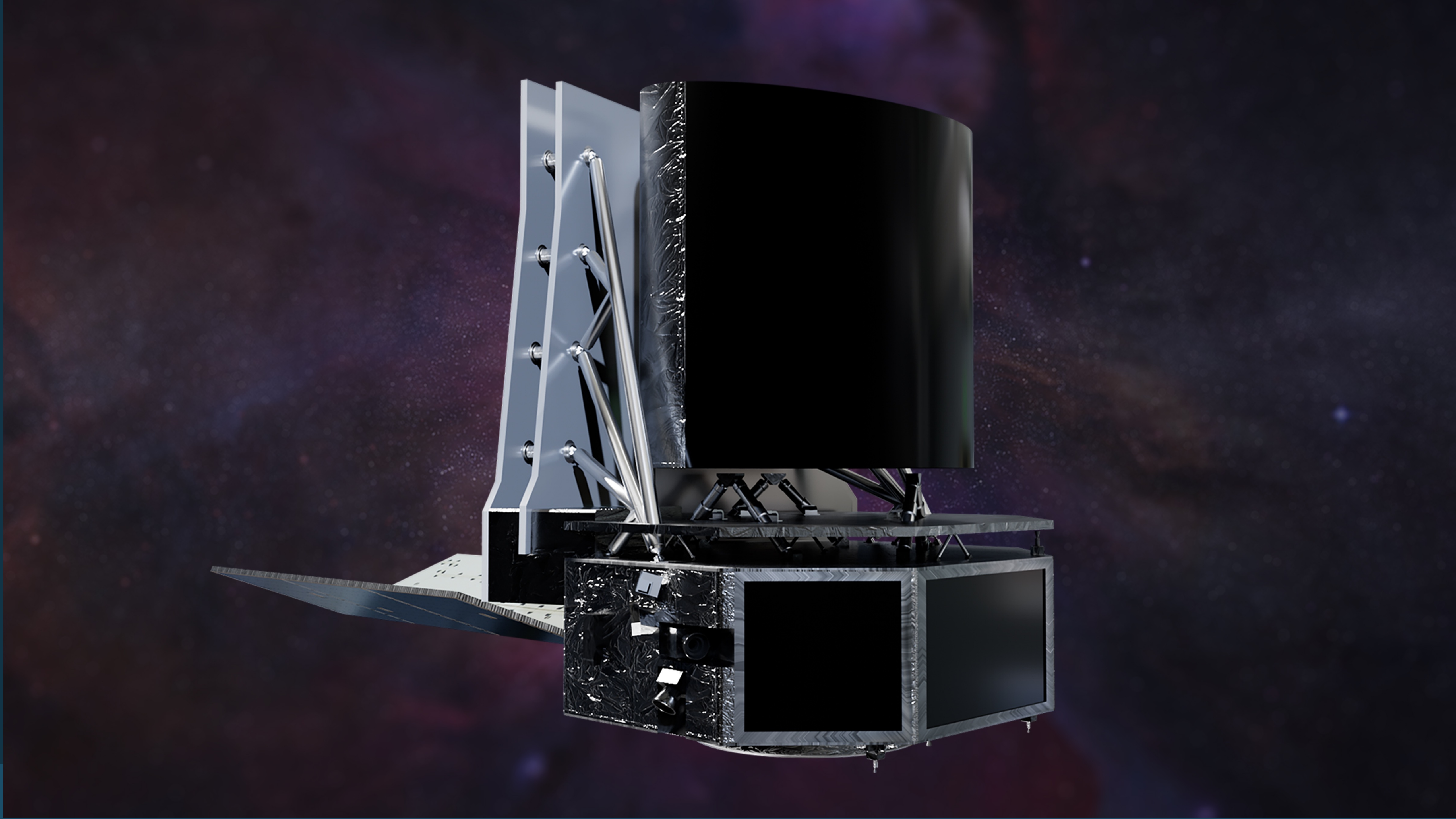
FIRSST: Far-Infrared Spectroscopy Space Telescope

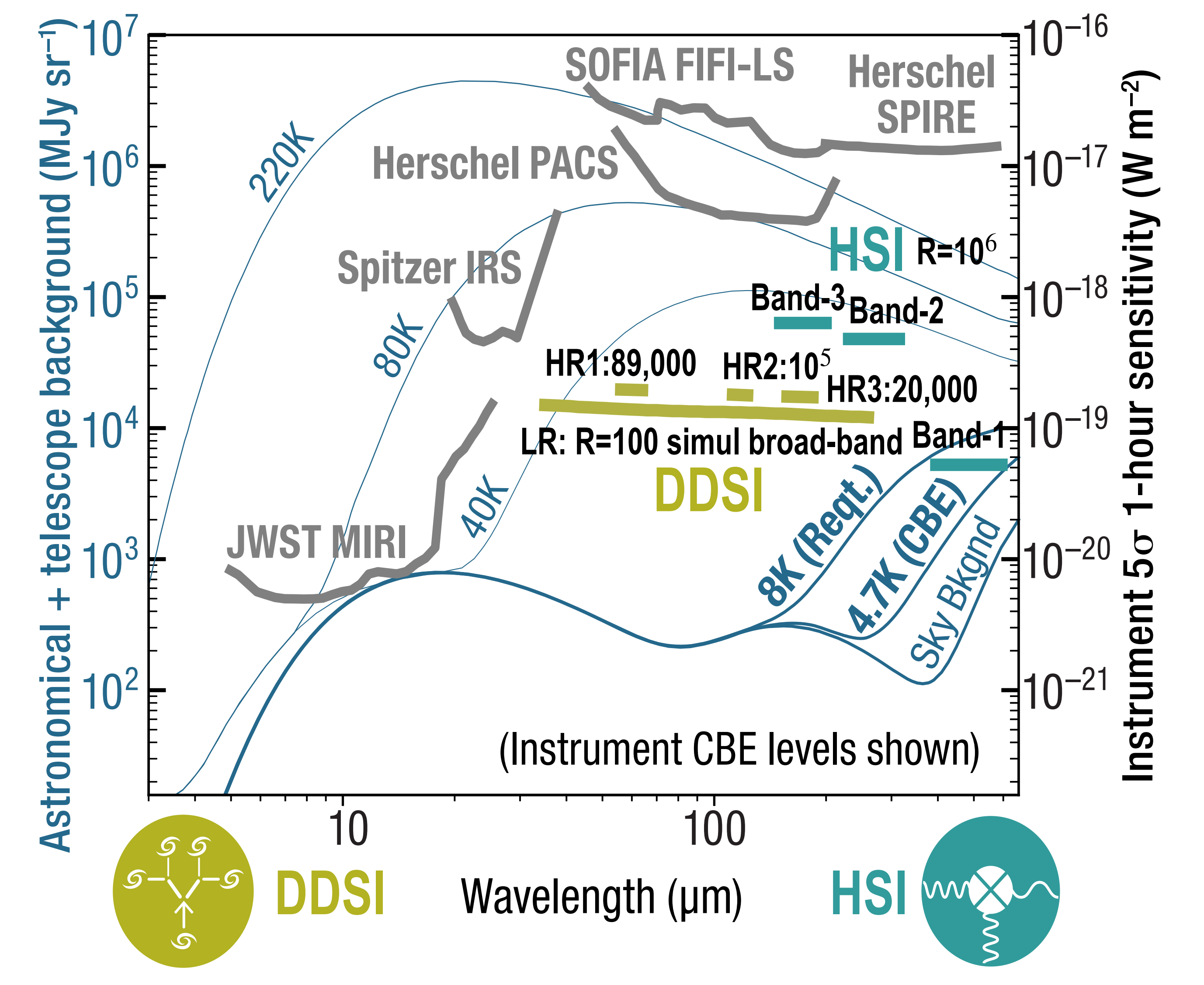
Asantha Cooray
Principal Investigator
University of California, Irvine
acooray@uci.edu



FIRSST at a Glance

- **Low-risk, Spitzer-like closed architecture with a 1.8m primary aperture, actively cooled to < 8K (Reqt; CBE ~ 4.7K)**
- **Two instruments dedicated for spectroscopy and spectro-imaging:**
  - DDSI (direct detection spectroscopy instrument)
    - Low resolving power (R=100) broad-band ~35-260μm simultaneous in 4 channels
    - Medium resolving power (R=20,000) in 156-180 μm (CII 157/H2O 180) in one channel
    - High resolving power (R=89,000-100,000) two channels with 10% BW (HD 112/OH 119; HD 56/OI 63)
    - Low resolution spectral mapping mode allowing spectral imaging surveys
    - High-resolution optimized for planet formation science objectives
  - HSI (heterodyne spectroscopy instrument)
    - Three-bands
    - Five-pixel x dual-polarization arrays per band, allow mapping and $R=10^6$-10^7 (<1 km/sec) spectroscopy
    - Optimized for water pathways
- **Five-year science mission operations: 25% PI-led & 75% GO science programs.**
- **$1B-class NASA science mission heritage at APL, delivered within budget.**
- **Substantial heritage designing, assembling, and delivering infrared space telescopes and IR instruments at Ball, with oversight from university PIs.**
- **Science Operations Center/Guest Observer Facility at IPAC.**

FIRSST at a Glance



- Observing time is proportional to the square of the sensitivity.
- At 4.7K and 1.8m FIRSST/DDSI is1600 (MEV) – 3600 (CBE) times faster than Herschel/PACS instrument.
- FIRSST opens up a deep discovery space beyond all prior far-infrared missions.
- *With a large sensitivity gain, it is guaranteed that any observation will lead to a new scientific discovery.*

FIRSST Highlights

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. – detailed in this talk.

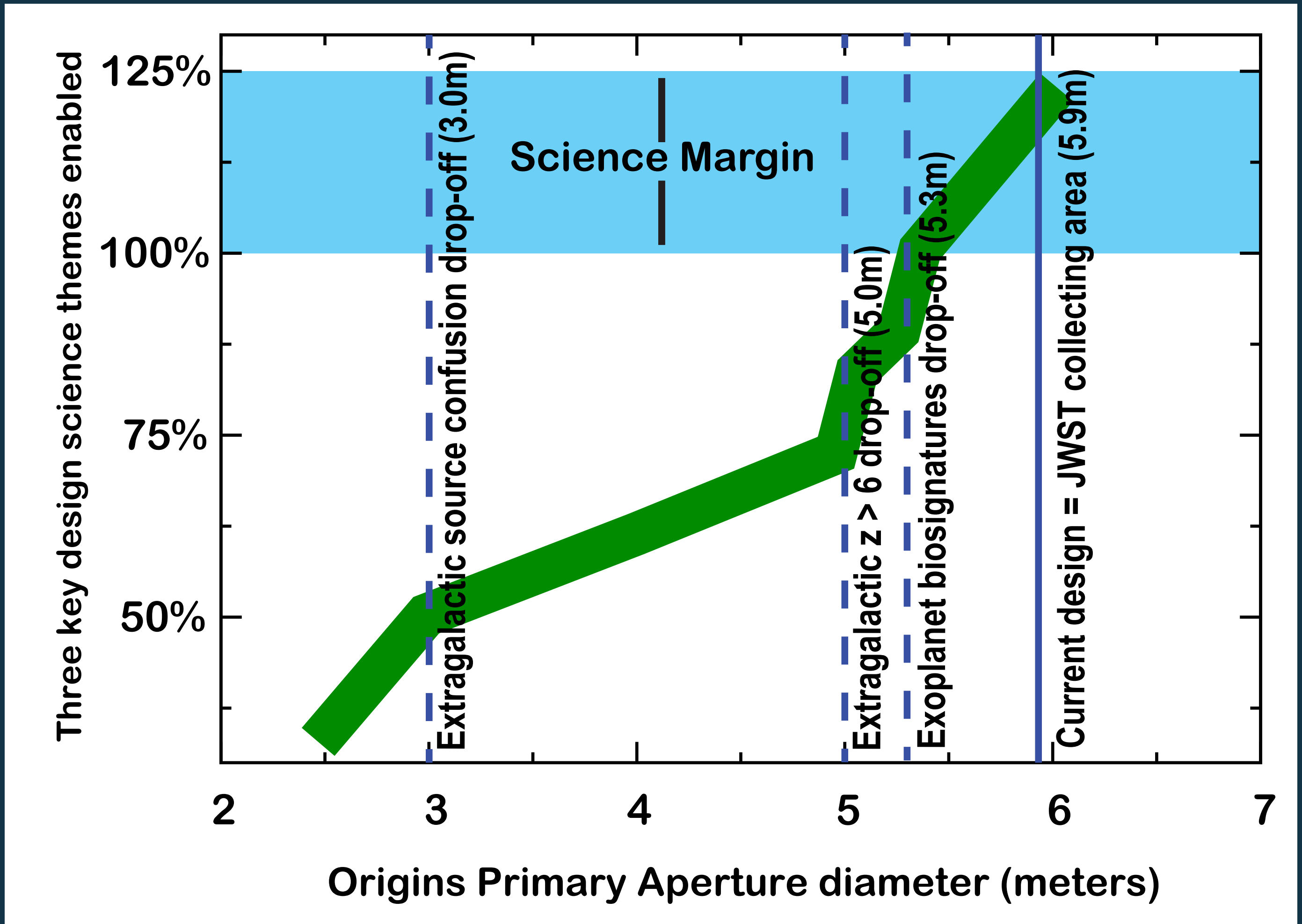
Science Implementation

- x40 (MEV) to x60 (CBE) more sensitive than ESA's Herschel Space Observatory, the previous mission (2009-2013) at far-infrared wavelengths.

Mission Implementation

- Substantial heritage with successful $1B class missions at APL, delivering within budget.
- Substantial heritage with science operations with past IR missions at IPAC.

FIRSST Emphasis on Spectroscopy



Origins Study Report; Origins Astro2020 Decadal Submission

Origins study showed imaging science objectives are significantly impacted at D < 3m.

Remaining science cases are all related to spectroscopic measurements.

Sufficiently large numbers of extragalactic and Galactic targets exist for spectroscopic measurements from existing (Herschel + Spitzer + JWST + ALMA) or upcoming facilities (e.g., SPHEREx, Euclid, Roman).

However, appropriately designed spectroscopy-focused instruments can also do wide area spectral line imaging and extragalactic surveys
– examples at the end with FIRSST.

With special thanks to

Elena April & Dipak Srinivasan
Formulation leads

Jim Kinnison
To remain as Project Systems Engineer

Mickie Courtney
Proposal manager

Michelle Goldman
Formulation leads

Yongsu Kim
Thermal Lead

Chanda Walker
Optics Lead

PI-led Science Team Leads

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

Nicole Cabrera Salazar
Movement Consulting

FIRSST IDEA Implementation Lead

Science Team

- A $1B-level multi-national science team.
- Phases A-F will last 15+ years; intent is to organically grow the next generation of far-IR proficient astrophysicists through training of post-docs and students.
- Already implemented through deputy roles assigned to early career scientists and engineers.

Dra. Nicole Cabrera Salazar

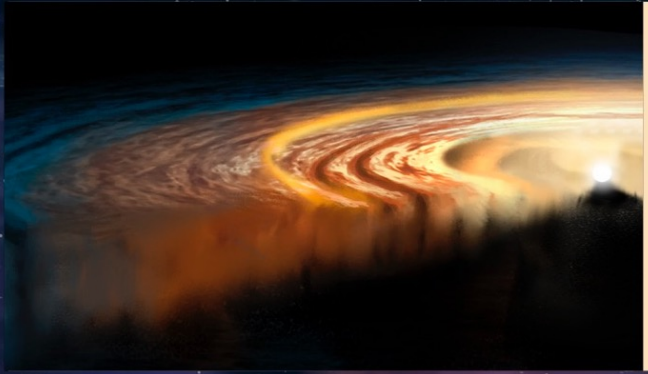
(Astrophysics PhD)

FIRSST Inclusion, Diversity, Equity, and Accessibility (IDEA) Implementation Lead. Prior experience working with NASA projects, including SMD Launchpad.

A separate company for evaluations and progress tracking.

FIRSST Addresses Key Astro2020 Science Questions

FIRSST Science Objectives



Fingerprinting Planetary Reservoirs: Determine how planets form in disks around young stars, and explain the observed diversity of planets.

Are we alone?

Tracing Water to Rocky Planets: Determine the source of water in planet-forming disks, and explain how water accumulates into oceans.

How did we get here?

Unveiling the Drivers of Galaxy Growth: Determine how the intergalactic medium influences star formation, and explain how galaxies grow.

How does the universe work?

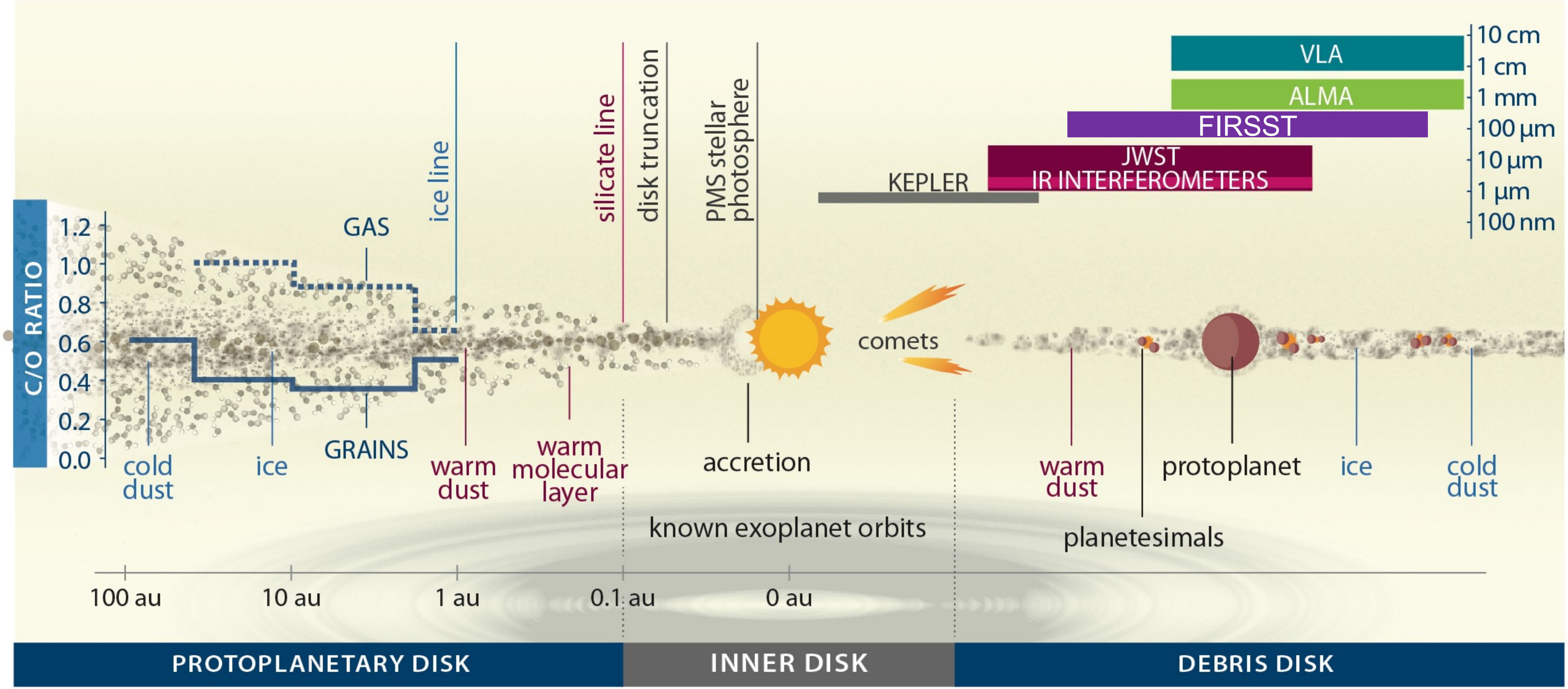
PI-Led Science Goals and Objectives

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.

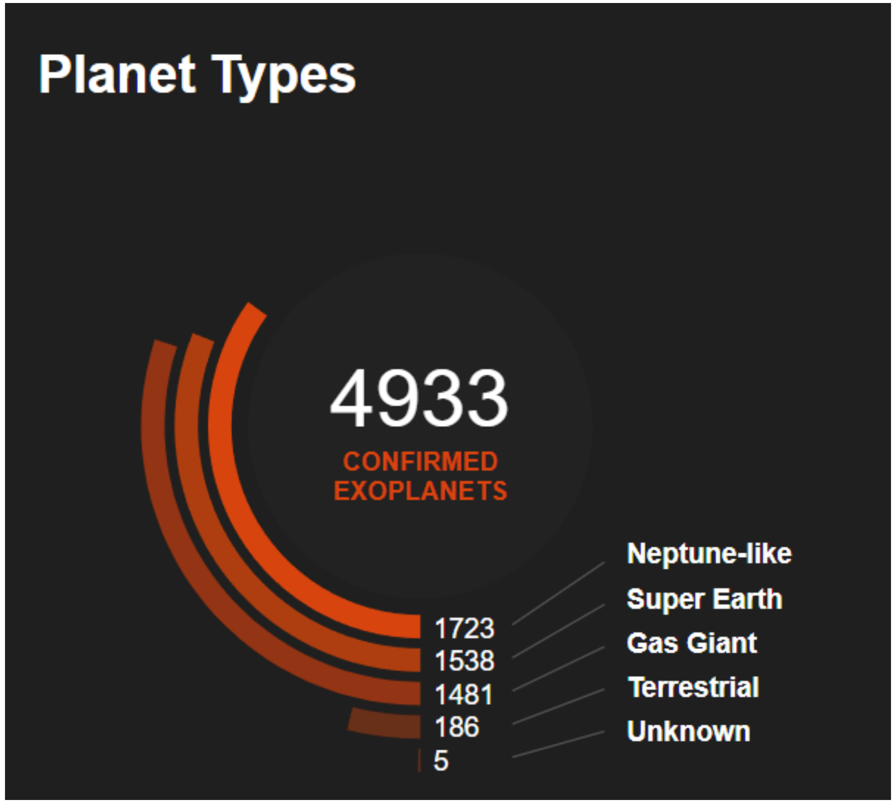
SG #5: Determine the influence of the intergalactic medium on galaxy-wide star formation.
SG #6: Determine the mass growth rate of galaxies from today to cosmic noon, across a range of galaxy properties, stellar masses, and environments.

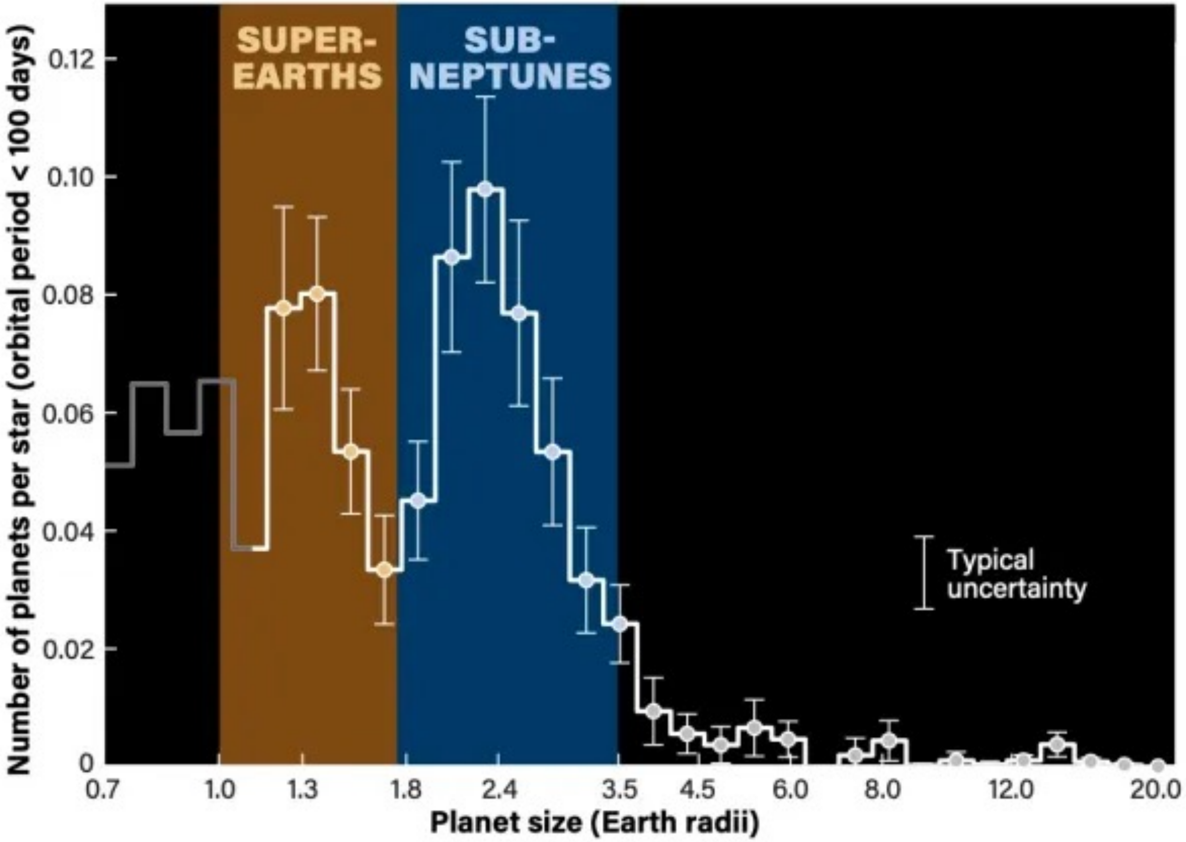
Fingerprinting Planetary Reservoirs



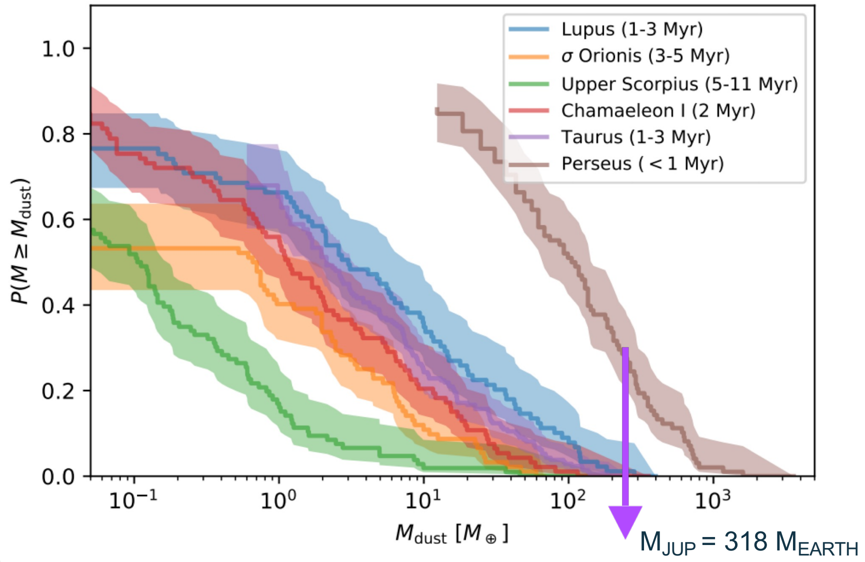
Fingerprinting Planetary Reservoirs

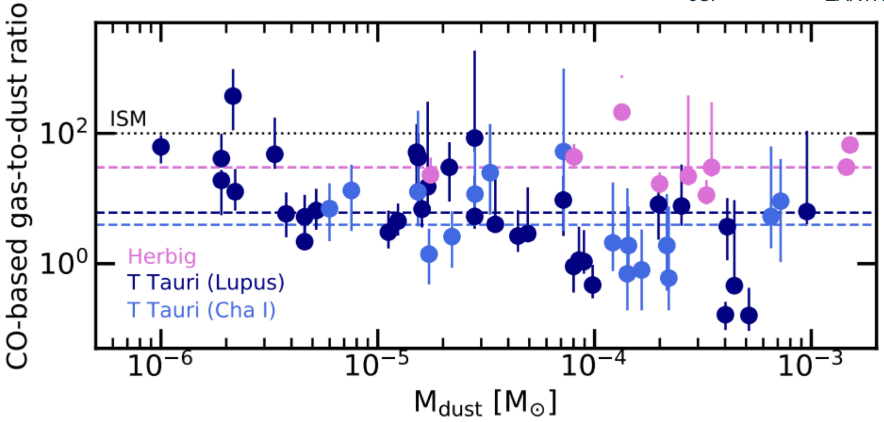
Why are more planets in our Galaxy super-Earths and mini-Neptunes?





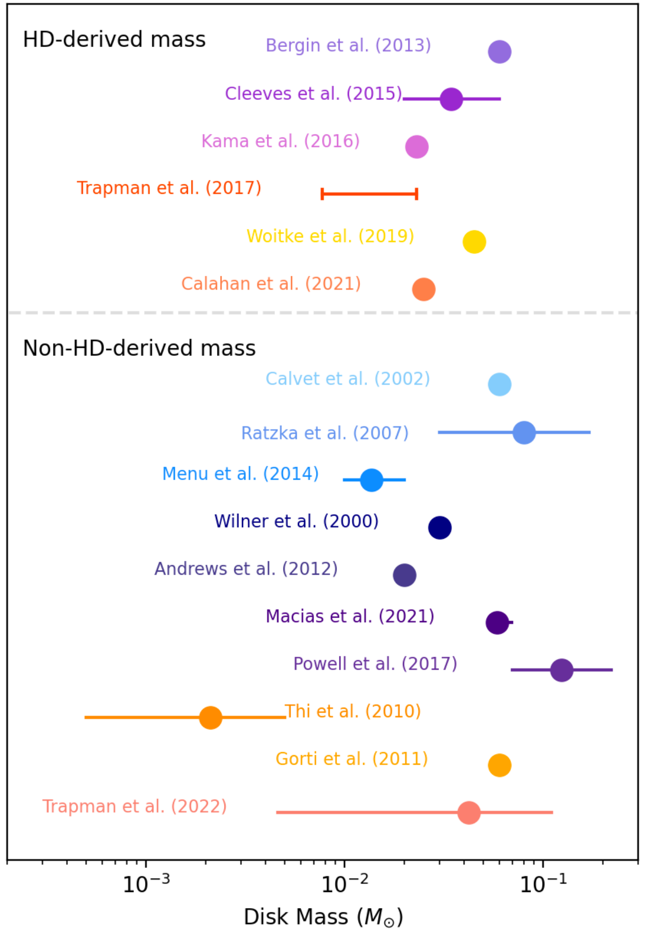
Fingerprinting Planetary Reservoirs





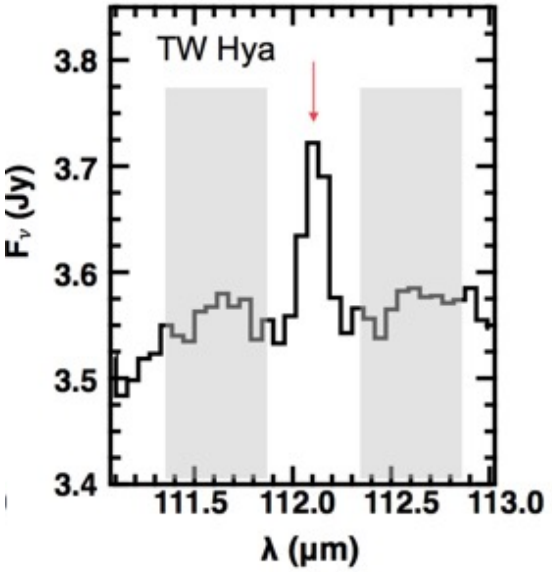
ALMA measurements suggest very few planet-forming disks would have enough mass to form Jupiter-sized planets.

How massive are planet forming disks?

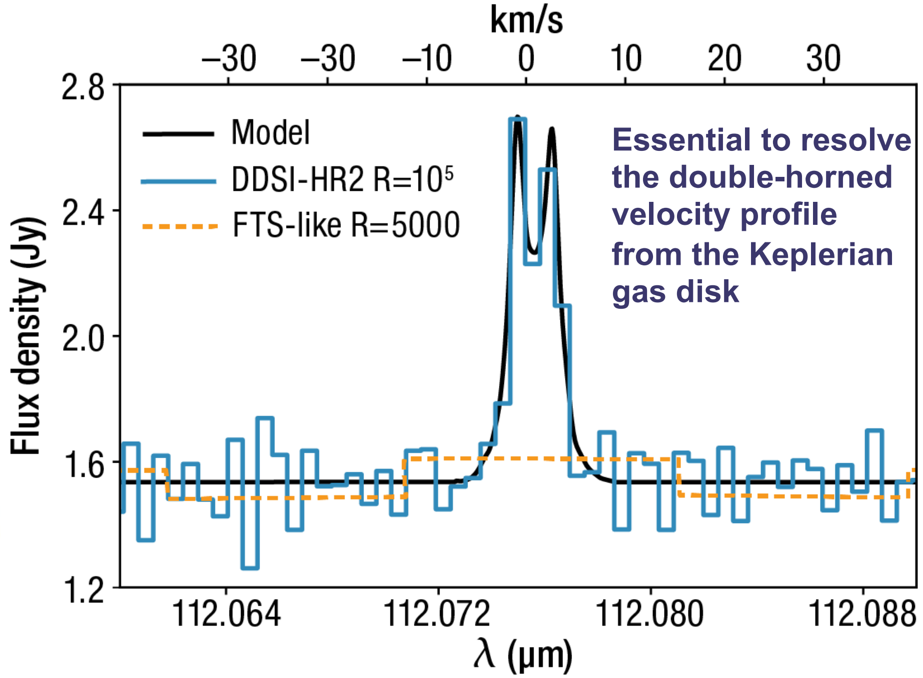


Fingerprinting Planetary Reservoirs

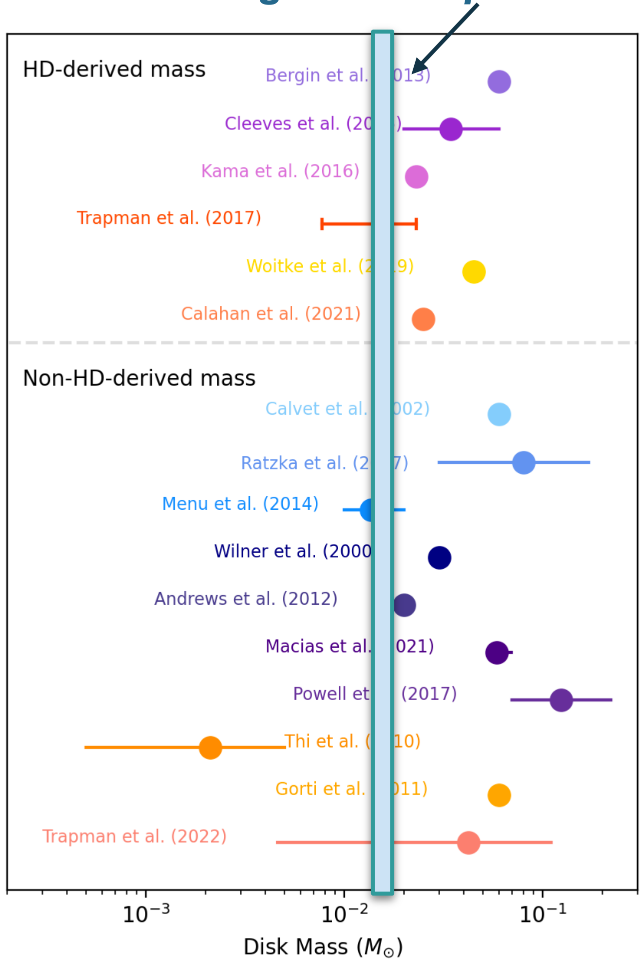
Resolving HD spectral lines is essential to:
(1) measure the true line flux and
(2) accurately measure disk gas masses.
(3) Break mass-temperature degeneracy with the ratio of HD J=2-1 and J=1-0 lines



Herschel/PACS R=1500



Expected FIRSST gas mass precision

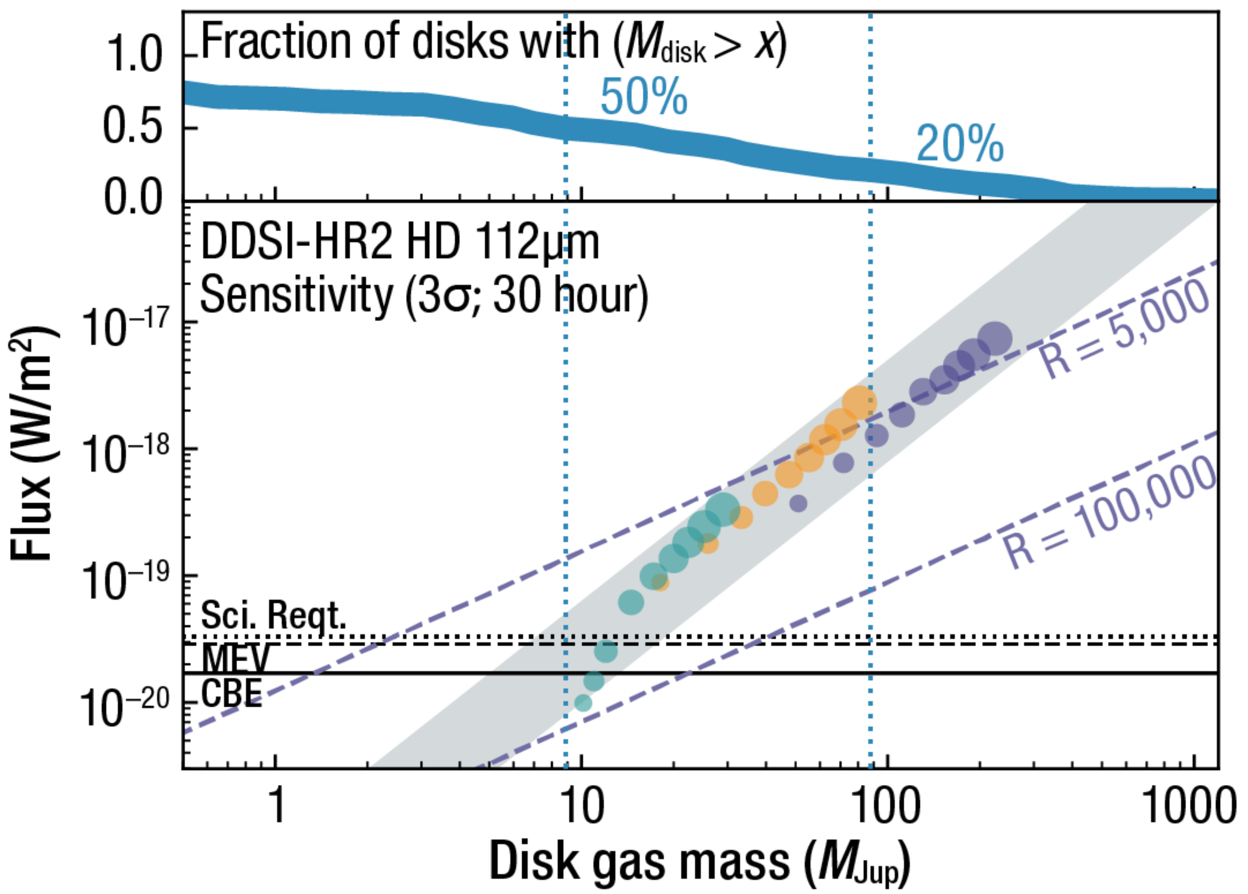


Fingerprinting Planetary Reservoirs

Objective: Assess total mass available to form planets, measure the statistical distribution of protoplanetary disk gas mass down to $0.001M_{\odot}$.

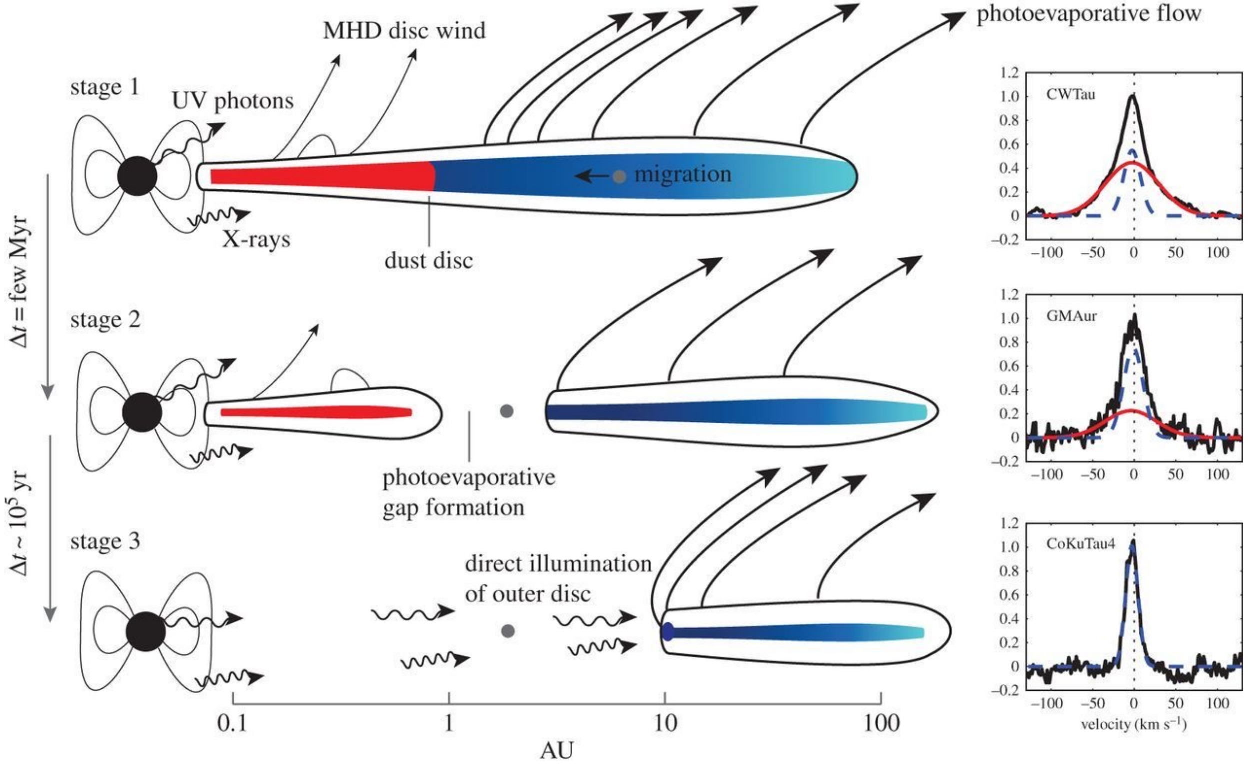
Observations: HD J = 1 – 0 at 112 μm (primary line) and J = 2 – 1 at 56 μm (breaks temperature degeneracy) for 300 planet-forming disks out to 200 pc in 2000 hours.

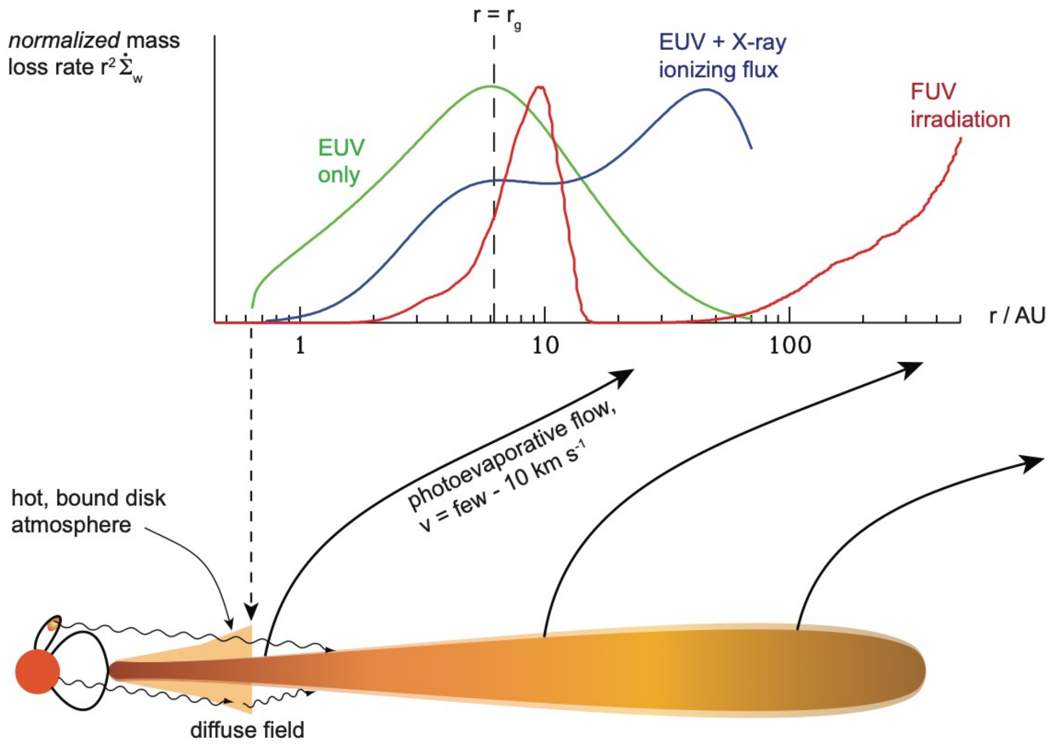
Requirements: Spectral line sensitivity of 3×10^{-20} W m^{-2} to detect a MMSN disk at 3σ in 30 hours, R (λ/Δλ) = 75,000 to spectrally resolve lines, and angular resolution < 25 arcsec to avoid confusion.



SO #2.1: Photo-evaporation and timescale for planet formation

Objective: Establish timescale for planet formation, measure the mass loss rates of protoplanetary disks down to $10^{-10} M_{\odot}\ yr^{-1}$.



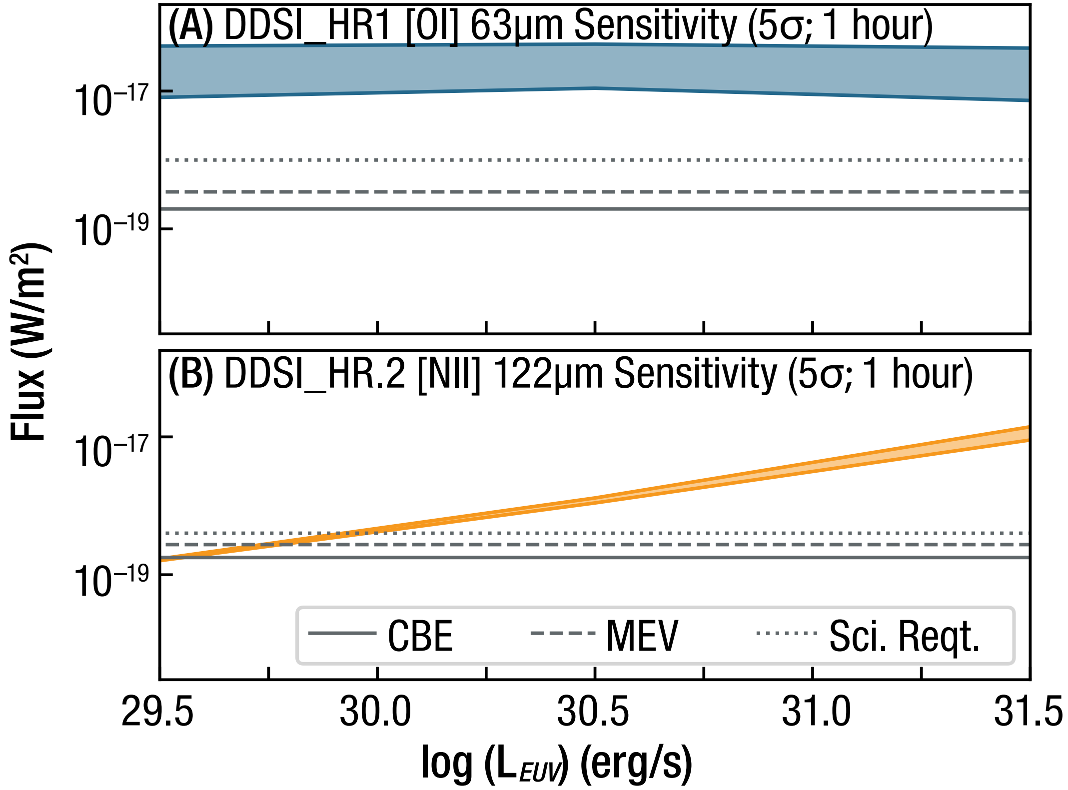


SO #2.1: Photo-evaporation and timescale for planet formation

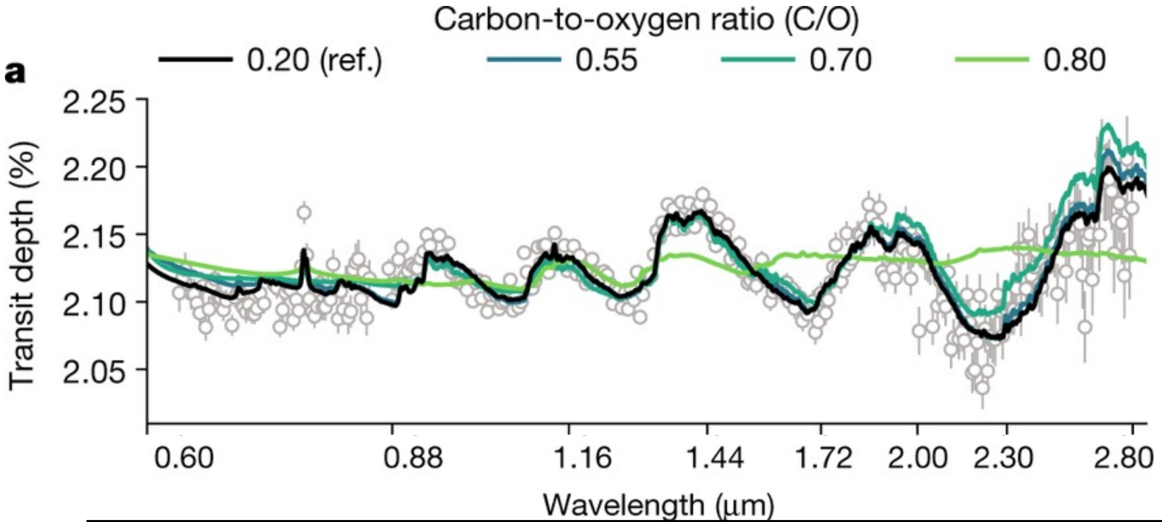
Objective: Establish timescale for planet formation, measure the mass loss rates of protoplanetary disks down to $10^{-10} M_{\odot}\ yr^{-1}$.

Observations: [OI] at 63 μm and [NII] at 112 μm for 1000 planet-forming disks out to 200 pc in 500 hours.

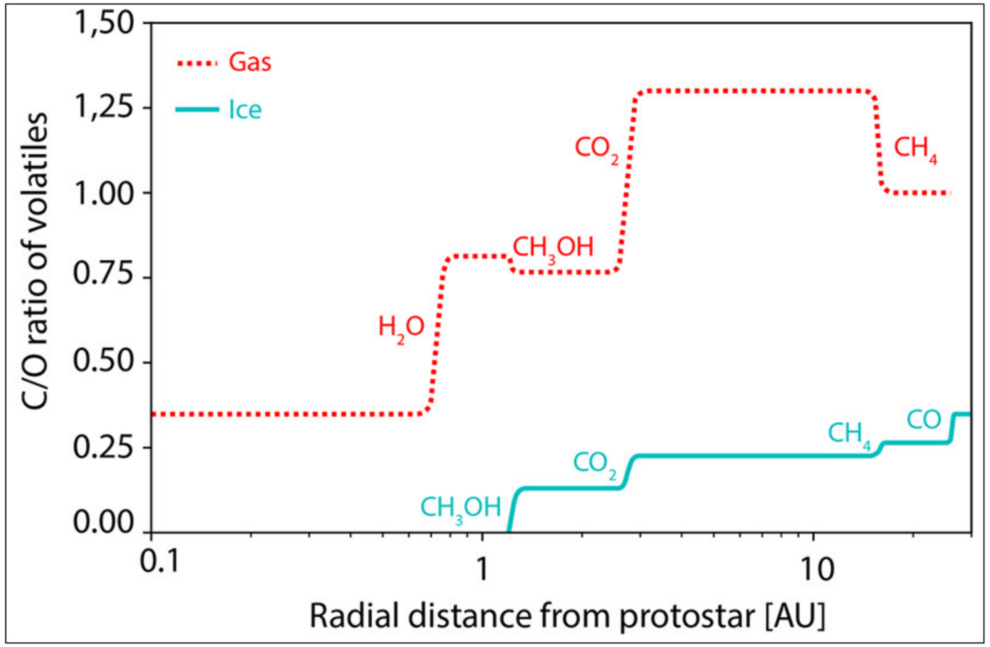
Requirements: Spectral line sensitivity of 4×10^{-19} W m^{-2} at 122 μm to detect a MMSN disk at 200 pc at 5σ in 1 hour, R (λ/Δλ) = 75,000 to spectrally resolve lines, and angular resolution < 25 arcsec to avoid confusion.

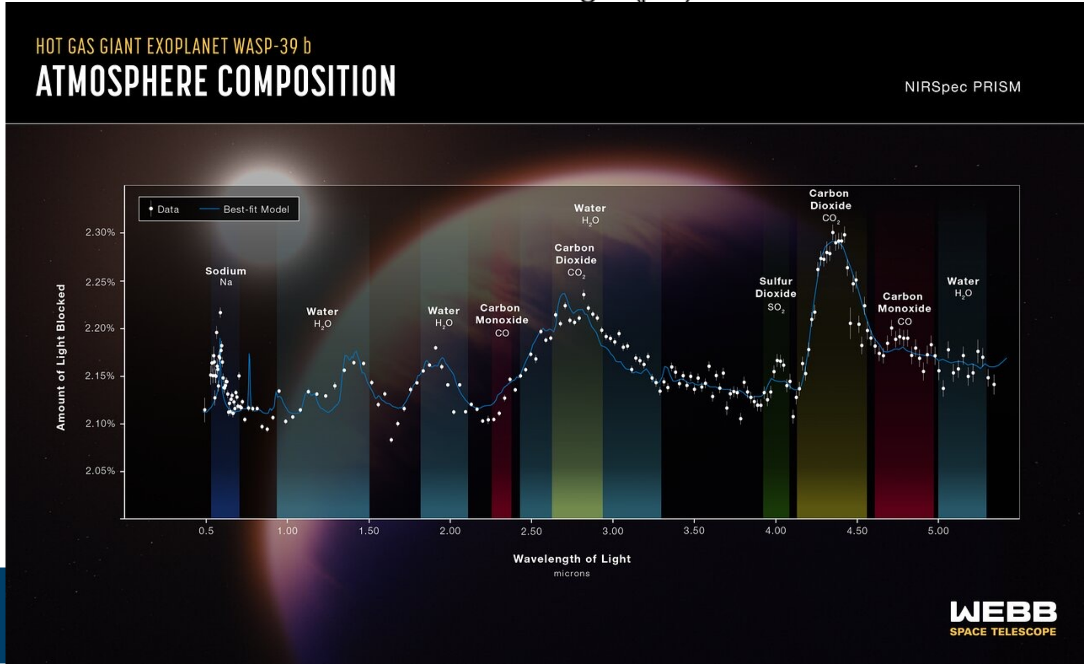


SO #2.2: Gas remaining in debris disks to connect disk Chemistry with planetary compositions



Objective: Connect disk chemistry with planet composition, measure the C/O ratio in gas-rich debris disks down to a CO gas mass of $10^{-6} M_{\oplus}$.



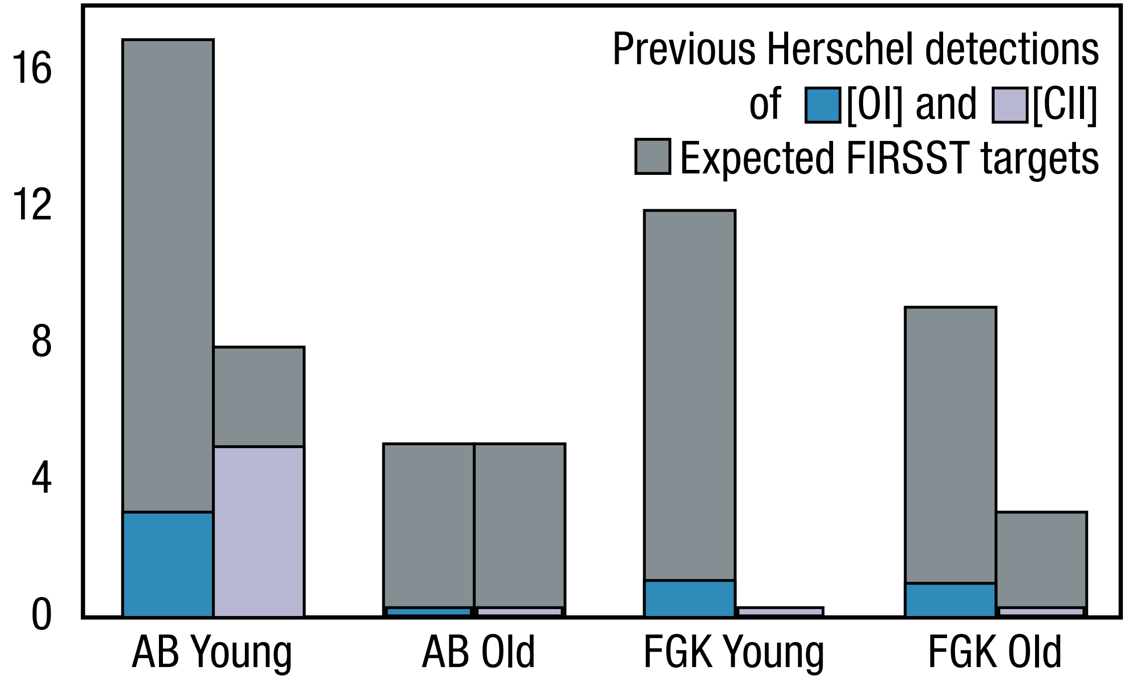


SO #2.2: Gas remaining in debris disks to connect disk Chemistry with planetary compositions

Objective: Connect disk chemistry with planet composition, measure the C/O ratio in gas-rich debris disks down to a CO gas mass of $10^{-6} M_{\oplus}$.

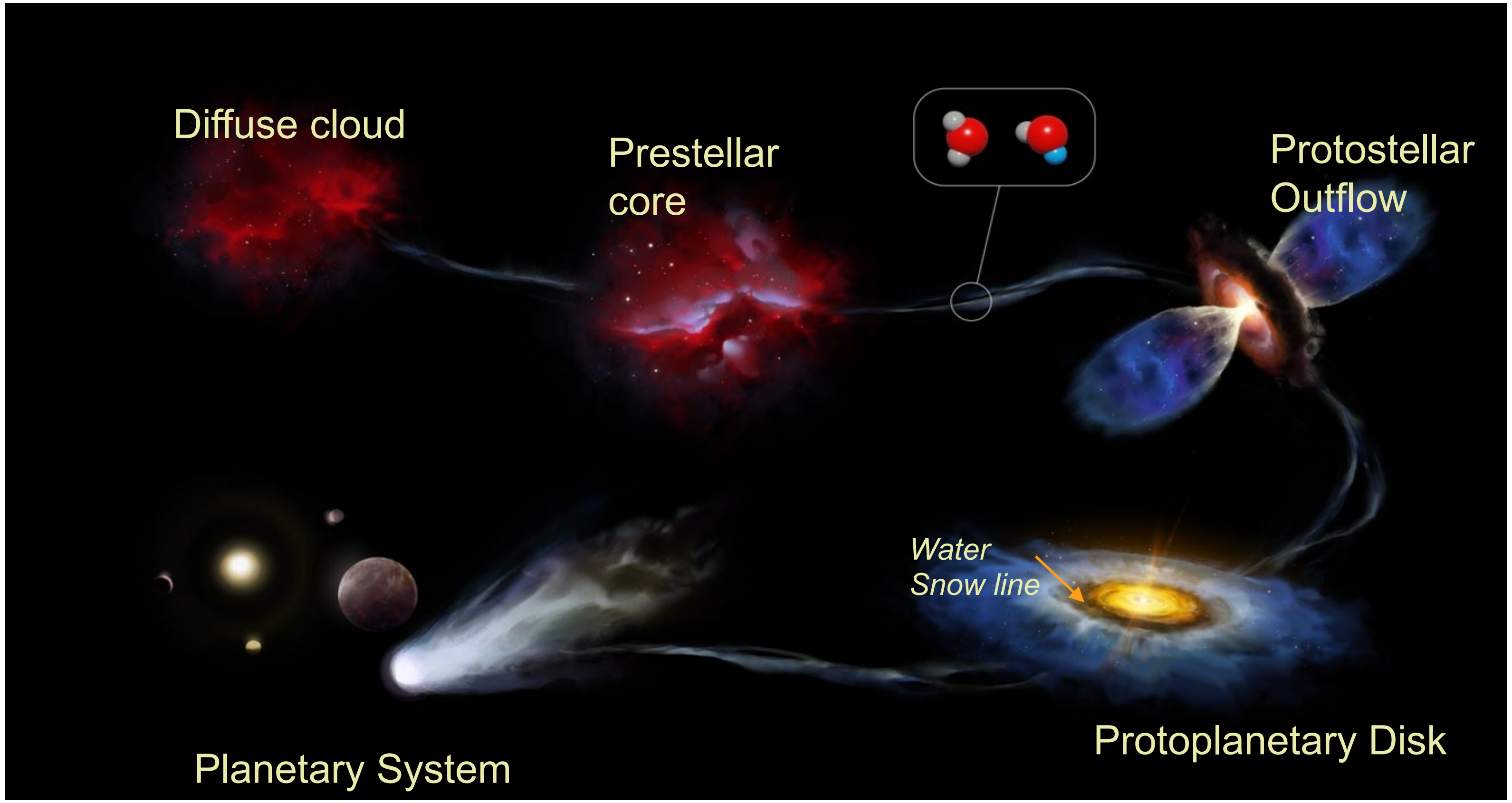
Observations: [OI] at 63 μm and [CII] at 158 μm for 40 gas-rich debris disks in 500 hours.

Requirements: Spectral line sensitivity of $4{\times}10^{-19}$ W m^{-2} to detect a CO gas mass $10^{-6} M_{\oplus}$ debris disk at 5σ in 1 hour, R (λ/Δλ) = 75,000 for [OI], R (λ/Δλ) = 10,000 for [CII], and angular resolution < 25 arcsec to avoid confusion



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.

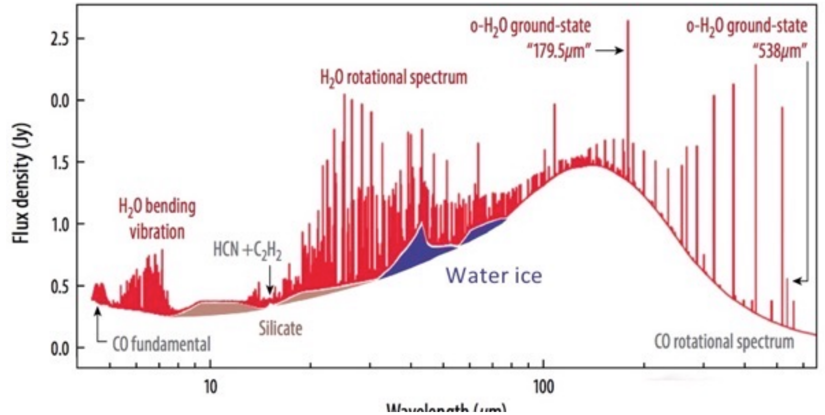
Water delivered to inner planets by comets.

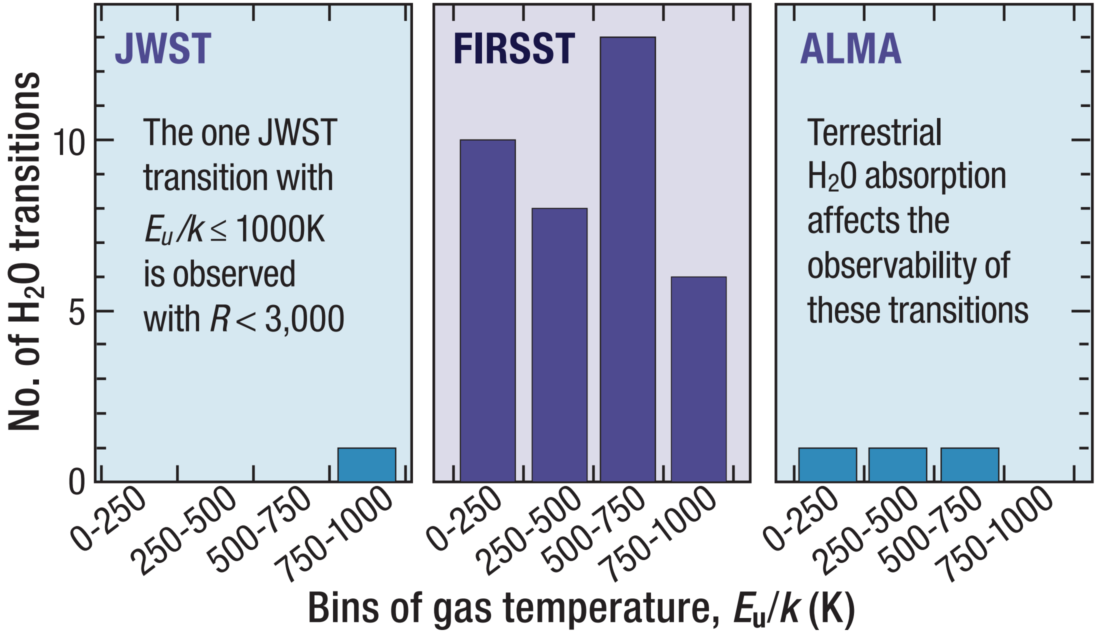
SO#3: Water chemistry in pre-stellar cores and planet forming disks

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

Observations: Multiple o-H2O, p-H2O and HDO emission lines in a total of 40 pre-stellar cores and 40 protoplanetary disks around A and FGK (solar type) stars in 4 star-forming regions, over 2800 hours.

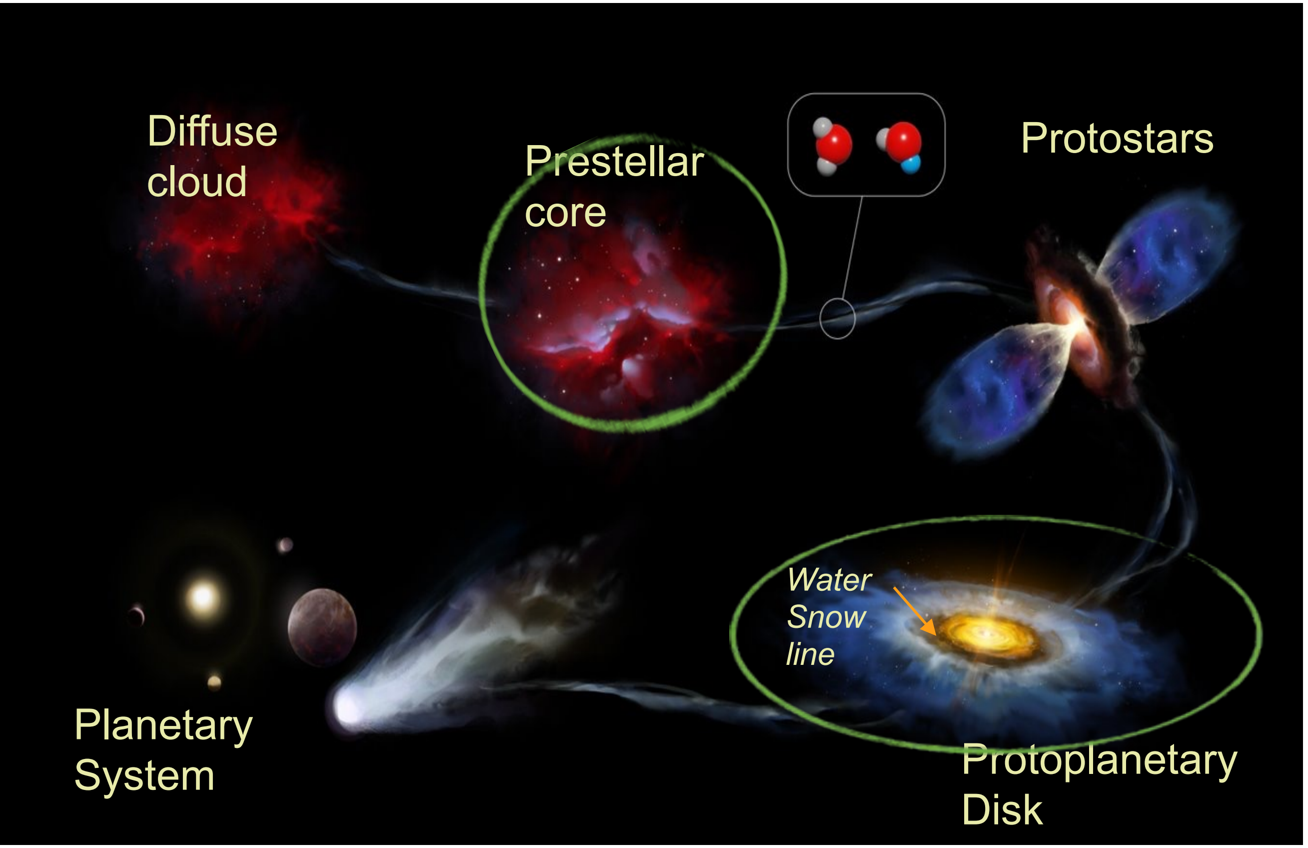
Requirements: Spectral line sensitivity (varies) to detect multiple water lines of cores and disks in 10 hours, R ($\lambda/\Delta\lambda$) = 10^6 to spectrally resolve infall and other water line structures.

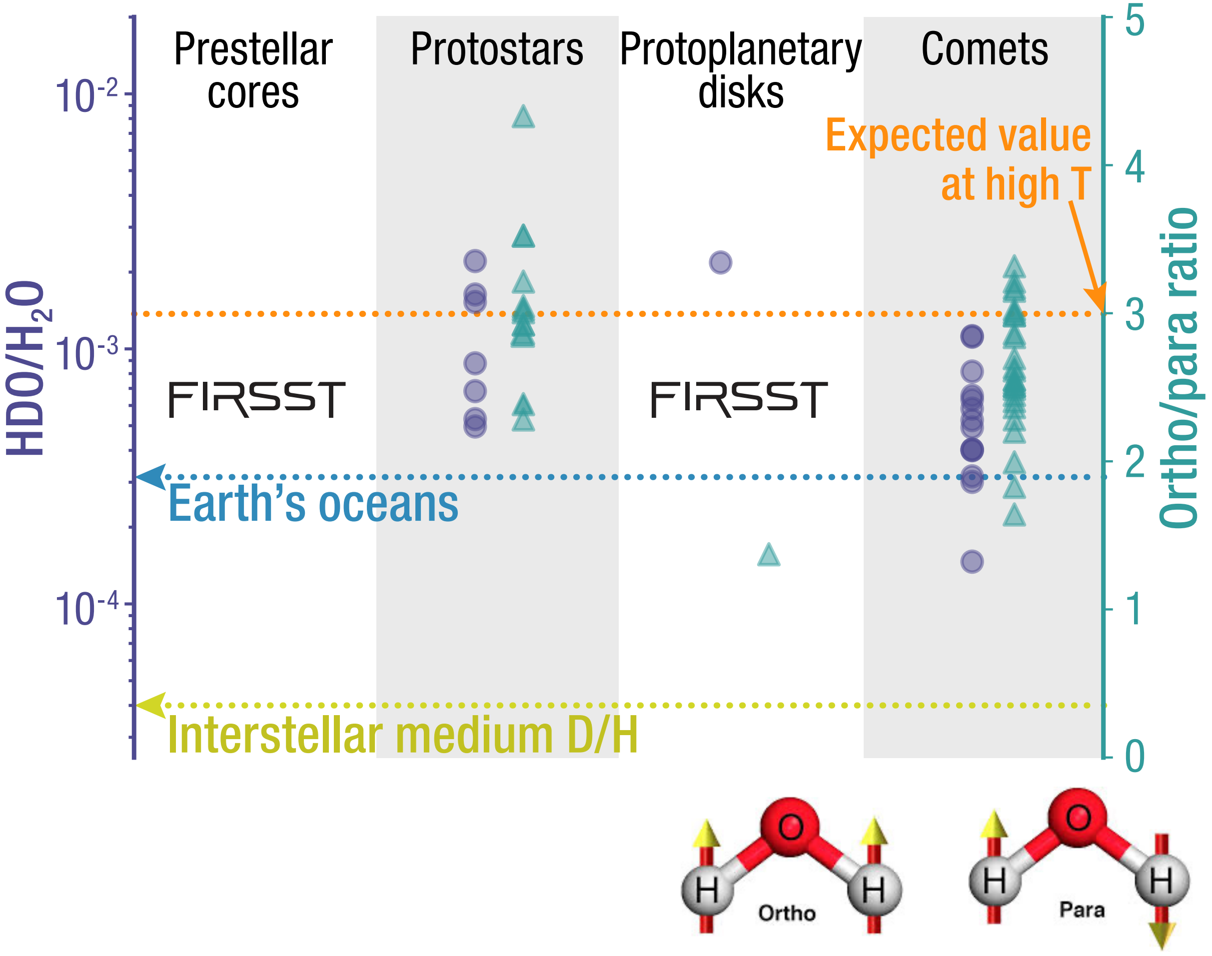




Credit: Pezzuto+ (2021)

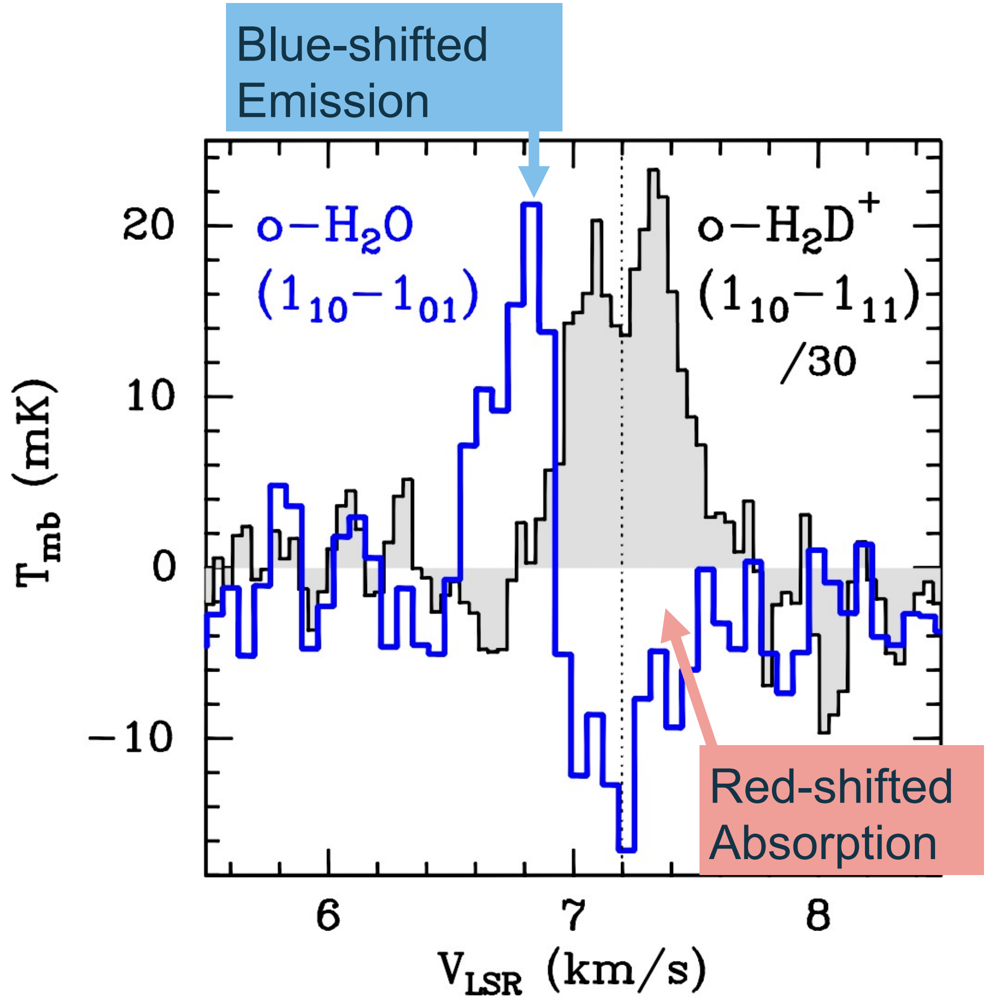
SO#3: Water chemistry in pre-stellar cores and planet forming disks

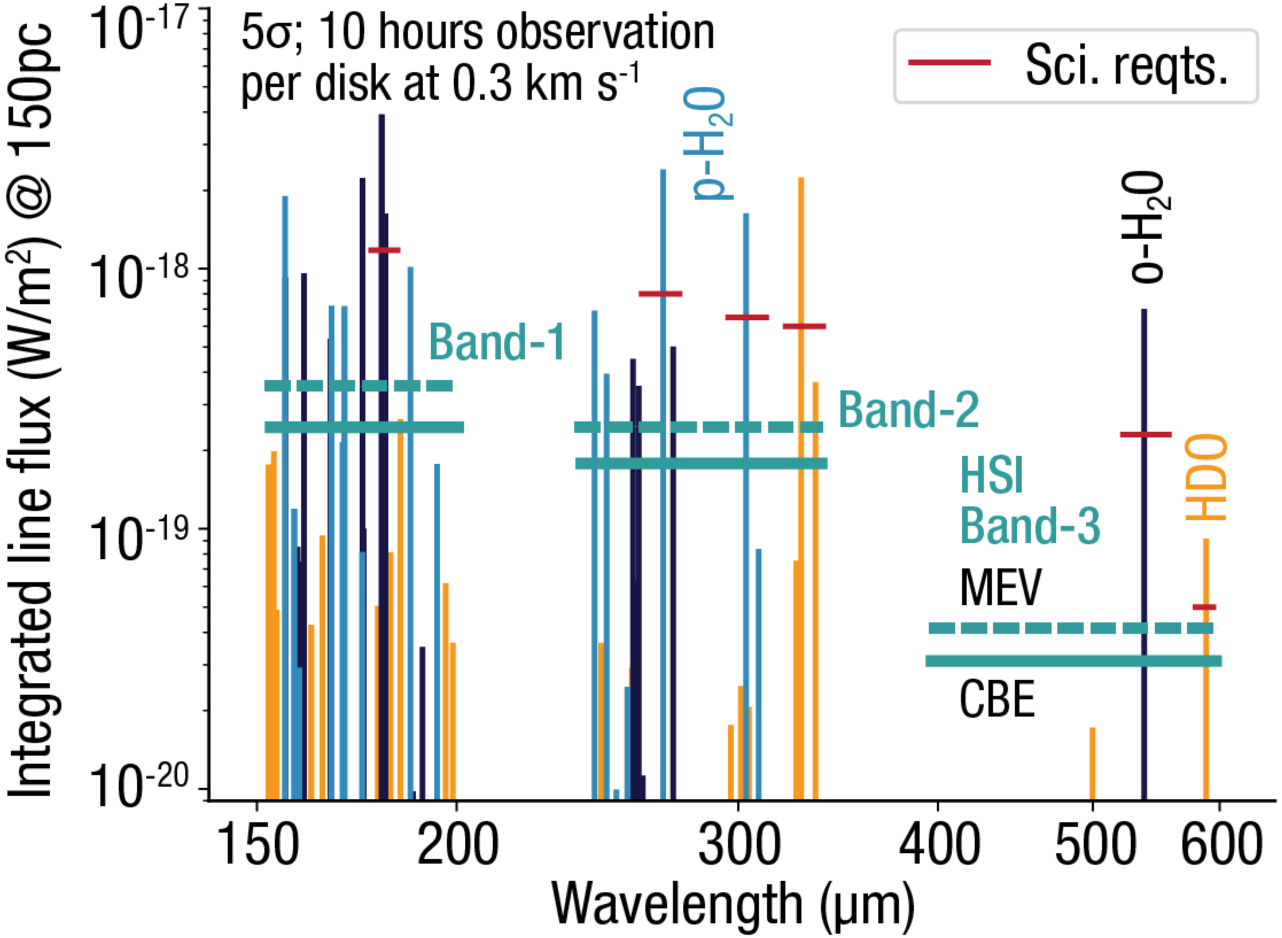




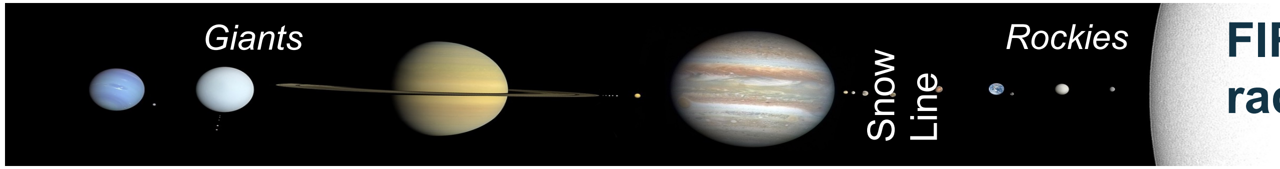
SO#3: Water chemistry in pre-stellar cores and planet forming disks

Infall in Pre-Stellar Core L1544 Herschel HIFI

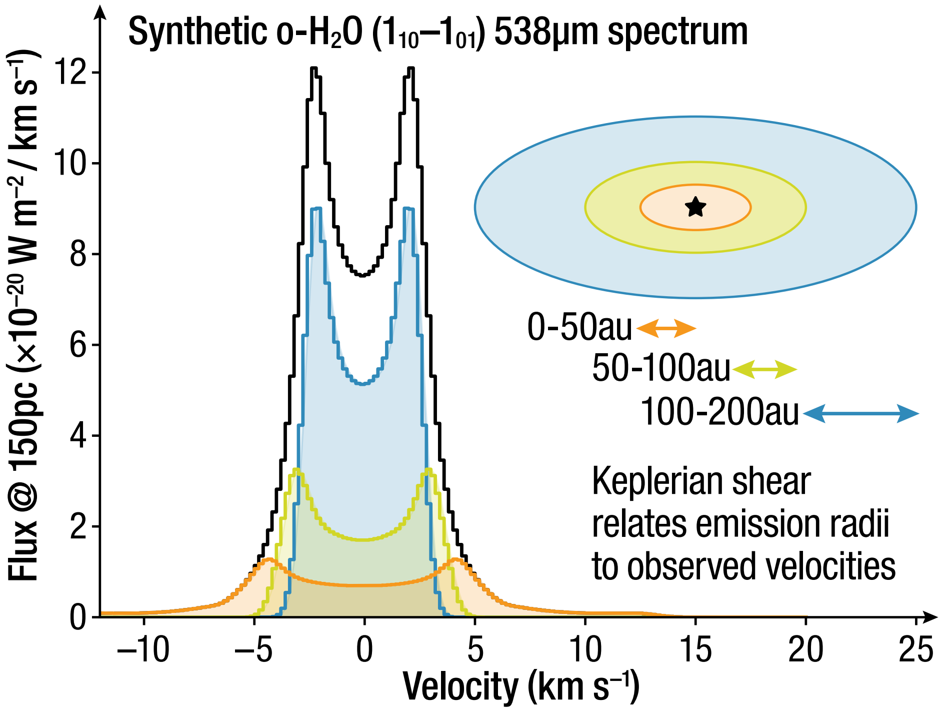


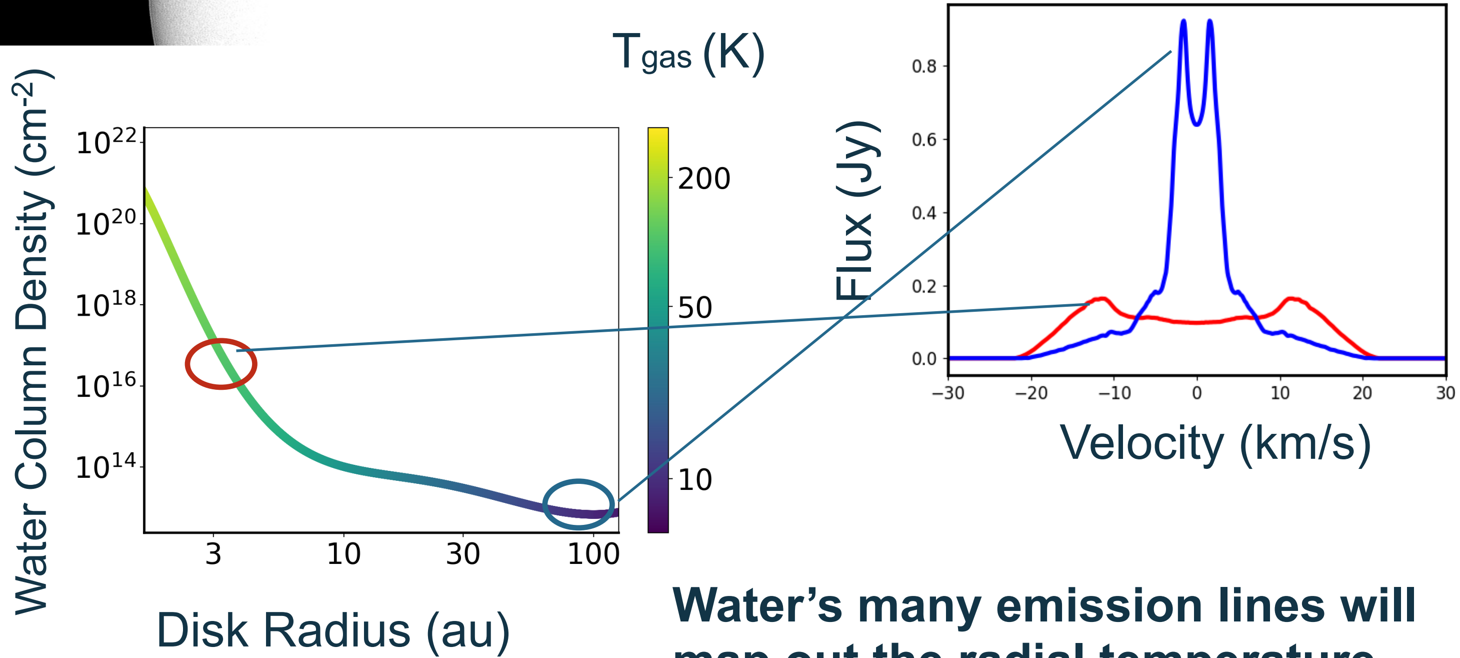


SO#3: Water chemistry in pre-stellar cores and planet forming disks



FIR lines will locate radial water snowline





Water's many emission lines will map out the radial temperature gradient at vertical snowline:

Inclination ⟶ Peak Emitting radius
Transition ⟶ Gas temperature
Flux ⟶ Water column

SO#4.1: Water content for fully formed planets.

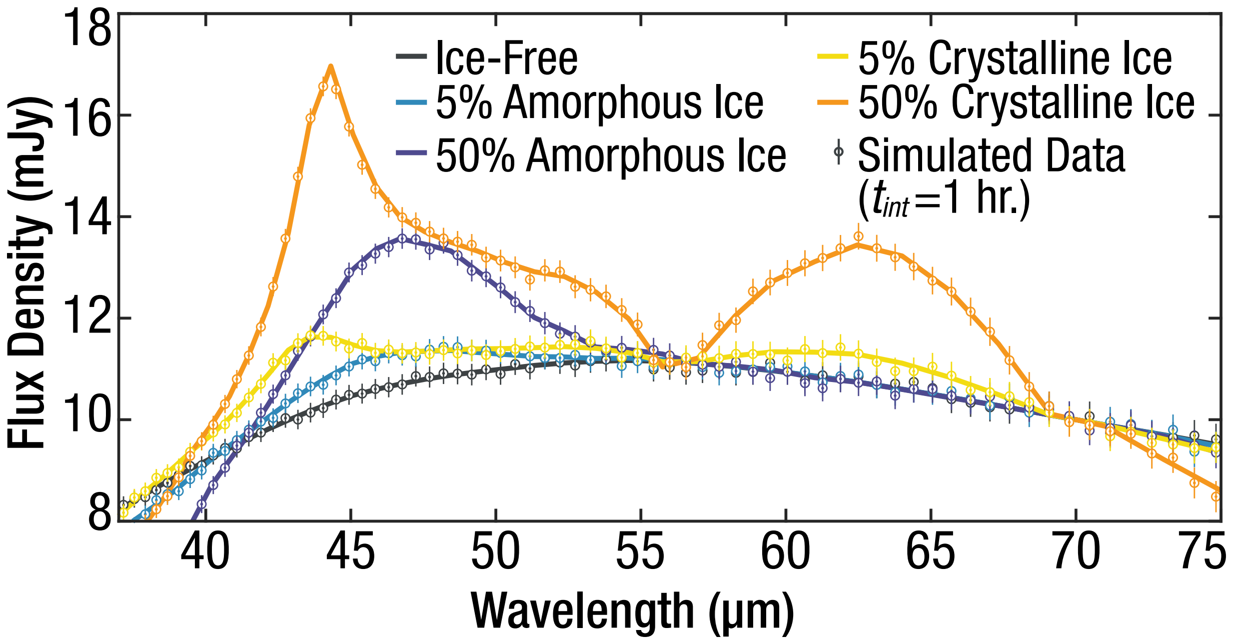
Objective: Determine the water content available for fully formed planets, measure the fraction of water ice mass to 5% in debris disks.

SO#4.1: 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.

Observations: Emission bands of amorphous and crystalline water ice in 40 debris disks around FGK (solar type) stars, over 200 hours.

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 ($\lambda/\Delta\lambda$) = 50.



SO#4.2: Address how inner planets, including Earth, received water

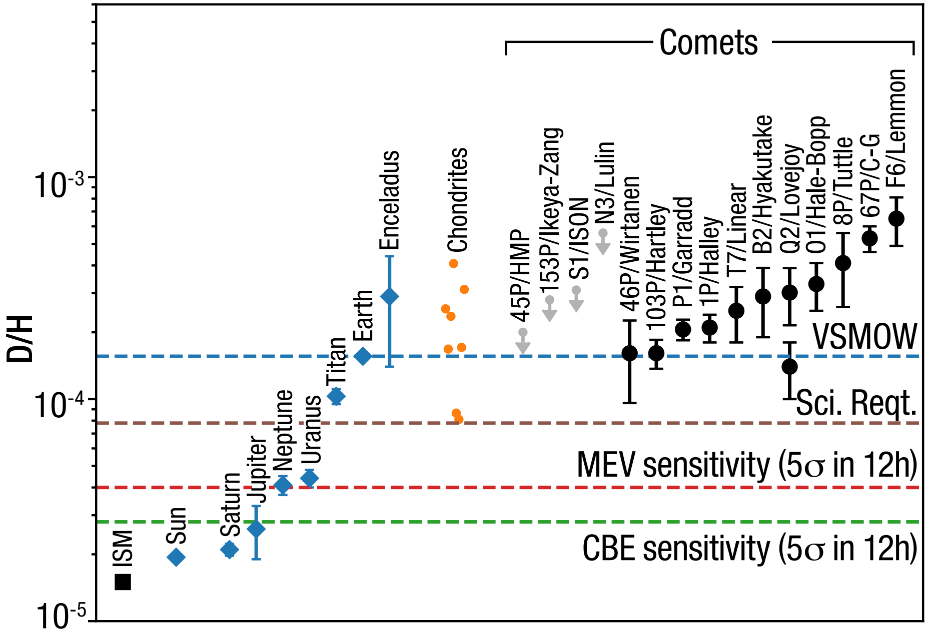
Objective: Address how inner planets, including Earth, received water by measuring the D/H ratio
below 5×10^{-4} and the D/H ratio variations across the outer regions of the solar system.

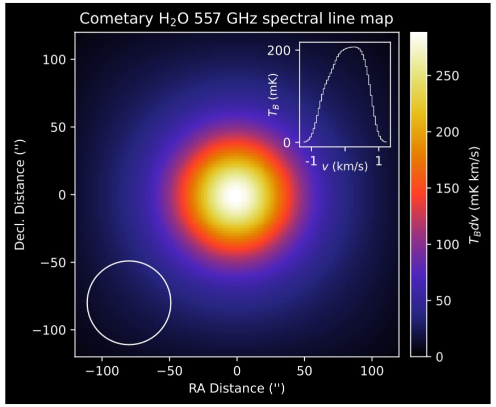
SO#4.2: Address how inner planets, including Earth, received water

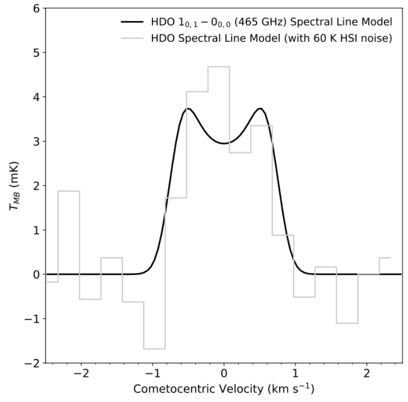
Objective: Address how inner planets, including Earth, received water by measuring the D/H ratio below 5×10^{-4} and the D/H ratio variations across the outer regions of the solar system.

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

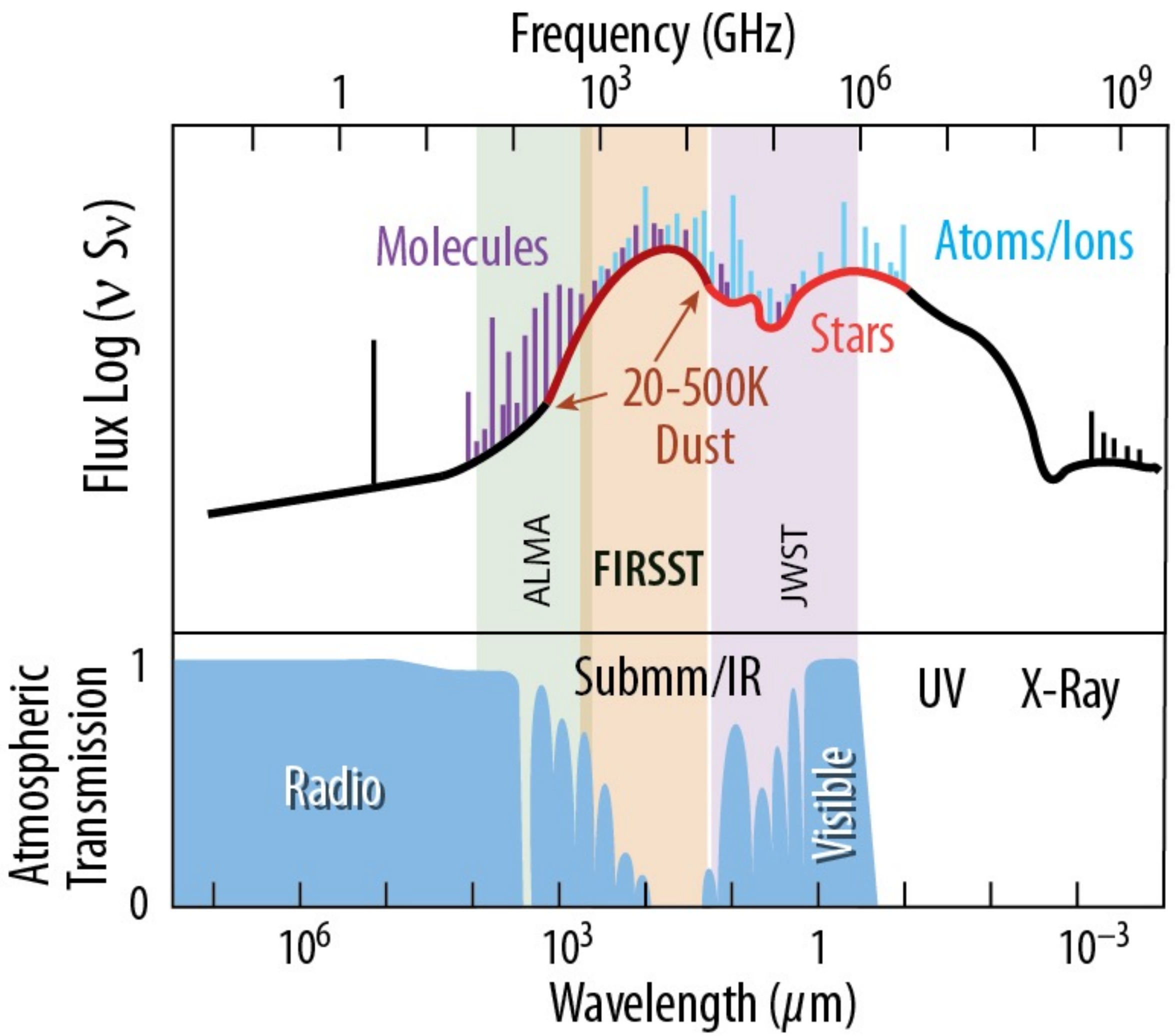
Requirements: Spectral line sensitivity of $1\text{x}10^{-19}$ W m^{-2} to detect H_2O and HDO lines in comets for D/H values similar to VSMOW disk at 5σ in 12 hour, R $(\lambda/\Delta\lambda) = 10^6$ to spectrally resolve lines, and HSI mapping capability to separate emission from coma and nucleus.







Unveiling the Drivers of Galaxy Growth



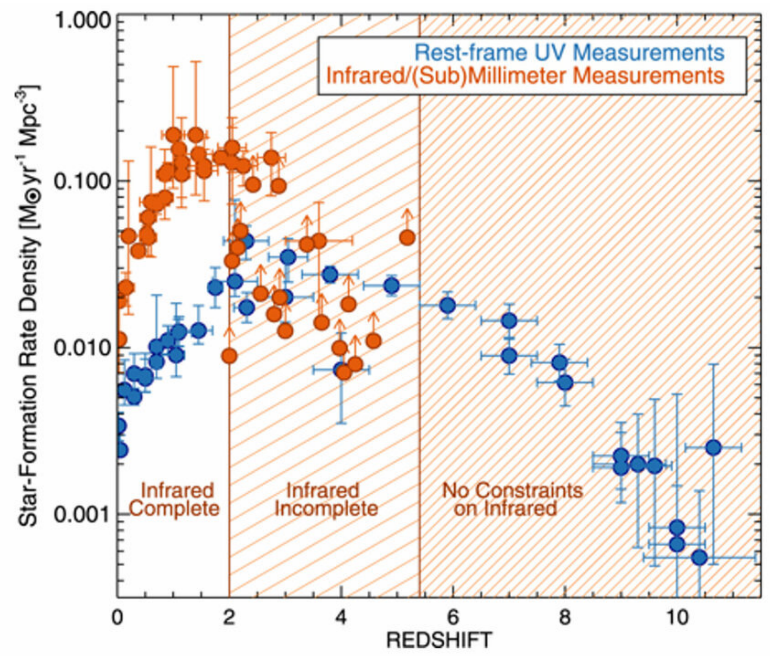
FIRSST bridges the crucial wavelength gap between ALMA and JWST.

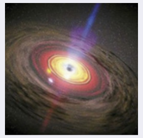
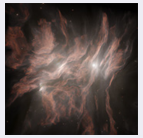
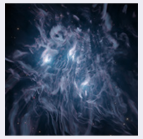
FIRSST allows studies in the peak of the dust emission.

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

SO #6: Galaxy mass growth over cosmic history

Objective: Establish the mass growth rate of galaxies using the evolution of O/H abundance, conduct a metal line survey out to cosmic noon in bins of redshift, stellar mass, IR luminosity, AGN activity, and environment, down to down to $10^{11}\ L_{\odot}$ at z=0.5, $10^{12}\ L_{\odot}$ at z > 1.



EMISSION FEATURE (WAVELENGTH IN μm)	IONIZATION POTENTIAL (eV)	OBSERVABLE REDSHIFT RANGE FOR DDSI	DIAGNOSTIC UTILITY	
Ionized Atomic Gas				
[Mg V] 13.5	109.0	$1.6 < z < 18$	AGN strength	
[Ne V] 14.3, 24.3	97.1	$1.4 < z < 9.7$	AGN strength, electron density	
[O IV] 25.9	54.9	$0.3 < z < 9.0$	AGN strength, radiation field hardness	
[S IV] 10.5	34.8	$2.3 < z < 24$	SF rate and strength, metallicity	
[Ne II] 12.3	21.6	$1.8 < z < 20$	SF rate and strength/HII region, metallicity	
[Ne III] 15.6, 36.0	41.0	$1.2 < z < 6.2$	SF rate and strength/HII region density, metallicity	
[S III] 18.7, 33.5	23.3	$0.8 < z < 6.8$	SF rate and strength/HII region density, metallicity	
[Ar III] 21.8	27.6	$0.6 < z < 11$	SF rate and strength/HII region	
[O III] 51.8, 88.4	35.1	$0.0 < z < 1.9$	SF rate and strength/HII region density, metallicity	
[N III] 57.3	29.6	$0.0 < z < 3.5$	SF rate and strength/HII region, metallicity	
[N II] 122, 205	14.5	$0.0 < z < 0.3$	SF rate and strength/HII region density, metallicity	
Neutral Atomic Gas and Photodissociation Regions				
[Si II] 34.8	8.20	$0.0 < z < 6.5$	Photodissociated region (PDR) density and temperature, radiation field strength, transition between WNM/CNM	
[O I] 63.1, 145	--	$0.0 < z < 0.8$		
[C II] 158	11.3	$0.0 < z < 0.7$		
Molecular Gas				
H2 9.66, 12.3, 17.0, 28.2		$1.8 < z < 8.2$ (3+ lines)	Feedback, shocks, X-ray dominated regions, gas mass and column density, abundance, PDRs	
HD 37.0, 56.0, 112		$0.0 < z < 1.3$		
OH 34.6, 53.3, 79.1, 98.7, 119, 163		$0.0 < z < 1.6$ (4+ lines)		
H_2O 73.5, 90.0, 101, 107, 180, 245, 258, 260		$0.0 < z < 1.4$ (4+ lines)		
High-J CO ~2600/J (J > 10)		$0.0 < z < 1.2$ (4+ lines)		
Dust				
PAH 6.25, 7.66, 8.55, 11.2, 17.0		$2.1 < z < 14$ (2+ lines)	PDR tracer, dust mass and distribution	
Silicate 9.70, 18.0		$2.6 < z < 13$	Grain properties, redshift indicator	

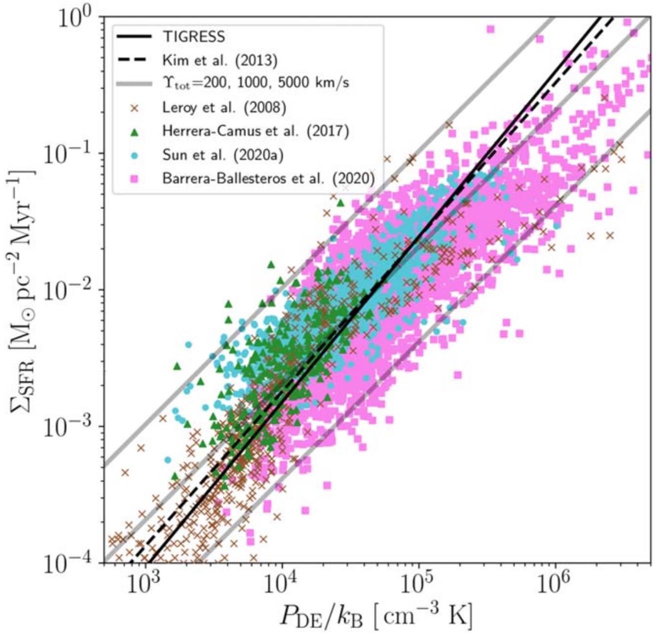
SO #5: Dominant Mode of Star Formation in Galaxies

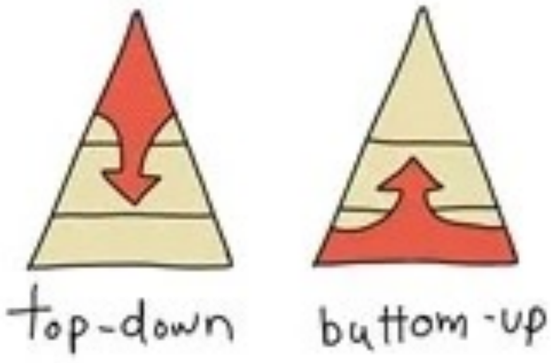
Top-down

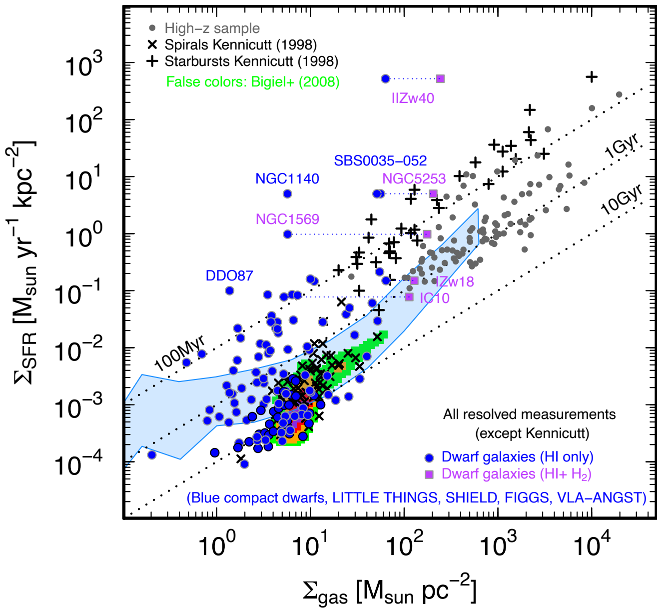
Pressure regulated, feedback modulated models relate star-formation rate (SFR) surface density with dynamical equilibrium pressure in stellar+gas disk

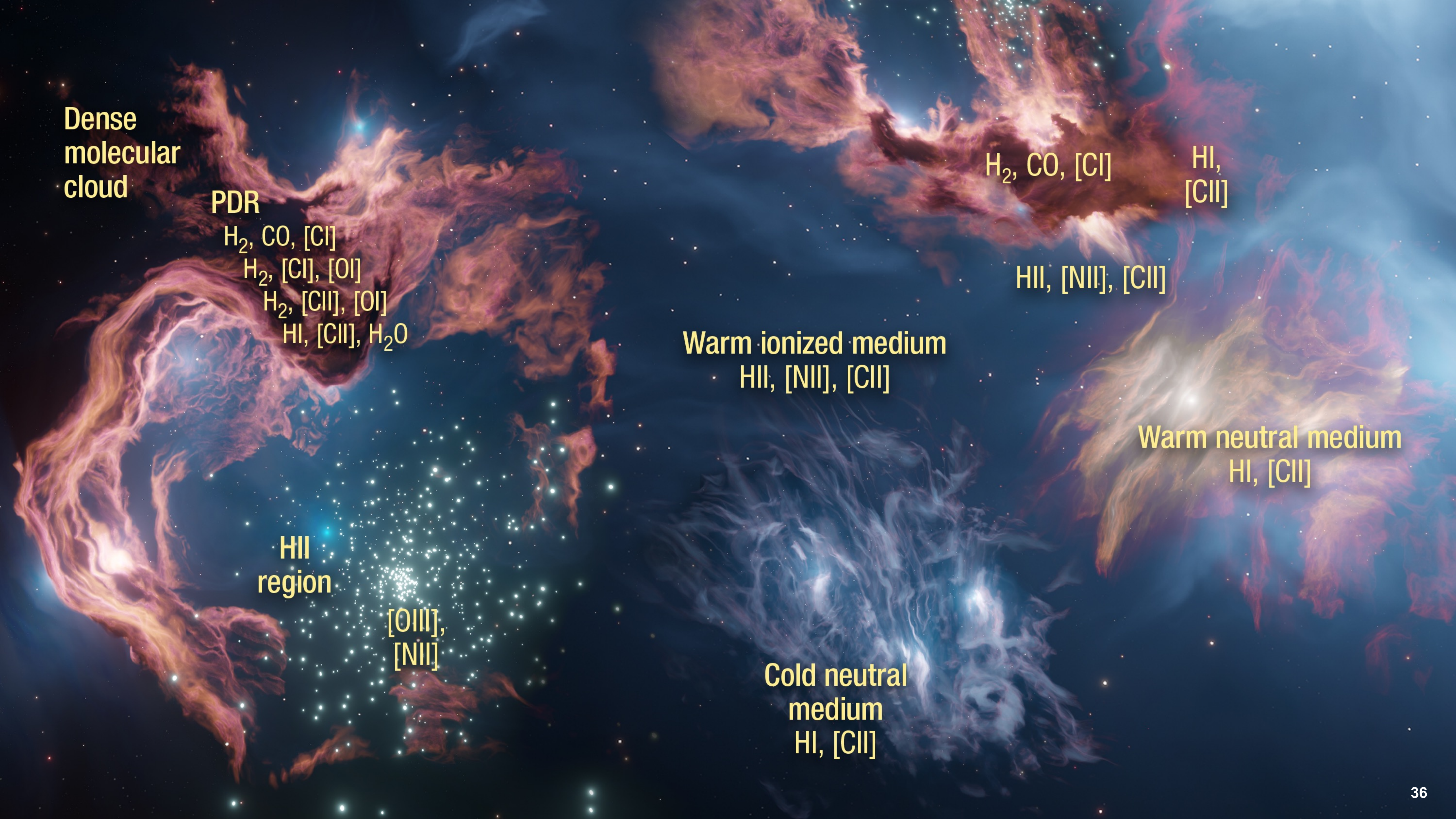
Bottom-up

Galaxy-scale star formation constructed from small-scale relations. Needs gas column densities and shielding to form H_2, thus SF depends on **metallicity**.



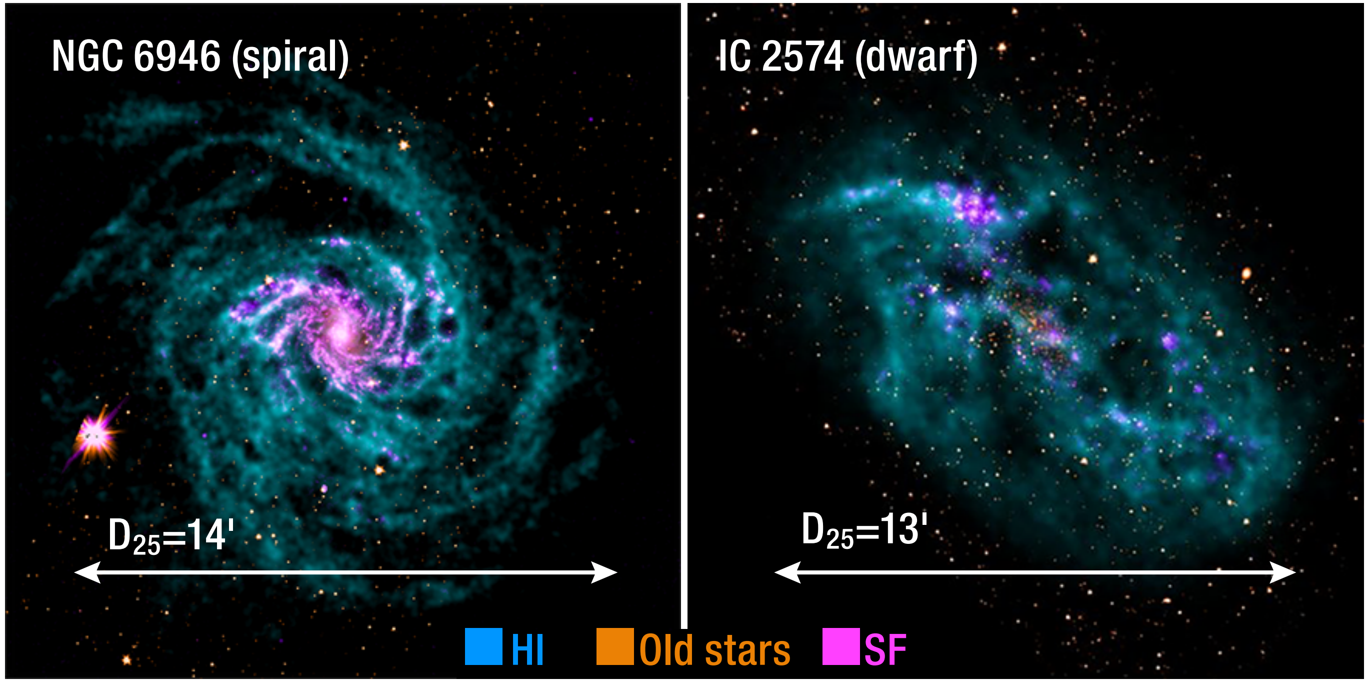


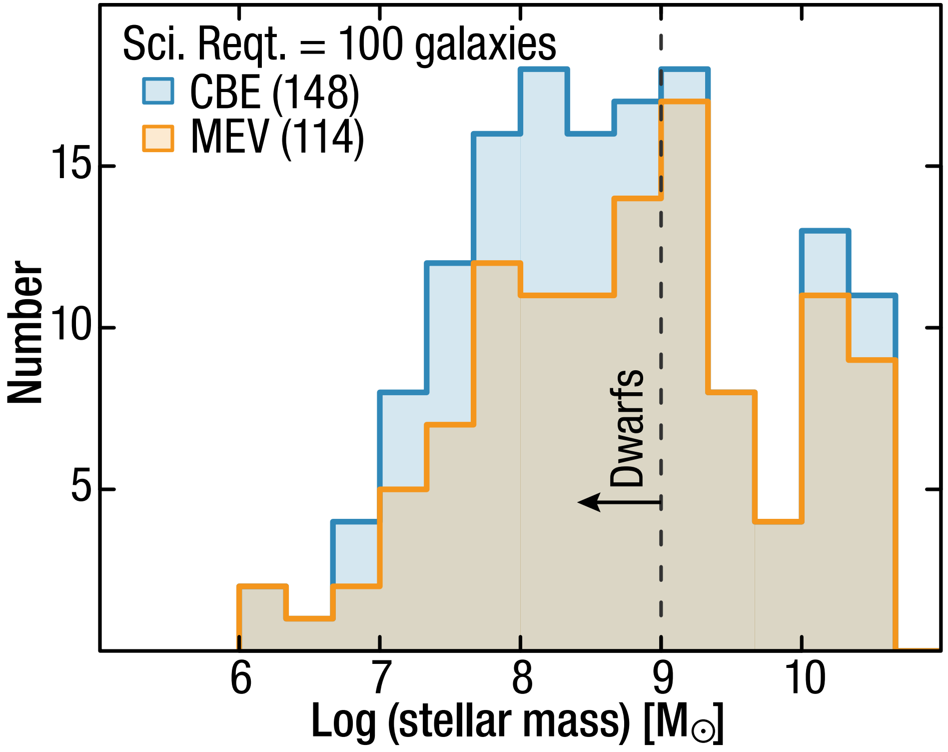



Dense molecular cloud
PDR
H_2, CO, [CI]
H_2, [CI], [OI]
H_2, [CII], [OI]
HI, [CII], H_2O
HII region
[OIII], [NII]
H_2, CO, [CI]
HI, [CII]
HII, [NII], [CII]
Warm ionized medium
HII, [NII], [CII]
Warm neutral medium
HI, [CII]
Cold neutral medium
HI, [CII]

SO #5: Dominant Mode of Star Formation in Galaxies

Objective: Distinguish between two competing models (top-down and bottom-up), map the ionized gas distribution in the multi-phase medium of galaxies down to dwarf galaxy masses of 10^6 $M_\odot$.





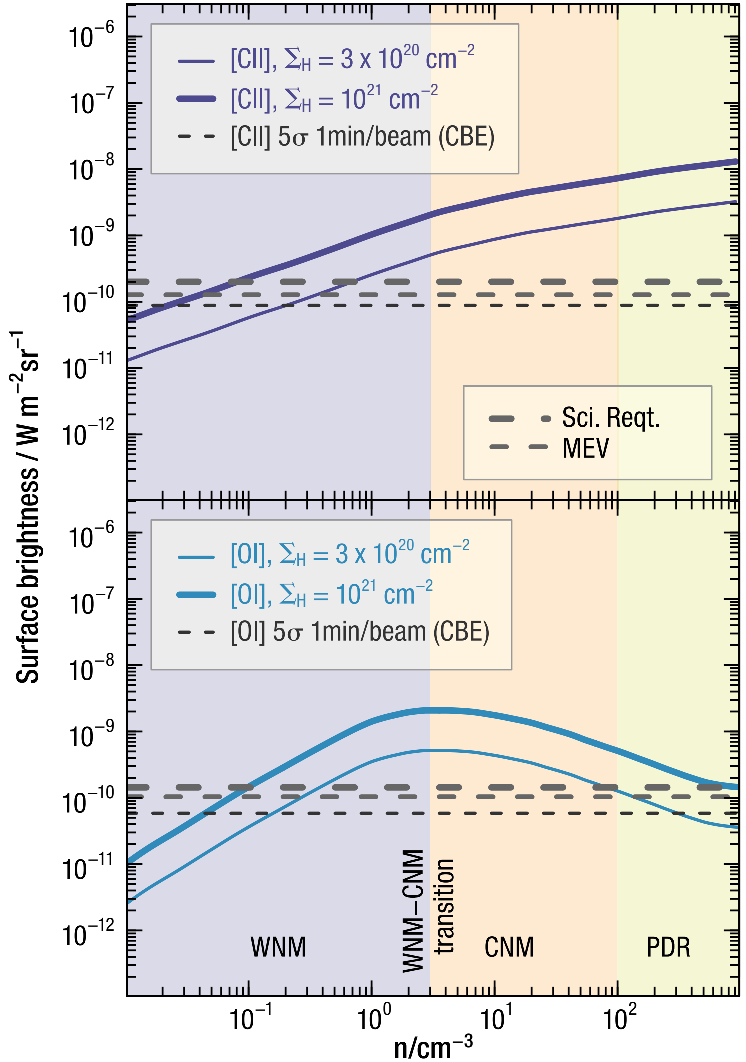
Selected from the volume-limited (D ≈ 11Mpc) Nearby Galaxy Catalogue (NGC).

SO #5: Dominant Mode of Star Formation in Galaxies

Objective: Distinguish between two competing models (top-down and bottom-up), map the ionized gas distribution in the multi-phase medium of galaxies down to dwarf galaxy masses of $10^6\ M_\odot$.

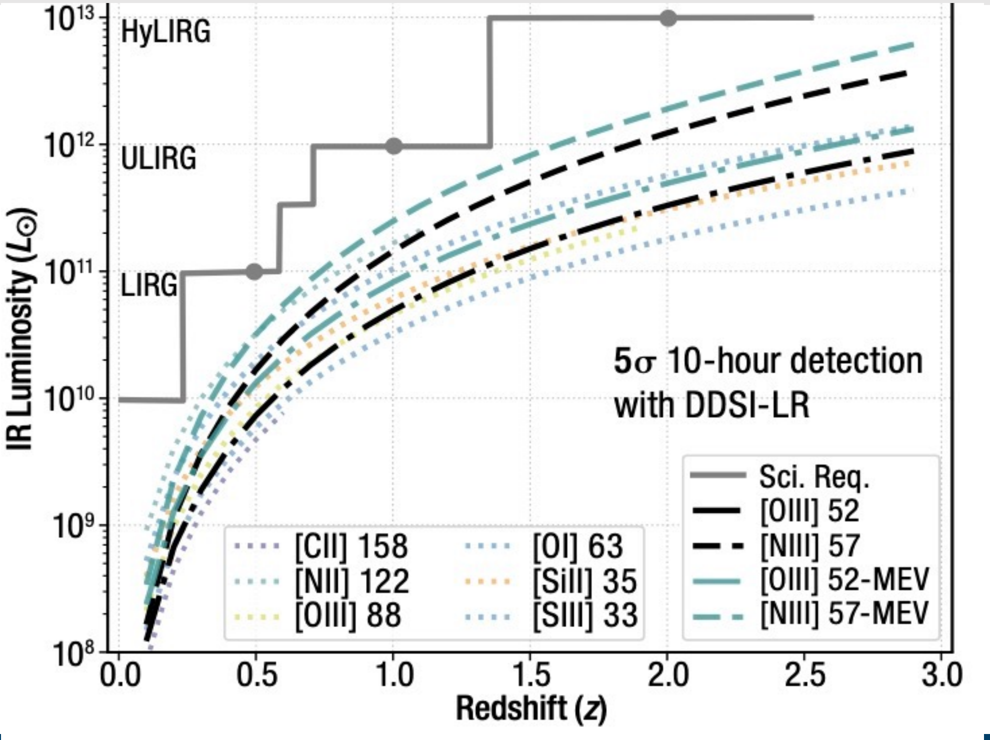
Lines of Interest: Velocity-resolved emission line maps of [OI], [NII], and [CII] for 150 galaxies selected form a volume limited nearby galaxy sample spanning a range of stellar mass and metallicity, over 1600 hours.

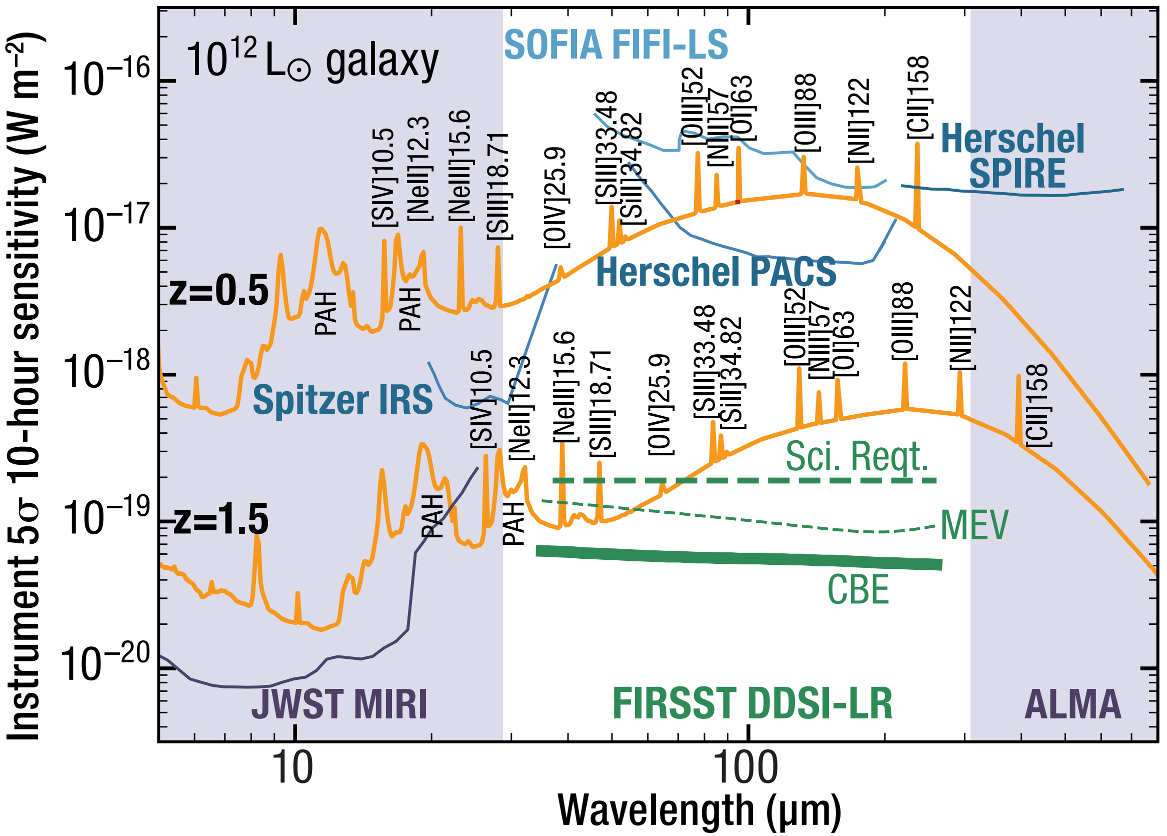
Requirements: Per-pixel line surface brightness sensitivity of [C II] 158 μm at 2.5×10^{-11} W m^{-2} sr^{-1} at 5σ in 1 hour, R (λ/Δλ) ≥ 10,000, and angular resolution < 25" at 158μm for kpc physical scales and ≥ 2 pixels for mapping speed.



SO #6: Galaxy mass growth over cosmic history

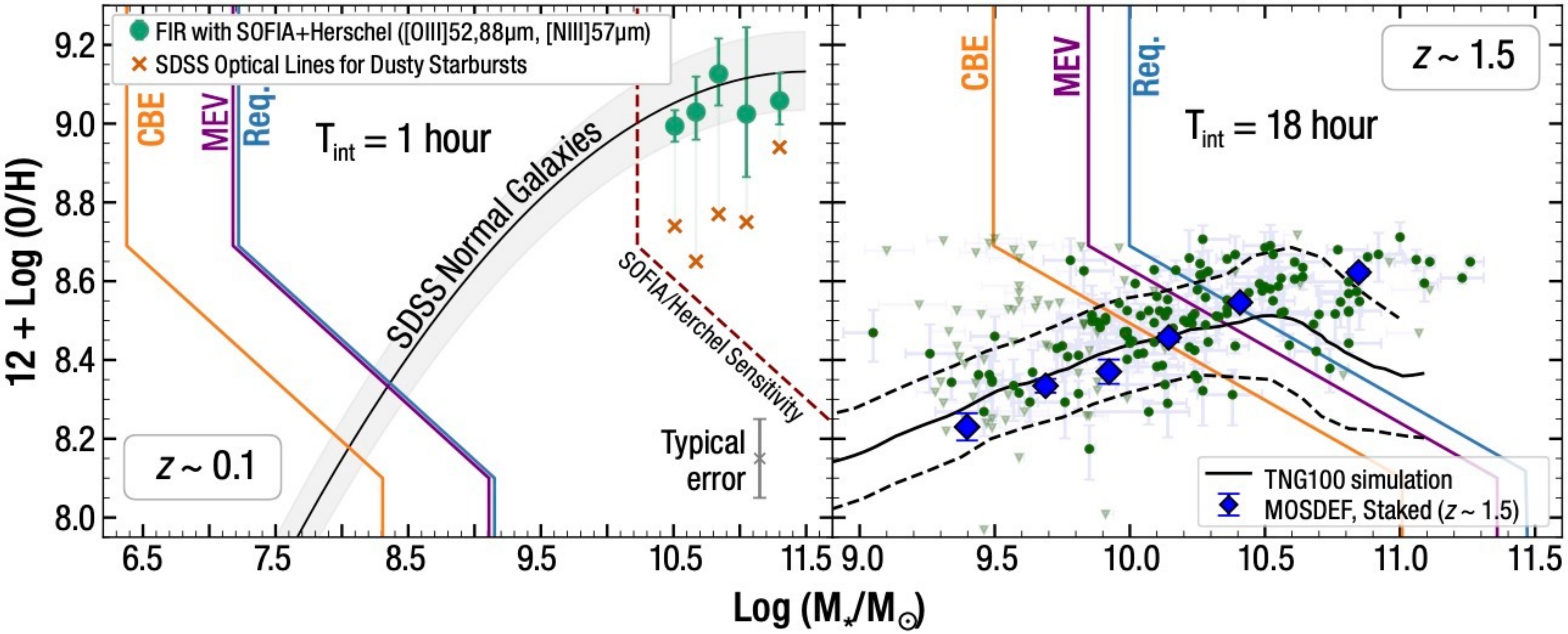
Objective: Establish the mass growth rate of galaxies using the evolution of O/H abundance, conduct a metal line survey out to cosmic noon in bins of redshift, stellar mass, IR luminosity, AGN activity, and environment, down to down to 10^{11} $L_{\odot}$ at z=0.5, 10^{12} $L_{\odot}$ at z > 1.



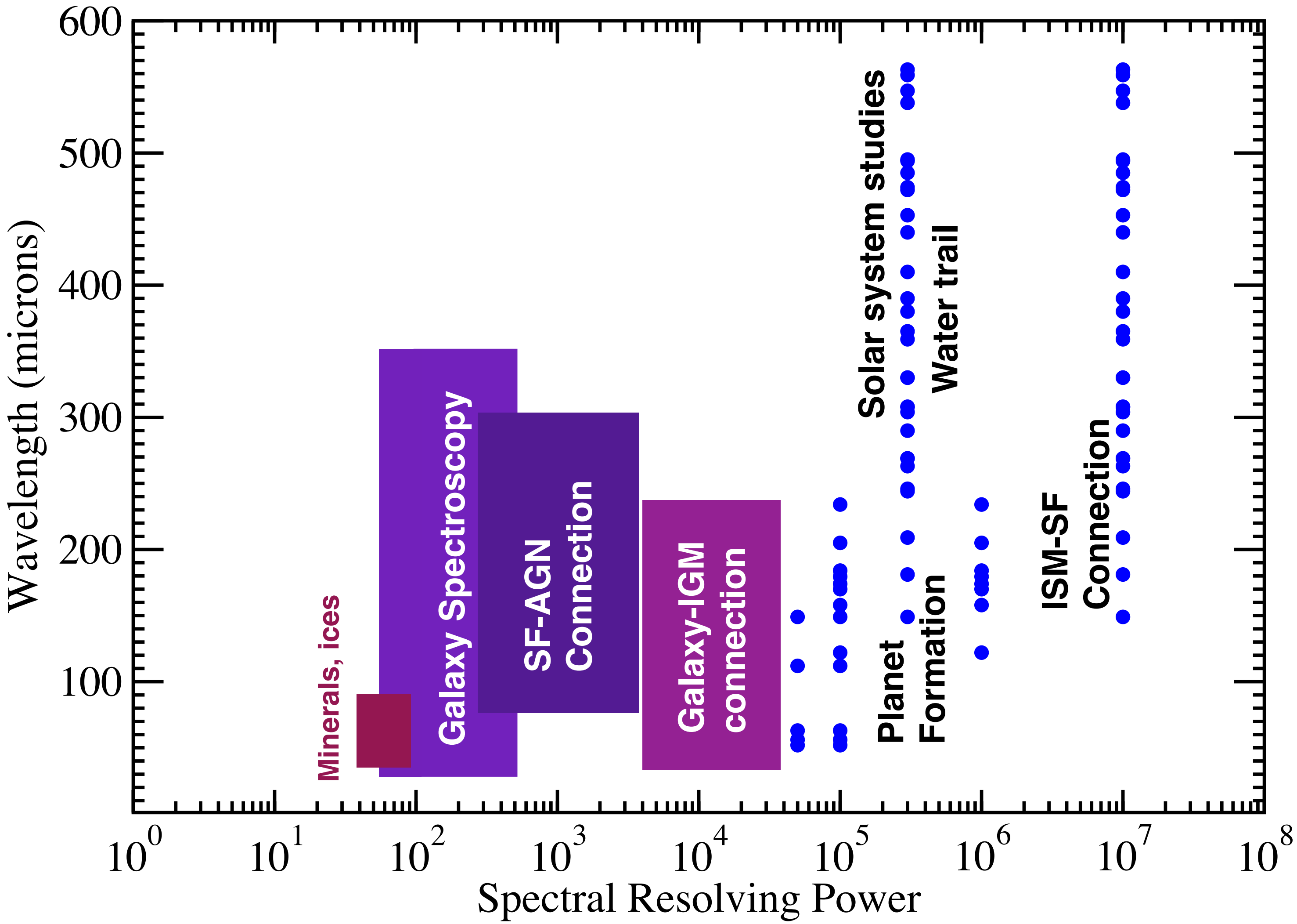


SO #6: Galaxy mass growth over cosmic history

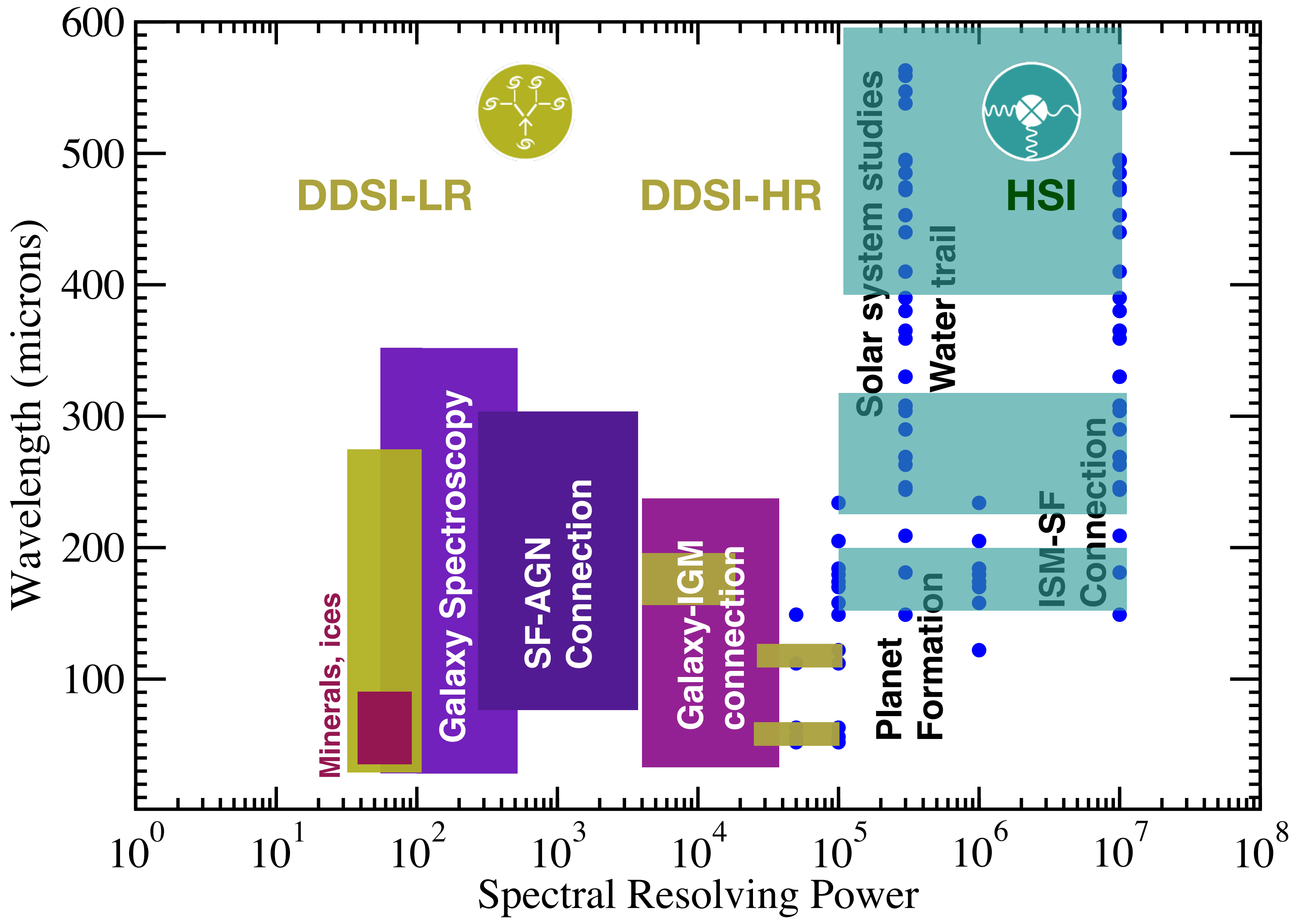
Requirements: Spectral line sensitivity of [NIII]57 μm at 1.9×10^{-19} W m^{-2} of a solar metallicity, 10^{12} L_{sun} galaxy at z=1.0 at 5σ in 10 hours, R (λ/Δλ) = 80 to spectrally resolve lines, ang. resolution < 40" at 114μm to avoid confusion



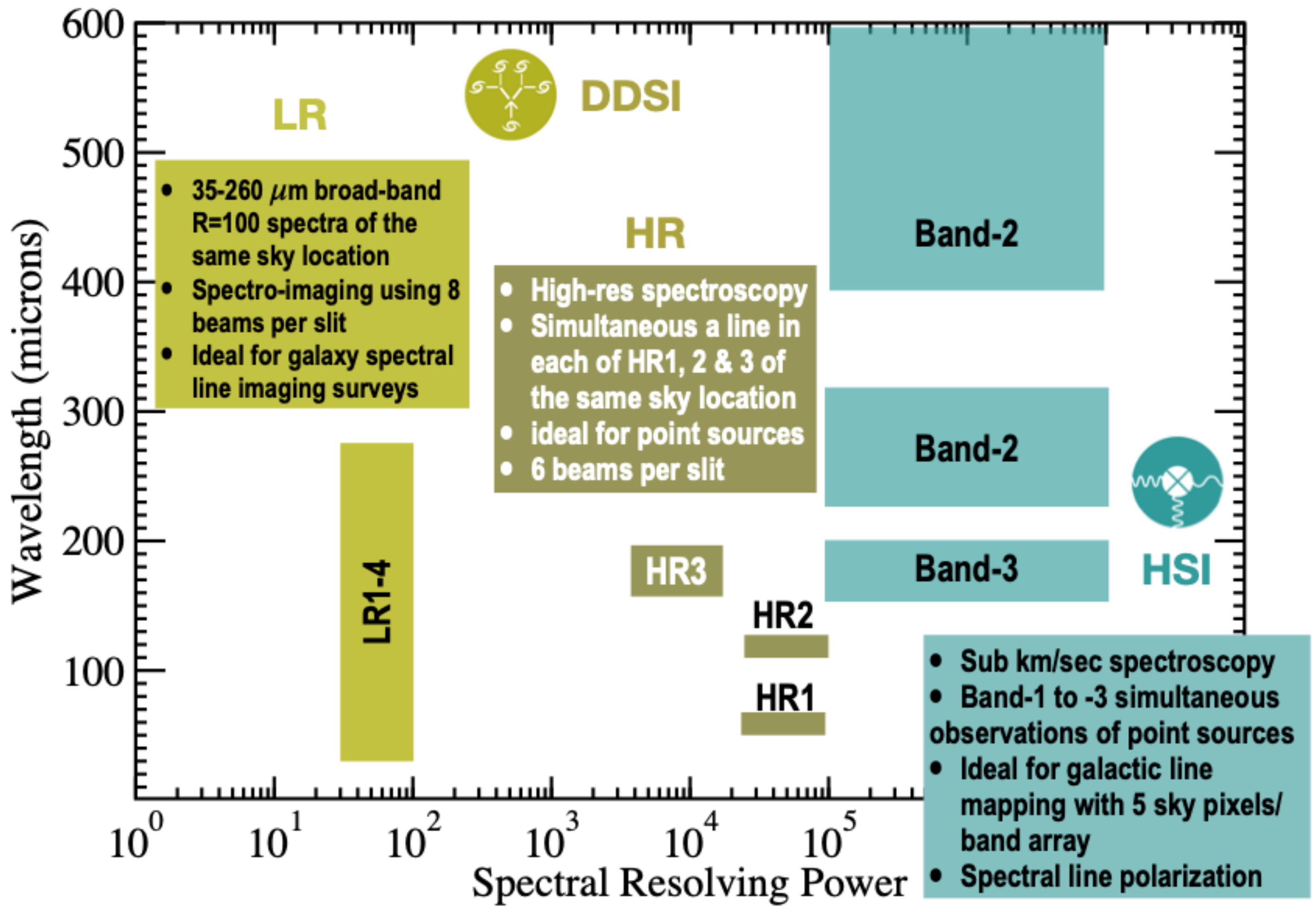
Optimizing the instruments for diverse science objectives



Optimizing the instruments for diverse science objectives



Optimizing the instruments for diverse science objectives



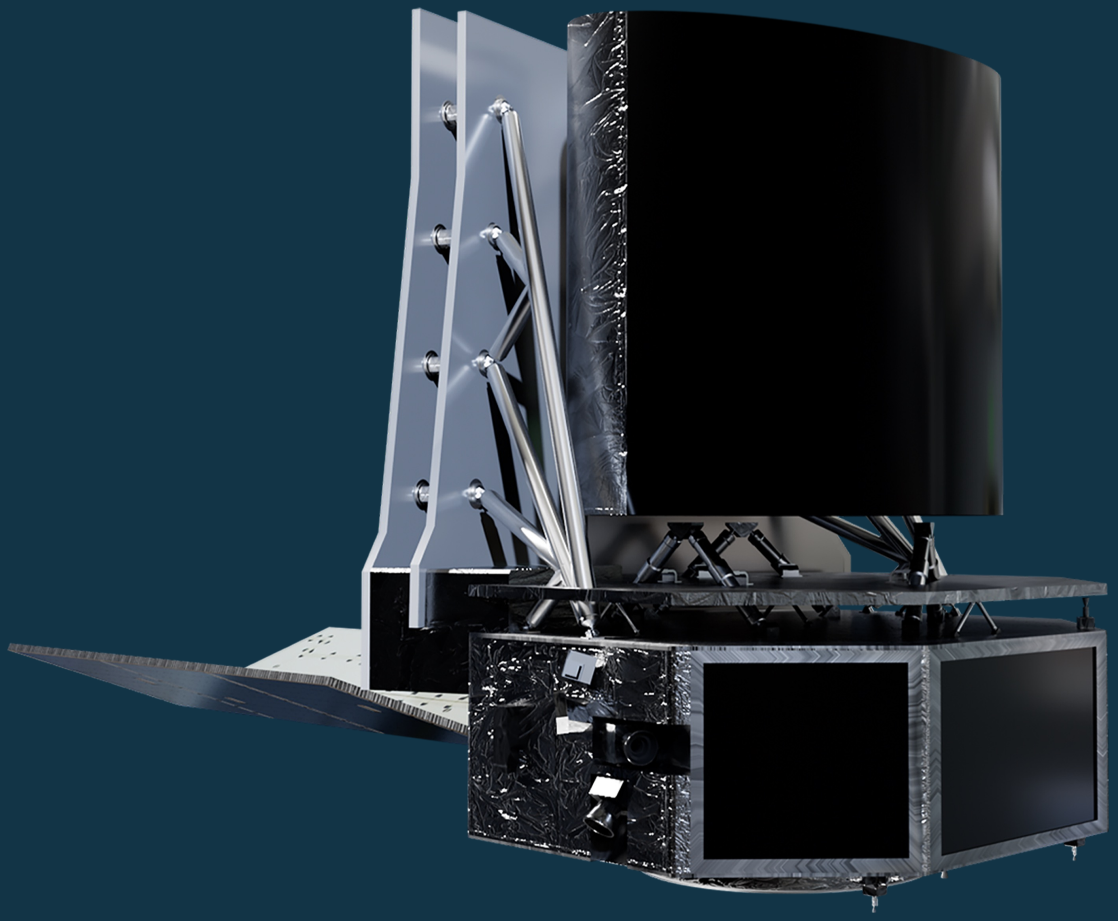
Unique features of FIRSST

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.

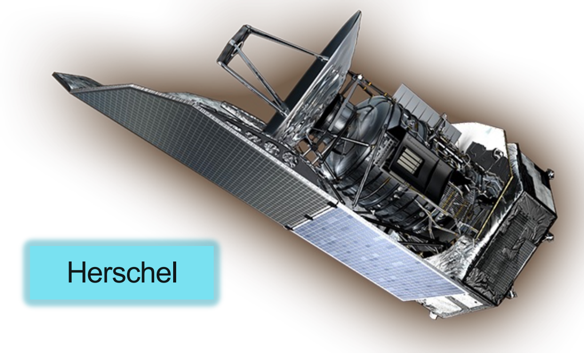
Science observing efficiency > 90%. Rapid response time < 48 hrs. Mission lifetime >= 5 years.



FIRSST Design: Enclosed Architecture

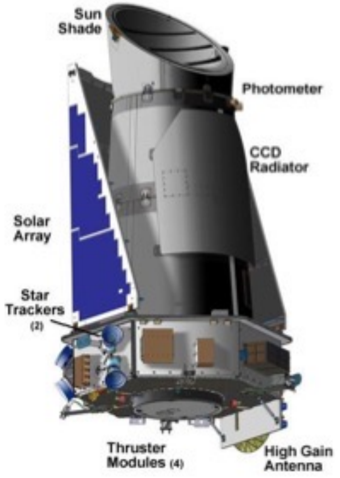
- **FIRSST's enclosed telescope** has several advantages compared to an open architecture.
  - **Substantially reduces straylight** and scattered backgrounds.
  - **Limits contamination** and its effects on science performance.
  - **Stabilizes the thermal environment**, and enables the primary mirror to achieve a lower temperature.
  - **Contributes to FIRSST's large FoR (instantaneous field of regard).**
  - **Minimizes systematics.**

Detailed trade studies led at APL and Ball conducted by the FIRSST team showed no real gain with an open design in terms of mass and cost savings vs. mission risks.
Closed architecture also proven by heritage examples.



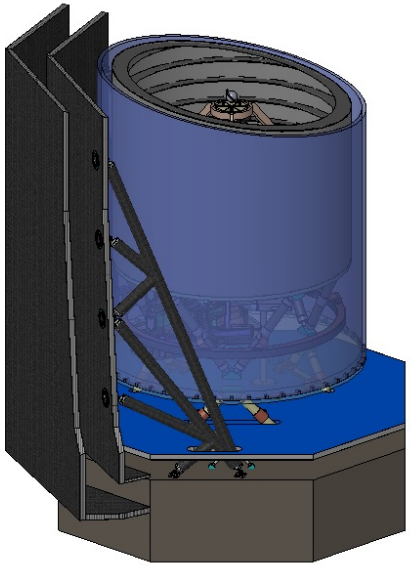
Herschel

Open architecture (Herschel was a passively cooled primary)



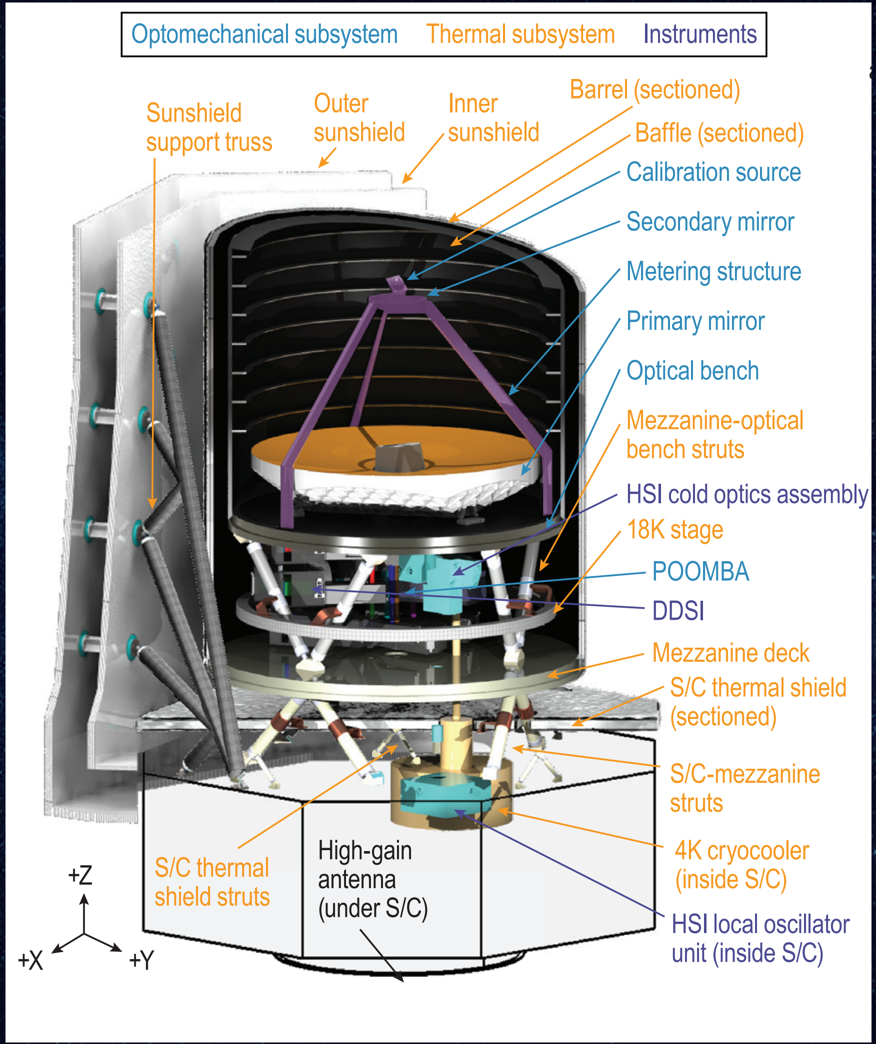
kepler

Spitzer



FIRSST

FIRSST Payload

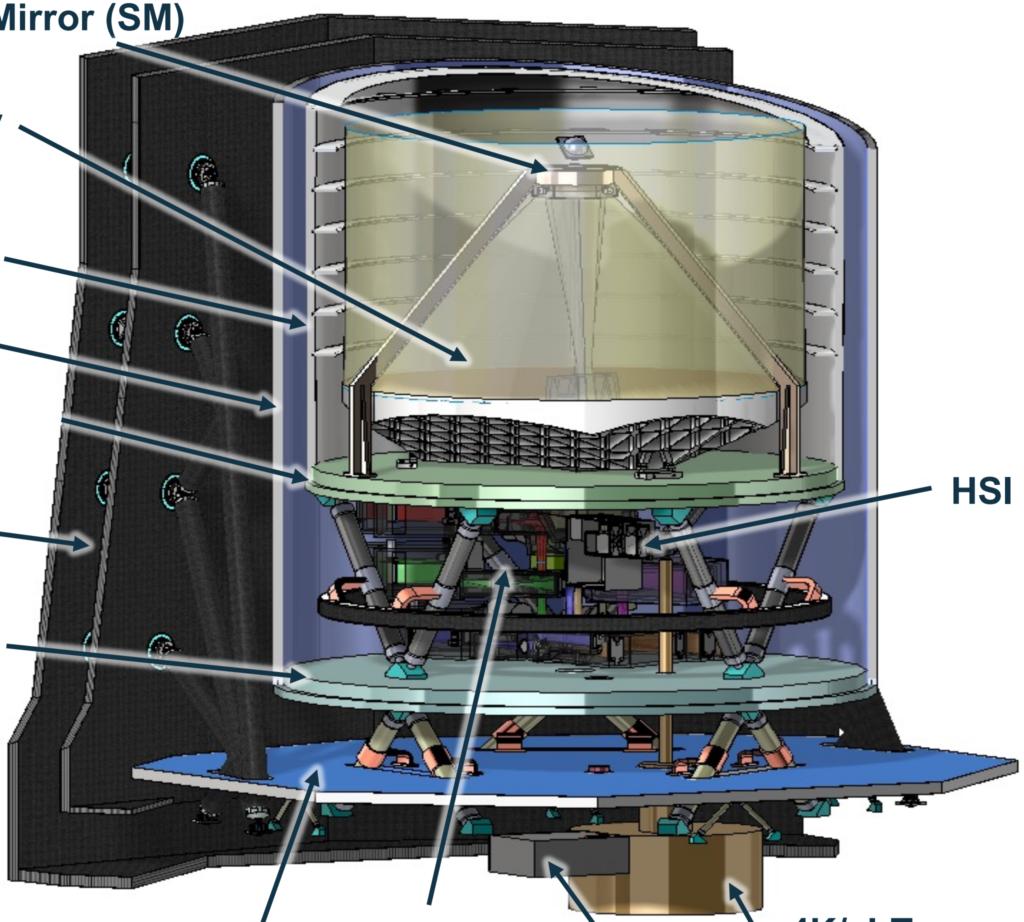


- **Payload has 3 major elements:**
  - **Optomechanical system**
    - 1.8 meter on-axis three mirror anastigmat (TMA).
    - POOMBA: Pick-Off Optics and Mirror Beamsteering Assembly
  - **Thermal Control System including mechanical structure**
    - 4K / J-T Cryocooler
    - ADR (GSFC)
    - Sun Shields, Radiator, Thermal Shield, IMLI.
  - **Instruments**
    - **DDSI:** 4 low resolution and 3 high resolution spectrometers
    - **HSI:** 3 bands
    - Payload Control Electronics, Cryocooler and instrument electronics are all within the SC bus

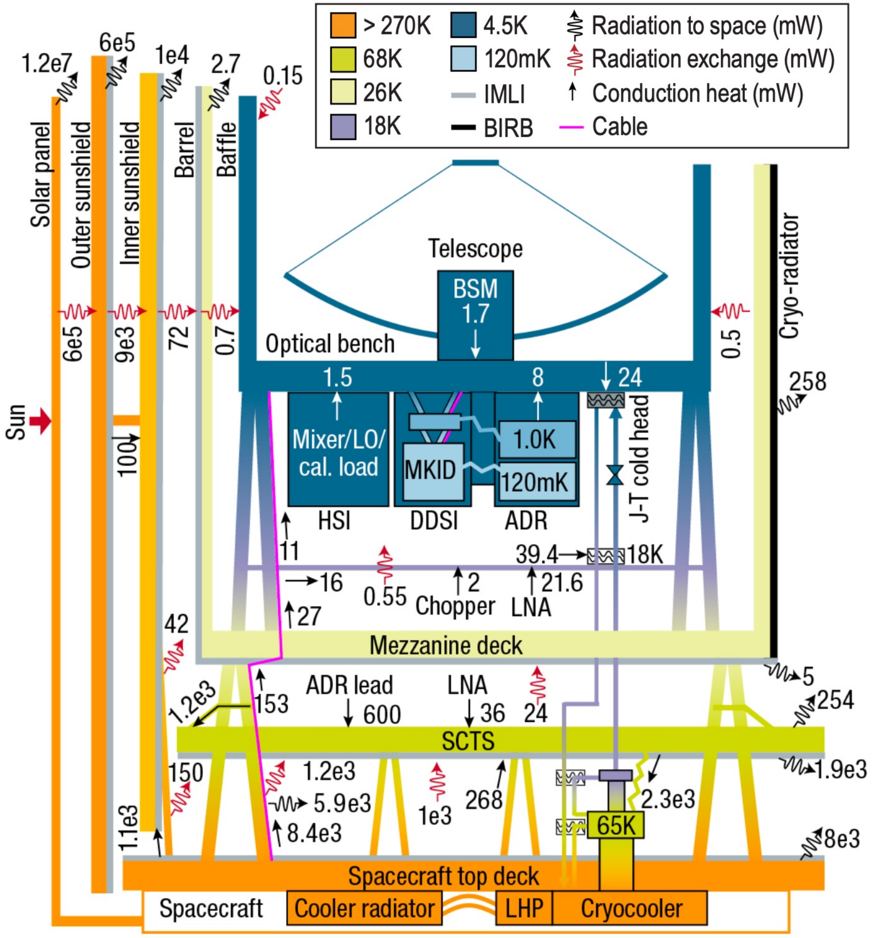
FIRSST Thermal Model

- FIRSST uses the staged design with passive and active cooling systems
  - Robust to the heat load
- Passive elements are leveraged from heritage programs
  - V-groove optimization, IMLI (integrated multilayer insulation)
  - Thermal stages from hot to cold (4.5 K)
    - ✓ Outer sunshield, inner sunshield, barrel, and baffle
    - ✓ Bus top deck, SCTS, mid deck, and optical deck
  - Thermomechanical design of DDSI package
    - ✓ Kevlar suspensions, thermal shield for 120mK thermal straps
- Active elements
  - J-T cryocooler system - Ball proprietary; Landsat 8/9 and other flight heritage, full details in the proposal.
    - Stirling cryocooler (65 K and 18 K)
      - ✓ Pre-cooling J-T cryocooler, cooling LNA and chopper, strut & harness heat intercept
    - J-T cryocooler (4.5 K)
      - ✓ Baffle, Telescope, ADR, BSM, DDSI, and HSI

    Existing cryo-cooler chain comes with vibrational damping requirements
  - ADR (adiabatic demagnetization refrigerator) – GSFC
    - Provide cooling solution for DDSI
      - ✓ 120 mK for DDSI MKID FPAs, 1 K for intermediate heat intercept
      - ✓ Based on Hitomi/XRISM heritage. TRL 9+.

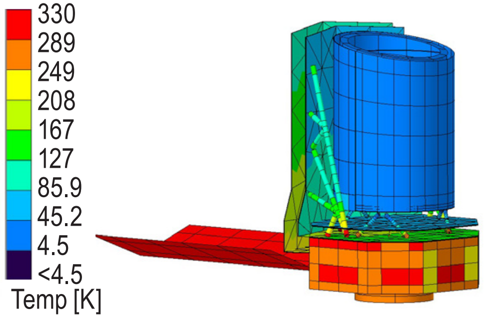


Thermal Margin is the key to mitigate risk

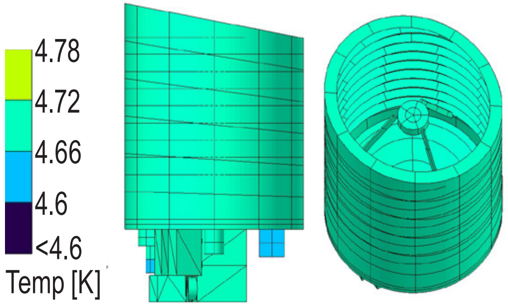


COOLING STAGE	COOLING CAPACITY (mW)	TOTAL CBE (mW)	MARGIN*	COMPONENTS (CBE IN mW)
120mK ADR	0.00409	0.00161	154%	Harness/suspension (0.00161)
1K ADR	0.55	0.196	181%	Harness/suspension (0.196)
4.5K interface 4K cryocooler	54	24.0	125%	ADR (8.0), LO/mixer/cal load (1.5), BSM (1.7), harness (5.2), strut (5.7), radiation (1.9)
18K interface 4K cryocooler	103	24.8 39.4	315% 161%	Chopper (2.0), LNAs (9, 21.6), heat intercept (15.8)
26K cold radiator	N/A	291	N/A	Harness (60), strut (93), radiation (138)
65K interface 4K cryocooler	4900	2290 2310	114% 112%	LNAs (15, 36), radiation (200), ADR lead joule loss (600), heat intercept (1206), strut (268)

Blue: DDSI active. Red: HSI active.
**(Cooling capacity – Total CBE) / Total CBE*
DDSI and HSI do not operate at the same time; both margins shown.



Outer surfaces

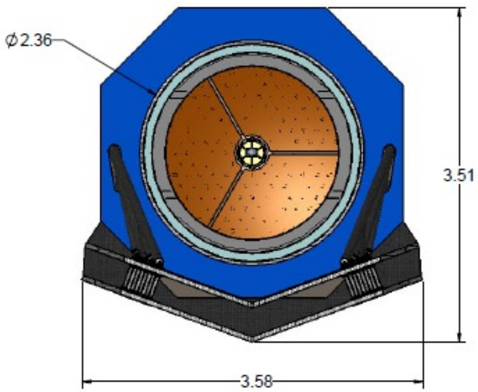


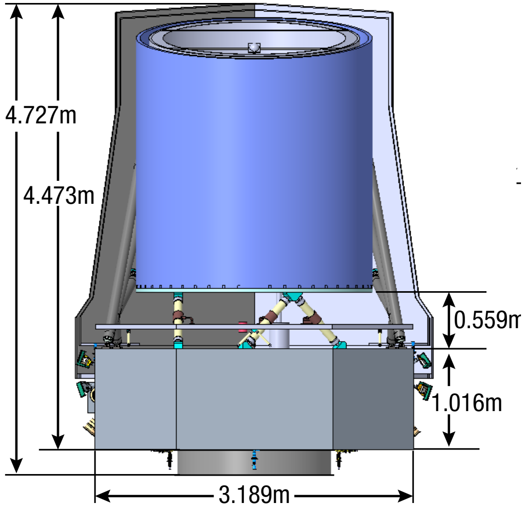
Baffle and instruments

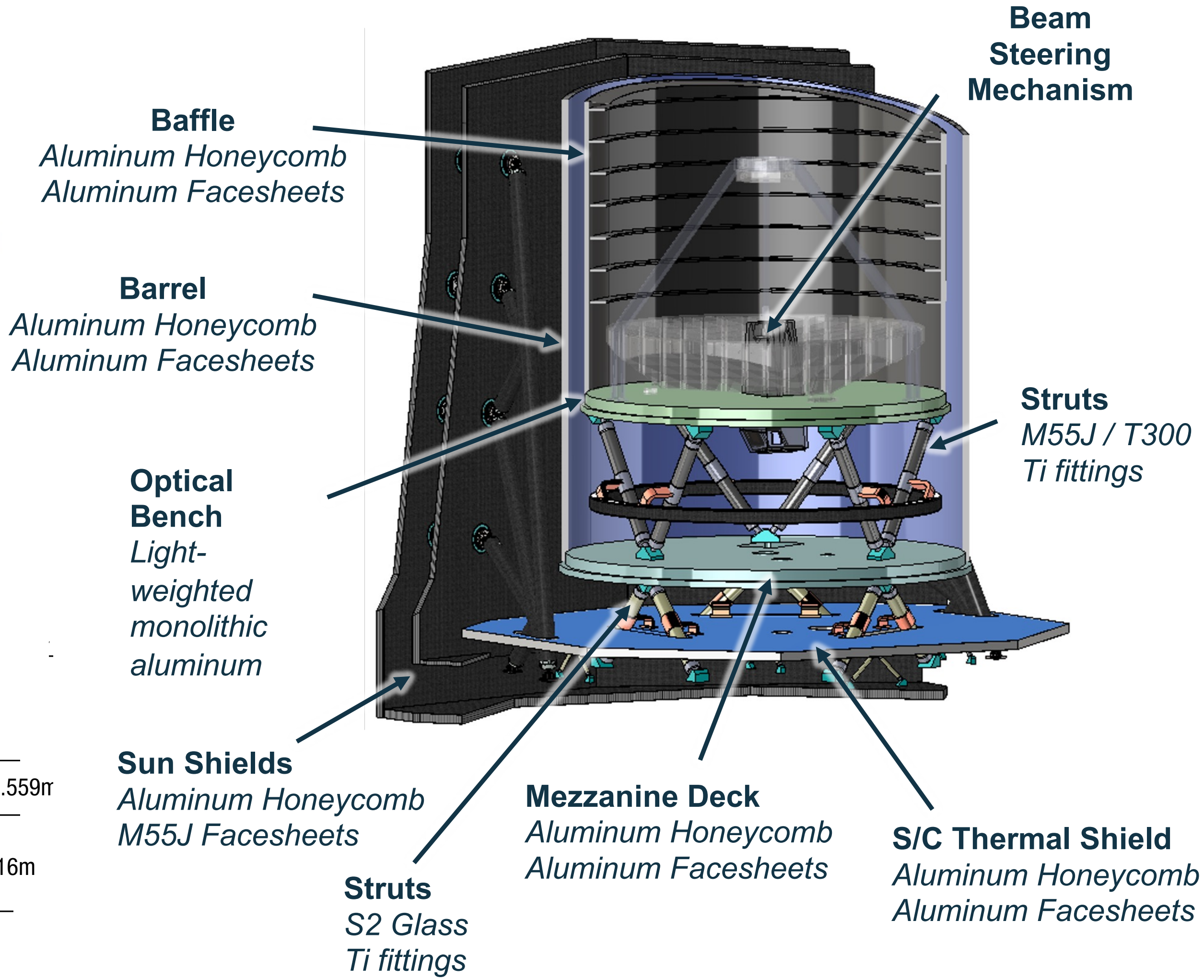
Going into Phase A, FIRSST requires and full observatory thermal models show at least **100% margin** in each cryocooler cooling stage.

FIRSST Structures

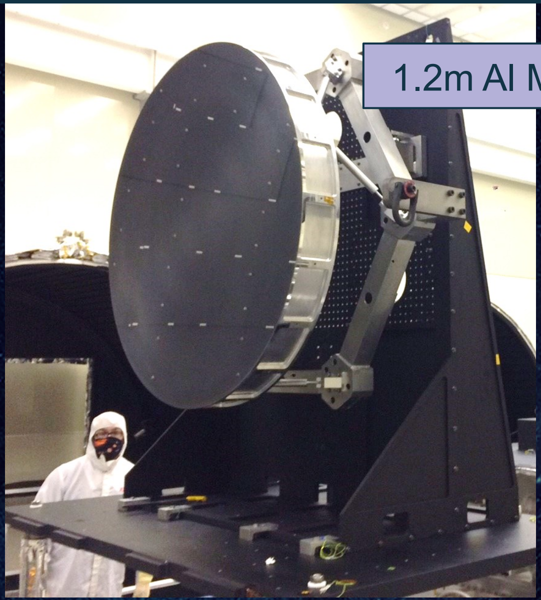
- Enclosed architecture
  - Barrel
    - Controls and stabilizes temperature for 4.5K telescope
    - Enhances contamination control
  - Baffle
    - Limits stray light
- Mechanism
  - Beam Steering Mechanism:
    - Slit Scanning
    - Small FOV mapping (6'x6’)
- Thermal Control System including
  - Outer sun shield extends below SC top deck
  - Inner sunshield
  - Radiator, S/C Thermal Shield, IMLI, etc.
- Structural Support
  - Struts between decks
  - Struts supporting thermal shields





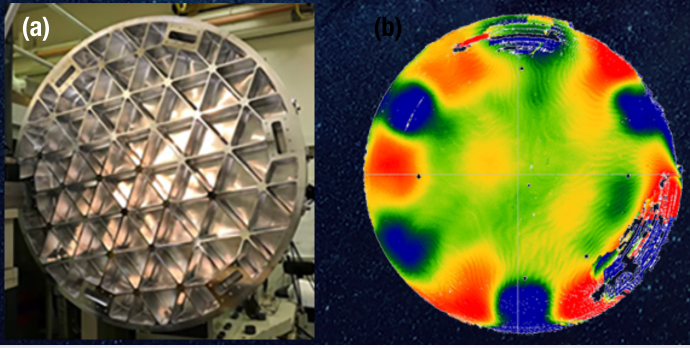


Telescope Key Flowed-Down Requirements



1.2m Al Mirror at MSFC

Marshall Space Flight Center

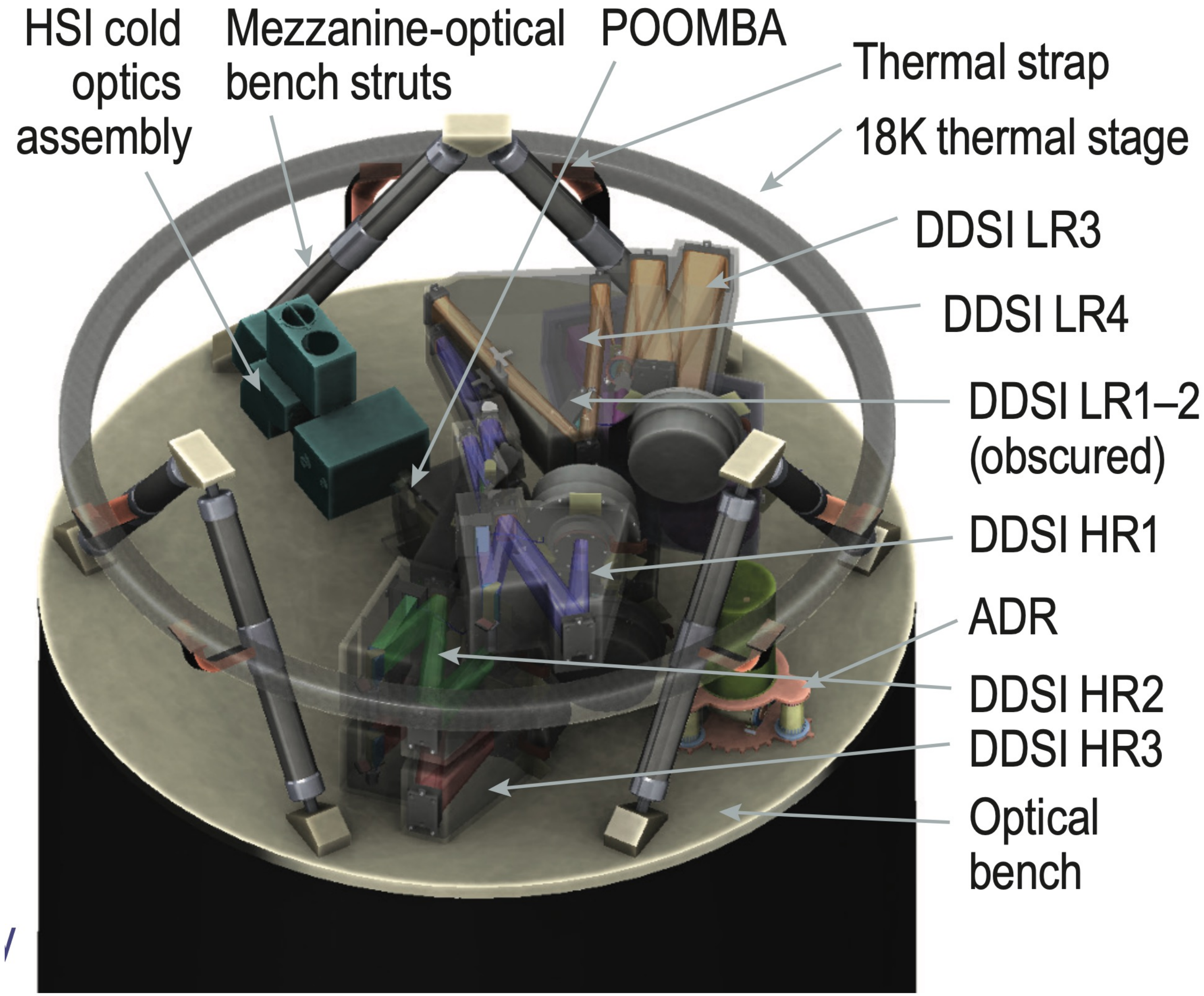


TELESCOPE (OTA)	
Height	<2m
Design form	Three-mirror anastigmat
Magnification	24.4X
F/#	7.3
Material (all mirrors)	6061 aluminum
Manufacture (all mirrors)	Diamond turn
Coating (all mirrors)	Gold
PM (PROCURED FROM MSFC)	
Clear aperture and full diameters	1.8m CA (1.85m full)
Mass (CBE with lightweighting)	282kg
Lightweighting factor	86%
F/#	0.735
RMS surface roughness	100nm
Provider	MSFC

Manufacturing capabilities have been proven at Marshall Space Flight Center with heritage of 1.2 m Al mirror

All Telescope requirements are achievable with FIRSST design

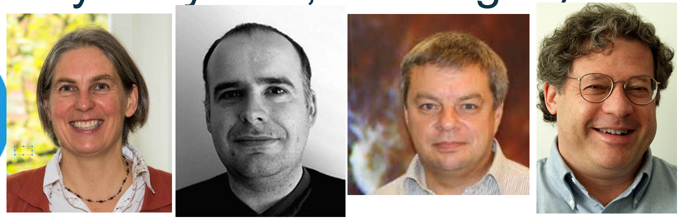
Science Implementation: Instruments



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%		

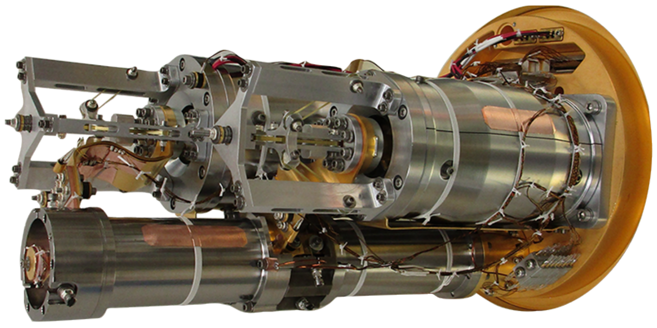
DDSI OPTICAL EFFICIENCIES

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

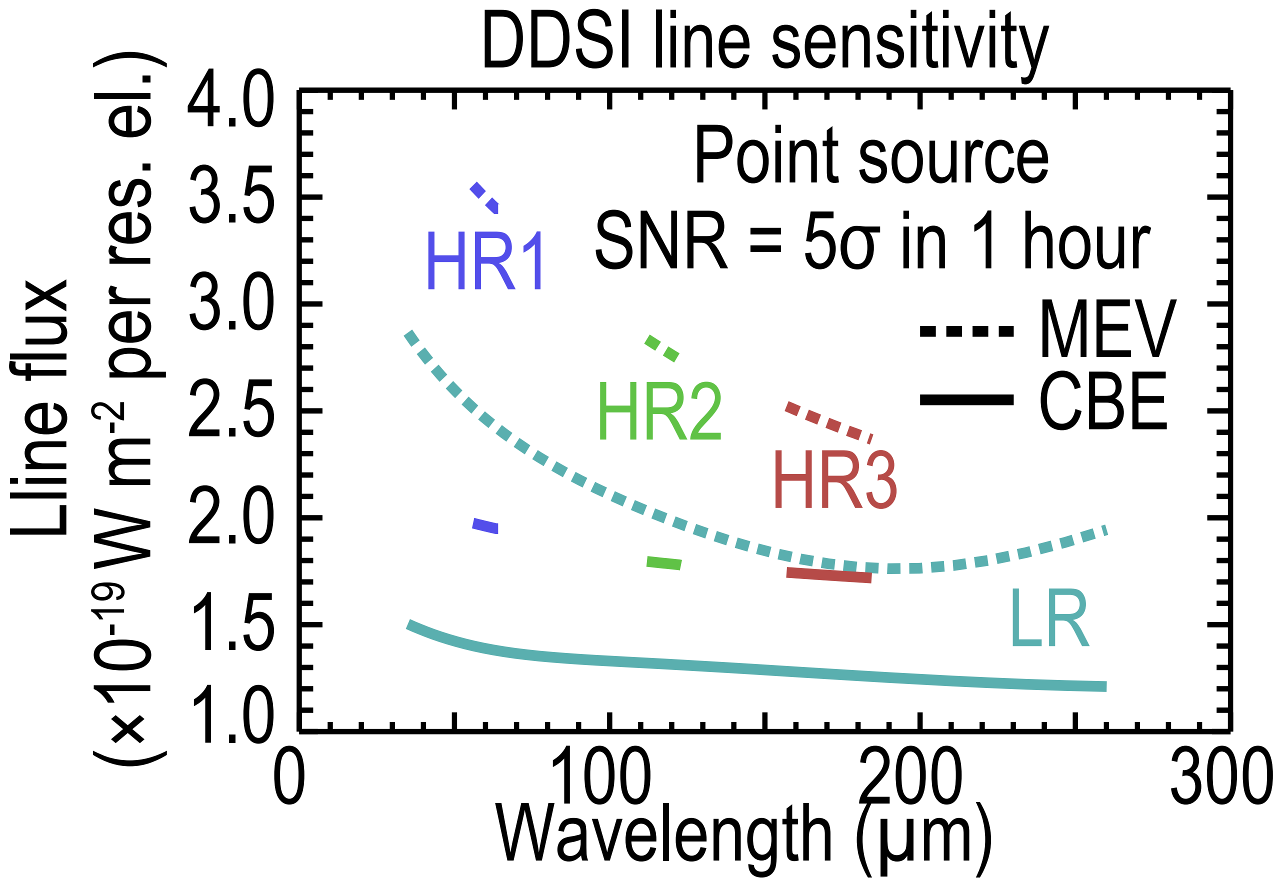
DDSI SENSITIVITY CALCULATIONS

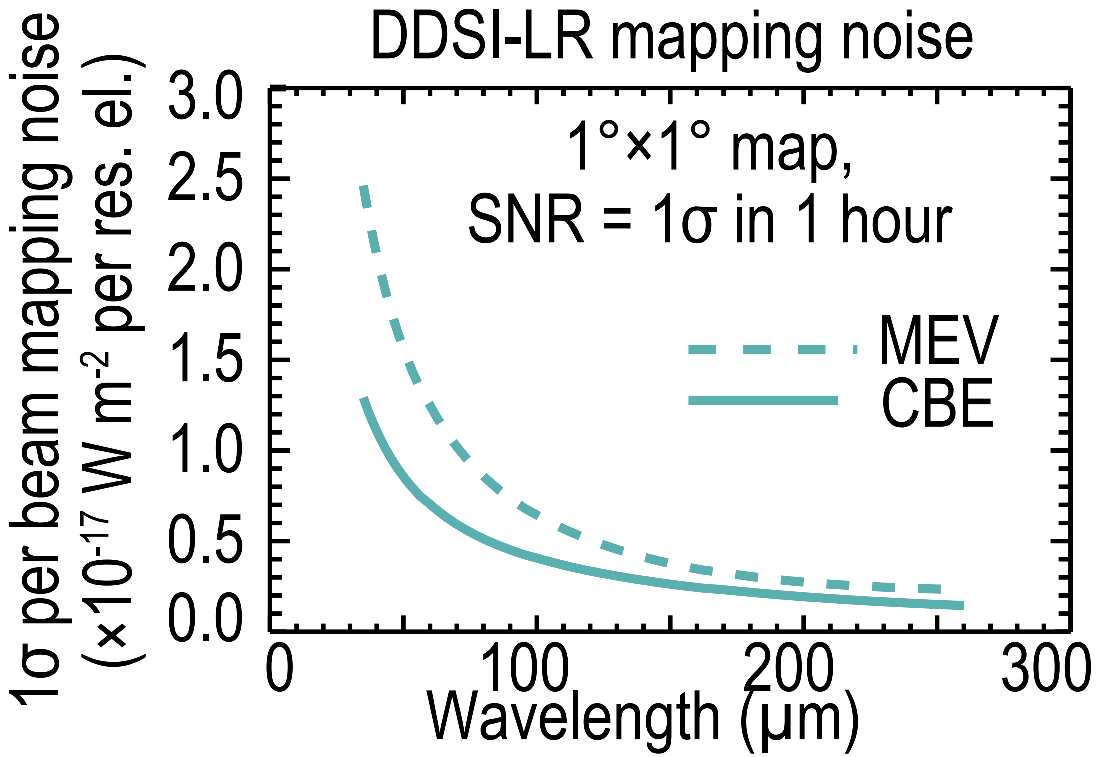
DDSI is detector noise-dominated (negligible photon noise) for telescope temperature (CBE 4.7K) and emissivity (2%): $NEF = NEP_{detector} / (A_{tel}\,\eta_{opt}\,\eta_{det}\,\eta_{mod})$		LR	HR
A_{tel}	Telescope collecting area (m^2)	2.47	
η_{det}	PSF to absorbed power at detector efficiency	0.4	
η_{mod}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

Sub-K ADR
Heritage: Hitomi/XRISM



Science Implementation: DDSI

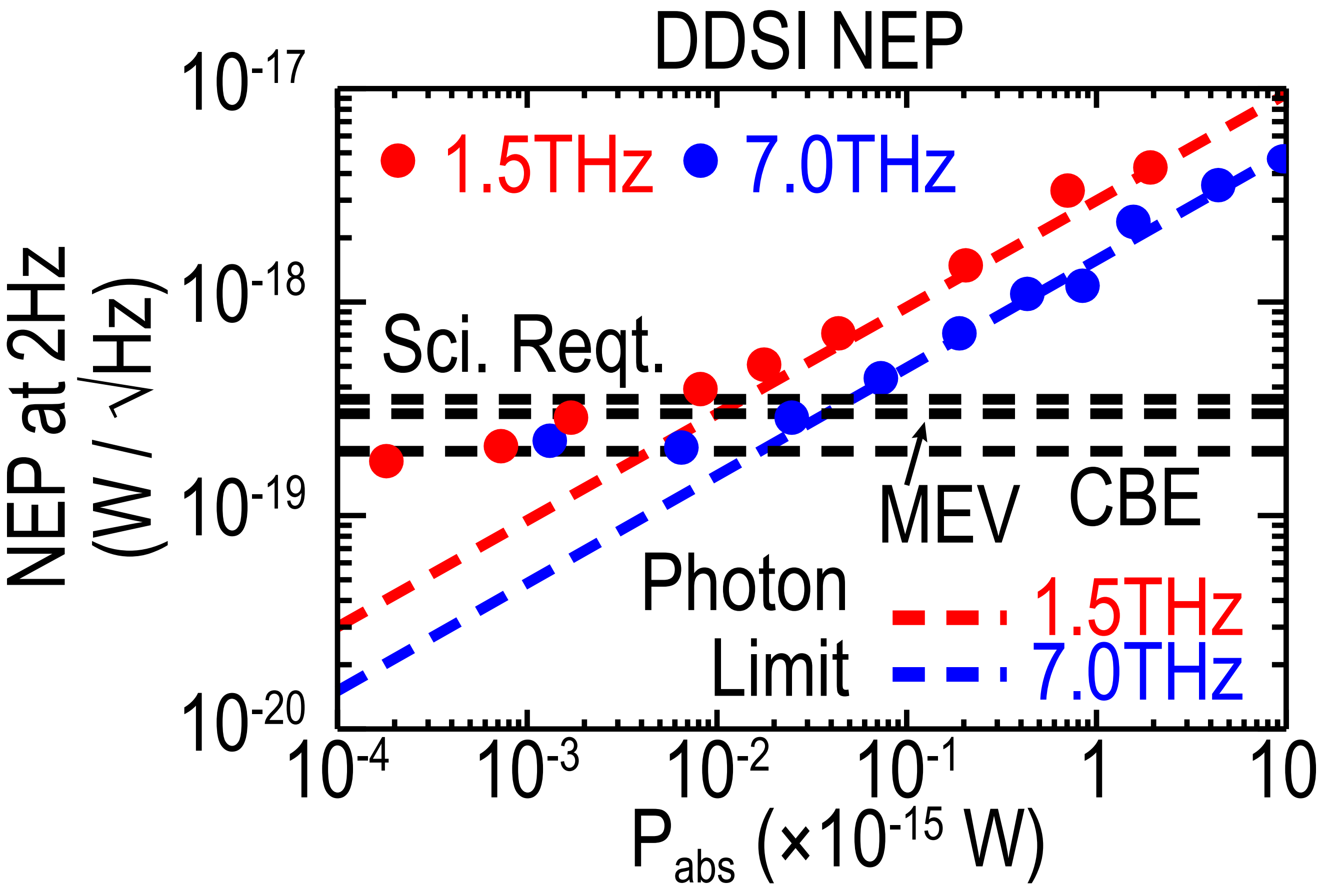


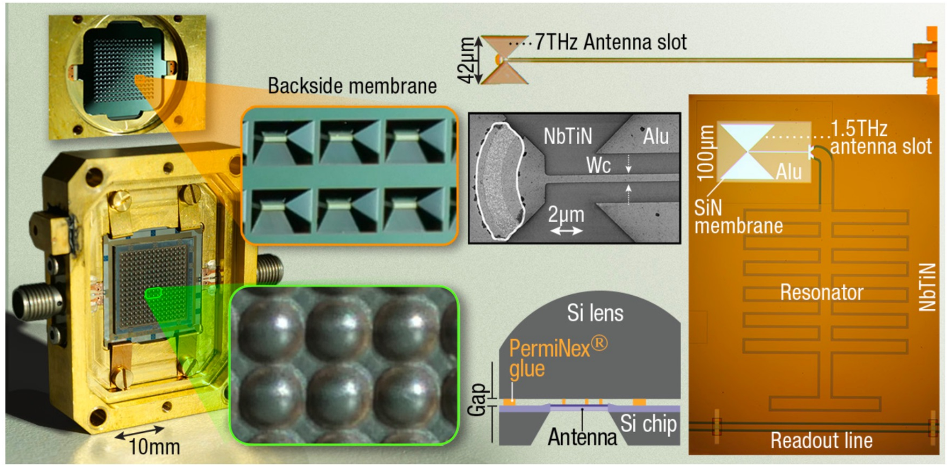


1. In LR mode, instantaneous 35-260 μm R=100 spectrum. Or map extended areas with slit movement.
2. In HR mode, instantaneous a line each in HR1 (R=89,000), HR2 (R=100,000), HR3 (R=20,000).

Science Implementation: DDSI

MKIDs detector requirements



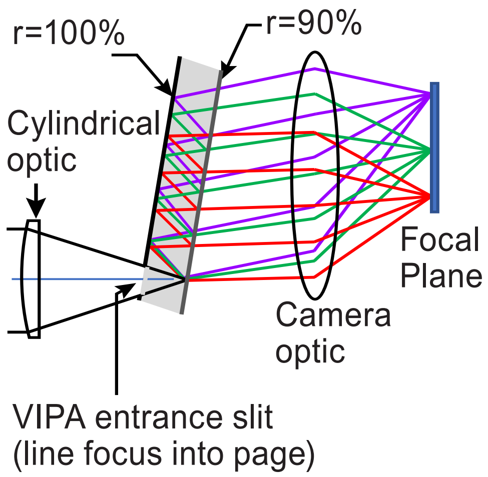


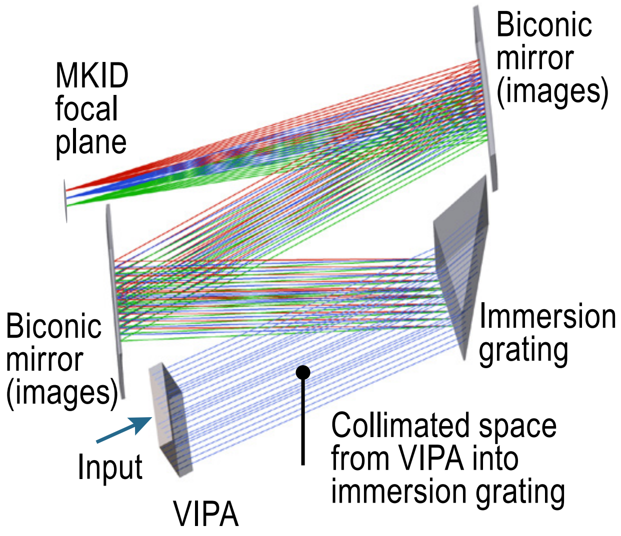
7 FPAs with a total of 2162 pixels (each array is about 348-392 pixels).

Vendor:

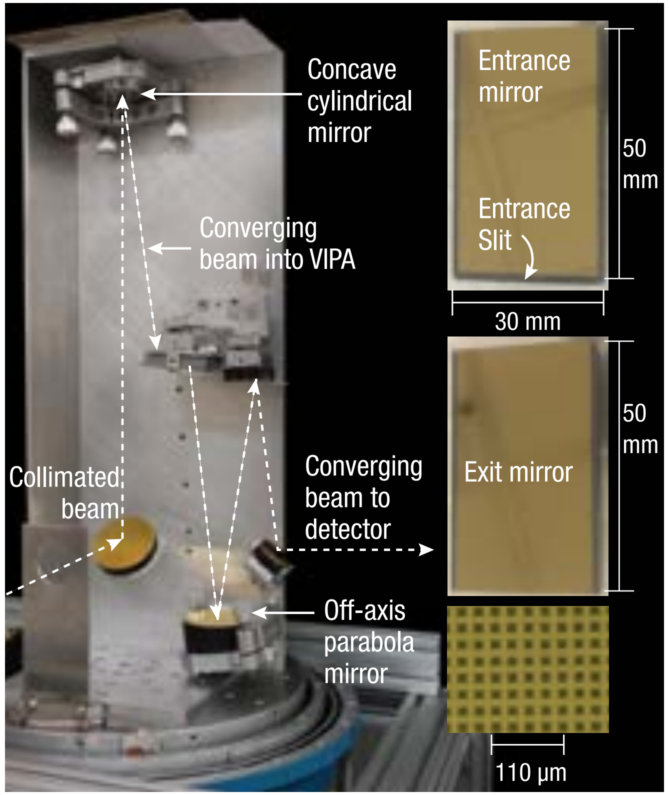
SRON Netherlands Institute for Space Research

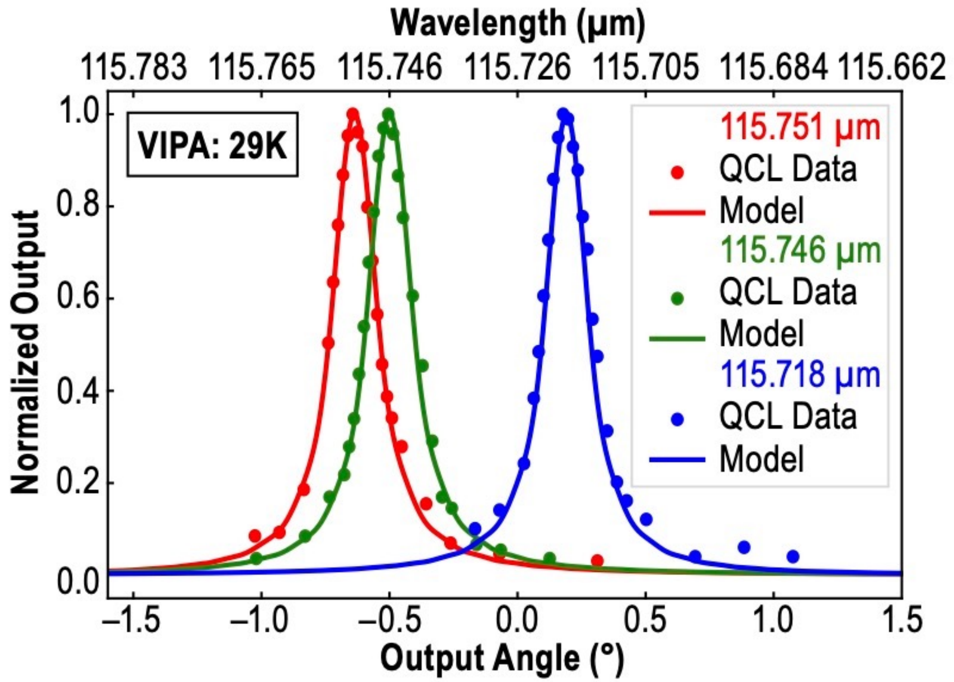
Science Implementation: DDSI-HR 3 bands





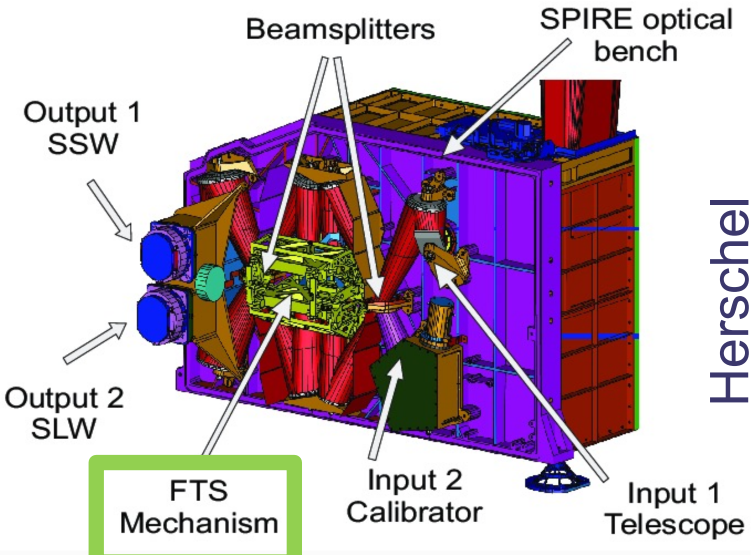
VIPAs (virtually imaged phase arrays)



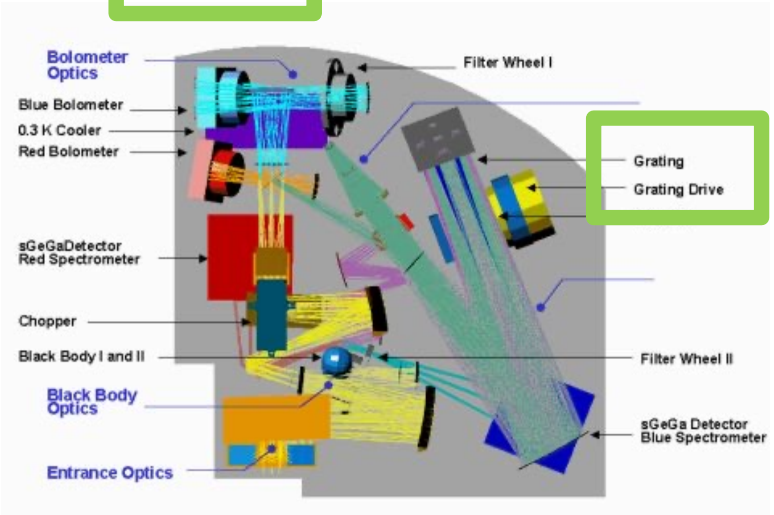


1. TRL 5 demonstration at Cornell for a R=15,000 at 29K/R=24,000 4.5K.
2. DDSI-HR2 flight prototype at R=100,000 at 4.5K for TRL 6 by mid 2025.

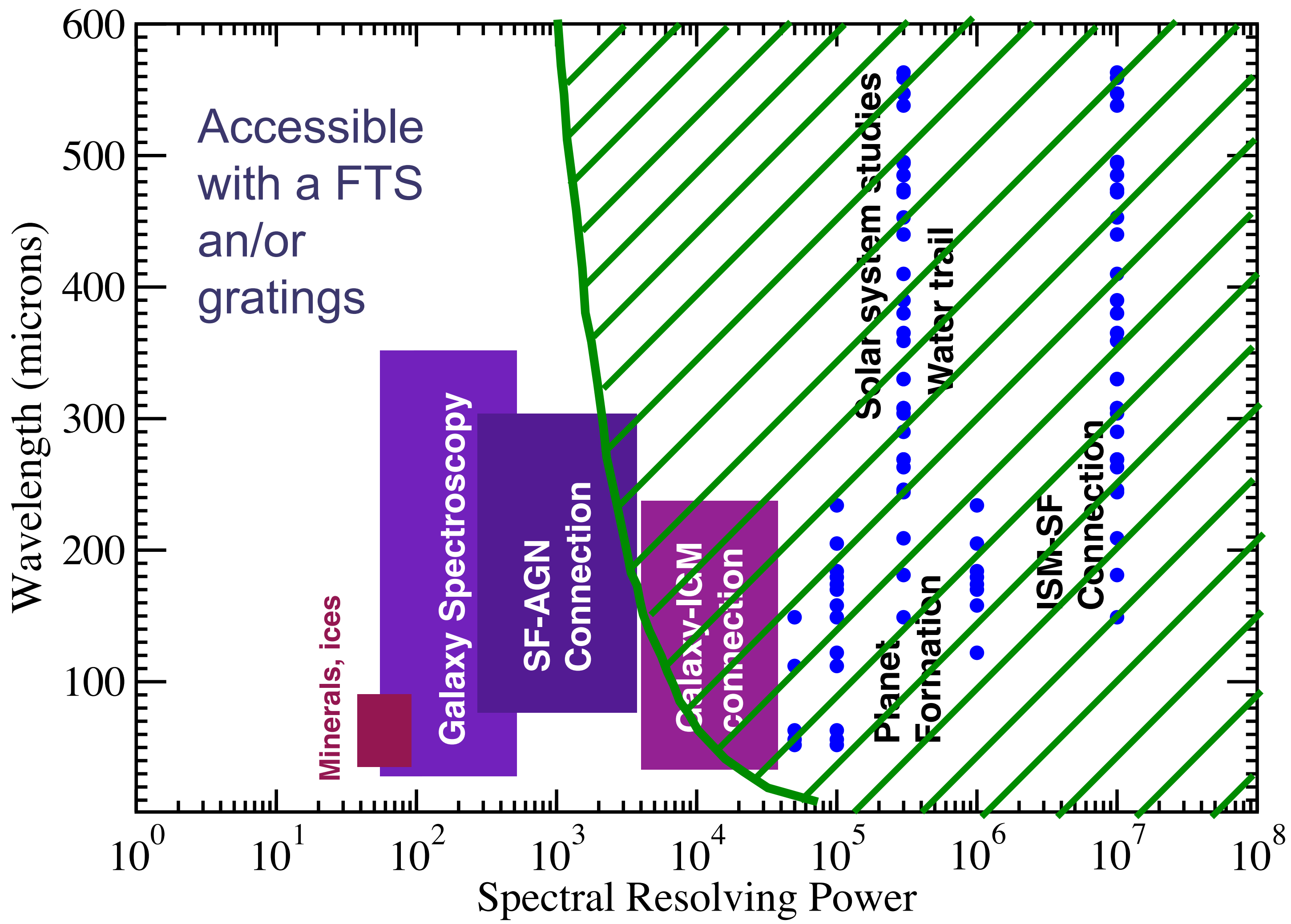
VIPAs vs gratings or an FTS



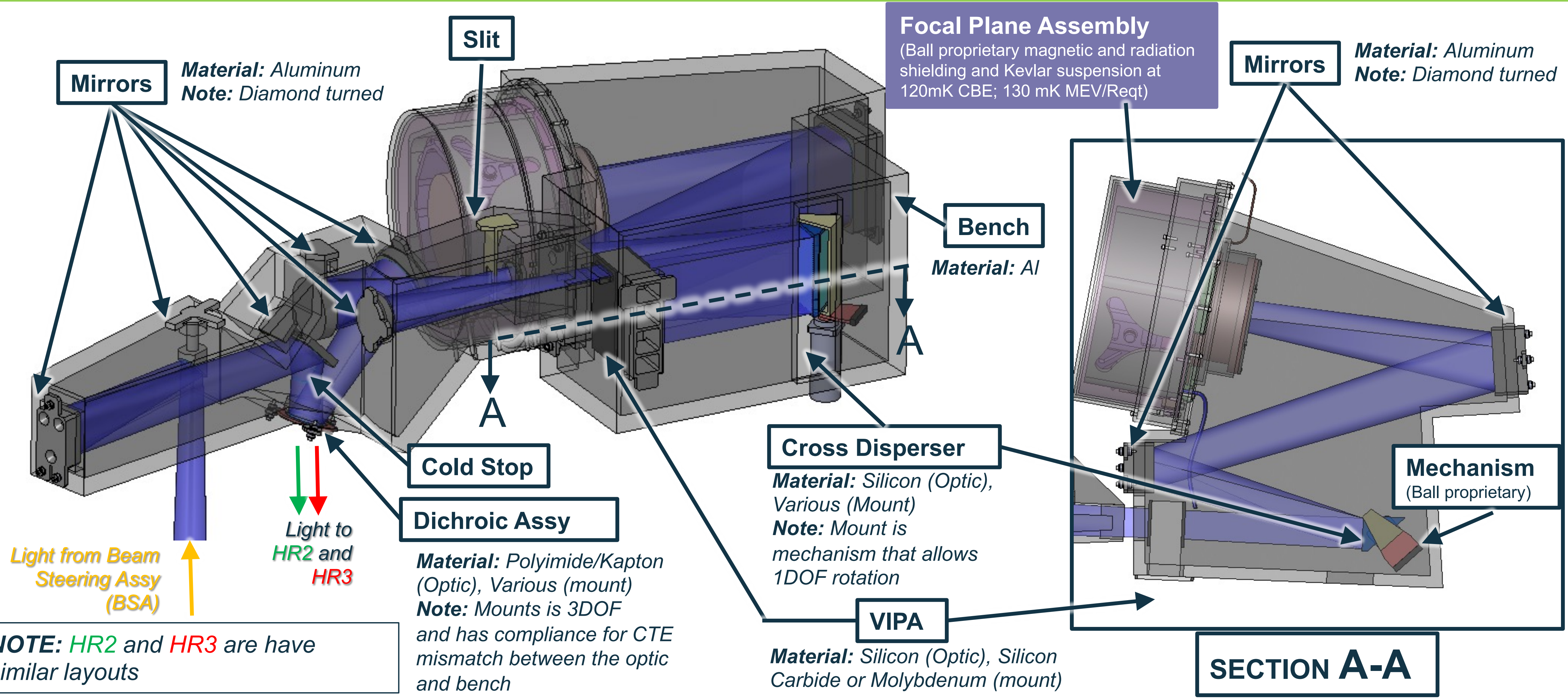
Herschel SPIRE with FTS



Herschel PACS with gratings

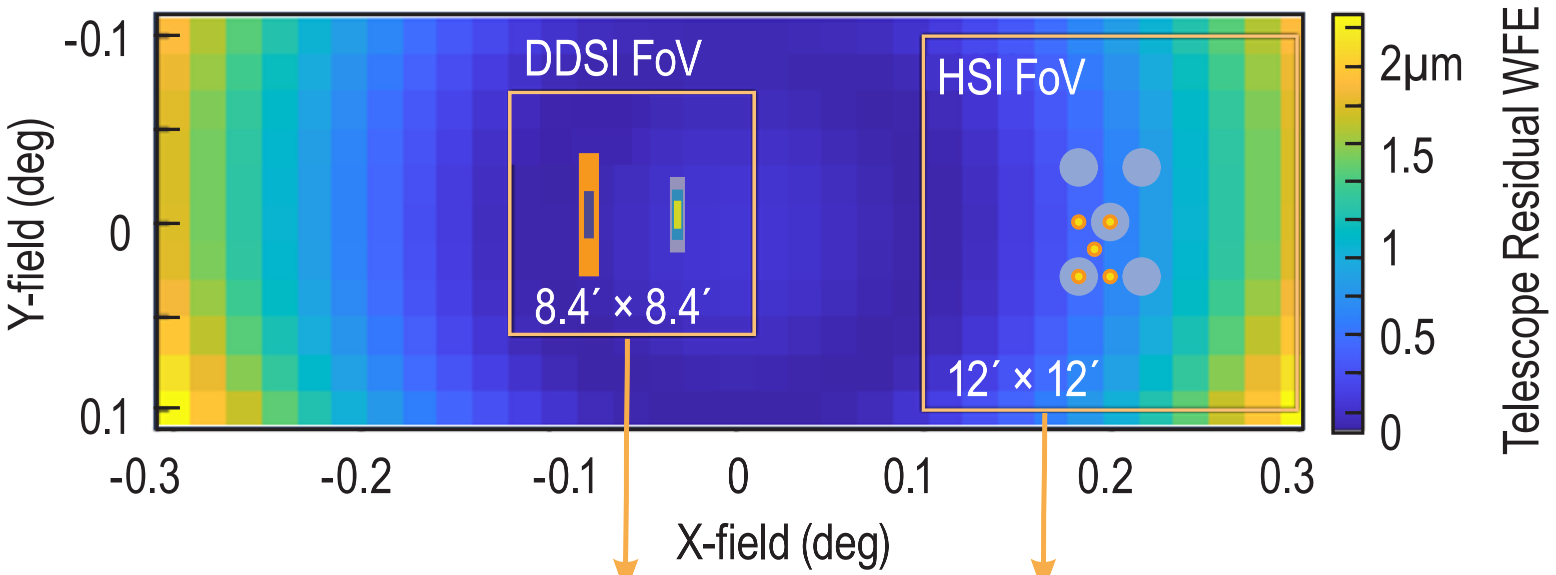


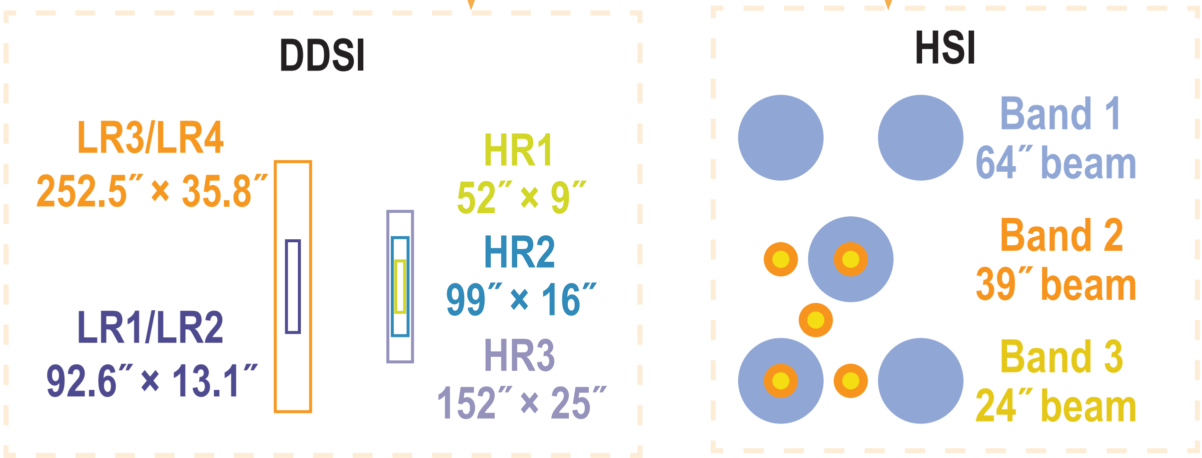
High Resolution Channel 1 (HR1)

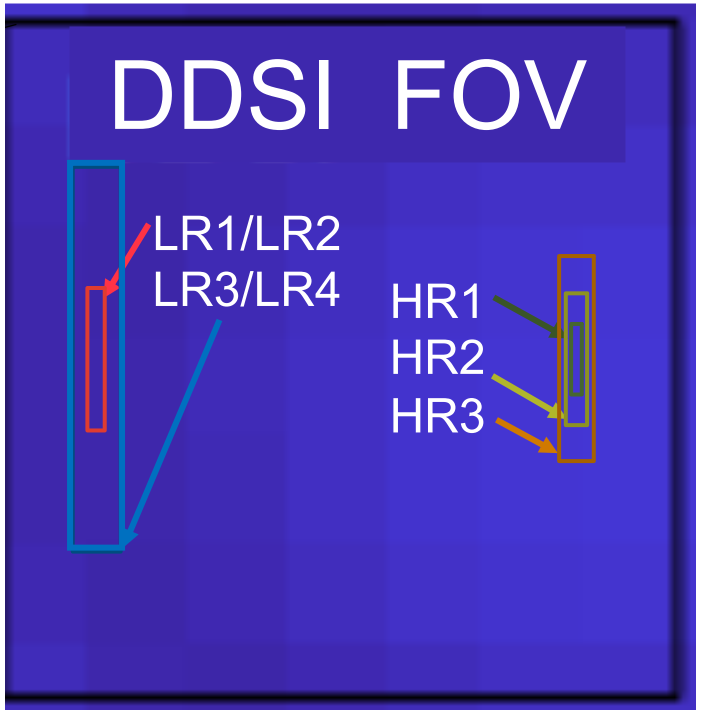


NOTE: HR2 and HR3 are have similar layouts

High Resolution Channel 1 (HR1)

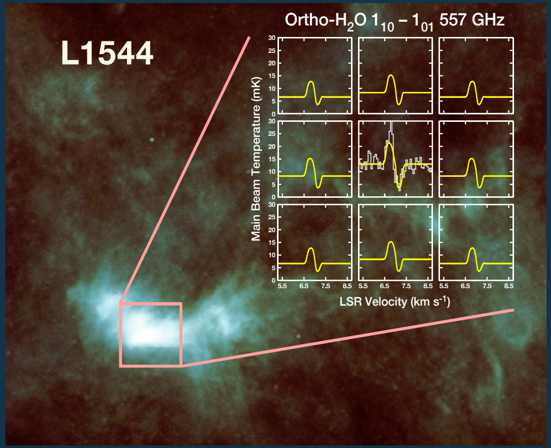






Coaligned slits allow efficient use of observatory time
LR 1, LR 2, LR 3, LR 4: simultaneous observations
HR 1, HR 2, HR 3: simultaneous observations

HSI Design Approach



Science Requirements:

Molecular line observations at high sensitivity

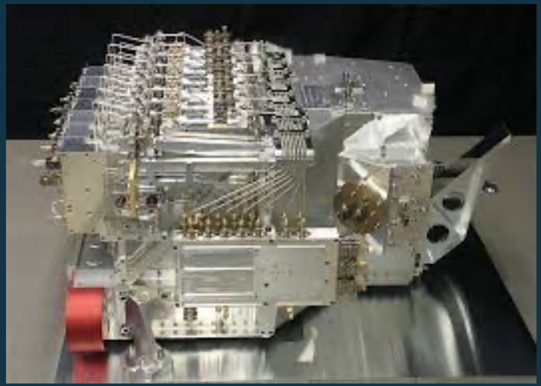
- several frequencies between 500 GHz and 2000 GHz, in particular H_2O lines
- at very high spectral resolution of 10^6 to 10^7 for point sources and small maps

→ **Heterodyne Instrument using superconducting mixers with several bands**

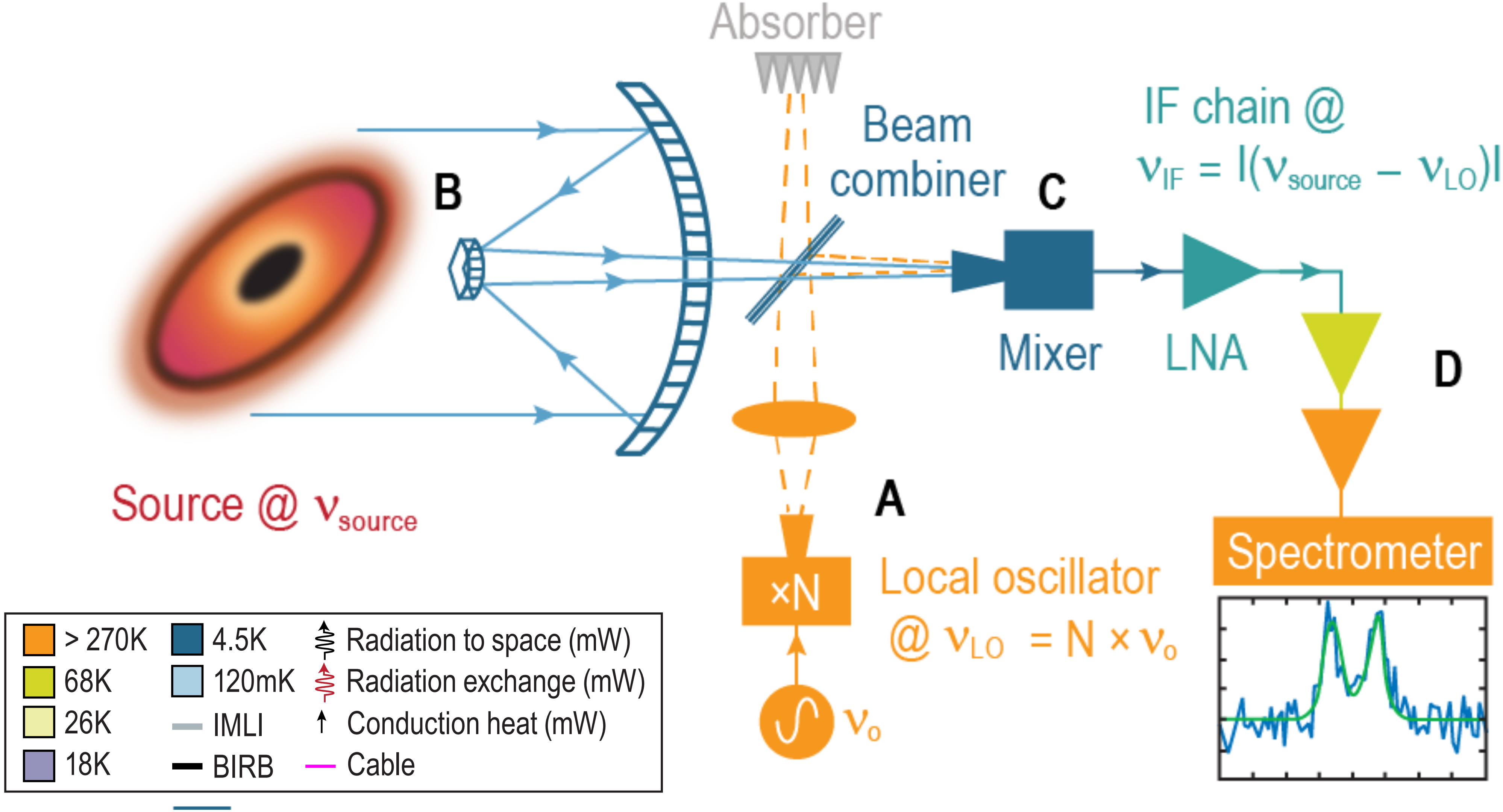
Design Approach:

- Use successful heritage from ground and space, in particular HIFI/Herschel
- Use innovative architecture and recent improvements/innovations to optimize efficiency and small Rx arrays

→ **Low risk instrument design using same heritage components as HIFI from (European and US) partners with plenty of experience and excellent track record**



Heterodyne Principle



Heterodyne Receiver Heritage

Ground Based Instruments

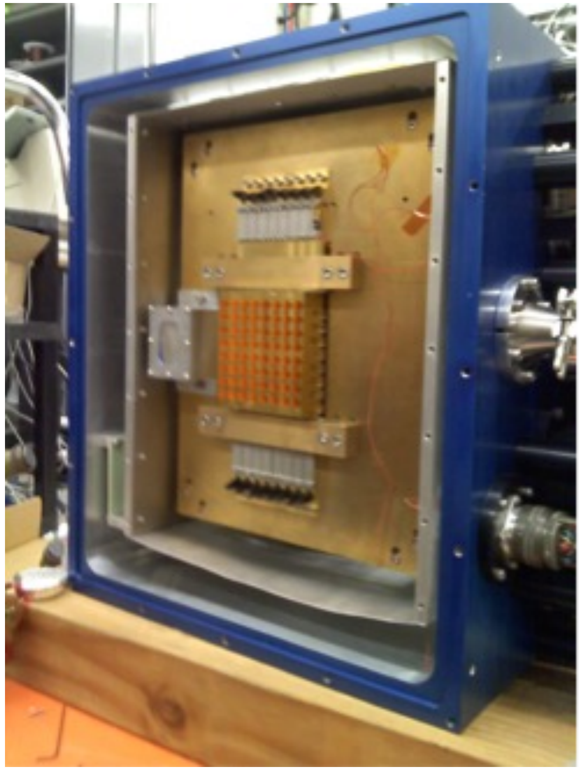
Airplane/ Balloon

Space

HIFI/Herschel

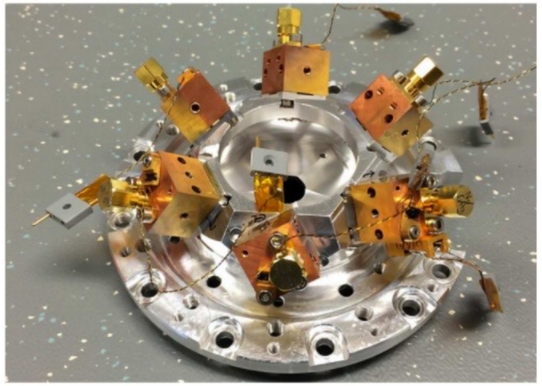
Hertitage For Heterodyne Array Receivers

Ground Based Instruments

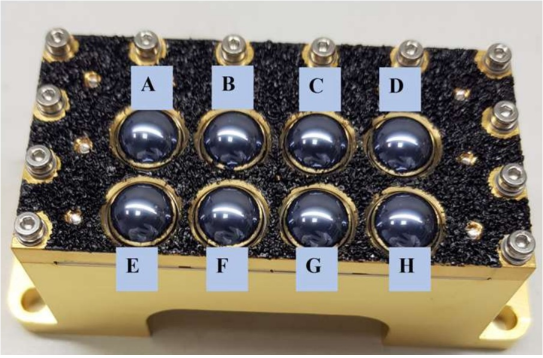


SuperCam 8 x 8 pixels, far-IR
X 8000, Uni. of Arizona, USA

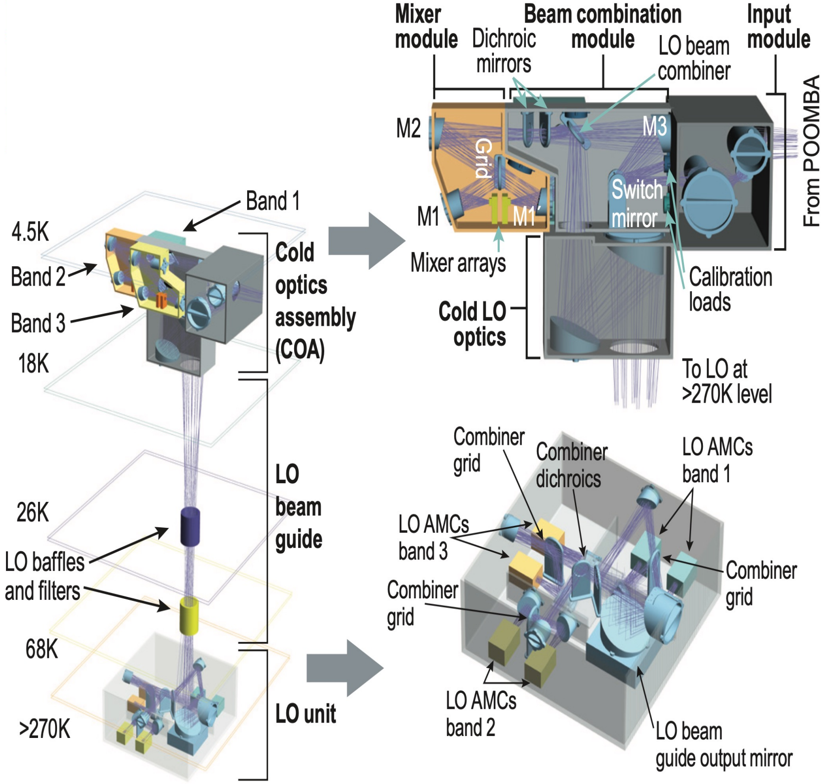
Airplane/ Balloon



up-GREAT/SOFIA (Germany)



GUSTO (SRON, Netherlands)



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

Science Implementation: HSI

HSI PARAMETERS				
PARAMETER		**BAND**		
		BAND 1	**BAND 2**	**BAND 3**
Wavelength (μm)		380 - 600	240 - 340	150 - 200
Frequency (GHz)		790 - 500	1250 - 882	2000 - 1500
Resolving power (λ/Δλ)*		10^6 to 10^7		
Beam size		52″ - 83″	33″ - 47″	21″ - 28″
Instantaneous FoV		300″×200″	150″×100″	150″×100″
Spectral channels*		1024 or 10,000		
Array size		5 pixels × 2 polarizations		
Aperture efficiency		80%		
Mixer Type		SIS	HEB	HEB
Receiver noise temperature (DSB)		60K	300K	400K
IF bandwidth		4GHz		
Optics bench temperature		4.7K with ±0.1K stability (not critical)		
LNA temperature		18K with ±0.1K stability during Allan time		
Mixer temperature		4.5K with ±10mK stability during Allan time		
RMS WFE budget (nm)	**Requirement**	<7500		
	Allocate	3000		
	Margin	250%		

Spectrometer type: autocorrelation or chirp transform

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

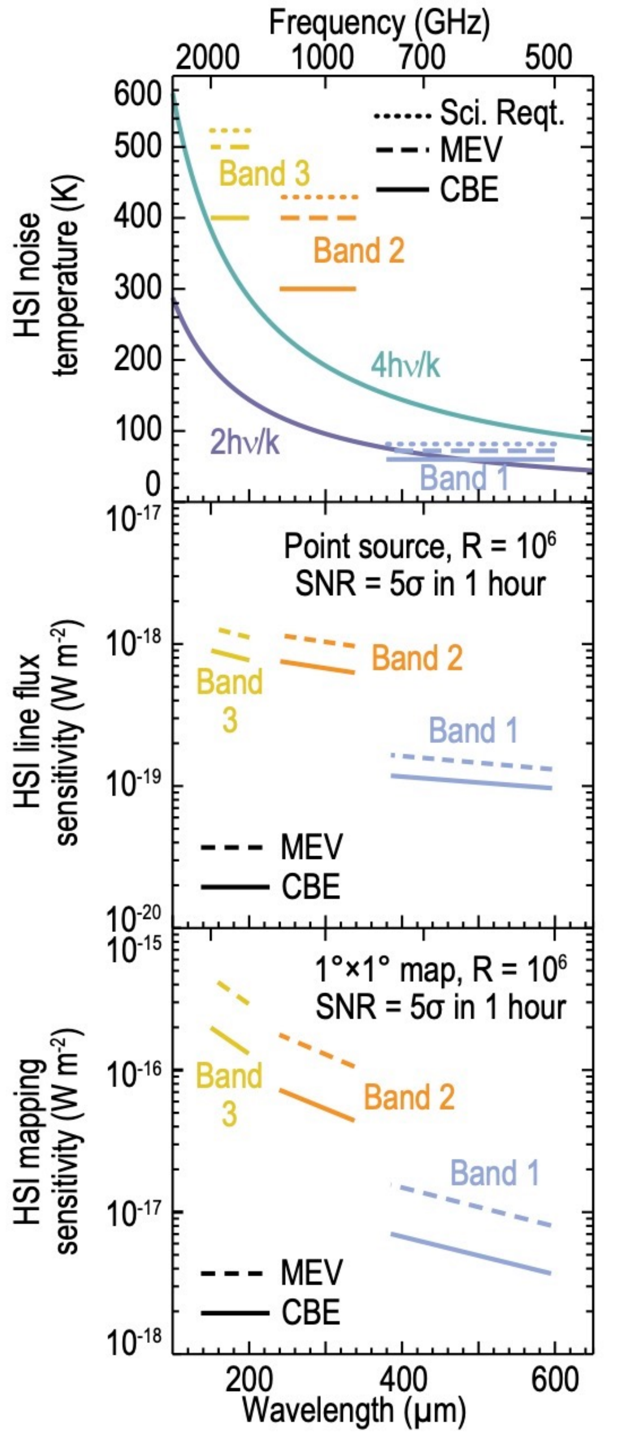
HSI is receiver/quantum noise-dominated; noise temperature (in K) given by:

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

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

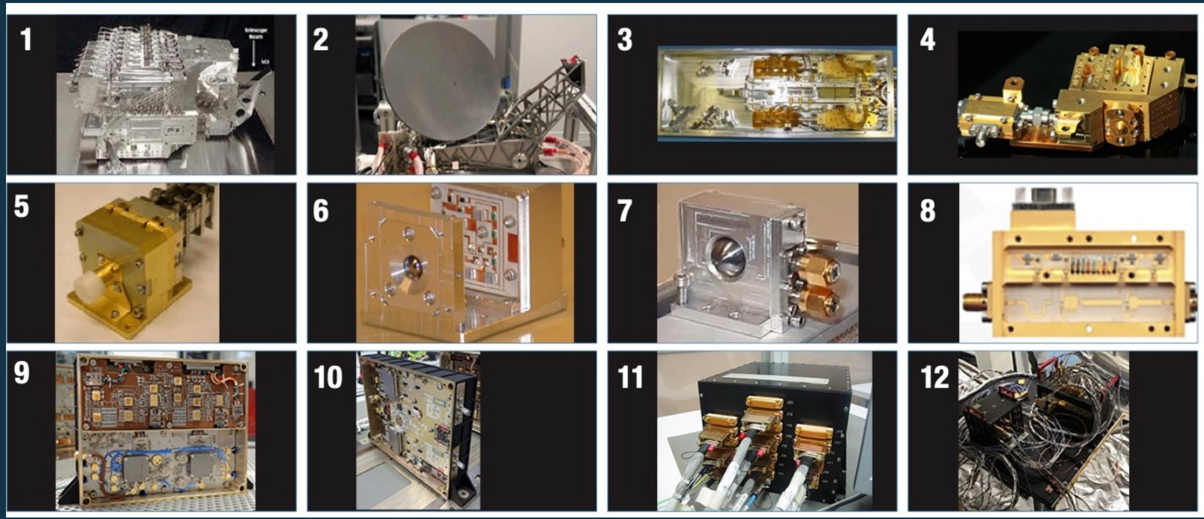
Conversion to flux (W m^{-2}) given by $\sigma=k\,T_{rms}\,\Delta\nu/A_{tel}$

		BAND		
		1	2	3
T_{Rx}	Receiver noise temp. (K)	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	$\left(\frac{1°}{\text{beam size}/2}\right)^2$		



Science Implementation: HSI

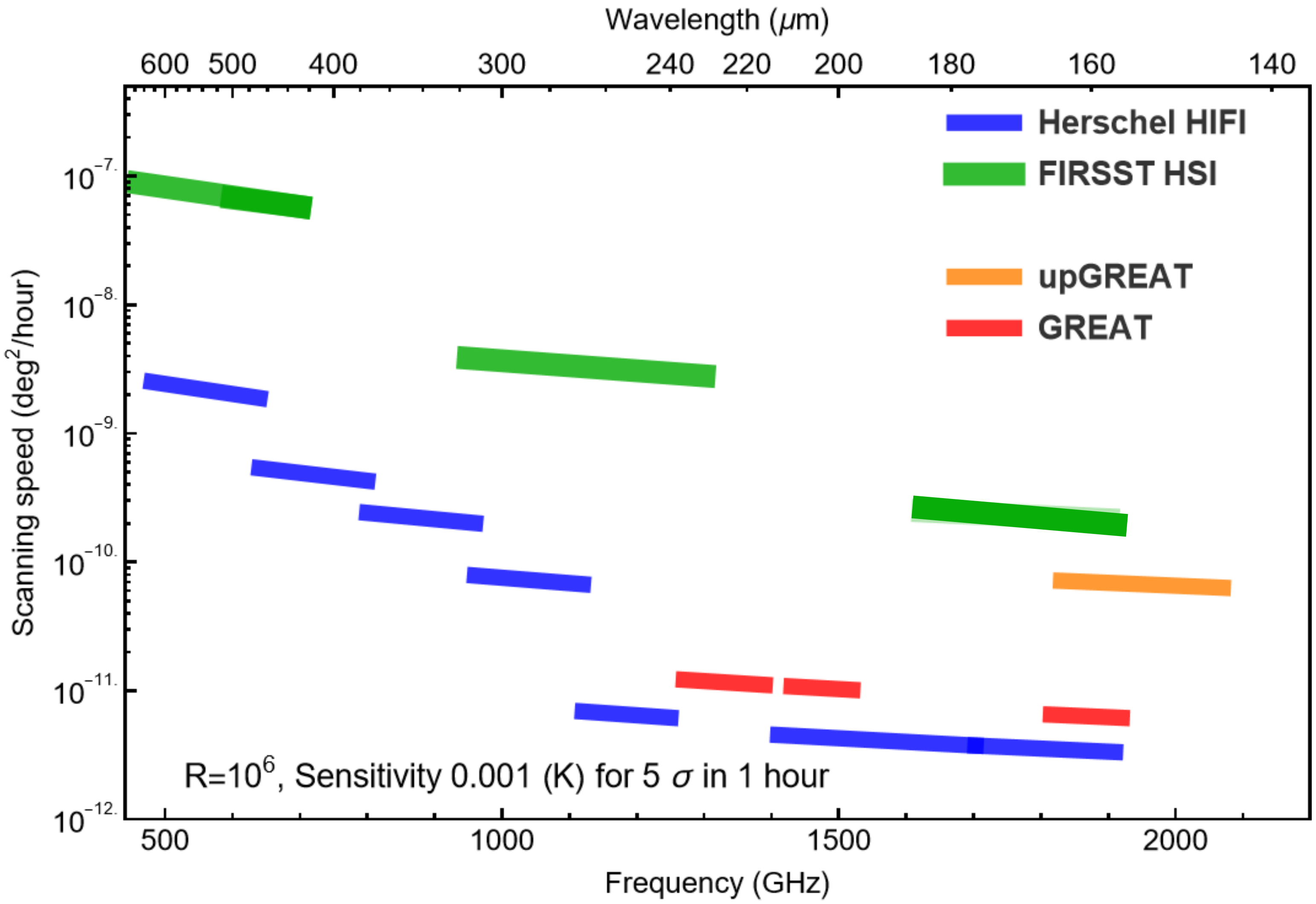
HSI SUBSYSTEMS AND SUPPLIERS					
SUBSYSTEM*	BASELINE SUPPLIER	HERITAGE			
		HERSCHEL /HIFI	JUICE /SWI	SOFIA/ UPGREAT	EUCLID
Optics, calibration mechanism: standard optics, metal-mesh dichroics, HIFI switch mirror mechanism	U. Groningen, NOVA, Cardiff U.	1	2		
LO: COTS synthesizer, AMC	Synth: Syrlinks AMC: RPG, Obs. de Paris	3	4		
SIS mixers (band 1)	Obs. de Paris	5			
HEB mixers (bands 2 and 3)	Chalmers U., Cologne U.	6		7	
IF chain: low-power InP LNAs	Yebes Obs.	8			
Spectrometer: 6 CTS 1GHz BW, 100kHz res.	MPS		9		
Spectrometer: 6×2 ACS 4GHz BW, 400kHz res.	Omnisys		10		
ICU	INAF Turin	11			12



With TRL 8-9 components, HSI provides a low-risk instrument strategy for the FIRSST mission.

Science Implementation: HSI

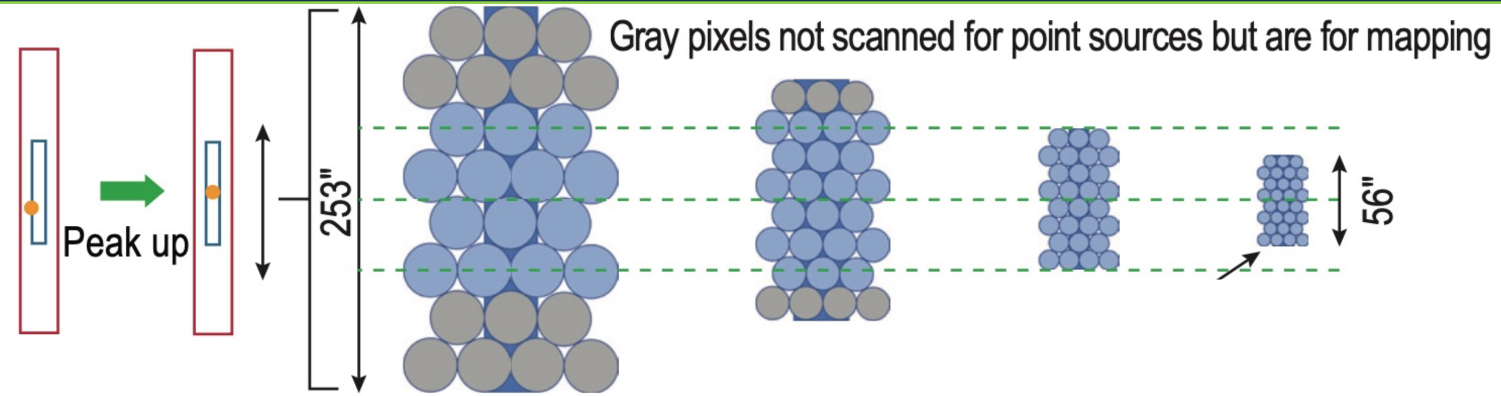
Better



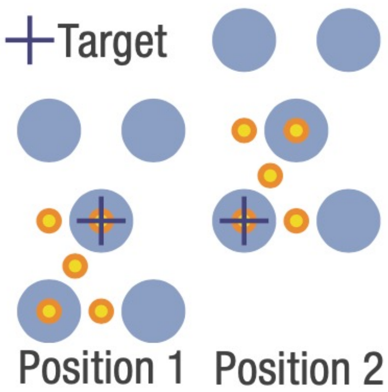
Instrument Operational Modes

OBSERVING MODE		ACQUISITION MECHANISM	MODULATION MECHANISM	SIGNAL READOUT
DDSI	Point-source spectroscopy	Spacecraft pointing within 3.5″, followed by the slit peak-up sequence: LR carries out a preliminary observation while the BSM makes fine adjustments to lock-in peak position. For HR mode, BSM acquires target in LR first and switches the target to the precise HR slit position.	BSM scans back-and-forth along shortest LR or HR slit direction at 72″/sec. Scan repetition number set by sensitivity requirement.	2Hz (LR4) and higher harmonics in LR1-3 to minimize detector noise
	Small maps <8.4′	Spacecraft pointing within 3.5″ of map center.	BSM executes raster or Lissajous scans at 72″/sec within its 8.4′×8.4′ FoV.	As above
	Medium maps 8.4′-30′	Partially overlapping 8.4′×8.4′ tiles (acquired as above for small maps) are combined		
	Large maps >30′	Spacecraft pointing within 3.5″ of map center	Spacecraft conducts scans at 20 or 60″/sec with scan lengths specified by map size.	2-100Hz, data read out at 2-10Hz during slow spacecraft turnaround
HSI	Point-source spectroscopy	Spacecraft pointing within 3.5″; pixel peak-up not performed as smallest HSI beam is 21″.	BSM pixel switching at 72″/sec	0.1Hz
	Small maps <12′	Spacecraft pointing within 3.5″ of map center.	BSM executes raster or Lissajous scans at 72″/sec within its 12′×12′ FoV.	2Hz
	Medium maps 12′-60′	As above for DDSI; individual HSI tiles larger than DDSI due to larger FoV.		
	Large maps >60′	As above for DDSI with spacecraft conducting scans at 20 or 60″/sec with scan lengths specified by map size.		

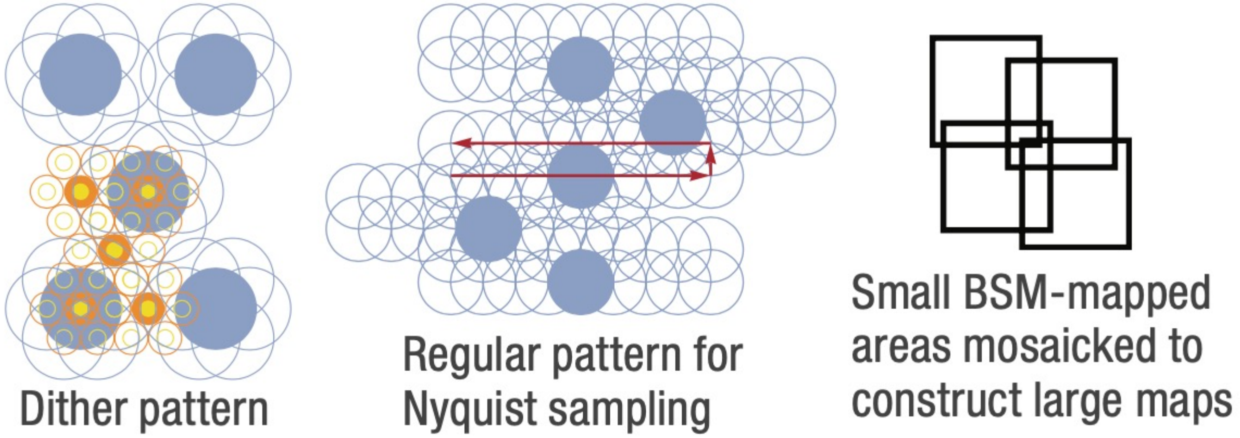
Instrument Operational Modes



Coaligned DDSI slits enable full LR wavelength range, or up to three wavelength orders in HR to be measured simultaneously



Overlapping HSI beams and arrangement of pixels allow point sources to be measured continuously with the background in all three bands through “pixel switching”

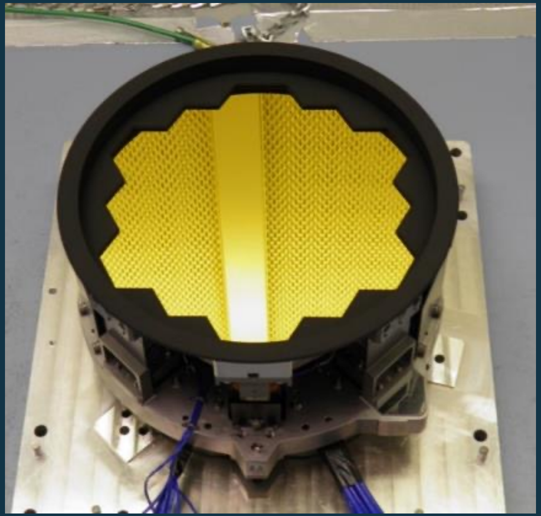


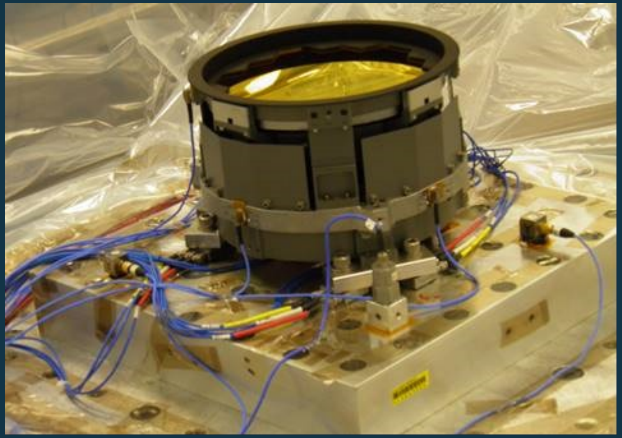
BSM allows for a variety of mapping patterns to be designed and implemented.

BSM – Beam Steering Mirror

- **FIRSST BSM leverages Ball's fine steering mirror (FSM) for JWST**
  - **Updated design for FIRSST include:**
    - **Mirror Size**
    - **Angular travel of full range required for FIRSST**
    - **Operating temperature (4.5K vs 30K)**
  - **Differential Impedance Transducers used for position feedback**
  - **Voice Coil Actuators (VCA) used to drive mechanism about rotational axis – Designed by Ball**

FIRSST BSM is a multi-purpose 2-dof steering mirror, adjustable angular speeds and supporting both DDSI and HSI. *It is not a chopper.*





Exact FIRSST BSM mechanism design is Ball proprietary (i.e. details are in the proposal).

Monolithic two-axis flexure provides 2-degrees of rotational freedom.

FIRSST Risk Reduction Strategies/Considerations

Two instruments with heterodyne and direct detection technologies.

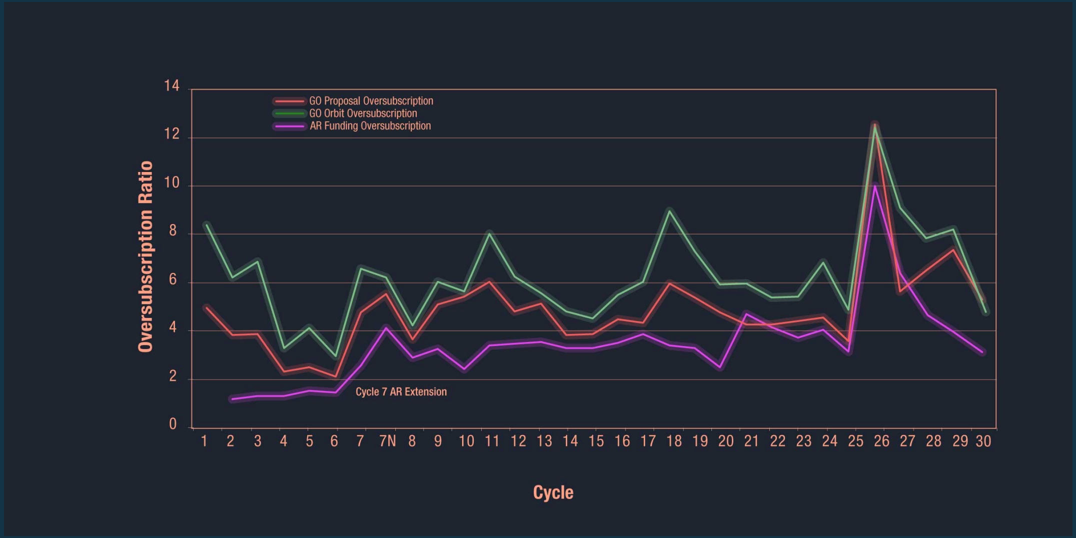
- Optimized focal plane and instrument packaging for efficient scientific observations.
- Spectroscopy and spectroimaging focus: Overall a low pixel count with 2162 MKIDs pixels, 30 heterodyne pixels.
- Minimize requirements on the 100 mK ADR – FIRSST uses TRL9 (Hitomi/XRISM heritage) single-shot ADR with a 22 hour duty cycle vs TRL5-6 Continuous ADR that requires further development. During ADR recycling FIRSST implements HSI science operations.
- Low pixel count – a substantially low data rate with 4-hour existing Ka-band DSN downloads ever 3-4 days.
- Heterodyne does not benefit from a cold aperture, but still requires the 4K temperature stage for low noise mixers. Thus, FIRSST is not wasting cooling resources by operating a heterodyne instrument in the focal plane.

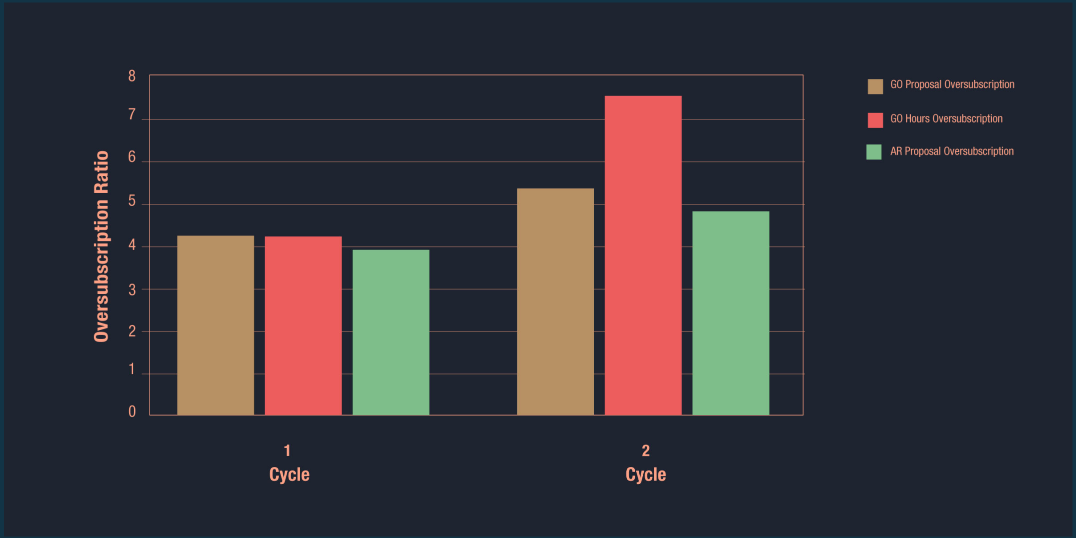
Guest Observer Program: 75% of mission lifetime

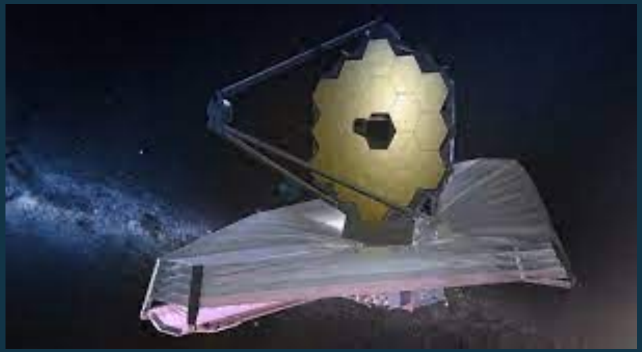
Requirements are set by the PI-led science objectives.

Uses 25% of mission 5-year lifetime.

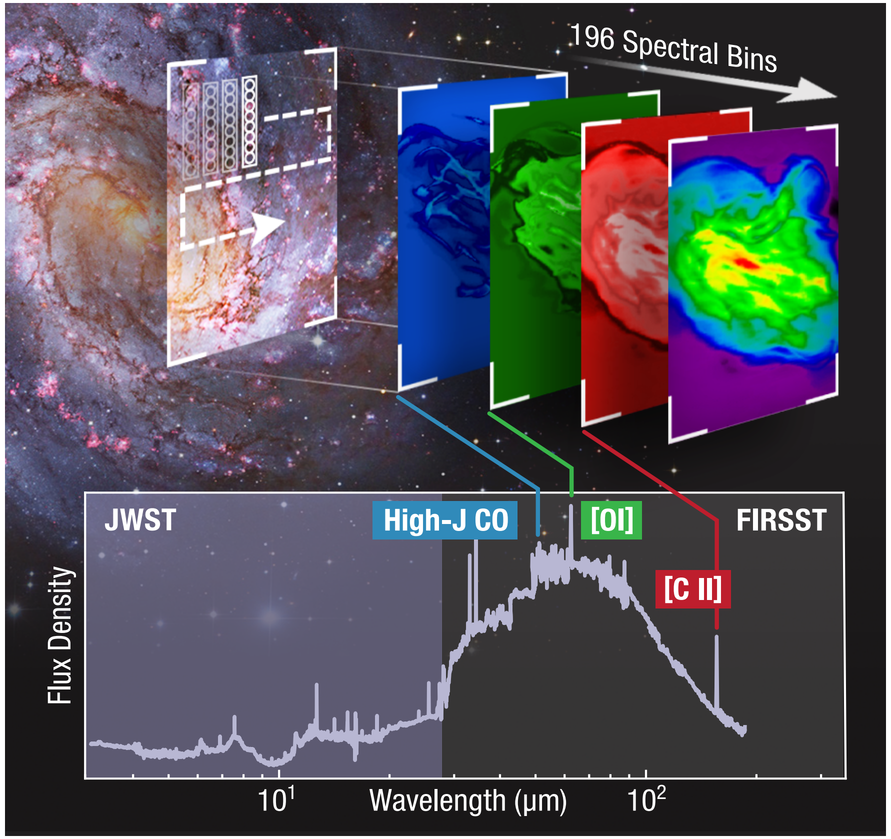
Design however takes into account the community needs and maximizes potential applications beyond PI objectives.



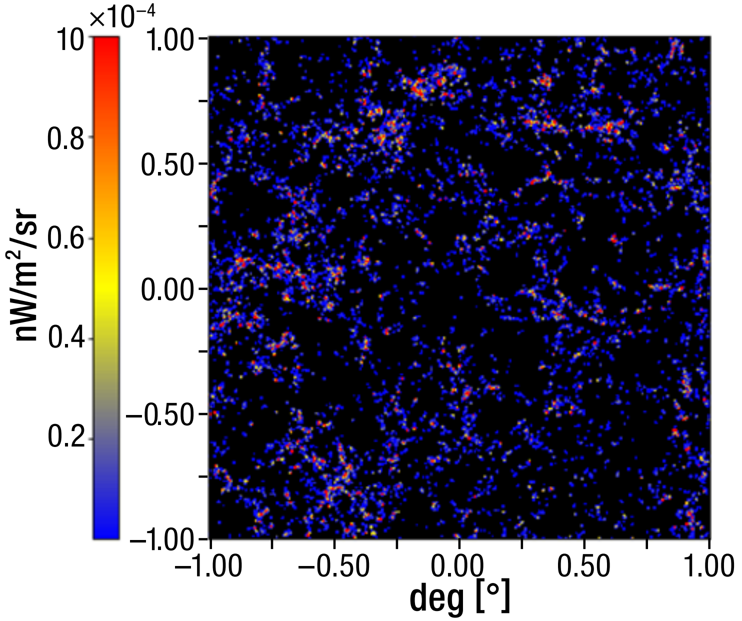


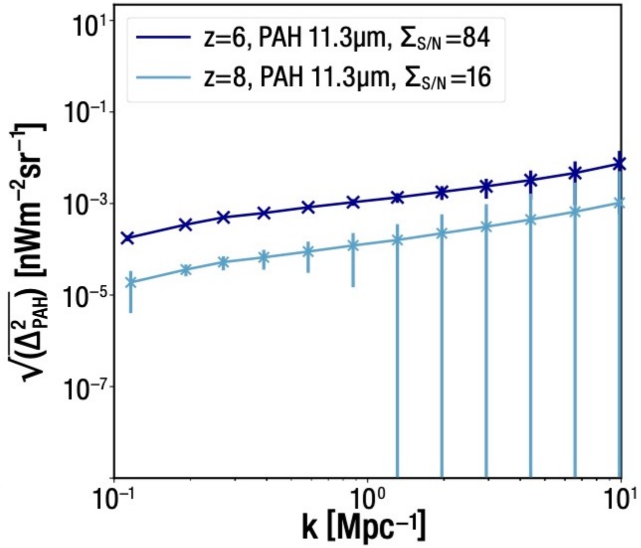


GO Program Example: Spectral Line Maps and Surveys



FIRSST, despite the name "spectroscopy" can make images and maps, and can also conduct spectral line imaging surveys – 196 line maps from 35-260 microns at R=100 simultaneously!



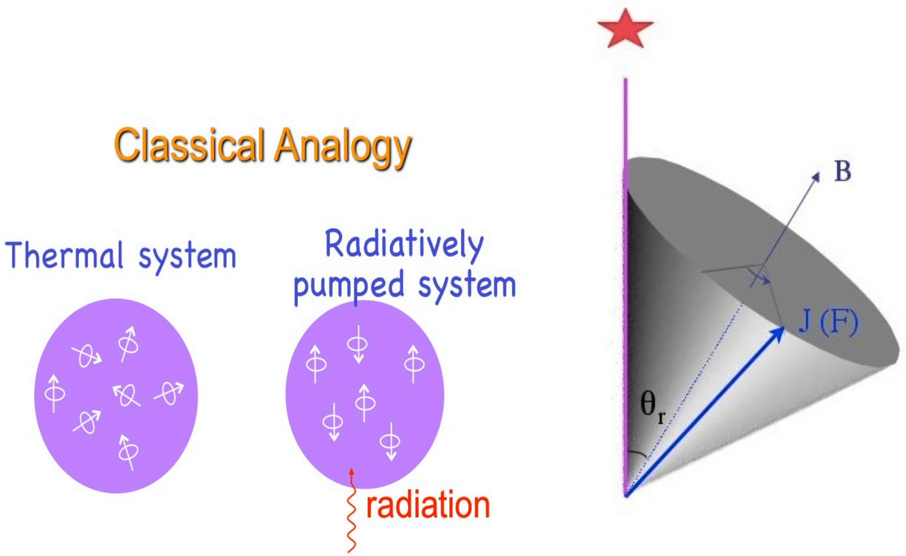


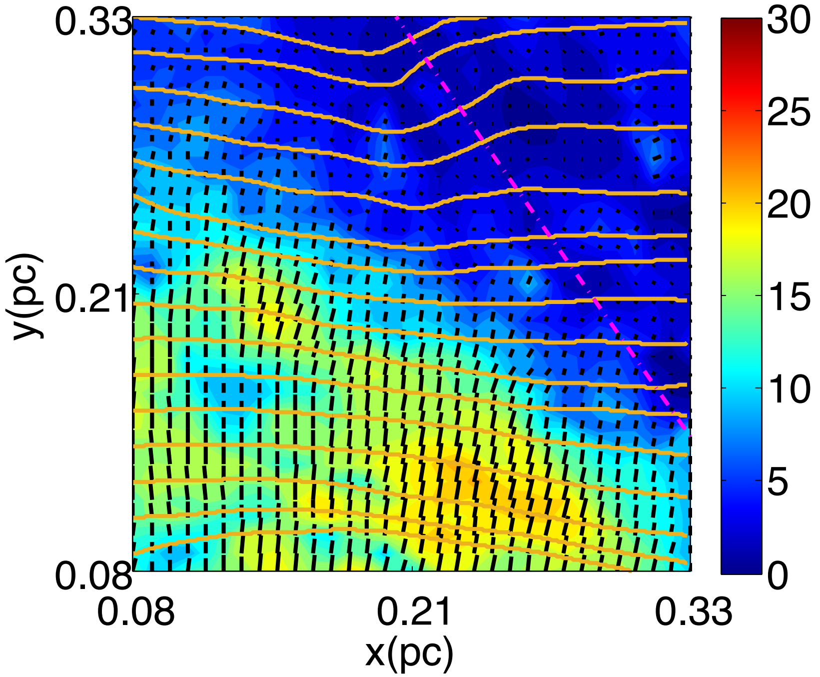
On the fly spectral-line mapping using DDSI-LR with BSM and spacecraft of an agile observatory.

Intensity mapping during reionization with PAH lines – 2x2 deg field lead to measurable signals.

GO Program Example: [CII] and other line polarization

FIRSST/HSI with dual polarization pixels could be used to measure spectral line polarization maps, especially polarization (polarization > calibration error ~ 5%).



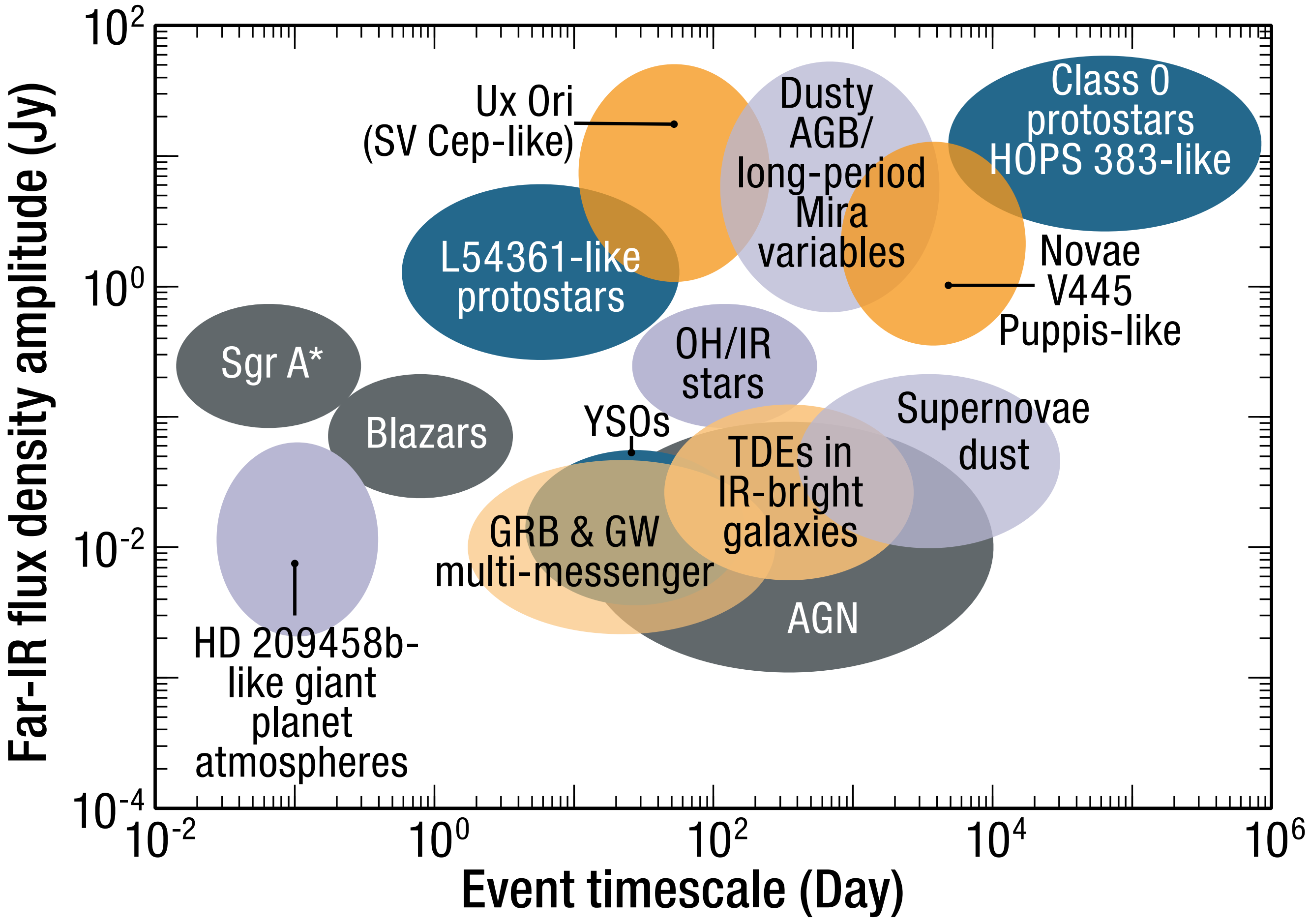


The [CII] 158 μm line polarization map from a simulation (Zhang & Yan 2017).

Models suggest a maximum [CII] 158 μm ***polarization of 28% a substantial degree of polarization which HSI could be able to easily test even with 5% level calibration errors.***

Ground state alignment (GSA) effect
Theory/models: Yan & Lazarian 2012 etc.
Simulations: Zhang & Yan 2017
Possible prelim detection with SOFIA/upGREAT in [CII]: Andersson et al. 2020 AAS

GO Program Example: Enabling Time Domain Astronomy

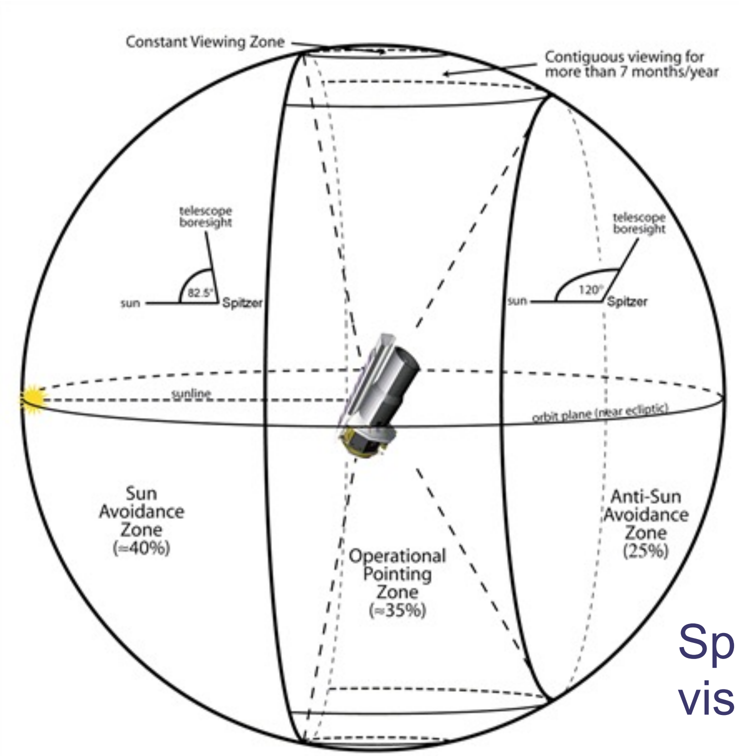


Astro2020 highlighted time-domain astronomy as a field ripe for scientific discovery.

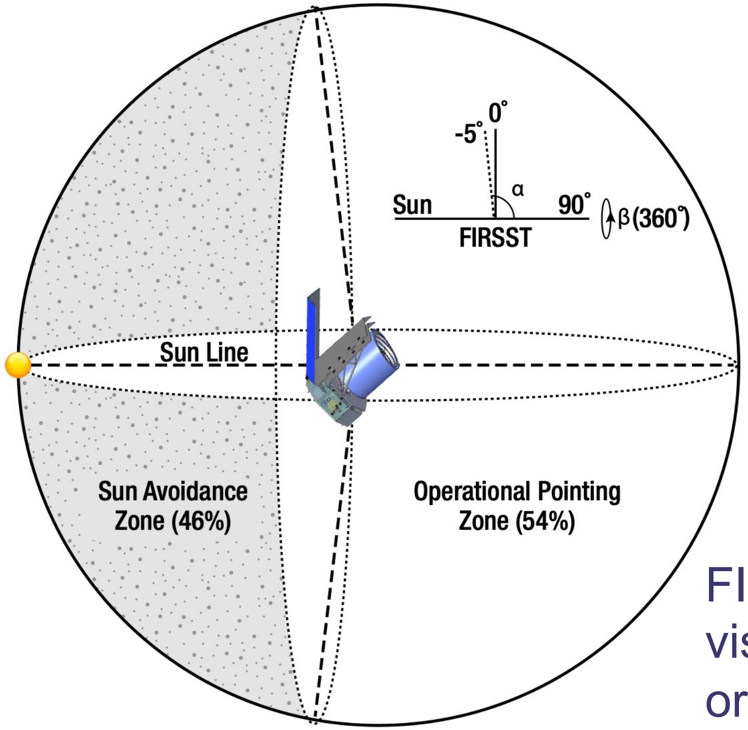
A FIR follow-up observatory is a key recommendation of Astro2020 for the 2030s when time-domain opportunities increase with Rubin and CMB-S4.

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 sk



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.

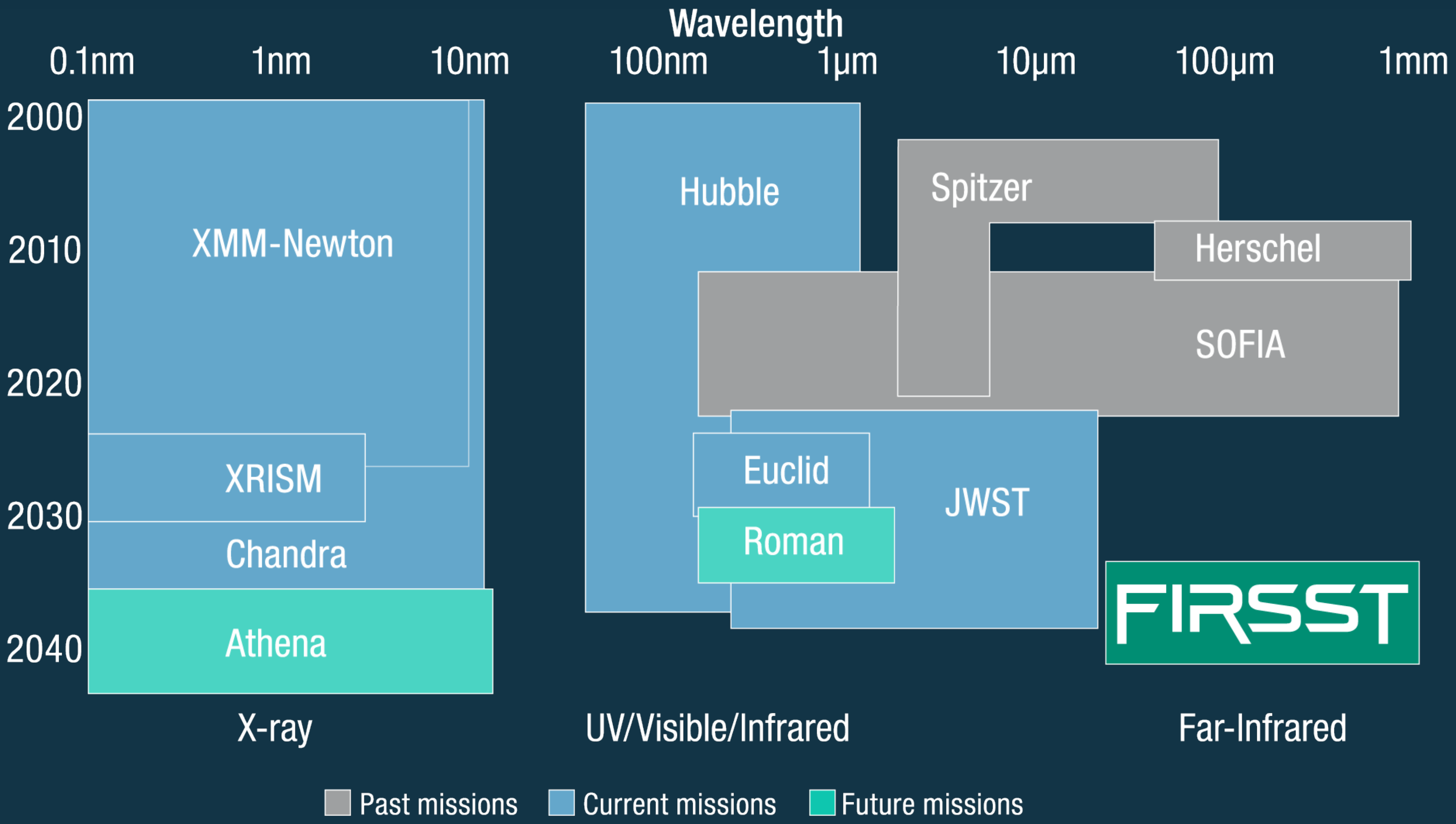
Instantaneous field of regard is greater than half of the sky (~54%) enabling time domain astronomy in the far-infrared. Full sky coverage in every six months.

Co-aligned on the sky multi-band/multi-channel pixels/slits, allowing simultaneous observations across the full range of wavelength of each instrument.

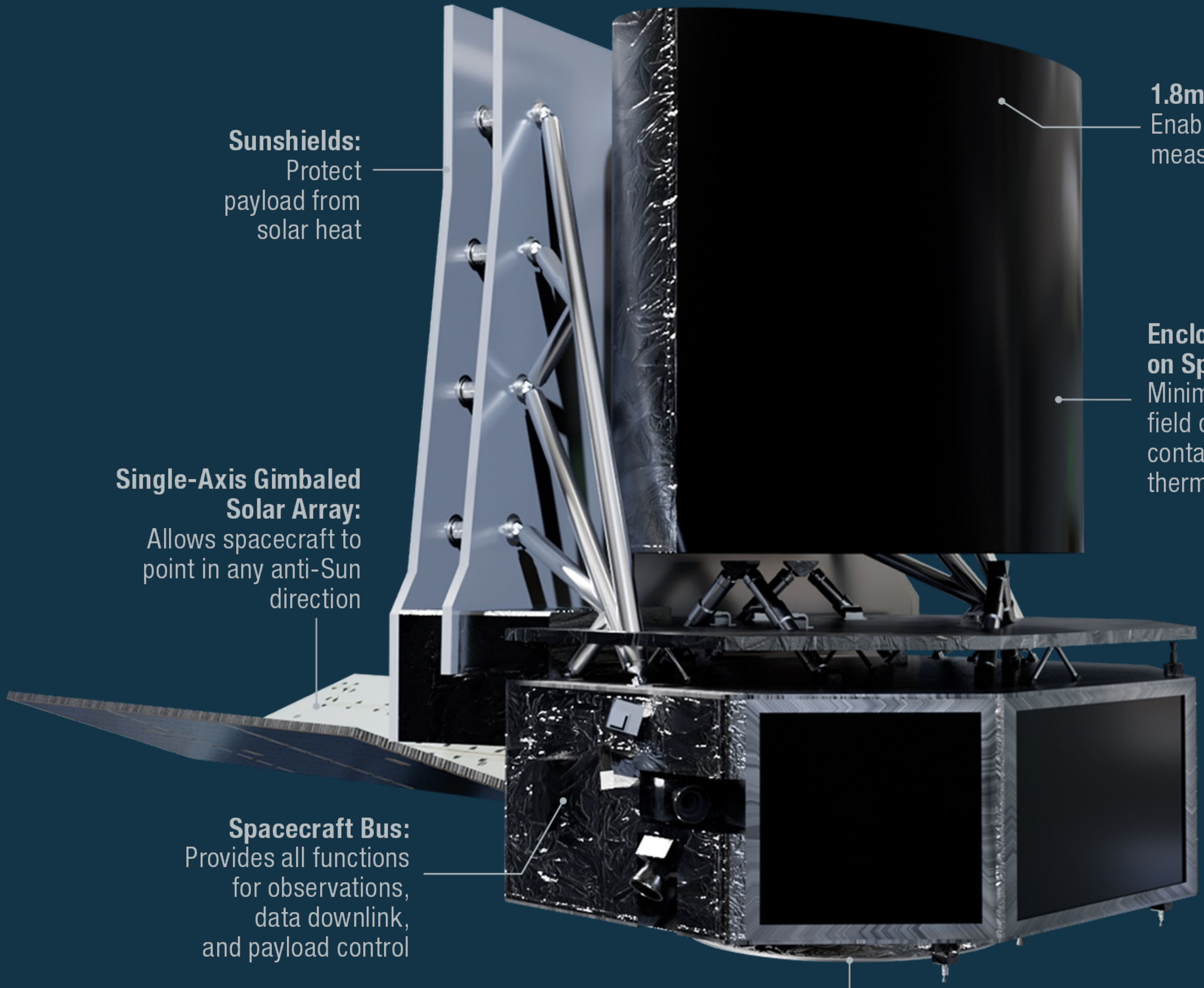
An agile observatory with minimum slew/settle times between targets. Science observing efficiency > 90%.

Responsive to science needs of 2030s, including unanticipated applications.

Guest Observer Program: Overview



FIRSST at a Glance



Sunshields: Protect payload from solar heat

Single-Axis Gimbaled Solar Array: Allows spacecraft to point in any anti-Sun direction

Spacecraft Bus: Provides all functions for observations, data downlink, and payload control

1.8m Cryocooled Telescope: Enables sensitrive far-infrared measuremnts

Enclosed Architecture Based on Spitzer and Kepler: Minimizes stray light, increases field of regard, controls contamination, and provides thermal stability

Thermal Management System: Protects payload from heat leaks and keeps ultra-sensitive detections at 120mK

Fixed High Gain Antenna: Simplifies communication and spacecraft control

FIRSST

FAR-INFRARED SPECTROSCOPY
SPACE TELESCOPE