ALMA BAND 2+3 SCIENCE CASES

Maite Beltrán

INAF – Osservatorio Astrofisico di Arcetri

ALMA Band 2 or 2+3

- Band 2 covers a frequency interval (~67-90 GHz) hardly investigated but that contains more than 1000 spectral lines of molecular species (potentially observable), which are important for both galactic and extragalactic studies.

- Band 2+3 would span from 67 to 116 GHz. Band 3 spans from 84 to116 GHz

- The backend bandwidth has to be decided. It could be of 8 GHz (2x4 GHz dual SB) or 16 GHz (2x8 GHz dual SB)

- Science cases:

  - *Italian Science Case for ALMA Band 2+3*: Beltrán et al. (2015) https://arxiv.org/abs/1509.02702

  - *The Science Case for ALMA Band 2 and Band 2+3*: Fuller et al. (2016) https://arxiv.org/abs/1602.02414

Band 2(+3) science drivers

1. Galactic science
   - Low-excitation lines of deuterated species
   - Formation of complex organic molecules (COMs)
   - Dust evolution in protoplanetary disks
   - Flaring emission from young stars

2. Extragalactic science
   - Cool gas in nearby galaxies
   - Properties and evolution of dense gas in nearby galaxies
   - Molecular outflows and AGN fueling/feedback cycle
   - The Sunyaev-Zel'dovic effect in galaxy clusters

1. Galactic science

- Low-excitation lines of deuterated species
- Formation of complex organic molecules (COMs)
- Dust evolution in protoplanetary disks
- Flaring emission from young stars

Low-excitation lines of deuterated species

- The main Galactic Science driver of Band 2 is the possibility of observing the fundamental, $J = 1 \rightarrow 0$ transitions of the deuterium analogs of common, abundant interstellar molecules including DCO^+, DCN, and N_2D^+. By combining Band 2 with Band 3 (Band 2+3) one could carry out simultaneous observations of the "hydrogenated" species and derive the deuterium abundance

- Deuterium is produced by primordial nucleosynthesis and destroyed in stars. In the local Universe [D/H] ~ 10^{-5} but in interstellar clouds, in particular in pre-stellar cores, [D/H] can be higher than 0.1 (Caselli & Ceccarelli 2012 for a review).

- The enhancement of deuterated species is initiated mainly from the proton-deuteron exchange exothermic reaction favored at $T < 20$ K (the reaction cannot proceed in the opposite sense)

$$H_3^+ + HD \rightarrow H_2D^+ + H_2 + 230\ \mathrm{K}$$

- The H_2D^+ formed can subsequently react with CO and N_2 to produce DCO^+ and N_2D^+ respectively

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

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

- With the freeze-out of neutral atoms and molecules on the surface of dust grains in high density, lower temperature regions (e.g. Caselli+1999), the dominant destruction routes for H_3^+ and H_2D^+ become less effective. This, combined with the enhanced rate of H_2D^+ production, leads to increasing levels of deuteration.

Low-excitation lines of deuterated species

Molecule	Transition	Frequency (GHz)
CH_2D^+	1(1,0)-1(1,1)	67.273
$D^{13}CO^+$	(1-0)	70.733
$D^{13}CN$ (1-0)	(1-0)	71.175
DCO^+ (1-0)	(1-0)	72.039
CCD (1-0)	(1-0)	72.098 – 72.200
DCN (1-0)	(1-0)	72.415
$DN^{13}C$ (1-0)	(1-0)	73.368
DNC (1-0)	(1-0)	76.306
DOC^+ (1-0)	(1-0)	76.386
N_2D^+ (1-0)	(1-0)	77.108
HDO	1(1,0)-1(1,1)	80.578
CH_2DOH	1(1,0)-1(0,1)	85.297*
Ortho-NH_2D	1(1,1)0-1(0,1)0	85.926*

* Band 3 can already observe this frequency

Low-excitation lines of deuterated species

Molecule	Transition	Frequency (GHz)	Molecule	Transition	Frequency (GHz)
CH_2D^+	1(1,0)-1(1,1)	67.273			
$D^{13}CO^+$	(1-0)	70.733	$H^{13}CO^+$	(1-0)	86.754*
$D^{13}CN$ (1-0)	(1-0)	71.175	$H^{13}CN$	(1-0)	86.339*
DCO^+ (1-0)	(1-0)	72.039	HCO^+	(1-0)	89.189*
CCD (1-0)	(1-0)	72.098 – 72.200	CCH	(1-0)	87.284*
DCN (1-0)	(1-0)	72.415	HCN	(1-0)	88.630*
$DN^{13}C$ (1-0)	(1-0)	73.368	$HN^{13}C$	(1-0)	87.091*
DNC (1-0)	(1-0)	76.306	HNC	(1-0)	90.664*
DOC^+ (1-0)	(1-0)	76.386	HOC^+	(1-0)	89.487*
N_2D^+ (1-0)	(1-0)	77.108	N_2H^+	(1-0)	93.172*
HDO	1(1,0)-1(1,1)	80.578	H_2O	1(1,0) - 1(0,1)	556.936
CH_2DOH	1(1,0)-1(0,1)	85.297*	CH_3OH	1(0, 1)- 0(0, 0)	48.372
Ortho-NH_2D	1(1,1)0-1(0,1)0	85.926*	NH_3	1(0,0)-0(0,1)	572.598

* Band 3 can already observe this frequency

Low-excitation lines of deuterated species

Molecule	Transition	Frequency (GHz)	Molecule	Transition	Frequency (GHz)
CH_2D^+	1(1,0)-1(1,1)	67.273			
$D^{13}CO^+$	(1-0)	70.733	$H^{13}CO^+$	(1-0)	86.754*
$D^{13}CN$ (1-0)	(1-0)	71.175	$H^{13}CN$	(1-0)	86.339*
DCO^+ (1-0)	(1-0)	72.039	HCO^+	(1-0)	89.189*
CCD (1-0)	(1-0)	72.098 – 72.200	CCH	(1-0)	87.284*
DCN (1-0)	(1-0)	72.415	HCN	(1-0)	88.630*
$DN^{13}C$ (1-0)	(1-0)	73.368	$HN^{13}C$	(1-0)	87.091*
DNC (1-0)	(1-0)	76.306	HNC	(1-0)	90.664*
DOC^+ (1-0)	(1-0)	76.386	HOC^+	(1-0)	89.487*
N_2D^+ (1-0)	(1-0)	77.108	N_2H^+	(1-0)	93.172*
HDO	1(1,0)-1(1,1)	80.578	H_2O	1(1,0) - 1(0,1)	556.936
CH_2DOH	1(1,0)-1(0,1)	85.297*	CH_3OH	1(0, 1)- 0(0, 0)	48.372
Ortho-NH_2D	1(1,1)0-1(0,1)0	85.926*	NH_3	1(0,0)-0(0,1)	572.598

* Band 3 can already observe this frequency

Low-excitation lines of deuterated species

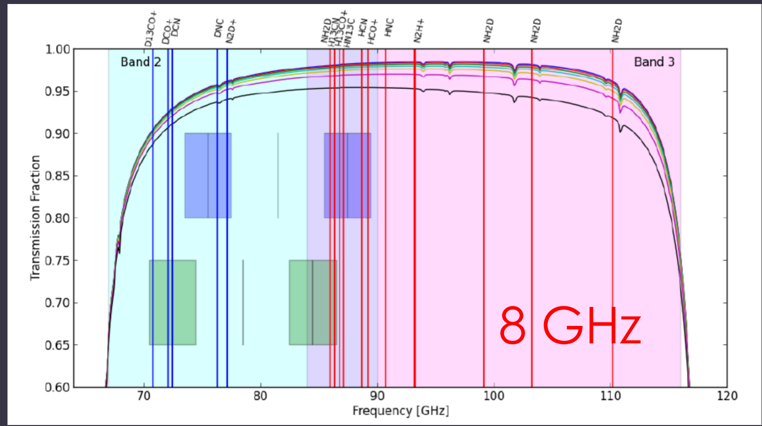
Molecule	Transition	Frequency (GHz)	Molecule	Transition	Frequency (GHz)
CH_2D^+	1(1,0)-1(1,1)	67.273			
$D^{13}CO^+$	(1-0)	70.733	$H^{13}CO^+$	(1-0)	86.754*
$D^{13}CN$ (1-0)	(1-0)	71.175	$H^{13}CN$	(1-0)	86.339*
DCO^+ (1-0)	(1-0)	72.039	HCO^+	(1-0)	89.189*
CCD (1-0)	(1-0)	72.098 – 72.200	CCH	(1-0)	87.284*
DCN (1-0)	(1-0)	72.415	HCN	(1-0)	88.630*
$DN^{13}C$ (1-0)	(1-0)	73.368	$HN^{13}C$	(1-0)	87.091*
DNC (1-0)	(1-0)	76.306	HNC	(1-0)	90.664*
DOC^+ (1-0)	(1-0)	76.386	HOC^+	(1-0)	89.487*
N_2D^+ (1-0)	(1-0)	77.108	N_2H^+	(1-0)	93.172*
HDO	1(1,0)-1(1,1)	80.578	H_2O	1(1,0) - 1(0,1)	556.936
CH_2DOH	1(1,0)-1(0,1)	85.297*	CH_3OH	1(0, 1)- 0(0, 0)	48.372
Ortho-NH_2D	1(1,1)0-1(0,1)0	85.926*	NH_3	1(0,0)-0(0,1)	572.598

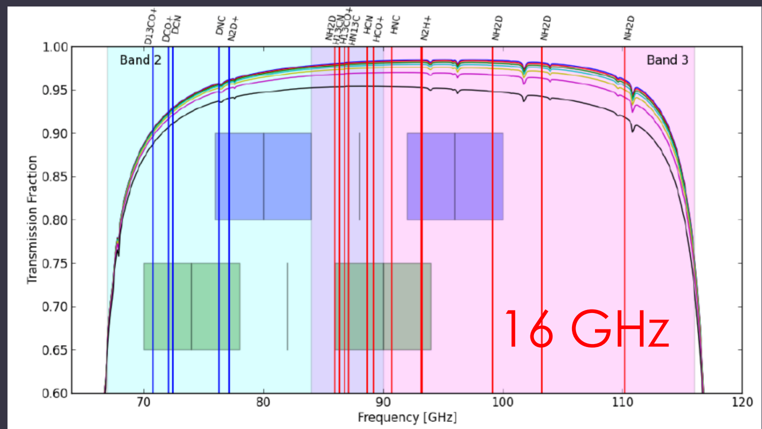
* Band 3 can already observe this frequency

Low-excitation lines of deuterated species

- If 8 GHz bandwidth (4 + 4 SB):
  - Maximum of 5 deuterated species:
    - $D^{13}CO^+$, $D^{13}CN$, DCO+, CCD, $DN^{13}C$
    - $DN^{13}C$, DNC, DCO^+, N_2D^+
  - Maximum of 2 deuteration ratios:
    - $D^{13}CN/H^{13}CN$, $DN^{13}C/HN^{13}C$
    - CCD/CCH, $DN^{13}C/HN^{13}C$
    - DNC/HNC, $DN^{13}C/HN^{13}C$
    - DNC/HNC, DOC^+/HOC^+

- If 16 GHz bandwidth (8 + 8 SB):
  - 9 deuterated species:
    - $D^{13}CO^+$, $D^{13}CN$, DCO+, CCD, DCN
      $DN^{13}C$, DNC, DCO^+, N_2D^+
  - 9 deuteration ratios:
    - $D^{13}CO^+/H^{13}CO^+$, $D^{13}CN/H^{13}CN$
      $DN^{13}C/HN^{13}C$, CCD/CCH, DCN/HCN
      $DN^{13}C/HN^{13}C$, DNC/HNC
      N_2D^+/N_2H^+

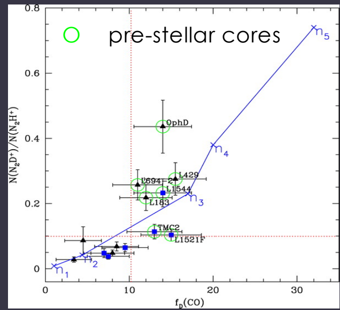




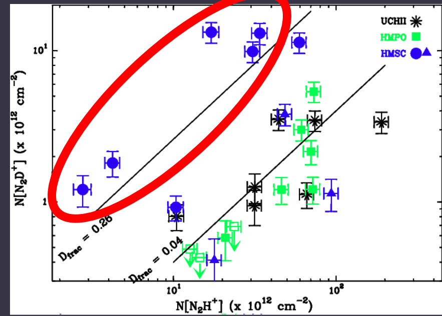
Fuller+ (2016)

Low-excitation lines of deuterated species

1. D_{frac} (N_2H^+): study initial conditions and evolution of prestellar (and protostellar) cores in both low- and high-mass star forming regions (e.g. Crapsi+ 2005; Fontani+ 2011)

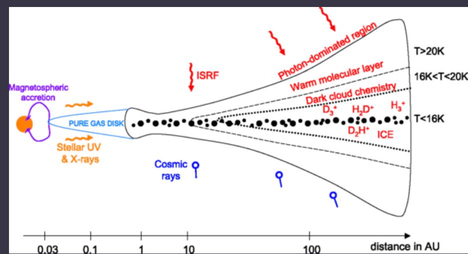


Crapsi+ (2005)



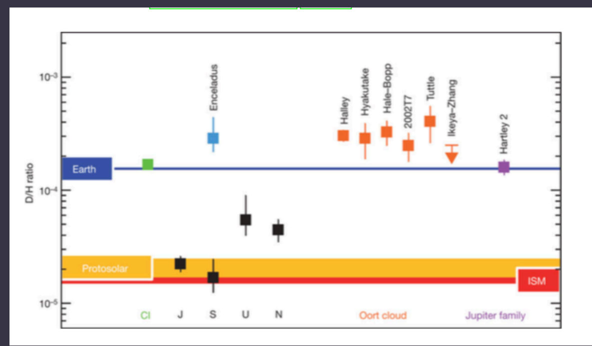
Fontani+ (2011)

2. Deuterated species are also important probes of the cold and dense mid-plane of proto-planetary disks where dust settles and coagulates. Can help to identify the radius of 'CO snowline' through DCO^+ (Matthews+ 2013)



Caselli & Ceccarelli (2012)

3. Deuterium fraction (in particular HDO/H_2O) in protoplanetary disks and our solar system can help to understand the origin and evolution of water on Earth and constrain the transport of volatiles from the disk to planets



Hartogh+ (2011)

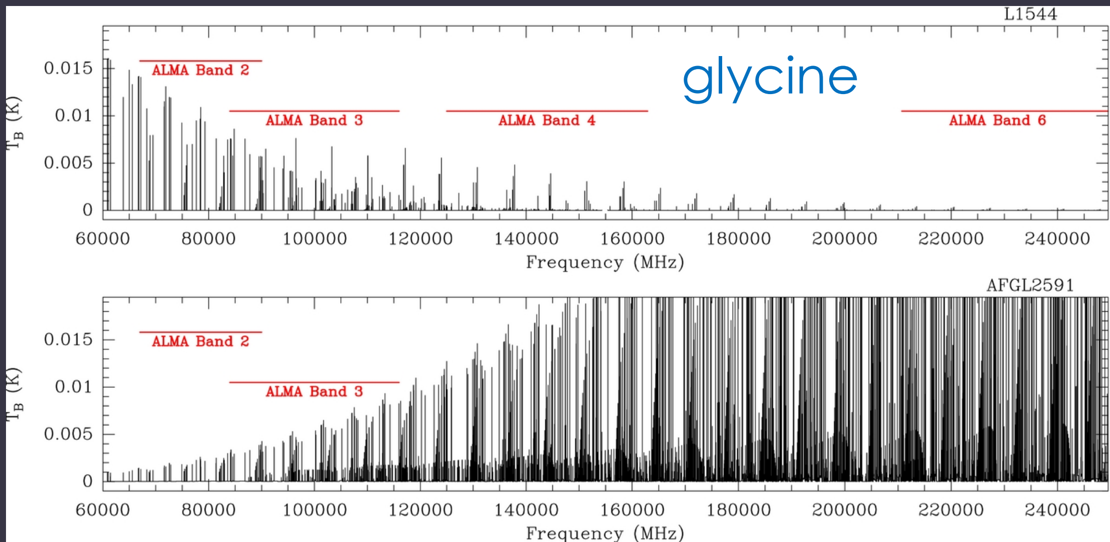
4. Study of DCN, DNC, DCO^+, N_2D^+ in nearby galaxies

1. Galactic science

- Low-excitation lines of deuterated species
- Formation of complex organic molecules (COMs)
- Dust evolution in protoplanetary disks
- Flaring emission from young stars

1. Galactic science

- Low-excitation lines of deuterated species
- Formation of complex organic molecules (COMs)
- Dust evolution in protoplanetary disks
- Flaring emission from young stars



Jiménez-Serra+ (2014)

Extragalactic science

- Cool gas in nearby galaxies
- Properties and evolution of dense gas in nearby galaxies
- Molecular outflows and AGN fueling/feedback cycle
- The Sunyaev-Zel'dovic effect in galaxy clusters

Cool gas in nearby galaxies

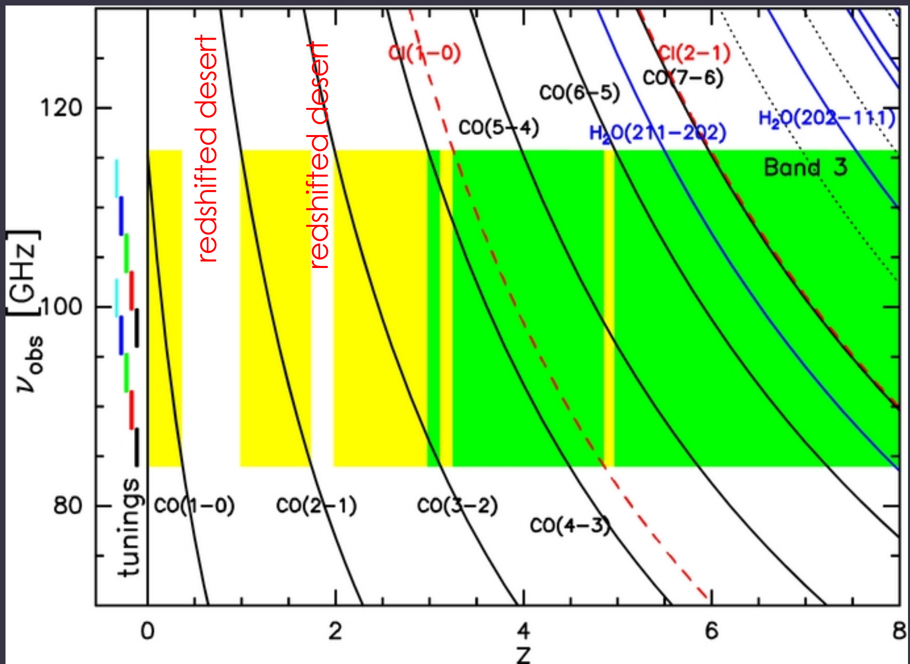
- The main Extragalactic Science driver of Band 2+3 is the study of redshifted molecular and atomic lines (CO, [CI], H_2O) for

   1. a more efficient redshifted determination:

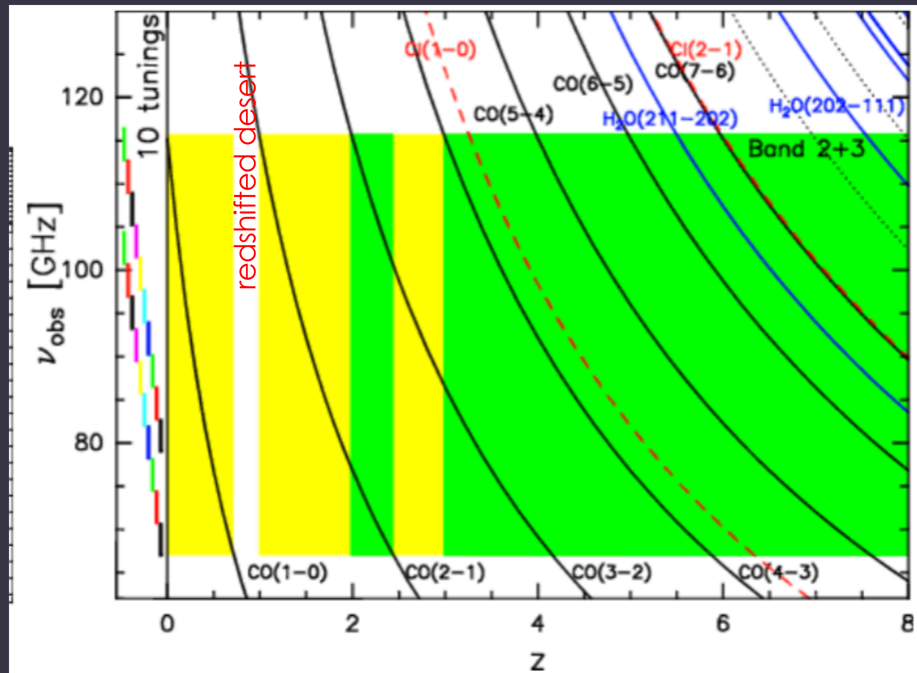
      - The lowest excitation CO lines available in Band 2+3 are the best suited for redshift determination, in particular in the "redshift desert" ranges $0.37 < z < 0.99$ and $1.74 < z < 2.00$

Cool gas in nearby galaxies

Band 3



Band 2+3



Weiss+ (2013)

Green: redshifts where 2 or more lines provide an unambiguous redshift

Yellow: redshift range where 1 line is detectable

The "redshifted desert" would be reduced to the range 0.72<z<0.99

[CI] 1-0, excellent tracer of diffuse gas, observable out to z = 6.3 (only z = 4.8 in Band 3)

Cool gas in nearby galaxies

- The main Extragalactic Science driver of Band 2+3 is the study of redshifted molecular and atomic lines (CO, [CI], H_2O) for

  1. a more efficient redshifted determination:

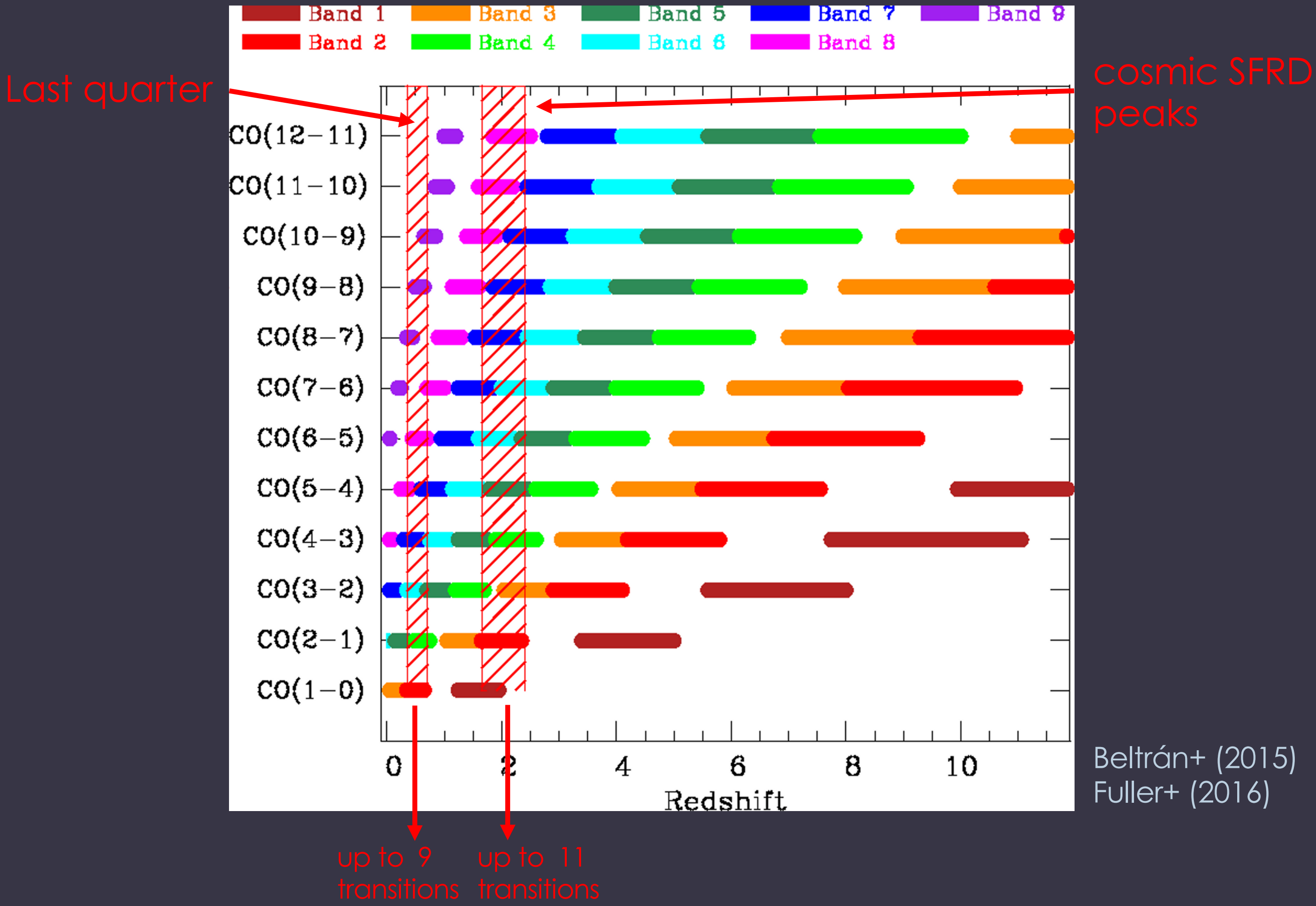
     - The lowest excitation CO lines available in Band 2+3 are the best suited for redshift determination, in particular in the "redshift desert" ranges 0.37< z<0.99 and 1.74<z<2.00

  2. a more efficient characterization of the cool gas content of galaxies over the epoch of galaxy formation by observing low-J CO transitions (estimate of gas masses is ultimately based on the CO (1–0) transition)

     - Epoch traced by cosmic star-formation rate density (SFRD), which peaks at z ~1-3 and then declines dramatically to lower redshift
     - Band 2 allows to observe multiple CO transitions in two crucial redshift regions:

       1. 1.6<z<2.4 range is essential as this is where the SFRD starts its decline, with relatively few sources covered
       2. z <1, where the Universe is 3/4 of its present age and has the most significant decrease of SFRD (crucial to understand why galaxies exhausted their fuel for star formation in the latest stages of the age of the Universe)

Cool gas in nearby galaxies



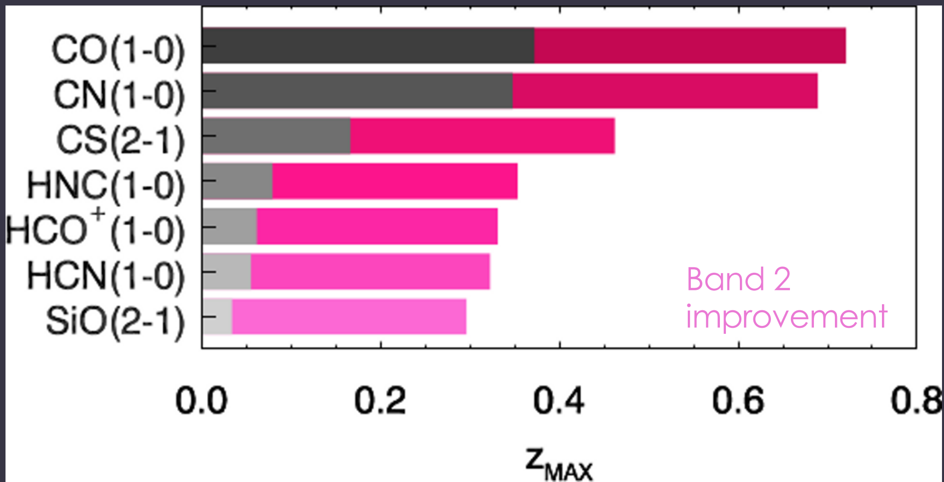
Beltrán+ (2015)
Fuller+ (2016)

Extragalactic science

- Cool gas in nearby galaxies
- Properties and evolution of dense gas in nearby galaxies
- Molecular outflows and AGN fueling/feedback cycle
- The Sunyaev-Zel'dovic effect in galaxy clusters

Extragalactic science

- Cool gas in nearby galaxies
- Properties and evolution of dense gas in nearby galaxies
- Molecular outflows and AGN fueling/feedback cycle
- The Sunyaev-Zel'dovic effect in galaxy clusters



Fuller+ (2016)