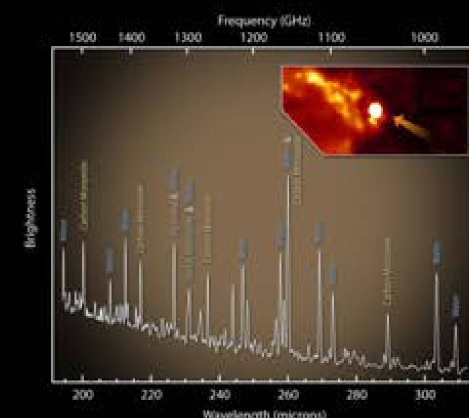
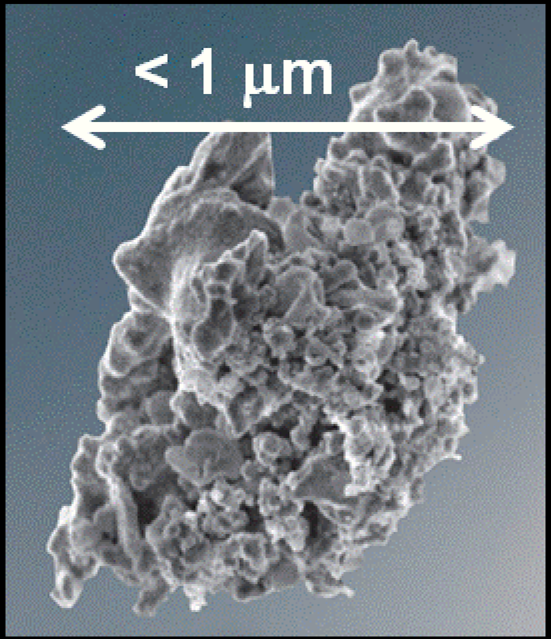
The *Herschel* Space Observatory and its Scientific Legacy

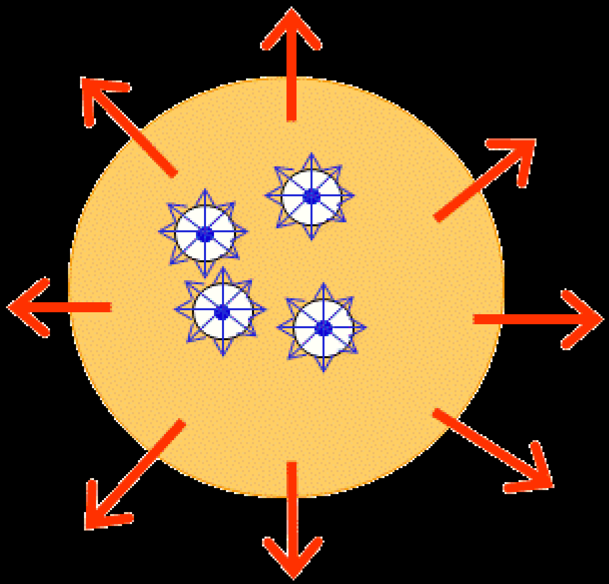
Matt Griffin, Cardiff University

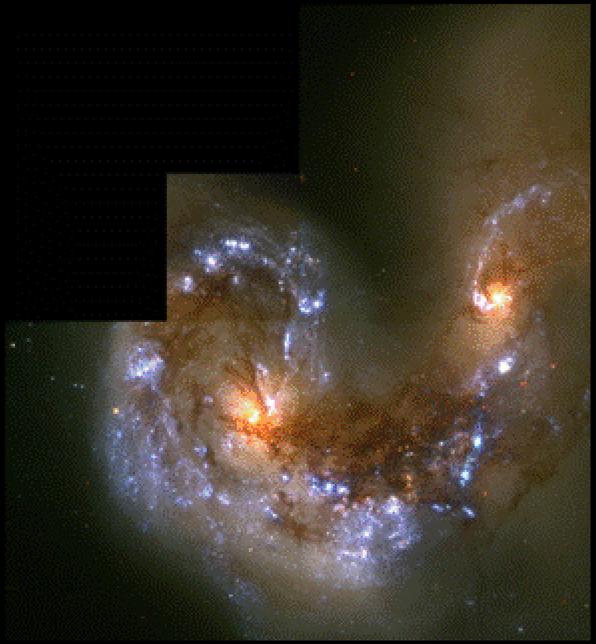


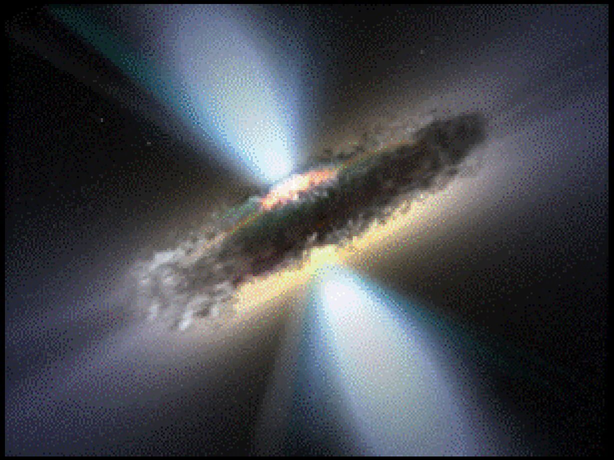
PMO April 15 2016

Conversion of Stellar Radiation and Accretion Energy to FIR

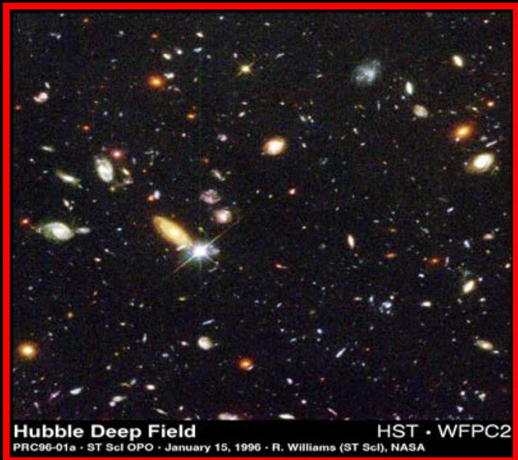


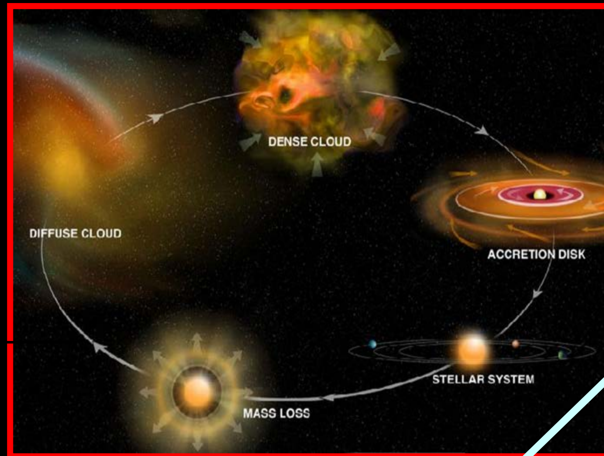


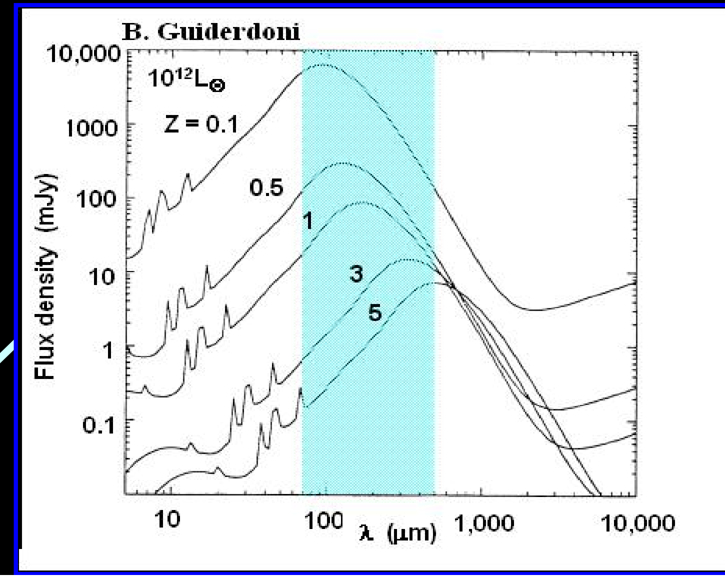


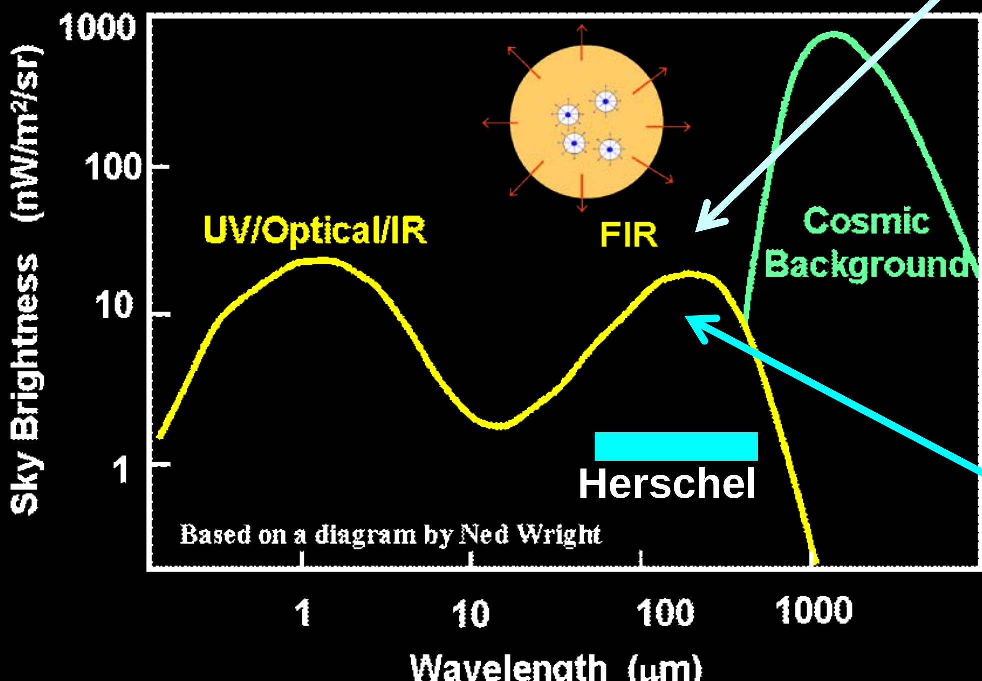


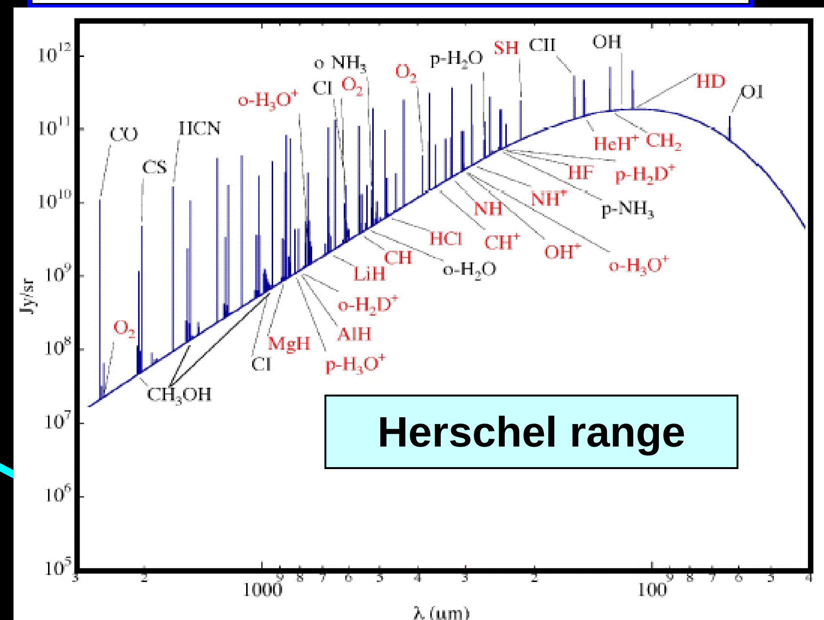
Herschel Science











Cosmic Infrared Background

Astron. Astrophys. 308, L5–L8 (1996)

ASTRONOMY AND ASTROPHYSICS

1996

Letter to the Editor

Tentative detection of a cosmic far-infrared background with COBE

J.-L. Puget[1], A. Abergel[1], J.-P. Bernard[1], F. Boulanger[1], W.B. Burton[2], F.-X. Désert[1], and D. Hartmann[2,3]

THE ASTROPHYSICAL JOURNAL

1998

THE COBE DIFFUSE INFRARED BACKGROUND EXPERIMENT SEARCH FOR THE COSMIC INFRARED BACKGROUND: I. LIMITS AND DETECTIONS

M.G. Hauser[1], R.G. Arendt[2], T. Kelsall[3], E. Dwek[3], N. Odegard[2], J.L. Weiland[2], H.T. Freudenreich[2], W.T. Reach[4], R.F. Silverberg[3], S.H. Moseley[3], Y.C. Pei[1], P. Lubin[5], J.C. Mather[3], R.A. Shafer[3], G.F. Smoot[6], R. Weiss[7], D.T. Wilkinson[8], and E.L. Wright[9]

Received 1998 January 6; accepted 1998 June 3

Previous Infrared Space Missions

IRAS (1983)

- 0.6-m telescope
- T = 2 K
- λ = 12, 25, 60, 100 μm

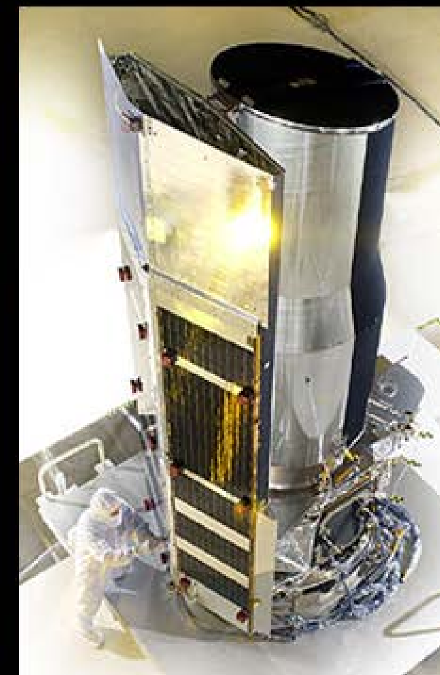
ISO (1995)

- 0.6-m
- T = 2 - 3 K
- λ = 3 – 200 μm

AKARI (2006)

- 0.6-m
- T = 6 K
- λ = 2 – 200 μm

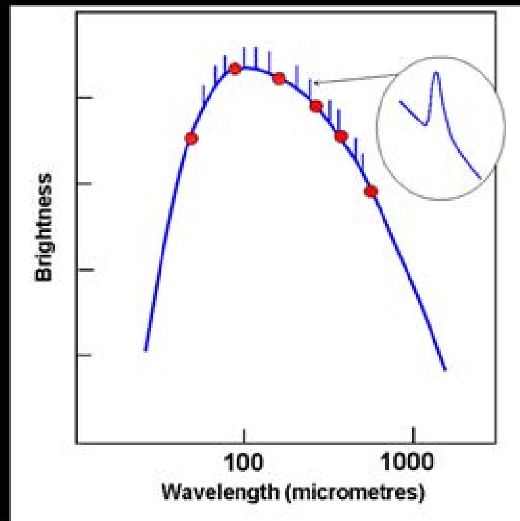
Spitzer (2003)

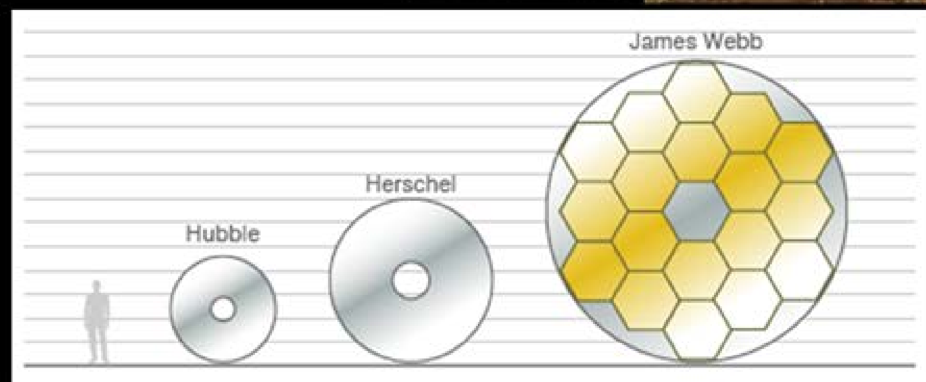


- 0.85-m
- T = 4 K
- λ = 3 – 180 μm

Herschel Summary

- **Telescope:**
  - D = 3.5 m
  - T = 85 K
- **Three instruments**
  - HIFI, PACS, SPIRE
  - Cameras:
    - 6 bands 70 - 500 μm
  - Spectrometers:
    - 52 - 670 μm
- **Launched (with *Planck*): May 14 2009**
- **Finished operation: April 29 2013**





<u>3-Band Camera</u>

250, 350, 500 μm (simultaneous)

<u>Imaging FT Spectrometer</u>

195 - 670 μm (simultaneously)

$\lambda/\Delta\lambda$ = 1200 – 300 (high-res)

= 50 – 15 (low res)

<u>7-channel Heterodyne Receiver</u>

480 - 1250 GHz (625 - 240 μm)

1410 - 1910 GHz (212 - 157 μm)

$\lambda/\Delta\lambda = 10^5 - 10^6$

Instantaneous BW: 4 GHz

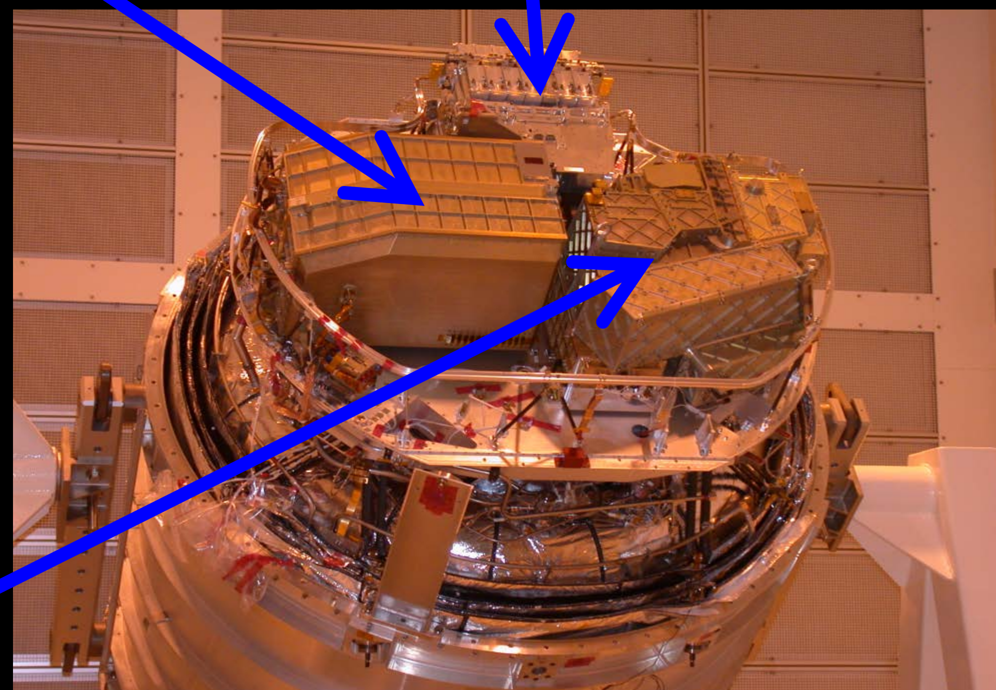
<u>3-Band Camera</u>

70, 100, 160 μm (2 simultaneous)

<u>Imaging Grating Spectrometer</u>

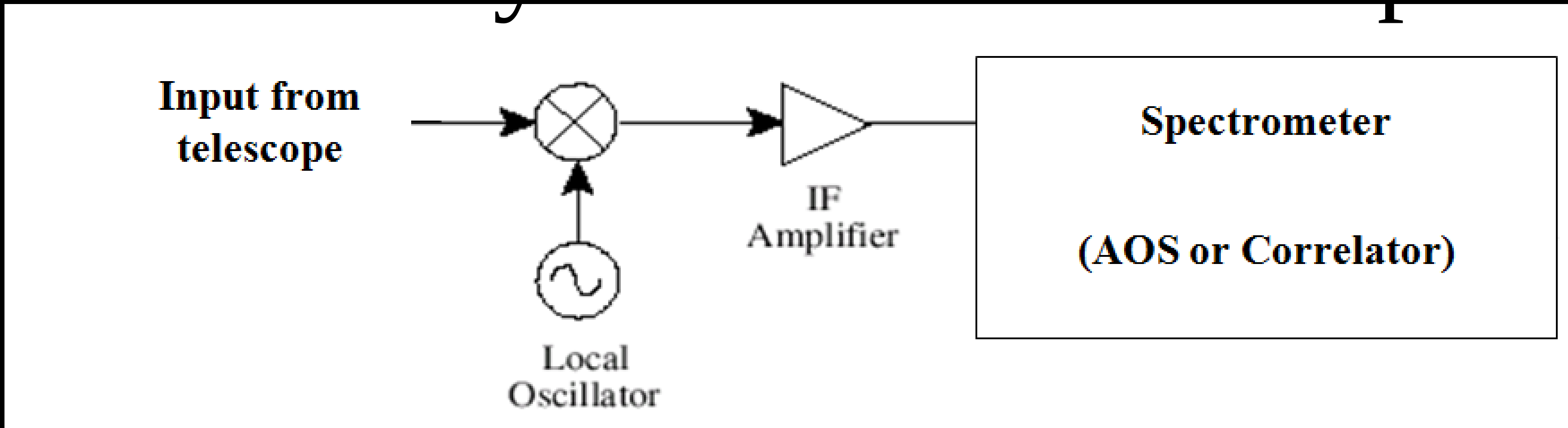
55 - 210 μm

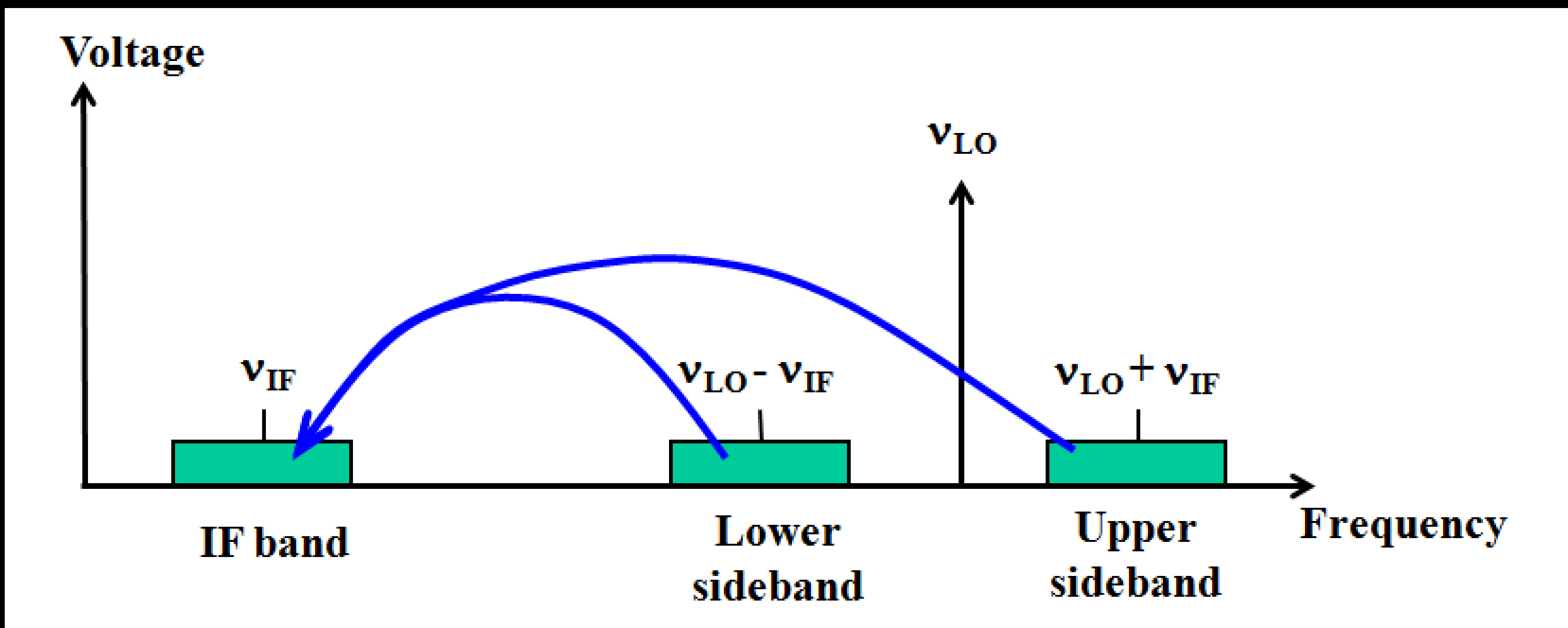
$\lambda/\Delta\lambda$ = 1000 – 4000



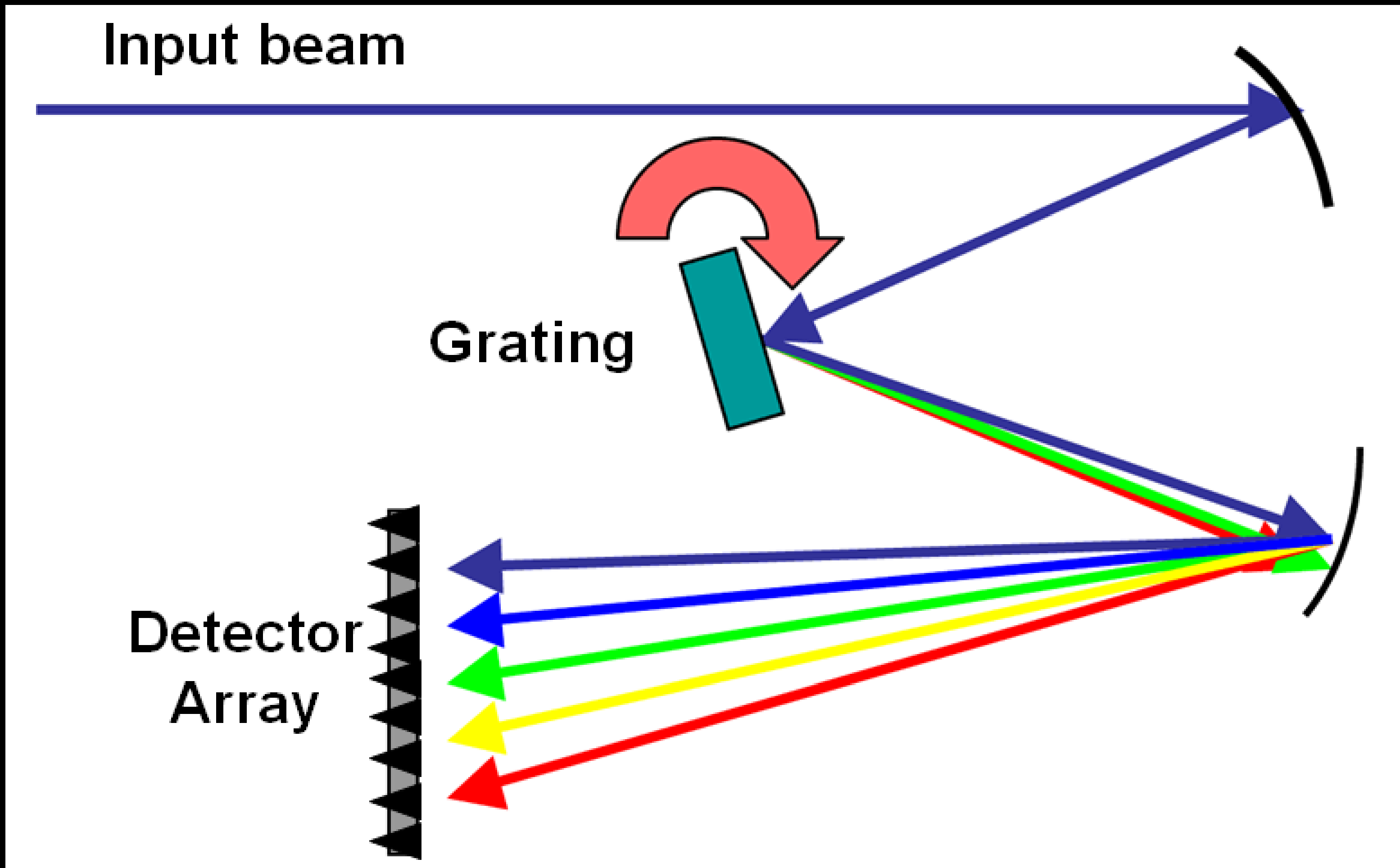
Build-up of the *Herschel* Satellite

Heterodyne Receiver (HIFI)

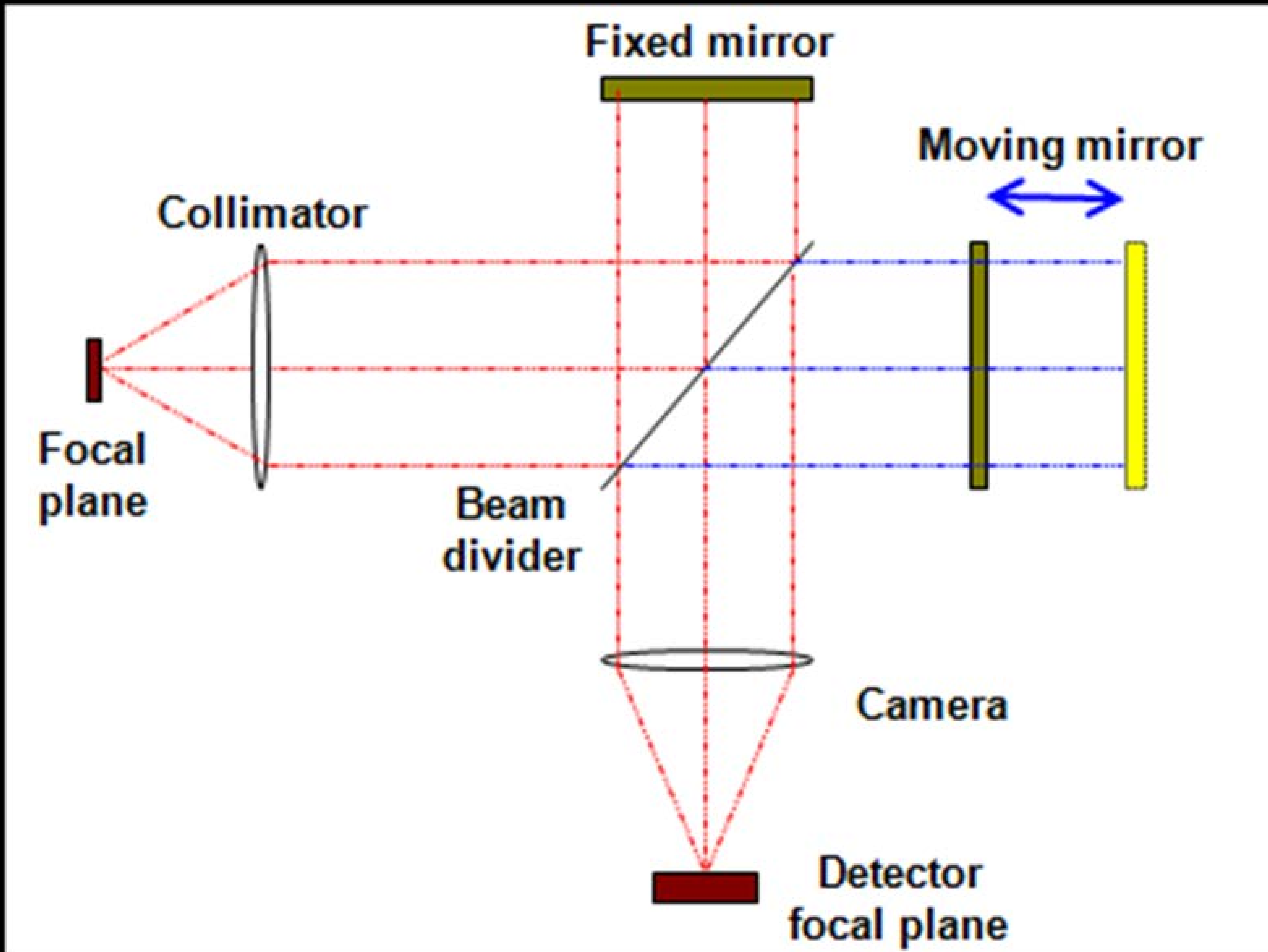




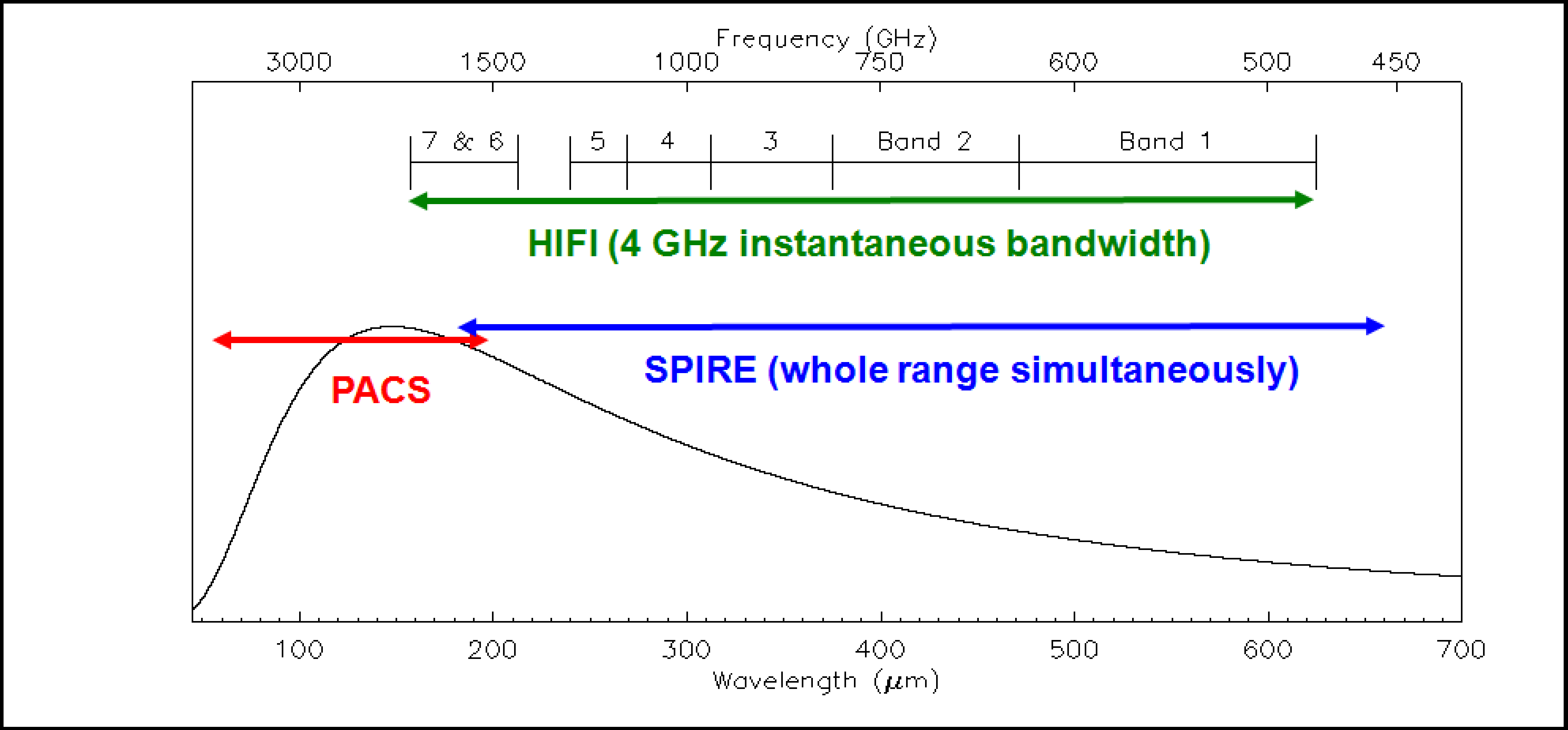
Grating Spectrometer (PACS)



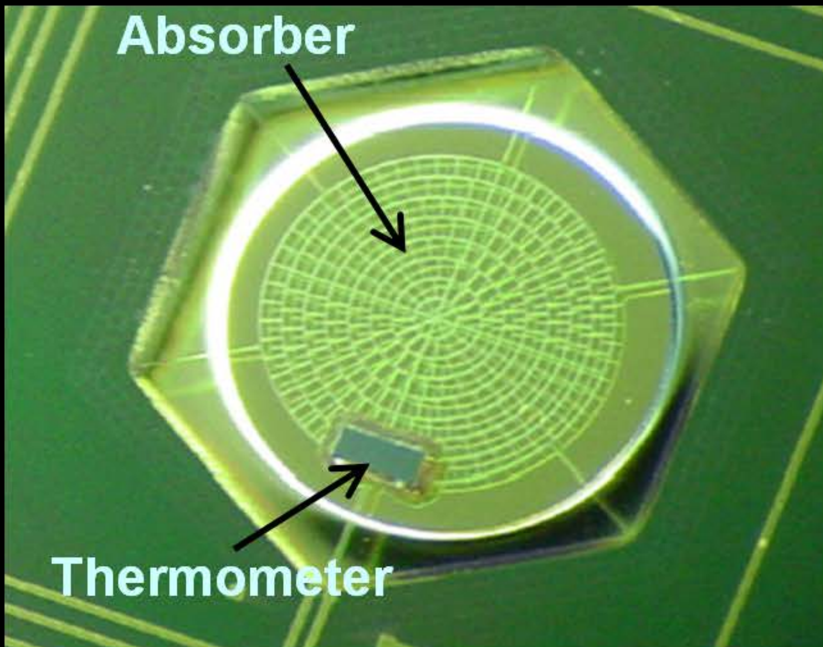
Fourier Transform Spectrometer (SPIRE)



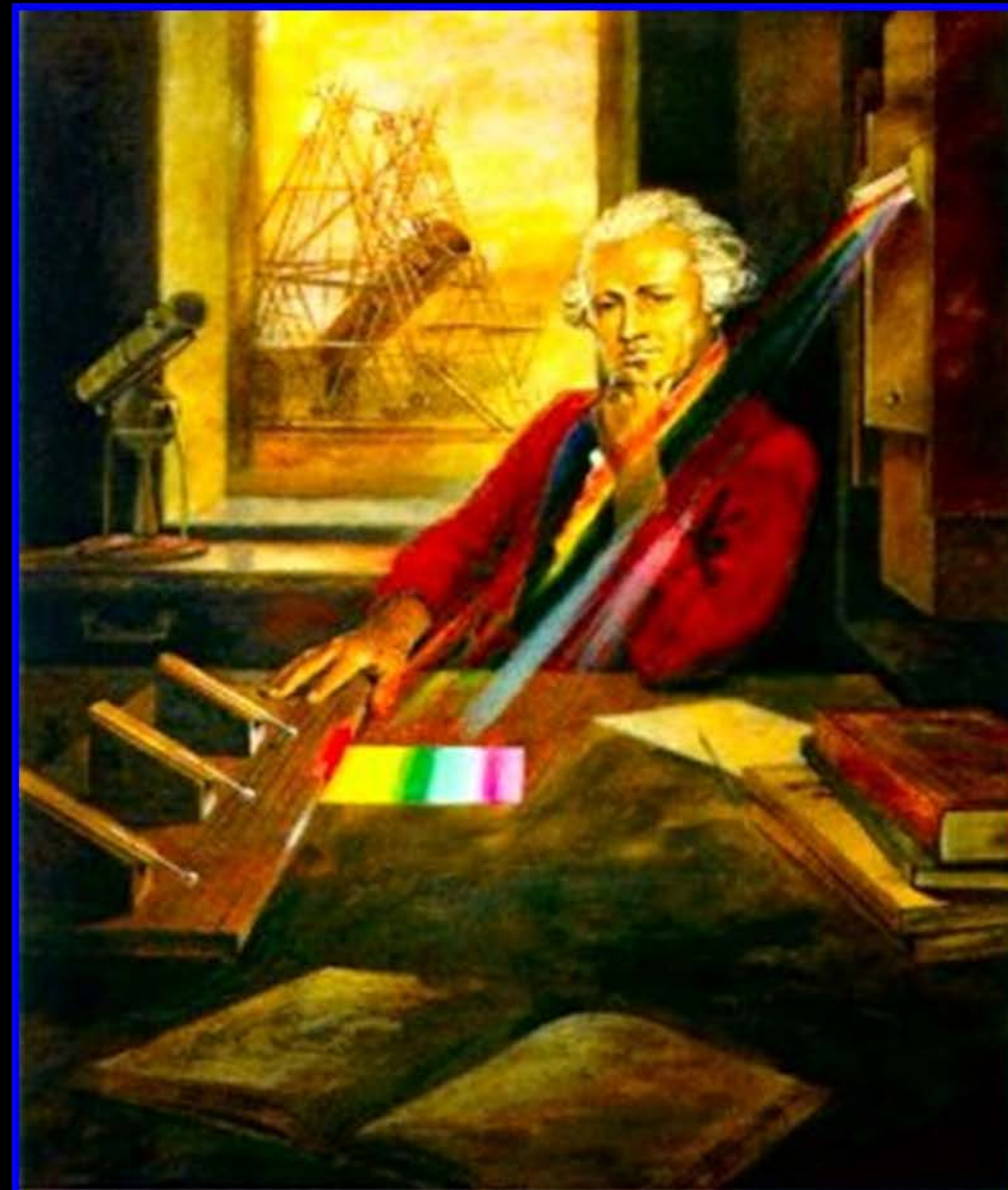
Herschel Spectrometers: Wavelength Coverage



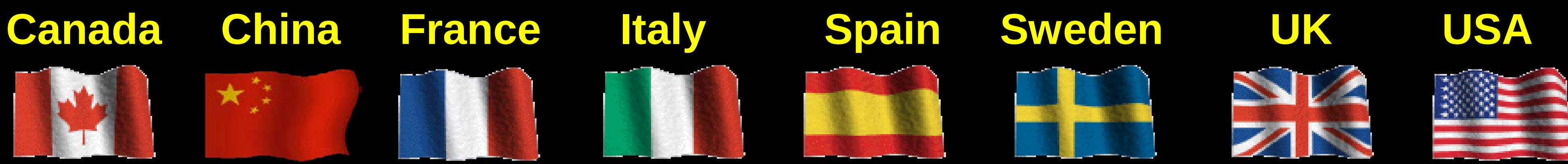
Bolometer Detectors

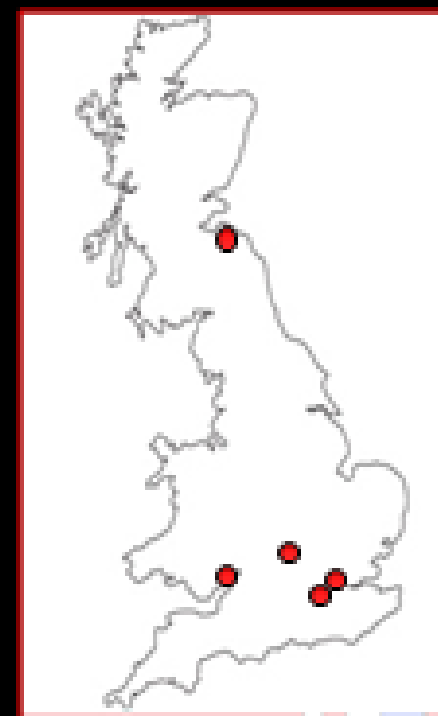


SPIRE Bolometer



The SPIRE Consortium





- 18 institutes in eight countries

The Official SPIRE Logo

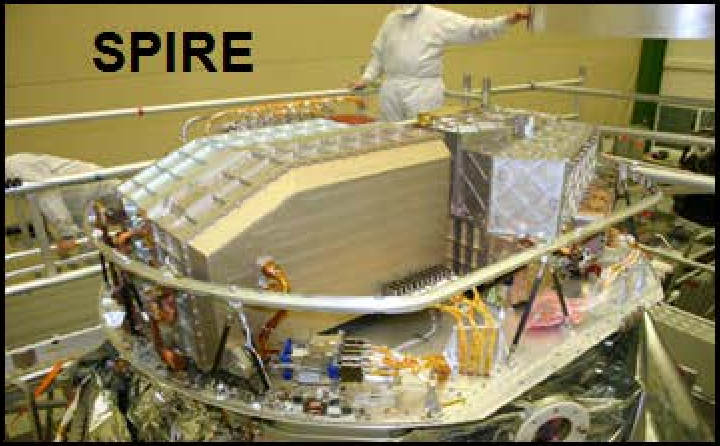
The Official SPIRE Logo

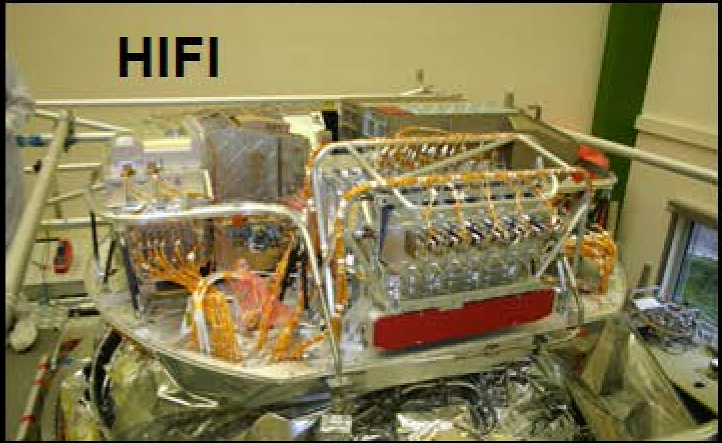
The Unofficial SPIRE Logo

SPIRE

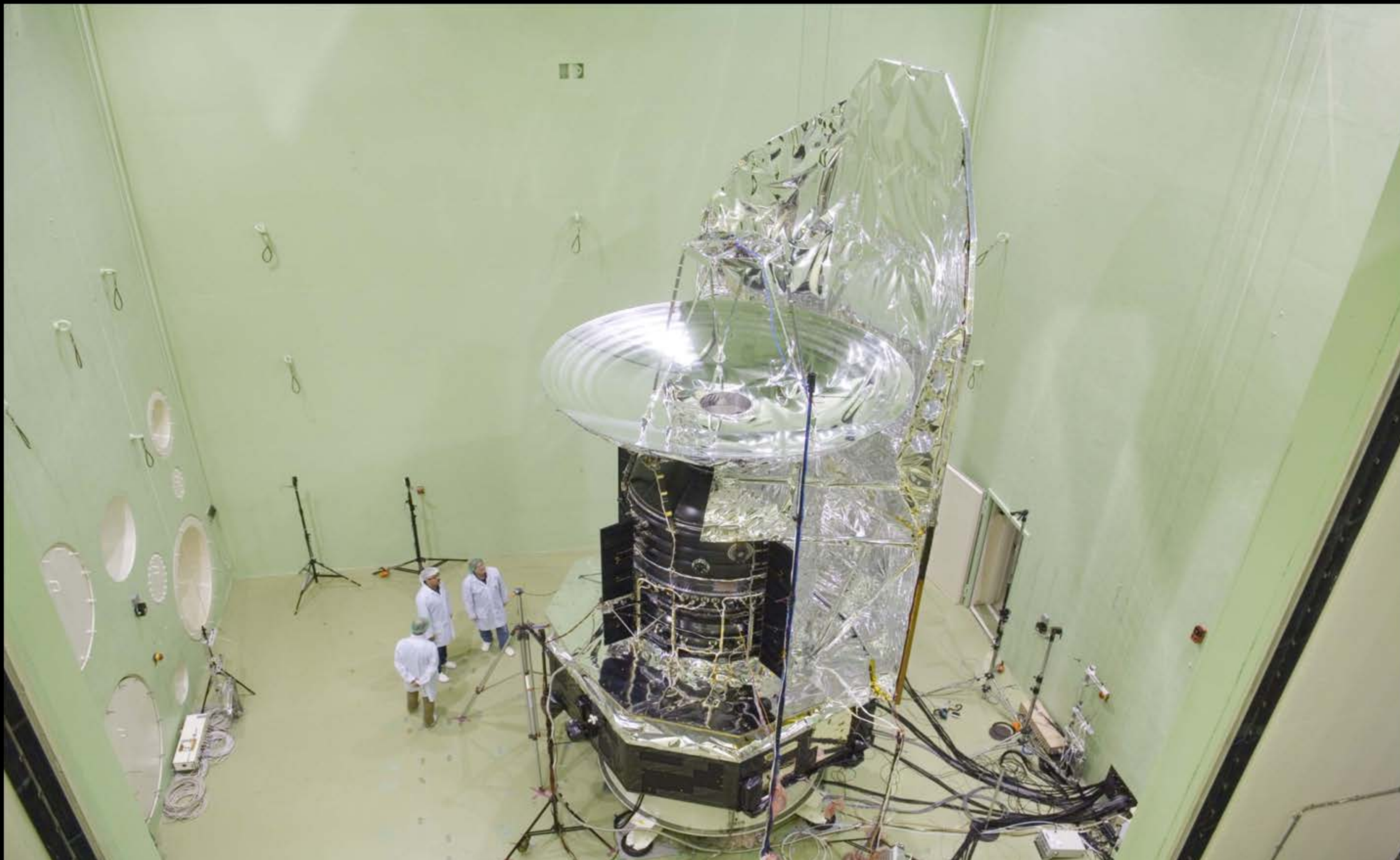

RAL

Herschel Instruments



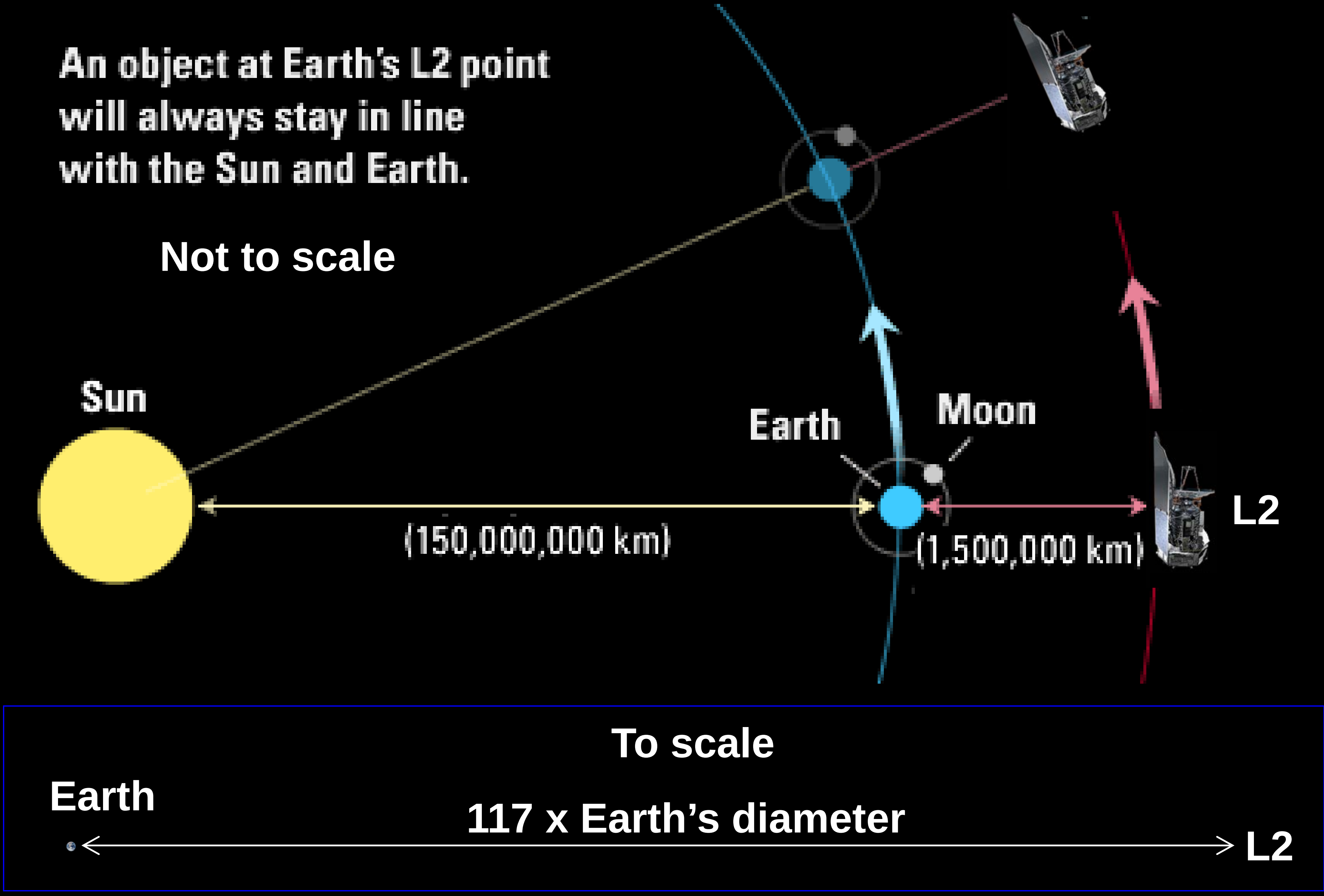


Preparation for Acoustic Test

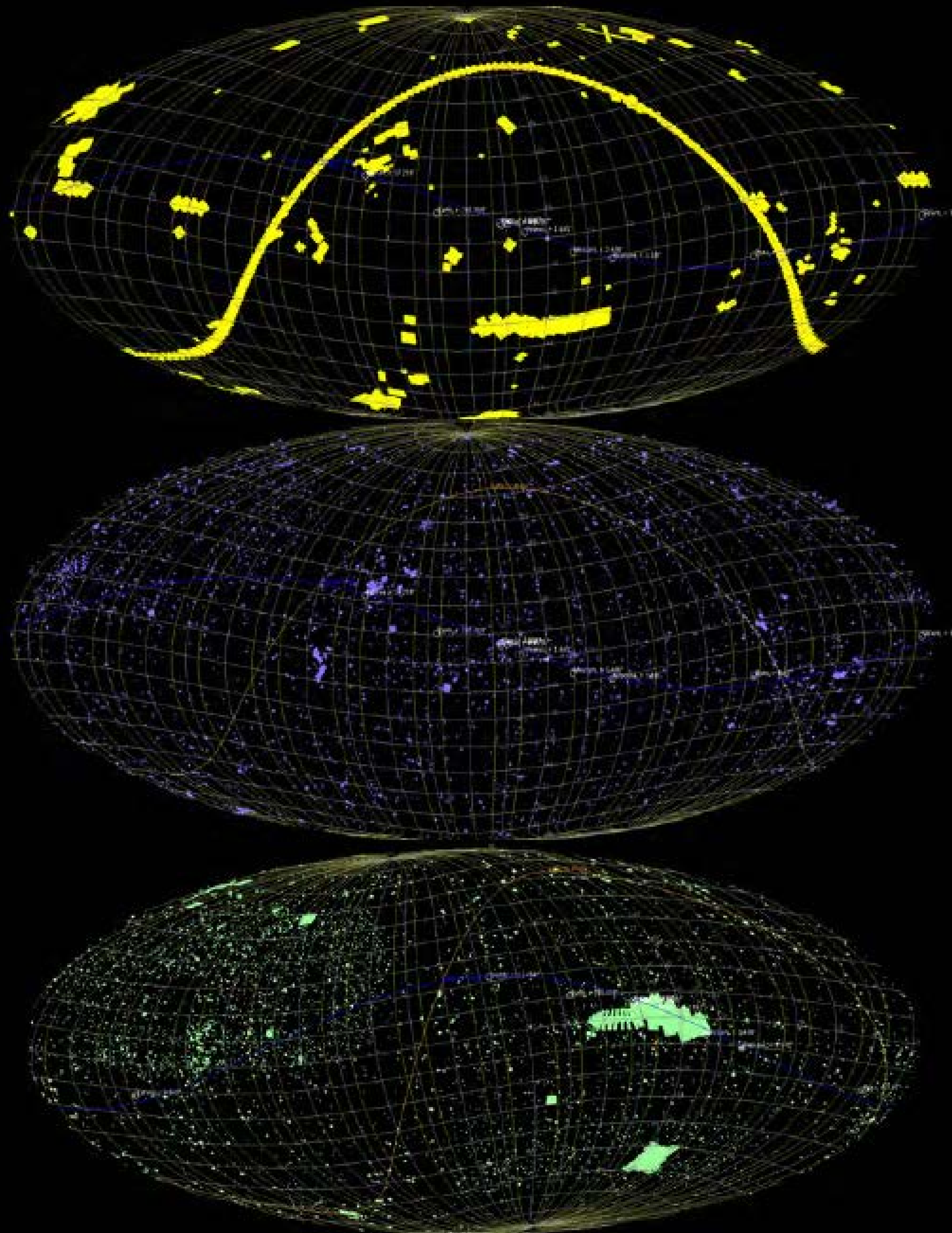


Fully Assembled Satellite

Launch Site: French Guiana


An object at Earth's L2 point
will always stay in line
with the Sun and Earth.
Not to scale
Sun
Earth
Moon
(150,000,000 km)
(1,500,000 km)
L2
To scale
Earth
117 x Earth's diameter
L2

Some Herschel Results



Herschel Sky Coverage

SPIRE/PACS Parallel	6.4%
PACS Phot	0.7%
SPIRE Phot	2.3%
PACS Spec	<0.01%
SPIRE Spec	<0.01
HIFI	0.06%
Total	9.5%

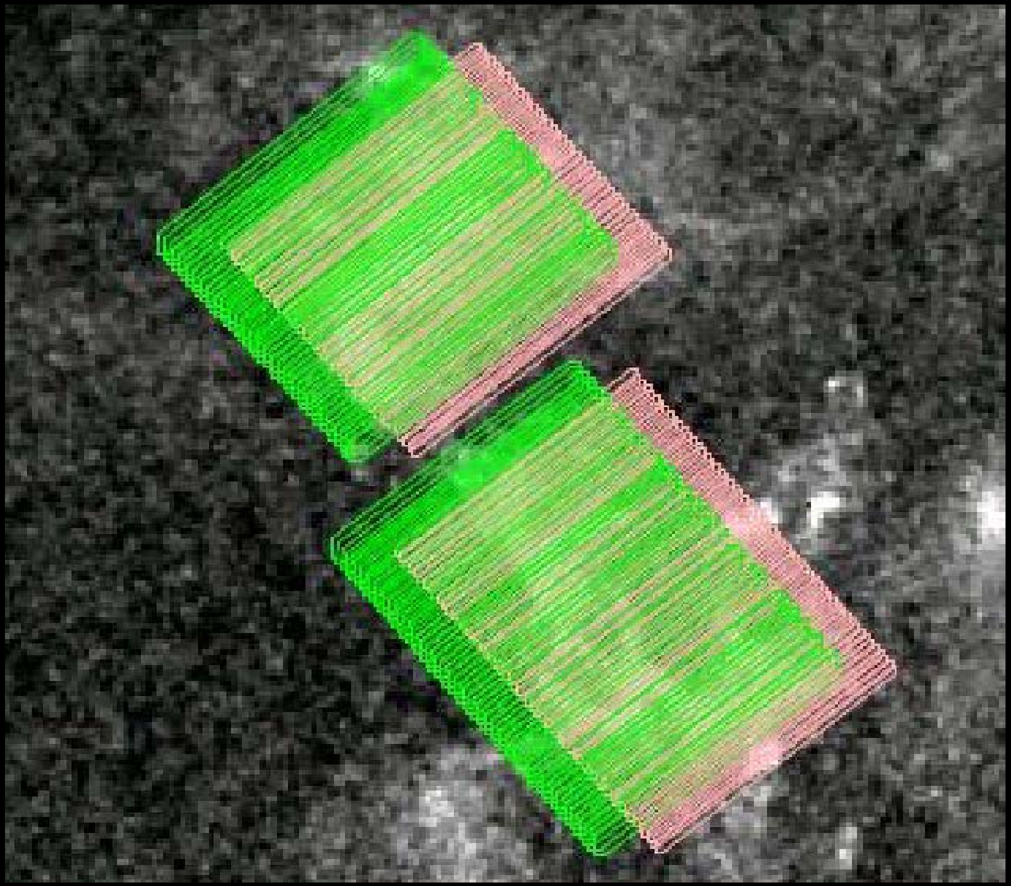
Total observing time:

23,400 hrs

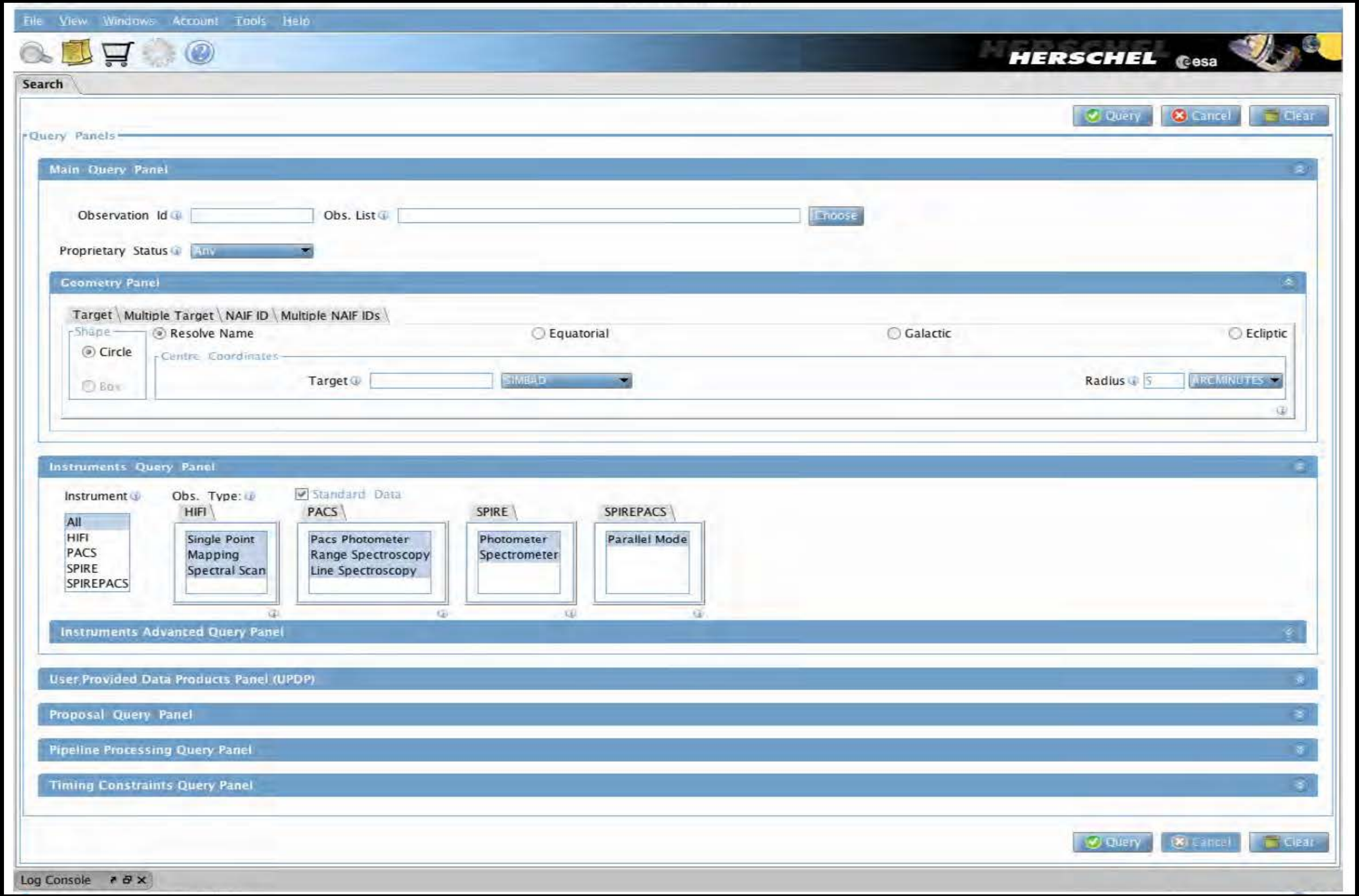
All Herschel data are public via the *Herschel Science Archive* (HAS)

SPIRE-PACS Parallel Mode

- Scan map with SPIRE and PACS
- Simultaneous 5-band mapping
  (3 SPIRE and 2 PACS bands)



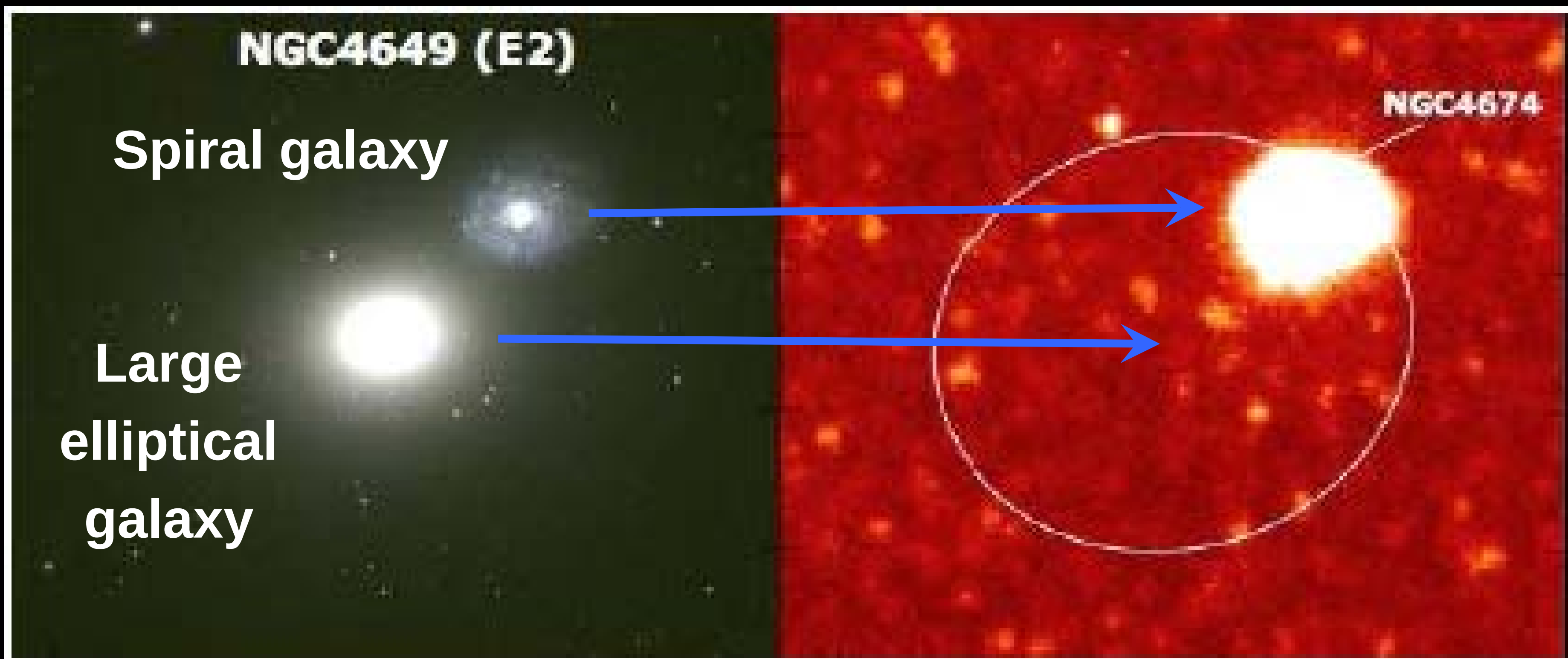
The Herschel Science Archive

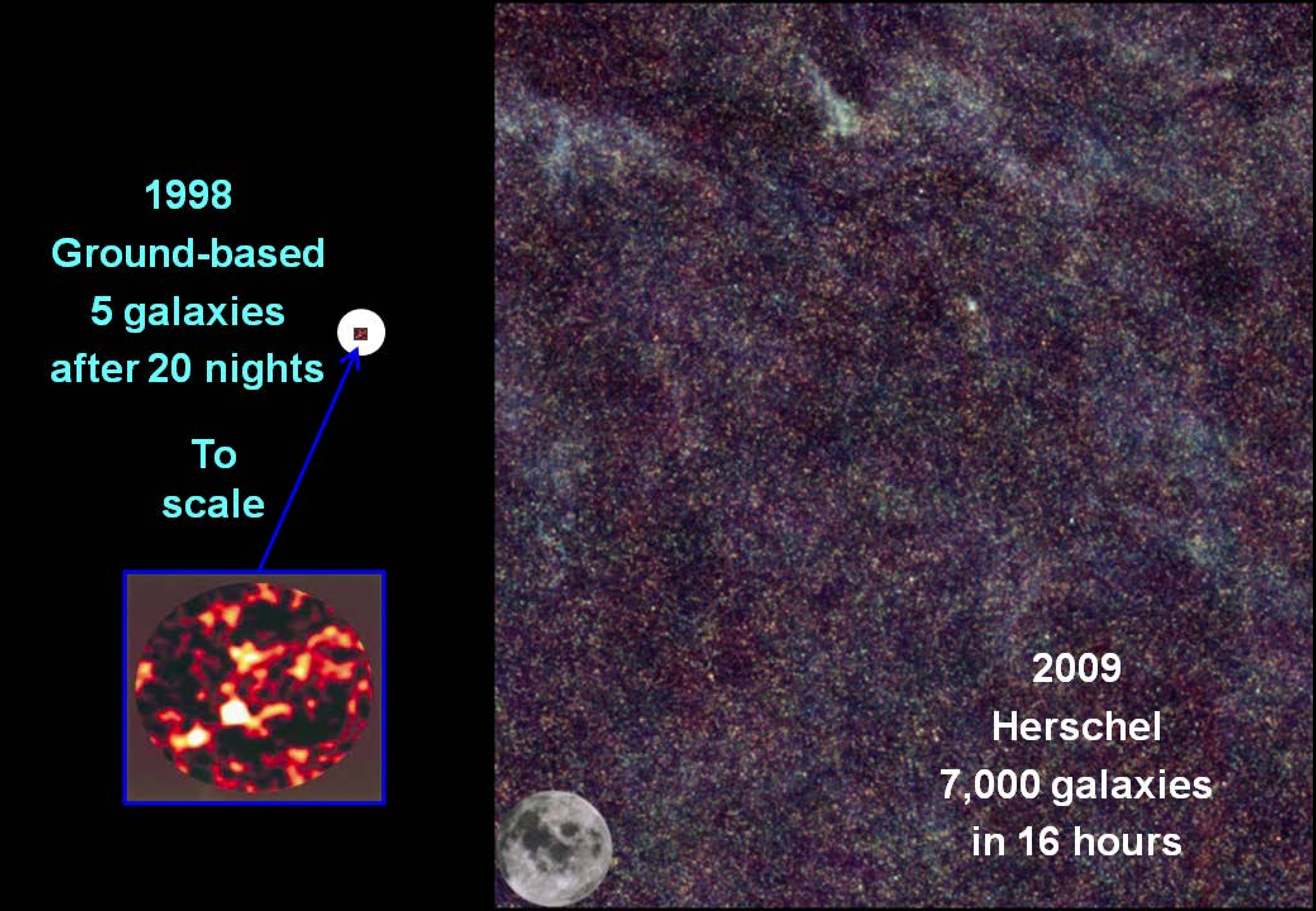


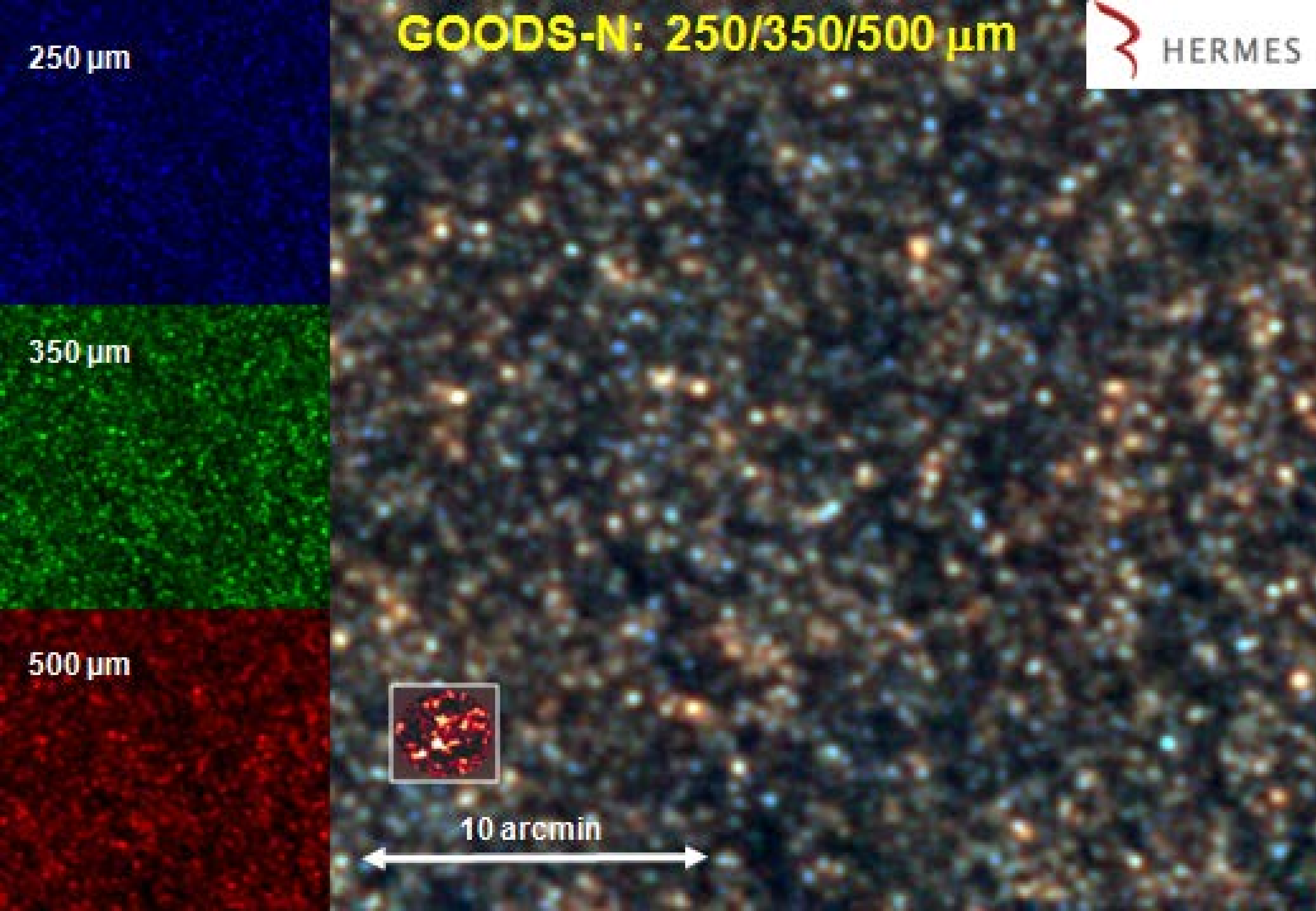
Elliptical Galaxies

Visible

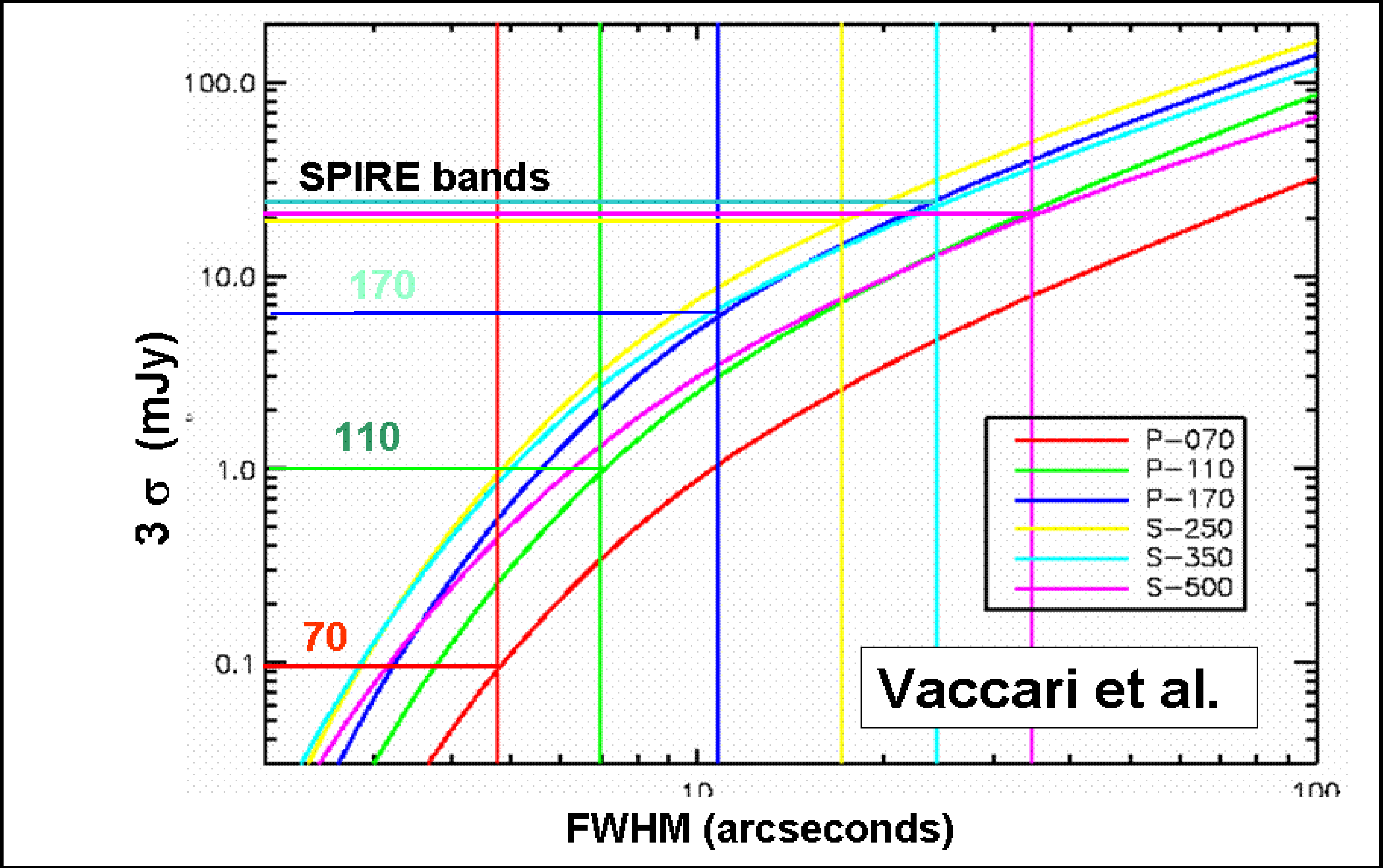
Herschel



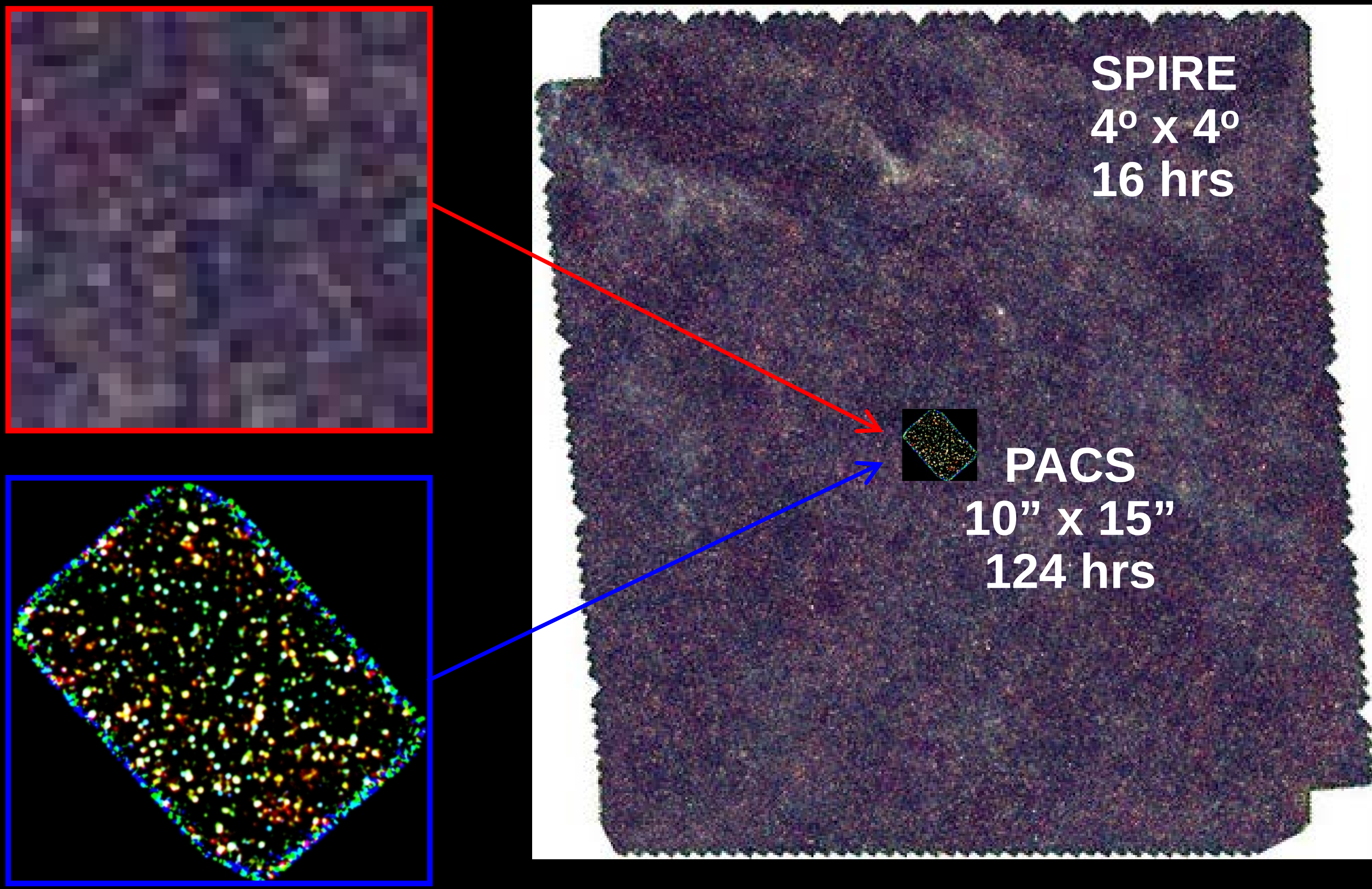

1998
Ground-based
5 galaxies
after 20 nights
To
scale
2009
Herschel
7,000 galaxies
in 16 hours


GOODS-N: 250/350/500 µm
HERMES
250 µm
350 µm
500 µm
10 arcmin

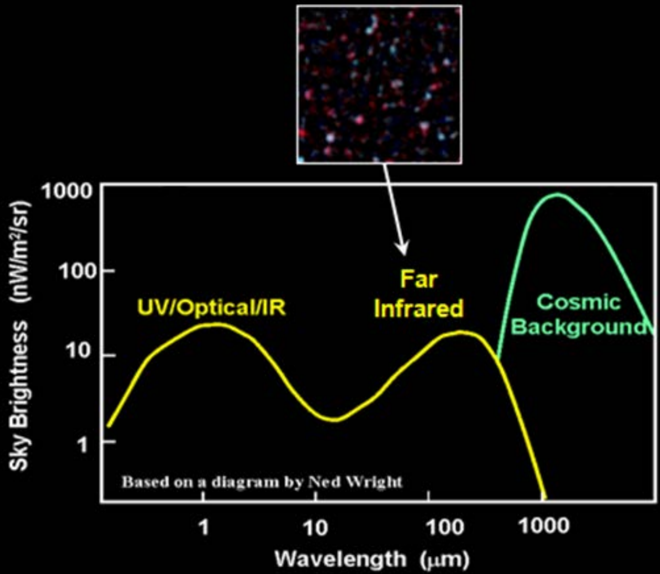
3-σ Extragalactic Confusion Fluctuations

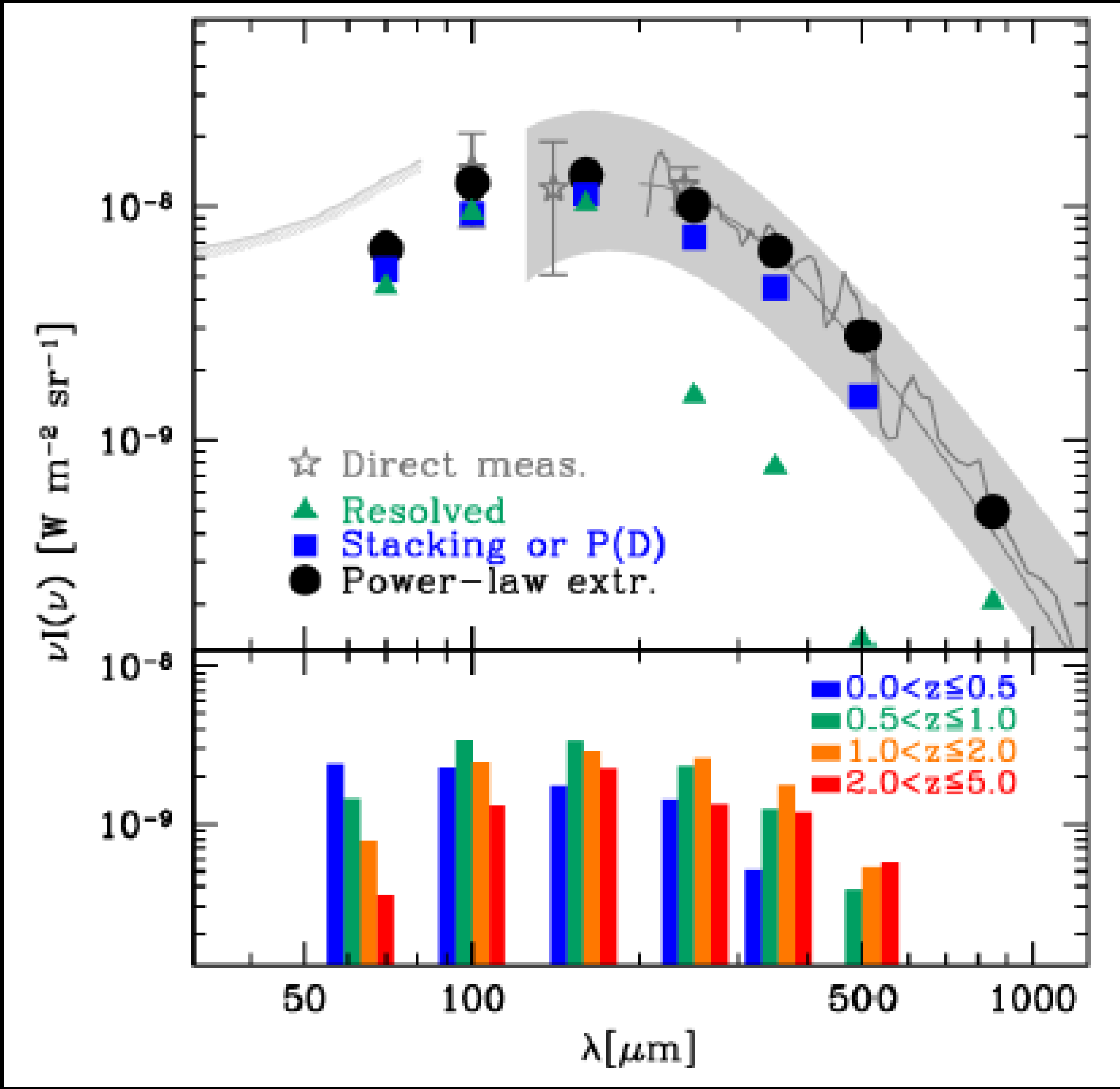


Extragalactic Surveys with PACS and SPIRE



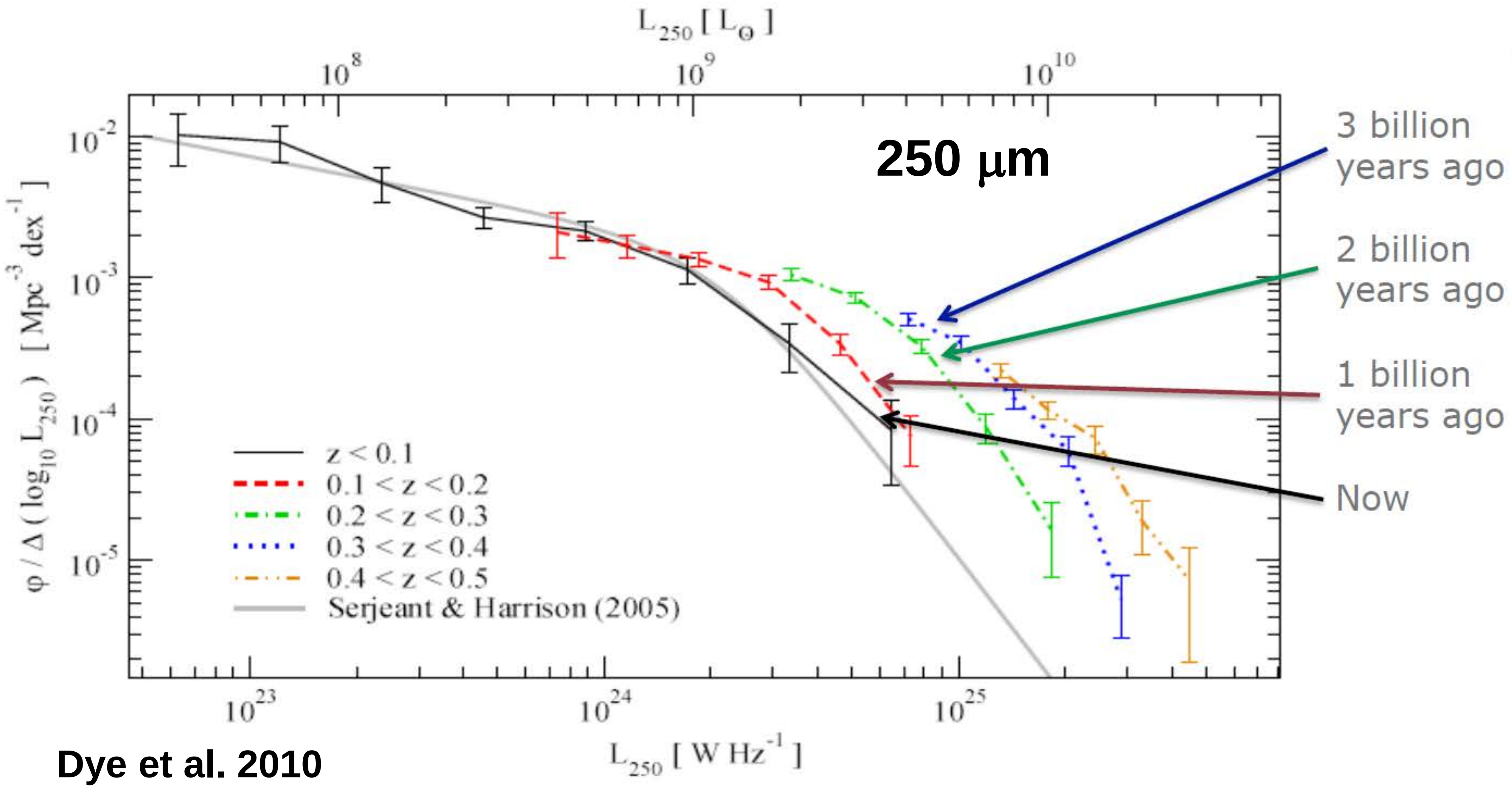
Resolution of the Cosmic Infrared Background





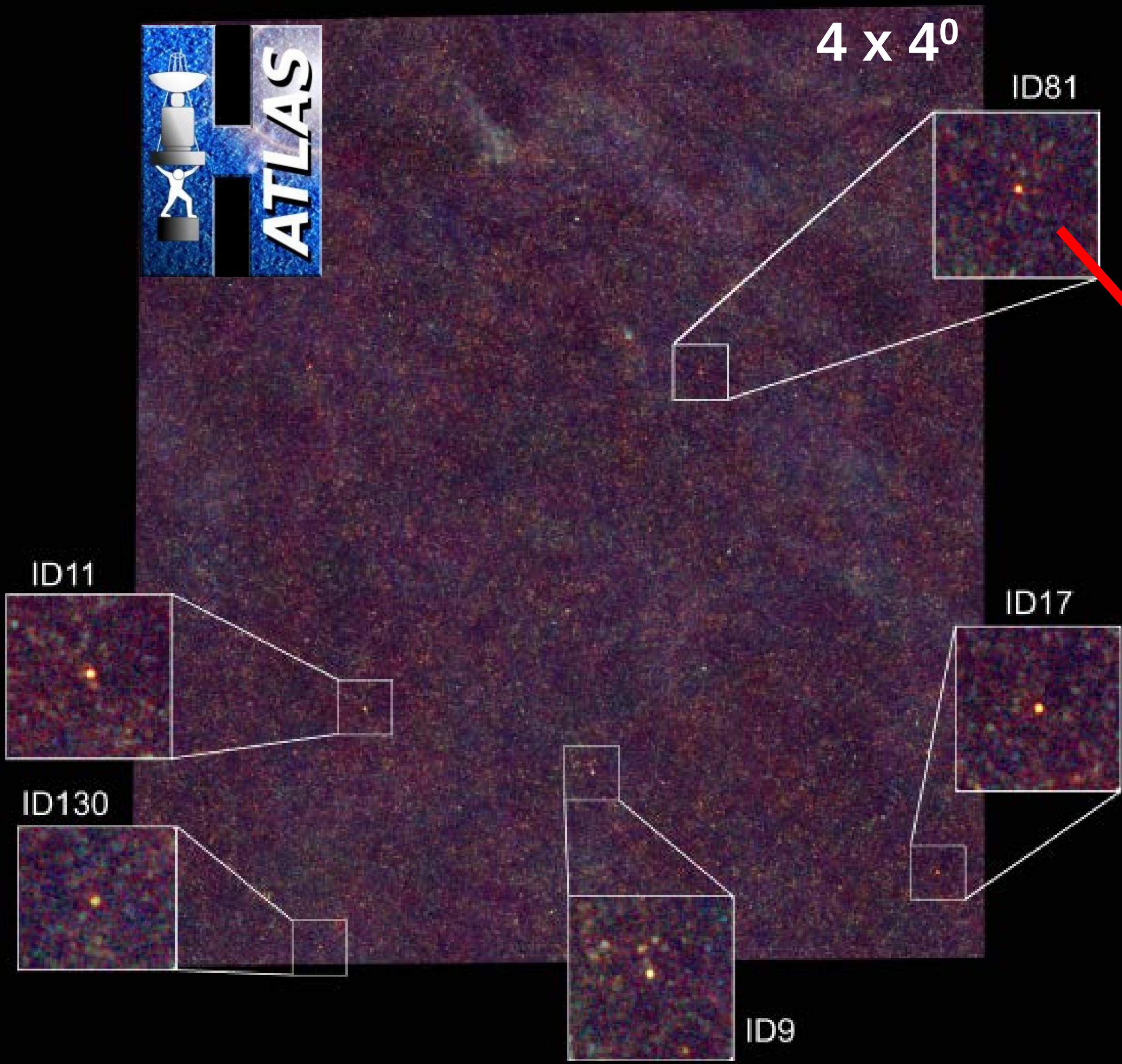
Numerous PACS and SPIRE results compiled by Lutz, 2013

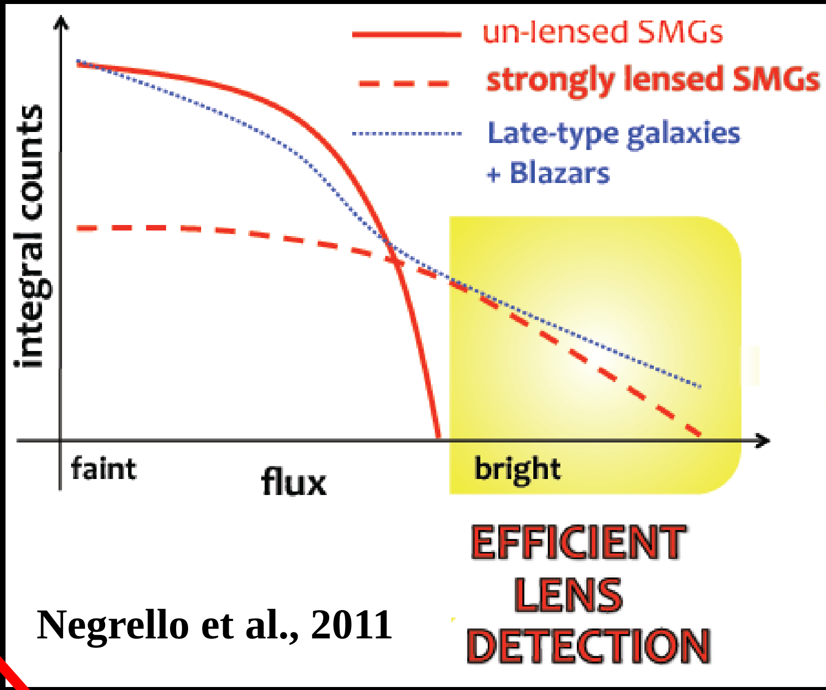
Luminosity Function Evolution

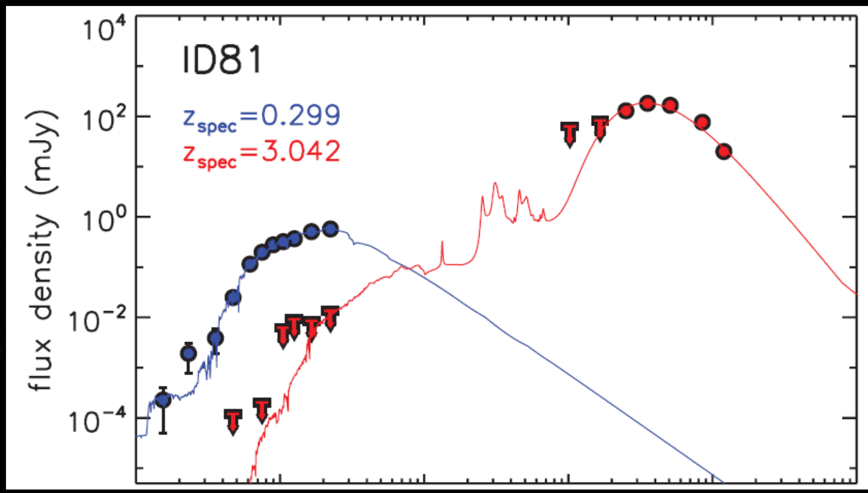


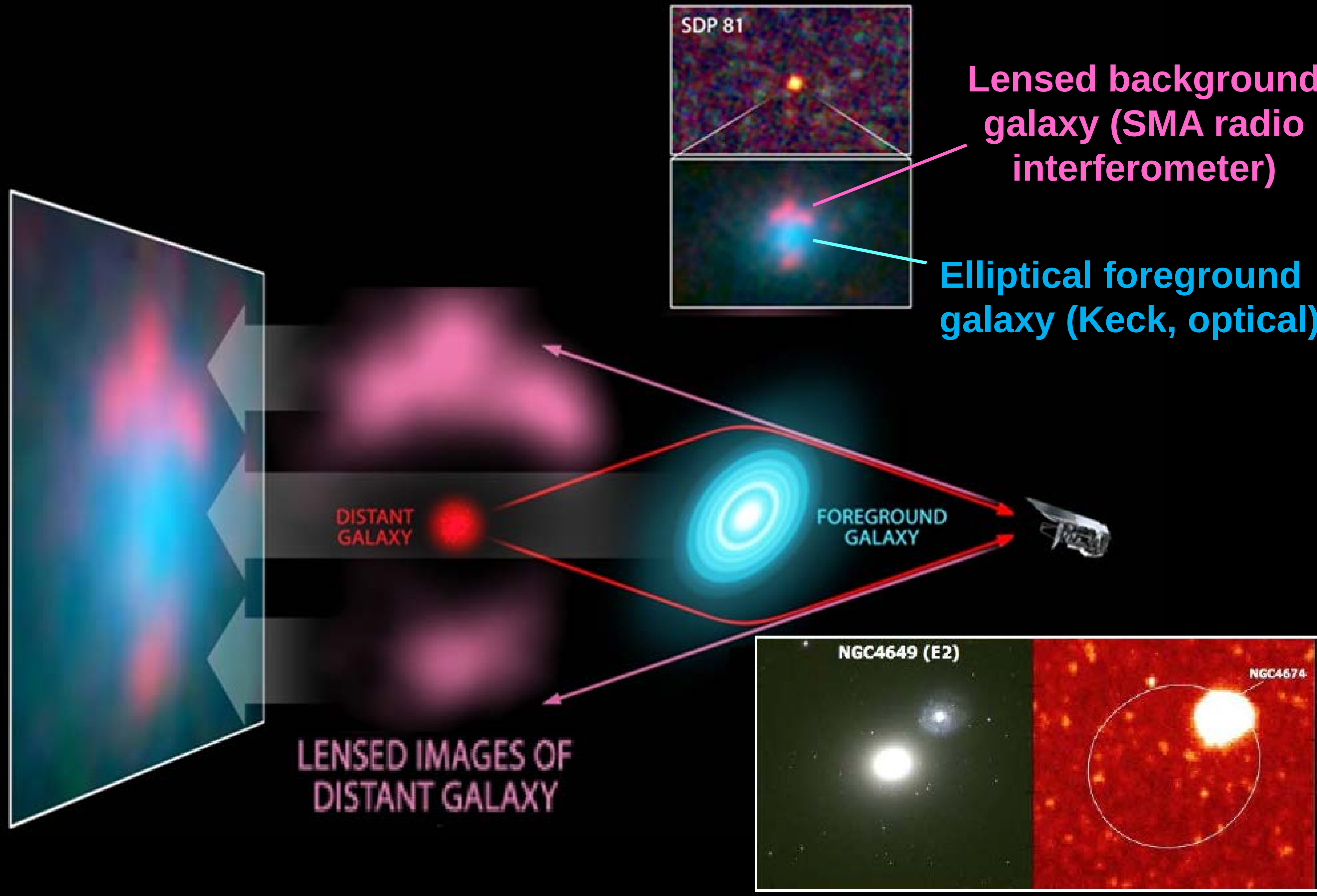
Dye et al. 2010

ATLAS Lensed SMGs

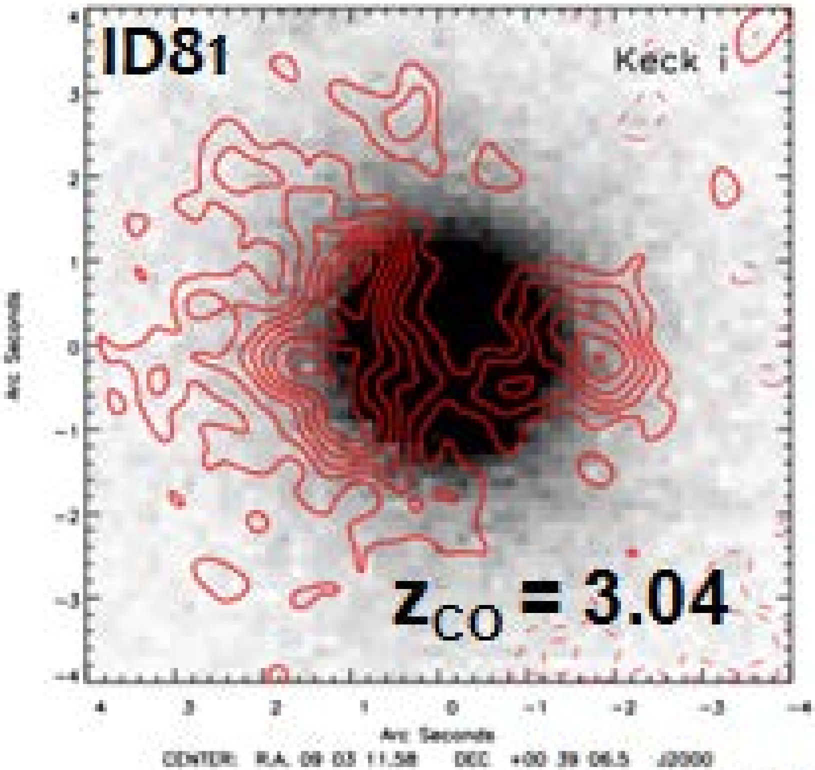


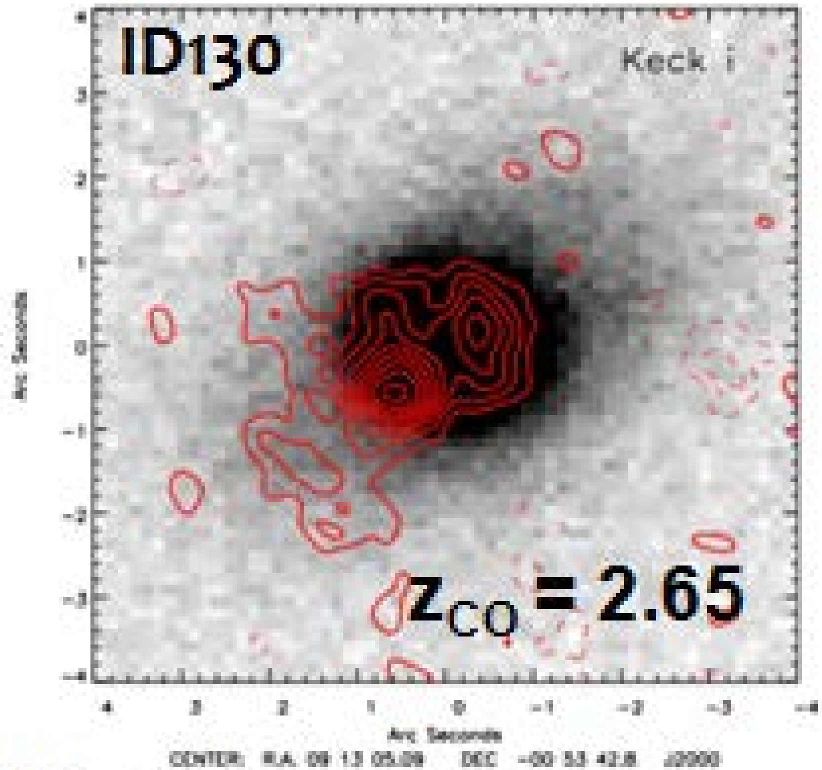




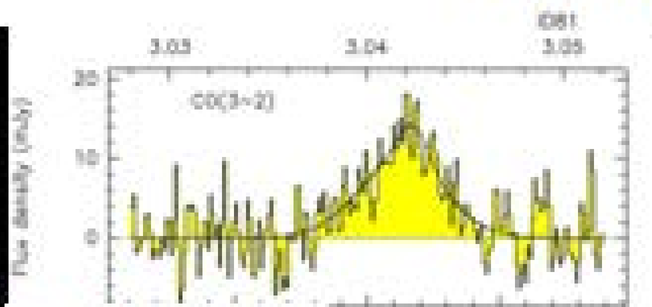

SDP 81
Lensed background galaxy (SMA radio interferometer)
Elliptical foreground galaxy (Keck, optical)
DISTANT GALAXY
FOREGROUND GALAXY
LENSED IMAGES OF DISTANT GALAXY
NGC4649 (E2)
NGC4674

ATLAS lenses confirmed with CO redshifts

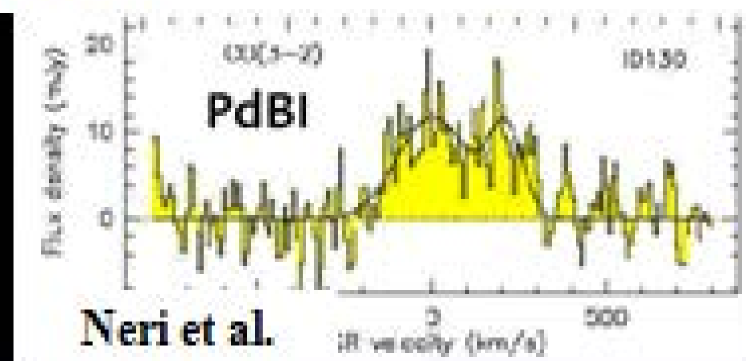




Negrello et al., ESLAB, May 2010

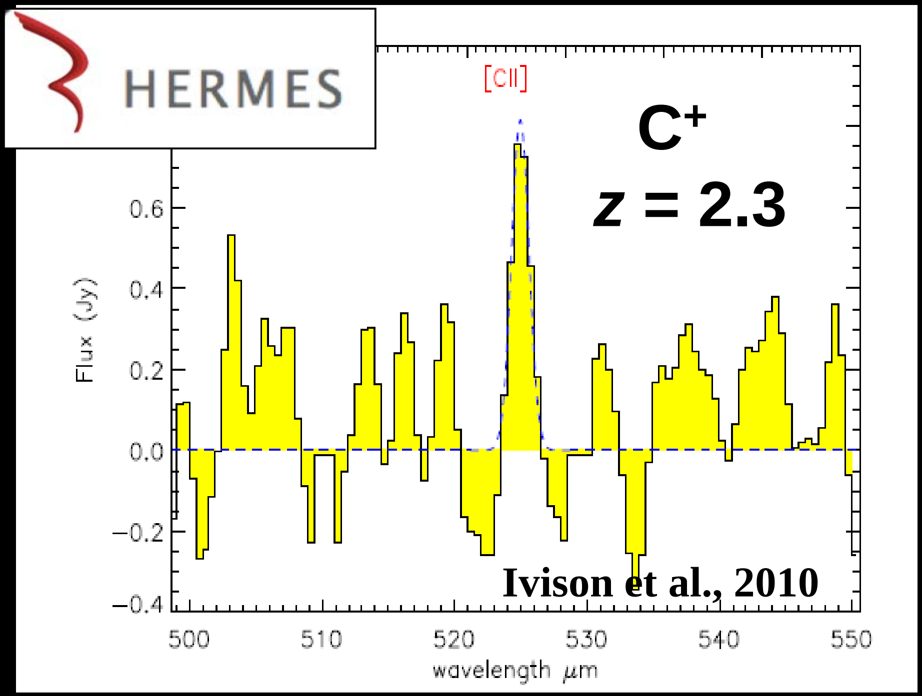


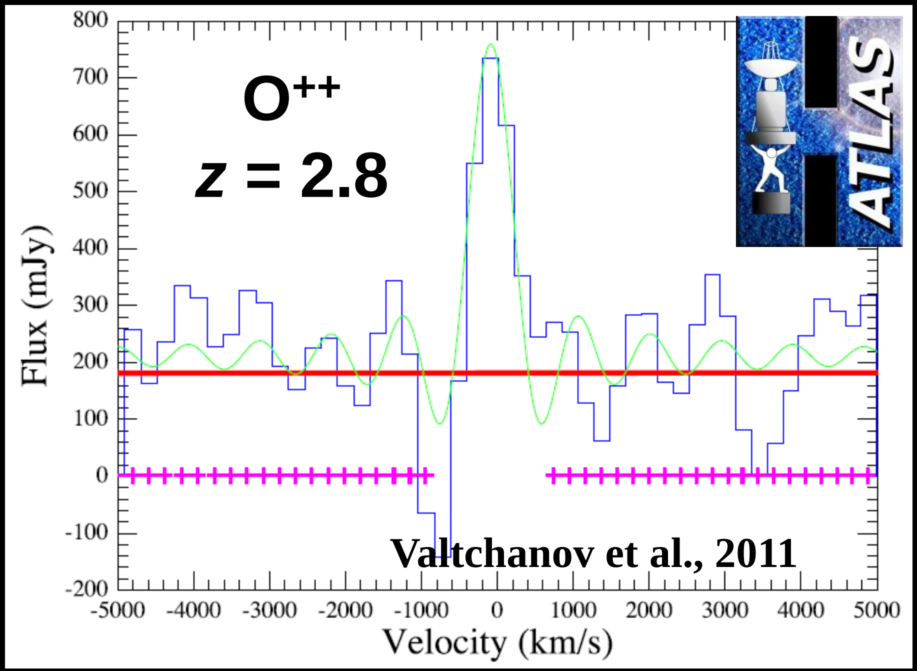
Aguirre et al.



Neri et al.

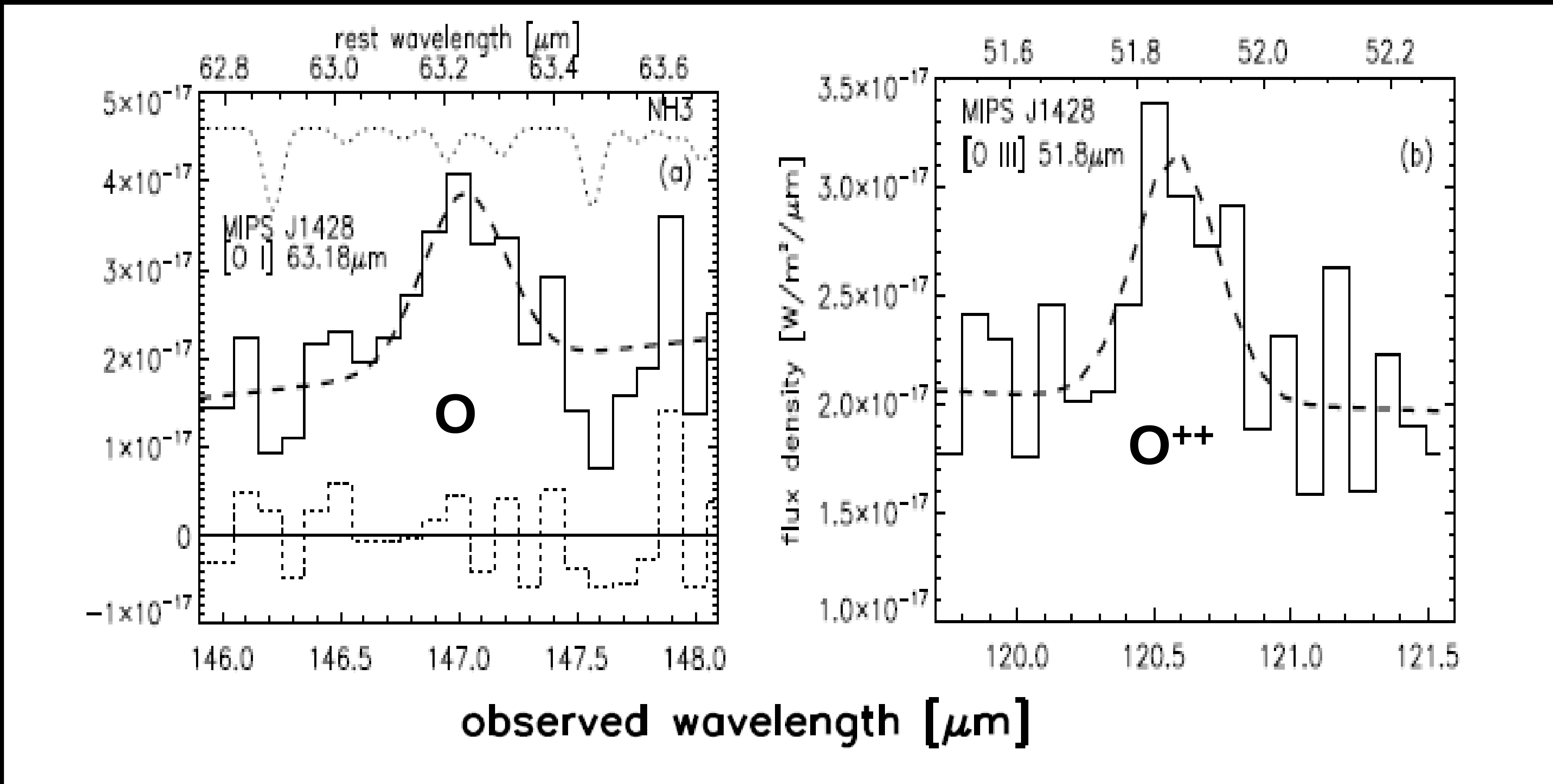
SPIRE Spectroscopy of Lensed Galaxies





- $L_{[CII]} / L_{dust}$ higher than in local ultra-luminous IR galaxies
- Star formation intensity similar to that of local ULIRGs but distributed over a larger volume
  - Not likely to be merger-driven

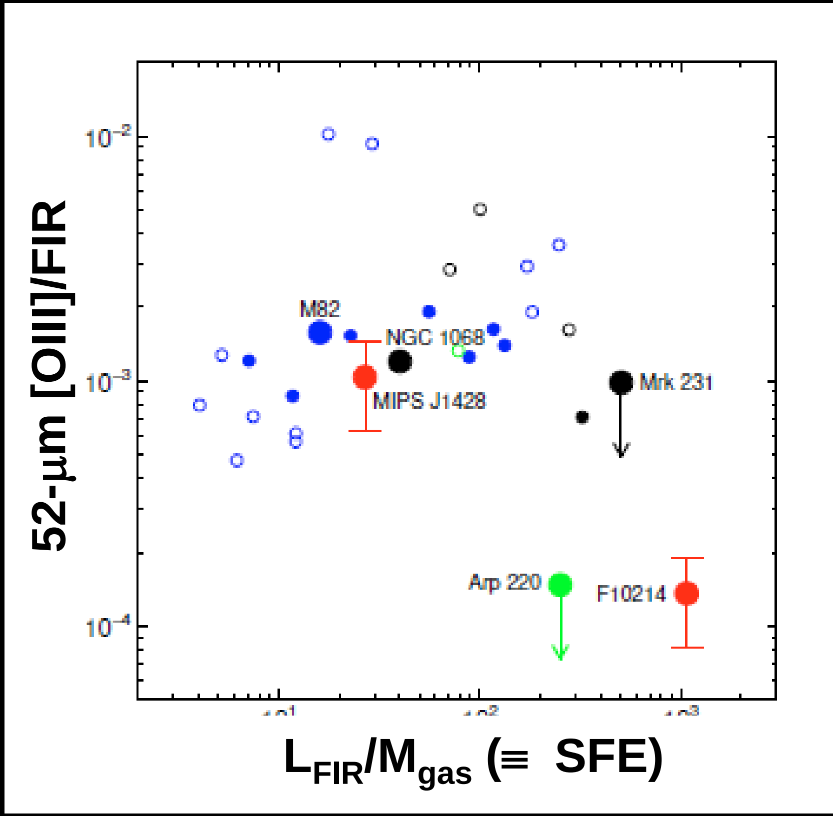
PACS Spectroscopy of a Lensed High-z Galaxy
MIPS J1428 z = 1.3 μ ≈ 8

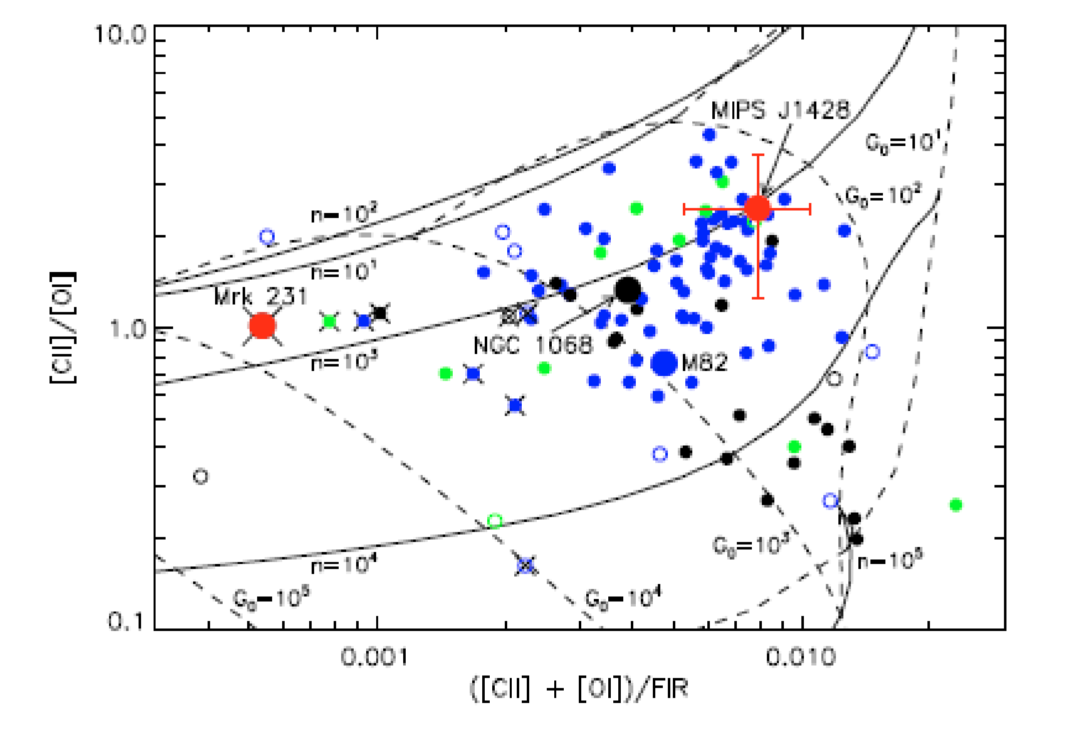


⇒ **High-z galaxies can have high luminosities without being major mergers**

Sturm et al. 2011

PACS Spectroscopy of a Lensed High-z Galaxy

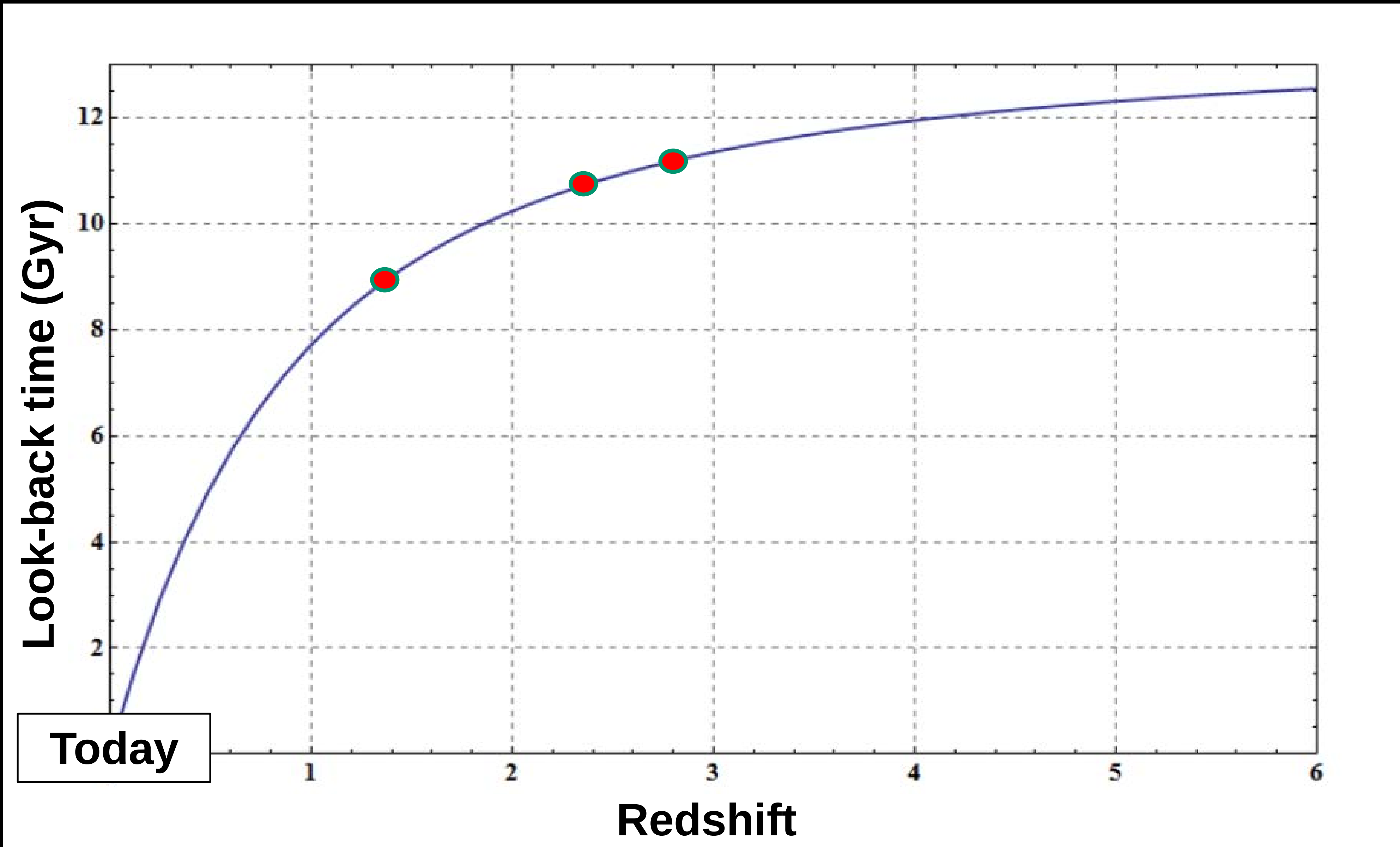




Sturm et al., 2010

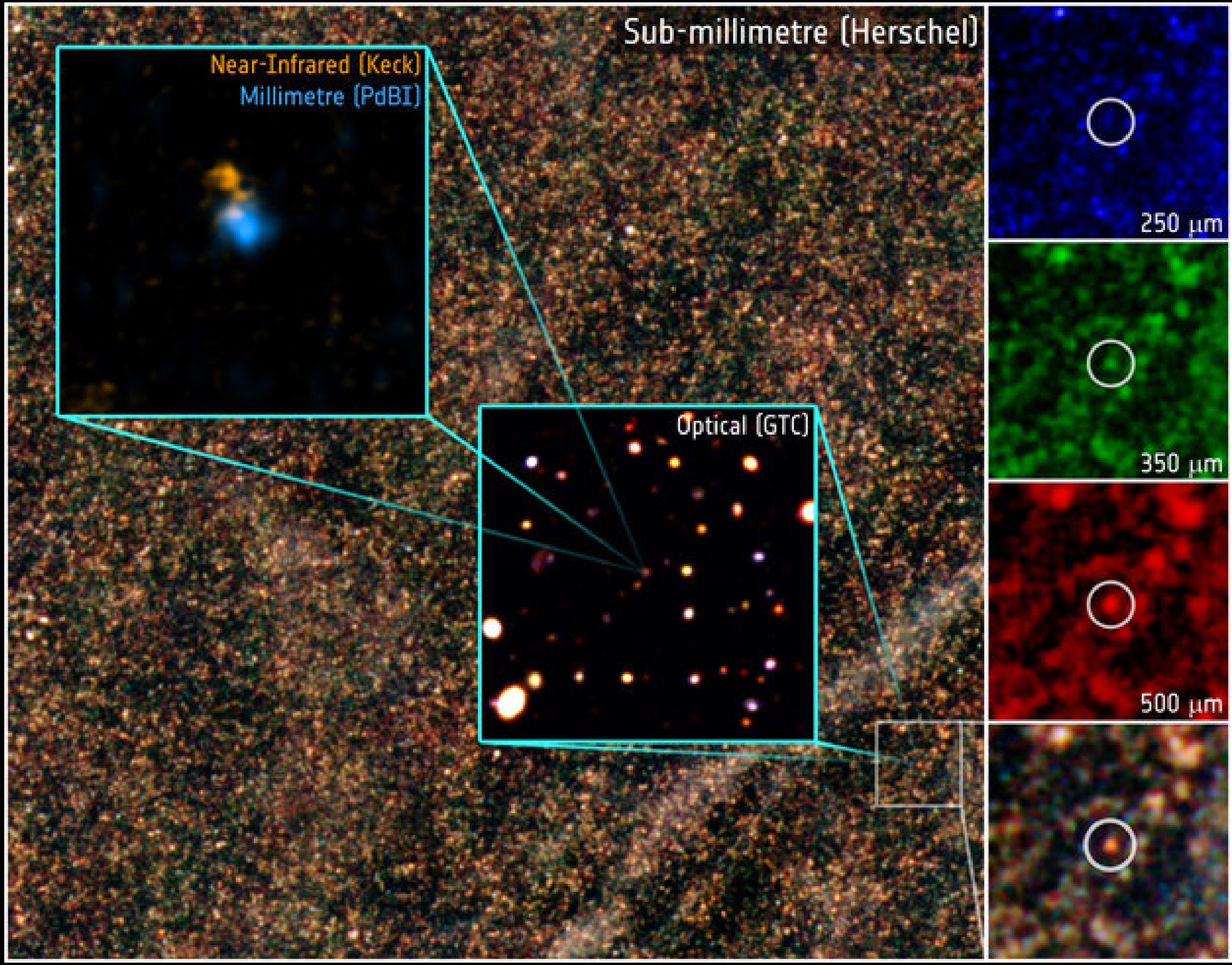
- ULIRG luminosity (SFR ~ 300 $M_{\odot}$/yr)
- But no [OI]/FIR deficit like local ULIRGs
- UV intensity, density, and SFE typical of a normal SB galaxy
  - But much larger gas reservoir
- High-z galaxies can have ULIRG luminosities without being major mergers

Look-back Time vs. Redshift



HFLS3

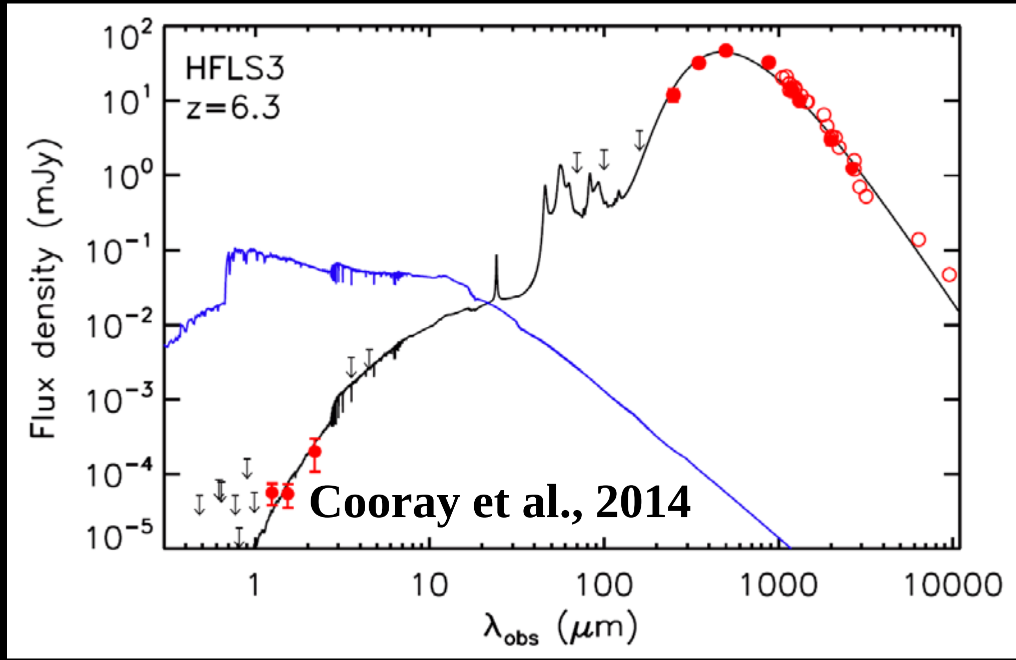
- $z = 6.34$
- Lookback time ~ 13 Gyr
- Massive, dusty galaxy only 800 Myr after Big Bang
- Discovered with *Herschel* and followed up with ground-based optical, IR, radio facilities



Riechers et al., 2013
Cooray et al., 2014

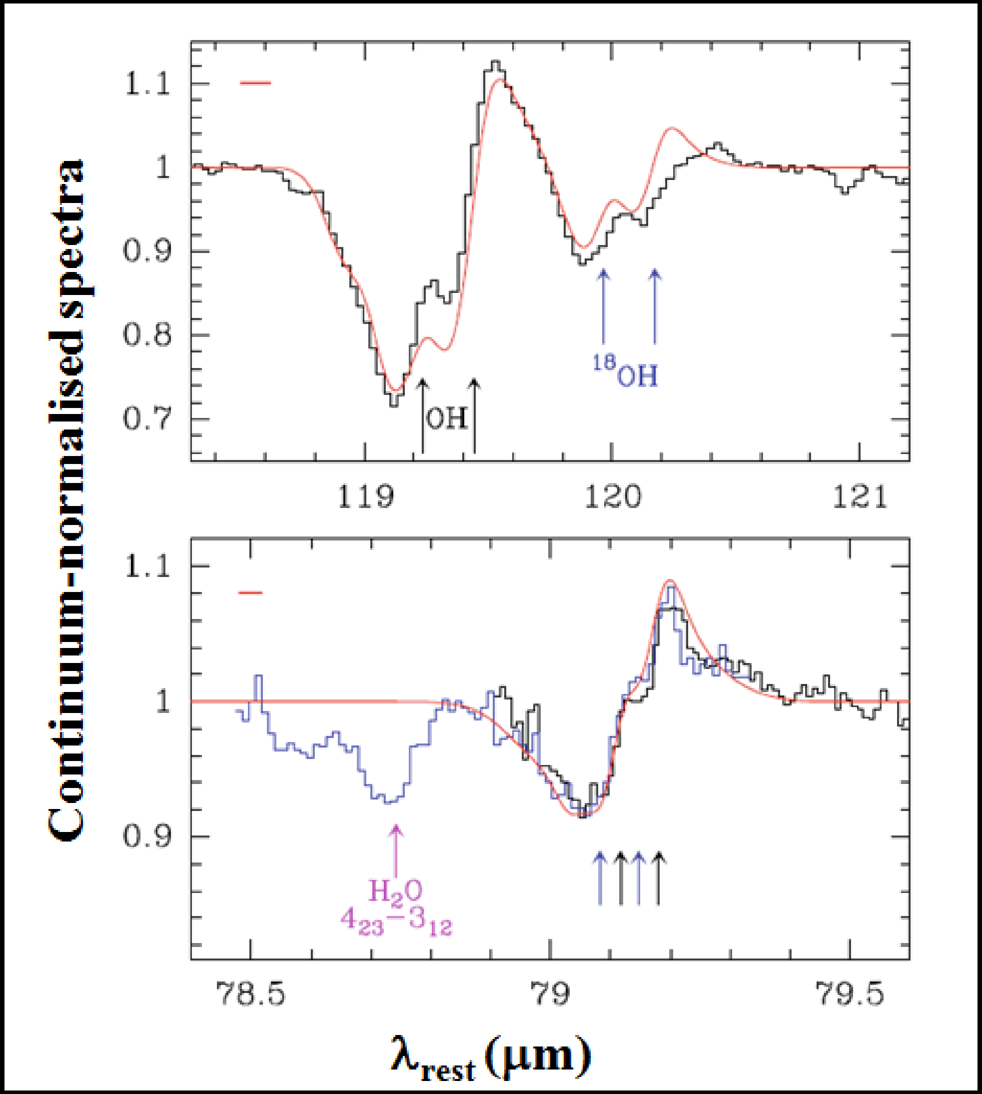
HFLS3

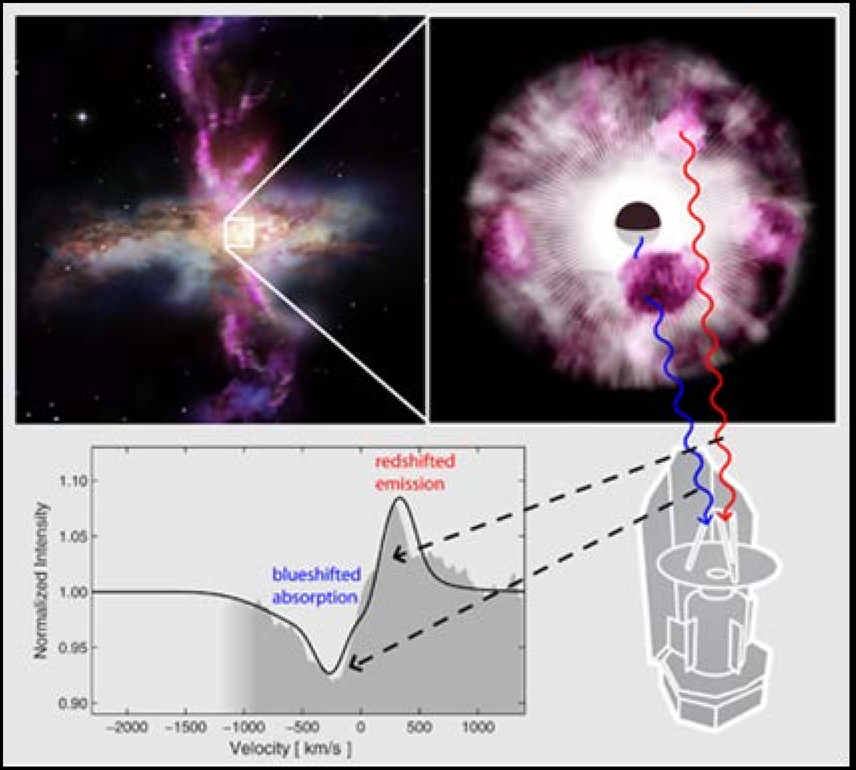
- Giant starburst galaxy, not strongly lensed (μ_{lens} = 2.2)
- SFR ~ 1300 $M_{\odot}$ yr^{-1} ~ 10 x Arp 220
- Tracing the peaks of SFR at early epochs



- ~ 500 high-z candidates (500-μm risers) found in 300 sq. deg of HerMES fields
  - More than predicted by galaxy evolution models
- Future follow-up of *Herschel* database with other facilities – ALMA, HST, JWST, SPICA etc.

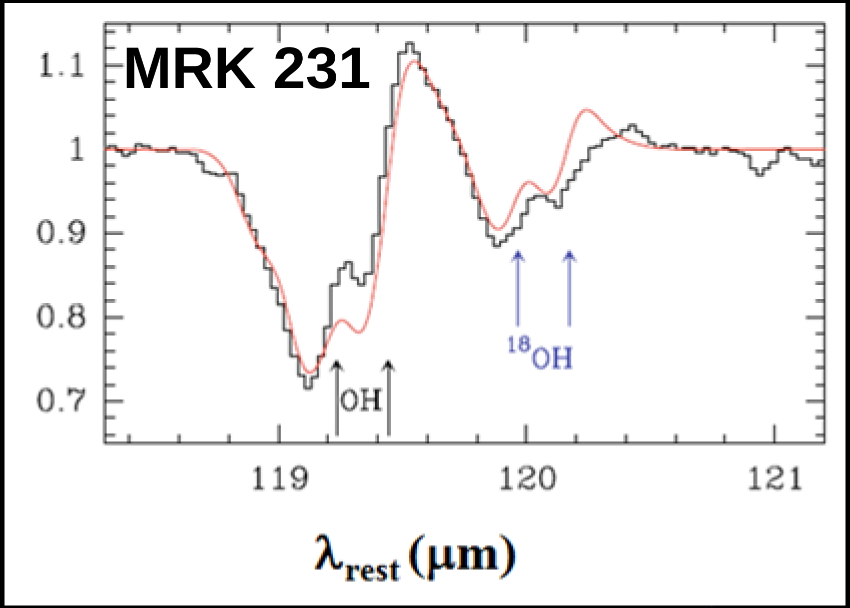
AGN-driven Outflow Suppressing Star-Formation?

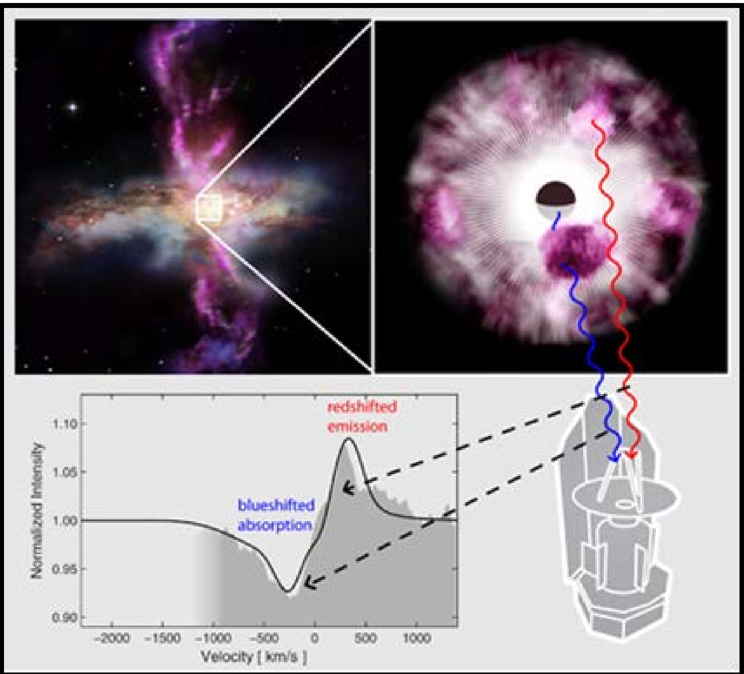




Fischer et al., 2010; Sturm et al., 2011

AGN-driven Outflow Suppressing Star-Formation?

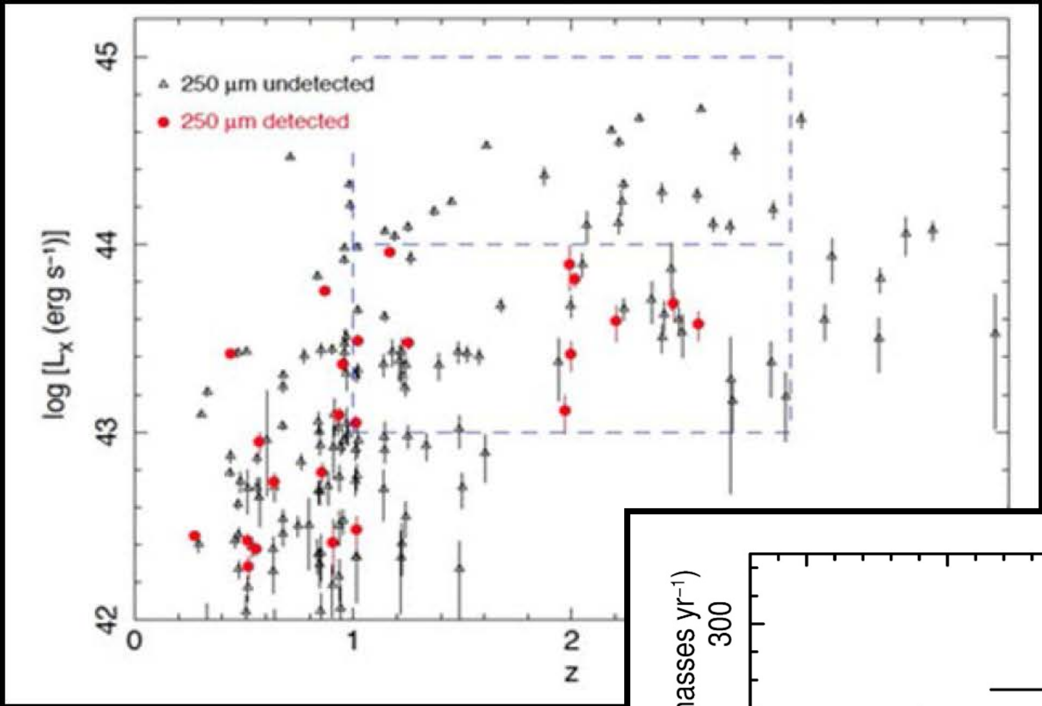


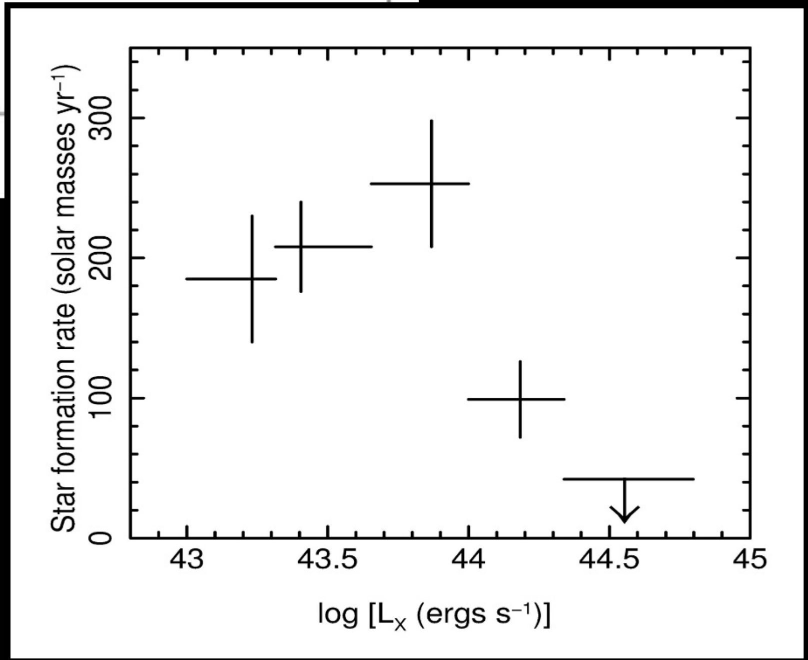


- **High-speed outflow:**
  - **~ 1000 km s^{-1}**
  - **Too fast to be driven by supernovae**
- **Mass loss rate ~ 1000 $M_{\odot}$/yr**
- **Gas reservoir clearing time ~ 10^7 yrs**

Fischer et al., 2010; Sturm et al., 2011

AGN with High L_x not Detected by SPIRE

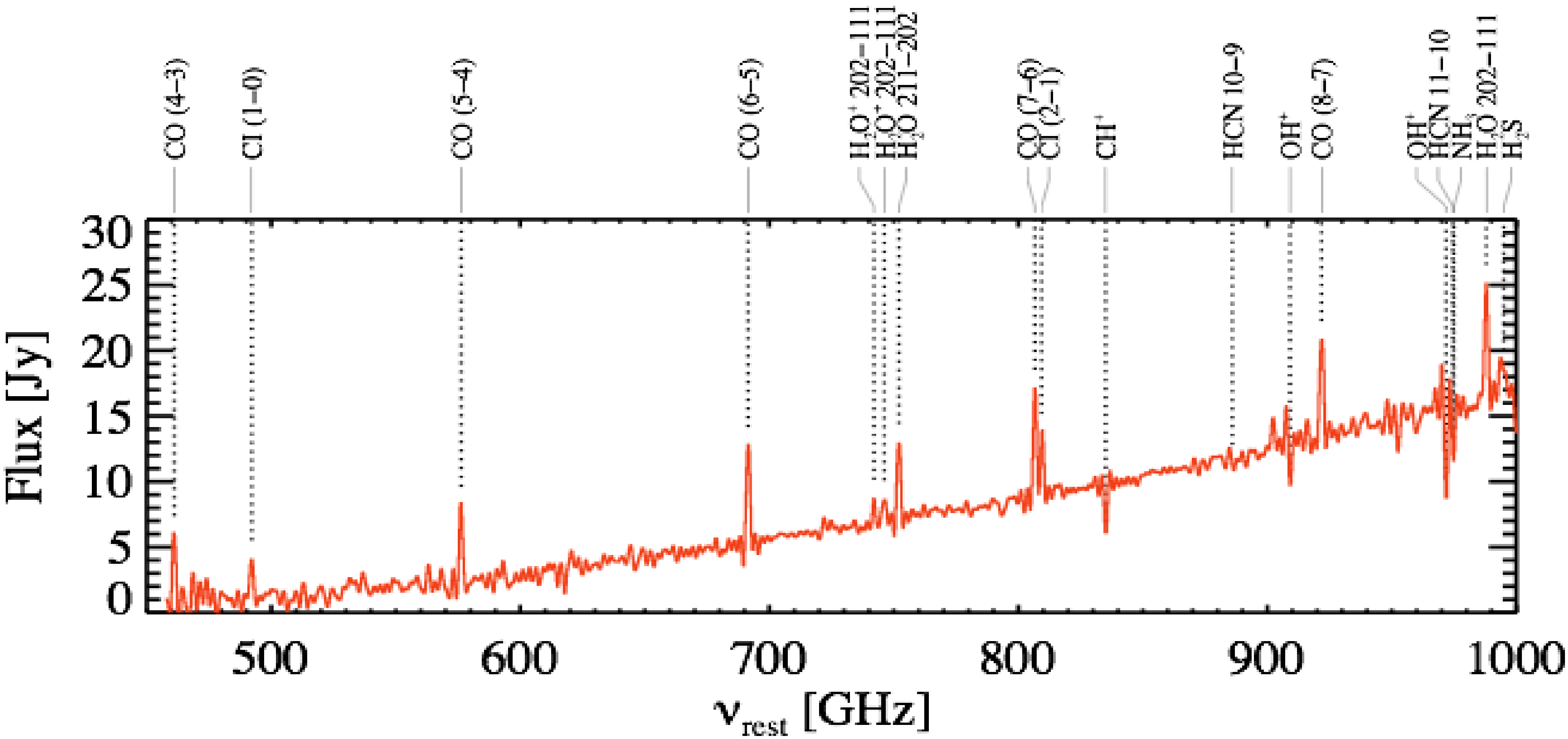




Evidence of AGN feedback at high z

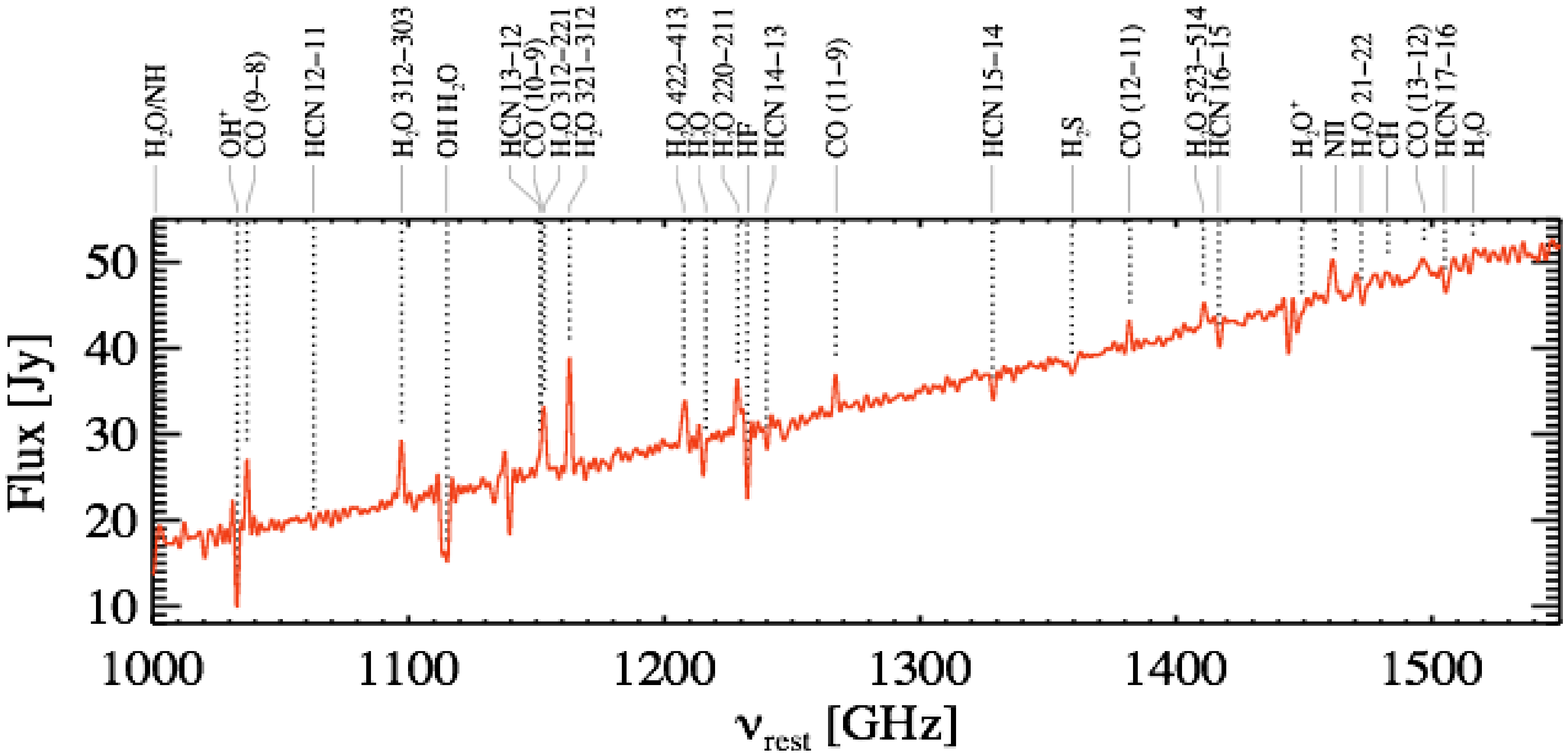
Page et al. 2012

ARP 220



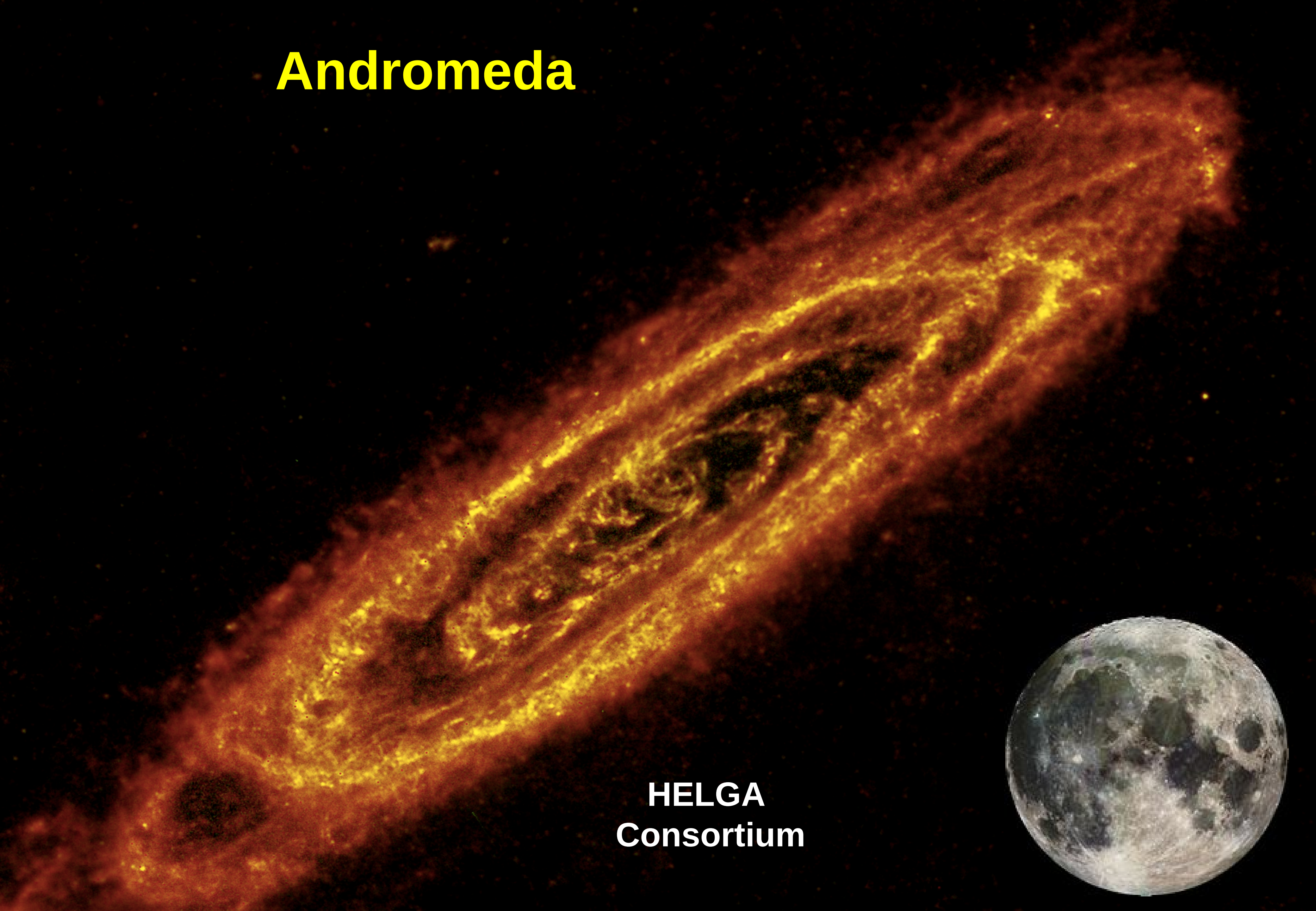
Rangwala et al., 2011

ARP 220



Rangwala et al., 2011

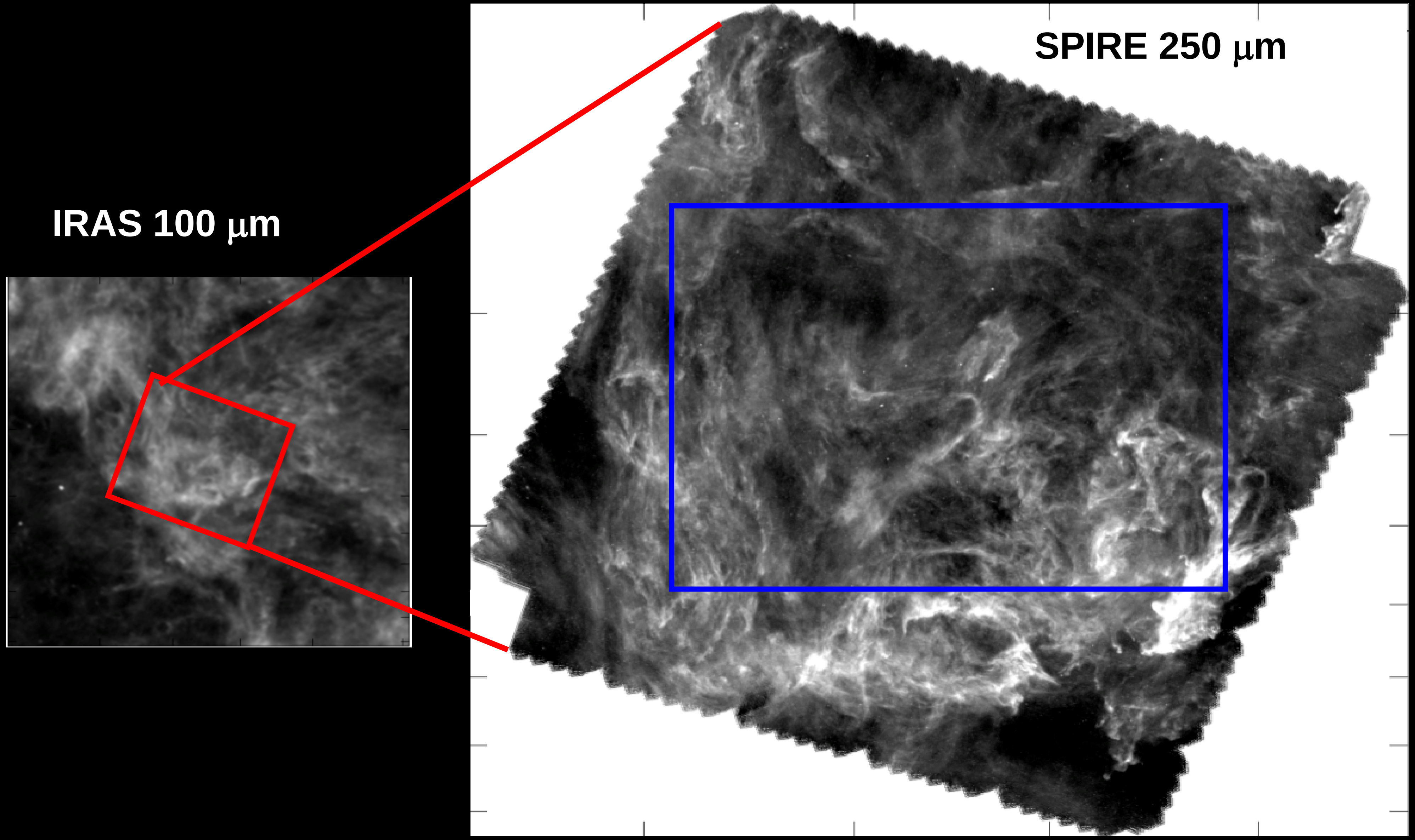

Andromeda

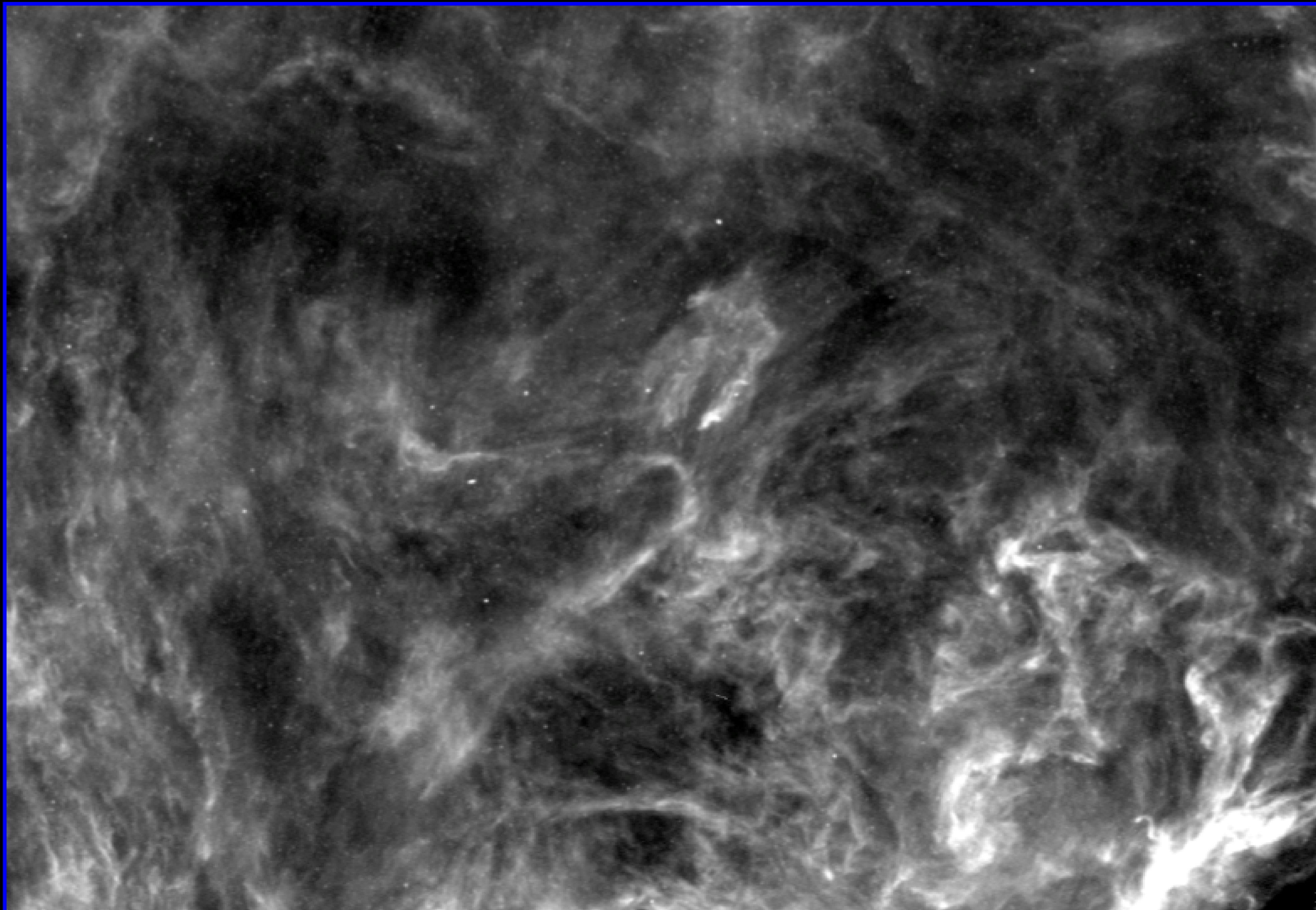

Andromeda
HELGA
Consortium

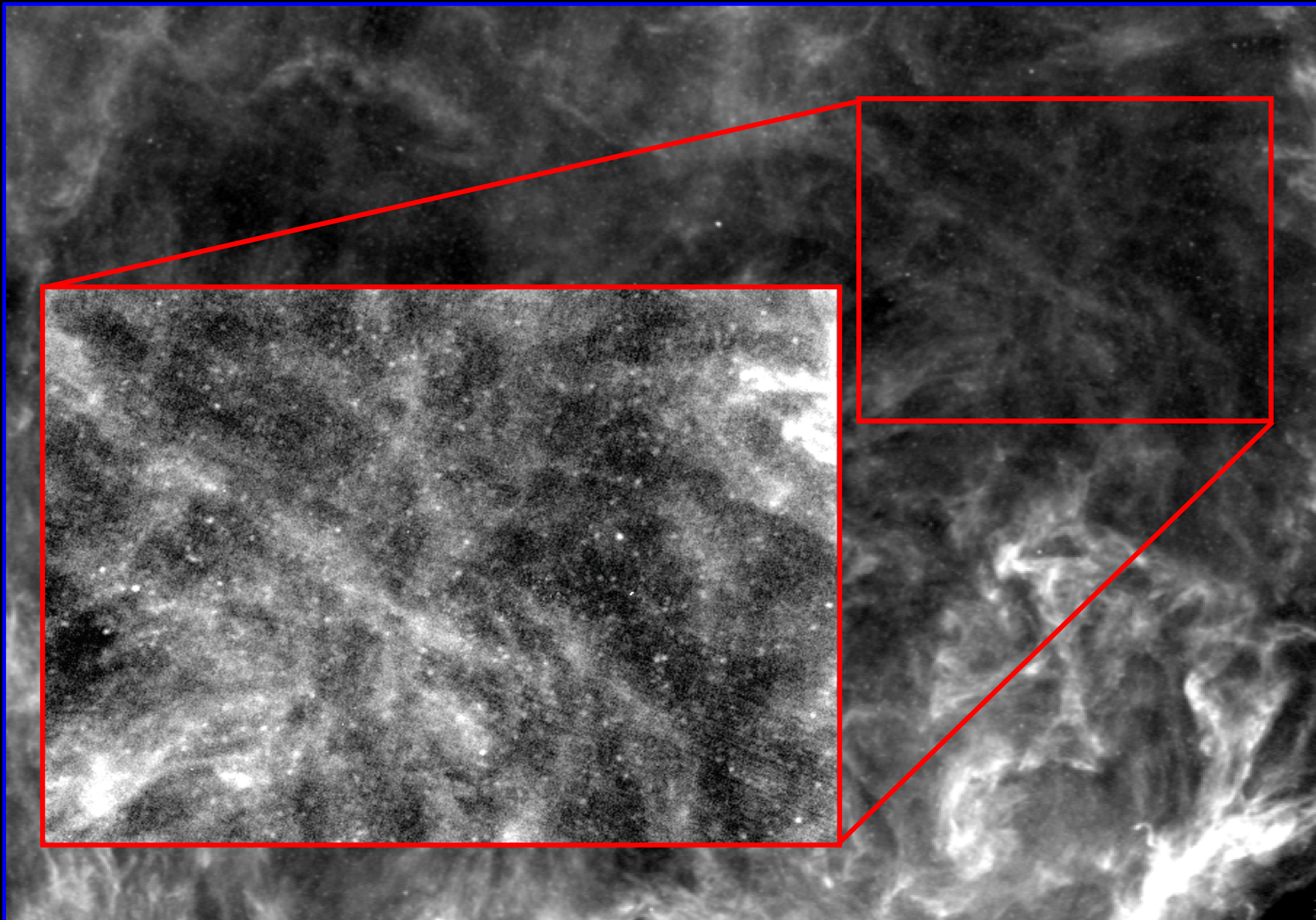
M104


MIPS24, PACS 160, SPIRE
composite (KINGFISH, image
credit M. Galametz)

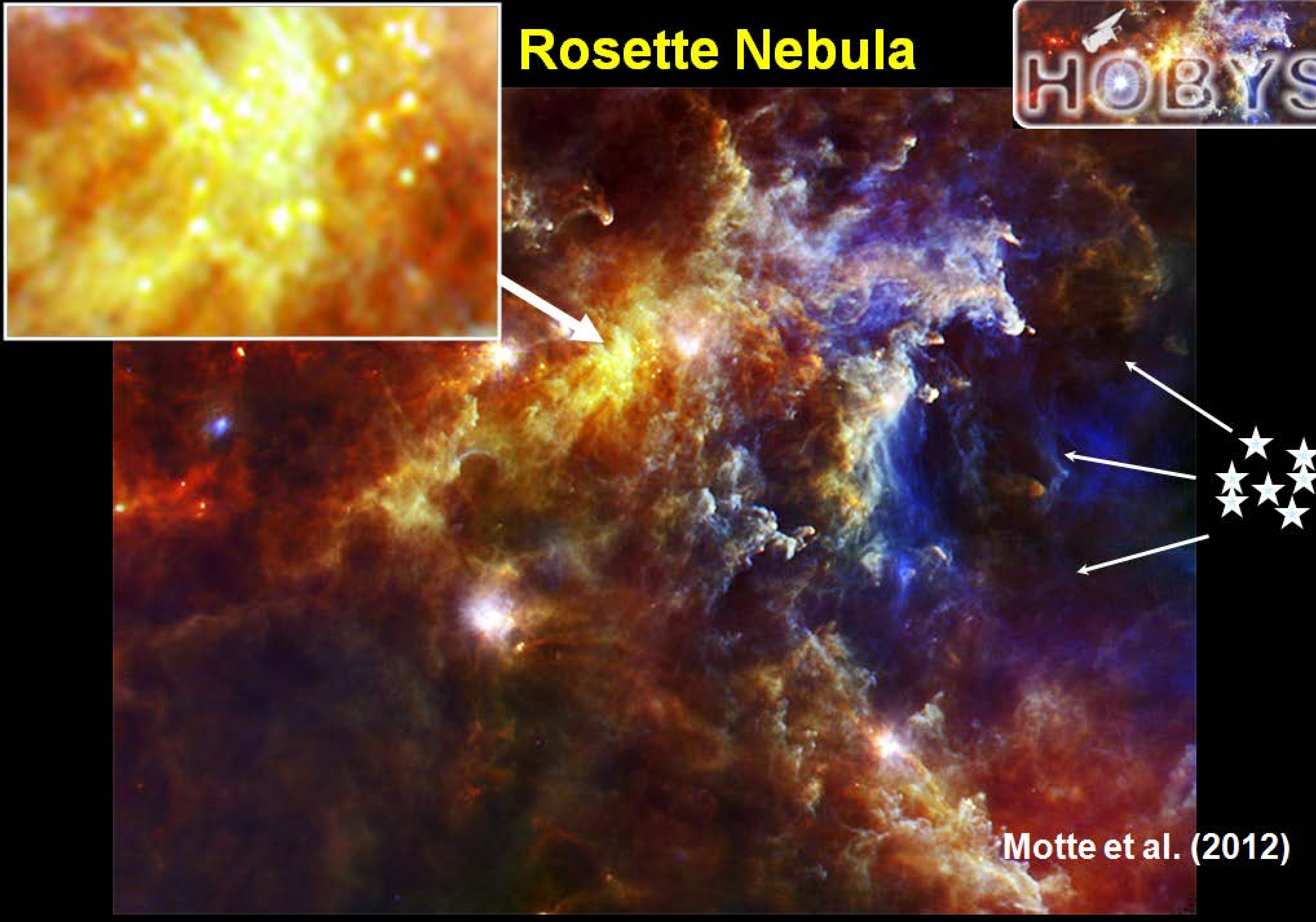
Polaris : Cirrus/Molecular Cloud





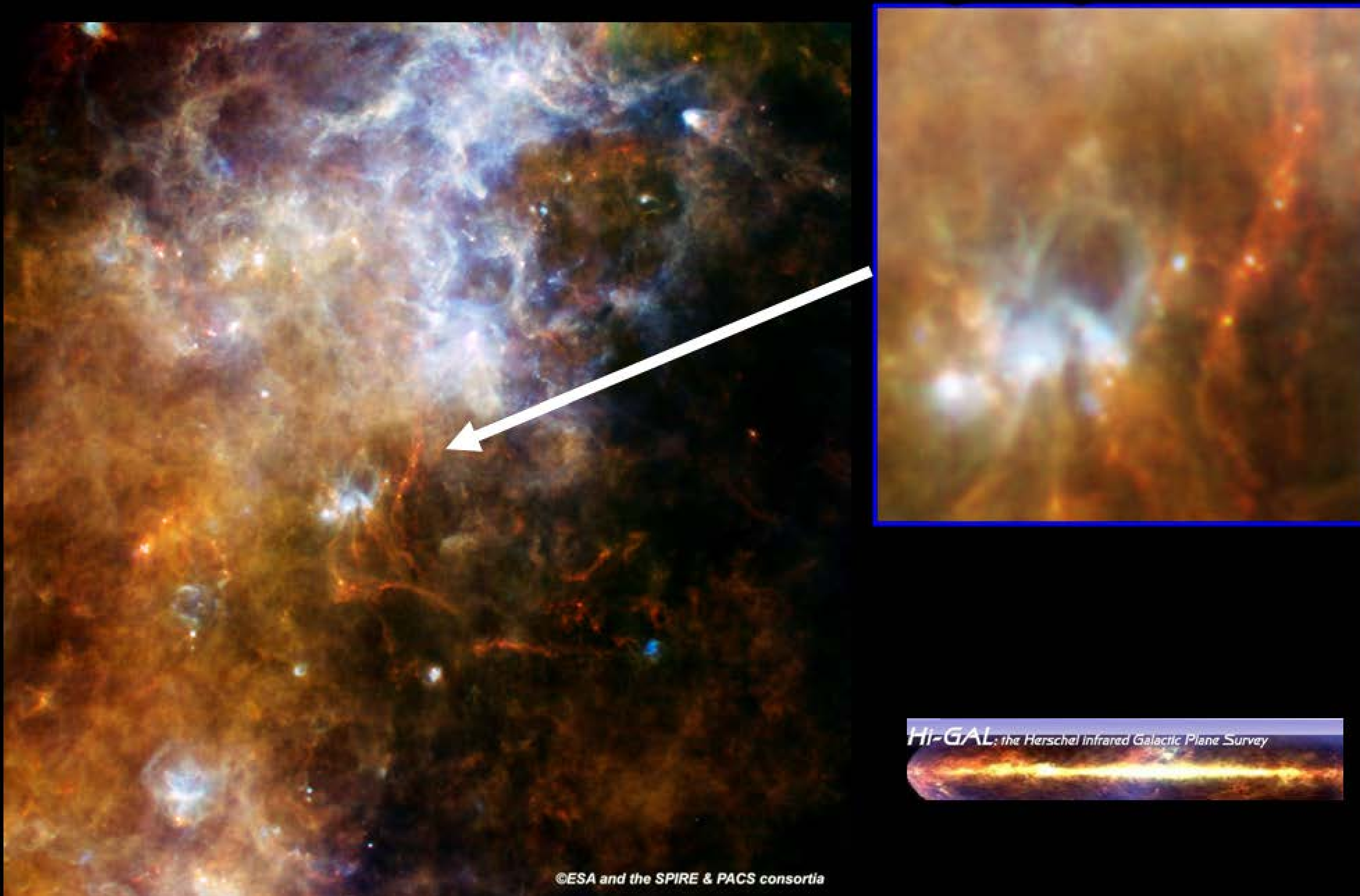


Rosette Nebula

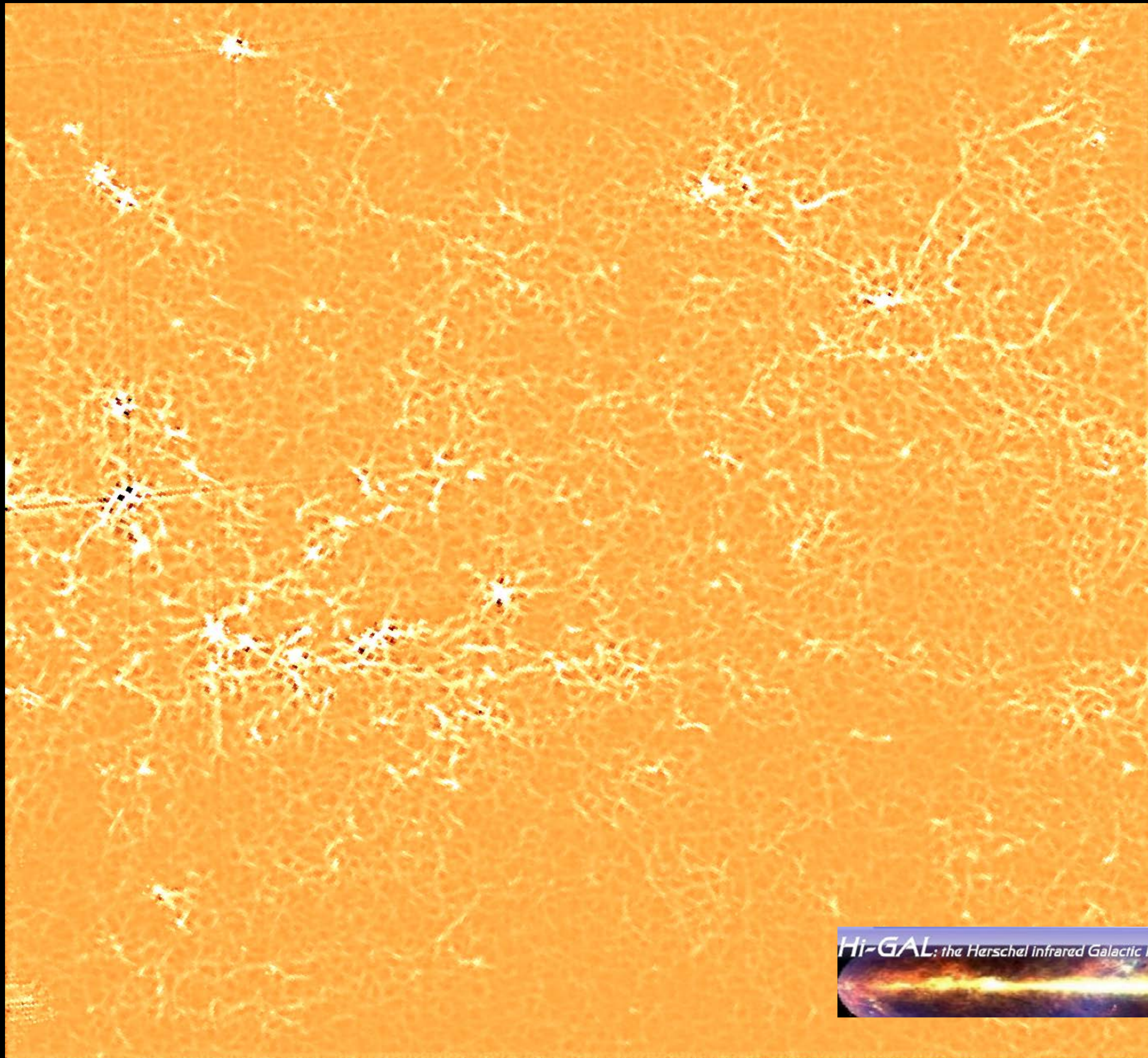


RCW 120: Triggered Star Formation

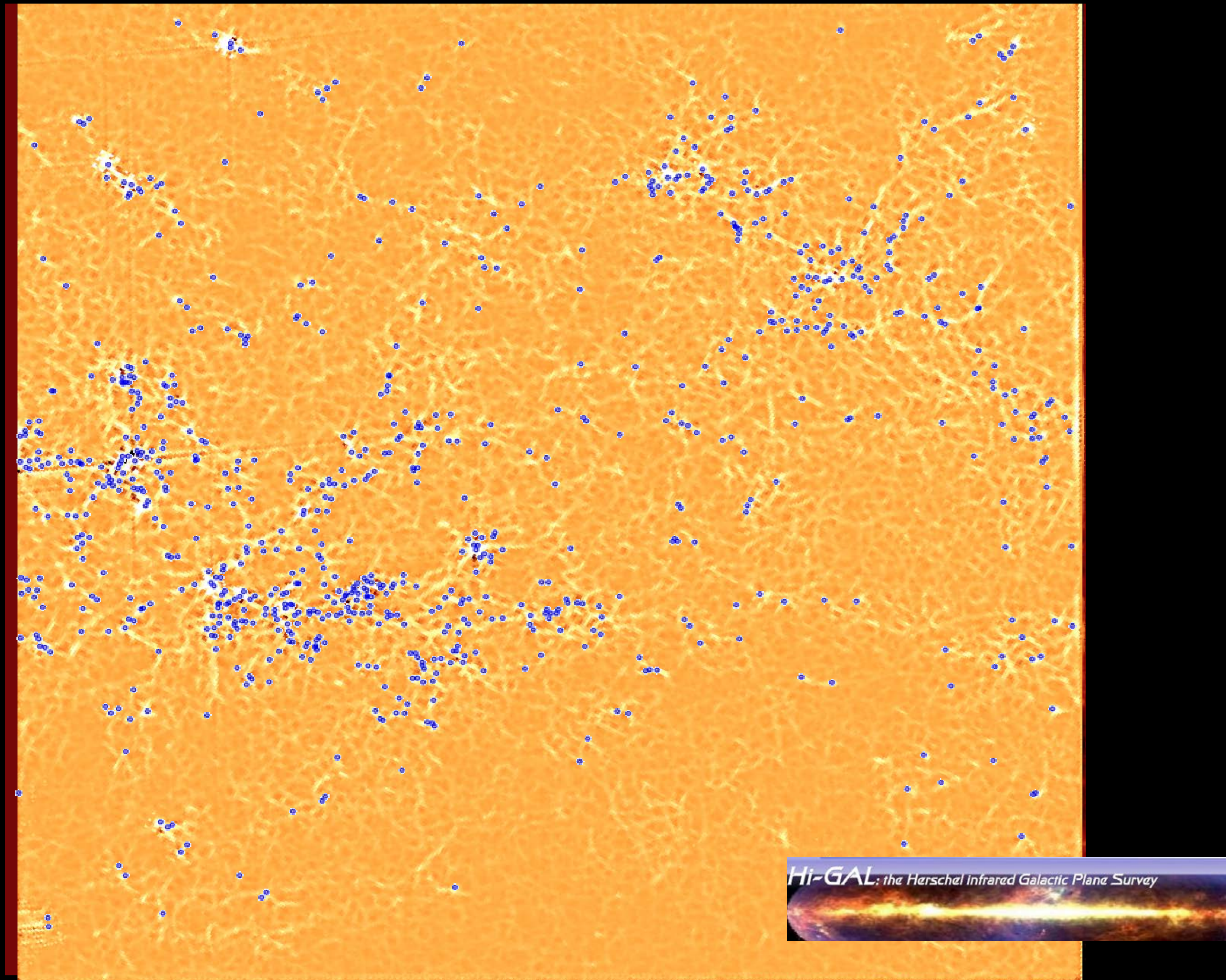
Zavagno et al. (2010)


Hi-GAL: the Herschel infrared Galactic Plane Survey
©ESA and the SPIRE & PACS consortia

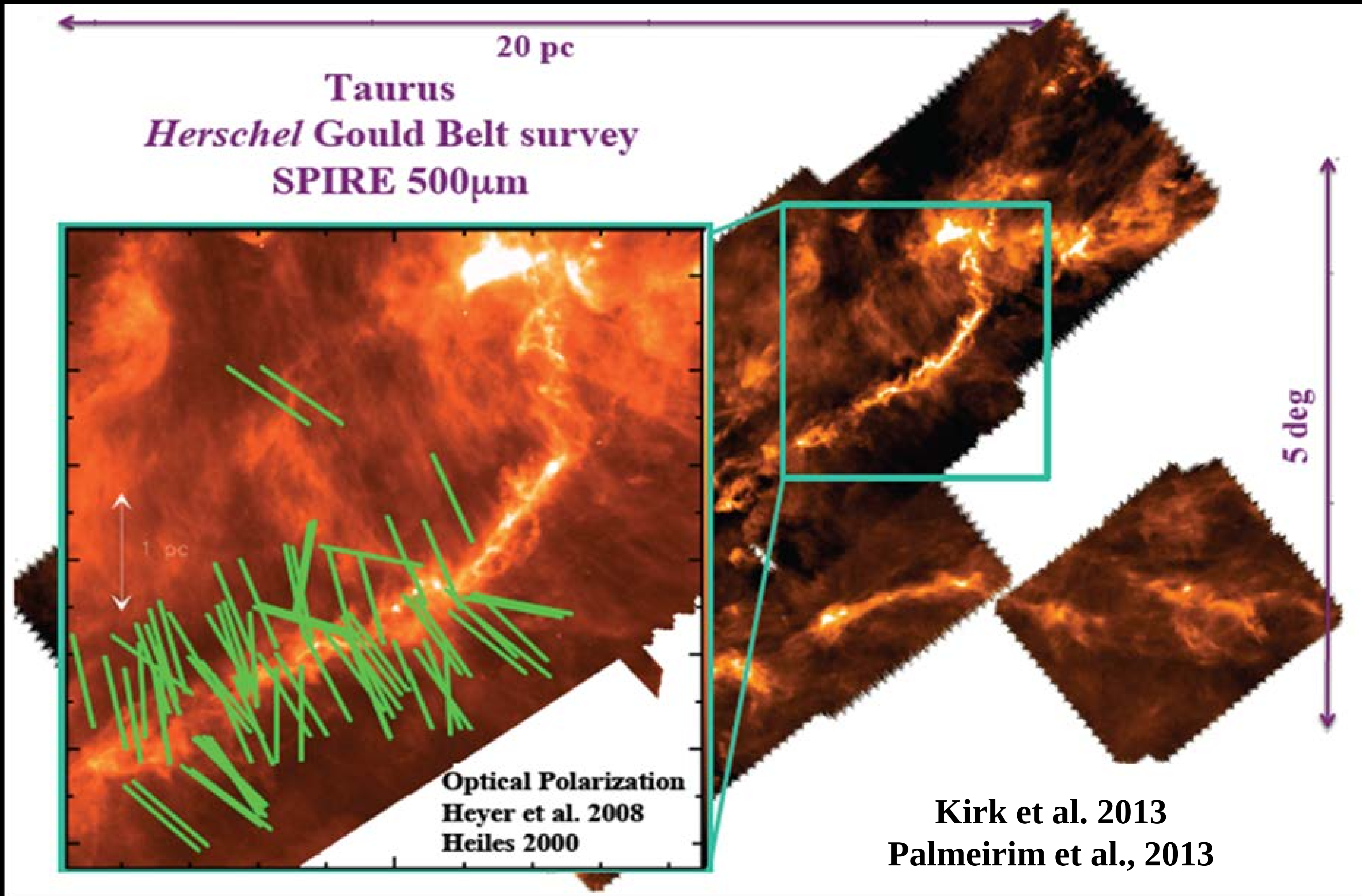
Galactic Plane: $l = 59^0$ 250 μm



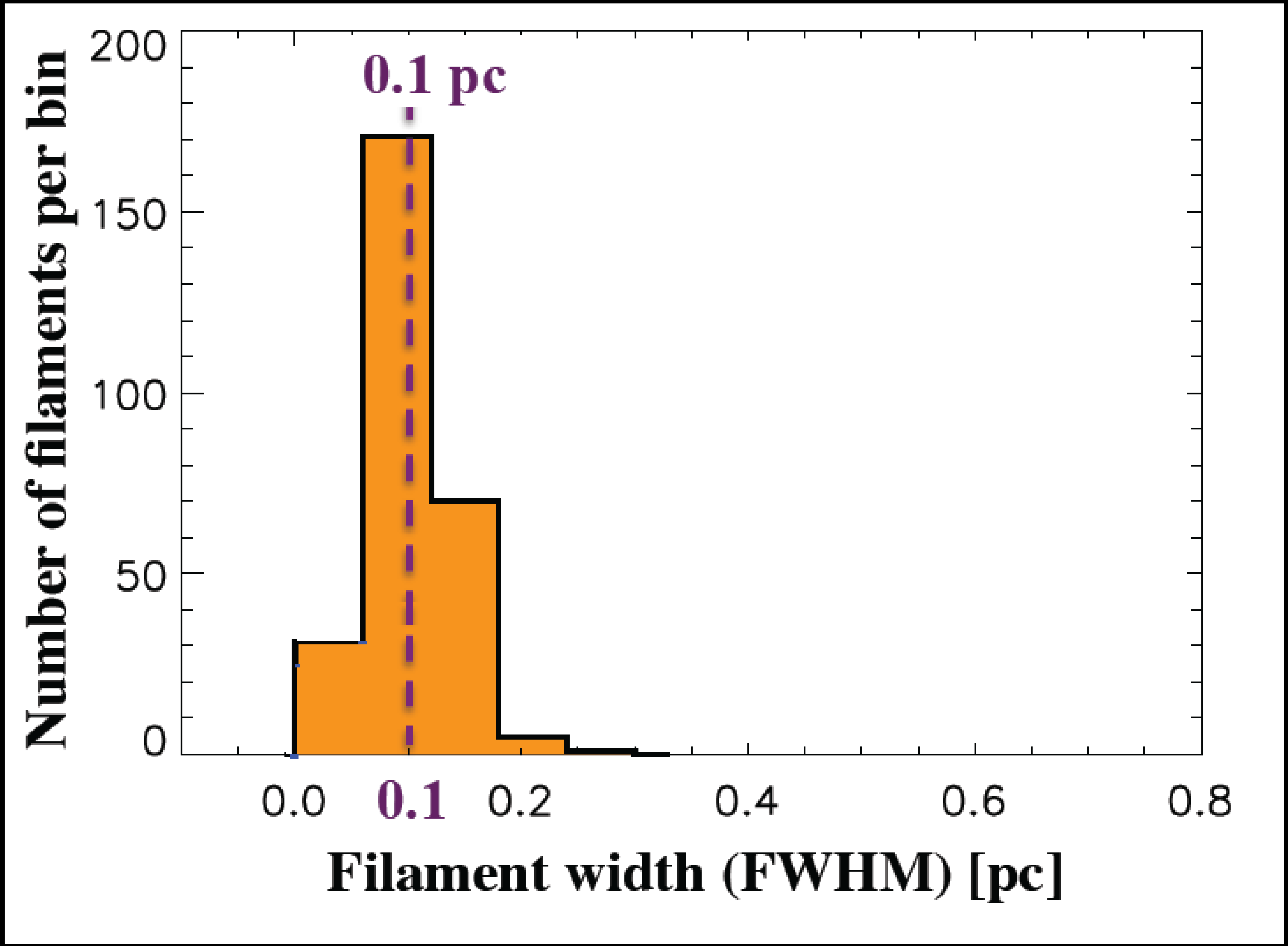
Hi-GAL: the Herschel infrared Galactic Plane Survey


Hi-GAL: the Herschel infrared Galactic Plane Survey

Accretion onto Filaments along Magnetic Field Lines



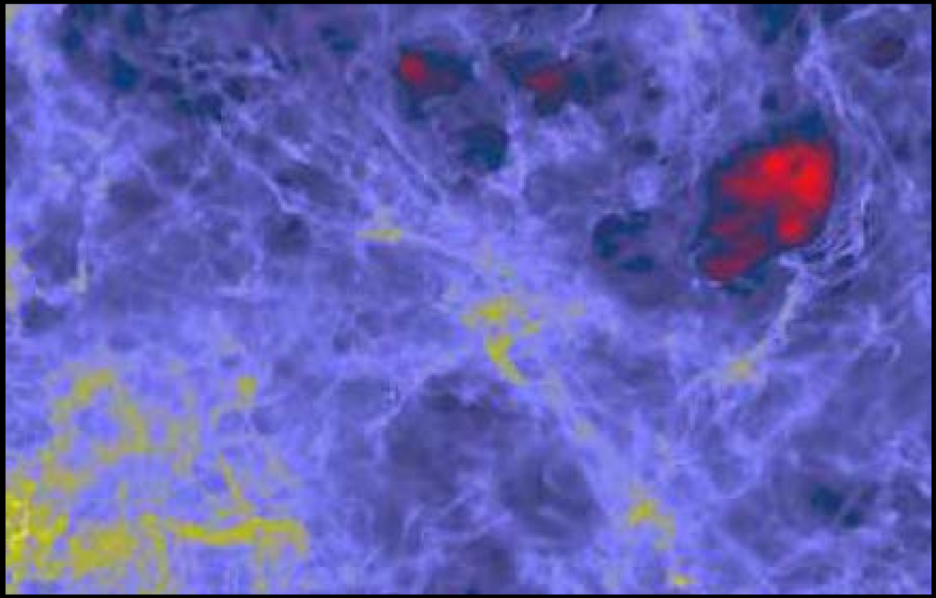
A Universal Size Scale for Filaments?

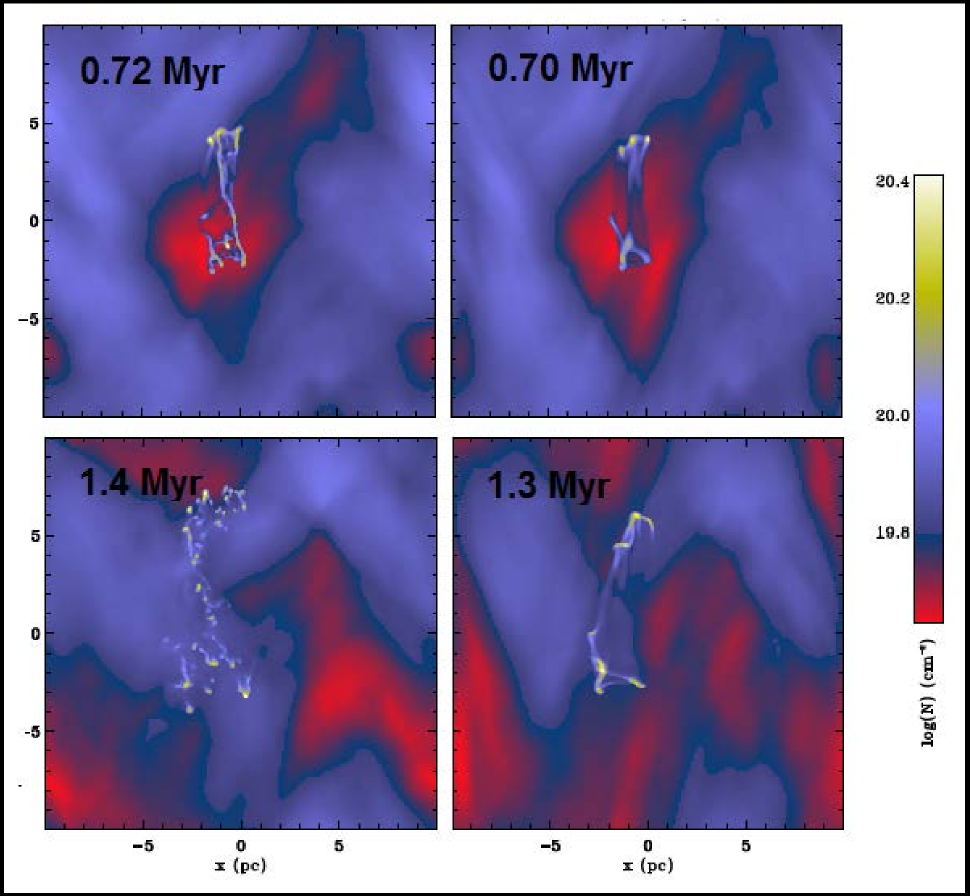


Arzoumanian et al. 2011

Origin of Filament Size Scale?

- 0.1 pc ~ energy dissipation scale of turbulence in the ISM
- Global magnetic field of the cloud maintains filament structure on Myr timescales



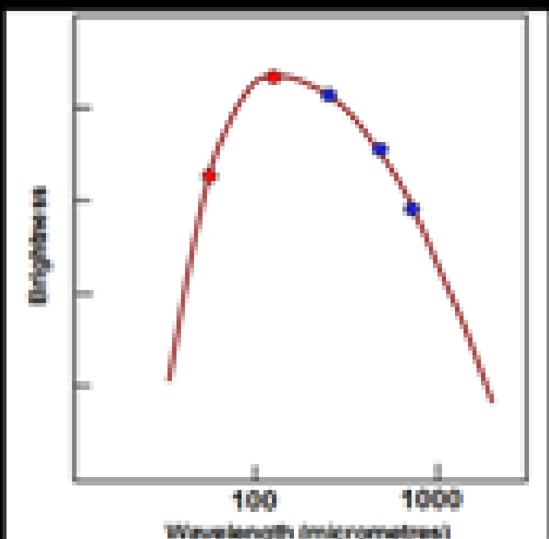


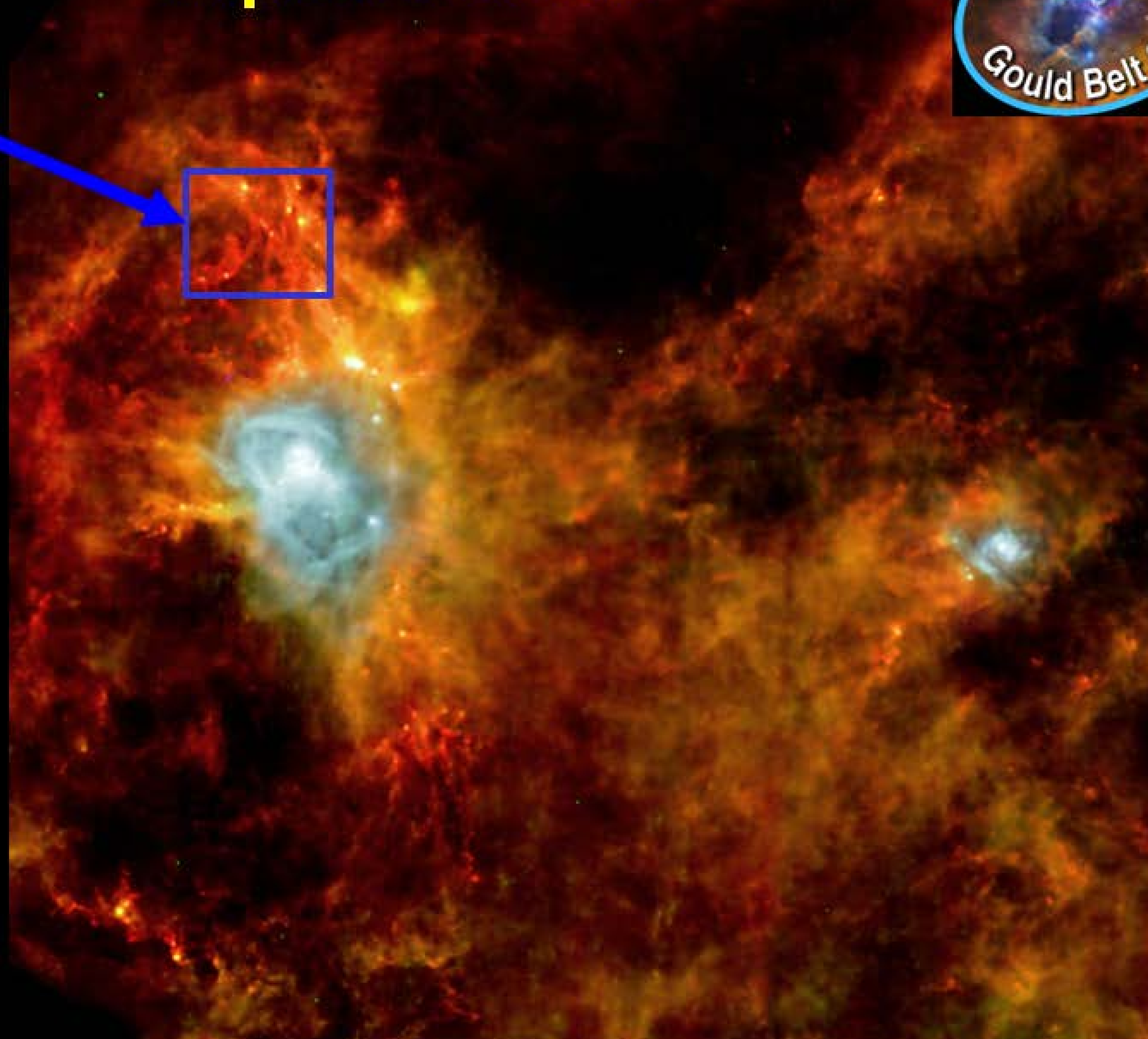
No mag. field

With mag. field

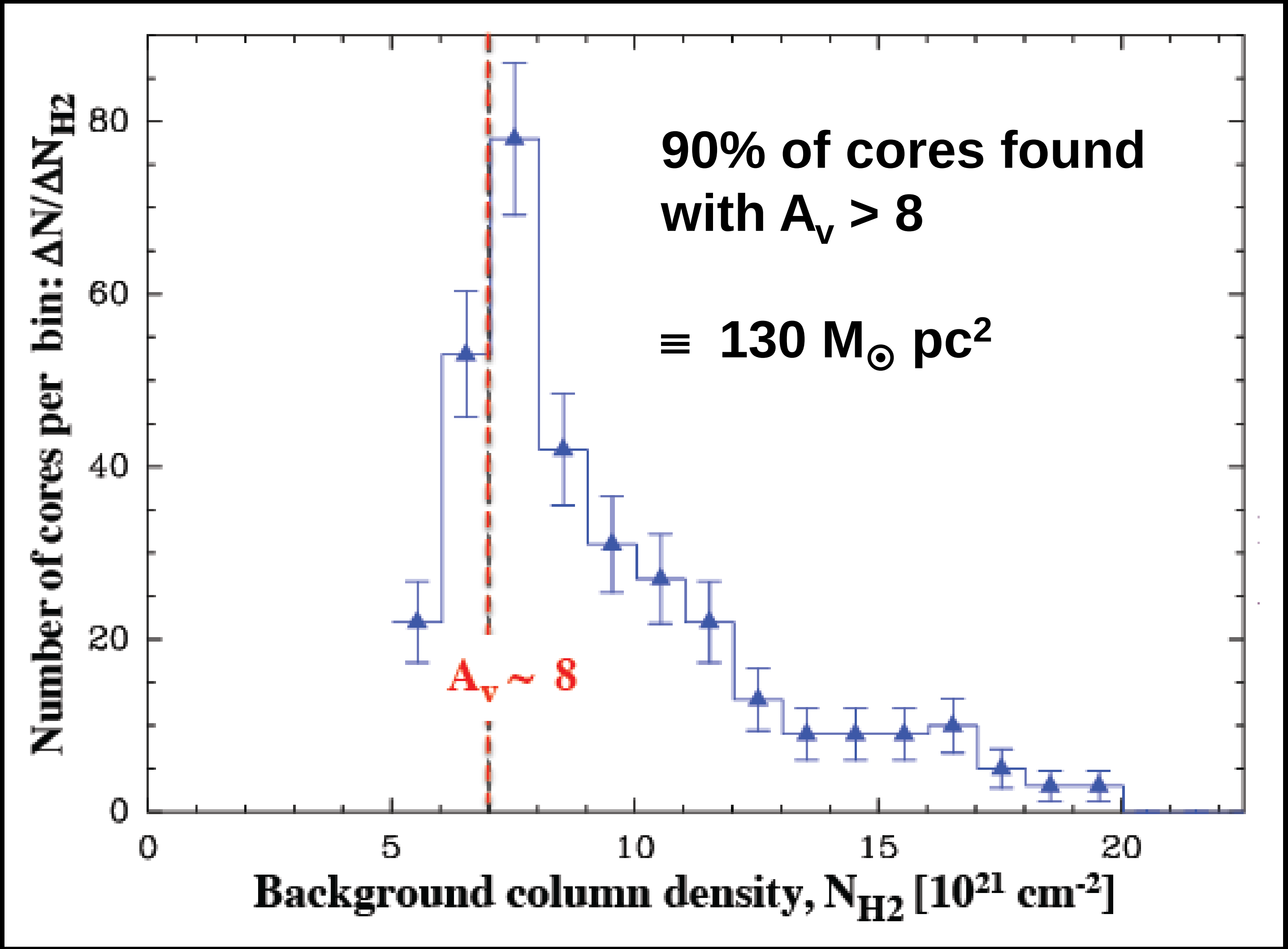
Simulations by Hennebelle 2013

Aquila Nebula





Density Threshold for Core Formation



Könyves etal. in prep, André et al. 2013

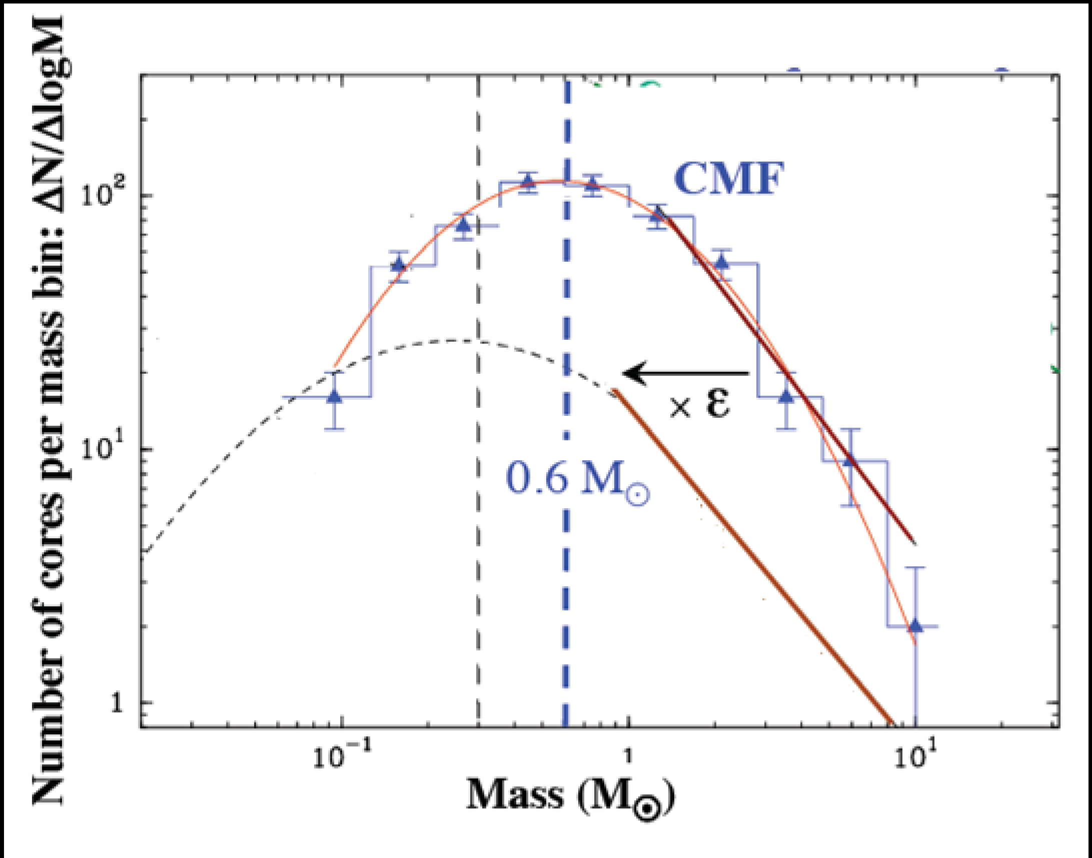
Core Mass Function in Aquila

- Critical M_{line} for gravitational instability ~ 16 $M_\odot$ pc^{-1} for T ~ 10 K

- This ≡ 160 $M_\odot$ pc^{-2} with 0.1 pc filament width

- CMF peaks at ~ 0.6 $M_\odot$ ≈ mass for marginally stable filaments

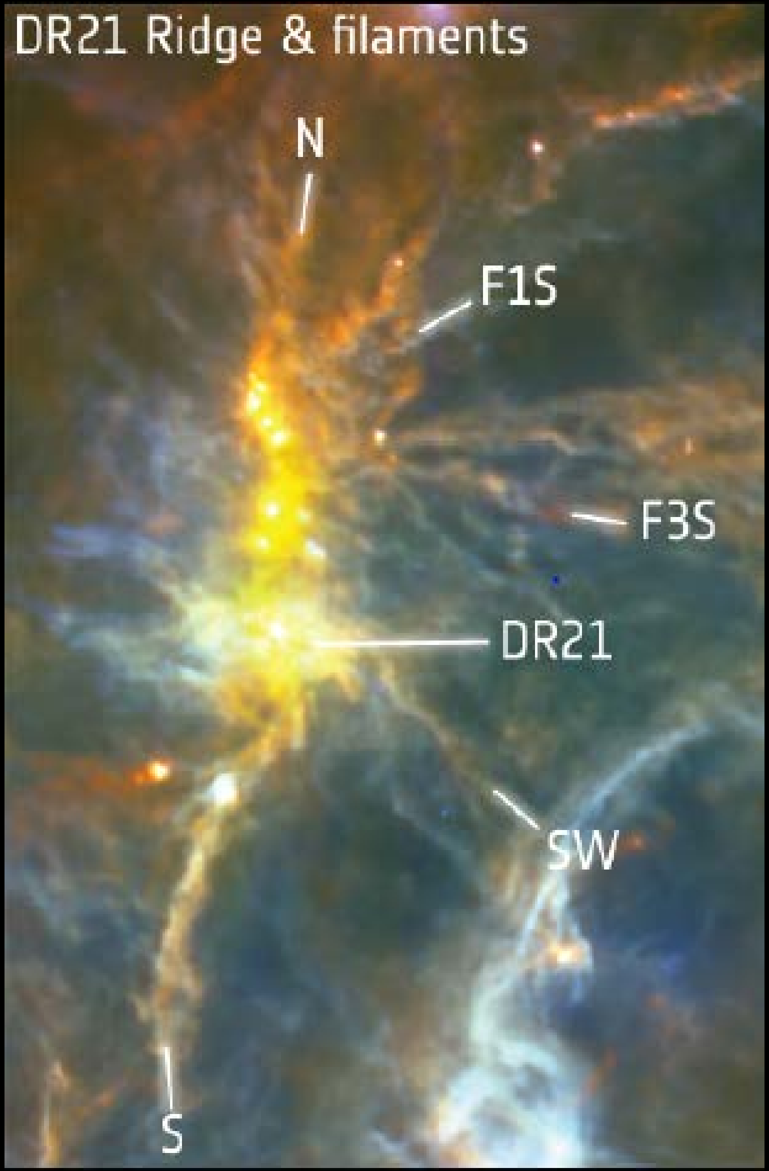
- ⇒ pre-stellar cores form mainly via gravitational fragmentation of filaments



André et al. 2010
Könyves et al. 2010

High-Mass Star Formation

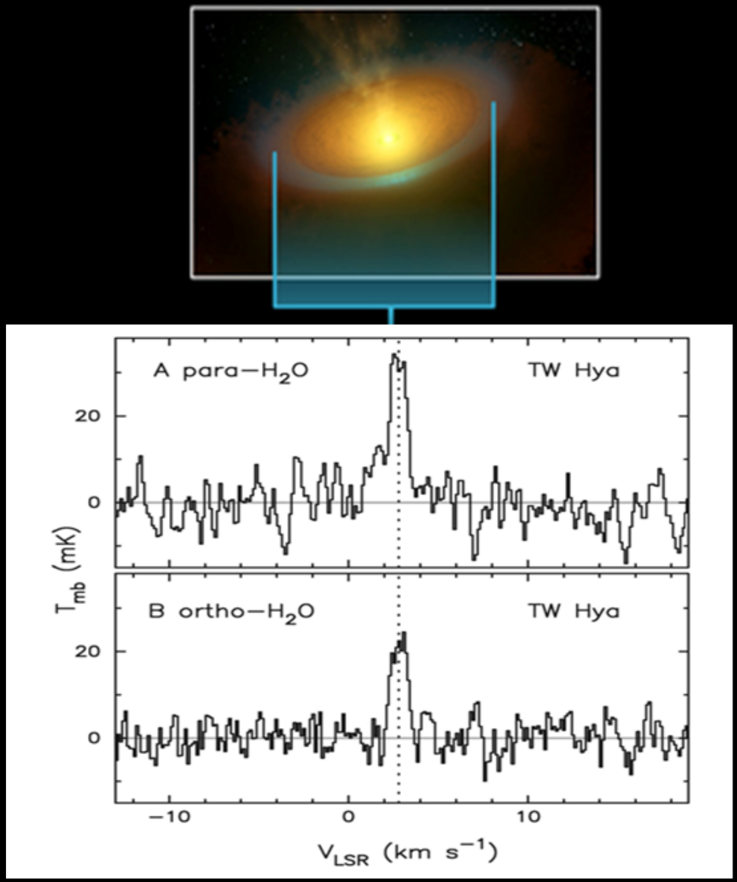
- Large-scale infall
- Merging of filaments into ridges and hubs to form clusters



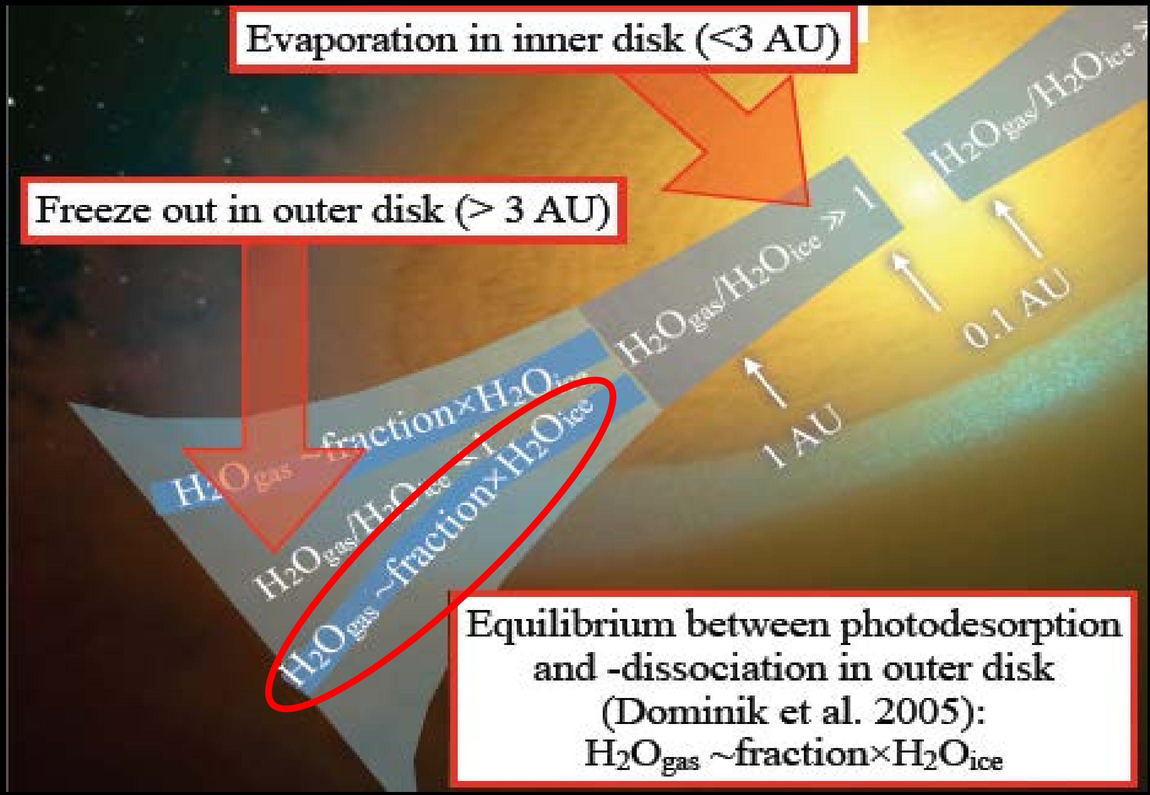
Hennemann et al. 2012

Water in Protoplanetary Disk of TW Hydrae

- Mass = 0.6 $M_\odot$ Age ~ 10 Myr
- Thin layer of H_2O at ~ 100 K
- Balance between photo-evaporation and freeze-out
- Implies large reservoir of water ice



Hogerheijde et al. (2011)

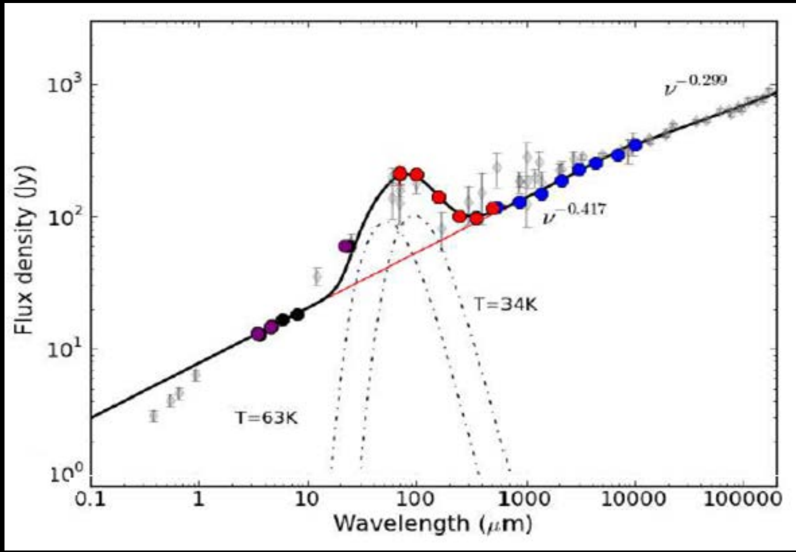


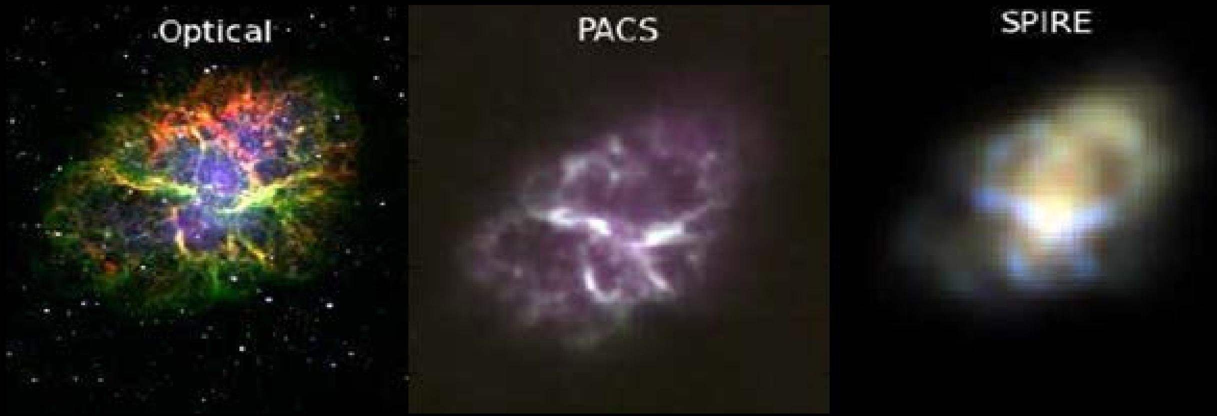
Dust in the Crab Nebula

(Gomez et al., 2012)

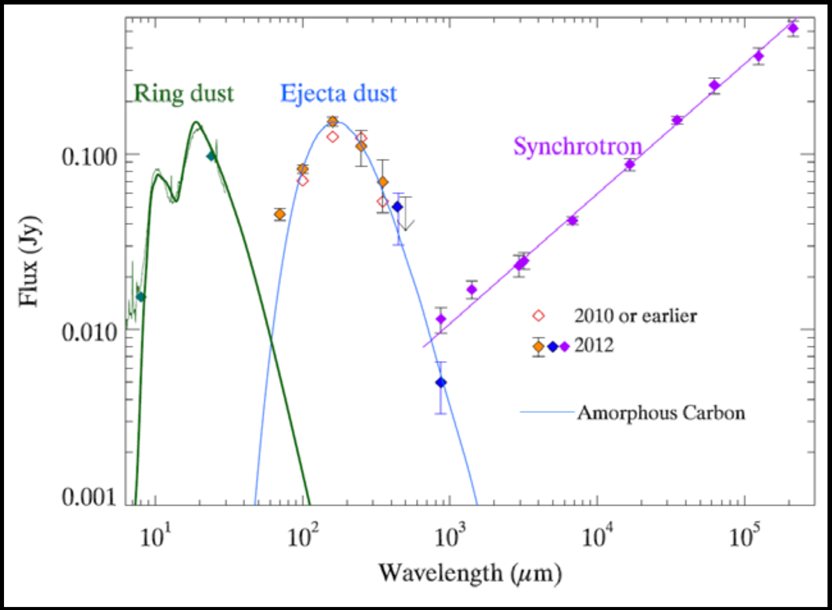
- *Herschel* + IR-radio ancillary data
- Synchrotron component removed
- Dust located along filaments (protecting dust from shocks?)
- Two components
  - ~ 0.2 $M_\odot$ of silicates; 28 K
  - ~ 0.1 $M_\odot$ amorphous carbon; 34 K

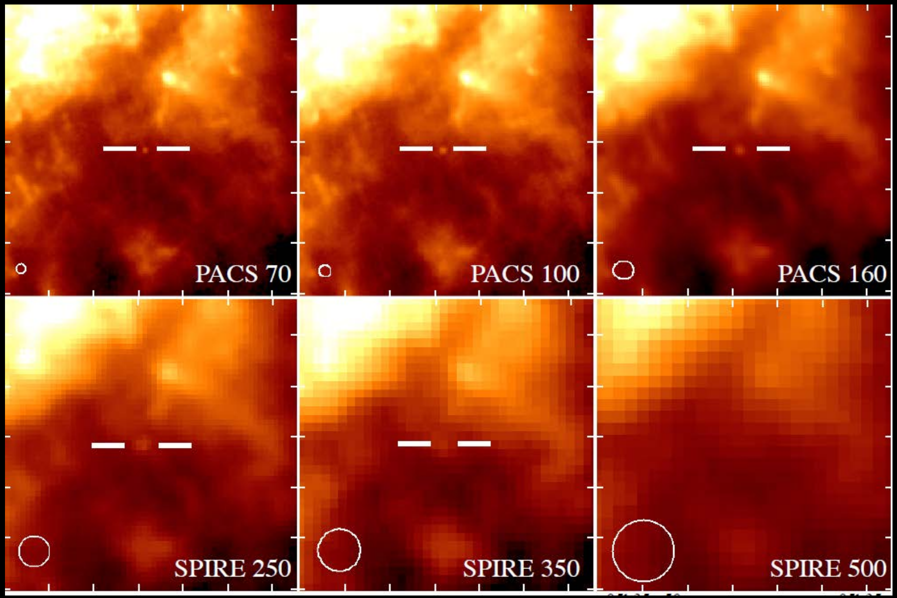
$\Rightarrow$ formation of dust in core-collapse supernova ejecta





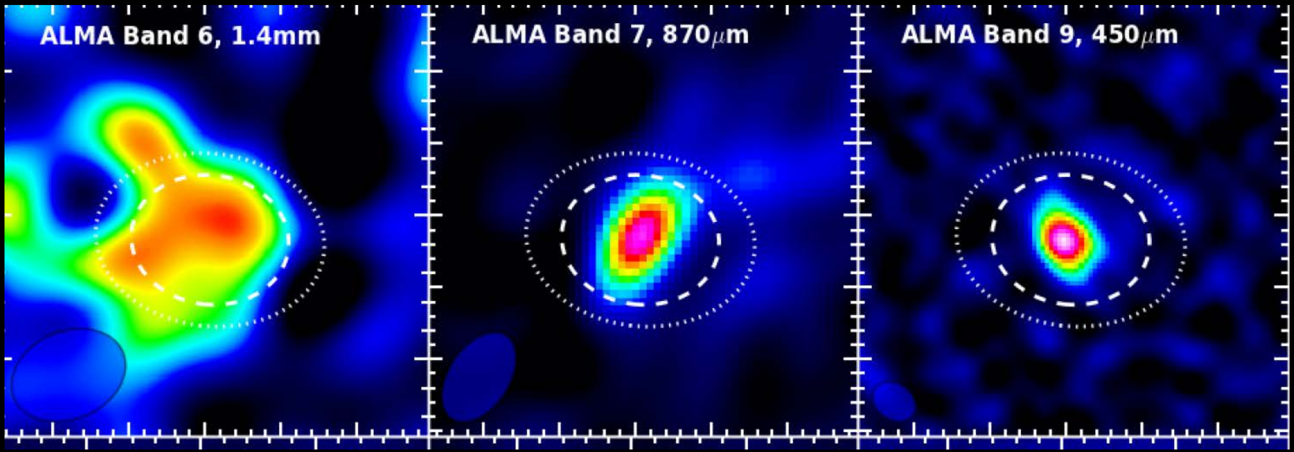
Dust in the SN1987A (*Herschel* and ALMA)
(Matsuura et al., 2012; Indebetou et al. 2014)

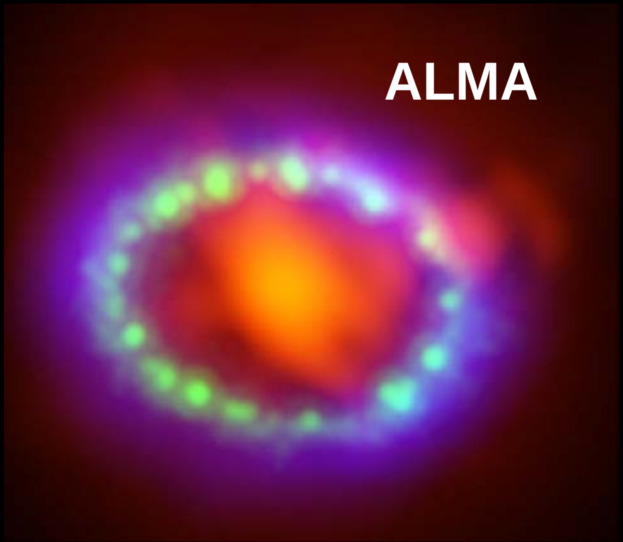




***Herschel* HERITAGE**

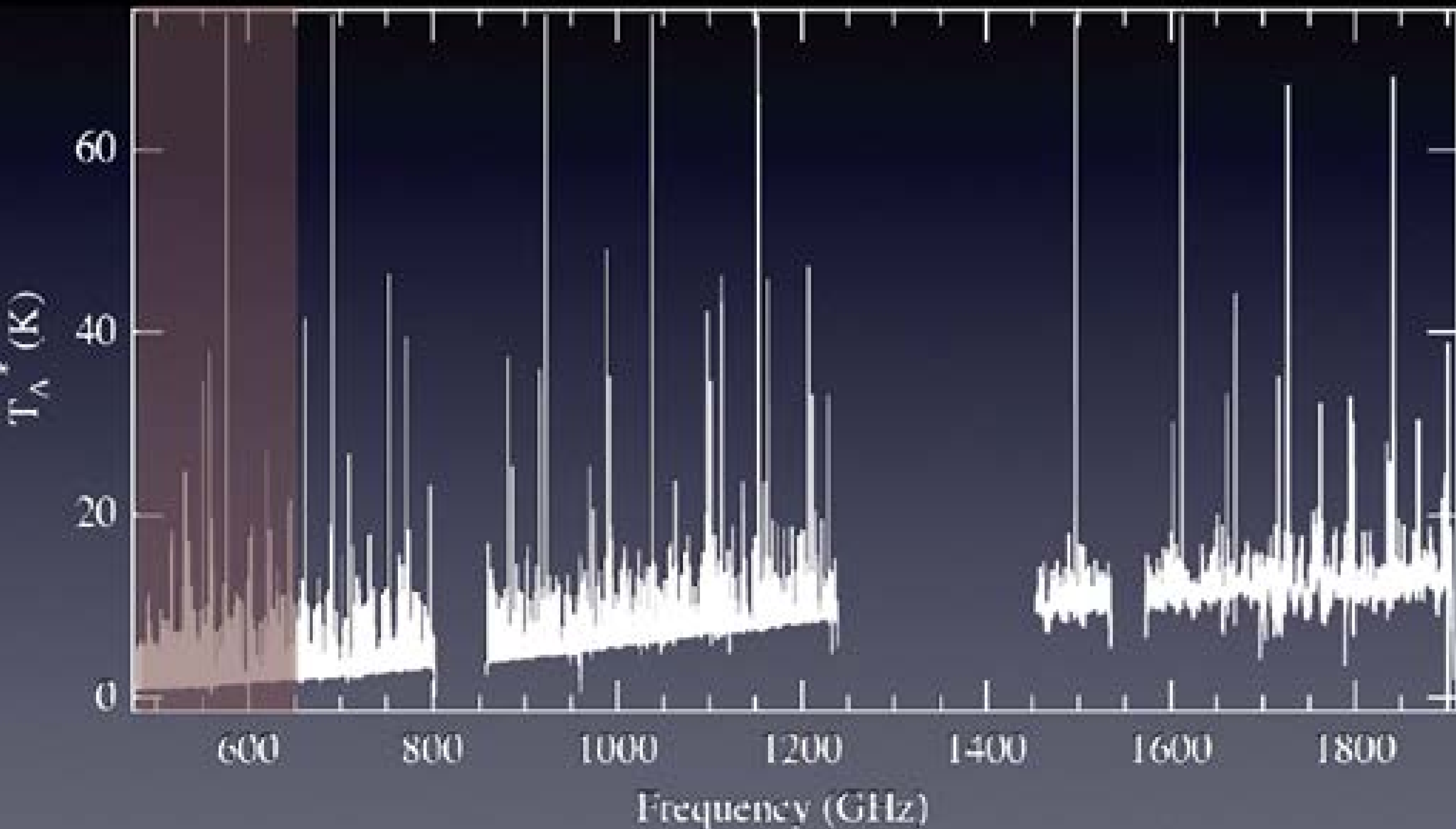
Dust mass 0.5 – 0.8 $M_\odot$





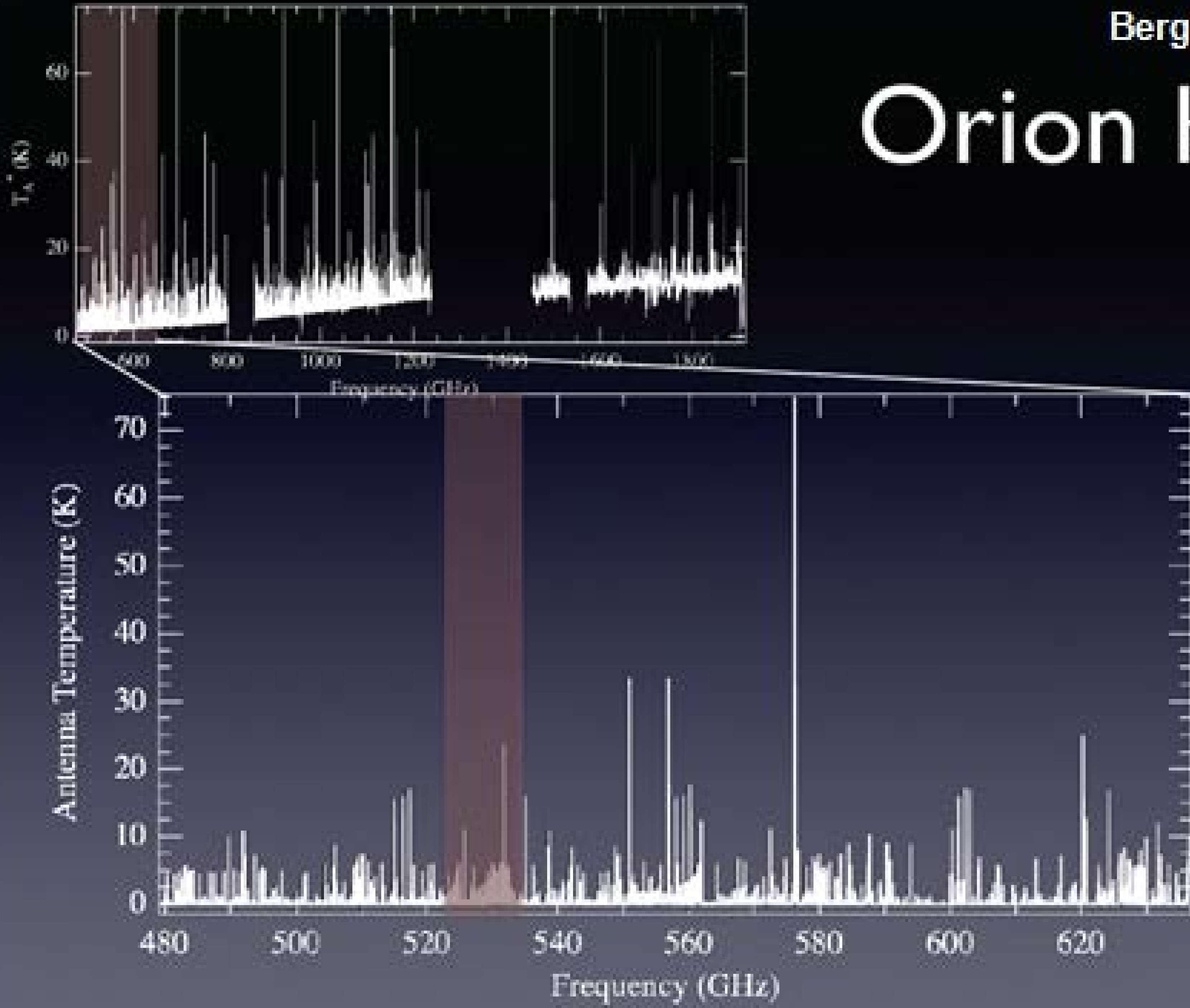
HIFI – Orion KL

Bergin et al. (2011)

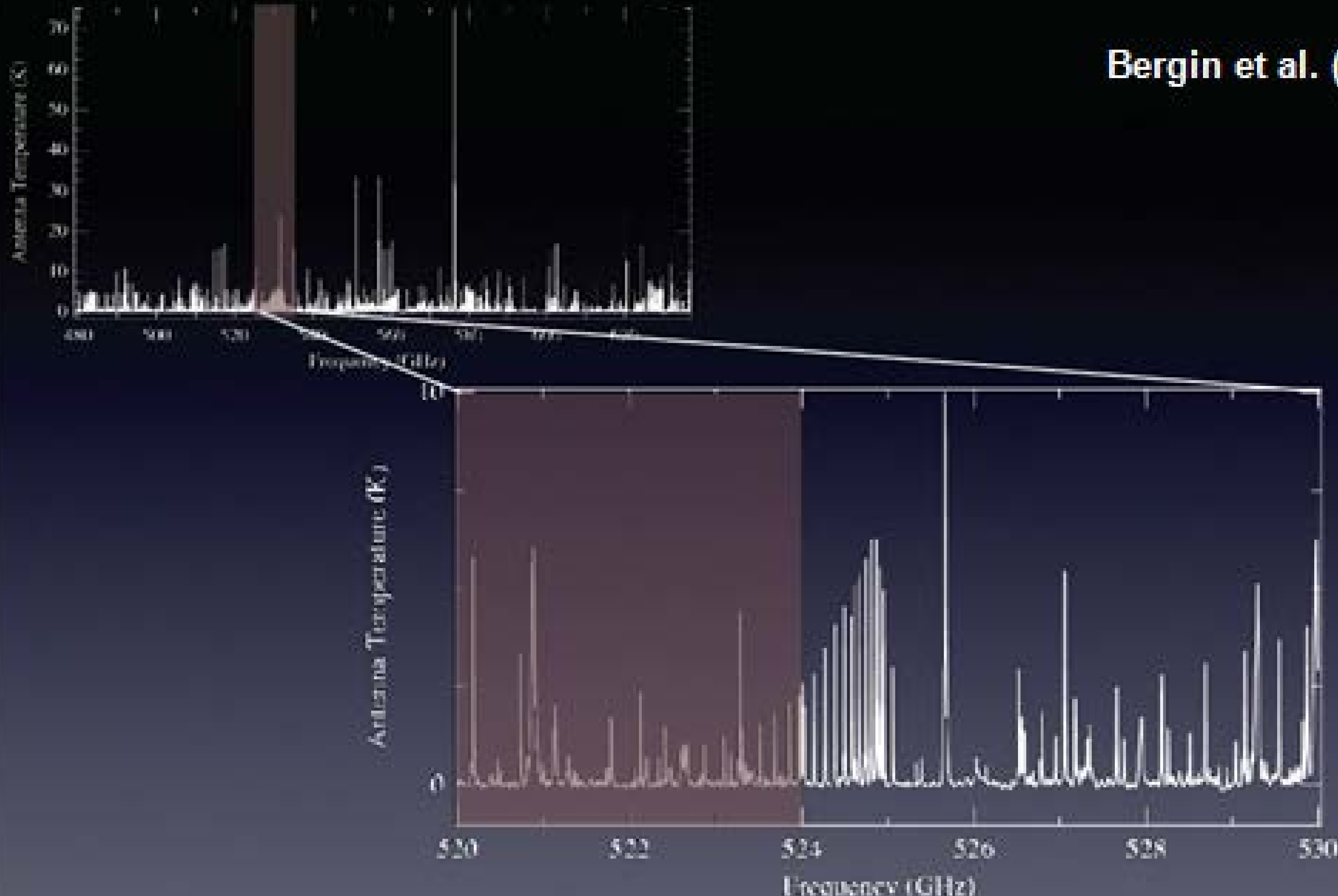


Bergin et al. (2011)

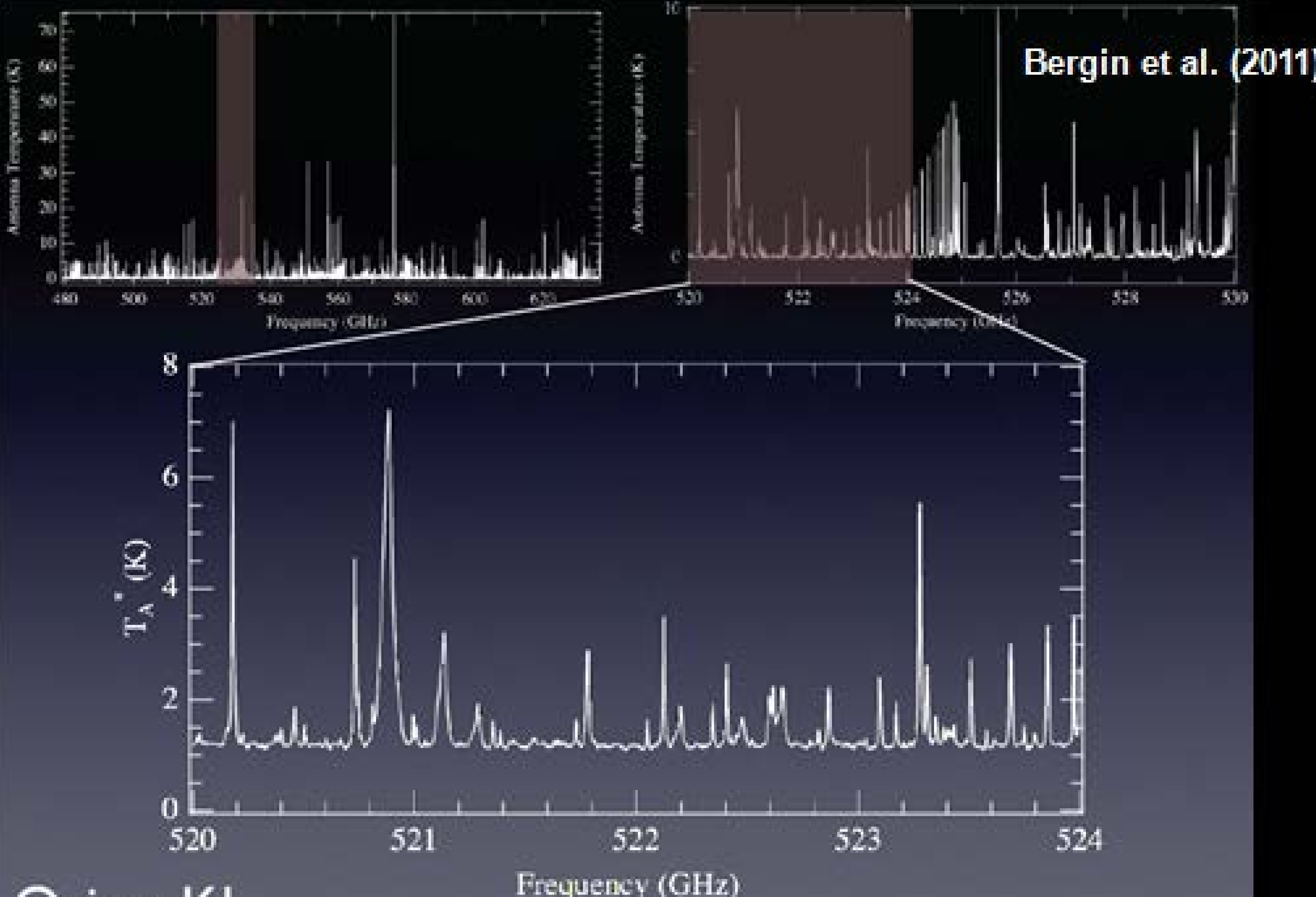
Orion KL



Bergin et al. (2011)



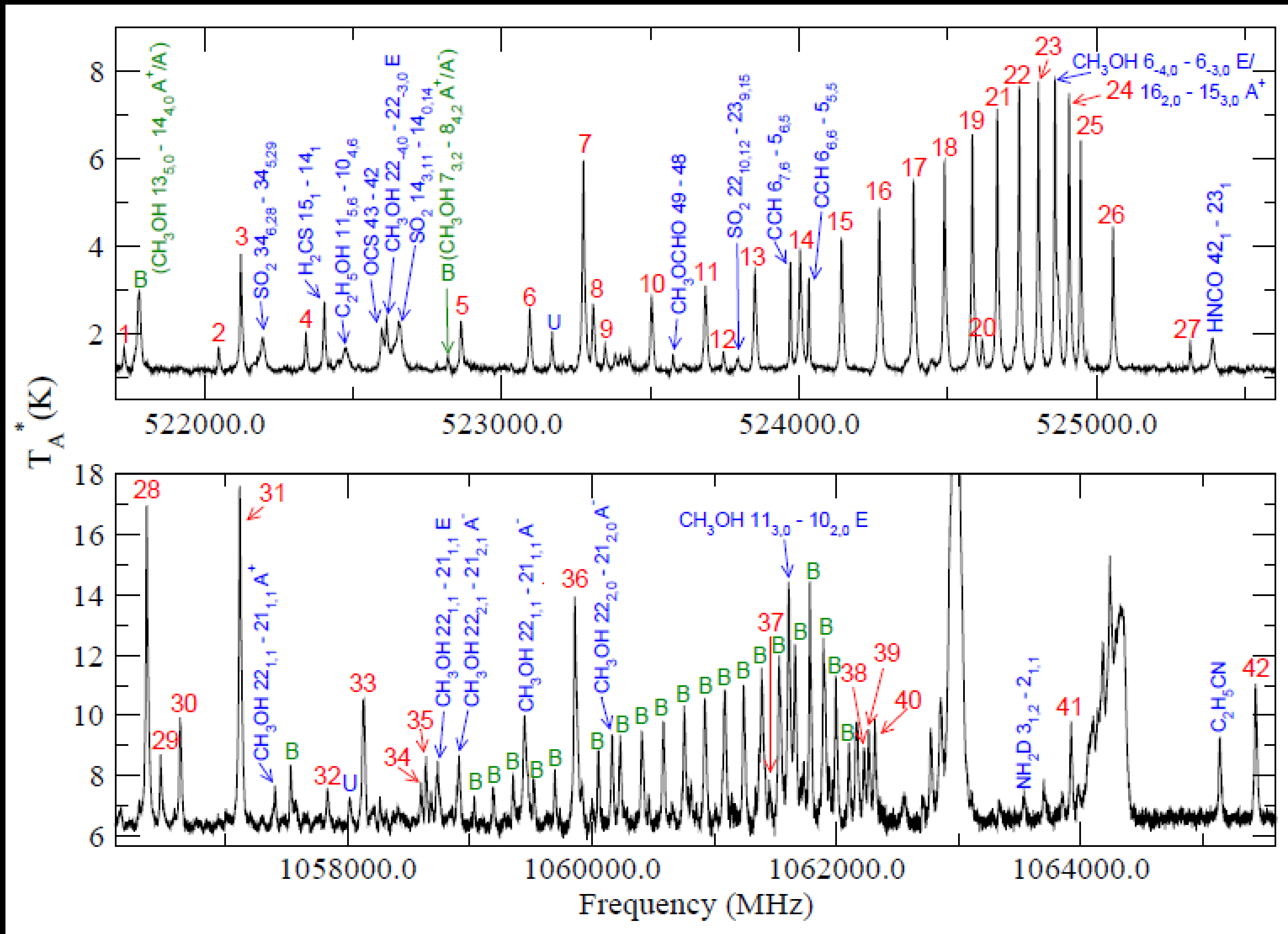
Orion KL - Band 1



Bergin et al. (2011)
Antenna Temperature (K)
Frequency (GHz)
T_A^* (K)
Frequency (GHz)
520
521
522
523
524

Orion KL

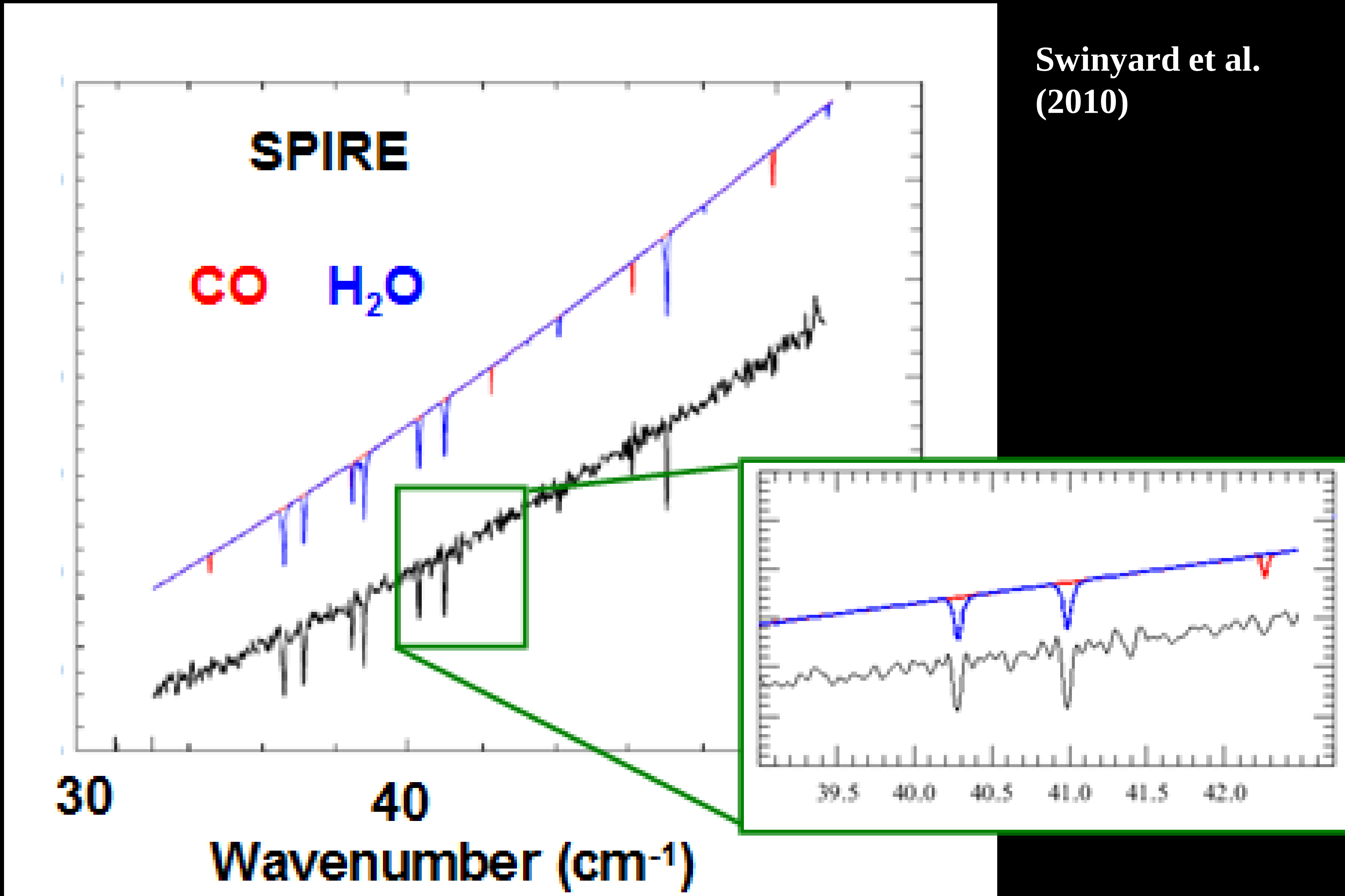
Methanol and Other Molecules in Orion



Wang et al. 2011

- NH_2CHO
- SiS
- C_2H_5OH
- H_2CS
- NO
- NS
- SO, ^{34}SO, ^{33}SO, $S^{18}O$
- SO_2, $^{34}SO_2$, $^{33}SO_2$
- HCN, $H^{13}CN$, $HC^{15}N$
- HNC, $H^{15}NC$, $HN^{13}C$
- SiO
- CH_3CN, $^{13}CH_3CN$, $CH_3{}^{13}CN$
- NH_3, $^{15}NH_3$, NH_2D
- HCl, $H^{37}Cl$
- H_2S, $H_2{}^{33}S$, $H_2{}^{34}S$
- H_2CO, $H_2{}^{13}CO$, HDCO
- $HCOOCH_3$
- CCH
- CN
- HC_3N
- H_2O, HDO, $HD^{18}O$, D_2O, $H_2{}^{18}O$, $H_2{}^{17}O$
- CH_3OH, $^{13}CH_3OH$, CH_3OD, CH_2DOH
- C_2H_5CN
- HNCO, $HN^{13}CO$
- HCS^+
- H_2CCO
- OCS
- CH_3OCH_3
- CS, $C^{34}S$, $C^{33}S$, ^{13}CS
- CO, ^{13}CO, $C^{17}O$, $C^{18}O$
- HCO^+

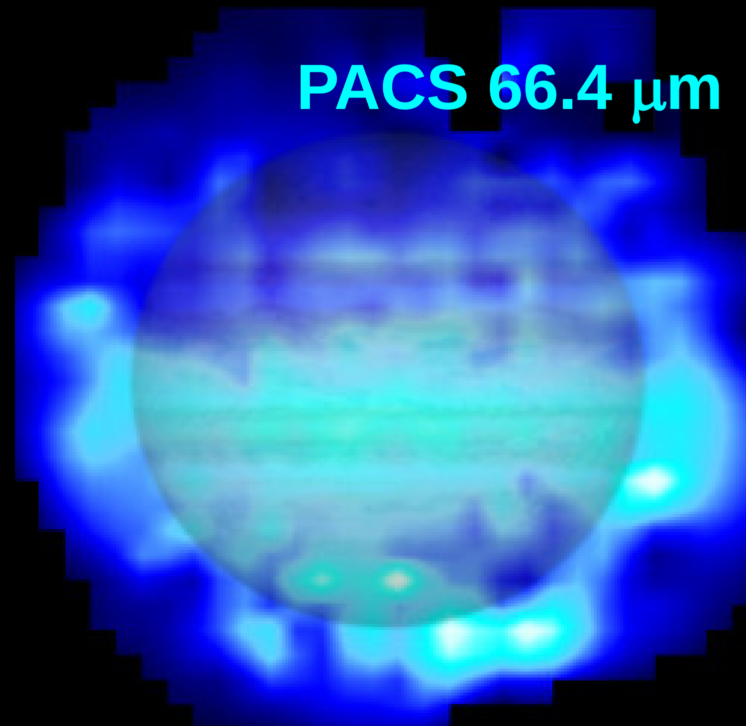
Herschel Discovers Water on Mars



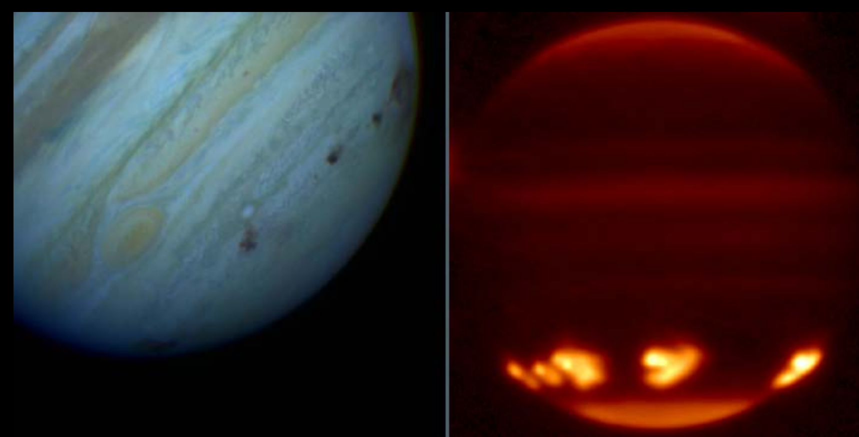
Swinyard et al. (2010)

. . . and in the Stratosphere of Jupiter

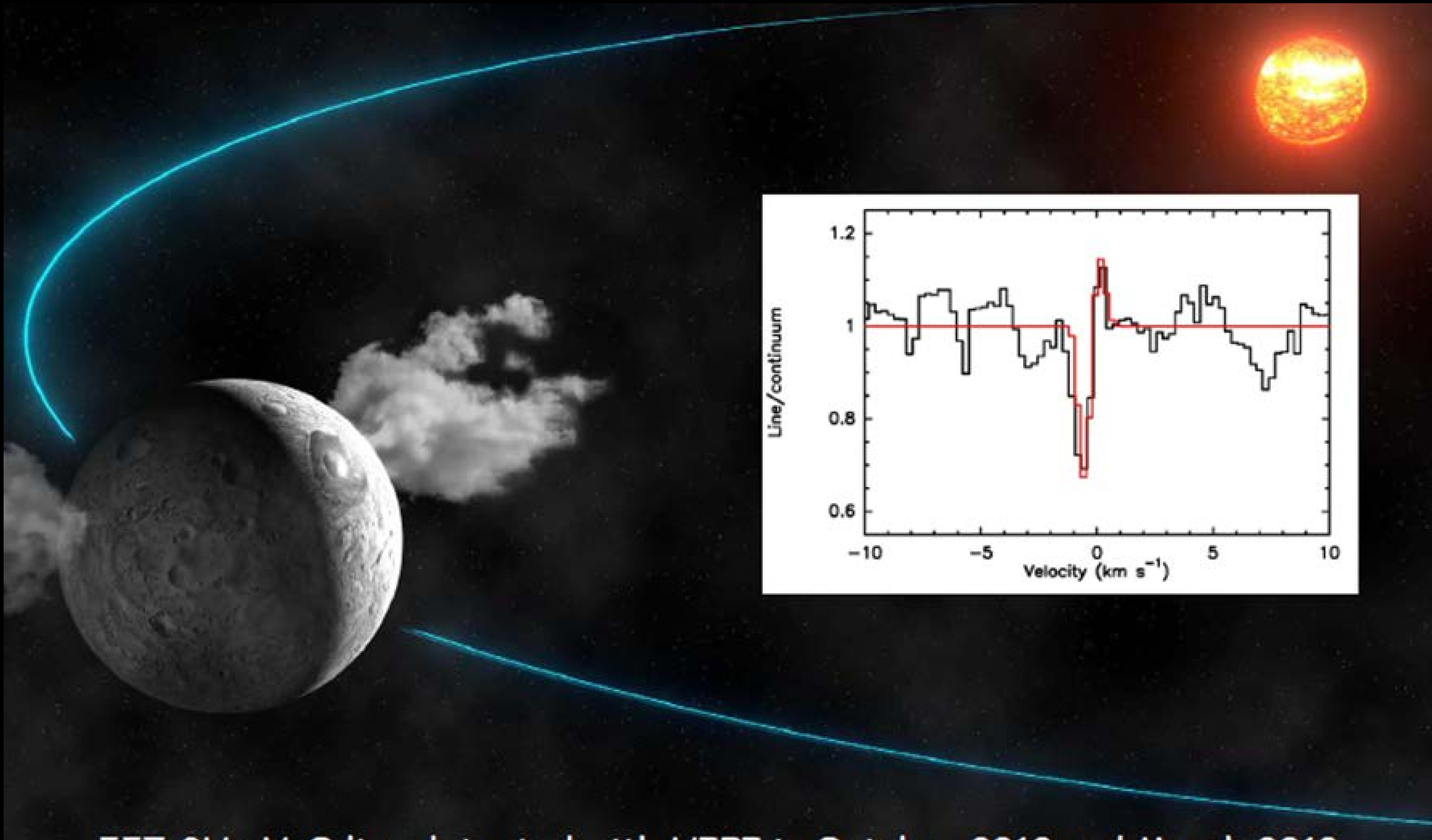
- PACS and HIFI spectroscopy
- No evidence of a satellite or ring source
- Vertcal distribution does not fit internal source
- Horizontal distributon and hemispheric asymmetry favour SL9 (1994) impact



Cavalie et al. 2013

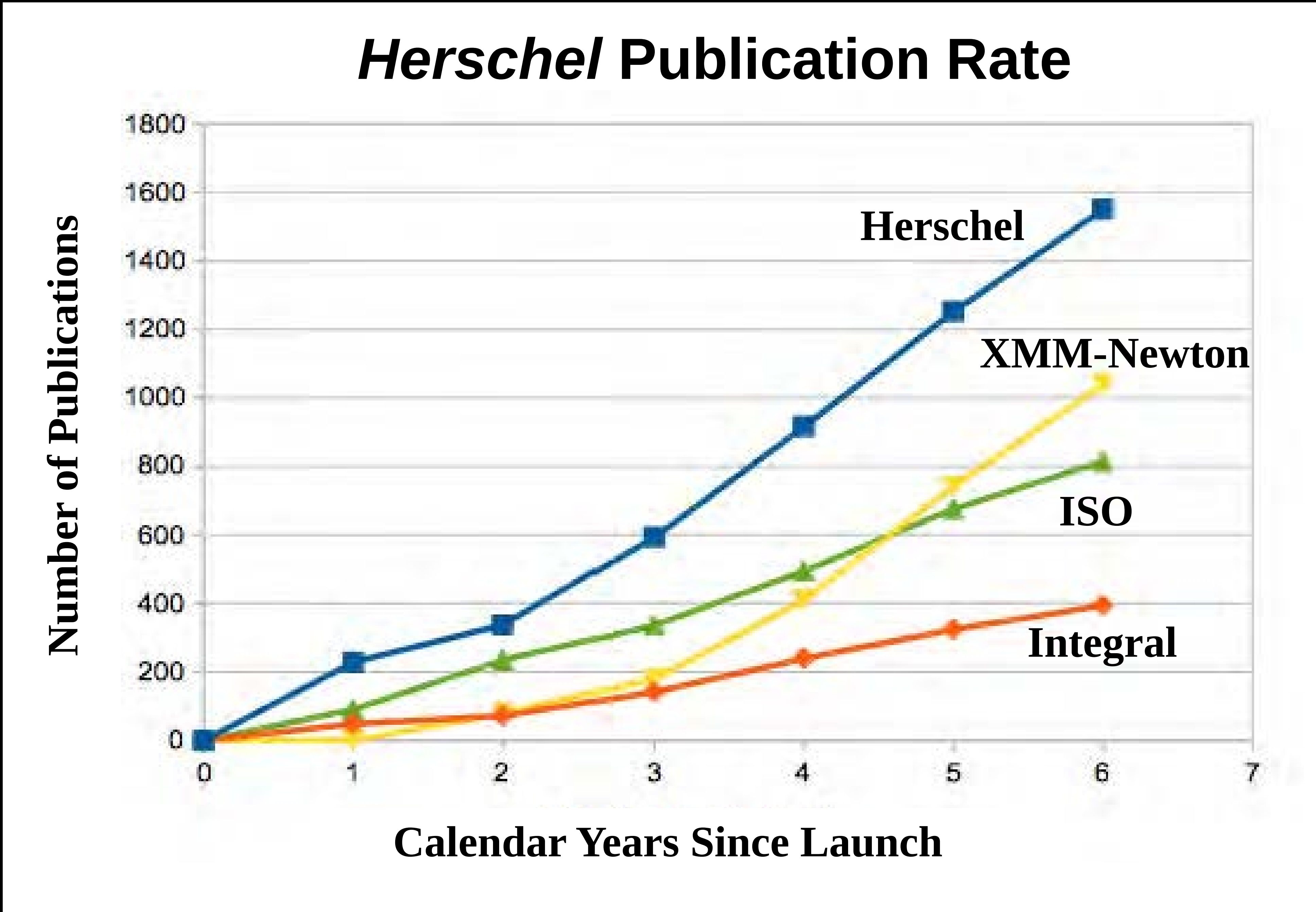


. . . and around Dwarf Planet Ceres



557 GHz H_2O line detected with HIFI in October 2012 and March 2013

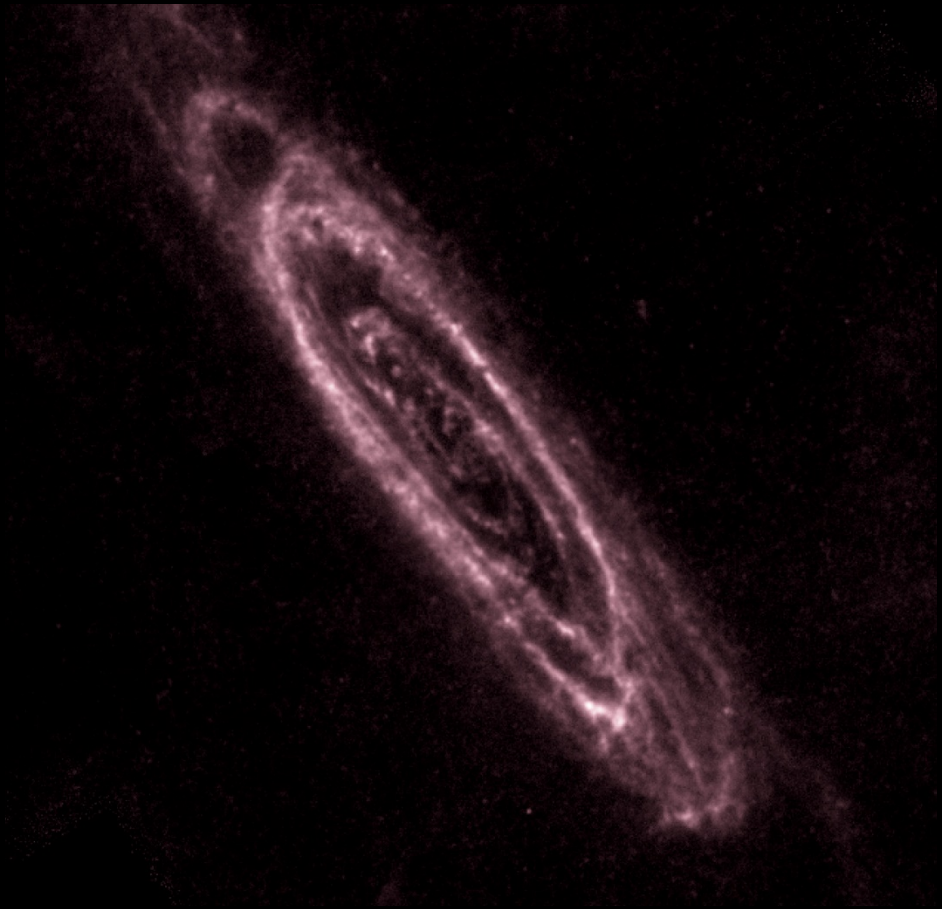
Keuppers et al., 2014



Herschel Publication Rate
Number of Publications
1800
1600
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
7
Calendar Years Since Launch
Herschel
XMM-Newton
ISO
Integral

HiRes Maps

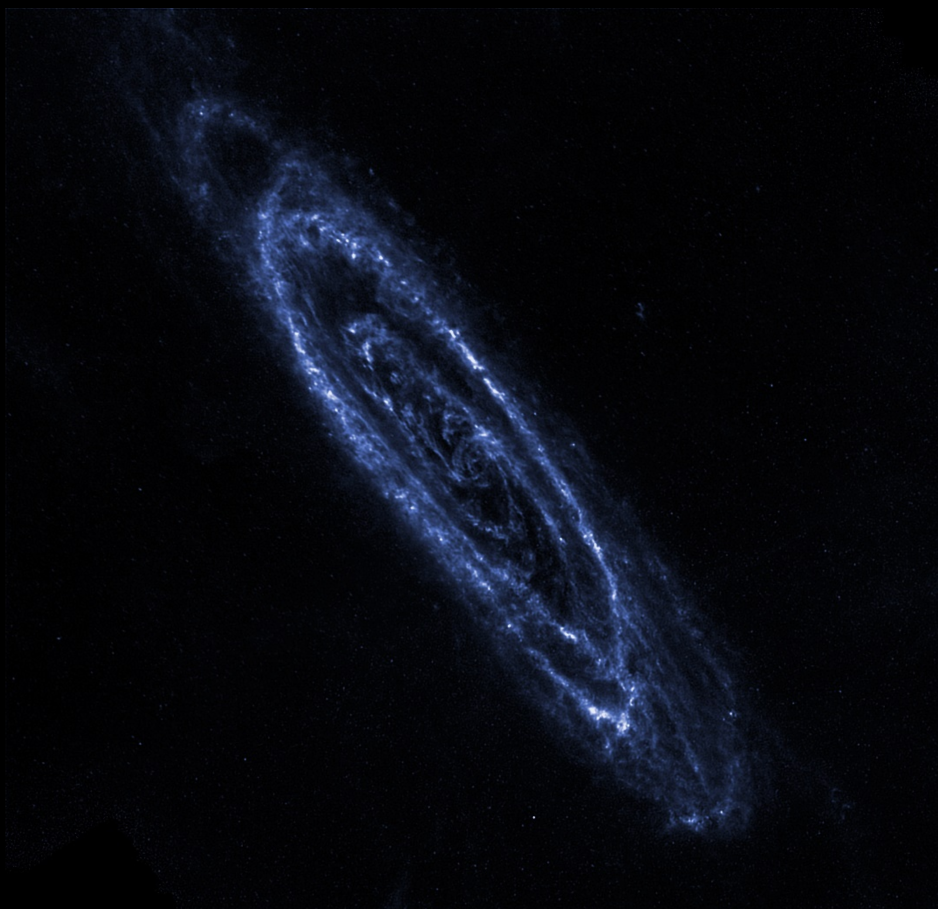
M31 500 μm: Nominal



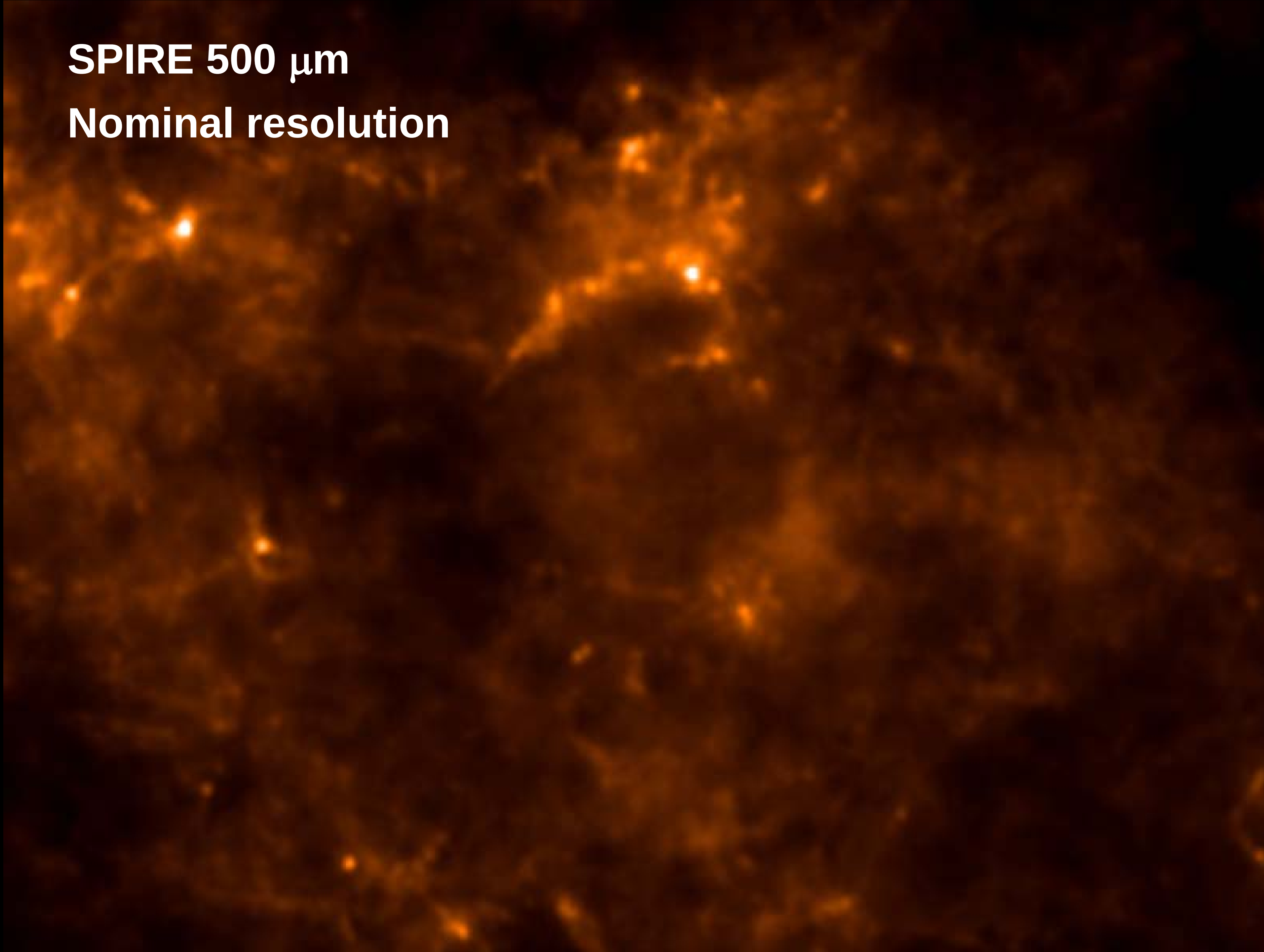
M31 500 μm: HiRes

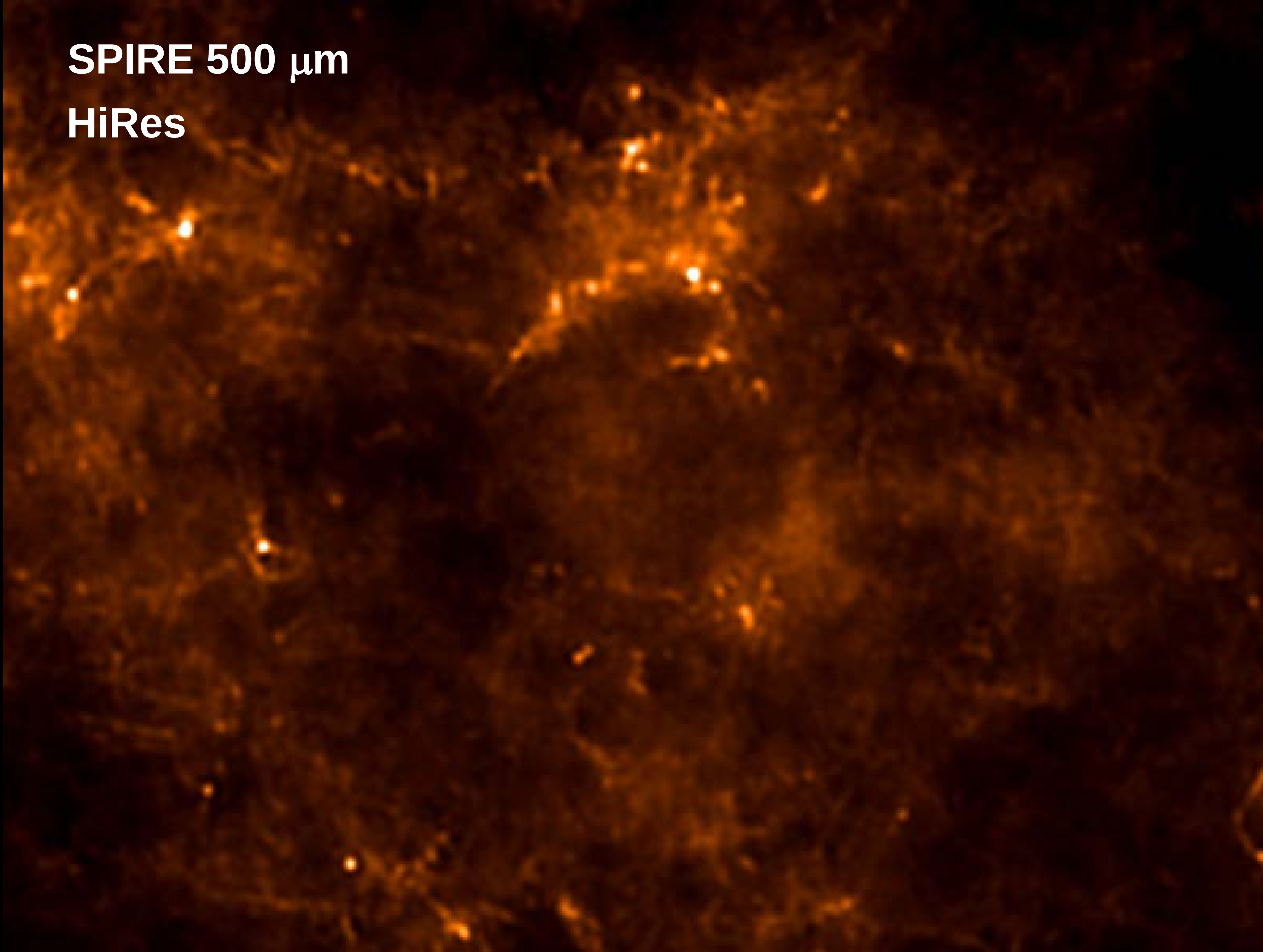
HiRes Maps

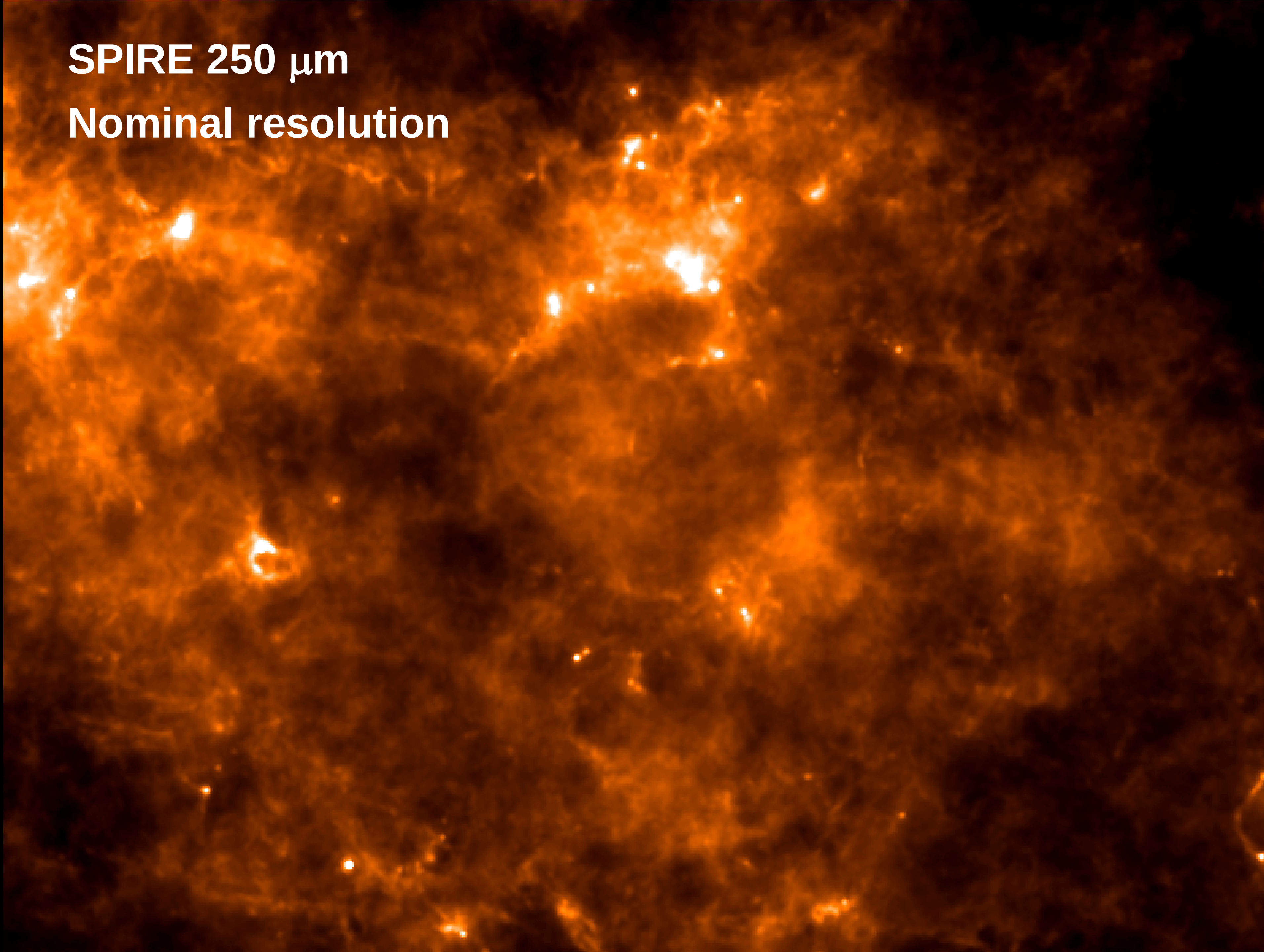
M31 250 μm: Nominal

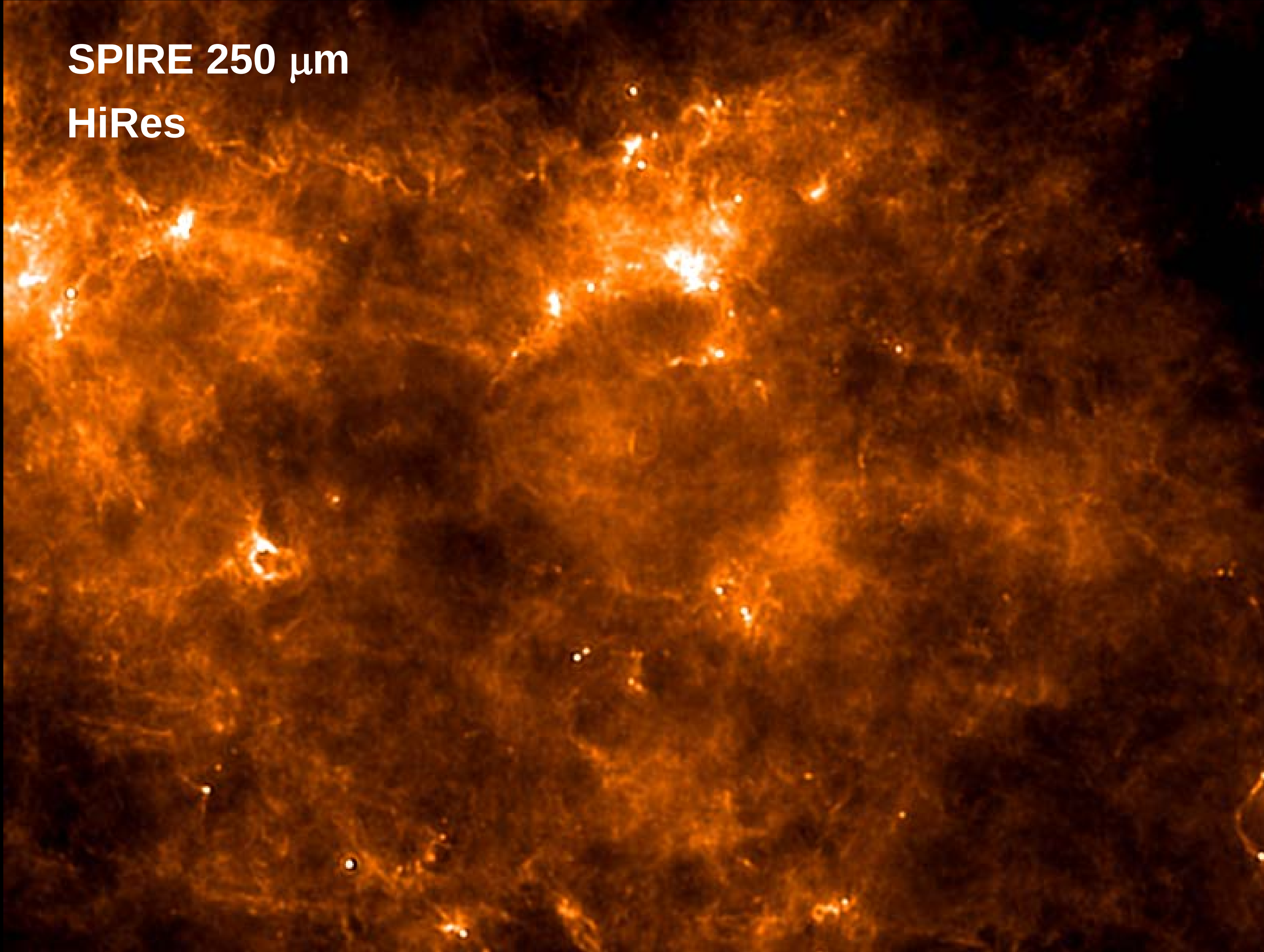


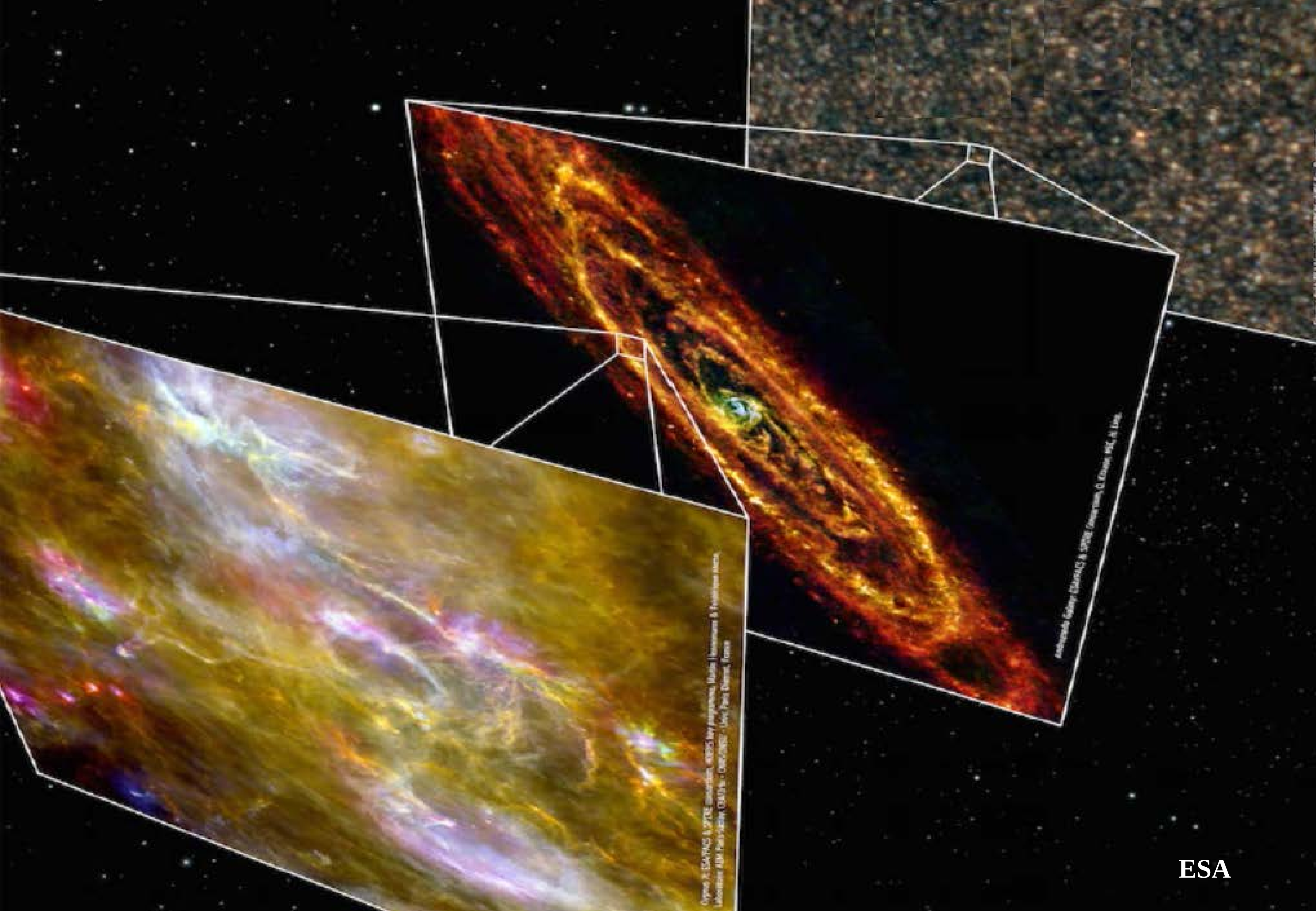
M31 500 μm: HiRes


SPIRE 500 μm
Nominal resolution


SPIRE 500 μm
HiRes


SPIRE 250 μm
Nominal resolution


SPIRE 250 μm
HiRes


ESA