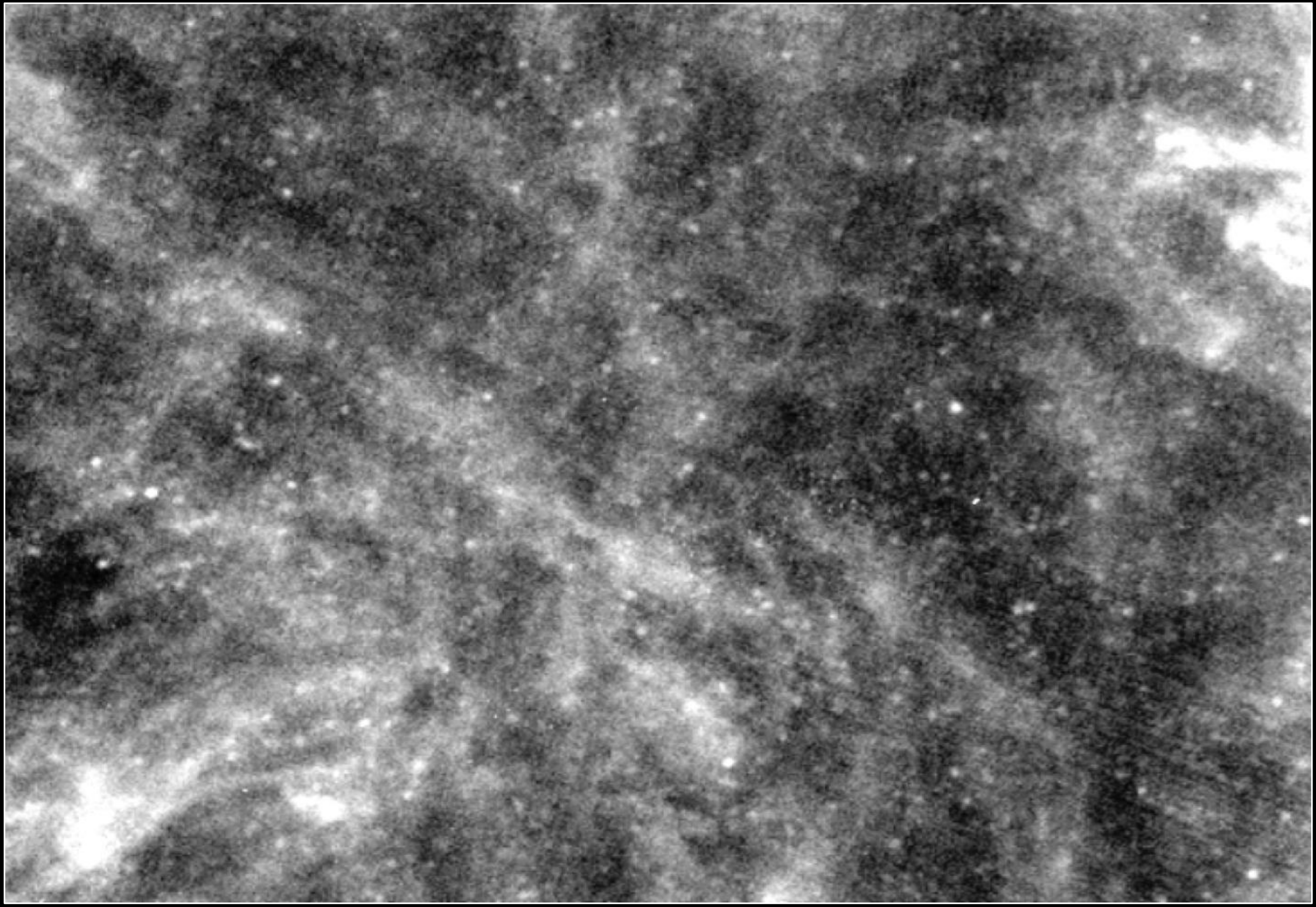
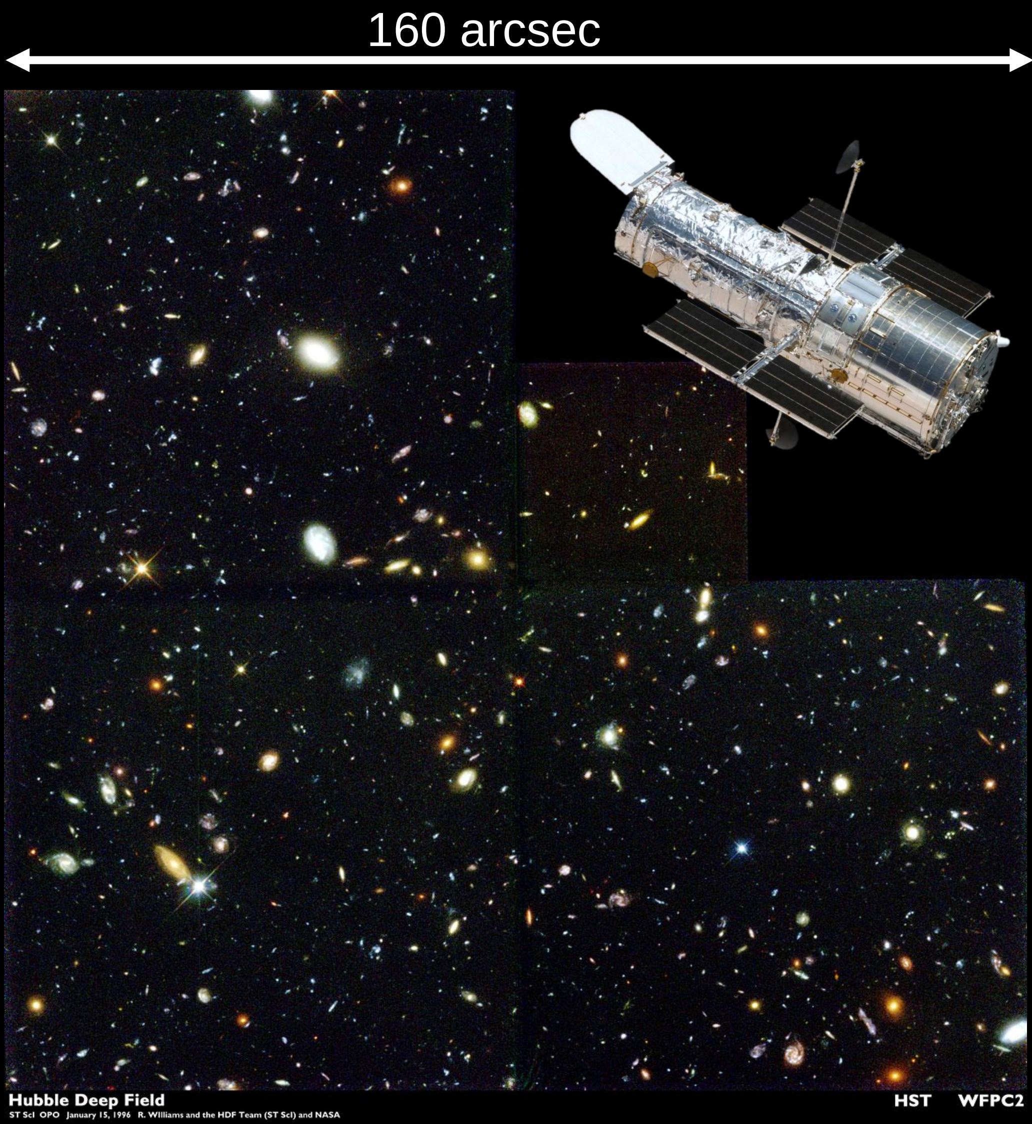
Les galaxies vues dans le domaine millimétrique

David Elbaz (CEA Saclay)



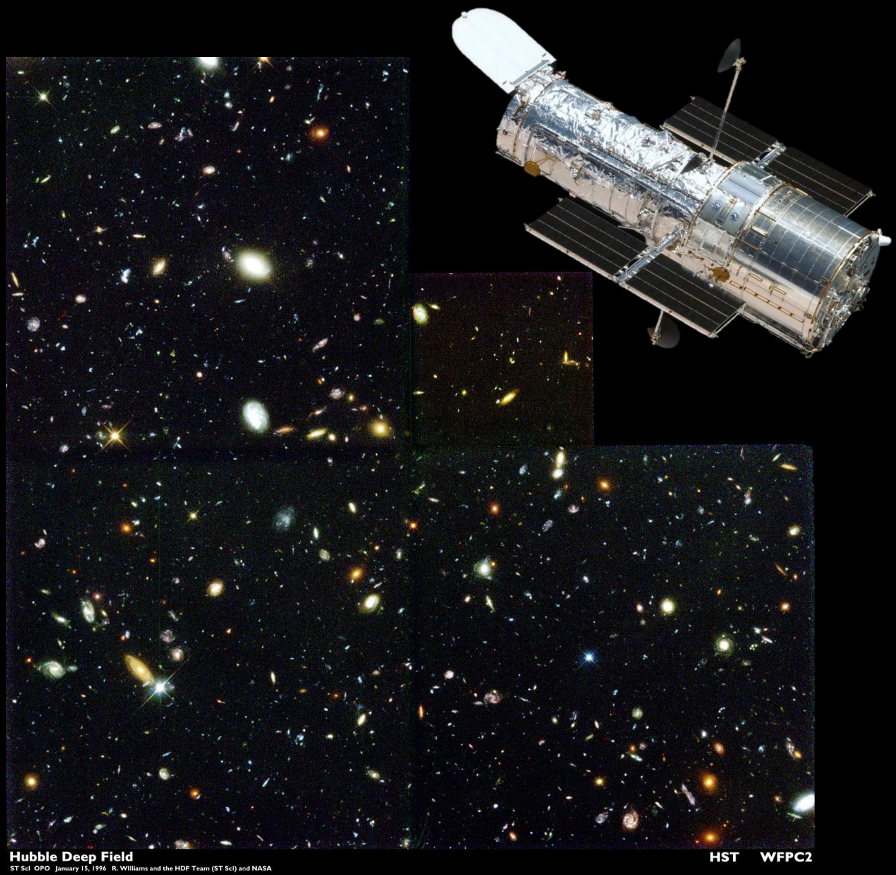


Hubble Deep Field

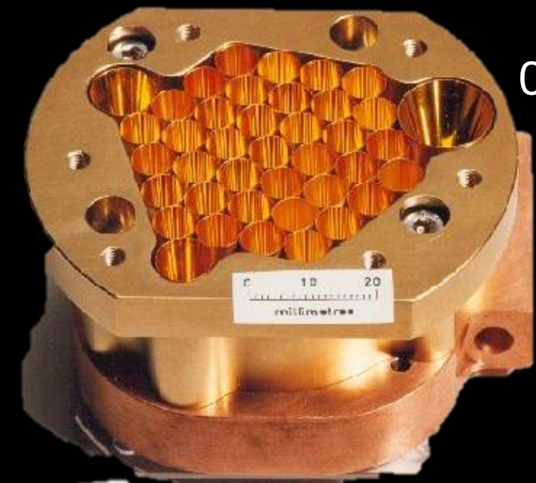
1500 galaxies

Magnitude 30
= 4 milliards de fois plus faibles
que la sensibilité de l'œil humain

160 arcsec

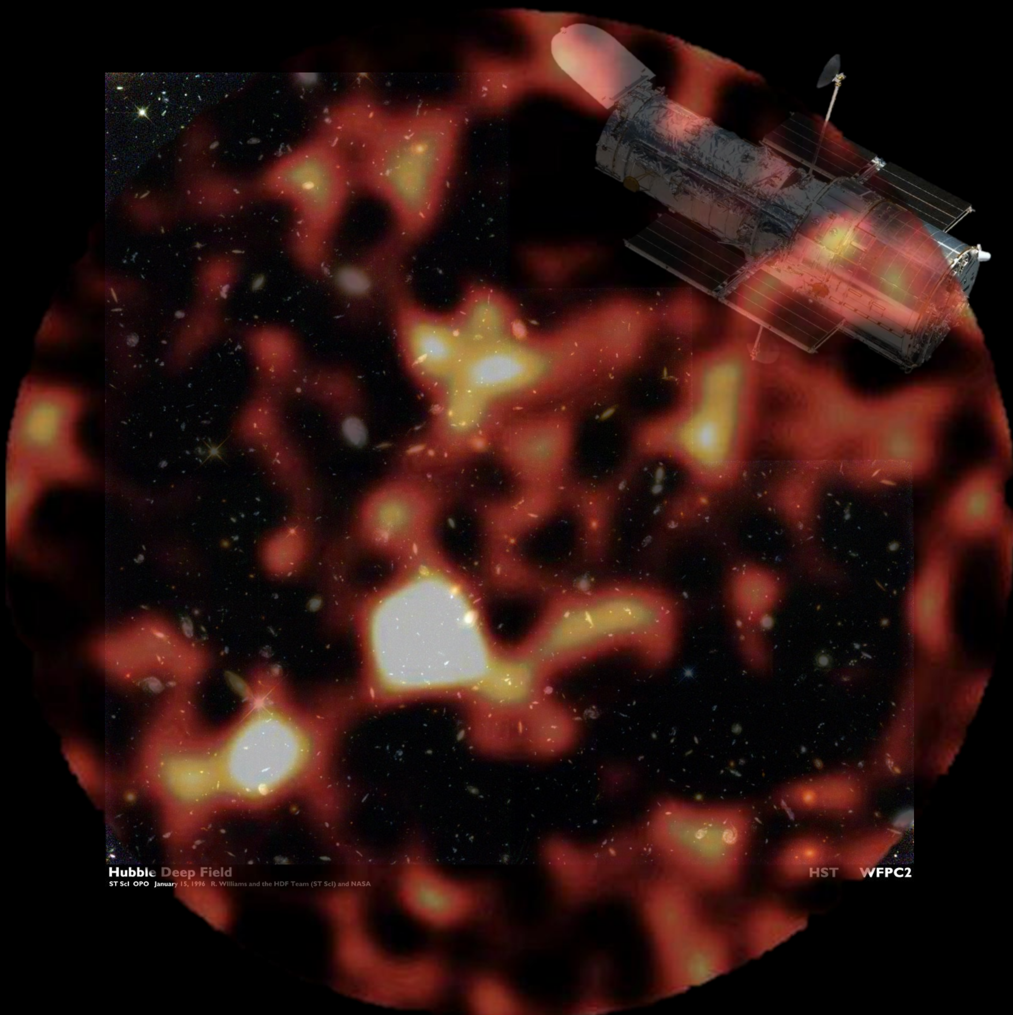


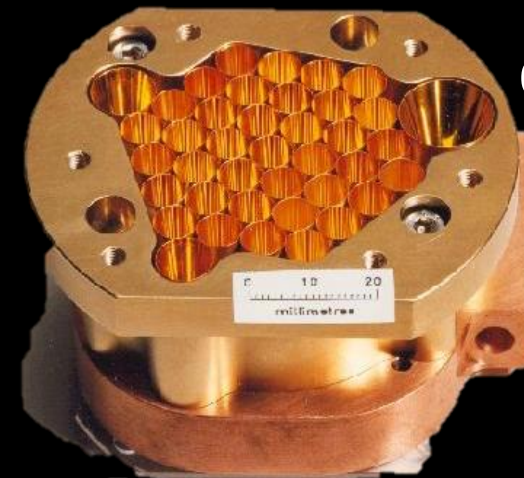
Submillimetre Common-User Bolometer Array (37 pixels) SCUBA 0.45 & 0.85mm



JCMT Hawaii (15m)

Submillimetre Common-User Bolometer Array (37 pixels) SCUBA 0.45 & 0.85mm

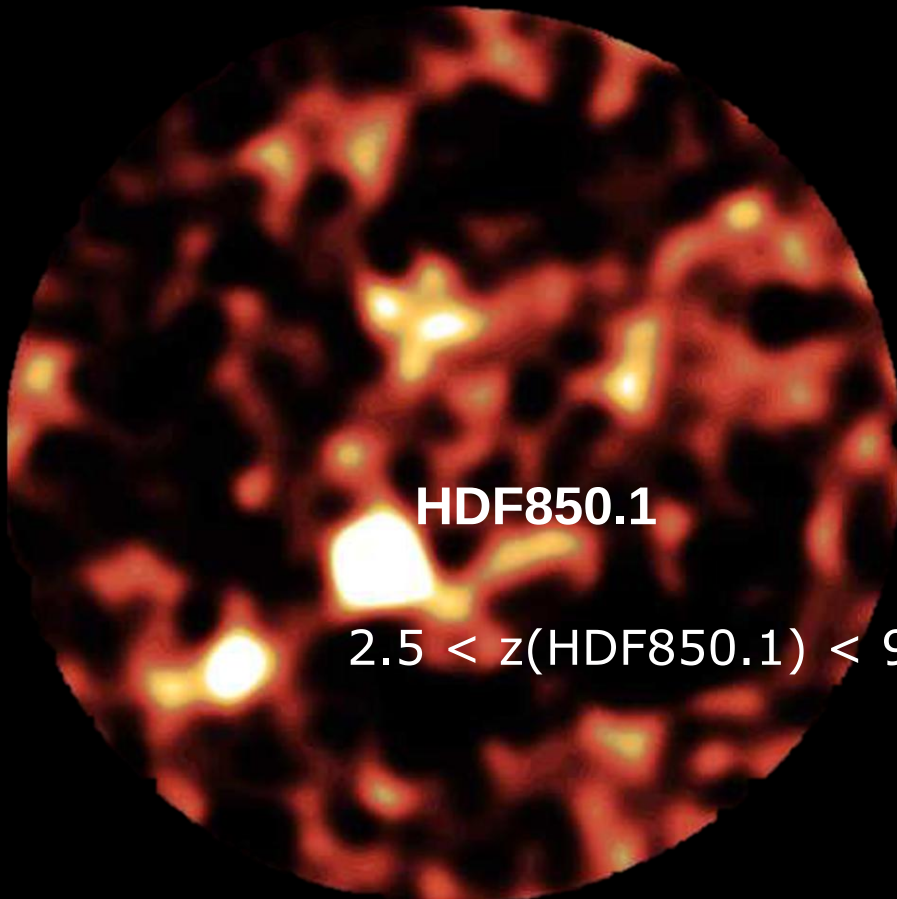




JCMT Hawaii (15m)

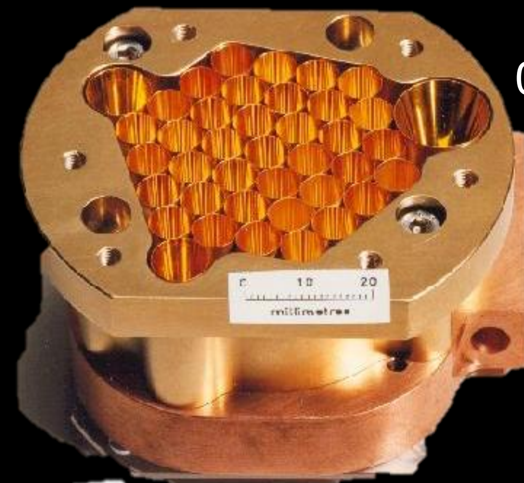
200 arcsec

Carte à 0.85mm



Tâche de diffraction = 14.7 arcsec
bruit = 0.45 mJy , HDF850.1: 7 mJy (S/N=15)
Hughes et al. (1998)

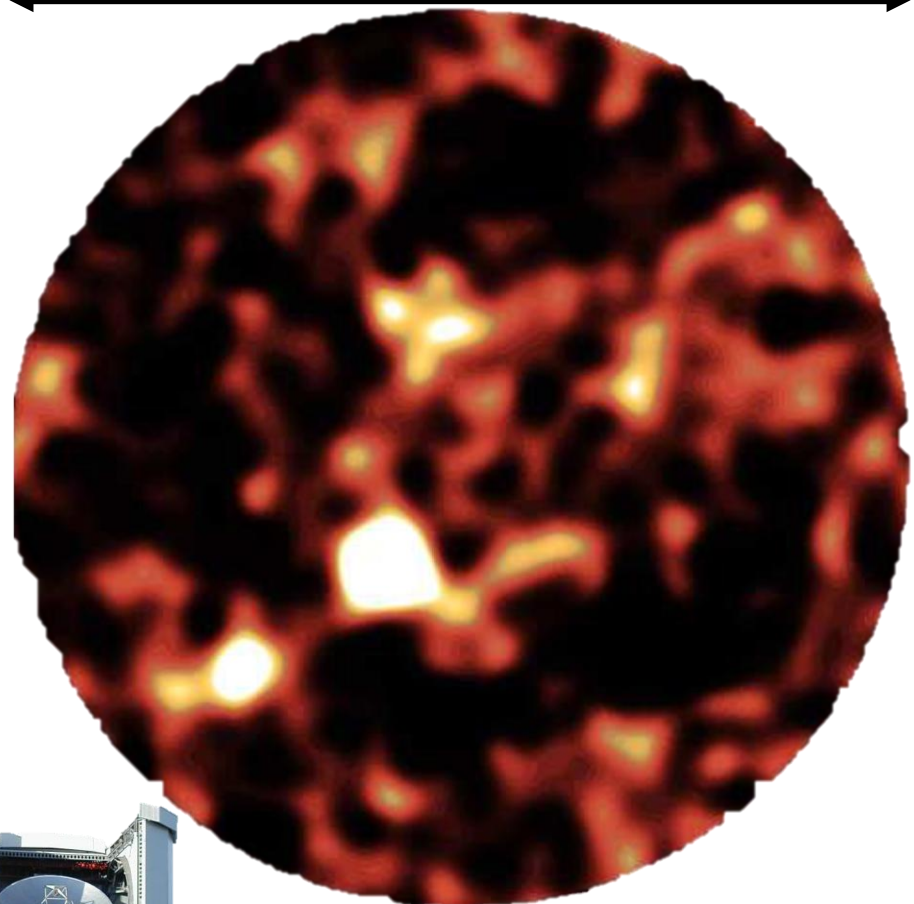
Submillimetre Common-User Bolometer Array (37 pixels) SCUBA 0.45 & 0.85mm



JCMT Hawaii (15m)

HDF850.1

200 arcsec



Tâche de diffraction = 14.7 arcsec
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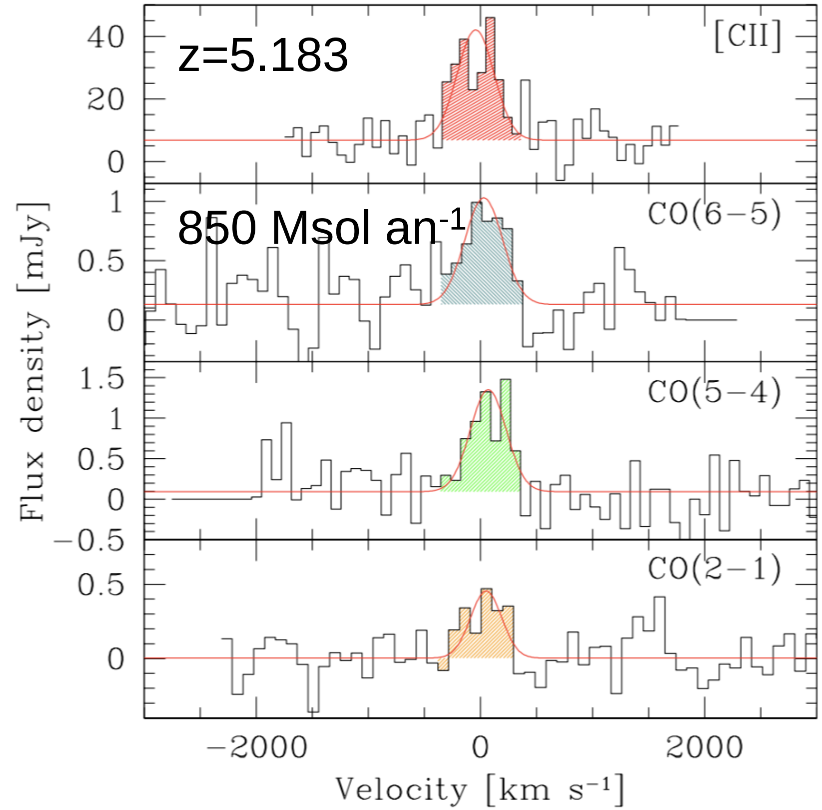
Hughes et al. (1998)

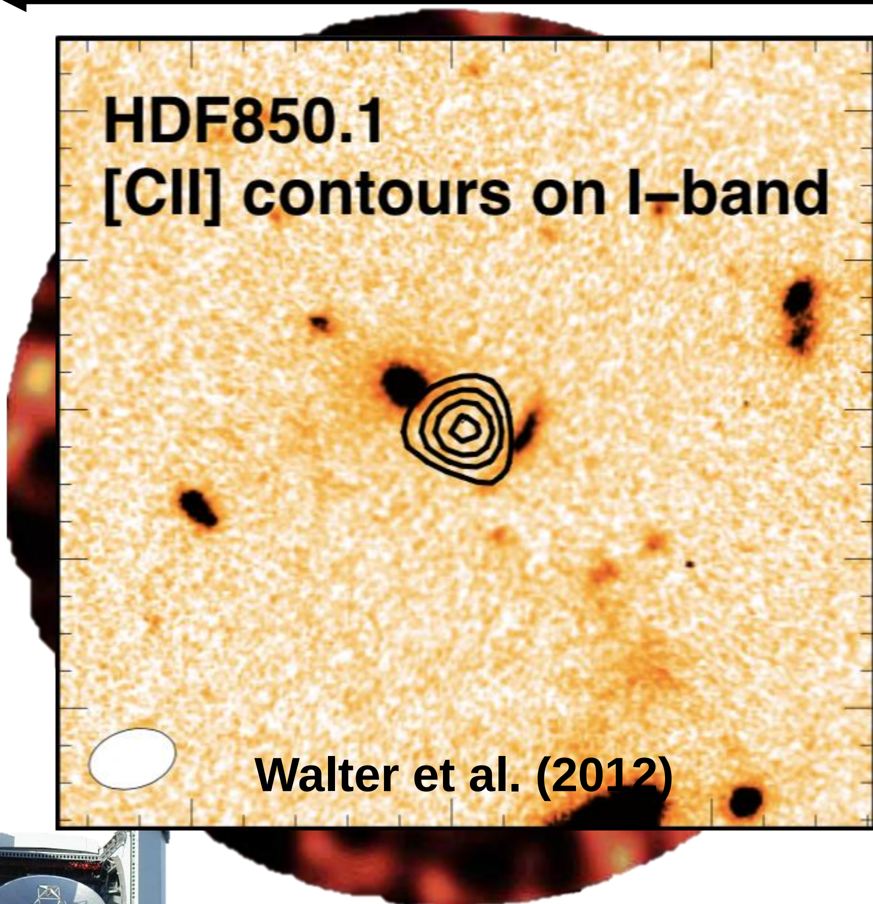


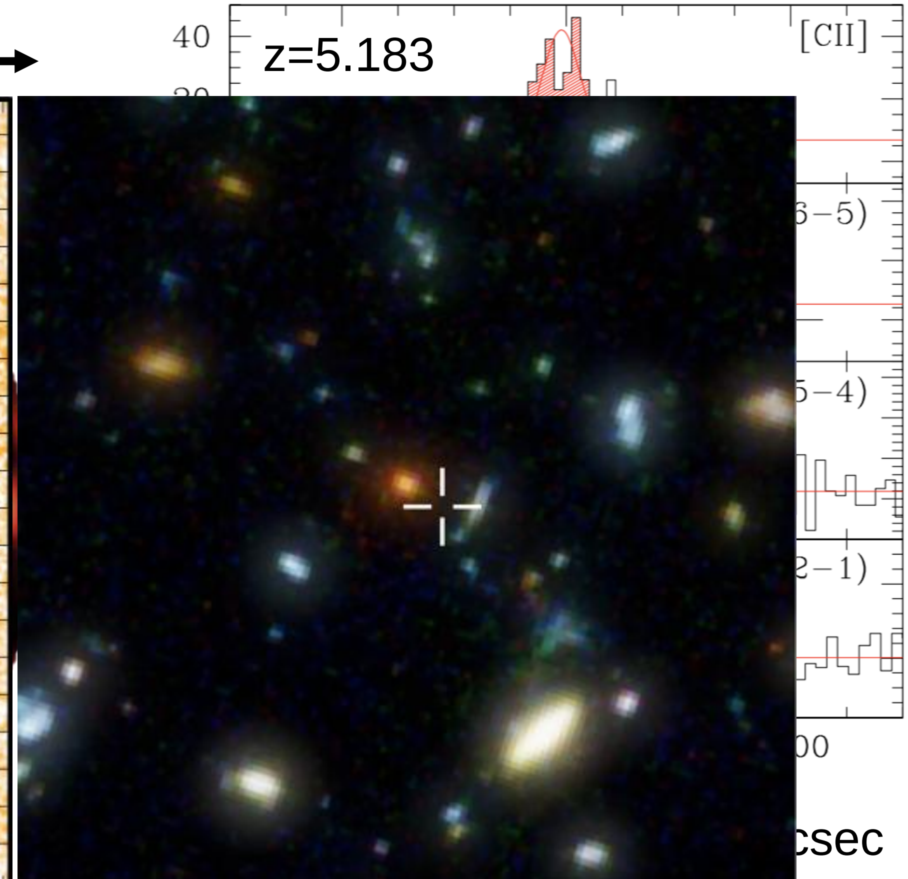
Tâche de diffraction = 2.3 arcsec
Walter et al. (2012)

Interféromètre Plateau de Bure
IRAM – 7 antennes de 15m

HDF850.1

200 arcsec



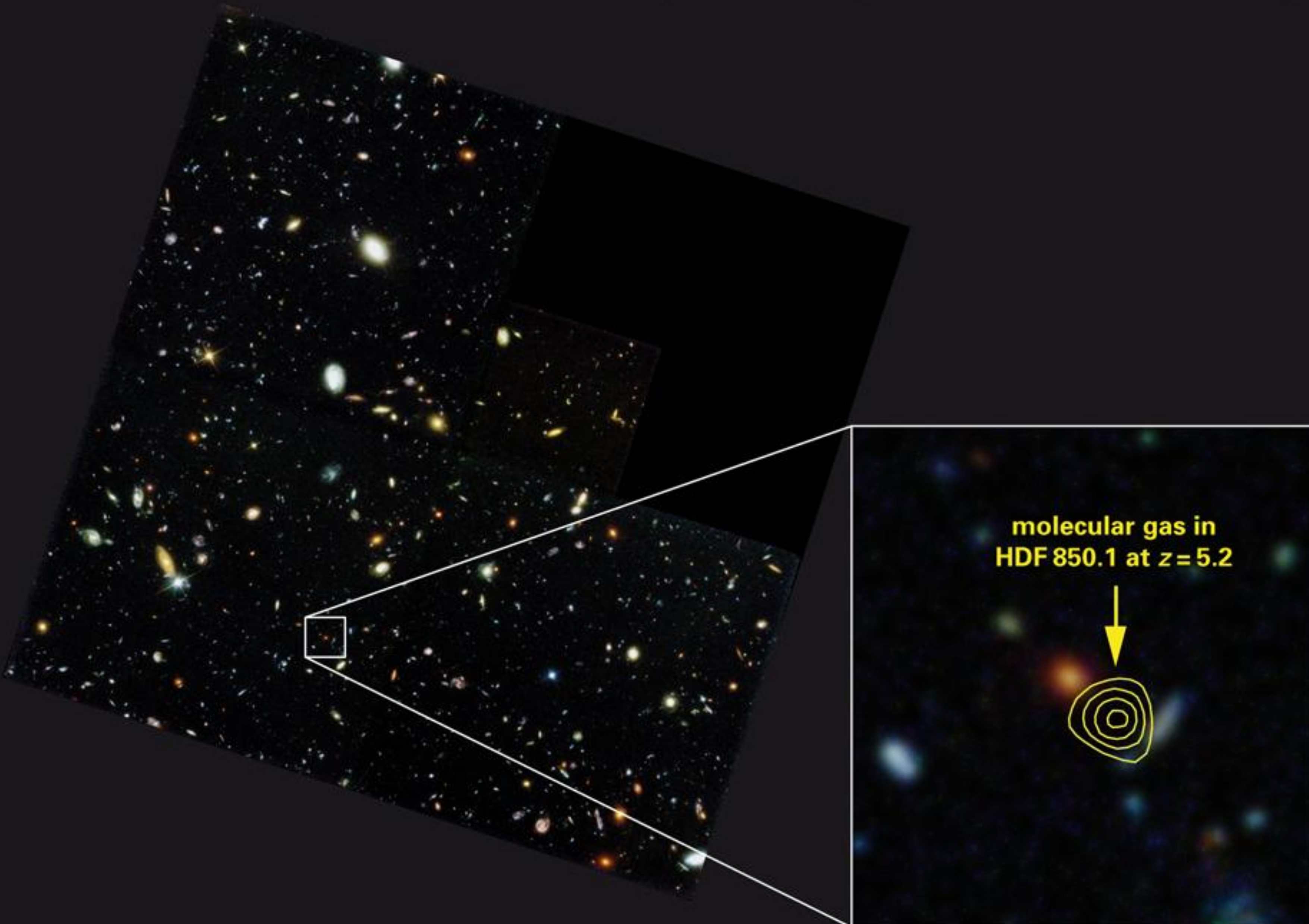


…csec
Walter et al. (2012)

Tâche de diffraction = 14.7 arcsec
bruit = 0.45 mJy , HDF850.1: 7 mJy (S/N=15)
Hughes et al. (1998)

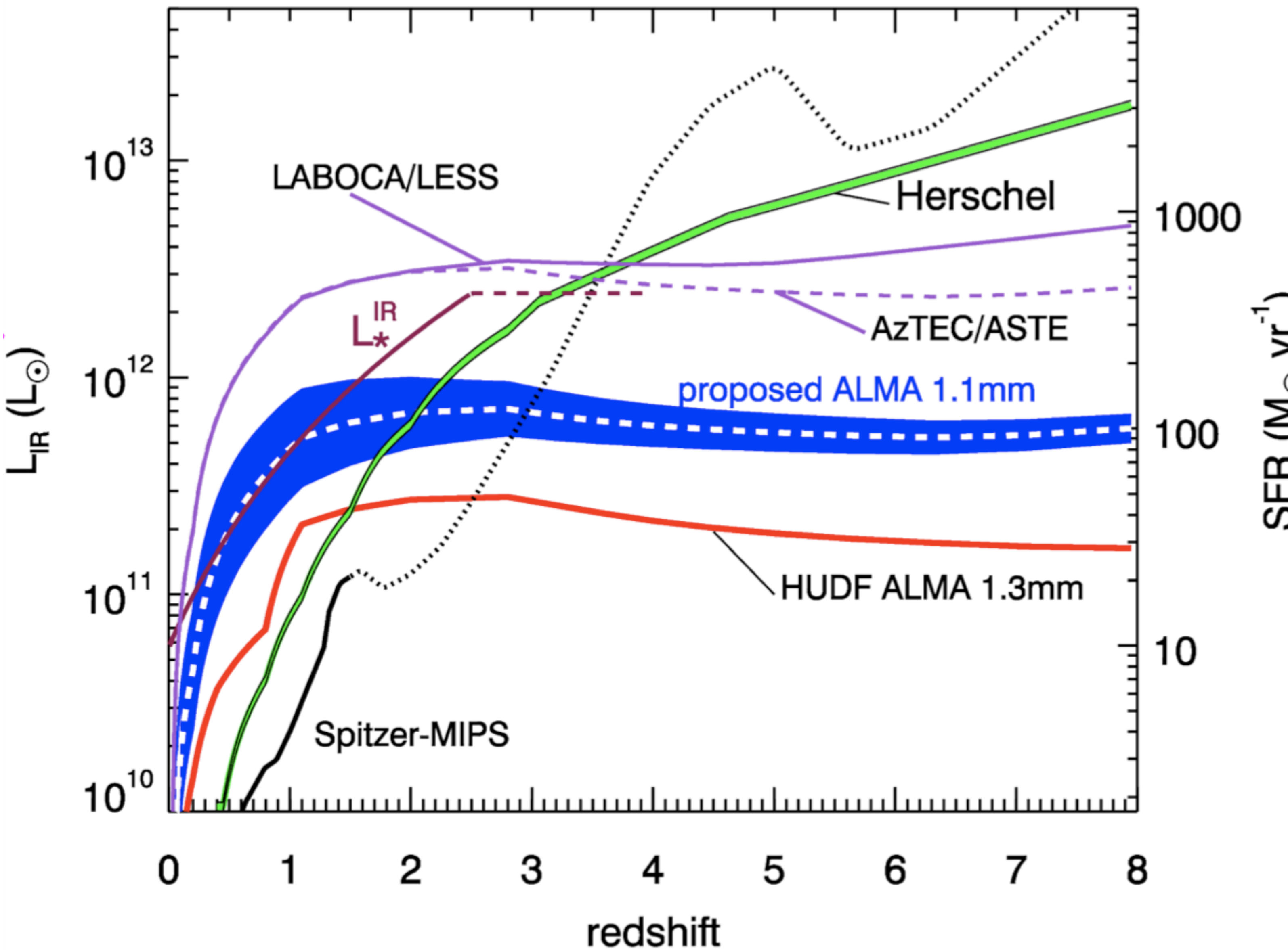
Interféromètre Plateau de Bure
IRAM

The Intense Starburst HDF 850.1 in a Galaxy Overdensity at $z = 5.2$ in the Hubble Deep Field

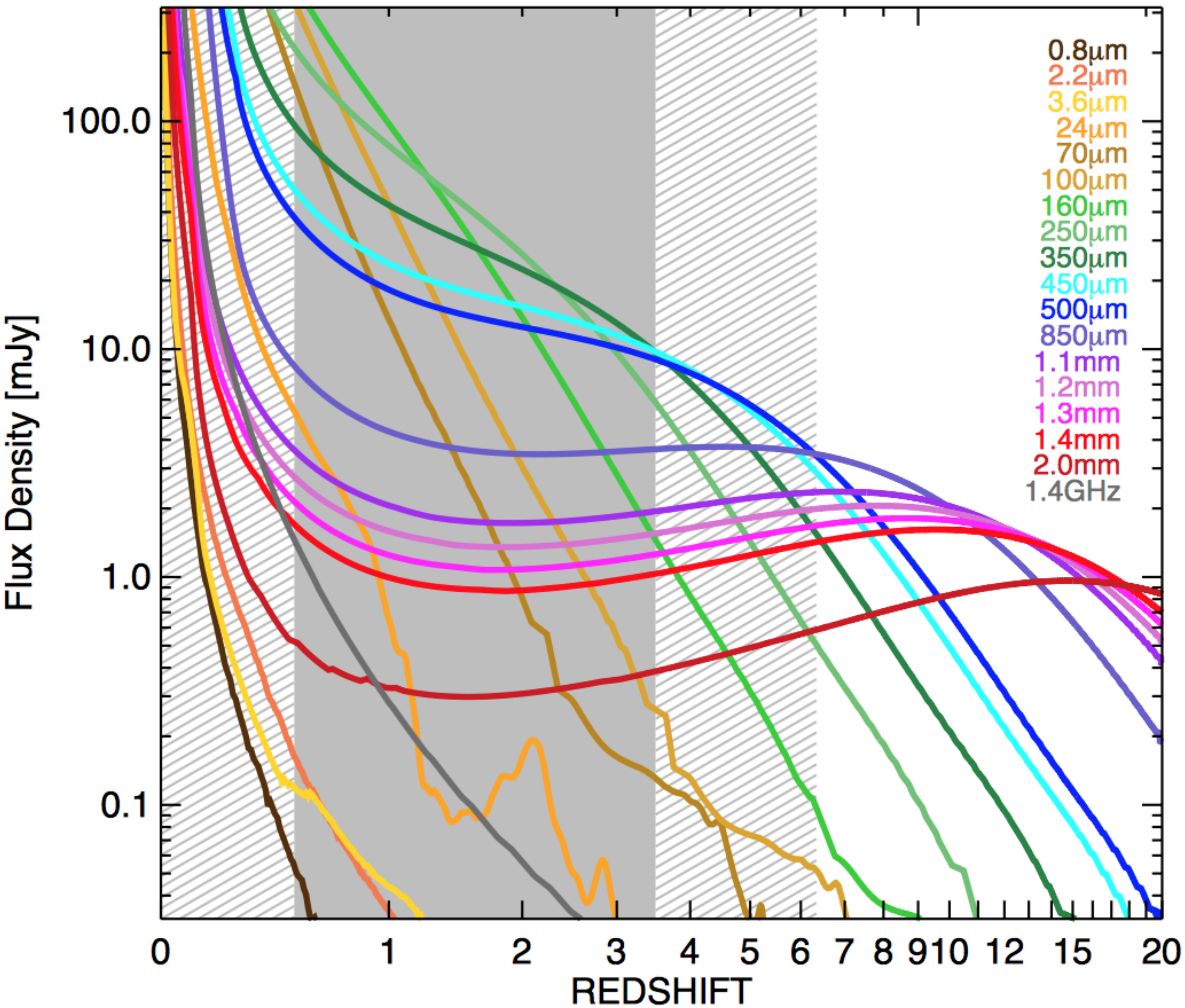


Hubble Deep Field: Image credit STScI and NASA

Walter et al., Nature, June 2012

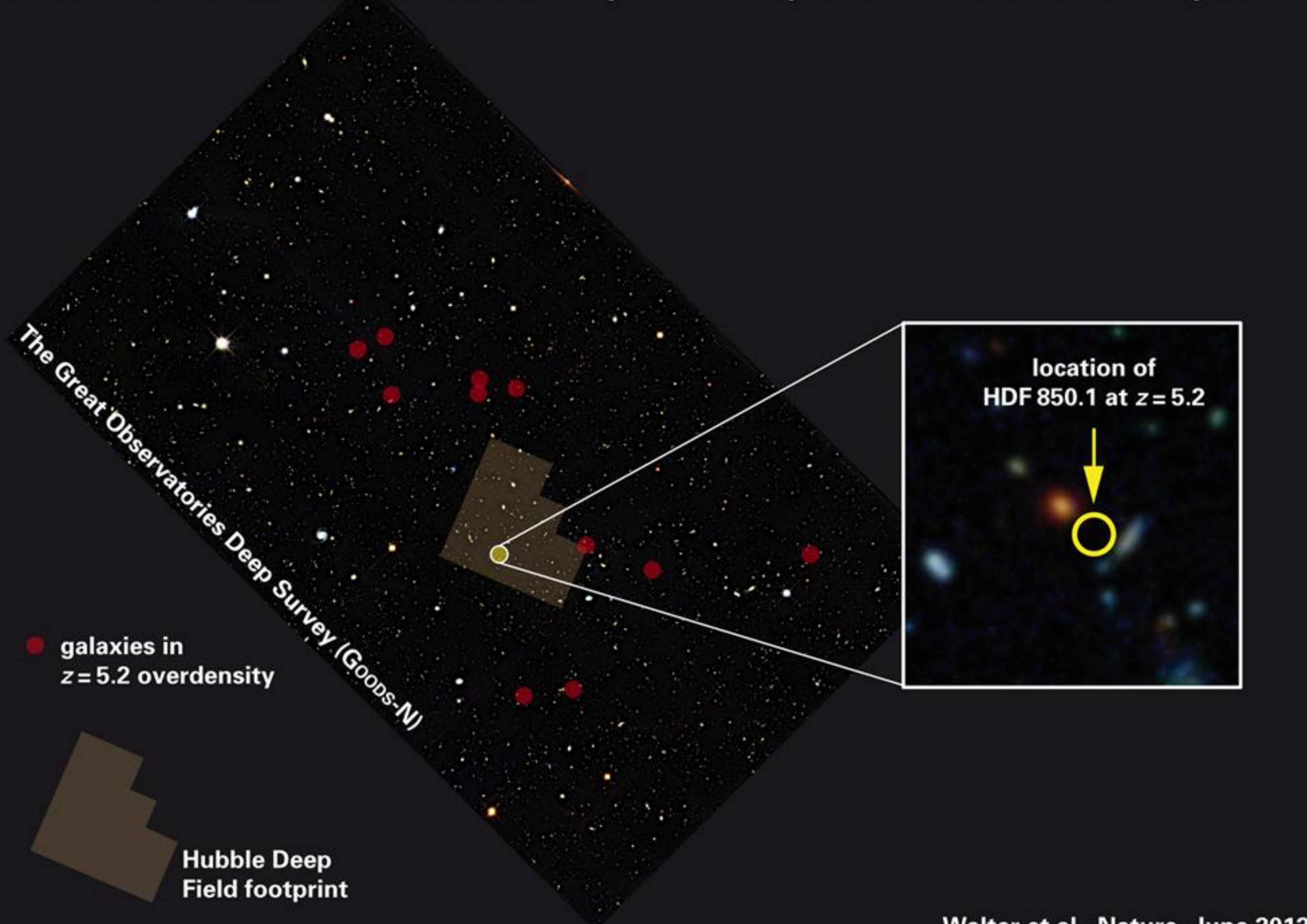

LABOCA/LESS
Herschel
AzTEC/ASTE
proposed ALMA 1.1mm
HUDF ALMA 1.3mm
Spitzer-MIPS
$L_\star^{IR}$
L_{IR} ($L_\odot$)
SFR ($M_\odot$ yr^{-1})
redshift
10^{10}
10^{11}
10^{12}
10^{13}
10
100
1000
0 1 2 3 4 5 6 7 8

ULIRG vs redshift



Casey et al. 2014

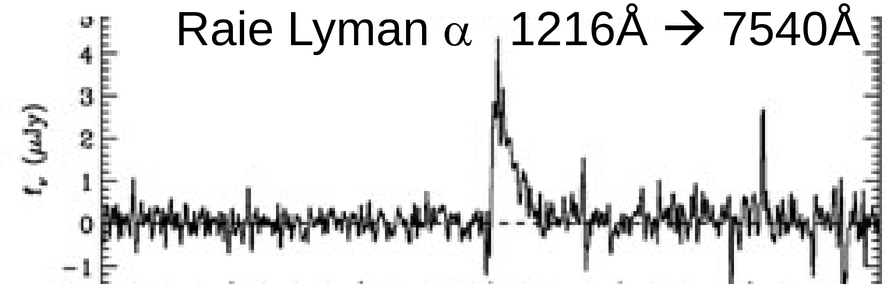
The Intense Starburst HDF 850.1 in a Galaxy Overdensity at $z = 5.2$ in the Hubble Deep Field

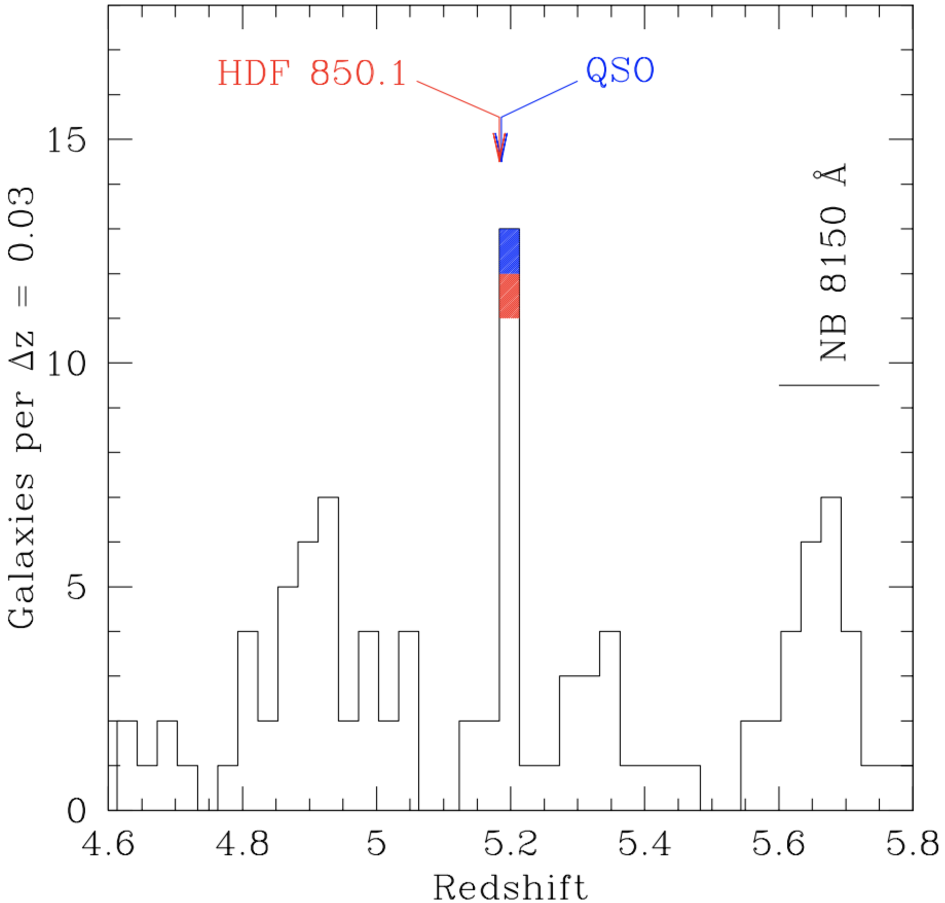


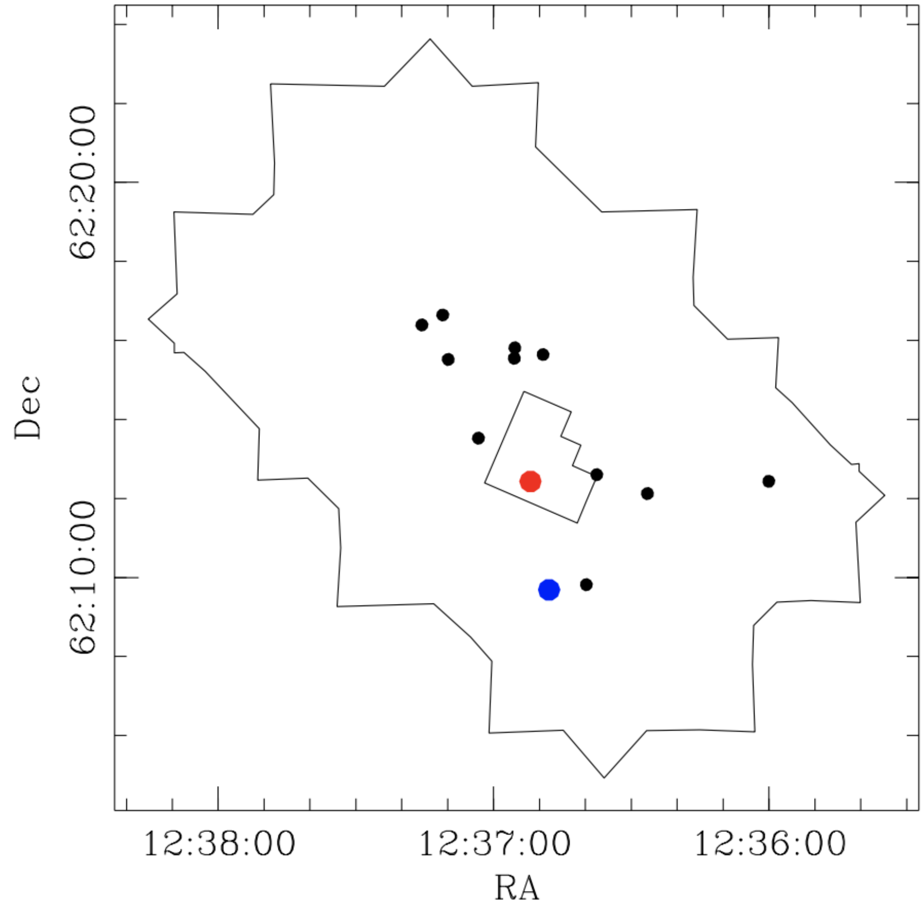
Walter et al., Nature, June 2012

HDF850.1 et son environnement

Une galaxie de la masse de la Voie lactée
1 milliard d'années après le Big Bang...
née dans une grande structure

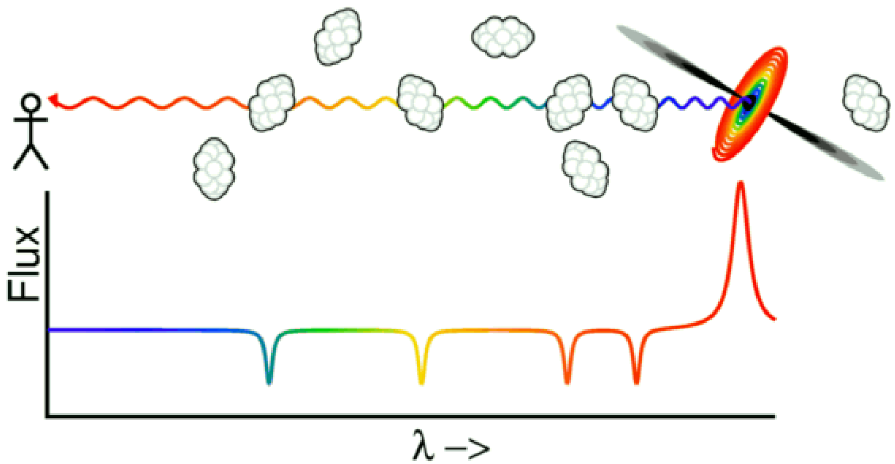




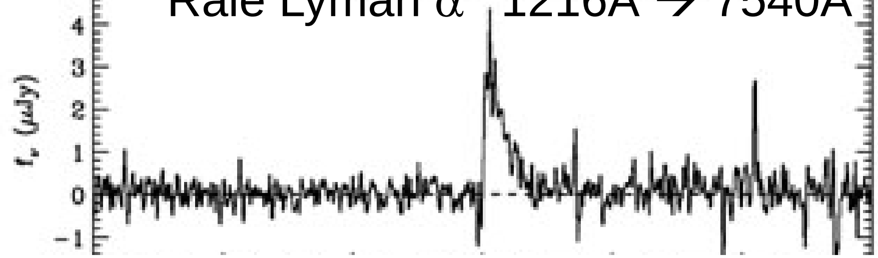


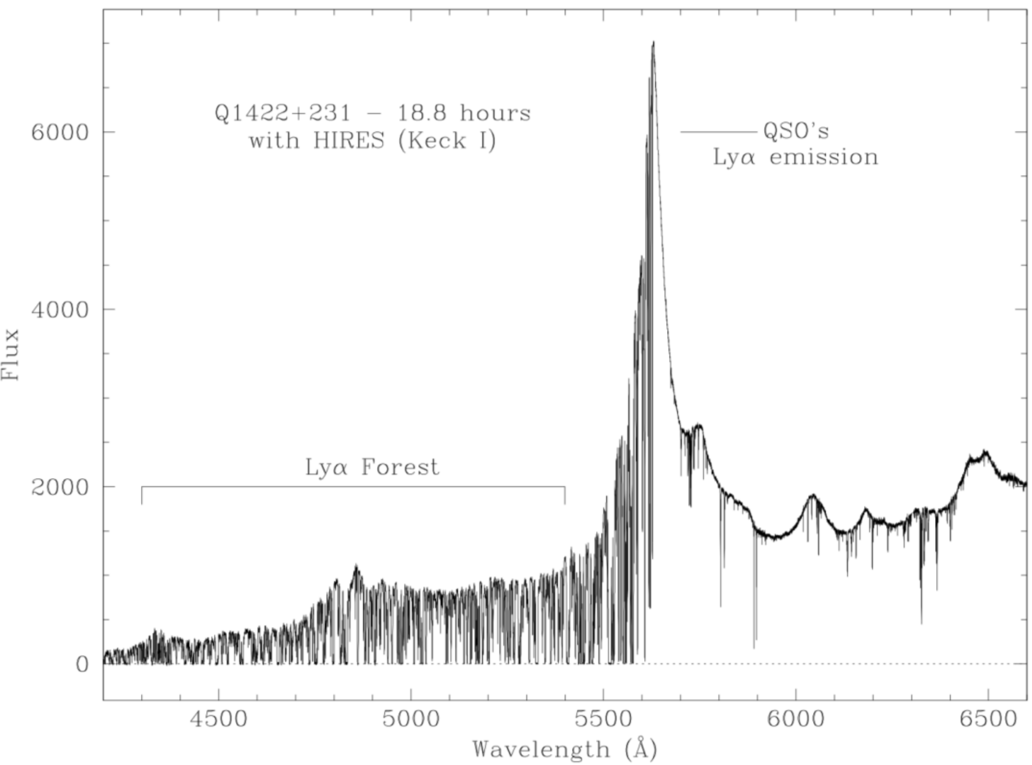
Walter et al. (2012)

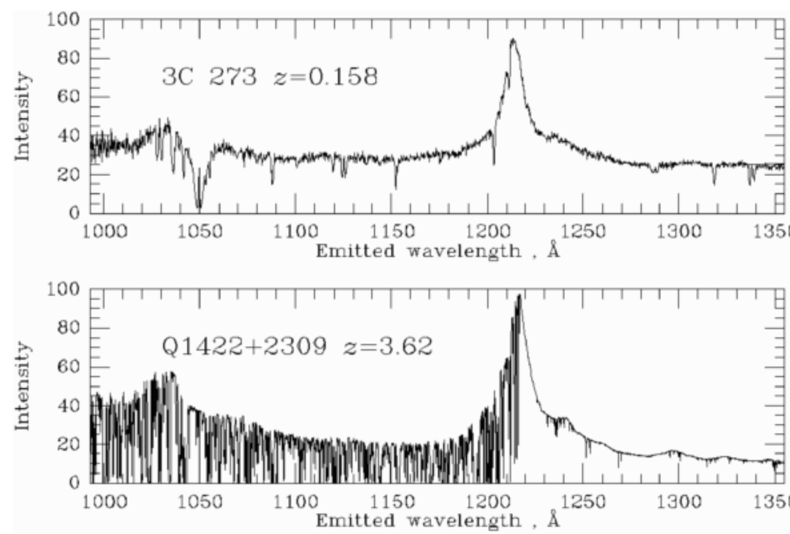
La forêt Lyman α

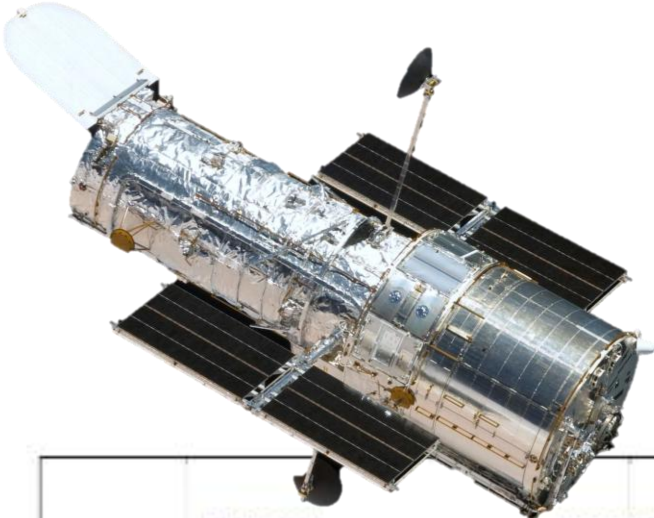


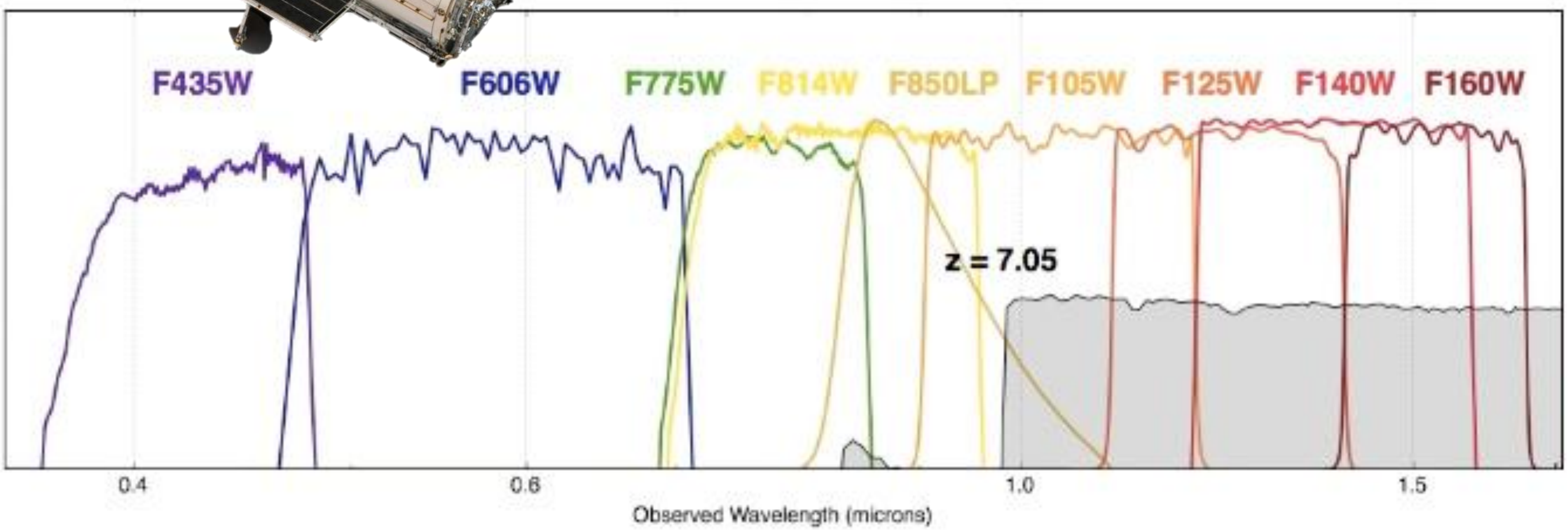
Raie Lyman α 1216Å → 7540Å



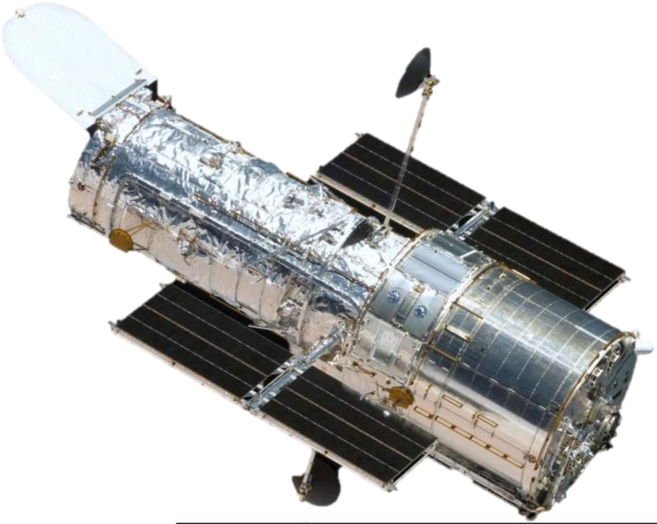


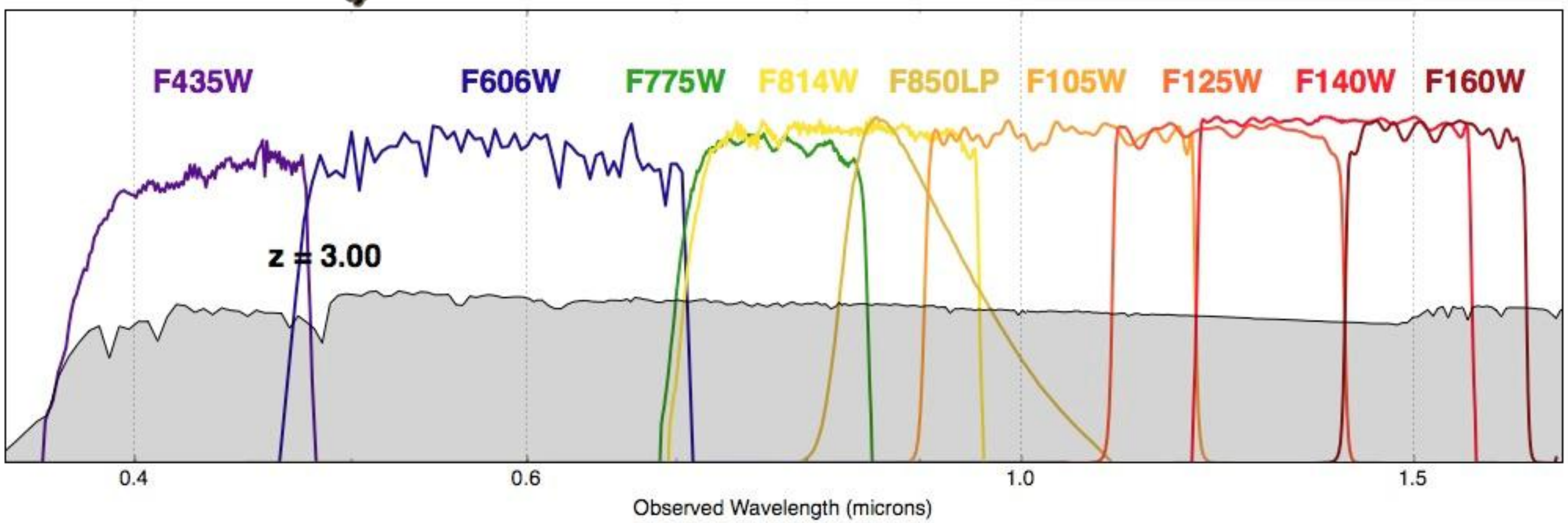


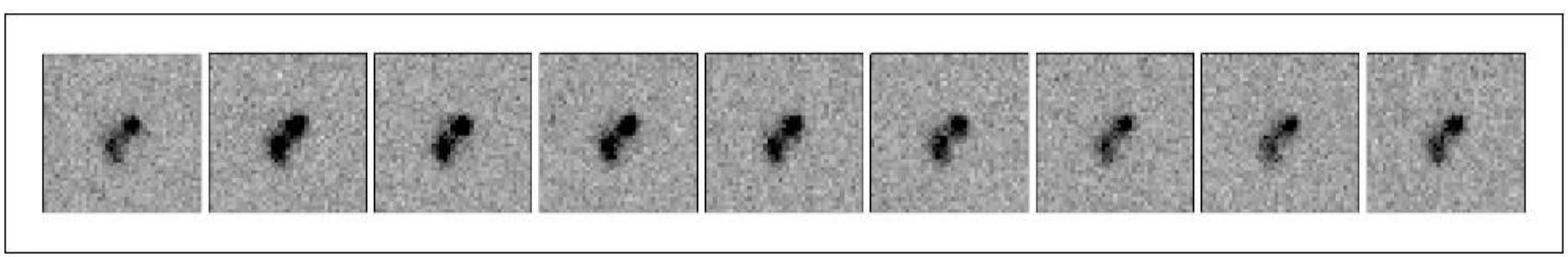


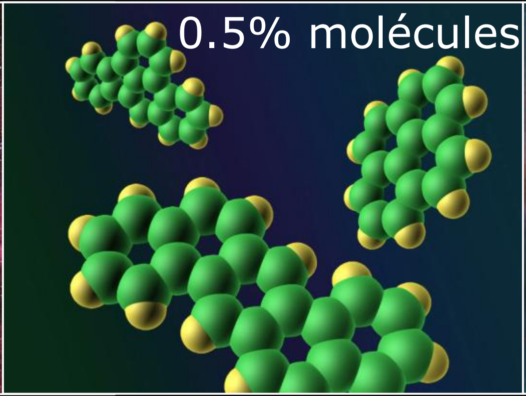


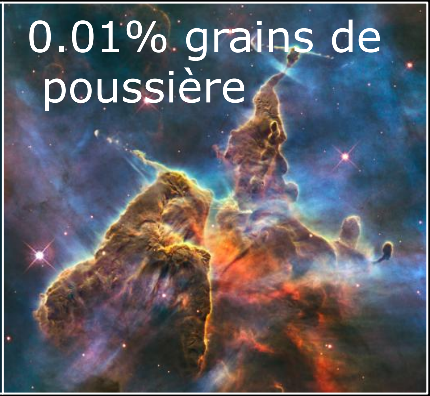
F435W F606W F775W F814W F850LP F105W F125W F140W F160W




F435W
F606W
F775W
F814W
F850LP
F105W
F125W
F140W
F160W
z = 3.00
0.4
0.6
1.0
1.5
Observed Wavelength (microns)

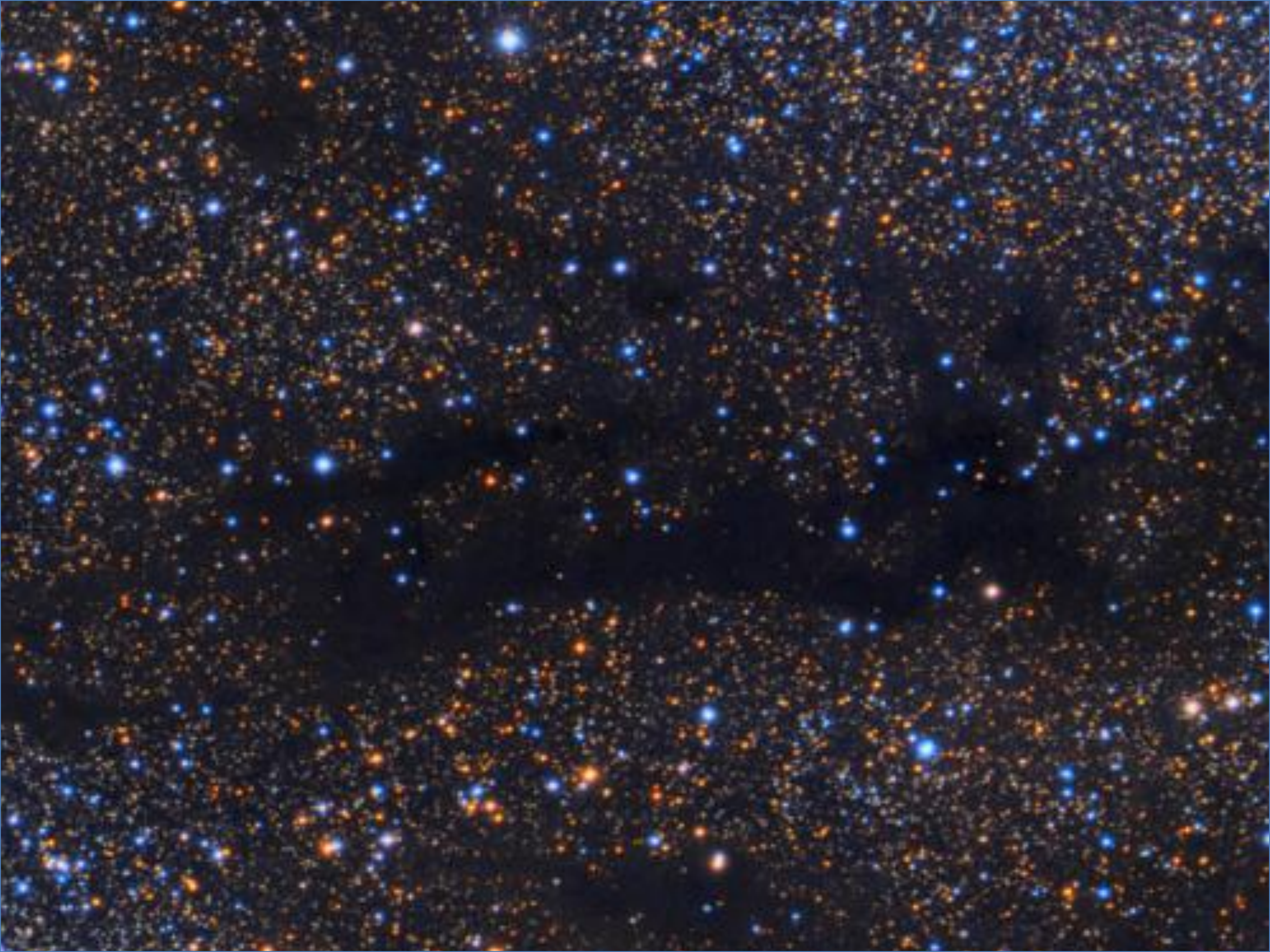




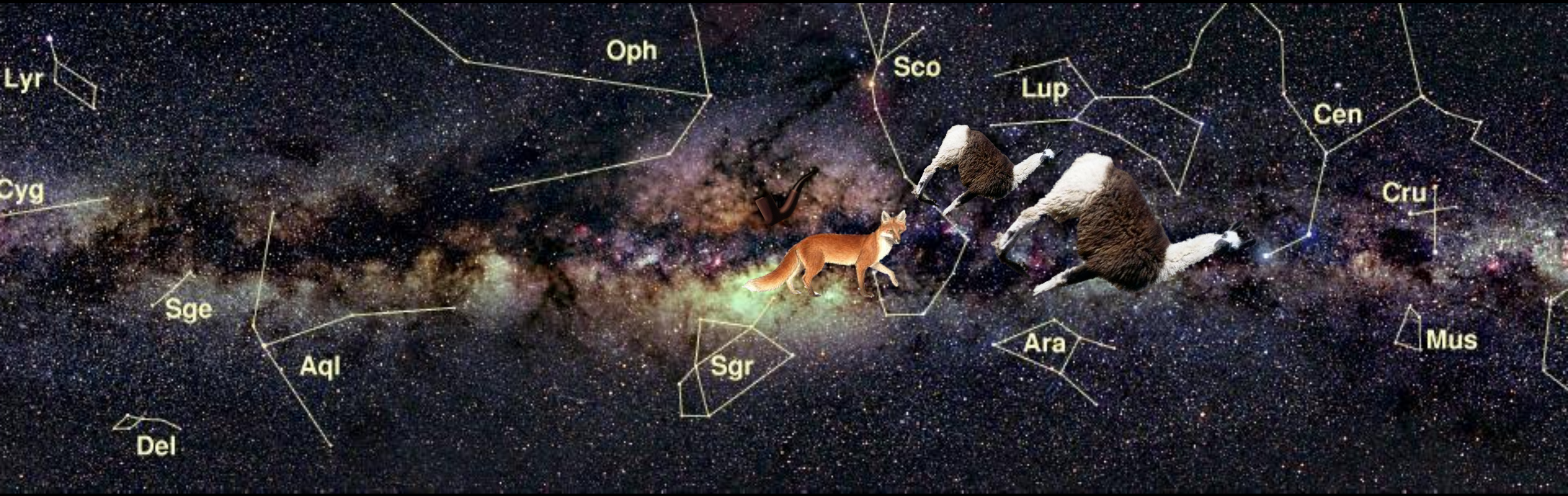


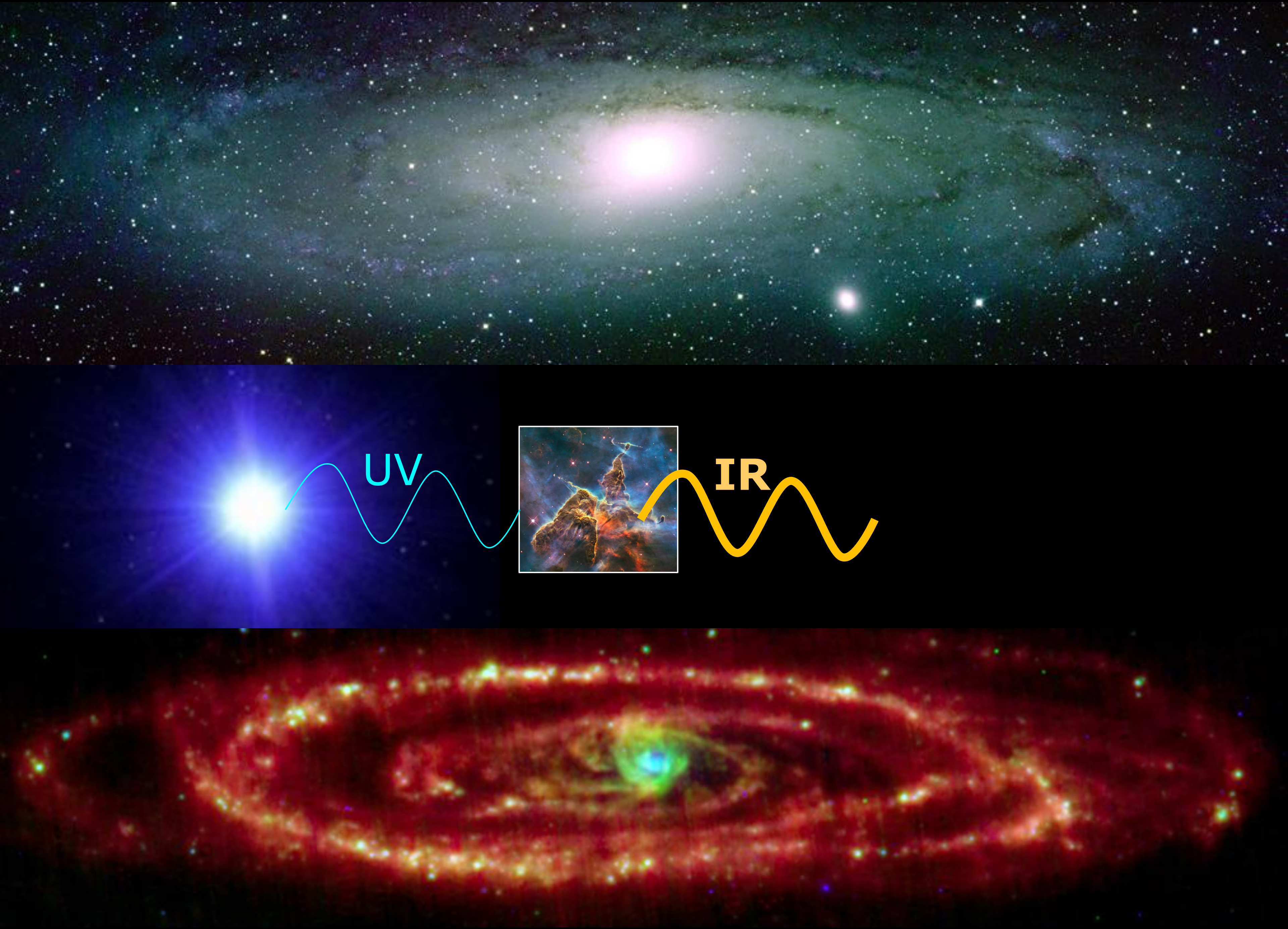
90% matière noire

« Personne ne peut supposer un instant que cette trace soit autre chose qu’un vide entre les étoiles » Ed Barnard 1919



La légende du lama et du renard

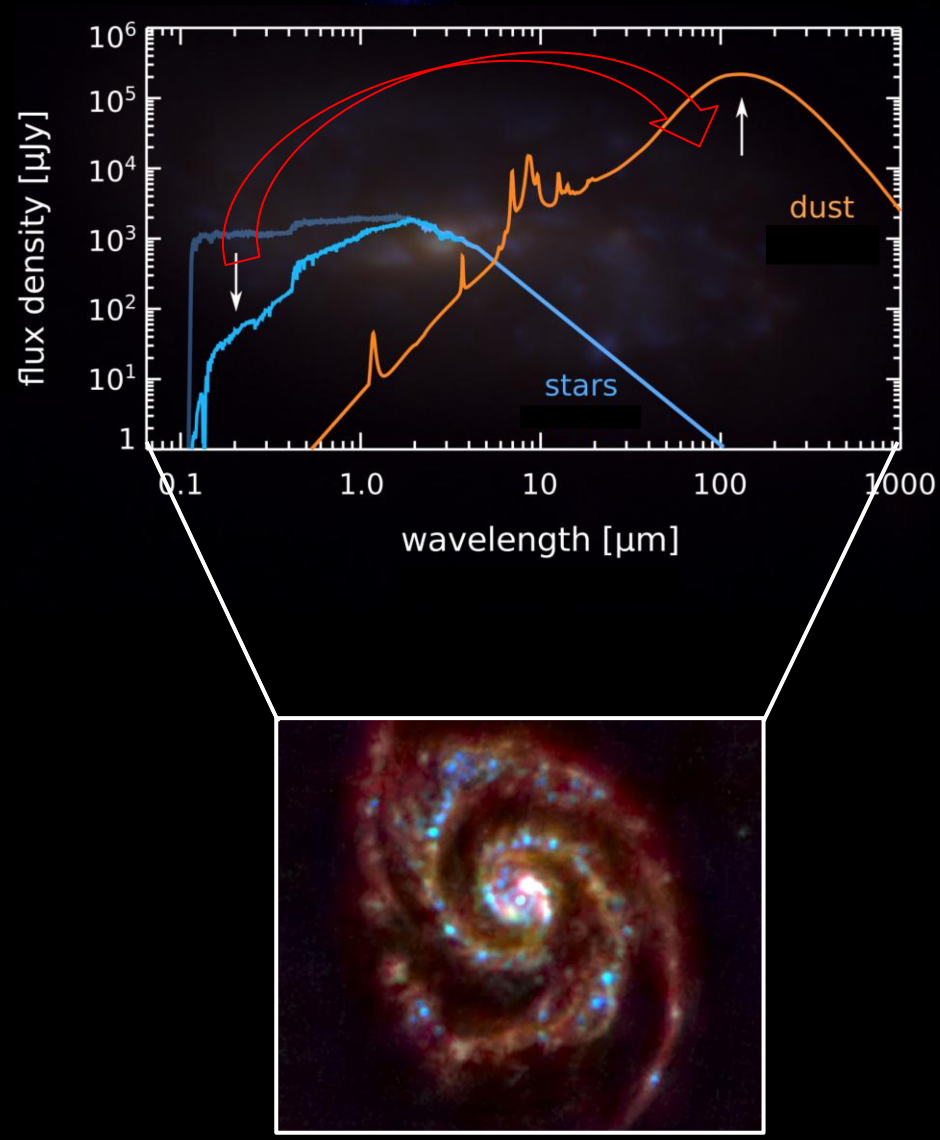


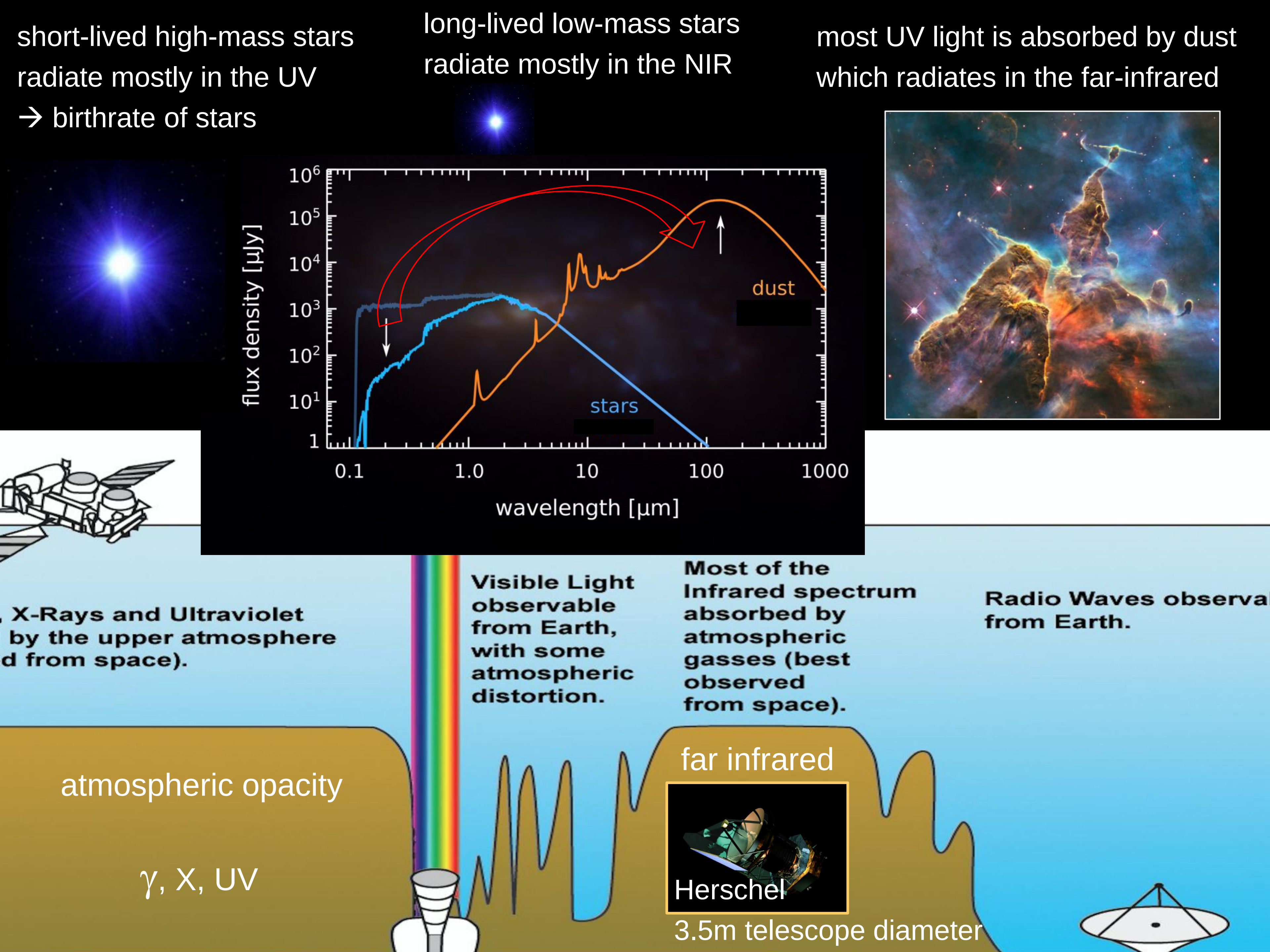

UV
IR

short-lived high-mass stars radiate mostly in the UV
→ birthrate of stars

long-lived low-mass stars radiate mostly in the NIR

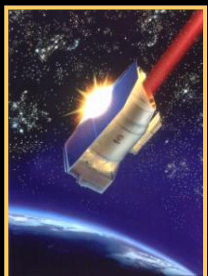
most UV light is absorbed by dust which radiates in the far-infrared




short-lived high-mass stars
radiate mostly in the UV
→ birthrate of stars
long-lived low-mass stars
radiate mostly in the NIR
most UV light is absorbed by dust
which radiates in the far-infrared
flux density [μJy]
10^6
10^5
10^4
10^3
10^2
10^1
1
0.1
1.0
10
100
1000
wavelength [μm]
dust
stars
, X-Rays and Ultraviolet
by the upper atmosphere
d from space).
Visible Light
observable
from Earth,
with some
atmospheric
distortion.
Most of the
Infrared spectrum
absorbed by
atmospheric
gasses (best
observed
from space).
Radio Waves observa
from Earth.
atmospheric opacity
γ, X, UV
far infrared
Herschel
3.5m telescope diameter

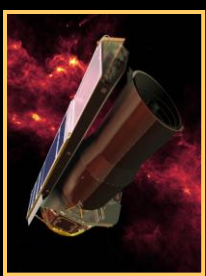
IRAS 1985
57 cm
41" fwhm

100 µm

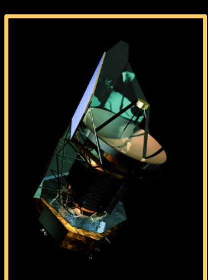


ISO 1995
60 cm

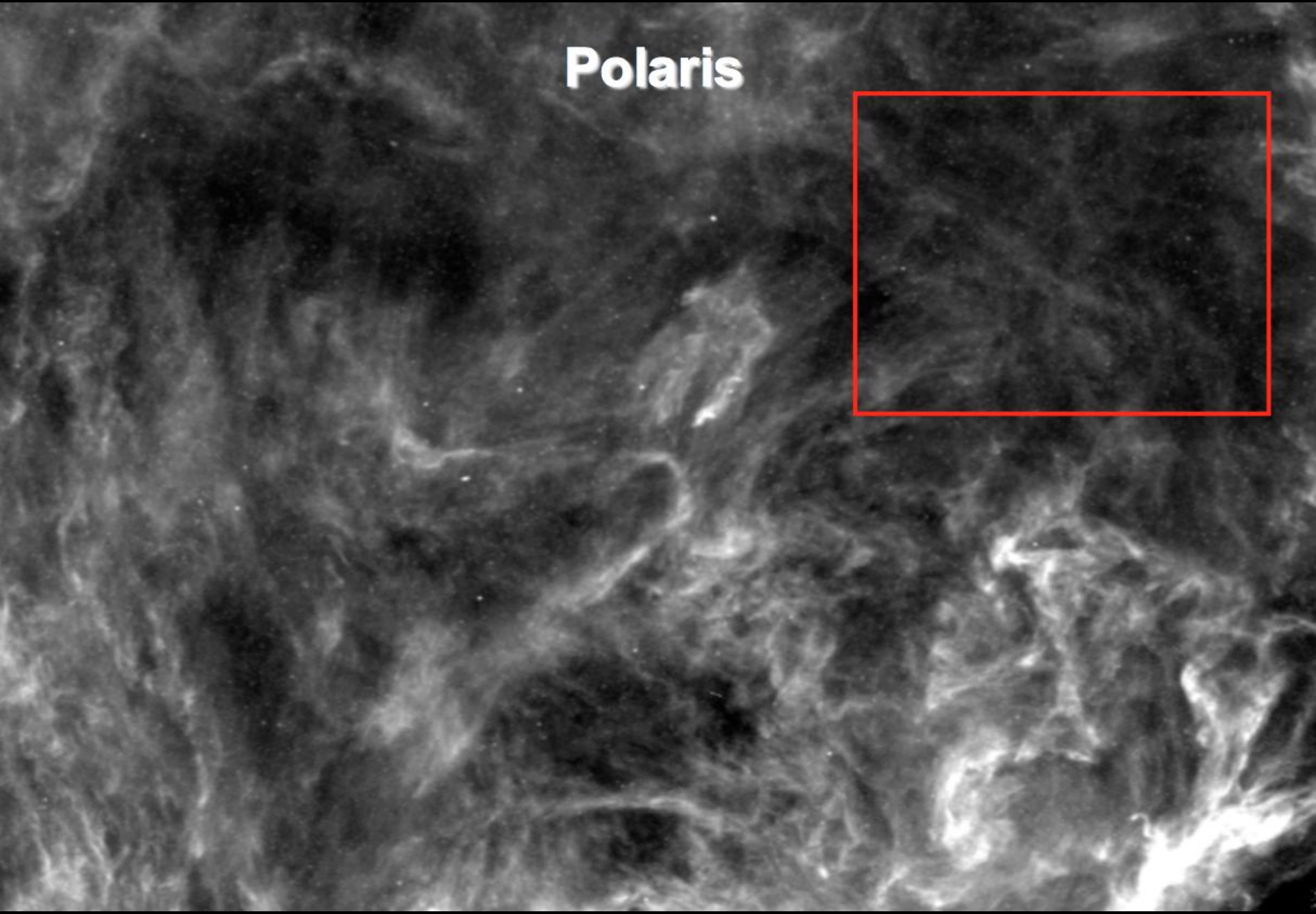
100µm



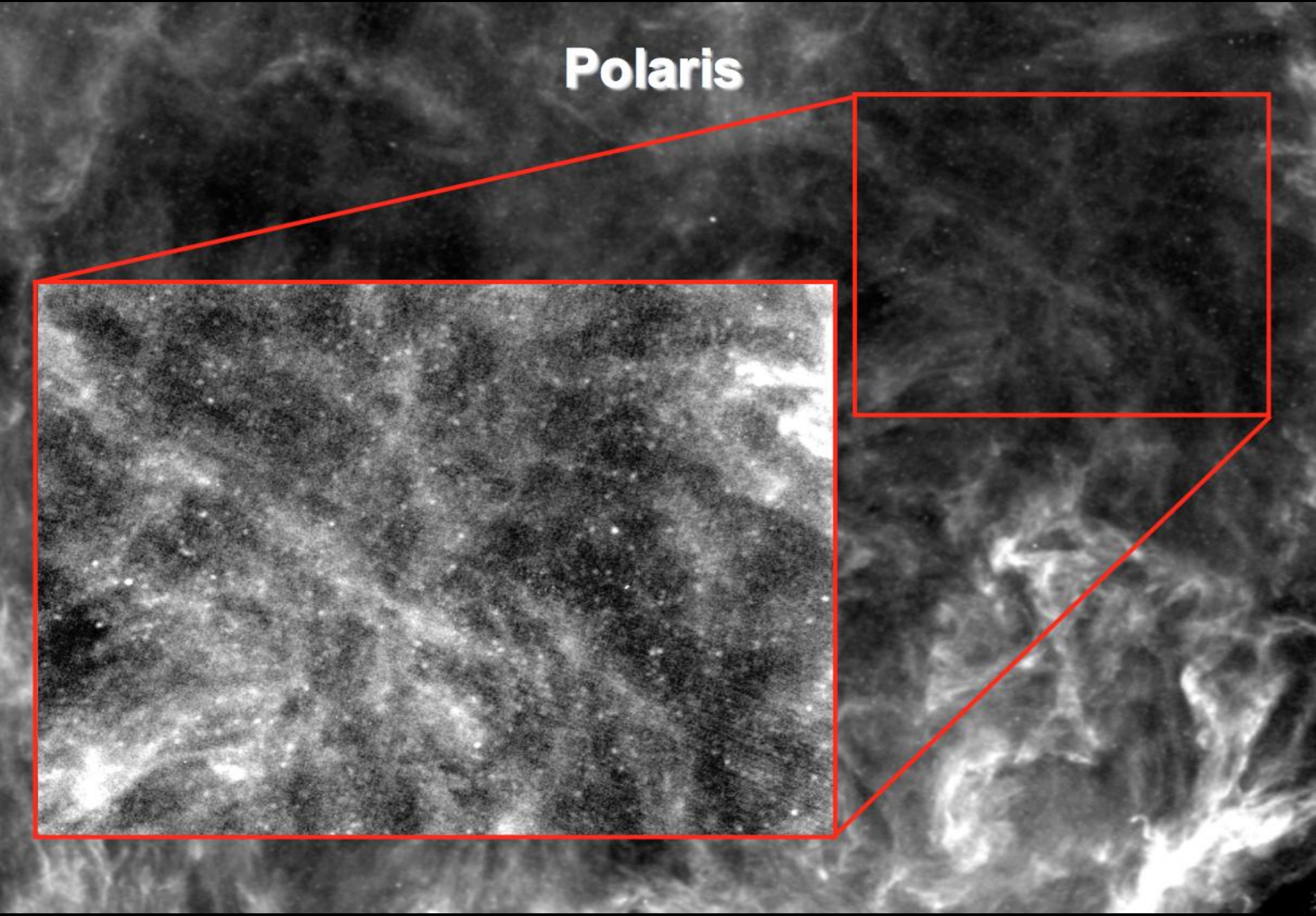
Spitzer 2003
85 cm



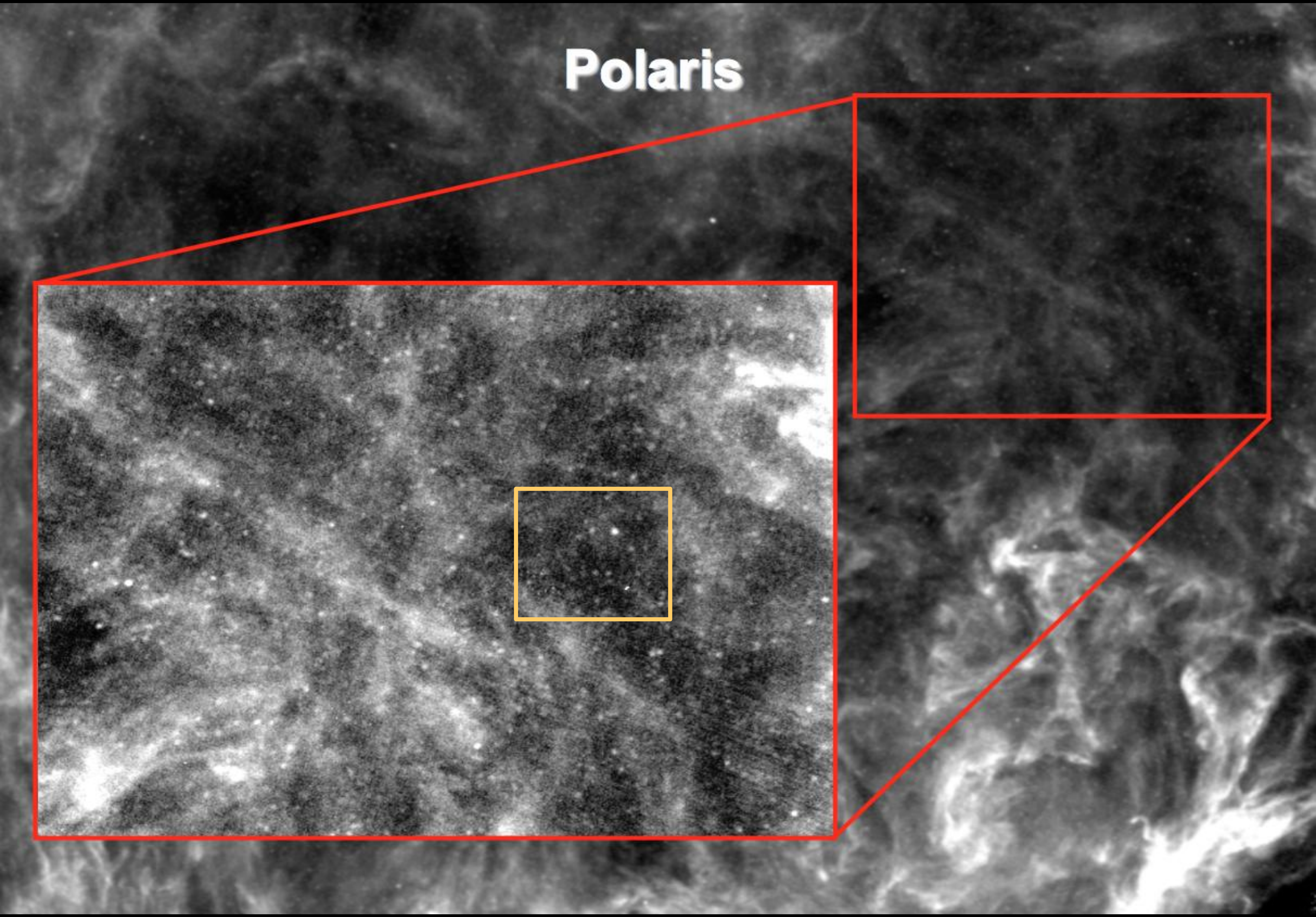
Herschel 2009
350 cm
FWHM
100µm=6.7 arcsec

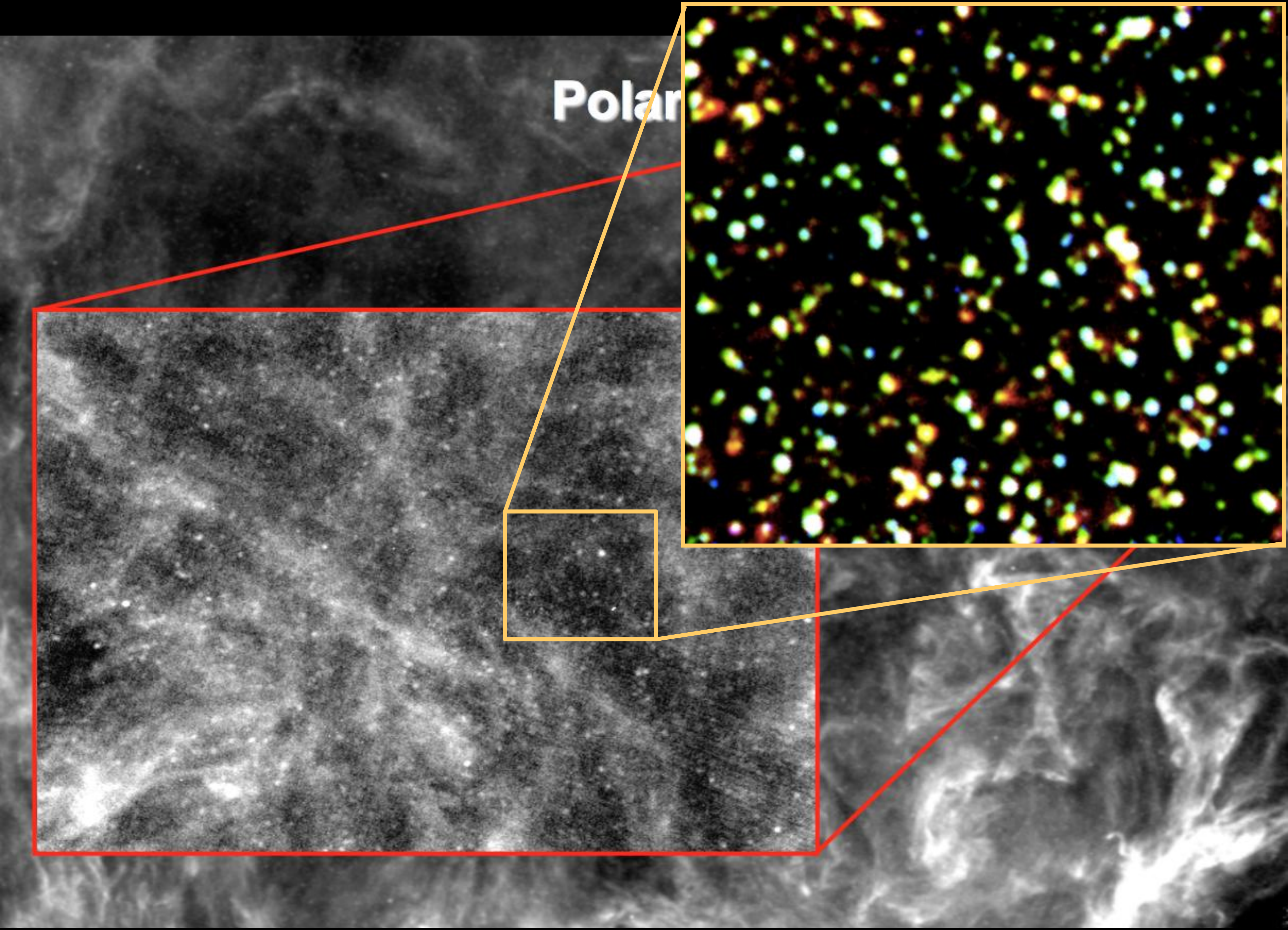

Polaris

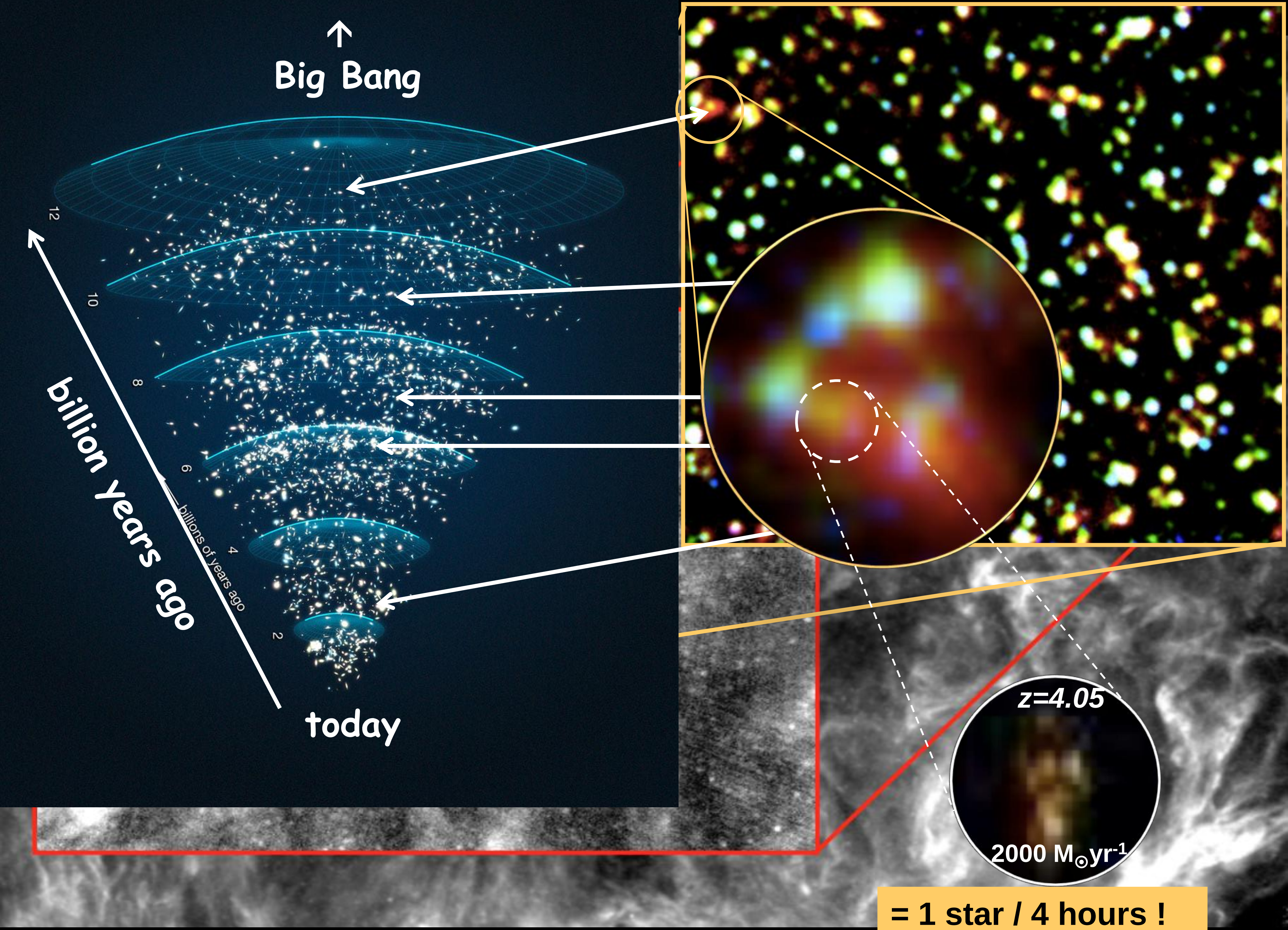
Polaris



Polaris

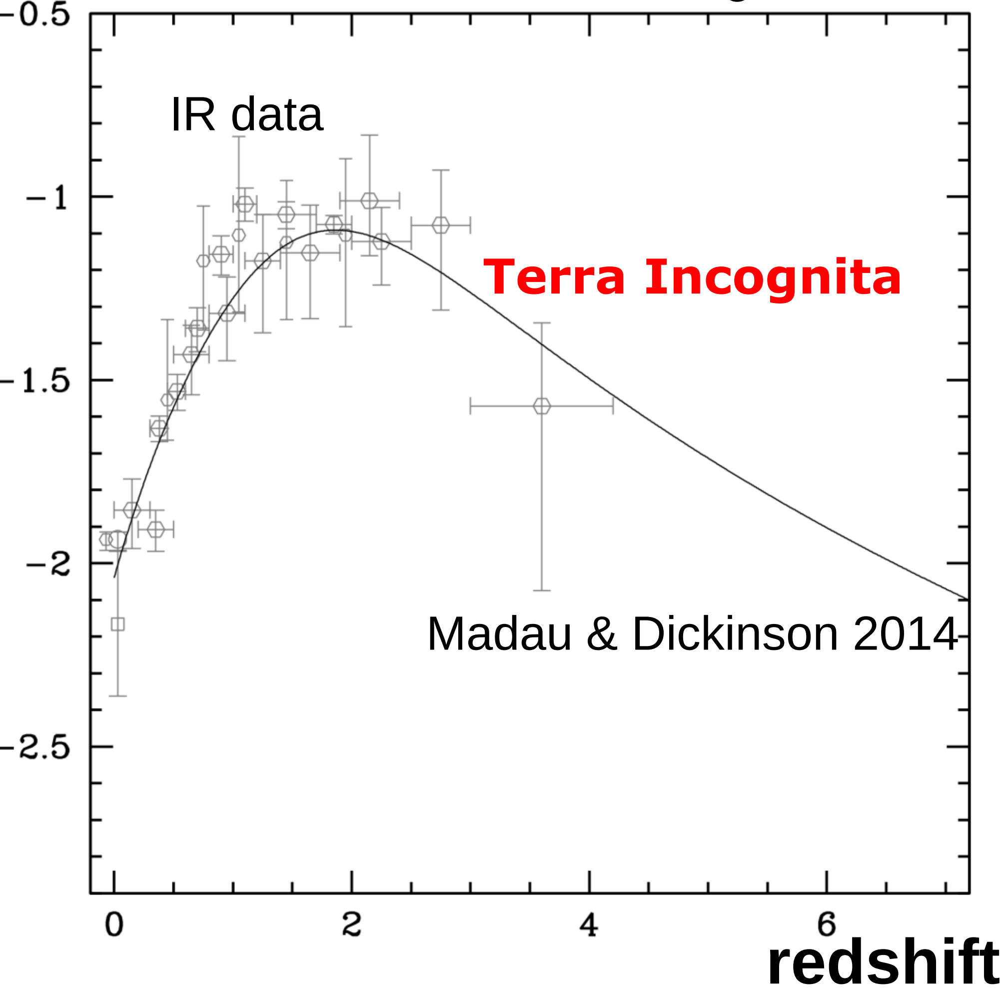


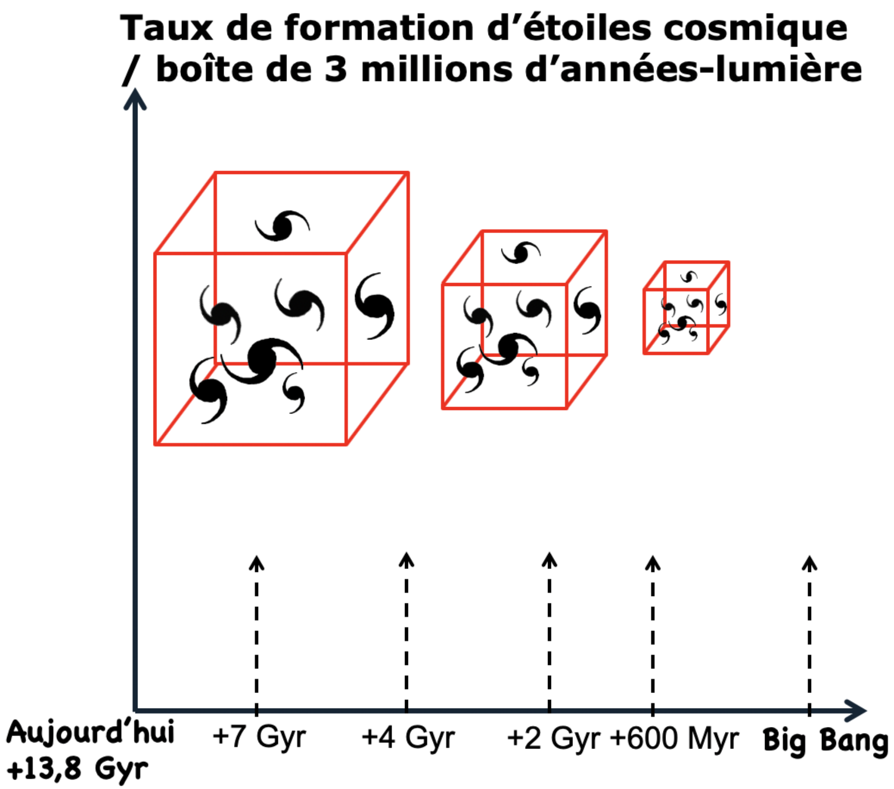

Polar


Big Bang
billion years ago
12
10
8
6
4
2
billions of years ago
today
z=4.05
2000 $M_{\odot}yr^{-1}$
= 1 star / 4 hours !

Exploring the Terra Incognita with ALMA

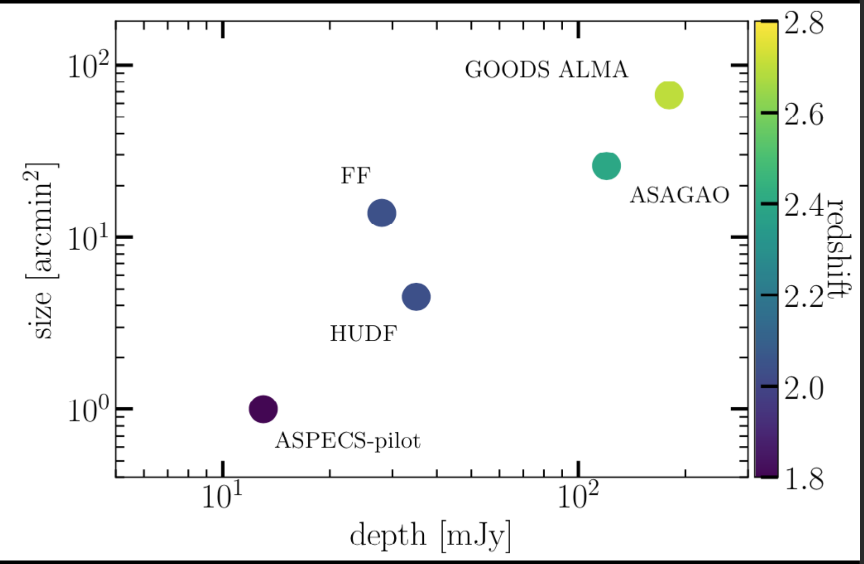
Cosmic SFR density ($M_\odot yr^{-1} Mpc^{-3}$)

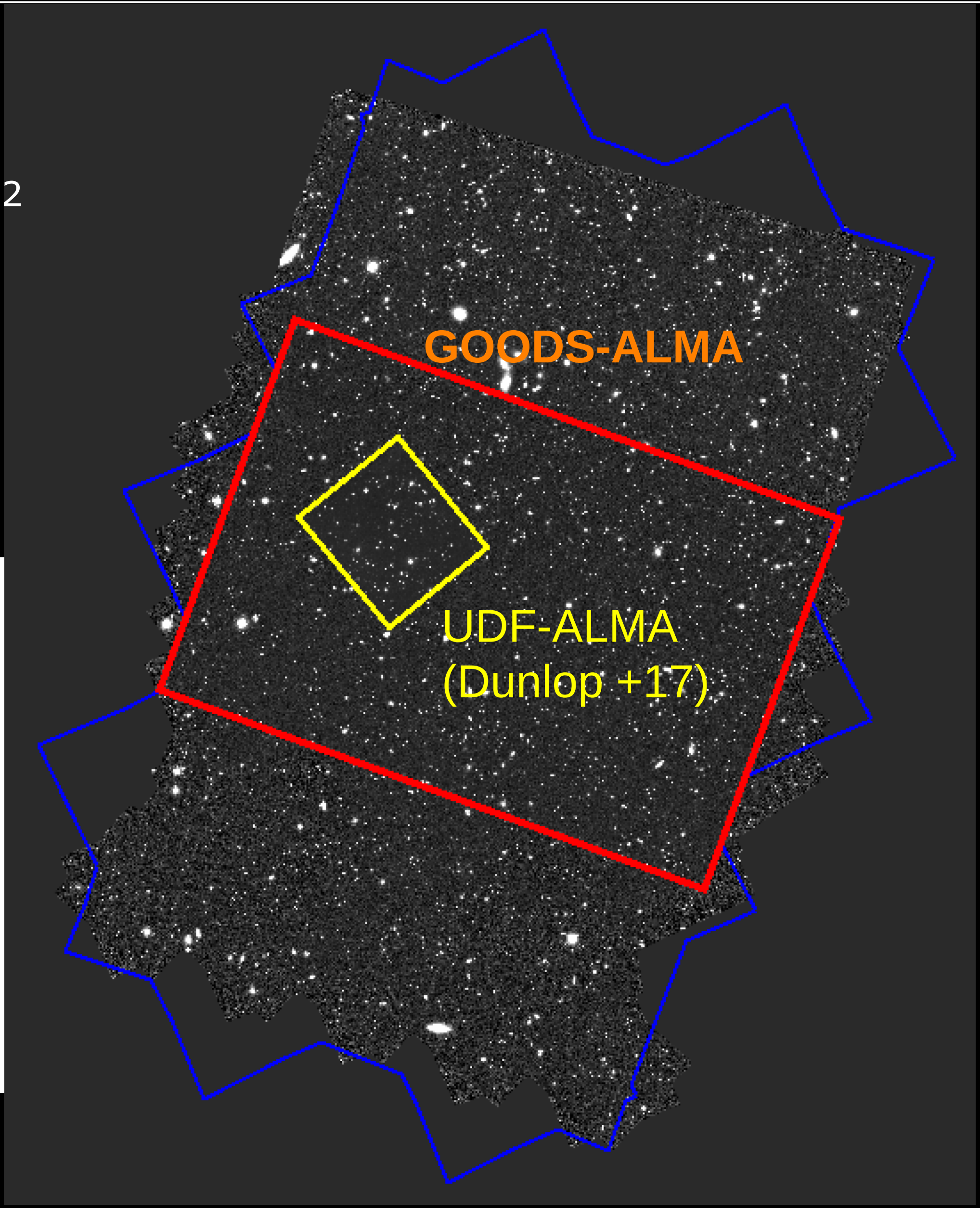


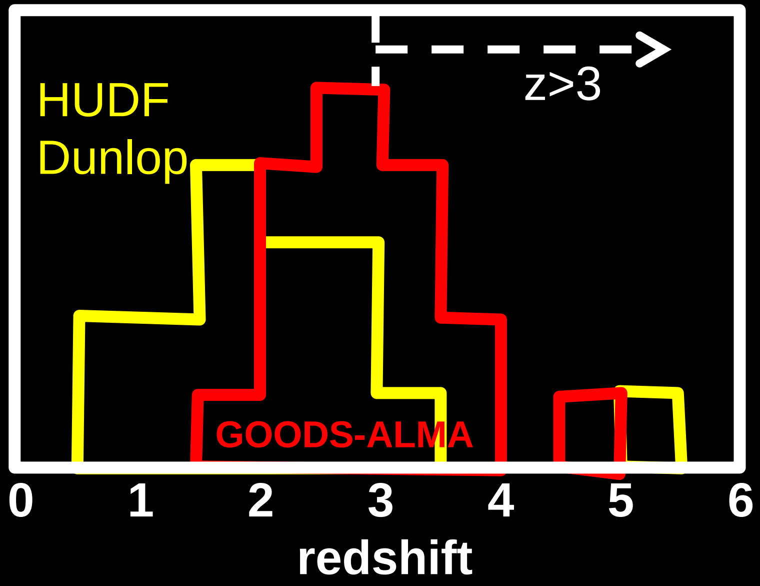


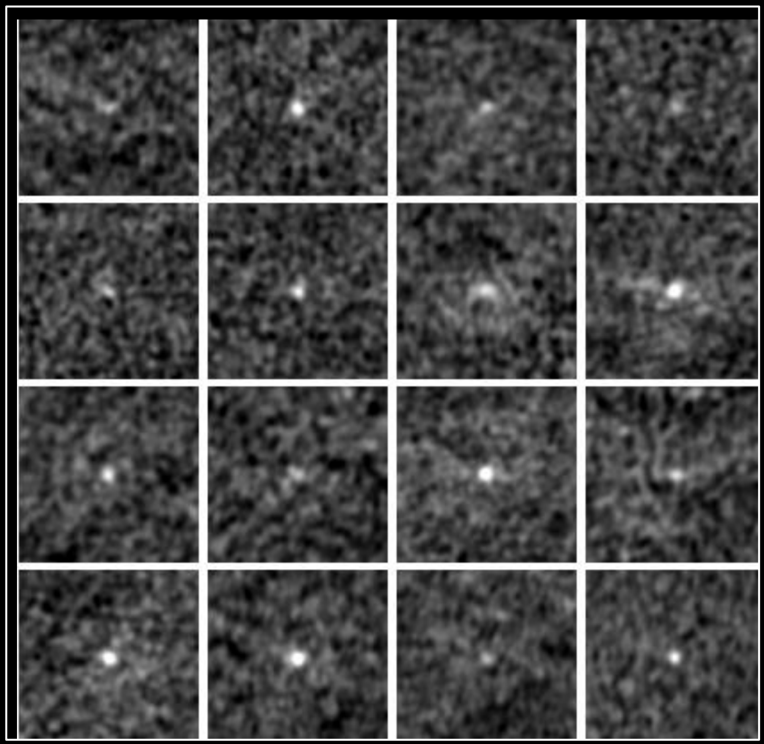
GOODS-ALMA survey

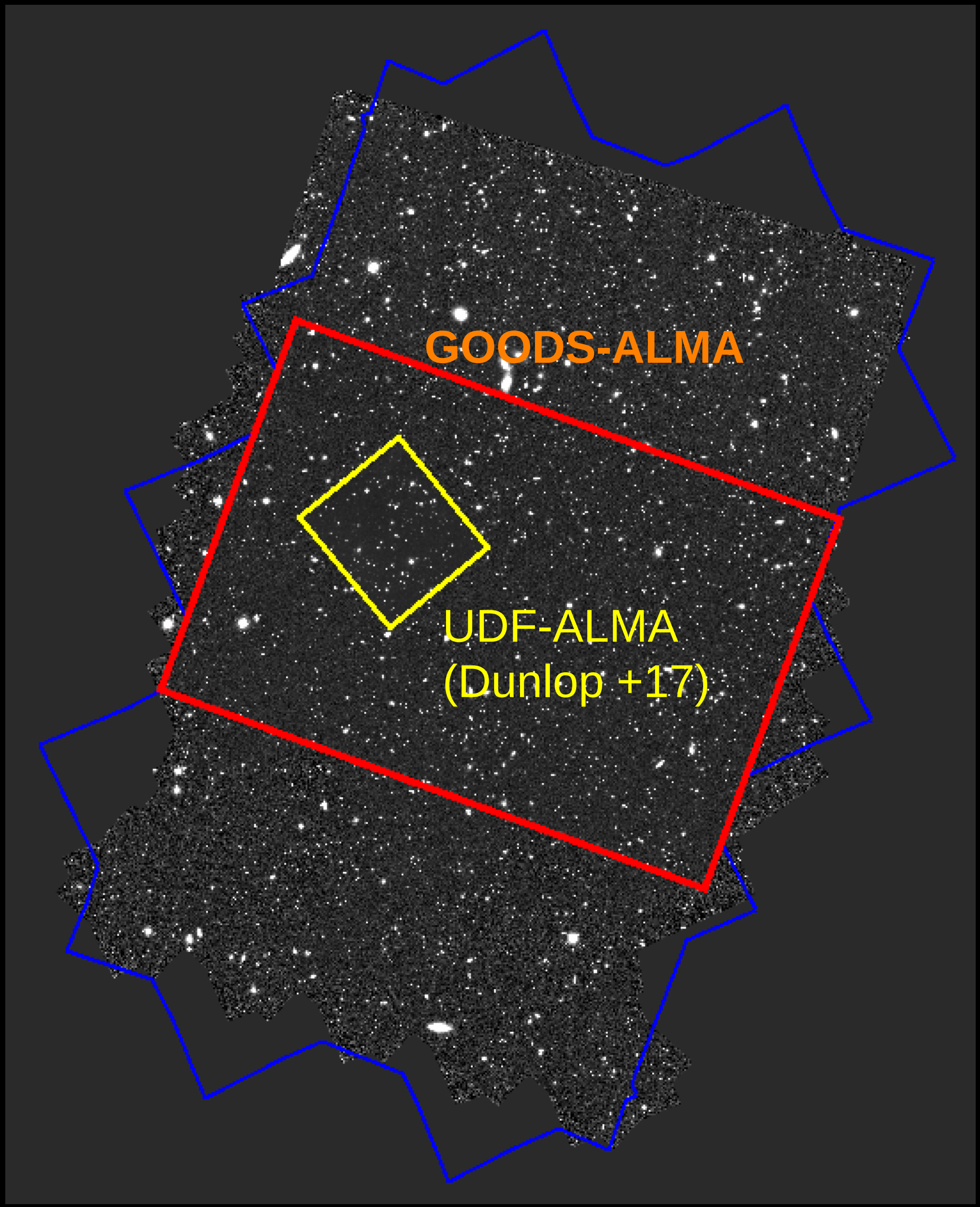
ALMA Cycle 3
Band 6, 1.1mm, $\sigma \approx 120\ \mu Jy$
846 ALMA pointings, 70 arcmin²

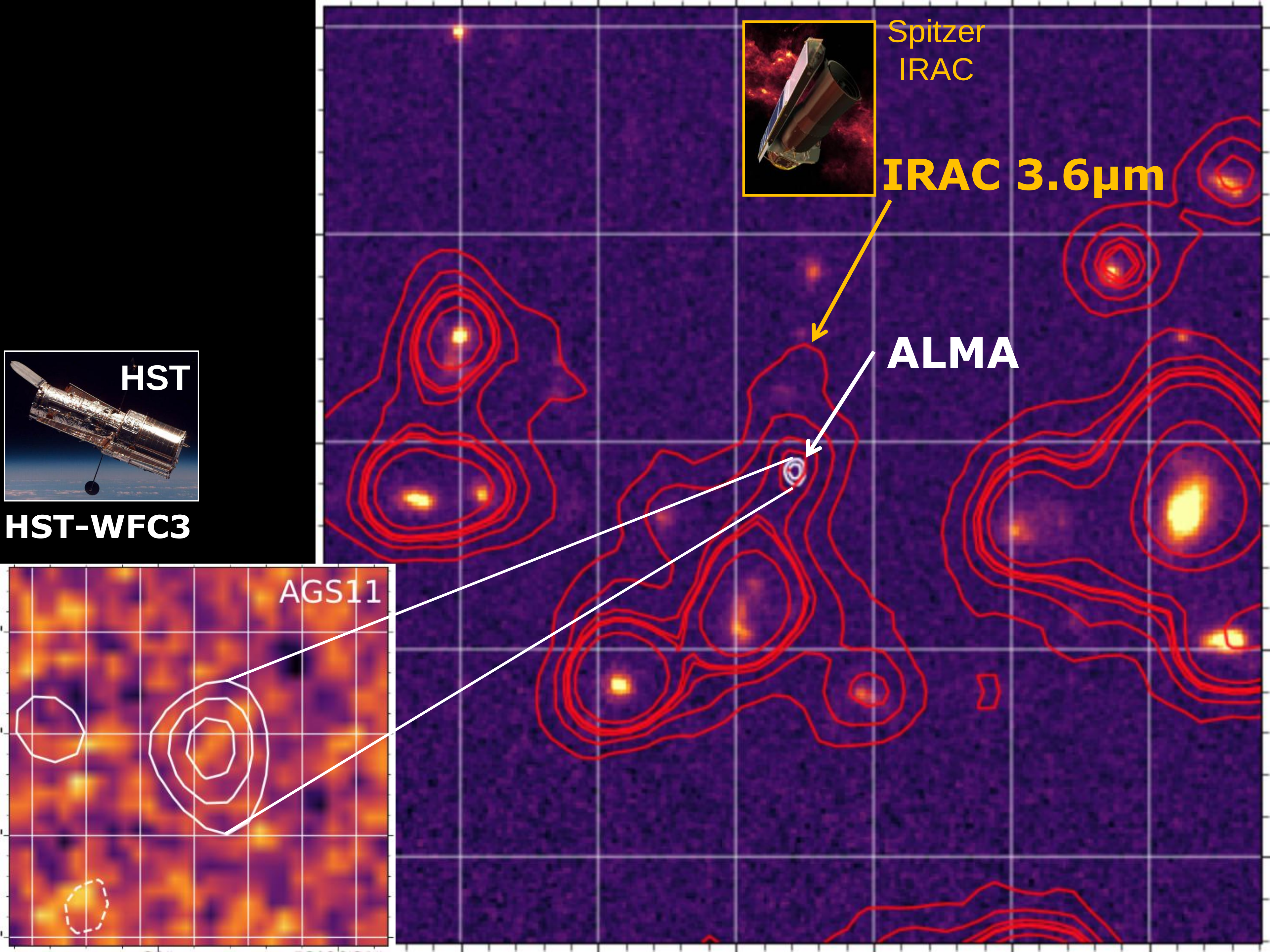




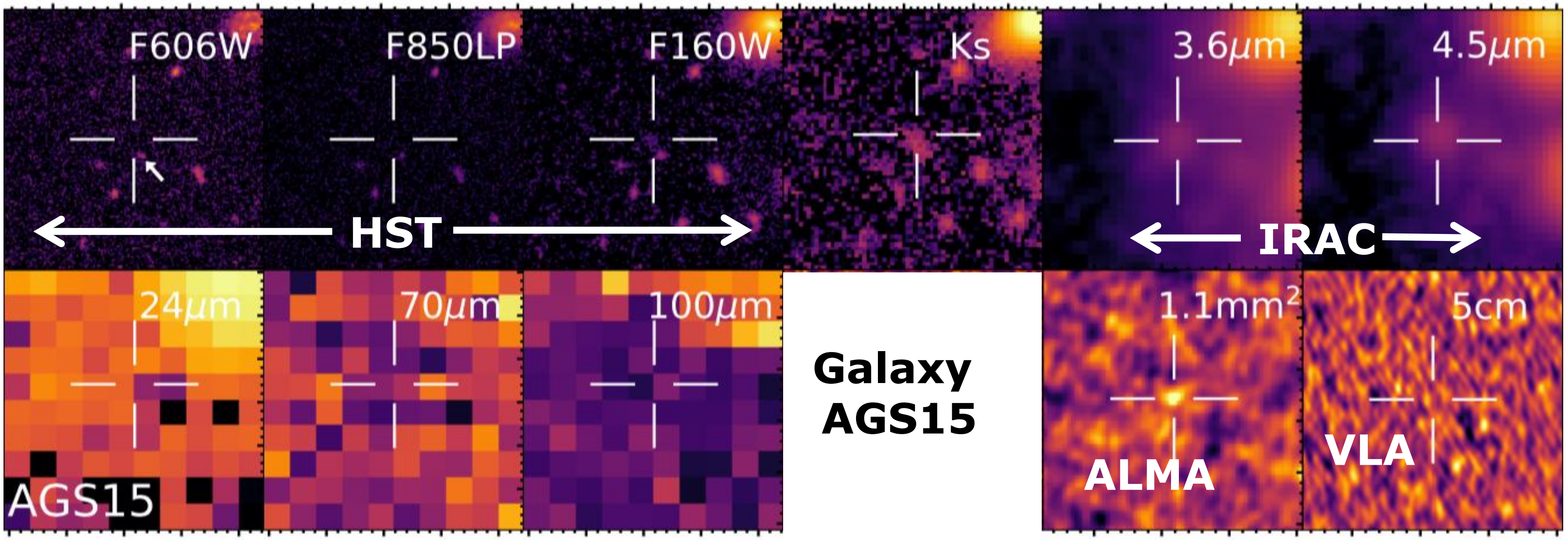

z>3
HUDF
Dunlop
GOODS-ALMA
0
1
2
3
4
5
6
redshift



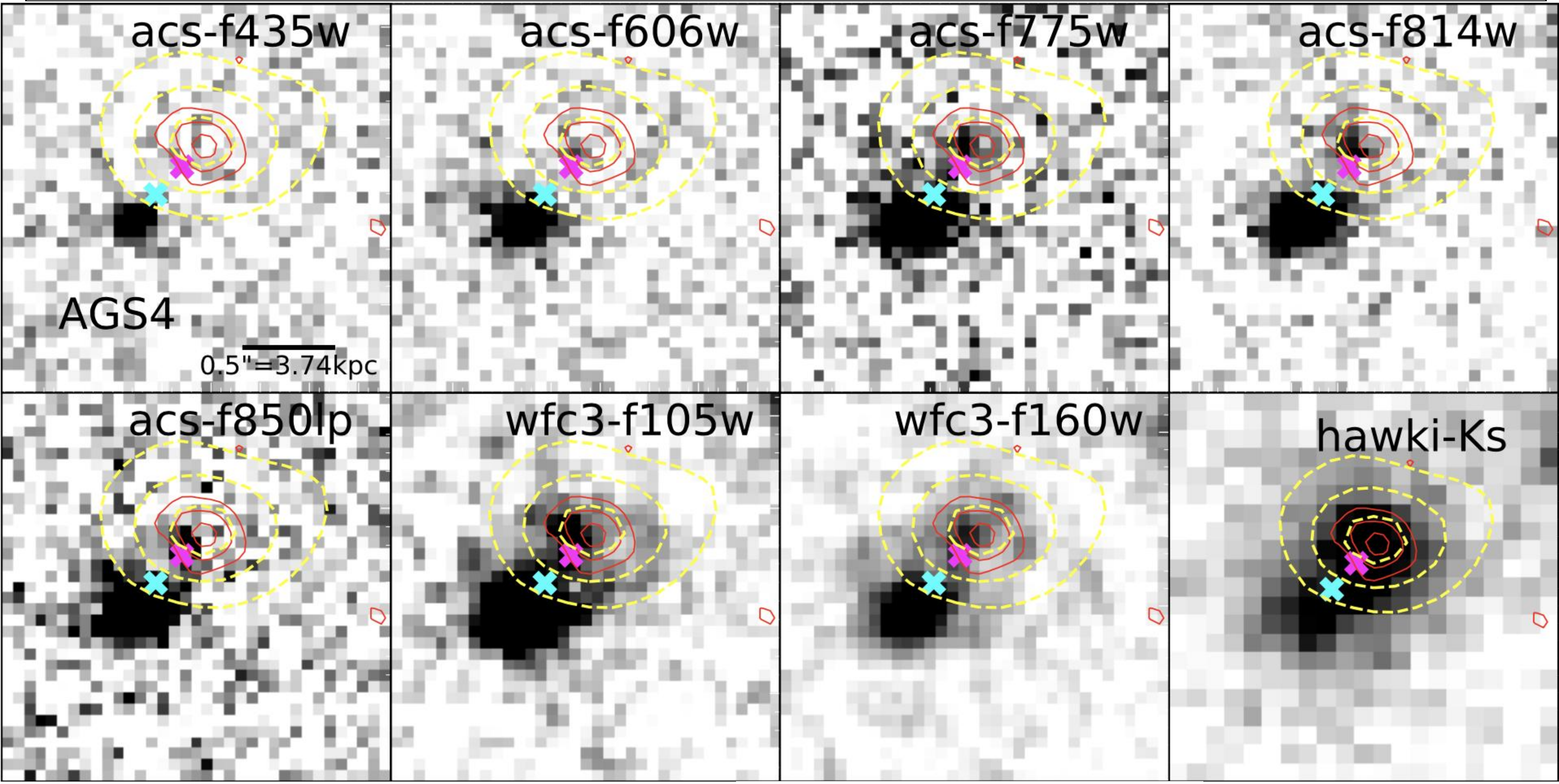

GOODS-ALMA
UDF-ALMA
(Dunlop +17)

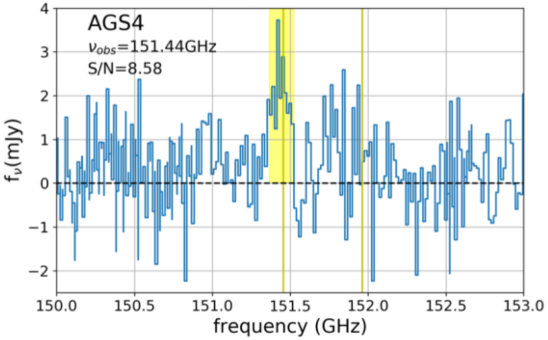

Spitzer
IRAC
IRAC 3.6μm
ALMA
HST
HST-WFC3
AGS11

HST-dark galaxies = 20% of the ALMA sources !



AGS4: z=3.556 : 1.7 Gyr après Big Bang



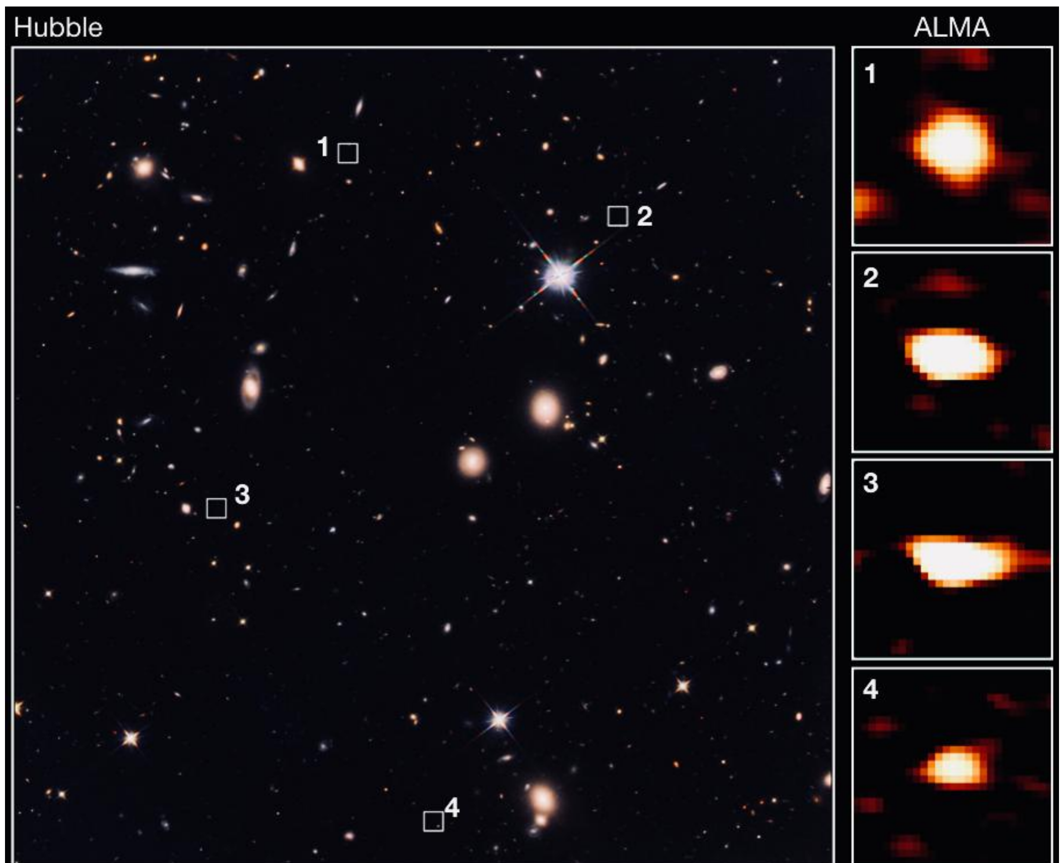


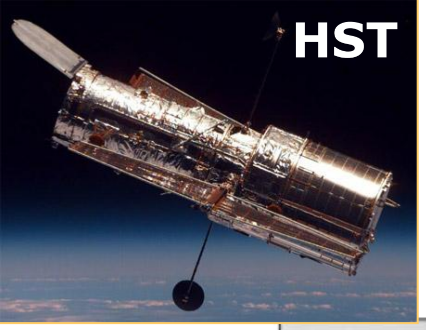
LETTER

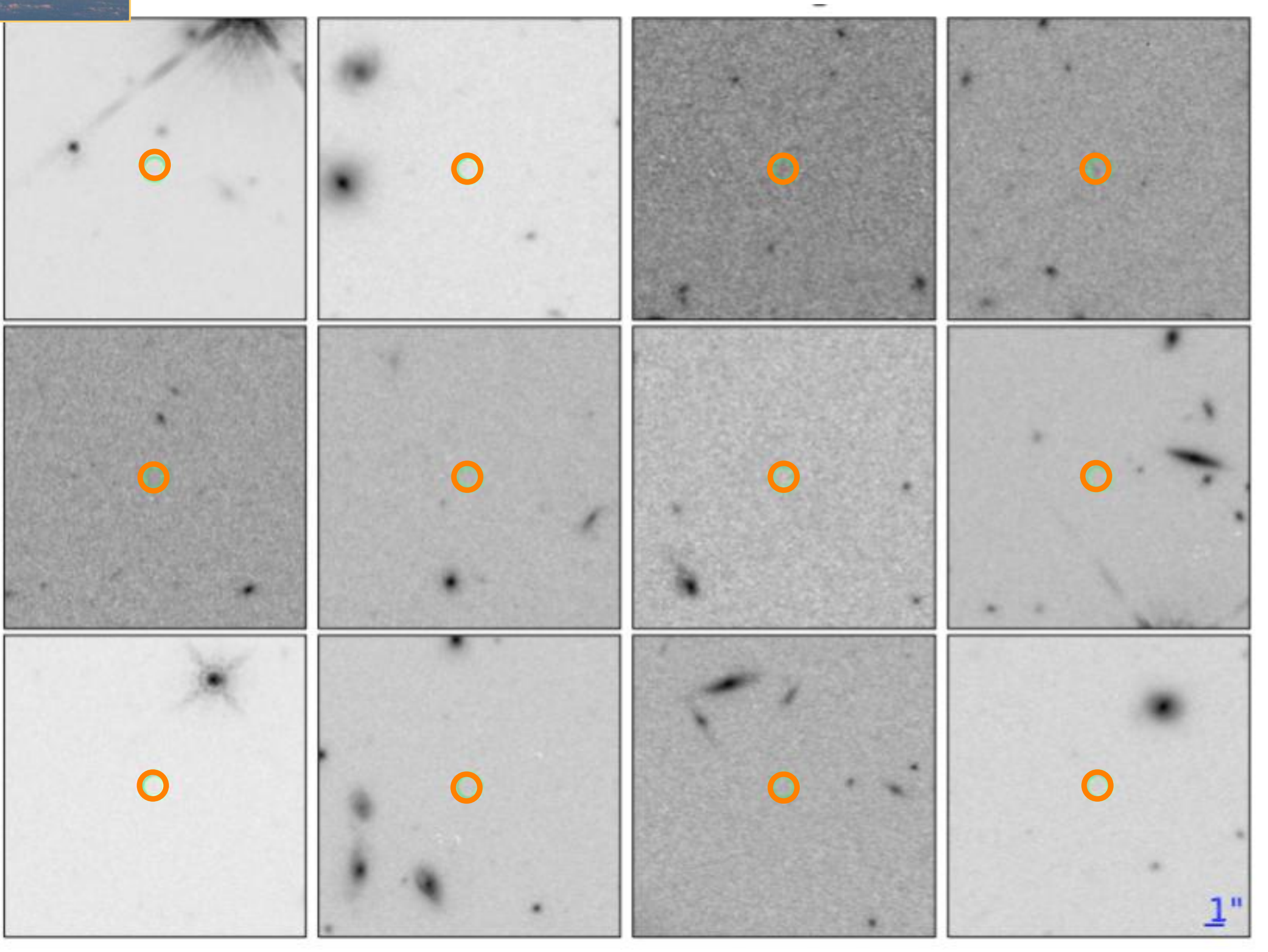
https://doi.org/10.1038/s41586-019-1452-4

A dominant population of optically invisible massive galaxies in the early Universe

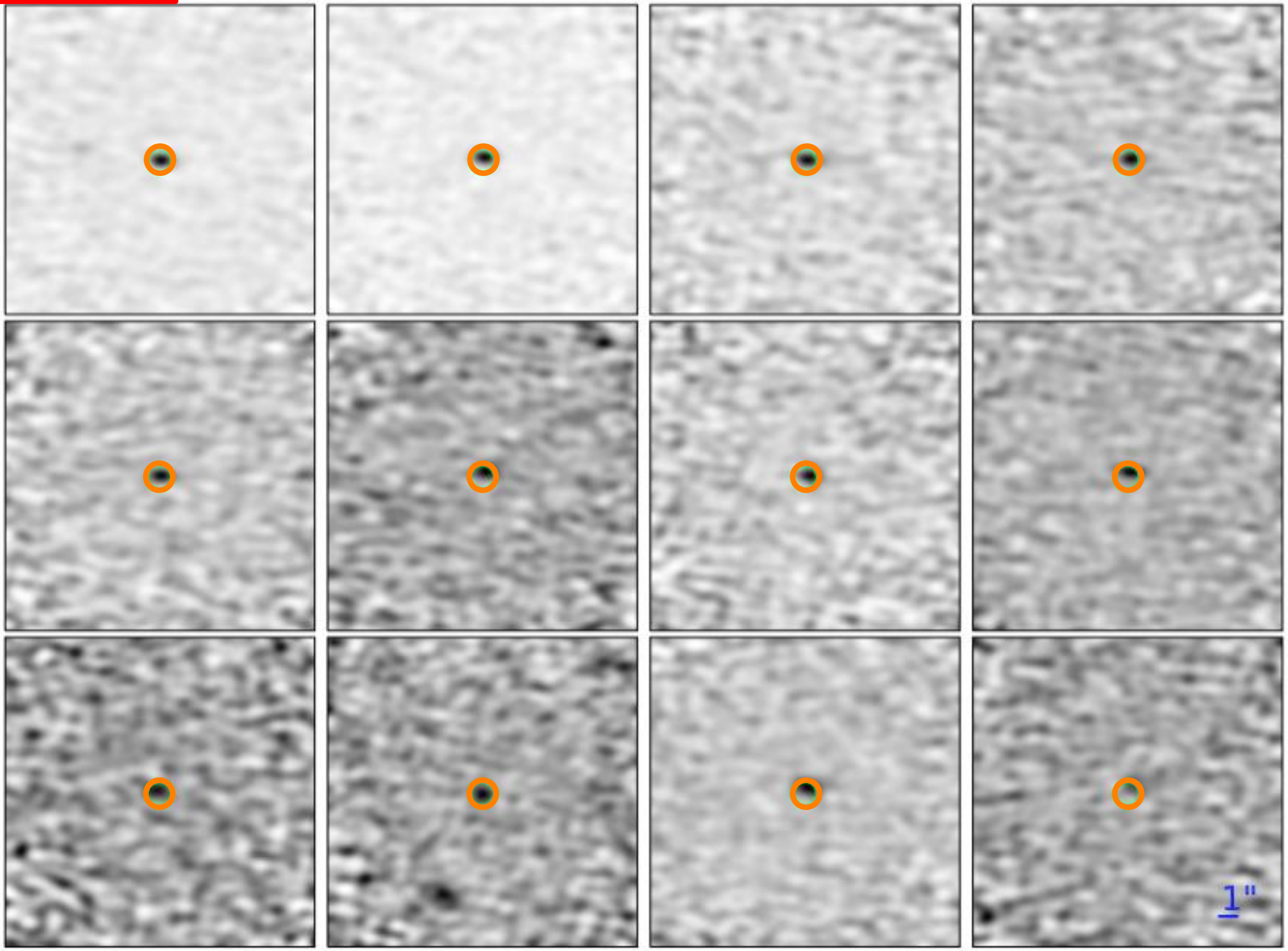
T. Wang[1,2,3]*, C. Schreiber[2,4,5], D. Elbaz[2], Y. Yoshimura[1], K. Kohno[1,6], X. Shu[7], Y. Yamaguchi[1], M. Pannella[8], M. Franco[2], J. Huang[9], C.-F. Lim[10,11] & W.-H. Wang[10]




HST

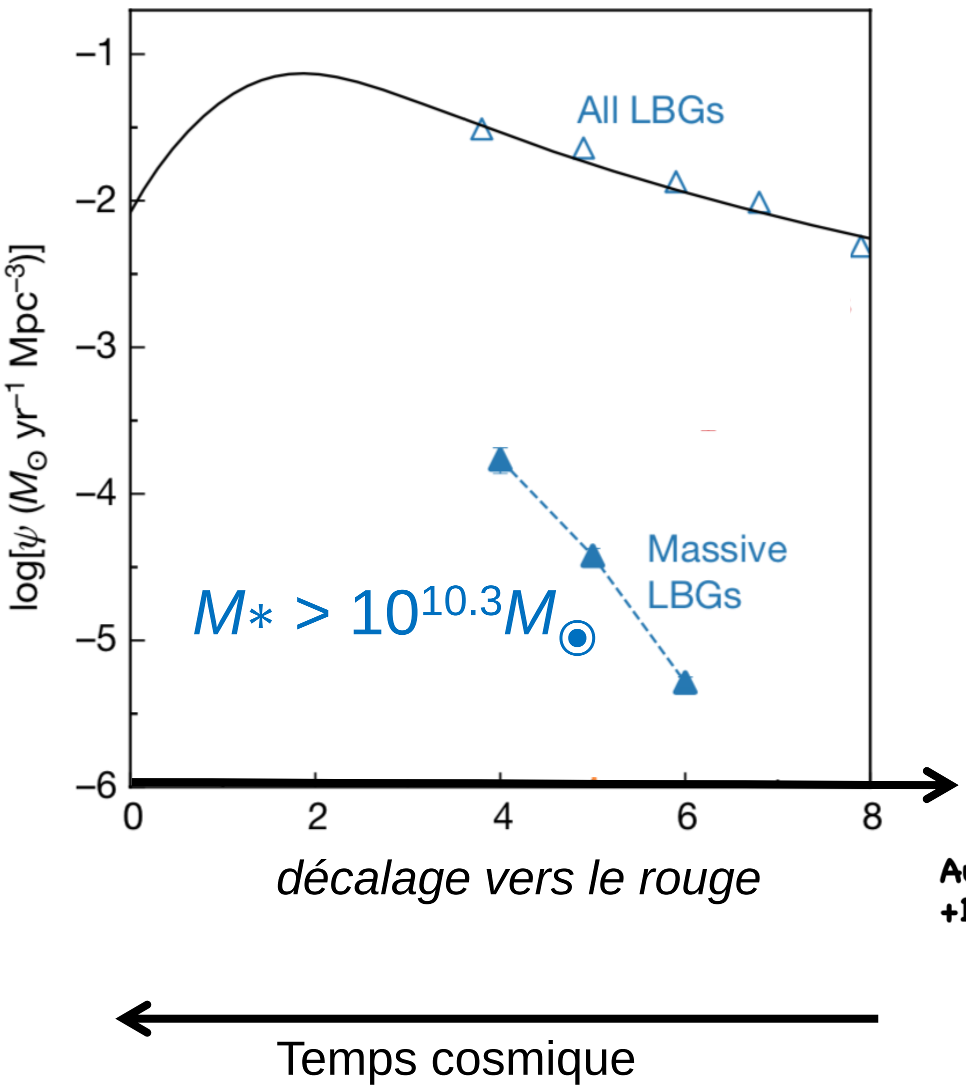

1"


ALMA

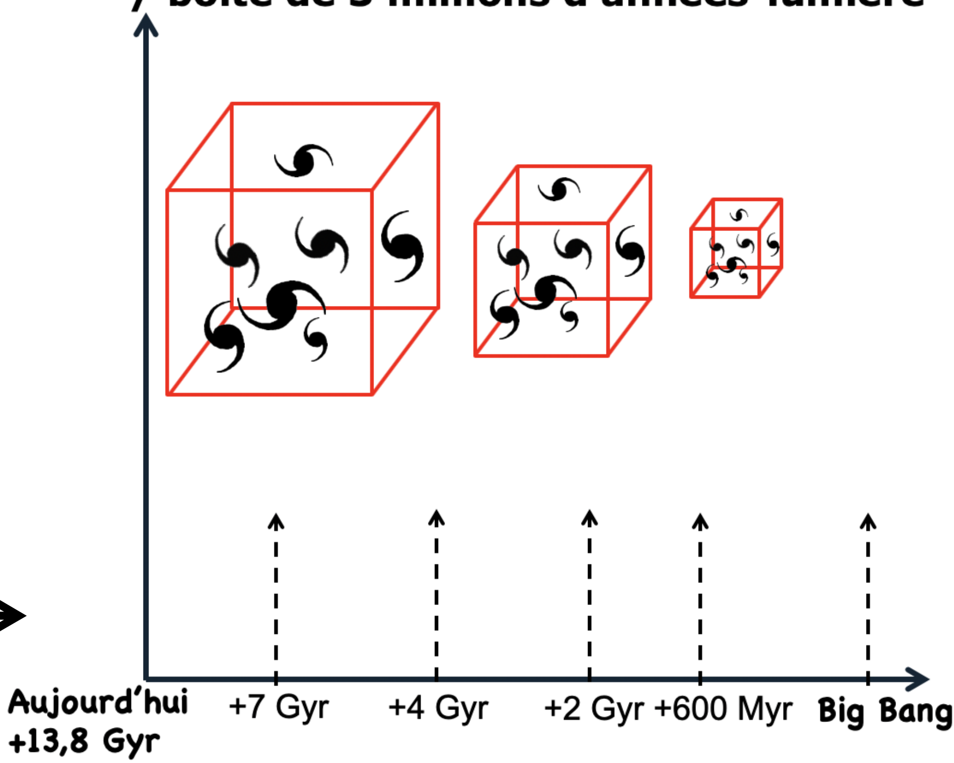

1"

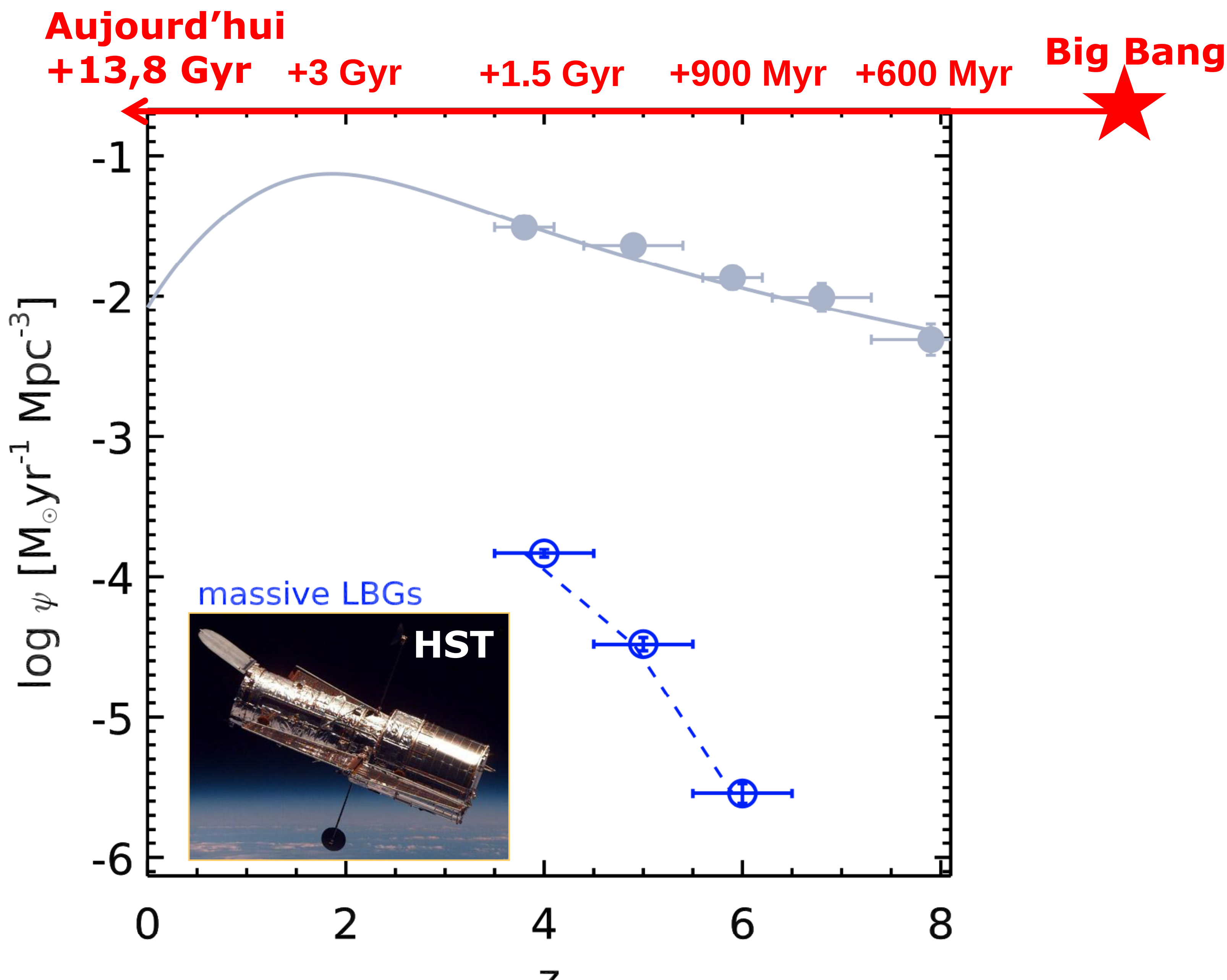
L'histoire cosmique de la formation d'étoiles

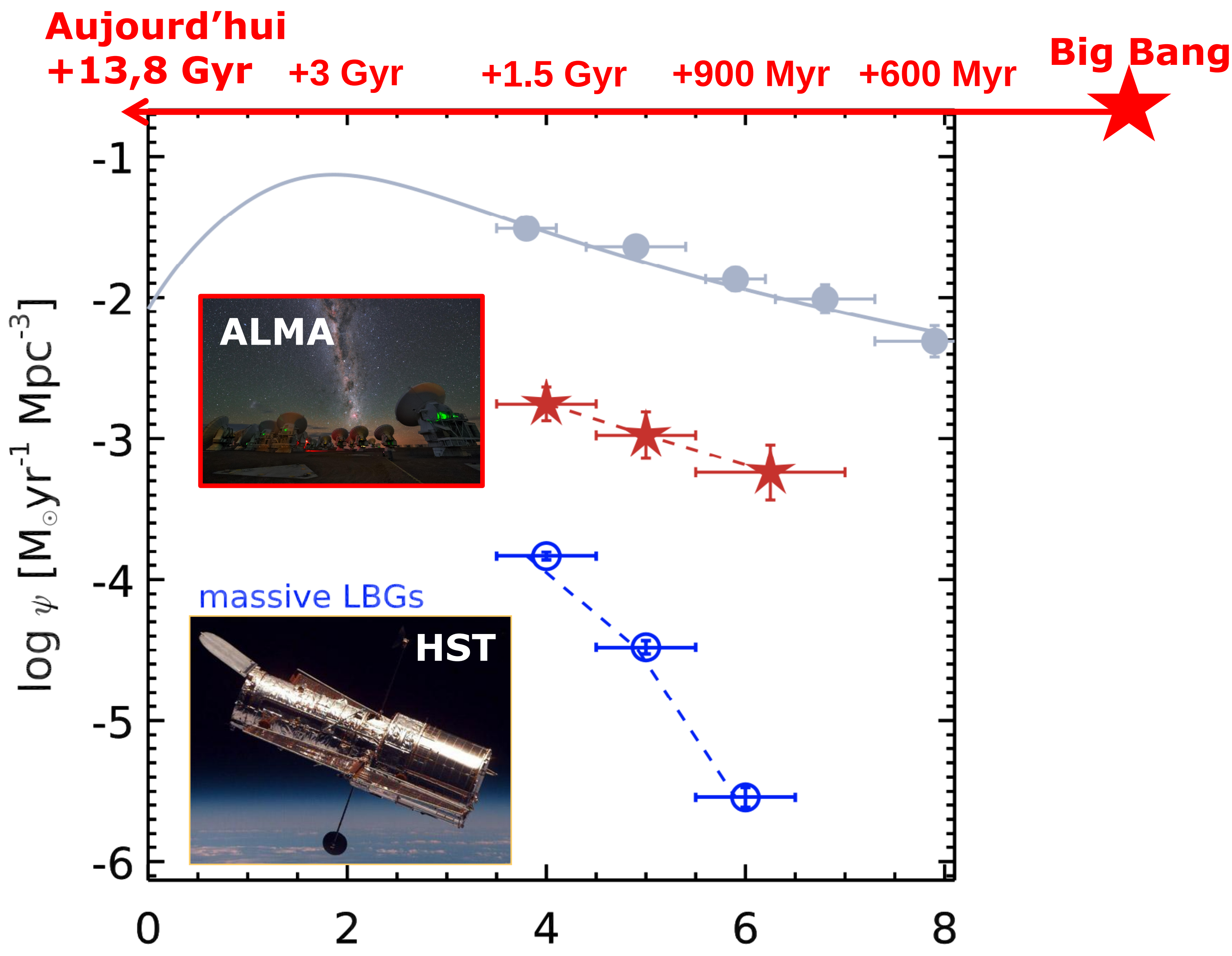
Taux de formation d'étoiles cosmique / boîte de 3 millions d'années-lumière



Taux de formation d'étoiles cosmique / boîte de 3 millions d'années-lumière




Aujourd'hui
+13,8 Gyr
+3 Gyr
+1.5 Gyr
+900 Myr
+600 Myr
Big Bang
log ψ [M⊙yr-1 Mpc-3]
-1
-2
-3
-4
-5
-6
0
2
4
6
8
z
massive LBGs
HST


Aujourd'hui
+13,8 Gyr
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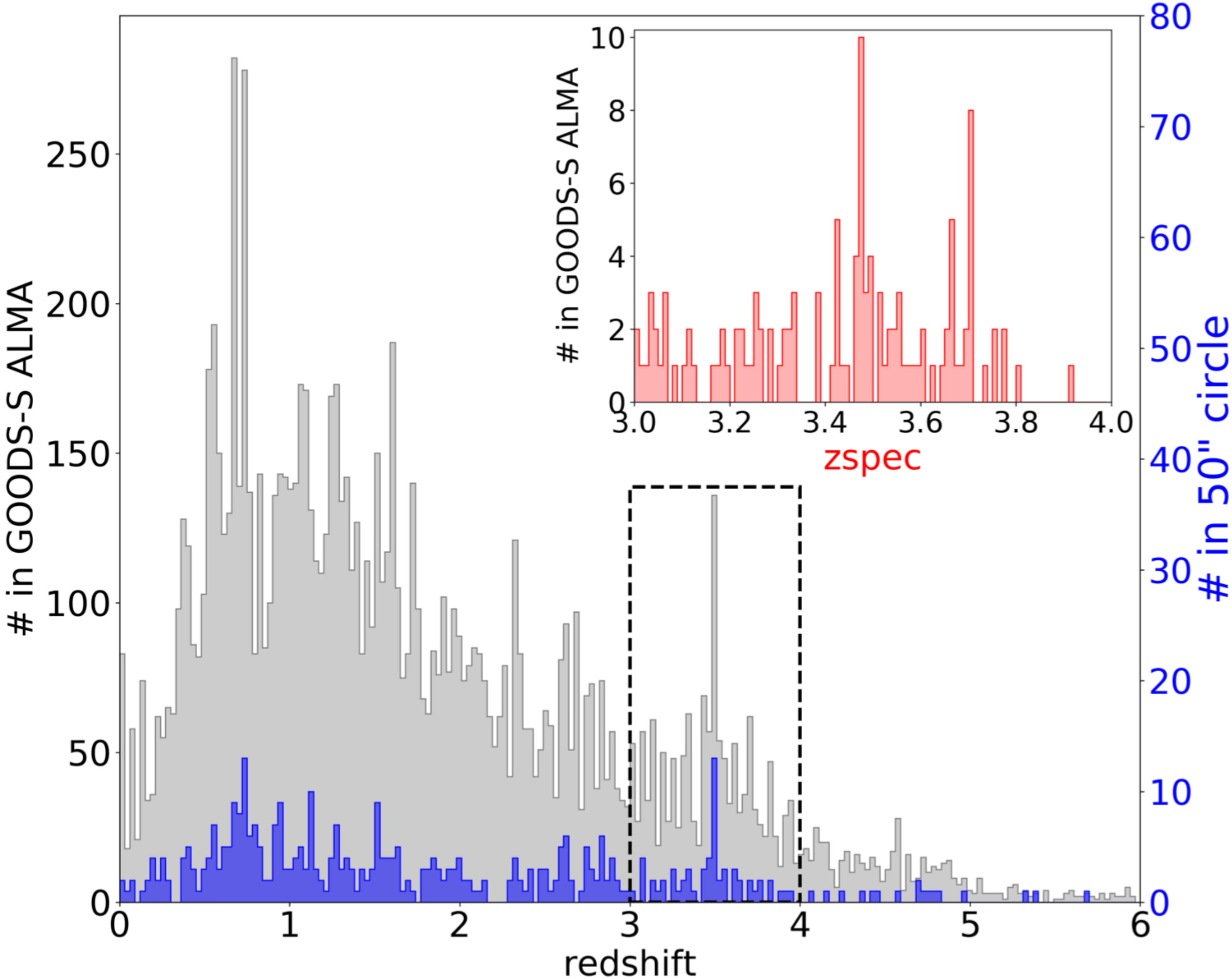
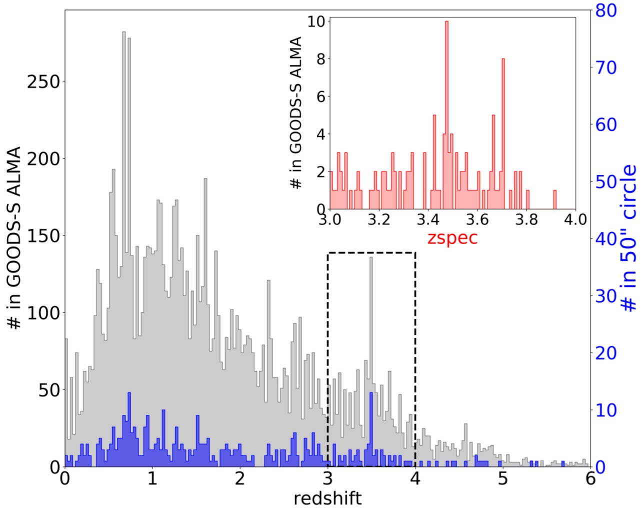
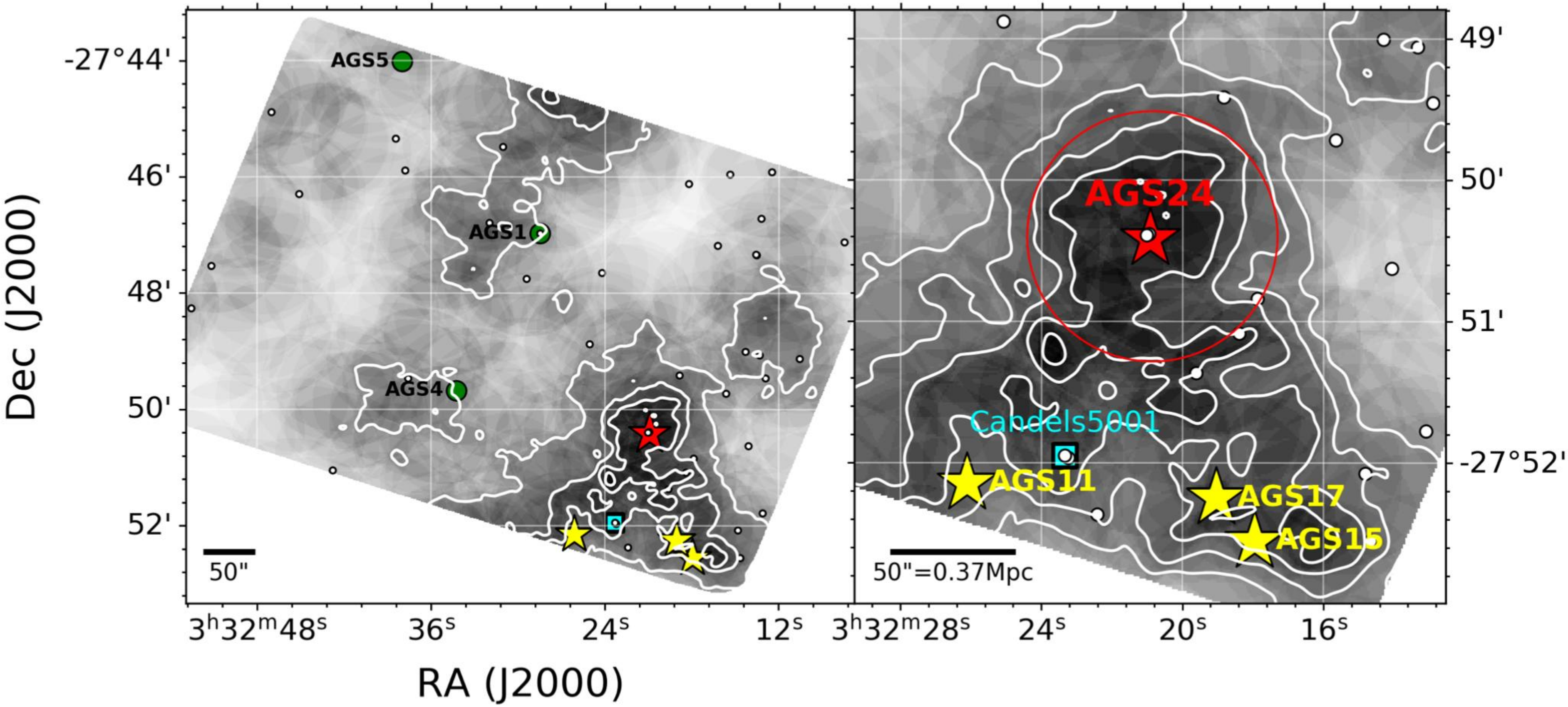
+900 Myr
+600 Myr
Big Bang
-1
-2
-3
-4
-5
-6
log ψ [M⊙yr-1 Mpc-3]
ALMA
massive LBGs
HST
0
2
4
6
8
z



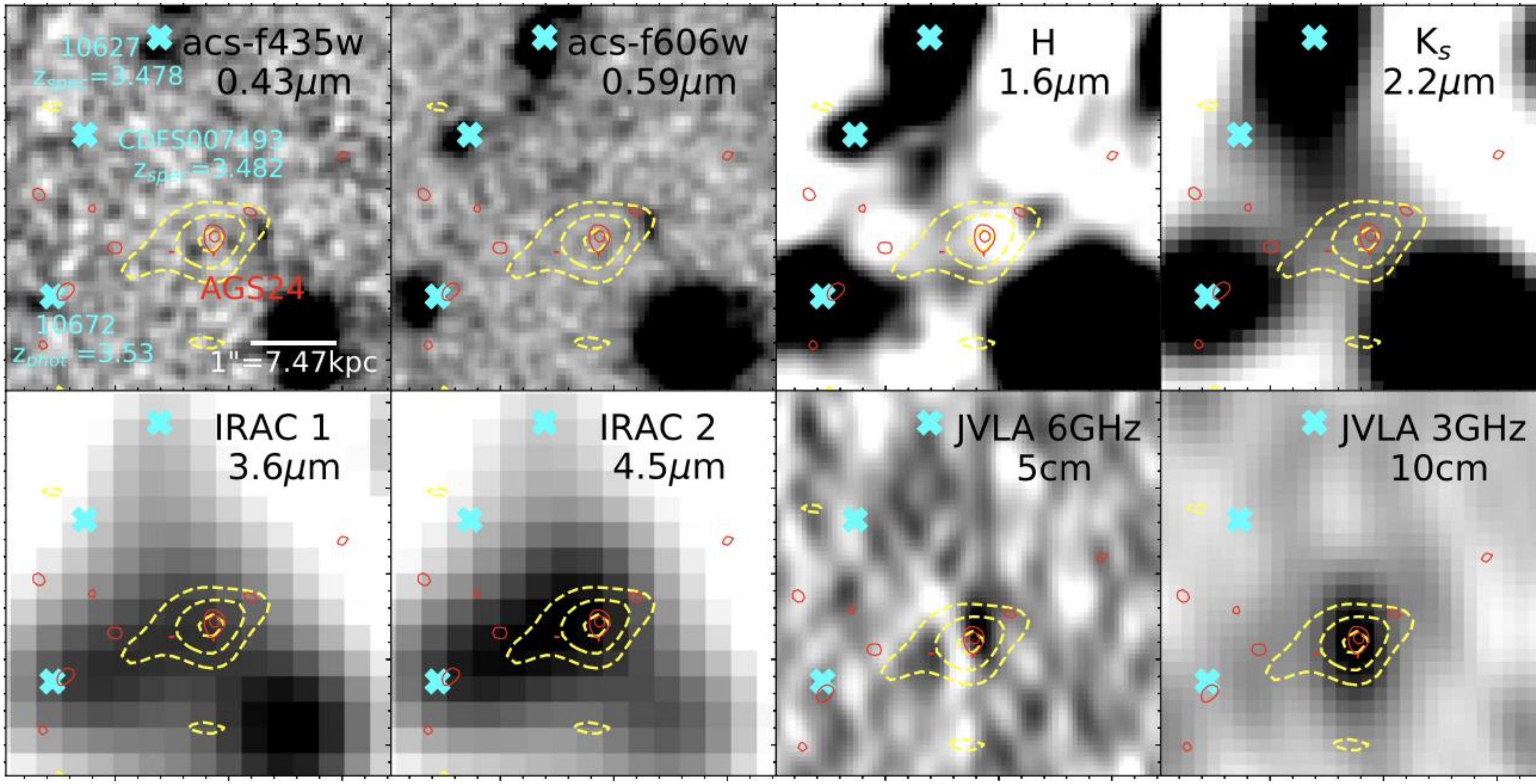
in GOODS-S ALMA
250
200
150
100
50
0
0
1
2
3
4
5
6
redshift
80
70
60
50
40
30
20
10
0
in 50" circle
in GOODS-S ALMA
10
8
6
4
2
0
3.0
3.2
3.4
3.6
3.8
4.0
zspec



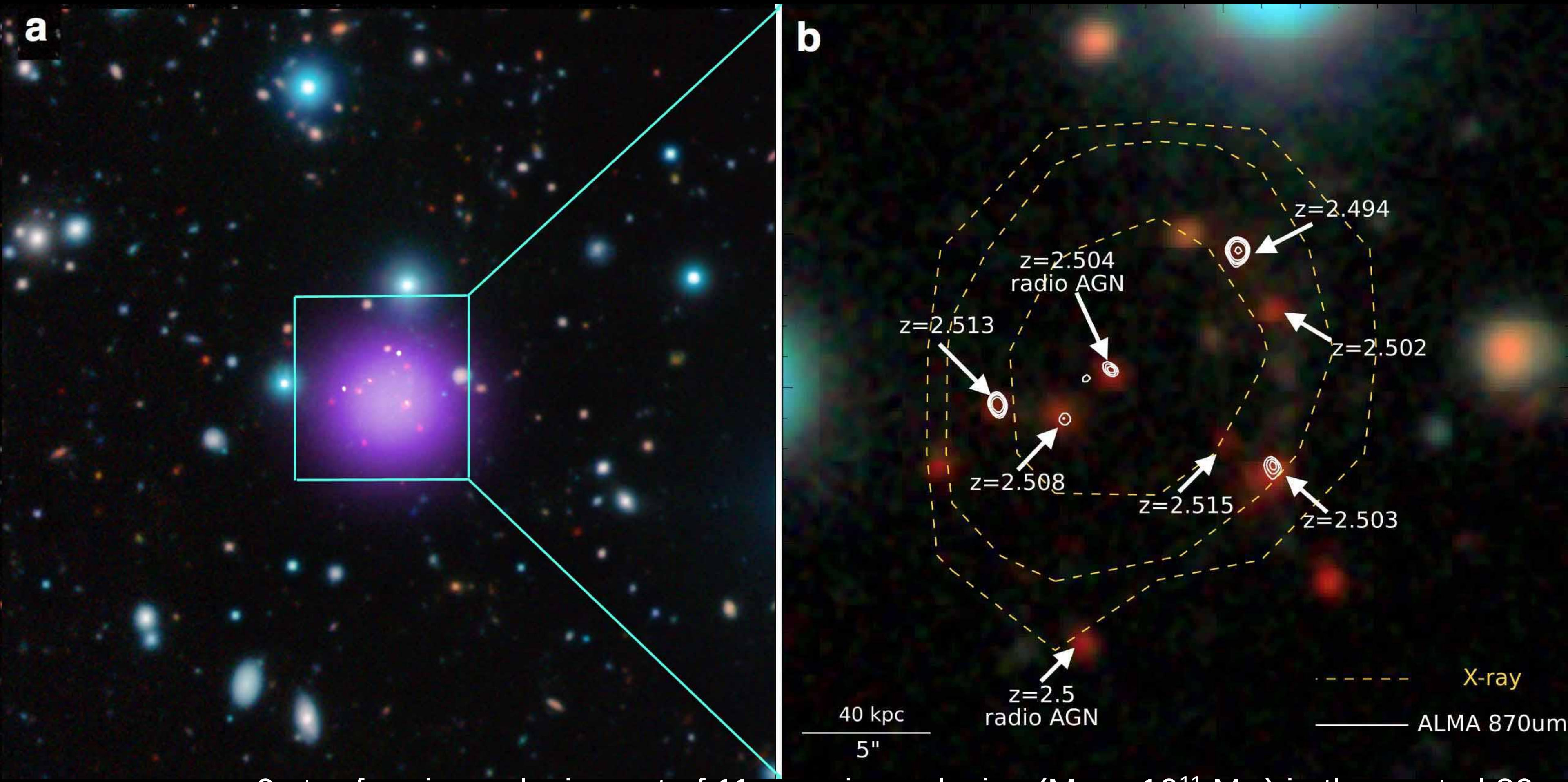
in GOODS-S ALMA
in 50" circle
redshift
zspec



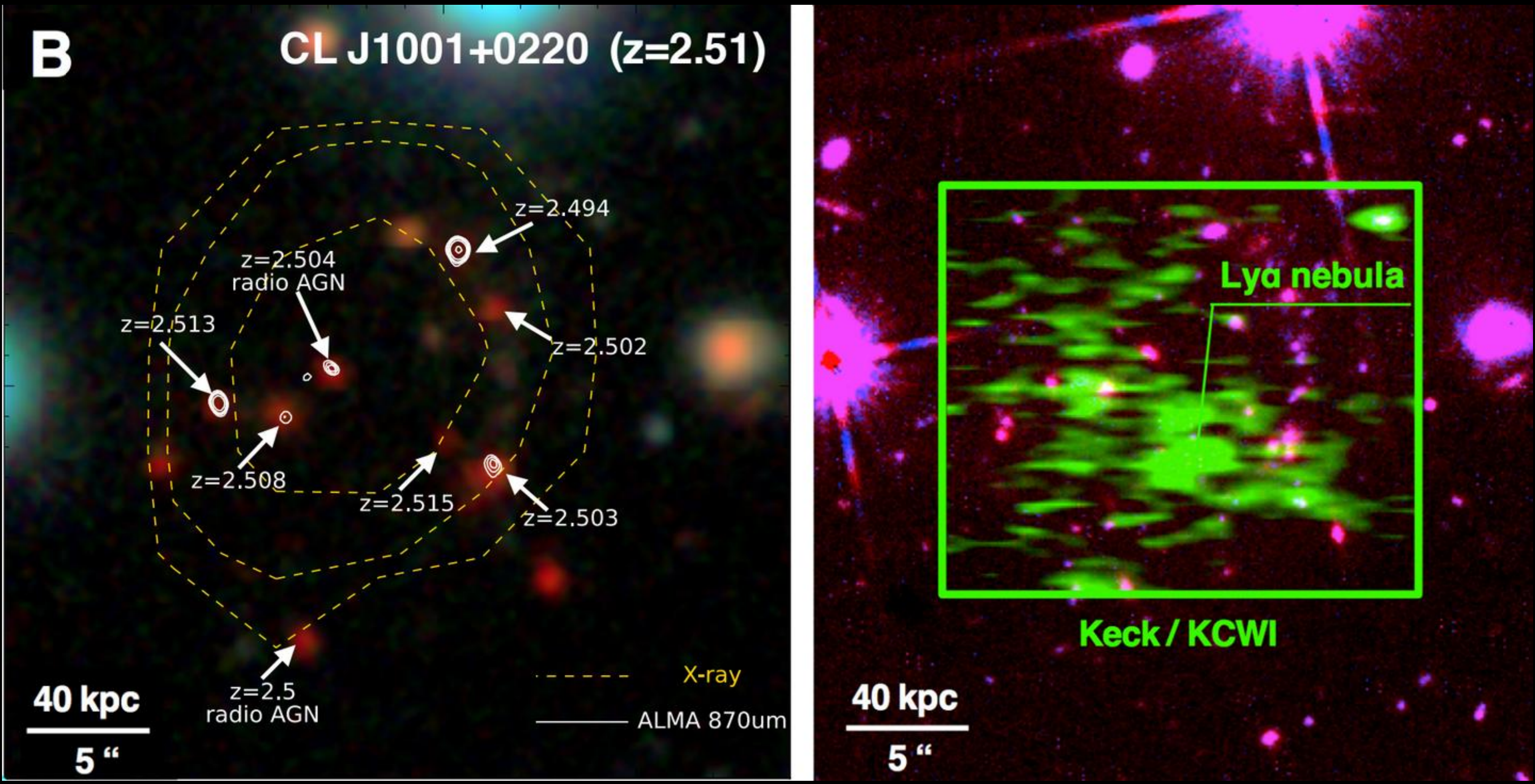
AGS5
AGS1
AGS4
AGS24
Candels5001
AGS11
AGS17
AGS15
50"
50"=0.37Mpc
Dec (J2000)
RA (J2000)


10627
z_{spec}=3.478
acs-f435w
0.43μm
CDFS007493
z_{spec}=3.482
AGS24
10672
z_{phot}=3.53
1"=7.47kpc
acs-f606w
0.59μm
H
1.6μm
K_s
2.2μm
IRAC 1
3.6μm
IRAC 2
4.5μm
JVLA 6GHz
5cm
JVLA 3GHz
10cm

J1001 was caught right after "birth" (i.e. virialization):
The galaxies are still star-forming: **total SFR~3400 $M_{\odot}yr^{-1}$**



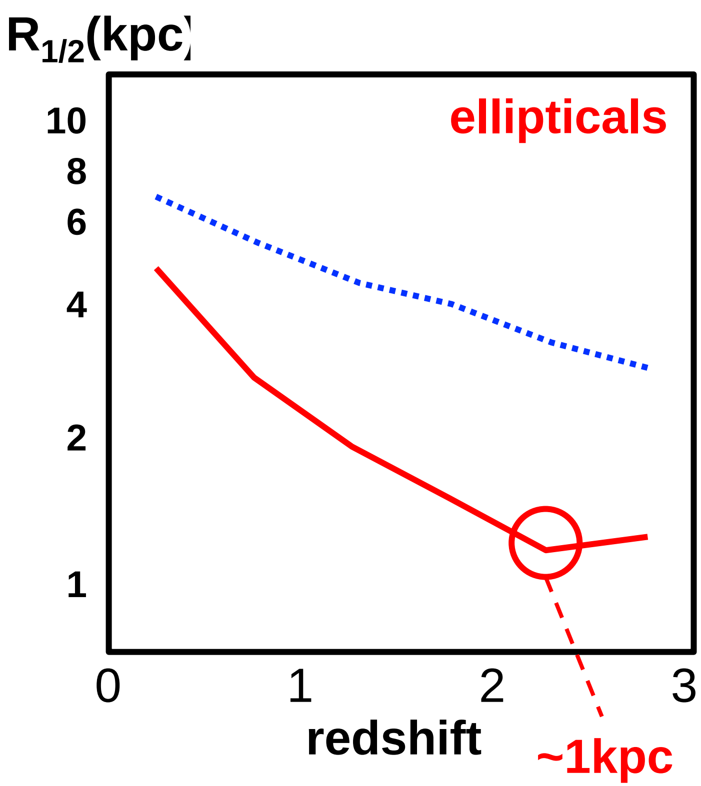
9 star-forming galaxies out of 11 massive galaxies ($M_{\star} > 10^{11}$ $M_{\odot}$) in the central 80 kpc

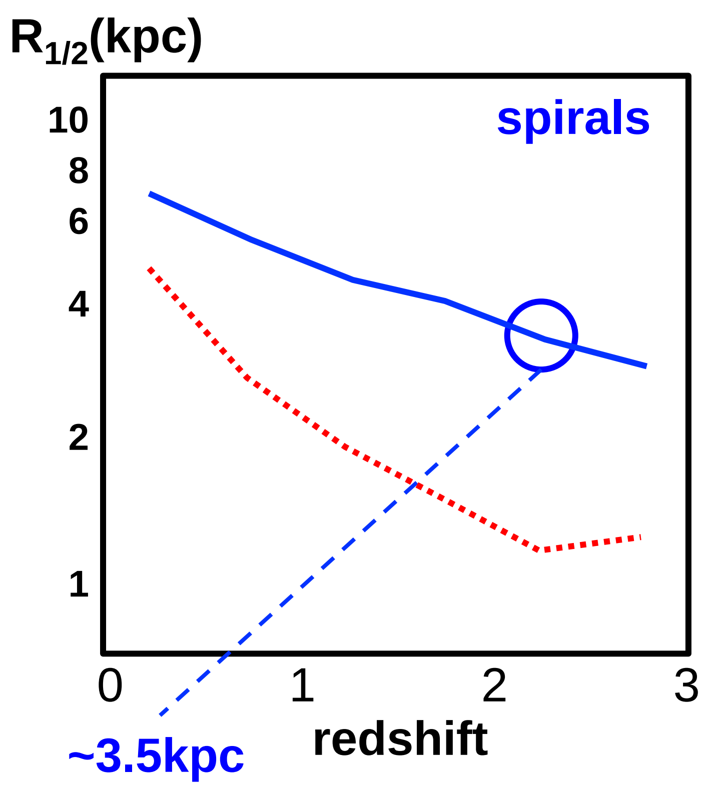

B
CL J1001+0220 (z=2.51)
z=2.494
z=2.504
radio AGN
z=2.513
z=2.502
z=2.508
z=2.515
z=2.503
z=2.5
radio AGN
X-ray
ALMA 870um
40 kpc
5 "
Lya nebula
Keck / KCWI
40 kpc
5 "


Ceci est une galaxie morte


Ceci est une galaxie vivante
VLT Antu, ESO

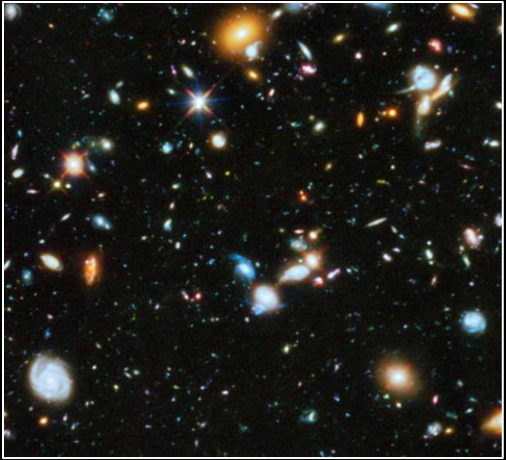
Size evolution of red and blue galaxies

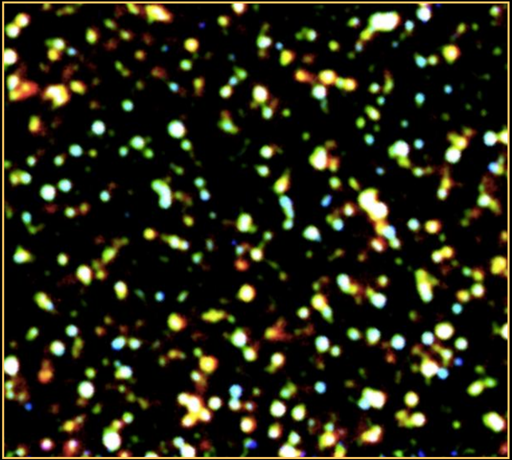


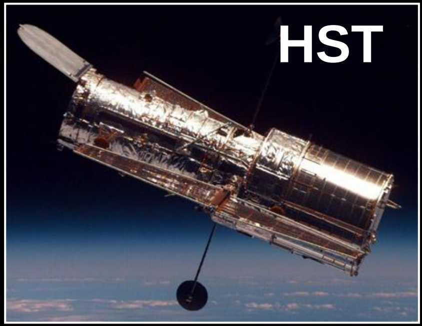


$Log(M_{\star})=10.5-11$

Resolved dusty star formation

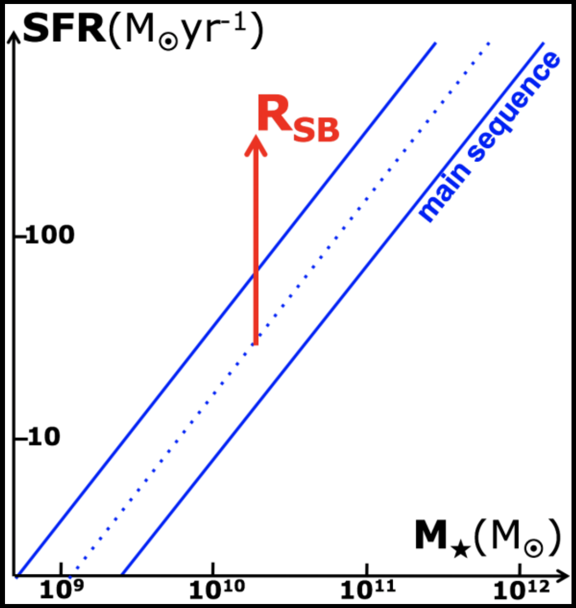


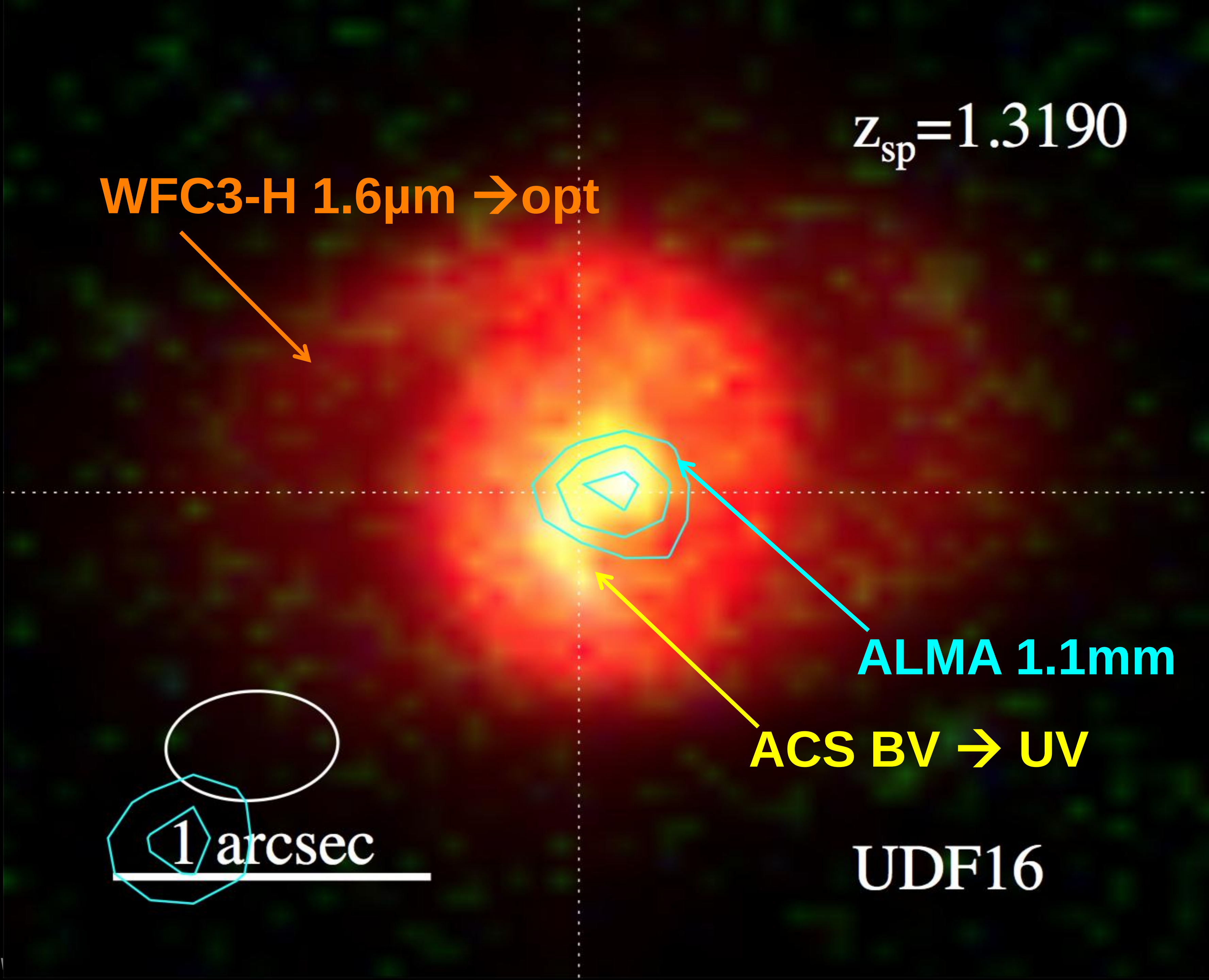


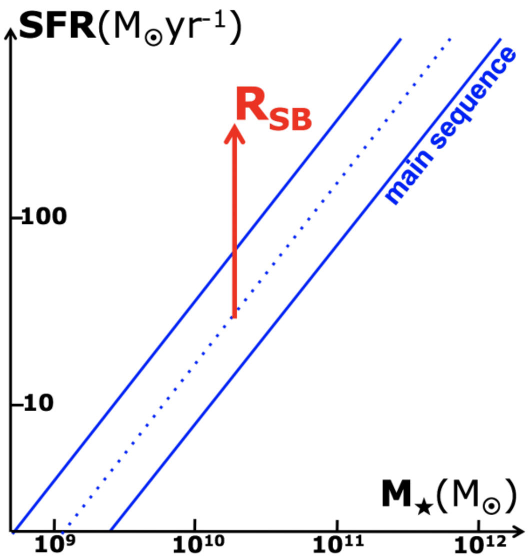


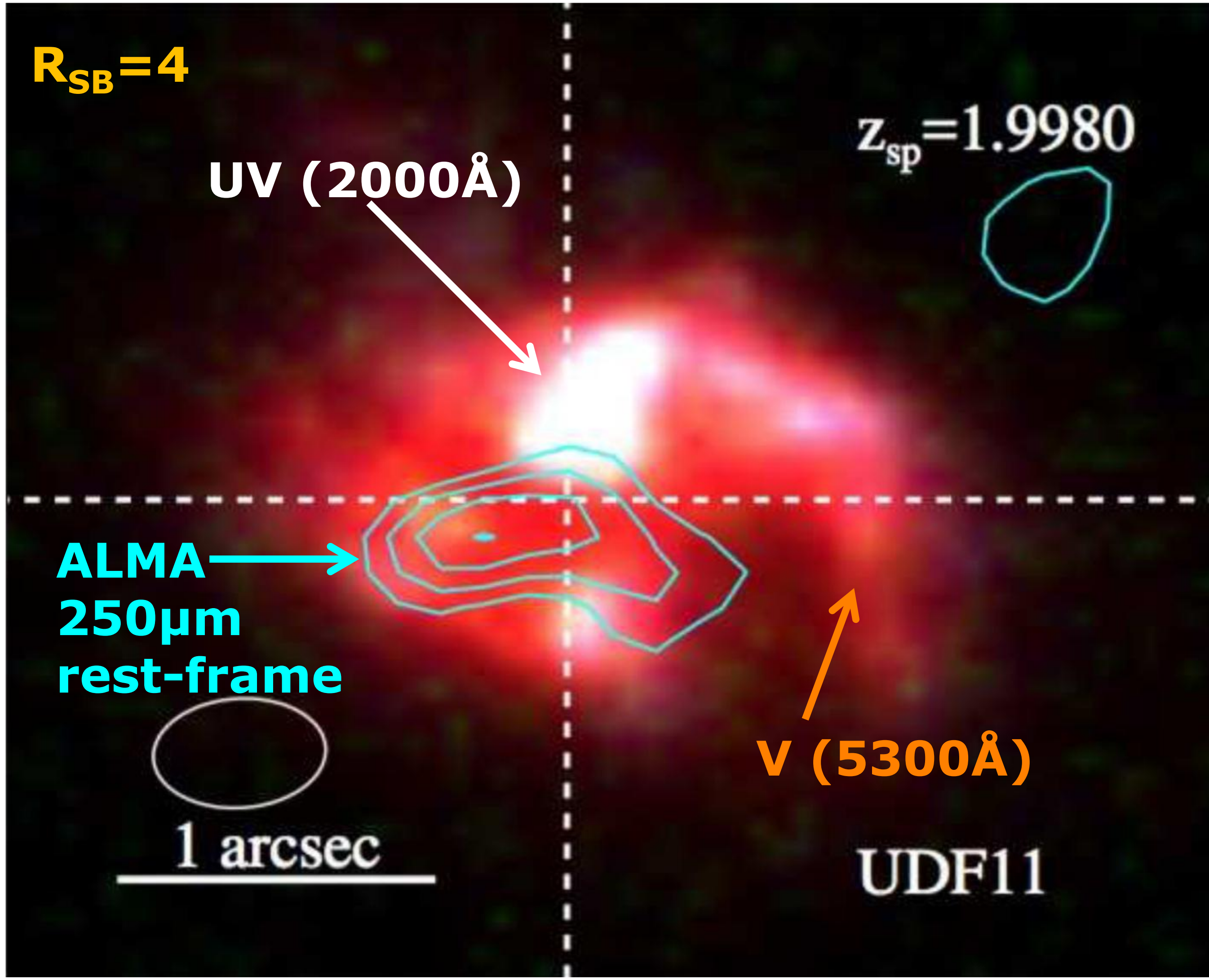
optical

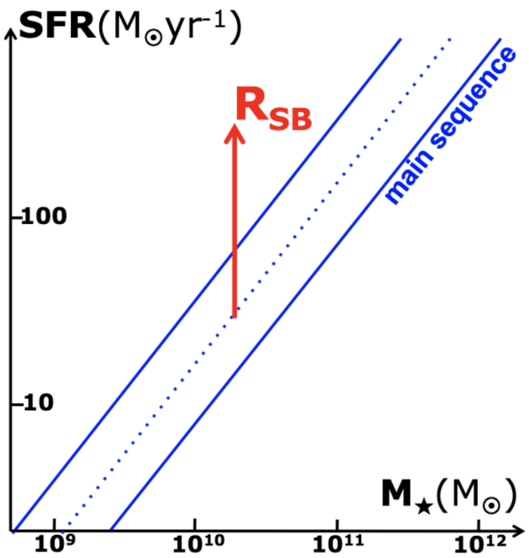
Far-IR



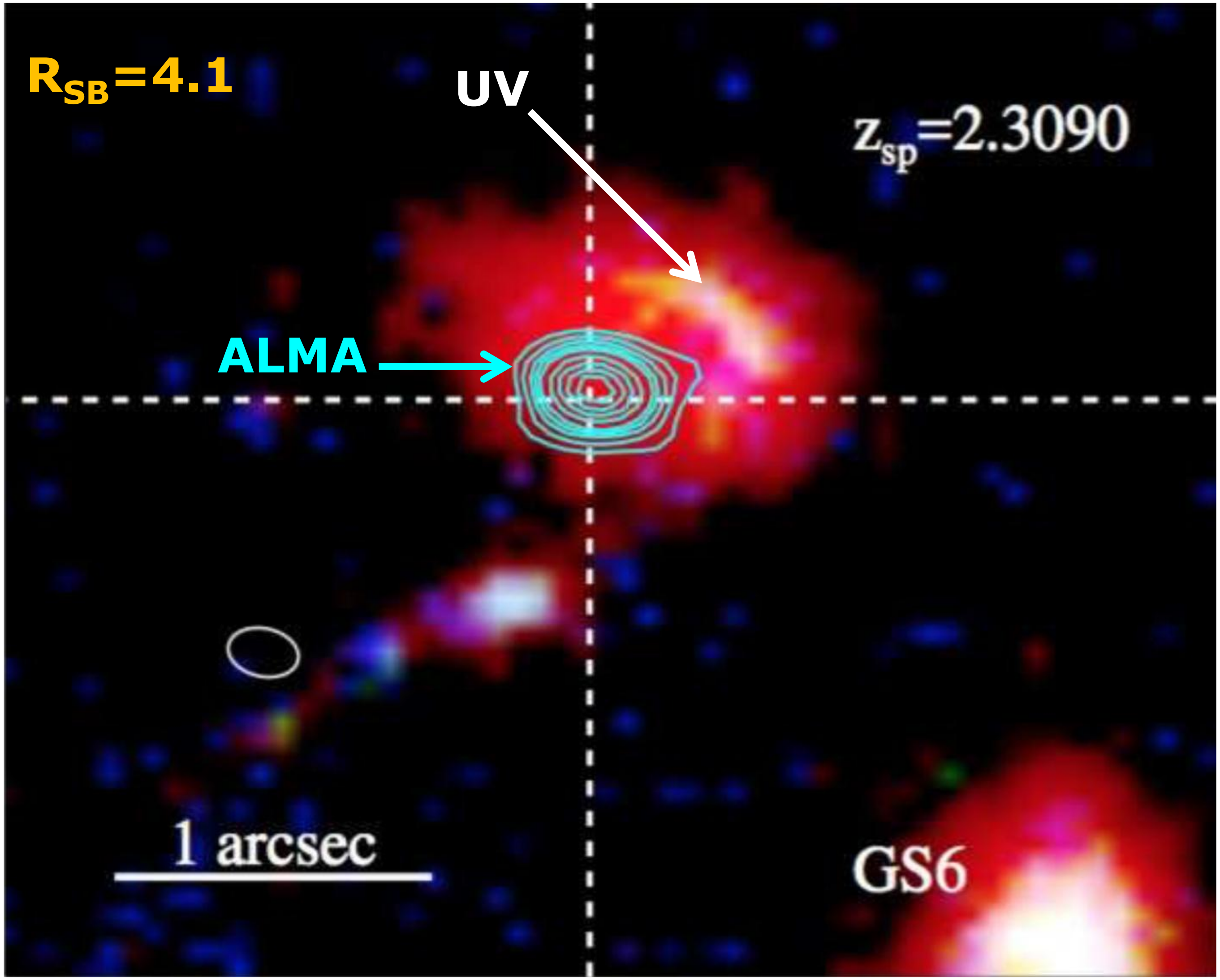

z_{sp}=1.3190
WFC3-H 1.6μm → opt
ALMA 1.1mm
ACS BV → UV
1 arcsec
UDF16


SFR(M☉yr-1)
RSB
100
10
main sequence
M★(M☉)
10^9
10^10
10^11
10^12

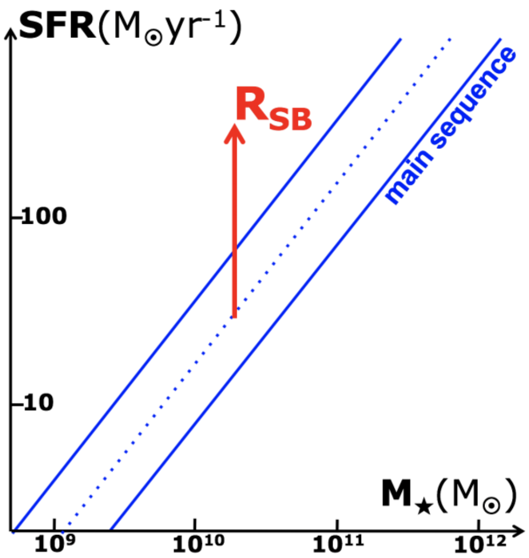

RSB=4
zsp=1.9980
UV (2000Å)
ALMA
250µm
rest-frame
V (5300Å)
1 arcsec
UDF11

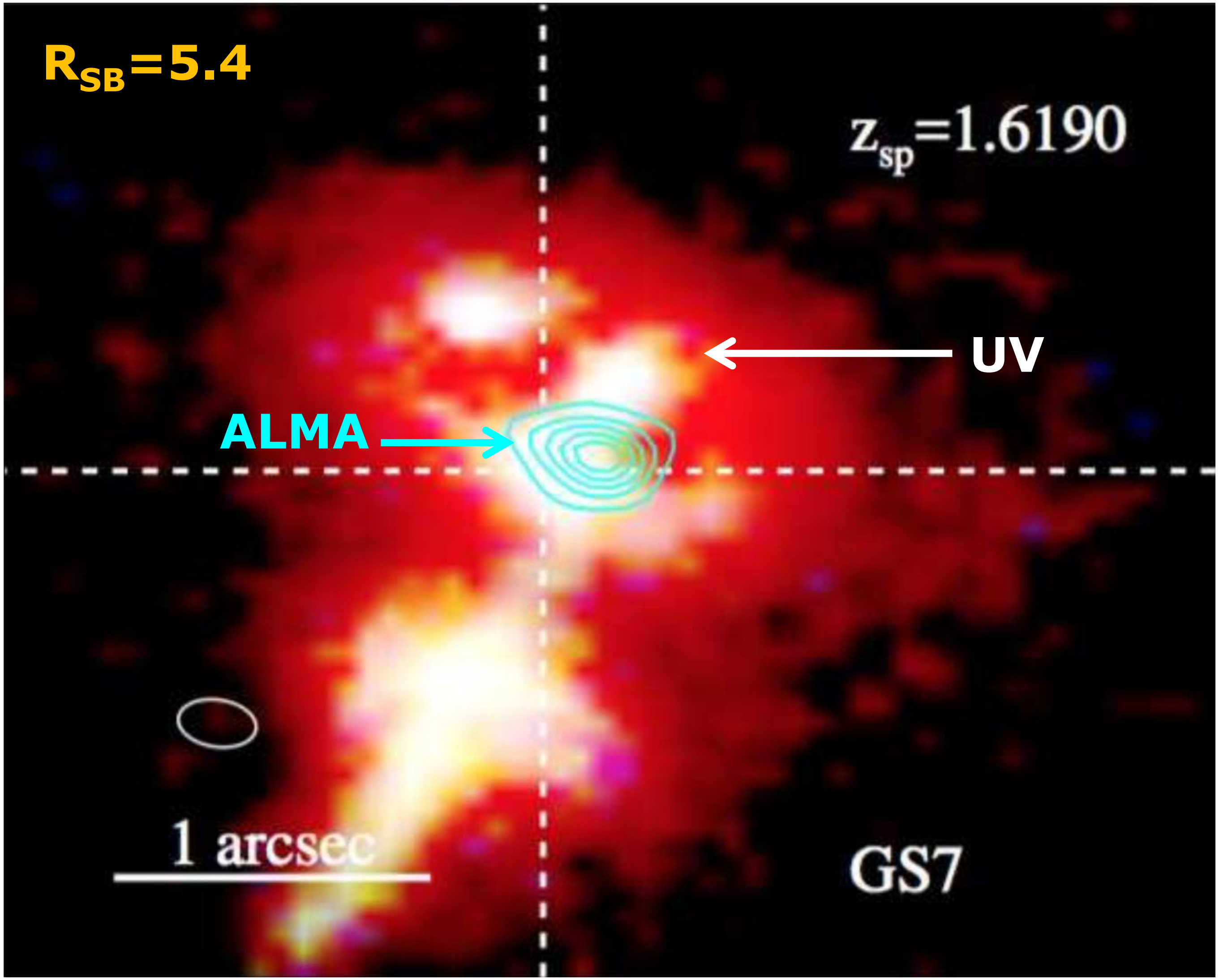


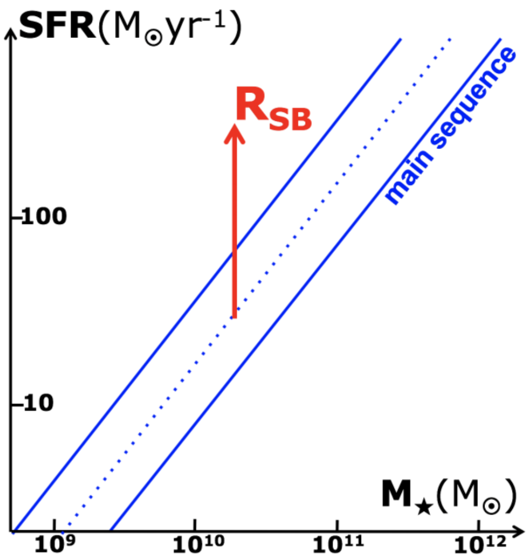
SFR(M⊙yr-1)
R_SB
main sequence
100
10
M★(M⊙)
10^9
10^10
10^11
10^12

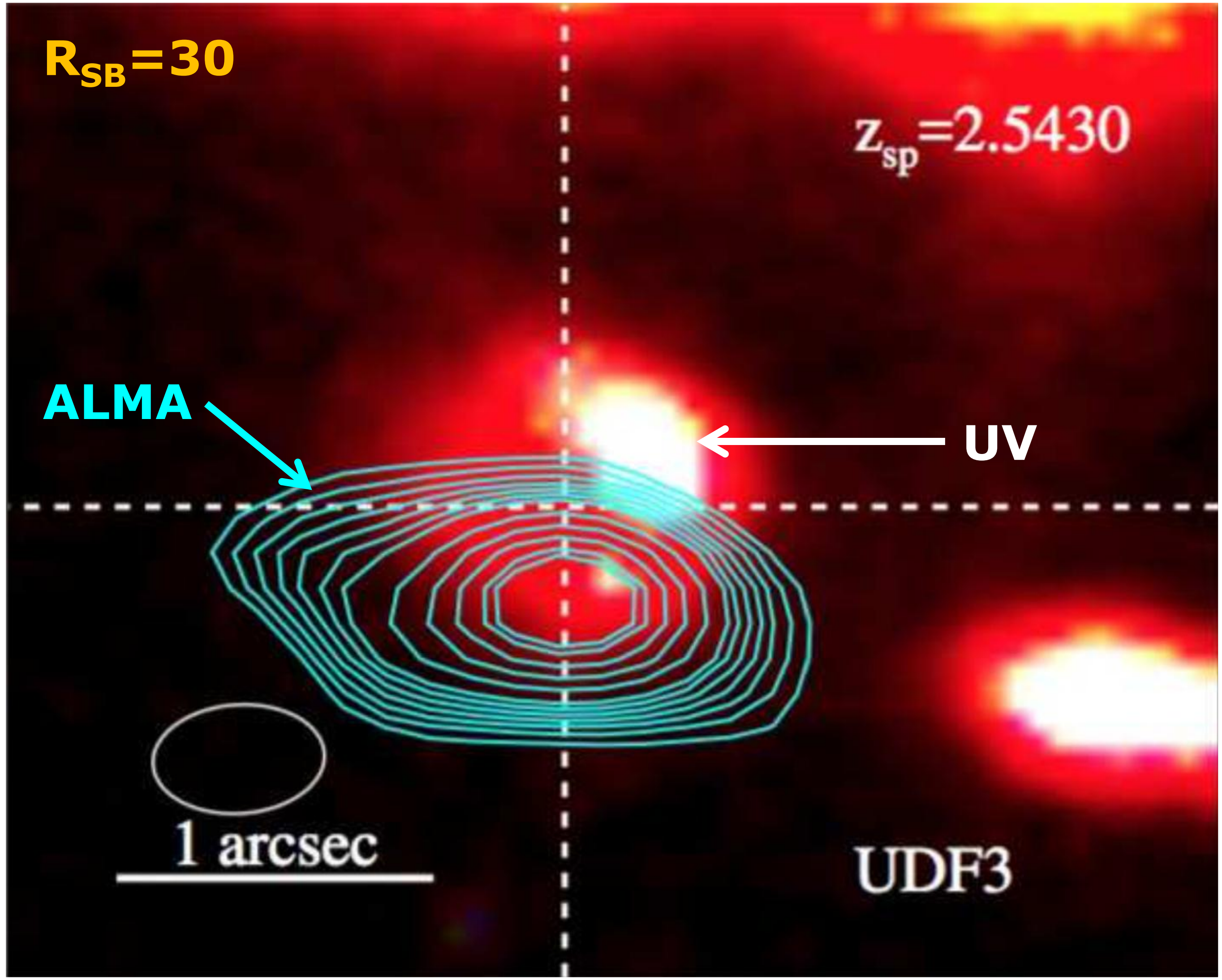


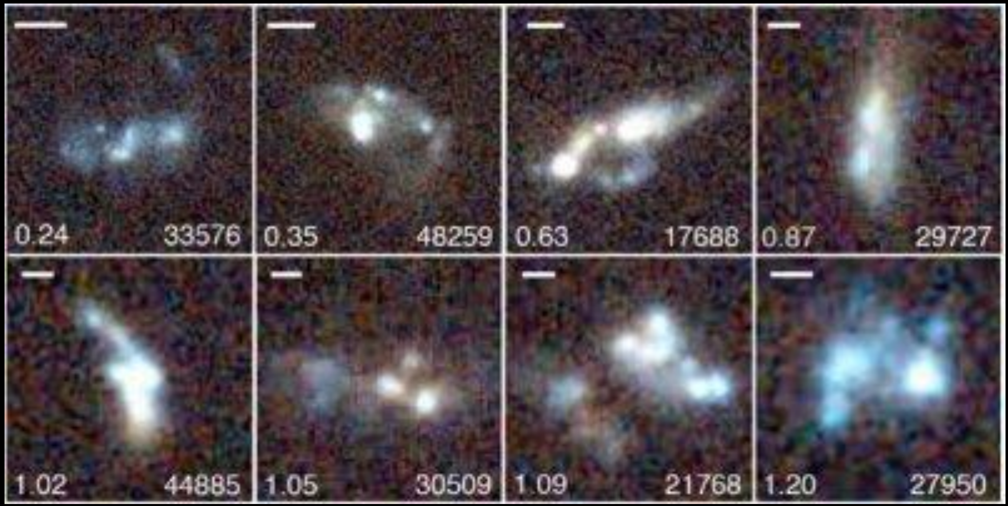
R_SB=4.1
UV
z_sp=2.3090
ALMA
1 arcsec
GS6

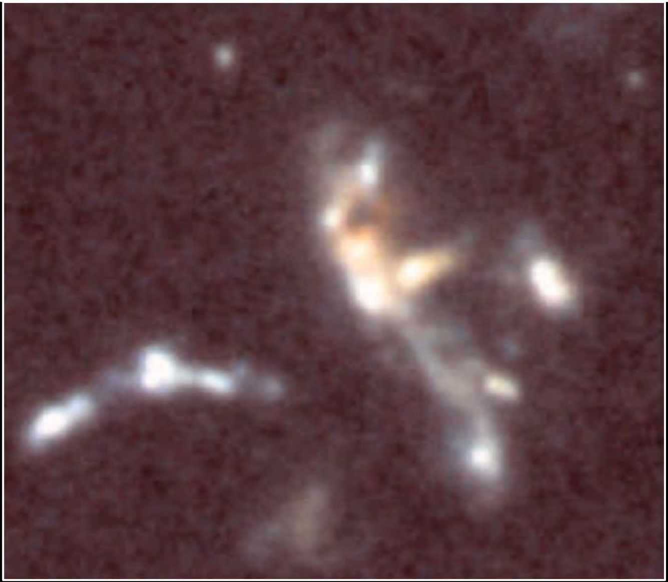

SFR($M_\odot yr^{-1}$)
R_{SB}
100
10
main sequence
$M_\star(M_\odot)$
10^9
10^{10}
10^{11}
10^{12}


R_{SB}=5.4
z_{sp}=1.6190
UV
ALMA
1 arcsec
GS7

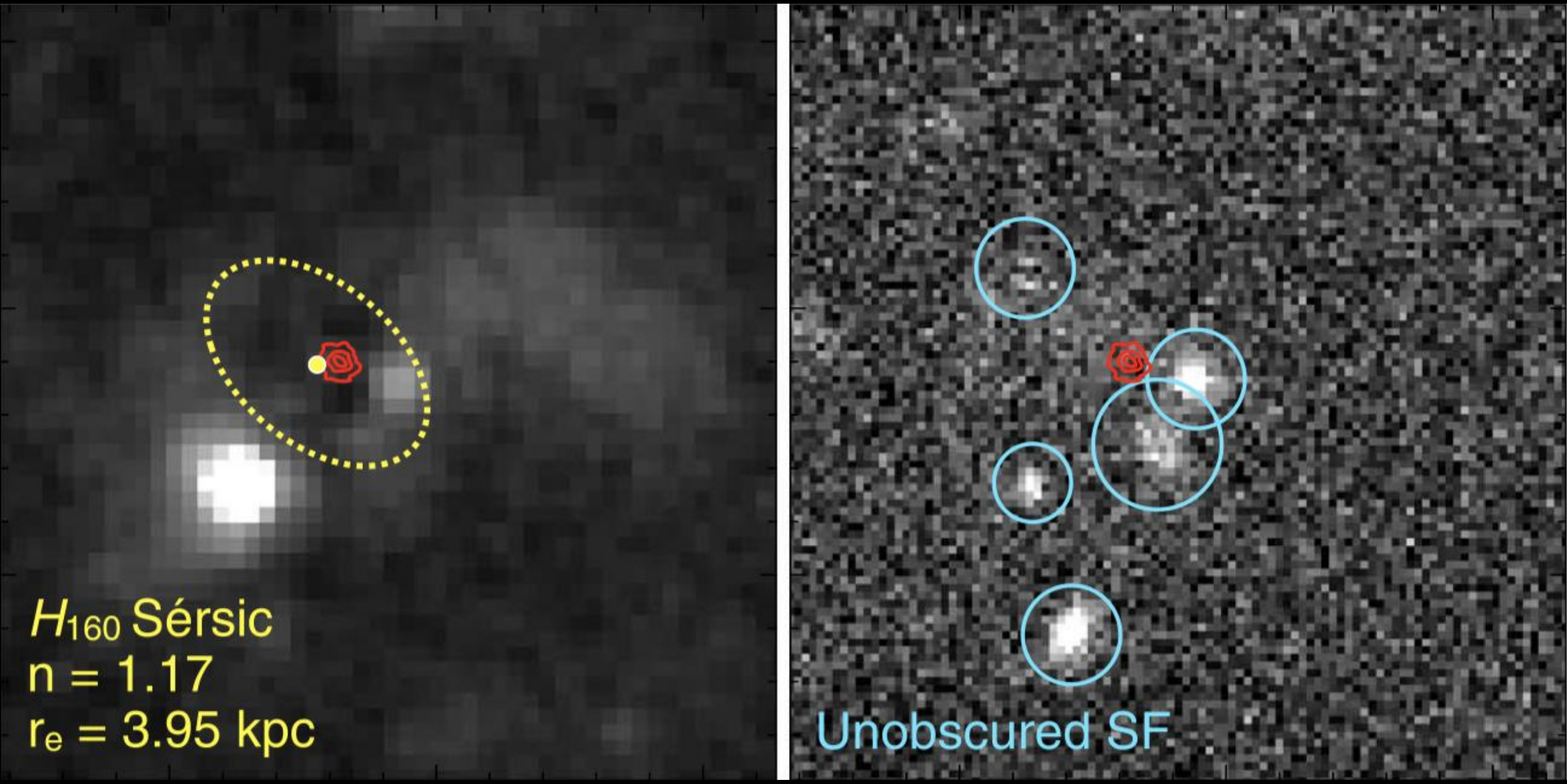

SFR(M⊙yr-1)
R_SB
100
10
main sequence
M★(M⊙)
10^9
10^10
10^11
10^12


R_SB=30
z_sp=2.5430
ALMA
UV
1 arcsec
UDF3


0.24 33576
0.35 48259
0.63 17688
0.87 29727
1.02 44885
1.05 30509
1.09 21768
1.20 27950

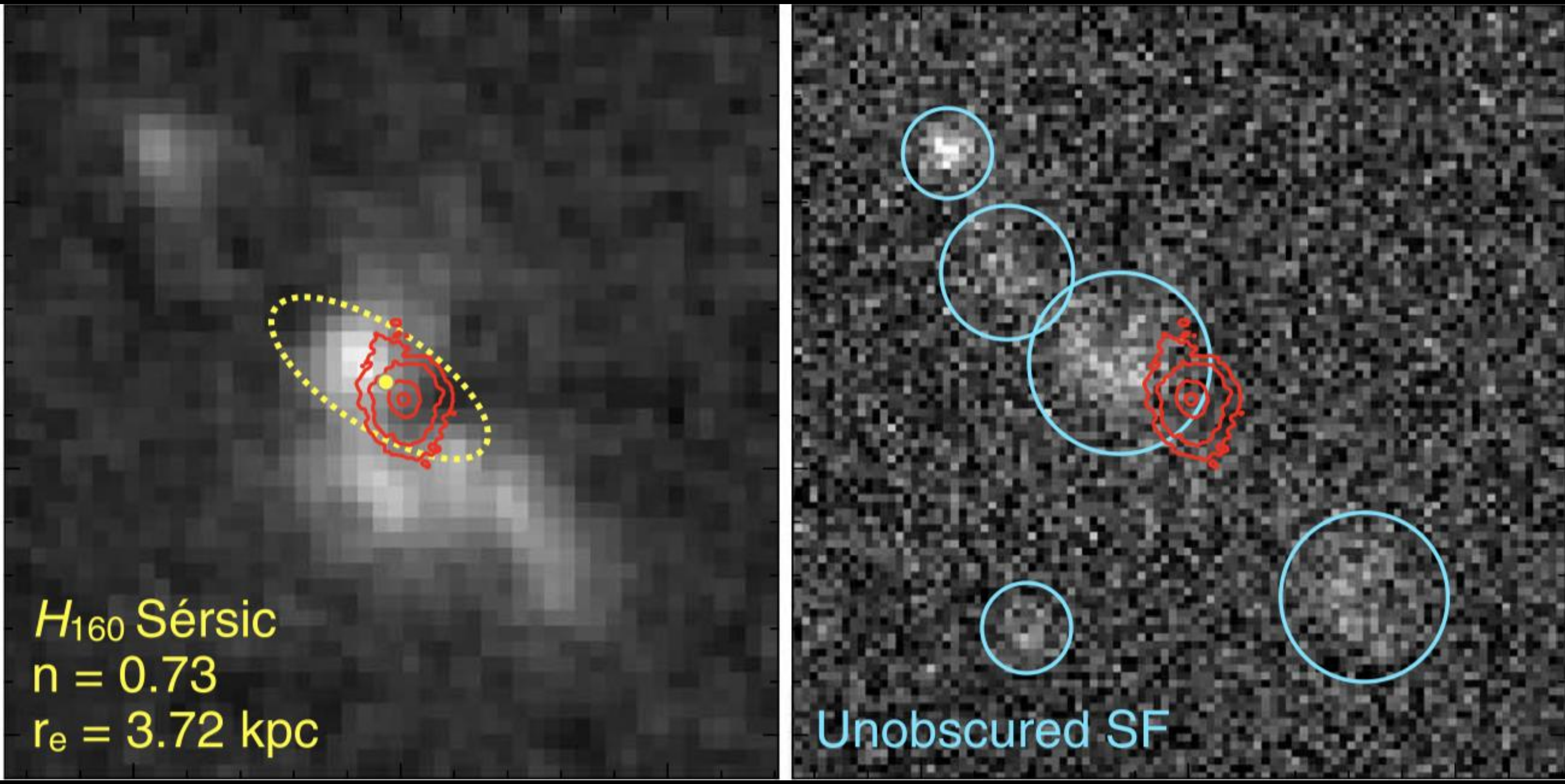


Dusty star-formation is not clumpy



Rujopakarn +2019

Dusty star-formation is not clumpy



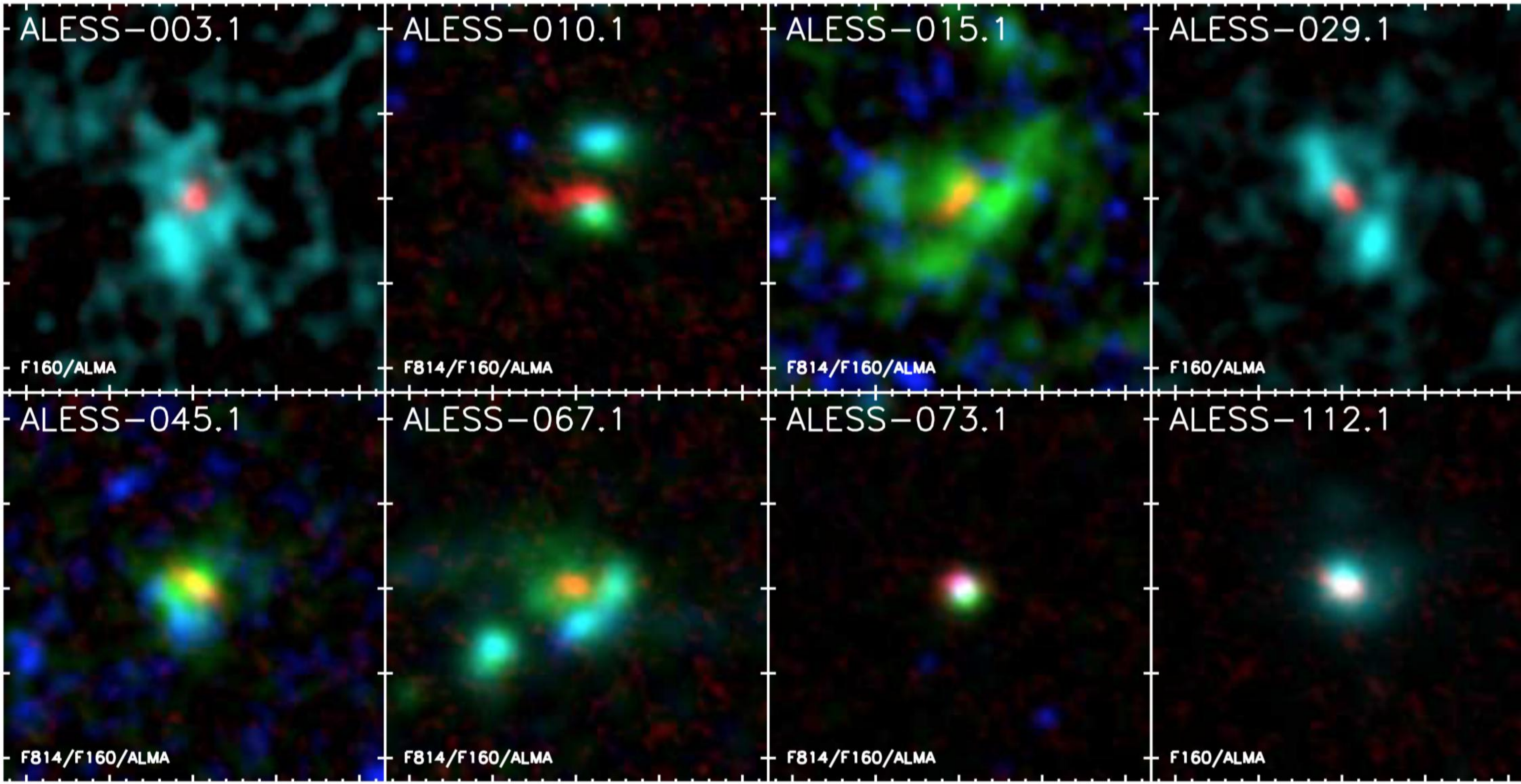
Rujopakarn +2019

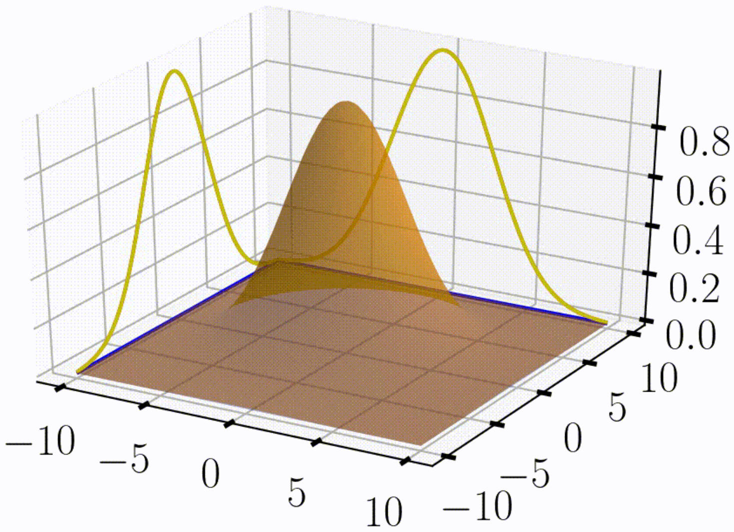
KILOPARSEC–SCALE DUST DISKS IN HIGH-REDSHIFT LUMINOUS SUBMILLIMETER GALAXIES

J. A. Hodge[1], A. M. Swinbank[2,3], J. M. Simpson[4], I. Smail[2,3], F. Walter[5], D. M. Alexander[2], F. Bertoldi[6], A. D.

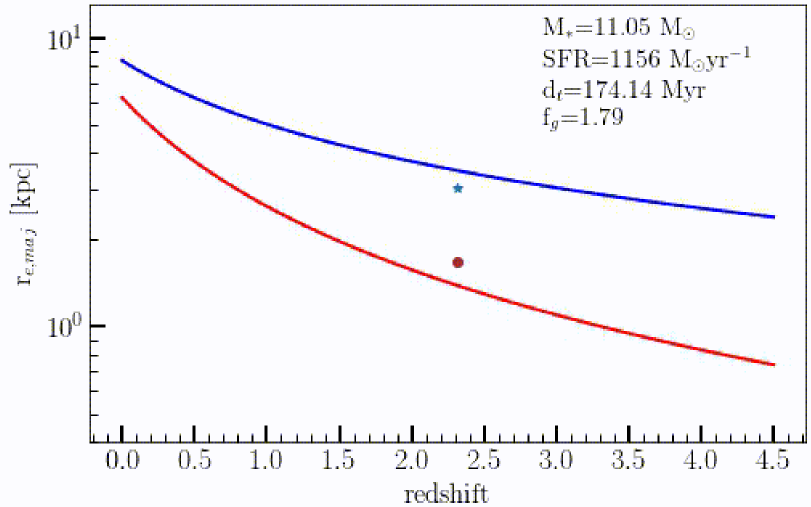
We present high–resolution (0.16″) 870μm Atacama Large Millimeter/submillimeter Array (ALMA) imaging of 16 luminous ($L_{IR} \sim 4 \times 10^{12} L_{\odot}$) submillimeter galaxies (SMGs) from the ALESS survey of

870μm (red), I_{814}–band (green) and H_{160}–band

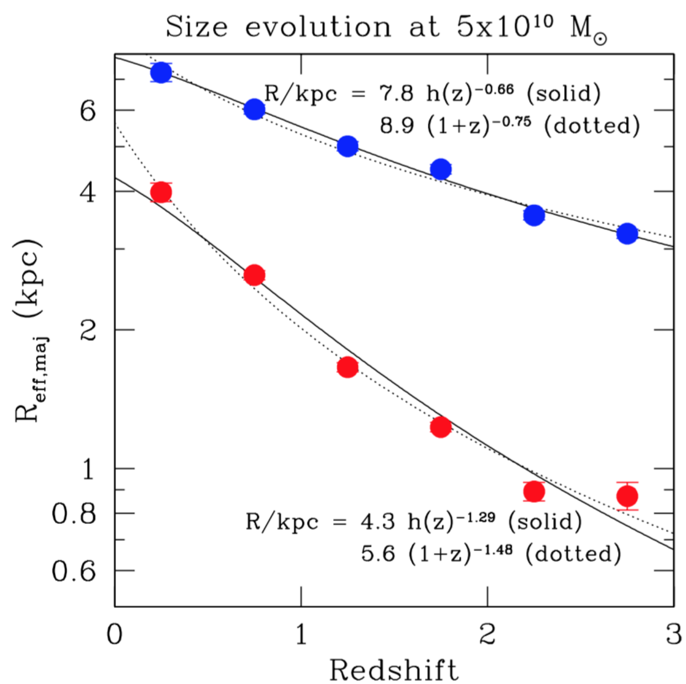




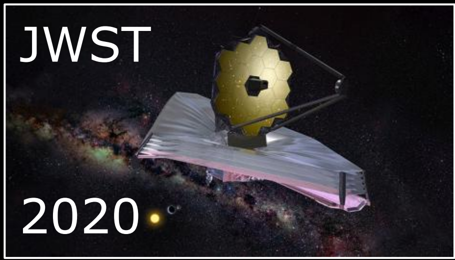
0.8
0.6
0.4
0.2
0.0
−10
−5
0
5
10
−10
−5
0
5
10



M* =11.05 M⊙
SFR=1156 M⊙yr−1
dt=174.14 Myr
fg=1.79
r_e,maj [kpc]
redshift



Size evolution at 5x10^10 M⊙
R/kpc = 7.8 h(z)^−0.66 (solid)
8.9 (1+z)^−0.75 (dotted)
R/kpc = 4.3 h(z)^−1.29 (solid)
5.6 (1+z)^−1.48 (dotted)
R_eff,maj (kpc)
Redshift



James Webb Space Telescope

The Cosmic Evolution Early Release Science (CEERS) Survey (NIRSPEC, MIRI, NIRCAM, 37h science, 63h total)

PI S.Finkelstein