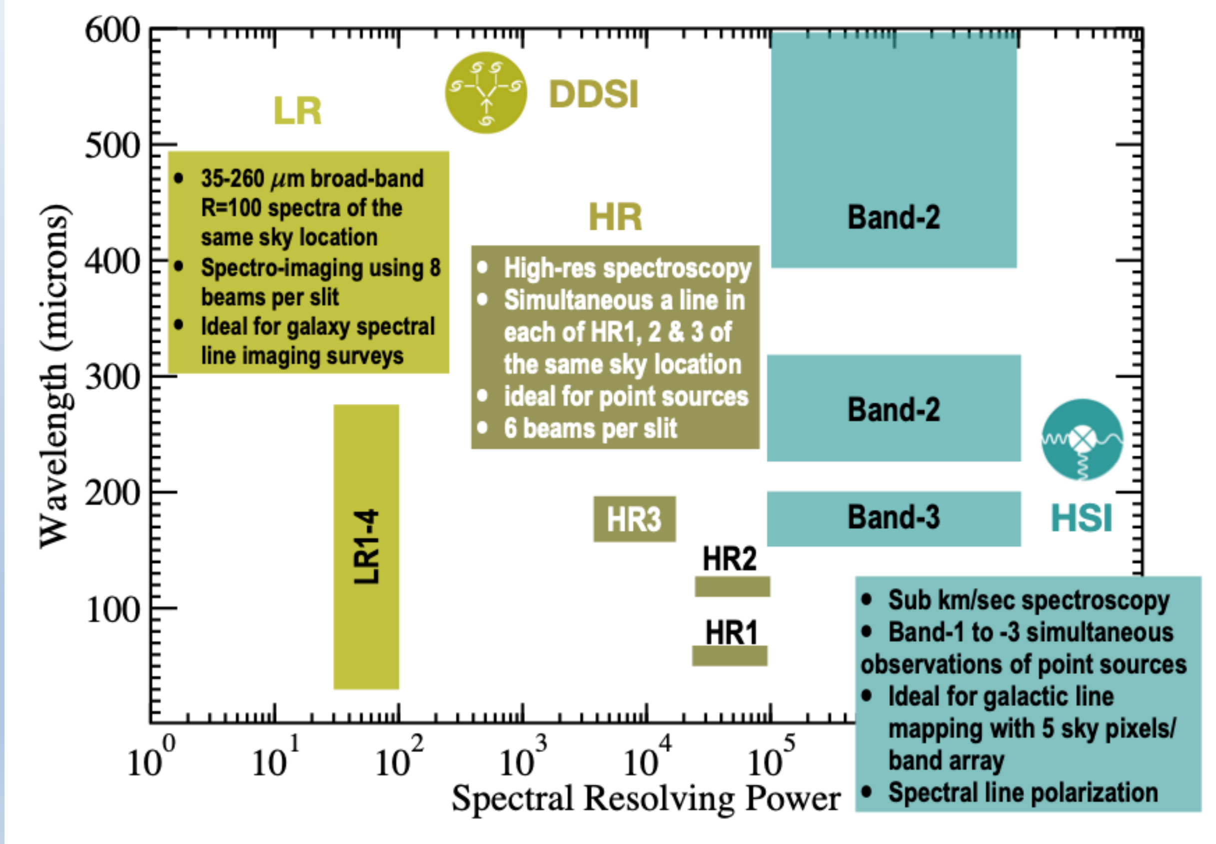


DDSI-HR can be used to map [CII], [NII], and [OI] at R ~ 20,000 to 100,000 to:

1. Reveal the currently missing CO-dark gas in galaxies,
2. Identify the phase transition between HI and H_2, and
3. Establish the CNM to WNM transitions

- CBE sensitivity allows all 148 NGC galaxies within 11Mpc to be studied.
- Science requirement calls for 100 galaxies.

Instruments Optimized for Diverse Science



Unique features of FIRSST

Enclosed architecture ensures thermal stability, minimizes stray backgrounds and other systematics.

Instantaneous field of regard is greater than half of the sky (~54%) allowing responsive observations to a large number of time sensitive targets, thus enabling time domain astronomy in the far-infrared. Full sky coverage in every six months.

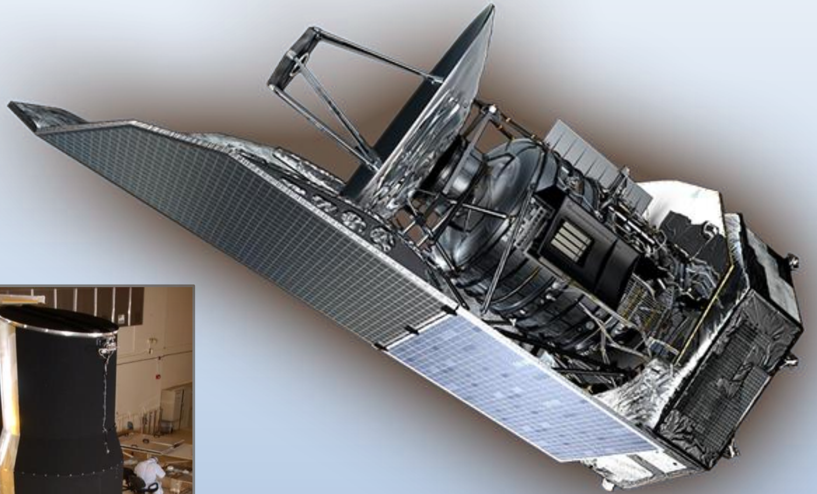
An agile observatory with minimum slew/settle times between targets.

Science observing efficiency > 90%. Rapid response time < 48 hrs. Mission lifetime >= 5 years.

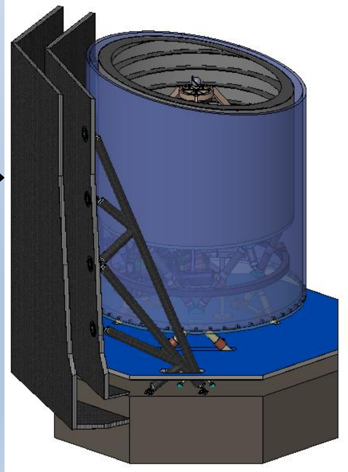
FIRSST Design: Enclosed Architecture has Heritage

kepler

Spitzer



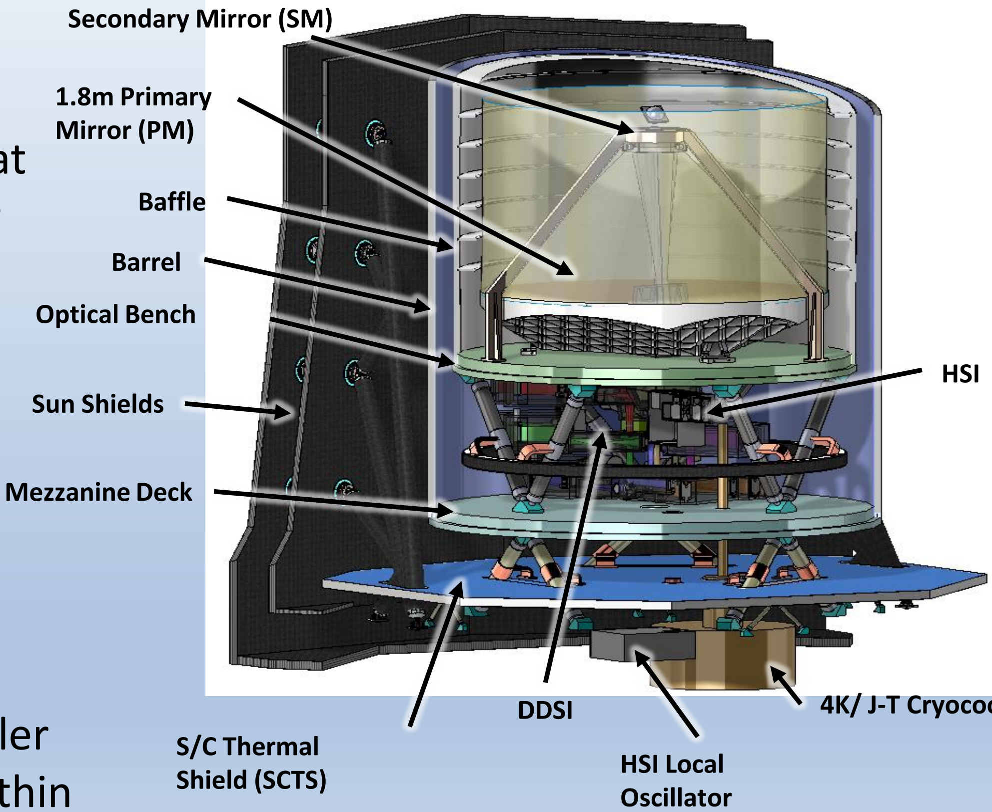
Herschel



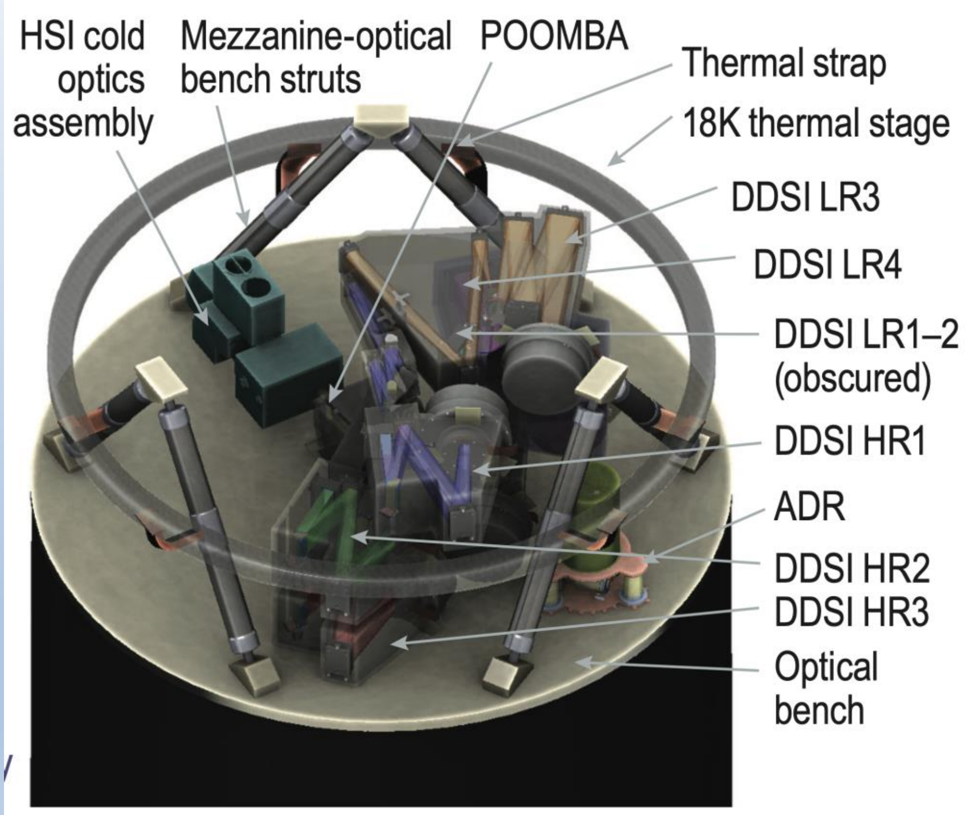
FIRSST

FIRSST Major Elements

- **Payload has 3 major elements:**
  - **Optomechanical system**
    - 1.8 meter on-axis 3-mirror anastigmat
    - POOMBA: Pick-Off Optics and Mirror Beam-steering Assembly
  - **Thermal Control System including**
    - 4K / J-T Cryocooler
    - ADR (GSFC)
    - Sun & thermal Shields, radiator,
    - **Instruments**
    - **DDSI:** 4 LR and 3 HR spectrometers
    - **HSI:** 3 bands
    - Payload Control Electronics, Cryocooler and instrument electronics are all within the SC bus



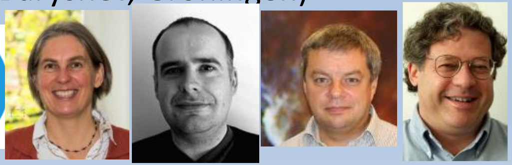
Science Implementation: Instruments



DDSI (Direct Detection Spectroscopy Instrument; Ball Instrument Lab; Instrument PI: Gordon Stacey, Cornell; DPI: Karwan Rostem, GSFC)

(follows Spitzer/IRS model, Ball instrument with a Cornell PI)

HSI (Heterodyne Spectroscopy Instrument; Integration & Testing at SAO; Instrument PI: Martina Weidner, Obs. de Paris; US DPI: Paul Grimes, SAO; EU DPI: Andrey Baryshev, Groningen)



(HSI consortium in Europe builds upon HIFI partnerships)

Science Implementation: DDSI

DDSI PARAMETERS

PARAMETER		BAND LR1	LR2	LR3	LR4	HR1	HR2	HR3
Wavelength (μm)	Begin λ End λ	35 58	58 95	95 158	157 260	56.206 64.027	112.029 123.520	157.355 184.727
Beam size (arcsec)	@ Begin λ @ End λ	5.0 7.9	8.0 13.1	13.0 21.7	22.0 35.8	8.0 9.0	15.0 16.0	24.0 25.0
Instantaneous FoV		92.6″×13.1″		252.5″×35.8″		52″×9″	99″×16″	152″×25″
Resolving power (λ/Δλ)		100				89,000	100,000	20,000
Dispersive element		First-order grating				VIPA with immersion grating cross-disperser		
Per band array size (spec × spat)		49×8 (hexagonal packing)				58×6 (hexagonal packing)		
F/#	Spectral Spatial	12.90 12.90	7.83 7.83	6.85 6.85	4.15 4.15	12.3 14.2	6.5 8.0	3.5 5.0
Spectral sampling (pixel pitch/F· λ)		~1.5 at center wavelength of each band						
Radiometric throughput		35%				25%		
Pixel NEP (W/√Hz) @ 2Hz		2.0×10^{-19} (CBE); 3.0×10^{-19} (MEV); 3.4×10^{-19} (science reqt.)						
Pixel yield per array		85% (CBE); 80% (MEV); 80% (science reqt.)						
Thermal background power (W)		$<7\times10^{-18}$				0.1×10^{-18}		
MEV radiant power per pixel (W)		50×10^{-18}				6×10^{-18}	4×10^{-18}	7×10^{-18}
Optics bench temperature		4.7K with ±0.1K stability during DDSI operation						
VIPA temperature		<5K (CBE); <10K (MEV, science reqt.) with ±0.1K stability						
MKID temperature		120mK (CBE); 130mK (MEV, science reqt.) with ±1mK stability						
rms WFE budget (nm)	Requirement Allocated Margin	<1400 528 165%				<1400 571 145%		

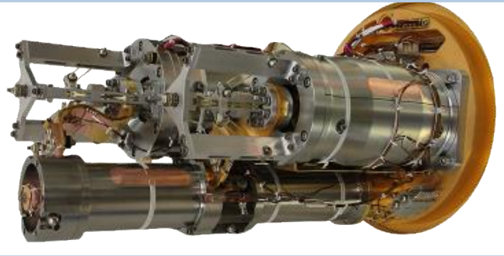
DDSI OPTICAL EFFICIENCIES

ELEMENT	LR (PER BAND) [#]	LR (PER BAND) η	HR (PER BAND) [#]	HR (PER BAND) η
Mirrors (PM to FPA)	15	0.98	13	0.98
Dichroics	2	0.90	2	0.90
Slits	1	0.80	1	0.80
VIPA	–	–	1	0.70
Grating	1	0.90	–	–
Cross-disperser	–	–	1	0.70
Metal-mesh filters	4	0.95	4	0.95

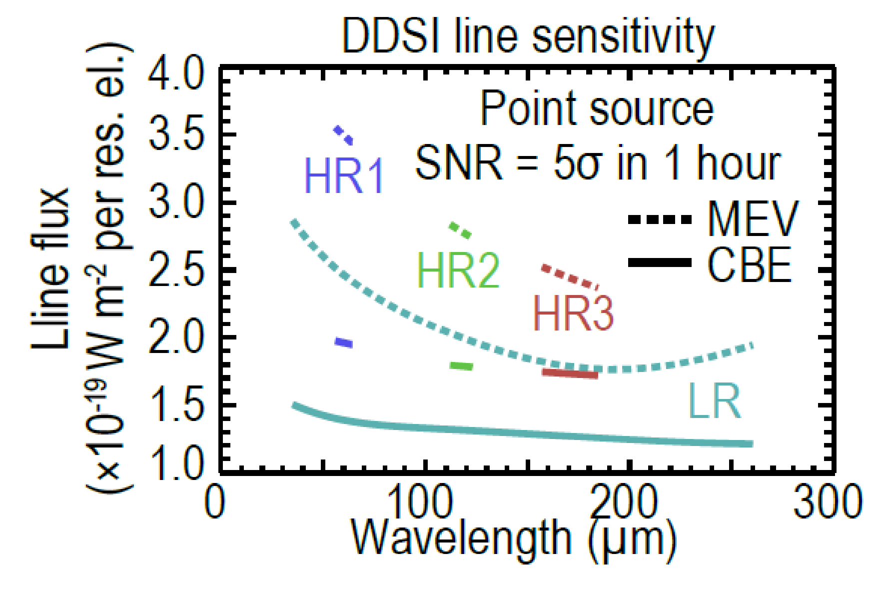
DDSI SENSITIVITY CALCULATIONS

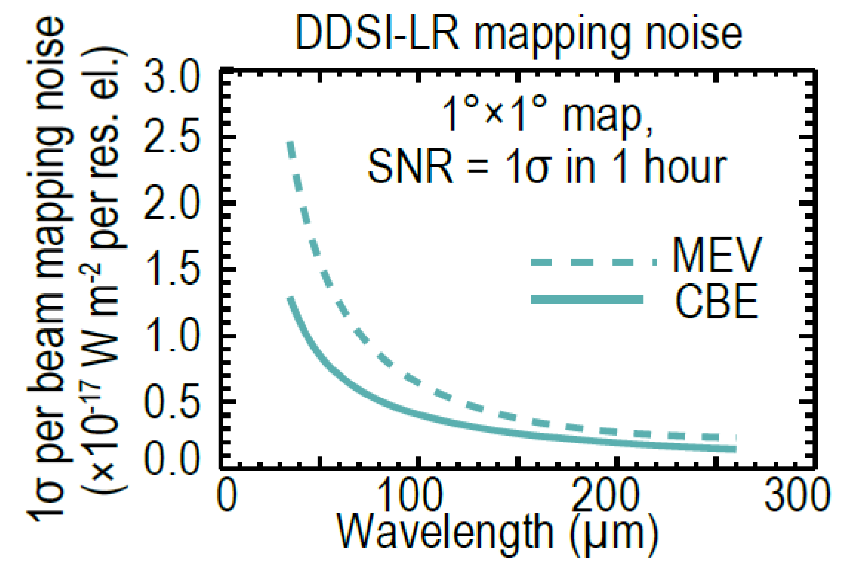
DDSI is detector noise-dominated (negligible photon noise) for telescope temperature (CBE 4.7K) and emissivity (2%): NEF = $NEP_{detector} / (A_{tel}\, \eta_{opt}\, \eta_{det}\, \eta_{mod})$		LR	HR
A_{tel}	Telescope collecting area (m^2)	2.47	
η_{det}	PSF to absorbed power at detector ef ciency	0.4	
η_{mod}	Optical modulation ef ciency	0.71	
η_{opt}	Total optical transmission ef ciency	0.35	0.25

Sub-K ADR
Heritage: Hitomi/XRISM

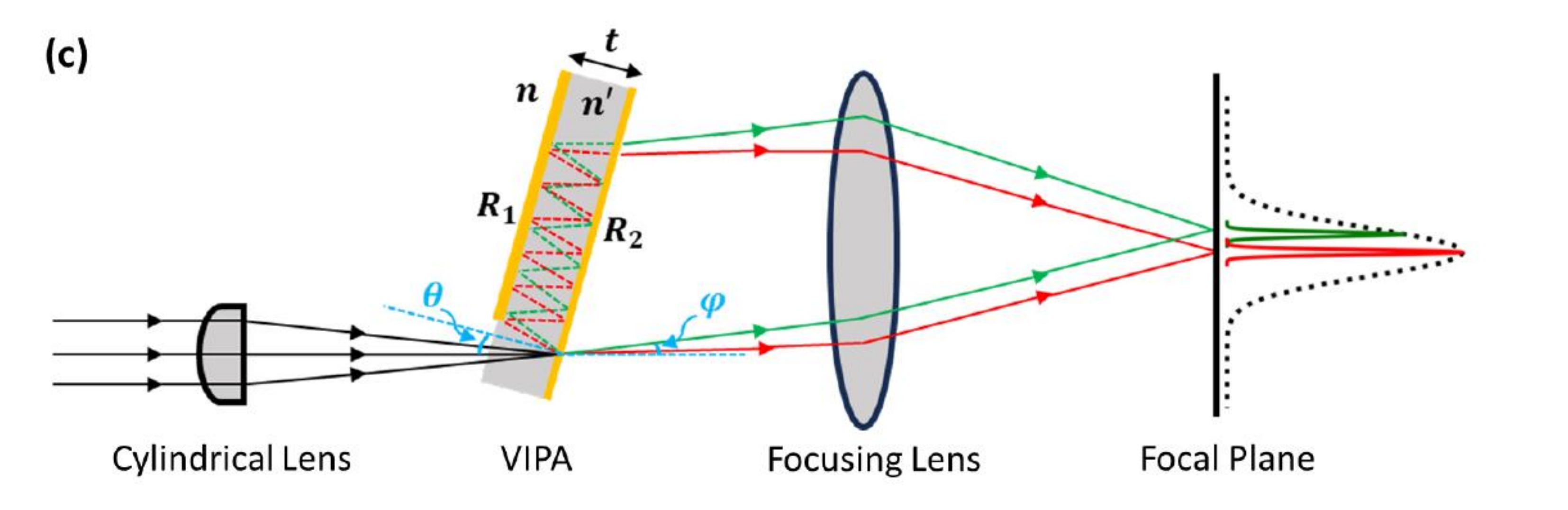


Sensitivity Maximum Expected Value and Current Best Estimates





Virtually Imaged Phased Array
VIPA: A Marvelous Device

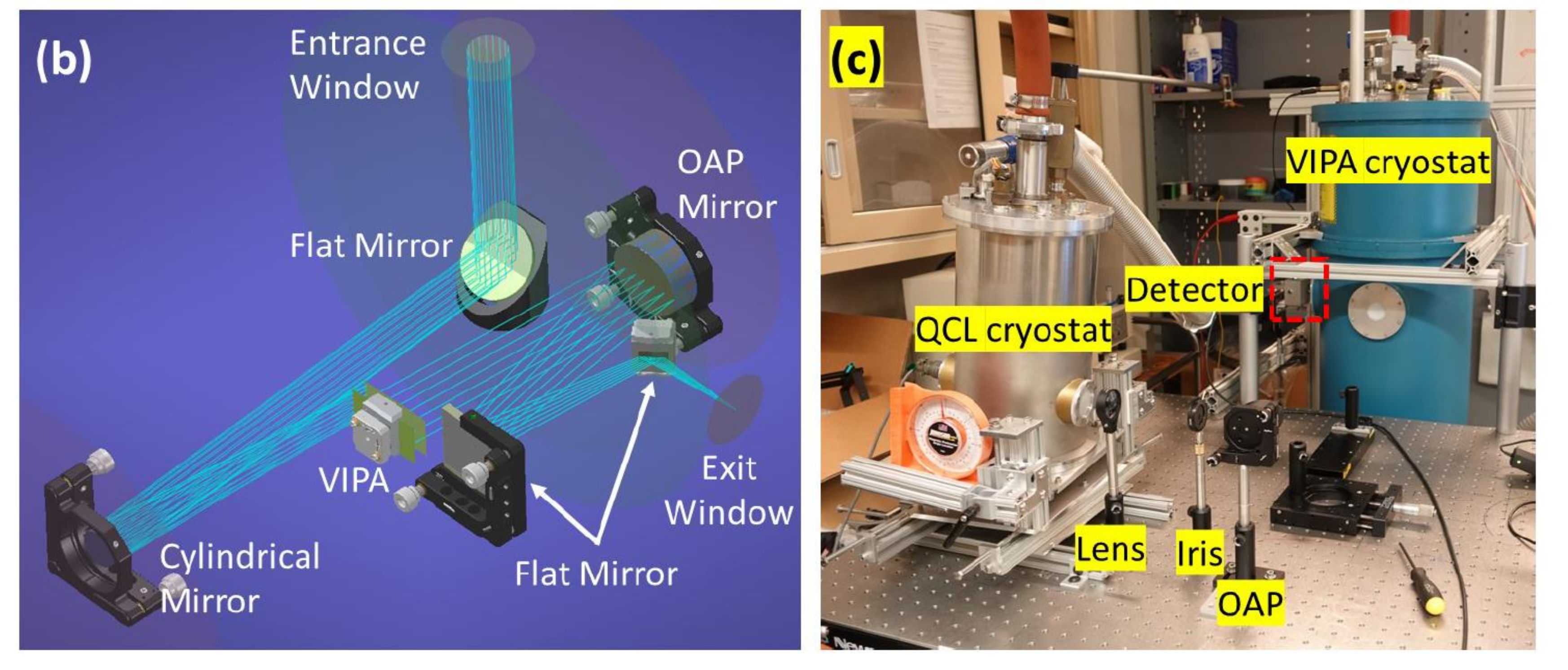


Silicon for 112 μm HD line is 3 cm thick, 3 cm wide × 9 cm long for RP ~ 100,000!

Yields a free spectral range of spectral samples (n ~ 70)

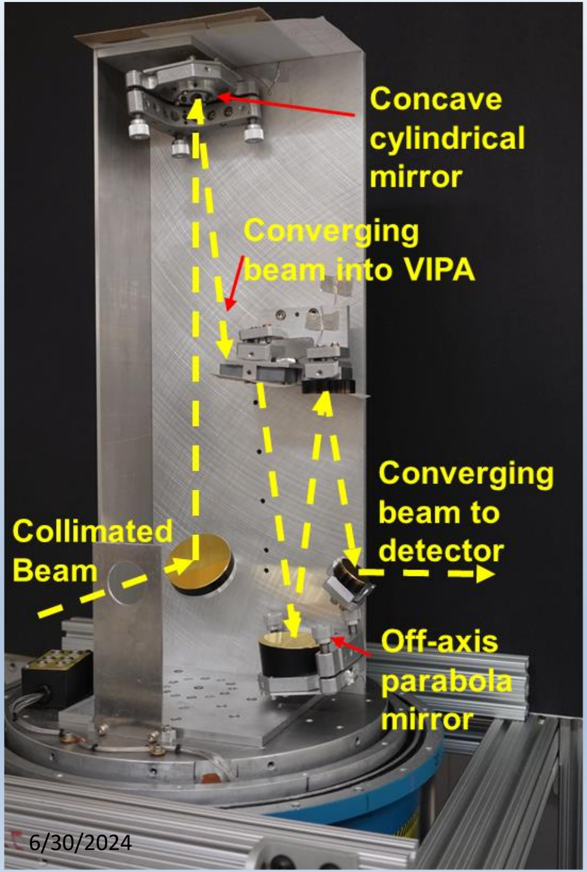
FIRSST VIPA's will have 58 spectral resolution elements sampled over 6 spatial beams ***with no moving parts***.

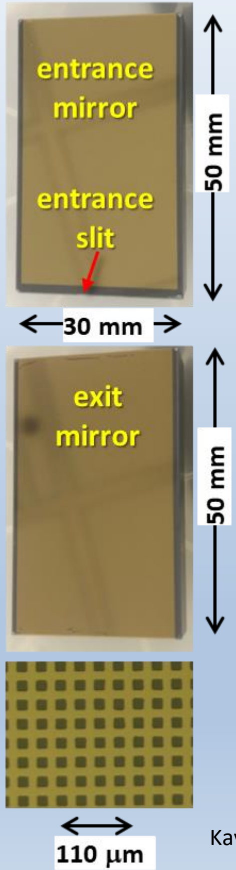
The Lab Settup



NASA ADAP Grants: NNX16AC72G and 80NSSC24K0041

VIPA Demonstration at 115 μm





RP ~ 14,500 (26 K),
RP ~ 16,500 (4 K)

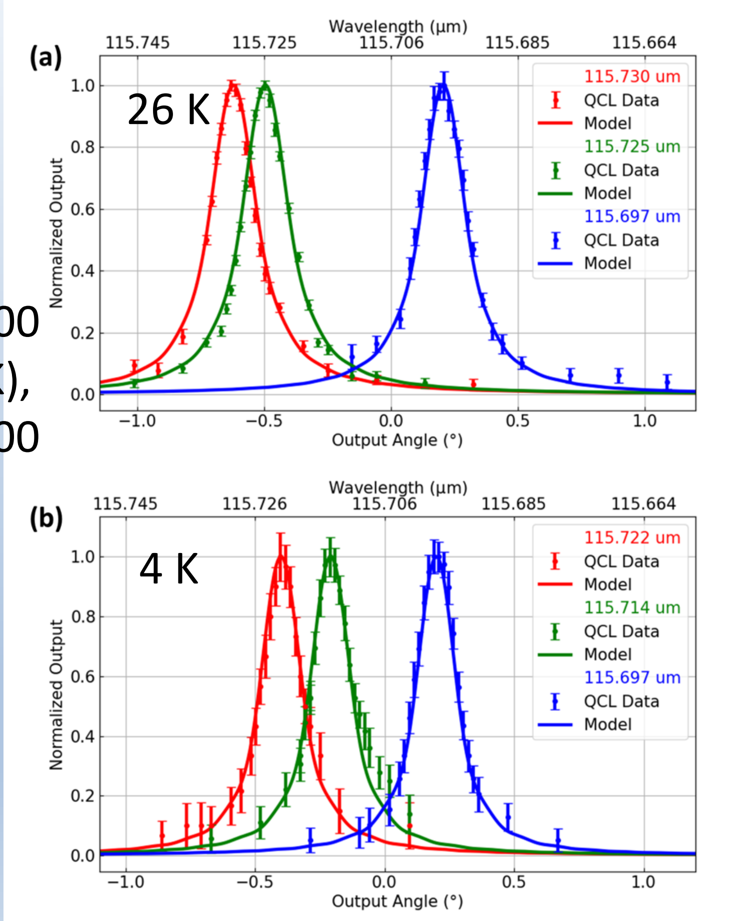
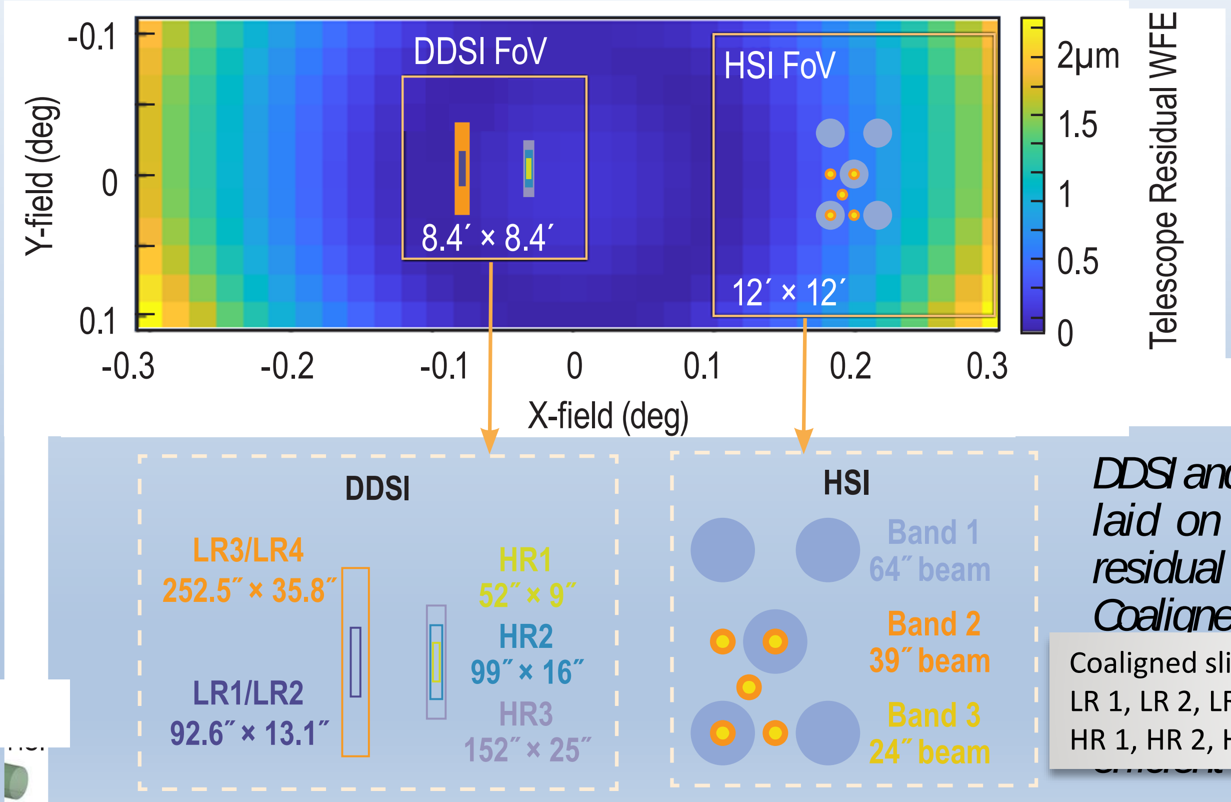
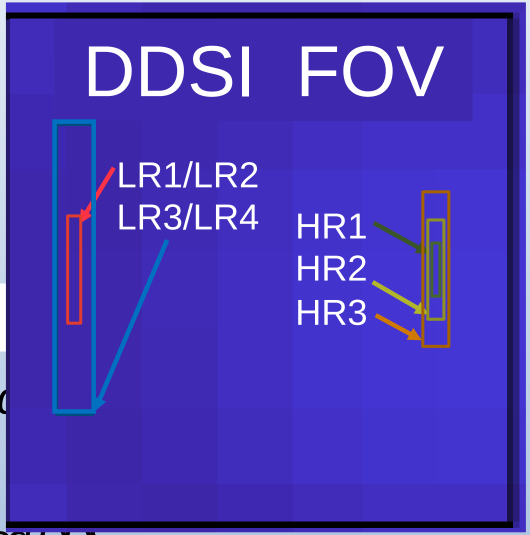


Image Plane



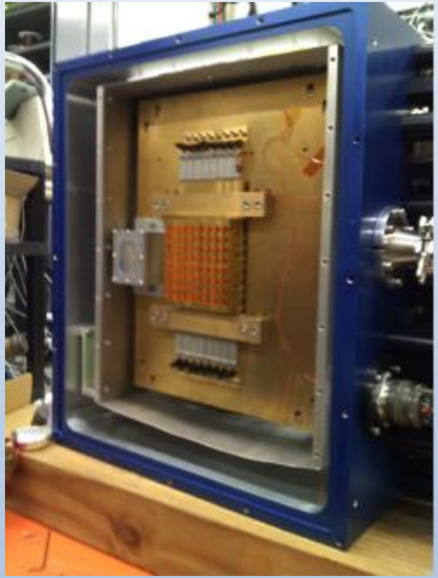


DDSI and
laid on
residual
Coaligned DDS

Coaligned slits allow efficient use of observatory time
LR 1, LR 2, LR 3, LR 4: simultaneous observations
HR 1, HR 2, HR 3: simultaneous observations

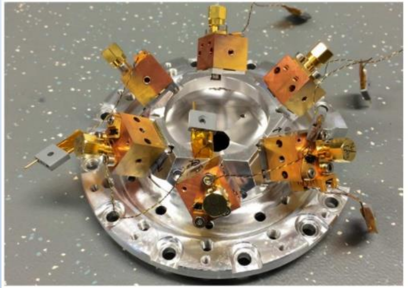
Heritage For Heterodyne Array Receivers

Ground Based Instruments

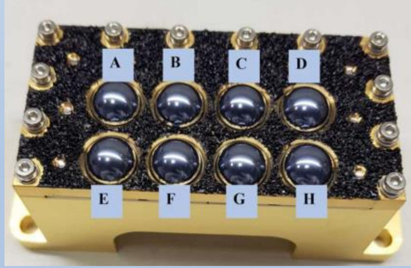


SuperCam 8 x 8 pixels, far-IR
X 8000, Uni. of Arizona, USA

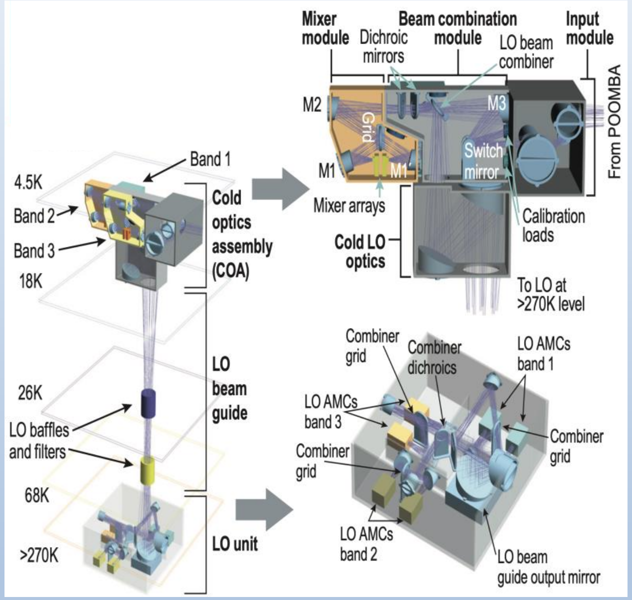
Airplane/ Balloon



up-GREAT/SOFIA (Germany)

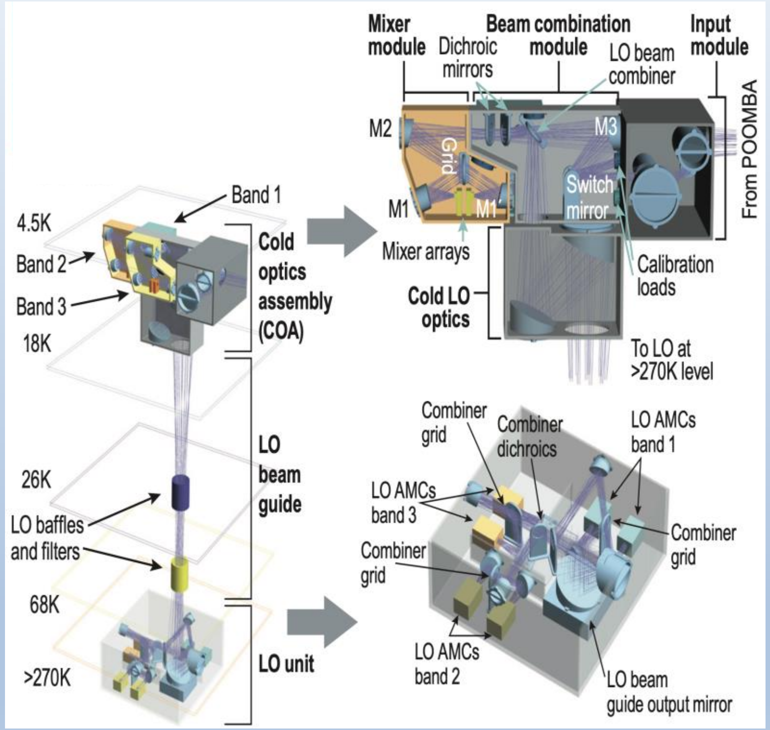


GUSTO (SRON, Netherlands)



FIRSST/HSI, 30 pixels total
5 pixels in each dual-pol per band

The Heterodyne Receiver (HSI)



FIRSST/HSI, 15 beams on sky

5 pixels in each dual-pol per band

HSI OPTICAL EFFICIENCIES		
ELEMENT	[#]	η
Mirrors (POOMBA to FPA)	8	0.997
Dichroics	2	0.97
Polarizing grid	1	0.99
Mixer feeds	1	0.99
Coupling of receiver to telescope (11dB edge taper)	1	0.81

HSI SENSITIVITY CALCULATIONS

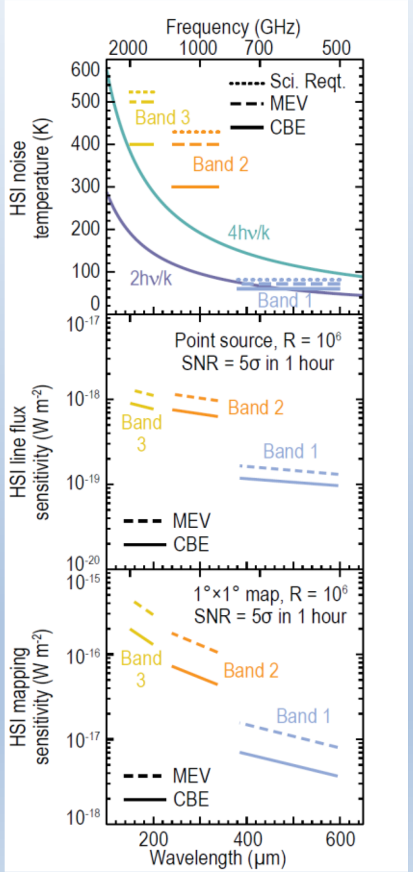
HSI is receiver/quantum noise-dominated; noise temperature (in K) given by:

Point source: $T_{rms}=2\,(1/\eta_{tel})\,T_{Rx}/\sqrt{\Delta t \cdot \Delta\nu}$

Mapping: $T_{rms}=(2/\sqrt{n_{pix}})(1/\eta_{tel})\,T_{Rx}/\sqrt{(\Delta t_{on\text{-}source}/n_{beam})\,\Delta\nu}$

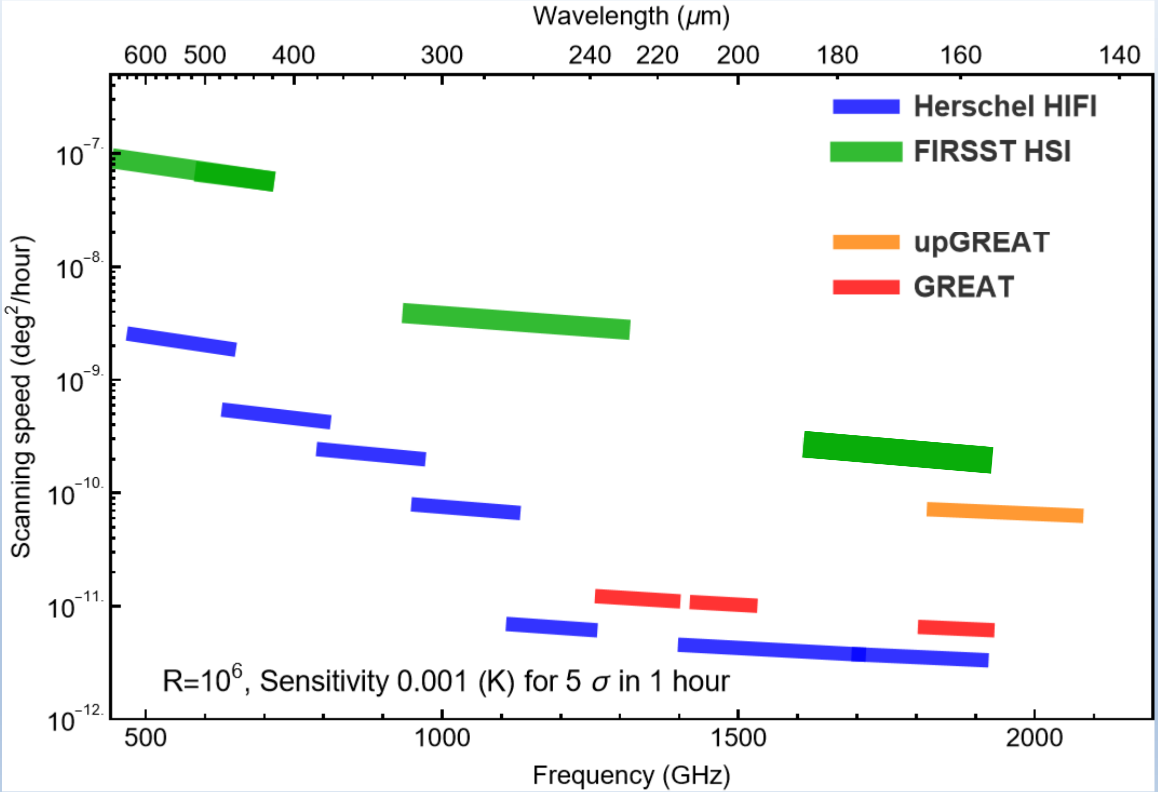
Conversion to flux (W m^{-2}) given by $\sigma=k\,T_{rms}\,\Delta\nu/A_{tel}$

		BAND		
		1	2	3
T_{Rx}	Receiver noise temp. (K) (CBE)	60	300	400
A_{tel}	Telescope collecting area (m^2)	2.47		
η_{tel}	Coupling efficiency (varies slightly w/source size)	0.8		
n_{pix}	Number of pixels in array	5		
n_{beam}	Number of Nyquist sampled beams in 1°×1° map	$\left(\frac{1°}{\text{beam size}/2}\right)$		



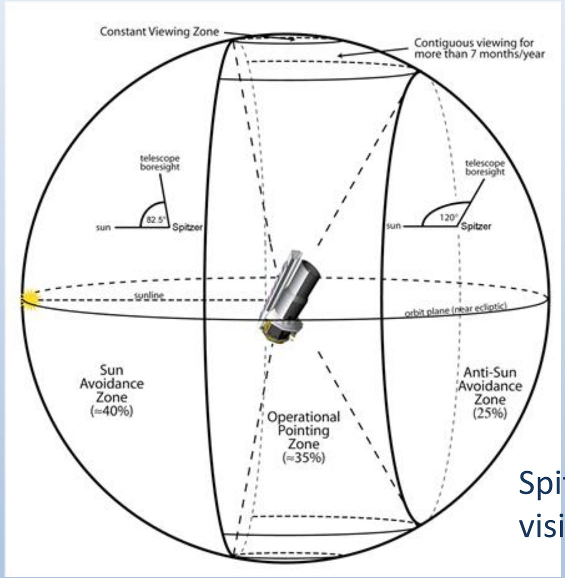
Science Implementation: HSI

Better

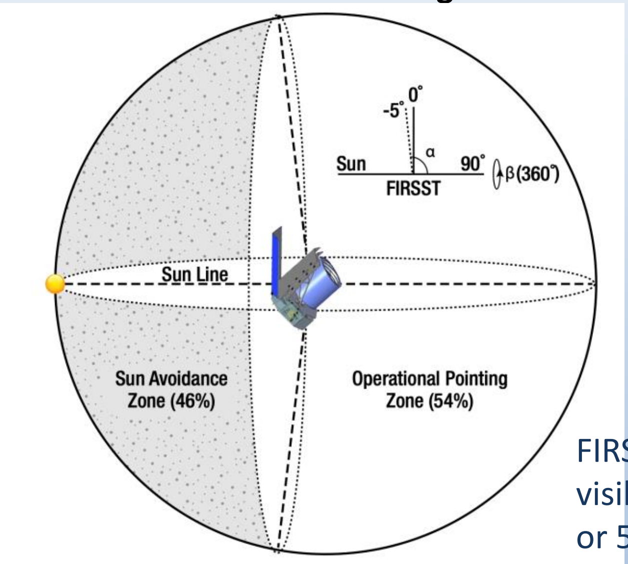


GO Program Example: Enabling Time Domain Astronomy

Time domain astronomy enabled by the large field of regard and the flexible scheduling of observations.



Spitzer instantaneous visibility: 35% of the sky



FIRSST instantaneous visibility: 54% of the sky or 50% more than Spitzer

An observatory with an anti-sunward keep-out zone (e.g., Spitzer shown above) is limited to an annulus of observable targets.
It must wait for most transients to move into its field.

FIRSST maximizes sky coverage and minimizes response time to enable the widest possible variety of time-domain observations.

Unique features of FIRSST for a successful GO program

- **A mission with a focus on far-IR spectroscopy,** but enables efficient wide area spectral line maps and surveys.
- **Enclosed architecture** ensures thermal stability, minimizes stray backgrounds and other systematics.
- **Instantaneous field of regard is greater than half of the sky (~54%)** enabling time domain astronomy in the far-infrared. Full sky coverage in every six months.
- **Co-aligned on the sky multi-band/multi-channel pixels/slits**, allowing simultaneous observations across the full range of wavelength of each instrument.
- **An agile observatory** with minimum slew/settle times between targets. Science observing efficiency > 90%.
- **Responsive to science needs of 2030s**, including unanticipated applications.

Thank you for your attention!