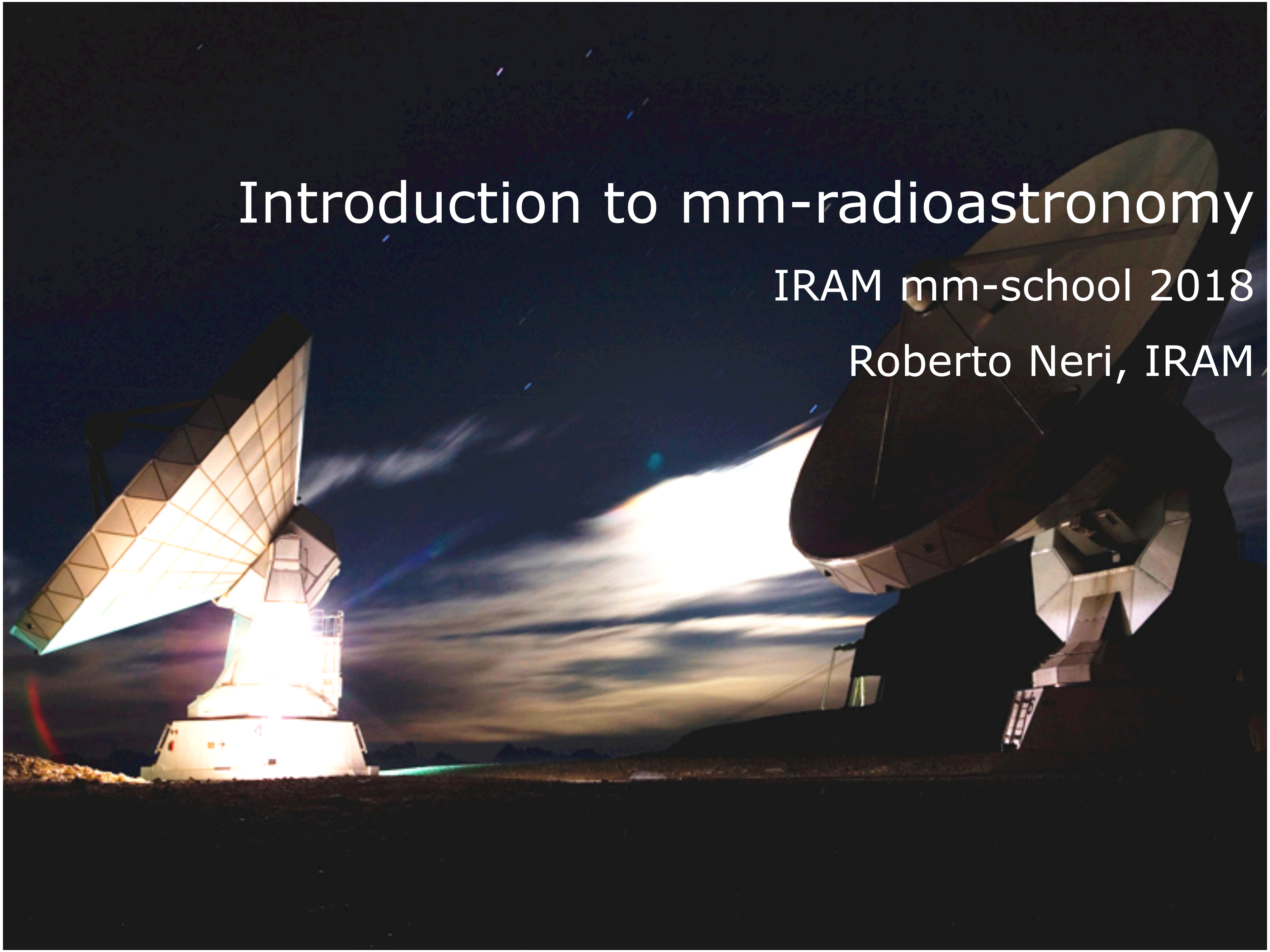
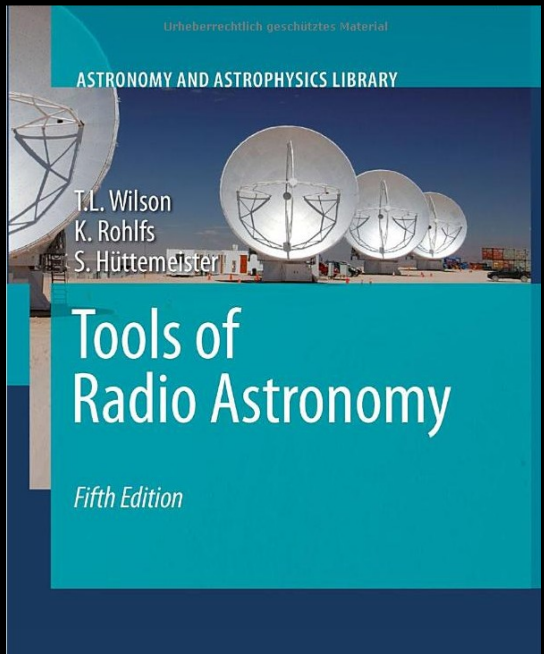
Introduction to mm-radioastronomy

IRAM mm-school 2018

Roberto Neri, IRAM



Literature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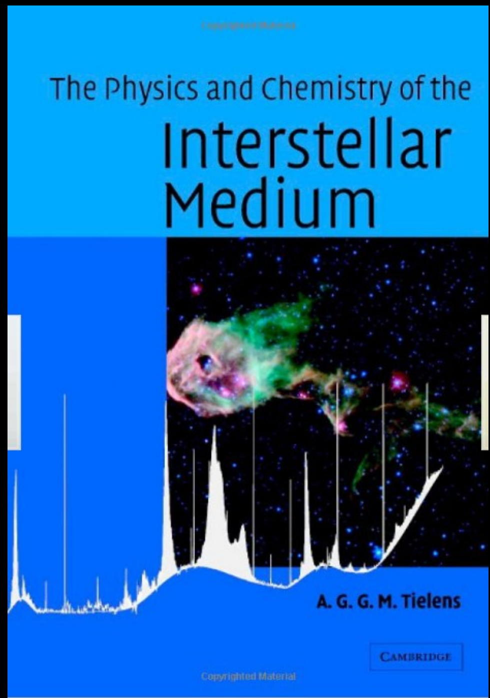
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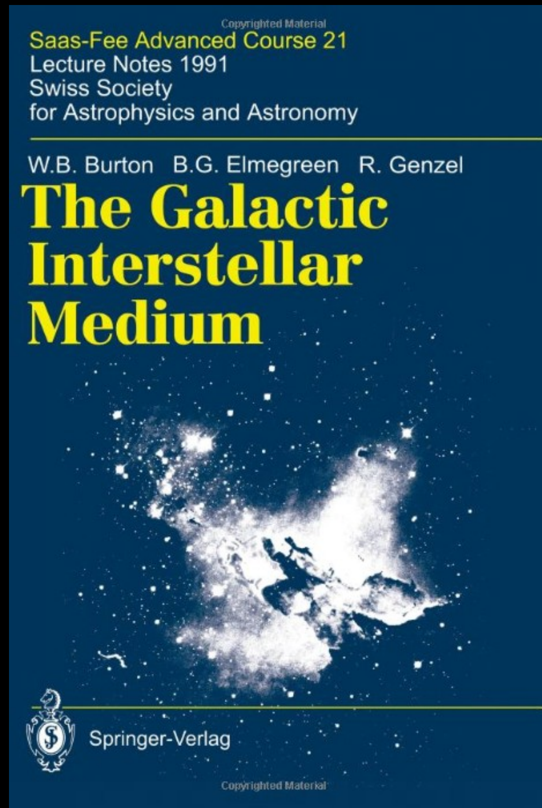
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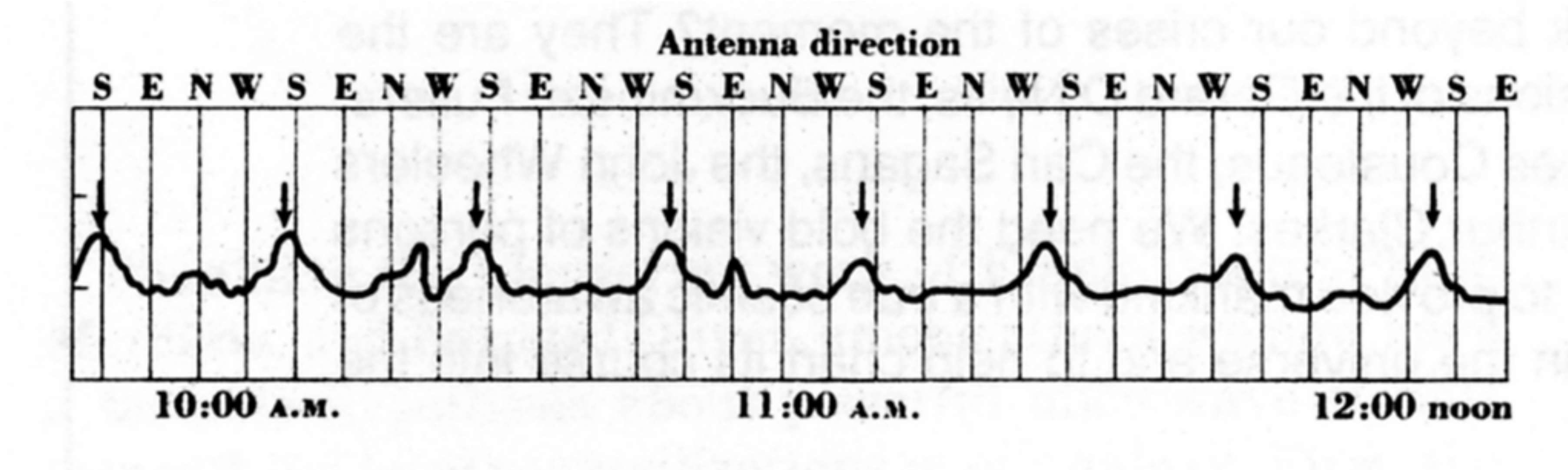
Historical Overview

- H.Hertz (1888)
  - Hertz oscillator : first radio wave transmitter
  - existence of electromagnetic waves
  - confirms Maxwell's theory

- G.Marconi (1901)
  - first transatlantic radio communication @ 820 KHz

- K.Jansky (1932)
  - azimuth rotating antenna @20.5 MHz
  - discovery of cosmic radio emission (GC)
  - 1 Jy = 10^{-26} $W.m^{-2}.Hz^{-1}$

Historical Overview



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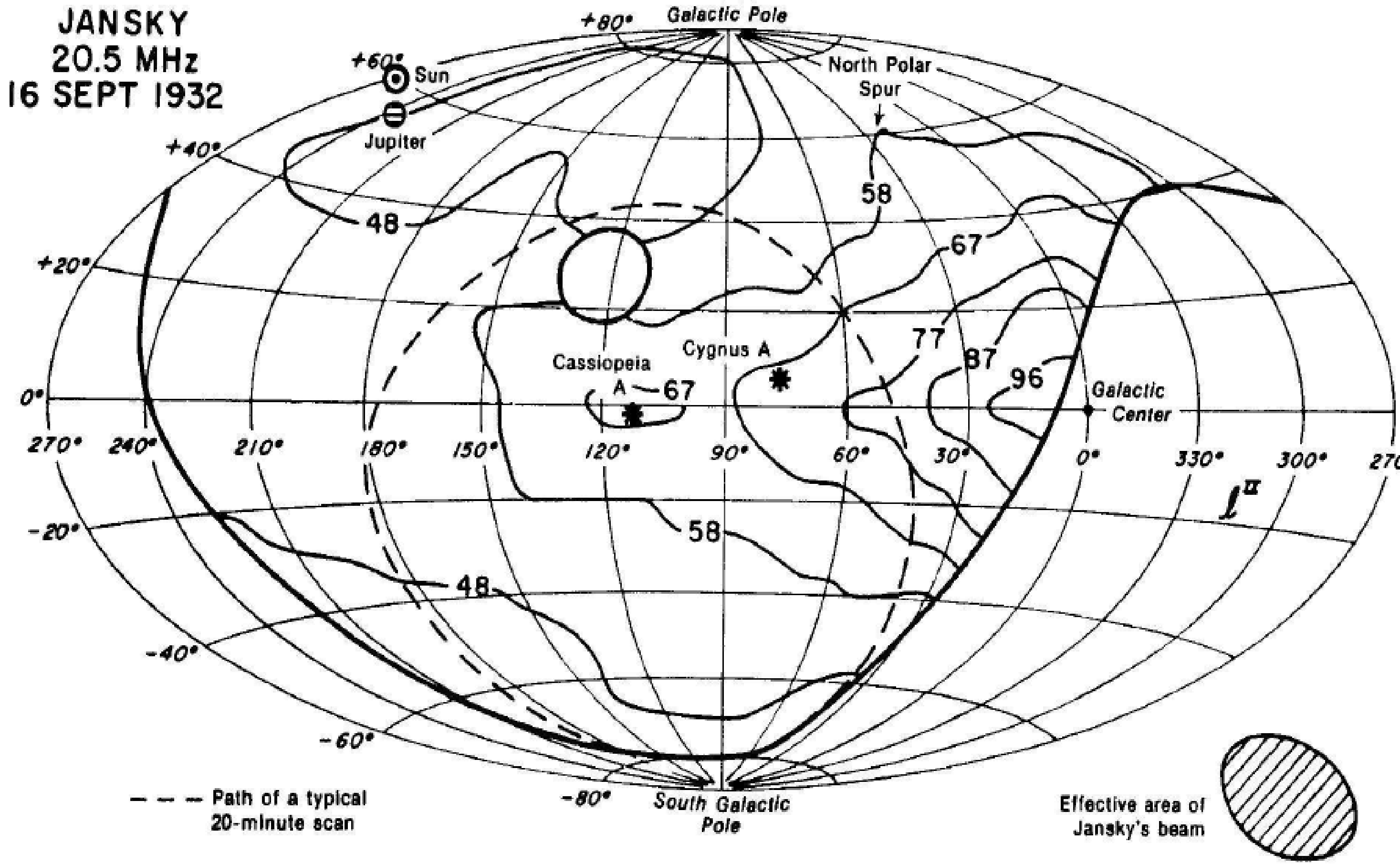
Historical Overview



Historical Overview

- G.Reber (1938)
  - first parabolic radio dish @ 160 MHz (=1.8 m)
  - confirms Jansky's discovery
  - first radio survey

Historical Overview

- G.Reber (1944, ApJ, 100, 279)

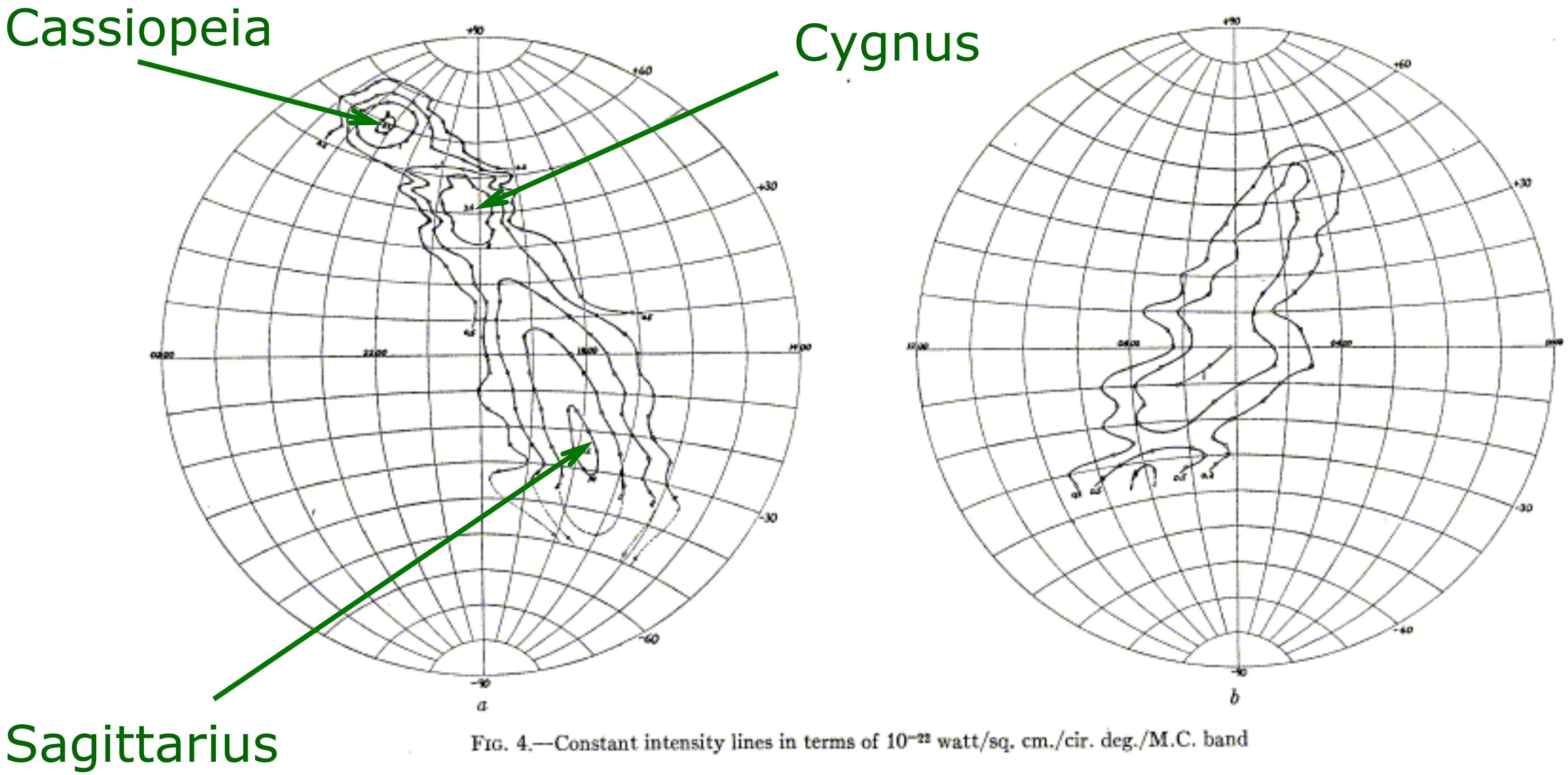


FIG. 4.—Constant intensity lines in terms of 10^{-22} watt/sq. cm./cir. deg./M.C. band

Historical Overview

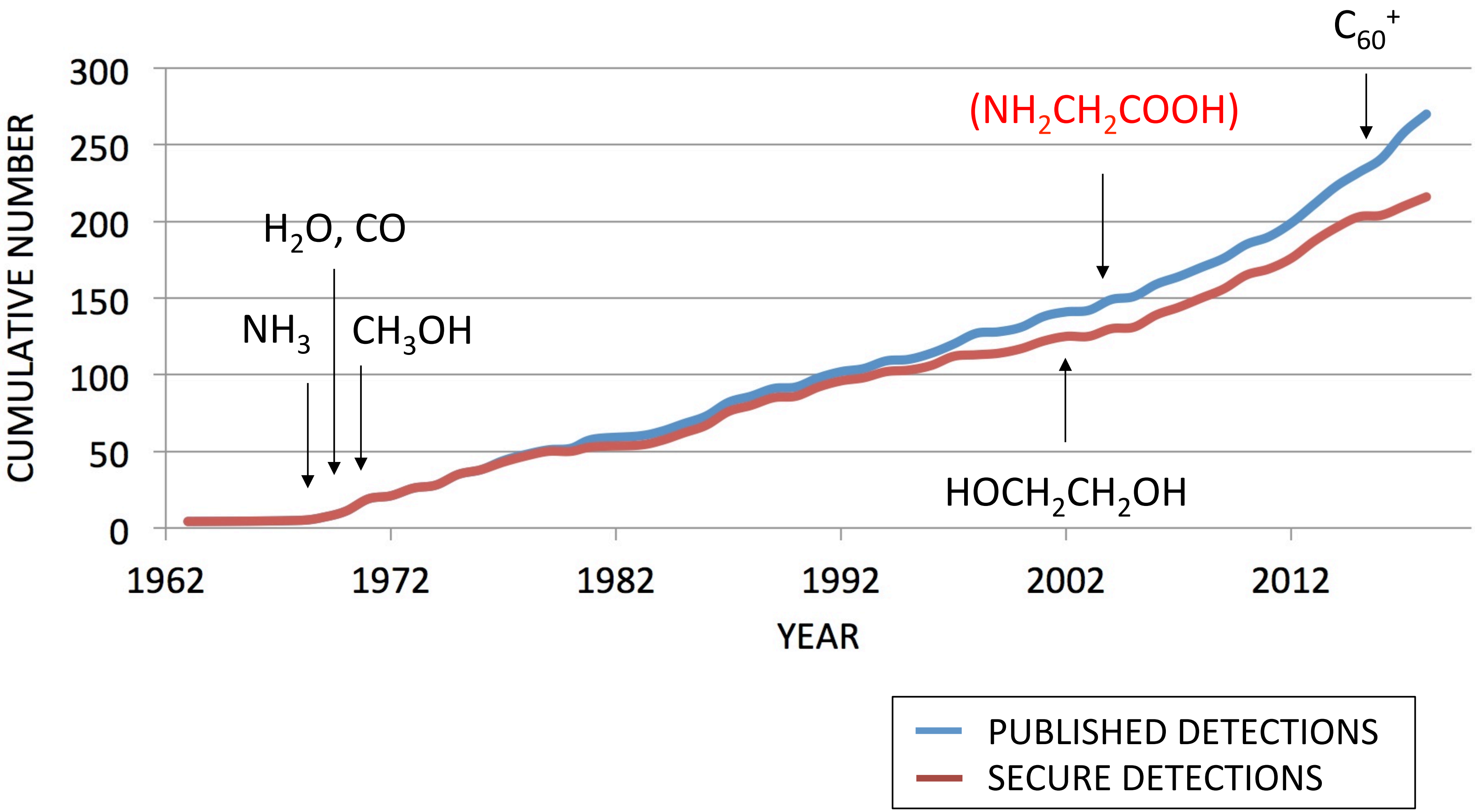
- G.Reber (1944, ApJ, 100, 279)
  - first parabolic radio dish @ 160 MHz (=1.8 m)
  - confirms Jansky's discovery
  - first radio survey - no detection @ 900 and 3300 MHz

- A.Penzias and R.Wilson (1965, ApJ, 142, 419)
  - discovery of the CMB @ 41 GHz

Historical Overview

- H I @ 21 cm : Ewen & Purcell 1951 ; Oort & Muller 1951
- OH @18 cm: Weinreb et al. 1963
- 1st polyatomic molecule in 1968: NH_3 (Cheung et al.)
- H2O @ 1.4 cm (22 GHz) : Cheung et al. 1969
- start of UV astronomy: H_2 in 1970
- 1970: CO by Wilson et al.
- many more molecules, more and more complex (e.g. C_2H_5COOH), and more and more long

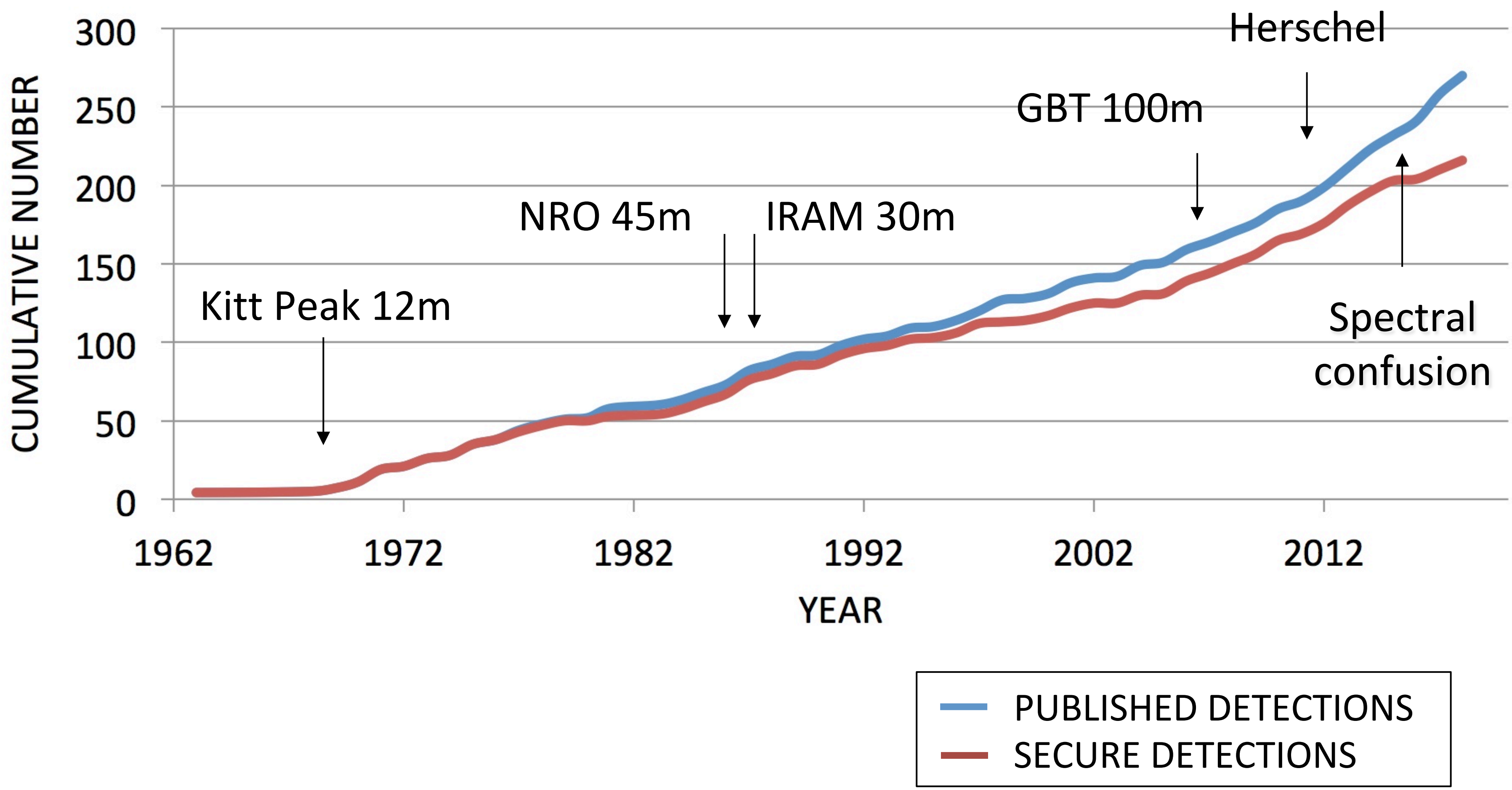
Historical Overview : detected molecules



Historical Overview : some (sub)mm-Telescopes

- 1964: Haystack 37-m tel. (λ>6mm)
- 1965: Green Bank 140ft telescope (λ>6mm)
- 1969: Kitt Peak 36'/12m telescope (λ>1mm)
- 1970: Effelsberg 100m telescope (λ>3mm)
- 1982: Nobeyama 45m telescope (λ>2mm)
- 1984: IRAM 30m telescope (λ>0.8mm)
- 1988: CSO 10.4m telescope (λ>0.3mm)
- 1990: IRAM Plateau de Bure Interferometer (λ>0.8mm)
- 2000: GBT 105m telescope (λ>3mm)
- 2004: APEX (λ>0.3mm)
- 2006: LMT (λ>0.8mm)
- 2012: ALMA (λ>0.1mm)
- 2014: NOEMA (λ>0.8mm)

Historical Overview : detected molecules



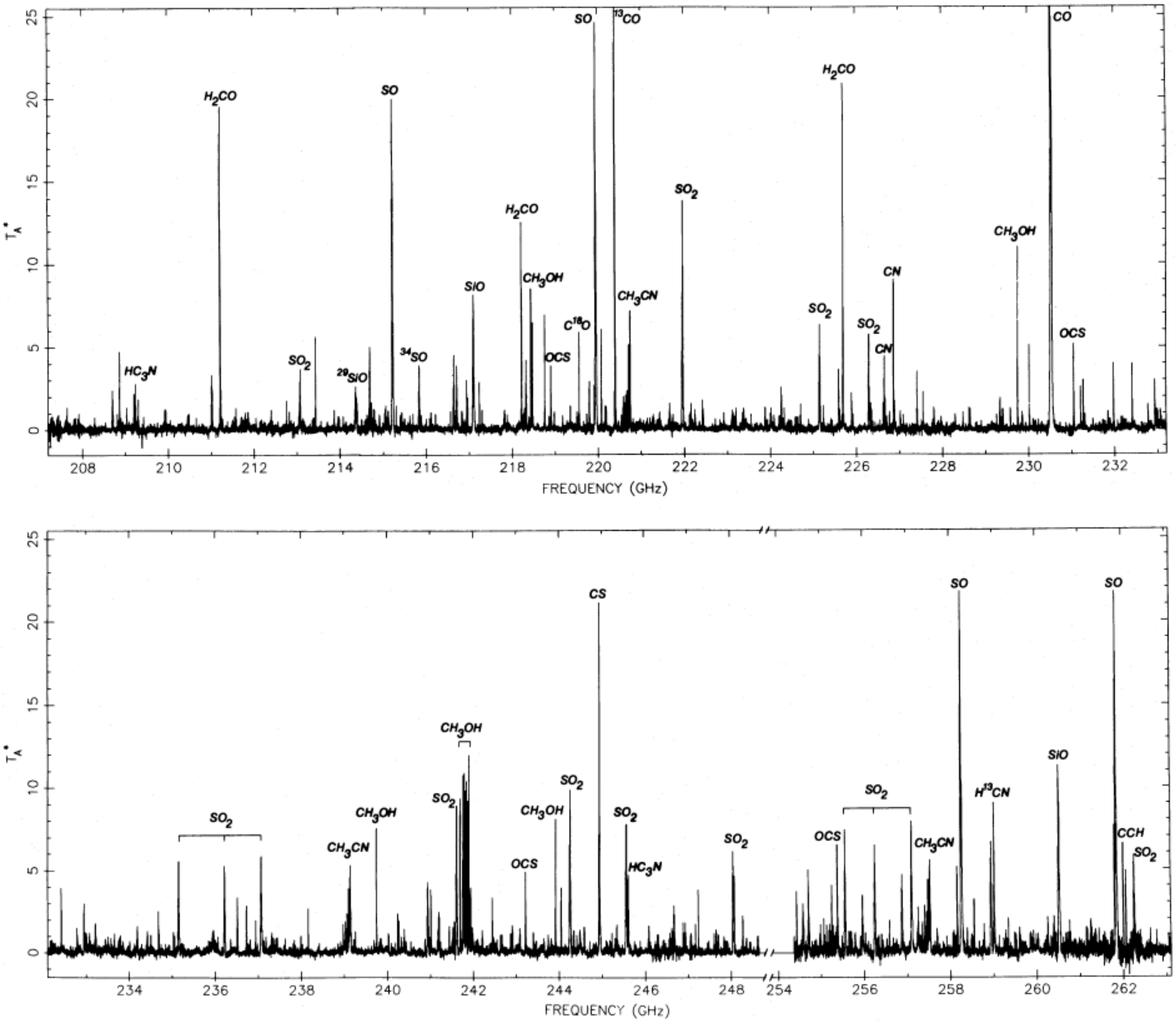


FIG. 1.—Compressed view of the OVRO spectral line survey of OMC-1

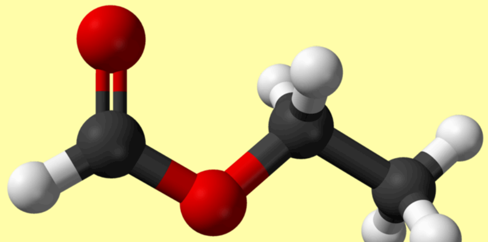
Molecules in the ISM

Cologne Data Base for Molecular Spectroscopy (CDMS)

- H_2 is by far the most abundant but invisible @ mm-waves
- CO is visible in almost all mm-windows
- more than 200 molecules
- observations, laboratory, theory
- organic chemistry but also species with S,P,F,Cl,Fe,Si,...
- many cations (HCO^+, H_2O^+, ...) and few anions (CN^-)
- many radicals: CH, C_2H, OH, HCO, CN, ...

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
H_2	C_3*	c-C_3H	C_5*	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	C_6H_6*	$HC_{11}N$
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	$C_2H_5OCH_3$?	C_{60}* 2010
AlCl	C_2O	C_3N	C_4Si	C_2H_4*	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	n-C_3H_7CN	C_{70}* 2010
C_2**	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO			
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	CH_3CHO	H_2C_6					
CH^+	HCN	C_2H_2*	H_2CCN	CH_3OH	CH_3NH_2	CH_2OHCHO					
CN	HCO	NH_3	CH_4*	CH_3SH	c-C_2H_4O	l-HC_6H*					
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	H_2CCHOH	CH_2CHCHO (?)					
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN					
CP	HOC^+	HNCO	HCOOH	NH_2CHO		H_2NCH_2CN					
SiC	H_2O	HNCS	H_2CNH	C_5N							
HCl	H_2S	$HOCO^+$	H_2C_2O	l-HC_4H*							
KCl	HNC	H_2CO	H_2NCN	l-HC_4N							
NH	HNO	H_2CN	HNC_3	c-H_2C_3O							
NO	MgCN	H_2CS	SiH_4*	H_2CCNH (?)							
NS	MgNC	H_3O^+	H_2COH^+	C_5N^-							
NaCl	N_2H^+	c-SiC_3	C_4H^-								
OH	N_2O	CH_3*	HC(O)CN								
PN	NaCN	C_3N^-									
SO	OCS	PH_3 ?									
SO^+	SO_2	HCNO									
SiN	c-SiC_2	HOCN 2010									
SiO	CO_2*	HSCN									
SiS	NH_2	H_2O_2 2011									
CS	H_3^+*										
HF 2010	H_2D^+, HD_2^+										
HD	SiCN										
FeO ?	AlNC										
O_2 2011	SiNC										
CF^+	HCP										
SiH ?	CCP										
PO	AlOH 2010										
AlO	H_2O^+ 2010										
OH^+ 2010	H_2Cl^+ 2010										
CN^- 2010	KCN 2010										
SH^+ 2011	FeCN 2011										

Ethyl-formate C_2H_5OCHO



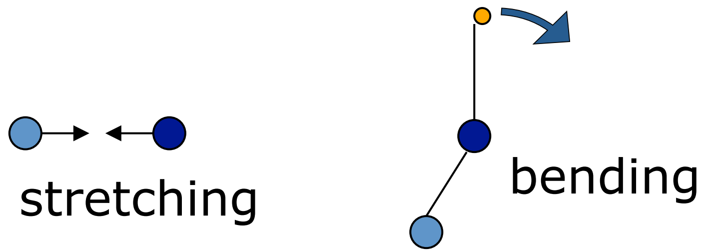
(Belloche et al. 2009 with the 30m)

Extragalactic Molecules (as of 06/2011)

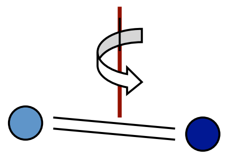
2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	>8 atoms
OH	H_2O	H_2CO	c-C_3H_2	CH_3OH	CH_3CCH		
CO	HCN	NH_3	HC_3N 2010	CH_3CN			C_{60}* 2010
H_2*	HCO^+	HNCO	CH_2NH				
CH **	C_2H	H_2CS ?	NH_2CN				
CS	HNC	$HOCO^+$					
CH^+ **	N_2H^+	*c*-C_3H					
CN	OCS	H_3O^+					
SO	HCO						
SiO	H_2S						
CO^+	SO_2						
NO	HOC^+						
NS	C_2S						
NH	H_2O^+ 2010						
OH^+ 2010							
HF 2010							

Energies involved in molecular states

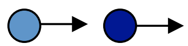
- electronic transitions
- vibrational transitions



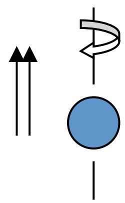
- rotational transitions



- translational transitions

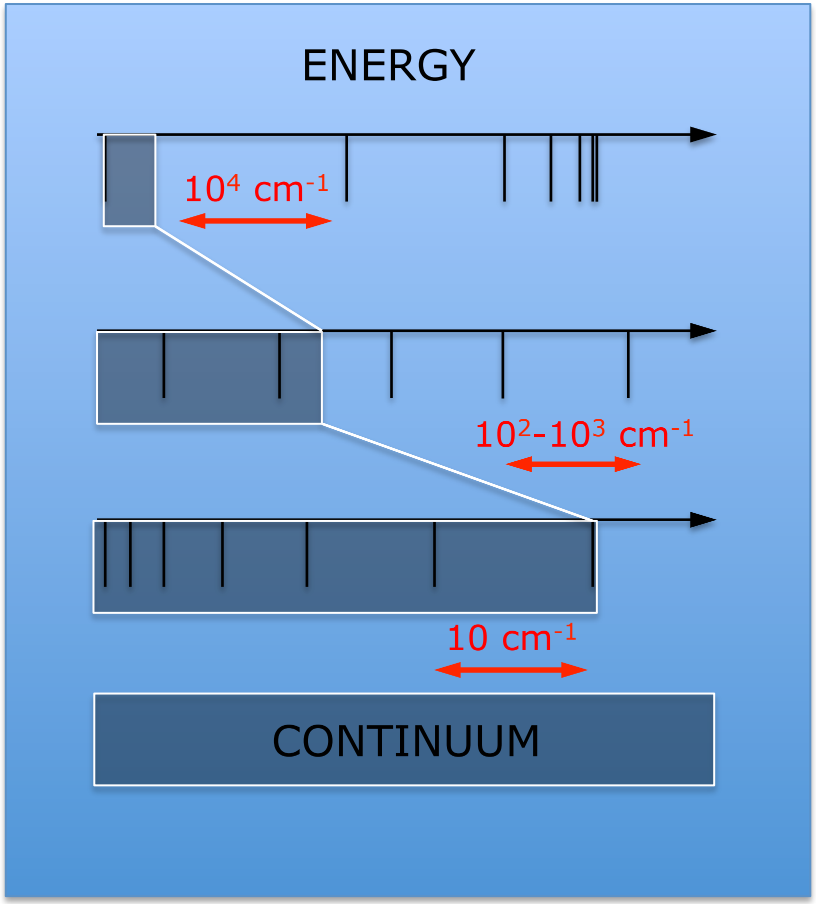


- electronic/nuclear spin transitions

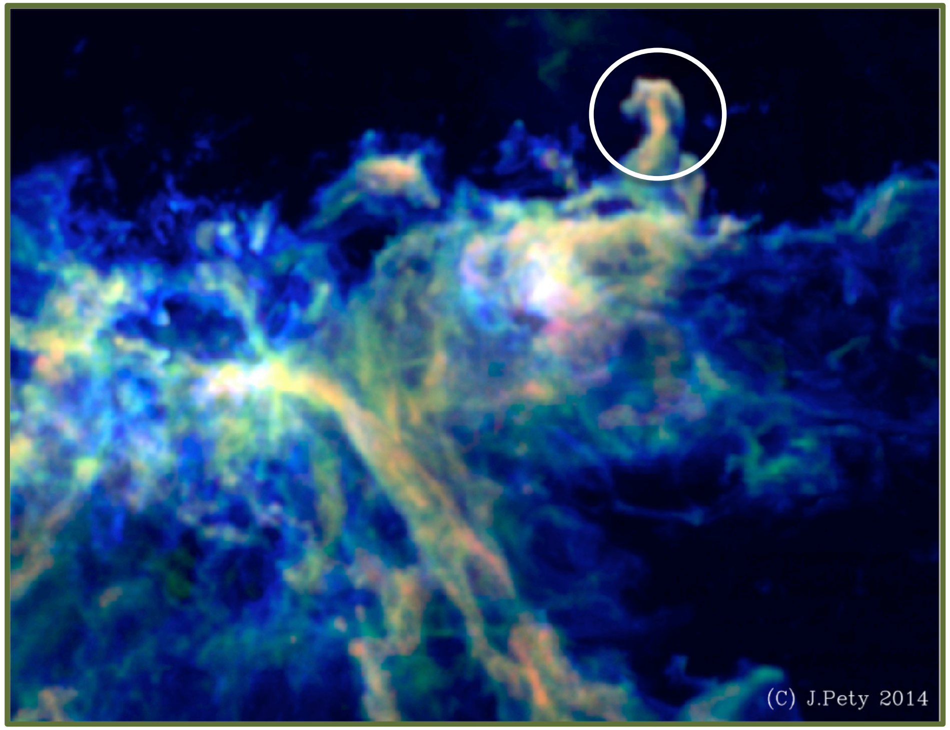


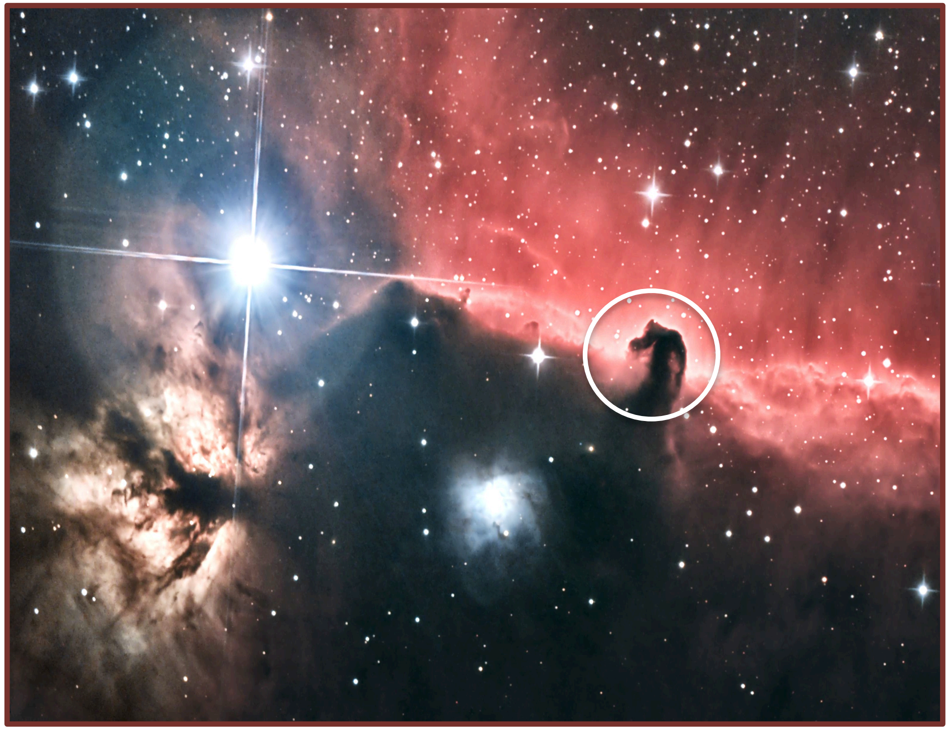
Energies involved in molecular states

- electronic transitions
- vibrational transitions
- rotational transitions
- *translational transitions*



⇨ Low-energy rotational transitions of small molecules lie at mm wavelengths





- visible = hot matter = stars/HII between 10^3 and 10^5 K
- millimeter = cold matter = dust/molecules between 10 and 100 K

⇨ stars are born in cold matter

$$h\nu = kT$$

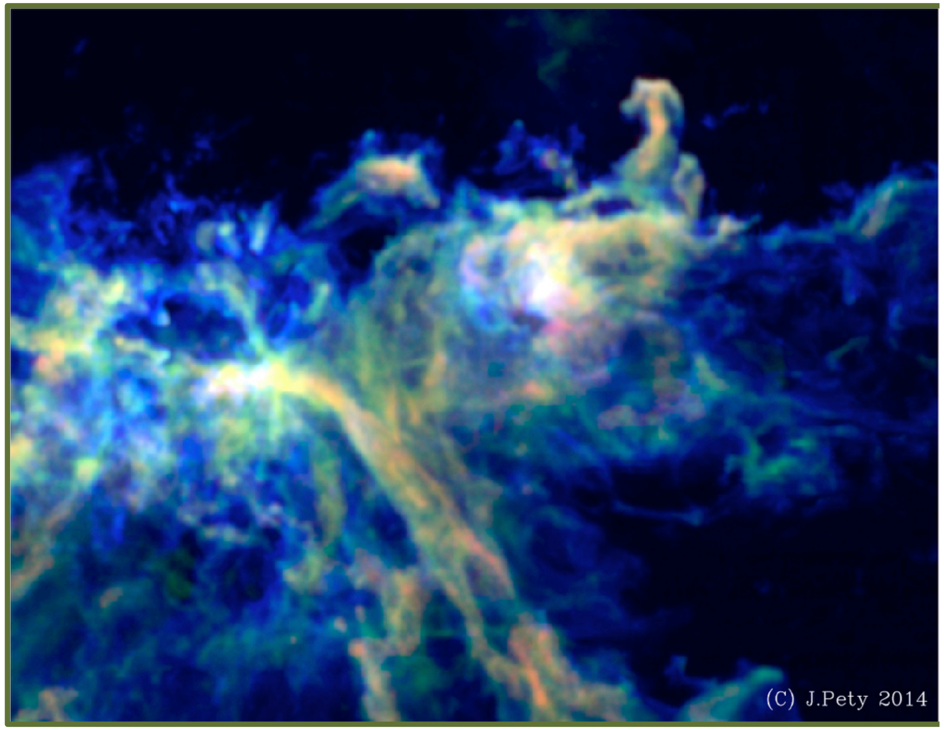
4.3 K = 90 GHz = 3 cm^{-1}

- mm-astronomy deals with

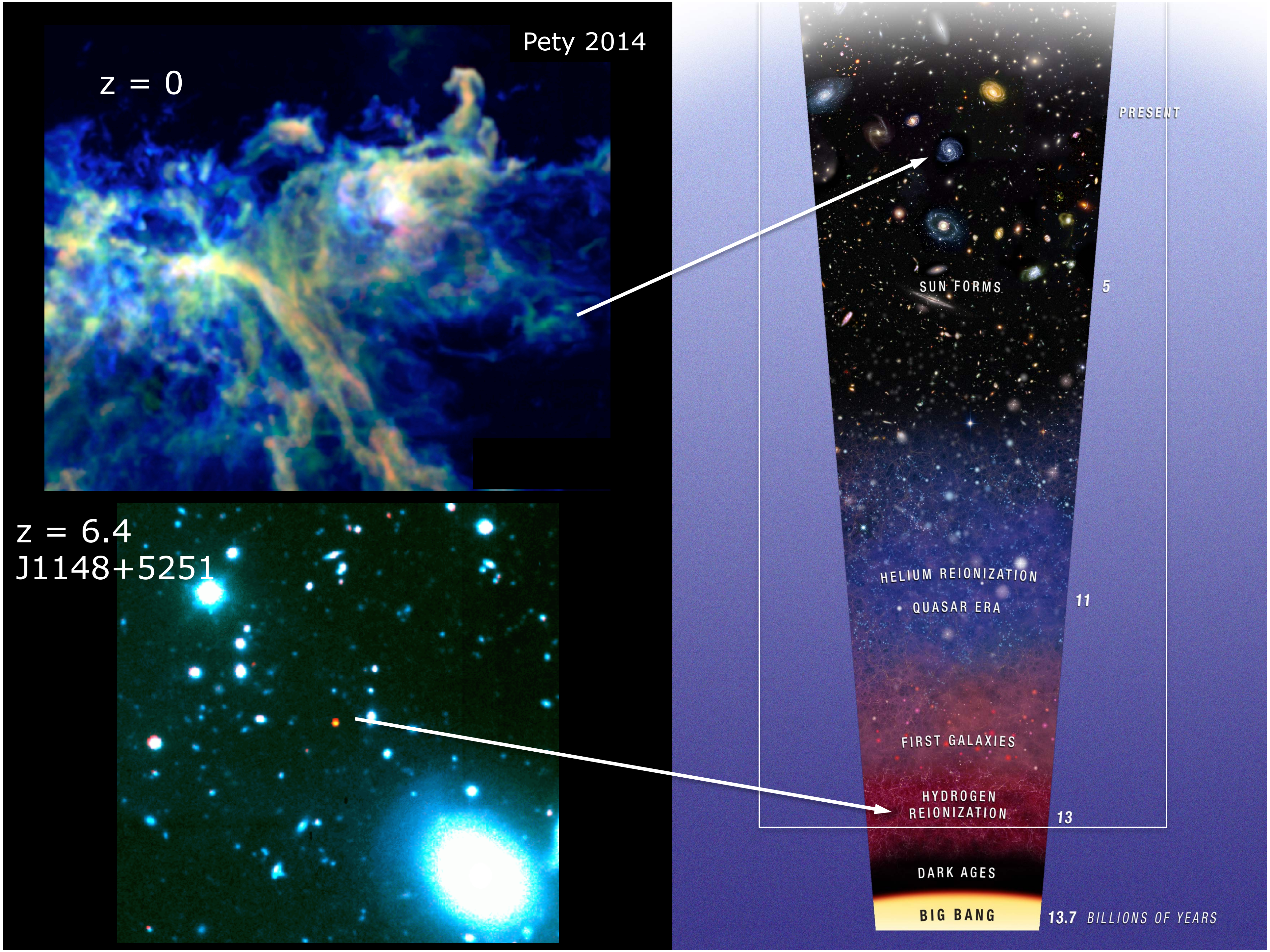
  - continuum emission: free-free, dust, synchrotron, compton scattering, SZ, …

  - line emission: mostly molecules but also atoms

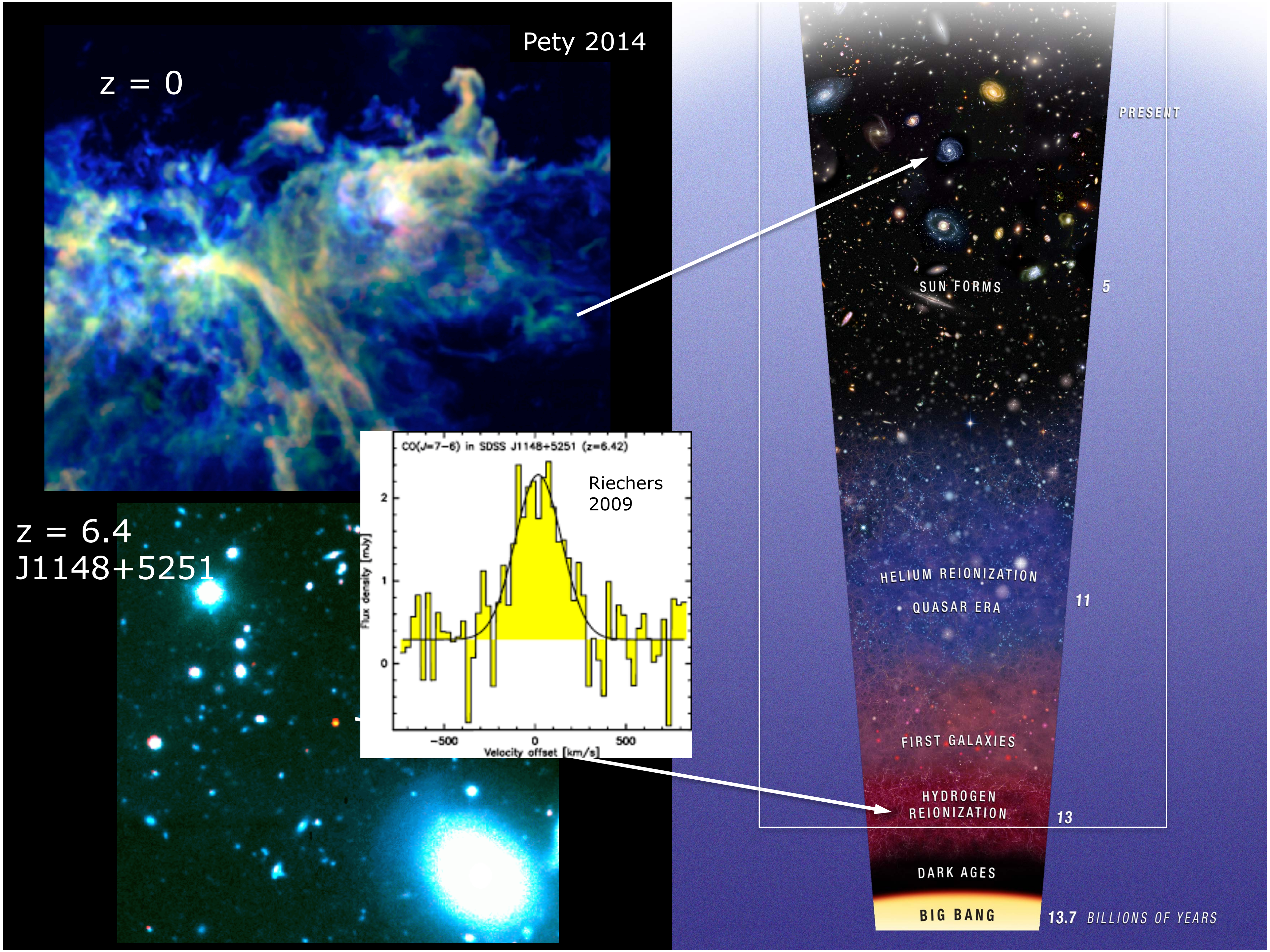
  - inter- stellar/galactic medium in various phases
    - matter in ionized, atomic, molecular state, dust grains, etc.
    - temperature, density of the matter



  - HII regions $T \sim 10^4$K, $n=10^1$-10^6/cm^3 e.g. H, He
  - molecular clouds/cores $T \sim 10$-10^3K, $n \sim 10^2$-10^8/cm^3 e.g. ^{12}CO



Pety 2014
z = 0
z = 6.4
J1148+5251
PRESENT
SUN FORMS
5
HELIUM REIONIZATION
QUASAR ERA
11
FIRST GALAXIES
HYDROGEN
REIONIZATION
13
DARK AGES
BIG BANG
13.7 BILLIONS OF YEARS


Pety 2014
z = 0
z = 6.4
J1148+5251
CO(J=7–6) in SDSS J1148+5251 (z=6.42)
Riechers 2009
Flux density [mJy]
Velocity offset [km/s]
PRESENT
SUN FORMS
5
HELIUM REIONIZATION
QUASAR ERA
11
FIRST GALAXIES
HYDROGEN REIONIZATION
13
DARK AGES
BIG BANG
13.7 BILLIONS OF YEARS

(sub)mm-telescopes

- need for powerful instruments to observe astronomical targets up to the EoR (z=8)

  ⇨ sensitivity and angular resolution

  ⇨ large telescopes e.g. ALMA, NOEMA/IRAM 30m

  ⇨ continuum and heterodyne receivers $R=10^7$-10^8

- water vapor reduces the ability to observe in the mm-range from the ground

  ⇨ high altitude sites i.e. above 2000m

advantages of interferometers

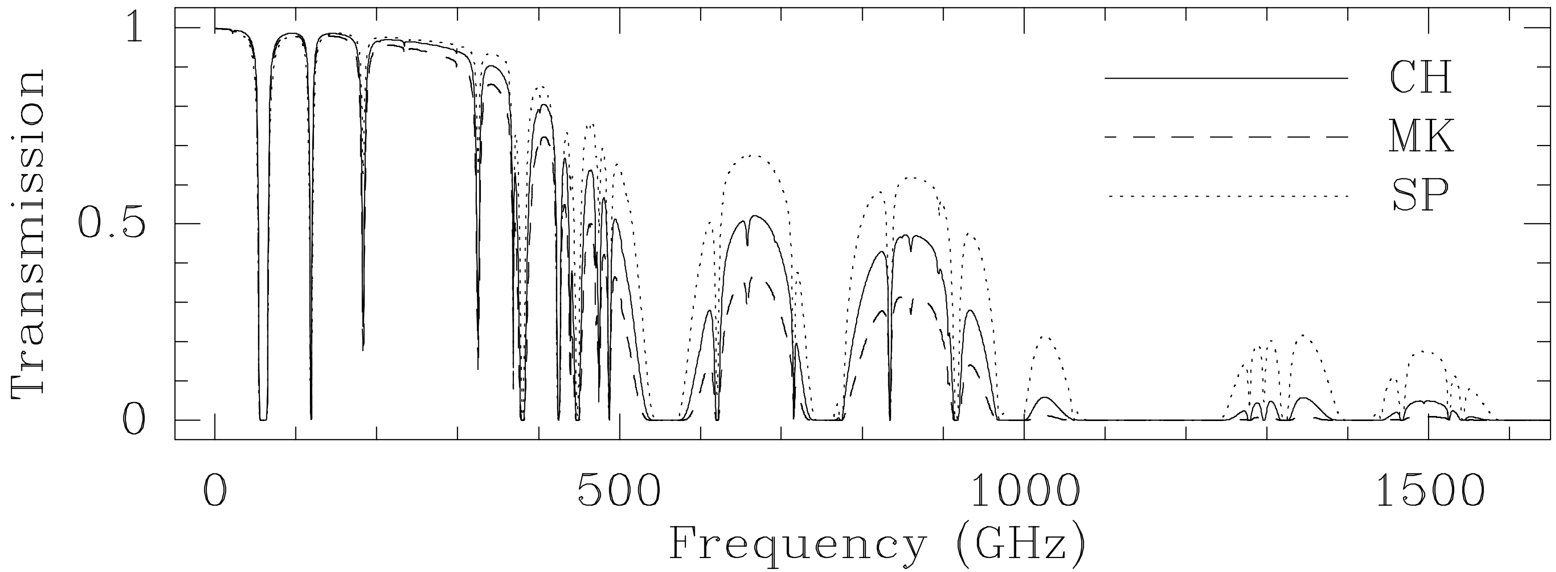
- high angular resolution
  - @ 230 GHz: 0.4” with NOEMA10 > 0.2” with NOEMA12
  - @ 350 GHz ~20 uas with VLBI (planned)

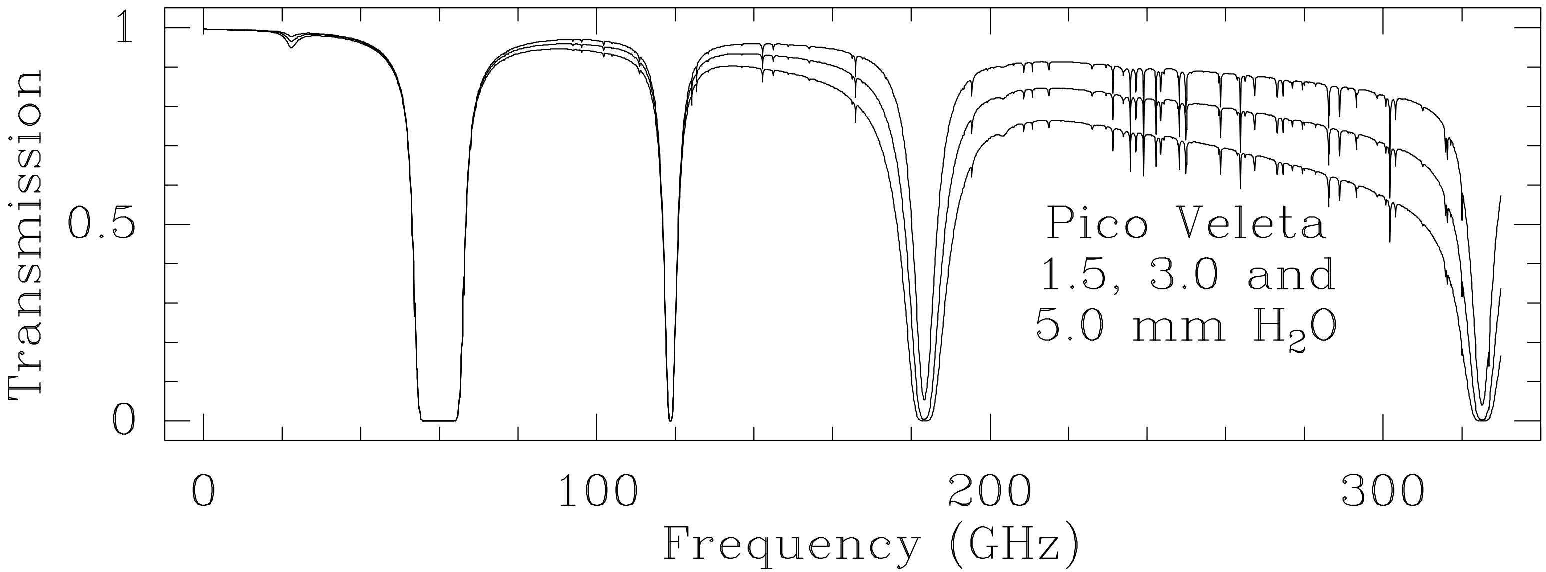
- large collective area
  - NOEMA12 = 50-meter antenna; ALMA45 = 80-meter antenna

- no need of reference sky position (gain of a factor √2 in sensitivity)
- flatter baselines, depend less on receiver/atmosphere stability
- field of view with many independent pixels ⇨ good noise statistics makes possible secure detections down to 4 sigma
- well suited for special observations e.g. polarimetry, SZ
- accurate source positions
- filter out extended (foreground/background) emission

atmospheric transmission

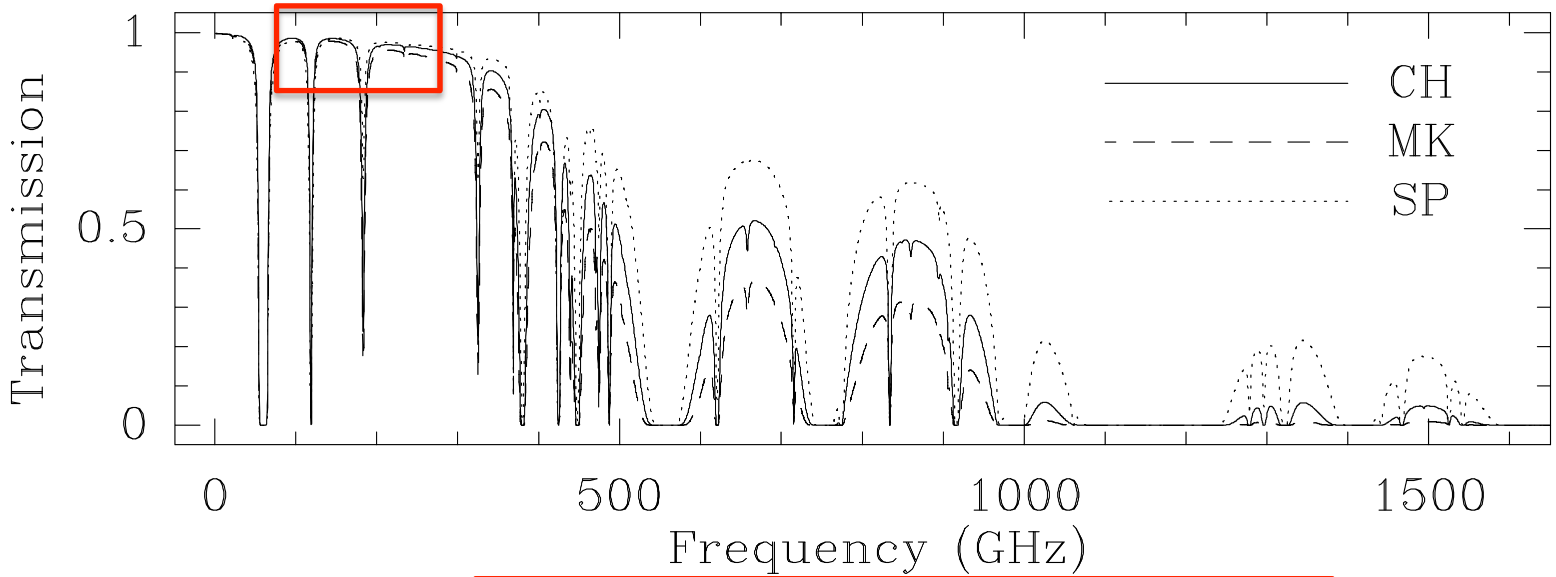
(calculations by J. Pardo)

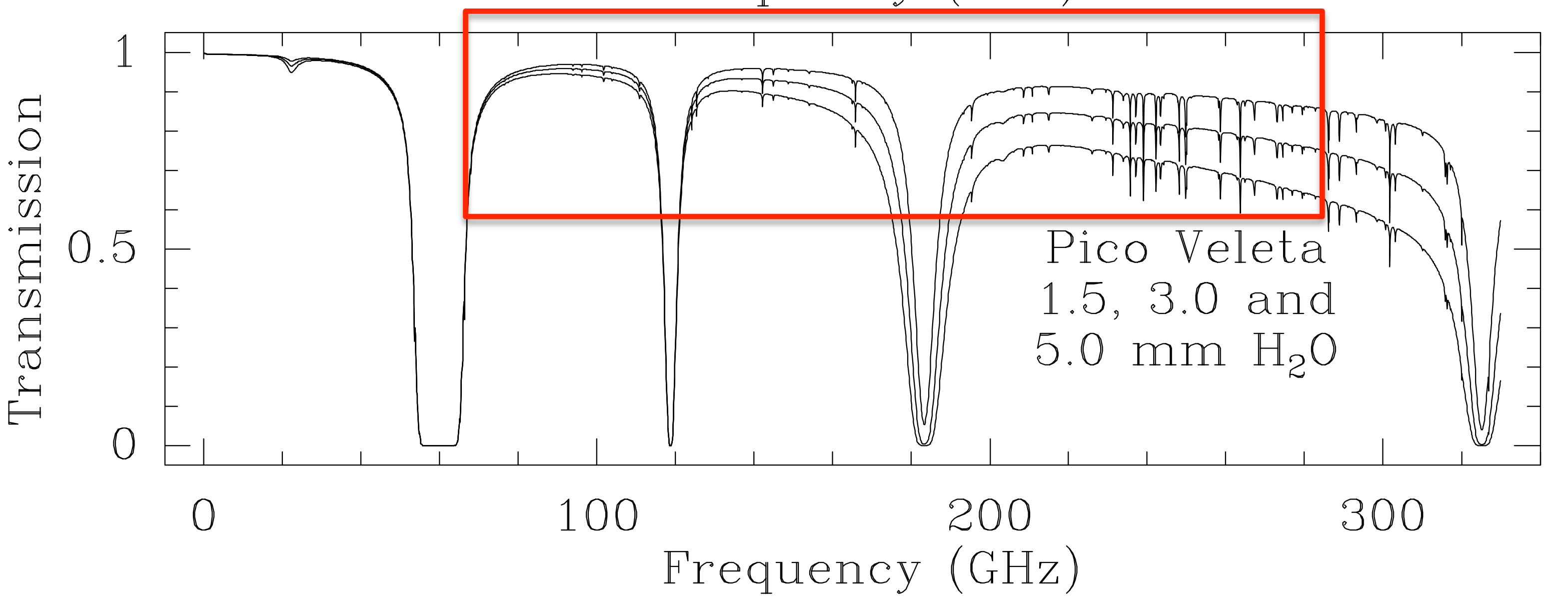




atmospheric transmission

(calculations by J. Pardo)



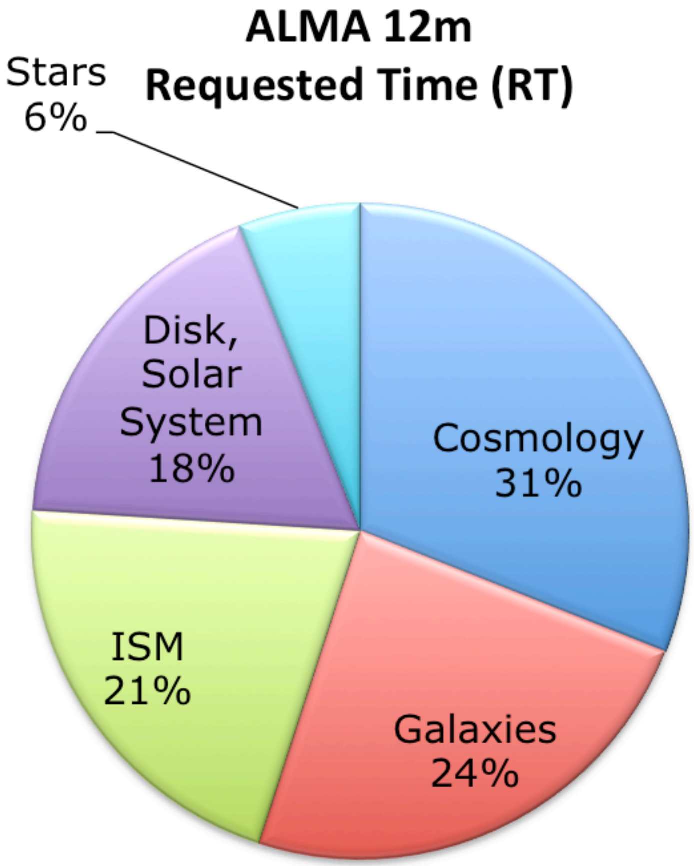


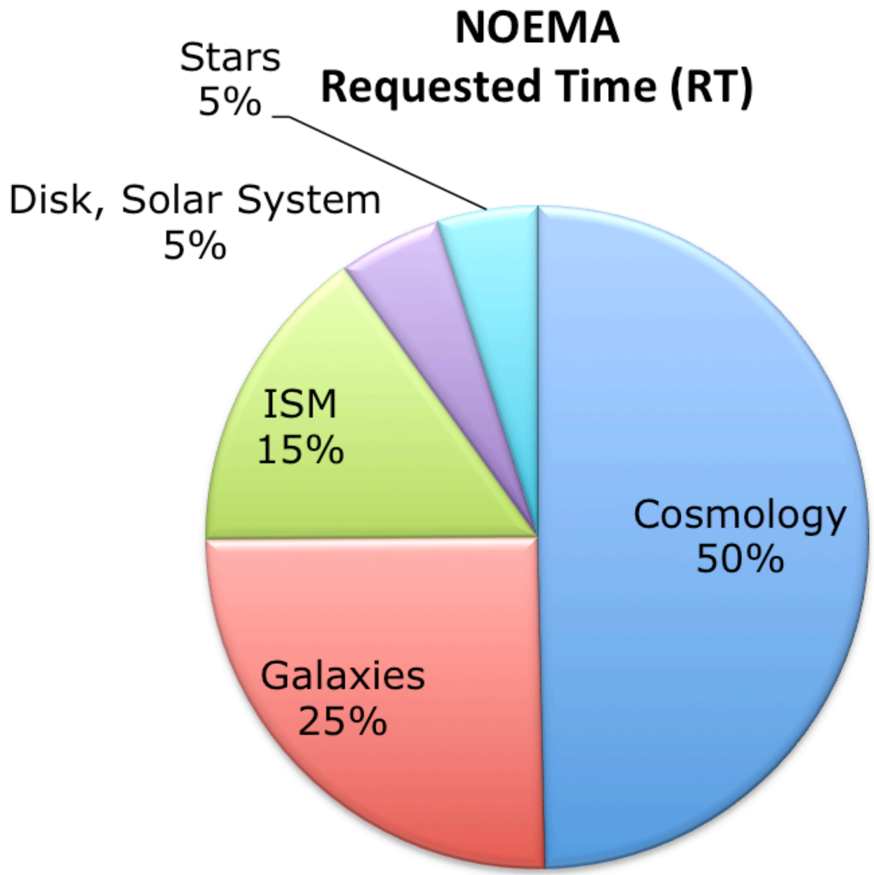




Telescope	Altitude	Frequencies
EFFELSBERG 100m	320	<90 GHz
ATCA	240	<105 GHz
GBT	320	<115 GHz
NOEMA/IRAM 30M	2500/2800	< 380 GHz
SMA 8	4030	<700 GHz
LMT	4600	<350 GHz
ALMA 50	5000	<1000 GHz

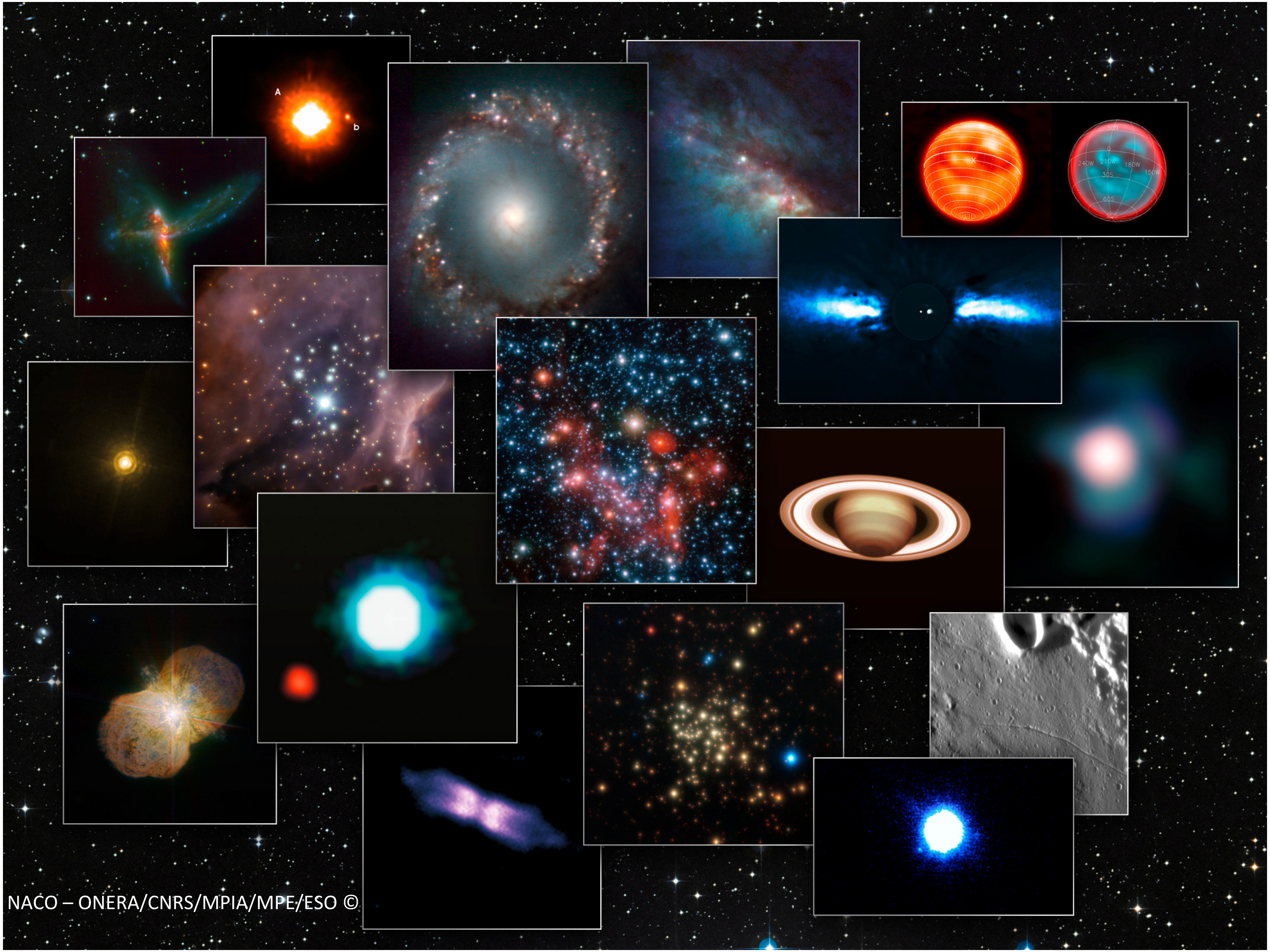
some statistics (Cy5 vs NOEMA 2017)





mm-astronomy ...

- ... not anymore in a proof-of-concept stage
- ... belongs to mainstream science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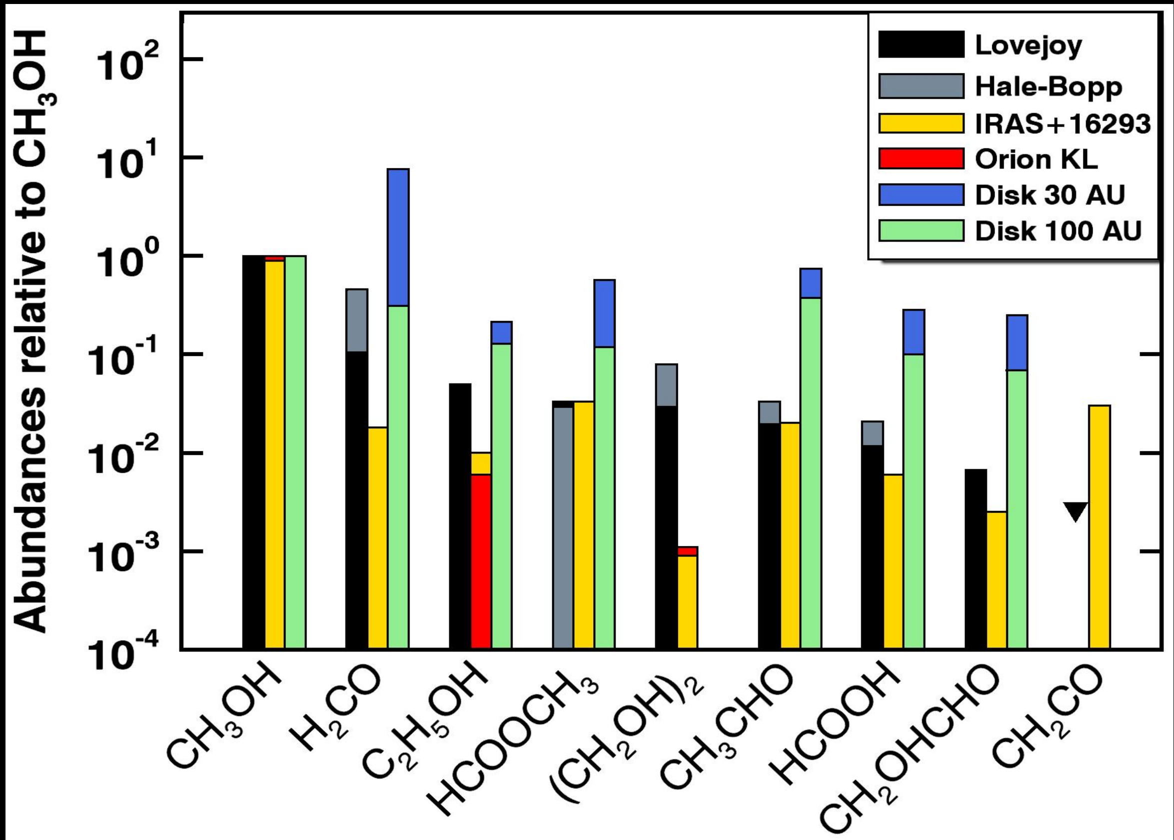
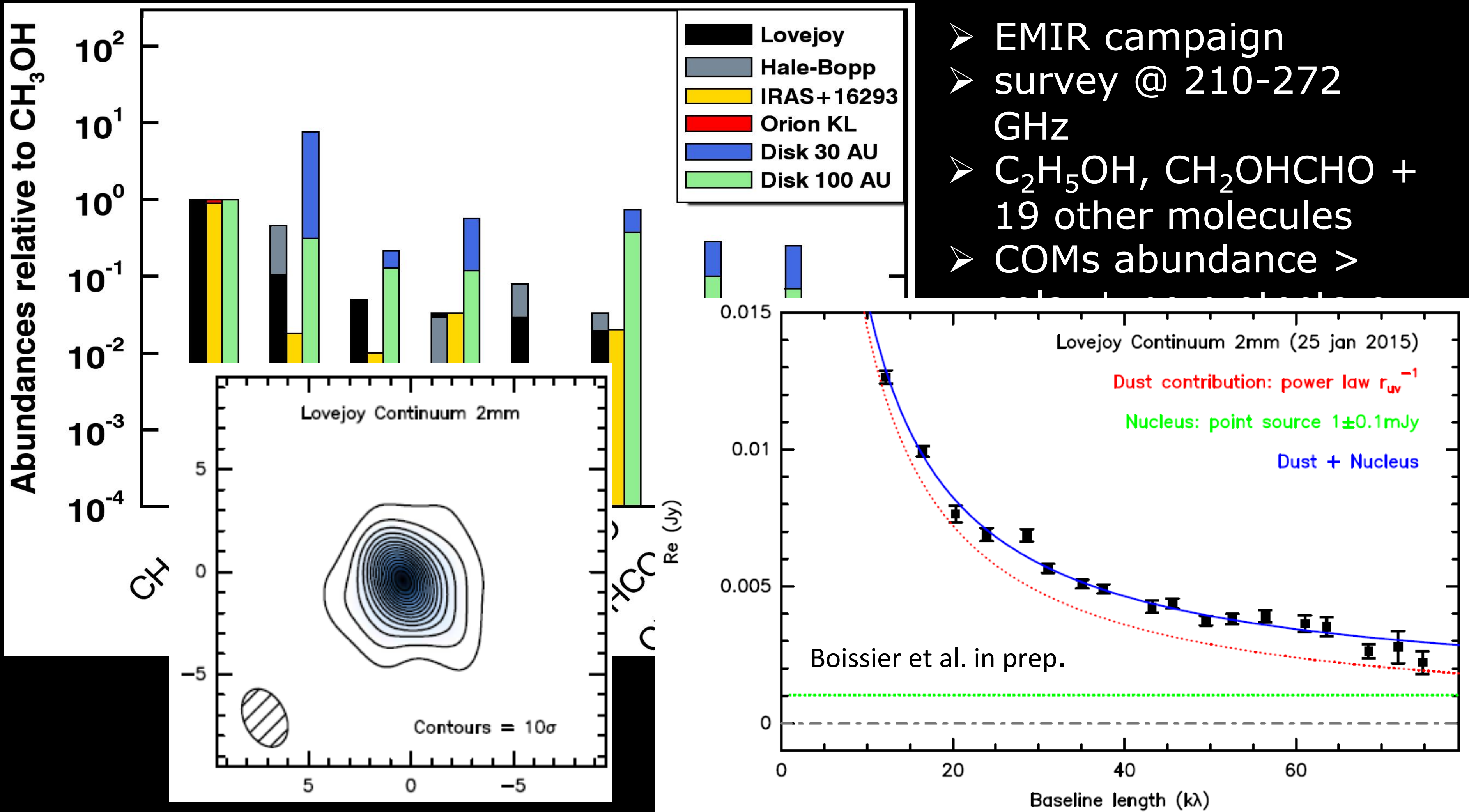
Ethyl alcohol and sugar in comet Lovejoy (C/2014 Q2)



- EMIR campaign
- survey @ 210-272 GHz
- C_2H_5OH, CH_2OHCHO + 19 other molecules
- COMs abundance > solar-type protostars ⟹ origin of COMs

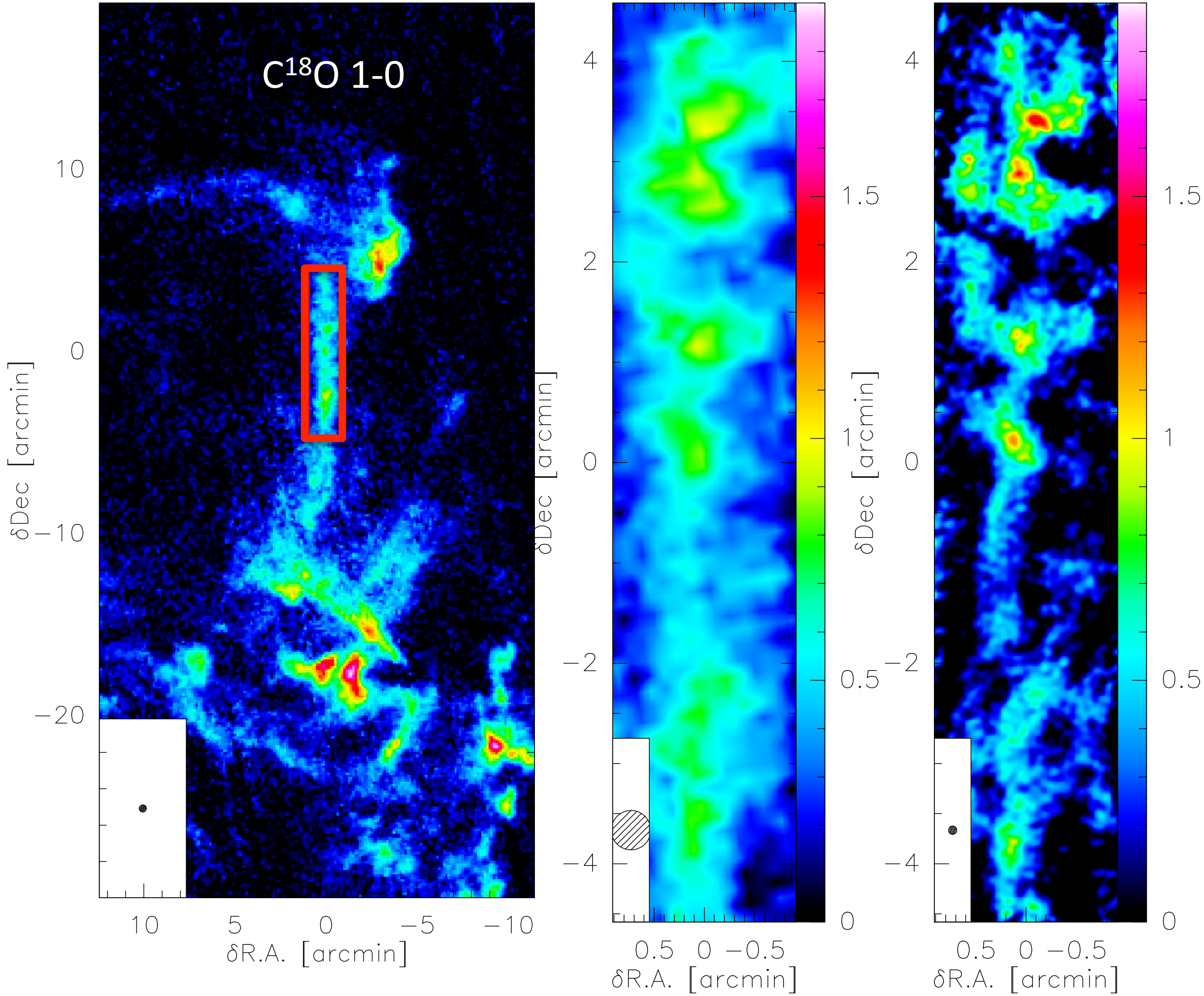
Biver et al. 2015

Ethyl alcohol and sugar in comet Lovejoy (C/2014 Q2)

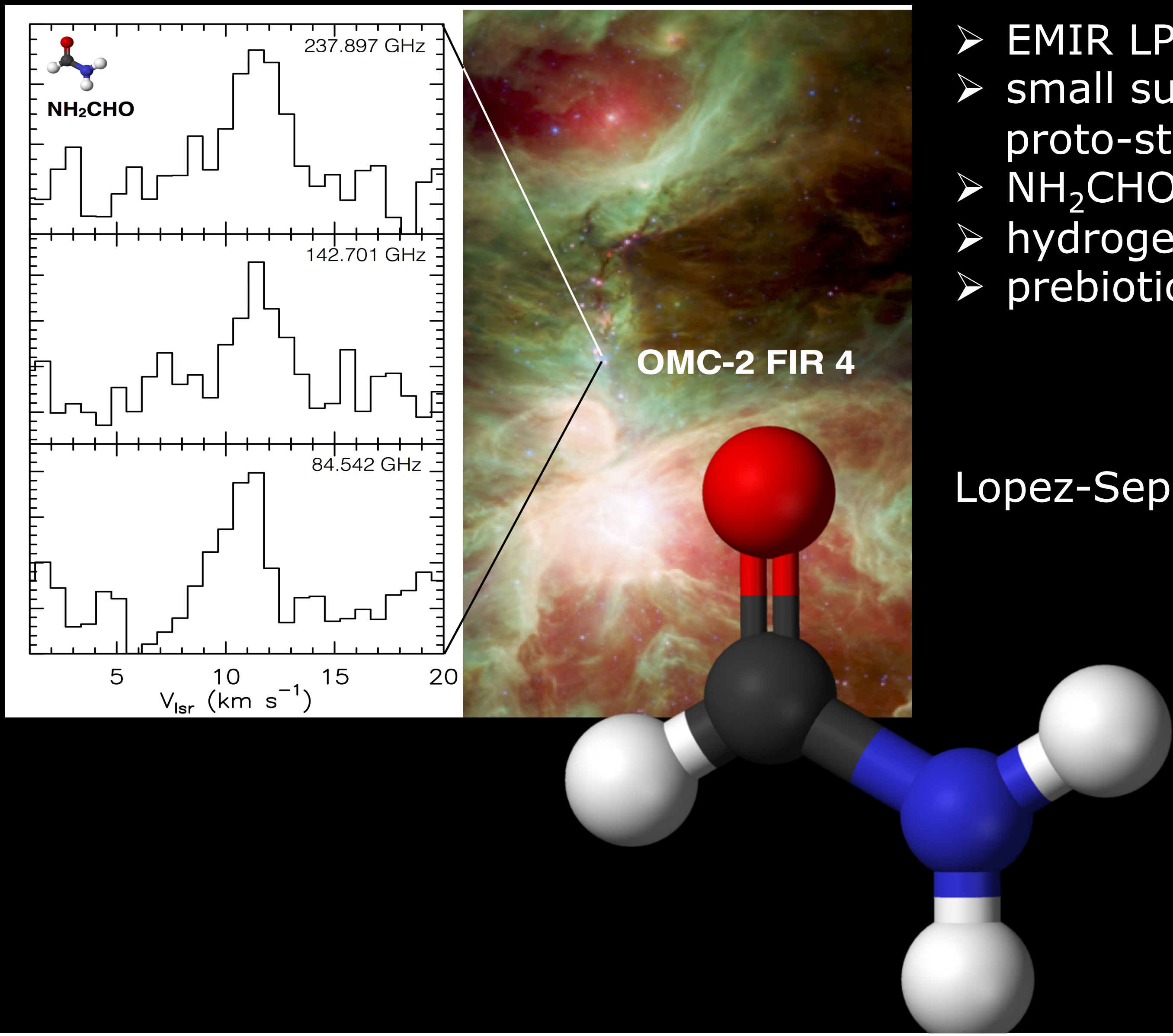


- EMIR campaign
- survey @ 210-272 GHz
- C_2H_5OH, CH_2OHCHO + 19 other molecules
- COMs abundance >

Filamentary structures in NGC 2024 - Jan Orkisz et al. in prep
First light with NOEMA 10 antennas + IRAM 30-meter telescope



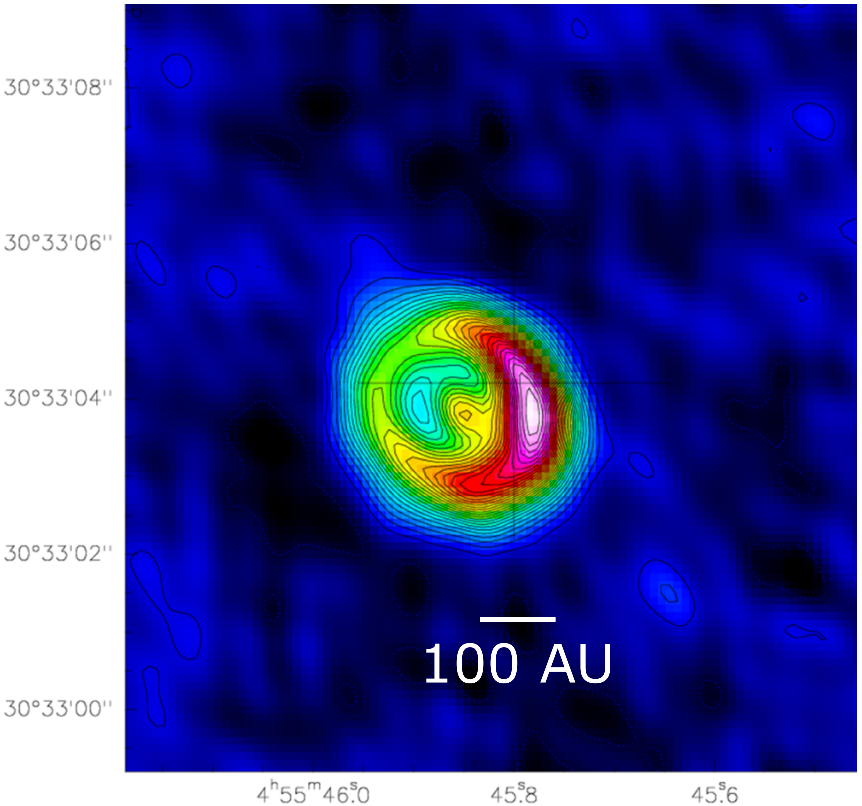
Search for NH_2CHO

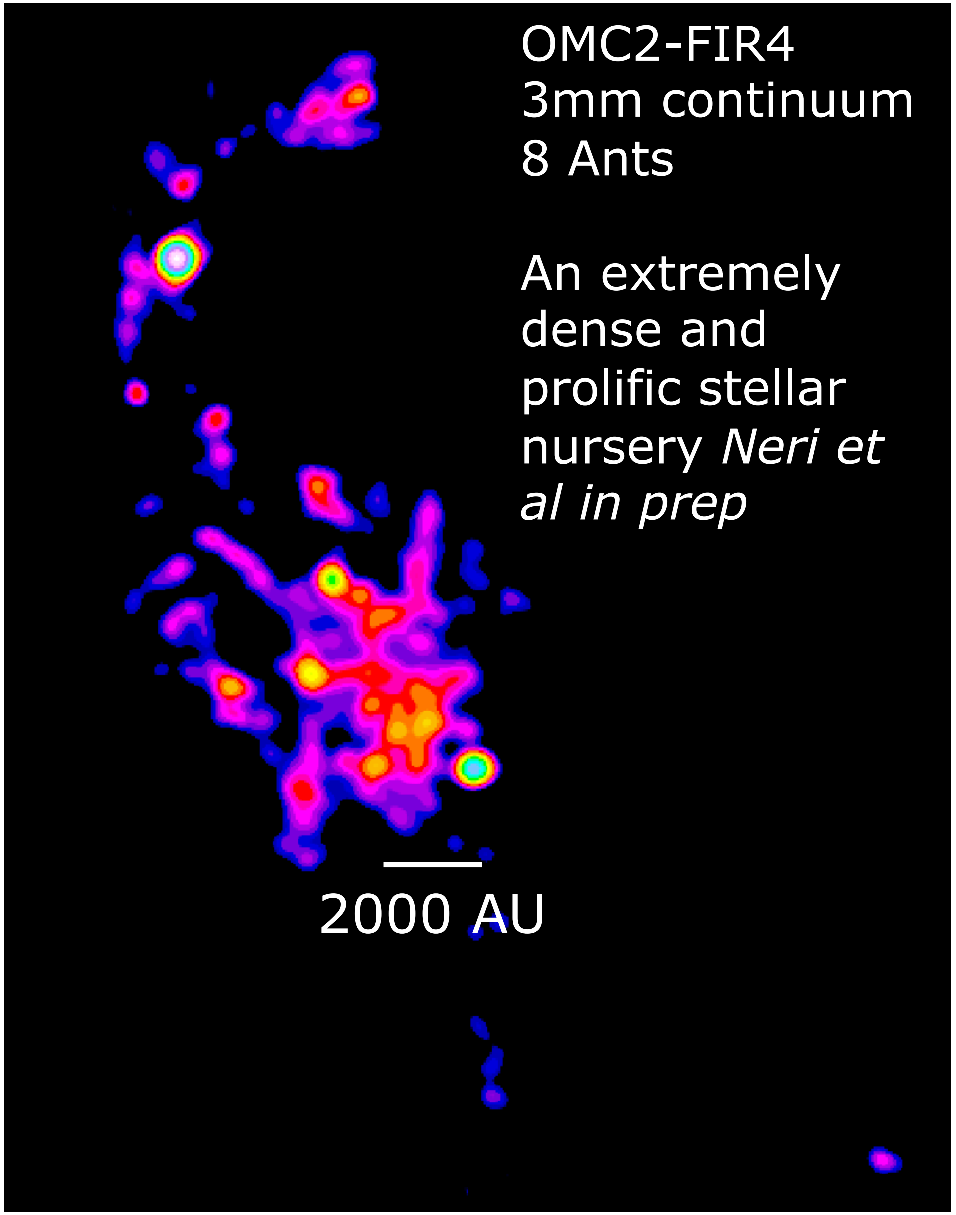


- EMIR LP
- small survey of pre- and proto-stellar objects ~ $1M_\odot$
- NH_2CHO vs HNCO
- hydrogenation of HNCO?
- prebiotic chemistry

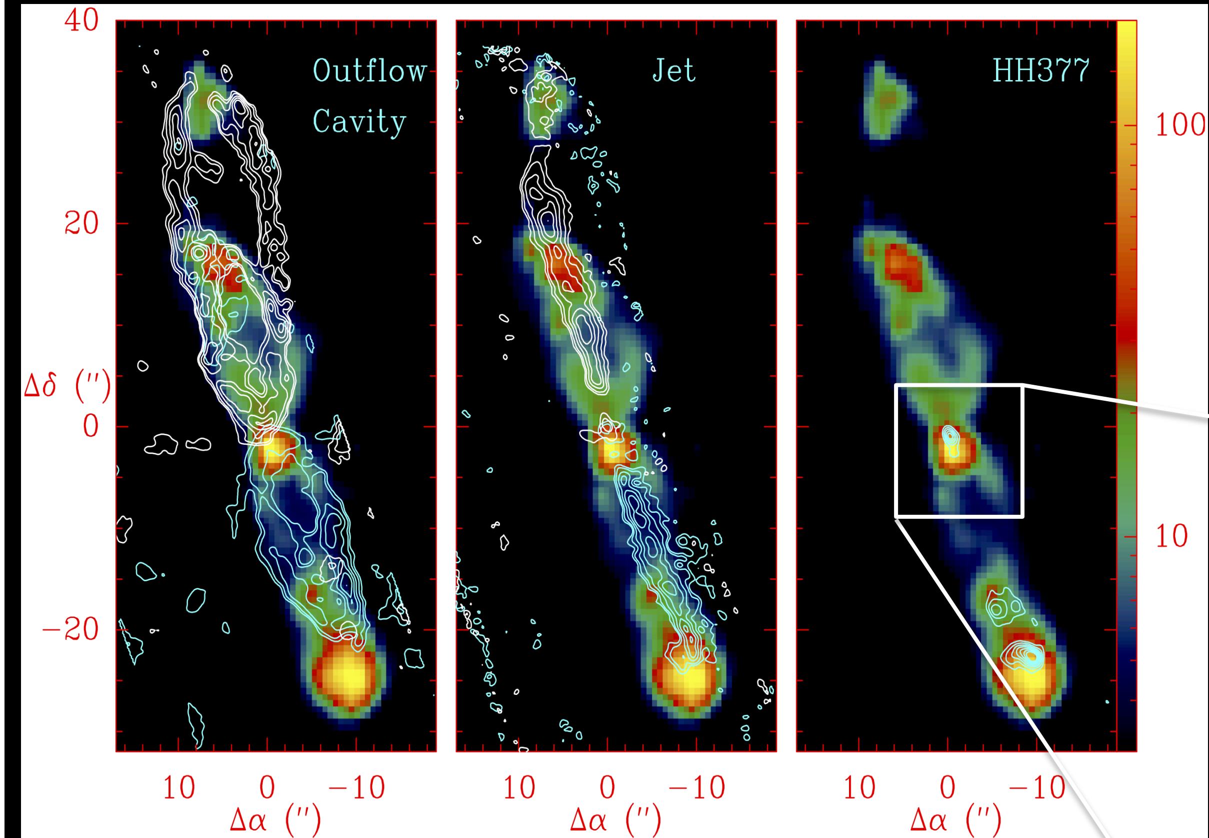
Lopez-Sepulcre ea 2015

A disk around a Herbig AeBe star, 2mm continuum, 8 Ants, *Fuente et al 2017*

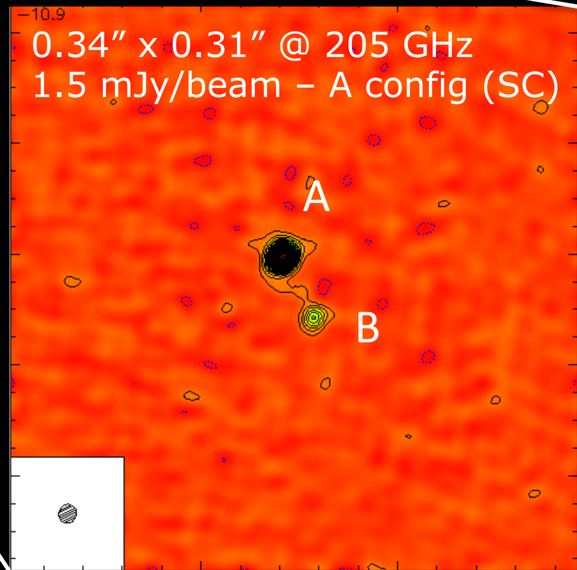




protostellar outflow Cepheus E

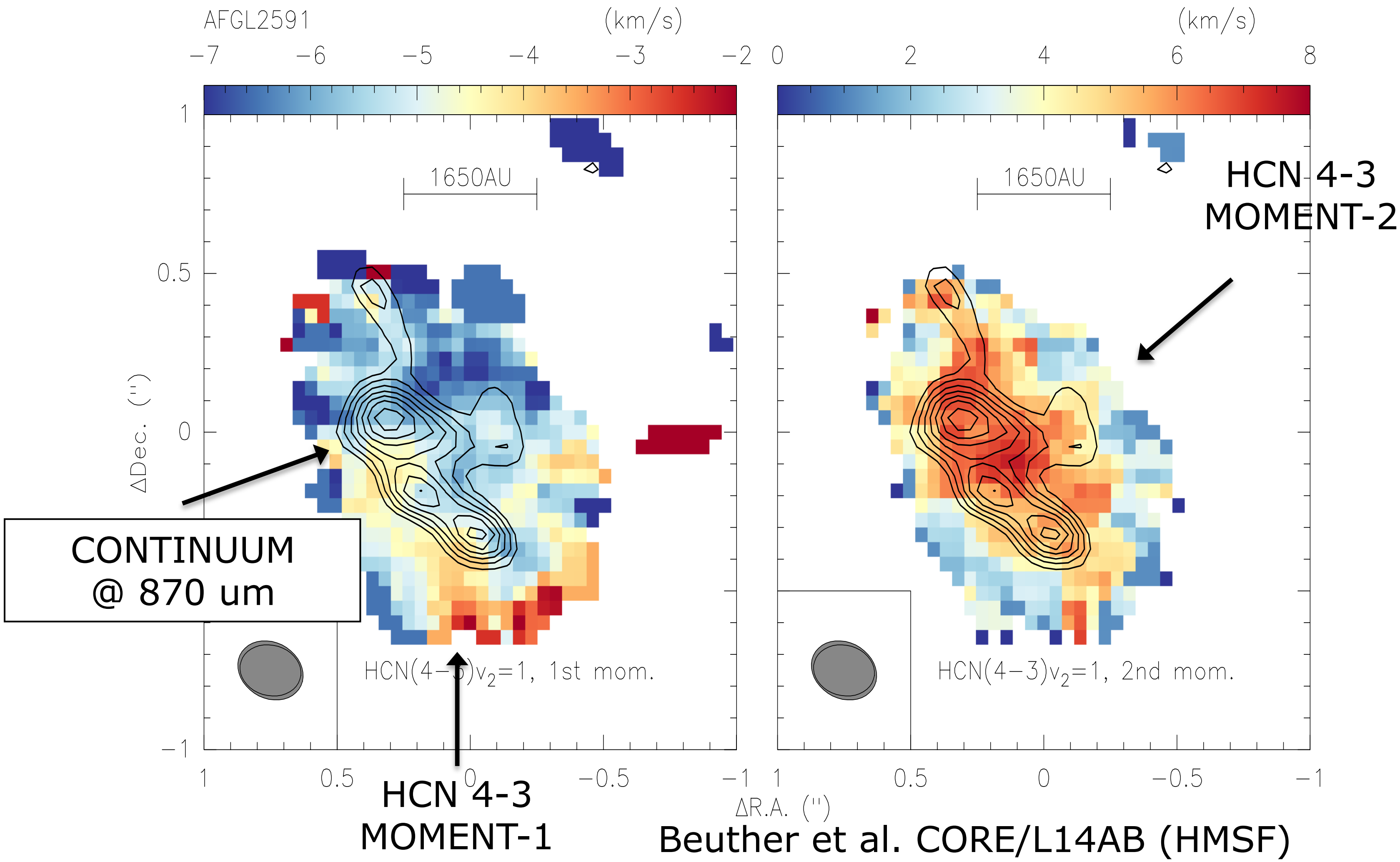


- Herschel, SOFIA, NOEMA, 30m = CO J=1-0 … J=16-15
- origin of the mass-loss?
- jet, cavity, bow-shock
- magnetized shock drives the formation of the outflow cavity
  - 20-30 km/s, ~500 yr old
- Lefloch et al. 2015



IRAC/Spitzer 24 um (color)
NOEMA CO 2-1 (contours)

star formation in afgl2591

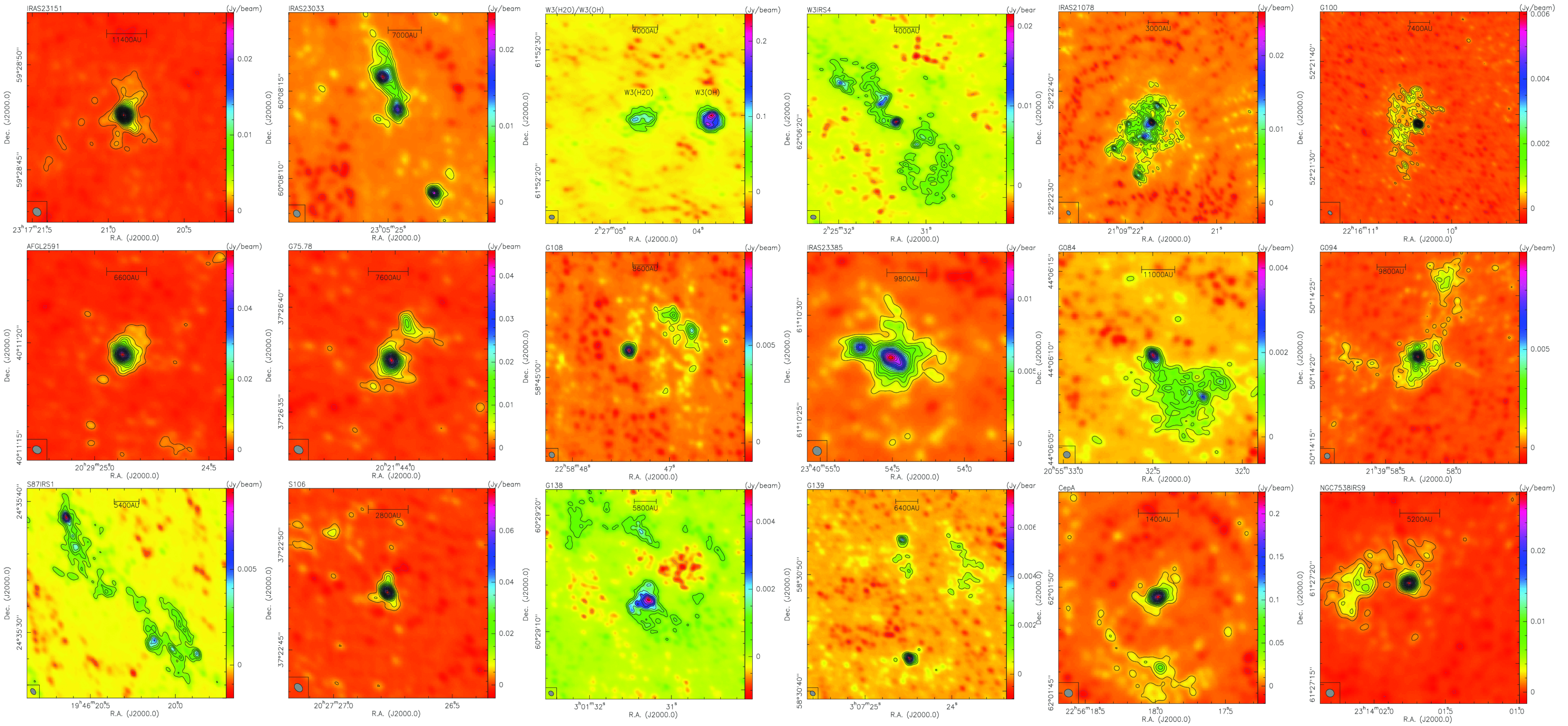


Beuther et al. CORE/L14AB (HMSF)

CORE: High-mass star formation – Beuther et al.

ABD configuration @ 220 GHz

1.3mm continuum data, ~0.4” resolution

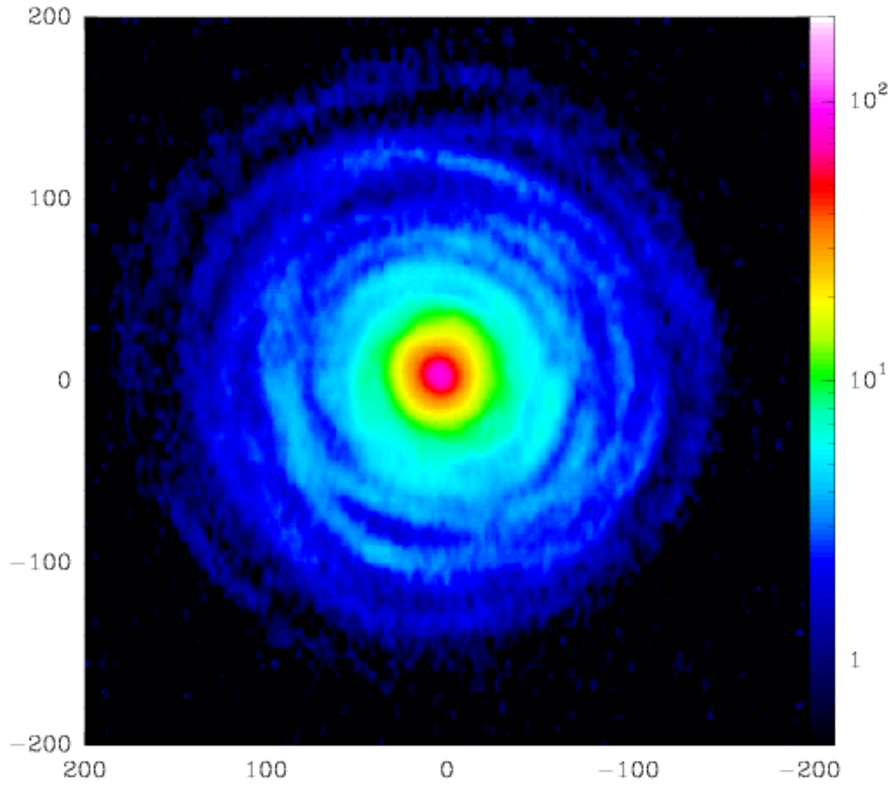


Galactic star formation:
Key questions

- Origin of the stellar initial mass function (IMF)?
- How is it related to the mass function of the cloud cores (CMF)?
- Generation of the prestellar cores & initiation of protostellar collapse
- Is there a threshold for star formation?
- Clustered vs. isolated mode of star formation
- Triggered vs spontaneous star formation
- A galaxy scale predictive model of star formation is still lacking
- Factors controlling the star formation efficiency (SFE) in GMCs ? Variation of SFE and the SFR as a function of the galactocentric distance, ISRF, metallicity etc.

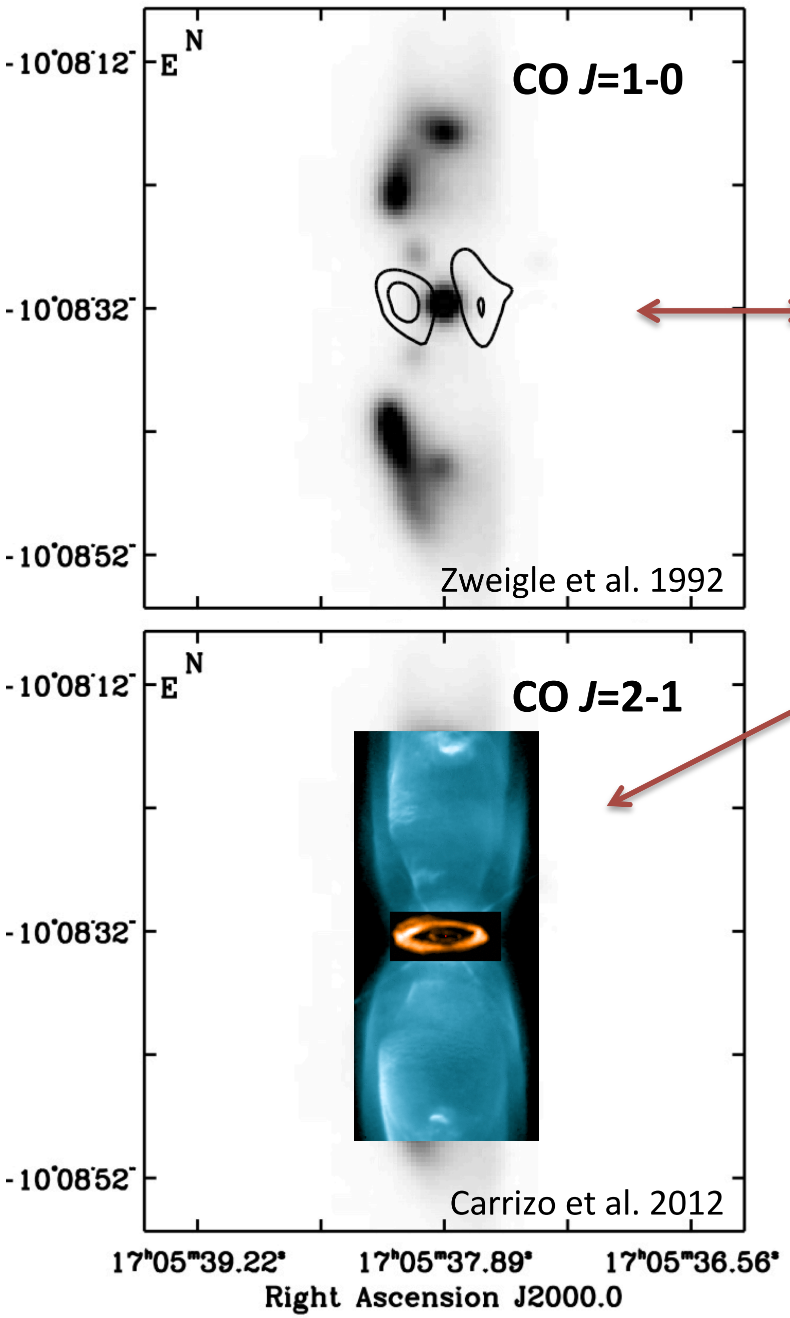
Recycling of gas and dust

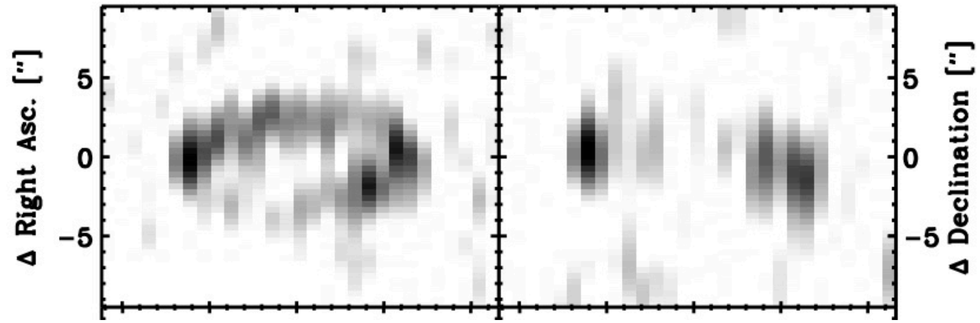
Mass-loss of massive stars during the last stages of stellar evolution. Example: IRC+10216

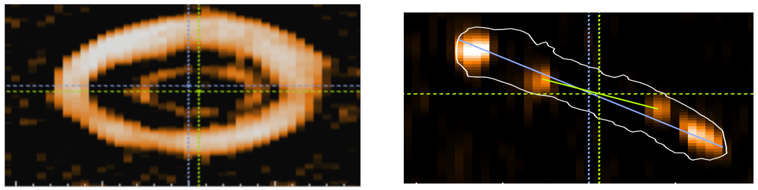


Expelled circular dust shell during the last 8000 years. Optical image.
Expansion velocity ~15 km/s,
One expulsion every ~800 years

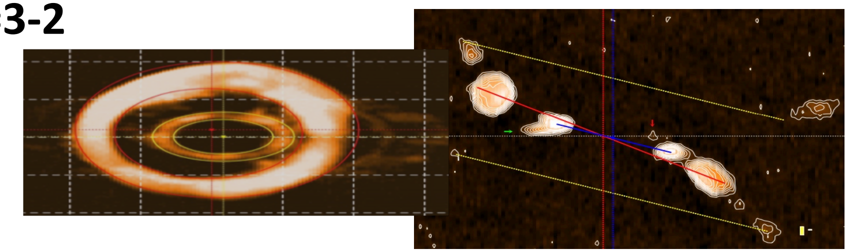
Expulsion of CO shells
Cernicharo et al. 2014







CO J=3-2

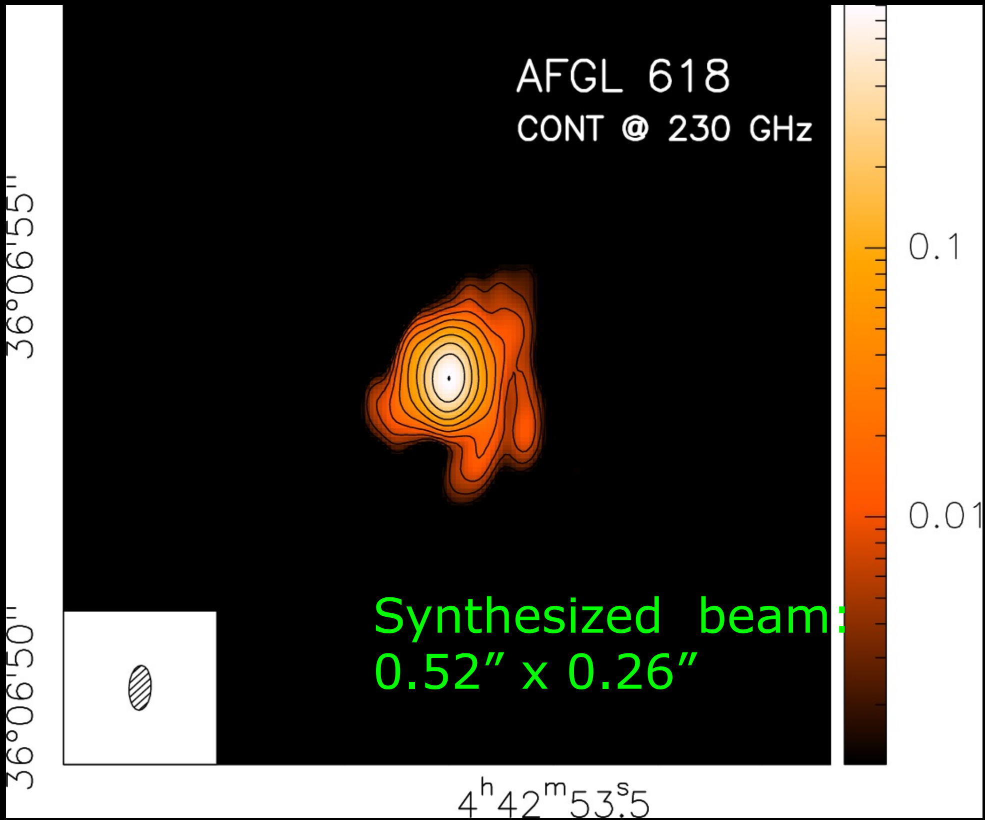


Carrizo et al. 2017

Young Planetary Nebula Minkowski 2-9

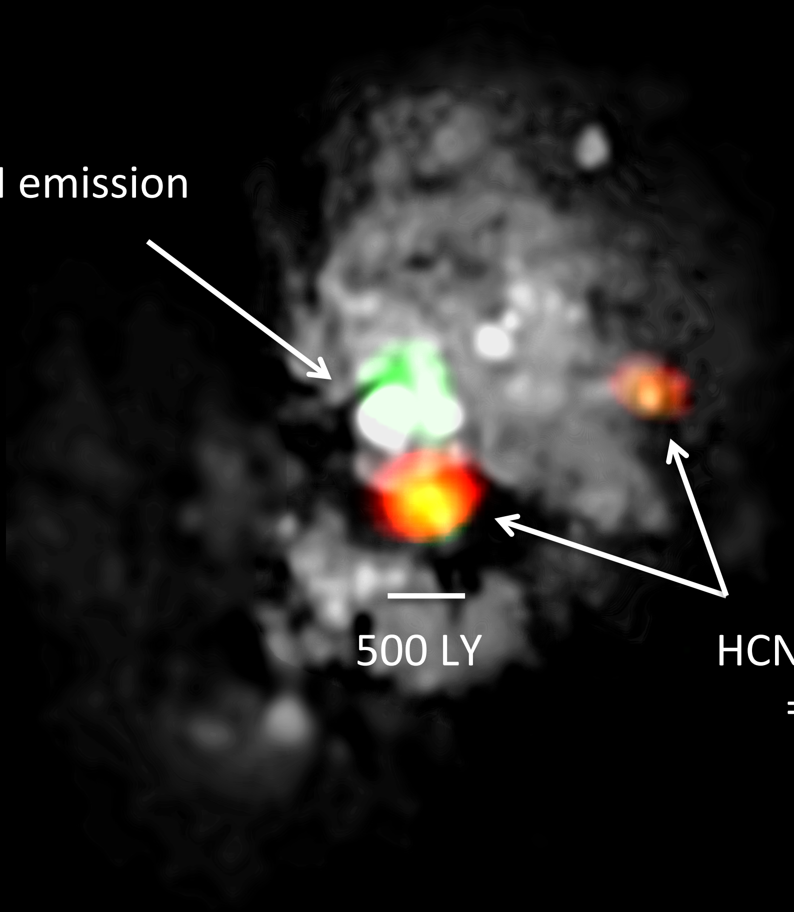
Two diverging equatorial ring-like outflows in the waist of the **Butterfly Nebula** to probe its central binary system

High dynamic range imaging (NOEMA)



- self-calibrated continuum map @ 1mm
- dynamic range 1000:1

Extreme star formation region in the 'Eye of Medusa'

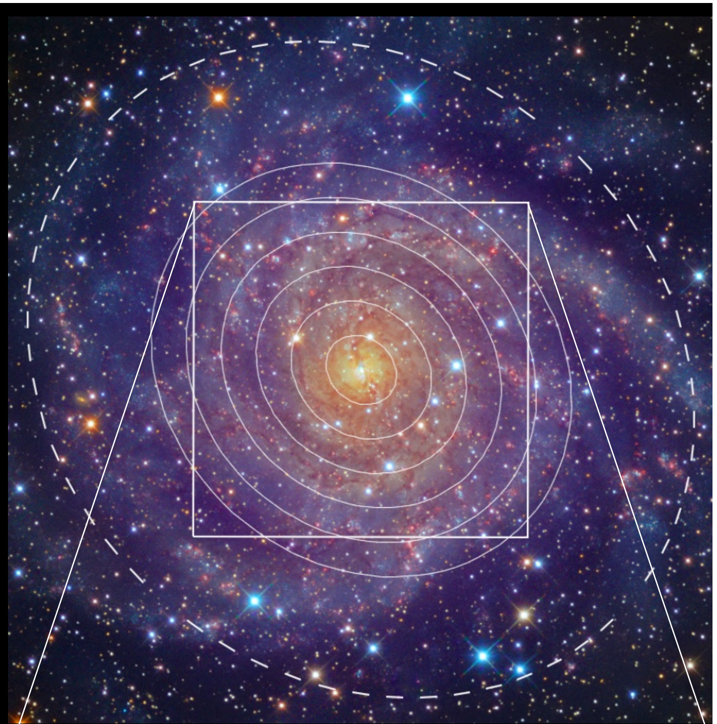


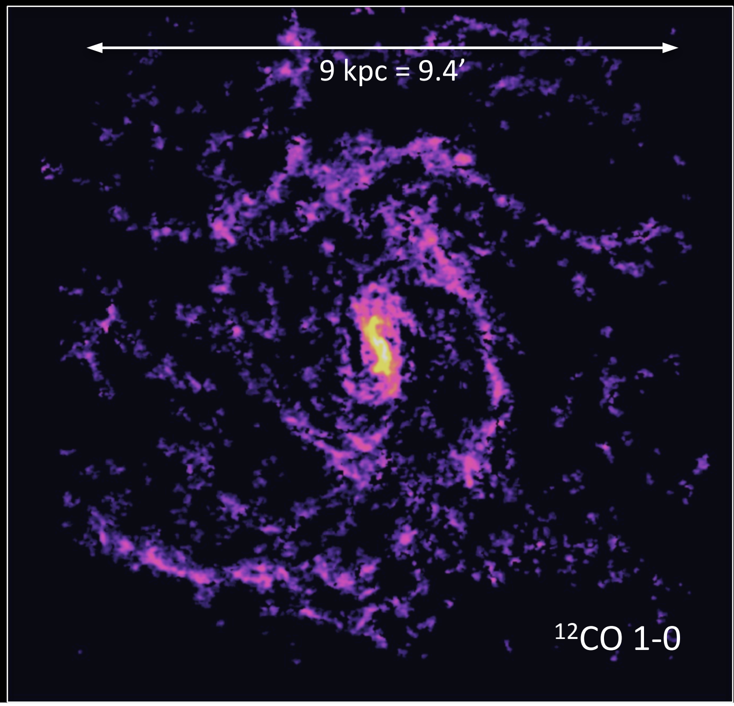
- high density tracers = HCN, HCO^+
- Eye is not detected in ^{12}CO!
  - low CO/HCN (1–0) luminosity ratio
  - SFE is similar to other regions
  - SF or feedback of SF regions?

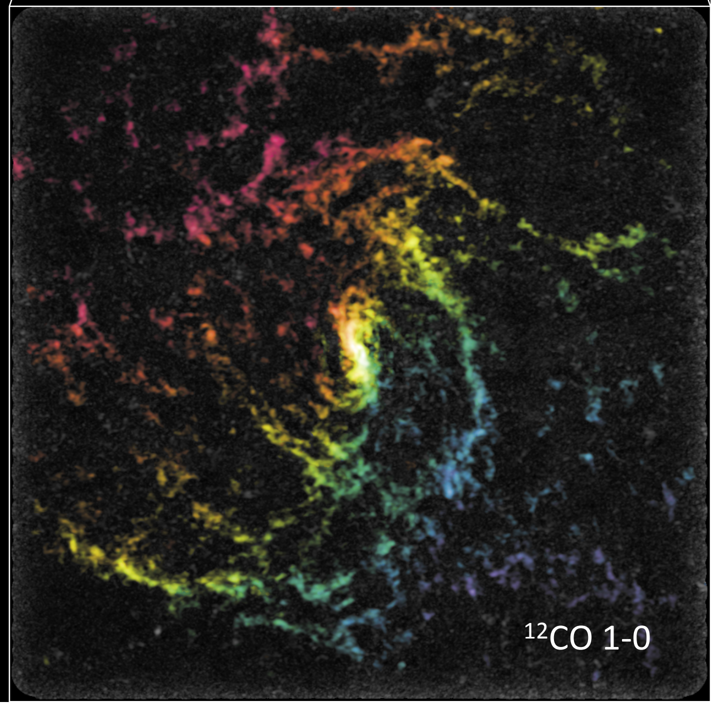
Koenig et al 2018

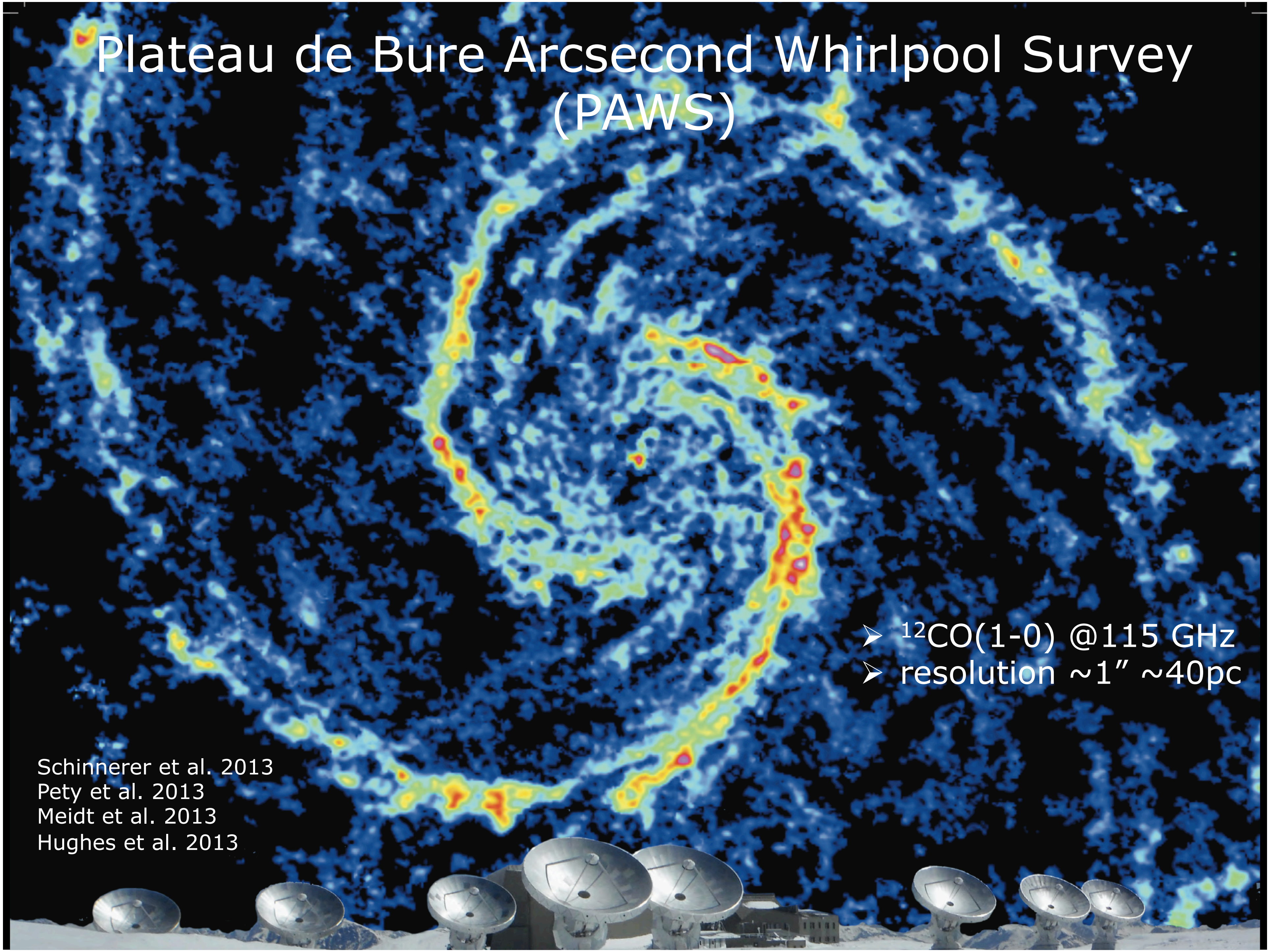
Molecular clouds in IC342
PI A.Schruba (MPE)

- D = 3.3 Mpc, M(gas) = 10^{10} $M_{\odot}$, SFR = 1.9 $M_{\odot}$/yr
- NOEMA + IRAM 30m cover 70% of the SF disk
- NOEMA = 1250-field mosaic, 60 pc resolution = 3.8"
- 1500 molecular clouds with S/N > 5





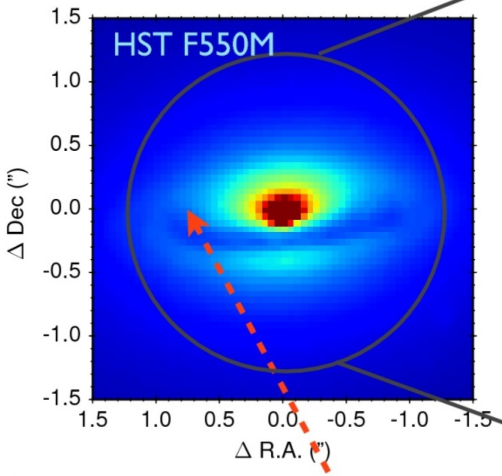


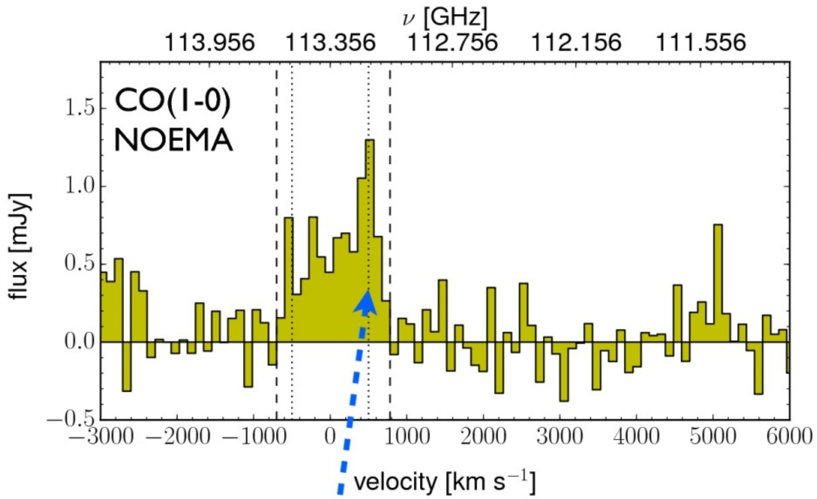

Plateau de Bure Arcsecond Whirlpool Survey
(PAWS)
➢ $^{12}CO(1\text{-}0)$ @115 GHz
➢ resolution ~1″ ~40pc
Schinnerer et al. 2013
Pety et al. 2013
Meidt et al. 2013
Hughes et al. 2013

CO-kinematic mass estimate for the over-massive black hole in NGC 1277

possibly ~100 times the typical M_{BH}/M_{bulge}!

(Scharwächter, Combes, Salomé, Sun & Krips, 2015, arXiv:1507.02292)

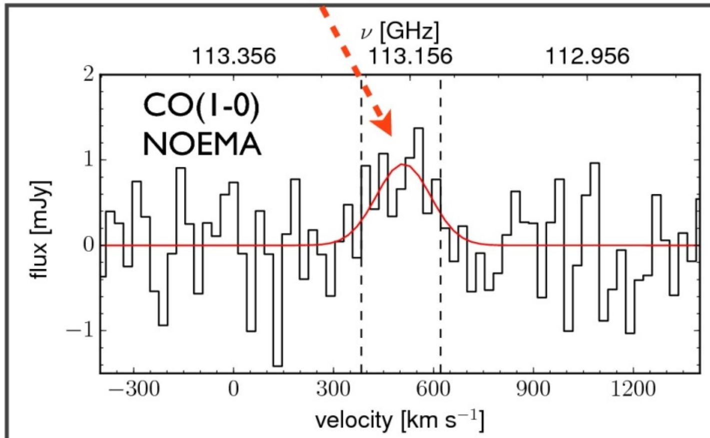




2.5" resolution

➡ CO in the dust lane

➡ rotational velocities of ~500 km/s



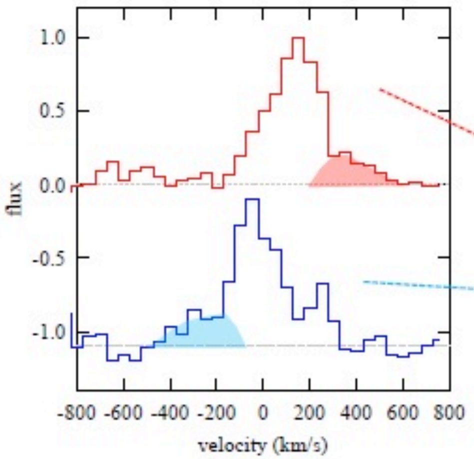
1" resolution

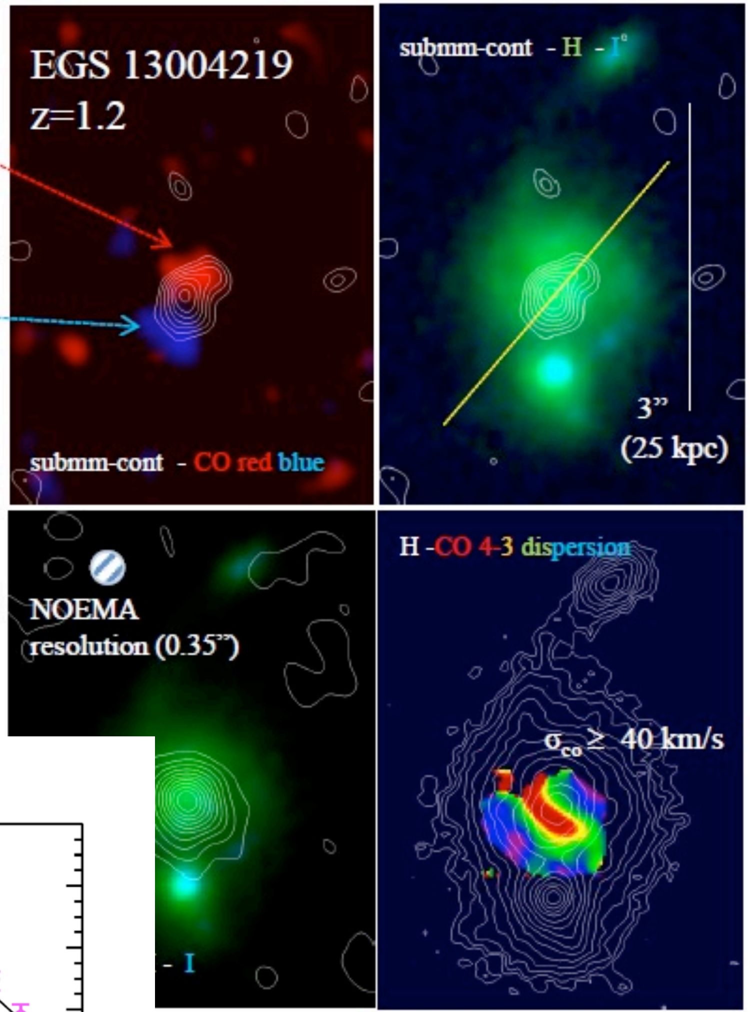
➡ +500 km/s peak probably from gas close to the eastern orbital node of the dust lane

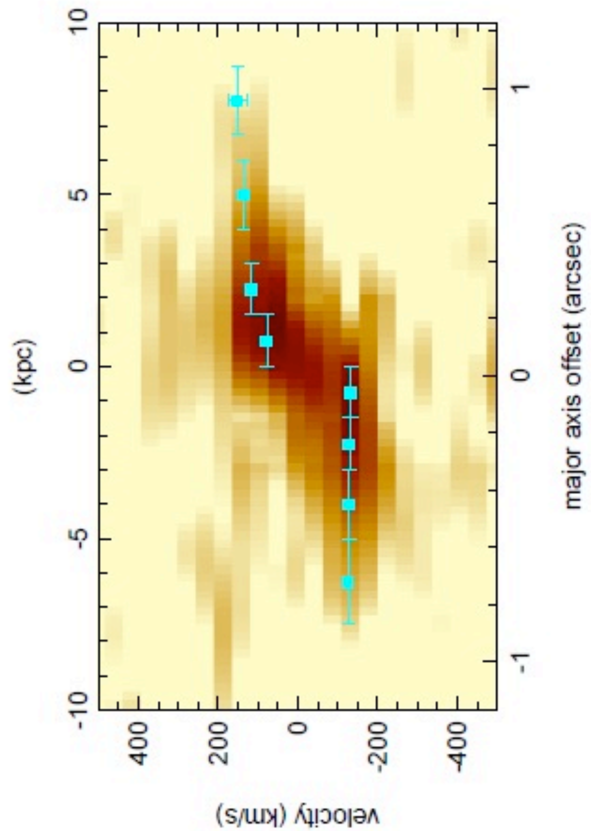
IRAM NOEMA results:

- CO data favour over-massive BH (consistent with stellar-kinematic mass by van den Bosch et al. 2012; Yıldırım et al. 2015)
- Lower BH mass still possible if stellar M/L is high

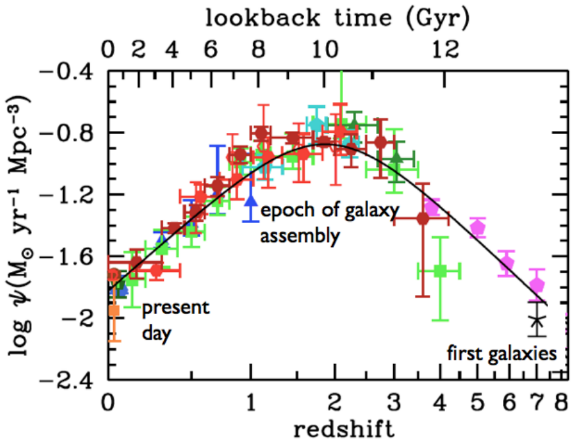
PHIBSS Cosmology Large Program 7/8 Ants







>1100 hr on-source time

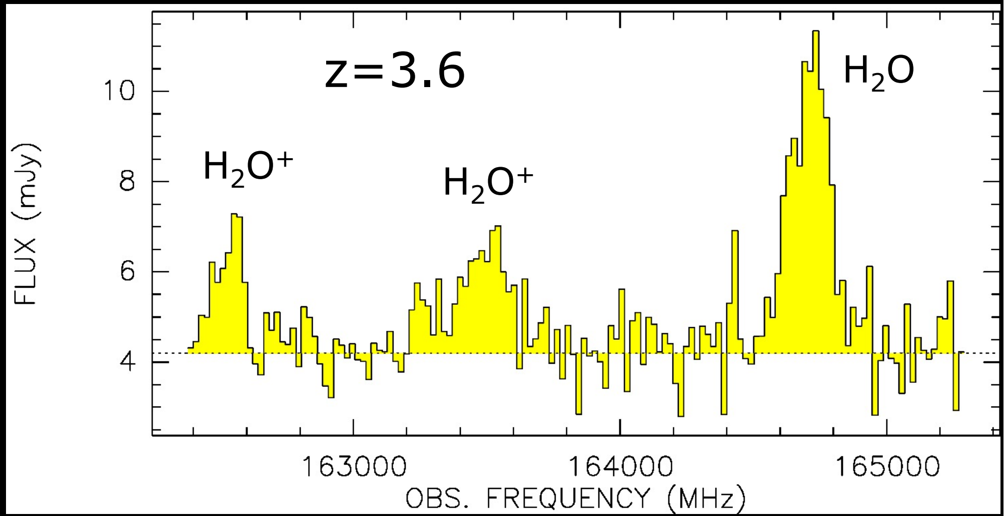


Tacconi, Combes, García-Burillo, Neri et al

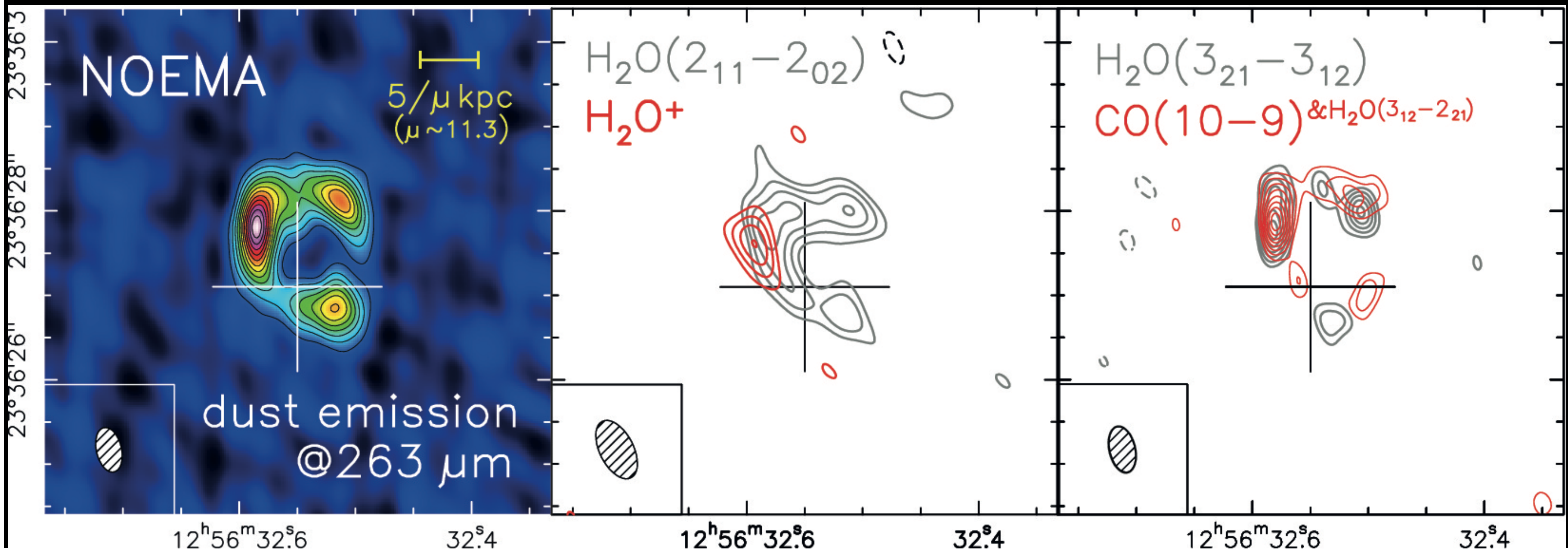
Spatial Distribution of H_2O Emission in a High-z Lensed Herschel Galaxy (NC.143)

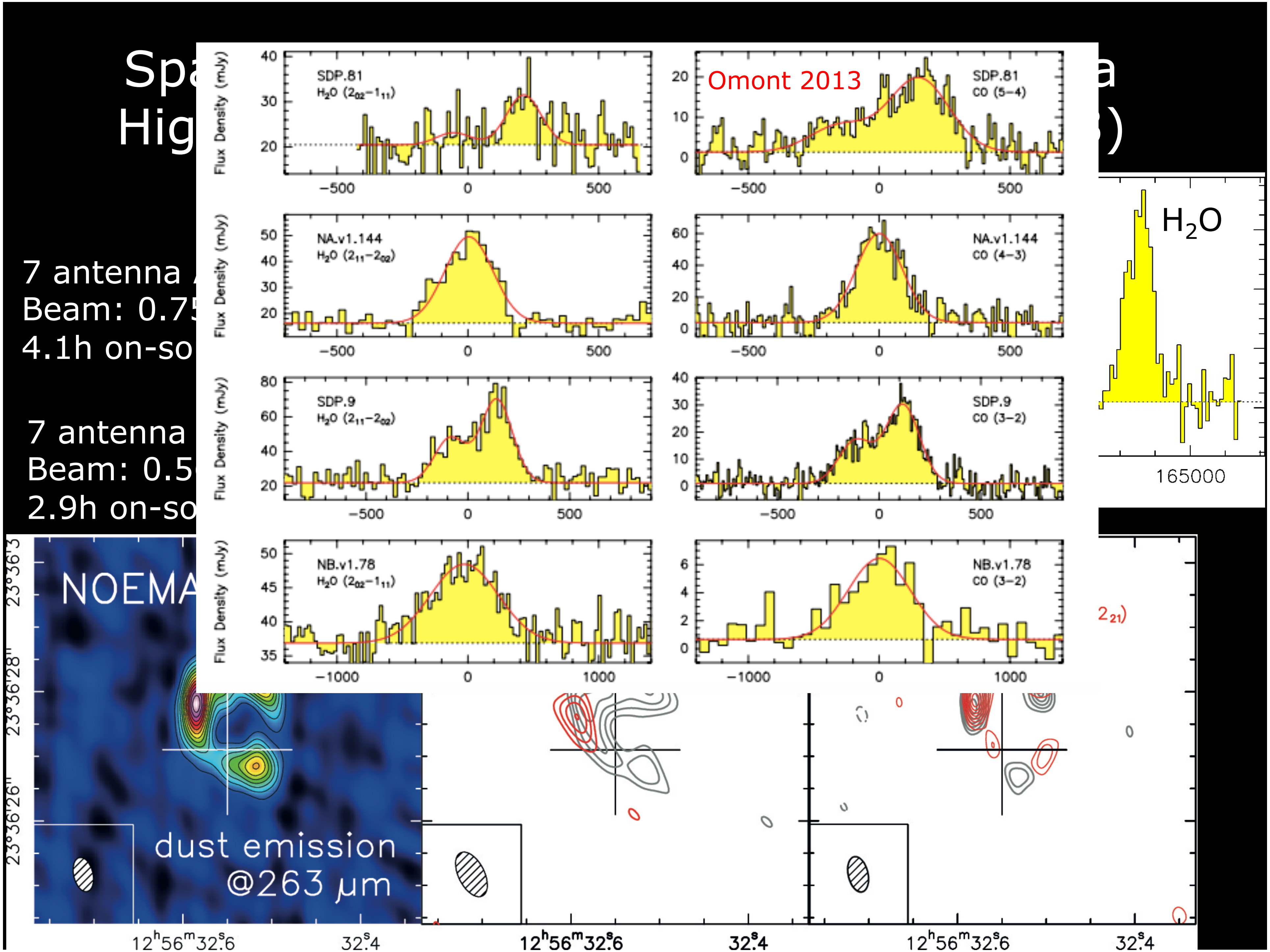
Chentao Yang et al. 2016

7 antenna AD configuration @ 2mm
Beam: 0.75" x 0.43" @ PA 30
4.1h on-source time



7 antenna A configuration @ 1mm
Beam: 0.56" x 0.32" @ PA 14
2.9h on-source time, selfcalibrated





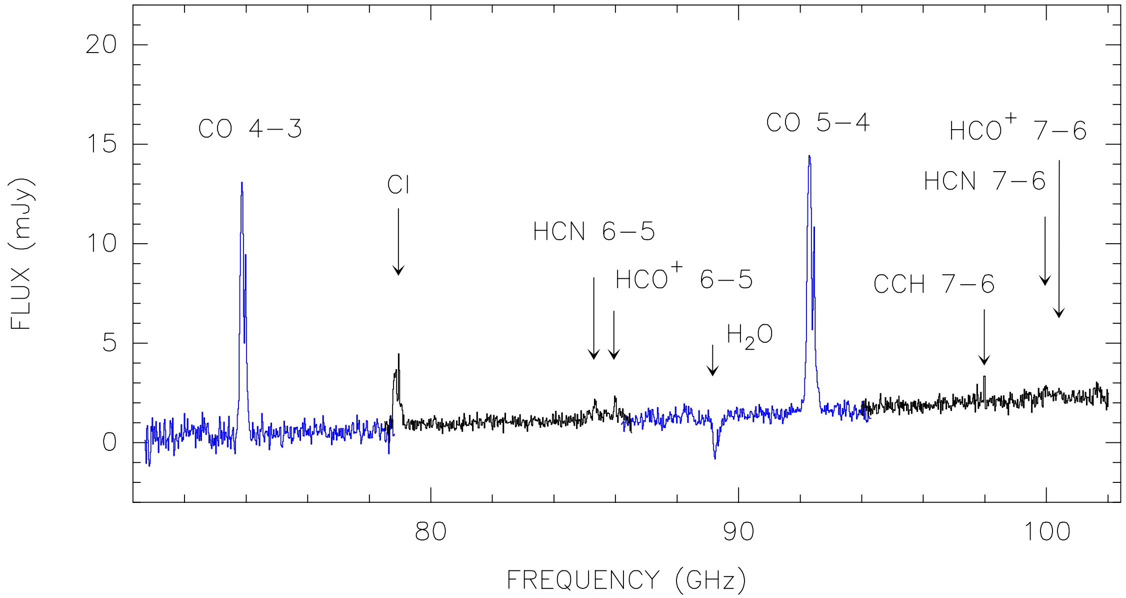
Spa
a
Hig
3)
7 antenna
Beam: 0.75
4.1h on-so
7 antenna
Beam: 0.5
2.9h on-so
Omont 2013
SDP.81
H2O (202−111)
SDP.81
CO (5−4)
NA.v1.144
H2O (211−202)
NA.v1.144
CO (4−3)
SDP.9
H2O (211−202)
SDP.9
CO (3−2)
NB.v1.78
H2O (202−111)
NB.v1.78
CO (3−2)
Flux Density (mJy)
H2O
165000
NOEMA
dust emission
@263 μm
12h56m32s.6
32s.4

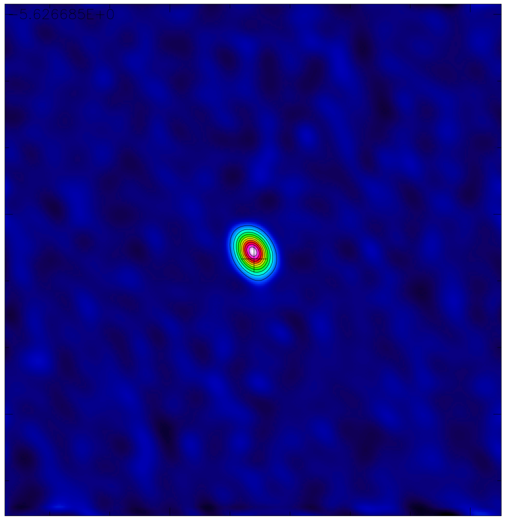
wide-band spectroscopy with PolyFiX

- 7.2 hr on-source with nine antennas, two frequency setups
- continuum detected with a dynamic range 200:1
- detection of several transitions allows to determine the redshift

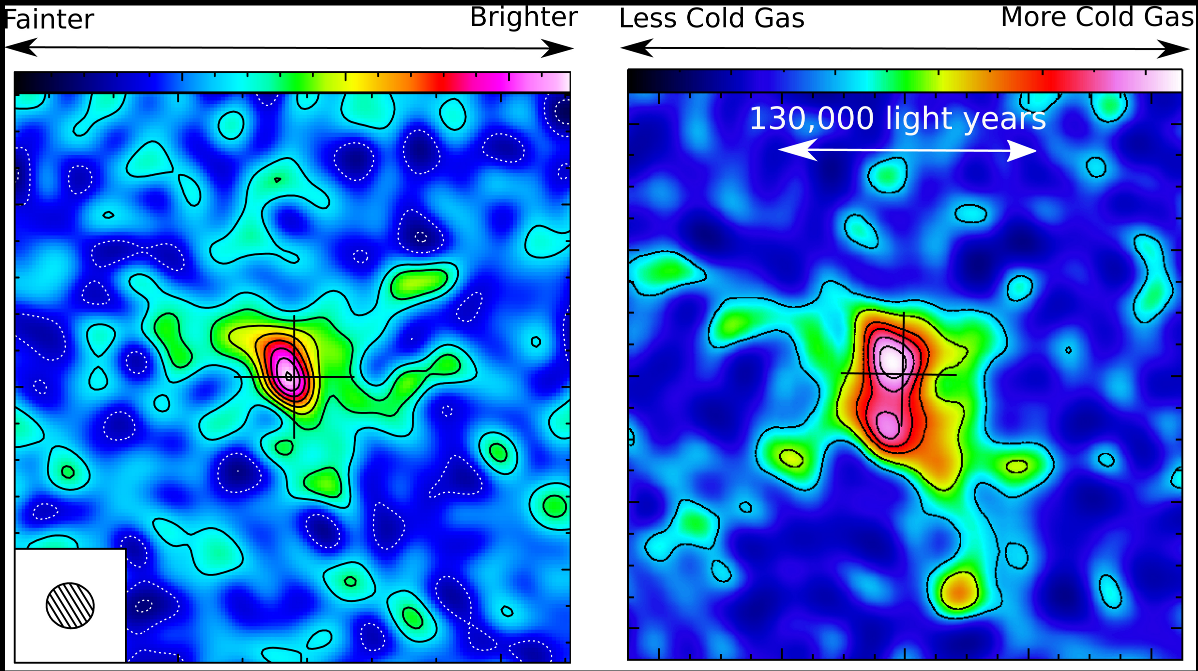
HLS J091828+5414223 (z = 5.2)

Herrera et al. in prep





Galactic hailstorm in the early Universe (J1148+5251 @ z=6.4)



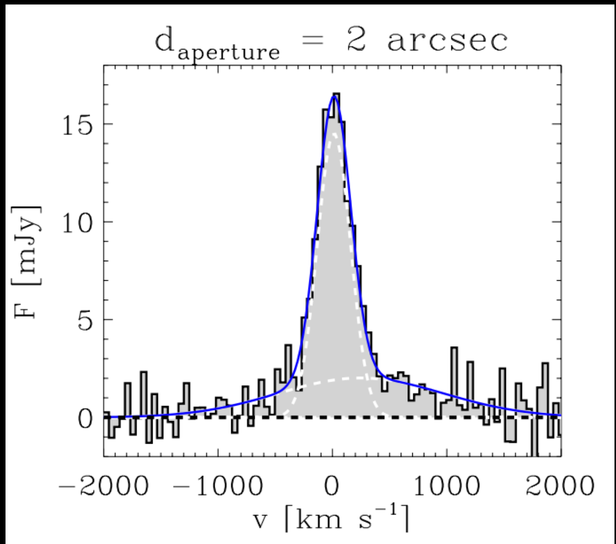
observations

simulations

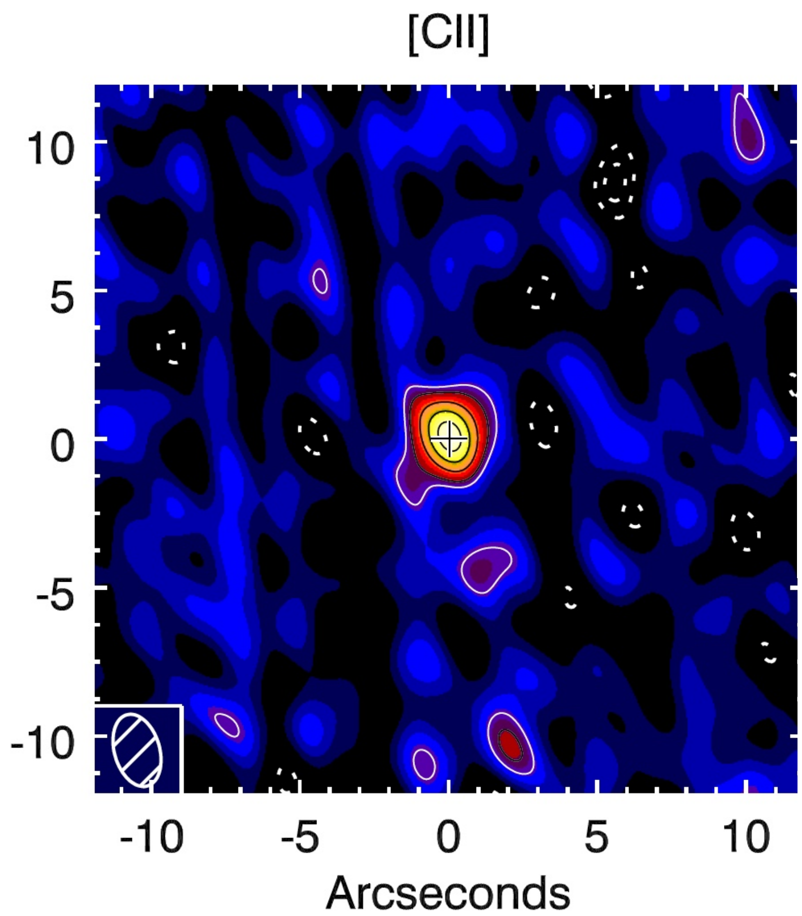
[CII] @ 256 GHz / NOEMA

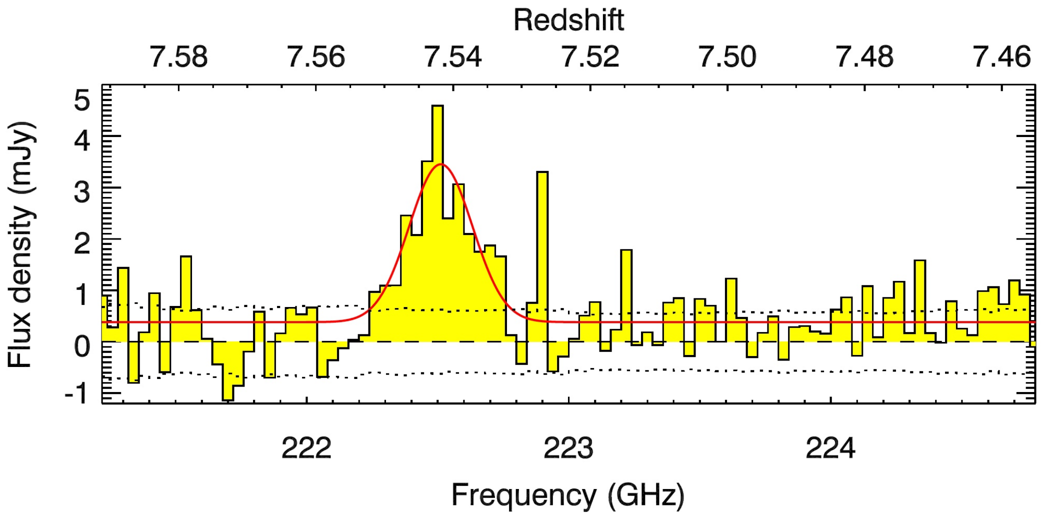
- CII @ 2000 km/s!
- 100 Myr old CII outflow
- CII up to 30 kpc

Cicone et al. 2015



The most distant quasar with confirmed redshift (z=7.54) 8 Ants





Venemans et al 2017

- ~10% younger than J1120+0641
- dust ~10^8 $M_{\odot}$, [CII] ~ 10^7 $M_{\odot}$
- SFR ~ 300 $M_{\odot}$/yr

Thank you for your attention.