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Science with ALMA Band 2/2+3

Gary Fuller

Jodrell Bank Centre For Astrophysics
&
UK ALMA Regional Centre Node
University of Manchester

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UNIVERSITY OF OXFORD
UNIVERSITY OF CAMBRIDGE
UK Astronomy Technology Centre
Rutherford Appleton Laboratory
Science & Technology Facilities Council

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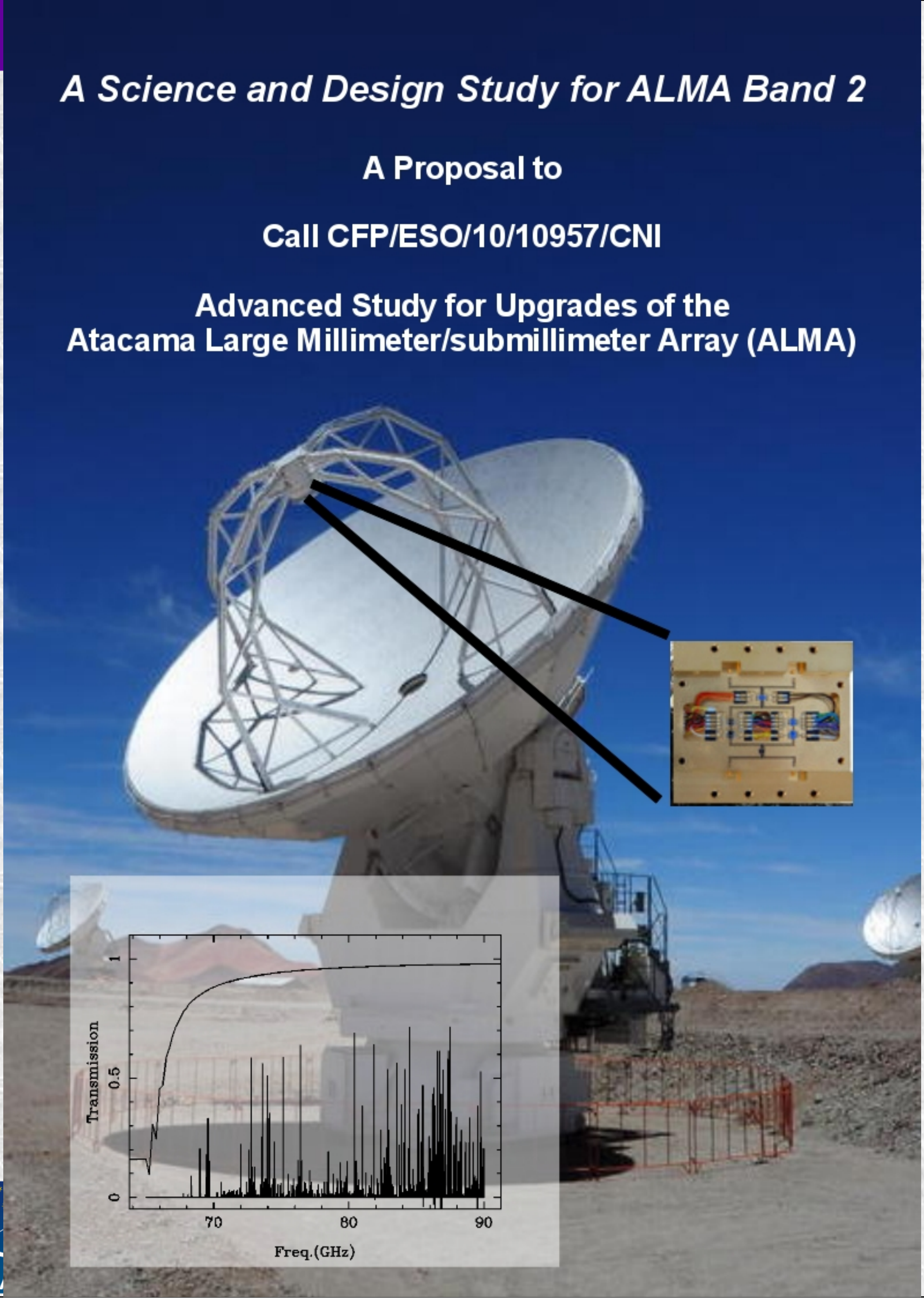

A Science and Design Study for ALMA Band 2

A Proposal to

Call CFP/ESO/10/10957/CNI

Advanced Study for Upgrades of the
Atacama Large Millimeter/submillimeter Array (ALMA)

PI: Gary Fuller

Collaboration:

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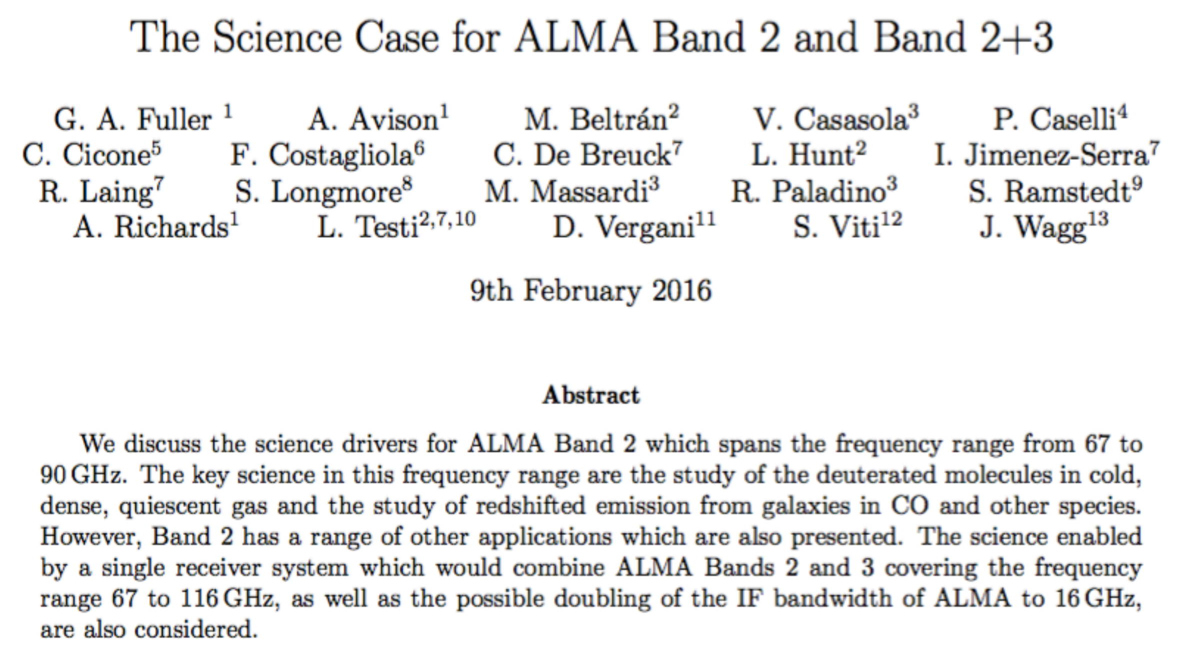
INAF

Science & Technology Facilities Council
Rutherford Appleton Laboratory

iram
Institut de
Radioastronomie
Millimétrique

Science Case



The Science Case for ALMA Band 2 and Band 2+3

G. A. Fuller [1] A. Avison[1] M. Beltrán[2] V. Casasola[3] P. Caselli[4]
C. Cicone[5] F. Costagliola[6] C. De Breuck[7] L. Hunt[2] I. Jimenez-Serra[7]
R. Laing[7] S. Longmore[8] M. Massardi[3] R. Paladino[3] S. Ramstedt[9]
A. Richards[1] L. Testi[2,7,10] D. Vergani[11] S. Viti[12] J. Wagg[13]

9th February 2016

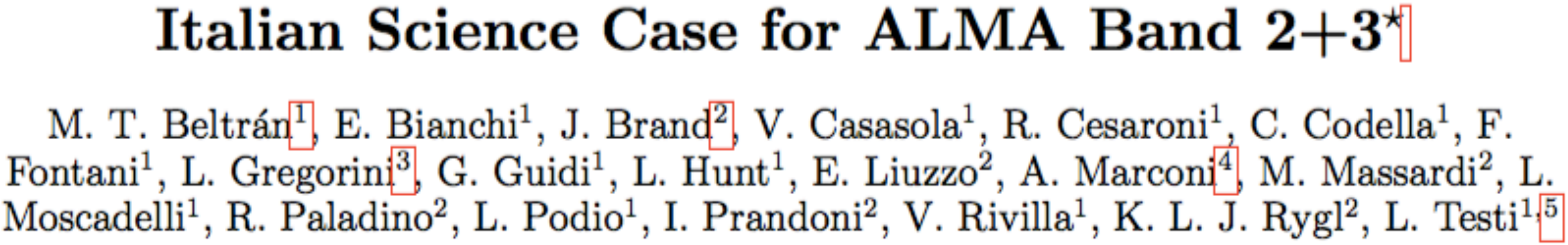
Abstract

We discuss the science drivers for ALMA Band 2 which spans the frequency range from 67 to 90 GHz. The key science in this frequency range are the study of the deuterated molecules in cold, dense, quiescent gas and the study of redshifted emission from galaxies in CO and other species. However, Band 2 has a range of other applications which are also presented. The science enabled by a single receiver system which would combine ALMA Bands 2 and 3 covering the frequency range 67 to 116 GHz, as well as the possible doubling of the IF bandwidth of ALMA to 16 GHz, are also considered.

arXiv:1602.02414

Affiliations

[1] Jodrell Bank Centre for Astrophysics & UK ALMA Regional Centre Node, School of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK
[2] INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
[3] INAF - IRA & Italian ALMA Regional Centre Via P. Gobetti 101, 40129 Bologna, Italy
[4] Max-Planck-Institut für extraterrestrische Physik Giessenbachstrasse 1, 85748 Garching, Germany
[5] Cavendish Laboratory, University of Cambridge, 19 J.J. Thomson Avenue, Cambridge CB3 0HE,UK; Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
[6] Instituto de Astrofísica de Andalucía, Glorieta de la Astronomía s/n, Granada, 18008, Spain
[7] European Southern Observatory (ESO), Karl-Schwarzschild-Str. 2, 85748, Garching, Germany
[8] Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK
[9] Department of Physics and Astronomy, Uppsala University, Box 516, 751 20, Uppsala, Sweden
[10] Excellence Cluster Universe, Boltzman str. 2, D-85748 Garching bei Muenchen, Germany
[11] INAF Osservatorio Astronomico di Bologna, via C. Ranzani 1, 40127, Bologna, Italy
[12] Department of Physics and Astronomy, University College London, WC1E 6BT London, UK
[13] Square Kilometre Array Organisation, Jodrell Bank Observatory, Lower Withington Macclesfield Cheshire, SK11 9DL, UK



Italian Science Case for ALMA Band 2+3[*]

M. T. Beltrán[1], E. Bianchi[1], J. Brand[2], V. Casasola[1], R. Cesaroni[1], C. Codella[1], F. Fontani[1], L. Gregorini[3], G. Guidi[1], L. Hunt[1], E. Liuzzo[2], A. Marconi[4], M. Massardi[2], L. Moscadelli[1], R. Paladino[2], L. Podio[1], I. Prandoni[2], V. Rivilla[1], K. L. J. Rygl[2], L. Testi[1,5]

2015 arXiv:1509.02702

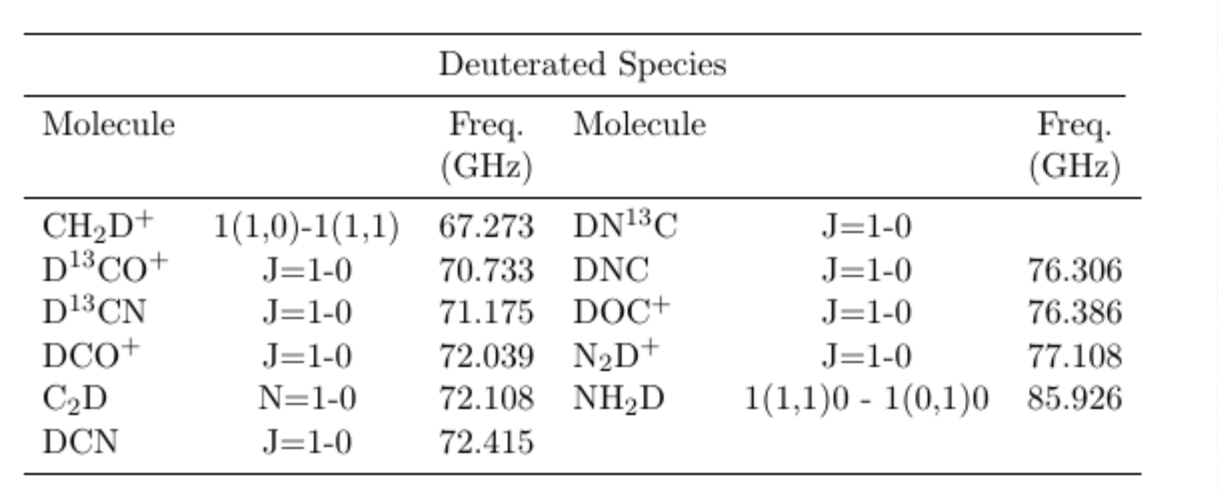
Level 1 Science Drivers

- Cold, dense, quiescent gas
  - Deuterated species J=1-0 transitions
- Closing the redshift desert
- Galaxy evolution

Level 2 Science Cases

- Finding protogalaxies
- Ignition of young massive stars
- From grains to planets
- Mixing in evolved stars
- VLBI
- Cold complex chemistry

Cold, Dense, Quiescent Gas: D-containing Species in Band 2



Deuterated Species

Molecule		Freq. (GHz)	Molecule		Freq. (GHz)
CH_2D^+	1(1,0)-1(1,1)	67.273	$DN^{13}C$	J=1-0	
$D^{13}CO^+$	J=1-0	70.733	DNC	J=1-0	76.306
$D^{13}CN$	J=1-0	71.175	DOC^+	J=1-0	76.386
DCO^+	J=1-0	72.039	N_2D^+	J=1-0	77.108
C_2D	N=1-0	72.108	NH_2D	1(1,1)0 - 1(0,1)0	85.926
DCN	J=1-0	72.415			

Deuteration

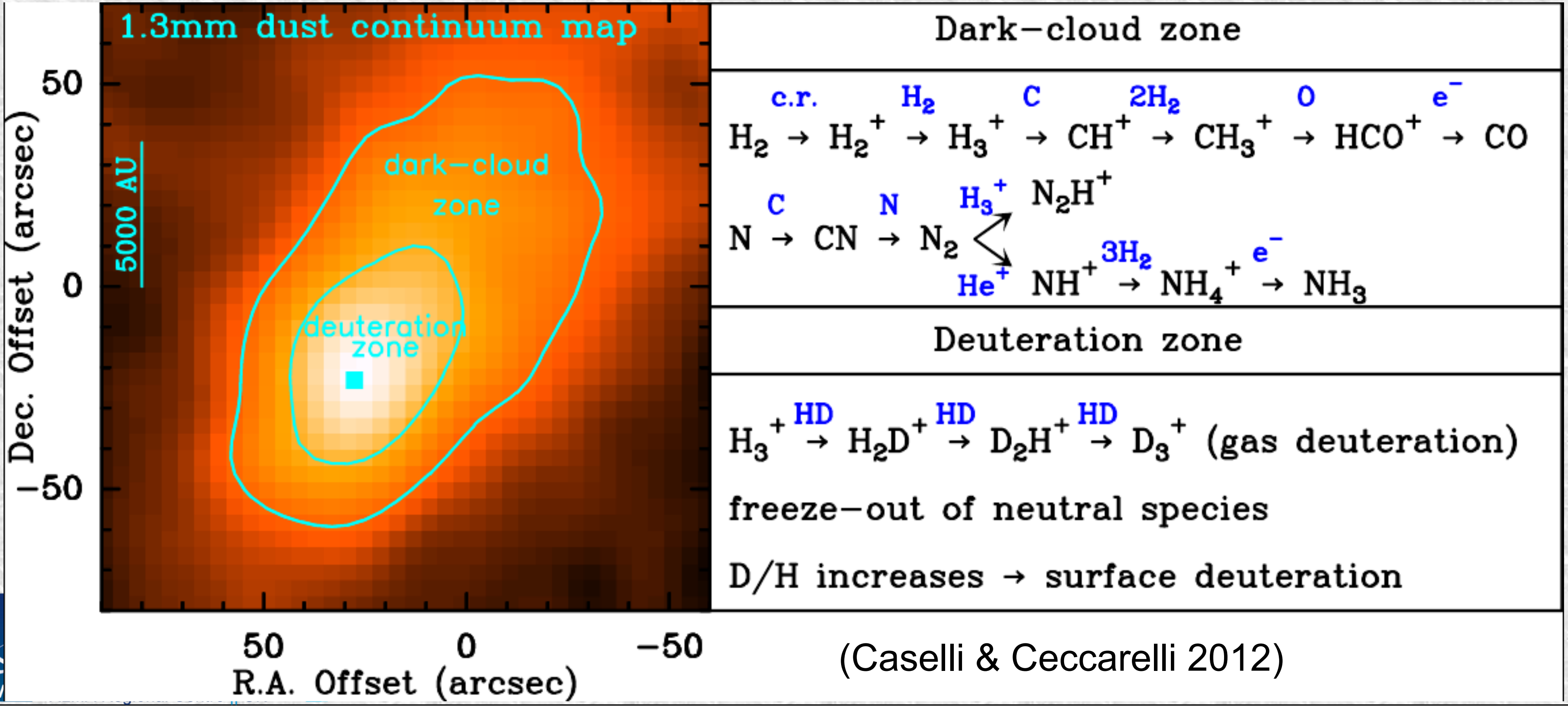
At T<20K

$$H_3^+ + HD \rightarrow H_2D^+ + H_2 + 230K$$

$$H_2D^+ + N_2 \rightarrow N_2D^+ + H_2$$

$$H_2D^+ + CO \rightarrow DCO^+ + H_2$$

~10^5 enhancement over cosmic [D/H] of 10^{-5}



Dark−cloud zone

$$H_2 \xrightarrow{c.r.} H_2^+ \xrightarrow{H_2} H_3^+ \xrightarrow{C} CH^+ \xrightarrow{2H_2} CH_3^+ \xrightarrow{O} HCO^+ \xrightarrow{e^-} CO$$

$$N \xrightarrow{C} CN \xrightarrow{N} N_2 \xrightarrow{H_3^+} N_2H^+$$

$$N_2 \xrightarrow{He^+} NH^+ \xrightarrow{3H_2} NH_4^+ \xrightarrow{e^-} NH_3$$

Deuteration zone

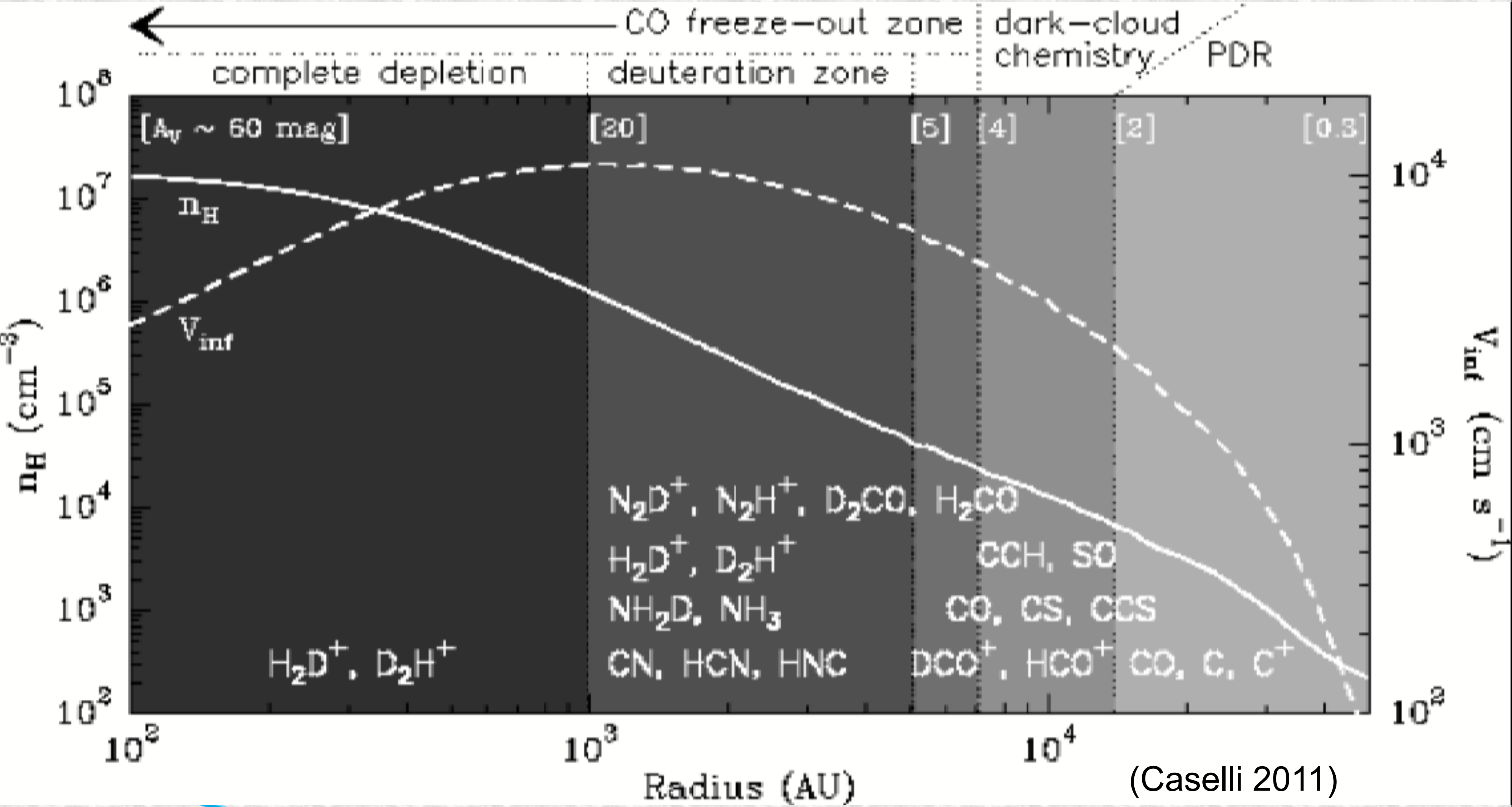
$H_3^+ \xrightarrow{HD} H_2D^+ \xrightarrow{HD} D_2H^+ \xrightarrow{HD} D_3^+$ (gas deuteration)

freeze−out of neutral species

D/H increases → surface deuteration

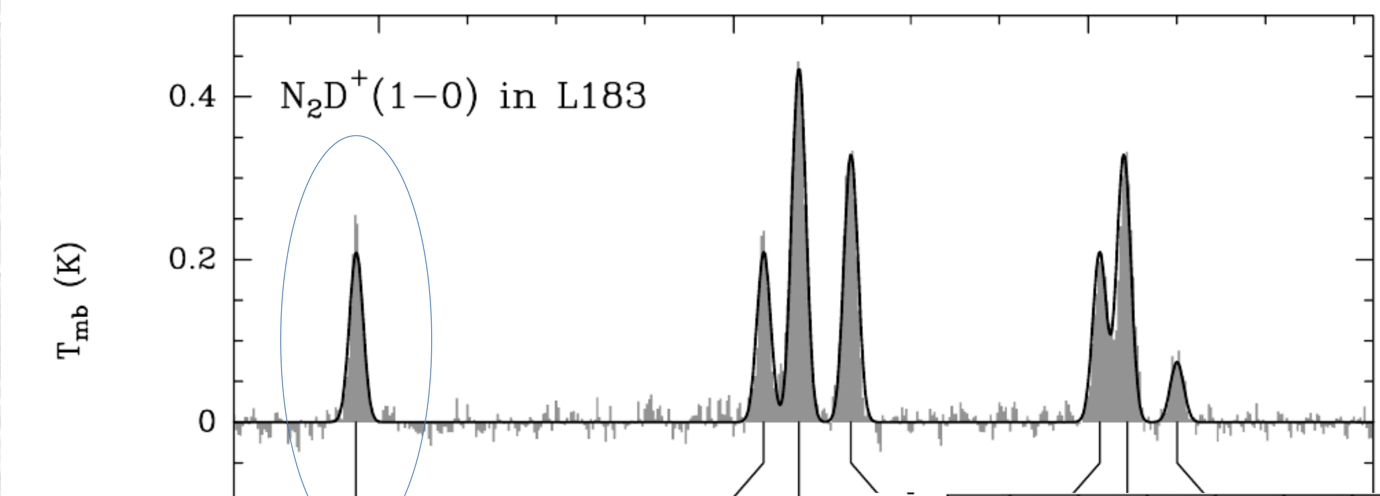
(Caselli & Ceccarelli 2012)

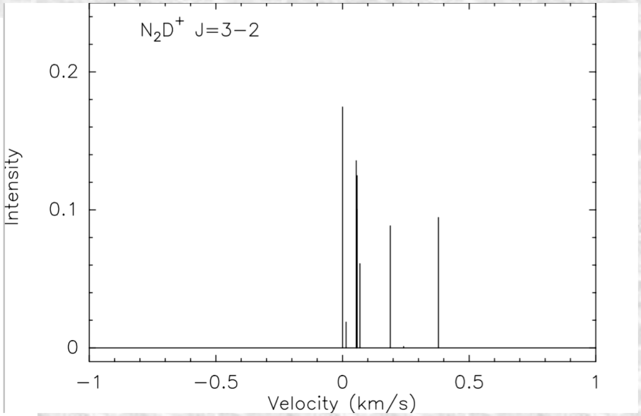
Pre-Stellar Core

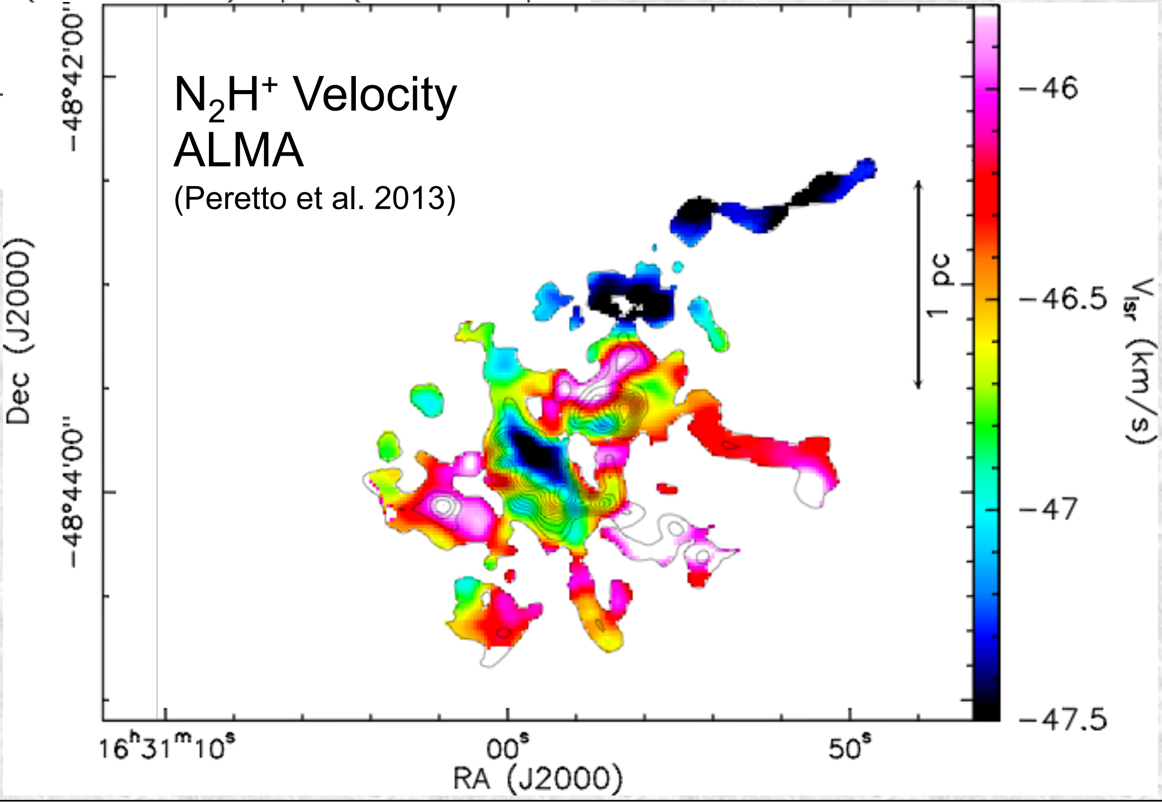


(Caselli 2011)

N_2D^+ J=1-0, 77.1 GHz

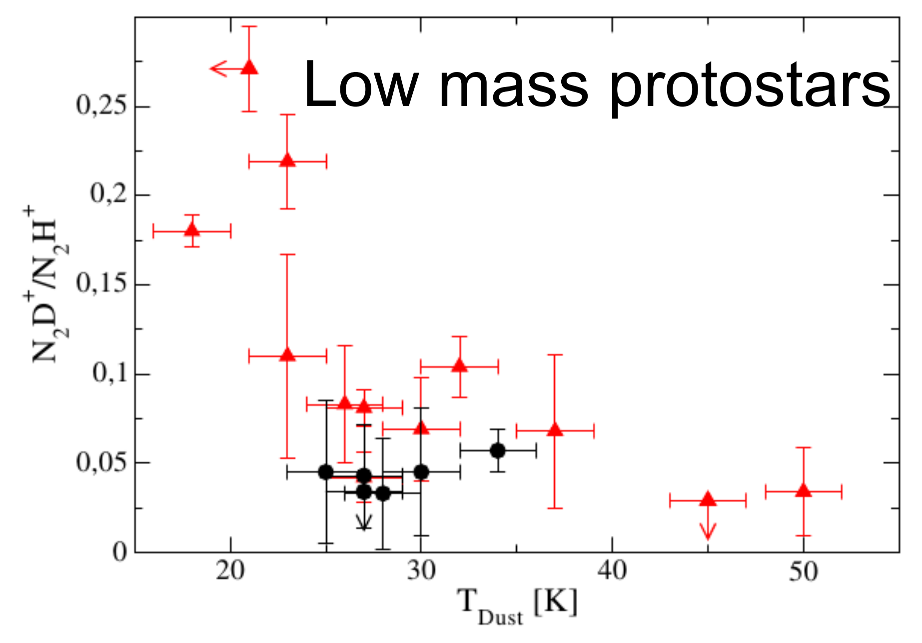





N_2H^+ Velocity
ALMA
(Peretto et al. 2013)

Isolated hyperfine component – sensitive probe of velocity and turbulence.

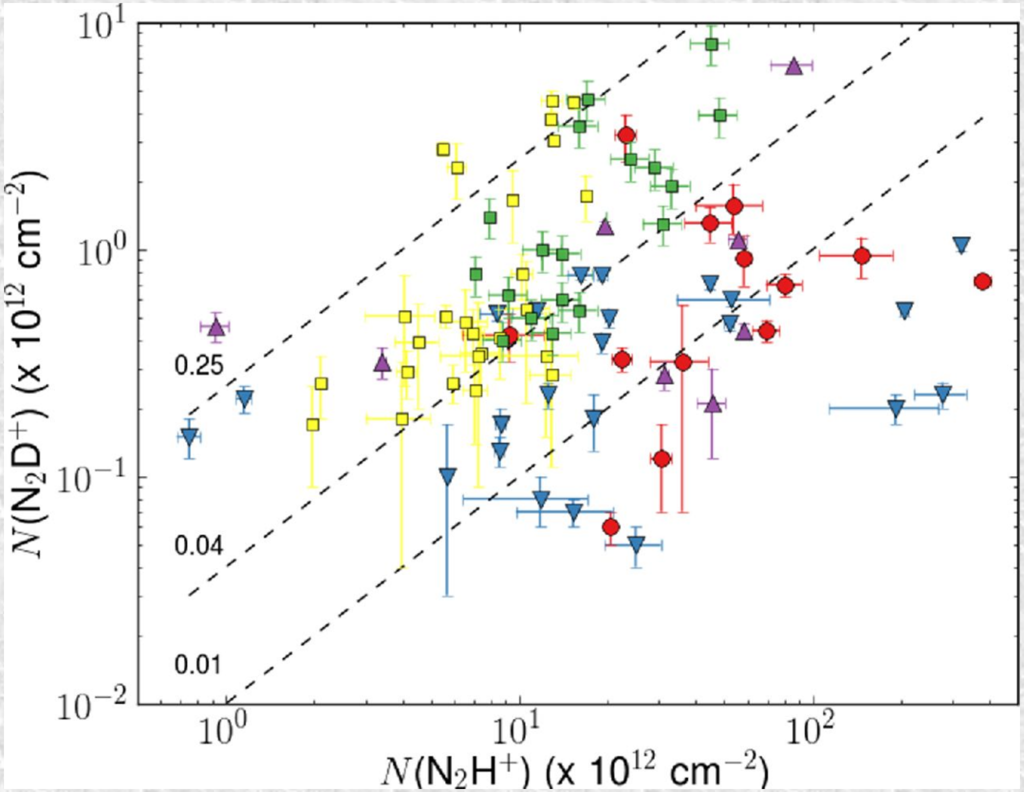
Evolution



Low mass protostars

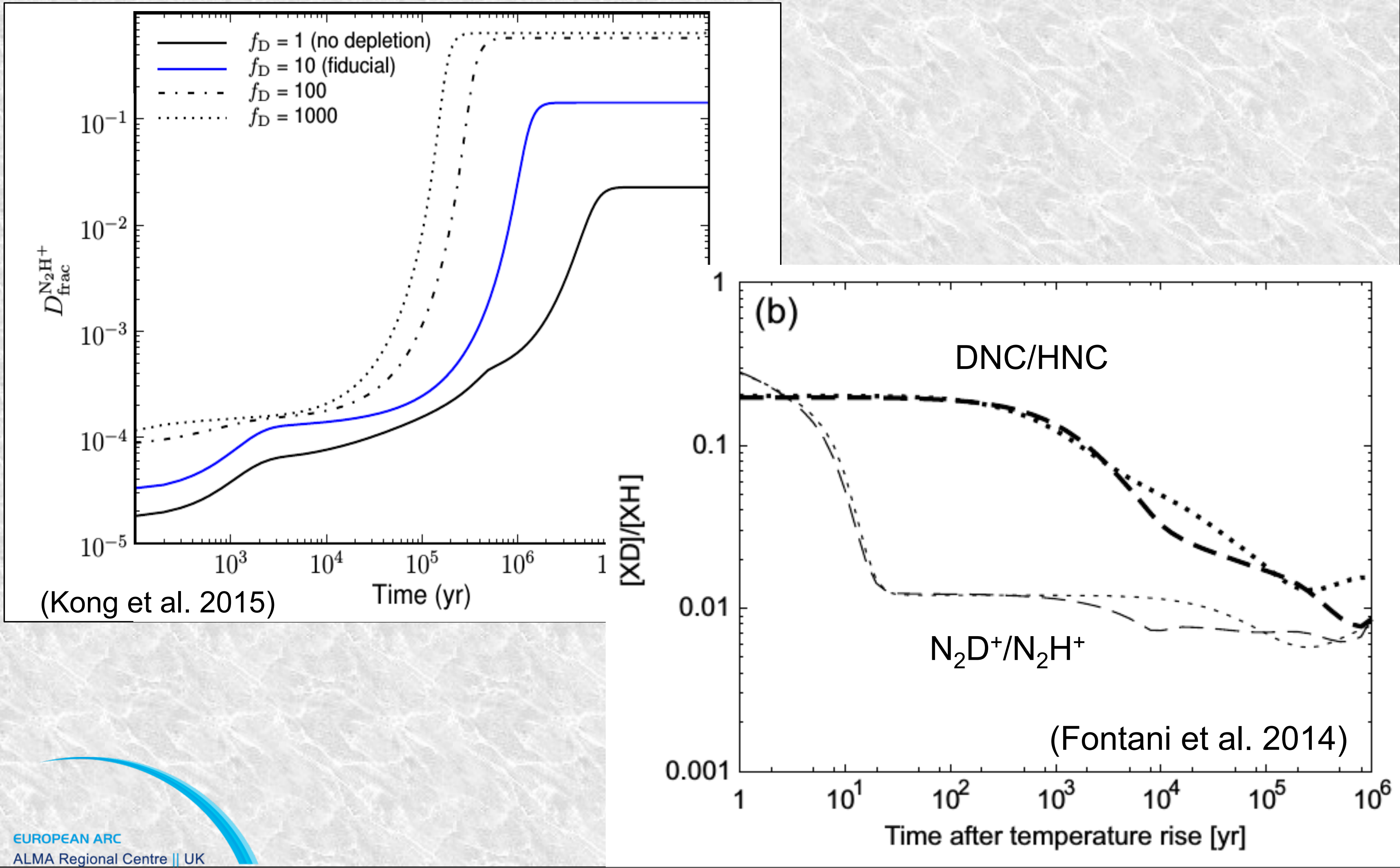
M. Emprechtinger et al 2009

Low & high mass protostars & cores



Matias Lackington et al. MNRAS 2016;455:806-819

Evolution of Deuterium Species

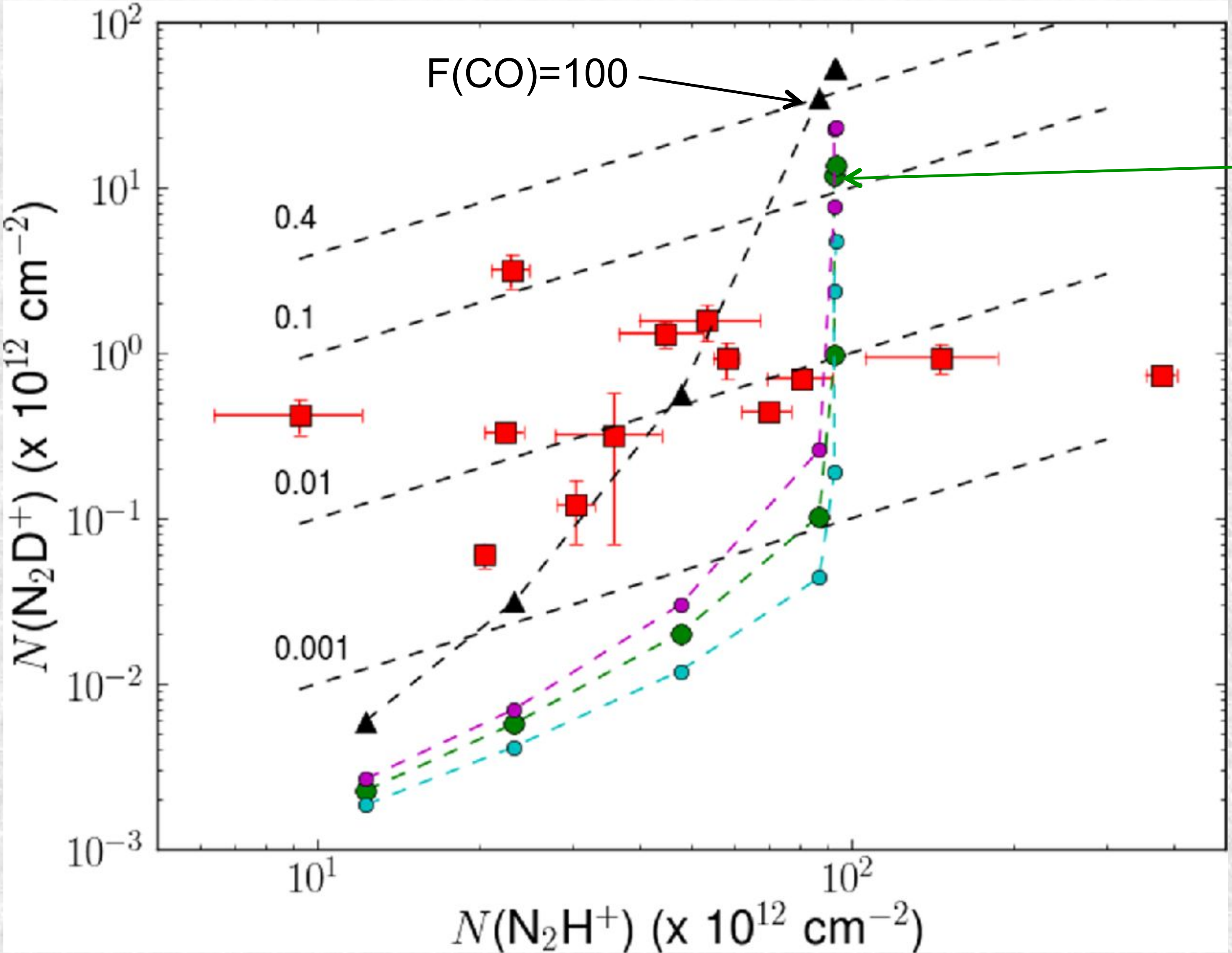


(Kong et al. 2015)

(Fontani et al. 2014)

Timescales

Matias Lackington et al. MNRAS 2016;455:806-819



Kong et al 2015
Fiducial model
F(CO)=10
n=10^4 cm^{-3}
n=10^5 cm^{-3}
n=10^6 cm^{-3}

Time markers:
5x10^4 y
10^5 y
2x10^5 y
to 3.2x10^6 y

Regions <few free-fall times old – Dynamically young

Applications of D Species

- Evolutionary history of gas
  - Classification of massive protostars
- Kinematics of gas on the verge of collapse
- CO snowline in proto-planetary disks
- Tracing ionization
  - Gas-magnetic field coupling
  - Cosmic ray heating rates – galactic & extragalactic
- In solar system (and proto-planetary disks ?) trace transport of volatiles

Efficiency

Species: HCN, HCO^+, HNC, N_2H^+
DCN, DCO^+, DNC, N_2D^+

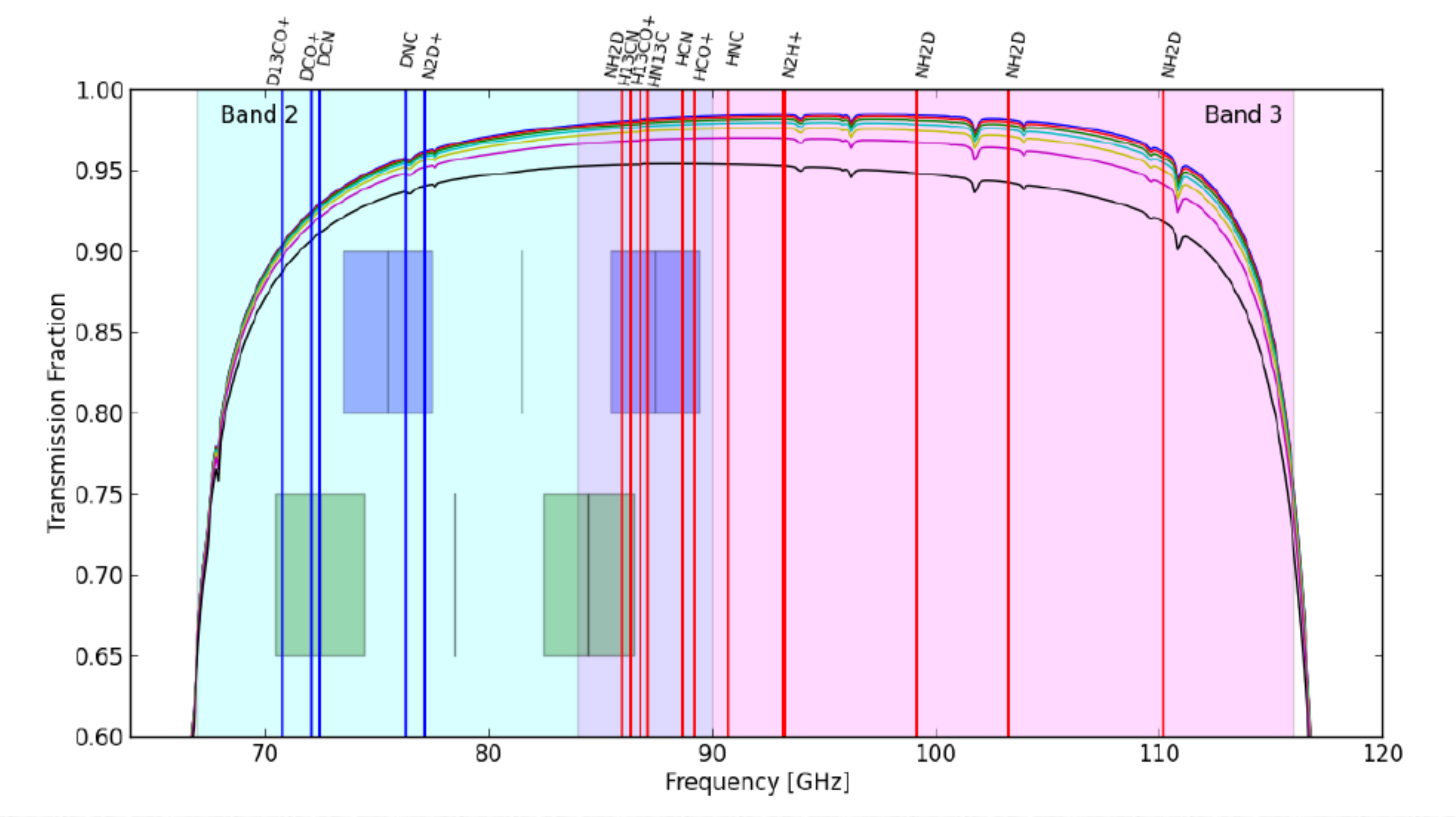
Band	**Number of Lines**	**D Species**	**Deuteration ratios**
2+3	5	2	DNC/HNC
4	3	3	–
5	2	0	–
6	4	4	–
7	4	2	–

8 GHz 2SB

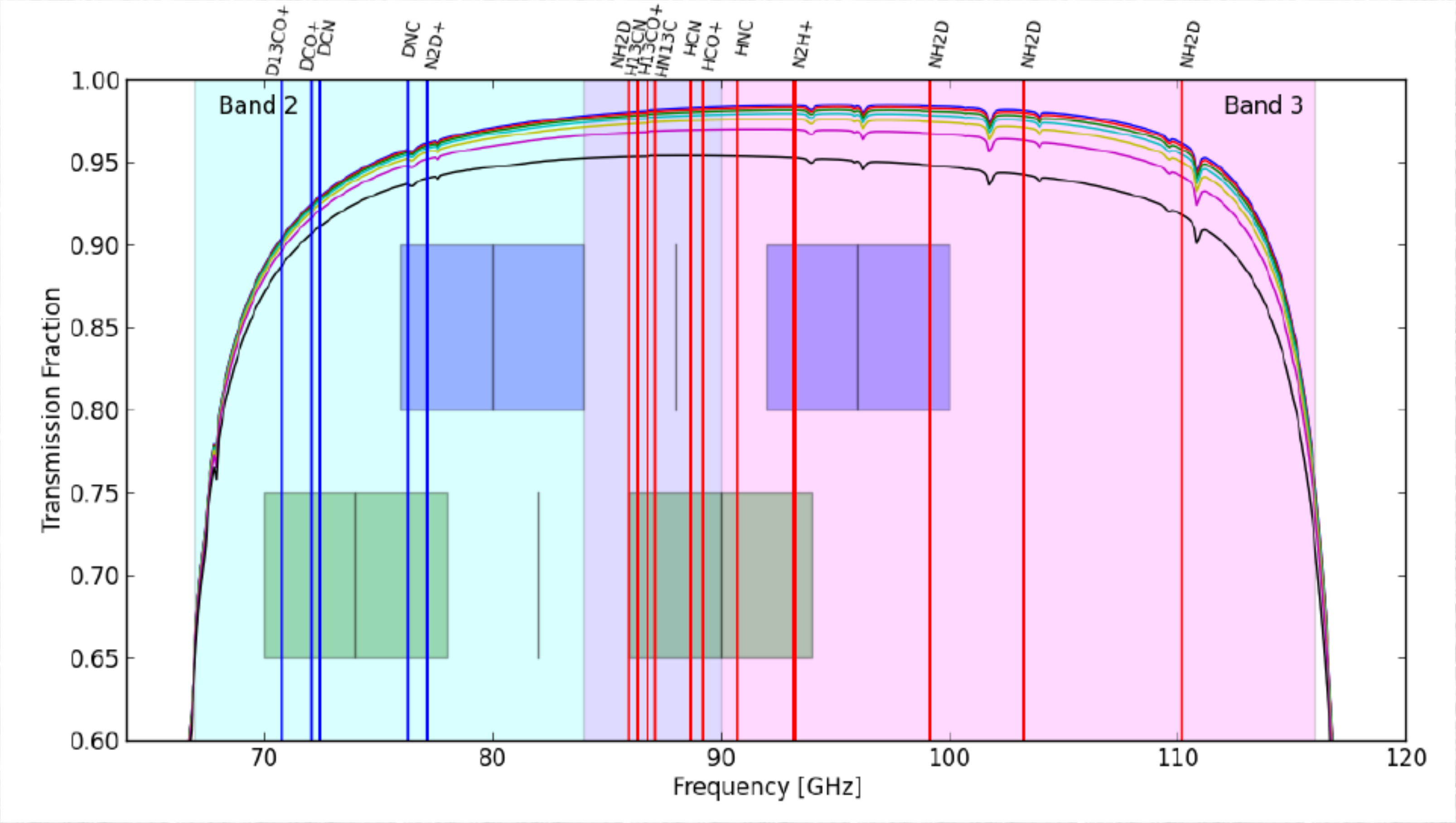
16 GHz 2SB

Band	**Number of Lines**	**D Species**	**Deuteration ratios**
2+3	8	4	DNC/HNC, N2D+/ N2H+ DCO+/HCO+ DCN/HCN
4	3	3	–
5	3	0	–
6	4	4	–
7	5	2	–

Observing D Species 'Now'



Observing D Species In The Future

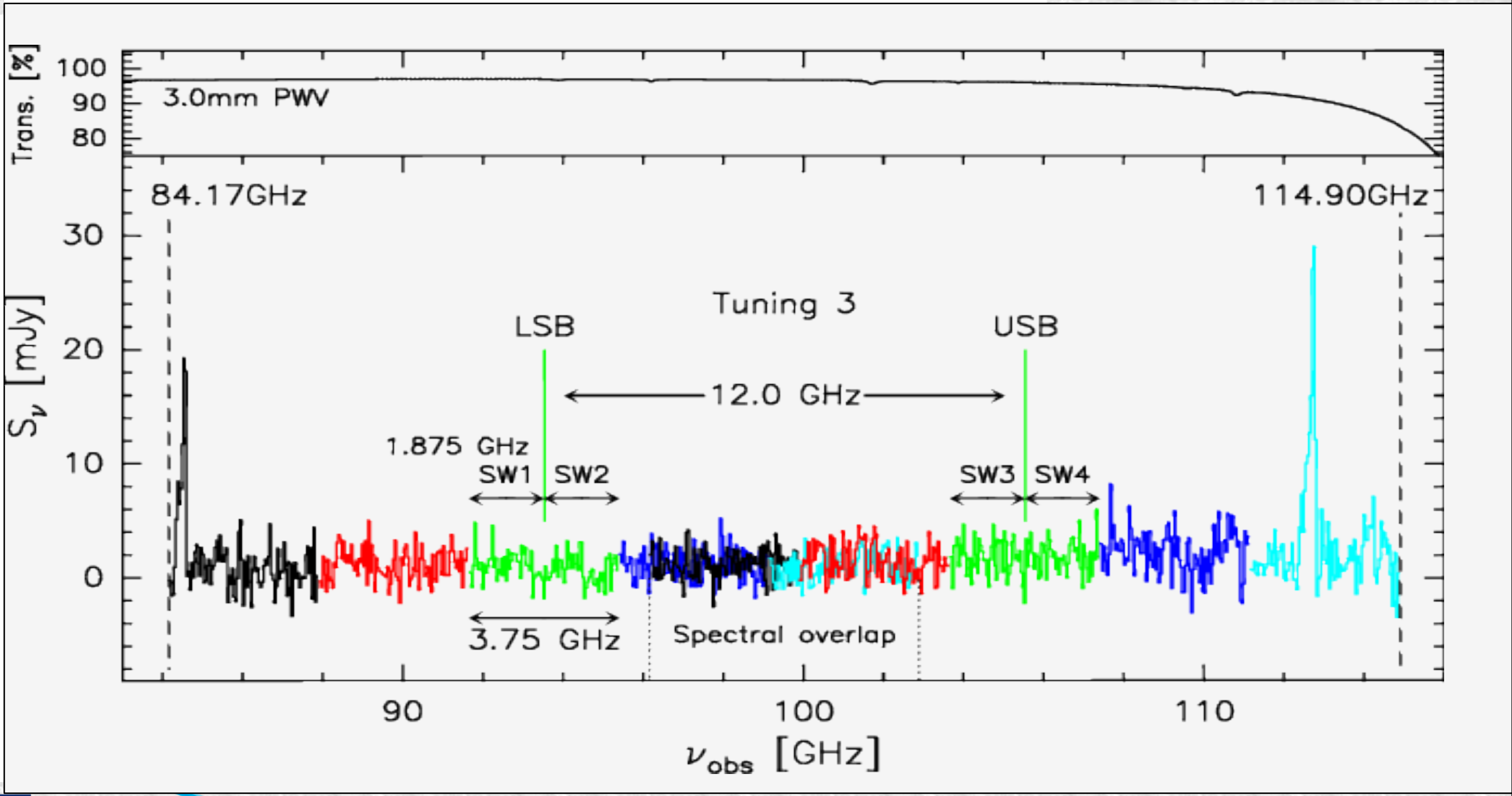


Band 2+3 uniquely rich in deuterium transitions.

Extragalactic Science

- Redshift searches
- Running down the molecular reservoir
- Evolution of the star forming gas & outflows
- Galaxy environment

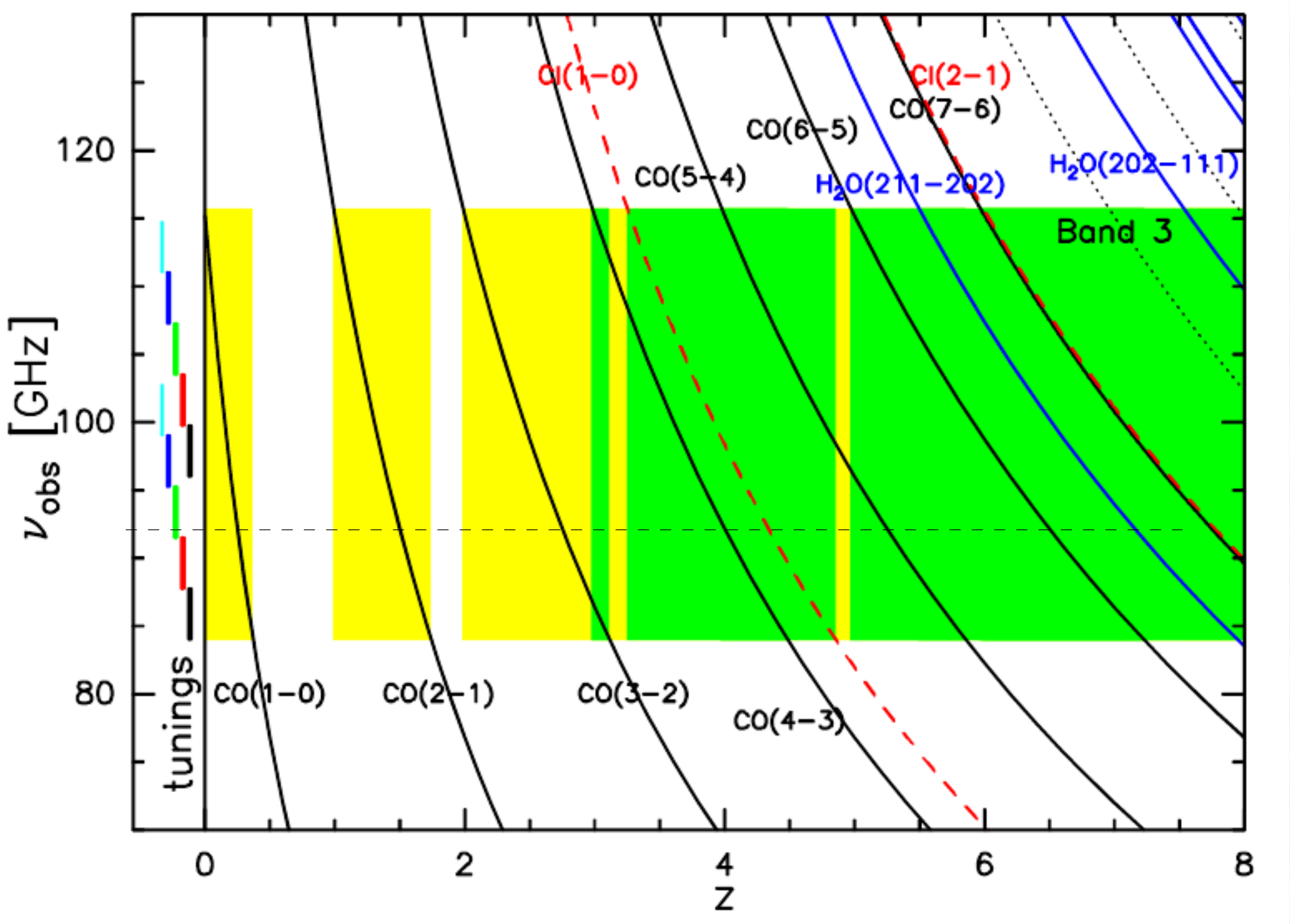
Redshift Searches



(Weiss et al 2013)

Band 3 only: Desert 0.37<z<0.99, 1.74<z<2.0

Redshift Searches



2 lines:
Unambiguous redshifts

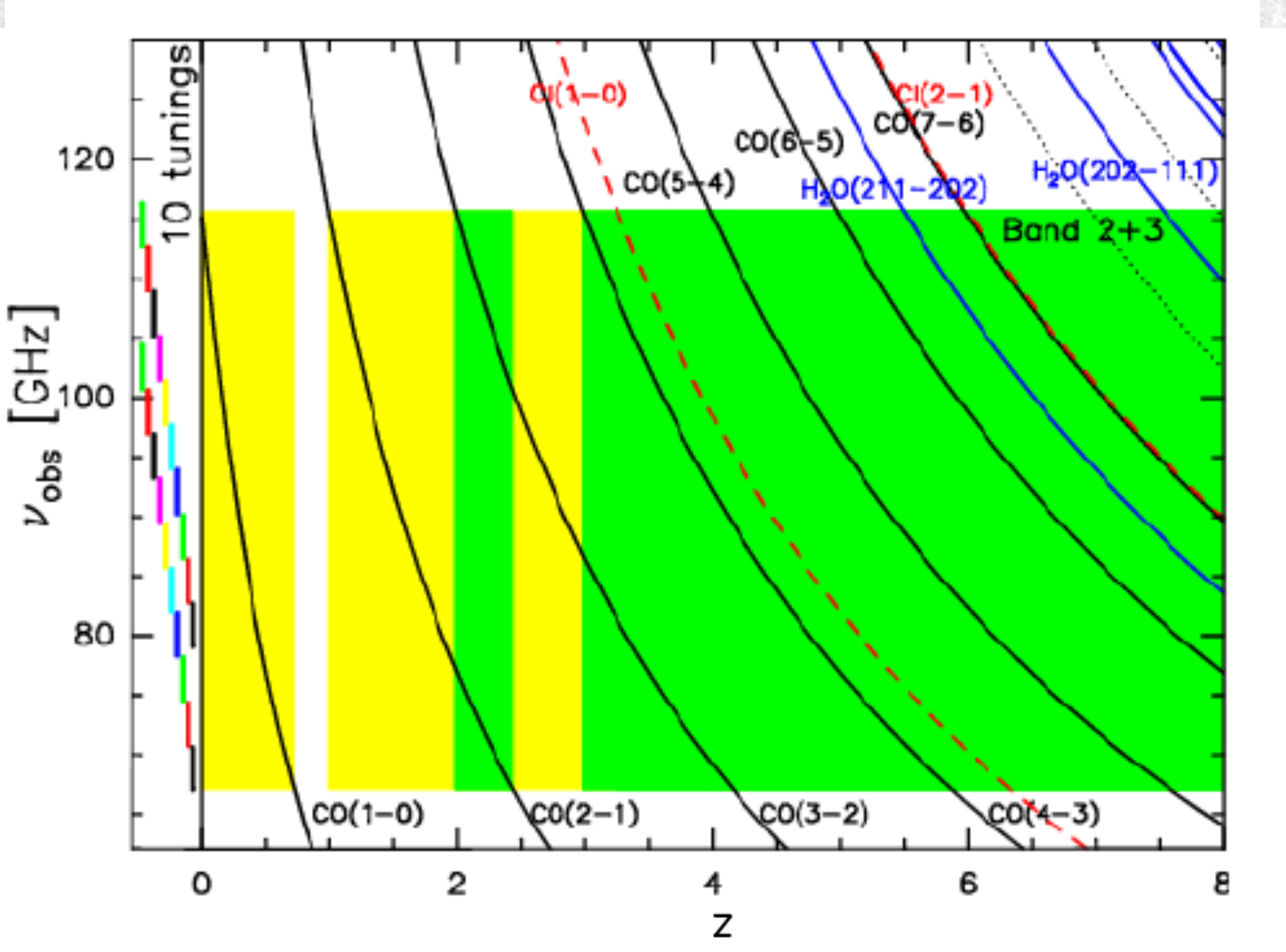
1 line

Coverage well matched to distribution of dusty galaxies. Implies increase success rate from ~70% to ~100% I surveys compared to 50% for optical surveys.

(Weiss et al 2013)

Band 3 only: Desert 0.37<z<0.99, 1.74<z<2.0

Redshift Searches



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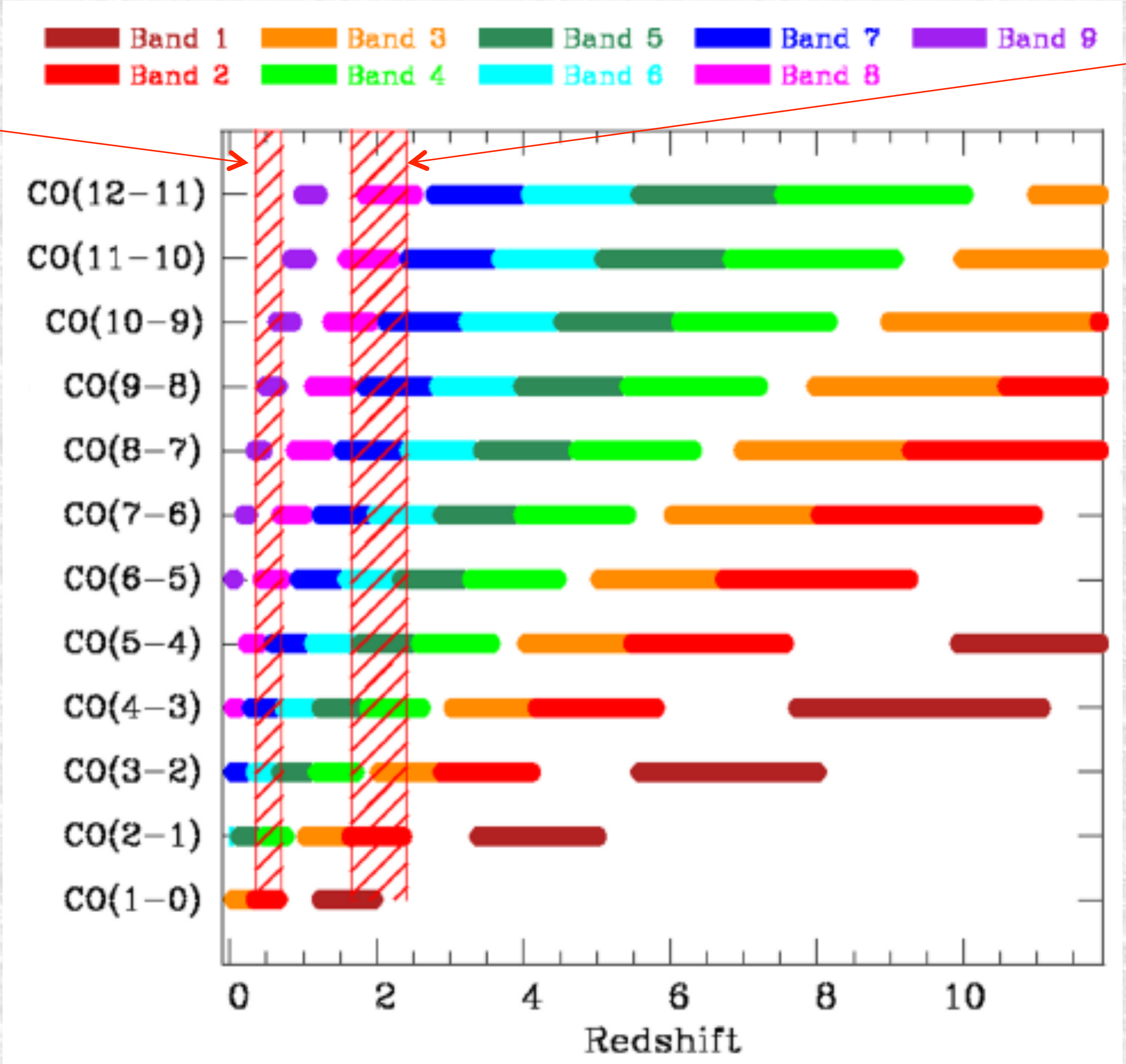
Running down the molecular reservoir

- Star formation peaks z~1-3 with factor 10 decline to z~0
- Corresponding factor 7 decline in molecular content z=2 to z=0, most quickly z<1
- How do galaxies evolve from peak to now?
- Varying excitation requires multiple CO transitions to determine mass
  - Need observations of the similar range of lines across z
  - Particularly low J transitions

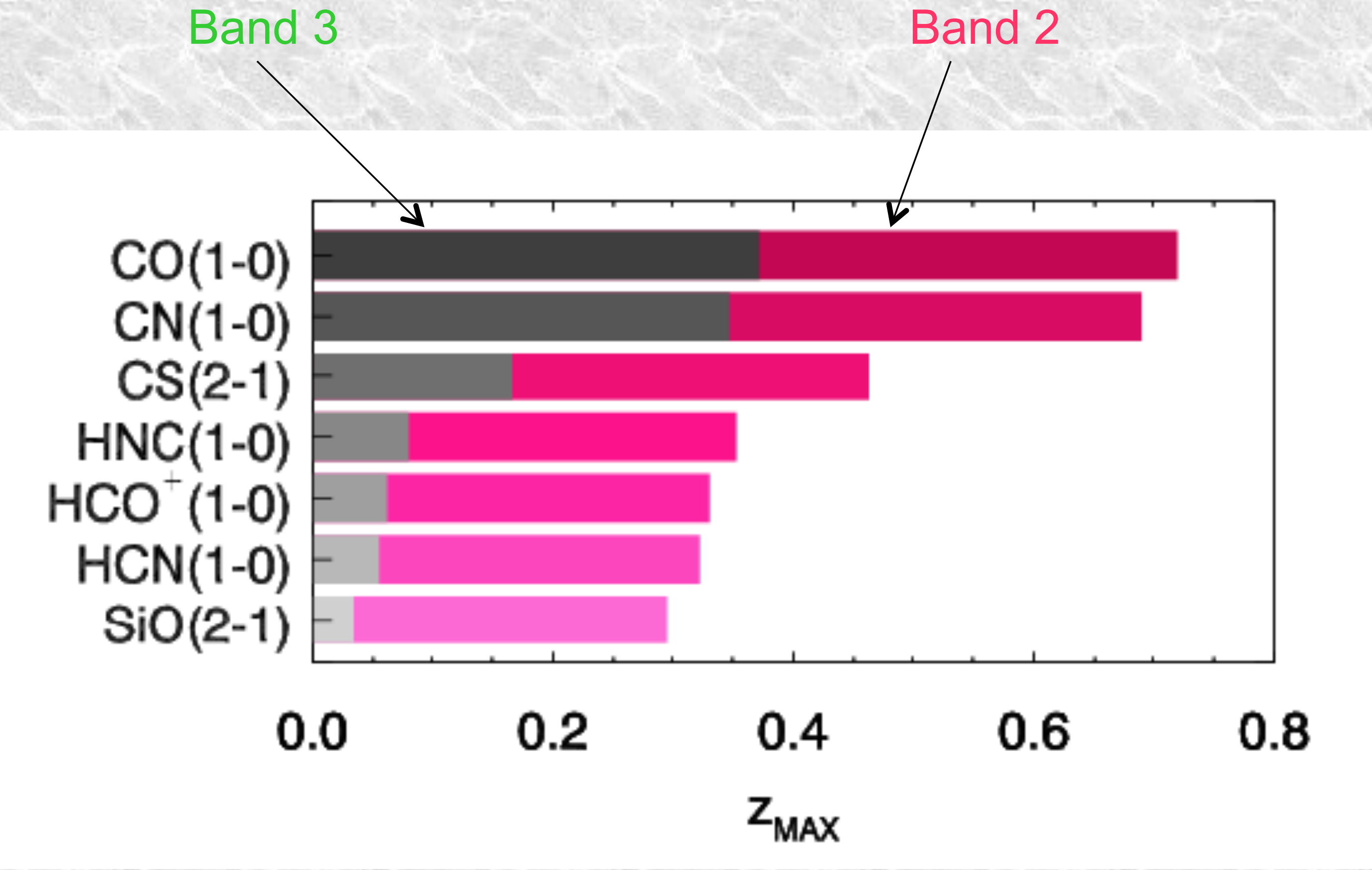


Last quarter

Peak of SFRD

Cluster and environmental effects – Larger primary beam an advantage

Tracing the dense gas



Increase volume accessible by factor ~200 to study objects rare in local universe but more representative of high z populations.

Feedback and outflows

Requirements

- 8+8 GHz 2SB system
  - D species but adds additional tuning for redshift surveys
- Sensitivity
  - 30K (37K) over 80% of band 2 (band 3)
  - Sufficient to image 10M$_o$ 10K gas fD=0.01 (at 4kpc) in DCO$^+$ J=1-0 with 1'' resolution, dv=0.1 km/s in 3 hr

Level 2 Science Cases

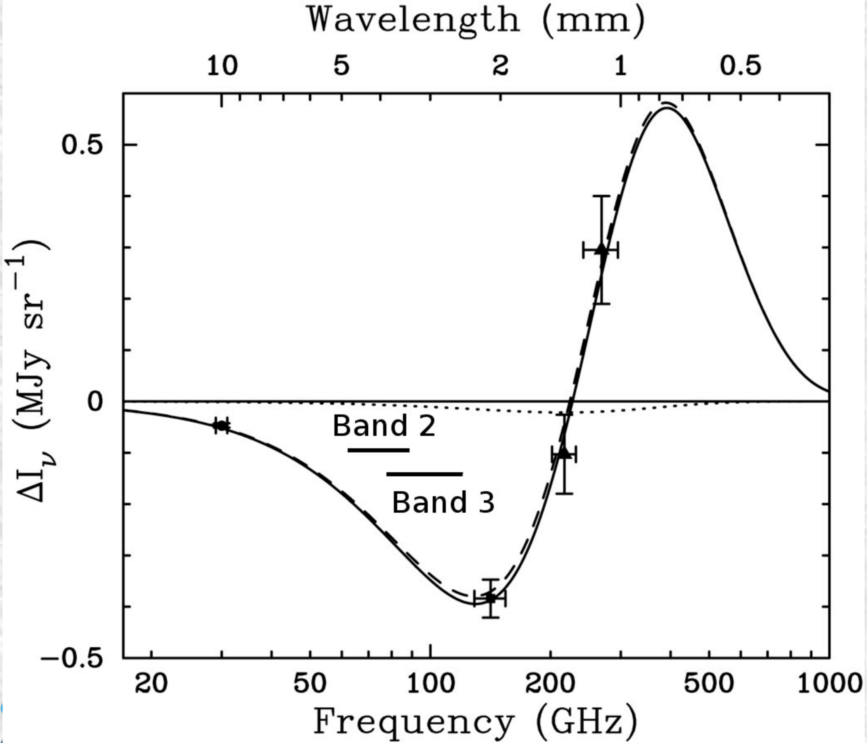
- Finding protogalaxies
- Ignition of young massive stars
- From grains to planets
- Mixing in evolved stars
- VLBI
- Cold complex chemistry

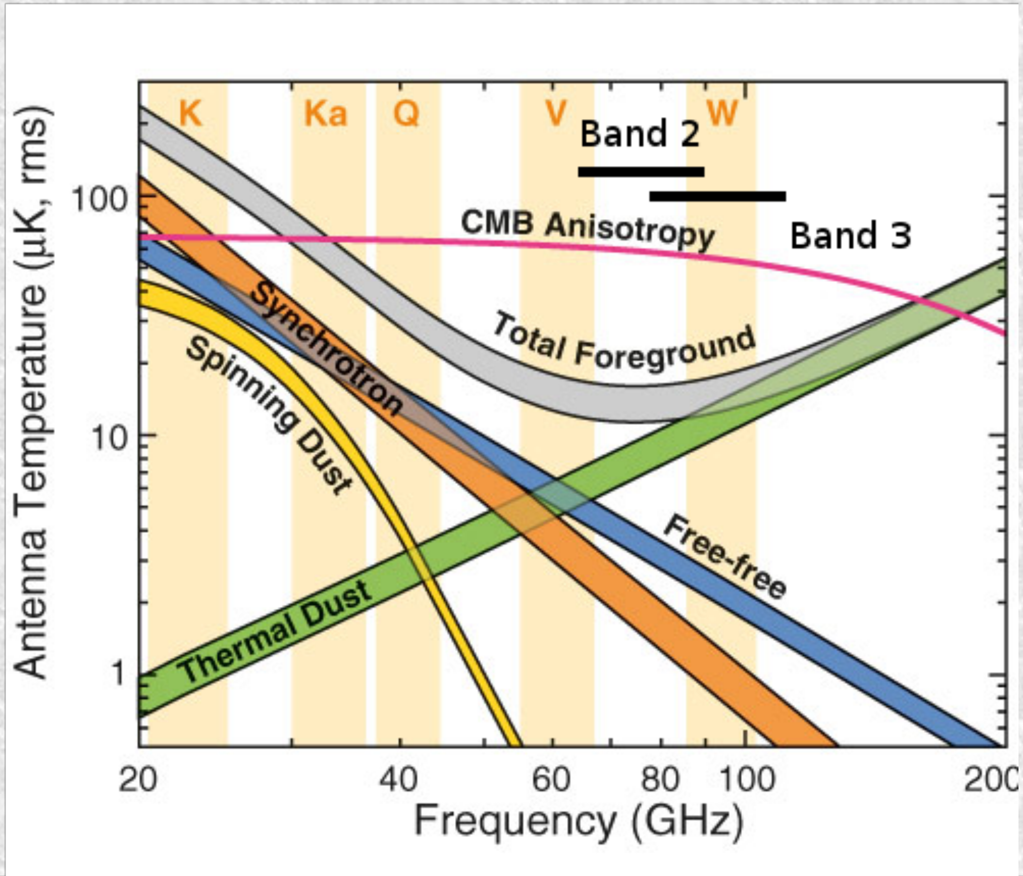
Finding Protogalaxies

SZ from ionised gas in haloes around protogalaxies (Massardi et al 2008)

10’’ size scales

1 microK signal





Additional Science

- The ignition of massive stars
  - Band 2 samples transition from optically thick to thin
  - Ionised gas kinematics in recombination lines
  - Band 2+3 cover most recombination lines of any ALMA band

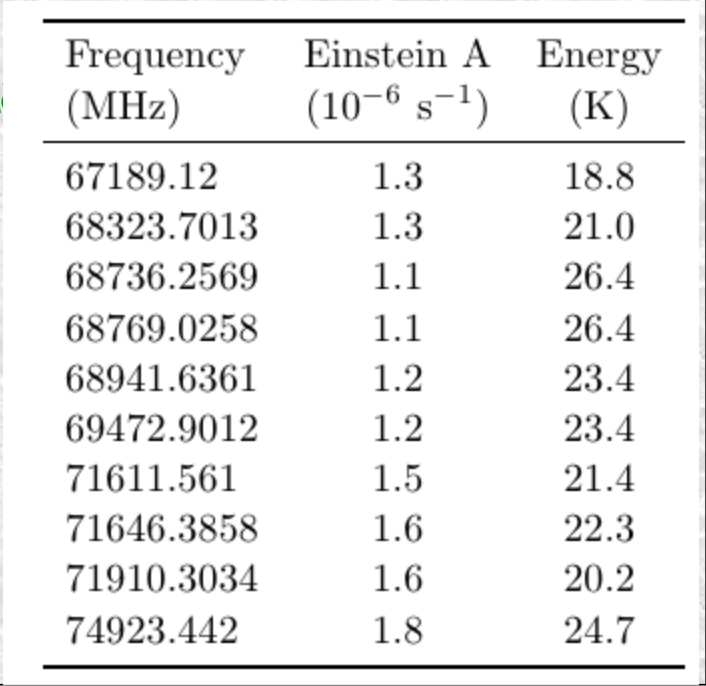
AS: From grains to rocks

- Band 2 long wavelength sweet spot to study grain growth minimizing contamination from free-free and spinning dust.
- Large fractional bandwidth to measure spectral index across band

AS: Cold Complex Chemistry

- Complex organics typically tracers of hot core chemistry
- But increasing evidence for these species in cold, 10K, gas
  - New mechanisms
  - Complex chemistry in low mass st regions – seeding disks & planets
- Glycine

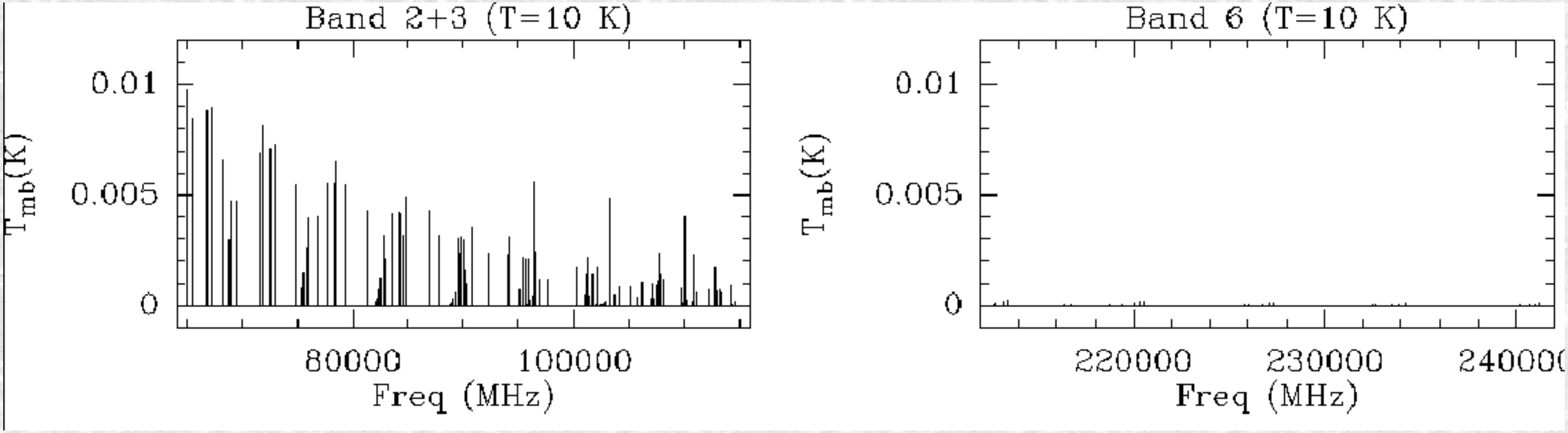
Jimenez-Serra et al. 2014



Frequency (MHz)	Einstein A (10^{-6} s^{-1})	Energy (K)
67189.12	1.3	18.8
68323.7013	1.3	21.0
68736.2569	1.1	26.4
68769.0258	1.1	26.4
68941.6361	1.2	23.4
69472.9012	1.2	23.4
71611.561	1.5	21.4
71646.3858	1.6	22.3
71910.3034	1.6	20.2
74923.442	1.8	24.7

AS: Glycine

Prestellar core (L1544)



Jimenez-Serra et al. 2014

More Additional Science

- Isotopic species in evolved stars
  - Constrain mixing and nuclear burning
- VLBI with LMT, Arizona, GBT, OSO and others
  - Class II methanol maser transitions closer to protostars
  - H_2CO maser ?
  - 96GHz water, z~1.5 183 GHz water maser (22 GHz detected at z=2.6)
  - Absorption line studies of AGN tori
  - Jet launching & blackholes

Evolved Star Mixing

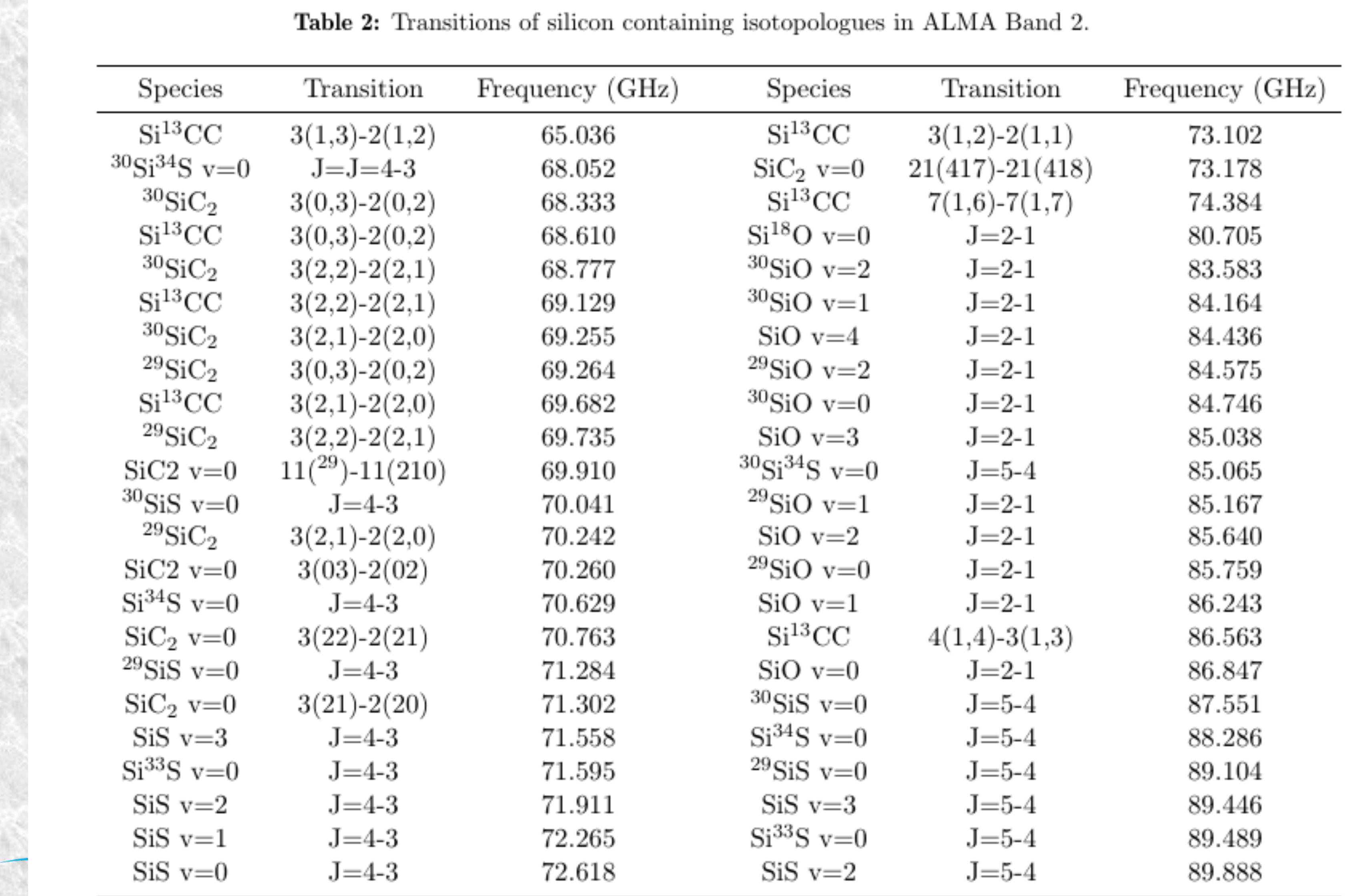
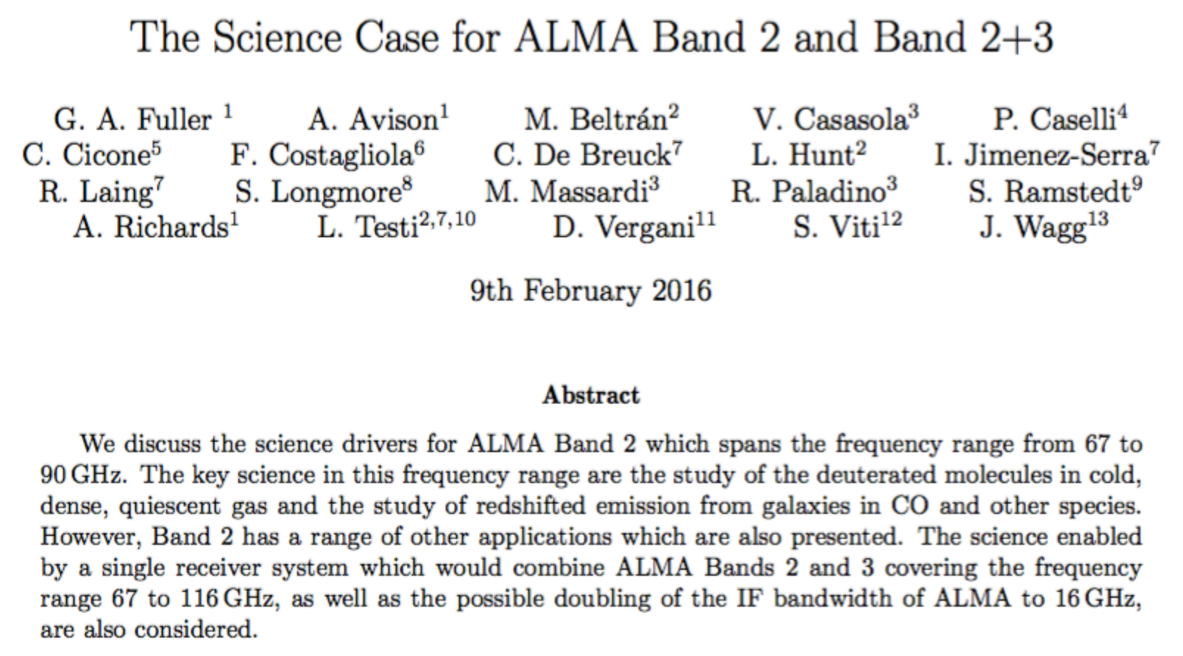


Table 2: Transitions of silicon containing isotopologues in ALMA Band 2.

Species	Transition	Frequency (GHz)	Species	Transition	Frequency (GHz)
$Si^{13}CC$	3(1,3)-2(1,2)	65.036	$Si^{13}CC$	3(1,2)-2(1,1)	73.102
$^{30}Si^{34}S$ v=0	J=J=4-3	68.052	SiC_2 v=0	21(417)-21(418)	73.178
$^{30}SiC_2$	3(0,3)-2(0,2)	68.333	$Si^{13}CC$	7(1,6)-7(1,7)	74.384
$Si^{13}CC$	3(0,3)-2(0,2)	68.610	$Si^{18}O$ v=0	J=2-1	80.705
$^{30}SiC_2$	3(2,2)-2(2,1)	68.777	^{30}SiO v=2	J=2-1	83.583
$Si^{13}CC$	3(2,2)-2(2,1)	69.129	^{30}SiO v=1	J=2-1	84.164
$^{30}SiC_2$	3(2,1)-2(2,0)	69.255	SiO v=4	J=2-1	84.436
$^{29}SiC_2$	3(0,3)-2(0,2)	69.264	^{29}SiO v=2	J=2-1	84.575
$Si^{13}CC$	3(2,1)-2(2,0)	69.682	^{30}SiO v=0	J=2-1	84.746
$^{29}SiC_2$	3(2,2)-2(2,1)	69.735	SiO v=3	J=2-1	85.038
SiC2 v=0	$11(^{29})$-11(210)	69.910	$^{30}Si^{34}S$ v=0	J=5-4	85.065
^{30}SiS v=0	J=4-3	70.041	^{29}SiO v=1	J=2-1	85.167
$^{29}SiC_2$	3(2,1)-2(2,0)	70.242	SiO v=2	J=2-1	85.640
SiC2 v=0	3(03)-2(02)	70.260	^{29}SiO v=0	J=2-1	85.759
$Si^{34}S$ v=0	J=4-3	70.629	SiO v=1	J=2-1	86.243
SiC_2 v=0	3(22)-2(21)	70.763	$Si^{13}CC$	4(1,4)-3(1,3)	86.563
^{29}SiS v=0	J=4-3	71.284	SiO v=0	J=2-1	86.847
SiC_2 v=0	3(21)-2(20)	71.302	^{30}SiS v=0	J=5-4	87.551
SiS v=3	J=4-3	71.558	$Si^{34}S$ v=0	J=5-4	88.286
$Si^{33}S$ v=0	J=4-3	71.595	^{29}SiS v=0	J=5-4	89.104
SiS v=2	J=4-3	71.911	SiS v=3	J=5-4	89.446
SiS v=1	J=4-3	72.265	$Si^{33}S$ v=0	J=5-4	89.489
SiS v=0	J=4-3	72.618	SiS v=2	J=5-4	89.888

Science Case



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Abstract

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[2] INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
[3] INAF - IRA & Italian ALMA Regional Centre Via P. Gobetti 101, 40129 Bologna, Italy
[4] Max-Planck-Institut für extraterrestrische Physik Giessenbachstrasse 1, 85748 Garching, Germany
[5] Cavendish Laboratory, University of Cambridge, 19 J.J. Thomson Avenue, Cambridge CB3 0HE,UK; Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
[6] Instituto de Astrofísica de Andalucía, Glorieta de la Astronomía s/n, Granada, 18008, Spain
[7] European Southern Observatory (ESO), Karl-Schwarzschild-Str. 2, 85748, Garching, Germany
[8] Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK
[9] Department of Physics and Astronomy, Uppsala University, Box 516, 751 20, Uppsala, Sweden
[10] Excellence Cluster Universe, Boltzman str. 2, D-85748 Garching bei Muenchen, Germany
[11] INAF Osservatorio Astronomico di Bologna, via C. Ranzani 1, 40127, Bologna, Italy
[12] Department of Physics and Astronomy, University College London, WC1E 6BT London, UK
[13] Square Kilometre Array Organisation, Jodrell Bank Observatory, Lower Withington Macclesfield Cheshire, SK11 9DL, UK