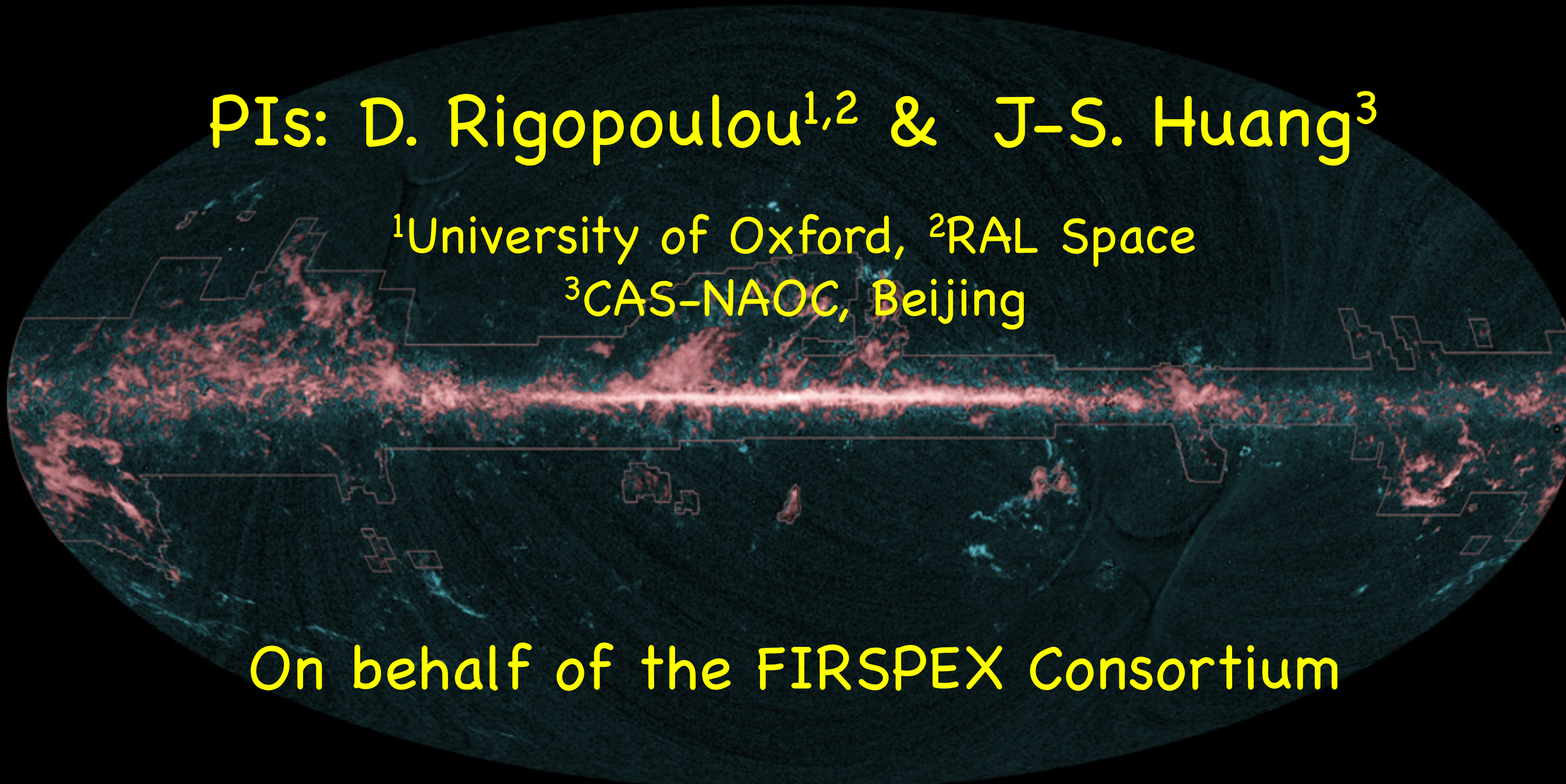
Far-Infrared Spectroscopic Explorer
- FIRSPEX -



PIs: D. Rigopoulou[1,2] & J-S. Huang[3]

[1]University of Oxford, [2]RAL Space
[3]CAS-NAOC, Beijing

On behalf of the FIRSPEX Consortium

RAL Space | UNIVERSITY OF OXFORD | NATIONAL ASTRONOMICAL OBSERVATORIES ,CHINESE ACADEMY OF SCIENCES

2nd ESA-CAS Workshop

Background image Planck-ESA team

FIRSPEX Team

PIs: D. Rigopoulou (UK) & J-S. Huang (NAOC)

Technical team: RAL: B. Swinyard, B. Ellison, C. Pearson
PMO: Y. Gao, S-C. Shi, J. Hu

- E. Caux (IRAP, FR)
- M. Huang (NAOC, China)
- D. Clements (IC, UK)
- S.C. Shi (PMO, China)
- Y. Delorme (Obs Paris, FR)
- V. Charmandaris (NOA, GR)
- W. Zhong (NAOC, China)
- X. Liu (China)
- M.J. Griffin (Cardiff, UK)
- J. R. Gao (SRON, NL)
- L. Hao (Shanghai, China)
- S. Molinari (IAPS-INAF, IT)
- F. Helmich (SRON, NL)
- S. Viti (UCL, UK)
- Yu Gao (PMO, China)
- E. Lichfield (Leeds, UK)
- C.N. Hao (Tianjin,NU, China)
- X.Y. Xia (Tianjin,NU, China)
- Je Hu (PMO)
- D. Li (NAOC, China)
- M. Wiedner (Obs. Paris, FR)
- Ji Yang (PMO, China)

What is FIRSPEX ?

- FIRSPEX is a joint ESA-CAS candidate small mission operating in THz (>0.5 THz) frequency range.

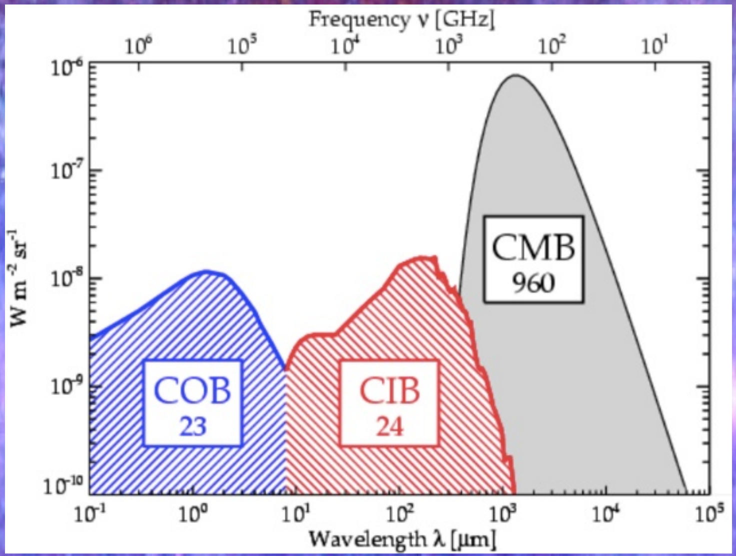
- Builds on European heritage in space technology and long standing collaboration with Chinese Institutions.

- Uses `old & tested' technology but with a `new twist' to push new technological frontiers, does NOT require cooling down to 4K (but only ~20K)

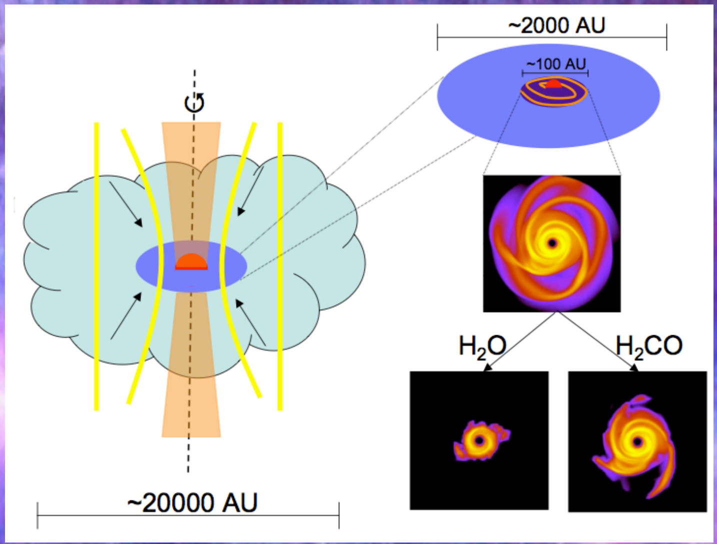
- Cost effective space mission aiming to push the supra-THz technology forward and deliver, for the first time, unique 3D maps of the infrared sky.

Why far-infrared?

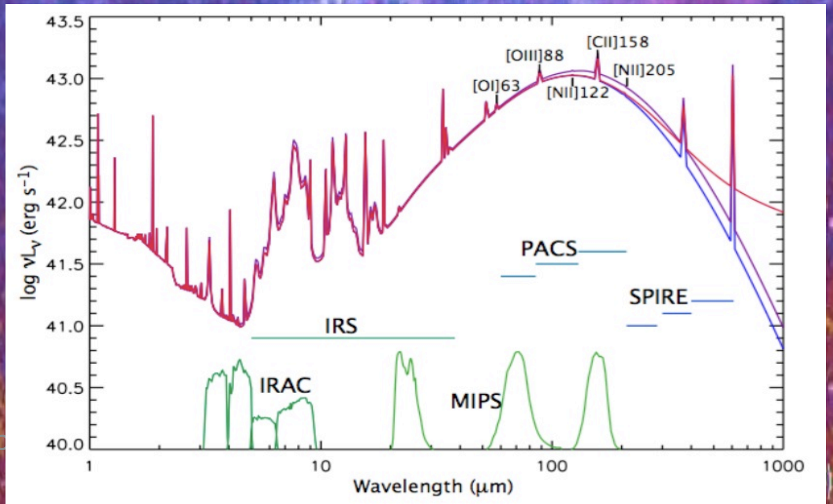
Cosmic Infrared Background



The dawn of protoplanetary disks



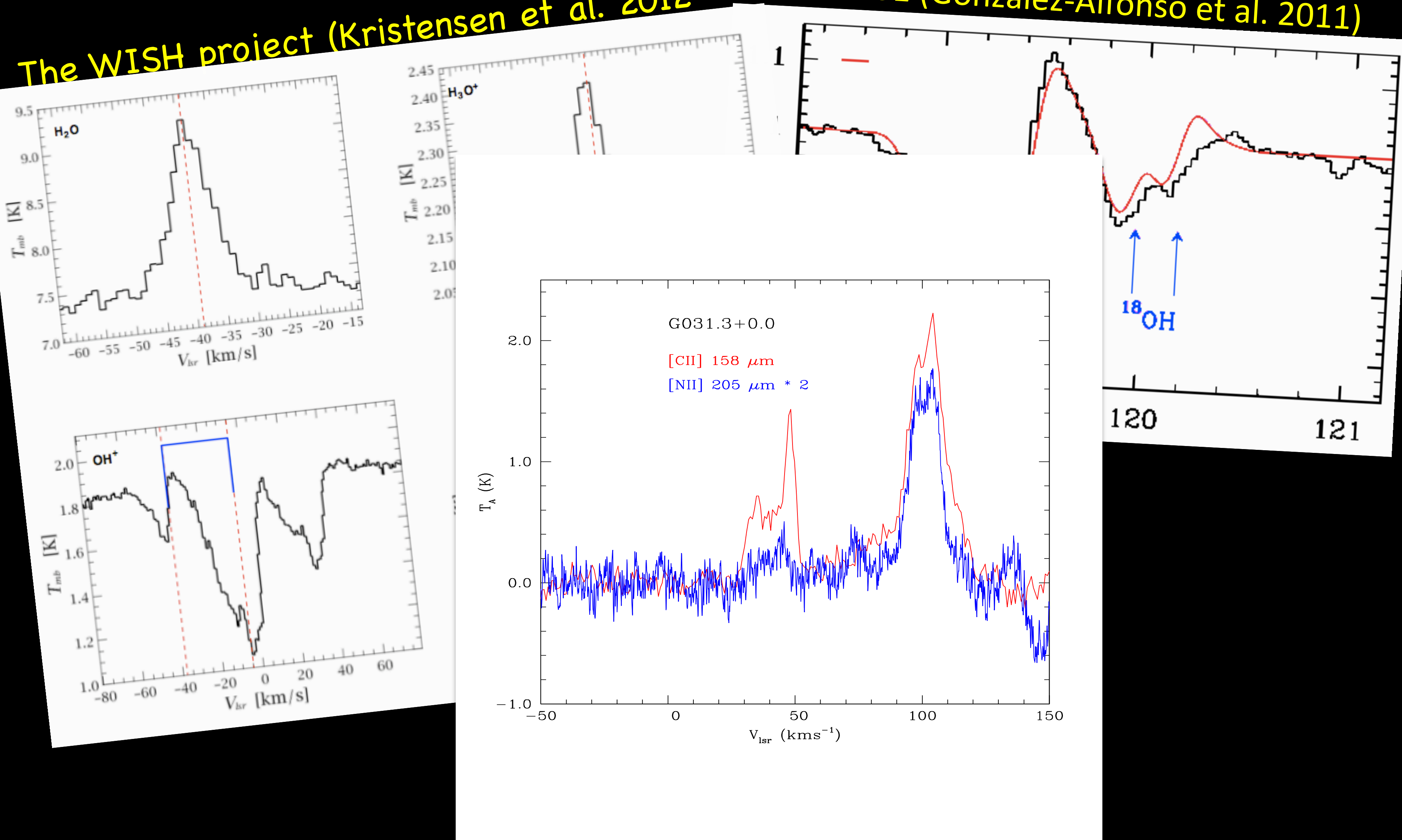
- ✧Study the ISM
- ✧Early stages of star formation
- ✧Cooling processes in galaxies
- ✧Formation of complex molecules
- ✧Gas Grain chemistry



Herschel Heritage

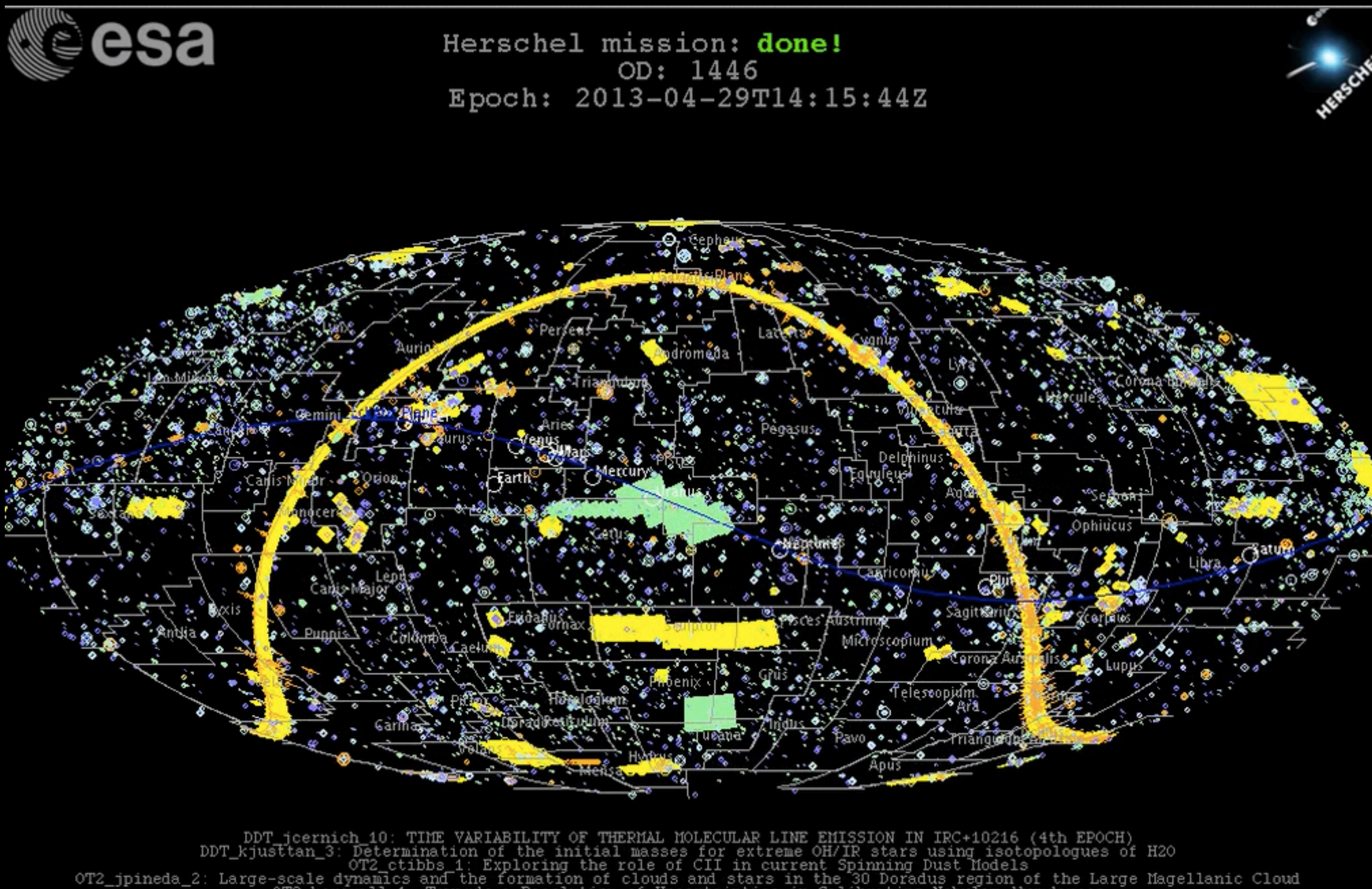
The WISH project (Kristensen et al. 2012

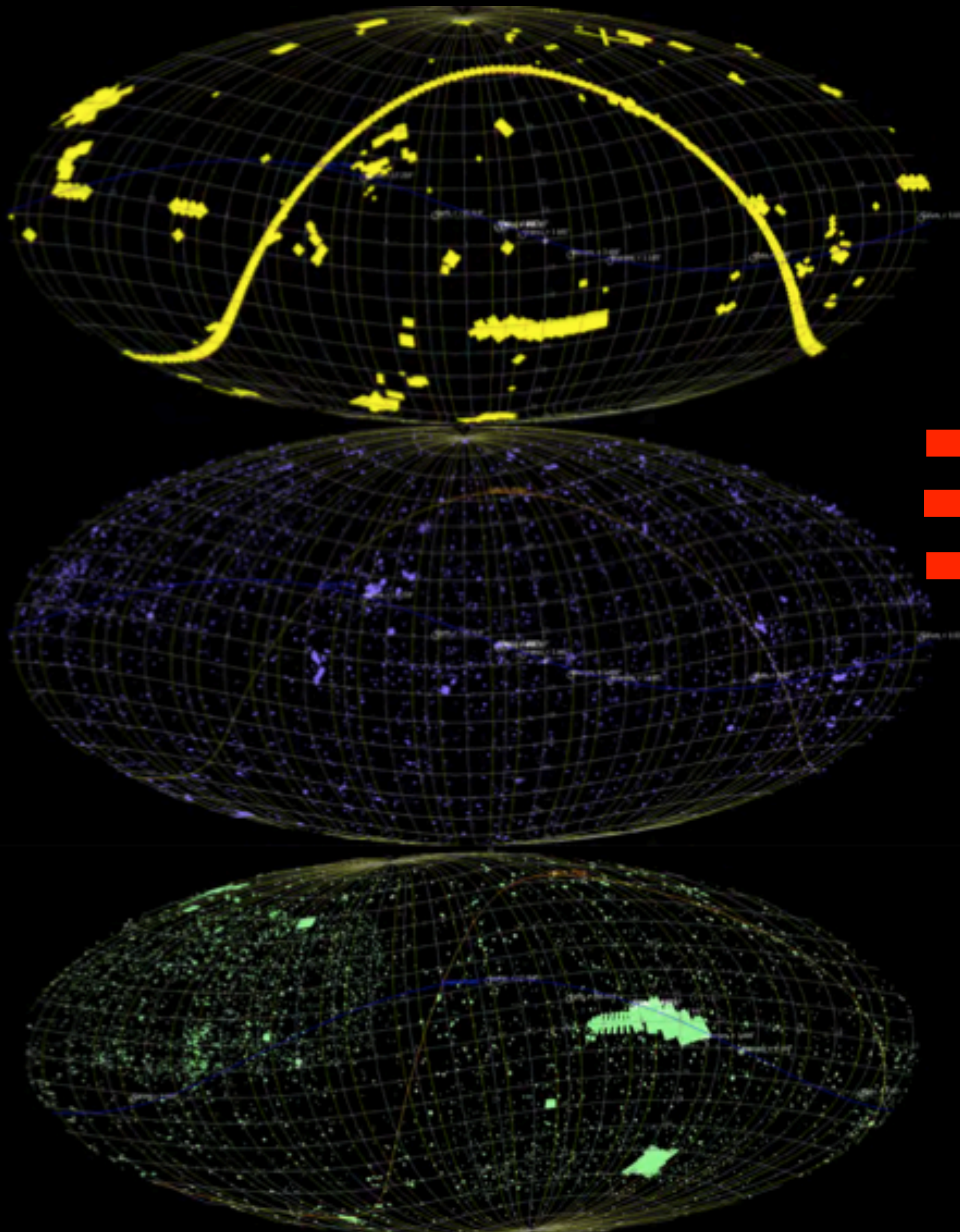
Mrk231 (Gonzalez-Alfonso et al. 2011)



GOT C$^+$ team (Pineda et al. (2013)

But Herschel surveyed 10% of the total IR sky!





Totals (uncert +/- 5%)

- S/P parallel 6.44
- PACS phot 0.67
- SPIRE phot 2.28
- PACS spec <0.01
- SPIRE spec <0.01
- HIFI 0.06
- Total Herschel 9.45

These numbers are %-ages of the entire sky (~41,000 sq deg)

Herschel has observed almost 1/10 of the entire sky!

By performing ~23,400 hr of HOTAC approved observing!

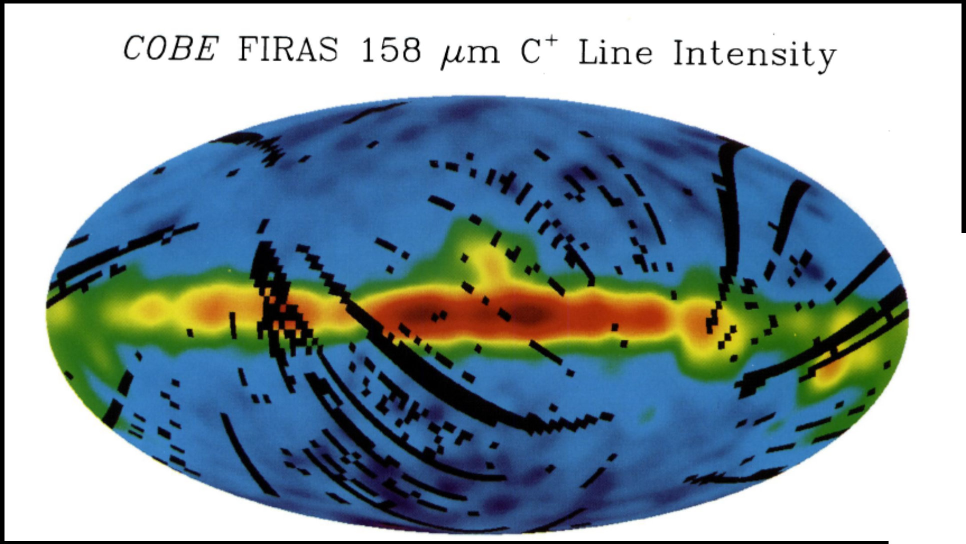
But no spectroscopic equivalent to the Herschel continuum survey of the Galactic Plane

The Herschel infrared Galactic Plane Survey (Hi-GAL)
PI: S. Molinari

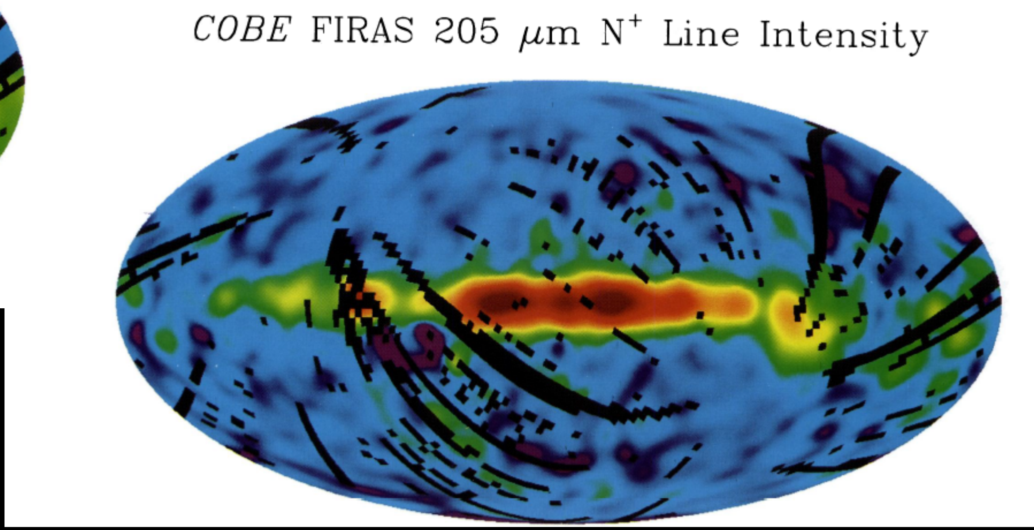
Heritage

COBE/FIRAS low resolution map in [CII],[NII] Bennett et al '94

probe the CNM (Bennet et al 94), WIM (Heiles et al 94)
PDRs (Cubick et al. 08)

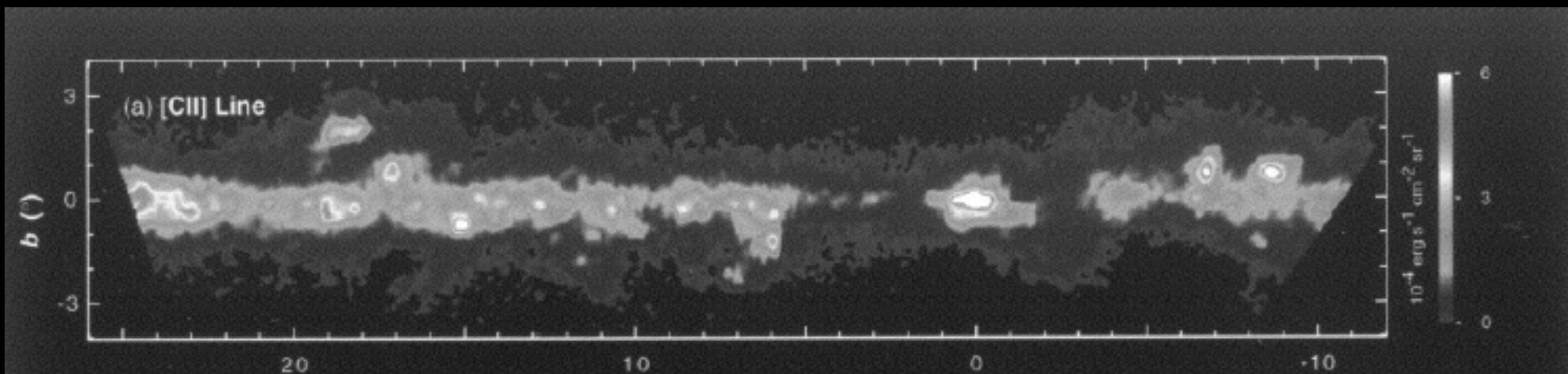


Spatial resolution 7°



Spectral res: 1000 km/sec

Balloon-borne Infrared [CII] Explorer (BICE)



Galactic Longitude in degrees

angular resolution: 15 arcmin
spectral resolution : 175 km/sec

Nakagawa et al. (1998)

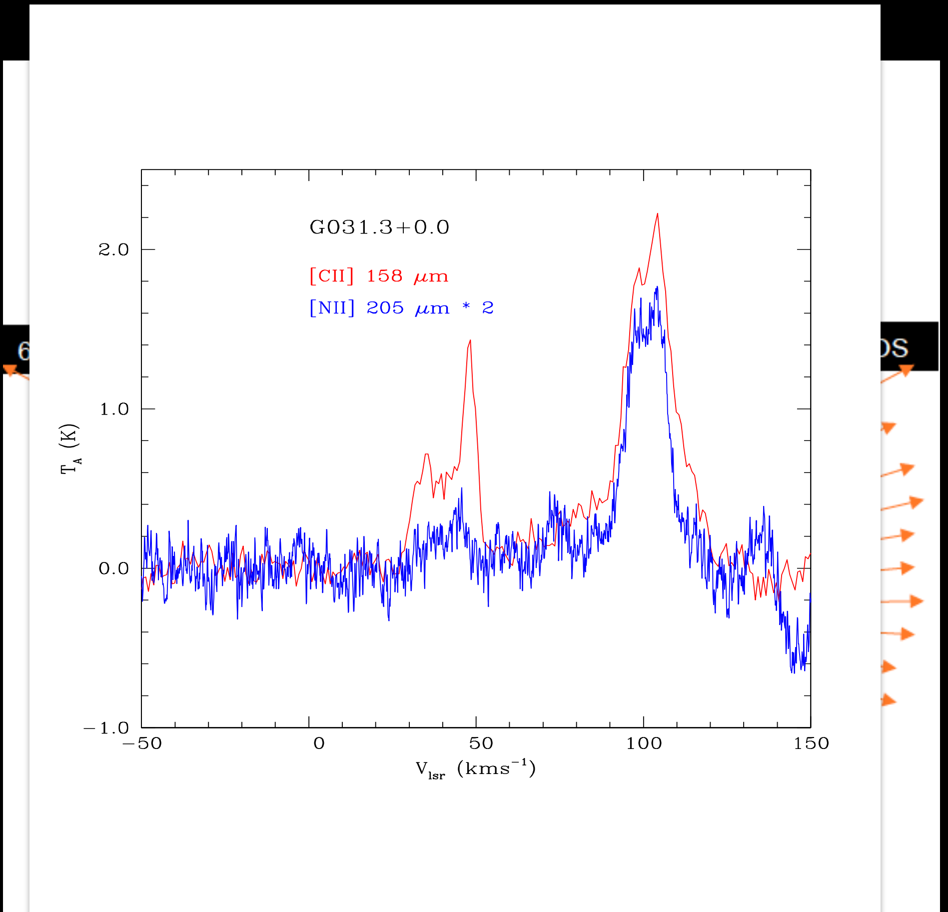
The Herschel-HIFI survey of [CII] in the Galaxy (the GOT C+ team)

Galactic Plane and Galactic Central Regions Survey

[CII] emission in the Galaxy mostly related to spiral arms, tracing clouds transiting from atomic to molecular.

But to fully trace properties of ISM we need large scale [CII] , [NII], [OI] maps of the Galaxy and Nearby Galaxies

FIRSPEX survey



GOT C+ team (Pineda et al. (2013)

What science can FIRSPEX deliver?

Two main considerations:

- Sensitivity
- Spectral Resolution

FIRSPEX science is unique and proposes to fill in an important gap: `a panoramic spectroscopic view' of the IR sky.

Sensitivities

Assumptions: 1 K in 5 sec @ 1.5 THz (conservative)
30 K in 5 sec @ 5 THz (based on LOCUS)
1 MHz resolution

Telescope: effective 1.0 m diameter

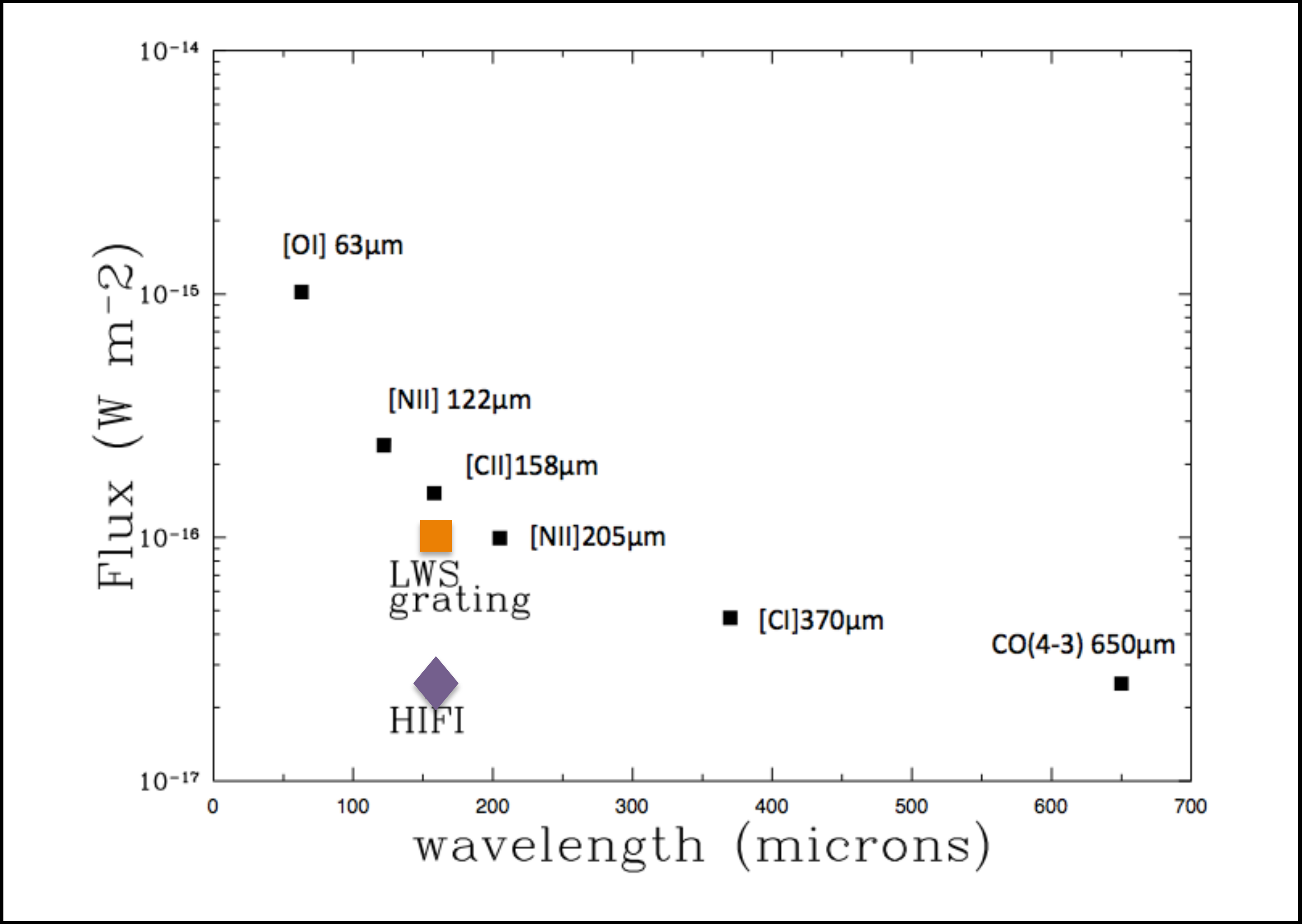
Antenna theorem: $A_e \Omega_a = \lambda^2$

$A_e = \eta_a A_p$

where, $\eta_a = 0.5$, $A_p = \pi (0.5)^2$

Conversion K to Jy: $K/Jy = A_e/2k$

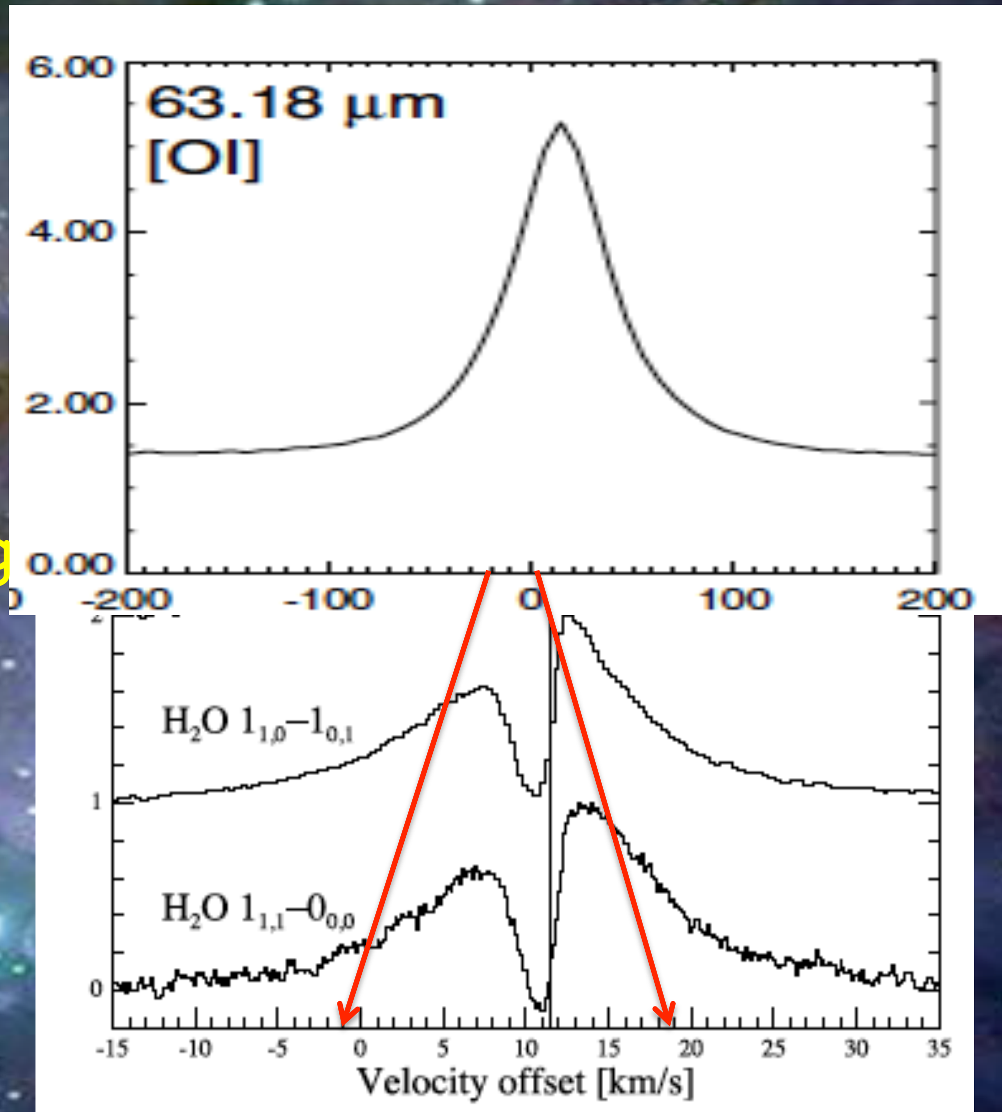
Sensitivities



Assuming 1 MHz resolution @ 1.5 THz

Resolution is key ….

Physical conditions in Star forming regions



[OI] in Orion -KL
ISO-LWS
Lerate et al. 2006

Water in Orion-KL
HIFI
Kama et al. 2013

The choice of spectral lines

Primary lines/channels:

- ✓ **(OI) 63 μ m** (4.7 THz)
- ✓ **[CII] 158 μ m** (1.9 THz)
- ✓ **[NII]205 μ m** (1.46 THz)

C,N,O

Additional bands/channels under consideration:

CO(4-3) 650 μ m (0.46 Thz): bootstrap FIRSPEX to ground based surveys

✓ [CI] 370 μ m (0.89THz) : crucial to obtain [CI]/[CII] ratio

=> C abundance

[OH] 119 μ m (interesting but hard), [NII] 122 μ m

FIRSPEX primary science goal

Perform "all-sky" survey
(spectroscopic equivalent of the IRAS/AKARI missions)

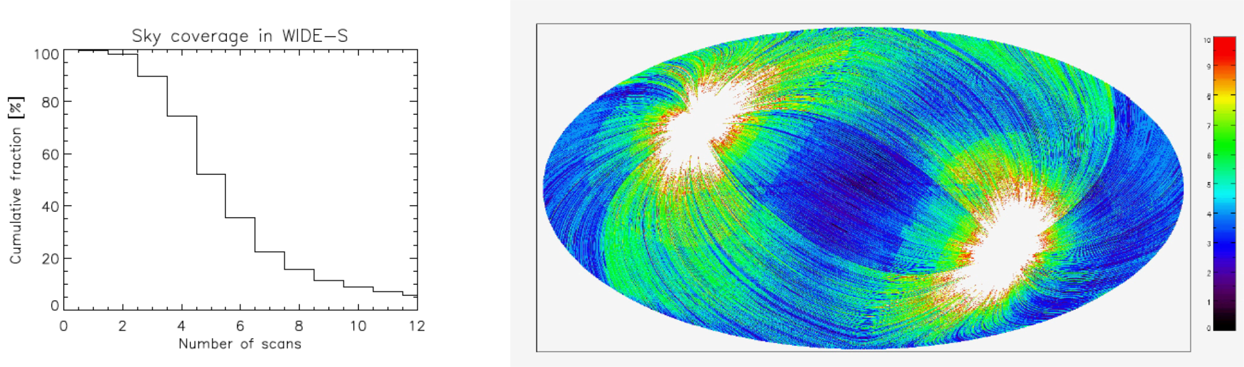
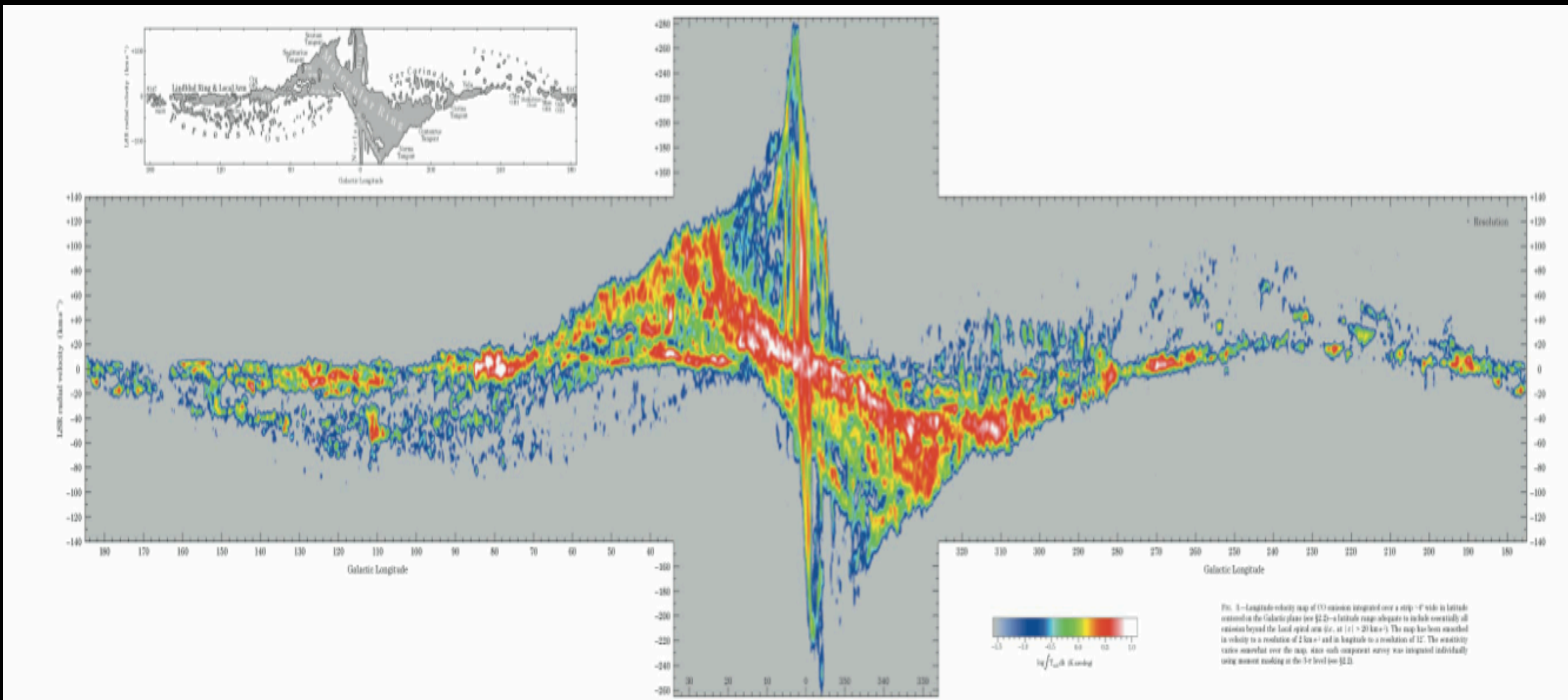


Figure 13: *Left:* The accumulative fraction of sky area observed more than the certain number of scans indicated in the X-axis. *Right:* Scan density map of the AKARI/FIS survey (WIDE-S = 90 μm band) in the Galactic coordinates, corresponding to the source distribution maps shown in Figure 6. The visibility gets higher at high lattitude regions. The scan density is not uniform and shows structures in the scale of the scan width ($\sim$ 10 arcmin).

What will the `full sky' survey offer? (or why wasn't Herschel enough?)

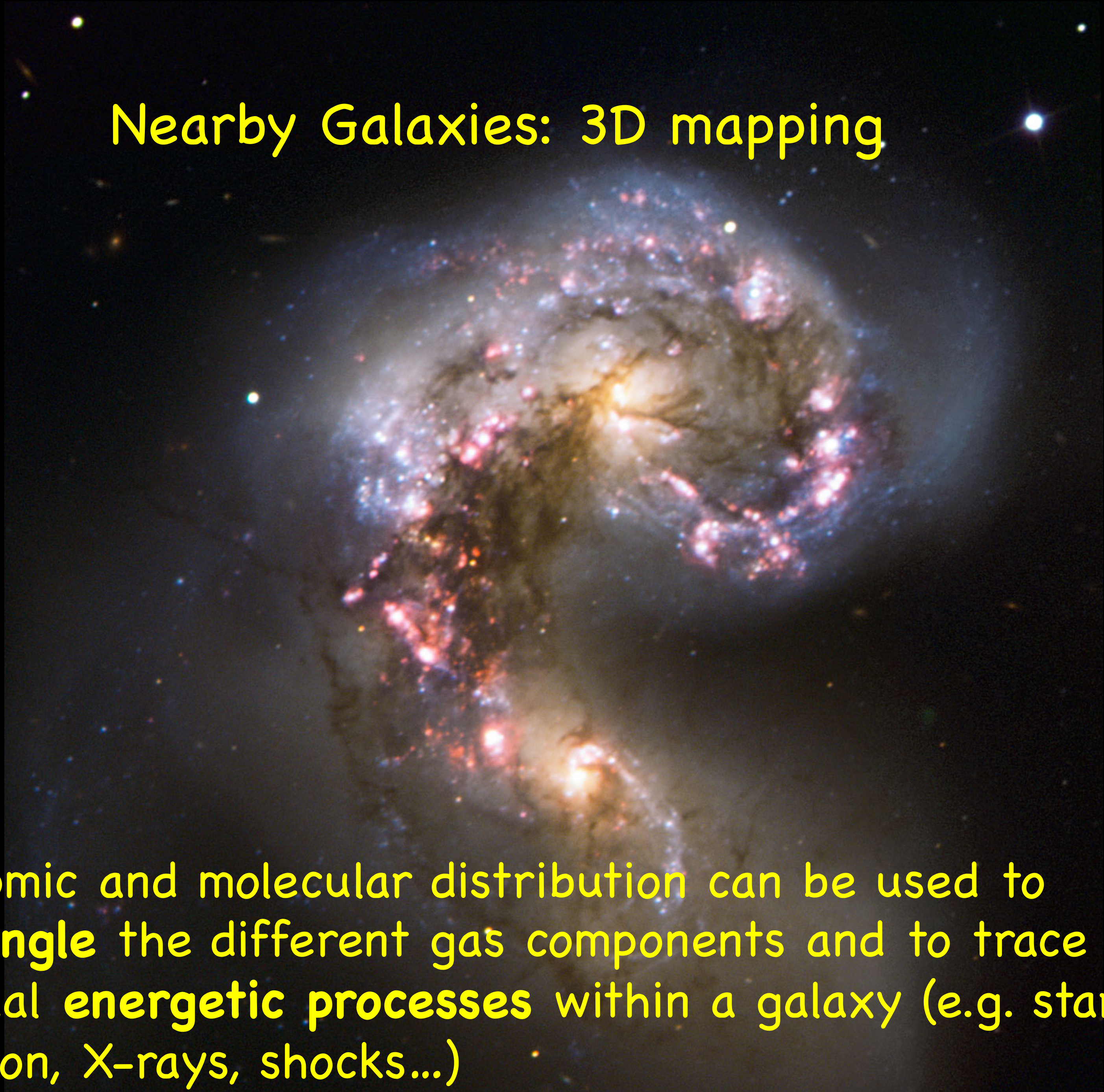
- Trace the distribution of fundamental elements: C, N, O
- Provide a first census of `how much stuff' is there of `atomic', `ionic', molecular material
- Delineate the transition of atomic to molecular clouds: essential for understanding stellar evolution

FIRSPEX All-Sky Survey



CO(1-0) map of the Milky Way (Dame et al. 2001)

Nearby Galaxies: 3D mapping



The atomic and molecular distribution can be used to **disentangle** the different gas components and to trace individual **energetic processes** within a galaxy (e.g. star formation, X-rays, shocks…)

"Decomposing a galaxy": the most important species

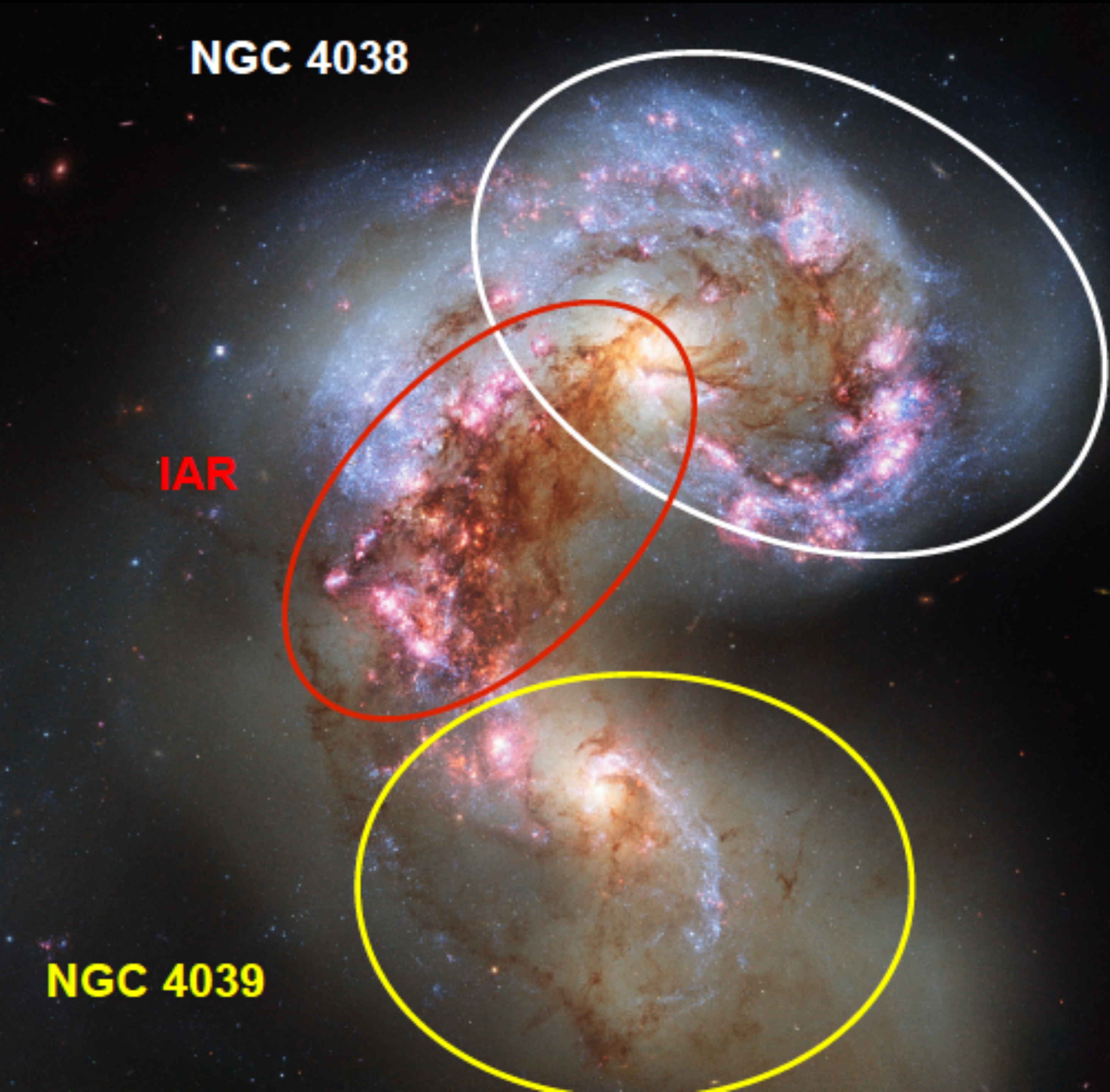
NII: can be used to estimate the ionized gas contribution to the CII fluxes

O: it is present in both atomic and molecular gas; ratios of its transitions can give the optical depth

CII: a true tracer of the PDR zone if its HII contribution is small;
OI/CII → diagnostics of temperature, densities and radiation field of the gas

C: very correlated with H_2 and CO

CO: traces the amount and distribution of molecular gas at large scale → mass of the galaxy



Luminosity

L ~ 7.5 x 10^{10} Lo
(Gao+ 2001)

They do not qualify as luminous IR galaxies. However, they maintain a high star formation rate.

Distance

D ~ 19.2 Mpc
(Whitmore+ 1999)

D ~ 22±3 Mpc
(Schweizer+ 2008)

D ~ 13 Mpc
(Saviane+ 2008)

Star Formation

* All regions have high SFR.

* IAR has the highest.

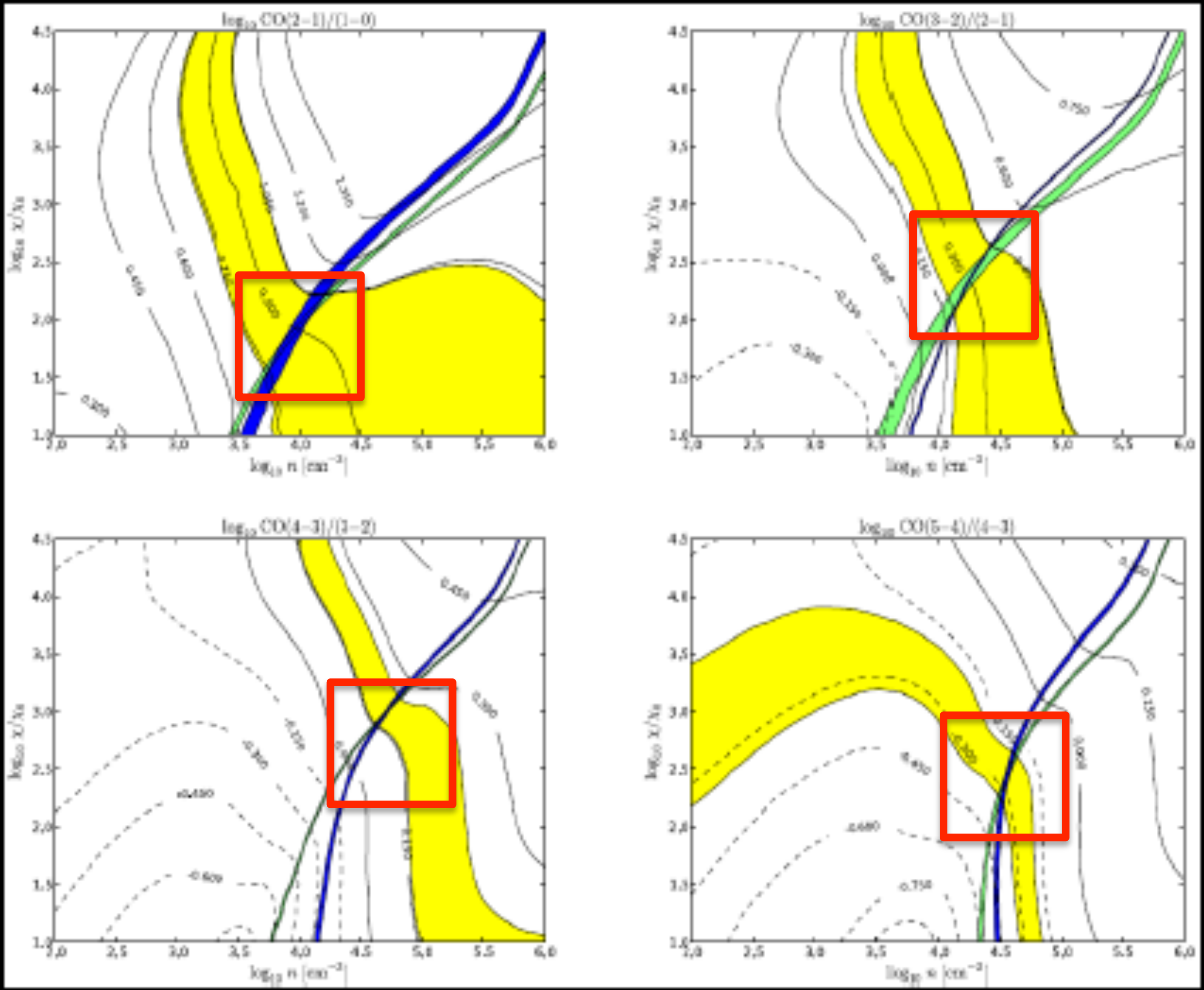
* PAH emission is coming from regions of recent star formation.
(Brandl+ 2009)

RESULTS

Constraining the best-fitting density range and the number of model clouds

Bisbas et al. 2014

Using 3D PDR model



We estimate the number of clouds using the relation:

$$N_{\rm clouds} = \frac{I_{\rm sim}}{I_{\rm obs}}$$

If less than one cloud is needed, then the best-fitting model is incorrect !

For a maximum depth of Av=2mag, we find:

$N_{\rm clouds} \sim 10^4 - 10^5$.

We find that for low-J transitions, we obtain a diagonal best-fitting region from low densities and low UV strengths. For high-J lines there is less dependence on the UV field strength. Best fit regions are located for $\sim 10^{4.5}$-$10^{5.2}$ cm^{-3}.

We find the lowest density which corresponds to the best-fitting ratio, and the highest density which corresponds to the area where the two individual lines intersect.

RESULTS

Best-fitting UV field strengths based on PDR fine-structure line diagnostics

Bisbas et al. 2014

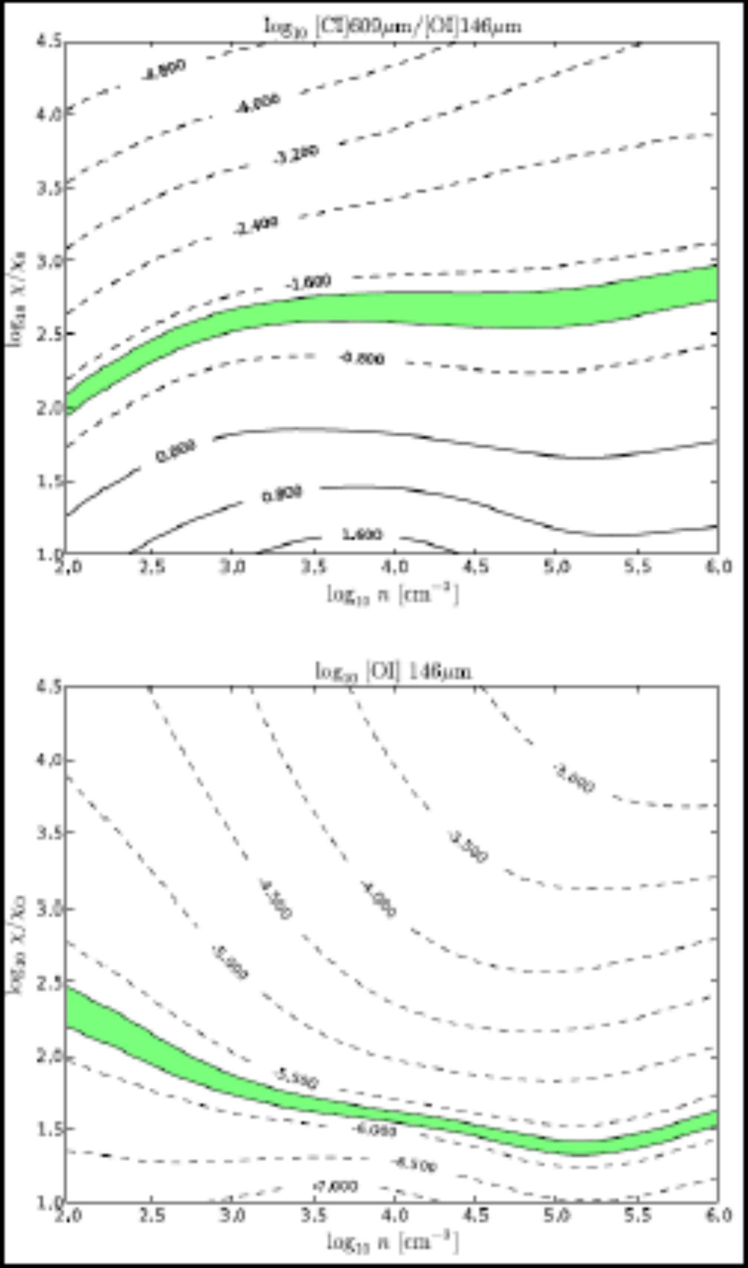
* The fine-structure lines are frequently used as diagnostics for the PDR properties (Kaufman+ 1999)

* The best fitting models for [CI]609μm/[OI]146μm indicate the presence of a strong radiation field, which is required to heat the gas in order to excite the [OI] 146μm line.

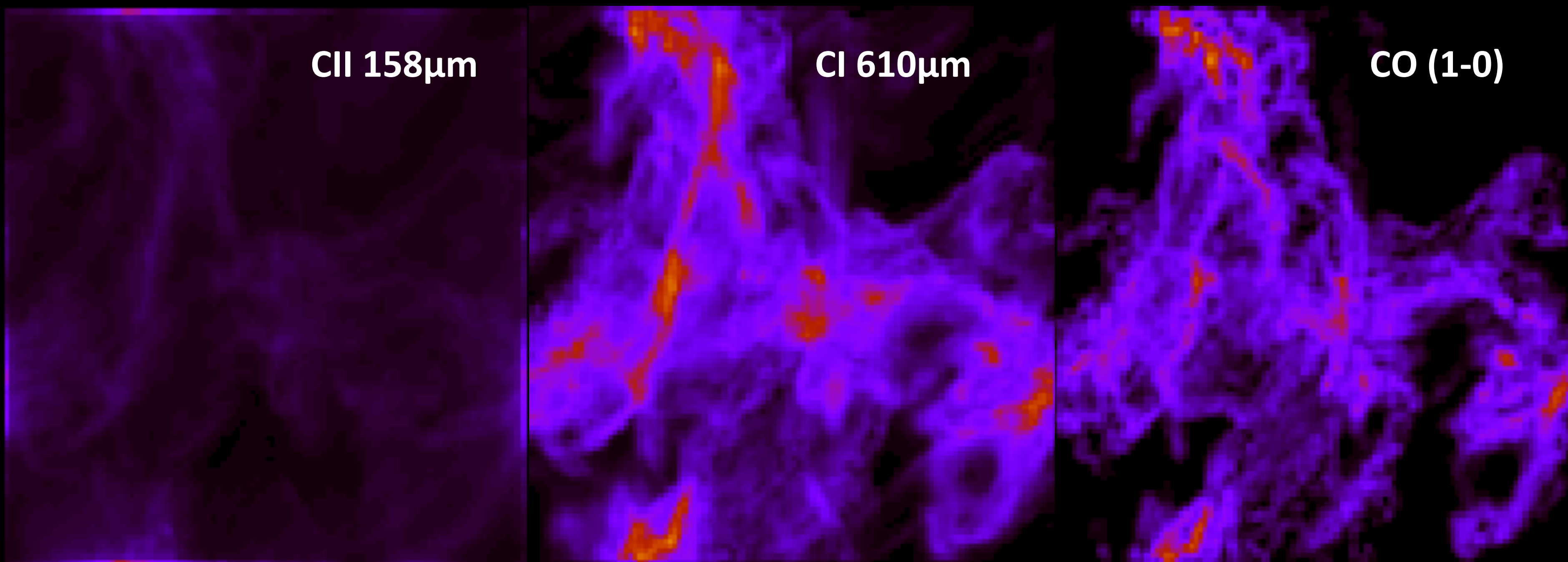
* We find that the intensity of UV field is **~$10^{2.5}$ Draines**.

* For the [OI] 146μm the model line emission shows little sensitivity to the density. From this model, we find a UV field of **$10^{1.5}$ – $10^{2.5}$ Draines**. If this emission is diluted by the beam, this would suggest an even stronger UV field, leading to a better agreement with the [CI]/[OI] ratio. We find that the dilution factor is **~10^{-2}**.

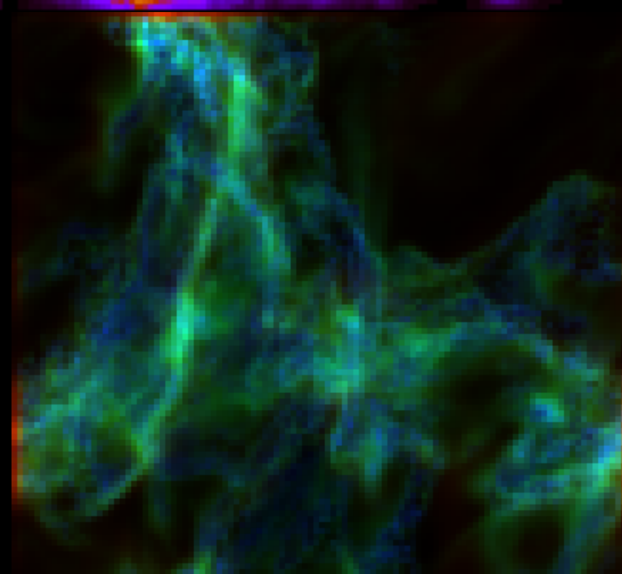
* The [CII] 158μm is matched by a very low radiation field (<10 Draines !): if the PDR surfaces cover the region and fill the beam, then the lower value cannot be a result of beam dilution. Therefore <u>either PDRs are not uniformly distributed or their layers are very thin, less than 2mag.</u>



3D study of nearby galaxies in C, CII, CO with 3DPDR



Emission maps of turbulent clouds simulated using the ORION hydro grid code and post-processed with 3D-PDR.

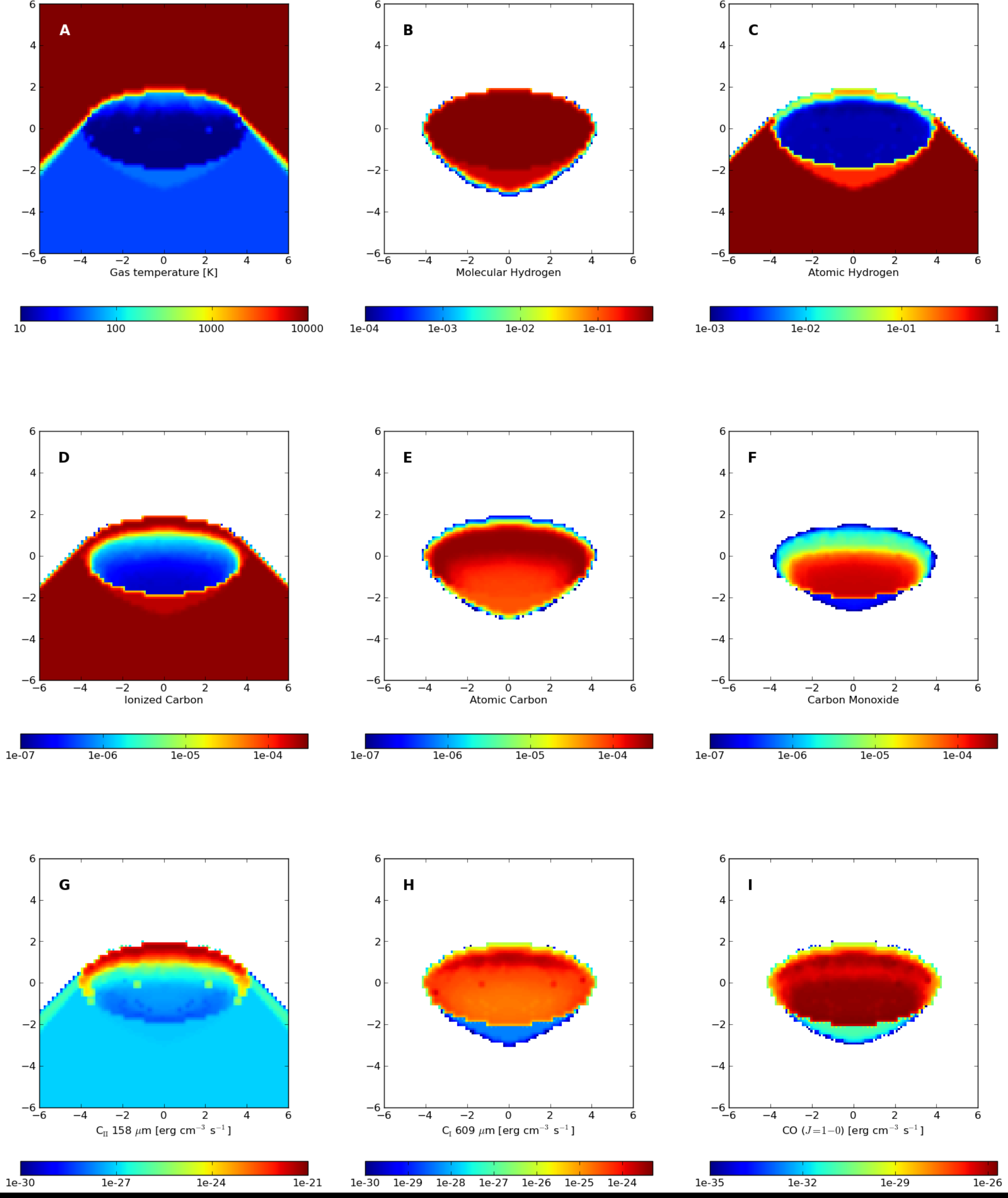


Red CII 158μm
Green: CI 610μm
Blue CO (1-0)

Offner et al. 2013

What is the next step?

TORUS-3DPDR (Bisbas et al. in prep): a 3D model of photoionization+PDR regions



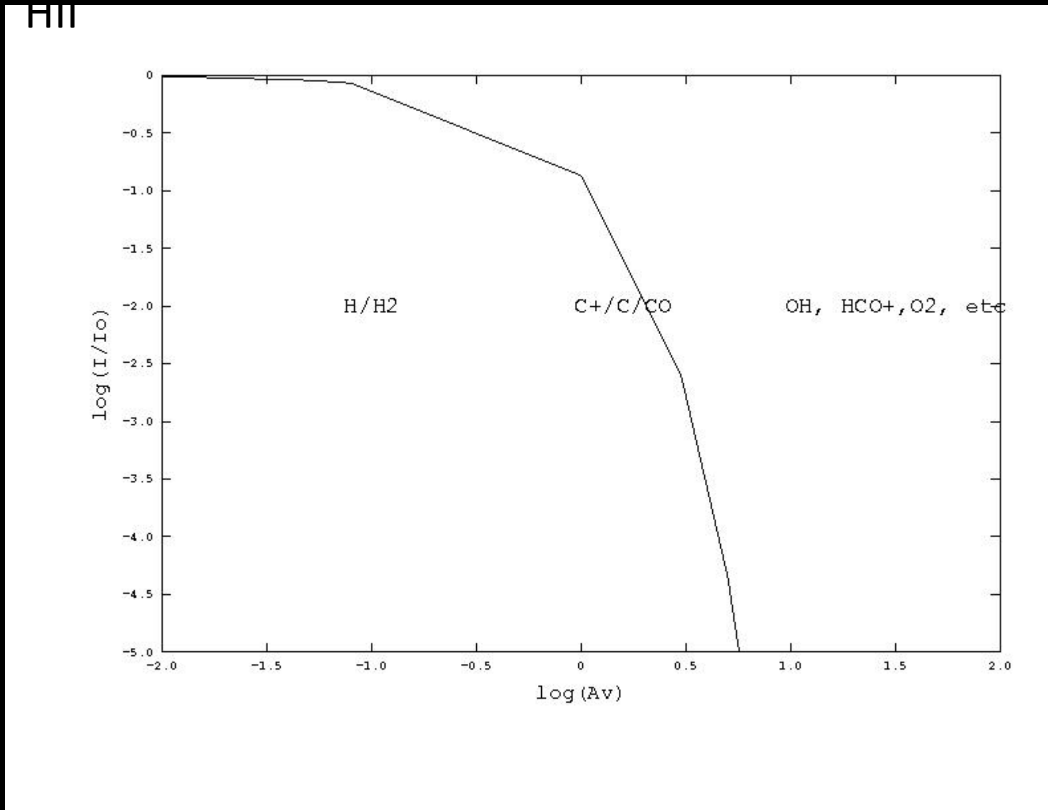
Bisbas et al. in prep

Nearby galaxies

With 3D surveys of key transitions of [NII], [CI], [CII] and [OI] we could get the average gas contained within each component (HII, PDR, neutral) for *each* type of galaxy

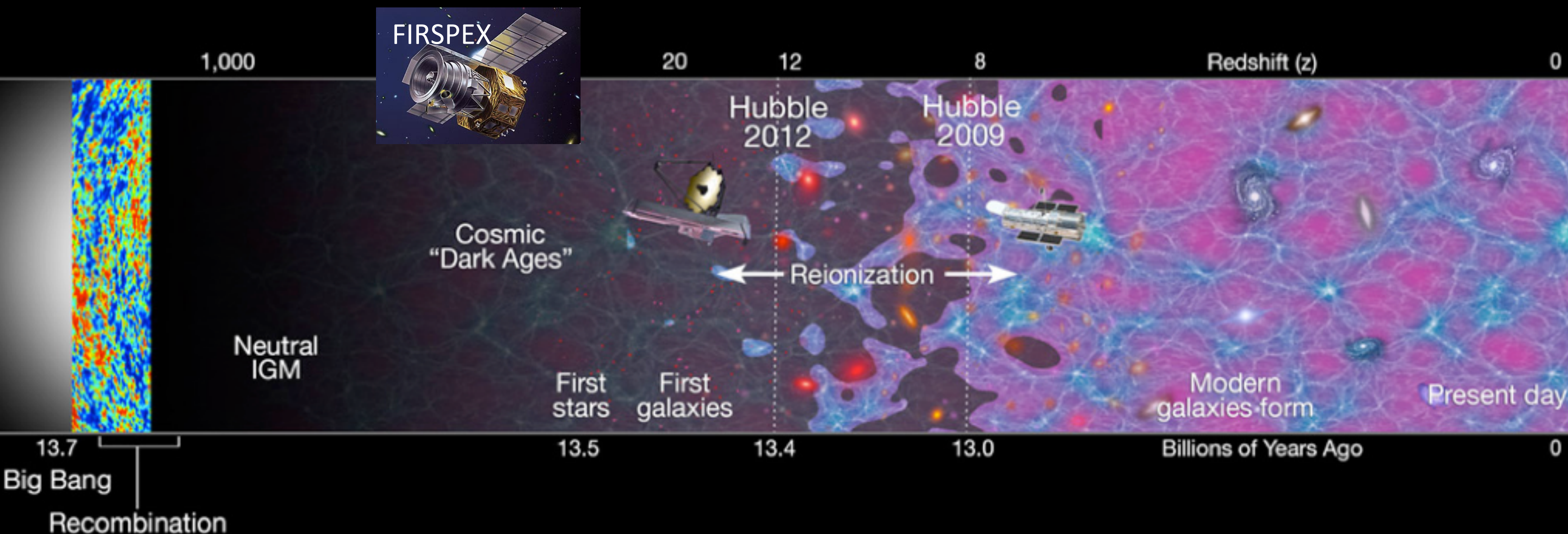
→ how do the contributions differ across types of galaxies?

→ The answer should be a lot since the differences between HII, PDRs and netrual gas is mainly to do with energetics!



'Canonical" PDR interfacing with an HII region and a molecular cloud, showing how UV intensity varies with depth, and the depths at which some important chemical transitions occur.

Very high redshift Universe



Can FIRSPEX `really' reach the `DARK AGES' ?

Molecular Hydrogen H_2 mid-infrared pure rotational transitions

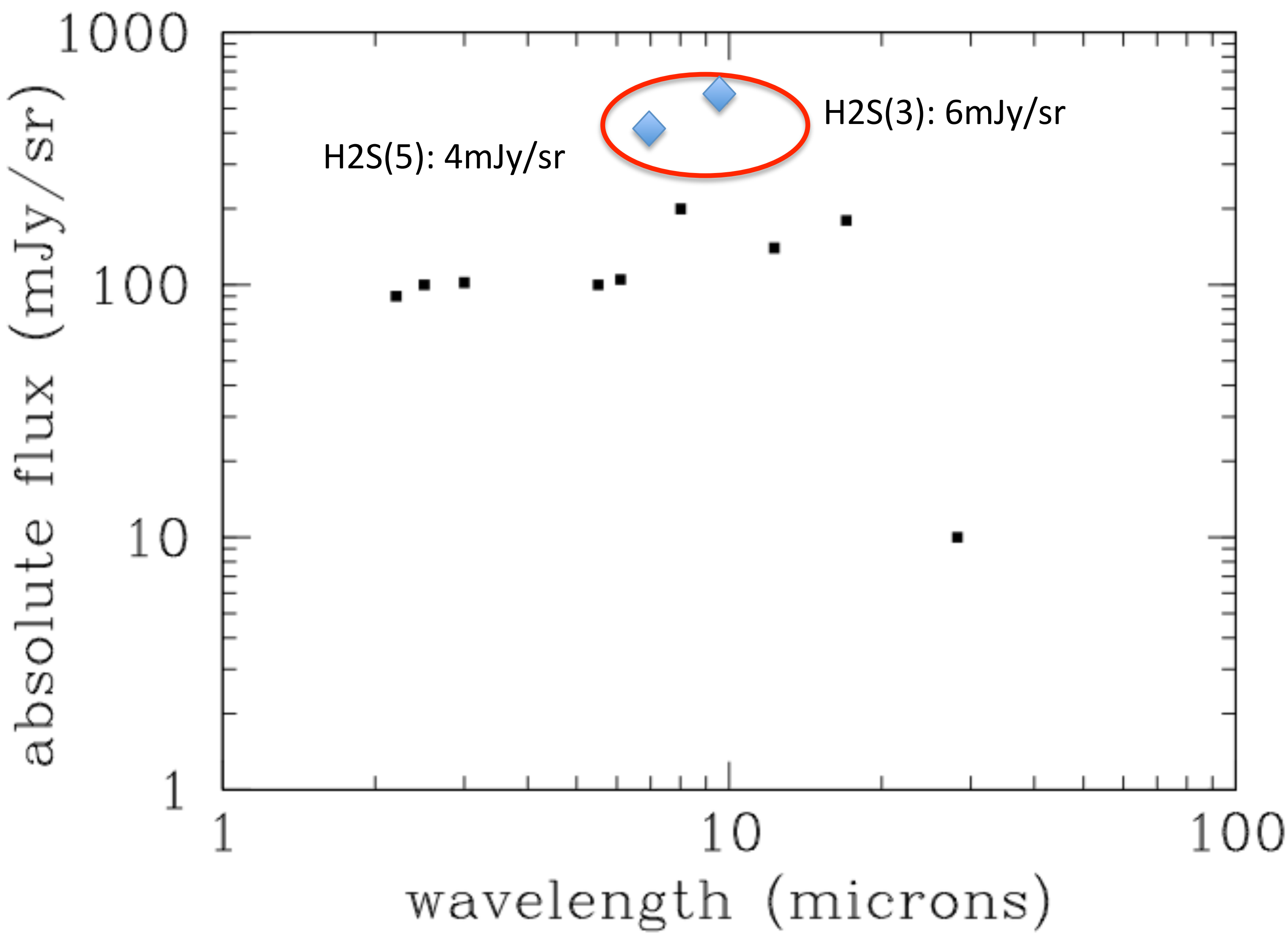
transition v=0	short notation	rest λ (μm)	spectral order	E_u/k (K)	A ($10^{-11}\,s^{-1}$)
J=2-0	S(0)	28.219	LH 14	510	2.95
J=3-1	S(1)	17.035	SH 12	1015	47.6
J=4-2	S(2)	12.279	SH 17	1681	275.
J=5-3	S(3)	9.665	SL 1	2503	980.
J=6-4	S(4)	8.025	SL 1	3473	2640.
J=7-5	S(5)	6.910	SL 2	4585	5880.
J=8-6	S(6)	6.109	SL 2	5828	11400.
J=9-7	S(7)	5.511	SL 2	7196	20000.

[a]The rotational upper level energies were computed from the molecular constants given by Huber & Herzberg (1979) and the transition probabilities are from Black & Dalgarno (1976).

For redshifts z~16 (Dark Ages) : H2S(3) shifts to [CII] 158 μm channel

But can FIRSPEX detect H2?

Strength of EoR mid-infrared H2 lines from Gong et al. 2013



Sensitivity Estimates

- Use 2×10^{-16} W/m^2 as sensitivity of each 1MHz channel = 2×10^4 Jy
- Assume 5GHz band => 5000 1MHz channels
- Combine these 5000 channels to get broadband sensitivity of 300 Jy
- Assume beamsize of 1′ given diffraction limit of 1m telescope at 200 microns
- Bin up signal over 1sr to get integrated SB sensitivity: 1sr = 3300 sq deg = 1.2×10^7 beams
- Sensitivity on sr scales is then 300/3400 = 0.9 Jy/sr
- Expected mean integrated H2 flux for 9.66 micron line is ~6Jy/sr => detection!

Preliminary Estimates

Other considerations

z=16.37 was chosen so that the next brightest H_2 line would lie in the FIRSPEX 158 band

Can do a correlation detection to remove foregrounds & boost robustness

z~16 also interesting as this is when first stars are thought to be forming => H_2 emission might be enhanced

The Payload

Payload

- Small mission provides excellent science opportunity.
- Limited payload resources – low power, low mass, and small volume.
- Cryogenic cooling to 4K too demanding with present technology, but ~20-50 K is viable.
- Semiconductor (Schottky) mixer technology compliant with higher ambient temperature operation
- Schottky offers good sensitivity and wide IF bandwidth.
- Quantum Cascade Laser (QCL) Technology provides sufficient mixer LO power.
- Proposed concept has the advantage of low cost cooling and relatively rapid mission deployment (~5-6 yrs)

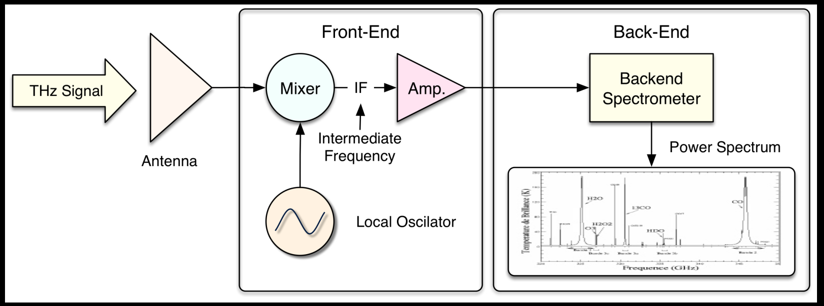
Detector Requirements

Target spectral regions (channels) from 0.4 THz to 4.7THz.

- Sufficiently sensitive to return useful science.
- High spectral resolution ~1MHz.
- Wide instantaneous bandwidth ~ 5GHz/channel.
- Simultaneous operation of channels.
- Compliant with small satellite operation ⇒ low mass, small volume and low power consumption.

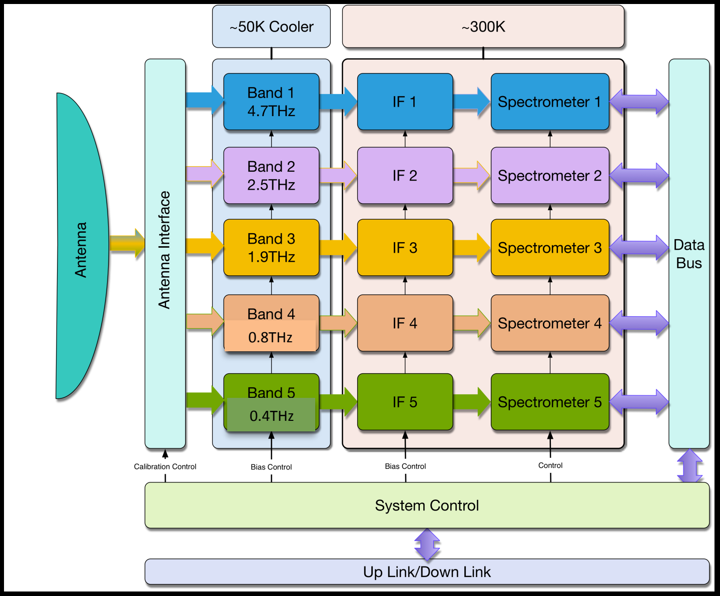
Detection Method

Spectral resolution requirement ⇒ heterodyne receiver technique.



THz frequency mixing used for front-end.

High-speed digital fast Fourier Transform spectrometer (FFTS) for back-end.

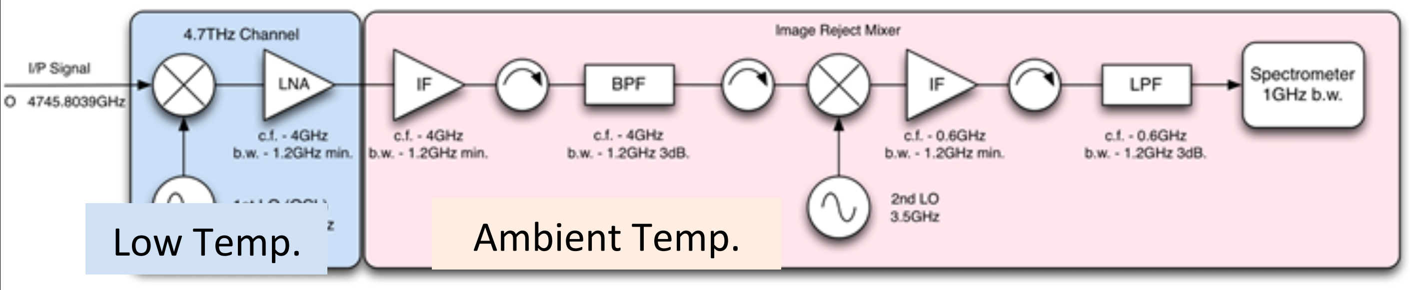


Cannot encompass entire frequency range via a single receiver

Subdivide into 5 discrete channels.

Receiver

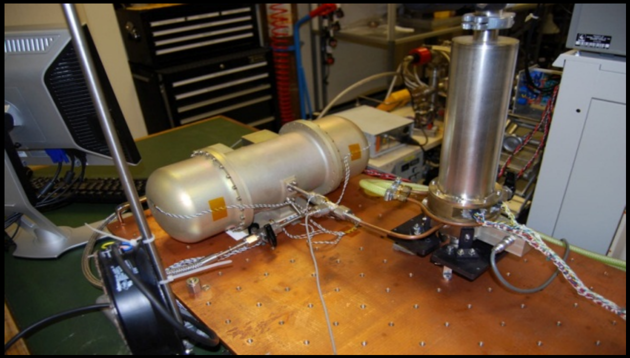
Five receiver channels arranged with separation between cold mixer/LO assembly and warm IF and backend digital spectrometer



Cooling based on long heritage in Stirling Cycle coolers in Europe

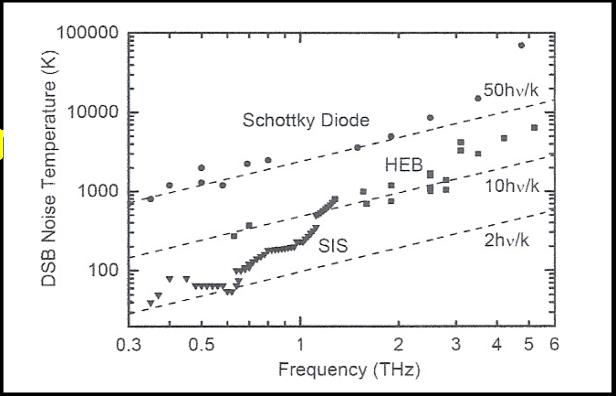
New generation "Large scale cooler" will lift ~3 W at 50 K

120 W input power and 7 kg mass



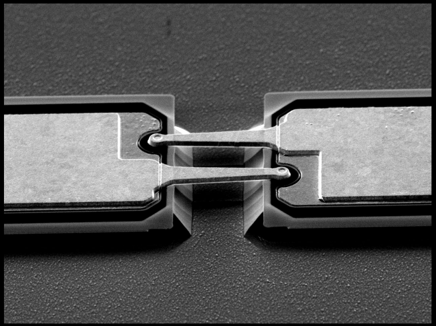
Front-end Mixer Selection

- Superconducting mixers offer best sensitivity <=1THz.
- At >1THz SIS devices less effective due to material energy gap limit.
- Supercon. HEB devices sensitive at >>1THz. But,
  - Have limited IF bandwidth, ~3GHz.
  - Present materials require 4K cooling ⇒ incompatibility with small satellite.
  - Some reported concerns over saturation and stability - maybe not relevant.
- Alternative is the Schottky diode mixer

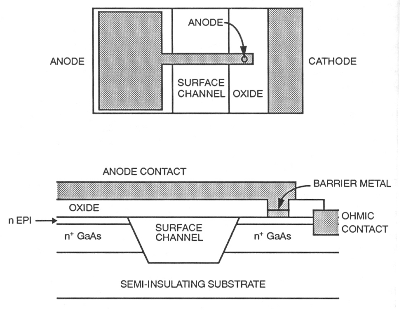


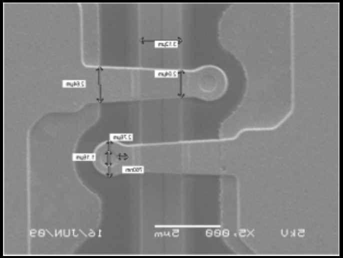
Schottky Mixer

- Semiconductor device capable of multi-THz operation.
- Historically a key detector in early mm/submm-wave astronomy. Now used extensively in Earth observation
- Used extensively in space and up to 2.5 THz.
- Wide IF bandwidth possible >>5GHz.
- Operates at room or cryogenic temperatures.
- Can be configured in single or balanced diode structures.
- Less sensitive than supercon. and needs more LO power.

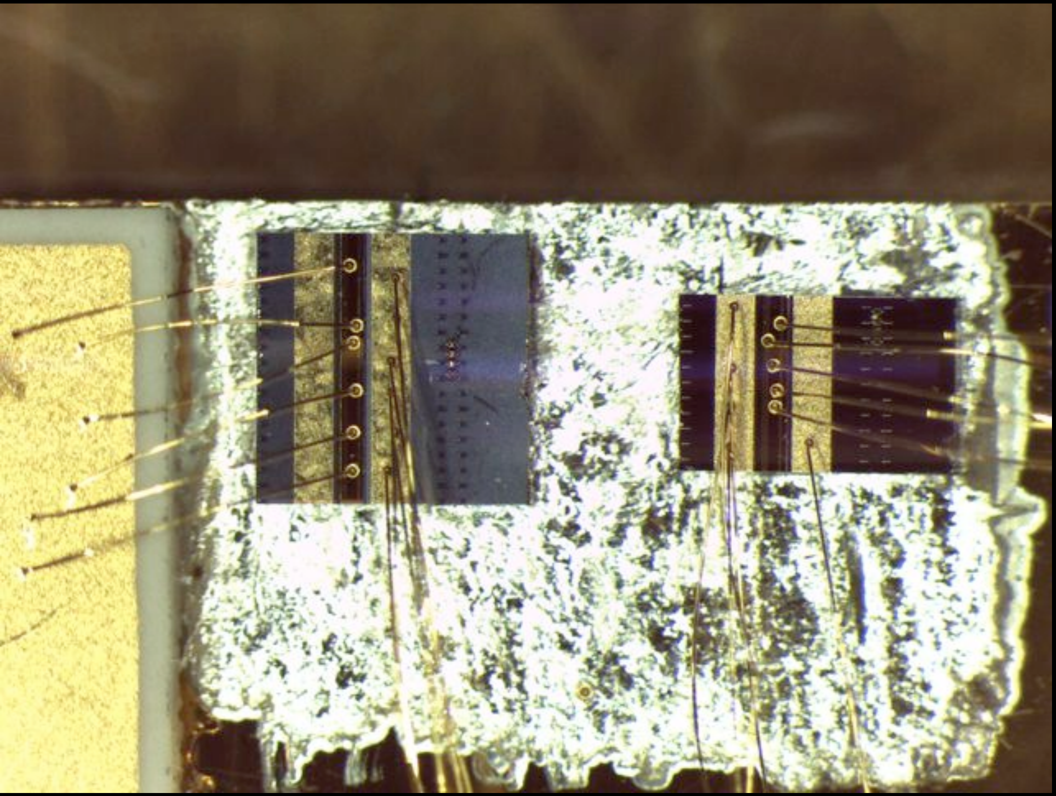


Planar Structure
Base Material GaAs
(Ref: Mass)

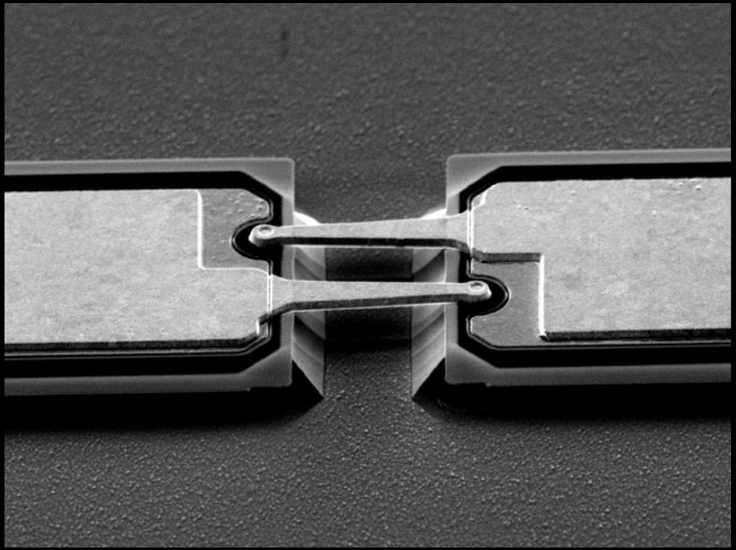




RAL Double Diode Example.



QCL FIR Laser device developed at Leeds University



Planar Schottky mixer diode developed at RAL-Space

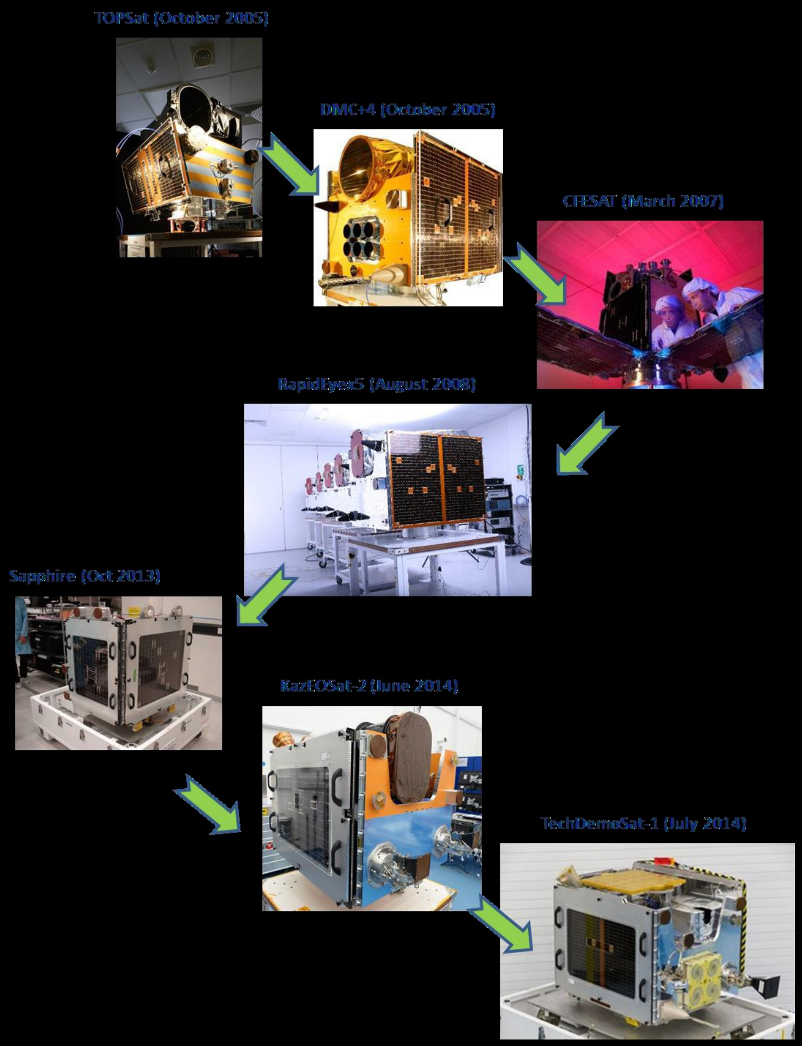
Exploring alternatives in collaboration with Purple Mountain Observatory colleagues

Work-Packages

Europe (RAL):	configuration of payload (joint)
(RAL/Obs Paris):	high frequency (THz) bands
(Leeds) :	QCLs
China (PMO):	configuration of payload (joint)
	low frequency (GHz) bands
Europe (SSTL):	bus
Europe/China:	launcher (under investigation)

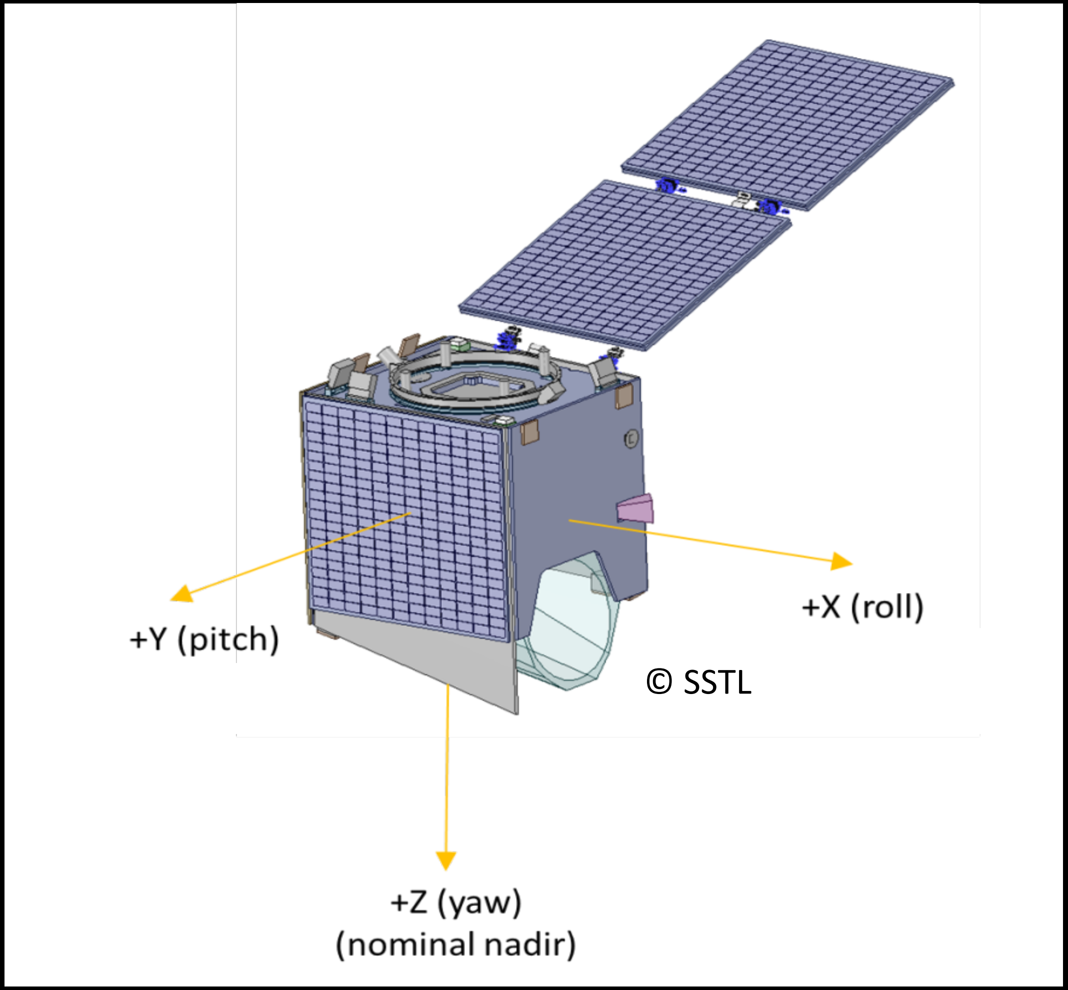
Opportunities for industry/other companies (e.g. Teratech)

Examples of platform options – SSTL-150

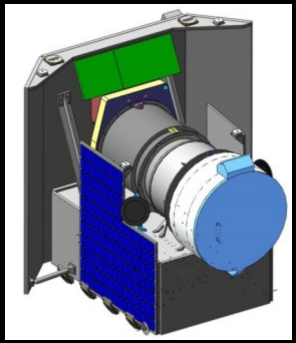


LOCUS as an example – extended SSTL-150

50 cm off axis Cassegrain
Receiver cooled to <100K
Mass ~ 265 kg
Payload 50 kg
Power ~ 190 W

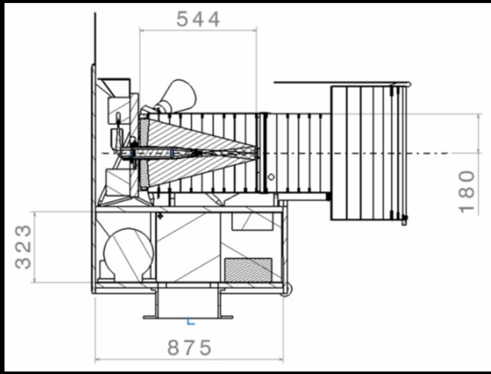


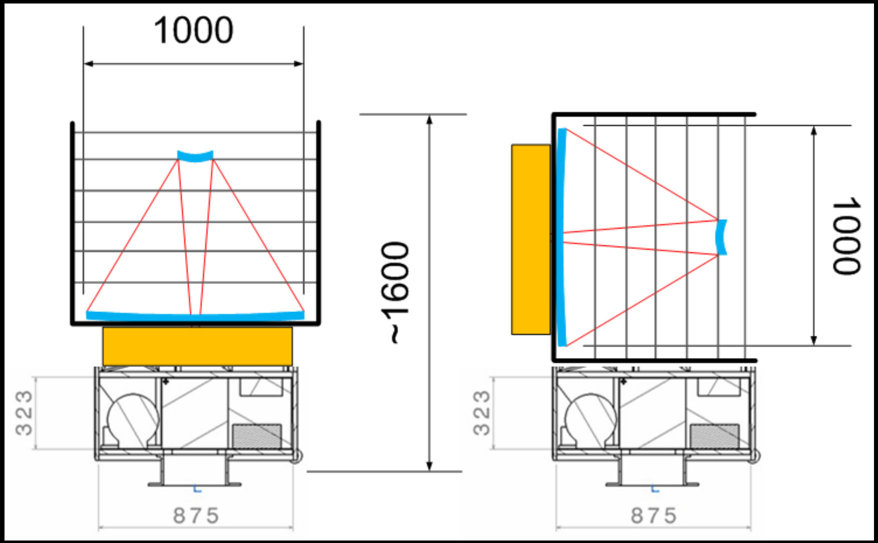
Alternative approach



Start from SSTL concept for CHEOPS (35 cm optical telescope)
Mass (S/C+payload) ~ 200 kg

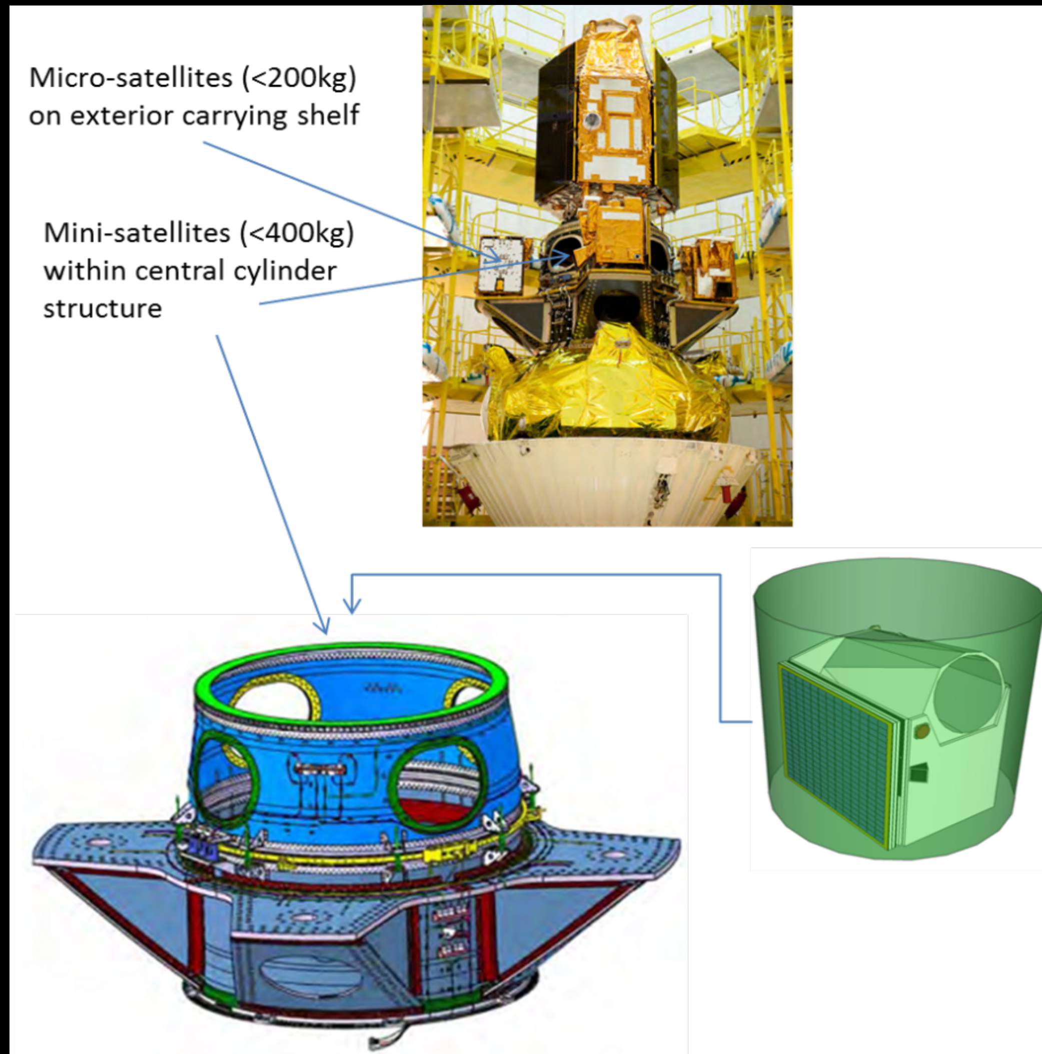
Take this "bus" and add 1m fast FIR telescope in tube



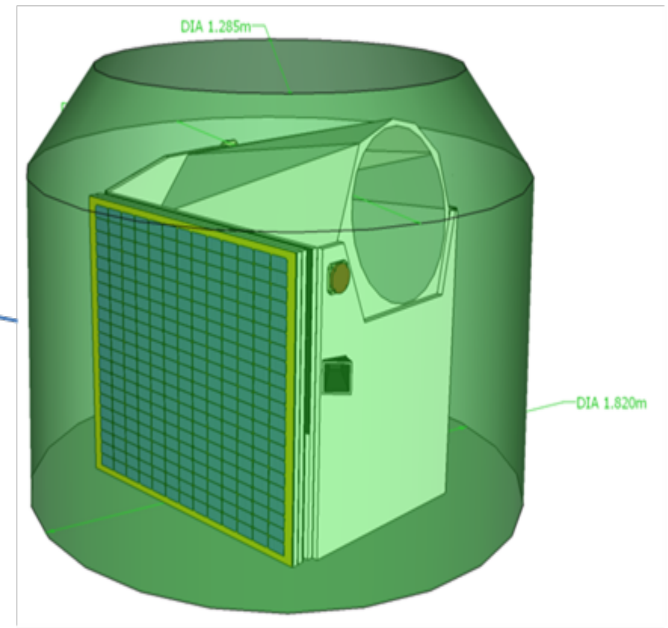


Mass ~250 kg (S/C + payload) assuming SiC mirror @25 kg/m^2
Lighter weight CFRP telescope possible?

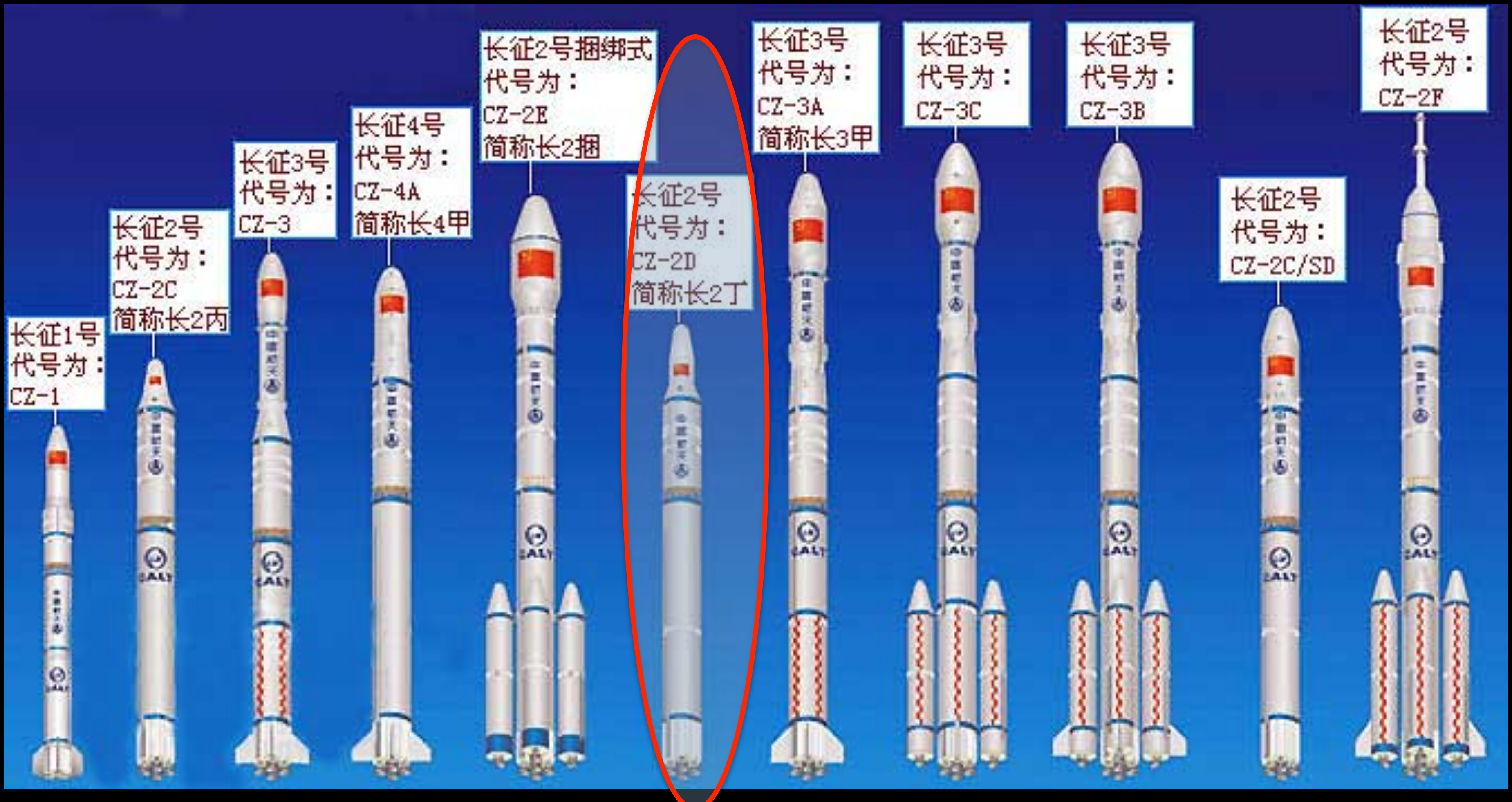
Accommodation - Soyuz



Accommodation - Vega



Accommodation --March 2D



Mission

Orbit is proposed as sun synchronous

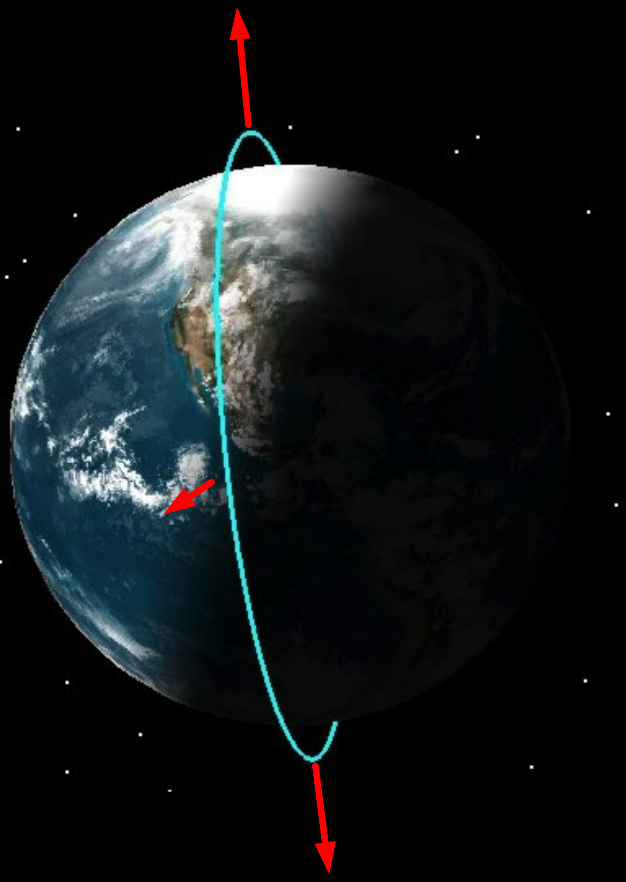
Viewing direction is anti-Earth

Solar panels constantly illuminated

Radiators constantly face deep space

Full survey in 6 months with multiple passes over sky "bins"

Followup targeted observations



Synergies with other facilities and community interest

There is a considerable IR community on both sides (ESA and CAS) that worked with Herschel

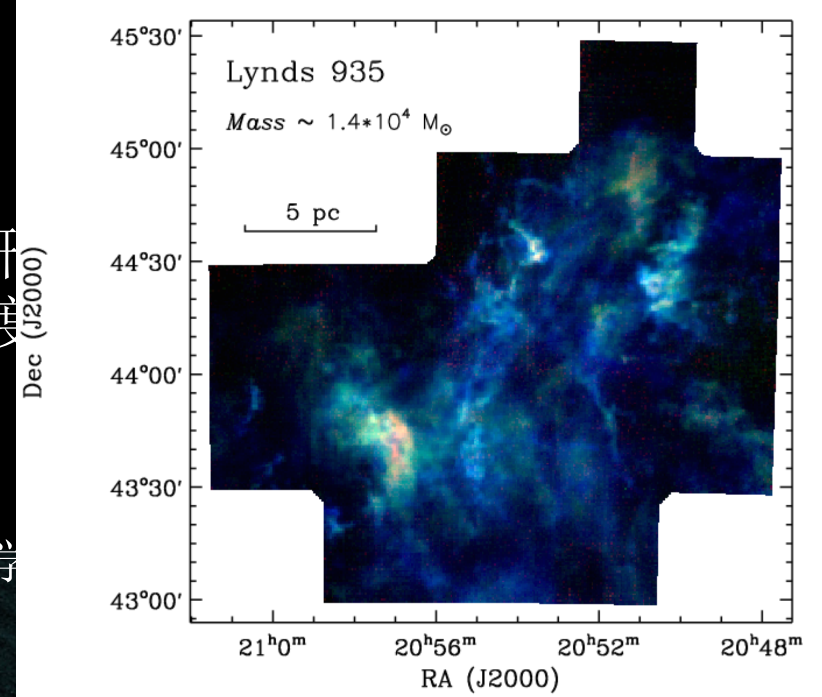
China has invested in an China-Chile ALMA centre
FIRSPEX will provide targets for ALMA followup (ALMA has superb spatial resolution whereas FIRSPEX can map large areas)

Europe (ESO) is a partner in the ALMA project

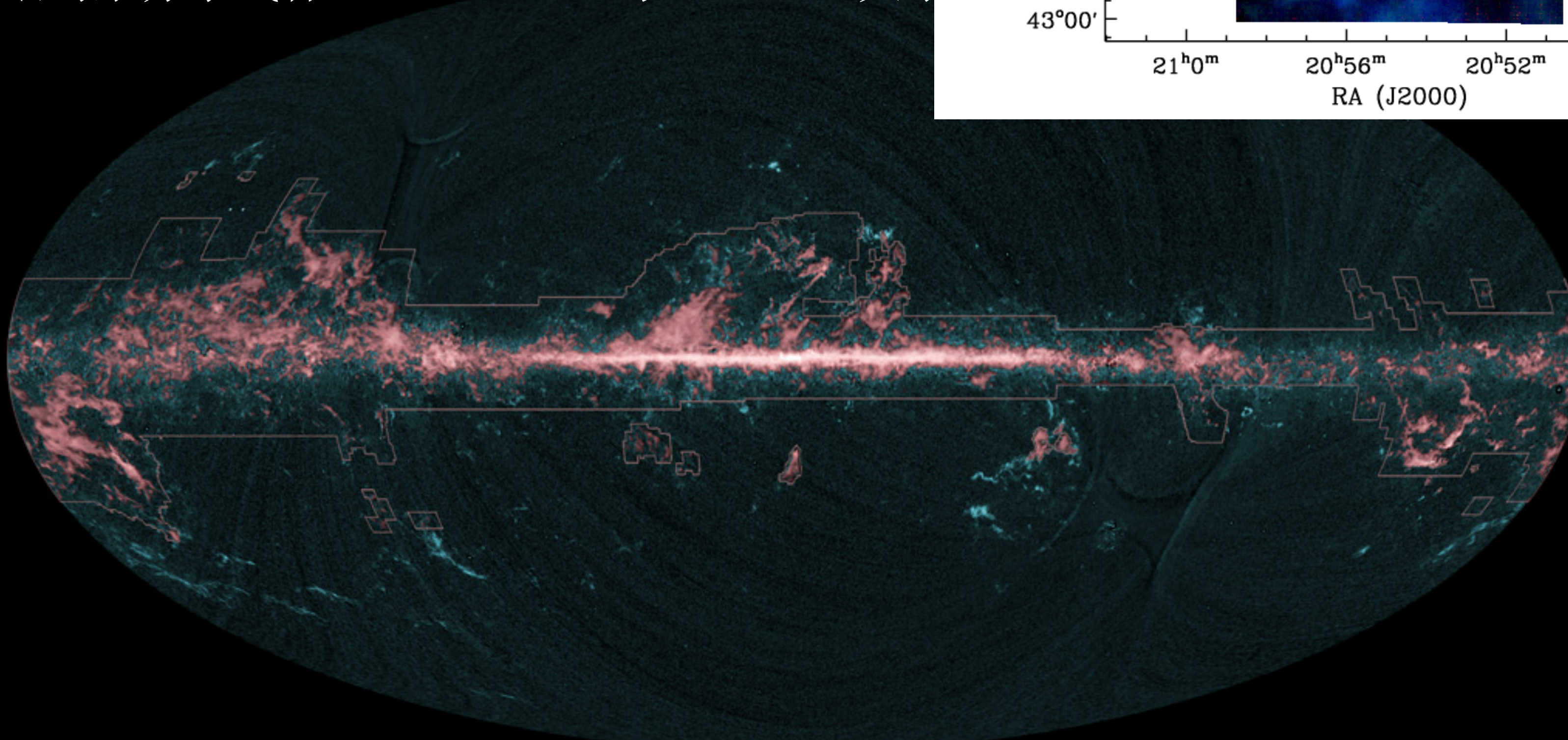
The Milky Way Imaging Scroll Painting (MWISP) project

- PMO 13.7 m telescope , 3*3 array SSAR, OTF mode
- 110–115GHz， rms 0.5K ^{12}CO, 0.3K ^{13}CO and $C^{18}O$ @ 0.16 km/s @ 30" cell
- First step Cover $-10° \leq l \leq 250°, |b| \leq 5°$, and some interesting regions， ~2600 deg^2
- Total spectra ~ 1×10^8
- 5- 8 years, since 2011/11

- 基于超过500平方度的观测数据，研
建立银河系分子云的丰度样本及梯度
云的转化-分子云的形成。



银河系分子气体：Planck卫星与Columbia大学



Planck Team, ESA

Conclusions

- We propose the implementation of a high spectral resolution Terahertz (THz) heterodyne receiver system for astronomical research.

- FIRSPEX will carry out the first ever `all sky' spectroscopic survey in five discreet bands providing unique 3-D maps of the Galaxy.

- FIRSPEX is a novel, highly integrated and power efficient (60W) mission compatible with a small scale mission and a low-cost envelope.

- Most of the payload technology already TRL>7. Parts of the Payload have been using in EO studies (e.g. LOCUS) and/or Space (eg JUICE). The mission is ITAR-free.

Thank you

谢谢你