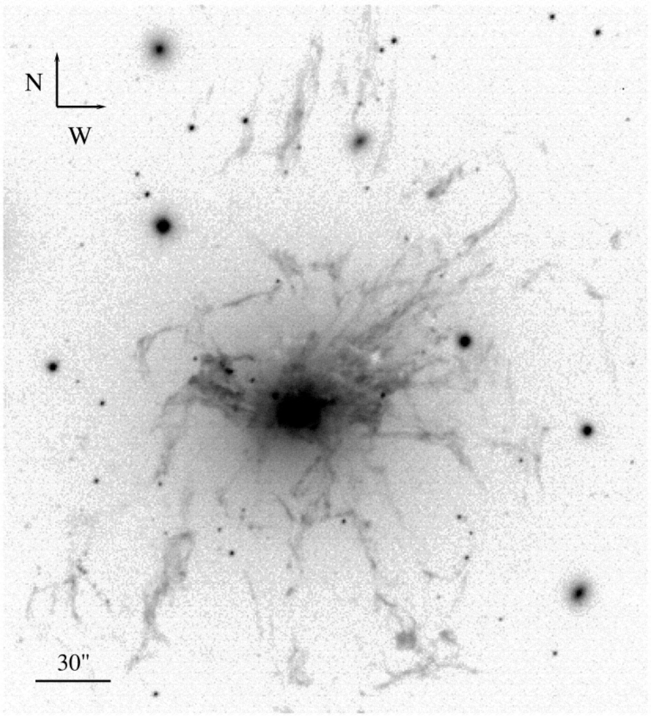
How do the cosmic rays influence the gas and grain chemistry in star-forming regions ?

Estelle Bayet – University of Oxford



The central galaxy in the Perseus Cluster seen in Hα (Conselice et al. 2001)

Collaborators: Serena Viti (UCL-UK), Tom Hartquist (Leeds-UK), David Williams (UCL-UK), Tom Bell (CSIC-Spain), Padelis Papadopoulos (MPIA-Germany)

Oxford Physics

CRISM2011

ALMA
ATACAMA LARGE MILLIMETER ARRAY

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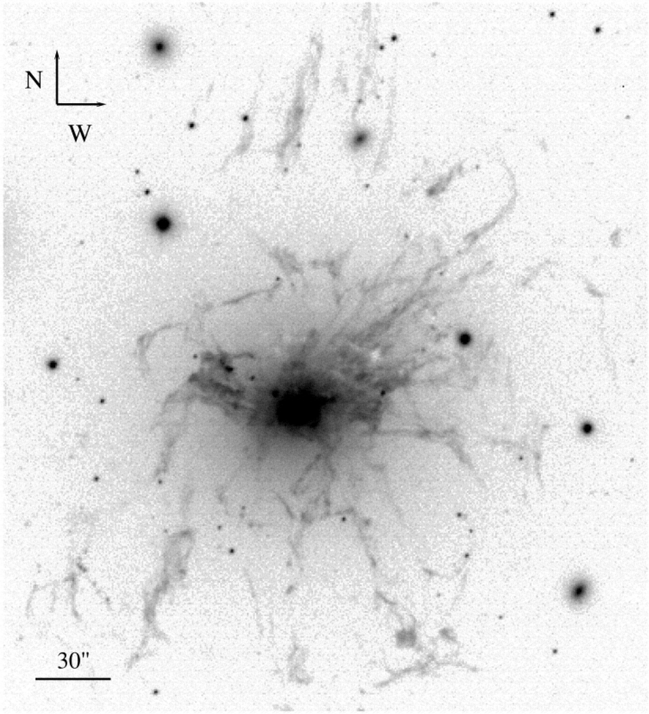

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I. What is a molecular cloud ?

Republic of astrophysics

Type: Identity card number: 054059-022730

1) Concentration of gas and dust
2) isolated in projection on the sky and in Doppler velocity
3) hierarchical structures and turbulence
4) weakly ionized: $e\text{-}/H_2=10^{-9}$ to 10^{-4}
5) magnetic field coupled to gas via charged particles only
6) physical & chemical state far from equilibrium
7) composition: H, He, CO, O, H, dust + great variety of molecules/atoms/ions

<<<<<<<<<<<<<<<<<< *Orion: horsehead* <<<<<<<<<<<<<<<<<<<<<<<<
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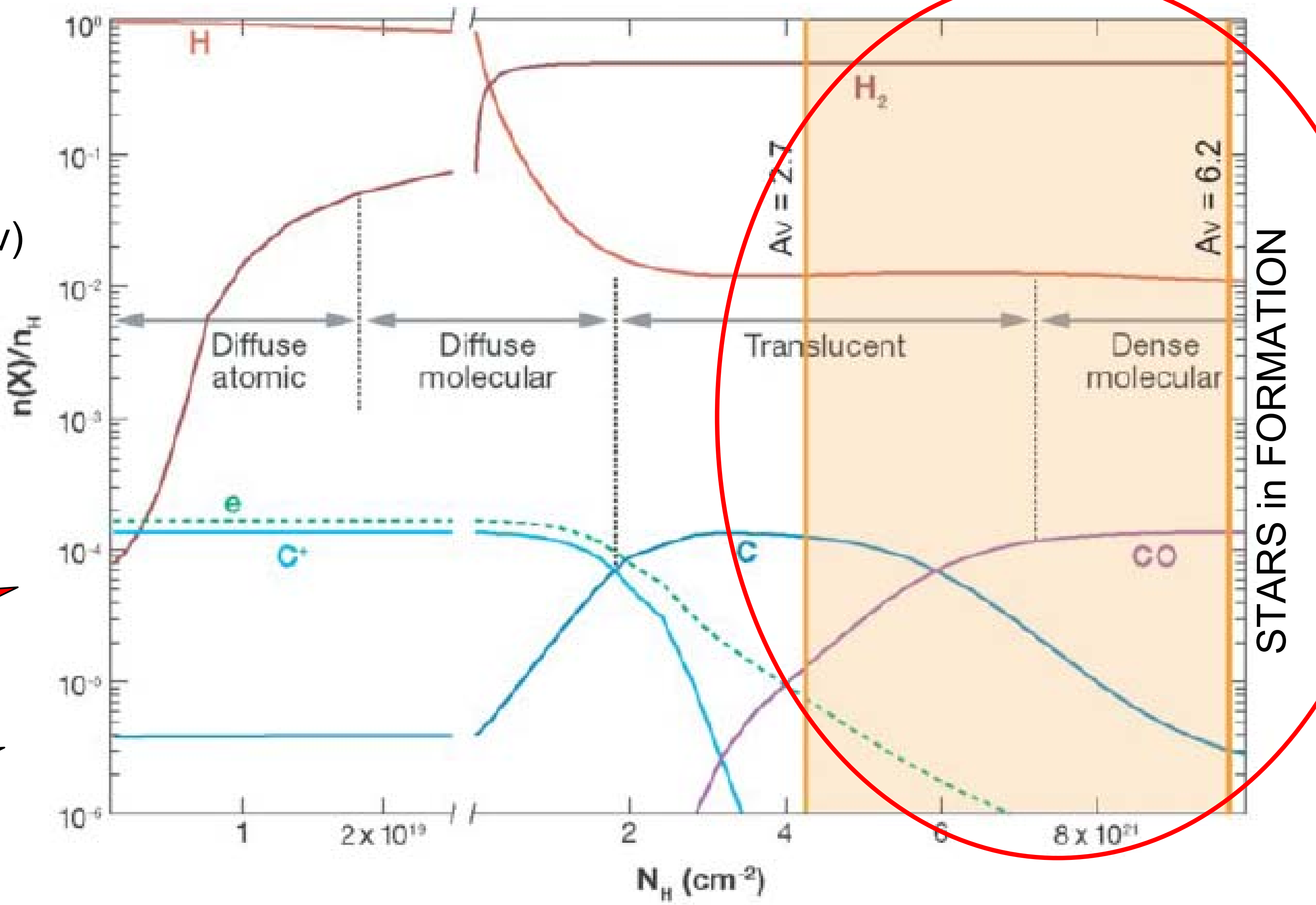
Illumination:

- UV-FUV:
(6ev→ 13.6ev)
- X-rays:
(> 1keV)
- CRs:
(≤100MeV)



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I. Influence of CR on such clouds ?

- ionisation: produce electrons

E (MeV) (1)	Total Ionization Ratio (2)	$f(H_2^+)$ (3)	$f(H^+)$ (4)	N(H) (5)	T (eV) (6)	h (eV) (7)
1.....	1.44	0.970	0.030	2.06	4.2	6.3
2.....	1.50	0.971	0.029	2.12	4.4	6.6
10....	1.61	0.970	0.030	2.25	4.7	7.0
20....	1.65	0.970	0.030	2.30	4.8	7.2
50....	1.71	0.969	0.031	2.36	5.0	7.5
100...	1.74	0.969	0.031	2.40	5.1	7.6

NOTE.—Column (2) gives the ratio of the total and primary ionization rates in H_2; columns (3) and (4), the fractions f of H_2^+ and H^+ ions; column (5), the number N(H) of hydrogen atoms; column (6), the kinetic energy T (eV) of the neutral hydrogen atoms; column (7), the heat h (eV) deposited into a gas of low fractional ionization per primary ionization event.

The cosmic ray ionization rate is a per second ionization rate from protons :

ζ_H: H + CRP -> H^+ + e^- + CRP

ζ_{H2}: H_2 + CRP -> H_2^+ + e^- + CRP

$\zeta_{H2} \approx 1.53\, \zeta_H$

CR protons up to 100 MeV listed: H_2 ionization, while 1-20 GeV CRs responsible for bulk of π^0 mesons → 2γ and, e.g., pp→pnπ^+

I. Influence of CR on such clouds ?

- ionisation: produce electrons

PROTON IMPACT IONIZATION CROSS SECTIONS $\sigma_i(E)$ IN cm^2 AND MEAN ENERGIES $\bar{w}_i$ IN eV OF THE SECONDARY ELECTRONS

E (MeV)	σ_i (cm^2)	$\bar{w}_i$ (eV)
1........	4.0×10^{-17}	24.3
2........	2.3×10^{-17}	26.0
10.......	5.7×10^{-18}	30.4
20.......	3.1×10^{-18}	32.1
50.......	1.4×10^{-18}	34.1
100......	7.2×10^{-19}	35.6

$$\zeta_H(N_H) = 1.8 \times \frac{5}{3} \times \int_0^{\infty} 4\pi\sigma_{i,\mathrm{H}}(E) j_{\mathrm{IC}}(E, N_H) dE$$

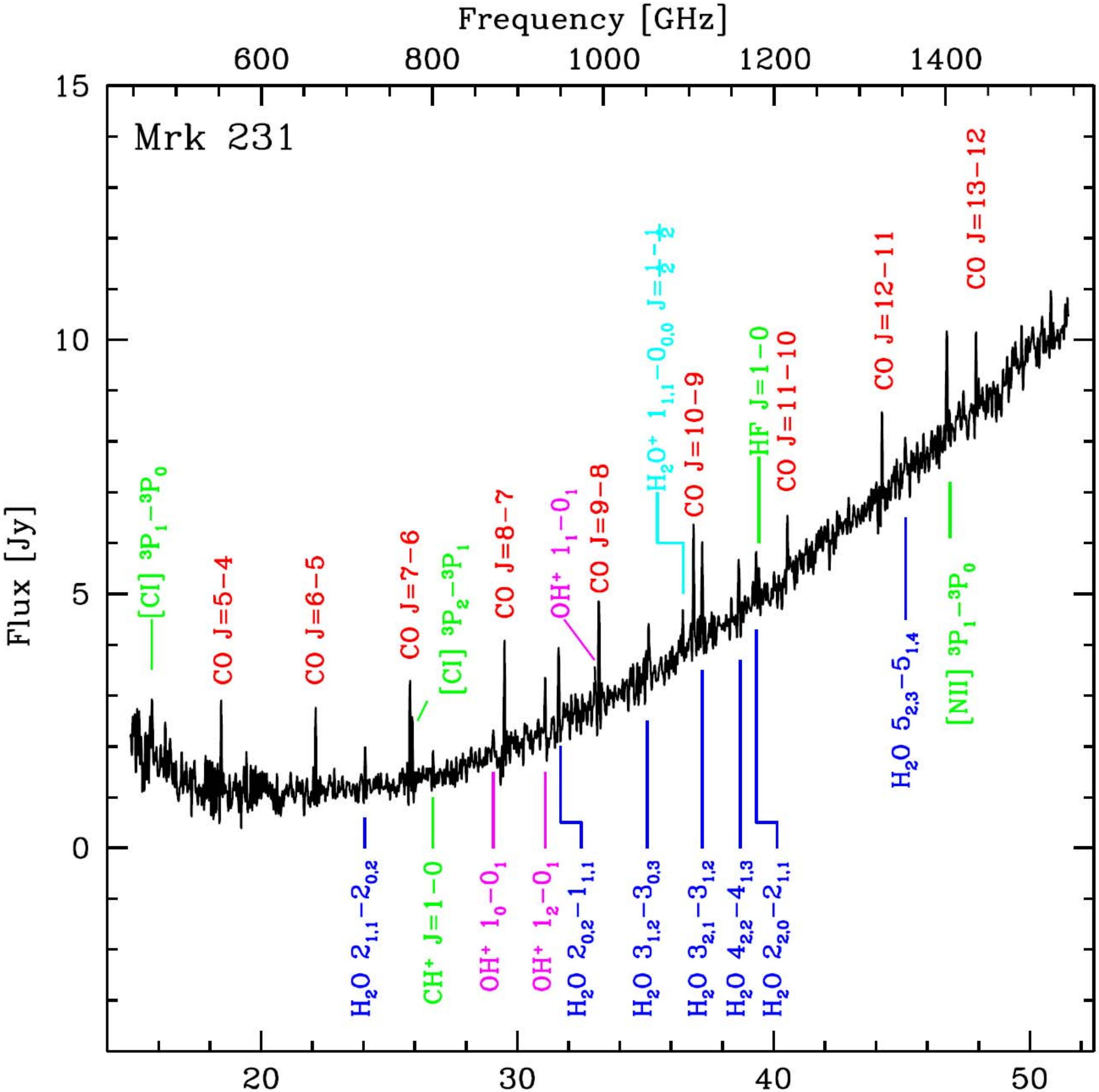
I. Influence of CR on such clouds ?

- ***drive a rapid ion-neutral chemistry even at T<10 K***
- ***heating: excess energy of secondary electron***
- ***pressure (Tom Hartquist)***
- ***destroy or modify dust particles***

II. Key tracers of CRDRs ?

- ***Mostly ions due to the increase of ionisation and especially O-bearing species affected such*** H_2O^+, H_3O^+, OH^+.

M2011, June, Montpellier



Mrk 231 SPIRE

van der Werf et al. (2010)

Illumination:

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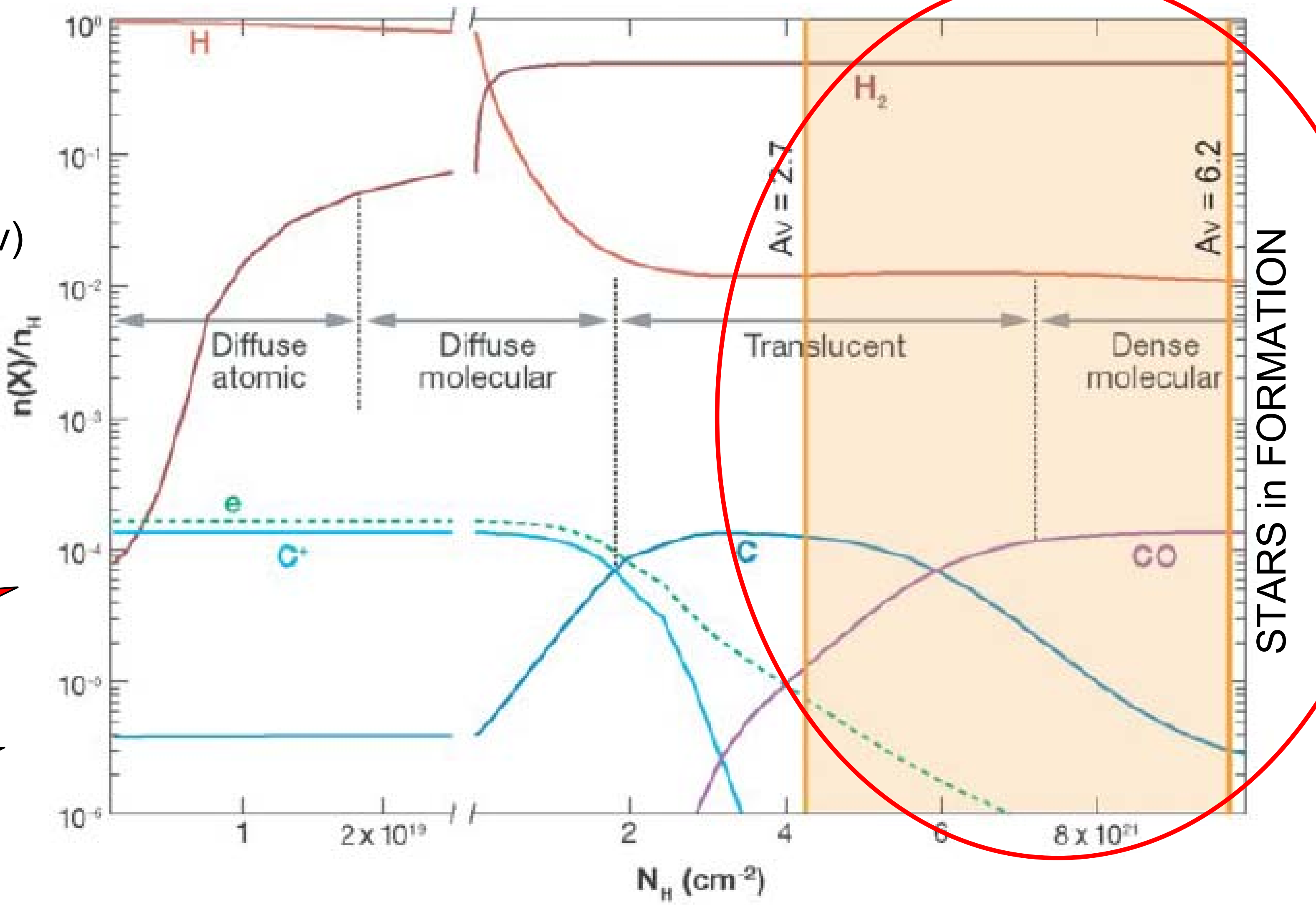
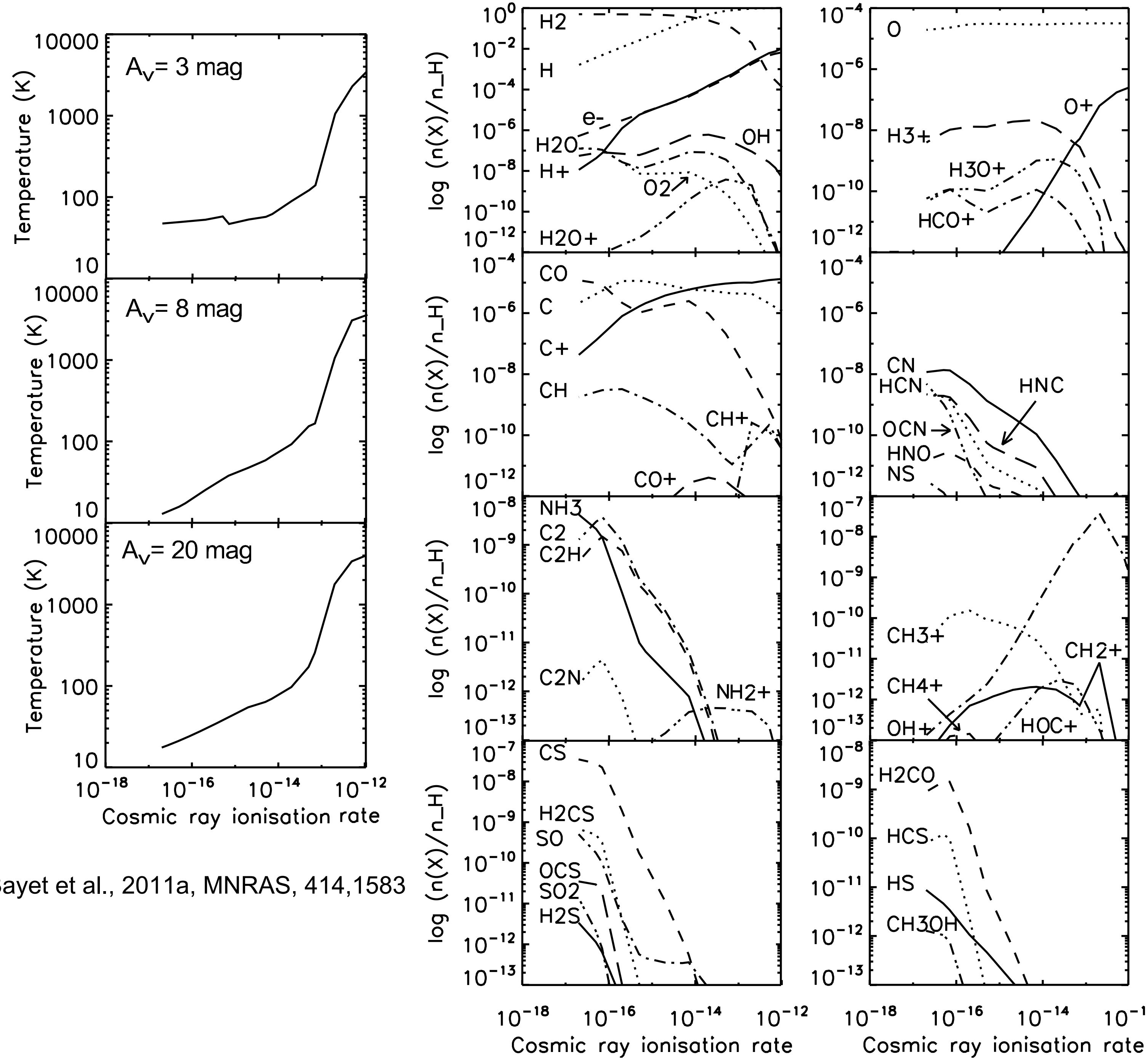


pellier



Bayet et al., 2011a, MNRAS, 414,1583

What's Special about 10^{-14} s^{-1}?

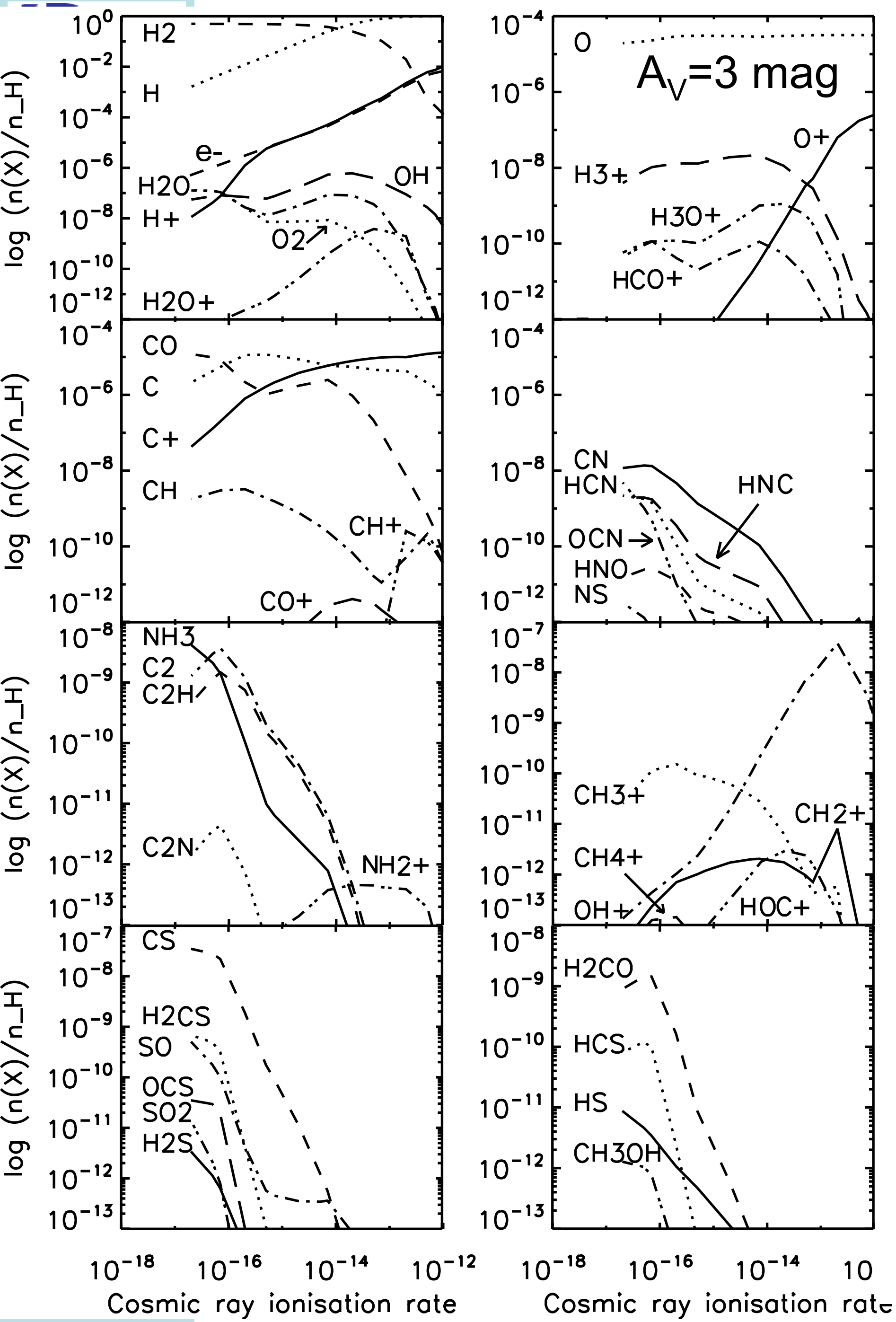
What is happening at about 10^{-14} s^{-1}?

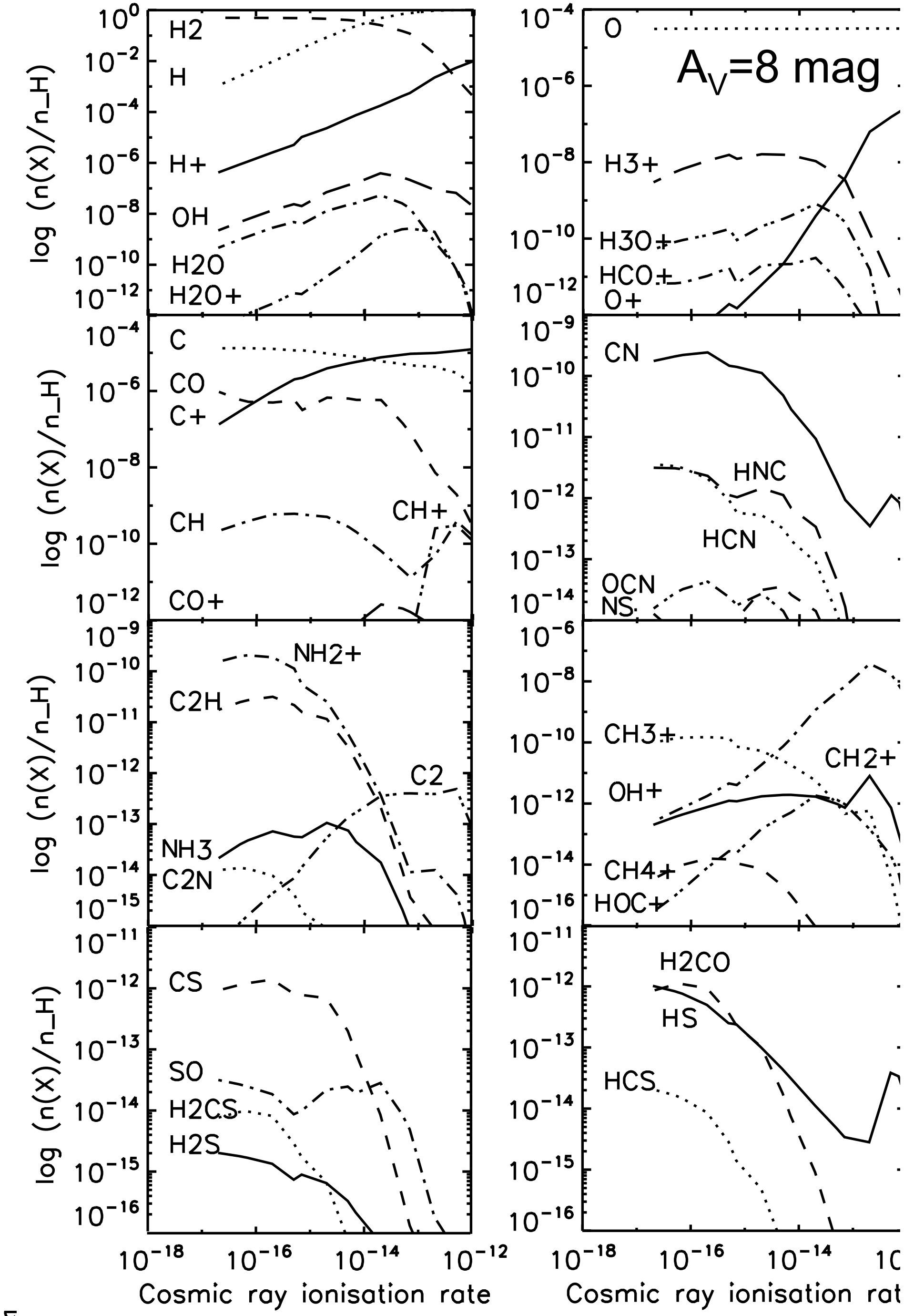
Most abundances eventually decrease with an increasing ζ?

- Because, as the electron fraction rises, electron recombination increases, and this depletes the ions.

Why at 10^{-14} s^{-1}?

- At this point, atomic hydrogen becomes ionized very rapidly, increasing the electron fraction substantially.


A_V=3 mag
log (n(X)/n_H)
Cosmic ray ionisation rate
H2
H
e-
H2O
H+
OH
O2
H2O+
O
H3+
H3O+
HCO+
O+
CO
C
C+
CH
CH+
CO+
CN
HCN
HNC
OCN
HNO
NS
NH3
C2
C2H
C2N
NH2+
CH3+
CH2+
CH4+
OH+
HOC+
CS
H2CS
SO
OCS
SO2
H2S
H2CO
HCS
HS
CH3OH


A_V=8 mag
log (n(X)/n_H)
Cosmic ray ionisation rate
H2
H
H+
OH
H2O
H2O+
O
H3+
H3O+
HCO+
O+
C
CO
C+
CH
CH+
CO+
CN
HNC
HCN
OCN
NS
NH2+
C2H
C2
NH3
C2N
CH3+
CH2+
OH+
CH4+
HOC+
CS
SO
H2CS
H2S
H2CO
HS
HCS

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- drive a rapid ion-neutral chemistry even at T<10 K

- heating: excess energy of secondary electron

- pressure

- destroy or modify dust particles

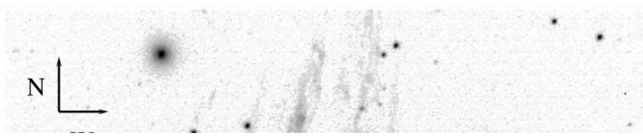
II. Key tracers of CRDRs ?

- Mostly ions due to the increase of ionisation and especially O-bearing species affected such H_2O^+, H_3O^+, OH^+.

- Except these species, it is very difficult to disentangle CR-driven chemistry from X-ray one.

III. In reality ?

You know that you have sometimes all the energies (photons // particles) involved at the same time: UV-FUV (PDR), X-rays (XDR), Cosmic-rays (CRDR), (+shocks)
➔ identify a combination of species or single species able to disentangle the mechanisms of excitation, with strong enough signals to be detected not only in ULIRGS!



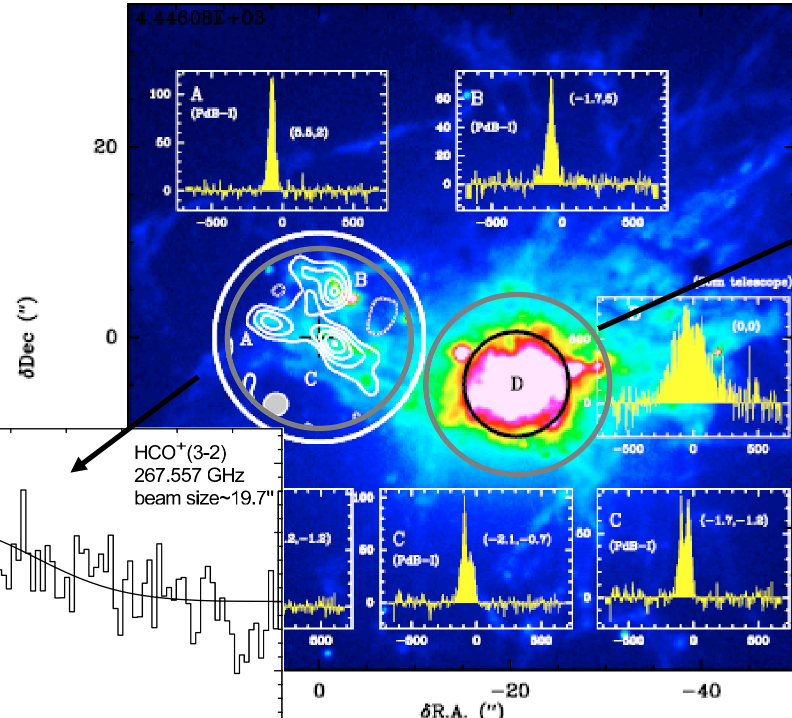
➔ C_2H, HCO^+ and CN

Model Parameters	C_2H centre	C_2H filament	CN centre	CN filament	HCO^+ centre	HCO^+ filament
Model A: I low, H high, ζ high	+	+	-	-	(3)	-
Model B: I low, H low, ζ low	-	-	+	+	(8)	(8)
Model C: I high, H low, ζ low	-	-	+	+	(8)	(8)
Model D: I low, H high, ζ low	-	-	+	+	(3)	(3)
Model E: I low, H low, ζ high	+	+	(3)	(3)	(3)	(3)

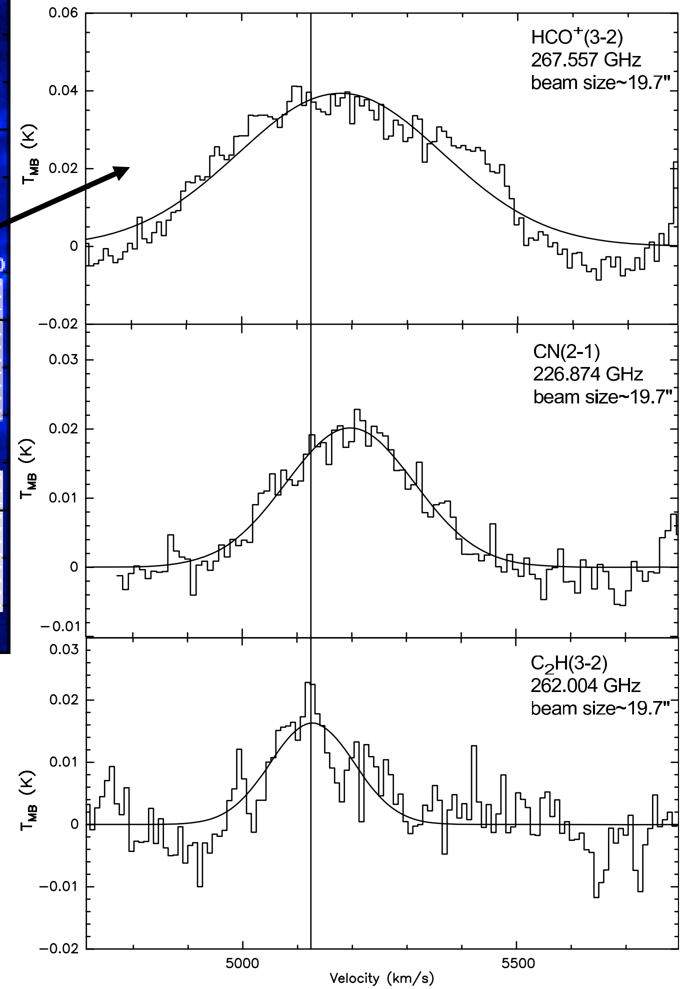
H from 10^{-19}-10^{-22} erg cm^{-3} s^{-1}, a 10^3cm^{-3} cloud receives similar heating from H=10^{-19} erg cm^{-3} s^{-1} than from CR~10^{-13} s^{-1}

Conselice et al., 2001

Bayet et al., 2010, A&A, 521, 16



Salome et al., 2006, 2008
Bayet et al., 2011b, accepted in MNRAS



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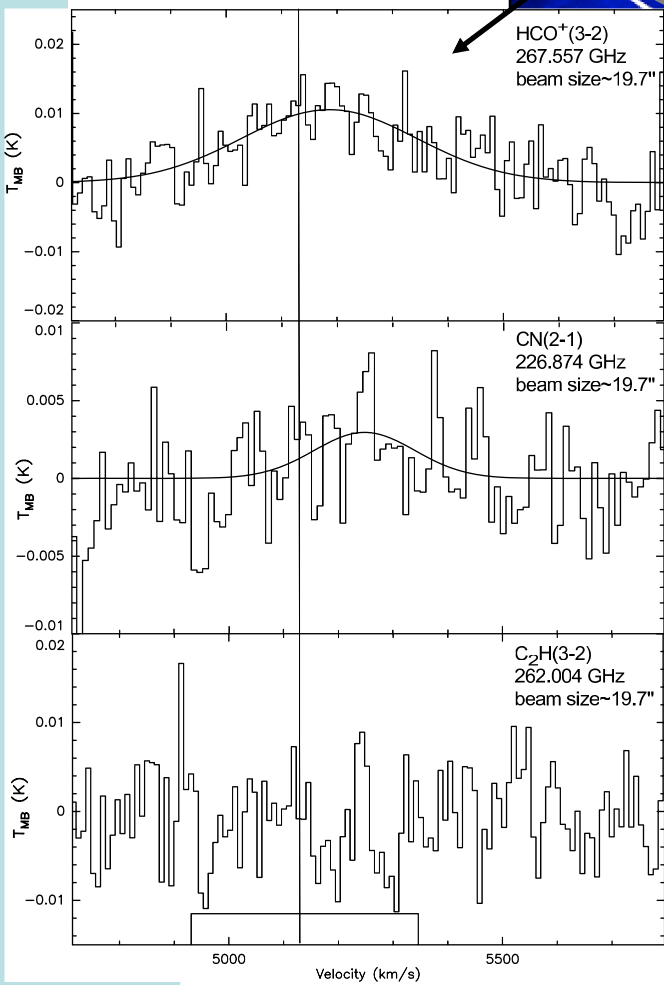

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Model D: I low, H high, ζ low	-	-	+	+	(3)	(3)
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- Complementary sets of observations of C_2H, HCO^+ and CN + isotopologues at low frequencies to infer better physical and chemical (abundances) conditions.

- Is there any star formation in CRDRs i.e. in filaments + central galaxies?
➔ Quest for dense gas (CH_3CN, CH_3OH, CS etc…)

- High resolution: access to energy sources positions but ALMA-ES not possible! Declination a bit too high…

IV. Summary:

Theory:

- CR are the major drivers of the chemistry in dense molecular gas + set the physical conditions such as temperature (where UV, FUV photons can not penetrate).

- CR ionise the gas

- CR increase O-bearing ions abundance when CR ionisation rate is high

- Difficult to disentangle XDR from CRDR when CR ionisation rate is not high

Observations:

- Can help disentangling heating mechanisms in galaxy cluster hence help constraining the influence of the feedback mechanism from AGN on the surrounding material (which is responsible of the creation of these filaments)

- CRs can dominate gas heating for SFR > 100 Mo/yr; think of Mkr231/Arp220 and IMF can be also better understood (Papadopoulos 2010).

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- CRDRs: do they form stars? Which stars?

Thank you !