A Probe Mission to Trace Water from Interstellar Clouds to the Solar System

A Proposal Submitted to the NASA APROBES 2016 Call

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Tracing Water from Interstellar Clouds to the Solar System

- Understanding the origins of the water on the Earth and other habitable planets requires following this molecule's trail from **interstellar clouds** to **dense cores** in which new stars form, to the **disks** surrounding the young stars and in which planets form, and finally to our **solar system**.
- Herschel observations have revealed water's ubiquity in all of these regions, especially in the solar system where it is found in comets, asteroids, satellites, as well as planetary atmospheres.

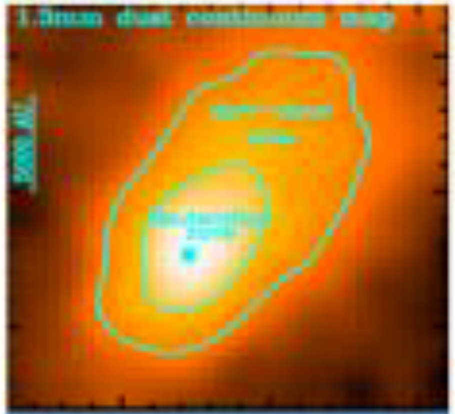
  High spectral resolution studies of the rotational transitions of water and its isotopologues (especially HDO) are essential for tracing water's formation, its role as a coolant, its processing in a variety of environments, and its relationship to ices on dust grain surfaces.

  The **linkages** between these different stages in the water trail have been emphasized by recent studies addressing water delivery from cores to disks (Furuya et al. 2016, Astron. Astrophys. In press) and from a protostellar disk to our solar system (Cleeves et al. 2014, Science, 345, 1590)

Four Interrelated Phases of the Water Trail

WATER IN INTERSTELLAR CLOUDS

Water formation in gas and on grains
Gas & grain processing
Water traces shocks & outflow chemistry
Water probes feedback from star formation

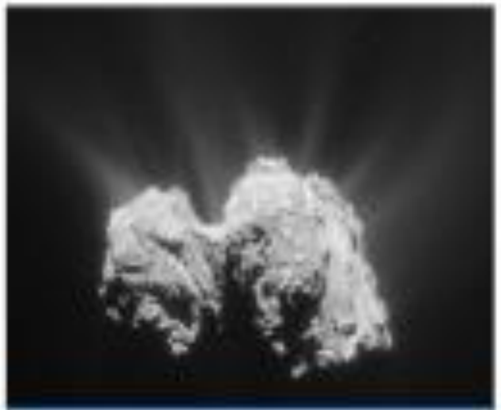


WATER IN CLOUD CORES

Water processing in cold environment
Deuteration
Water traces kinematics of collapsing star forming cores

WATER IN PROTOSTELLAR DISKS

Water processing by visible, UV, X-rays
Thermal environment determines the snowline that defines the gas phase water distribution

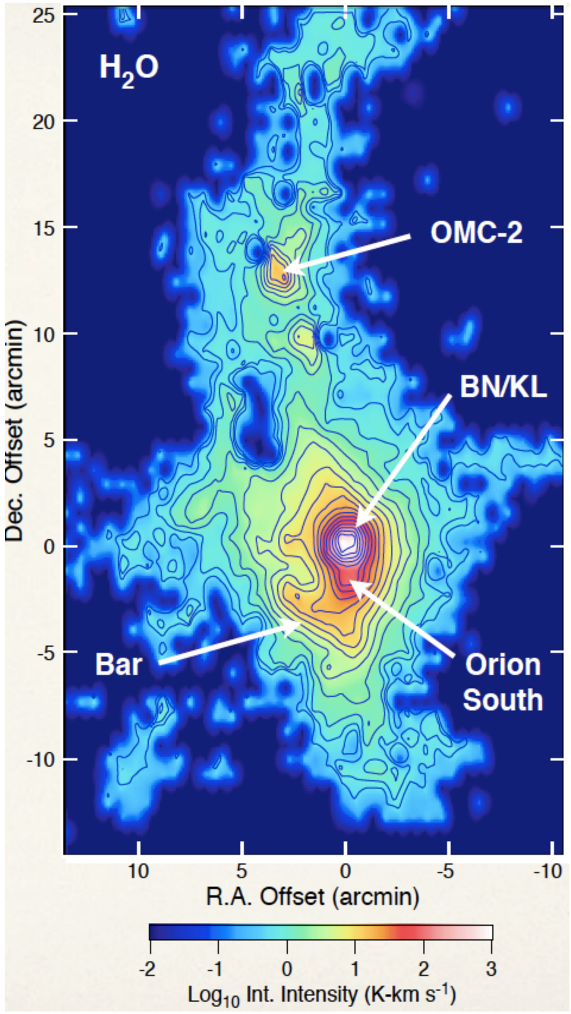


WATER IN THE SOLAR SYSTEM

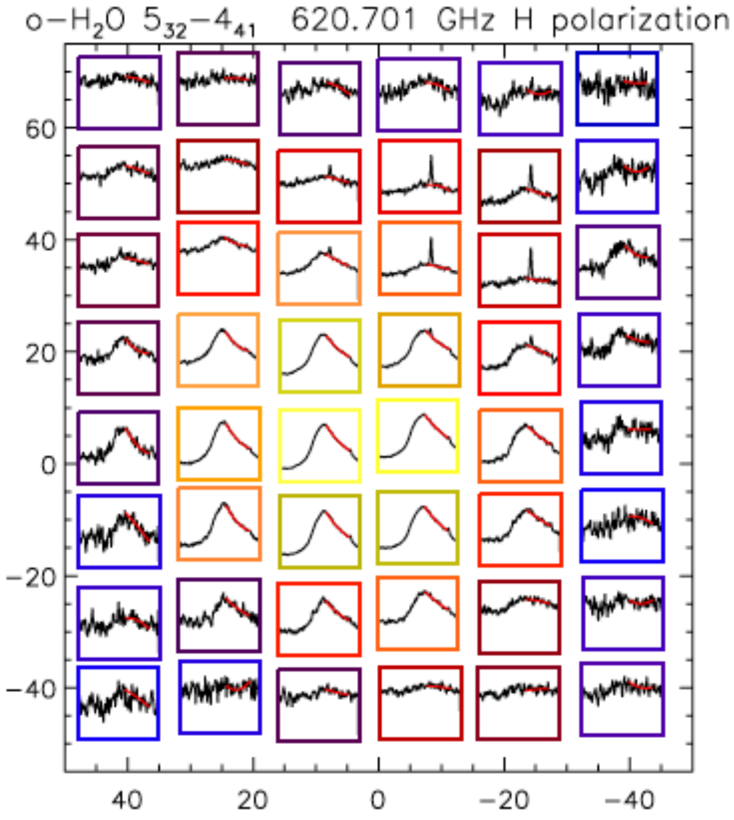
Segregation of water with planetesimals
Water distribution determined
Water transported to the Earth in the early history of Solar System

Water Emission in Orion

Ground State (557 GHz) Emission
Dominated by Broad Outflow



Excited State –
Thermal & Maser Emission



Offset (arc seconds)

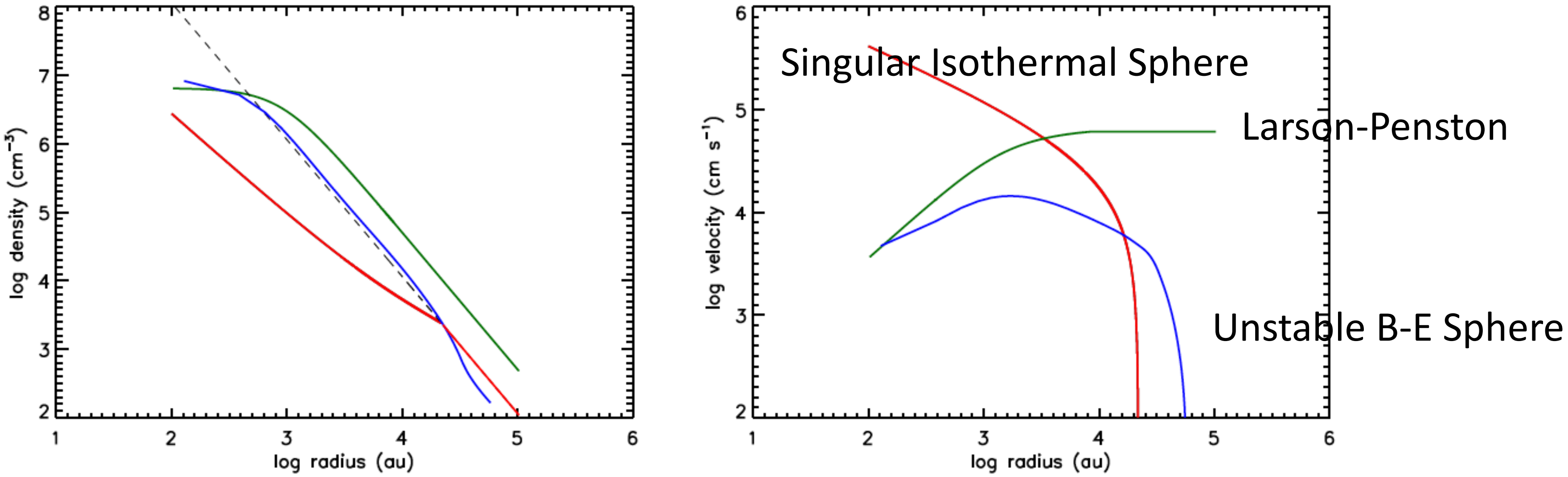
Herschel

Water as Tracer of Dense Core Kinematics

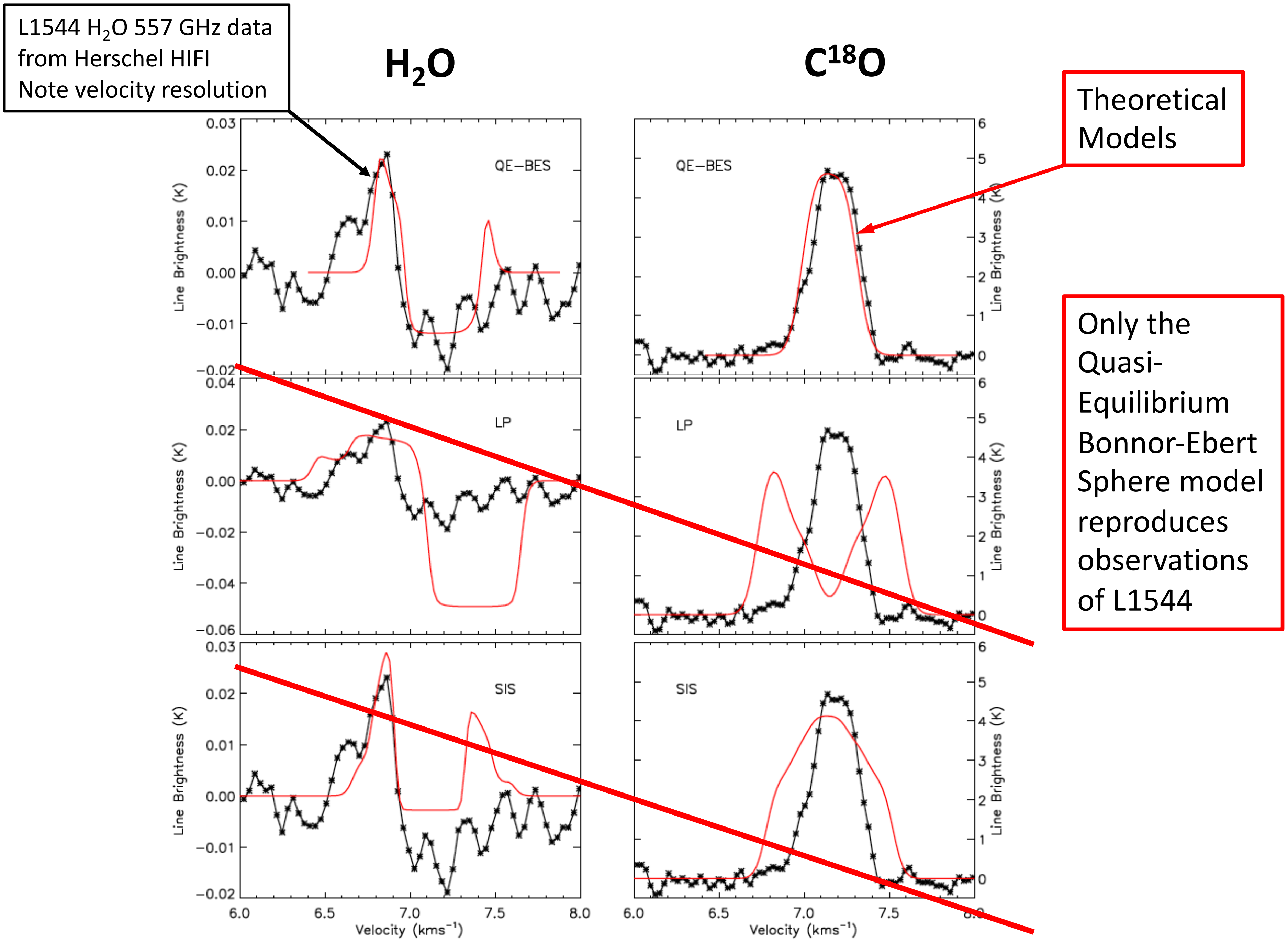
Cold (8-12 K), compact (0.1 pc) dense(10^3-10^7 cm^{-3})
Precursors to new stars; should be collapsing
What is the velocity field in collapsing cores?

All models have **~same** n(r) but vastly **different** v(r)

Keto, Caselli, Rawlings 2015

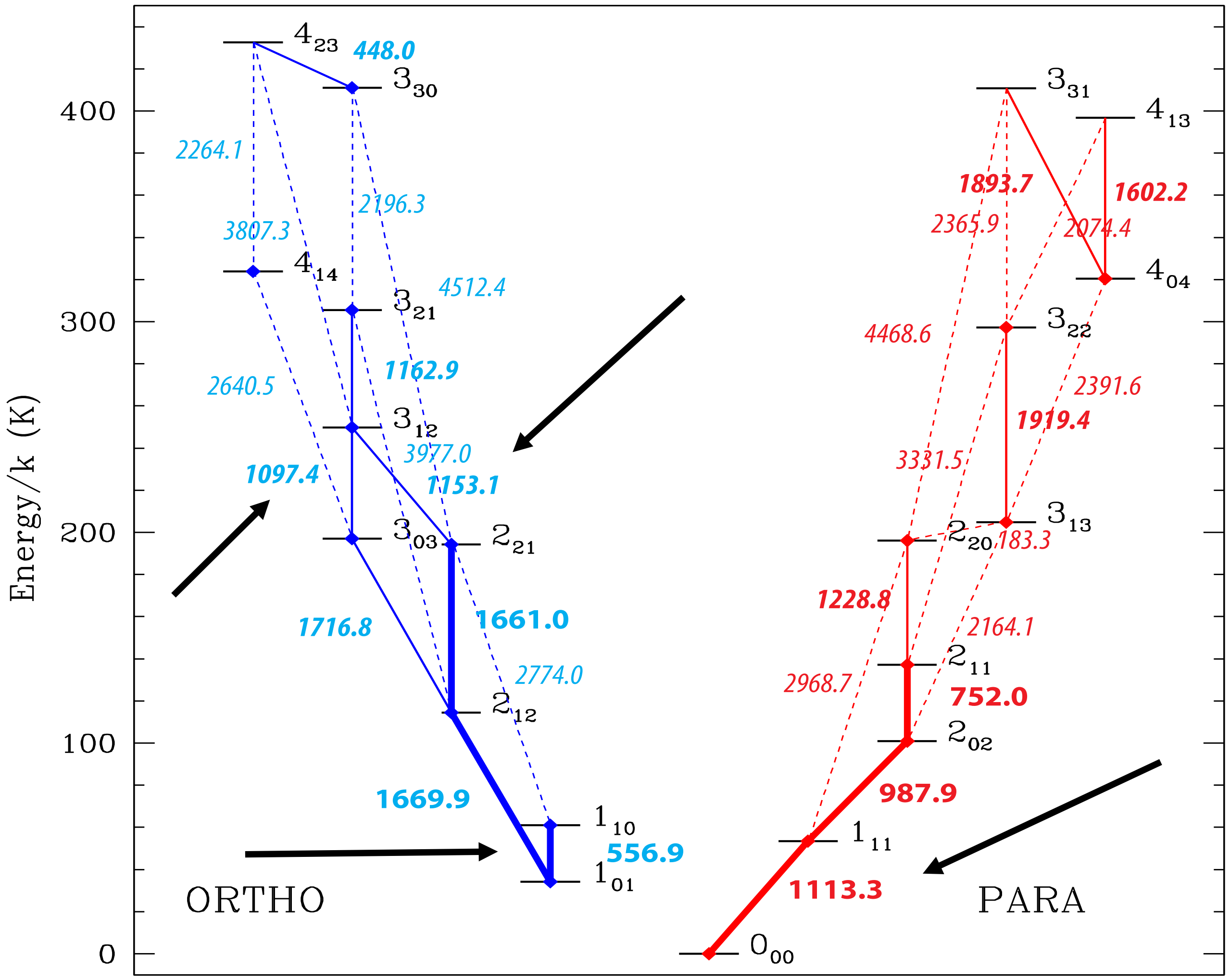


Water: demanding excitation => tracers innermost, densest regions
$C^{18}O$: easy to excite--traces overall core and its motions



L1544 H_2O 557 GHz data from Herschel HIFI
Note velocity resolution
H_2O
$C^{18}O$
Theoretical Models
Only the Quasi-Equilibrium Bonnor-Ebert Sphere model reproduces observations of L1544
QE–BES
LP
SIS
Line Brightness (K)
Velocity (kms⁻¹)

Water Lines to be Observed



Water in the **Interstellar Medium:**

in absorption: Lowest ortho- and para- transitions

in emission (shocks; outflows)

Lowest transitions + excited lines near 1100 GHz

Water in **Dense Cores**: Probably lowest transitions only will be detectable

Water in **Disks:** A range of transitions is possible

Water in the **Solar System**: Lowest ortho– and para- transitions; isotopologues essential

Water Transitions to be Observed

Transitions of H_2O

Freq (GHz)	Transition	Species
509.3	$1_{10} - 1_{01}$	(HDO)
547.7	$1_{10} - 1_{01}$	(o-18)
552.0	$1_{10} - 1_{01}$	(o-17)
556.9	$1_{10} - 1_{01}$	(o-16)
987.9	$2_{02} - 1_{11}$	(p-16)
994.7	$2_{02} - 1_{11}$	(p-18)
1107.2	$1_{11} - 0_{00}$	(p-17)
1009.9	$2_{11} - 1_{01}$	(HDO)
1113.3	$1_{11} - 0_{00}$	(p-16)
1097.4	$3_{12} - 3_{03}$	(o-16)
1153.1	$3_{12} - 2_{21}$	(o-16)

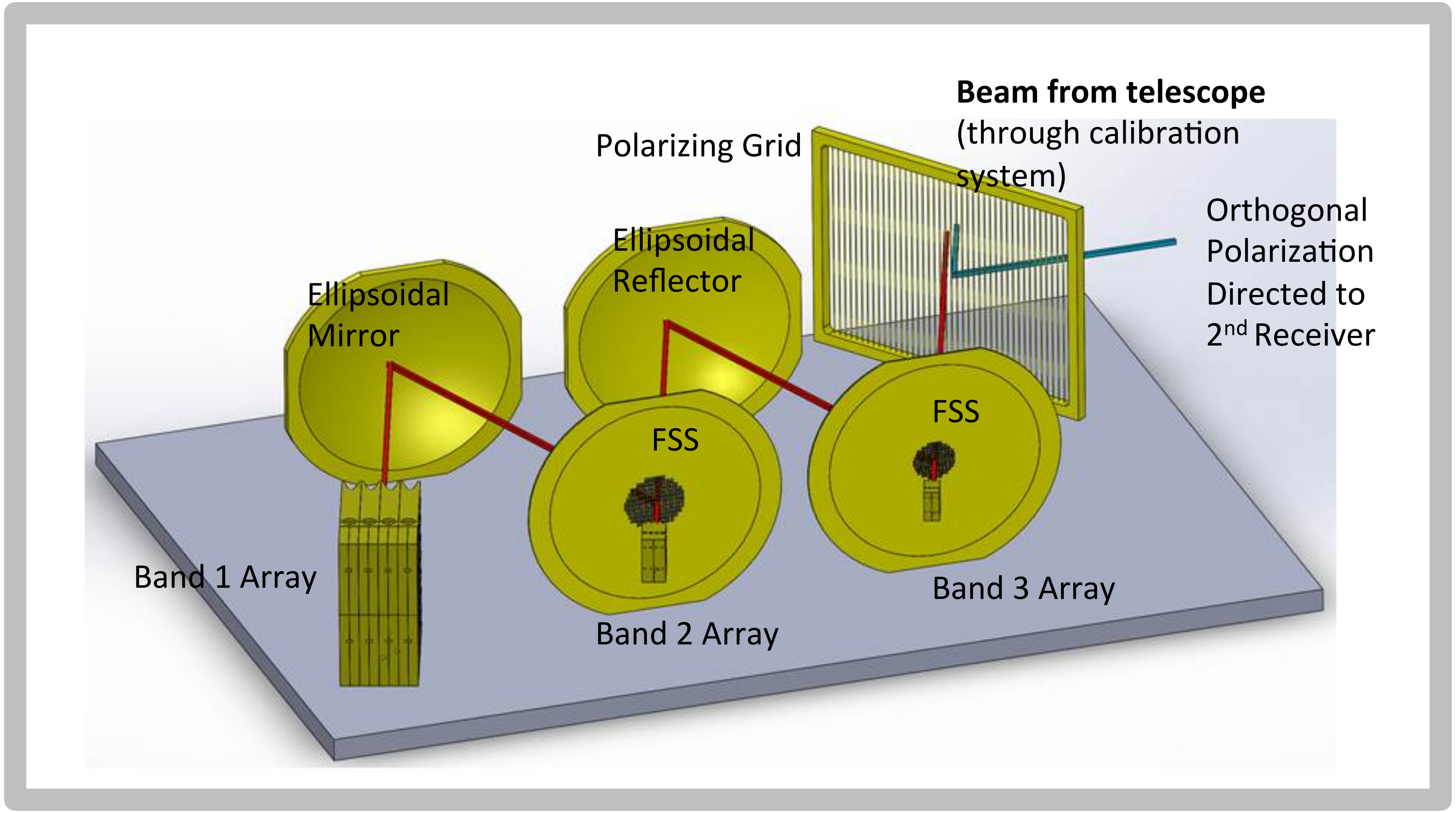
Details depend on bandwidth of receivers which will be SIS mixers

Frequency-multiplied local oscillator sources have advanced significantly and should not be a problem

Inject local oscillator either through waveguide directional coupler or employ balanced mixers

Some receivers can cover more than one line with multiple second local oscillators

Receiver Concepts to Increase Sensitivity



1. Use Dichroic Filters (Frequency Selective Surfaces) and operate all channels simultaneously
2. Employ an array (size depends on budget, cooling, and power) for imaging ISM and Cores
3. Beam switch between two pixels for observation of small sources (internal mirror)
4. Dual polarization receivers for all frequencies
5. Improved materials for 1 THz SIS junctions
6. Cooled with closed-cycle refrigerator to get 5 yr lifetime

Spectrometer for Heterodyne Receivers

This has been an issue at mm/submm wavelengths because **of required large bandwidth** and multiplicity of lines

Solutions have included filterbanks (typically used on atmospheric sounders), chirp spectrometers (low power; used on planetary missions), and acousto-optical spectrometers (complex, heavy; used on SWAS (SMEX) and Herschel/HIFI)

Digital signal processing, offering many advantages, is now feasible but FPGA approach is relatively **power hungry** (~4W/GHz BW)

Ideal technology is custom VLSI using technology developed for cell phones and other communications systems

Dr. Adrian Tang at JPL has unique partnership with UCLA team and Qualcomm for development of CMOS VLSI chips for space applications

"SPECTROCHIP II" has 750 MHz bandwidth, 512 spectral channels, includes digitizer, data accumulator, and USB output interface

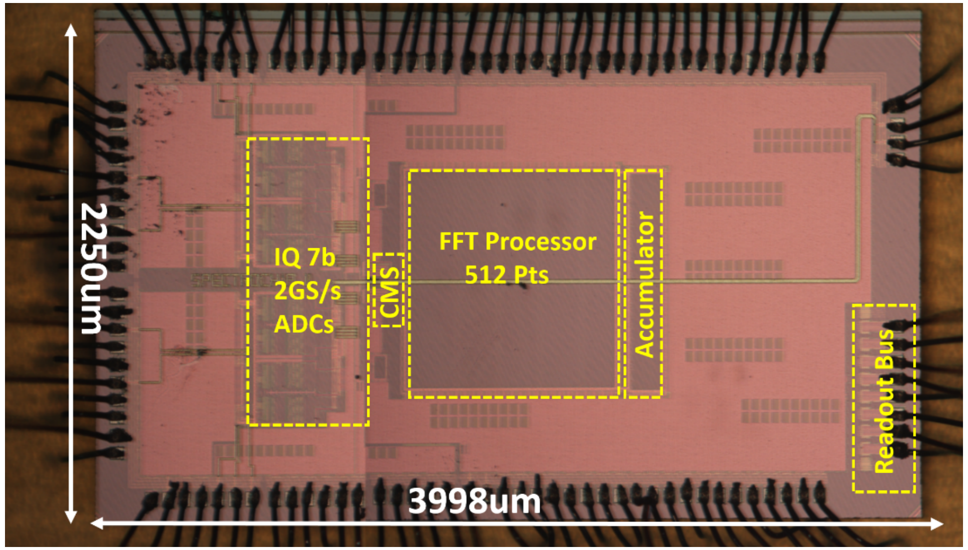
5x10cm size on board with support circuitry; 200mW DC power

The next generation will have 3 GHz bandwidth, 8K channels

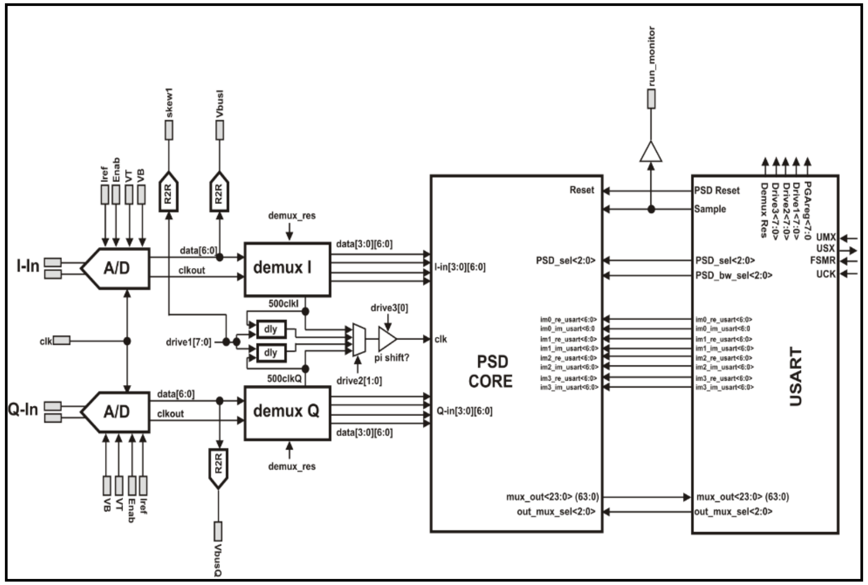
The low power and mass will allow simultaneous operation of multiple receivers

Spectrochip II

Full SoC Die Photo

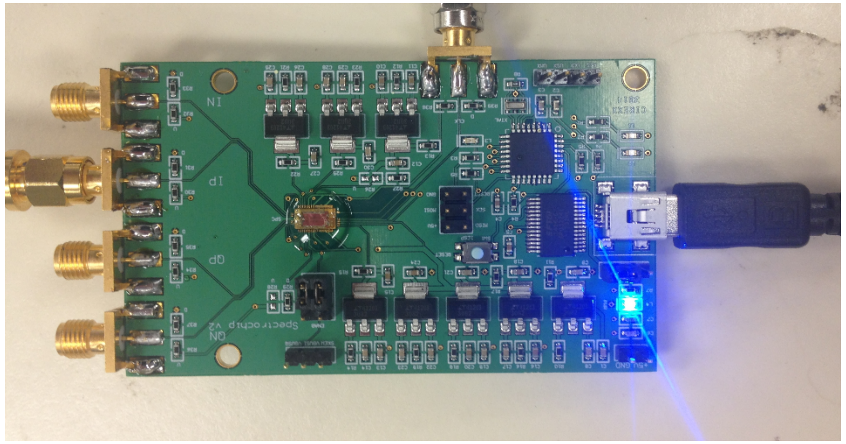


Full SoC Block Diagram



- A Full 1.5 GS/s spectrum analyzer chip in advanced 65nm CMOS was developed by UCLA's high speed electronics lab.
- Integrated 7b digitizers, offset and interleaving calibration functions, clock management system and vector accumulation.
- 256dsb/512ssb channel quadrature output with integrated USB 2.0 controller

Module Assembly

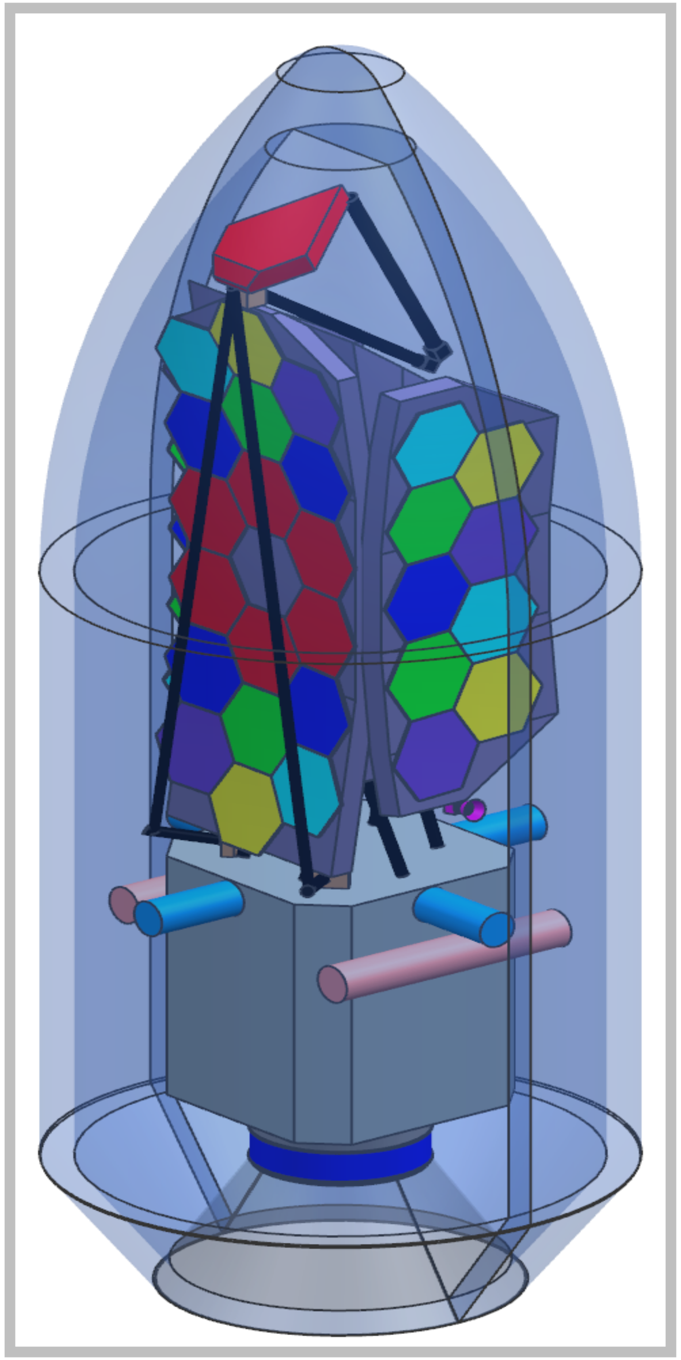


Increased Sensitivity (wrt Herschel) Requires a Larger Telescope

- Increase sample of comets: 5/year minimum to get 15-25 in 3 to 5 year mission will dramatically improve statistics and coverage of different types This requires 2-4x higher sensitivity; comet emission & mission modeling required
- Increased sensitivity to study water isotopologues in absorption; signal proportional to collecting area
- Greater sensitivity essential to make study of water in disks beyond the nearest few possible
- Improved angular resolution to image velocity field throughout cores including more distant high-mass cores (Herschel had 40” FWHM at 557 GHz)

Water Probe Mission Telescope

Narrow linewidths require high resolution (< 0.25 km/s; R >10^6)
The only viable approach is heterodyne receivers
The emissivity of optics at 250 µm is low enough (and receiver noise high enough) that **TELESCOPE TEMPERATURE IS UNIMPORTANT**
Telescope and mission design require reasonable thermal stability to maintain surface and pointing accuracy (σ < 15 µm)
L2 is a good location from these viewpoints. Passive radiation will likely bring telescope to ~100 K (needs further study)
Will need large sunshield
Observing mode similar to Herschel: targets in 40° wide cone having axis along spacecraft-sun direction between observable



Thanks to Otto Polanco for graphics

Water Probe Telescope

6-7m dia. Deployable Cassegrain Reflector fits in shroud of Falcon 9 Heavy

This version employs 36 ~1m hexagonal panels

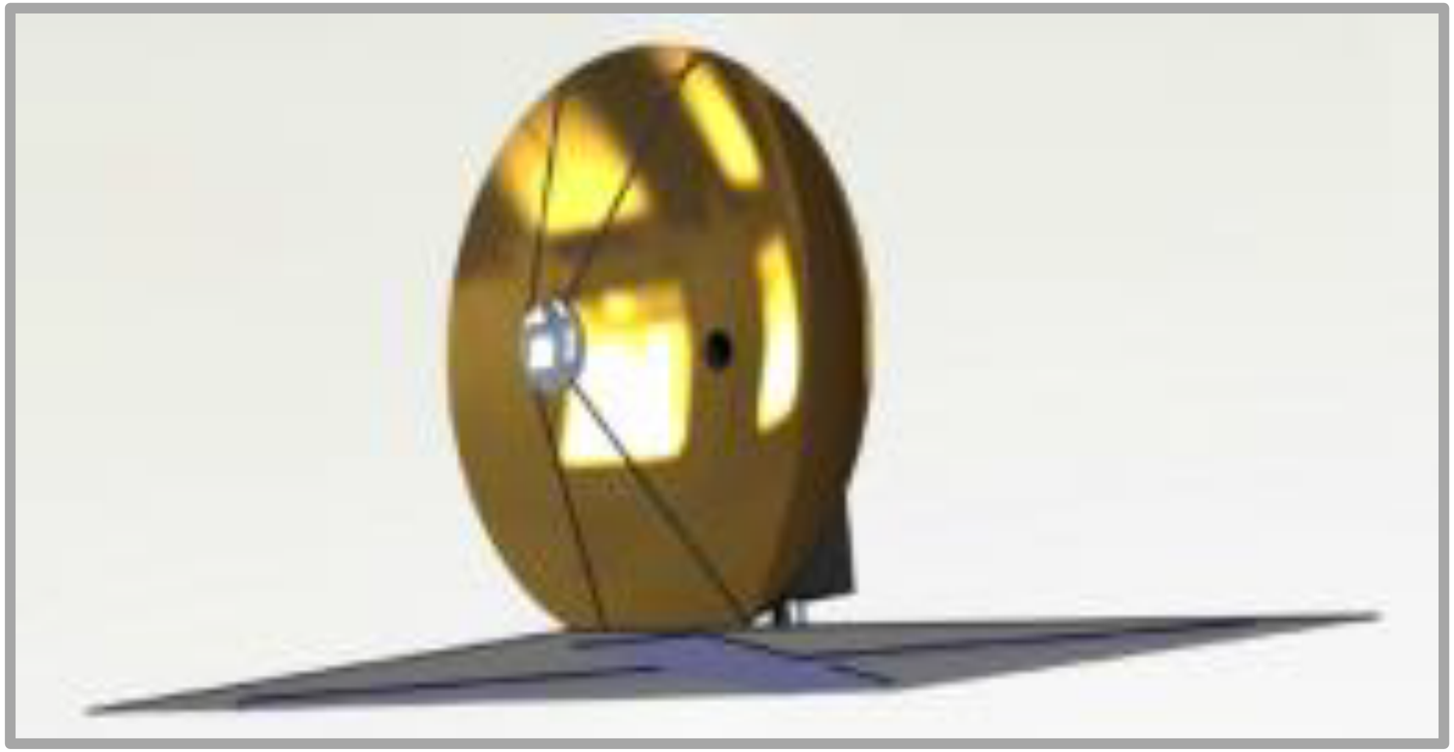
Original engineering study employed an “optical” f/D ratio with very long secondary support struts

Relatively “JWST-like”

Limiting minimum wavelength to 250 µm means that accuracy requirement is 100x less demanding

Possible materials include SiC (as Herschel) but could also be made of carbon fiber core + aluminum skins

Deployable Quasi-Monolithic Telescope Structure



10m x 12m single-layer sunshade with solar panels on lower side

Water Probe Mission

- Proposal submitted on 15 November to NASA
- 15-month study proposed including Team-X study at JPL
- Open to community; two workshops to define instrument and mission
- Selection based on scientific interest and plausibility of < $1B total cost
- Selection – some time in Spring 2017