

Bringing Fundamental Astrophysical Processes Into Focus: A Community Workshop to Plan the Future of Far-Infrared Space Astrophysics

NASA Goddard Spaceflight Center

May 12-13, 2014

**A report to Far-Infrared Science Interest Group
Cosmic Origins Program Analysis Group (COPAG)**

Paul Goldsmith, JPL
David Leisawitz, GSFC

The Far-Infrared Community did Engage in Discussion and Planning Activities In Run-up to the 2010 Astronomy & Astrophysics Decadal Survey

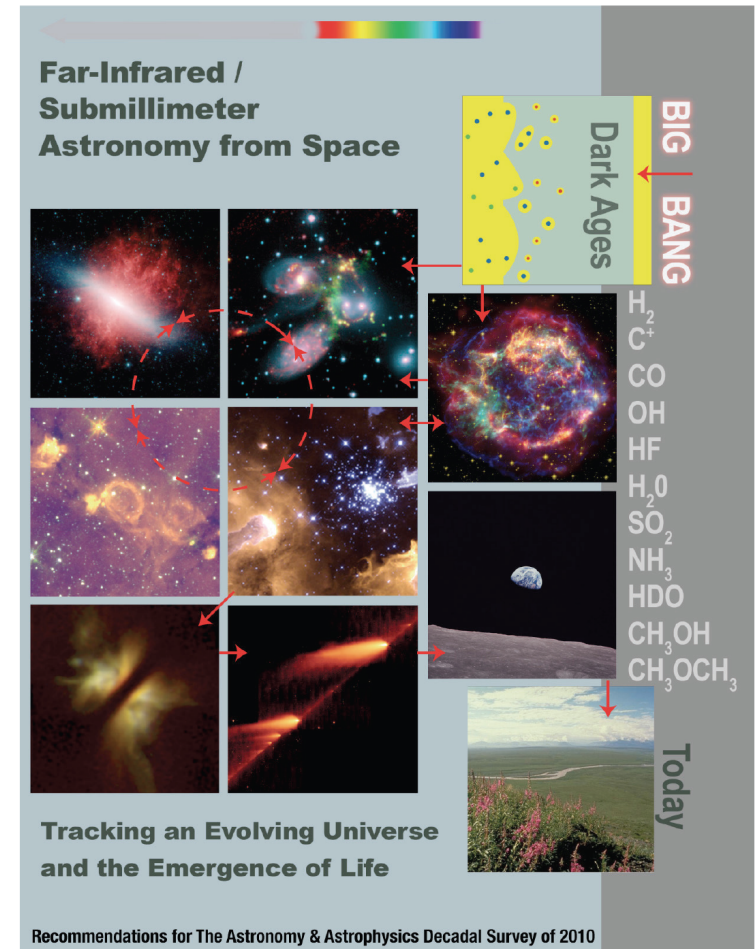
Major events were a workshop in Pasadena in 2008 and Special Session at AAS in 2009

A “white paper” grew out of these with input from ~100 individuals with smaller “editorial” group led by Martin Harwit

Started with a descriptive and “catchy” title

Far-Infrared/Submillimeter Astronomy from Space
Tracking an Evolving Universe and the Emergence of Life

39 pages in total with considerable detail
but two key recommendations -



Martin Harwit, George Helou, Lee Armus, C. Matt Bradford, Paul F. Goldsmith, Michael Hauser, David Leisawitz, Daniel F. Lester, George Rieke, and Stephen A. Rinehart,

The Two Key Recommendations

- 1. The US has an unparalleled opportunity to participate in the Japanese-led Great-Observatories-class mission, SPICA, to be launched in 2017. SPICA will have a cryogenically cooled 3.5-m telescope and thus unsurpassed Far-Infrared/Submillimeter sensitivity. The astronomical insights enabled by a highly sensitive, background-limited spectrometer on this mission will profoundly affect our understanding of cosmic evolution. US participation, at a fraction of the SPICA mission total cost, is also a logical step toward two other more advanced missions, previously recognized in the 2000 Decadal Review.⁽⁴⁰⁾**
- 2. We propose a dedicated effort, during 2010 – 2020, to advance several technologies essential to these two other powerful next-generation missions to be launched between 2020 and 2035. The 10-m class cryogenically-cooled Single Aperture Far Infrared Telescope, SAFIR, and a Michelson spatial interferometer, both of which are natural successors to SPICA and all other ongoing efforts, will probe the Universe to greater distances and earlier epochs, with far higher sensitivity and spatial resolution than ever possible before.**

A convenient definition is that Far Infrared (FIR) covers 30 μm – 300 μm with more generous definition of 25 μm – 400 μm .

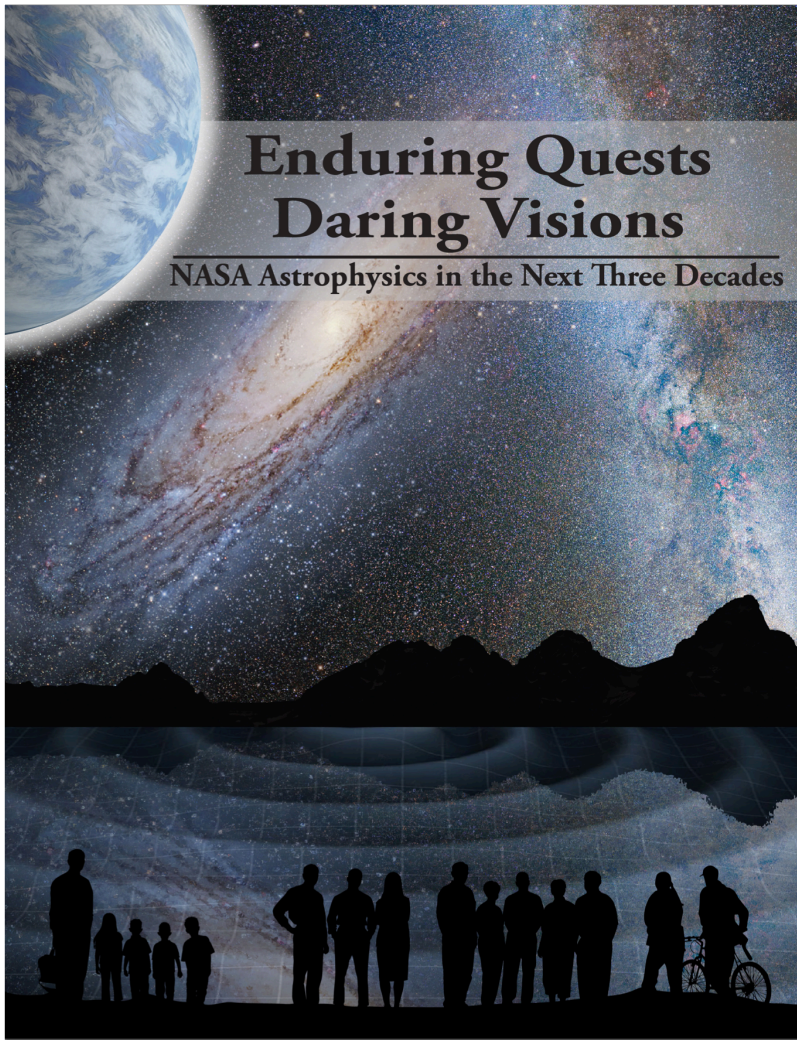
What Happened?

- Decadal Review did pay attention to the FIR Whitepaper to a degree
 - Endorsed participation in SPICA at \$150M level, but with caveat about availability of funds
 - Support for technology development but not specific or very enthusiastic
- FISCAL reality intruded during the first half of 2010+ decade –
 - NASA decided that funds were “not” available; thus SPICA participation has been stalled
 - Limited technology development through COPAG
 - APRAs and SATs

Looking Ahead to 2020 Decadal Review – FIR Community Needs to Start Planning Activities

- What did we learn from previous decadal experience?
 - *Herschel* was waiting for launch and it seemed premature to be asking for major new mission at that time
 - We did achieve some degree of consensus, but there was lack of rabid enthusiasm
 - We need to have more connection with other communities (wavelengths)
- It is “early days” for 2020, but there is a rich variety of possibilities
- Dave Leisawitz felt it was not too soon to have a “community workshop” and he undertook organization thereof with help from myself and a dedicated SOC

A New Ingredient for Future Planning: NASA – Astrophysics Division Roadmap



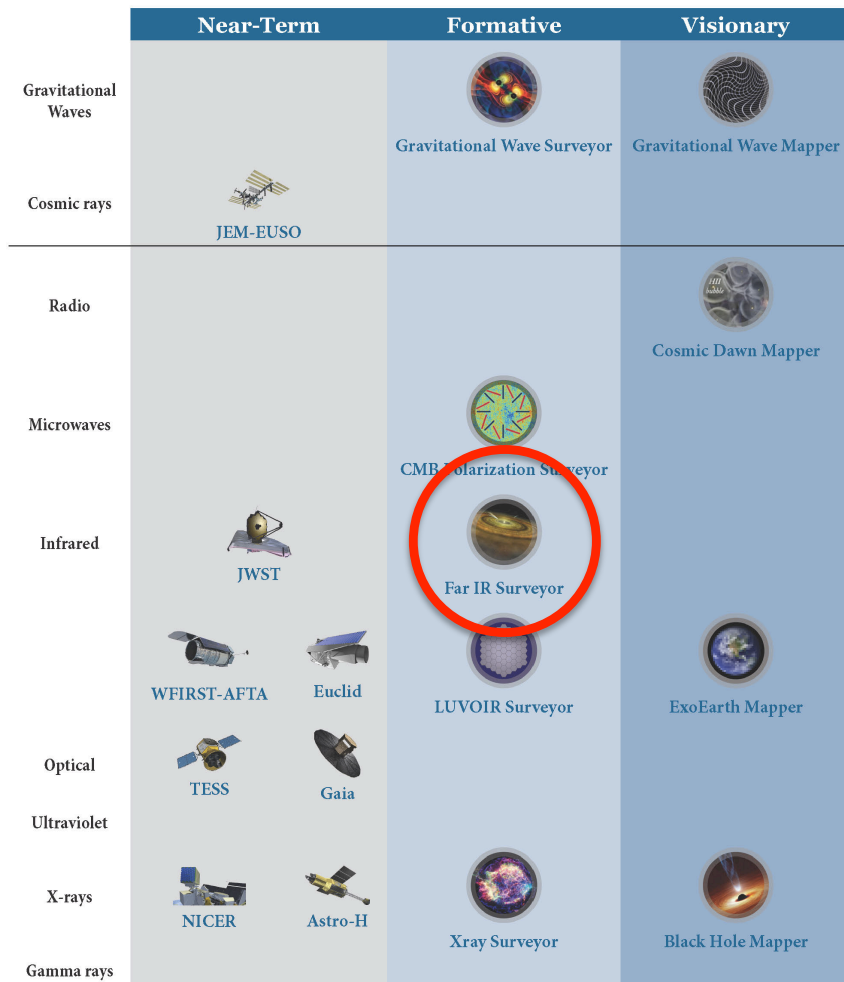
Charter:

- Provide a compelling 30-year vision
- Build on Astro 2010 Decadal Survey
- Science based notional missions
- Developed by a task force of the APS
- Include community input
- Be delivered to the APS

A long-range vision document with options, possibilities, w/ visionary futures

Charter is not a mini-decadal survey, does not have recommendations or priorities, is not an implementation plan

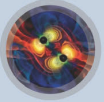
NASA – Astrophysics Division Roadmap



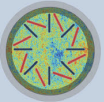
Three eras:

- Near-Term (current or planned)
- Formative (10-20 years)
 - Notional Mission Surveyors
- Visionary (20+ years)
 - Notional Mission

Near Term Surveyors



Gravitational Wave Surveyor



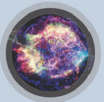
CMB Polarization Surveyor



Far IR Surveyor



LUVOIR Surveyor



Xray Surveyor

Far-IR Surveyor:

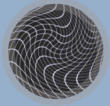
- Large gains to be achieved by actively cooled large dish (super-Herschel).
- Large aperture + high res spec and ultimately interferometry to get sub-arcsec FIR images.
- Low risk / platform for other interferometry missions

Tech needs:

- Segmented large single-aperture (10-20m) FIR telescopes
- Sub-Kelvin focal-plane coolers
- Space-qualified 4 K mechanical coolers
- Detectors and readout electronics
- Wide-field or multi-beam spectrometers

From a leading detector expert: “Tell us what you need and we’ll make it for you”

Visionary



Gravitational Wave Mapper



Cosmic Dawn Mapper



ExoEarth Mapper



Black Hole Mapper

Far IR Mission

“As for large single-aperture telescopes, the technical requirements for interferometry in the FIR are not as demanding as for shorter wavelength bands, so FIR interferometry may again be a logical starting point that provides a useful training ground while delivering crucial science. “

- *Enduring Quests, Daring Visions, NASA 30 Yr. Roadmap*

FIR Community Workshop

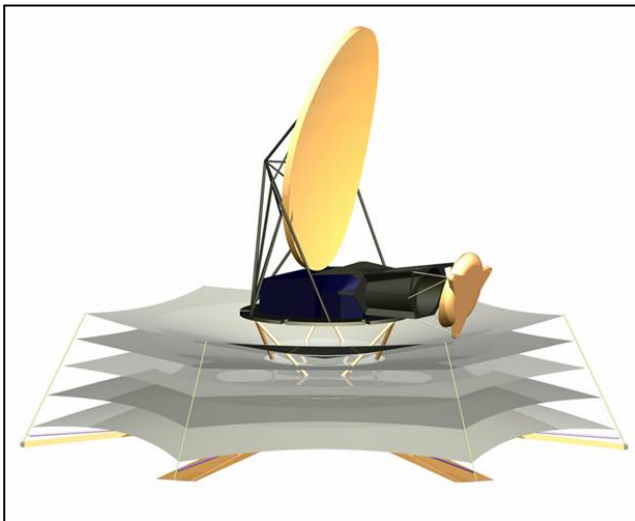
- At GSFC May 12 and May 13, 2014
- 147 individuals registered; approximately 135 attended
- Overview Talks on Missions, Enabling Technology, and Science
 - Large-scale structure & early galaxies
 - AGNs, starburst galaxies & Star-formation history
 - Nearby galaxies
 - Star formation, dust, gas, and the ISM
 - Disks, planetary systems & solar system objects
- Splinter Groups
- Posters & Poster Shorts
- Discussion panel
- <http://asd.gsfc.nasa.gov/conferences/FIR/> .

SINGLE-APERTURE FAR- INFRARED SPACE TELESCOPES

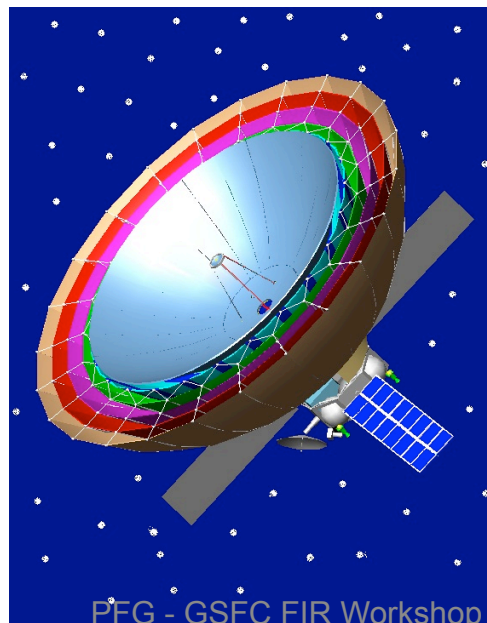
CONCEPTS for MAJOR FIR SPACE MISSIONS + MORE

Paul F. Goldsmith
Jet Propulsion Laboratory, California Institute of Technology

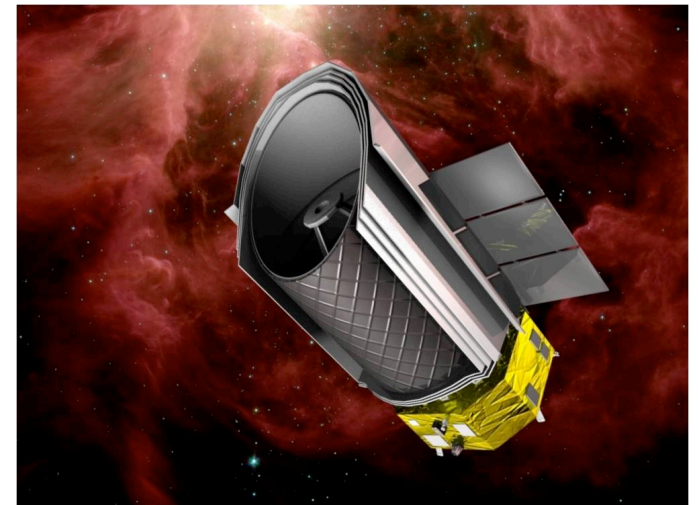
FIR WORKSHOP – Goddard Spaceflight Center
May 12, 2014



6/3/14



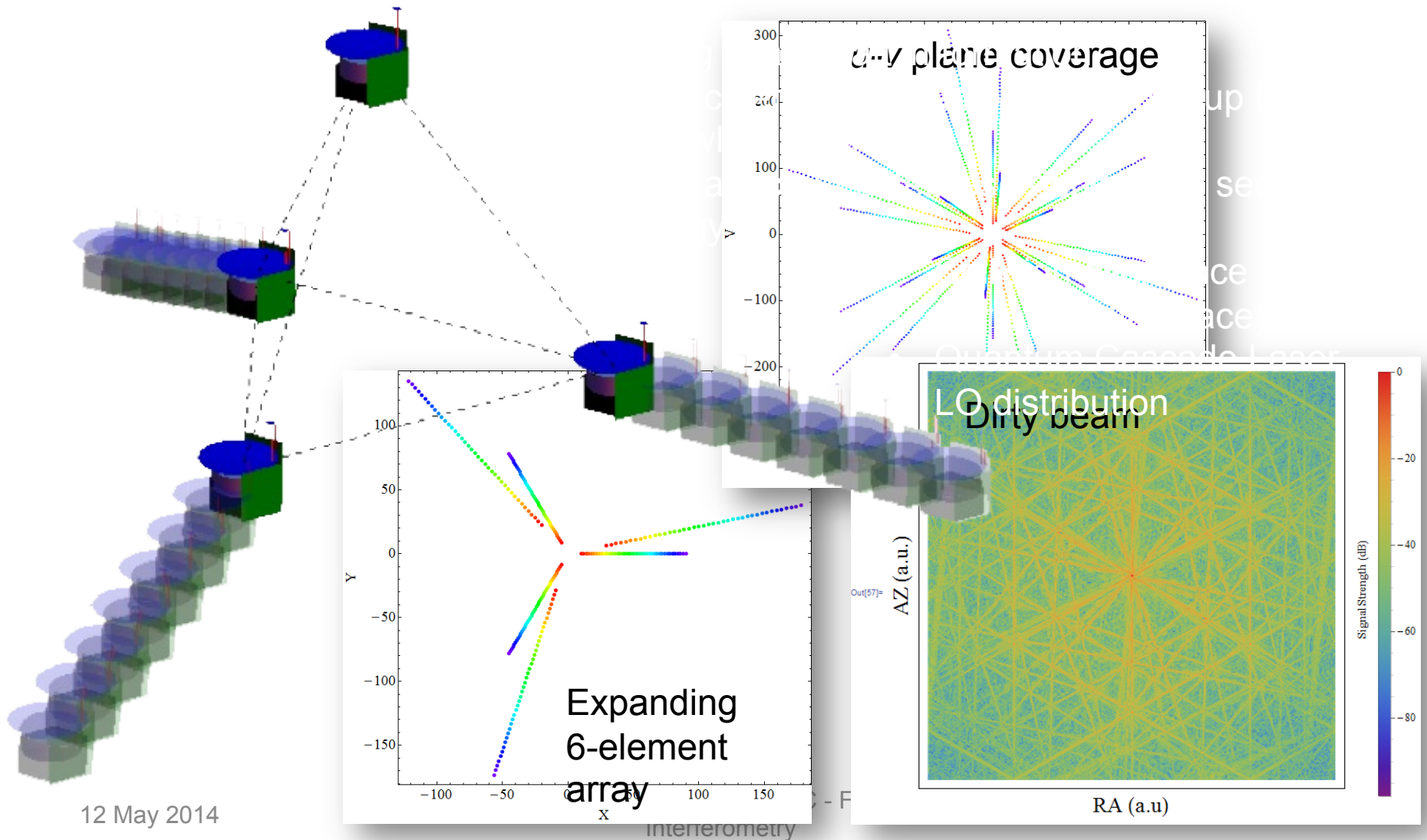
PFG - GSFC FIR Workshop



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ESPRIT Concept:

Exploratory Submillimeter Space Radio-Interferometric Telescope
Heterodyne

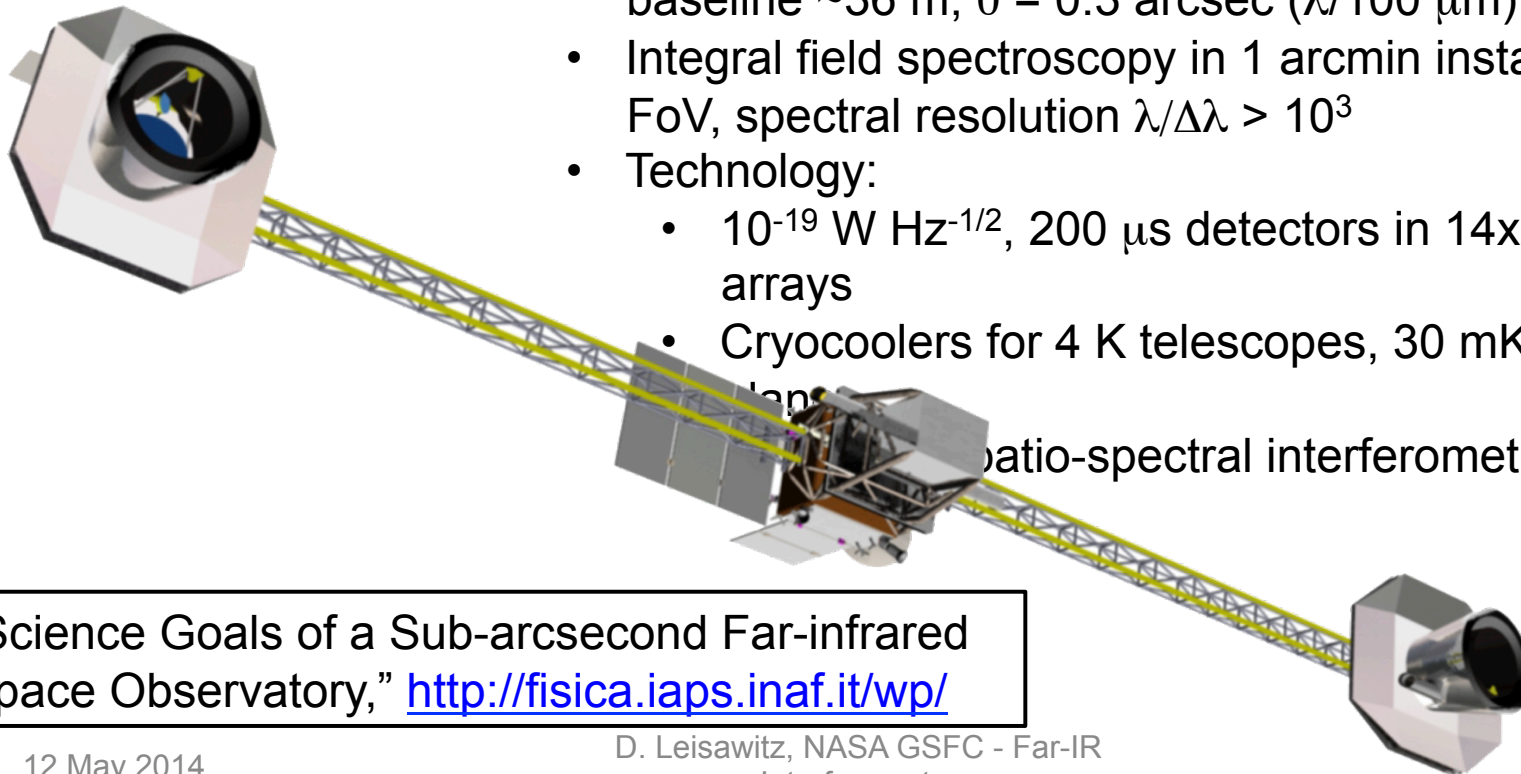


12 May 2014

SPIRIT Concept: Direct Detection

Submillimeter Interferometric Telescope

- Structurally-connected interferometer
 - Two 1-m afocal off-axis telescopes
 - Telescopes move radially, and structure rotates to provide dense u - v plane coverage with maximum baseline ~ 36 m, $\theta = 0.3$ arcsec ($\lambda/100$ μ m) imaging
 - Integral field spectroscopy in 1 arcmin instantaneous FoV, spectral resolution $\lambda/\Delta\lambda > 10^3$
 - Technology:
 - 10^{-19} W Hz $^{-1/2}$, 200 μ s detectors in 14x14 pixel arrays
 - Cryocoolers for 4 K telescopes, 30 mK focal plane
- Radio-spectral interferometry



“Science Goals of a Sub-arcsecond Far-infrared Space Observatory,” <http://fisica.iaps.inaf.it/wp/>

A Brief and Biased Summary

- Three major single-antenna concepts and two interferometer concepts were presented - All can do a variety of exciting science
- Some areas of astronomy seem to be non-FIR, such as stellar evolution, exoplanets, CMB
- Some areas appear to have untapped potential – galaxy formation, star + planetary system formation, first stars, first SNe,
- Some areas have (from Herschel and others) been shown to have a wealth of information in FIR (star formation, disks, solar system objects)
- One constraint to keep in mind is the capability of ALMA covering mm and submm windows to possibly 800 GHz or even 1000 GHz (350 μm). Especially powerful for continuum and CO and other lines in terms of sensitivity and high angular resolution
- The challenge is to identify the “killer apps”: **What are the exciting science questions that can ONLY be answered by new FIR mission?**
- A (small) selection of science topics follows ----

Herschel: Powerful Molecular Outflows in Local ULIRGs and FIR-Bright Quasars

(Fischer + 2010; Sturm + 2011; Veilleux + 2013; Spoon + 13; Gonzalez-Alfonso + 2012, 2014)

OH 65 / 79 / 119 μ m PACS Spectroscopy

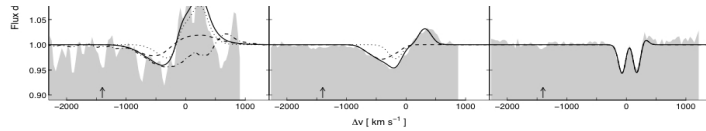
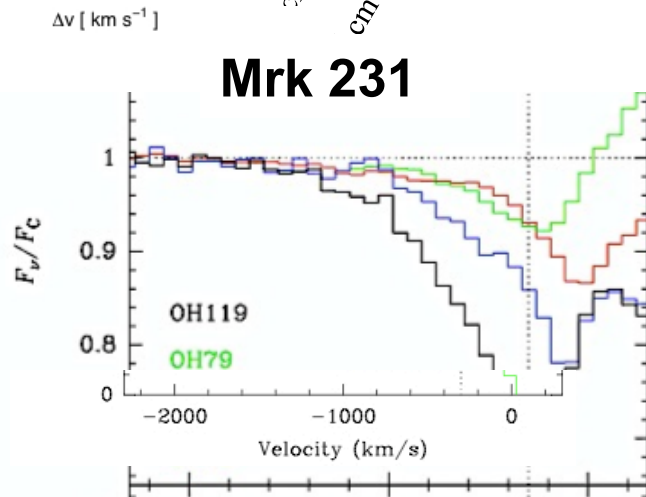


Fig. 1.— Observed PACS spectra (continuum normalized) of the OH transition at 79 μ m (grey). Overplotted are the low velocity (dotted) and high velocity (dashed) fit components and the total fit (full). The arrow indicates the rest position of H₂O 4₂₃-3₁₂. The dash-dotted line for IRAS 14378 shows the observed spectrum of the OH transition at 119 μ m for this object.

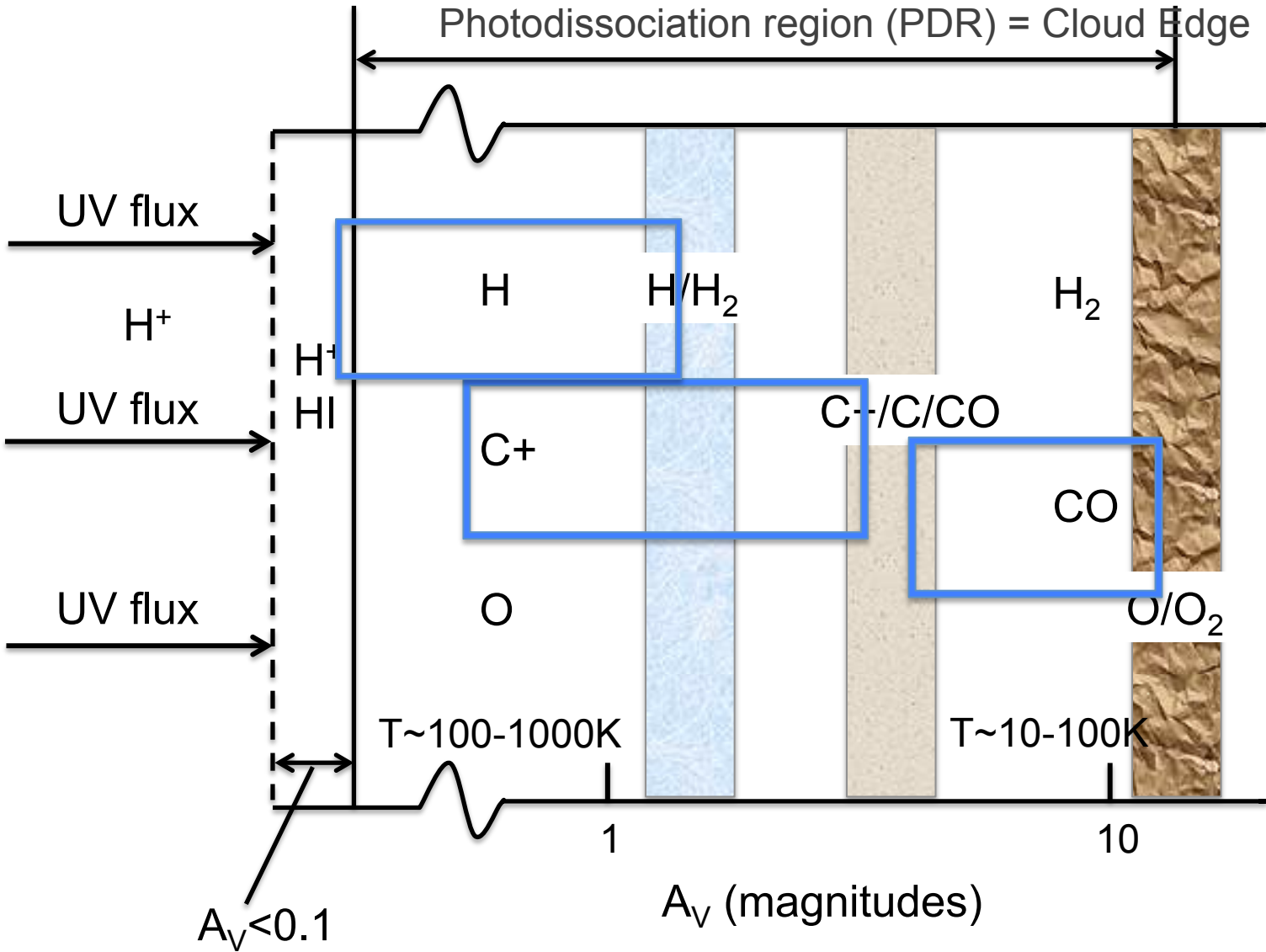
- **Statistics:** ~70% of local ULIRGs have molecular (OH) winds
→ wide-angle geometry (~145°)
- **Outflow velocities:** $\langle v_{50} \rangle$, $\langle v_{84} \rangle$, $\langle v_{\max} \rangle \sim -200, -500, -925 \text{ km s}^{-1}$
- **Kinematic trend with L_{AGN} :** → **AGN plays a dominant role**
when L_{AGN} exceeds $\sim 10^{11.8} L_{\text{sun}}$
- **Energetics** (from profile comparison of multiple OH transitions):
 - dM / dt up to $1000 M_{\text{sun}} \text{ yr}^{-1}$
 - $L_{\text{mech}} = 10^{10} - 10^{11} \text{ erg s}^{-1} \dots$
 - $E_{\text{mech}} = \text{few} \times 10^{56} \text{ ergs}$
 - $dp/dt = (1 - 30) L_{\text{AGN}}/c$

Table 1: Target properties, outflow rates and outflow velocities (1σ uncertainties in brackets)

| Source | SFR M_{\odot}/yr | α^a % | L_{AGN} $10^{11} L_{\odot}$ | M_{gas}^b $10^9 M_{\odot}$ | \dot{M}^c M_{\odot}/yr | v_{peak}^d km/s | $v_{85\%}^e$ km/s | v_{max}^f km/s |
|-----------------|------------------------------|-----------------|---|--|--------------------------------------|-----------------------------|----------------------|----------------------------|
| Mrk 231 | 101 (15) | 71 (11) | 28 (4) | 4.2 (1.3) | 1190^{+4700}_{-890} | -600 | -660 | -1170 |
| IRAS 08572+3915 | 42 (6) | 72 (11) | 12 (2) | 1.3 (0.4) | 970^{+2900}_{-730} | -700 | -740 | -1260 |
| IRAS 13120-5453 | 168 (25) | 9 (1.4) | 1.8 (0.3) | 5.8 (1.7) | 130^{+390}_{-95} | -520 | -600 | -860 |
| IRAS 14378-3651 | >79 | <45 | <7.2 | 4.2 (1.3) | 740^{+2200}_{-550} | -800 | -860 | -1170 |
| IRAS 17208-0014 | 274 (41) | 11 (1.7) | 3.4 (0.5) | 12.2 (3.7) | 90^{+270}_{-65} | -100 | -170 | -370 |
| NGC 253 | 1.7 (0.3) | 0 | 0 | 0.7 (0.2) | $1.6^{+4.8}_{-1.2}$ | -75 | -130 | -280 |

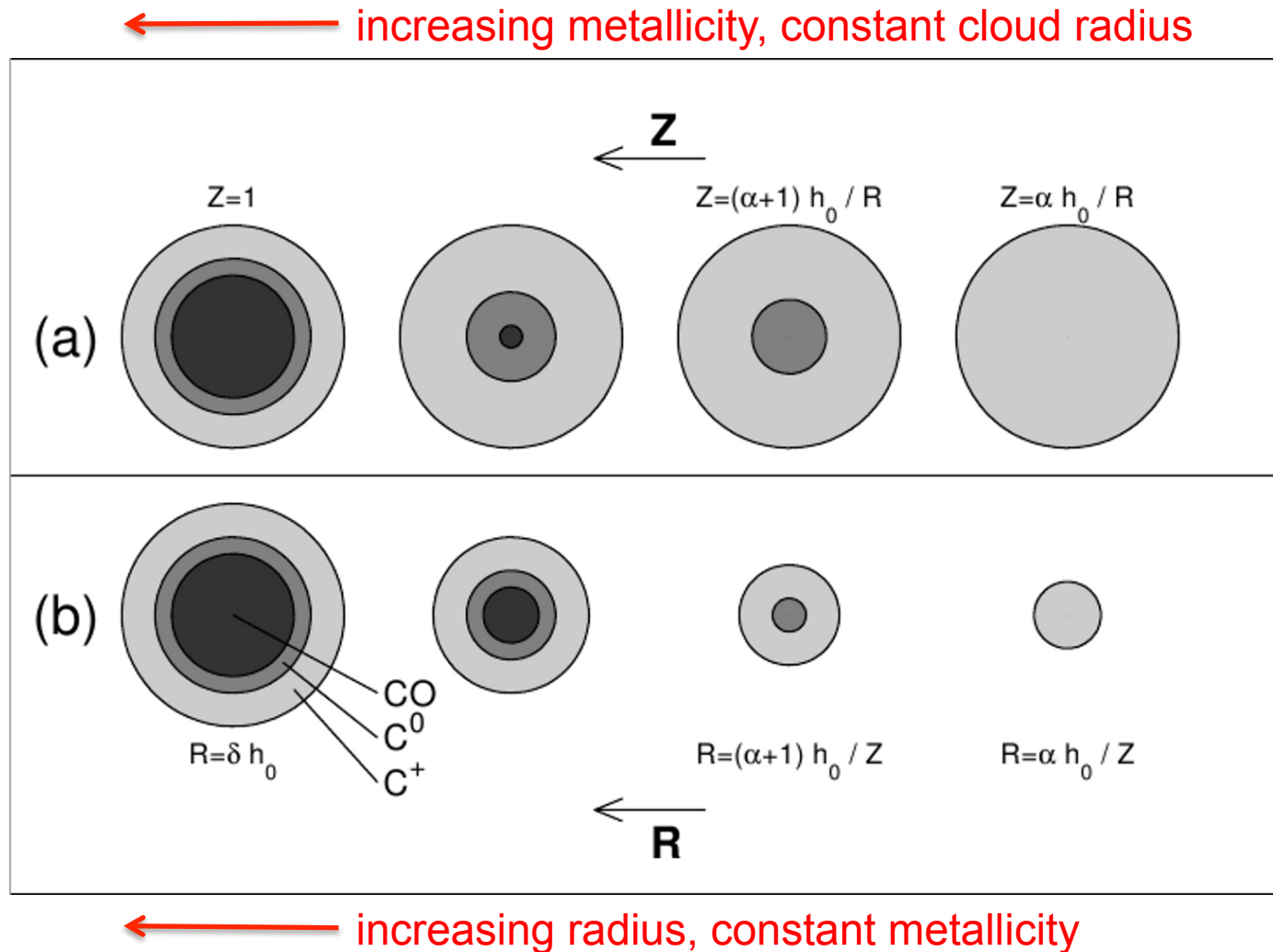


CO Dark Molecular Gas



(adapted from Wolfire & Kaufman 2011)

PDR structure changes at low metallicity



(taken from Bolatto+ 1999)

CO-Dark H₂ Through [CII] Observed in Herschel GOT-C+ Project

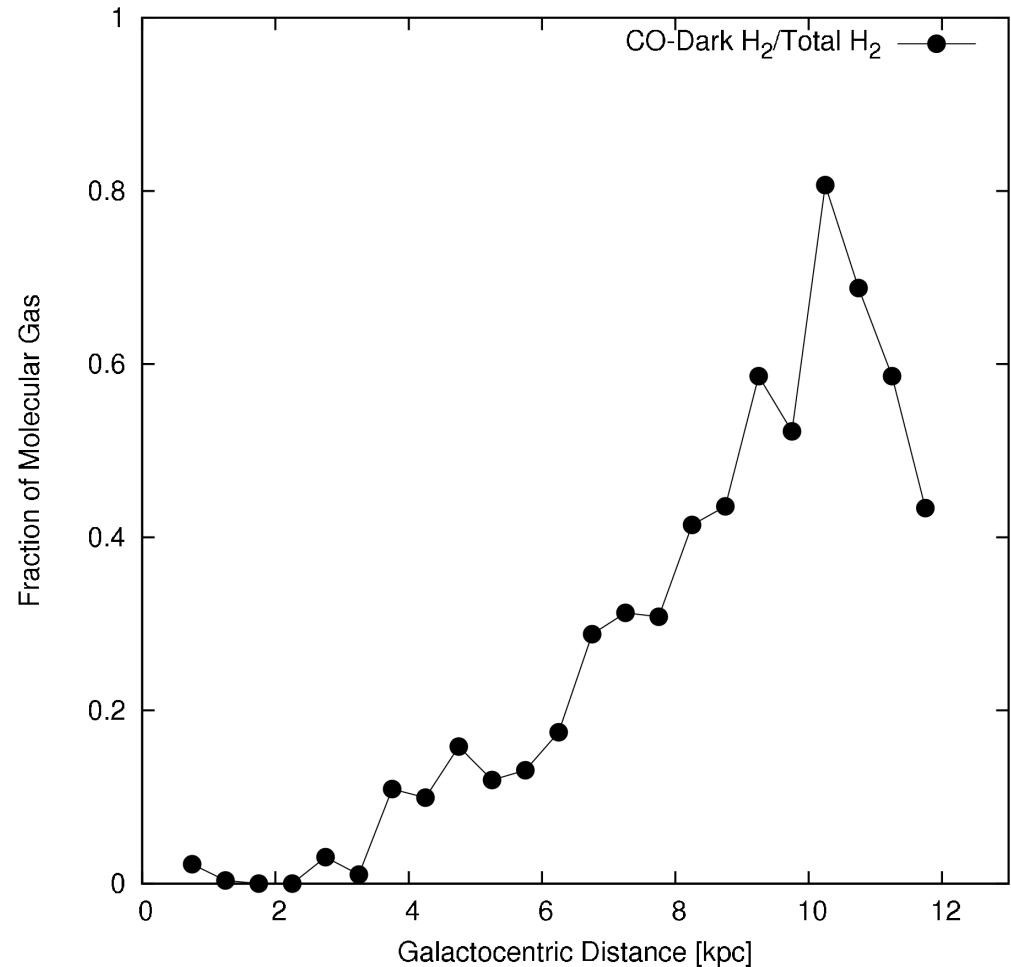
Method: Calculate CII, HI, CO and ¹³CO azimuthally averaged emissivity. Subtract HI, e⁻, PDRs, contributions to [CII] intensity.

Result: Gives the Galactic distribution of the CO-dark gas component. The average CO-dark H₂ fraction ~0.3 .

Applies to: Entire Galactic plane

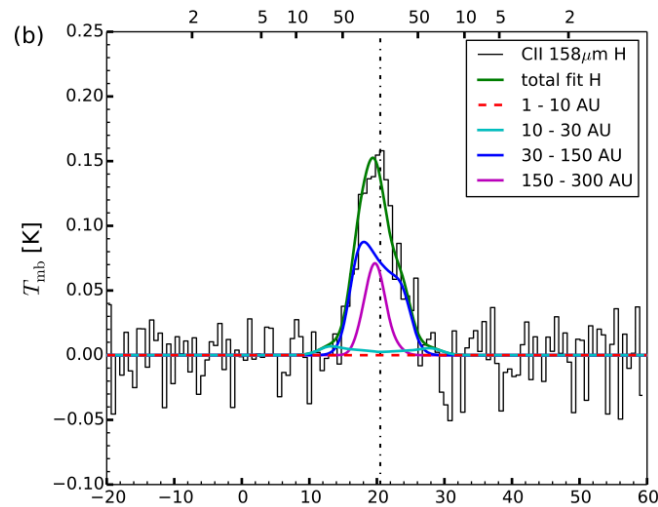
Caveats: Needs assumptions on the physical conditions (n,T) of the CO-dark H₂ layer.

Future: Study scale height of CO-Dark gas; Extend to nearby galaxies



CO-Dark H₂ Fraction of Molecular Gas

β Pictoris Gas

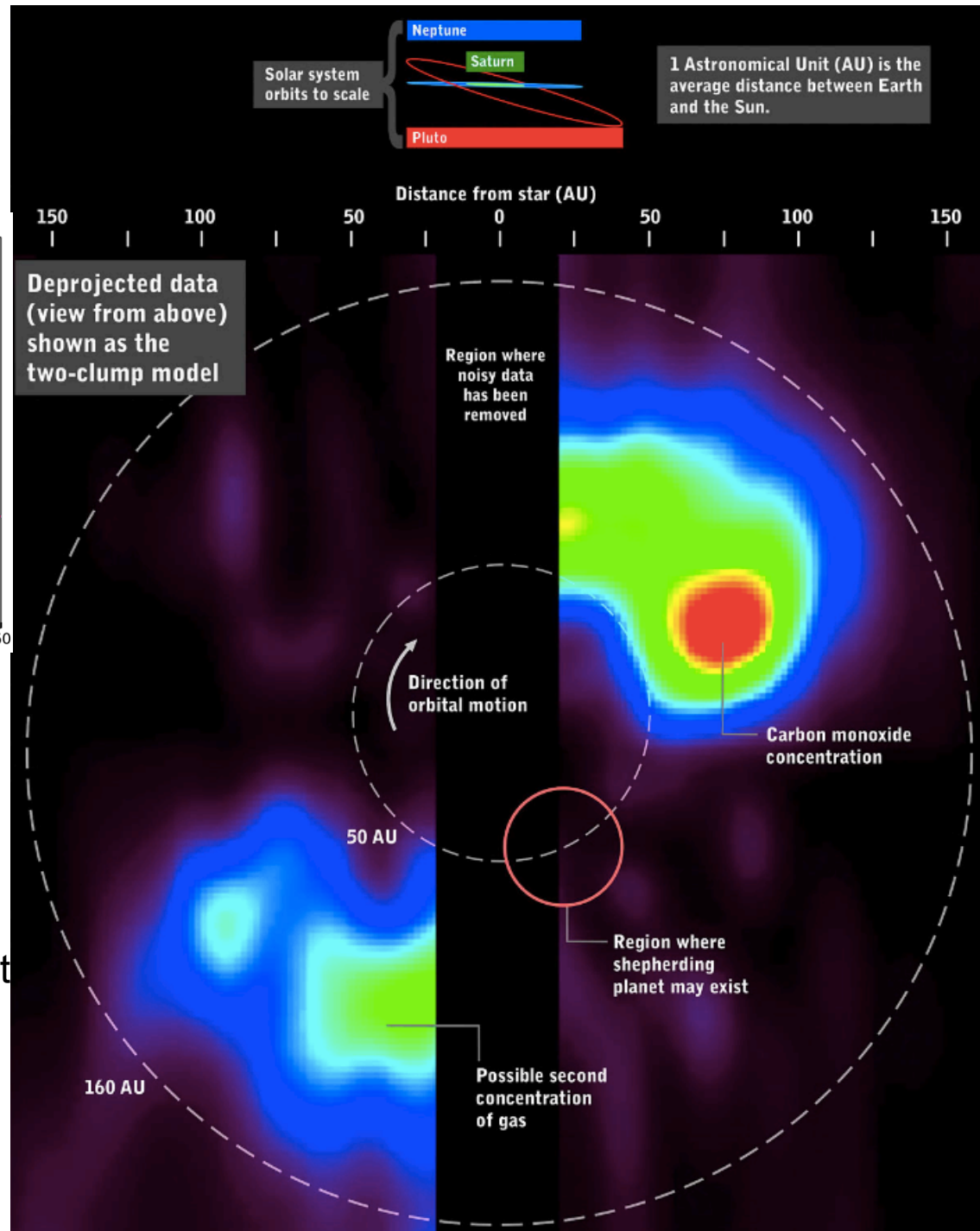


Herschel OI and C II line detections (e.g. Cataldi et al. 2014):

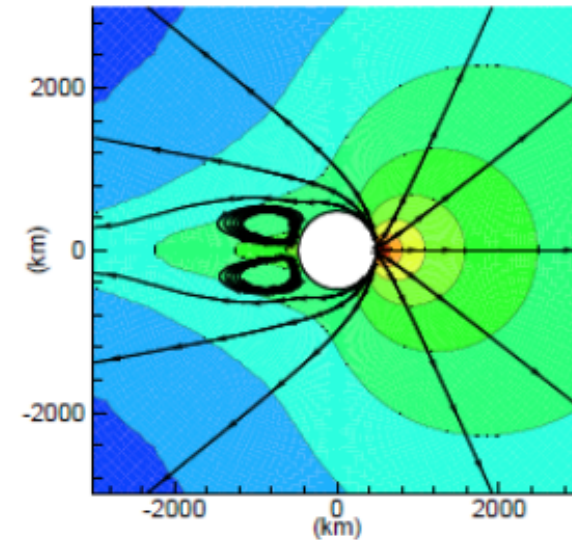
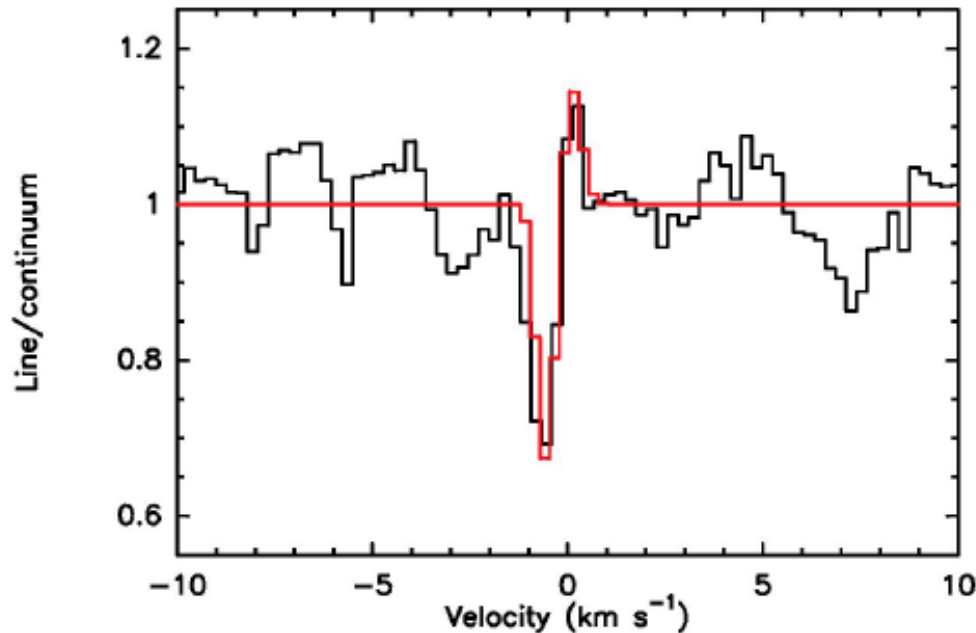
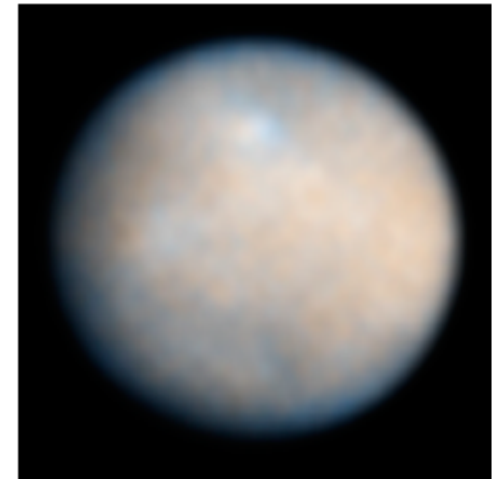
- Photo dissociation products of molecular gas

ALMA CO J=3-2 Emission map (Dent et al. 2014):

- The clump may indicate that there is an additional $>10 M_{\text{earth}}$ planet that traps the comets in the 2:1 and 3:2 mean motion resonances



An unexpected discovery:
The detection of water vapor
around Ceres (HIFI)



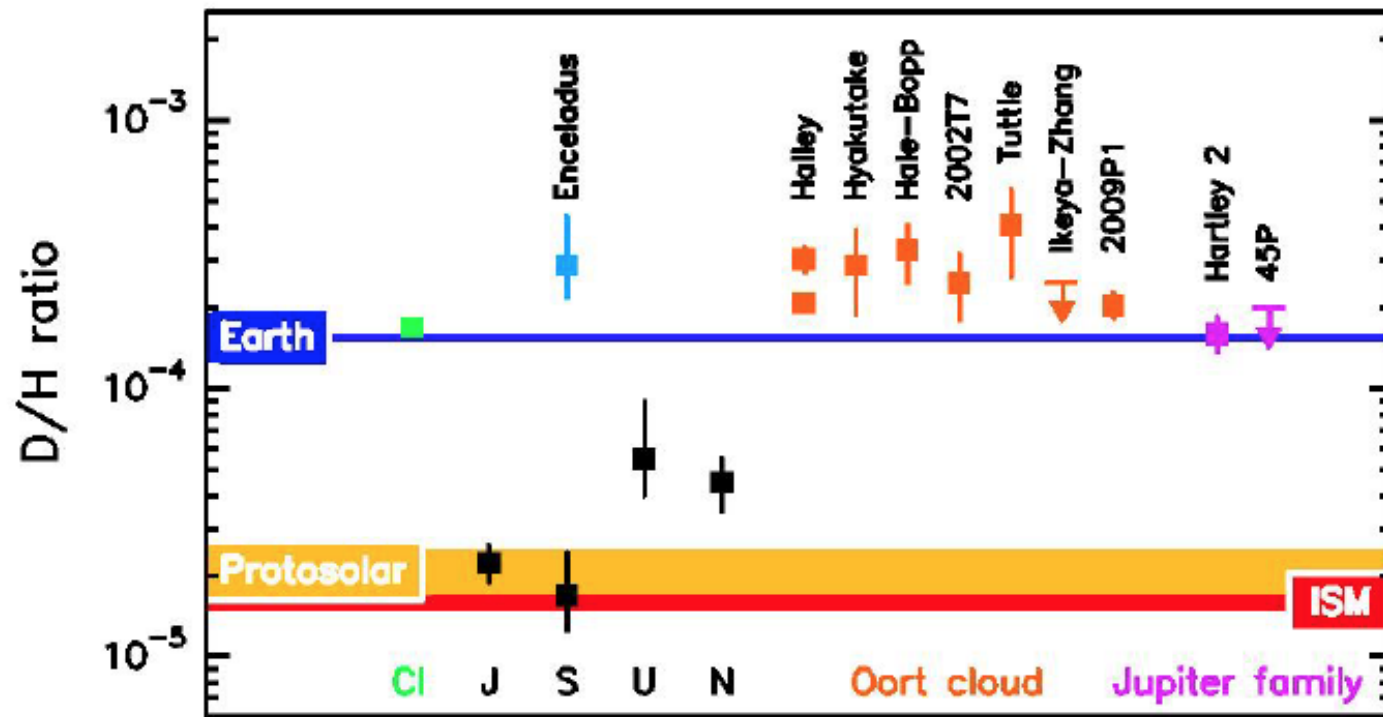
557 GHz H₂O line detected with HIFI in October 2012 and March 2013

Kueppers et al., 2014

What is the frontier between asteroids and comets???

What is the origin of terrestrial oceans?

A diagnostic: the D/H ratio in water



Lis et al. 2013

$$[D/H]_E = 1/2 \times [D/H]_{\text{Oort-cloud-comets}}$$

$$[D/H]_E = [D/H]_{\text{CC-Meteorites}} \text{ but also } = [D/H]_{\text{Kuiper-Belt-comets}}$$

-> Origin of oceans: D-type MBA or Kuiper Belt comets?

The Next Steps

- The May 2014 Community Workshop was envisioned to be the first of a sequence of activities
- The workshop did define a number of exciting problems and loosely defined the observational requirements for pursuing FIR observations
- There was little agreement about the best way forward in terms of missions; even the basic question of single aperture vs. interferometer was not resolved
- Some clarity may emerge with SPICA in 2017 when ESA and JAXA decisions will be known. “With-SPICA” and “Without-SPICA” paths may be evident and are certainly distinct
- There was no specific identification of “FIR killer apps”, but there was some progress. Additional work needed!
- Need to plan for subsequent workshops
- **What YOU can do – join the FIR SIG!**
- **Contact Susan Neff, NASA COPAG Chief Scientist (susan.g.neff@nasa.gov)**