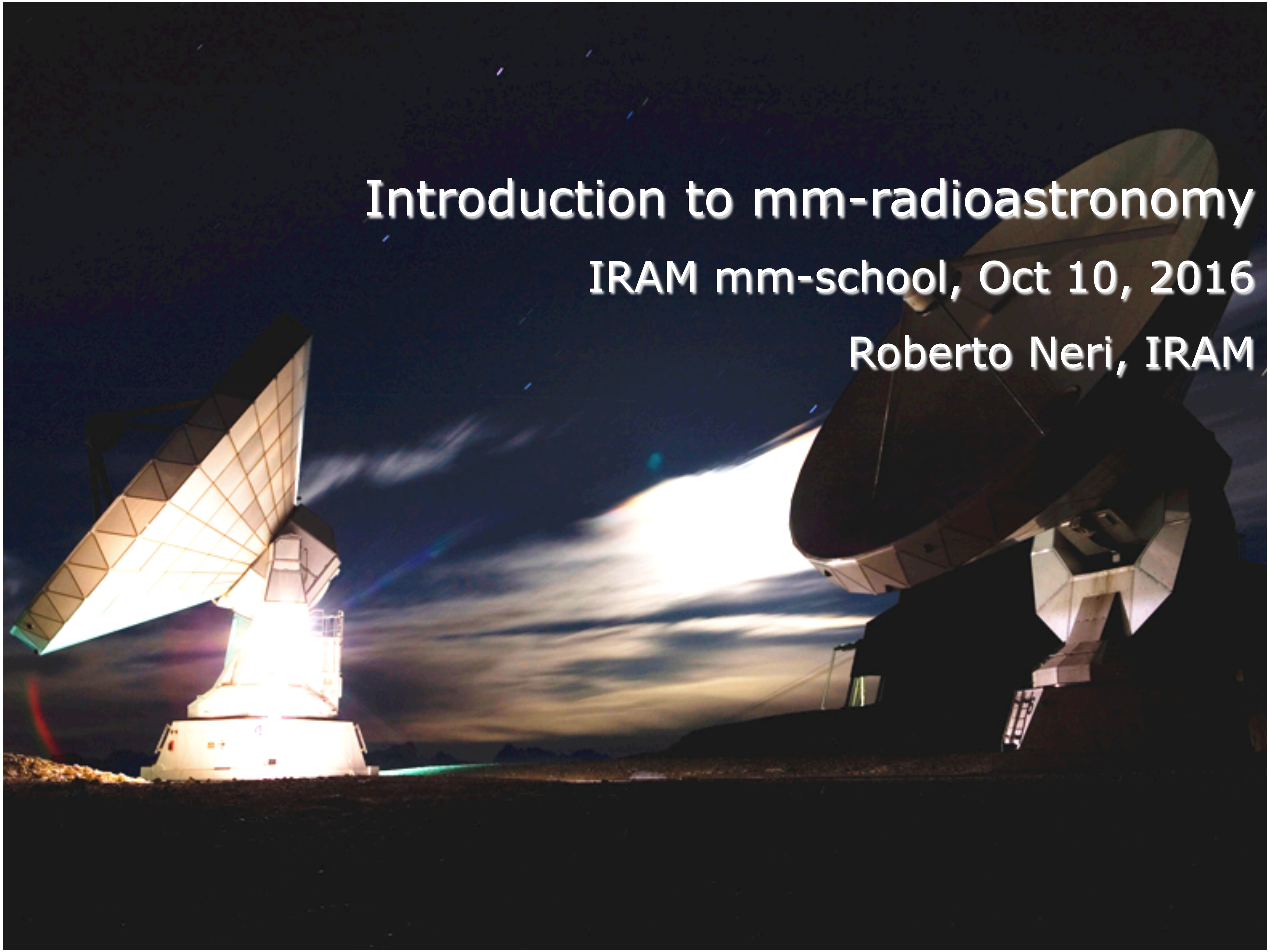
Introduction to mm-radioastronomy

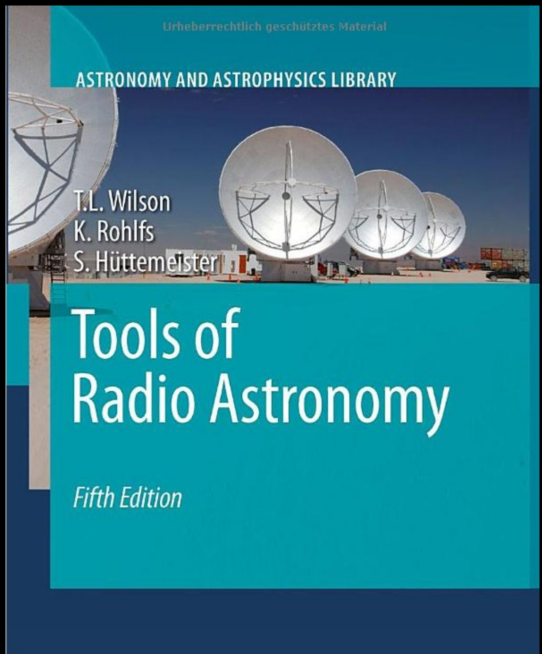
IRAM mm-school, Oct 10, 2016

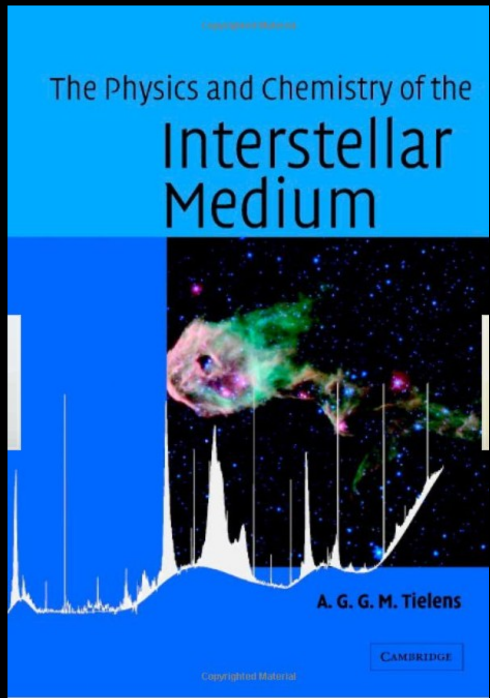
Roberto Neri, IRAM

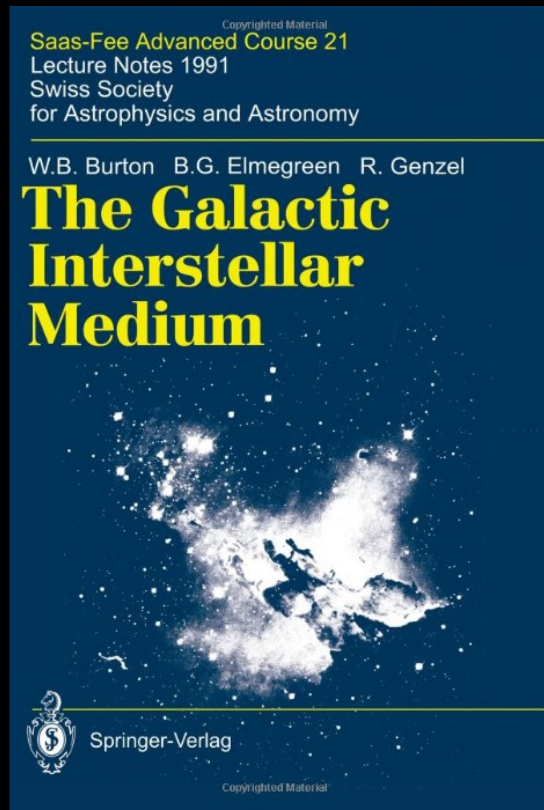


iram
Institut de
Radioastronomie
Millimétrique

Literature







4. Astrochemistry lecture series by Ewine van Dishoeck:

http://www.strw.leidenuniv.nl/~sanjose/astrochem

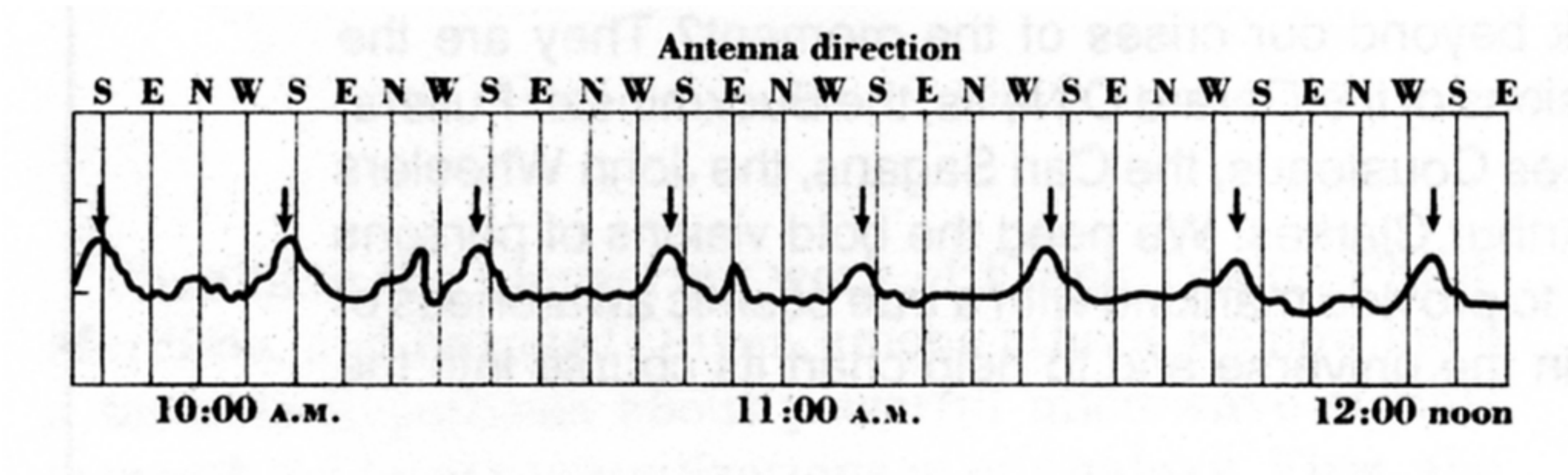
Historical Overview

- 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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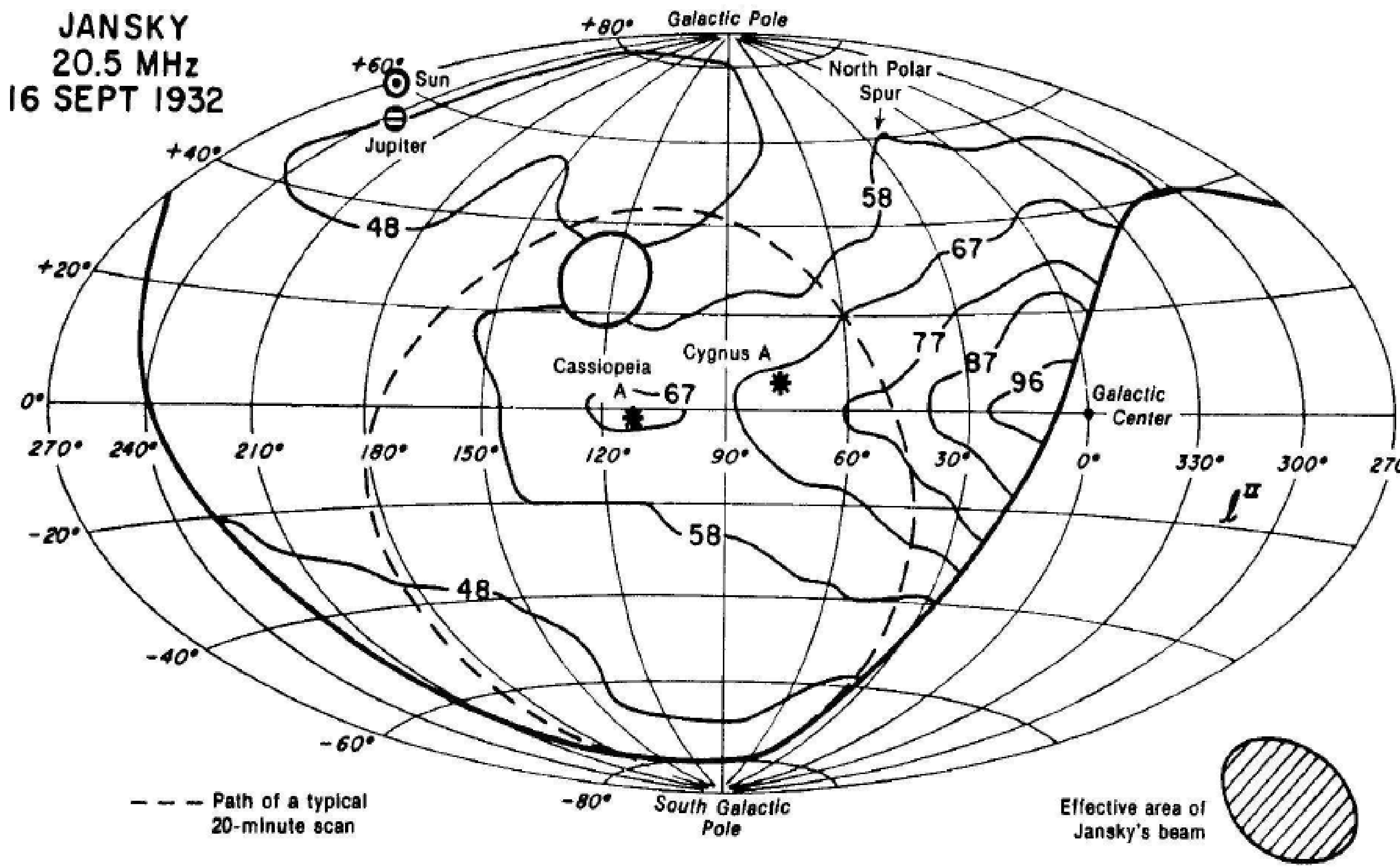
Historical Overview



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)

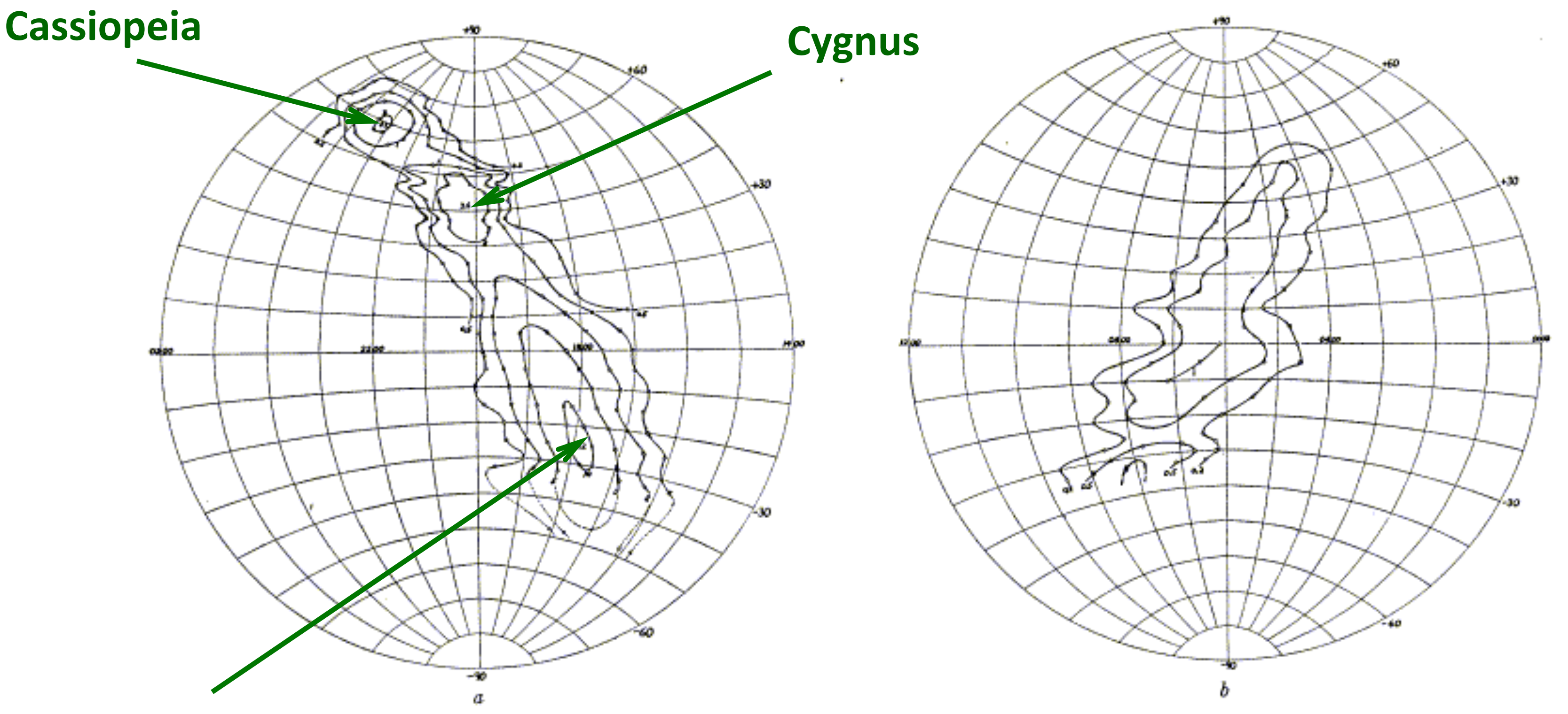


FIG. 4.—Constant intensity lines in terms of 10^{-22} watt/sq. cm./cir. deg./M.C. band

Historical Overview

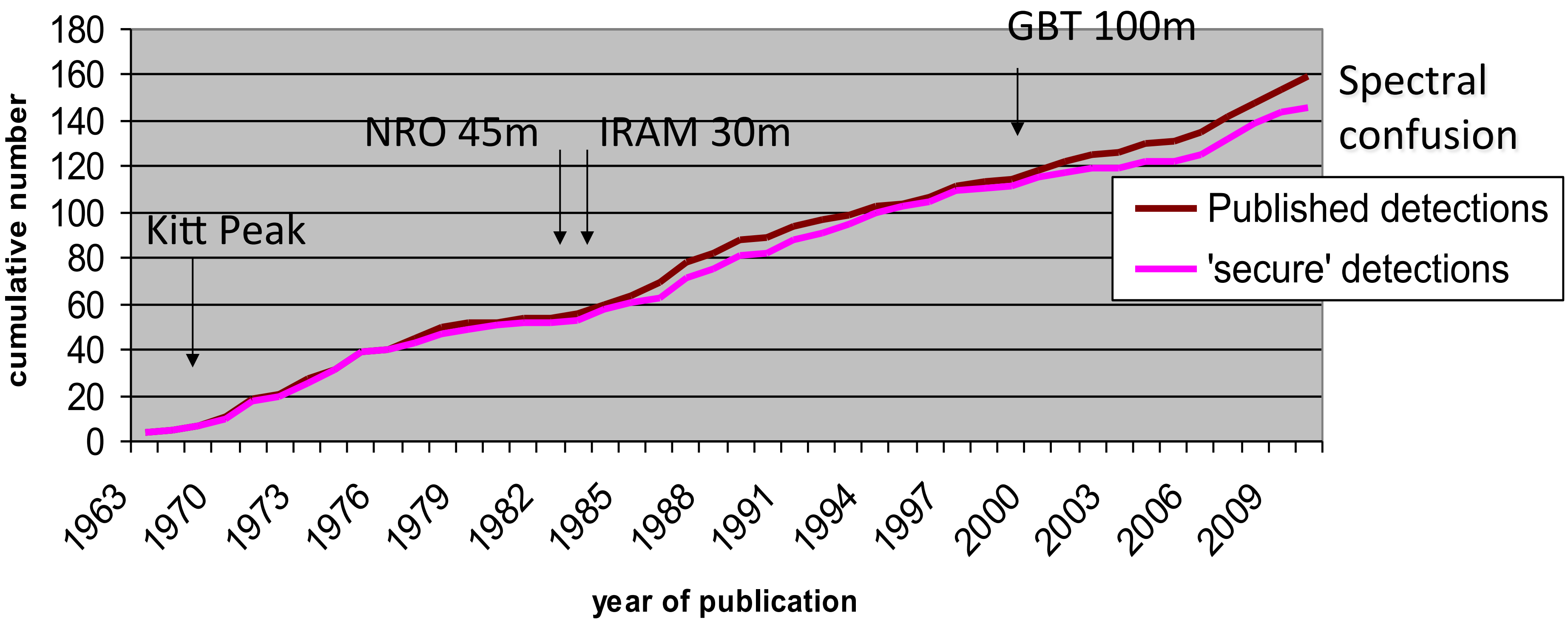
- G.Reber (1944, ApJ, 100, 279)
  - first parabolic radio dish @ 160 MHz (=1.8 m)
  - confirms Jansky's discovery
  - first radio survey - no detection @ 900 and 3300 MHz

- 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

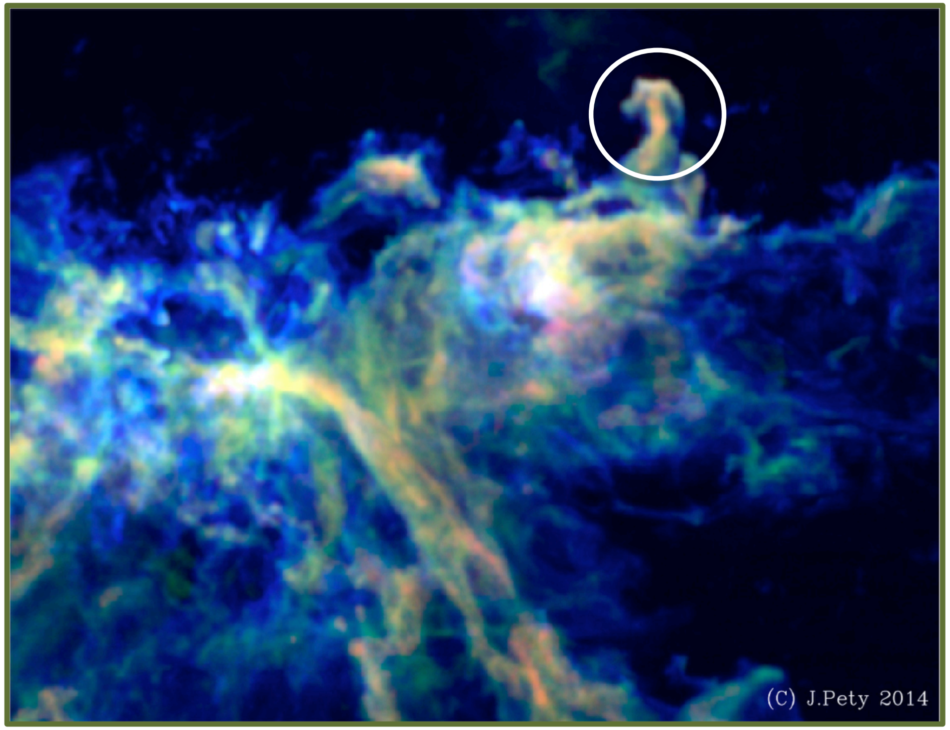
Historical Overview : detected molecules

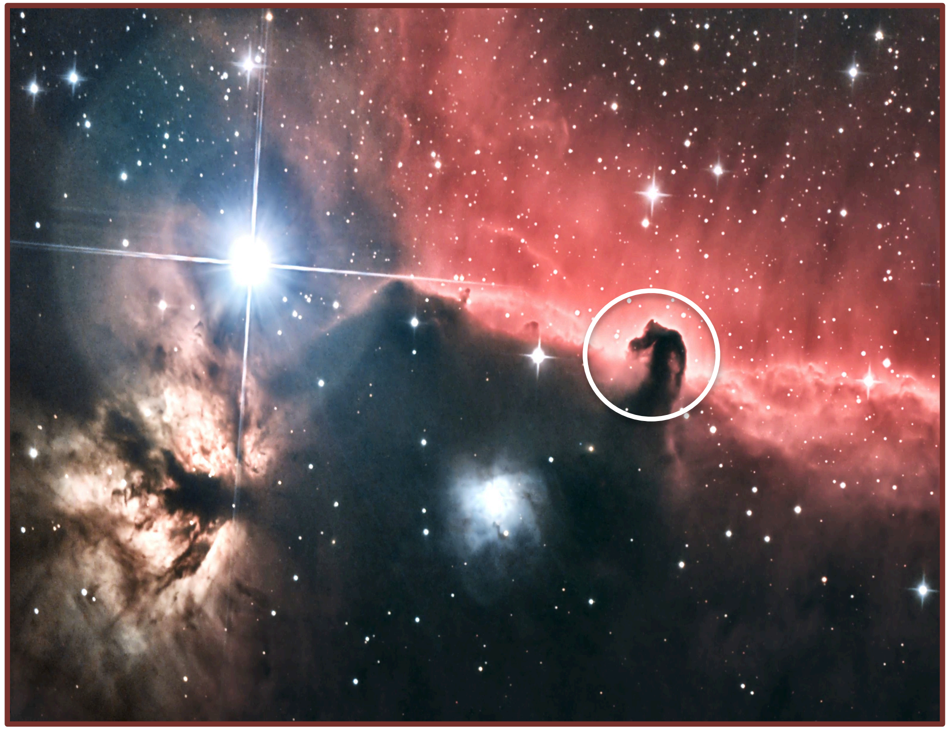


Guélin, priv.comm.

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)



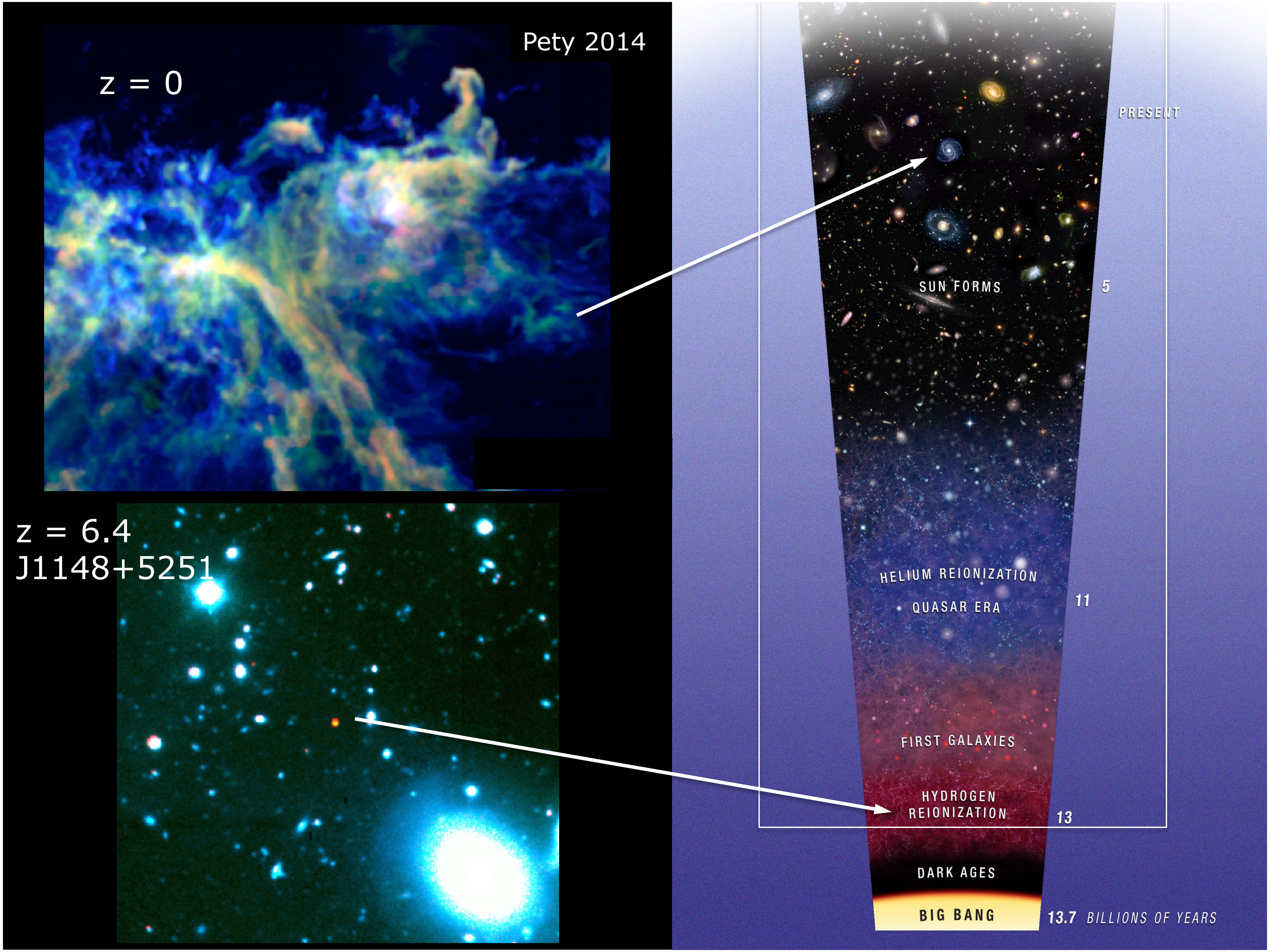


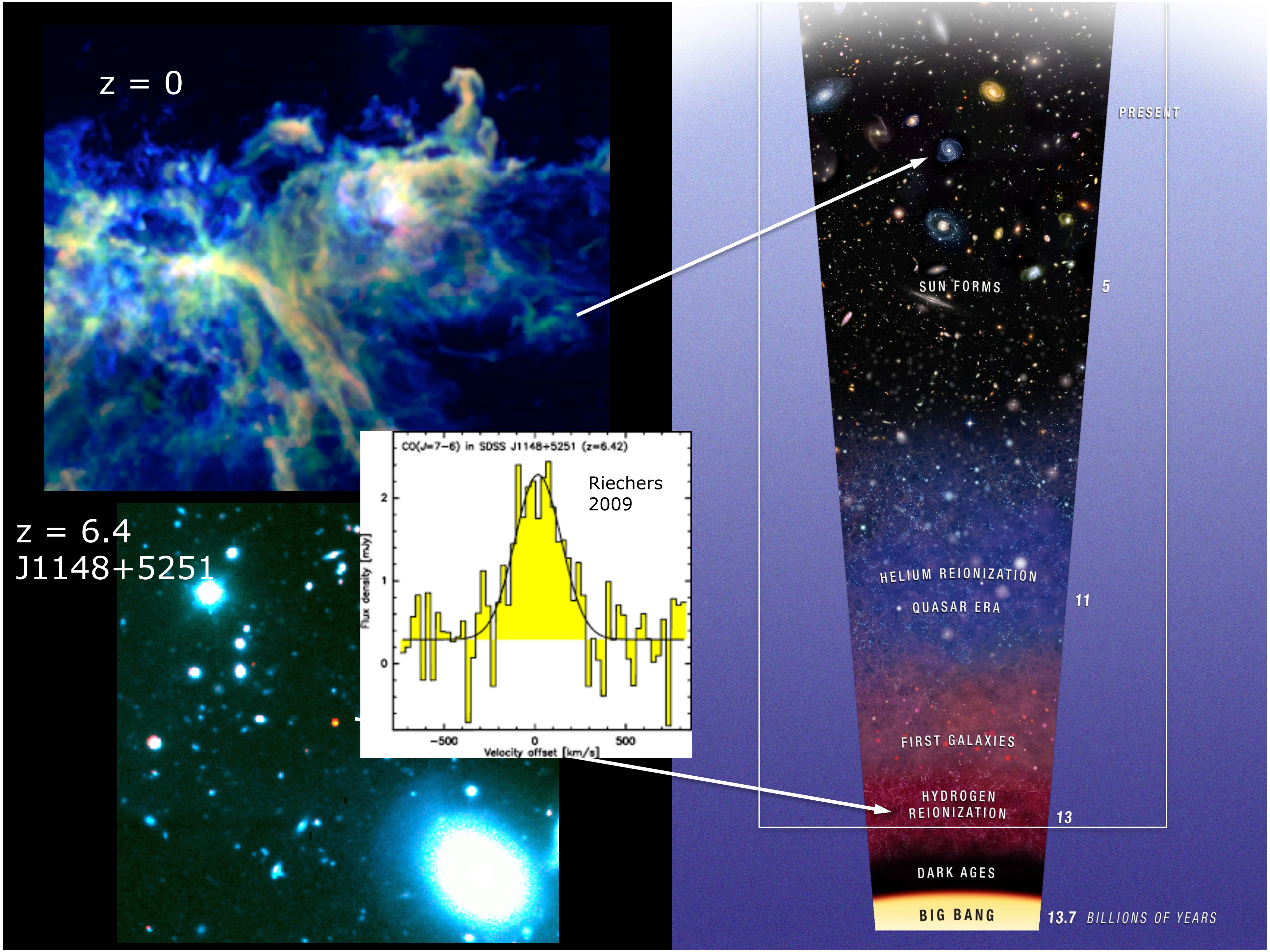
- visible = hot matter = stars/HII between 10^3 and 10^5 K
- millimeter = cold matter = dust/molecules between 10 and 100 K

⇨ stars are born in cold matter

$$h\nu = kT$$

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


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



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]
−500
0
500
0
1
2
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=6)

  ⇨ sensitivity and angular resolution

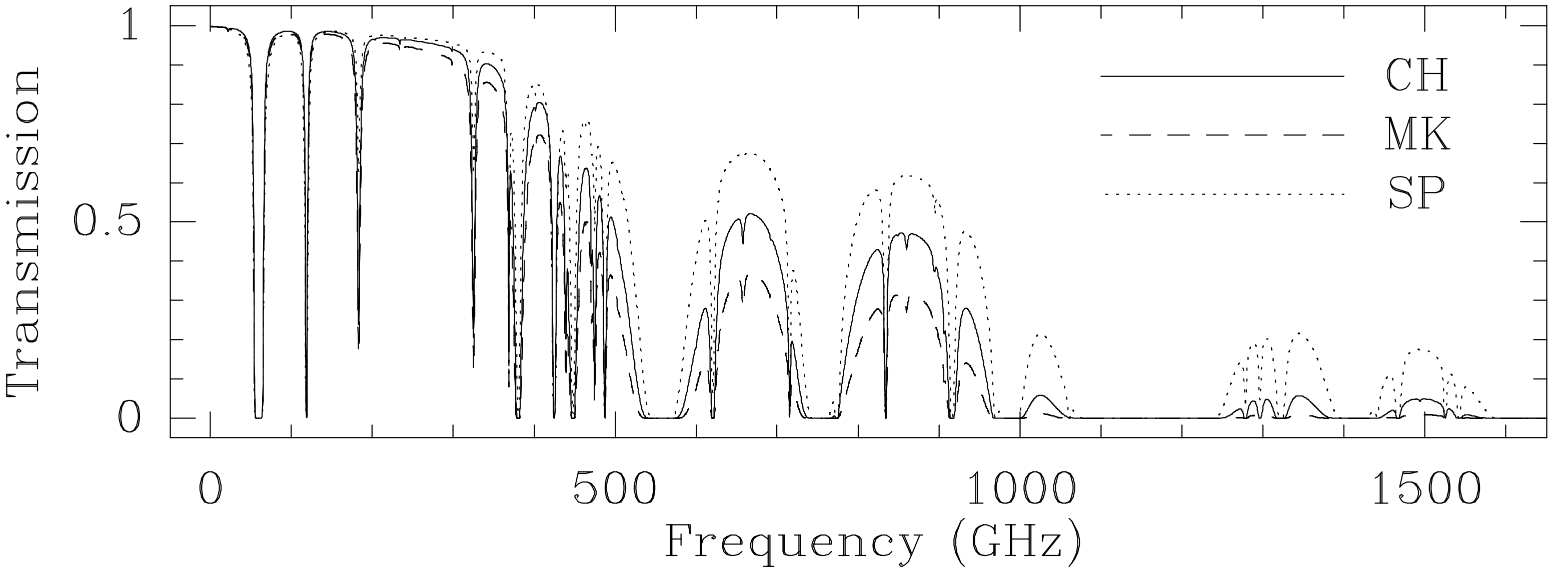
  ⇨ large telescopes e.g. ALMA, NOEMA/30m

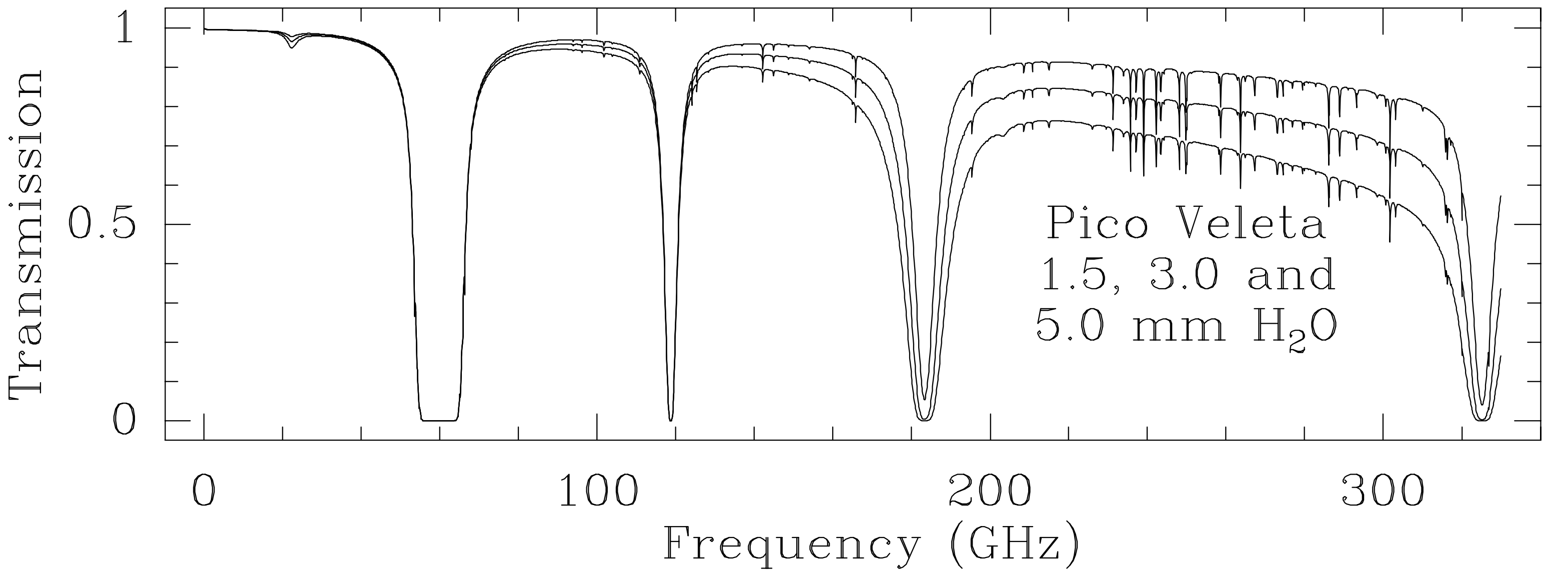
  ⇨ continuum and heterodyne receivers $R=10^7$-10^8

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

  ⇨ high altitude sites i.e. above 2000m

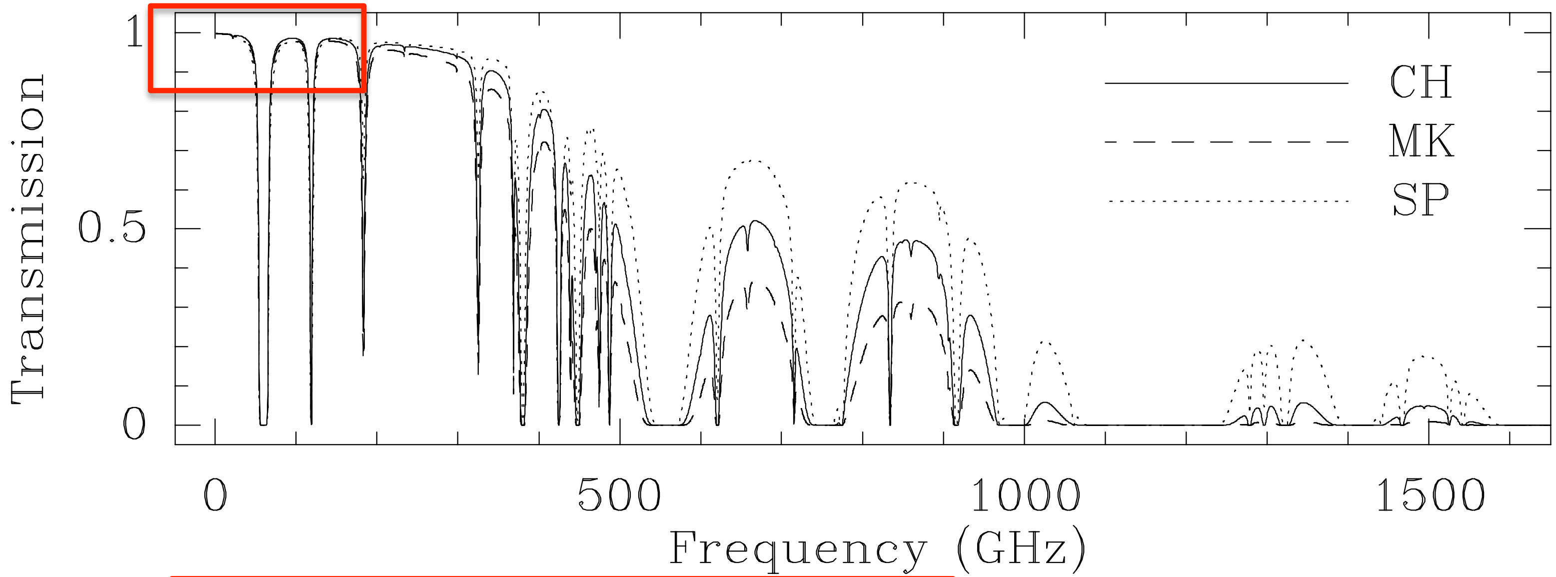
atmospheric transmission
(calculations by J. Pardo)

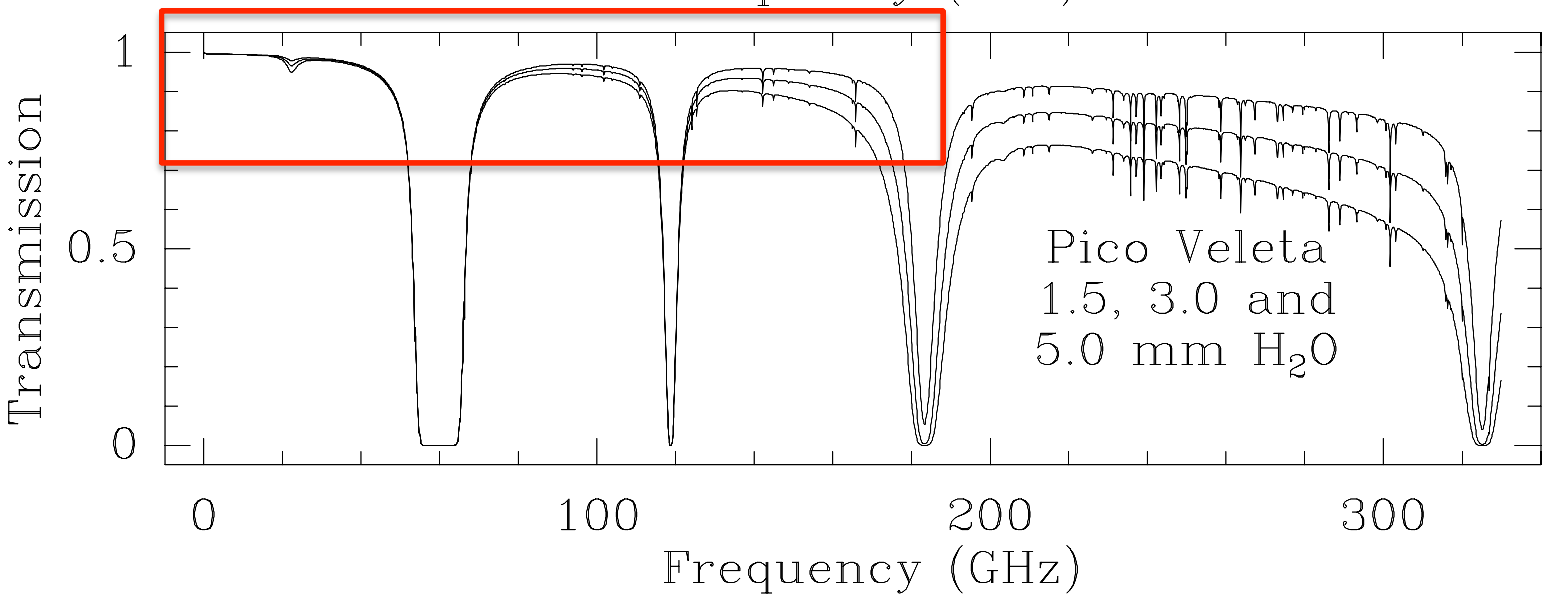




atmospheric transmission

(calculations by J. Pardo)



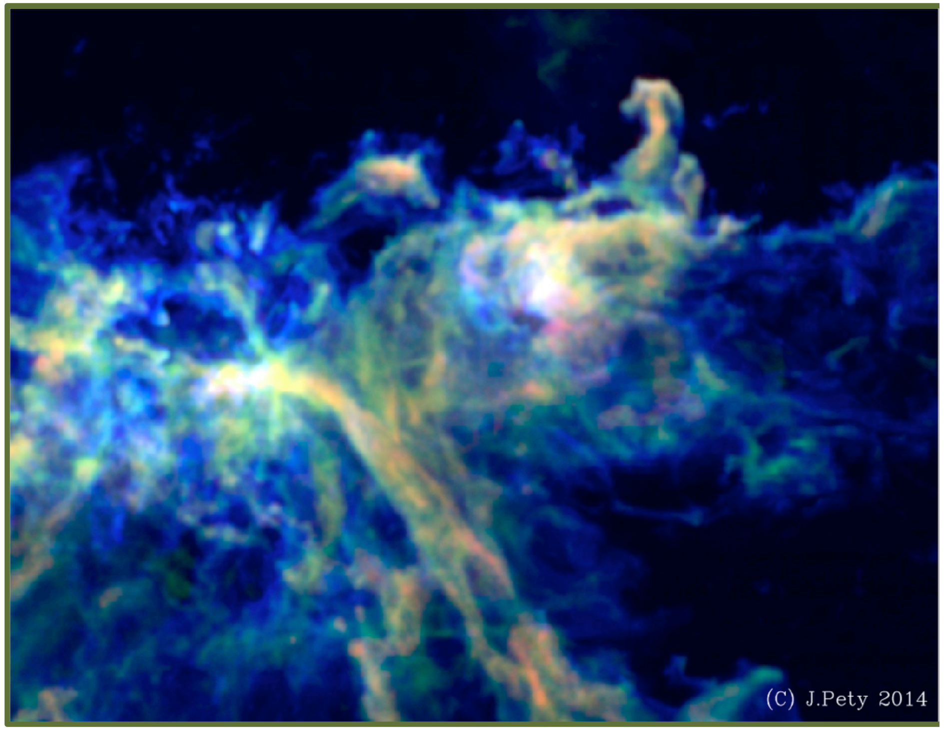


Telescope	Altitude	Frequencies
EFFELSBERG 100m	320	<90 GHz
ATCA	240	<105 GHz
GBT	320	<115 GHz
NOEMA/30M	2500/2800	< 380 GHz
SMA 8	4030	<700 GHz
LMT	4600	<350 GHz
ALMA 50	5000	<1000 GHz

advantages of interferometers

- high angular resolution
  - @ 230 GHz: 0.2” with NOEMA; 0.00002” with VLBI
- large collective area
  - NOEMA = 50-meter antenna; ALMA = 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

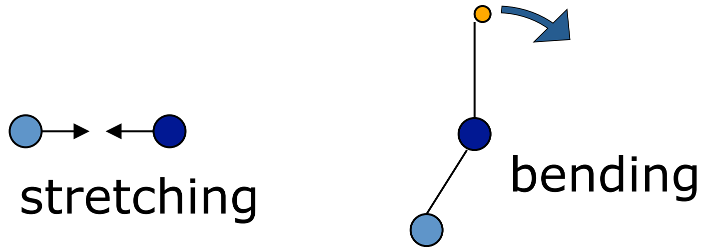
- mm-astronomy deals with
  - continuum emission: free-free, dust, synchrotron, compton scattering, SZ, …
  - line emission: mostly molecules but also atoms
  - inter- stellar/galactic medium in various phases
    - matter in ionized, atomic, molecular state, dust grains, etc.
    - temperature, density of the matter



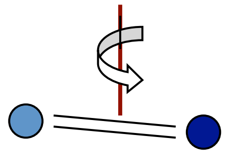
- HII regions $T \sim 10^4 K$, $n=10^1-10^6/cm^3$ e.g. H, He
- molecular clouds/cores $T \sim 10-10^3 K$, $n \sim 10^2-10^8/cm^3$ e.g. ^{12}CO

Energies involved in molecular states

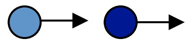
- electronic transitions
- vibrational transitions



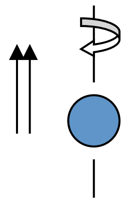
- rotational transitions



- translational transitions

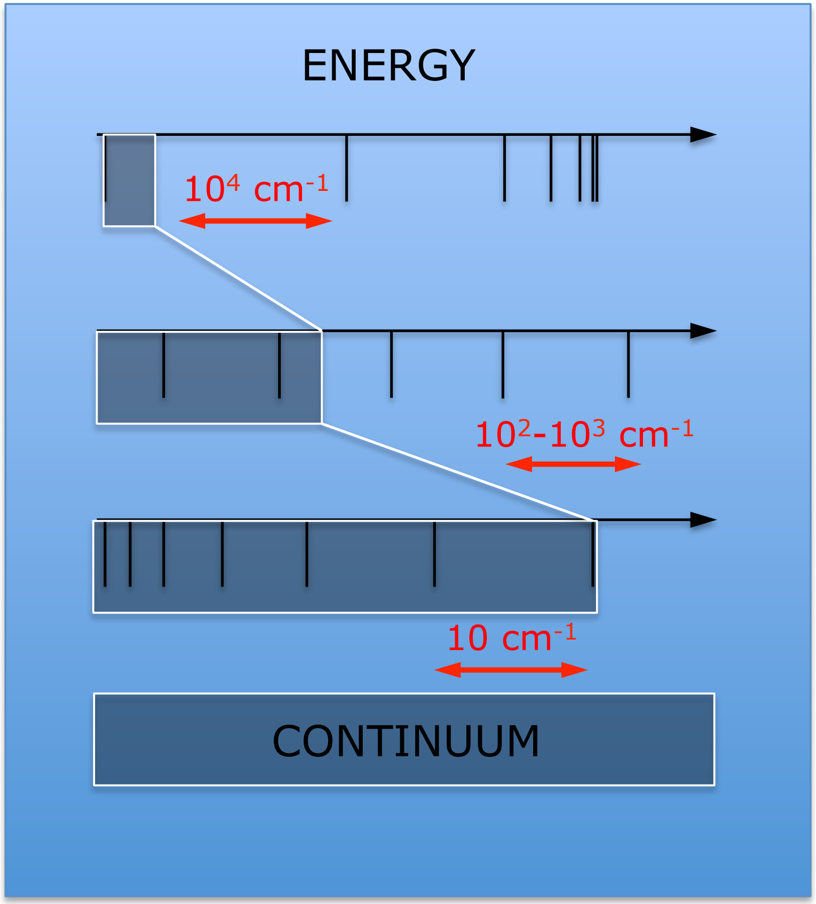


- electronic/nuclear spin transitions



Energies involved in molecular states

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



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

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	HC_7N				
CH^+	HCN	$C_2H_2^*$	H_2CCN	CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H				
CN	HCO	NH_3	CH_4^*	CH_3SH	c-C_2H_4O	l-HC_6H^*	$CH_3C(O)NH_2$				
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	H_2CCHOH	CH_2CHCHO (?)	C_8H^-				
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
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										

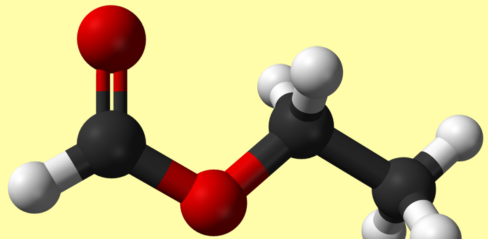
Molecules in the ISM

(08/2011)

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 150 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, ...

Ethyl-formate C_2H_5OCHO



(Belloche et al. 2009 with the 30m)

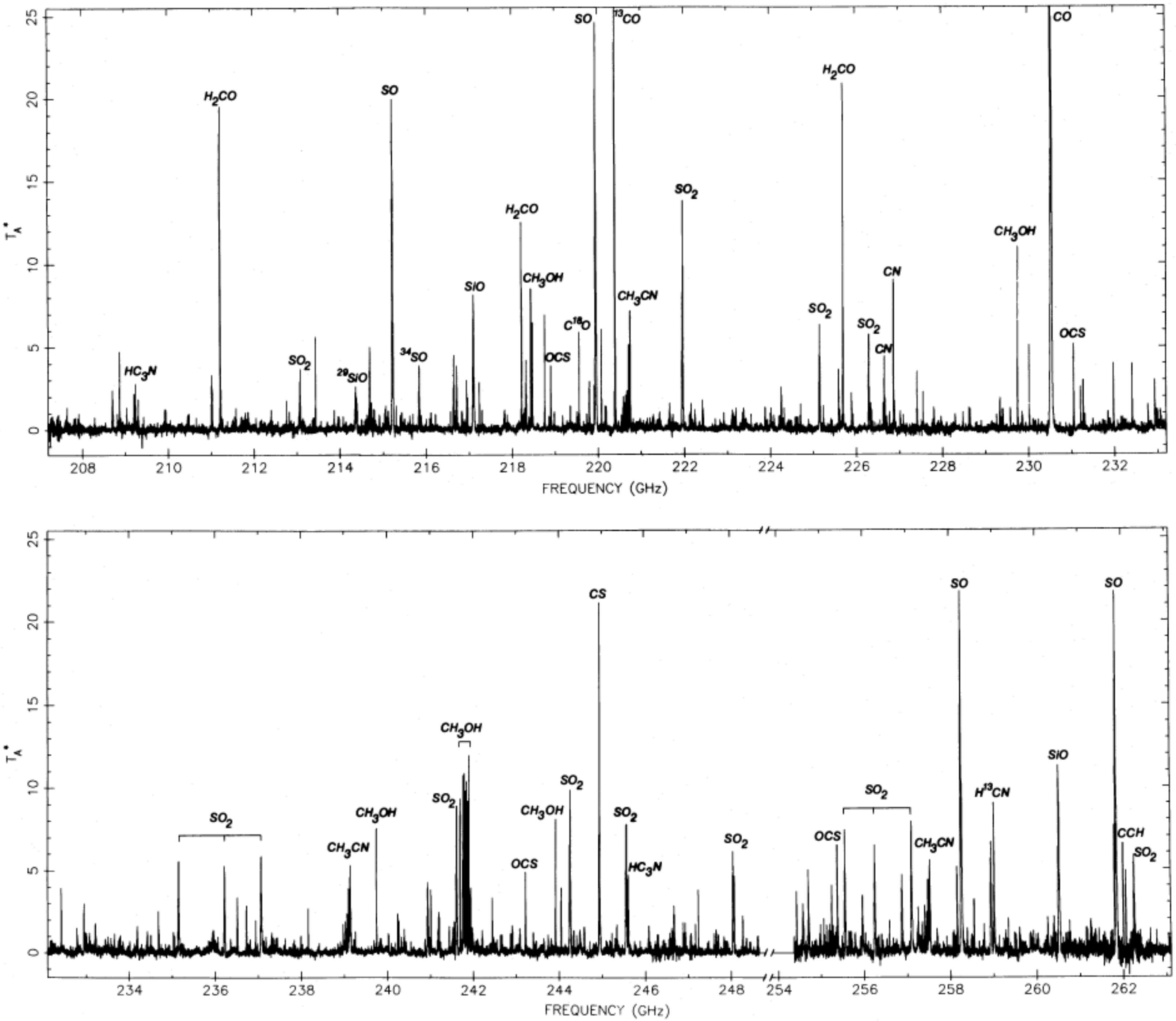
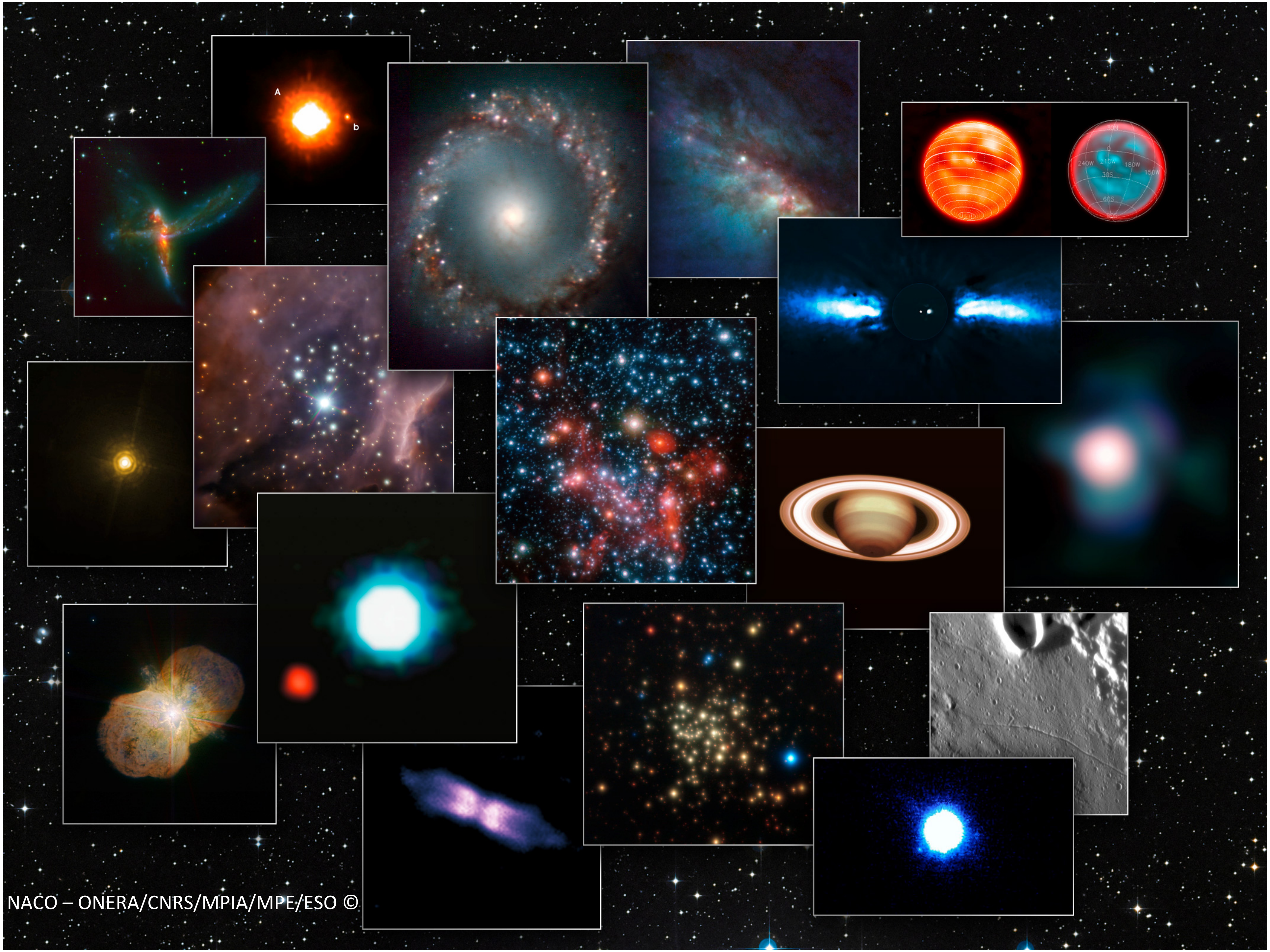


FIG. 1.—Compressed view of the OVRO spectral line survey of OMC-1

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							


A
b
NACO – ONERA/CNRS/MPIA/MPE/ESO ©

What can be observed in the mm-range?

Science	IRAM Time	Keyword
Galaxies @ high-z : LBG, SMM, ERO, RG	30%	"CSF history"
Nearby Galaxies : Spirals, (U)LIRGs	30%	"dynamics + structure"
YSO : Prestellar Clouds → T-Tauri Stars	30%	"SF + evolution"
Evolved Stars	5%	"mass loss"
Chemistry, Solar System, …	5%	

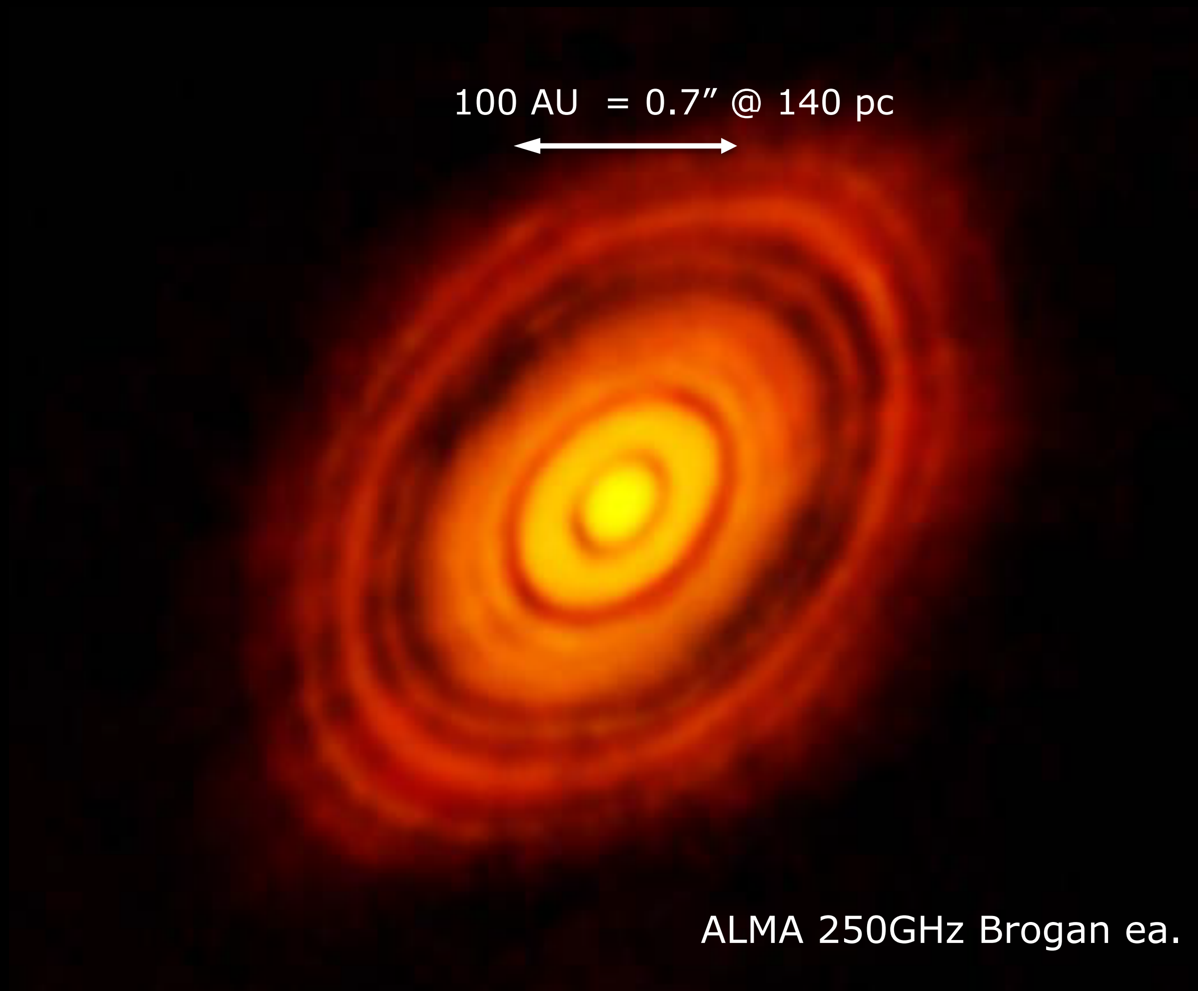
VLBI	10 days	

mm-astronomy ...

→ ... not anymore in a proof-of-concept stage

→ ... belongs to mainstream science

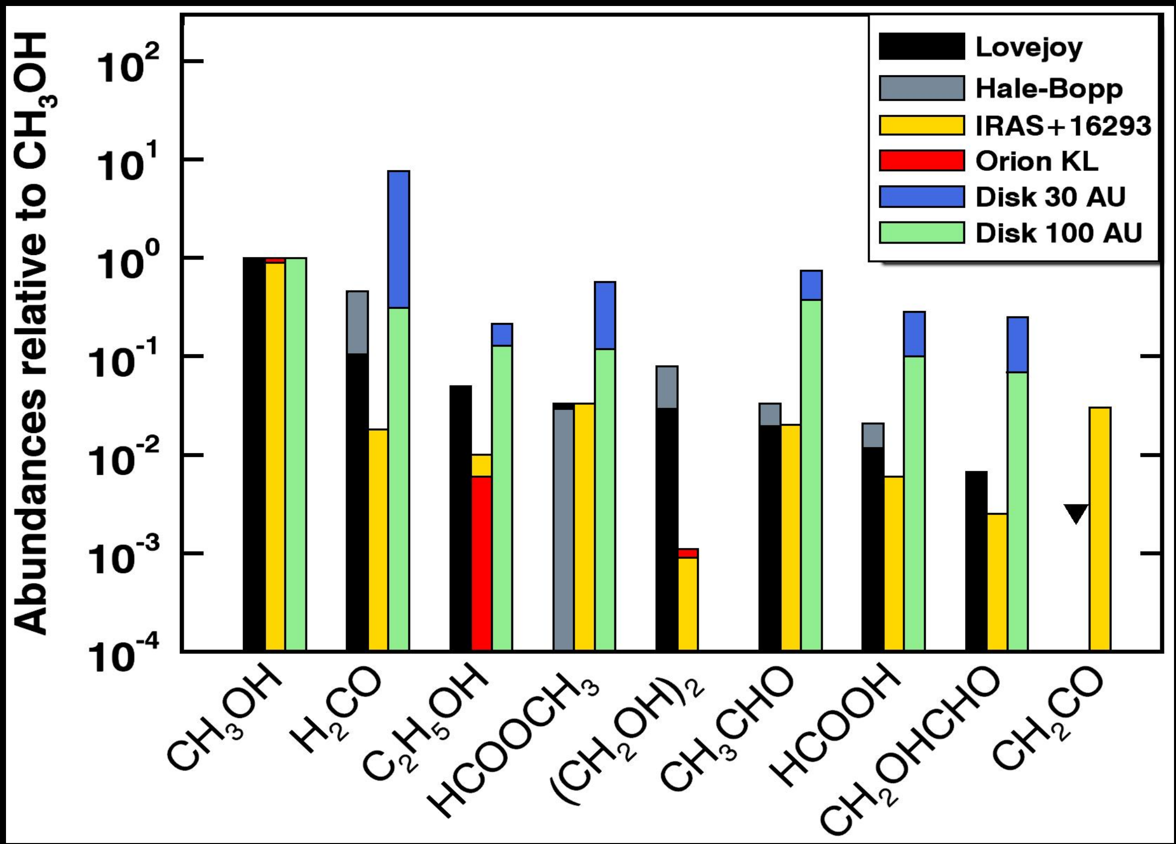
Protostellar disk of HL Tau



- inner 30 AU are optically thick @ mm
- rich of prebiotic chemistry

ALMA 250GHz Brogan ea.

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



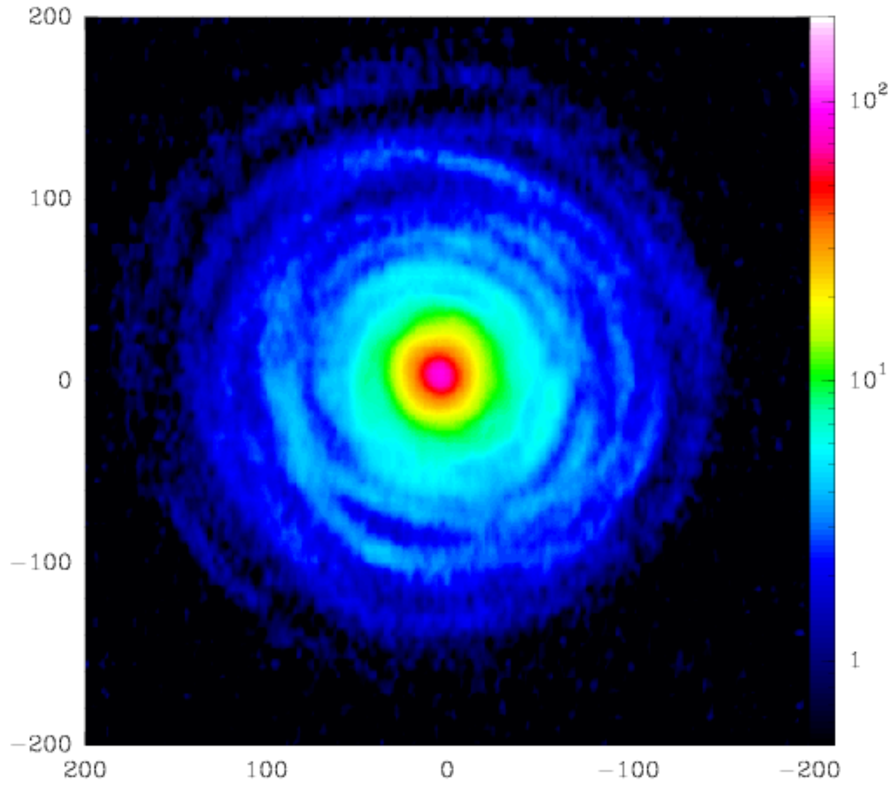
- EMIR campaign
- survey @ 210-272 GHz
- C_2H_5OH, CH_2OHCHO + 19 other molecules
- COMs abundance > solar-type protostars ⟹ origin of COMs

Biver et al. 2015

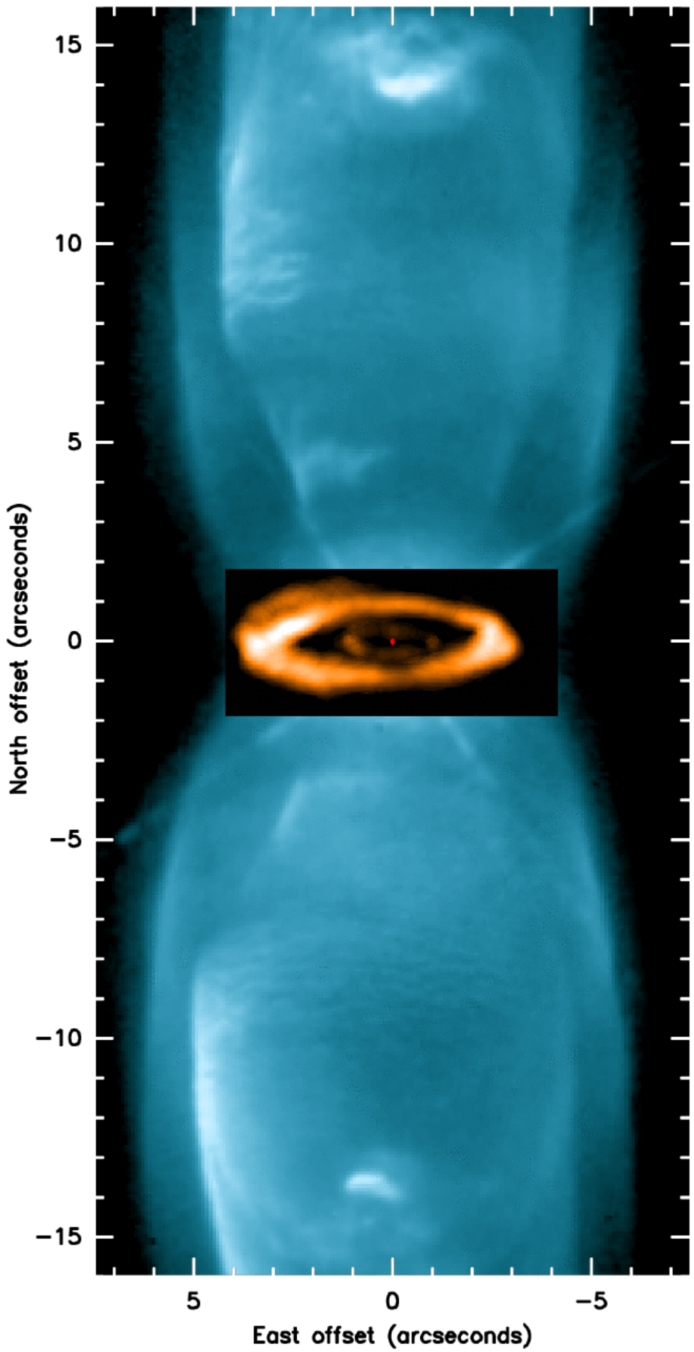
Recycling of gas and dust

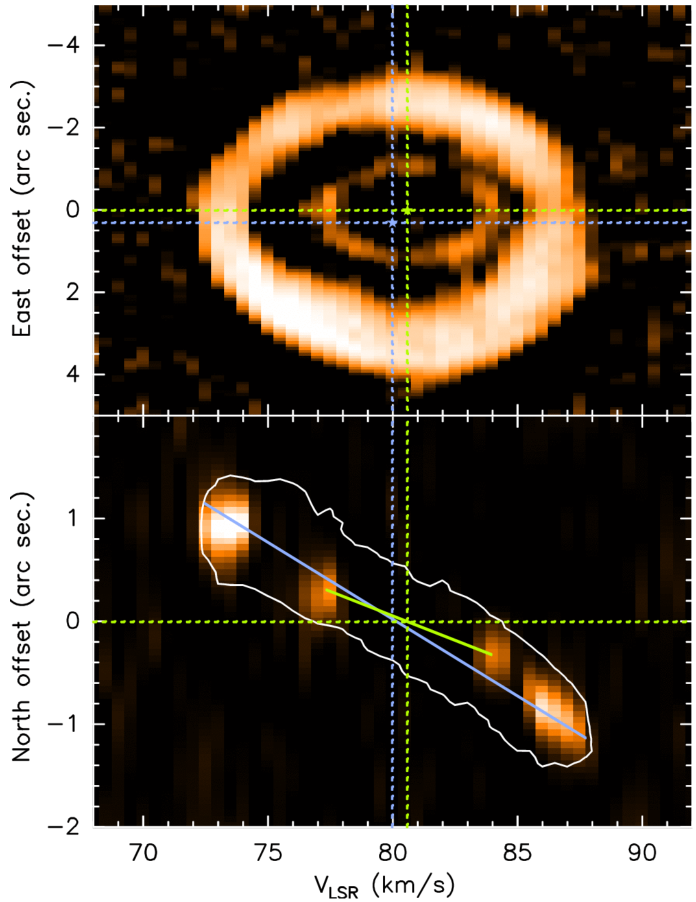
Mass-loss of massive stars during the last stages of stellar evolution. Example: IRC+10216

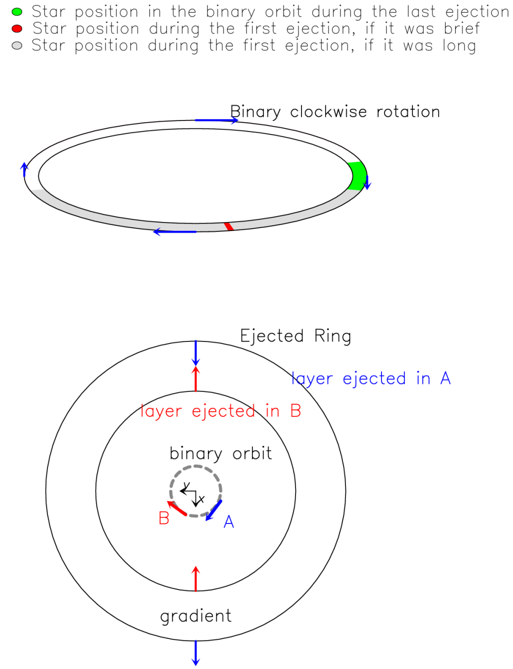
Expelled circular dust shell during the last 8000 years. Optical image. Expansion velocity ~15 km/s, One expulsion every ~800 years



Expulsion of CO shells
Cernicharo et al. 2014







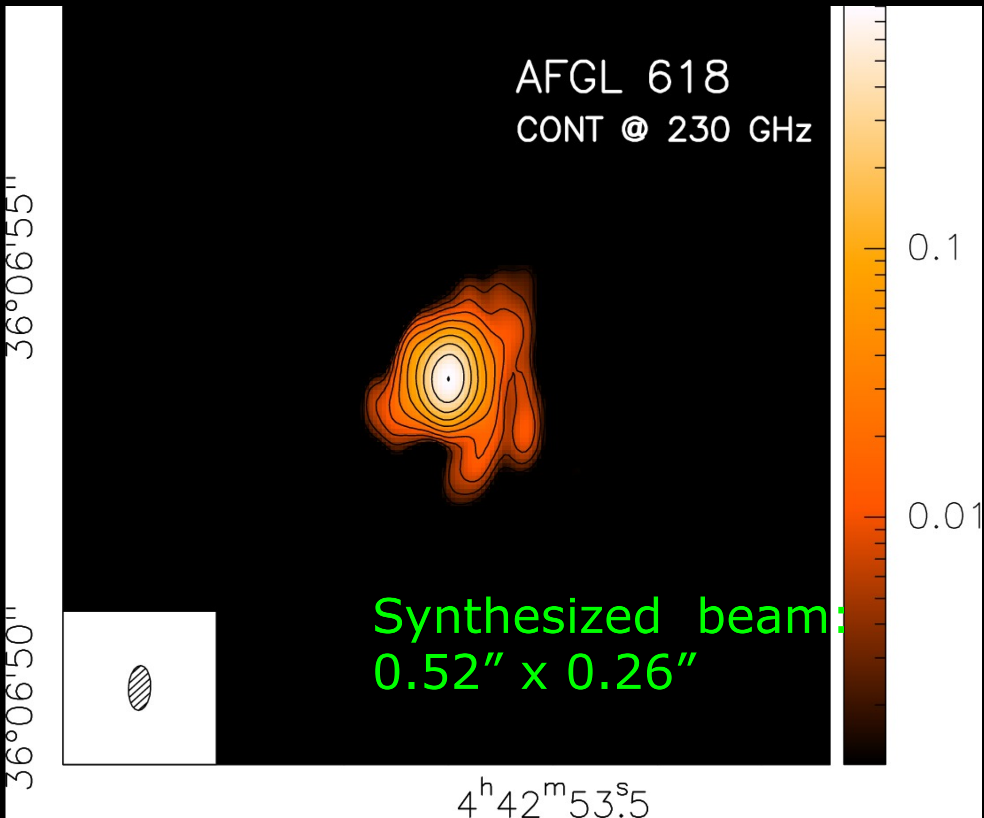
Young Planetary Nebula Minkowski 2-9

CO *J*=2-1 emission

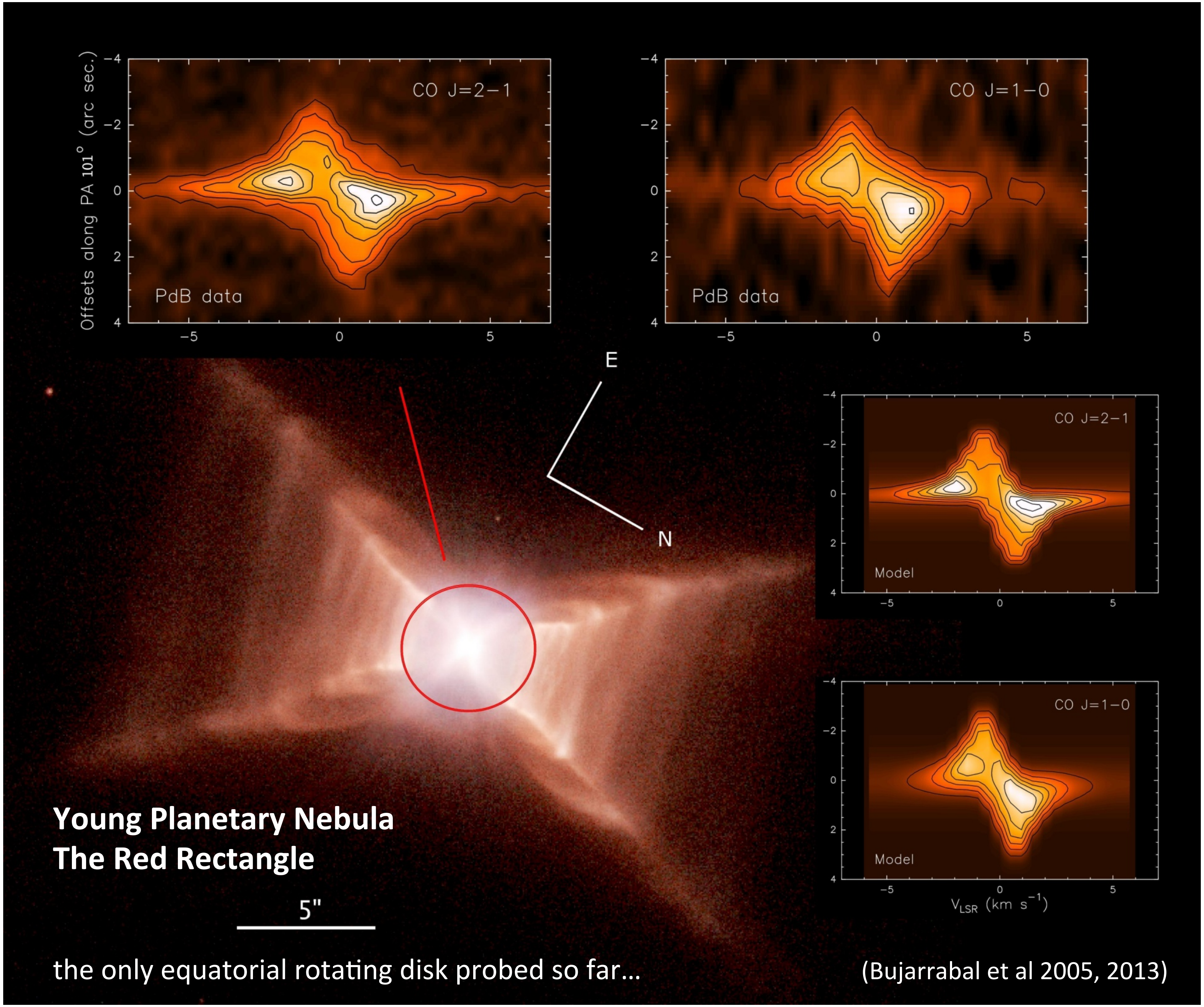
Two diverging equatorial ring-like outflows in the waist of the **Butterfly Nebula** to probe its central binary system

(Castro-Carrizo et al. 2012)

High dynamic range imaging (NOEMA)

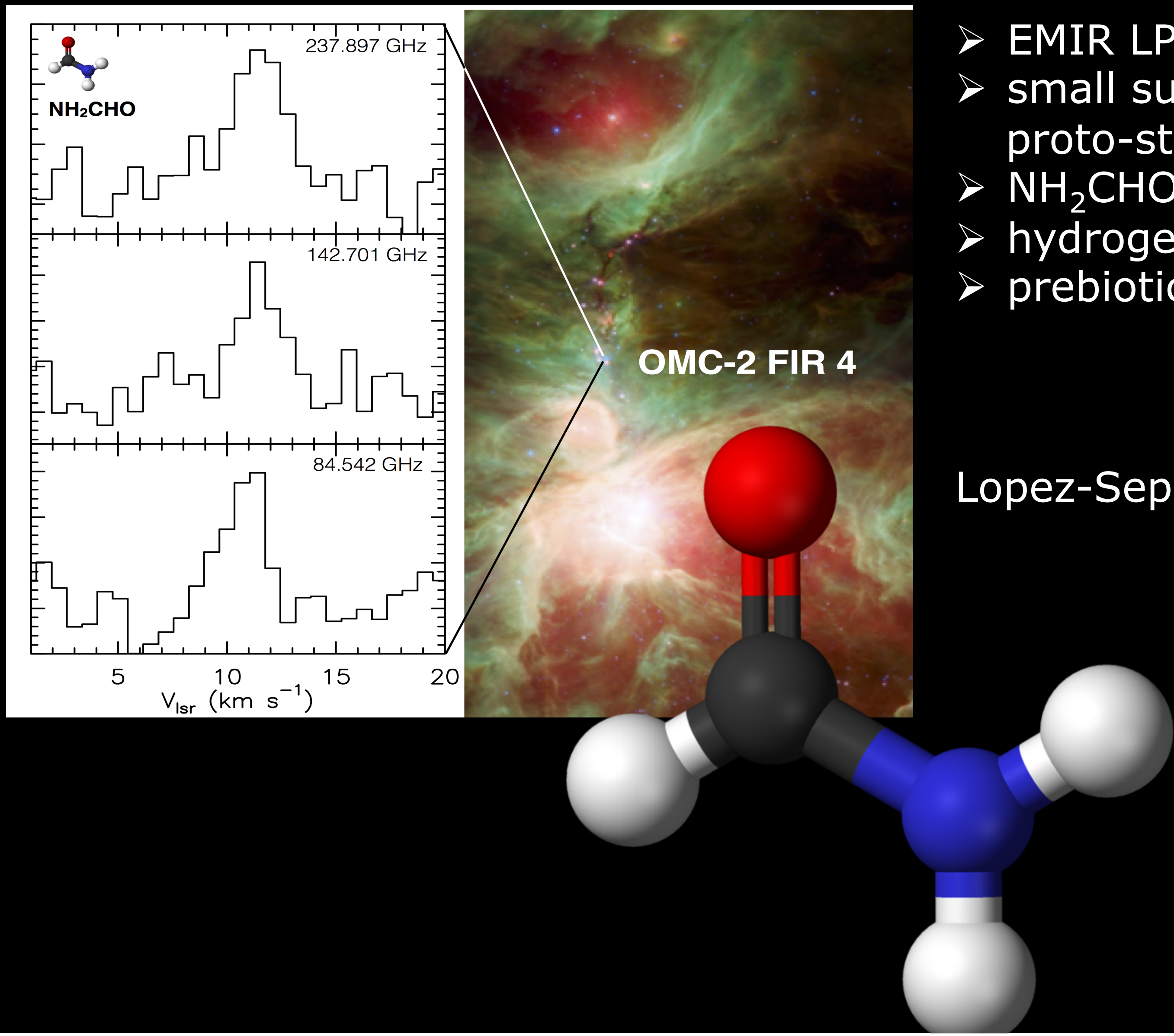


- self-calibrated continuum map @ 1mm
- dynamic range 1000:1, one order of magnitude better than achieved ever before



CO J=2−1
PdB data
CO J=1−0
PdB data
Offsets along PA 101° (arc sec.)
E
N
CO J=2−1
Model
CO J=1−0
Model
V_{LSR} (km s^{-1})
5"
Young Planetary Nebula
The Red Rectangle
the only equatorial rotating disk probed so far…
(Bujarrabal et al 2005, 2013)

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

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
- 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.
- 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

Waves on the Orion Molecular Cloud: Feedback of massive stars

a)
red: Spitzer MIR

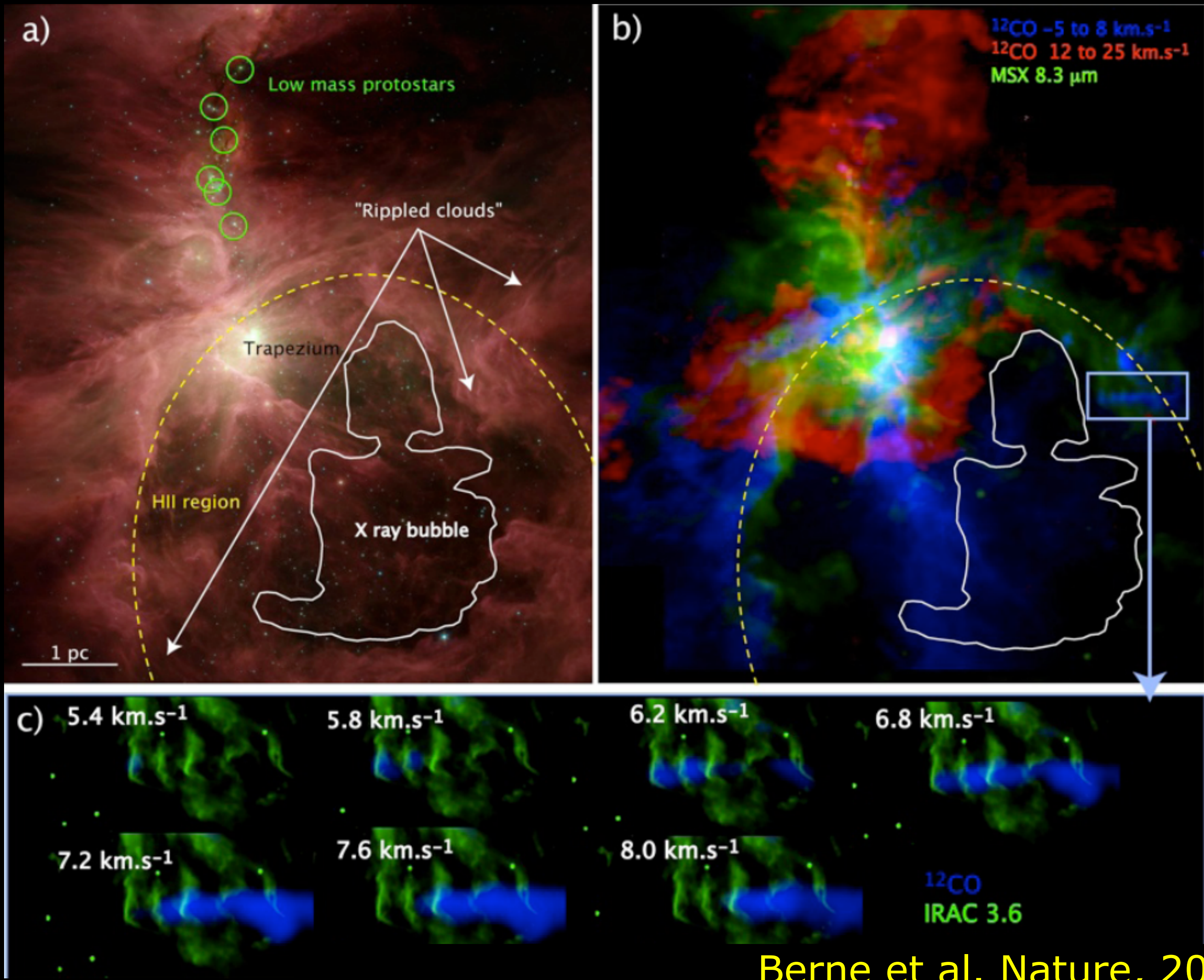
b)
CO 2-1 HERA/30m
(far and near side)
8um MSX

c)
Blue:
CO 2-1 30m
green:
IRAC/Spitzer 3.6um

Trapezium OB cluster
HII region expanding
Low mass protostars
Hot plasma by winds

+Periodicity
+Geometry
+Velocity structure

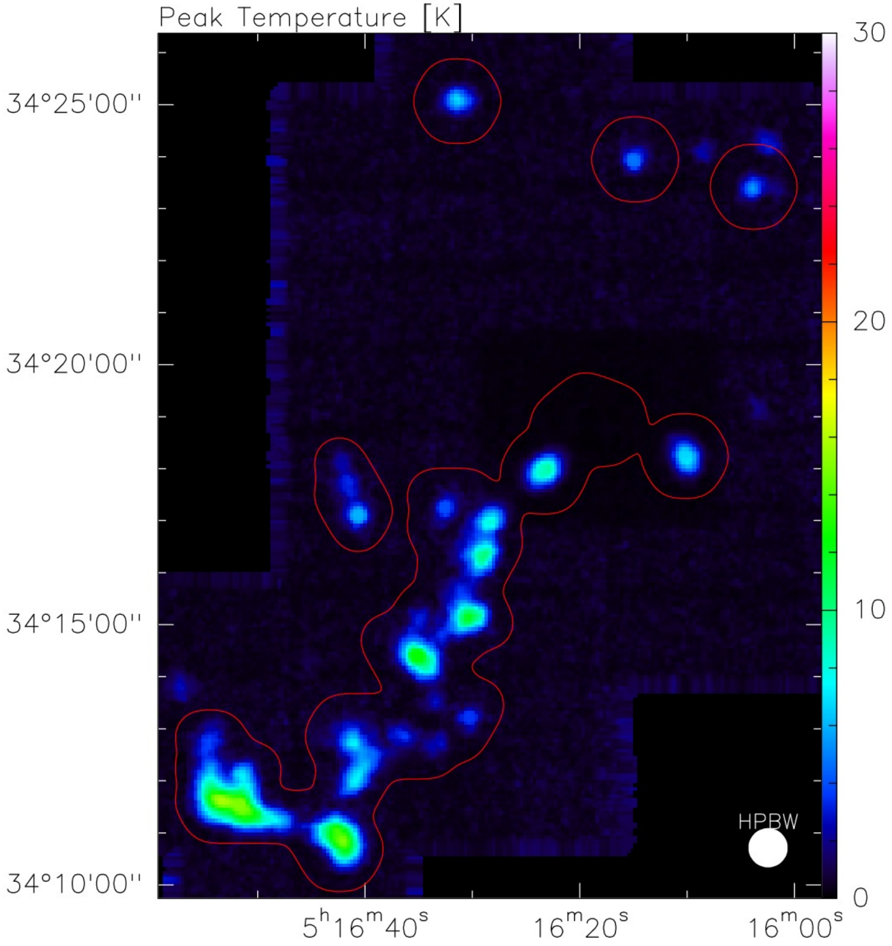
Flow of plasma and radiation of massive stars shapes the cloud by forming a train of molecular globules ?



Berne et al. Nature, 2010

Bright CO resulting from the interaction of a runaway O star with the diffuse ISM: 1. 30m only

PI: P.Gratier, J.Pety, P.Boisse, S.Cabrit, P.Lesaffre, A.Witt, G.Pineau des Forets, M.Gerin



AE Aurigae (a.k.a HD 34078)

- O9.5V runaway star (ejected from the Orion Trapezium region).
- Distance: 530 pc.
- Velocity: 120 km s^{-1} ⇒ 1.2° on-sky every 10^5 yr.

The diffuse IC 405 nebula

- No CO detected in neither Dame et al. (9′) nor Planck (15′) at ∼ 1 K km s^{-1} sensitivity.
- 10 K clumps detected with the 30m in ^{12}CO (J=1–0) (23″) mainly (but not only) at the edge of the diffuse gas (200 square arcminutes mapped at 0.2 K sensitivity in 0.5 km s^{-1} channels in 30hrs).
- 30 K sub-structures when mapped at 4″ resolution at PdBI (150-fields mosaic).
- Hα extinction ⇒ Translucent gas (A_V ∼ 2 – 3) but the standard X_{CO} factor applies.

⇒ Response of a diffuse cloud to the sudden excitation by an O star
⇒ A template for high mass stellar feedback.

Bright CO resulting from the interaction of a runaway O star with the diffuse ISM: 2. 30m + PdBI

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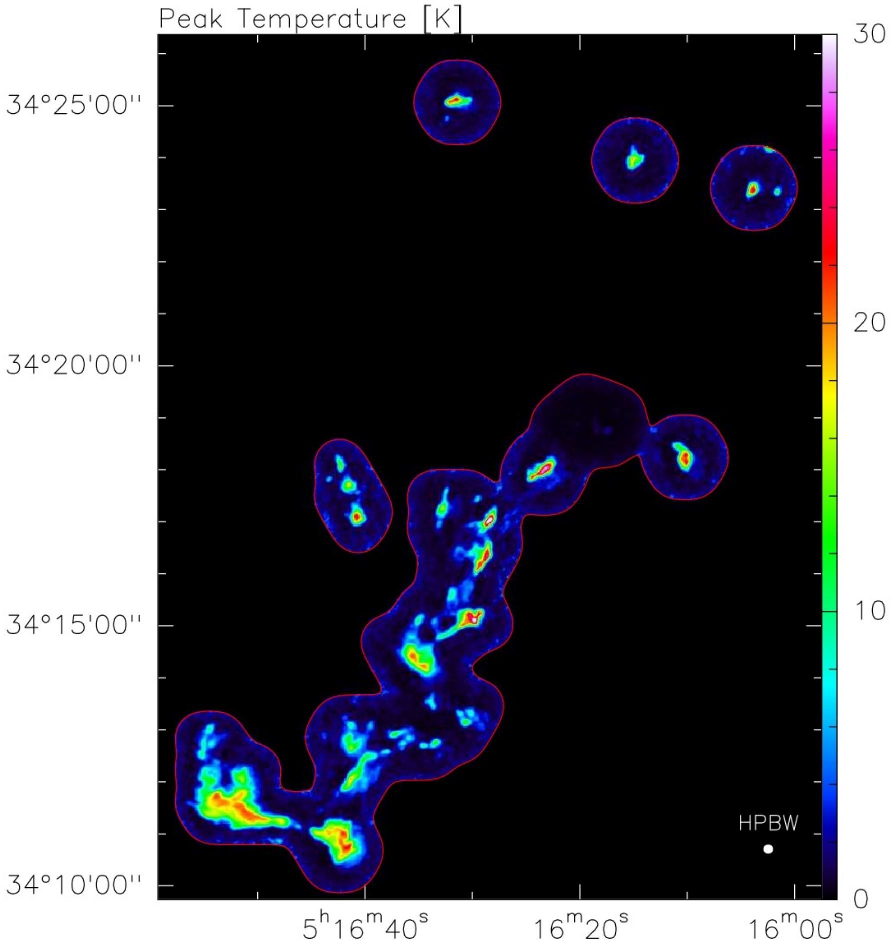

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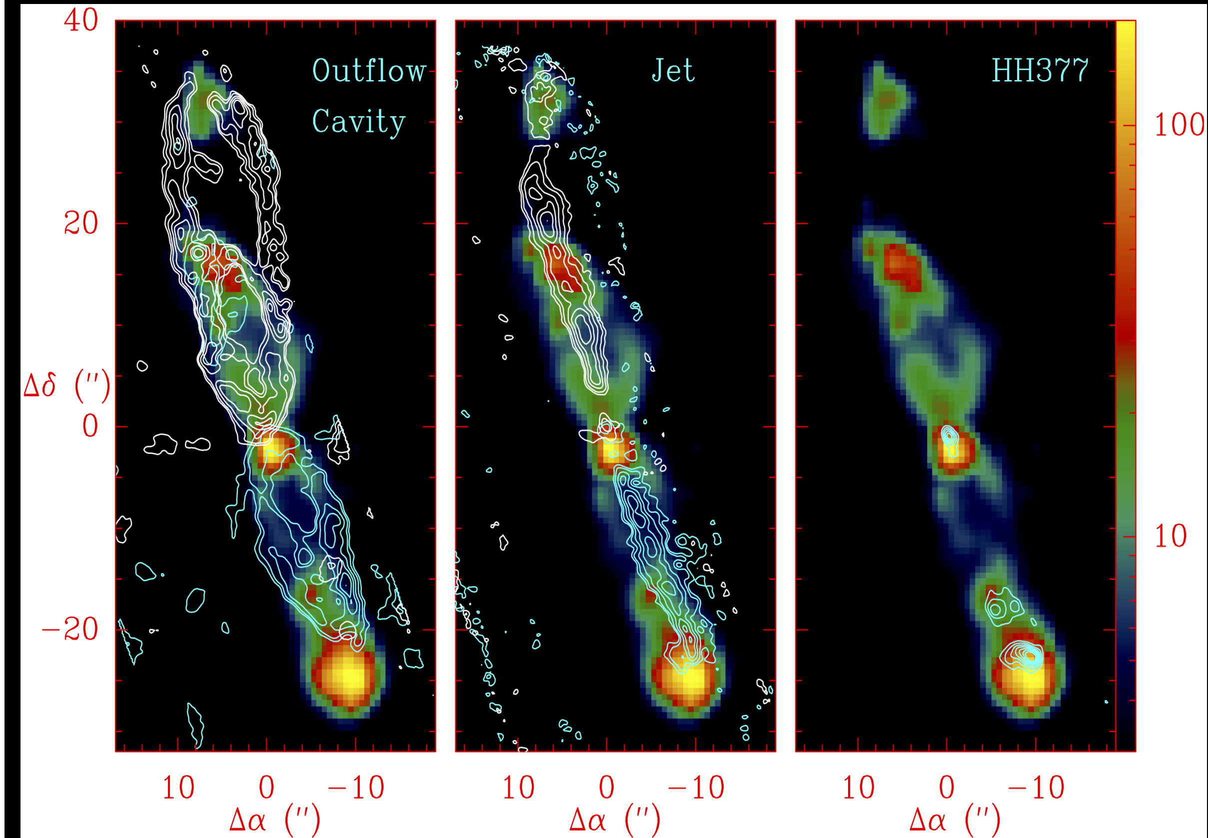
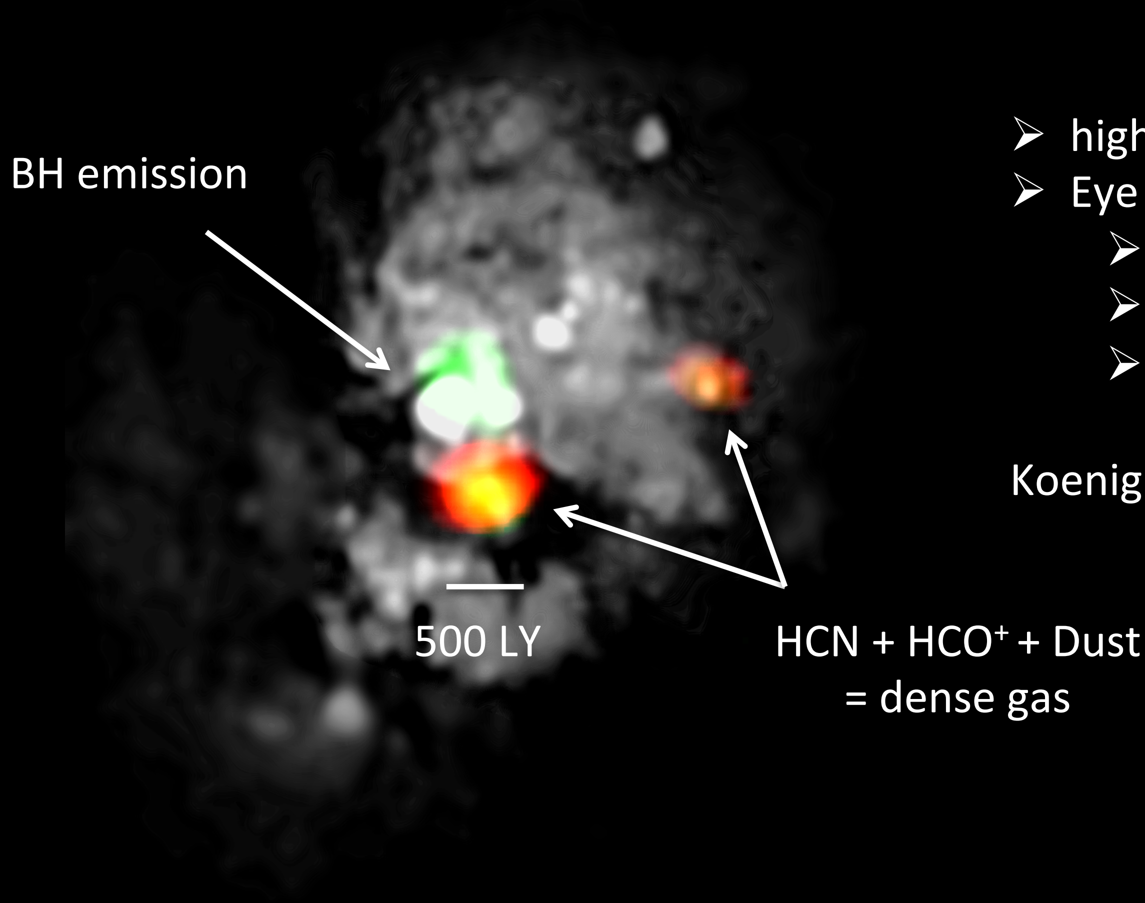
protostellar outflow Cepheus E



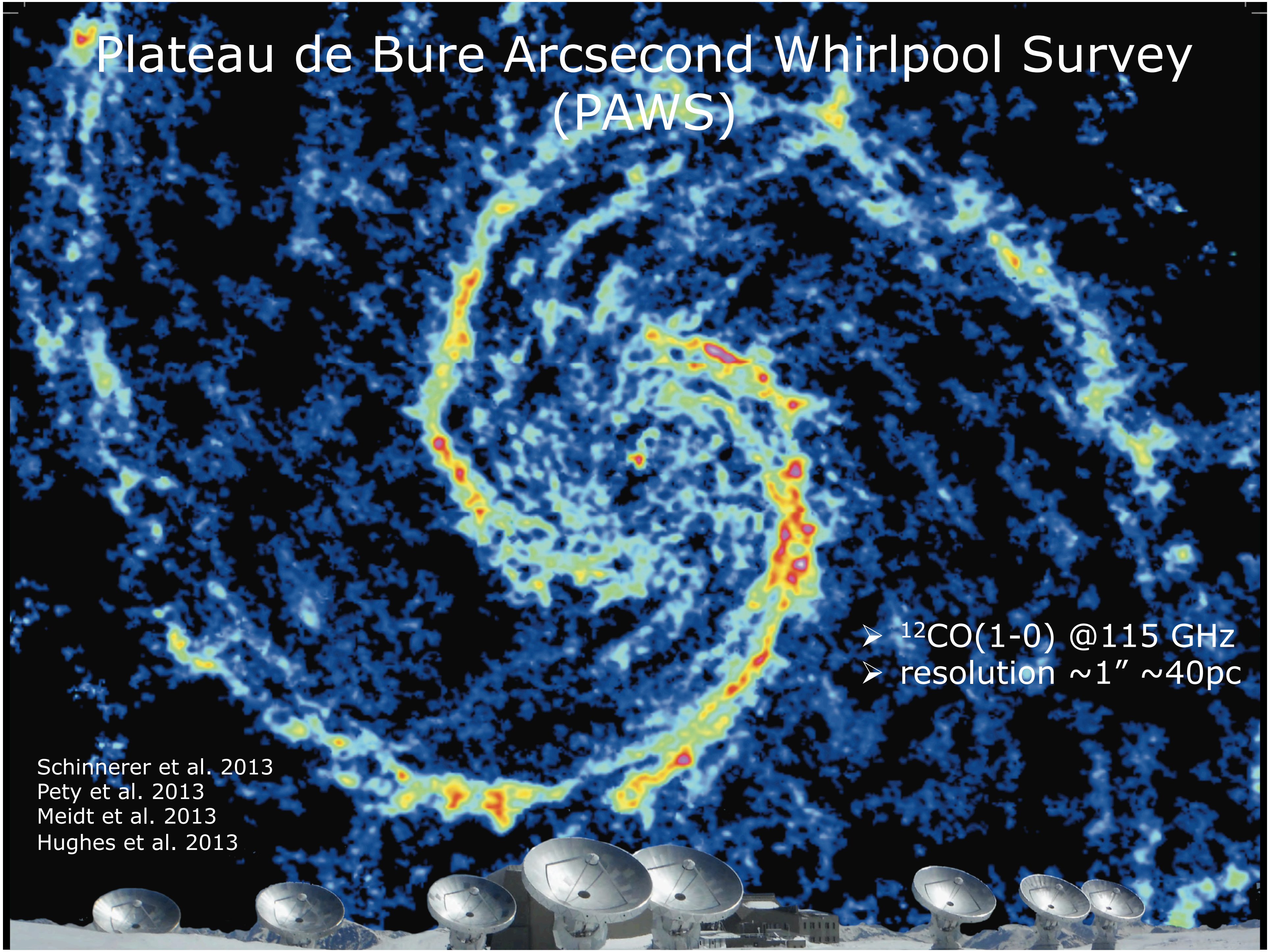
- Herschel, SOFIA, NOEMA, 30m = CO J=1-0 … J=16-15
- origin of the mass-loss?
- jet, cavity, bow-shock
- magnetized shock drives the formation of the outflow cavity
  - 20-30 km/s, ~500 yr old
- Lefloch et al. 2015

Extreme star formation region in the 'Eye of Medusa'



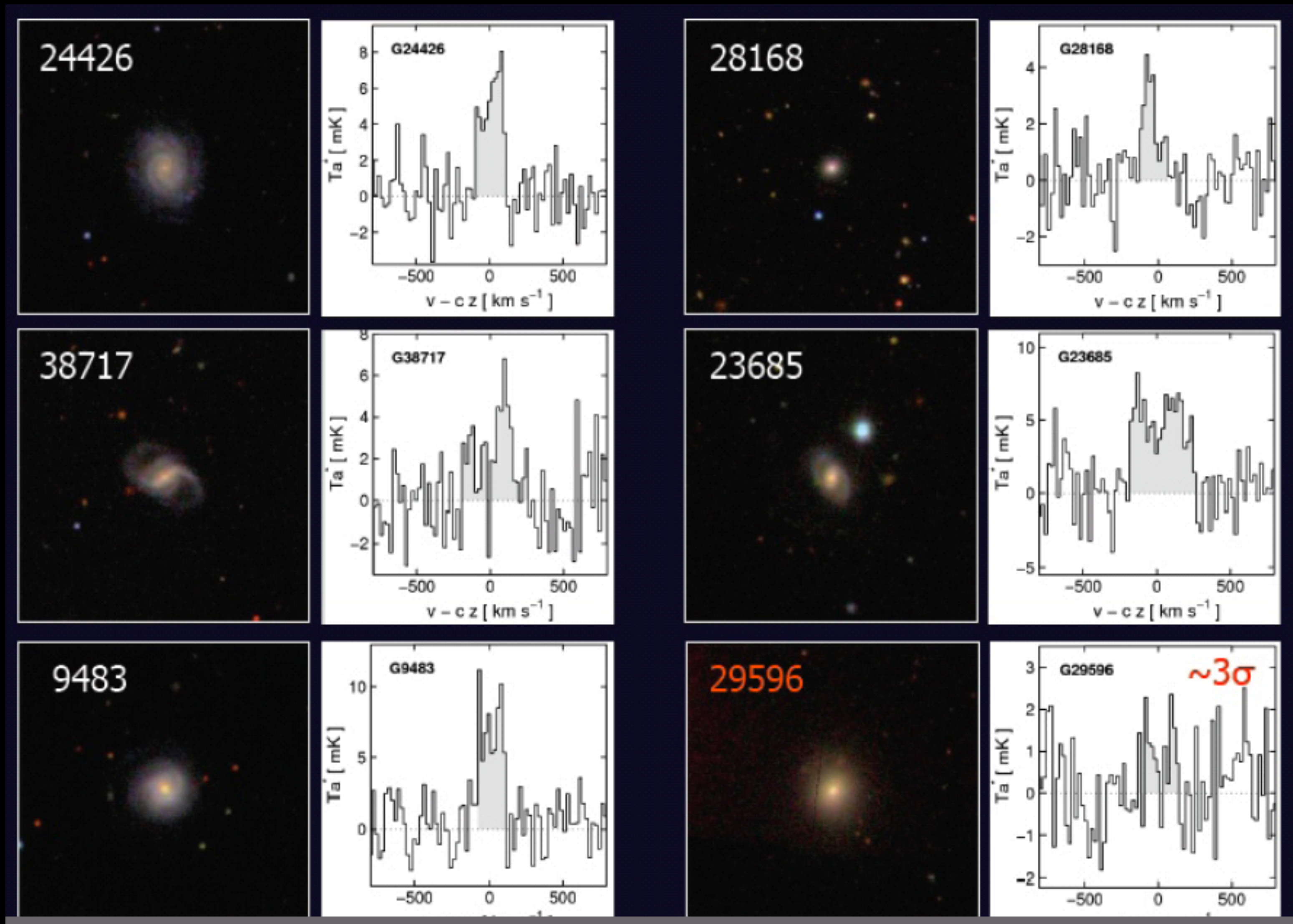
- high density tracers = HCN, HCO^+
- Eye is not detected in ^{12}CO!
    - low CO/HCN (1–0) luminosity ratio
    - SFE is similar to other regions
    - SF or feedback of SF regions?

Koenig ea 2015

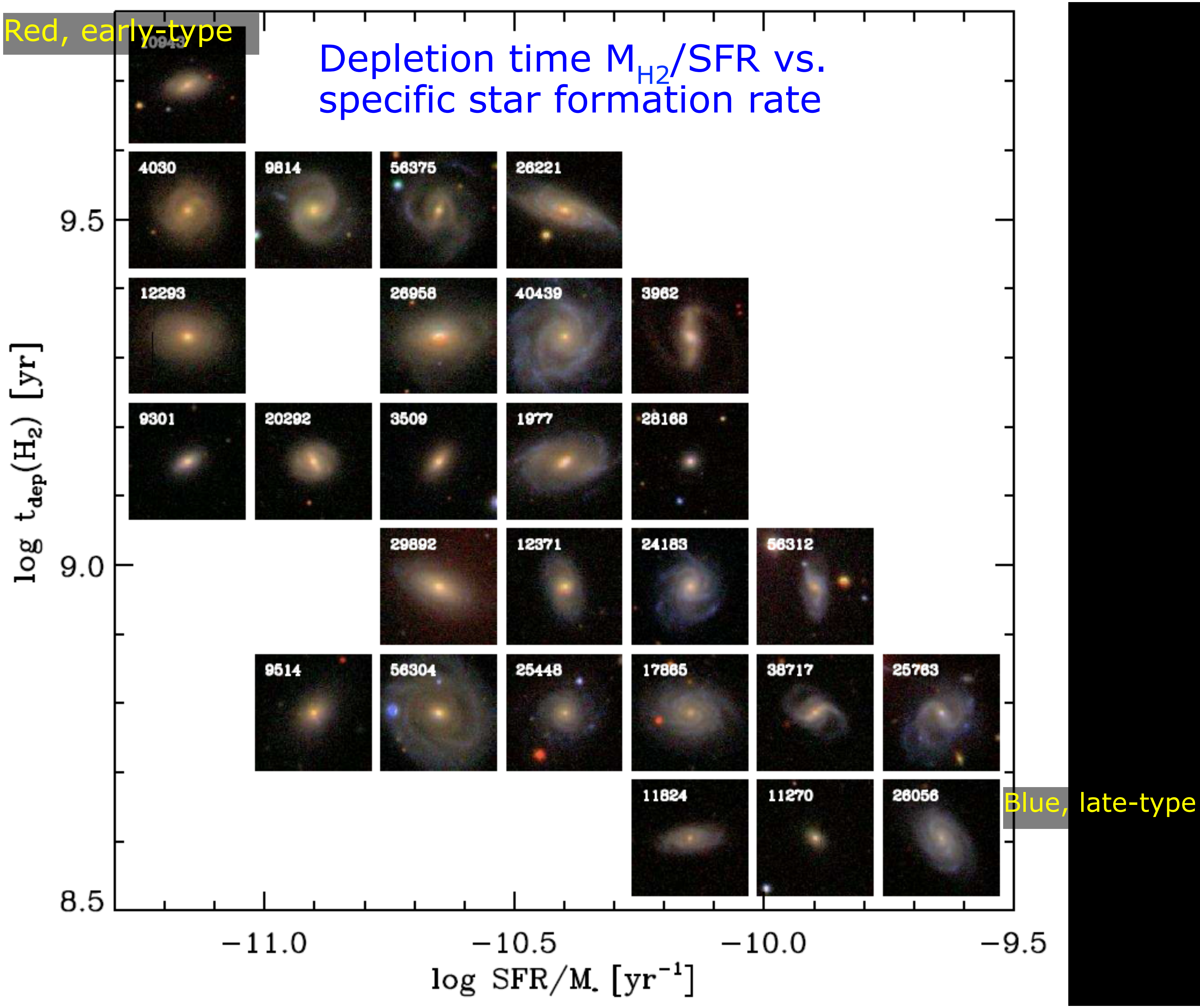

Plateau de Bure Arcsecond Whirlpool Survey
(PAWS)
➤ 12CO(1-0) @115 GHz
➤ resolution ~1″ ~40pc
Schinnerer et al. 2013
Pety et al. 2013
Meidt et al. 2013
Hughes et al. 2013

The COLD GASS survey

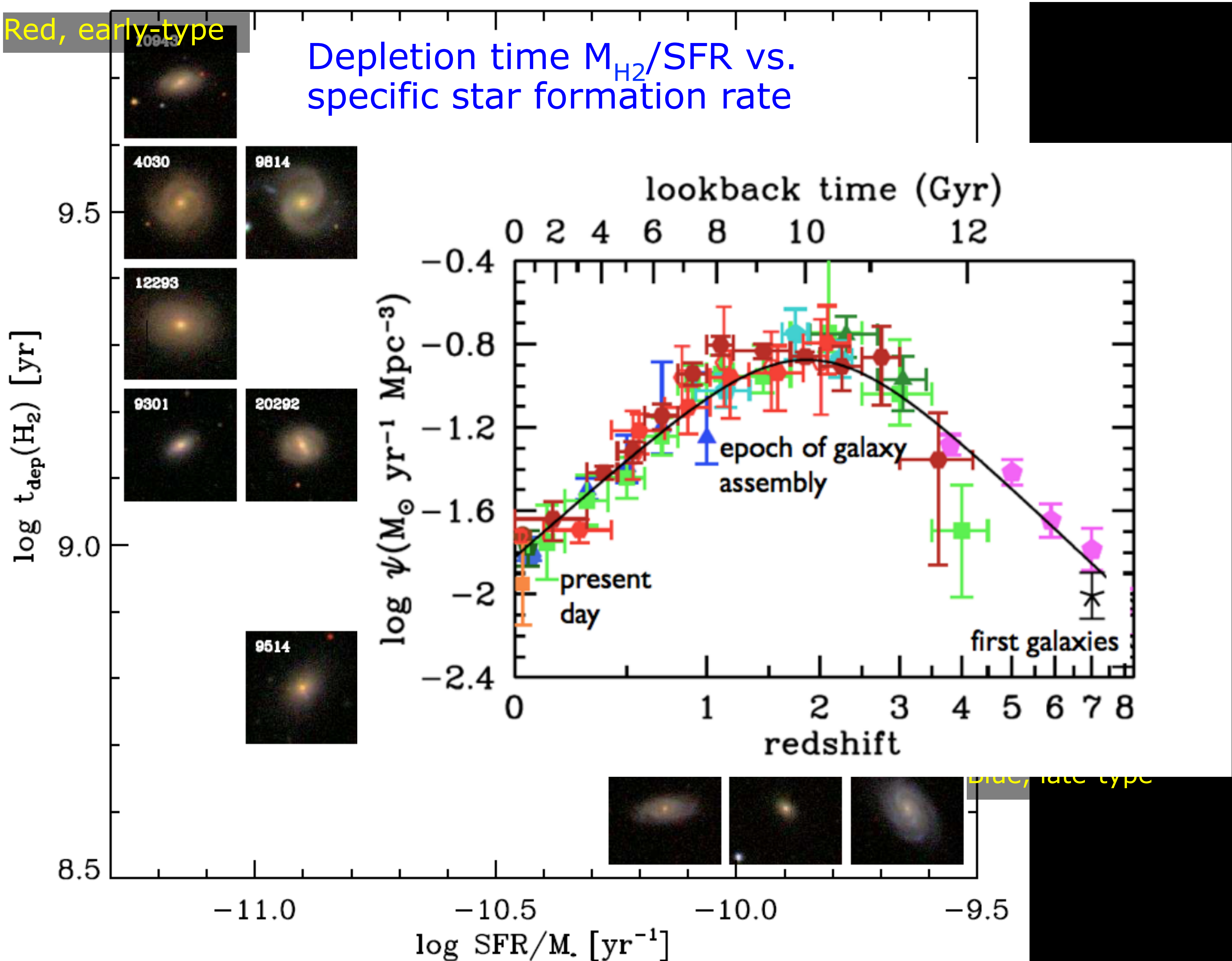
350 galaxies at 100-200 Mpc, $M_* > 10^{10}$ M_{sun}



Combining UV, optical, and HI data with 30m CO 1-0 spectra
(Saintonge et al. 2011a, b)

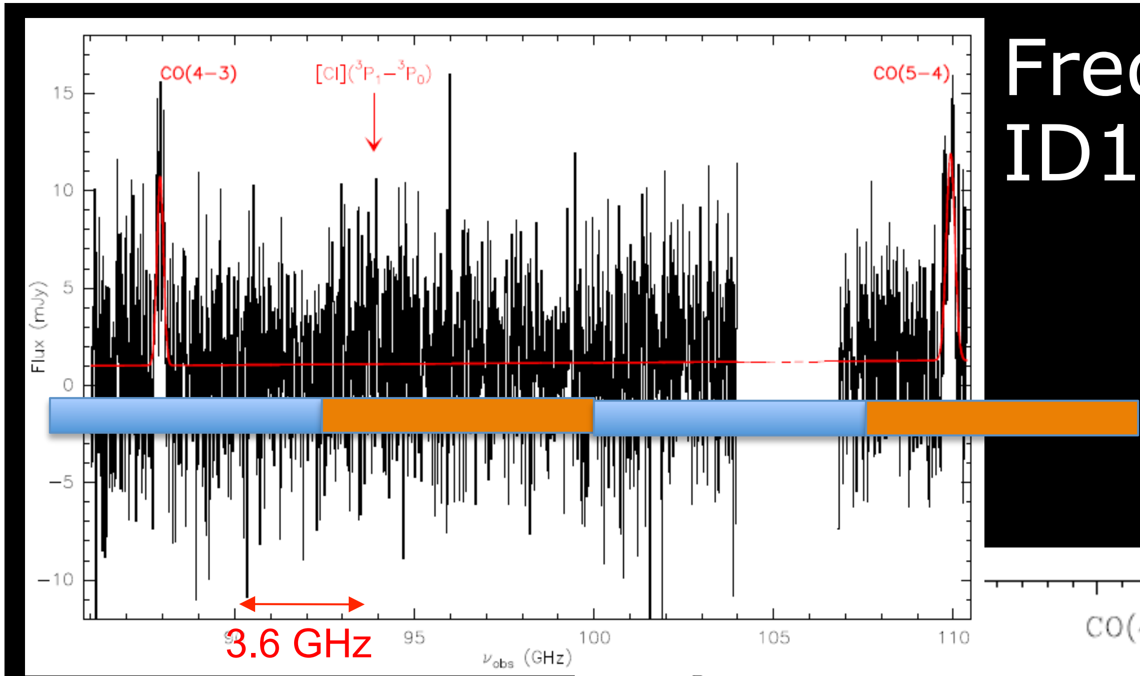

Red, early-type
Depletion time M_{H2}/SFR vs. specific star formation rate
Blue, late-type
4030
9814
56375
26221
12293
26958
40439
3962
9301
20292
3509
1977
28168
29892
12371
24183
56312
9514
56304
25448
17865
38717
25763
11824
11270
26056
9.5
9.0
8.5
−11.0
−10.5
−10.0
−9.5
log $t_{dep}(H_2)$ [yr]
log SFR/M_* [yr^{-1}]

Depletion time M_{H2}/SFR vs. specific star formation rate



[redacted]

Frequency sweep of ID141 at the PdBI



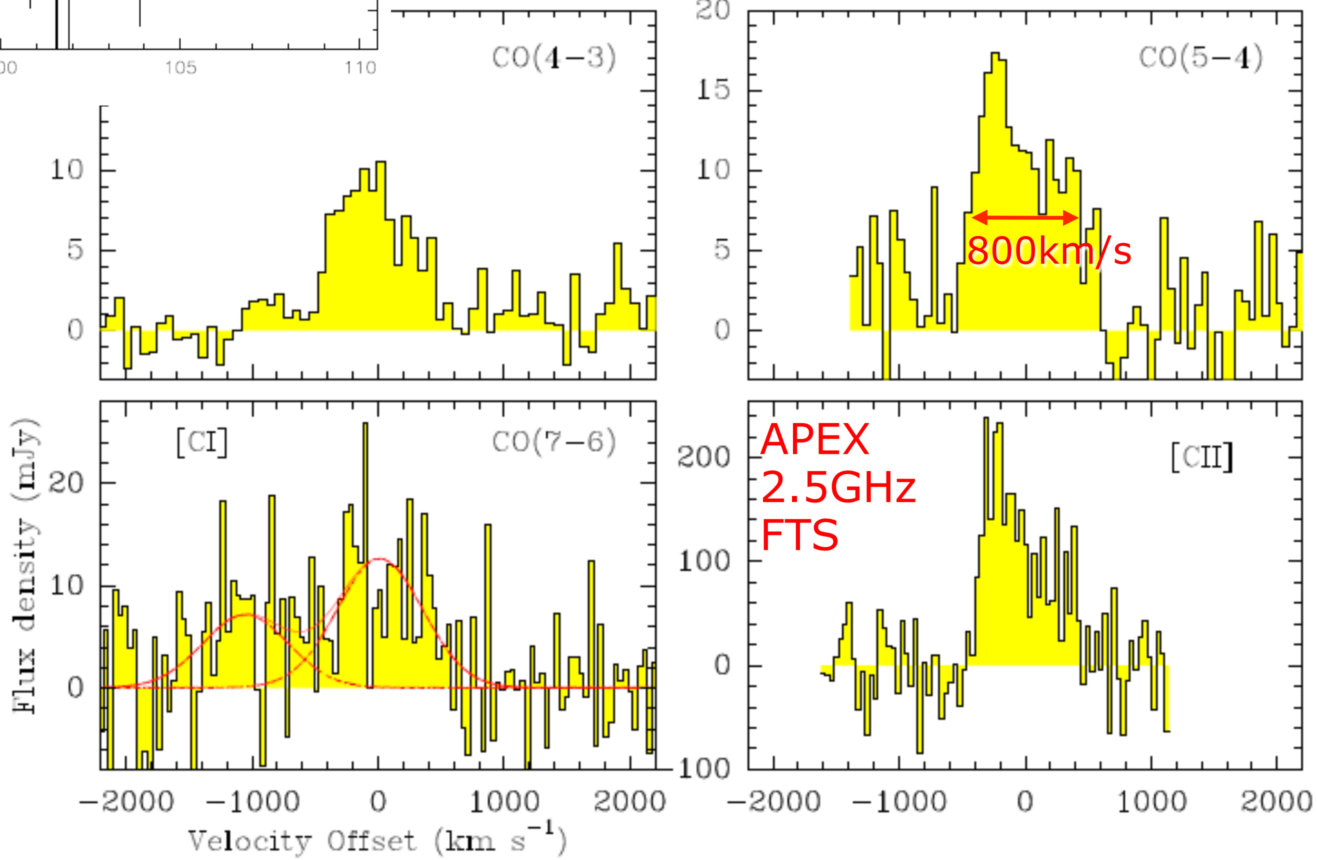
2011: 6 tunings = ~22 GHz
2017: 2 tunings = ~32 GHz

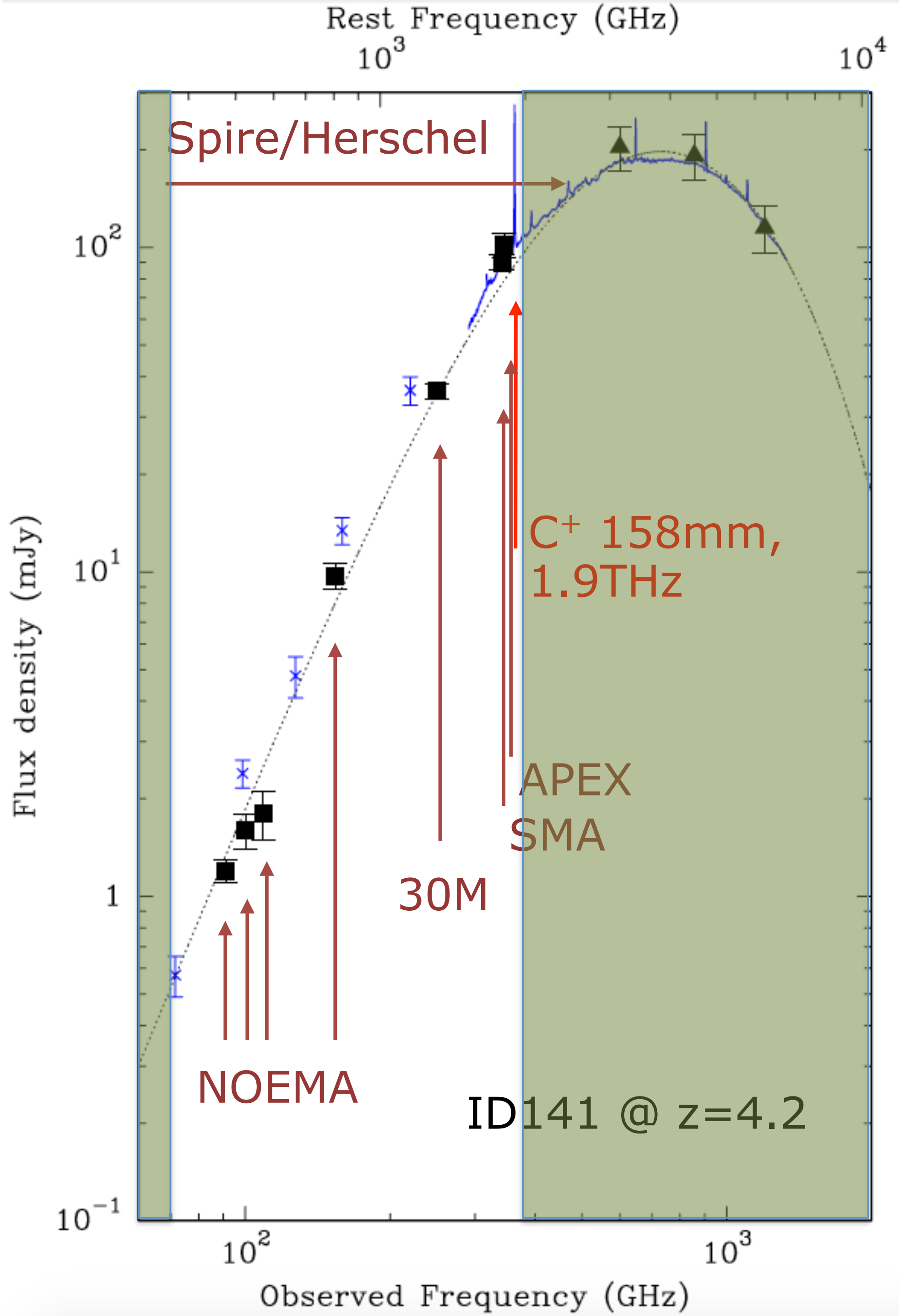
Cox et al. 2011

Detection of several CO transitions allows to determine redshift z=4.243

$v = v_0/(1+z)$
CO 4-3:
460/(1+4.243)
= 87.7

[CII]:
1900/(1+4.243)
= 362.45



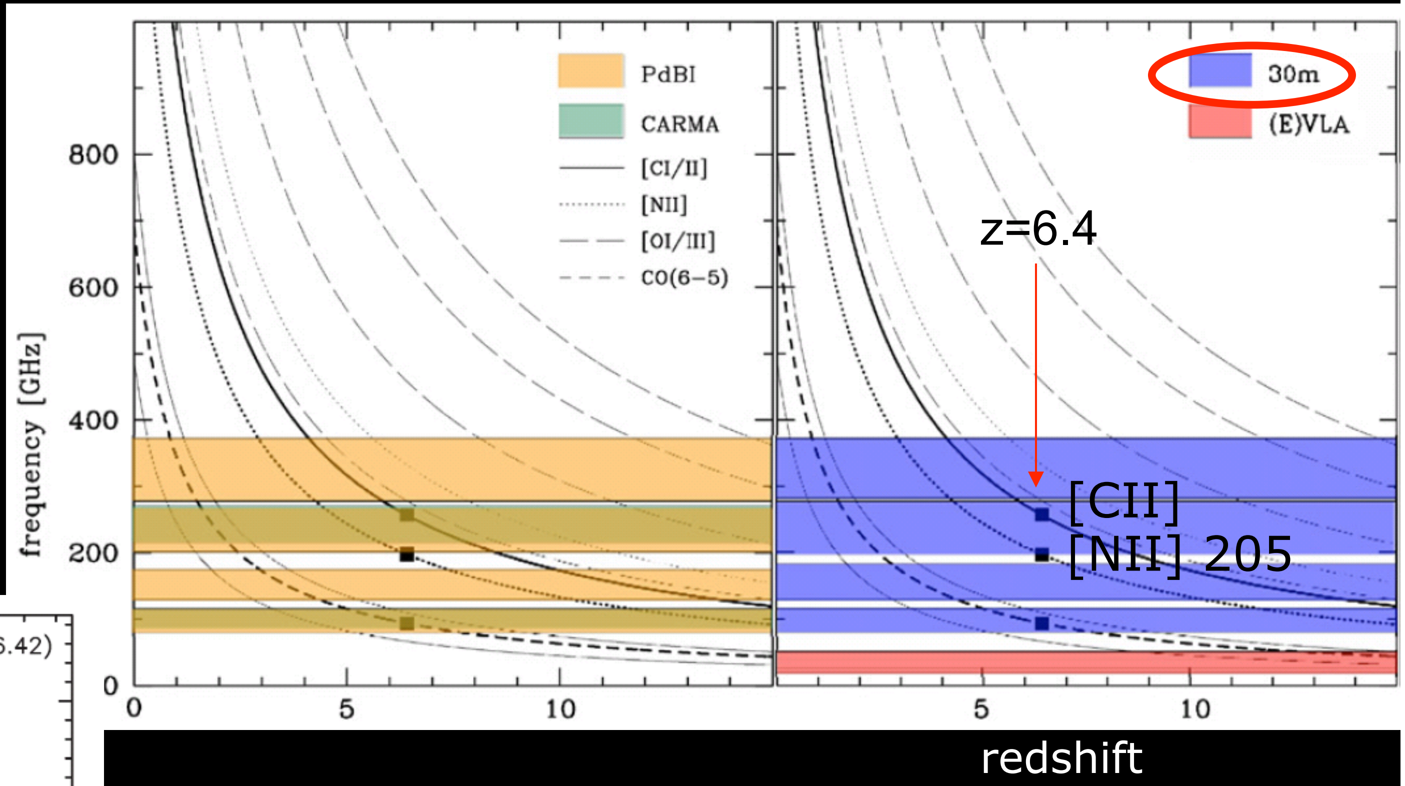


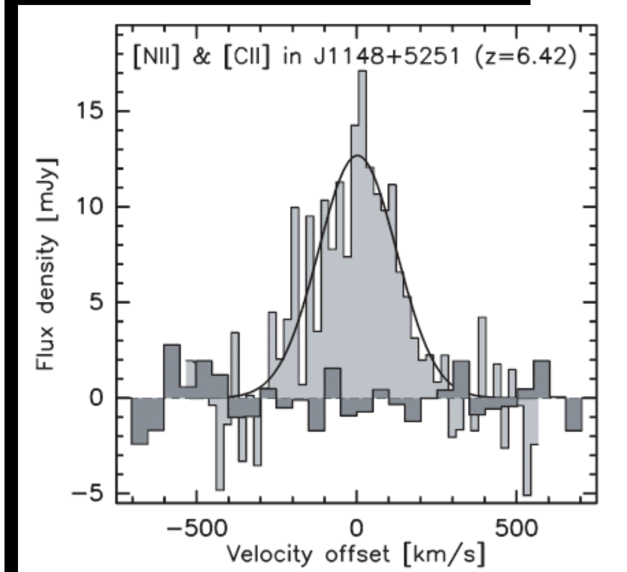
Spectral energy distributions (SEDs)

Continuum:
Best fit of a single component optically thin grey body gives T_{dust}=38 K and b=1.7.

Blue stars: M82 (shifted & scaled)
Blue line: ISO/LWS scan

Observations of the fine structure lines of C^+ and N^+ with the IRAM observatories



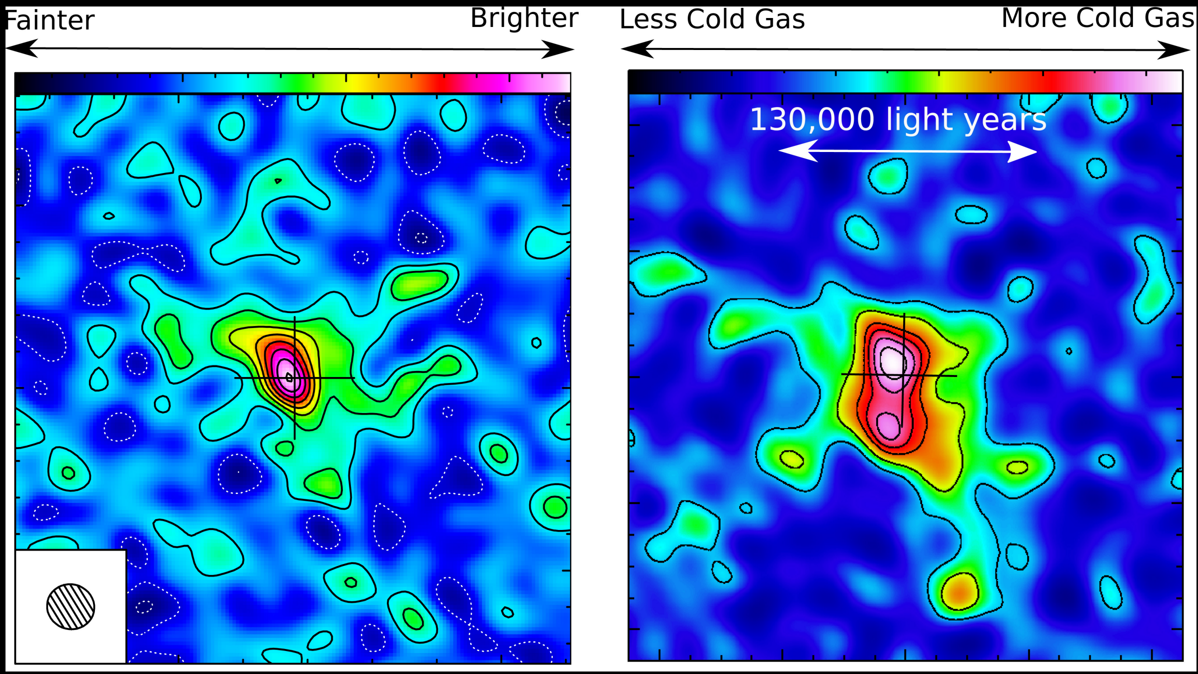


$n = n_0/(1+z) = 1.9\text{THz}/(1+6.4) = 256\text{GHz}$ for [CII]

$n = n_0/(1+z) = 1.46\text{THz}/(1+6.4) = 197\text{GHz}$ for [NII]

Walter et al. 2009

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



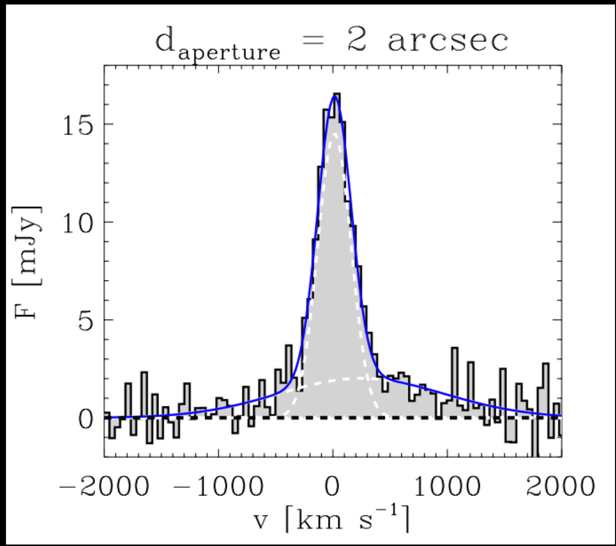
observations

simulations

[CII] @ 256 GHz / NOEMA

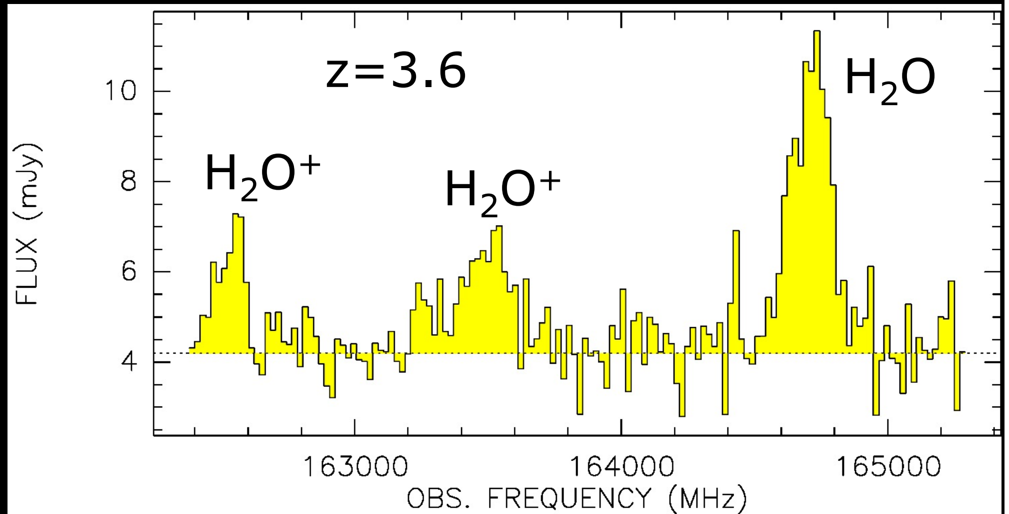
- CII @ 2000 km/s!
- 100 Myr old CII outflow
- CII up to 30 kpc

Cicone et al. 2015

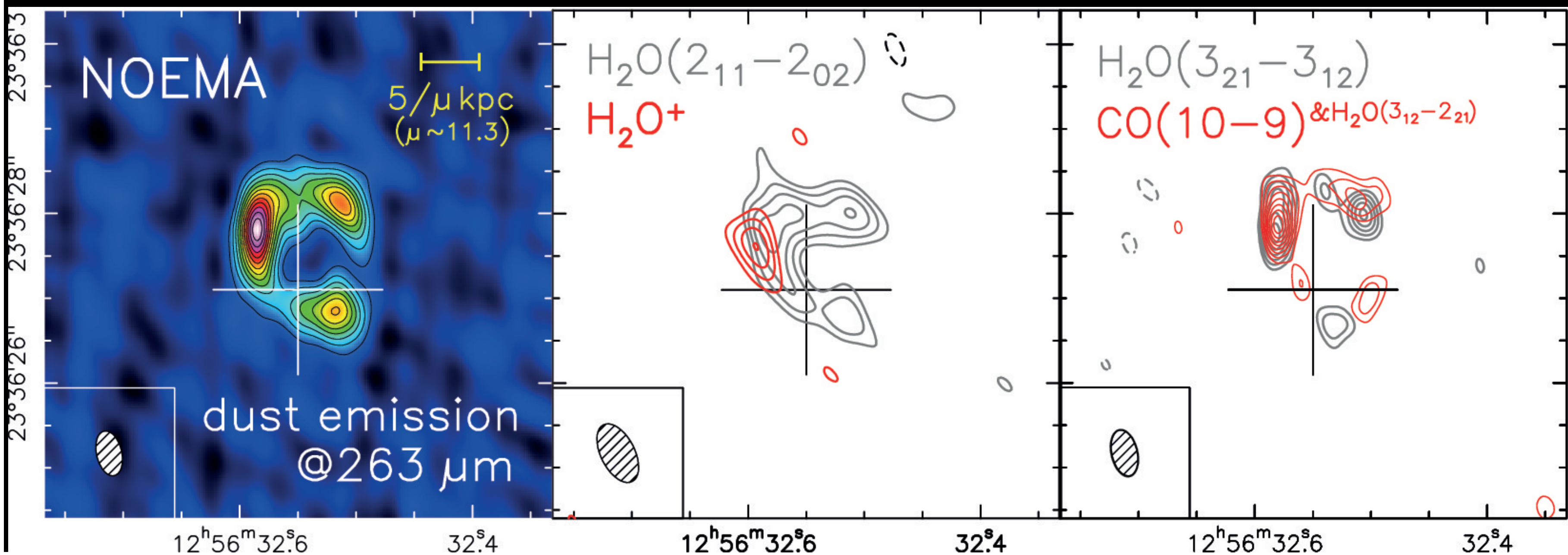


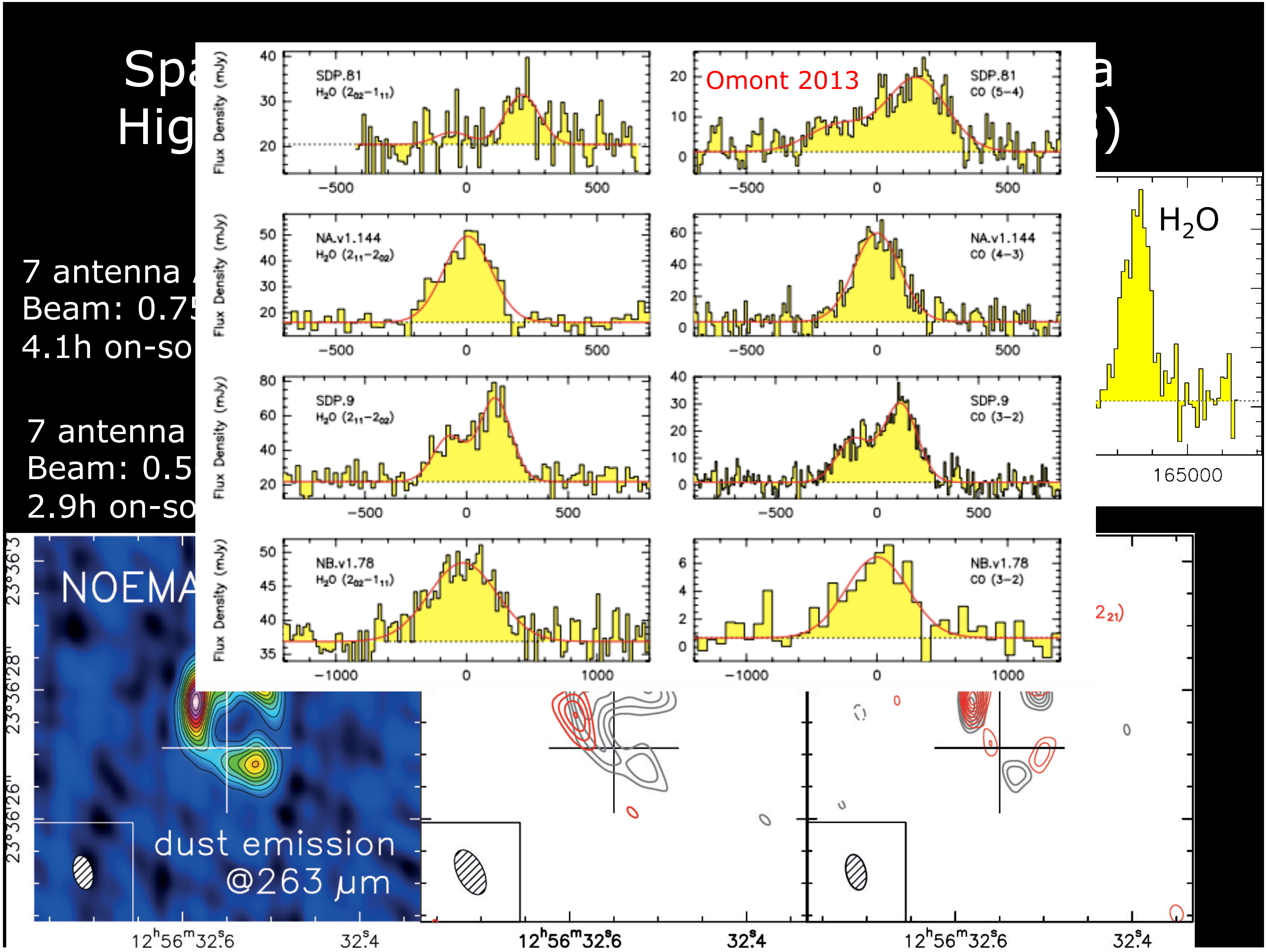
Spatial Distribution of H_2O Emission in a High-z Lensed Herschel Galaxy (NC.143)

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



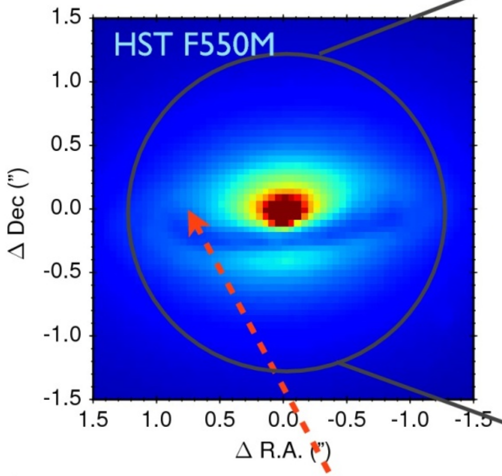


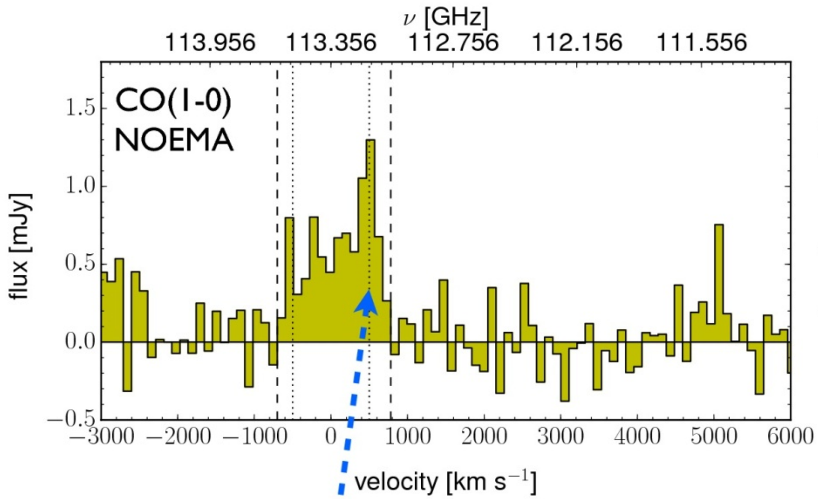
Omont 2013
SDP.81
H2O (202–111)
SDP.81
CO (5–4)
NA.v1.144
H2O (211–202)
NA.v1.144
CO (4–3)
SDP.9
H2O (211–202)
SDP.9
CO (3–2)
NB.v1.78
H2O (202–111)
NB.v1.78
CO (3–2)
Flux Density (mJy)
H2O
165000
NOEMA
dust emission
@263 μm
12h56m32.6
32.4

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)

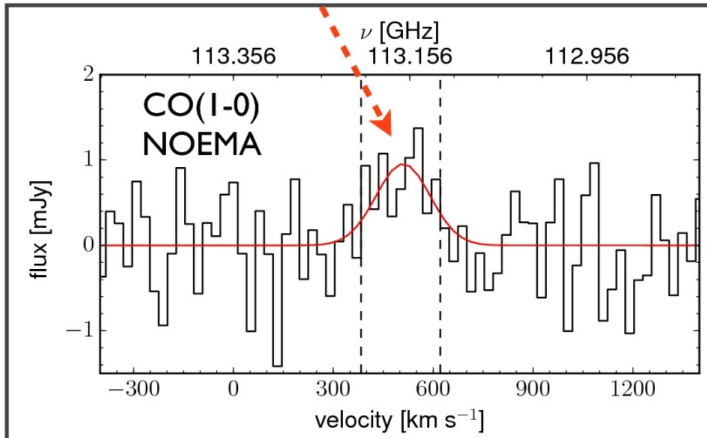




2.5" resolution

➡ 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