Herschel

Heritage and Directions for Millimetron

Göran Pilbratt, ESA, Herschel Project Scientist

Millimetron Capabilities and Science Objectives, Paris, 9-11 September 2019

Herschel - in a nutshell

Horizon 2000 Cornerstone mission 4

Inflight operations 2009-2013

Post-operations until end of 2017 (2019)

'New' spectral window

~55-670 μm – bridging the far infrared & submillimetre (i.e. space & ground) regimes

Studying the poorly explored 'cool' universe

Telescope & instruments

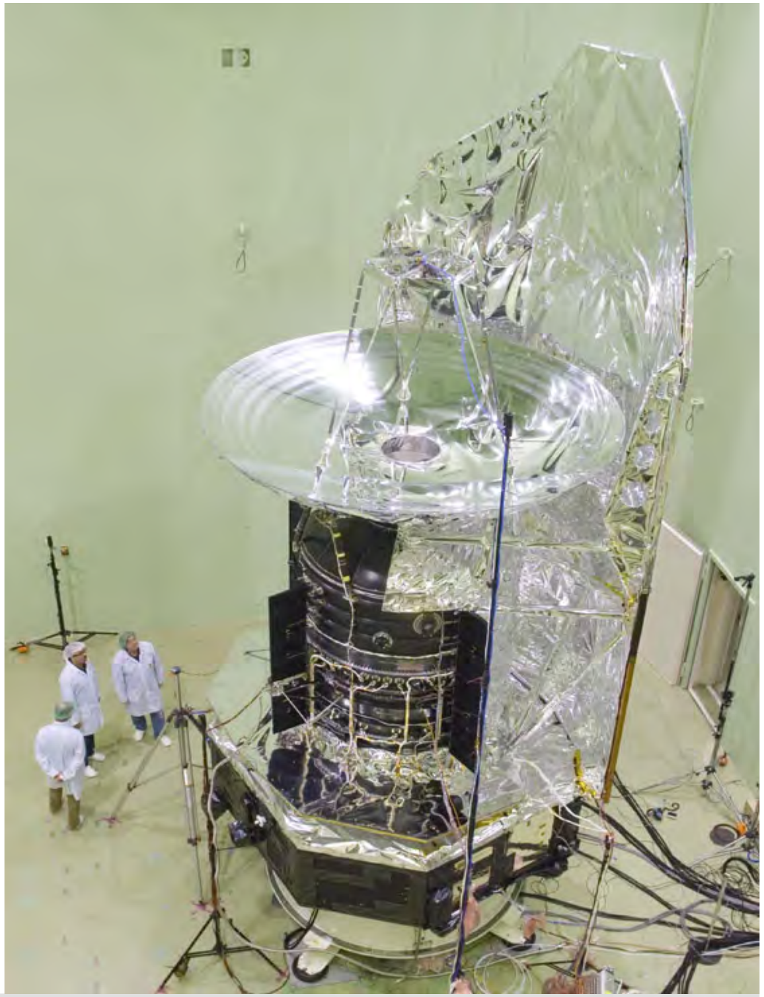
3.5 m Cassegrain silicon carbide telescope

Passively cooled, M1 ~88 K, low emissivity

Cryogenically (SLHe) cooled focal plane units

Direct det imaging photometry & spectroscopy

Single pixel heterodyne spectroscopy



Herschel – science payload

<u>3-band camera</u>
250 + 350 + 500 μm
4 x 8 arcmin FOV

<u>Imaging FT spectrometer</u>
194 - 671 μm (simultaneously)
$\lambda/\Delta\lambda$ = 1300 – 370 (high-res)
= 60 – 20 (low-res)

SPIRE

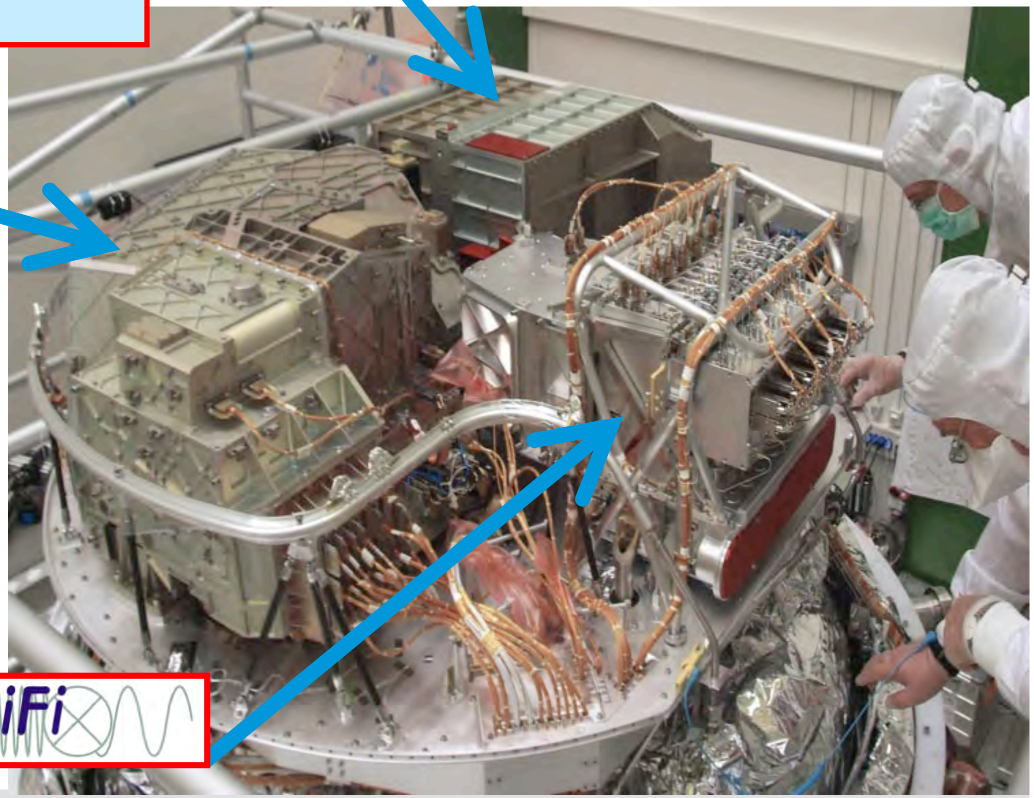
<u>3-band camera</u>
70 or 100 + 160 μm
1.75 x 3.5 arcmin FOV

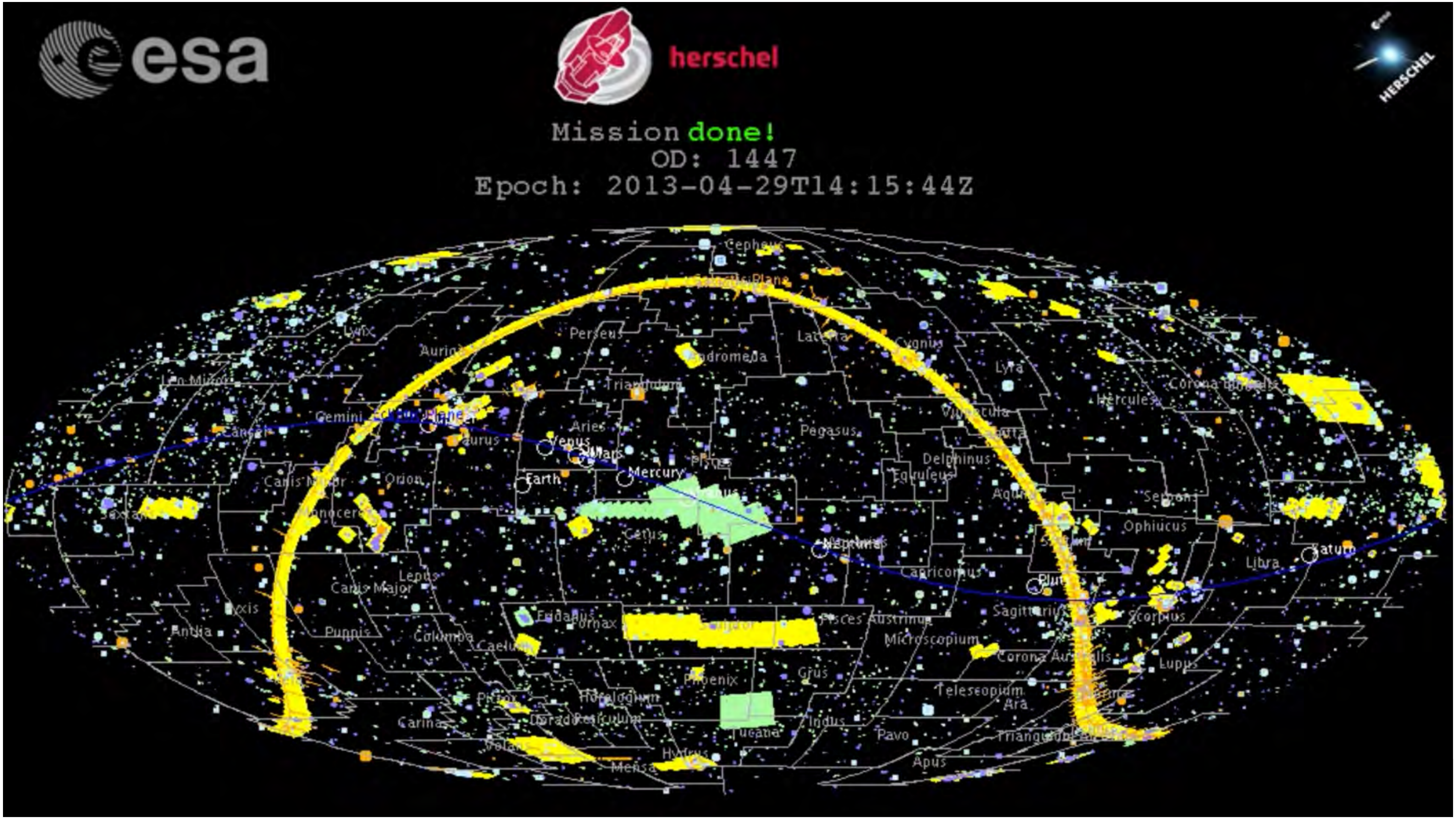
PACS

<u>Imaging grating spectrometer</u>
55 - 210 μm (3 orders)
$\lambda/\Delta\lambda$ = 1000 – 4000

<u>7-channel heterodyne receiver</u>
480 - 1250 GHz (625 - 240 μm) SIS mxrs
1410 - 1910 GHz (212 - 157 μm) HEB mxrs
$\lambda/\Delta\lambda$ = 10^5-10^6 w. BW = 4 GHz AOS & corr

HiFi




esa
herschel
Mission done!
OD: 1447
Epoch: 2013-04-29T14:15:44Z

Science categories (HOTAC allocations)

Galaxies/AGNs	6503 hr	28%
Cosmology	5074 hr	22%
ISM/Star formation	9044 hr	39%
Solar system objects	956 hr	4%
Stars/Stellar evolution	1899 hr	8%
Total	23476 hr	

Observing statistics

HOTAC allocated	~23400 hr	~37,000 AORs
Science calibration	~2600 hr	~6600 AORs
Total	~26000 hr	~43,600 AORs

(cf. 26,000 ~ 1238 x 21)

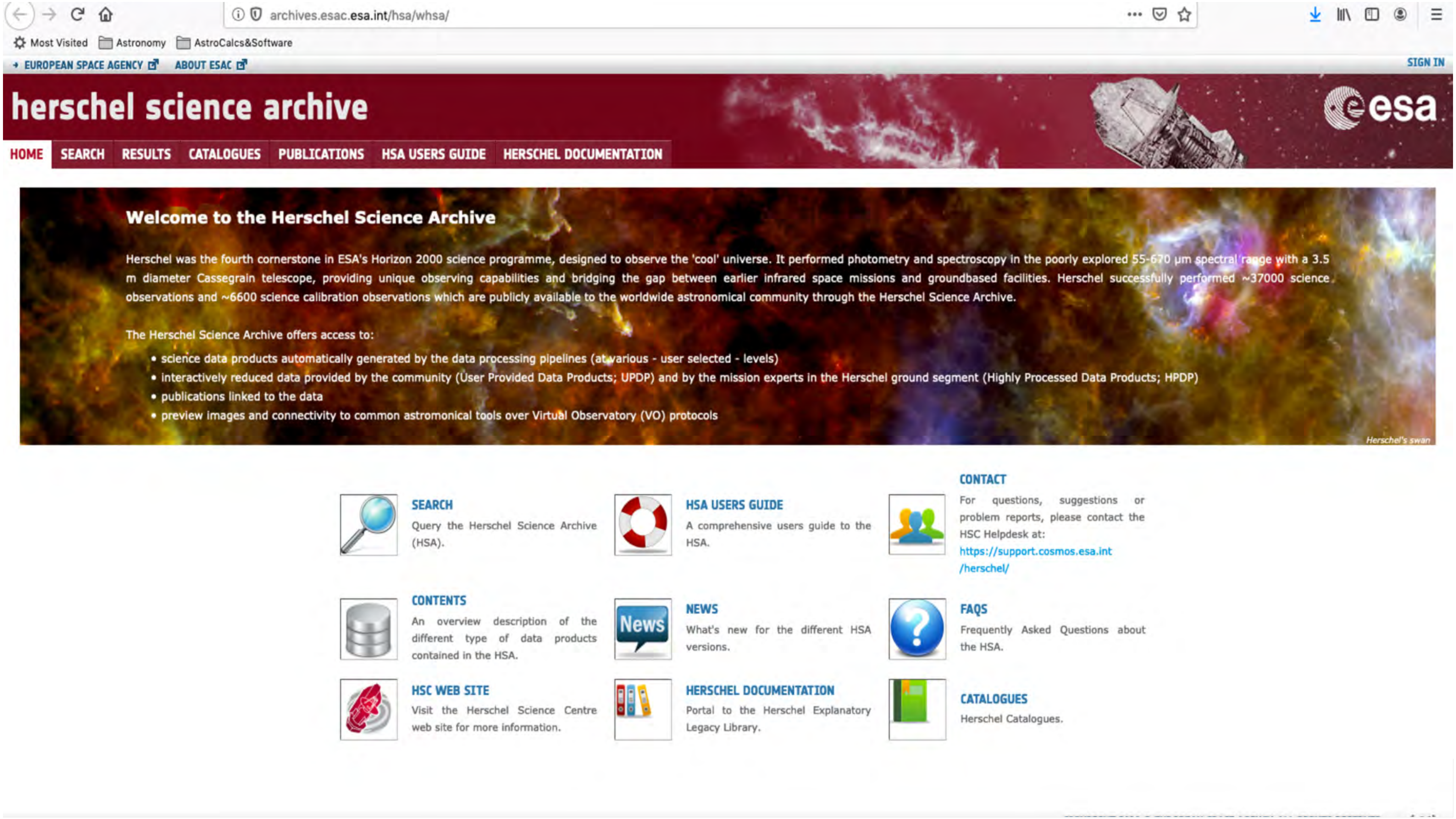
Totals (+/- 5%)

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!


archives.esac.esa.int/hsa/whsa/
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Welcome to the Herschel Science Archive
Herschel was the fourth cornerstone in ESA's Horizon 2000 science programme, designed to observe the 'cool' universe. It performed photometry and spectroscopy in the poorly explored 55-670 μm spectral range with a 3.5 m diameter Cassegrain telescope, providing unique observing capabilities and bridging the gap between earlier infrared space missions and groundbased facilities. Herschel successfully performed ~37000 science observations and ~6600 science calibration observations which are publicly available to the worldwide astronomical community through the Herschel Science Archive.
The Herschel Science Archive offers access to:
• science data products automatically generated by the data processing pipelines (at various - user selected - levels)
• interactively reduced data provided by the community (User Provided Data Products; UPDP) and by the mission experts in the Herschel ground segment (Highly Processed Data Products; HPDP)
• publications linked to the data
• preview images and connectivity to common astronomical tools over Virtual Observatory (VO) protocols
Herschel's swan
SEARCH
Query the Herschel Science Archive (HSA).
HSA USERS GUIDE
A comprehensive users guide to the HSA.
CONTACT
For questions, suggestions or problem reports, please contact the HSC Helpdesk at:
https://support.cosmos.esa.int/herschel/
CONTENTS
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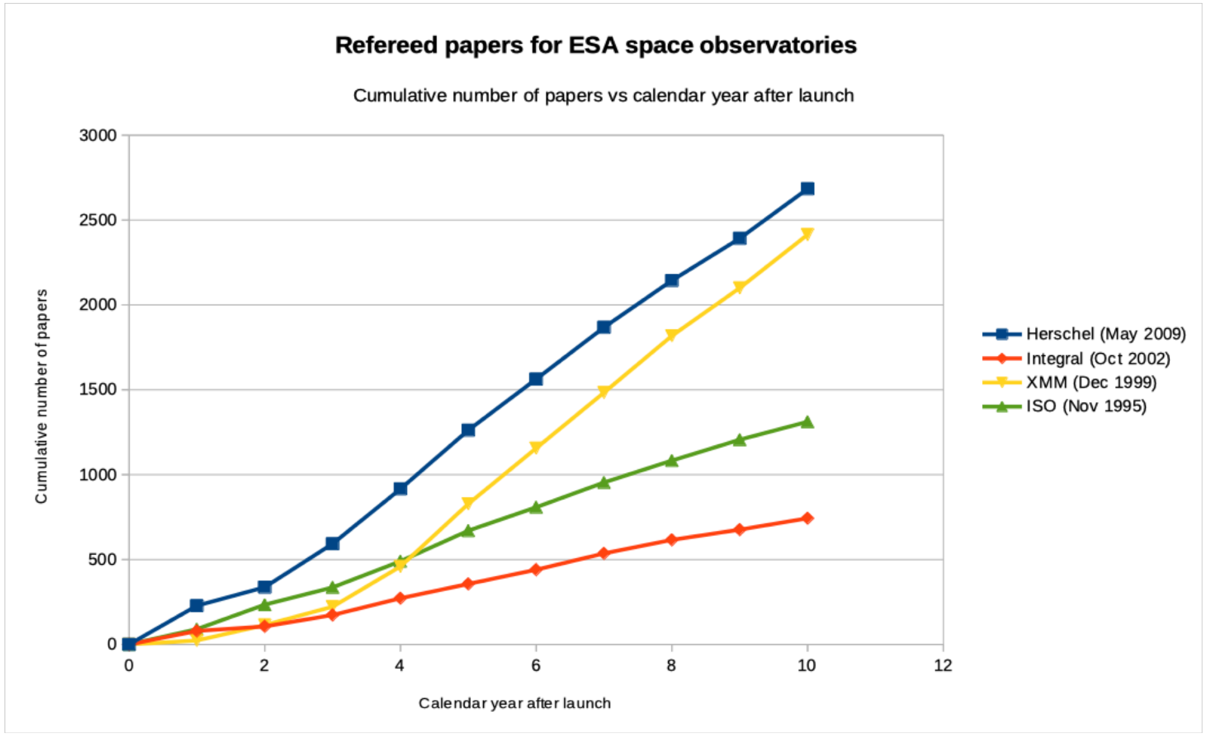
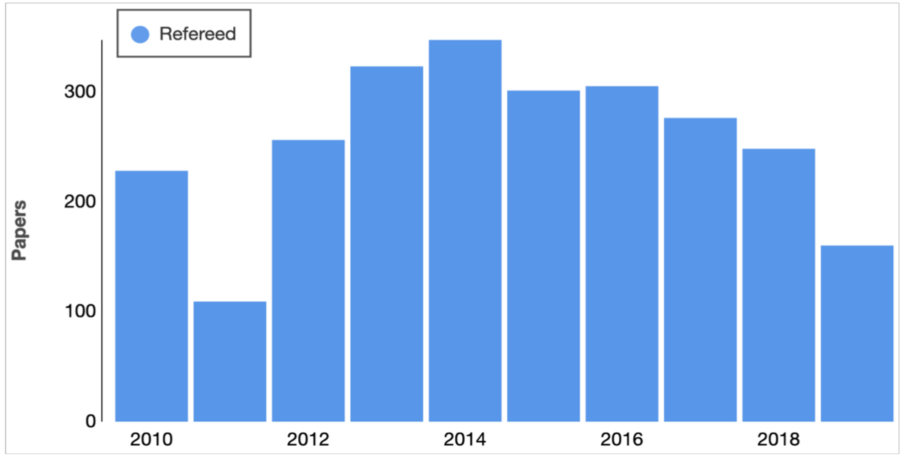
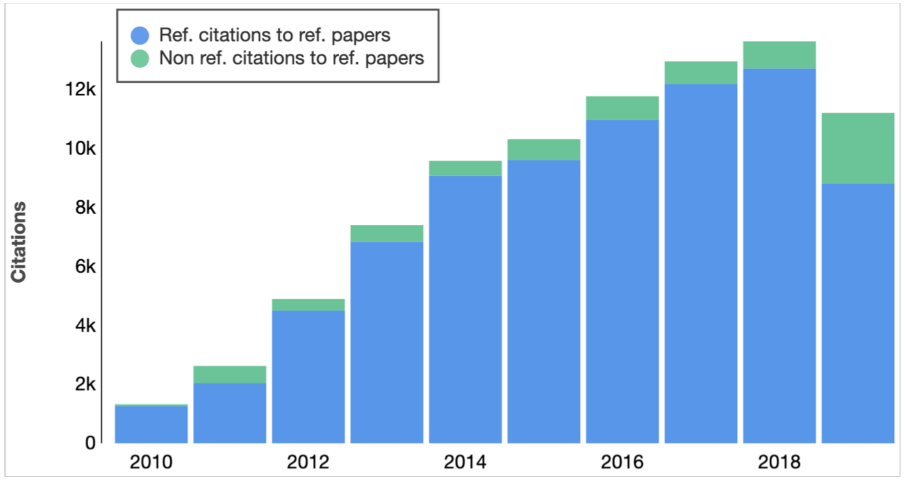
Herschel Catalogues.

Science exploitation & impact

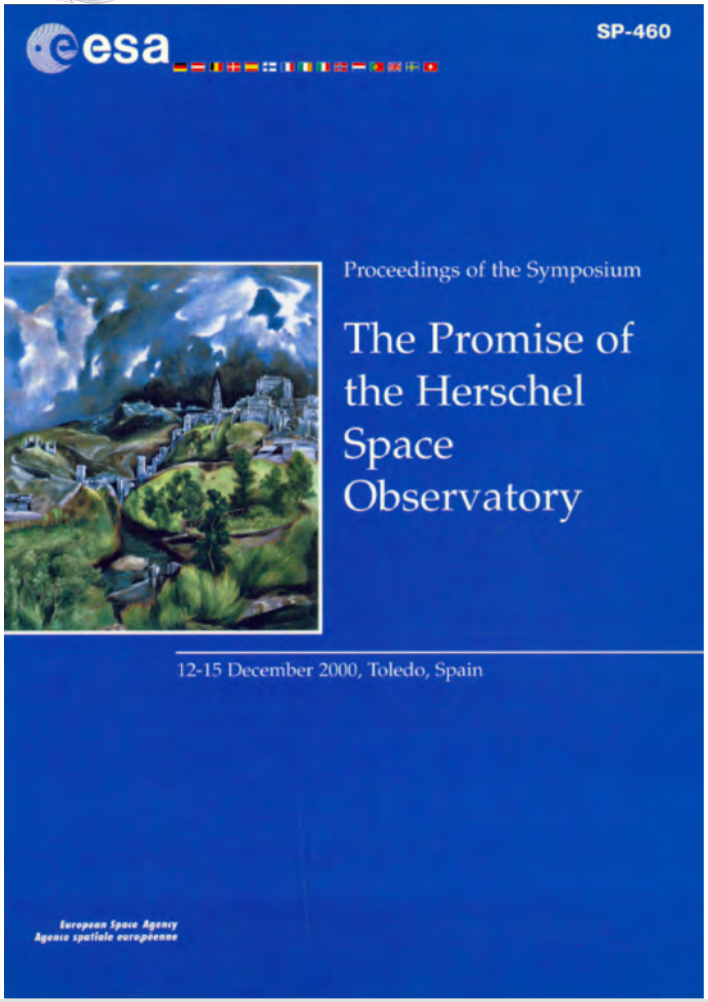






- Good publication record
- Good citation record – h=115, i100=145
- ISO lifetime ~2.5 yrs, Herschel ~4 yrs
- XMM-Newton & Integral are still observing

Science objectives



Top level science objectives

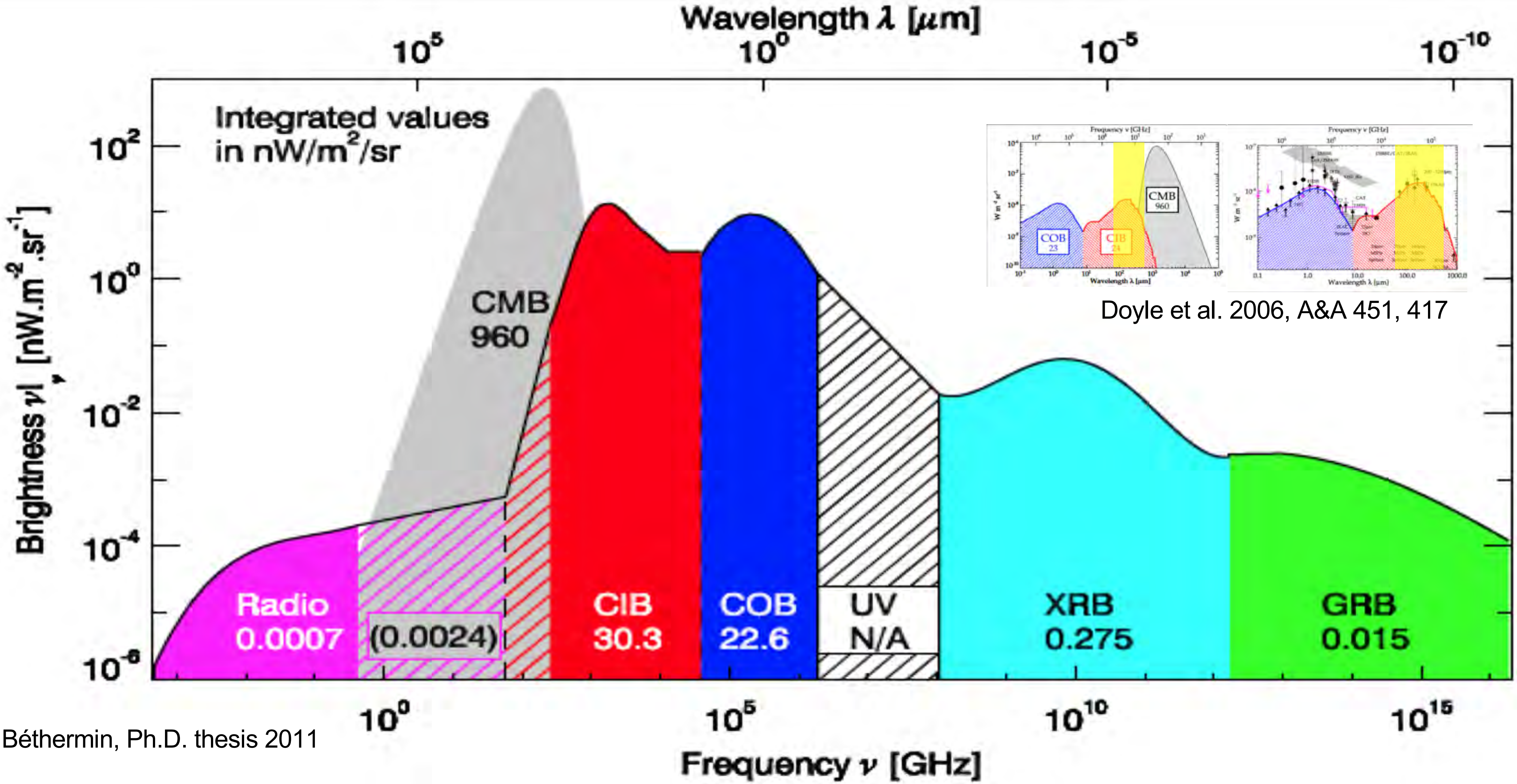
- Deep unbiased extragalactic photometric surveys
- Photometric surveys of active and quiescent molecular clouds
- Follow-up spectroscopy of specially interesting galactic and extragalactic survey sources
- Spectral surveys of different types of objects, including early epoch starburst and active galaxies
- Studies of 'individual' sources in detail
- Studies of comets and other solar system objects

Herschel-centric approach!

- What Herschel did and did not /could not do


Cosmology & galaxy evolution

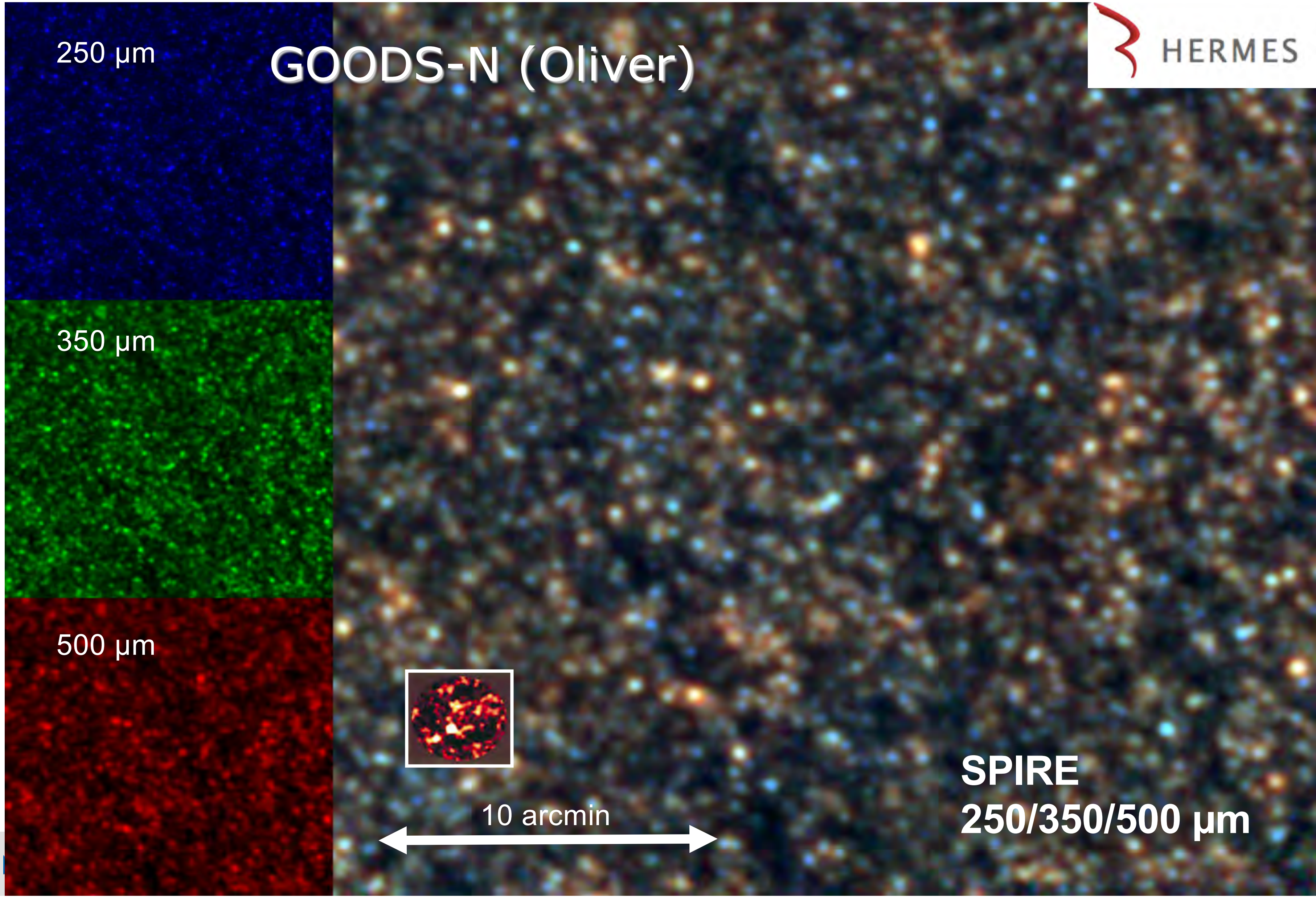
Cosmic backgrounds

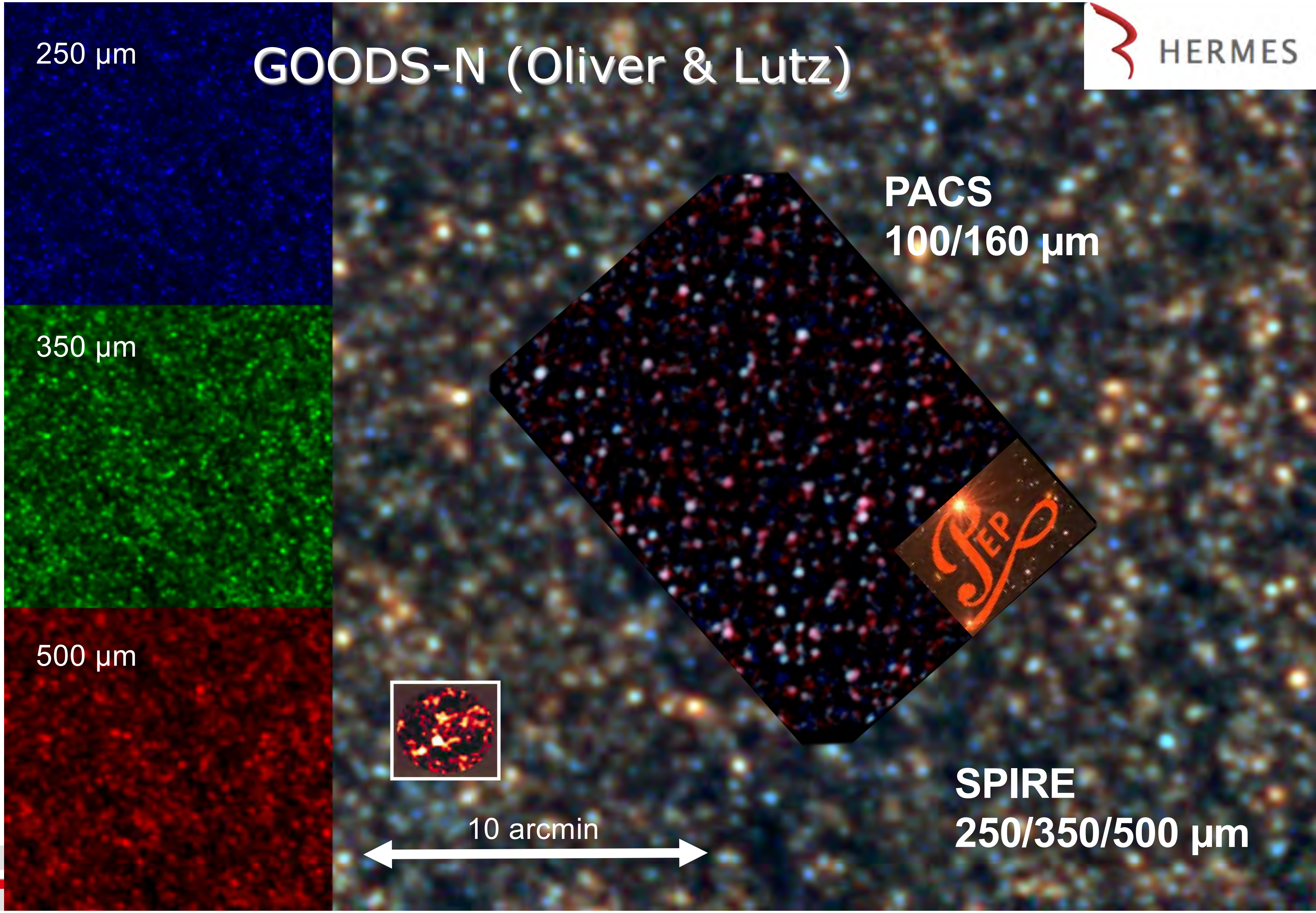


Doyle et al. 2006, A&A 451, 417

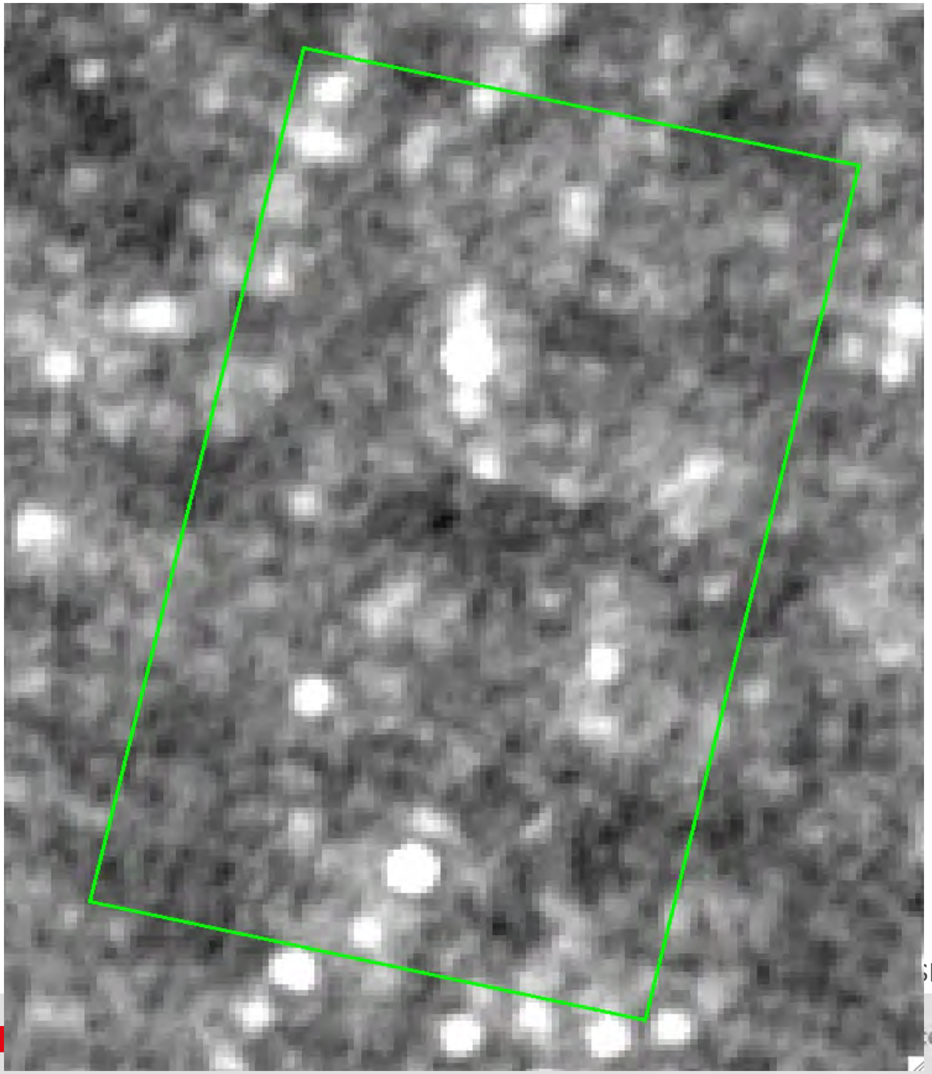
Béthermin, Ph.D. thesis 2011

GOODS-N (Oliver)

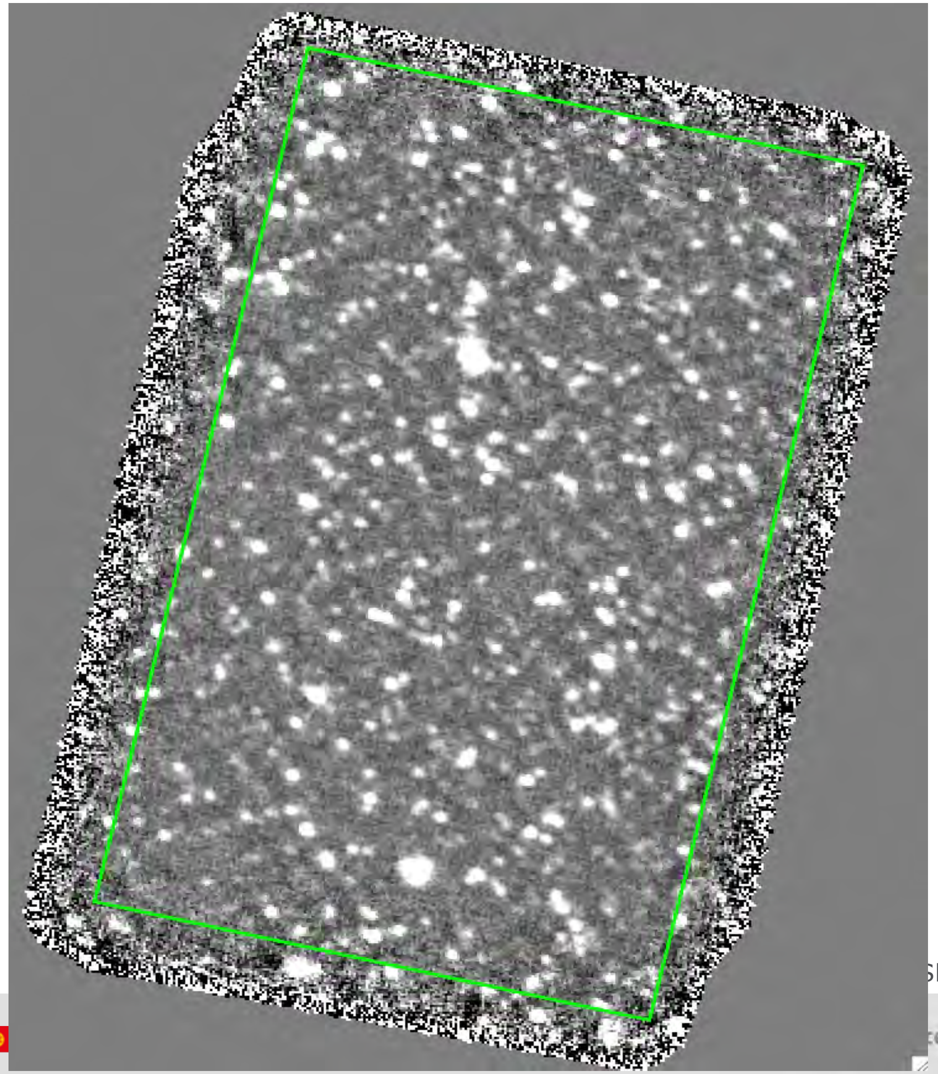



GOODS-N (Oliver & Lutz)
250 µm
350 µm
500 µm
PACS
100/160 µm
SPIRE
250/350/500 µm
10 arcmin
HERMES

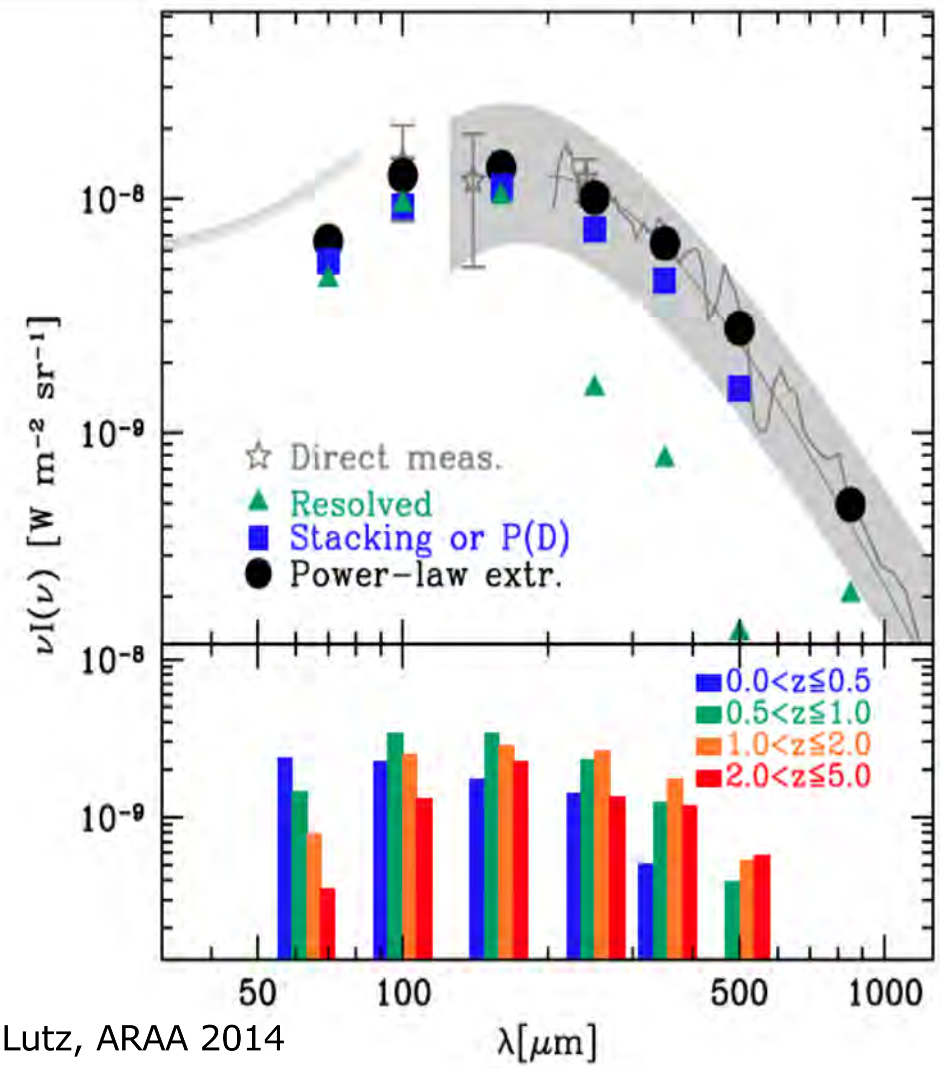
Extragalactic surveys & CIRB



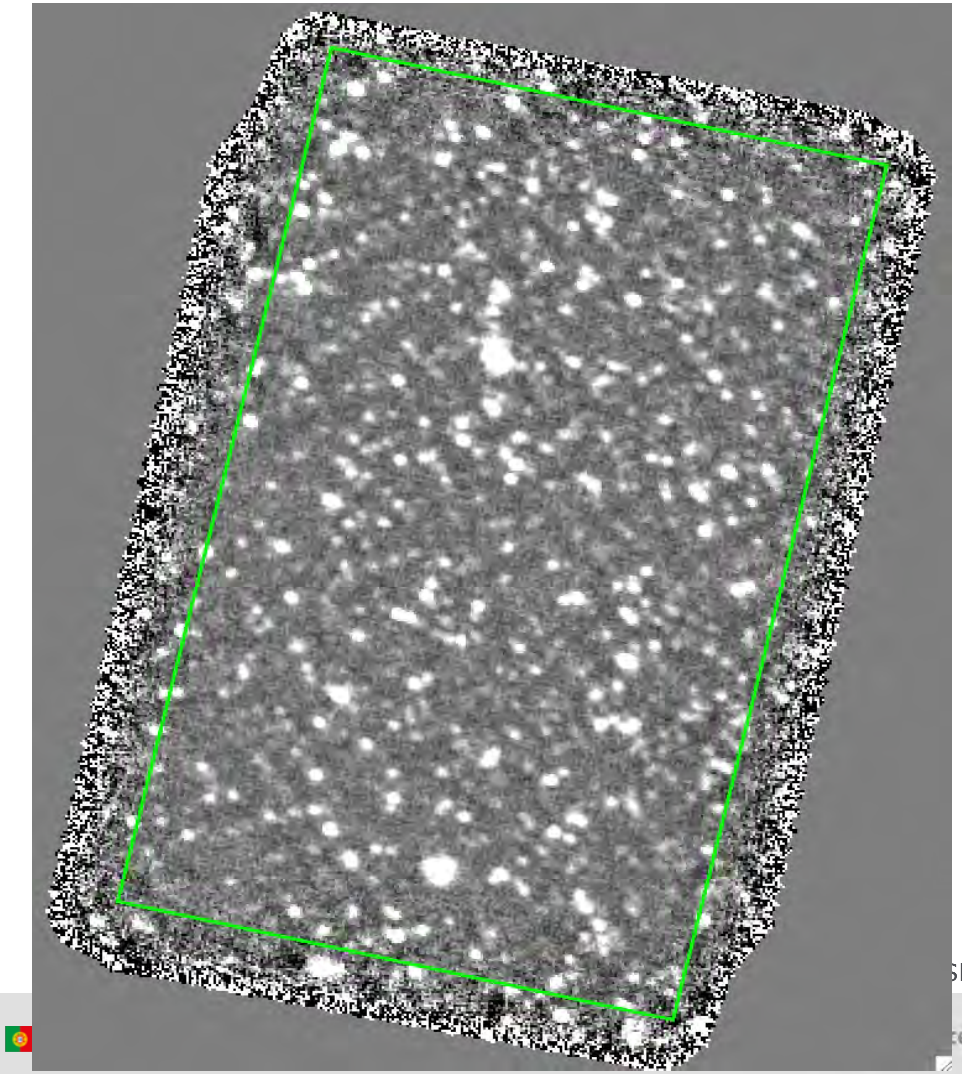
Extragalactic surveys & CIRB



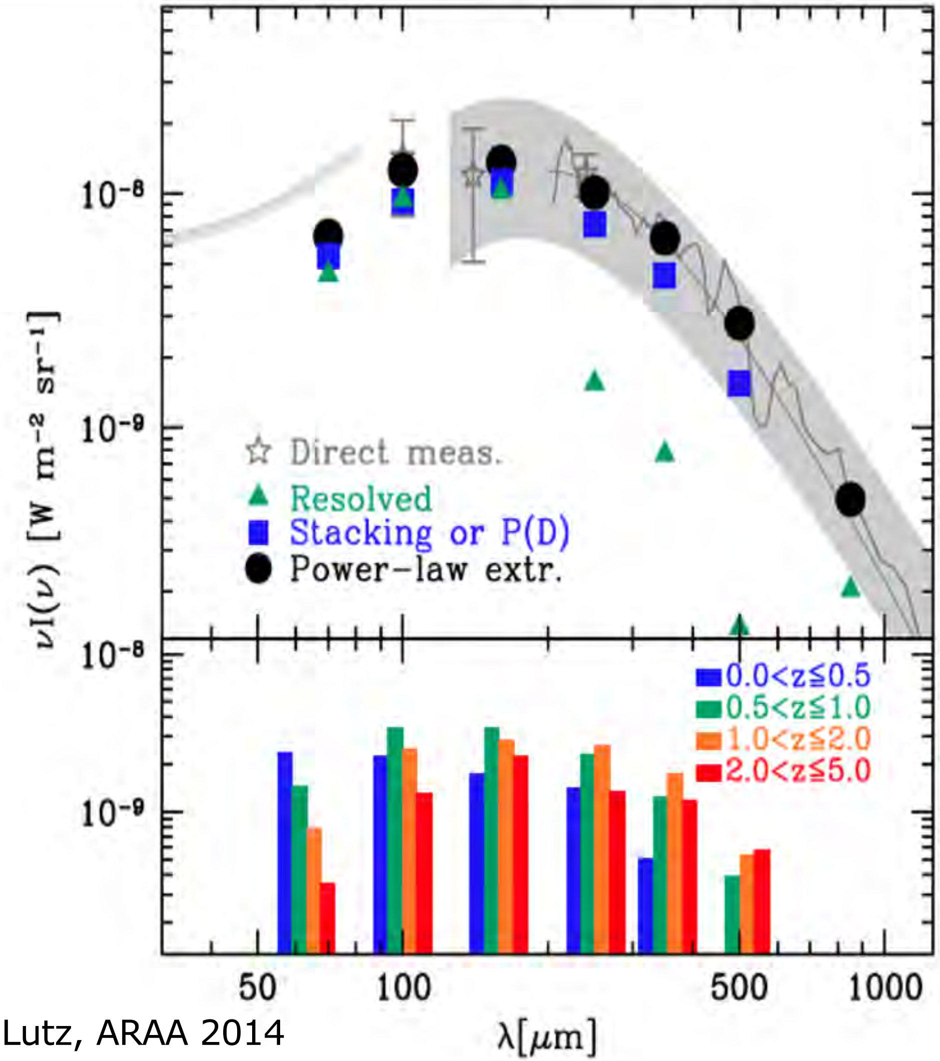
Extragalactic surveys & CIRB



Lutz, ARAA 2014



Extragalactic surveys & CIRB

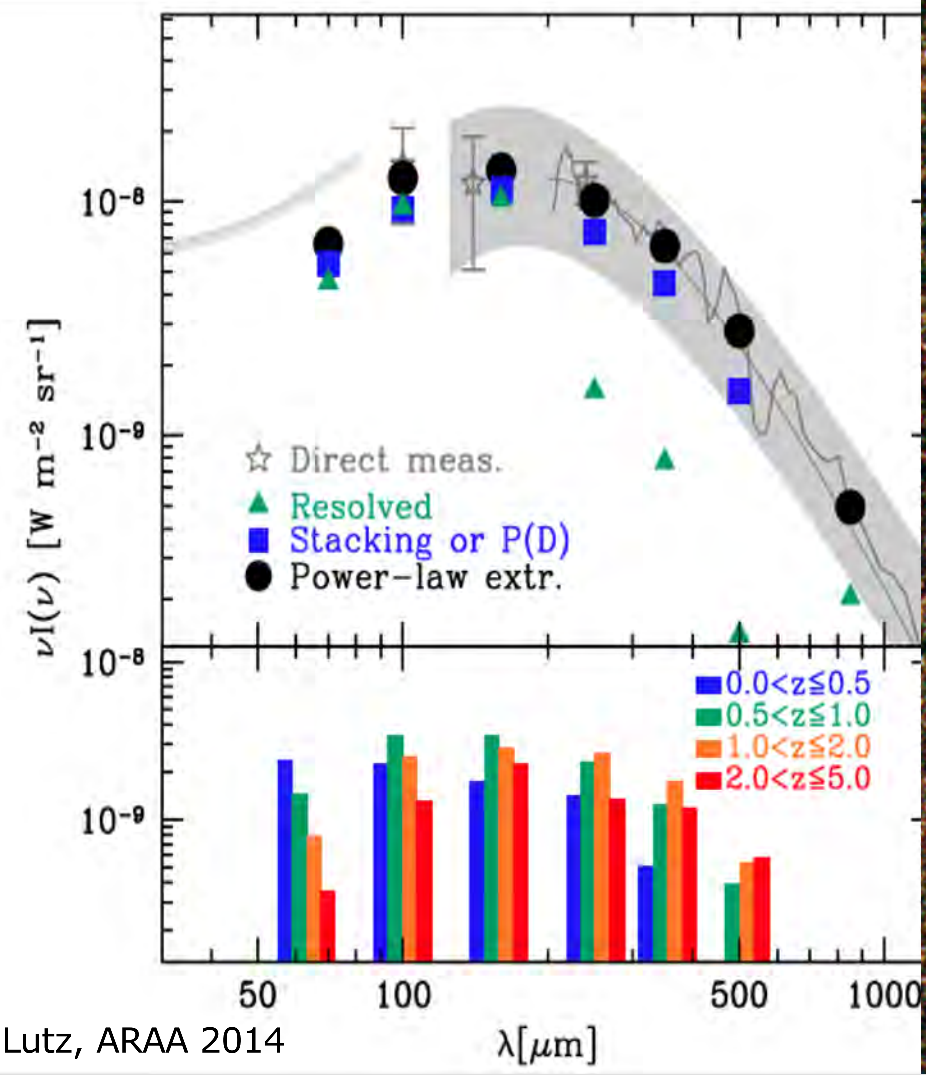


Lutz, ARAA 2014

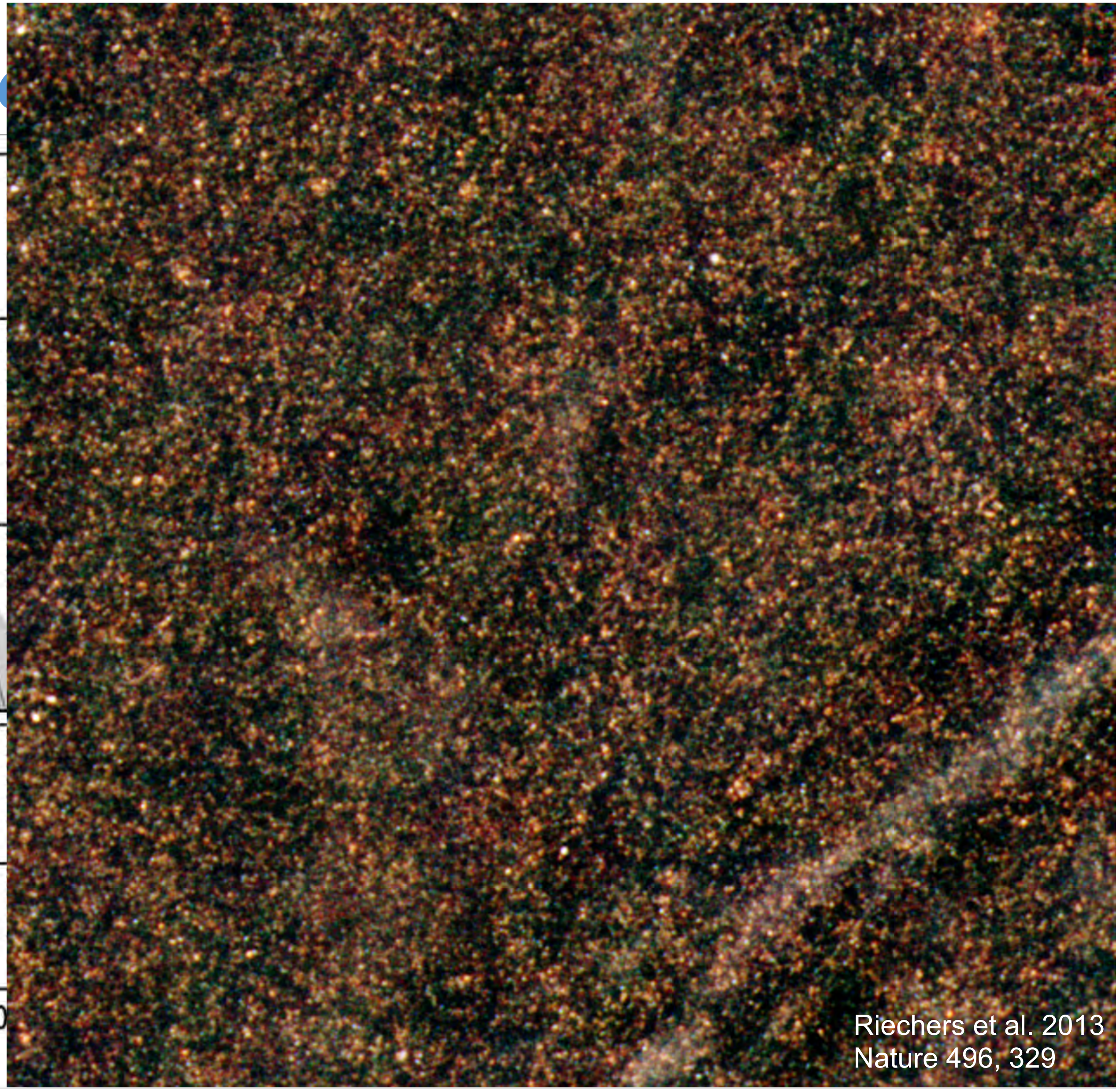
CIRB essentially resolved

- PACS: directly resolved
- SPIRE: by stacking
- Confusion noise:
  - 70/100/160 μm: not reached/0.15/0.68 mJy
  - 250/350/500 μm: 5.8/6.3/6.8 mJy
- The longer the wavelength the greater the contribution from high-z galaxies
- Herschel observes tip-of-iceberg extreme start-burst galaxies >1000 $M_\odot yr^{-1}$, want to study underlying bulk population
- **To study the high-z universe need to break the confusion!**
- Herschel: 'deblending' based on priors
- Ground (APEX, JCMT, SP & ALMA) & future space (Origins, Mmtron): higher resolution

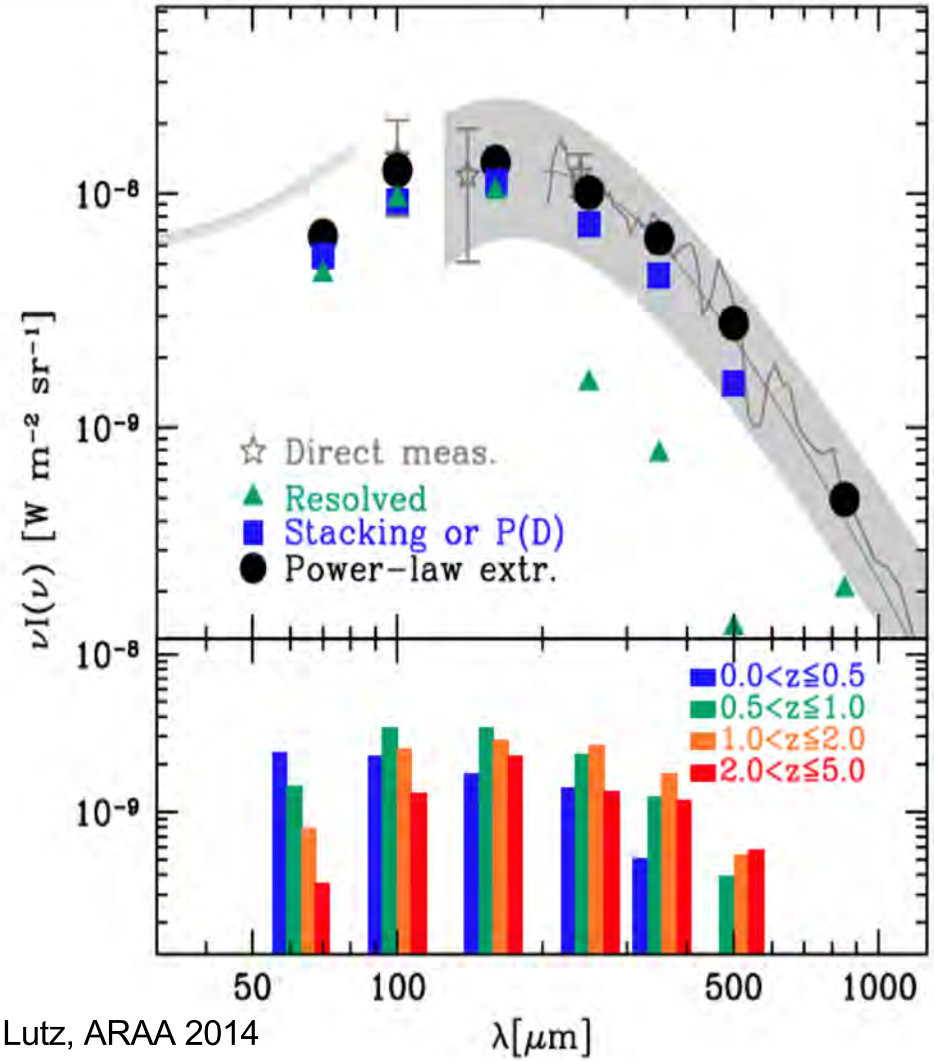
Extragalacti



Lutz, ARAA 2014



Extragalactic high-z objects



Lutz, ARAA 2014

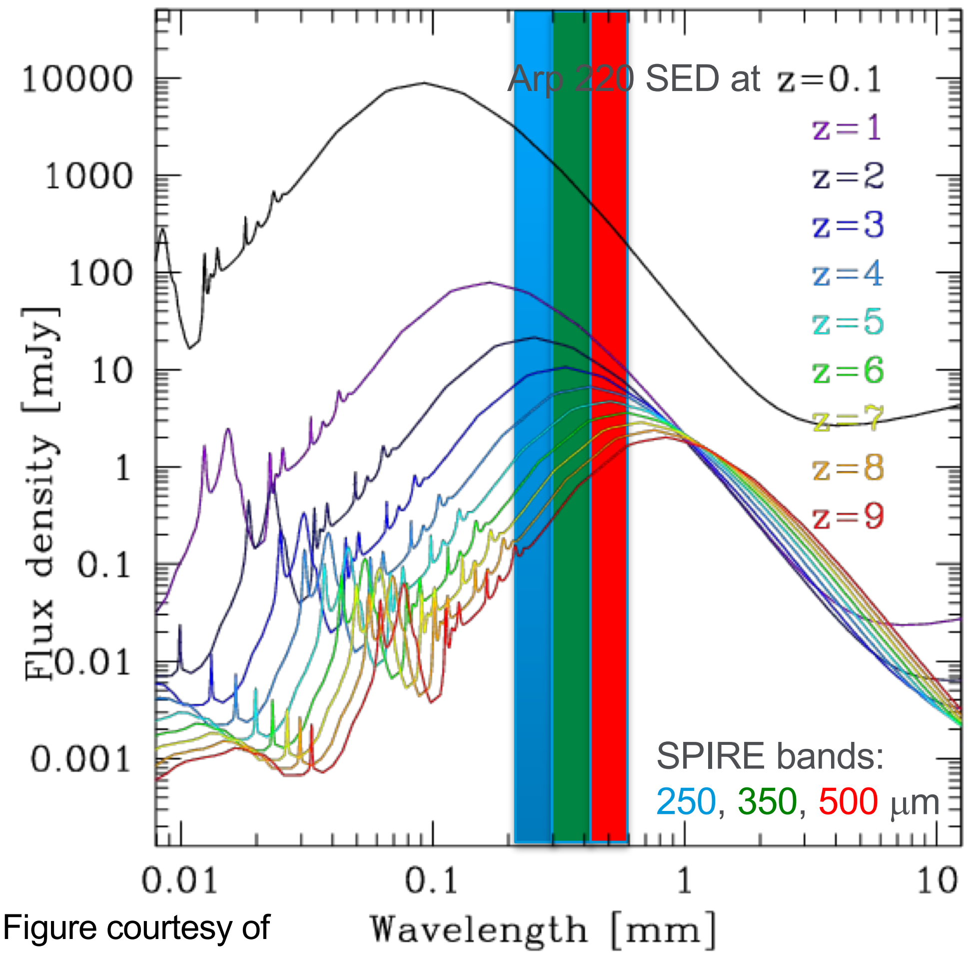
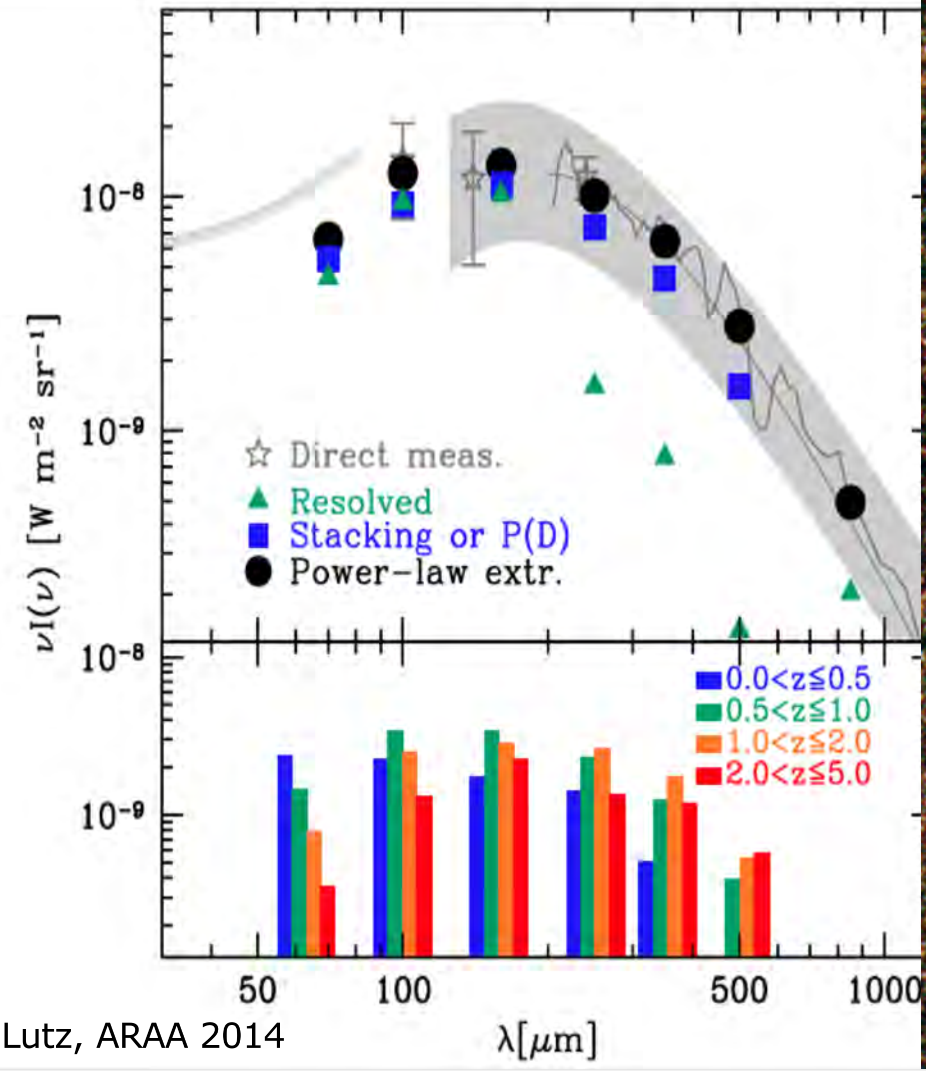
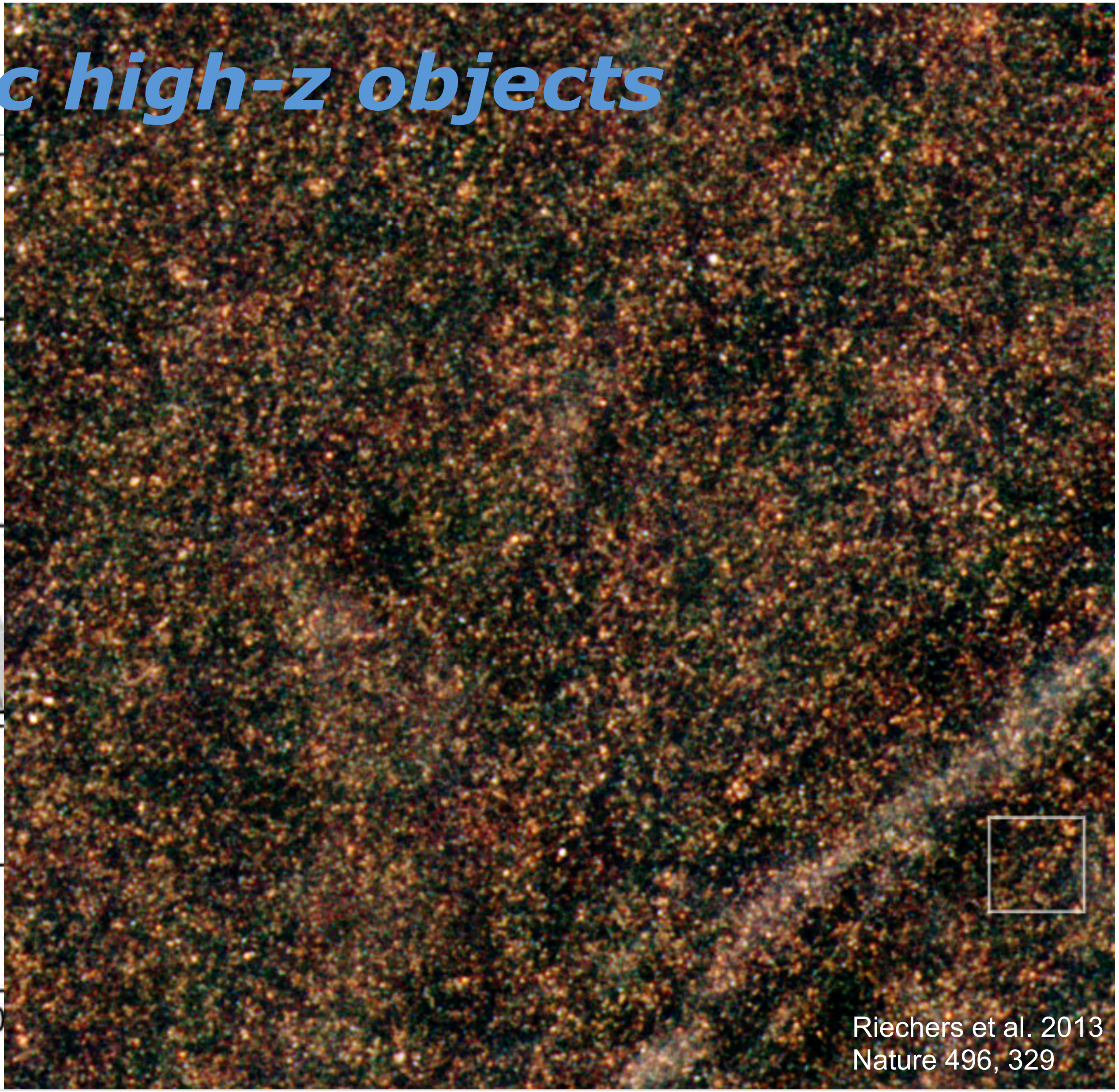


Figure courtesy of Roberto Decarli

Extragalactic high-z objects

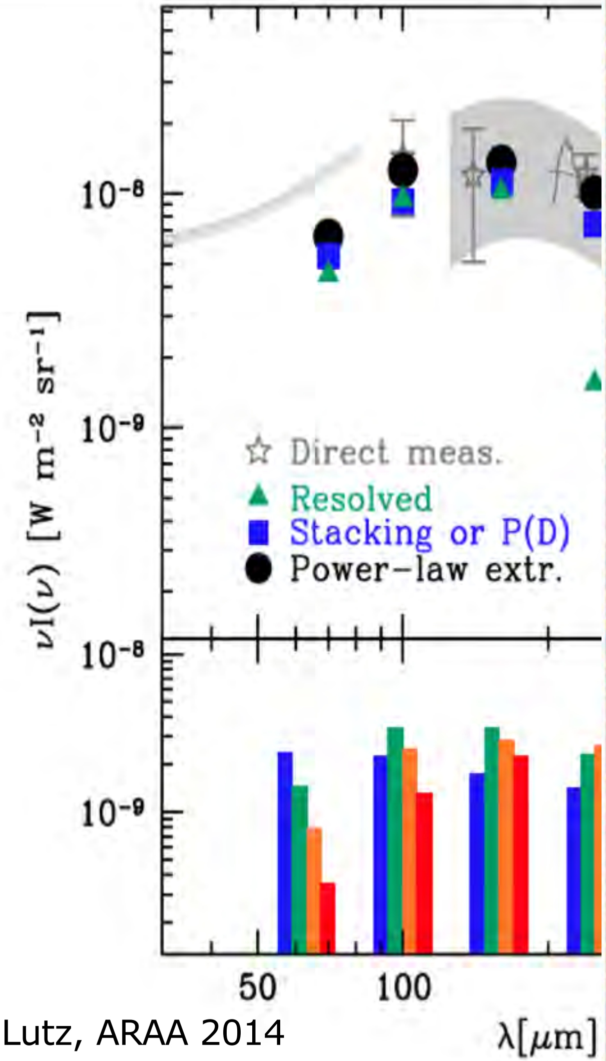


Lutz, ARAA 2014

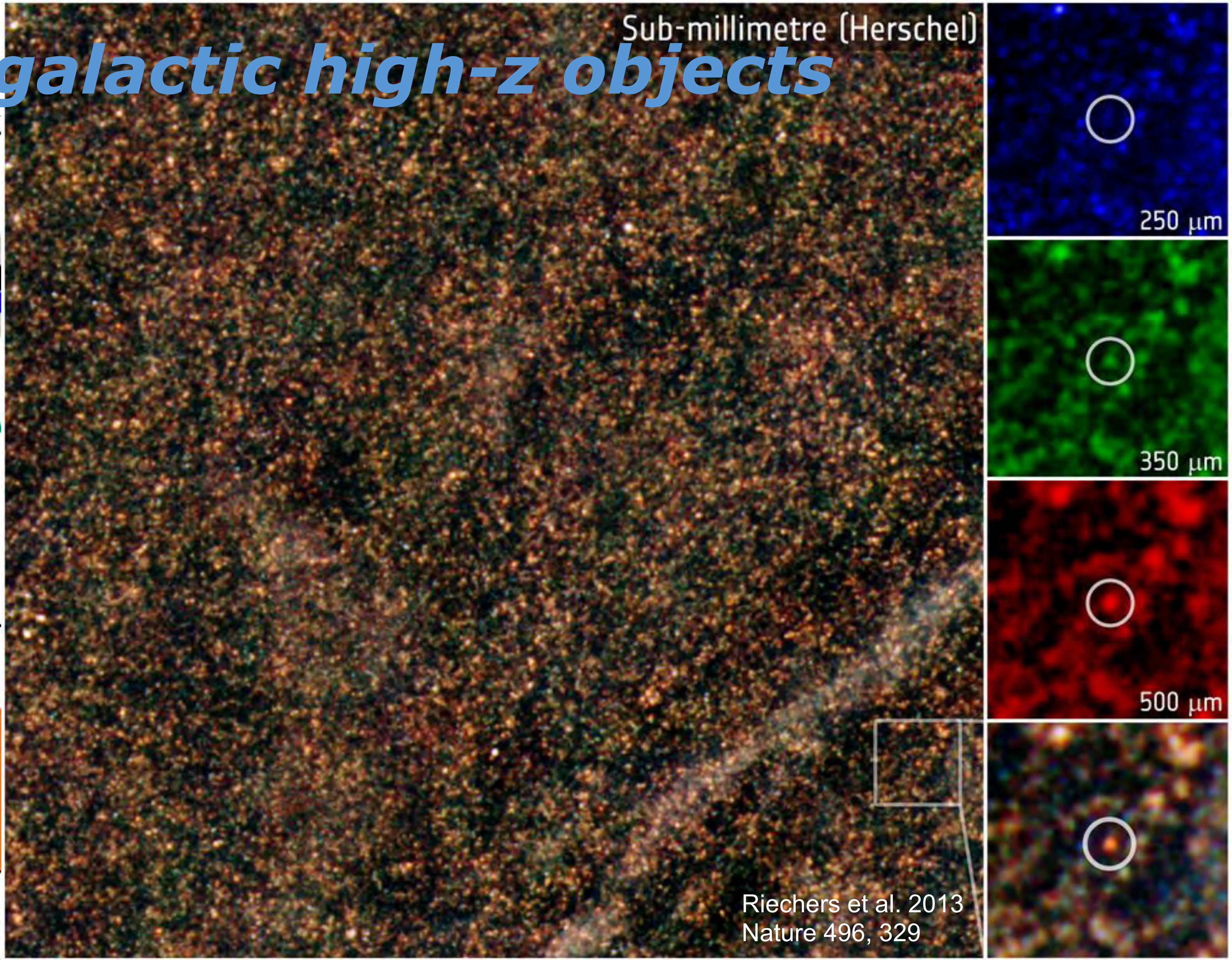


Riechers et al. 2013
Nature 496, 329

Extragalactic high-z objects

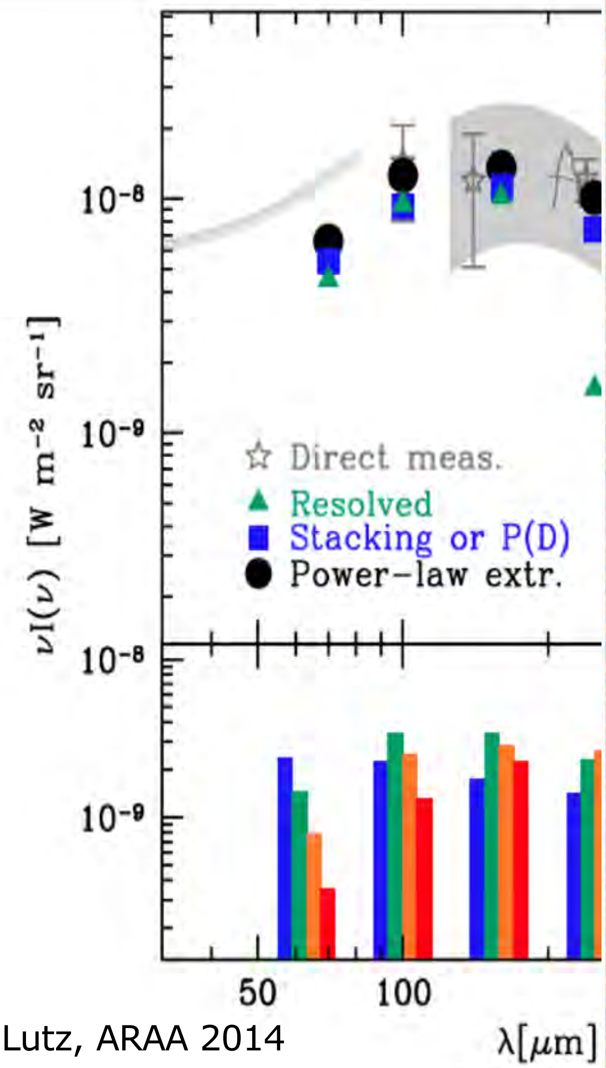


Lutz, ARAA 2014

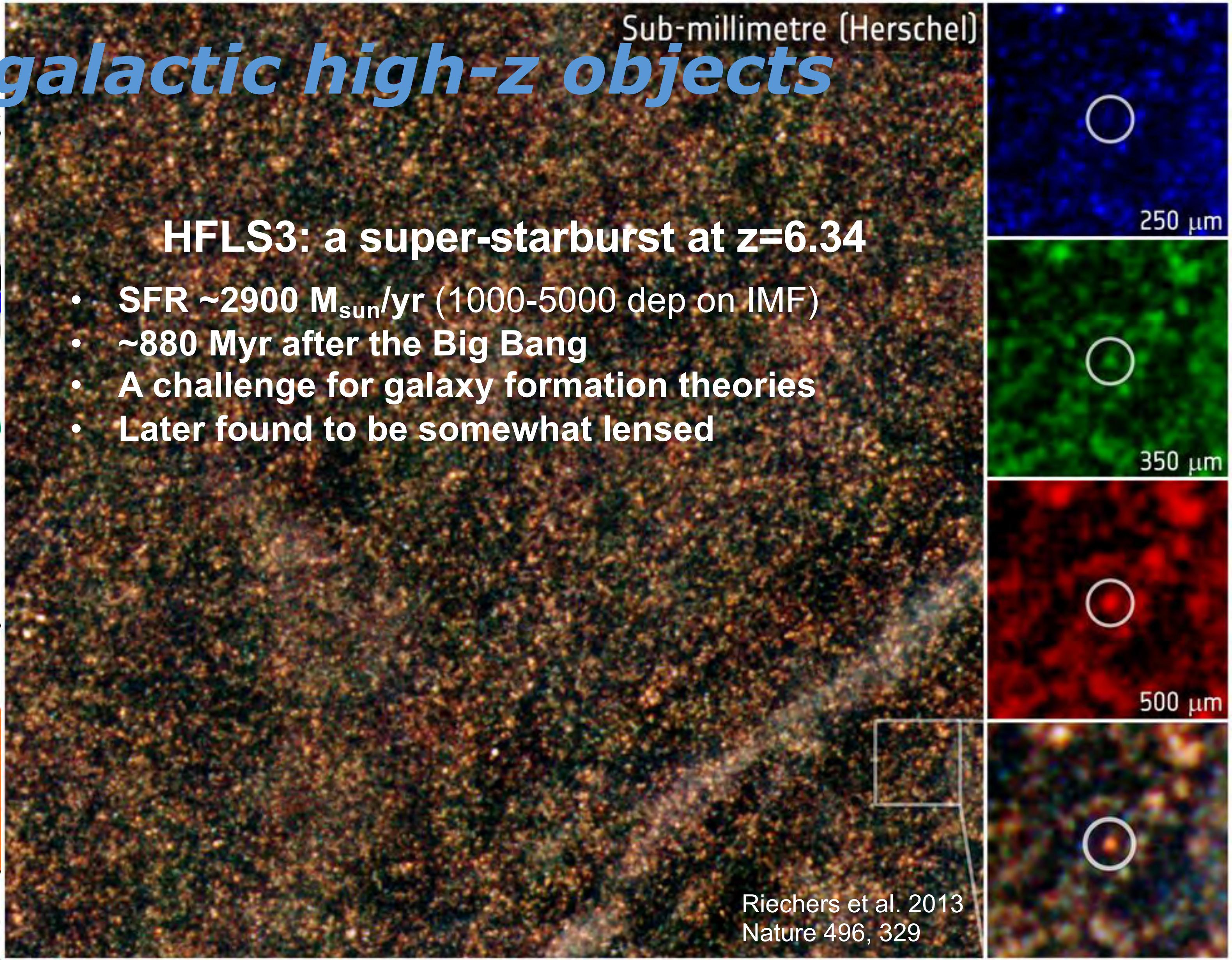


Riechers et al. 2013
Nature 496, 329

Extragalactic high-z objects



Lutz, ARAA 2014

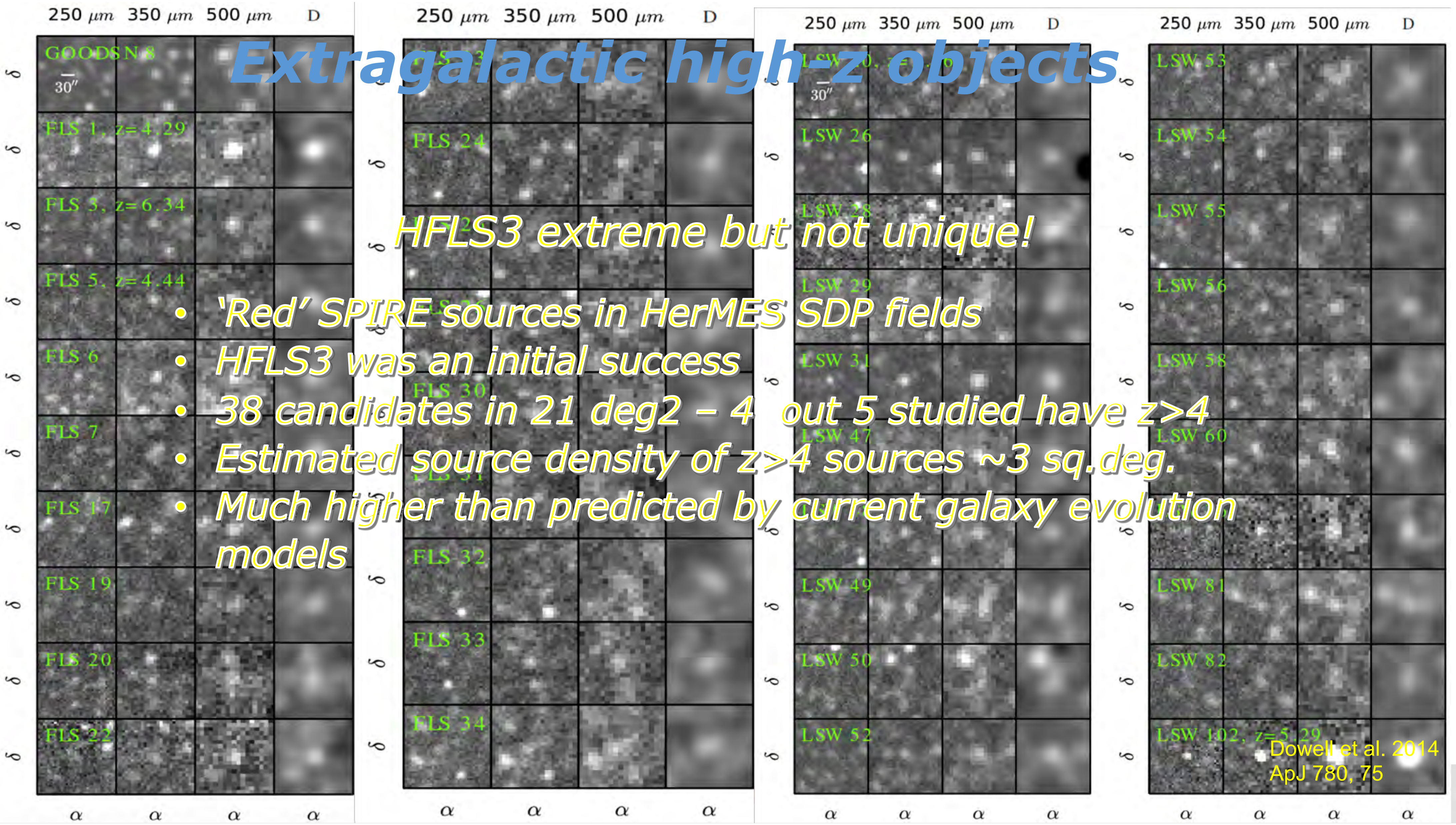


HFLS3: a super-starburst at z=6.34

- **SFR ~2900 M_{sun}/yr** (1000-5000 dep on IMF)
- **~880 Myr after the Big Bang**
- **A challenge for galaxy formation theories**
- **Later found to be somewhat lensed**

Riechers et al. 2013
Nature 496, 329

Extragalactic high-z objects

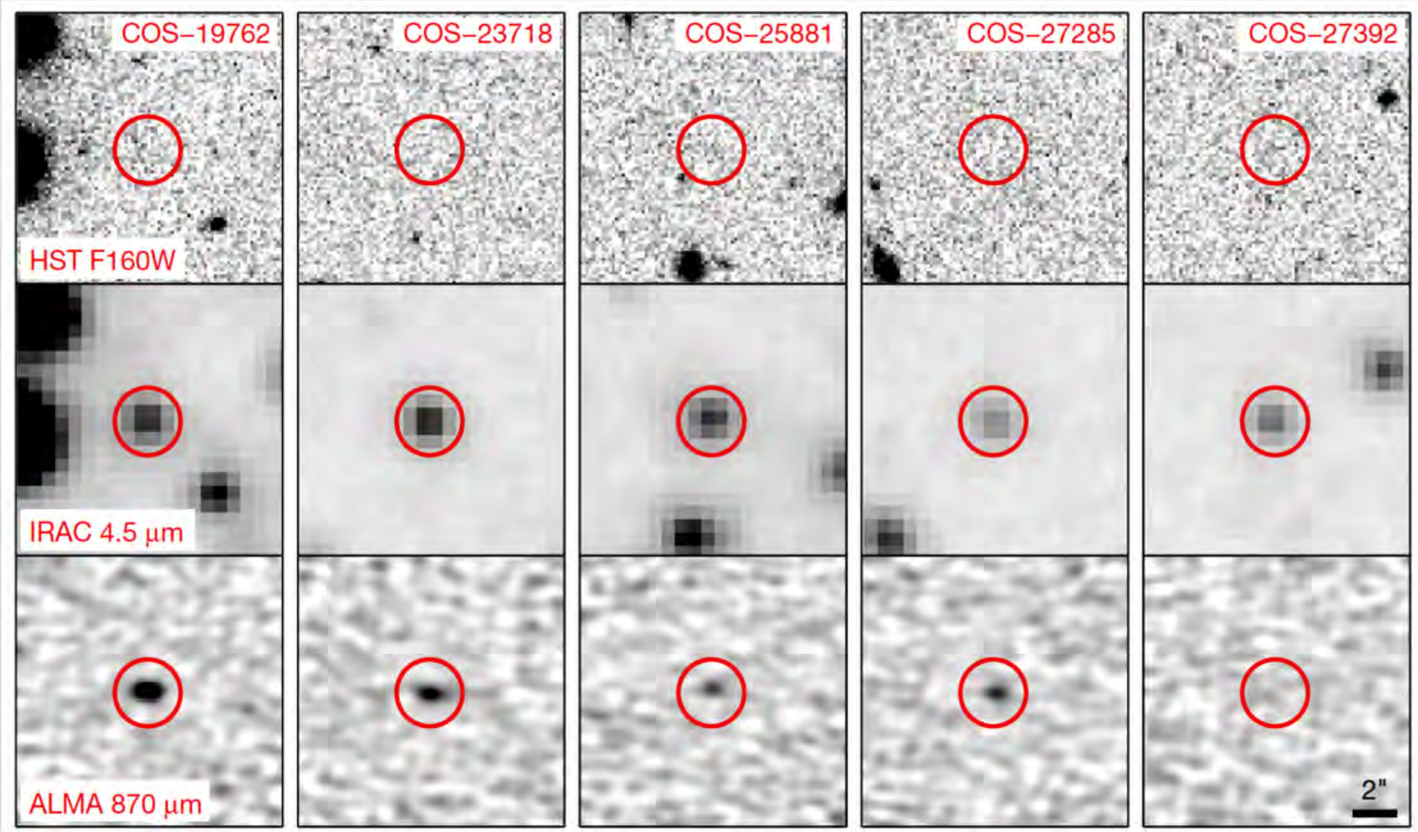


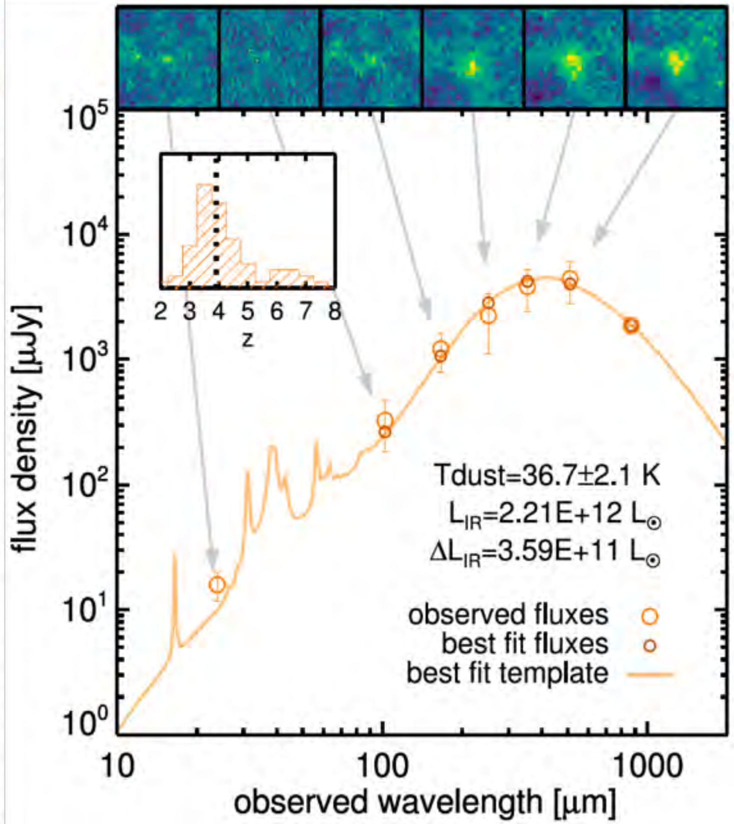
HFLS3 extreme but not unique!

- 'Red' SPIRE sources in HerMES SDP fields
- HFLS3 was an initial success
- 38 candidates in 21 deg2 – 4 out 5 studied have z>4
- Estimated source density of z>4 sources ~3 sq.deg.
- Much higher than predicted by current galaxy evolution models

Dowell et al. 2014
ApJ 780, 75

Very recently ALMA





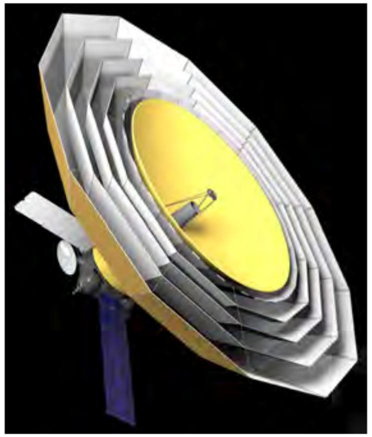
- ALMA at 870 μm of 'H-drop-outs', ~530 deg^{-2}, SFR ~200 $M_{\odot} yr^{-1}$
- Contribute 10x SFR density of UV-bright galaxies z>3

Wang et al. 2019 Nature 572, 211

High-z objects

Herschel photometry

- Cosmic IR background essentially resolved
- Tip-of-the-iceberg z~4-6+ extreme starburst (>1000 $M_{\odot}yr^{-1}$) galaxy population unexpectedly detected – confusion important
- ALMA detection of underlying z~4 bulk (~200 $M_{\odot}yr^{-1}$) population
- Galaxy SF-ing 'main sequence' – with outliers at each z



Millimetron photometry

- Raw sensitivity 1-3+ orders of magnitude better
- Requires 'good enough' instruments/detectors
- Need confusion simulations
- Want to study underlying 'bulk' population at all z – star formation as function of z, …
- Make friends with ALMA

High-z objects

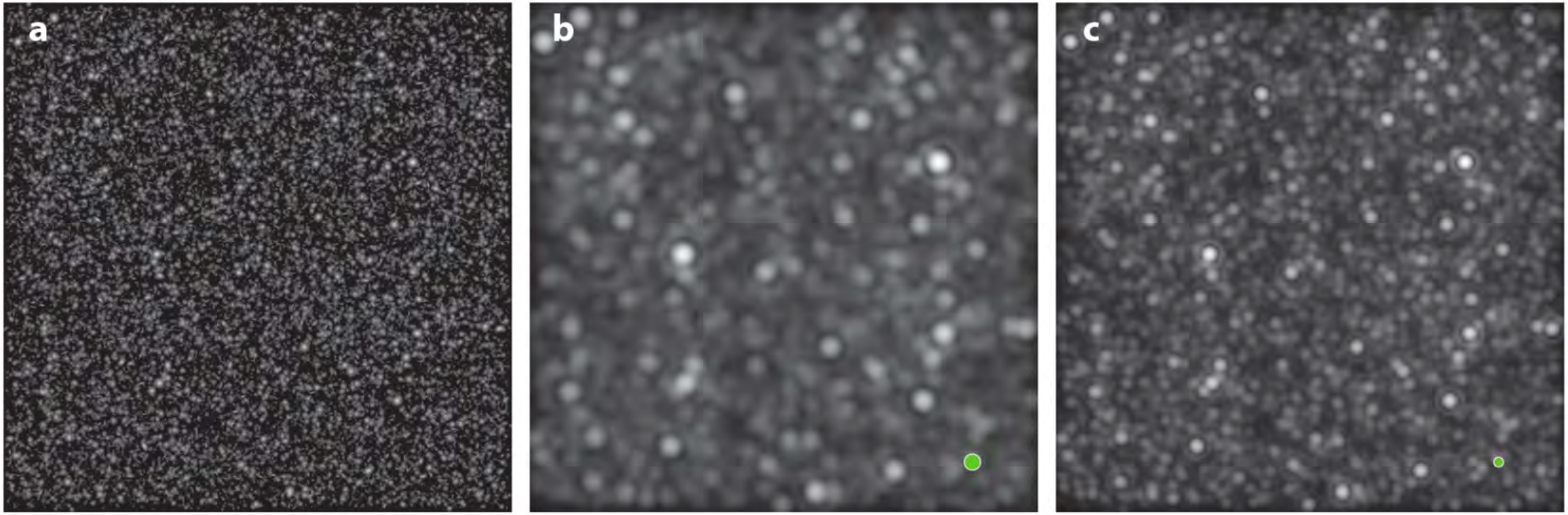
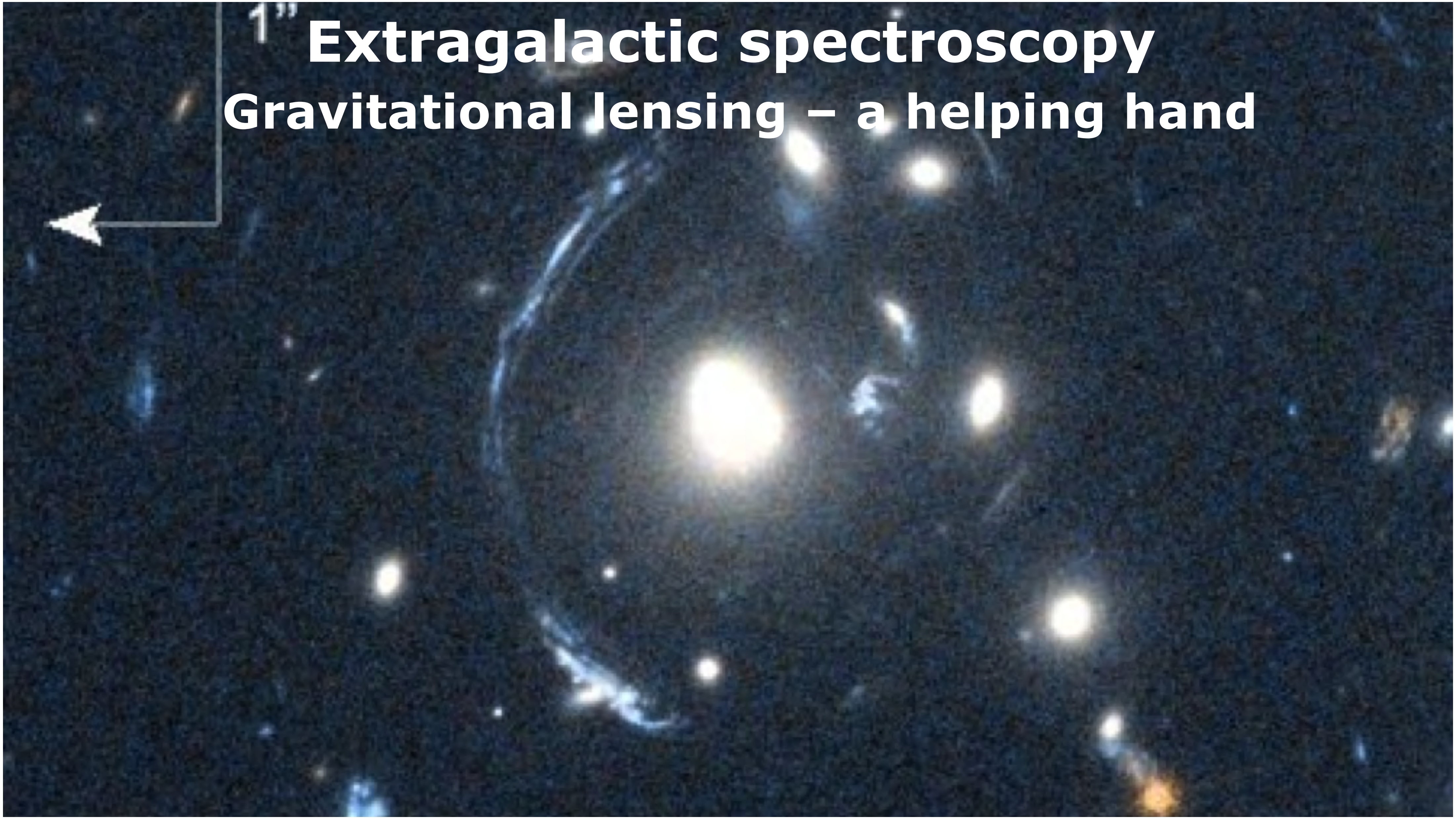


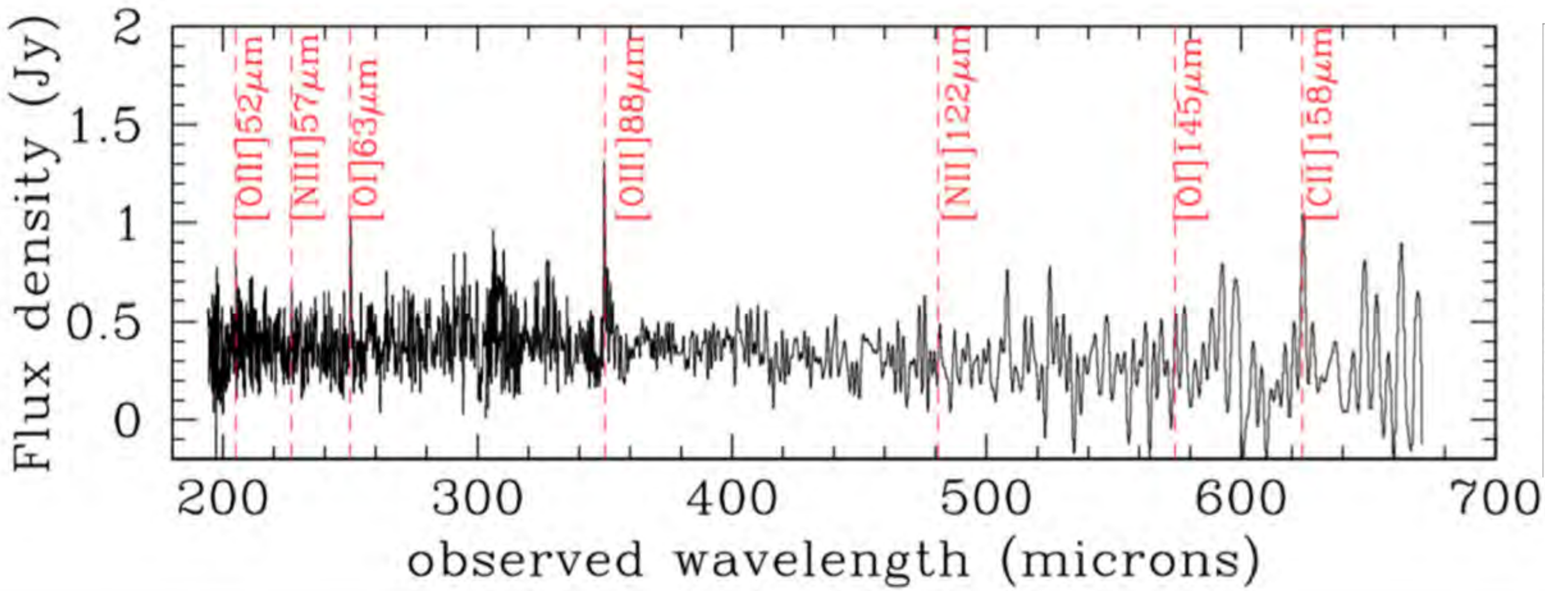
Figure 1-20: *Origins* has a deeper confusion limit than Herschel. a) Sky simulation of 9.5 arcmin x 9.5 arcmin at 250 µm, matched to the FoV of the FIP instrument. b) The same map convolved with Herschel/SPIRE 250 PSF. c) The expected *Origins*/FIP 250 µm map over the same area showing the substantial improvement in the source identification and the depth of continuum imaging data relative to previous Herschel/SPIRE surveys. Green circles to the bottom right show the PSF size.

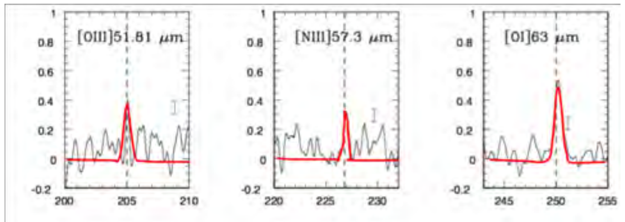
Extragalactic spectroscopy

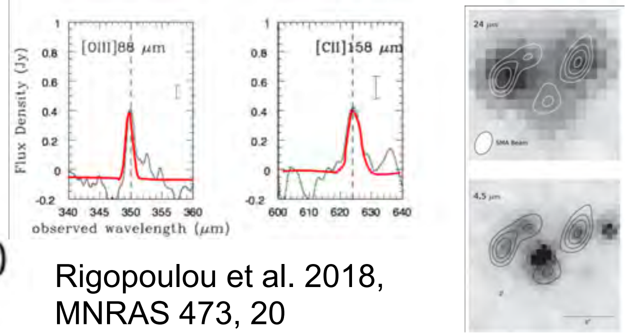
Gravitational lensing – a helping hand



Spectroscopy







Rigopoulou et al. 2018, MNRAS 473, 20

- Herschel SPIRE/FTS 4 hr single pointing on HLSW-01 – brightest lensed HerMES source
- Redshift z~3 (2.9574), magnification μ = 10.9 ± 0.7
- Herschel/SPIRE fluxes at 250/350/500 μm 425/340/233 ± 10 mJy   Conley et al. 2011, ApJL 732, L35
- SMA at 880 μm resolve into four components 53 ± 0.5 mJy

Molecular outflows

SHINING local ULIRG sample

Mrk 231:

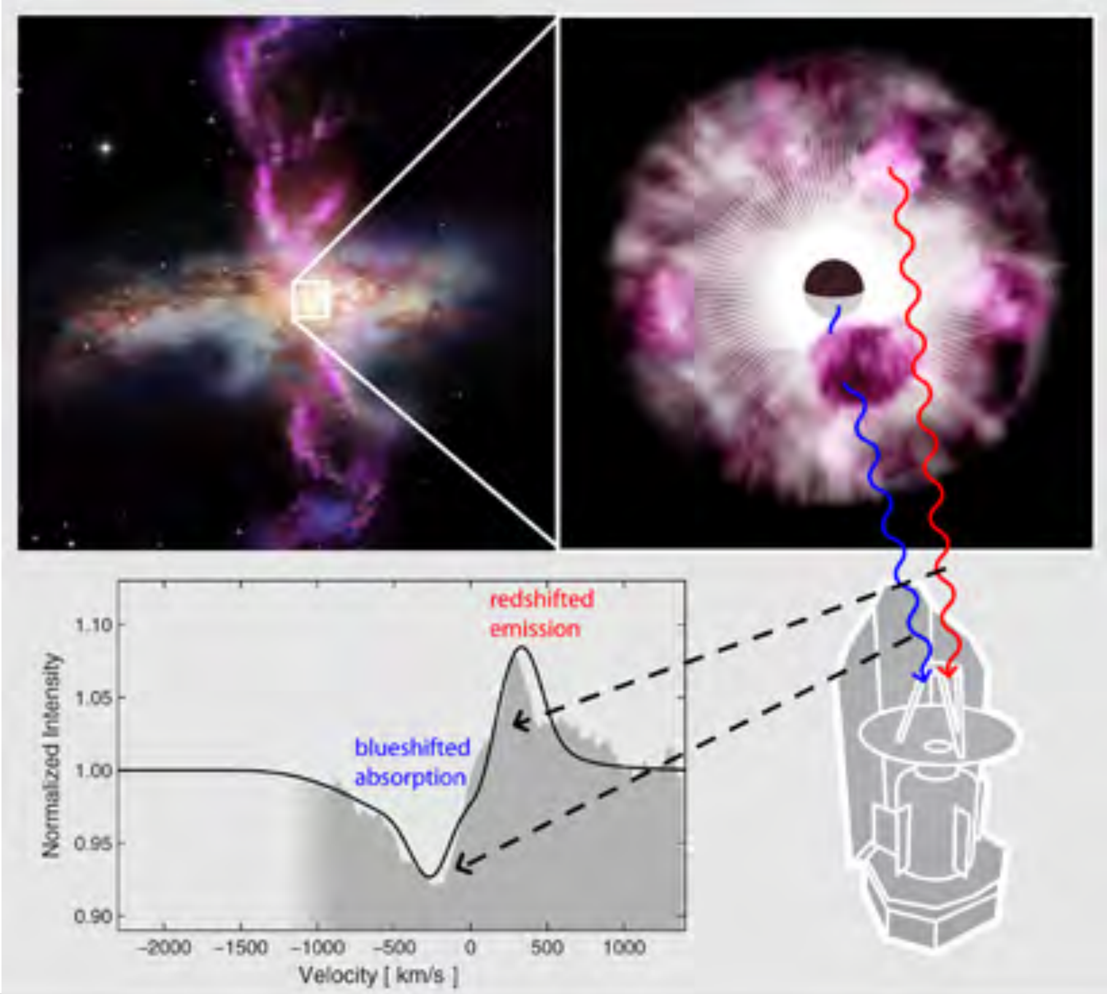
$L_{IR} = 3.2 \times 10^{12} L_{\odot}$ (70% AGN)

P-Cygni profile with blue-shifted absorption and red-shifted emission

$\Delta v \sim 1170$ km/s

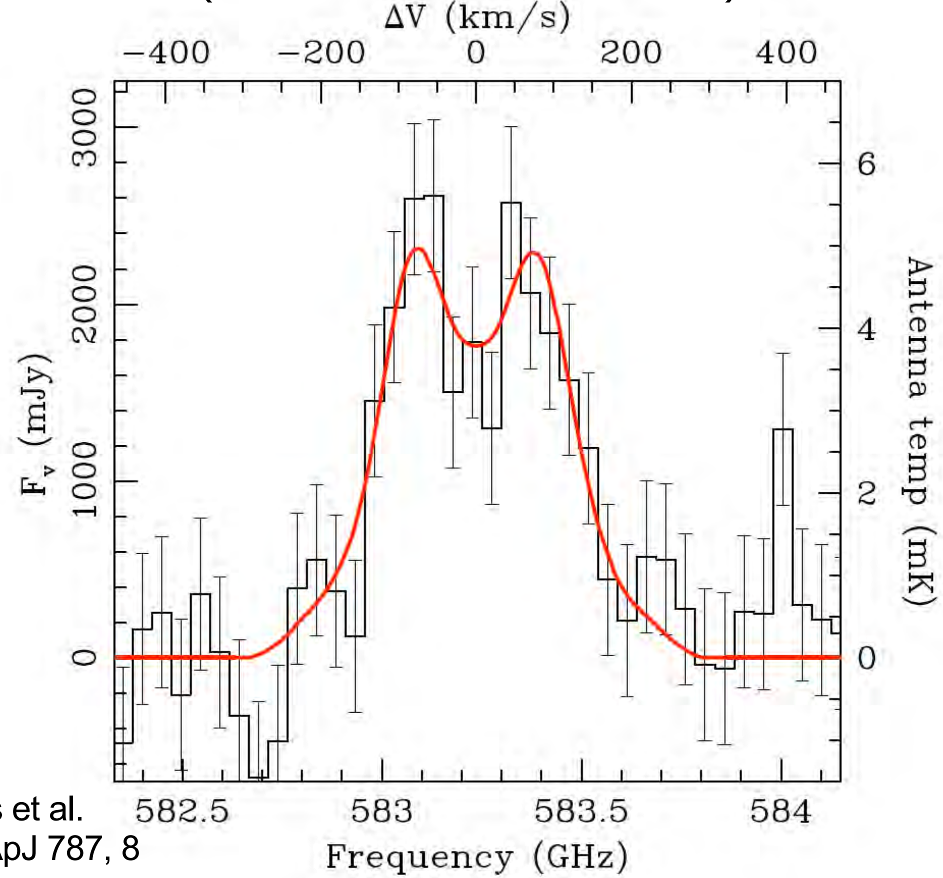
Depletion timescale $M_{gas}/\dot{M}$ $\sim 4 \times 10^{6}$ yr

Sturm et al. 2011; ApJL 733, L16



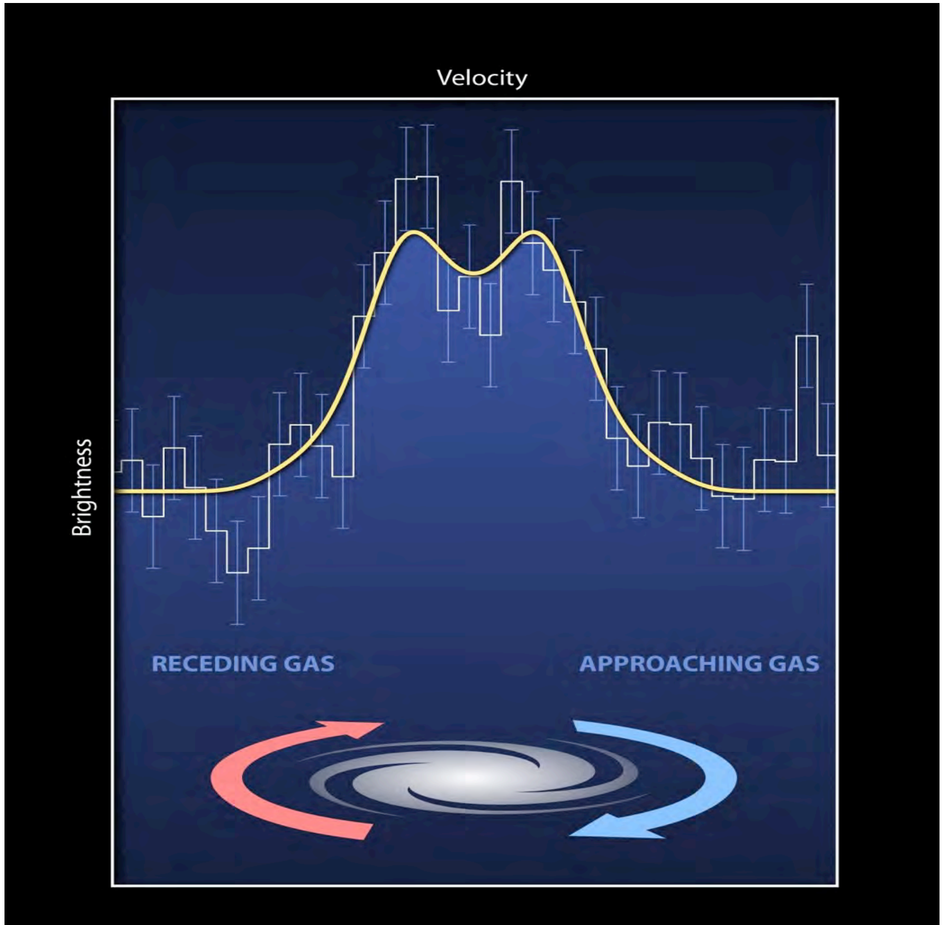
Kinematics

S0901 at z=2.2558
(SDSS090122.37+181432.3)



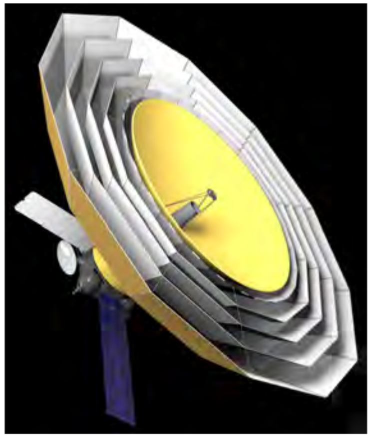
Rhoads et al. 2014; ApJ 787, 8

Herschel/HIFI band 1b C[II] observations, 885 s onsource



HELLO: Herschel extreme lensing line obs

Extragalactic spectroscopy



Herschel

High-z

- In general Herschel is not sensitive enough (FTS >200 mJy)
- Gravitational lensing can help – few objects & few lines

Low-z

- Studies of ISM – FIR cooling lines, CO ladders
- Massive molecular outflows in local ULIRGs (starbursts)

Nearby

- Detailed spatially resolved studies of ISM

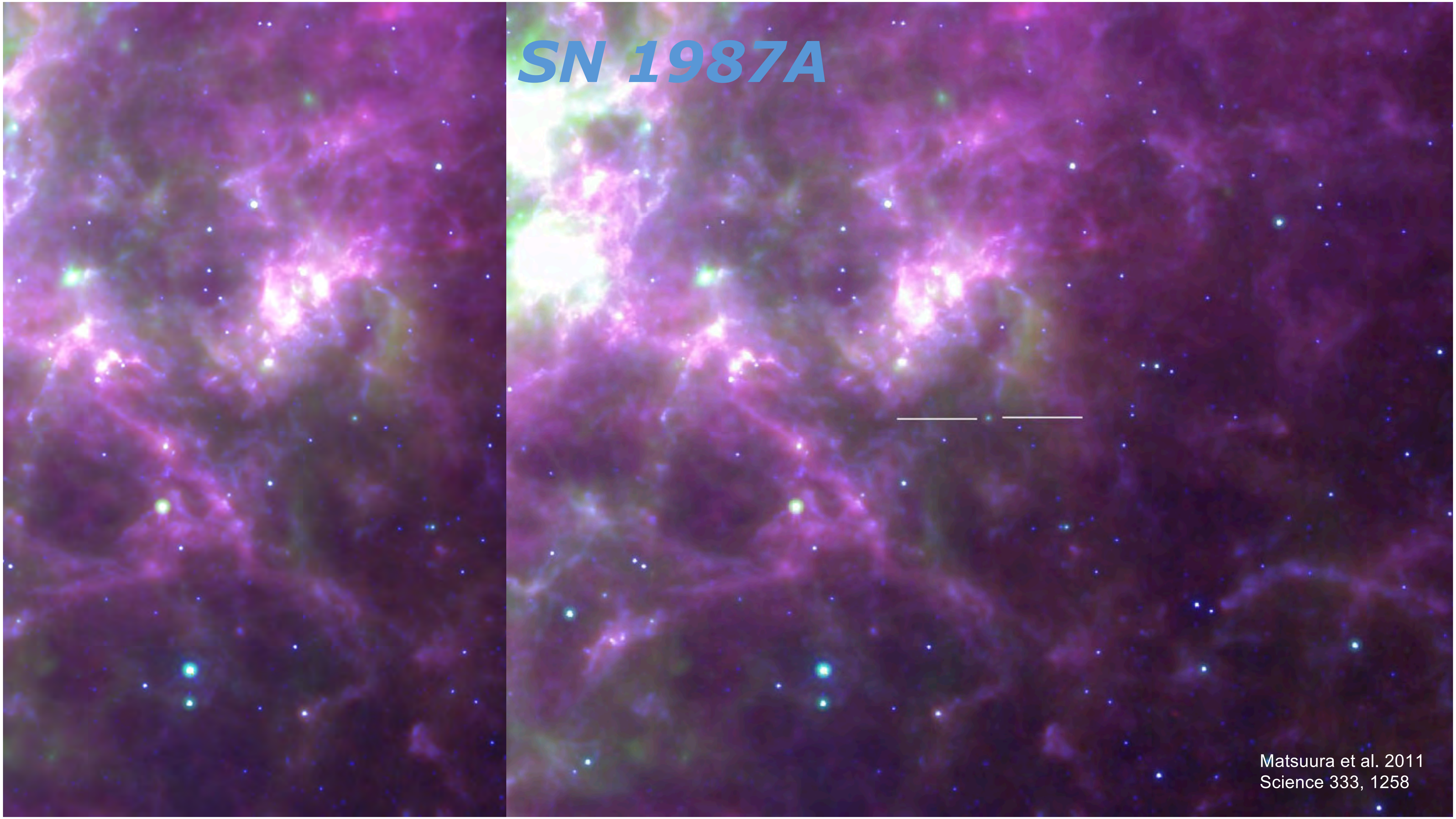
Millimetron

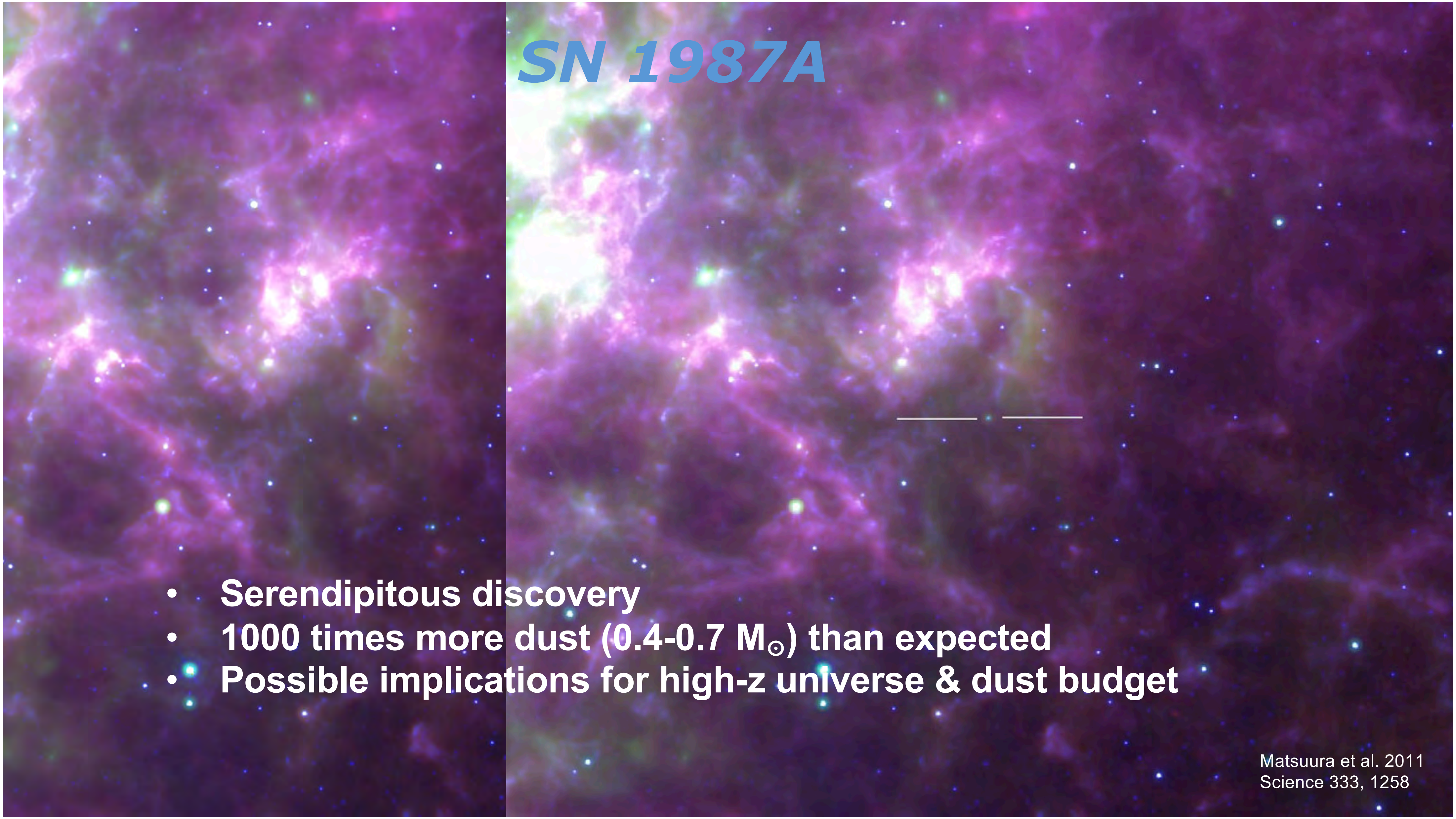
- Want to study ISM at ‘all’ redshifts – how do galaxies work
- Massive molecular outflows at ‘all’ z?
- How interesting is kinematics?
- Make friends with ALMA


Dust

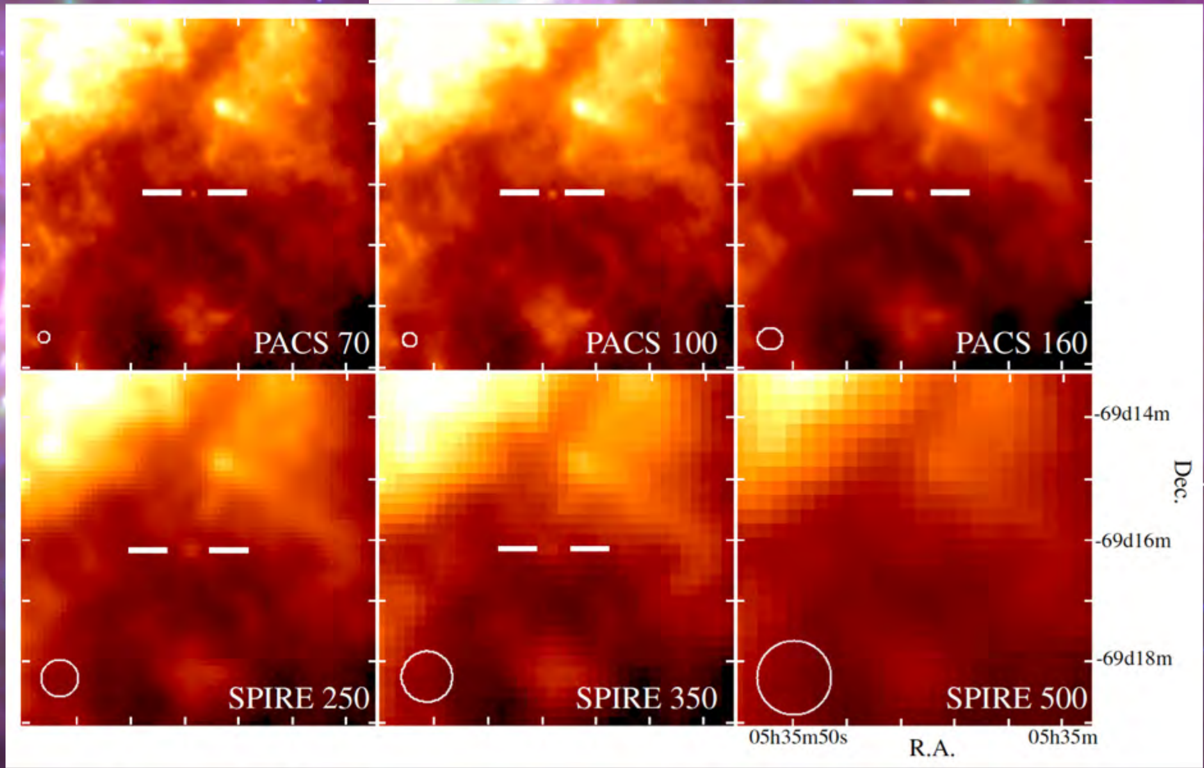

Betelgeuse


SN 1987A


SN 1987A
Matsuura et al. 2011
Science 333, 1258


SN 1987A
• Serendipitous discovery
• 1000 times more dust (0.4-0.7 $M_{\odot}$) than expected
• Possible implications for high-z universe & dust budget
Matsuura et al. 2011
Science 333, 1258

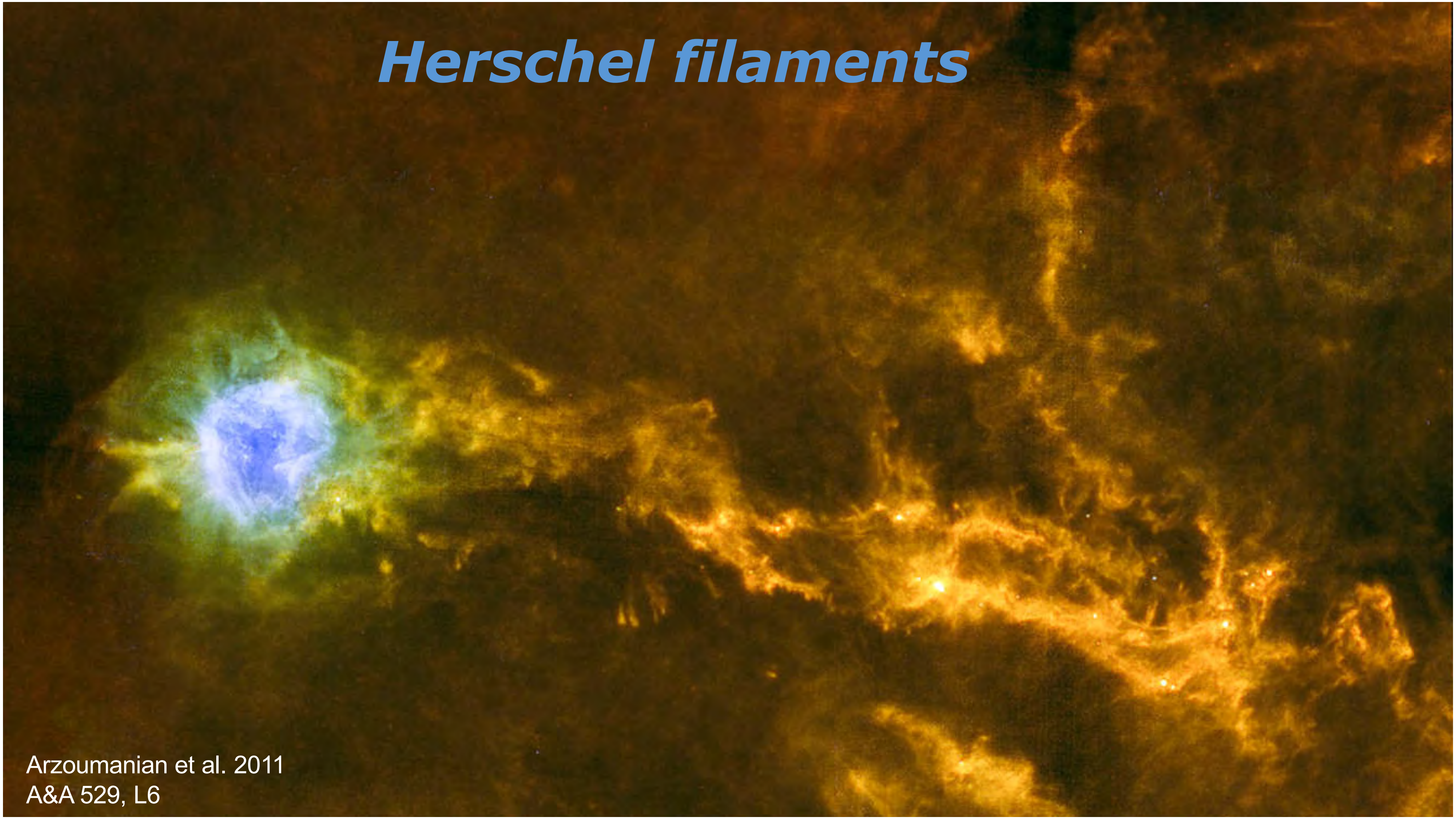
SN 1987A



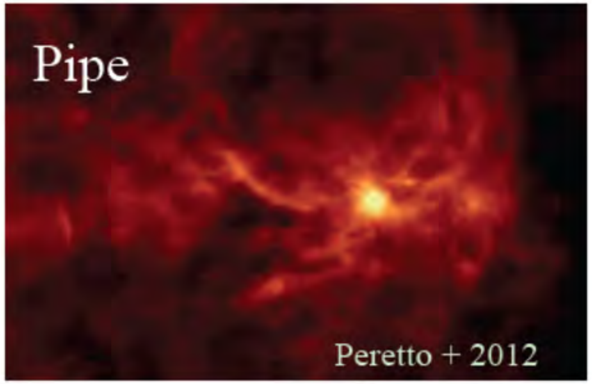
- Dedicated Herschel follow-up observations
- Model 0.8 $M_\odot$ (0.5 $M_\odot$ silicates & 0.3 $M_\odot$ amorphous) dust
- Longevity (shock destruction) unclear

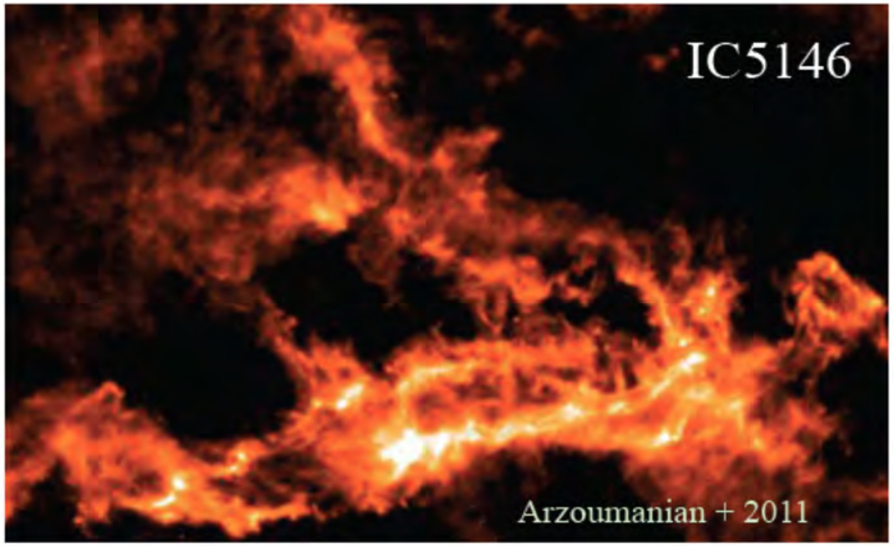
Matsuura et al. 2015
ApJ 800, 50

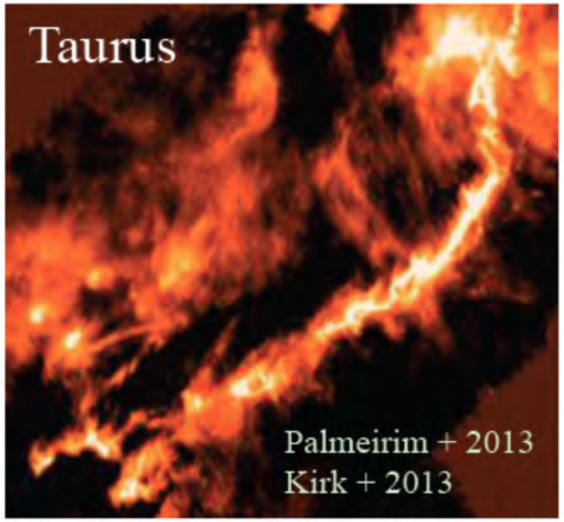

Galactic astronomy

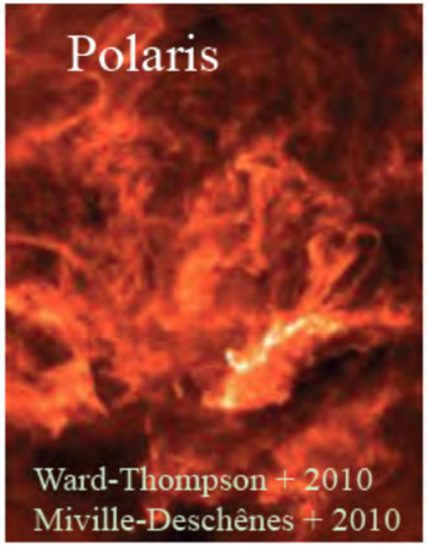

Herschel filaments
Arzoumanian et al. 2011
A&A 529, L6

Herschel reveals a “universal” filamentary structure in the cold ISM





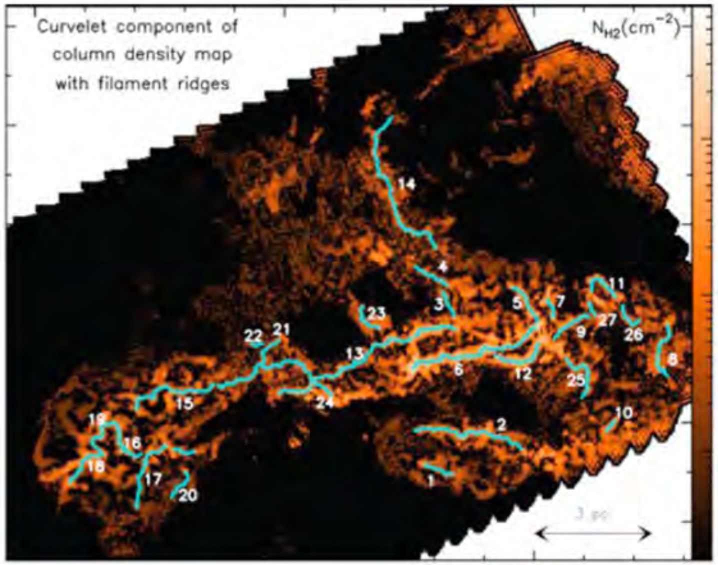




Filament formation

The turbulent fragmentation naturally fits the observed ~0.1 pc filament width => sonic scale of ISM turbulence

Network of filaments in IC5146

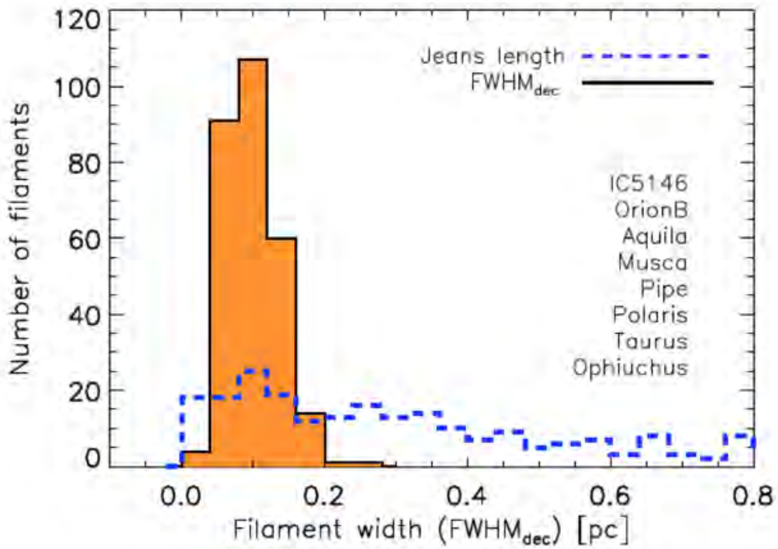


Arzoumanian et al. 2011

See also Arzoumanian et al. 2019; A&A 621, A42

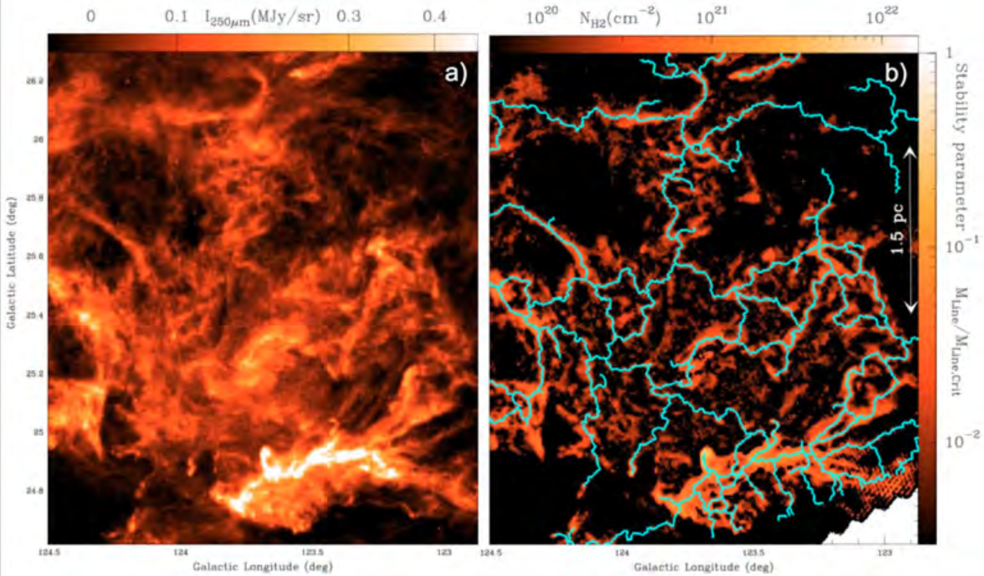
Using the DisPerSE algorithm (Sousbie 2011) to trace the ridge of each filament

278 filaments in 8 regions



➢ Consistent with the view that filaments form as a result of the dissipation of interstellar turbulence (cf. Padoan et al. 2001)

Filament fragmentation

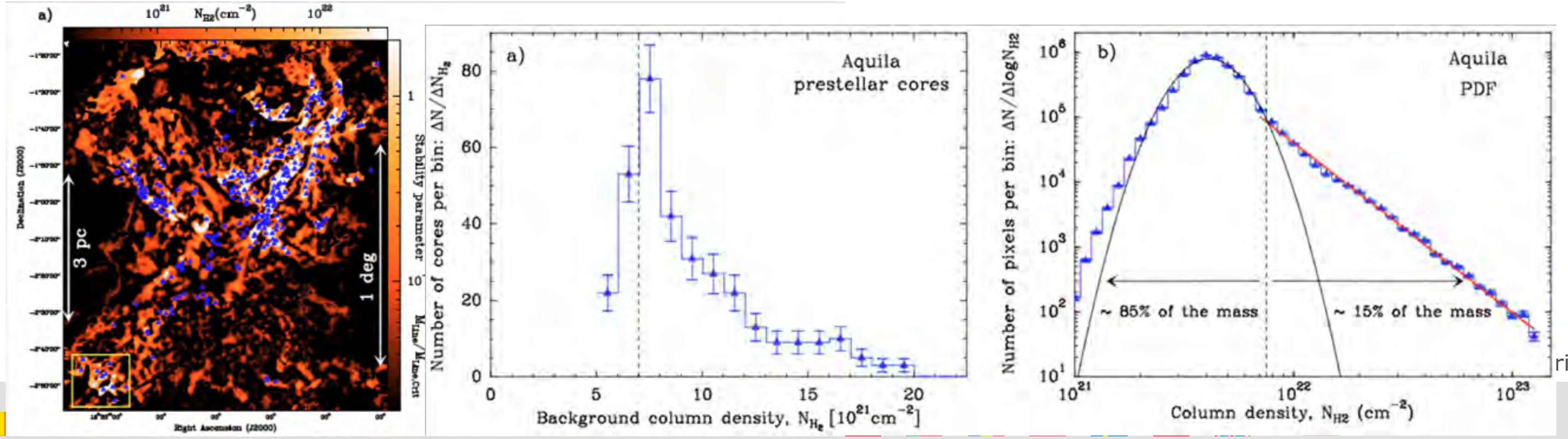


Polaris (left)

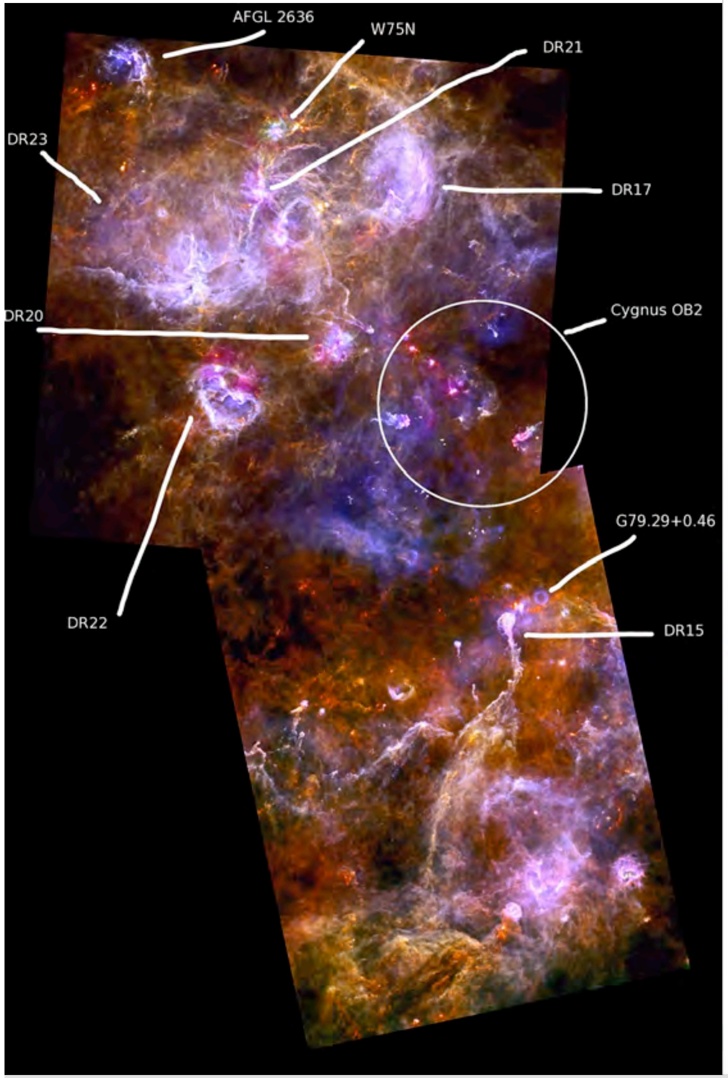
- Filaments – but no sign of star formation

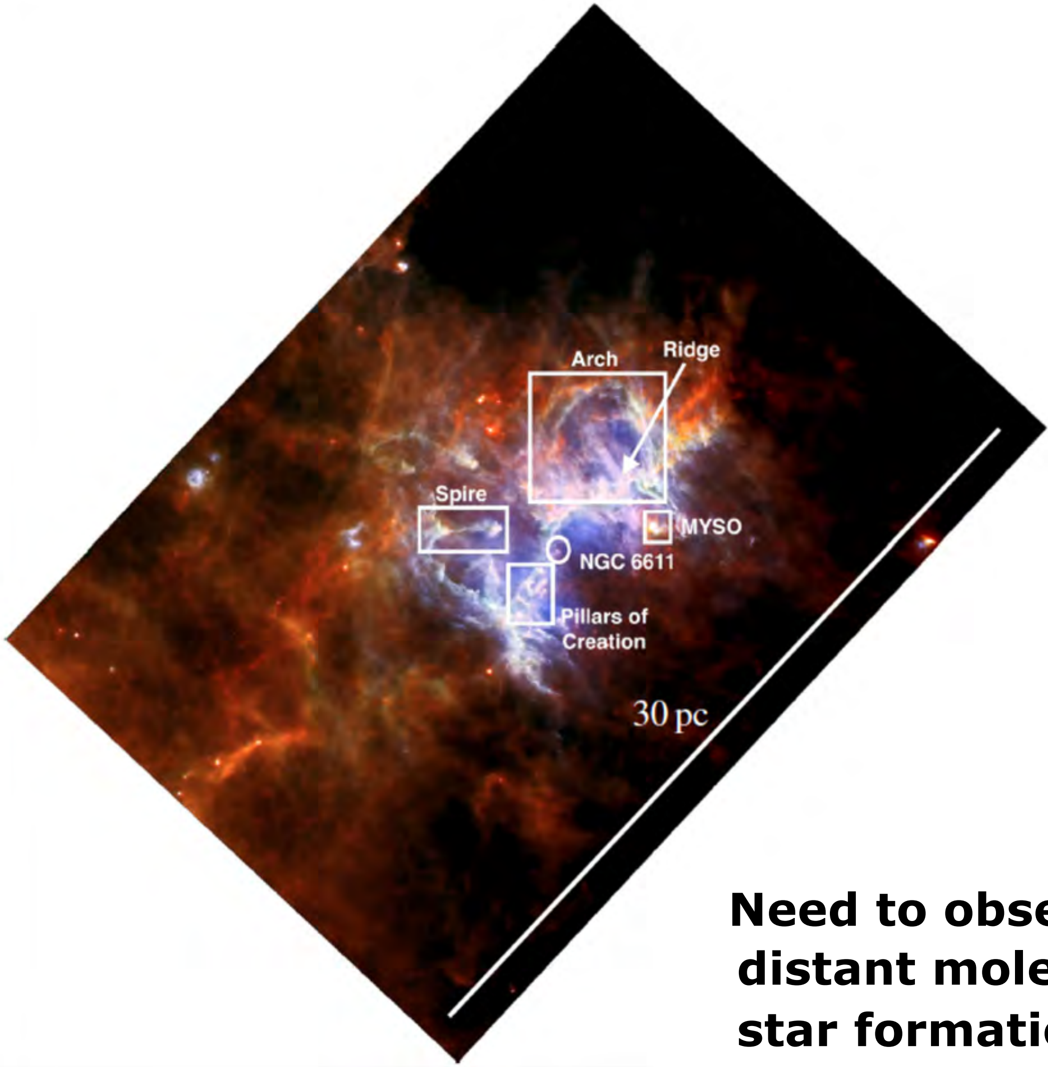
Aquila (below)

- Apparent ‘threshhold’ for pre-stellar cores Av~7
- PDF with power-law ‘tail’ – gravitation dominating over turbulence



High-mass star formation



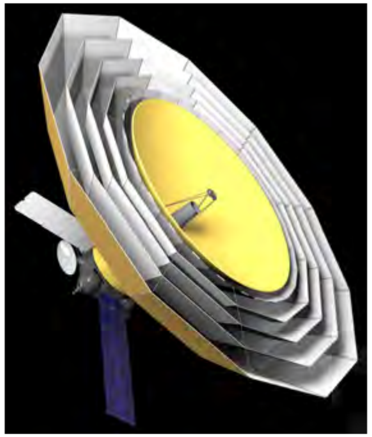


Need to observe more distant molecular clouds/ star formation regions

Filaments

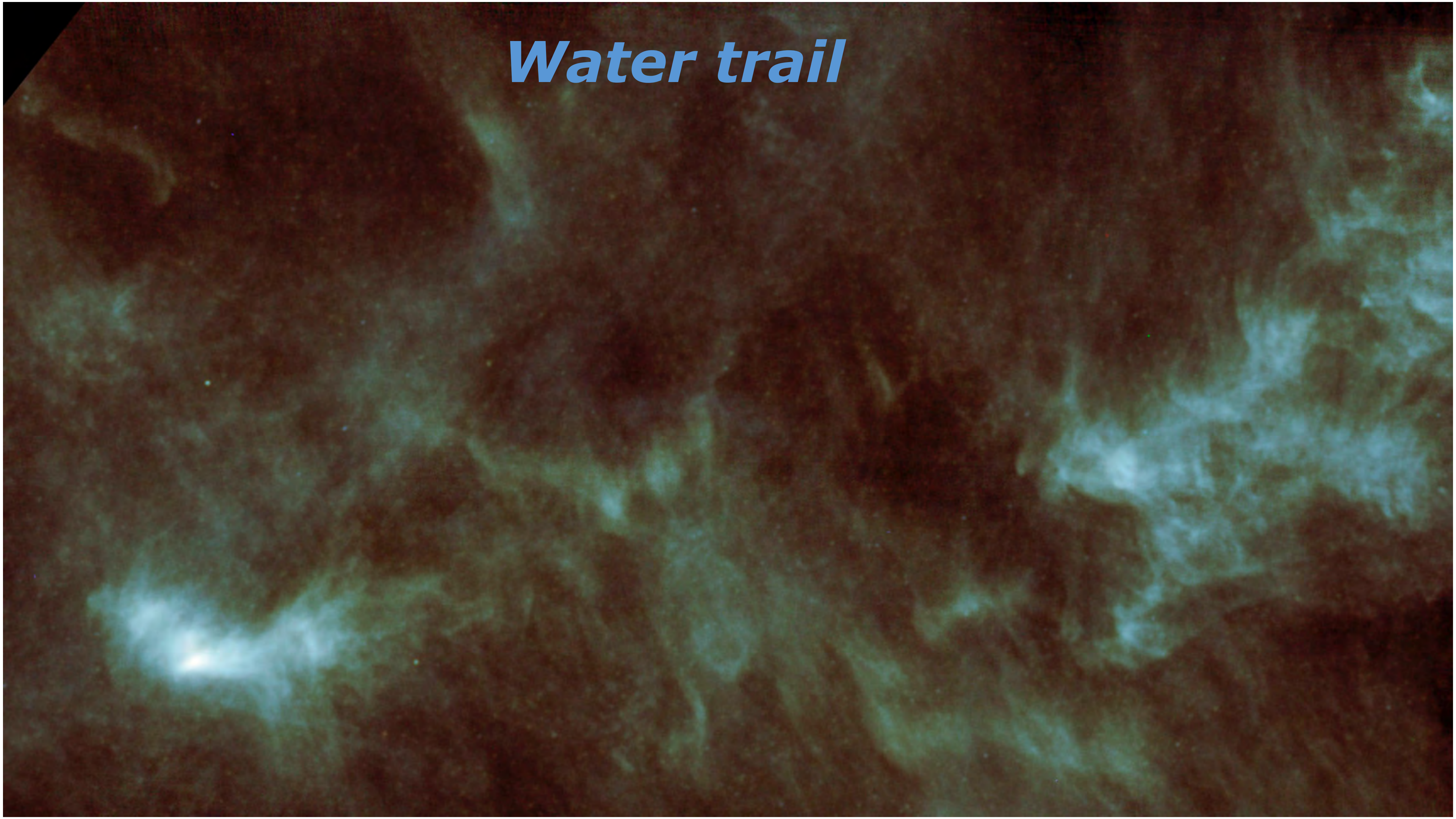
Herschel

- Established filaments ‘everywhere’ – ’universal’ structure
- Most forming stars appear connected to filaments
- Threshold for star formation
- Connection CMF and IMF – handle on SF ‘efficiency
- Filament formation & fragmentation – still many questions

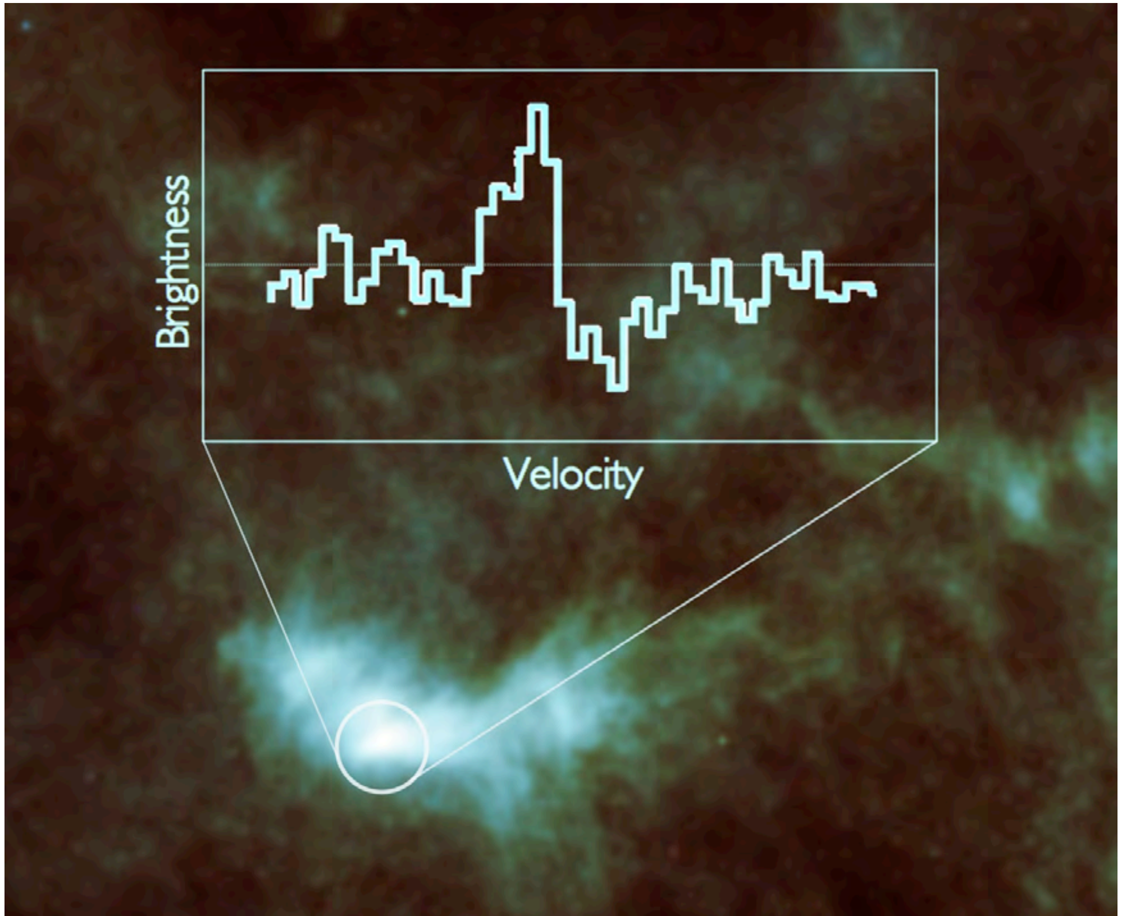


Millimetron

- High(er) angular resolution – more distant (high-mass SF) MCs
- High(er) spatial dynamic range
- Sensitivity to low surface brightness
- Polarimetry – survey of MCs – role(?) of magnetic fields in filament formation and fragmentation
- Make friends with ALMA


Water trail

Water trail – L1544

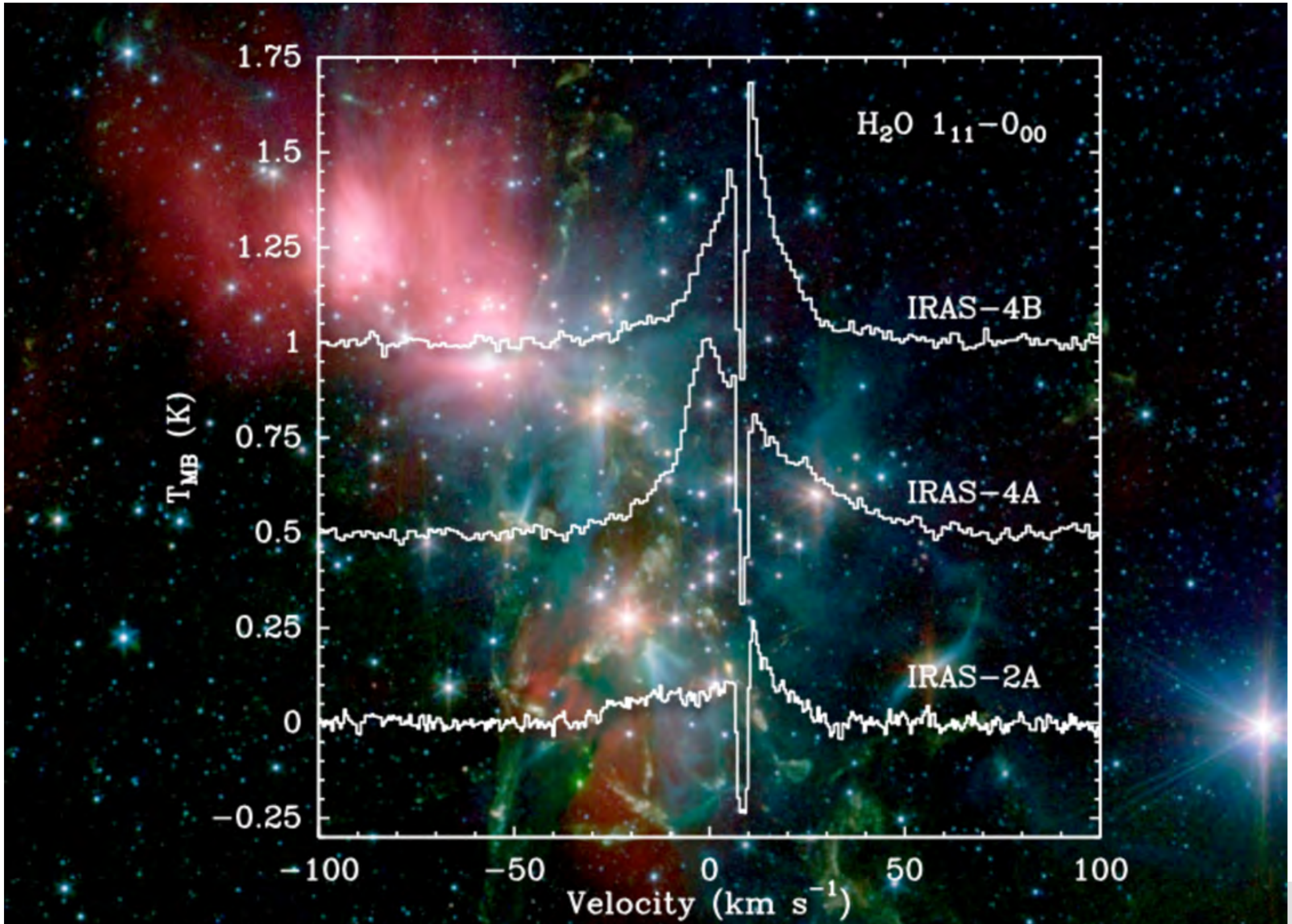


Caselli et al. 2012; ApJL 759, L37

First detection of water vapour in pre-stellar core

- 13.6 hr of HIFI observations at the ground-state 557 GHz (1_{10}-1_{01} line)
- ~2000 'earth oceans' as water vapour
- ~3 million 'eo' as water ice on dust
- Vapour liberated by UV radiation, created by ionising particles colliding with H_2 molecules
- Line profile indicates infall at 1000 AU

Water trail – protostars



Kristensen et al. (2010, 2012), Mottram et al. (2014)

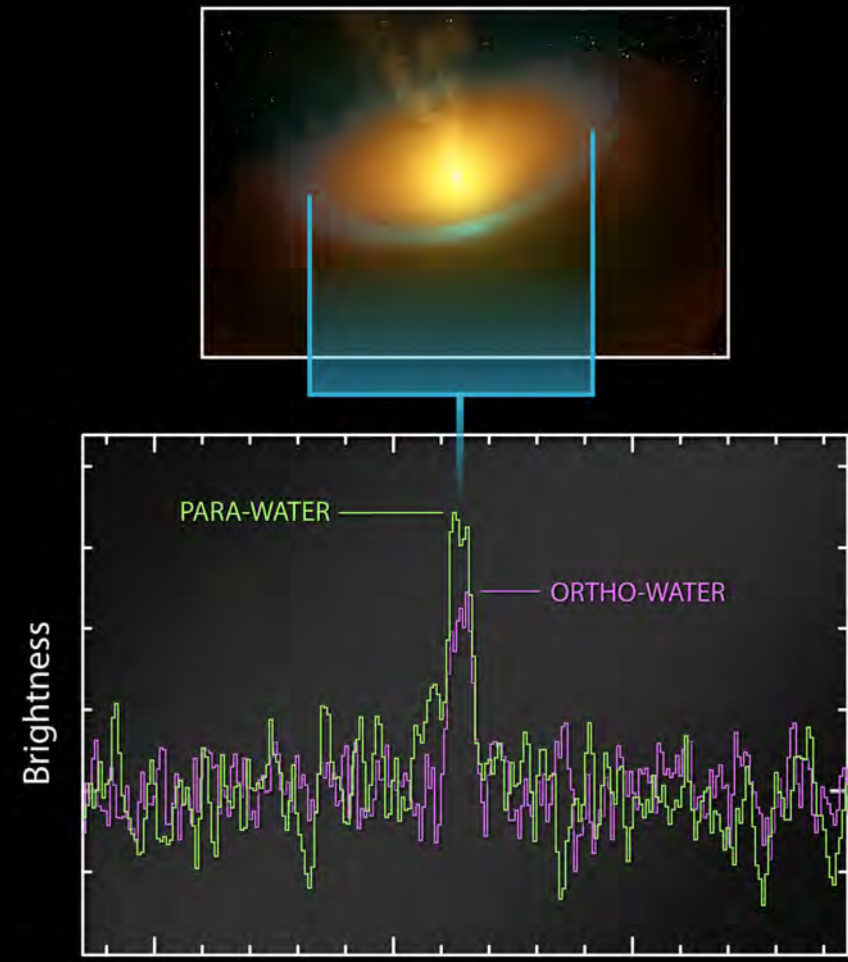
Water ubiquitous in protostars

- Multiple lines
- Multiple components, bulk emission in:
  - Envelope (em & abs)
  - Broad outflows
  - 'Bullets'
- Complex sources
- Additional lines e.g. CO
- Velocity resolved lines necessary for interpretation

Water in disk of TW Hya

- TWHya: ~55 pc, ~ 12 Myr, ~0.6M_{sun}
- Water vapour ~0.05 ‘earth oceans’
- Water ice ~x1000 ‘earth oceans’
- On source int time 181 min at 557 GHz
- On source int time 326 min at 1113 GHz

Hogerheijde et al. 2011
Science 334, 338

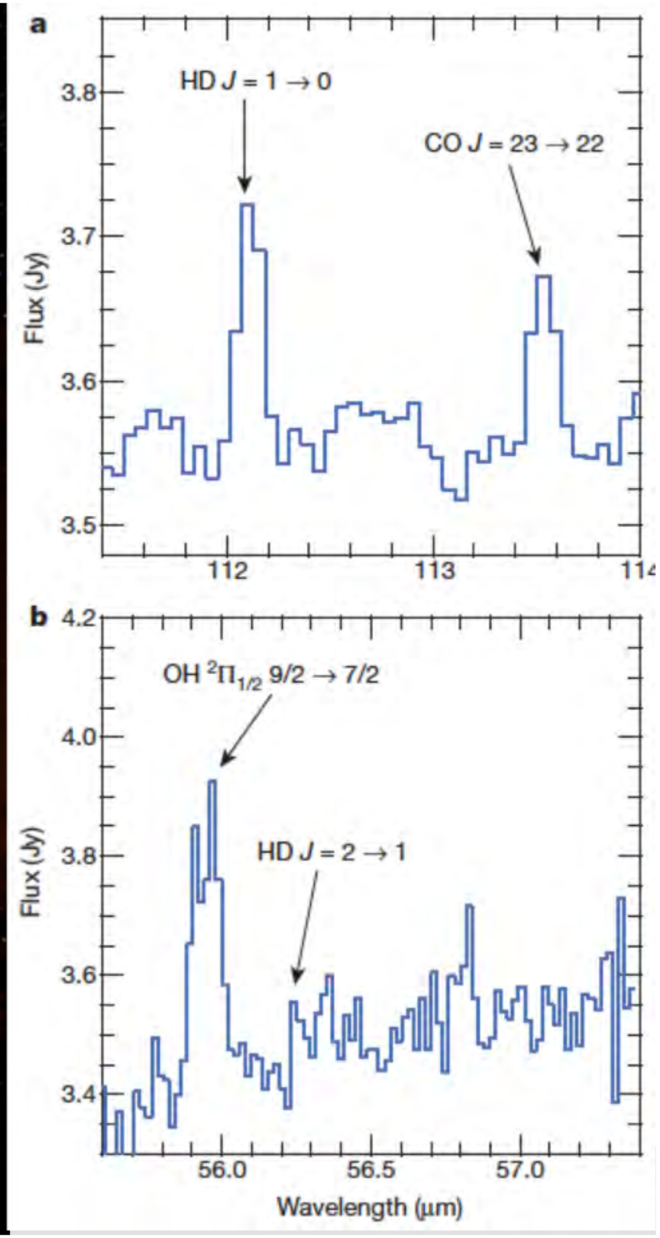


HIFI Spectroscopic Signatures of Water Vapor in TW Hydrae Disk
ESA/NASA/JPL-Caltech/M. Hogerheijde (Leiden Observatory)

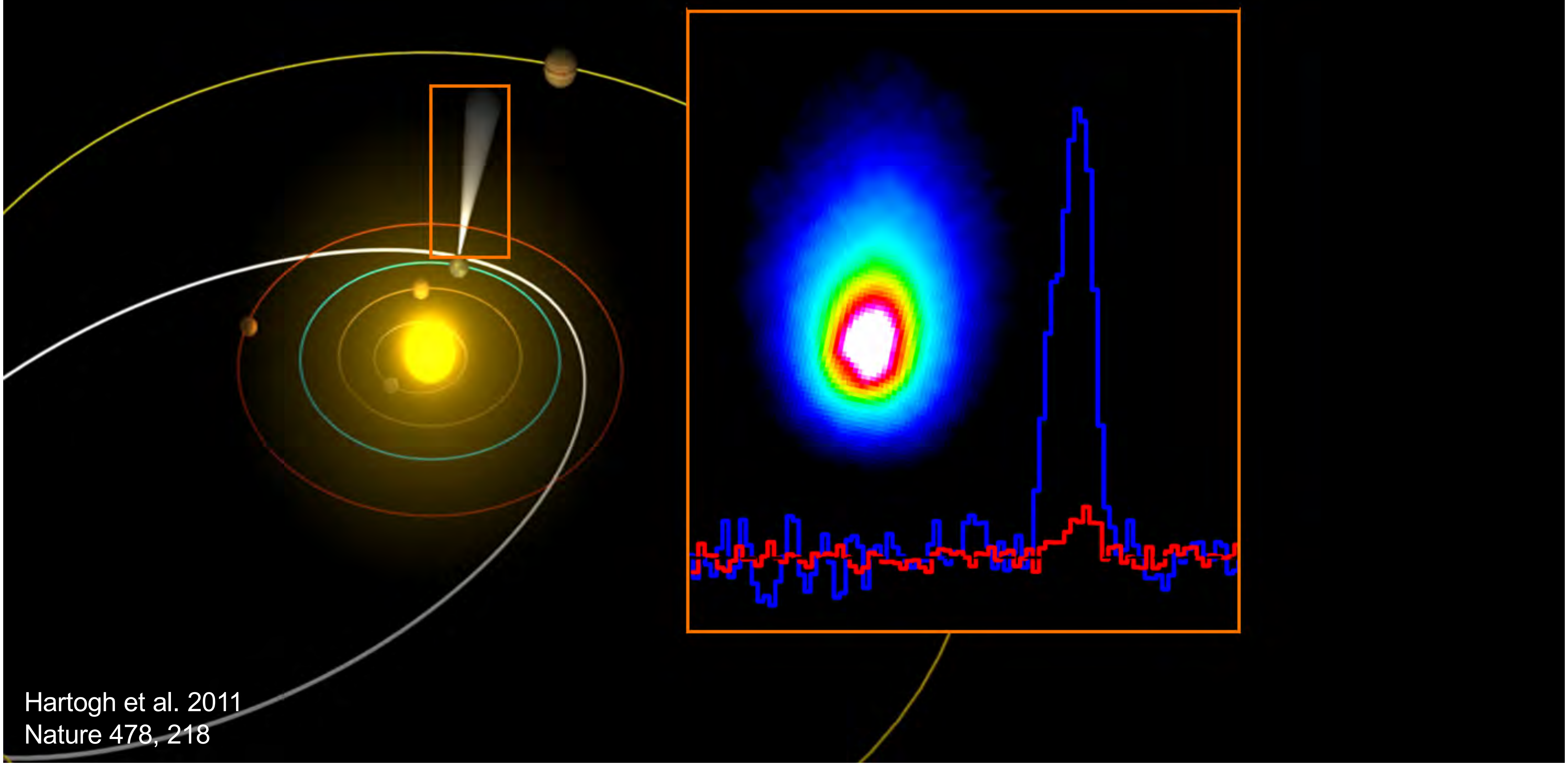
HD (112 μm) in disk of TW Hya

- TWHya: ~55 pc, ~ 3-10 Myr, ~0.6 M_{sun}
- Disk mass 0.0005-0.06 M_{sun}
- Hogerheijde et al. assumed 0.02 M_{sun}
- This work: 0.06 M_{sun}
- => greater water reservoir ~x2

Bergin et al. 2013
Nature 493, 644

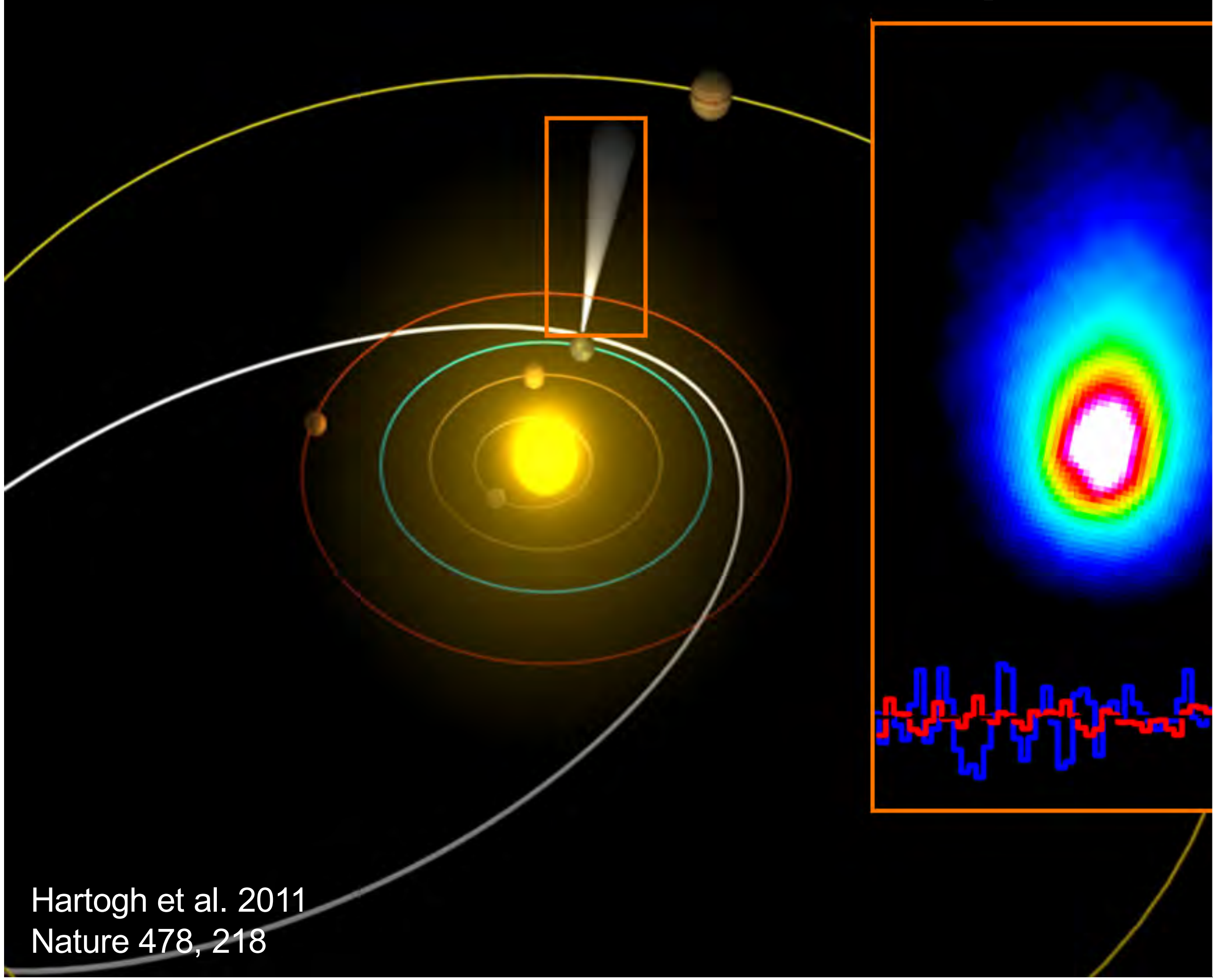


Water in comet 103P/Hartley 2

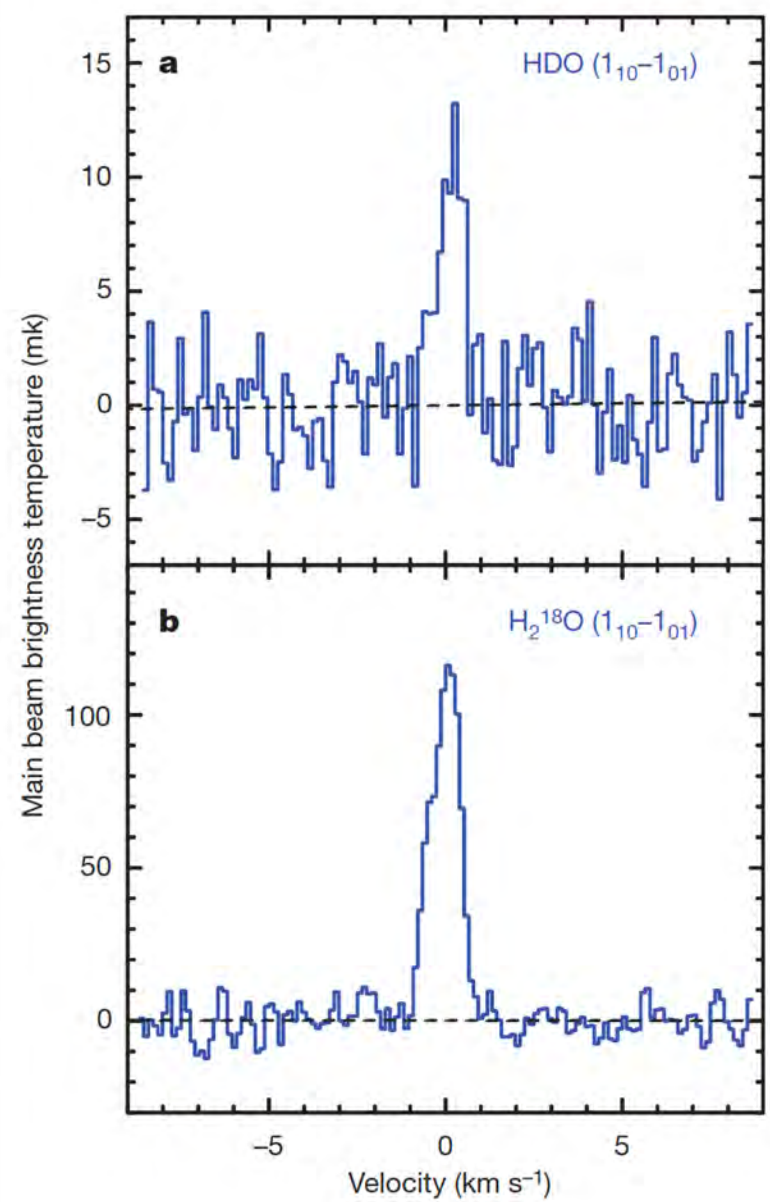


Hartogh et al. 2011
Nature 478, 218

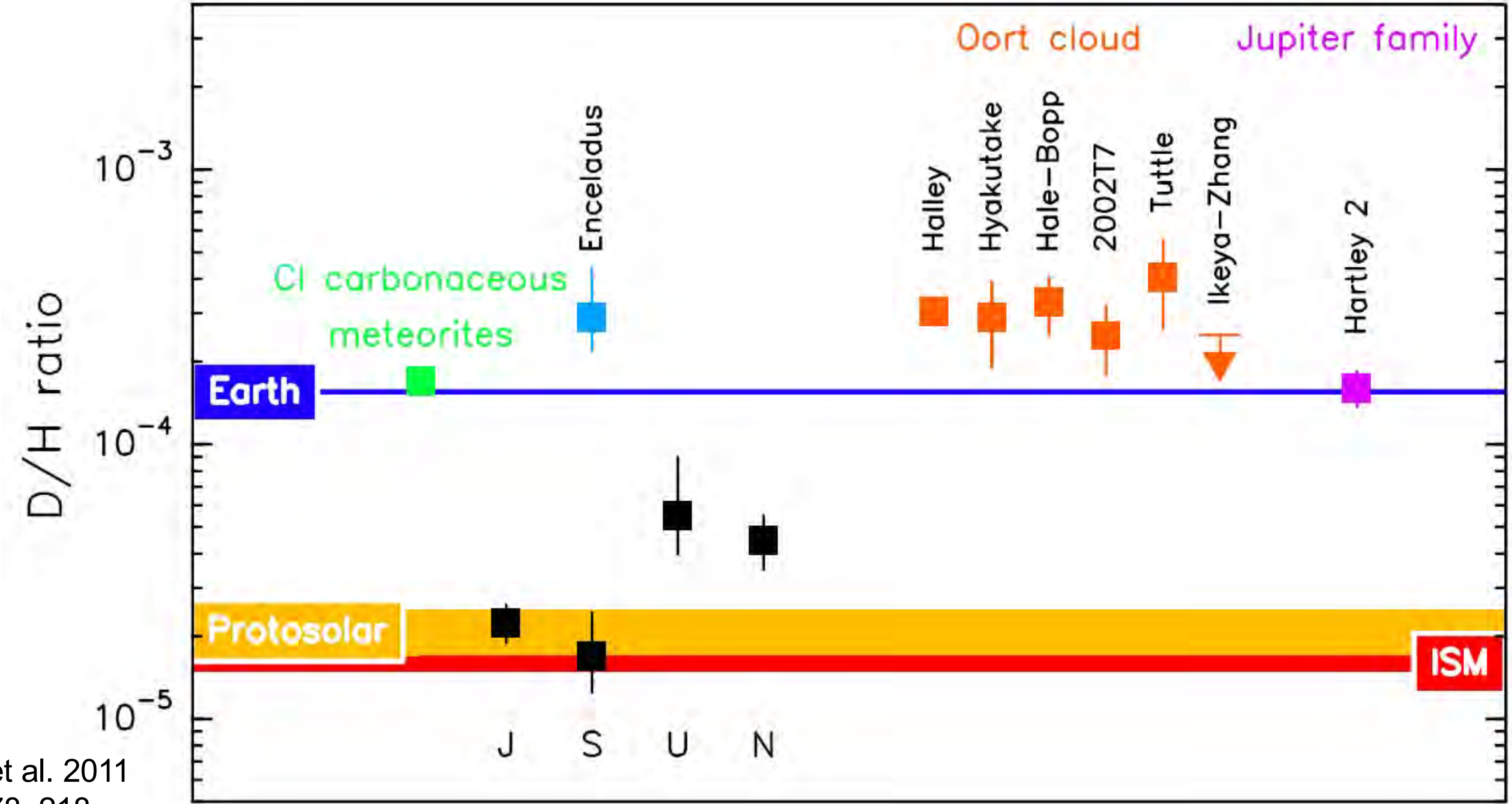
Water in comet 103P/Hartle



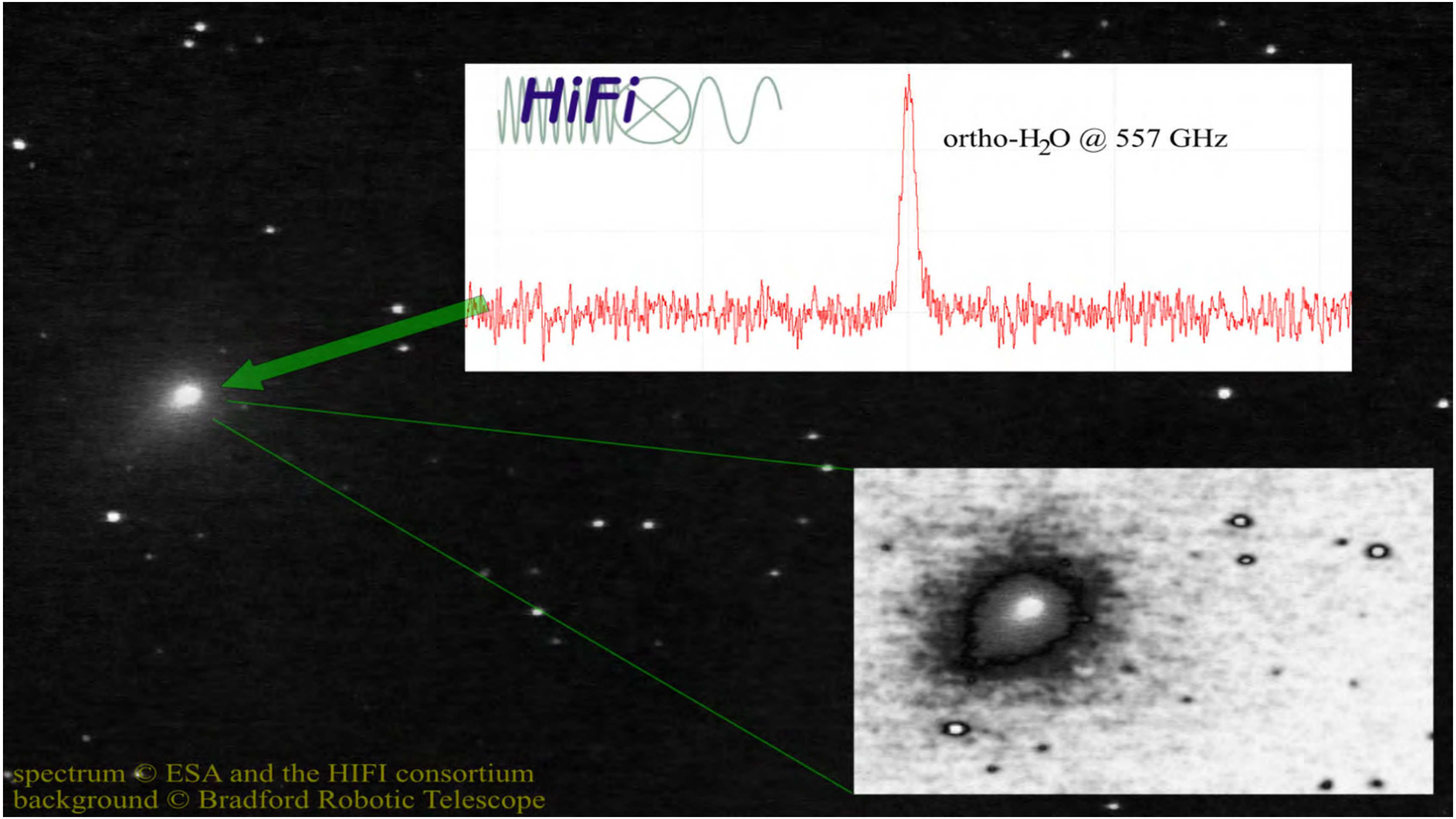
Hartogh et al. 2011
Nature 478, 218



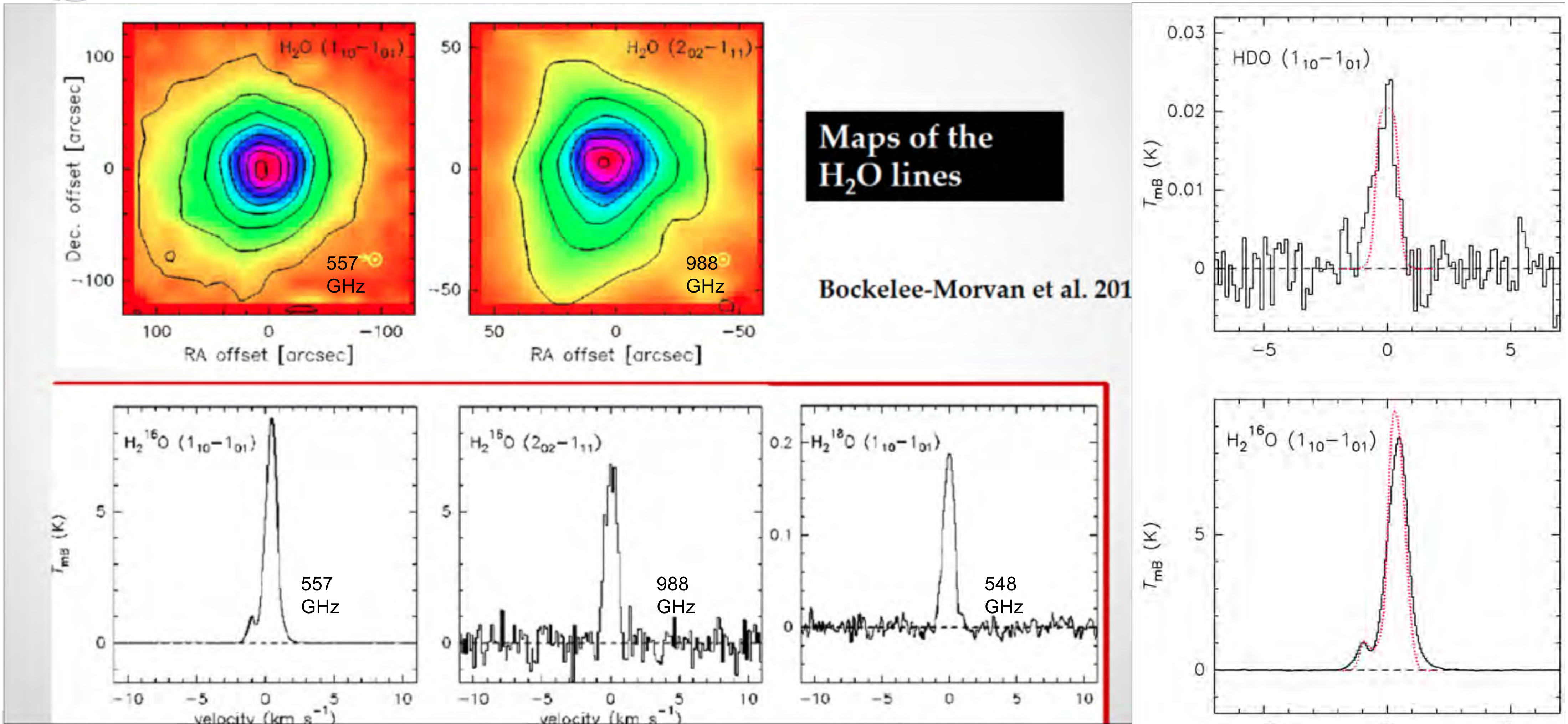
H/D ratios



Hartogh et al. 2011
Nature 478, 218

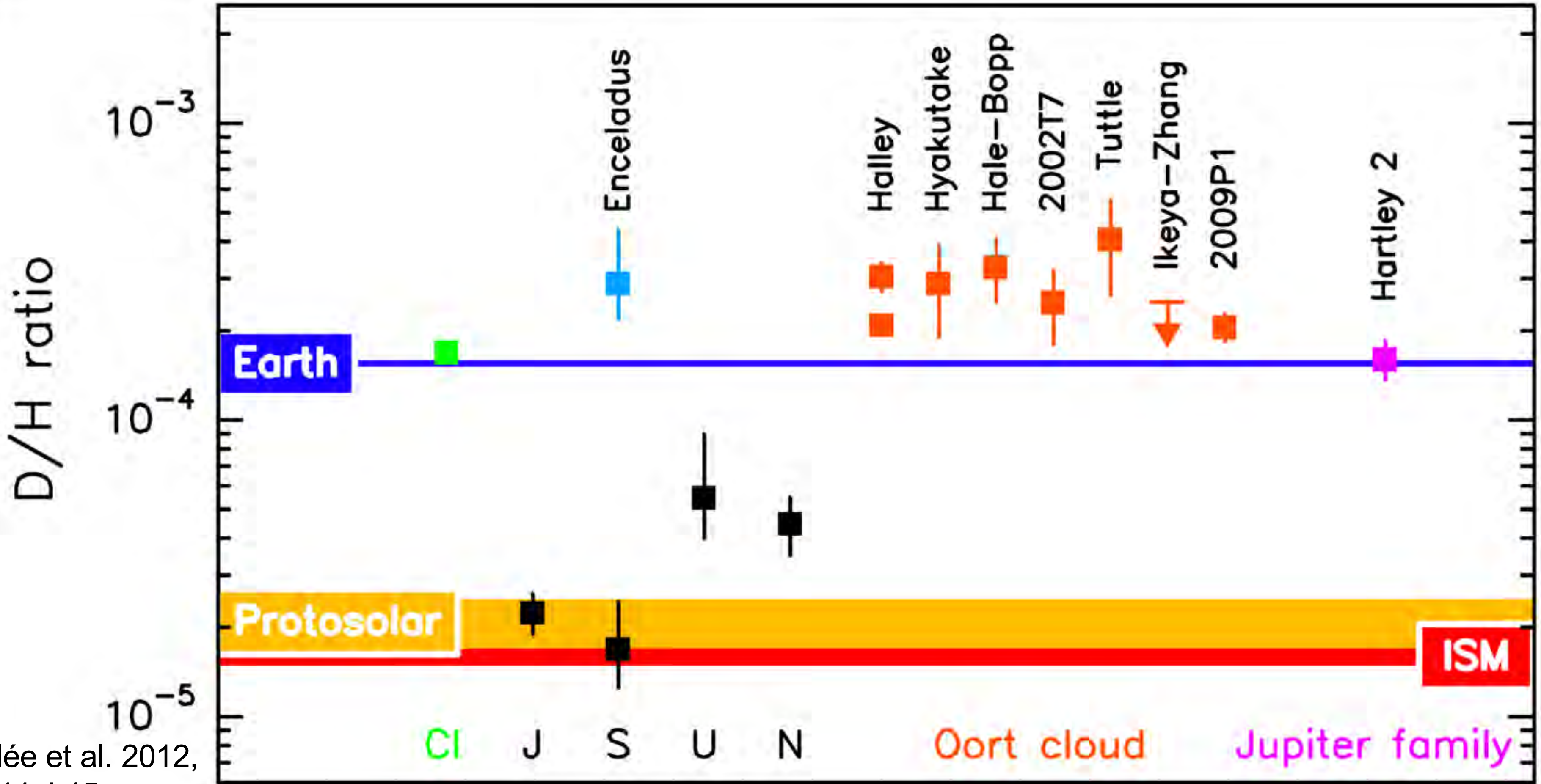

HiFi
ortho-H_2O @ 557 GHz
spectrum © ESA and the HIFI consortium
background © Bradford Robotic Telescope

C/2009 P1 (Garradd)



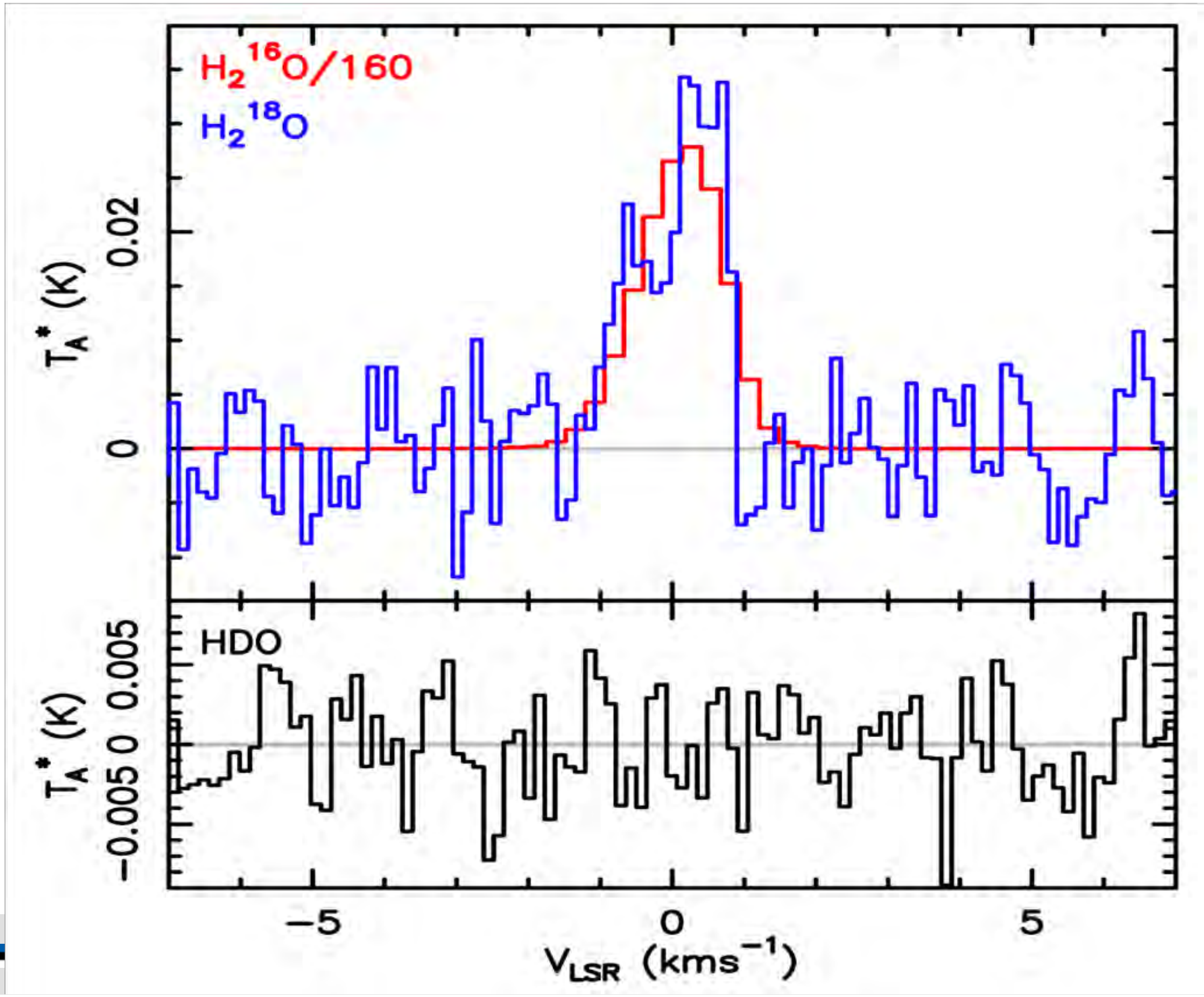
H_2O lines observed simultaneously with HDO in comet C/2009 P1 (Garradd)

H/D ratios

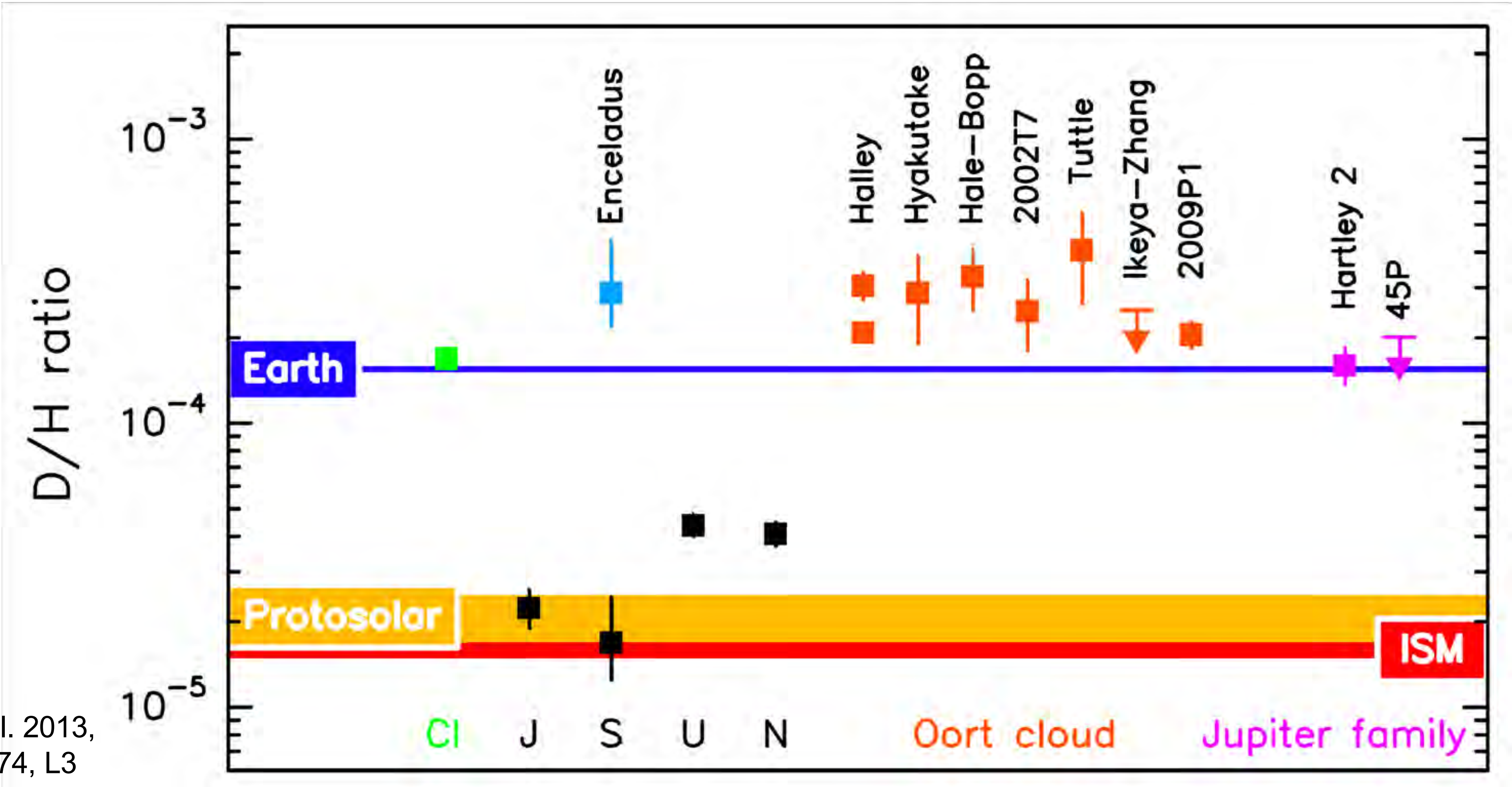


Bockelée et al. 2012,
A&A 544, L15

C/45P(HMP)

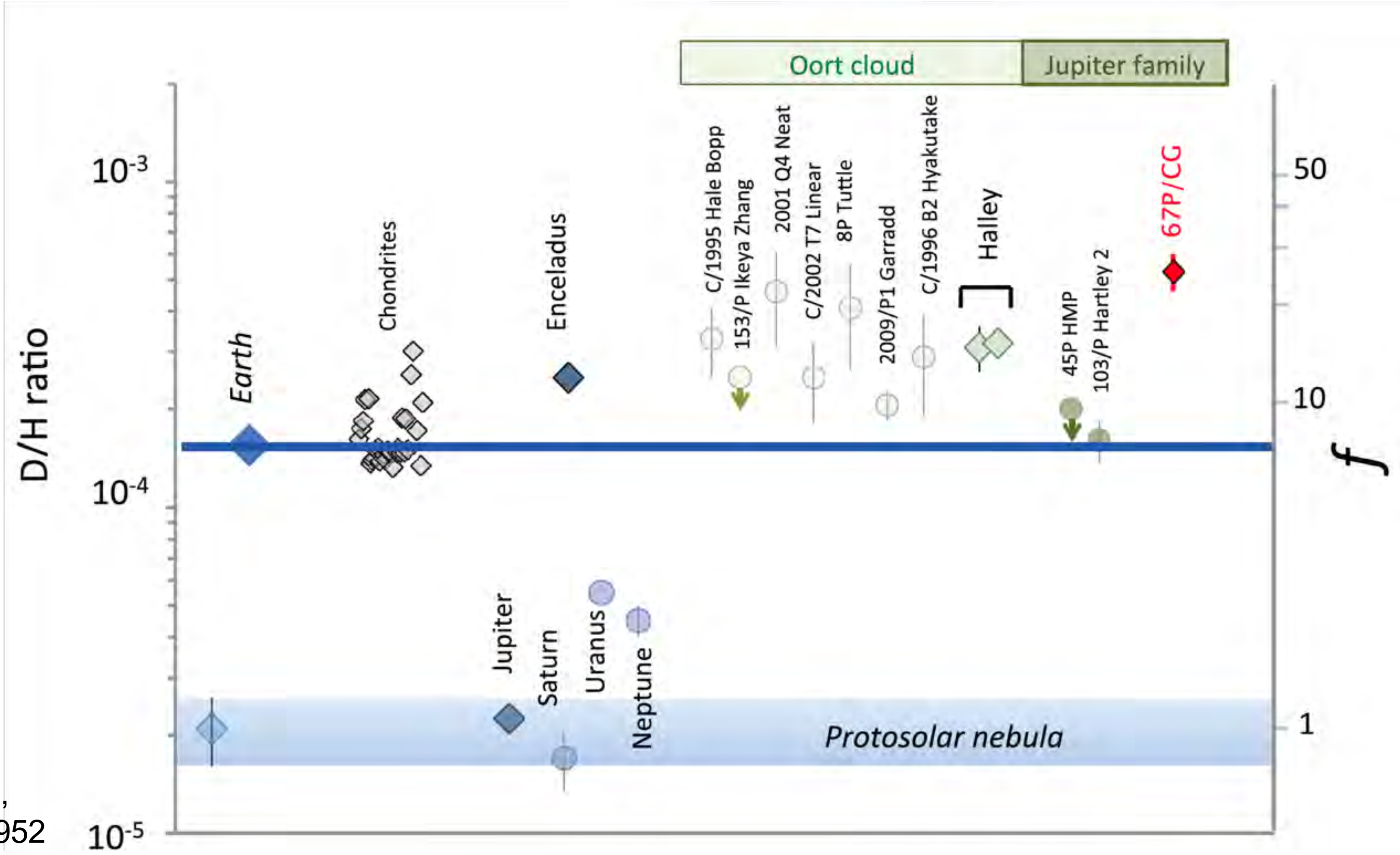


H/D ratios

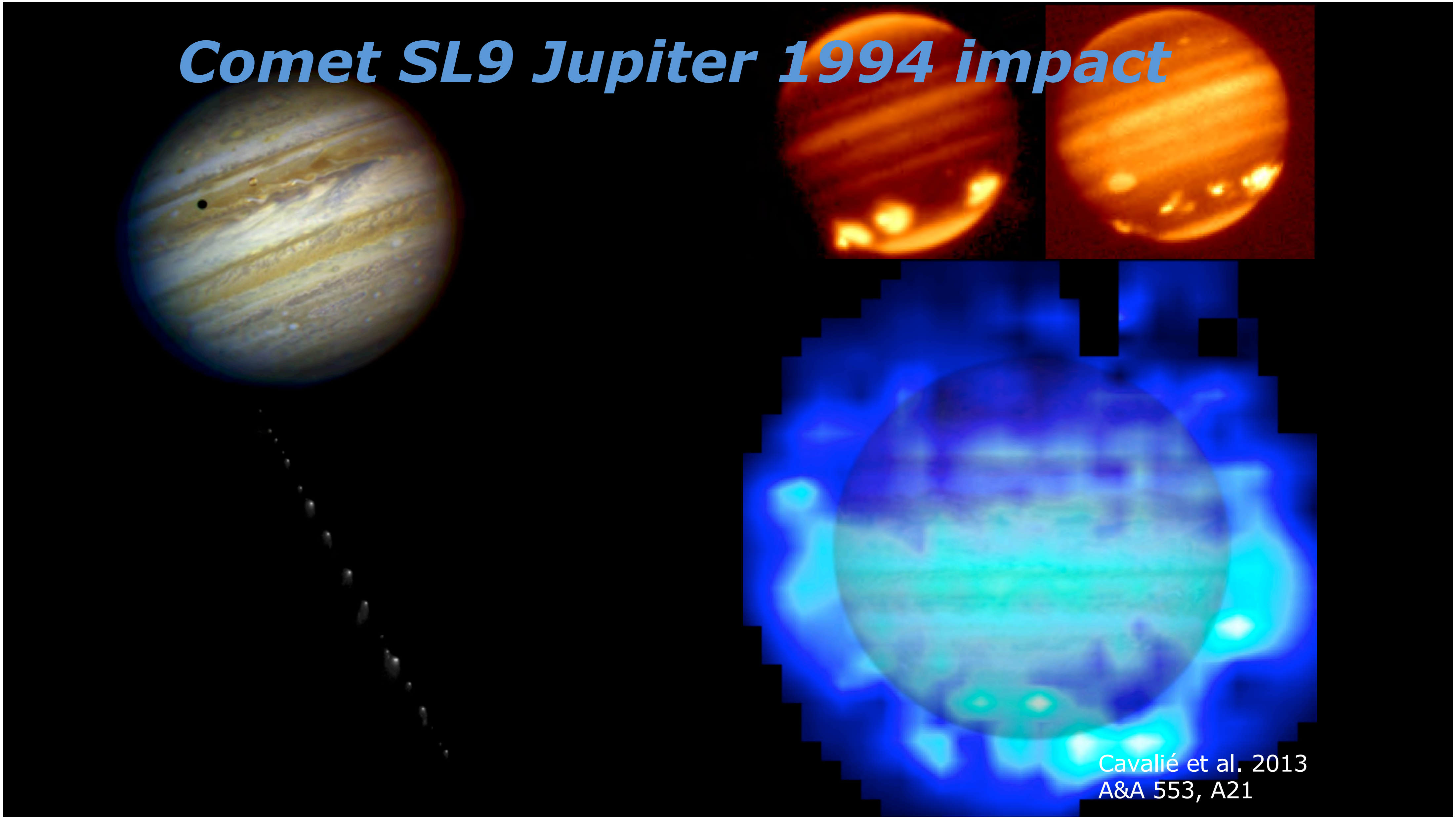


Lis et al. 2013,
ApJL 774, L3

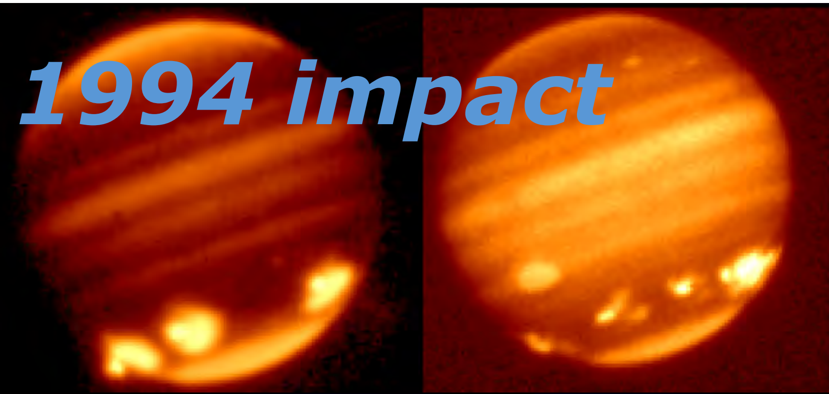
H/D ratios



Altwegg et al. 2015, Science 347, 1261952

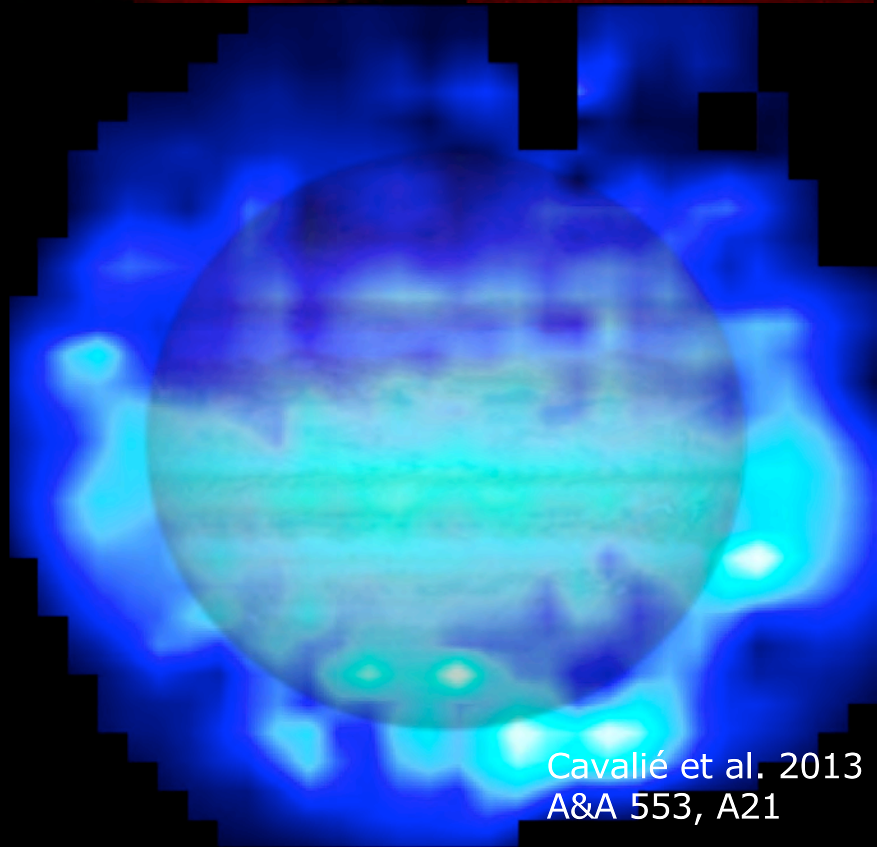

Comet SL9 Jupiter 1994 impact
Cavalié et al. 2013
A&A 553, A21

Comet SL9 Jupiter 1994 impact



Herschel water observations =>

- PACS provides extent across disc
- HIFI provides vertical (pressure) profile
- ‘All’ water high in the stratosphere – well above tropospheric cold trap => external
- Asymmetry between hemispheres suggest single event – rules out moons / icy rings
- **The observed water originates from the July 1994 SL9 impacts!**



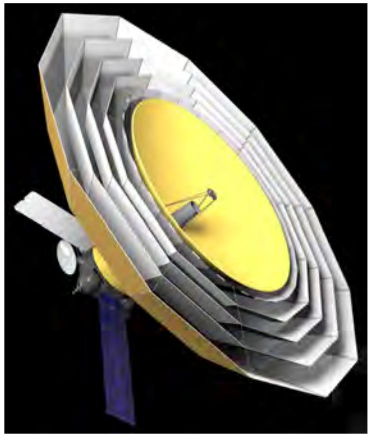
Cavalié et al. 2013
A&A 553, A21

Water trail

Herschel

- Traced water from prestellar core to planet (Jupiter) delivery (SL9)
- Prestellar core – only 1
- Protostars everywhere – but interpretation complicated
- Protoplanetary disks – only 2
- Solar system – ‘everywhere’ – and delivery
- Origin of water on Earth – D/H in (only) 3 comets
- Protoplanetary disk mass from HD – only 1

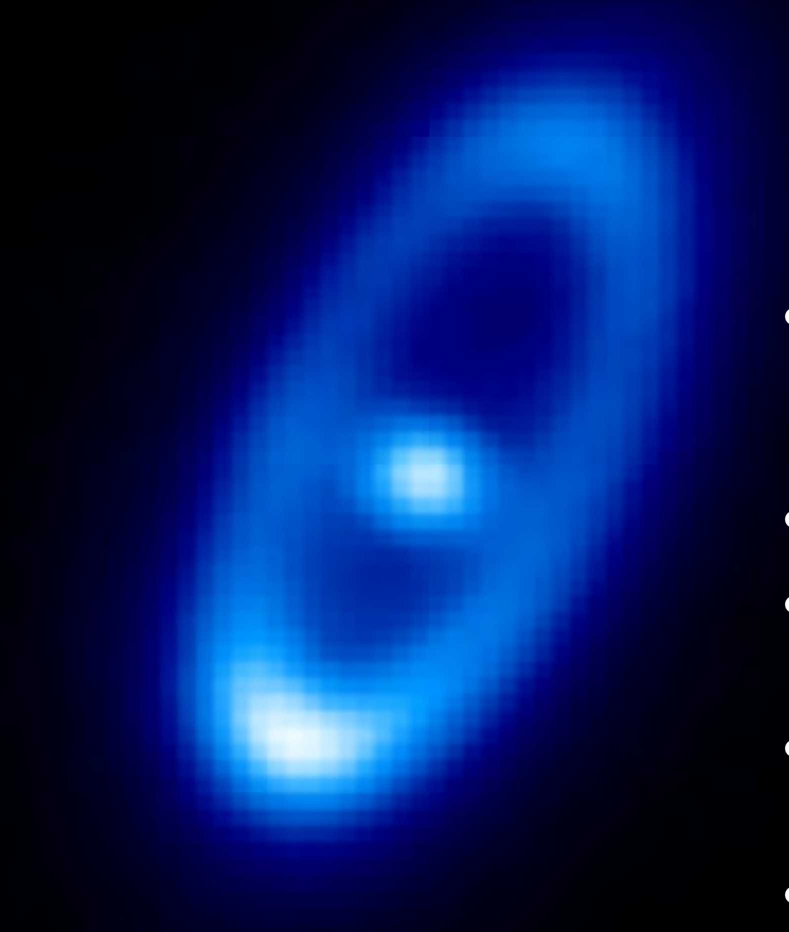
Millimetron



- For point sources >x10 more sensitive than Herschel (even protoplanetary disks are point sources, at 140 pc 0.1”-0.3”)
- Need many water lines (spectral coverage)
- HD argument for 112/56 μm (2.67/5.33 THz) heterodyne spectrometers

Debris disks

Fomalont

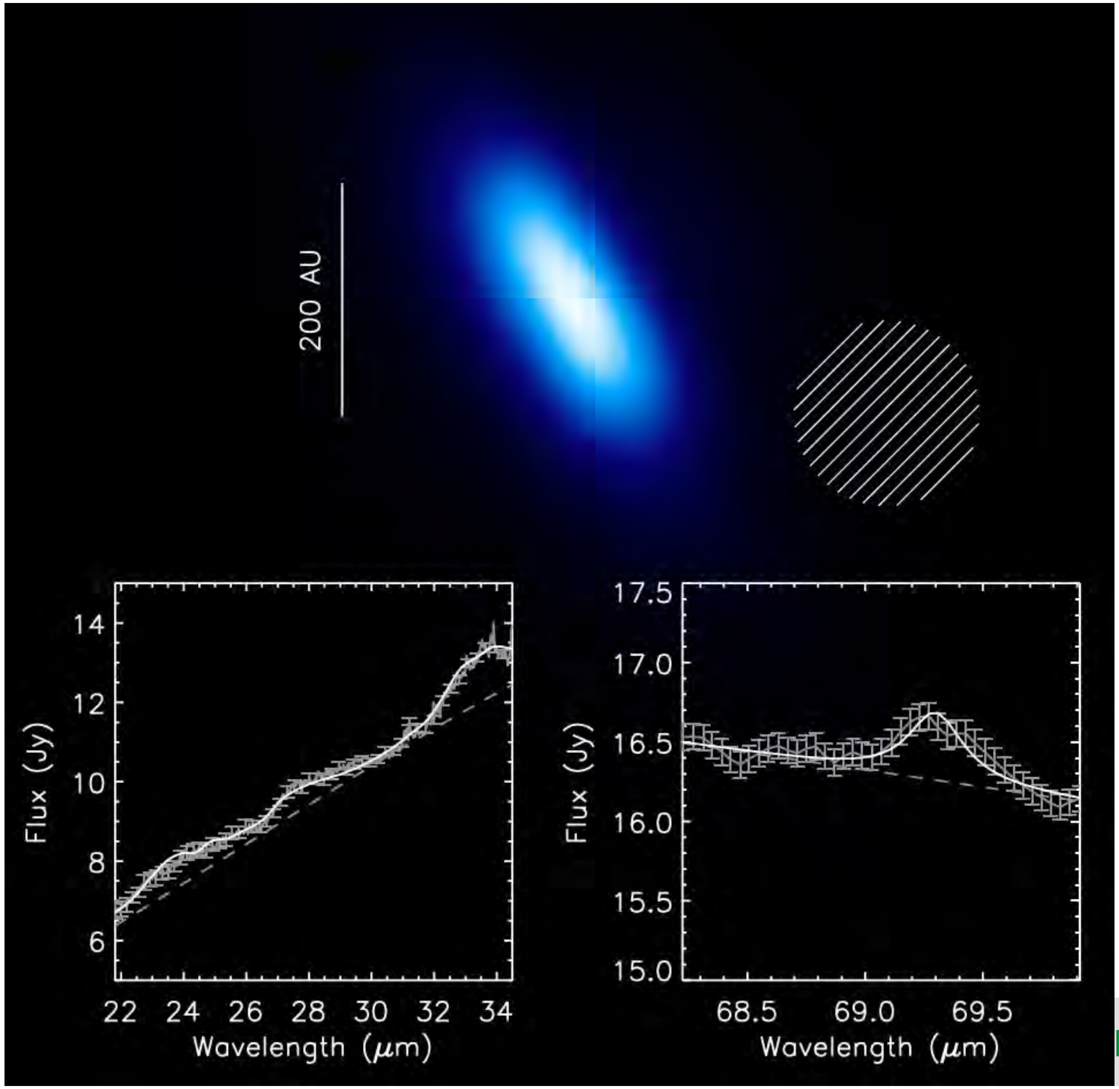


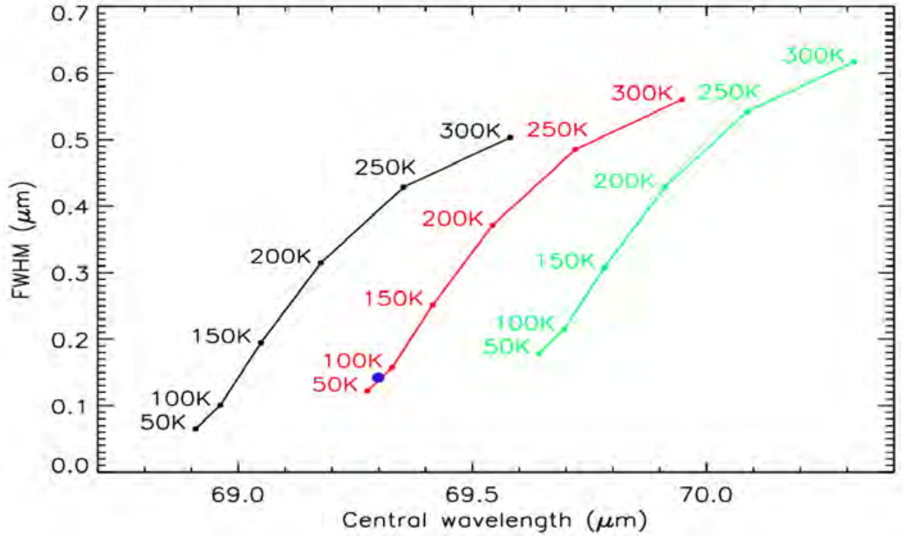
Modelling

- Optical large >50 um grains, thermal small (blow-out) grains => fluffy aggregates
- Replenishment time ~1700 yrs
- Mass loss (=production) rate ~2000 (1 km) comets per day
- Reservoir of ~10^{13} comets, total ~100 M_{Earth}
- Currently a remarkably violent system!

Acke et al. 2012
A&A 540, A125

β Pictoris





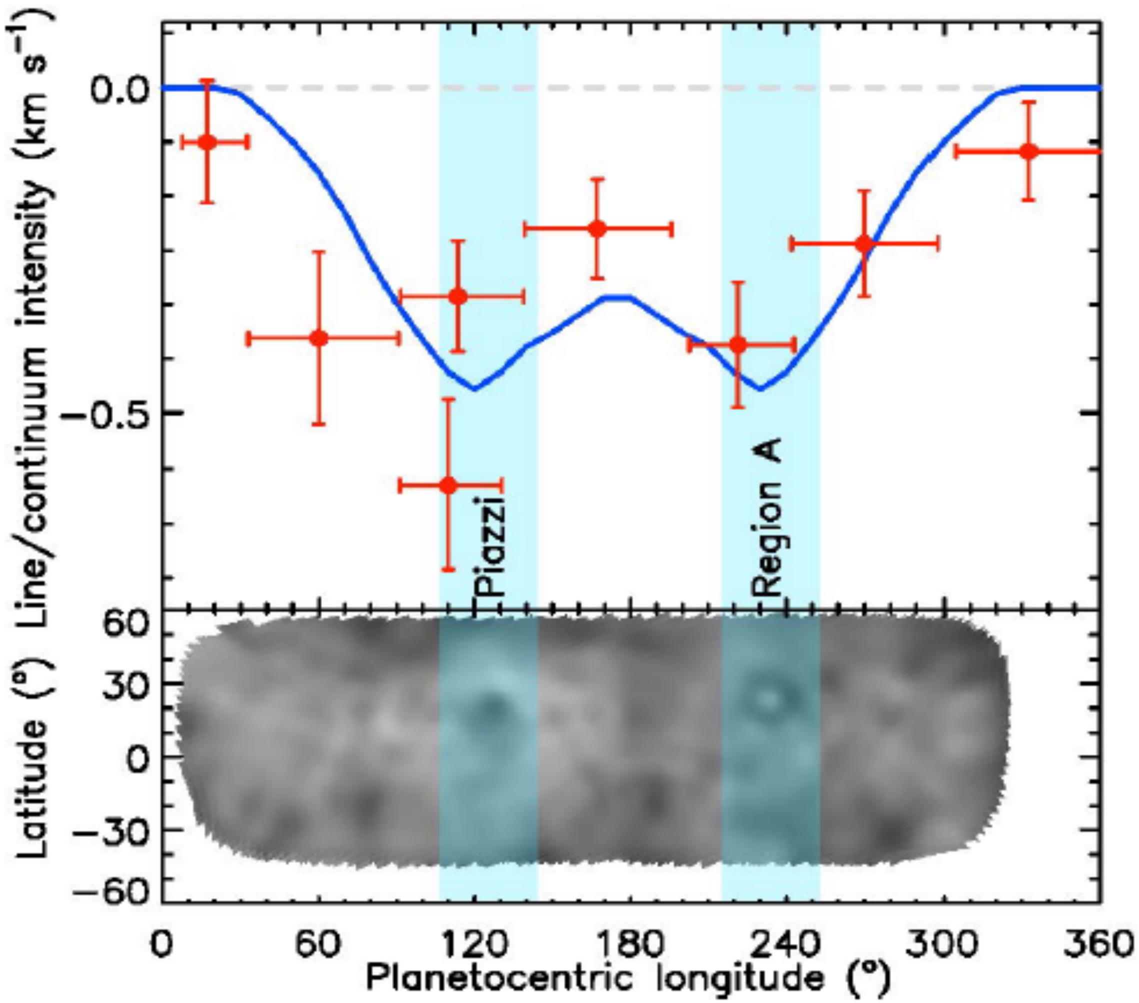
- Spitzer/IRAC 22-34 um
- Herschel/PACS 69 um band => Mg-rich crystalline olivine
- Mg-rich => pristine
- Fe-rich => 'processed'

De Vries et al. 2012 Nature 490, 74

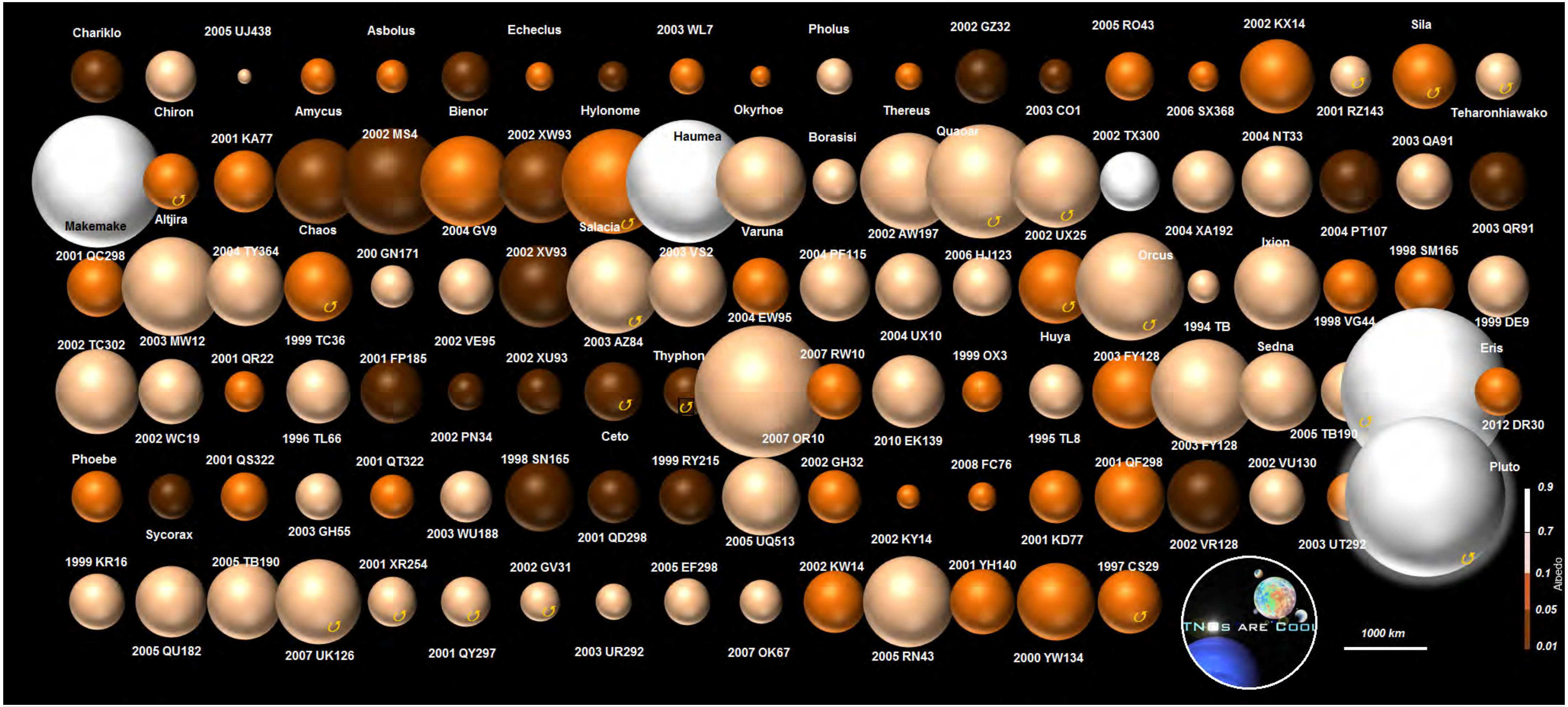
Ceres

- Water in the asteroid belt!
- Four epochs of observations
- On last occasion monitoring for entire Ceres revolution => ‘resolve’ surface features
- Source of water expected connected to two surface features
- For each source: $Q(H_2O) = 10^{26}$ mol/s (3 kg/s continuously)
- Corresponds to ~0.6 km^2 of ice at the surface => 10^{-7} of Ceres surface and 10^{-5} of source regions

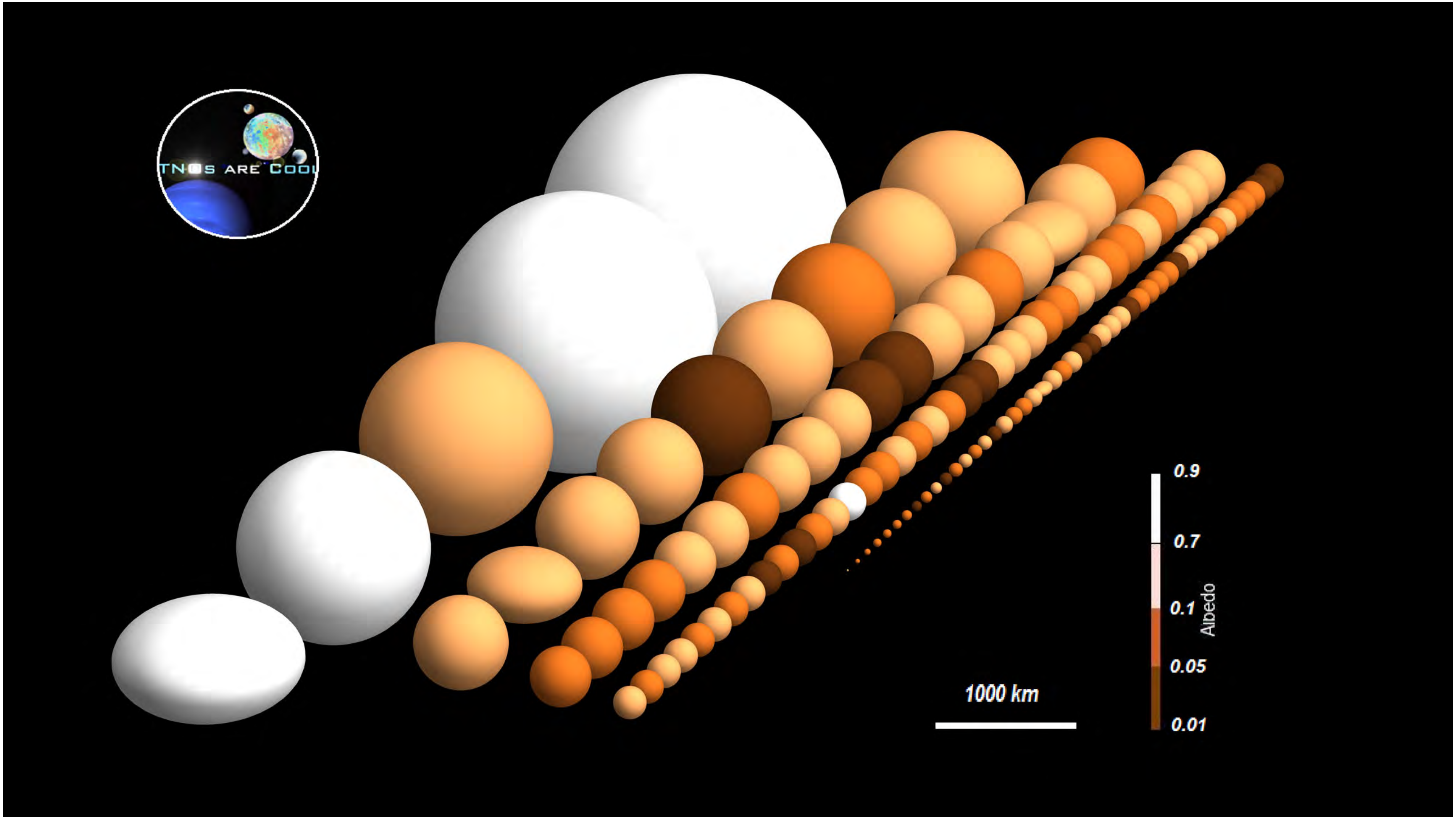
Küppers et al. 2014; Nature 505, 525



TNOs



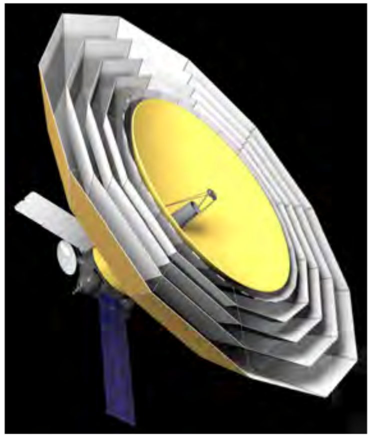
European Space Agency


TNOs are Cool
1000 km
0.9
0.7
0.1
0.05
0.01
Albedo

Debris disks

Herschel

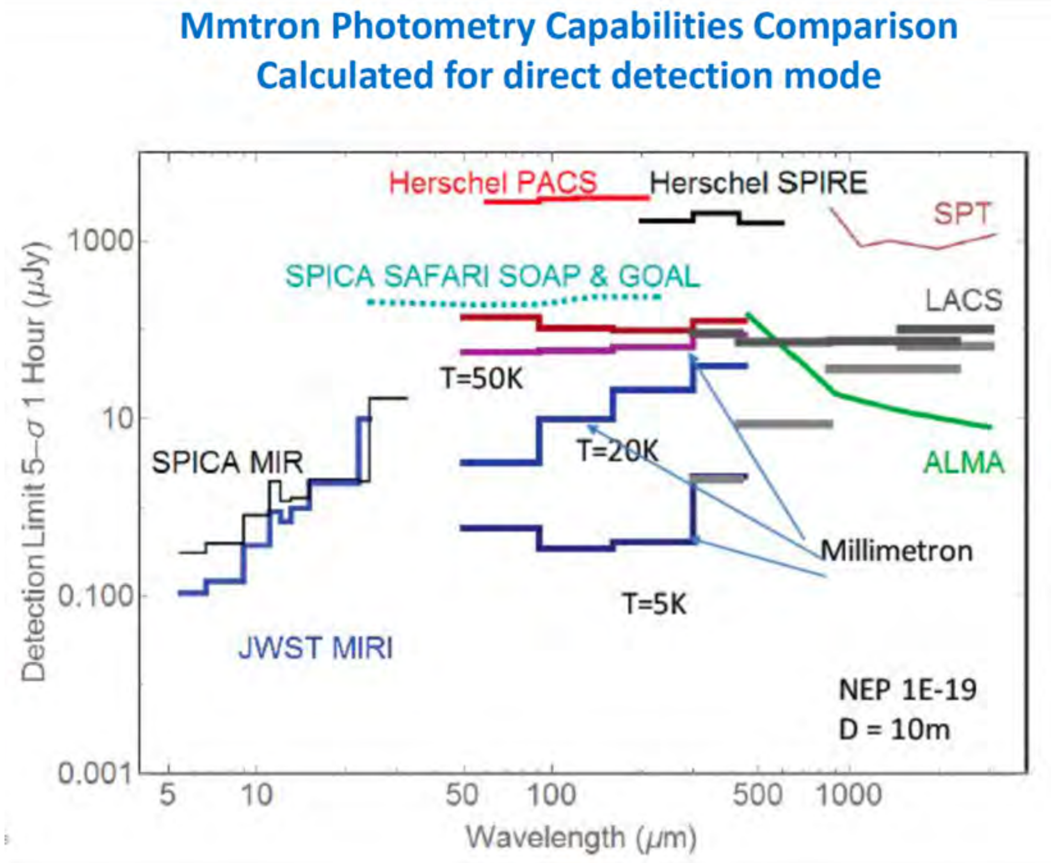
- Herschel surveys of debris disks – increased number of detected DDs and increased number of resolved DDs
- Fomalont – water
- β Pictoris – pristine material
- Solar system asteroid belt – Ceres
- Solar system Kuiper belt – TNOs
- Also water in many places in the solar system

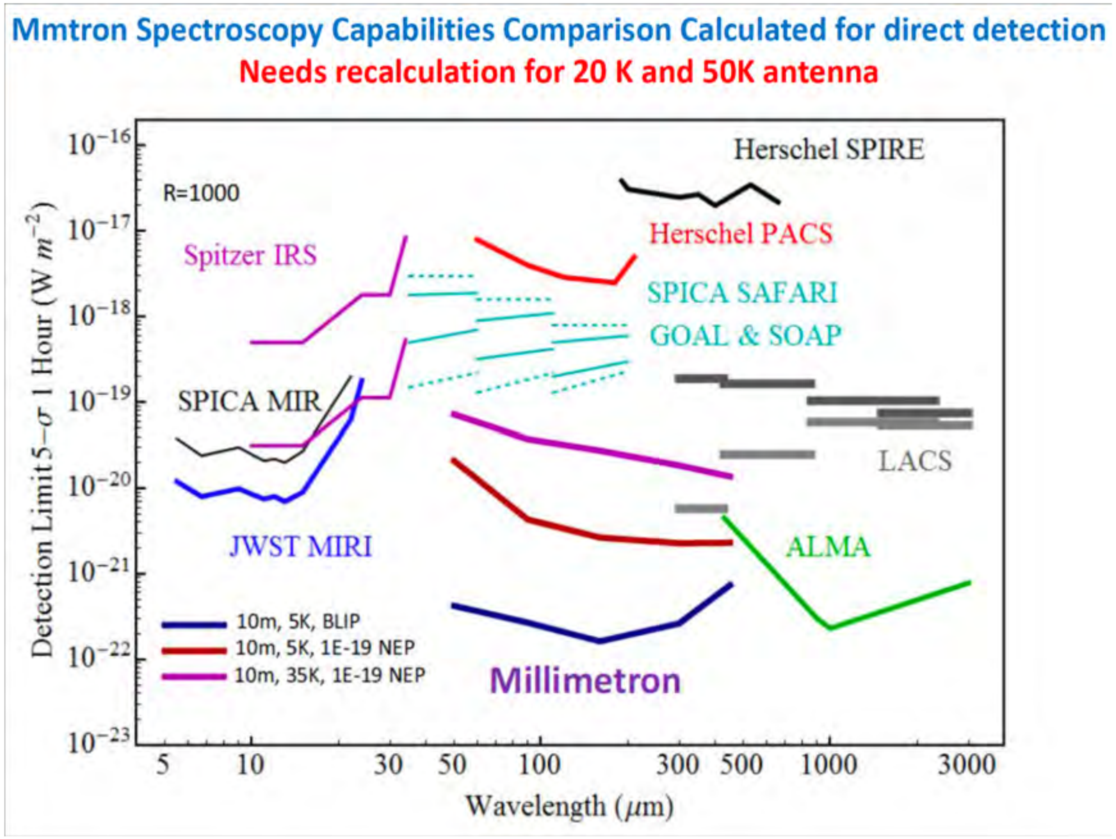


Millimetron

- Can push to even fainter (lower fraction L_{disk}/L_{star}) debris disks
- Will resolve even more debris disks
- Can observe even fainter solar system objects, photometrically and spectroscopically

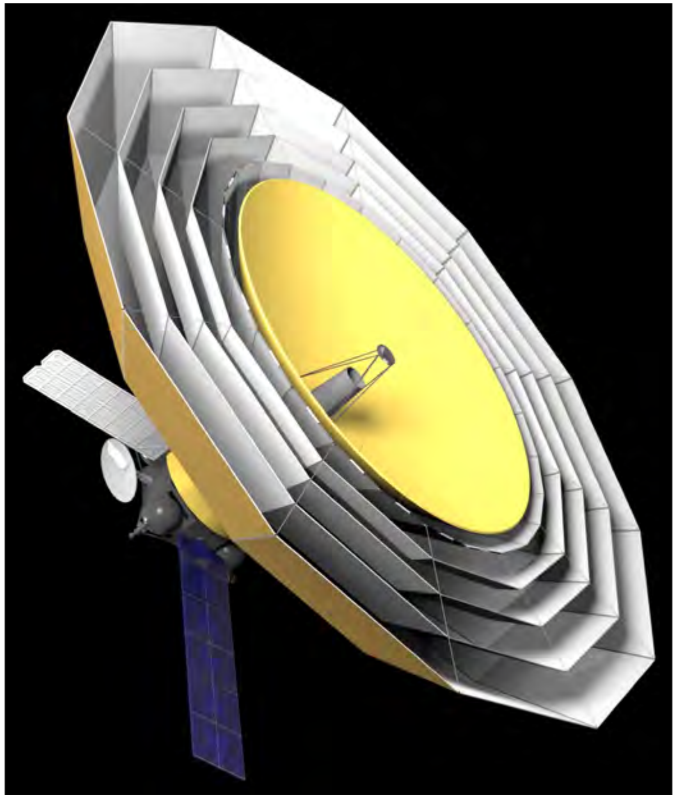
Millimetron capabilities





Baryshev, Aug 2019

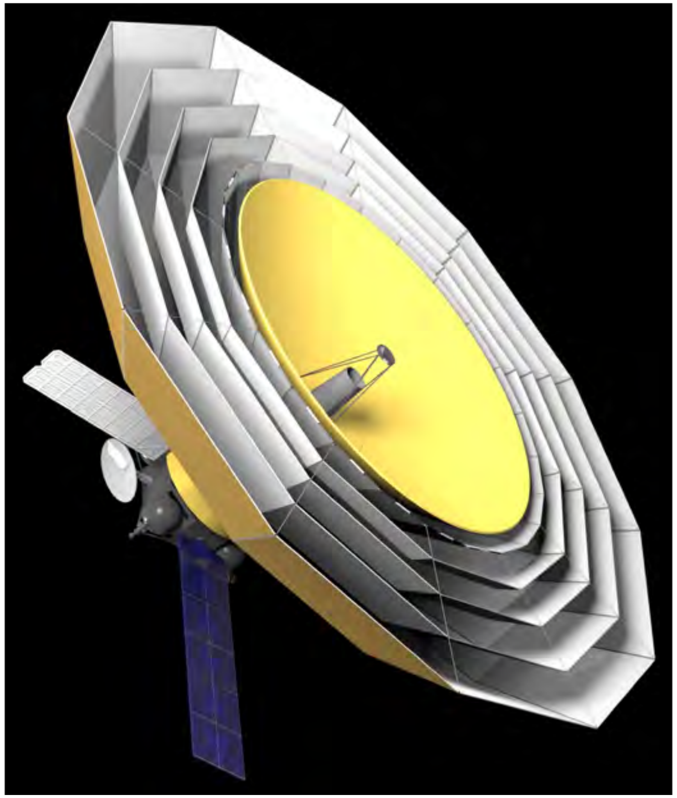
Millimetron killer objectives



Extragalactic, mainly high-z

- Want to study underlying ‘bulk’ population at ‘all’ z – star formation as function of z, ... (’all’ z => z<6?)
- Want to study ISM at ‘all’ redshifts – how do galaxies actually work?
- Massive molecular outflows at ‘all’ z?
- Dust (‘metal’) production & budget at ‘all’ z

Millimetron killer objectives



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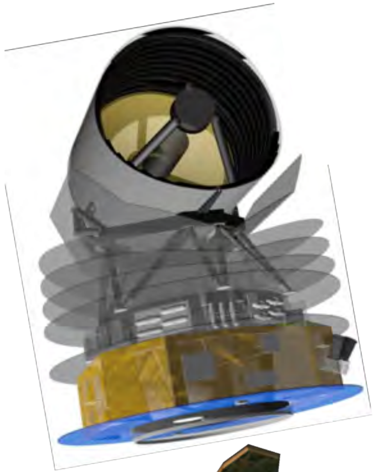
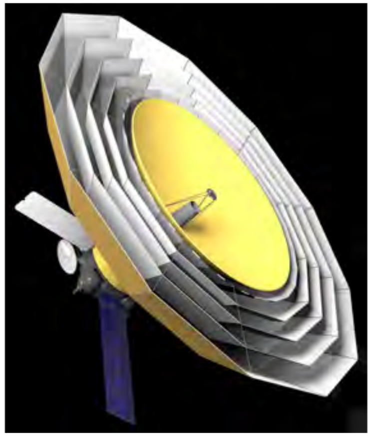
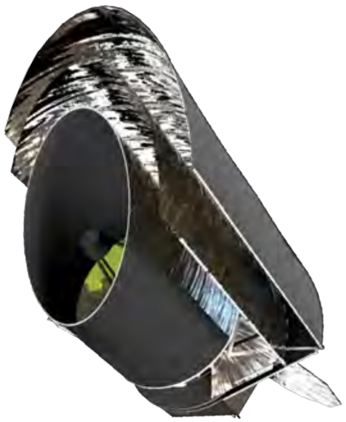
Galactic & solar system

- Polarimetry – survey of MCs – role(?) of magnetic fields in filament formation and fragmentation
- More distant filaments – high-mass star formation
- Water trail – more objects
- Disk masses and debris disks (planetary formation)

Some thoughts for the future







Telescope size

- Prime driver (angular resolution & collecting area) for photometry & high-res spectroscopy
  - Extragalactic ‘point source’ surveys: confusion & ‘raw’ sensitivity (time needed)
  - Resolved (extra-)galactic objects: detail observed
  - All heterodyne spectroscopy work

Telescope background (temp & emissivity)

- Prime driver for non-heterodyne spectroscopy
- Enables exquisite sensitivity – cf. SPICA
- Requires ‘good enough’ instruments/detectors

and

- Lifetime is big deal – last year best observations
- Community interaction – helpdesk, data products, archive, data reduction software, …

Thank you!

Herschel Cosmos website:
https://www.cosmos.esa.int/herschel

European Space Agency