Image credits: NASA/JPL

Molecular complexity in the distant universe

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Pisa, Italy

SCUOLA NORMALE SUPERIORE PISA

Astronomical Complex Organic Molecules in different environments - Palazzo Strozzi, Firenze, March 10-11, 2016

Talk Outline

- Interest of extragalactic chemistry

Results and challenges about:

- Complex molecules at early cosmic epochs
- Complex molecules in the mid age universe
- COMs at the current cosmic epoch in the extragalactic environment

Molecular complexity in the universe

Four points of view

- **Cosmologist**:
  Chemistry governs cosmological galaxy growth/evolution
  Nature of the gas: similar/different to MW chemistry?

- **Astrophysicist**: Star formation and (proto)-planet formation

- **Chemist**: origins of chemistry on the Planet

- **Human being**: The pathway(s) to life on the Planet
  How common is life in the universe?

Molecular complexity in the universe

Four points of view

- **Cosmologist**:
  Chemistry governs cosmological galaxy growth/evolution
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4 orders of mag gap in physical scale

- **Astrophysicist**: Star formation and (proto)-planet formation
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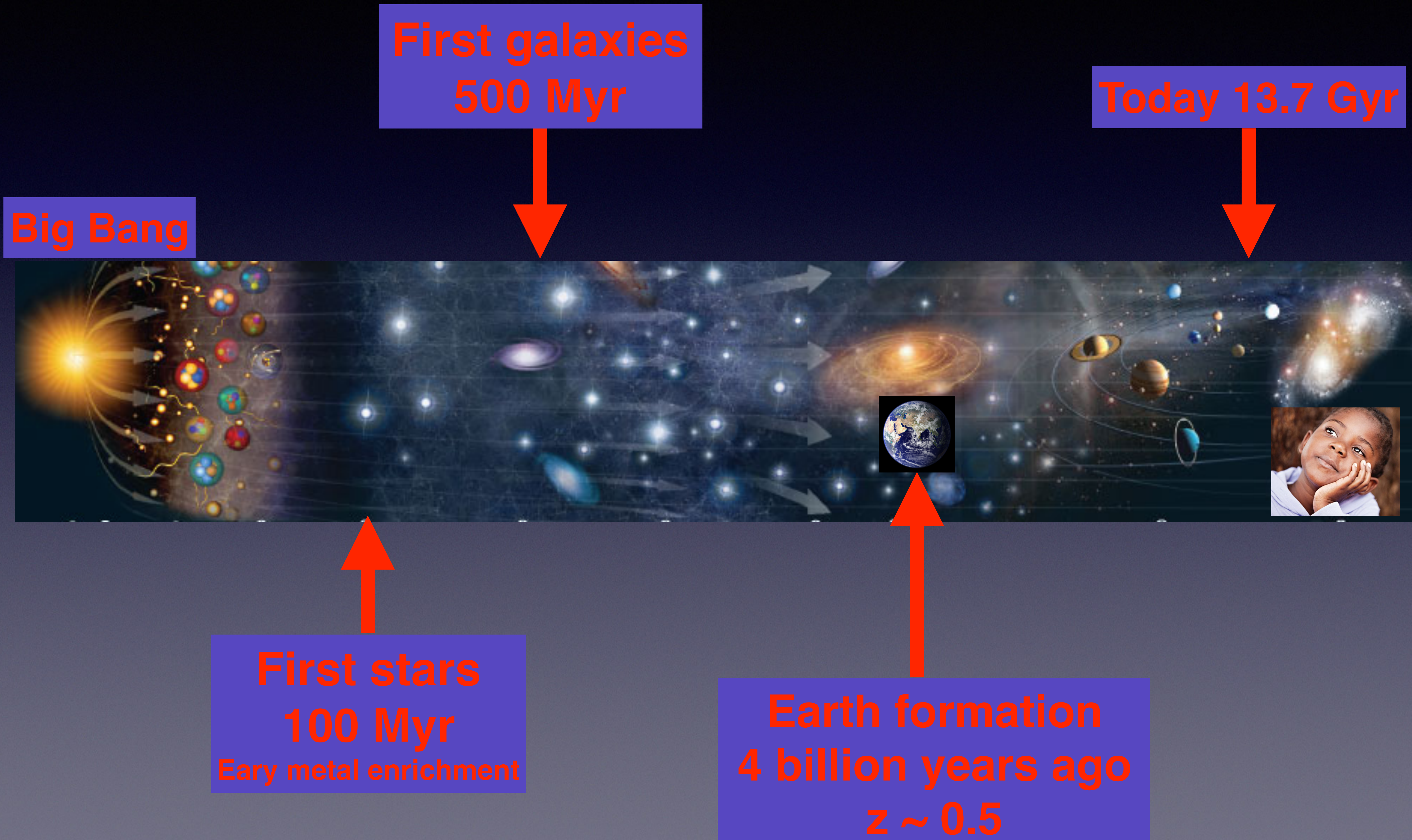
  How common is life in the universe?

Molecular complexity in the universe



Detecting molecules in the distant universe

Rotational ad vibrational transitions from molecules at (sub)-mm wavelenghts

SKA-MID (?)

Detecting molecules in the distant universe

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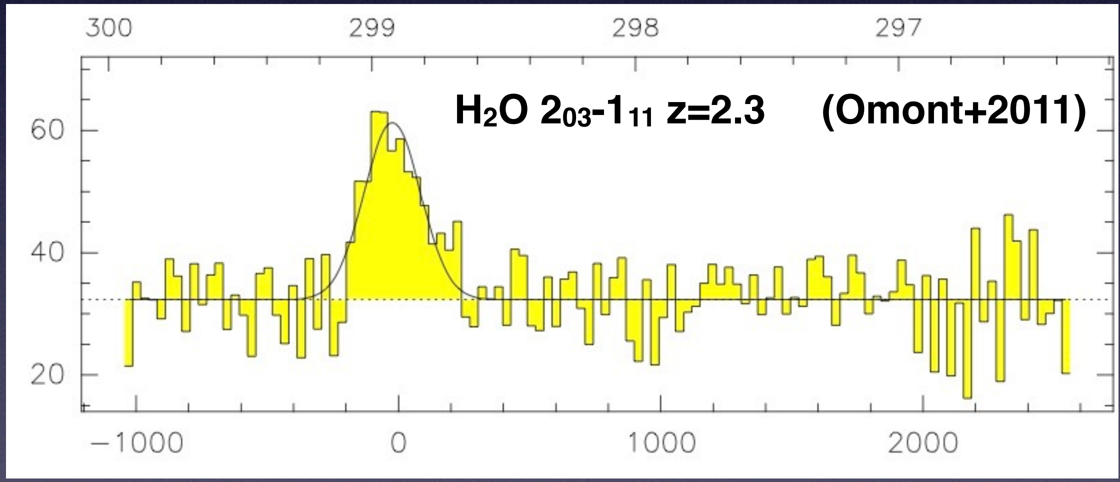


Emission line studies:

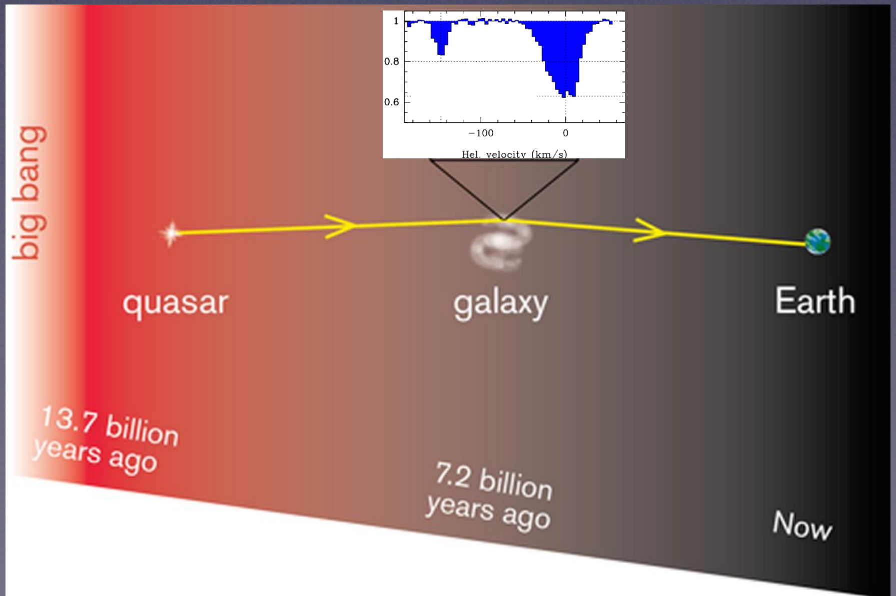
- luminous high redshift galaxies
- molecular gas reservoirs, mainly dense gas
- limited by beam resolution / distance dilution

Asborption line studies:

- no distance dilution, only limited by bkg continuum source
- outstanding spatial resolution (size of bkg source, ~pc scale)
- low density regime, excitation dominated by CMB photons

optical depths/columnn densities easily derived

- limited by # of mm absorbers (only a handful known)



Extragalactic molecules (as of 10/2015)

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	HC_6H	*c*-C_6H_6 *
CO	HCN	NH_3	HC_3N	CH_3CN	CH_3NH_2		C_{60}* (?)
H_2 *	HCO^+	HNCO	CH_2NH	HC_4H *	CH_3CHO		PAHs
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OH^+	HCS^+						
HF	H_2Cl^+ 2014						
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Extragalactic molecules (as of 10/2015)

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- **Cations and simple hydrides**: basis of ISM chemistry

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- **Organic molecules:** up to 8 atoms
- **Large C-bearing chains:** seen at early epochs

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A challenge for astrochemists:

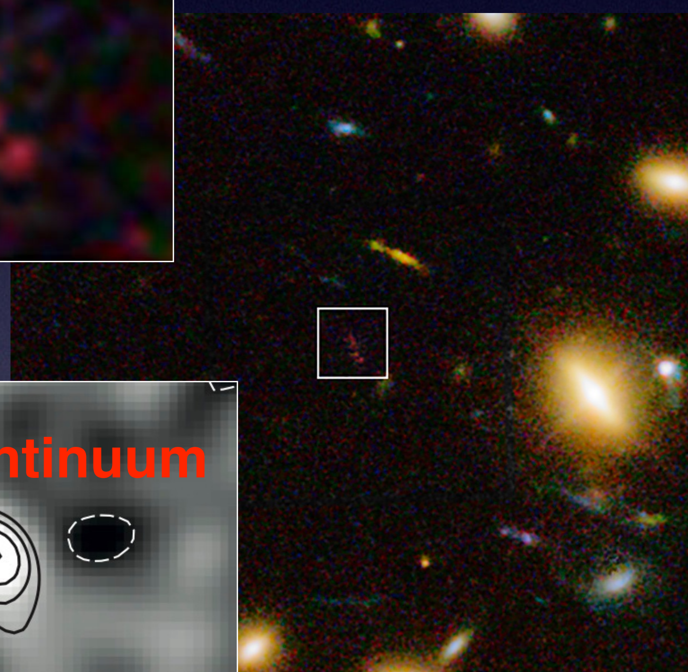
- How are they formed?
- Are other species (not yet detected) likely to be present?
- Gas properties similar to Milky Way's?
- Are there COMs present, possibly relevant for pre-biotic chemistry?

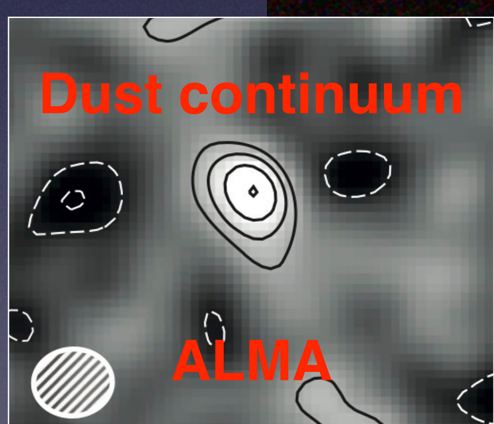
The first billion years: Dust & Gas

Large amounts of dust and gas in place when universe was ~5% of its age

e.g. Watson+2014, Gallerani+2010,2014, Jiang+2010

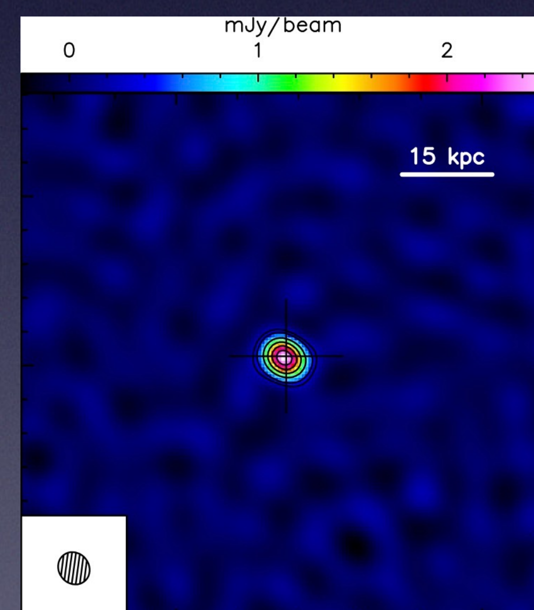
galaxy A1689
z ~7.5



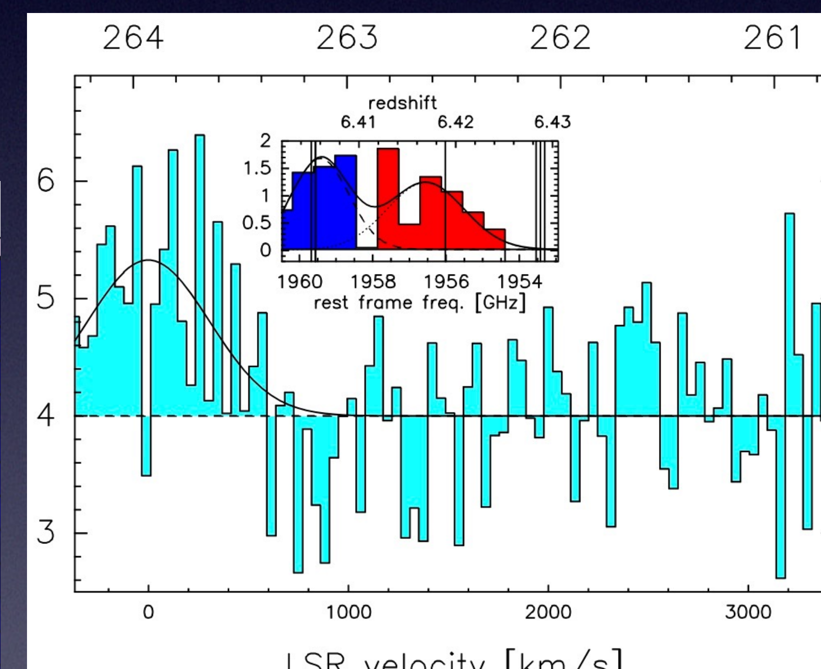


Quasar J1148 z=6.4

DUST



GAS CO J=17-16



Gallerani+2014

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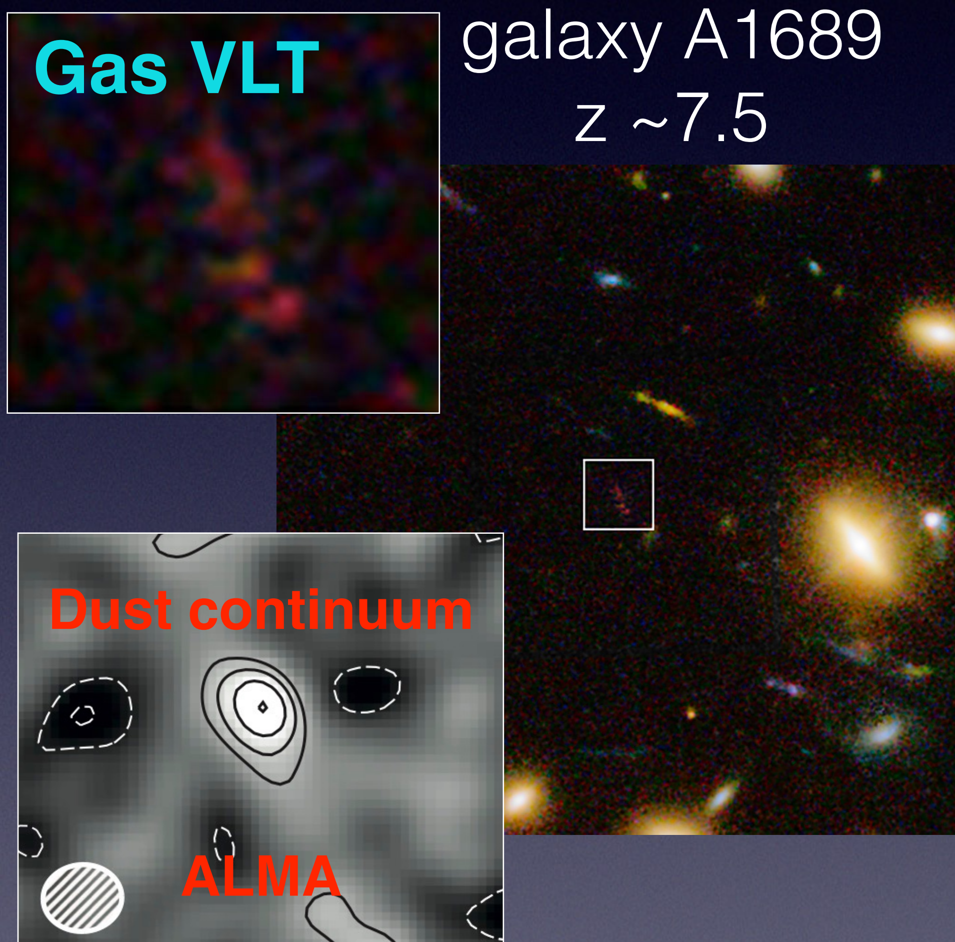

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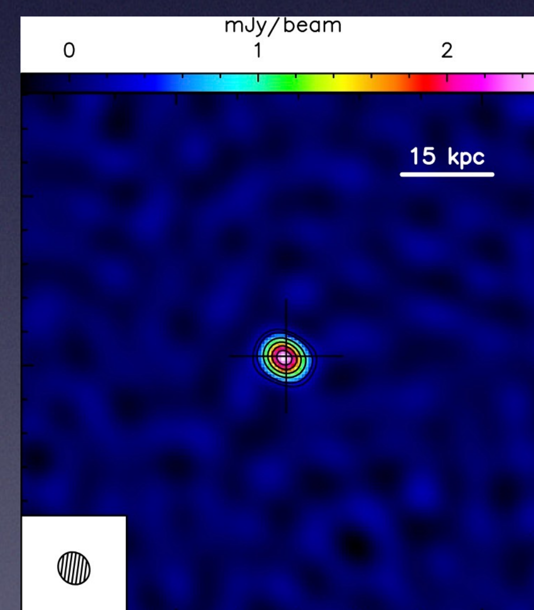

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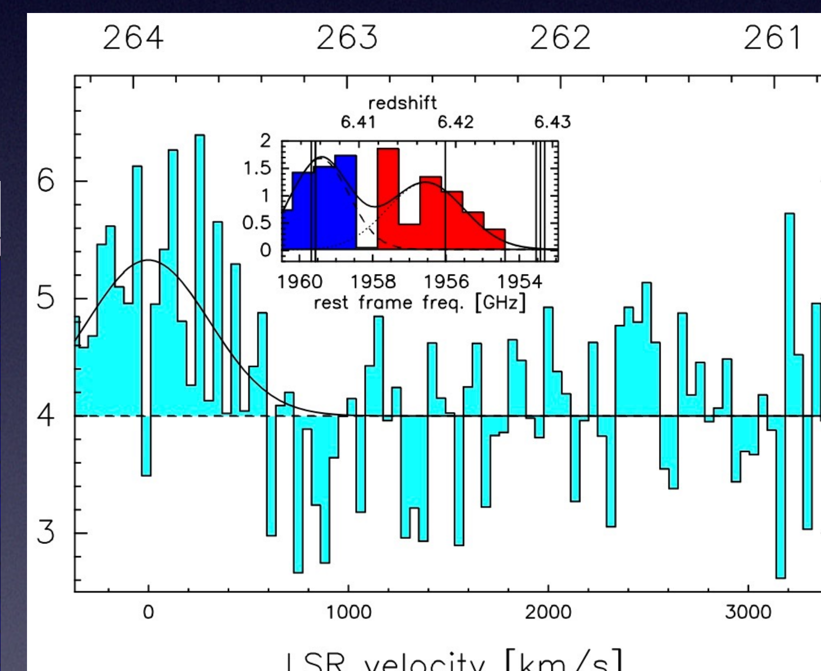


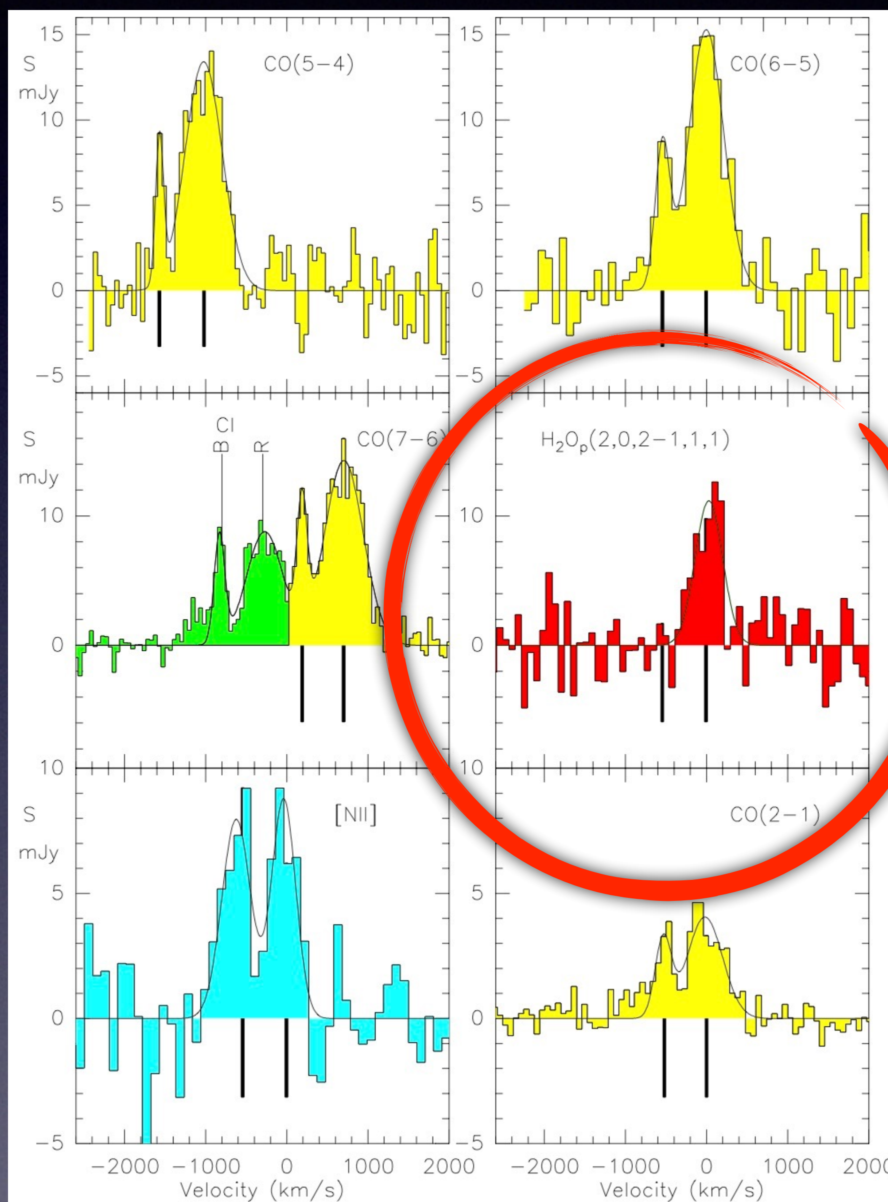
Gallerani+2014

Only CO molecule detected, but grain surface chemistry possible at very early cosmic epochs

The second billion years: Water

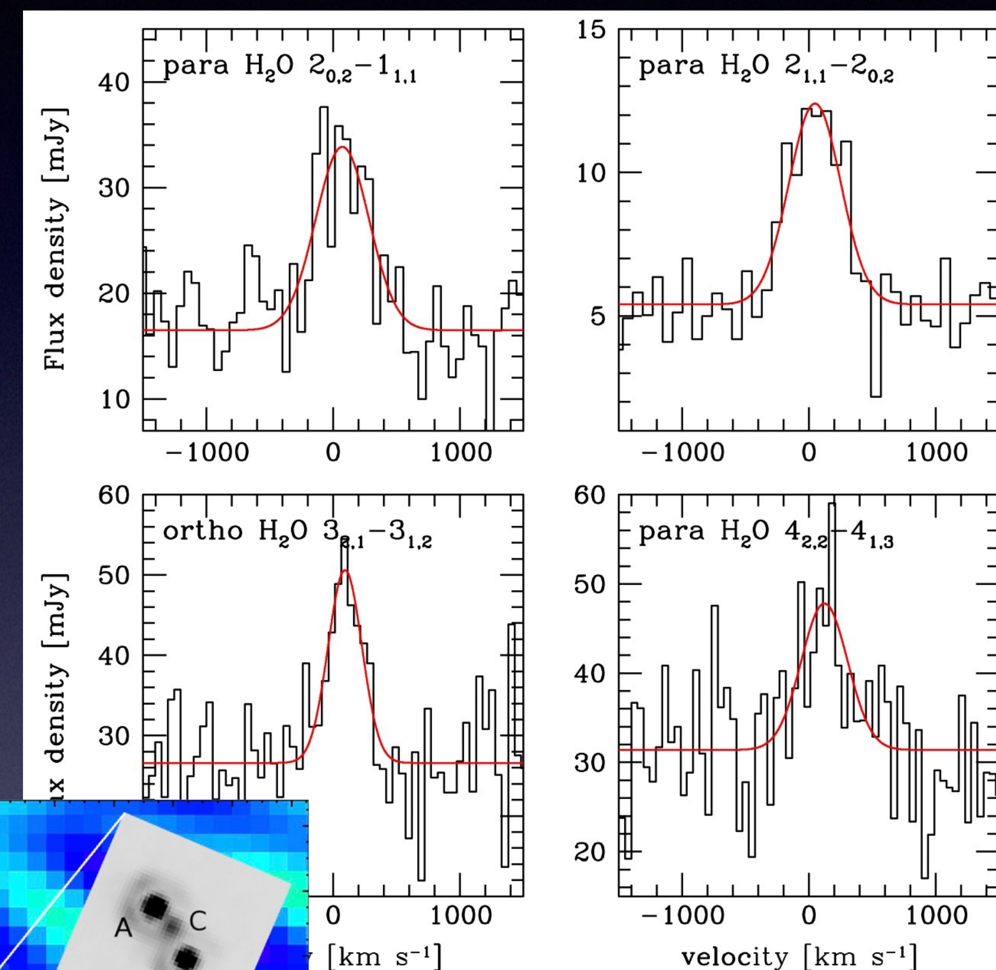
HLSJ091828.6+514223 at z=5.3

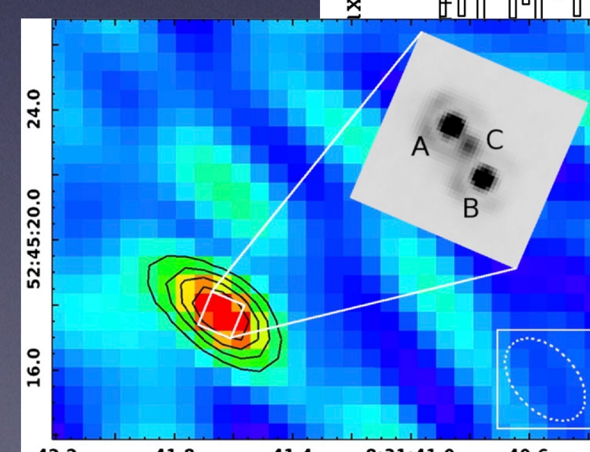
Combes+2012



Quasar APM08279+5255 z=3.9

van der Werf+2011



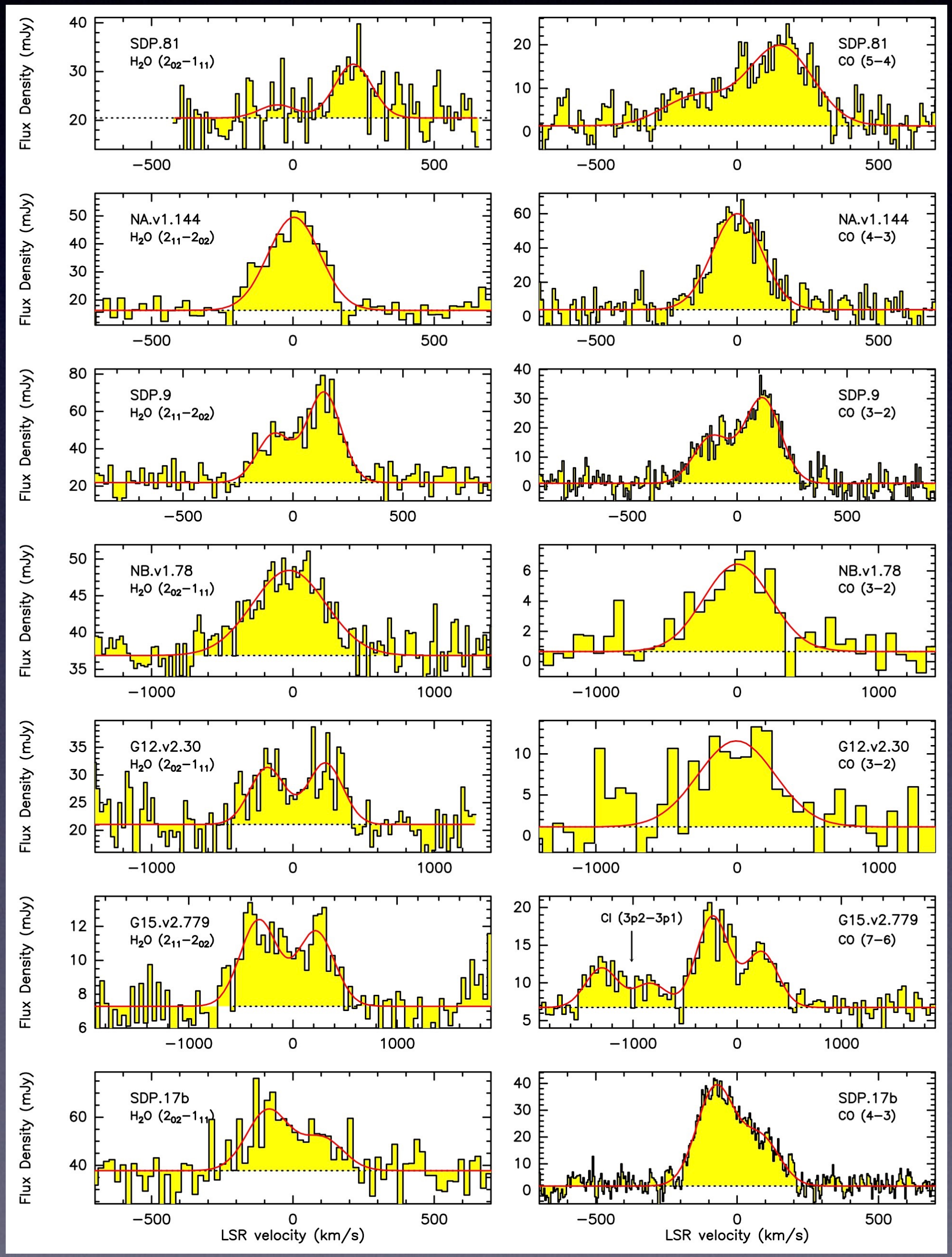


H_2O luminosities comparable to CO lines: large water vapor reservoirs at early cosmic epochs

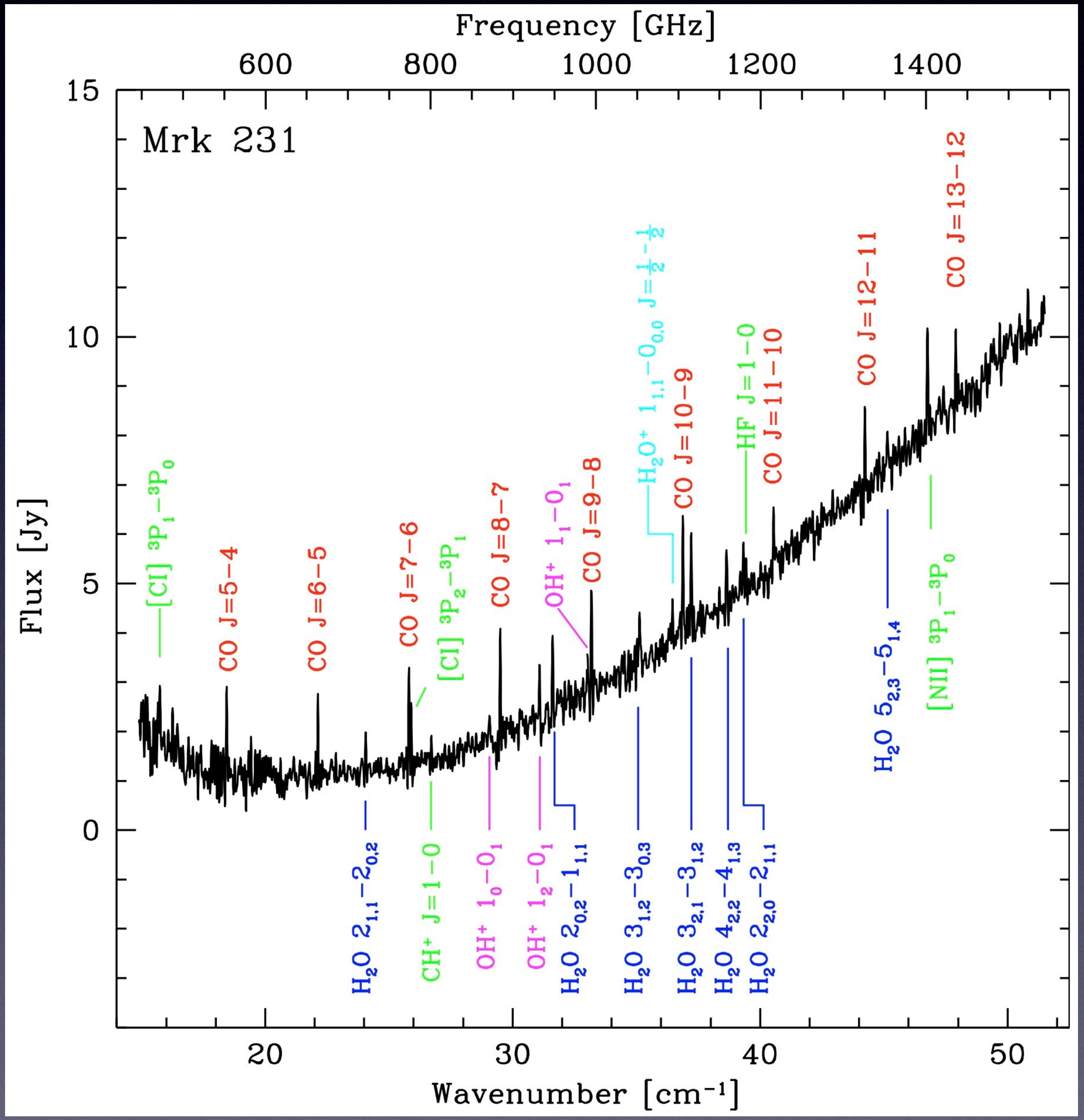
Water is everywhere

Water widespread in luminous galaxies/AGN at z=4 to z=0

Omont+2013



van der Werf+2010



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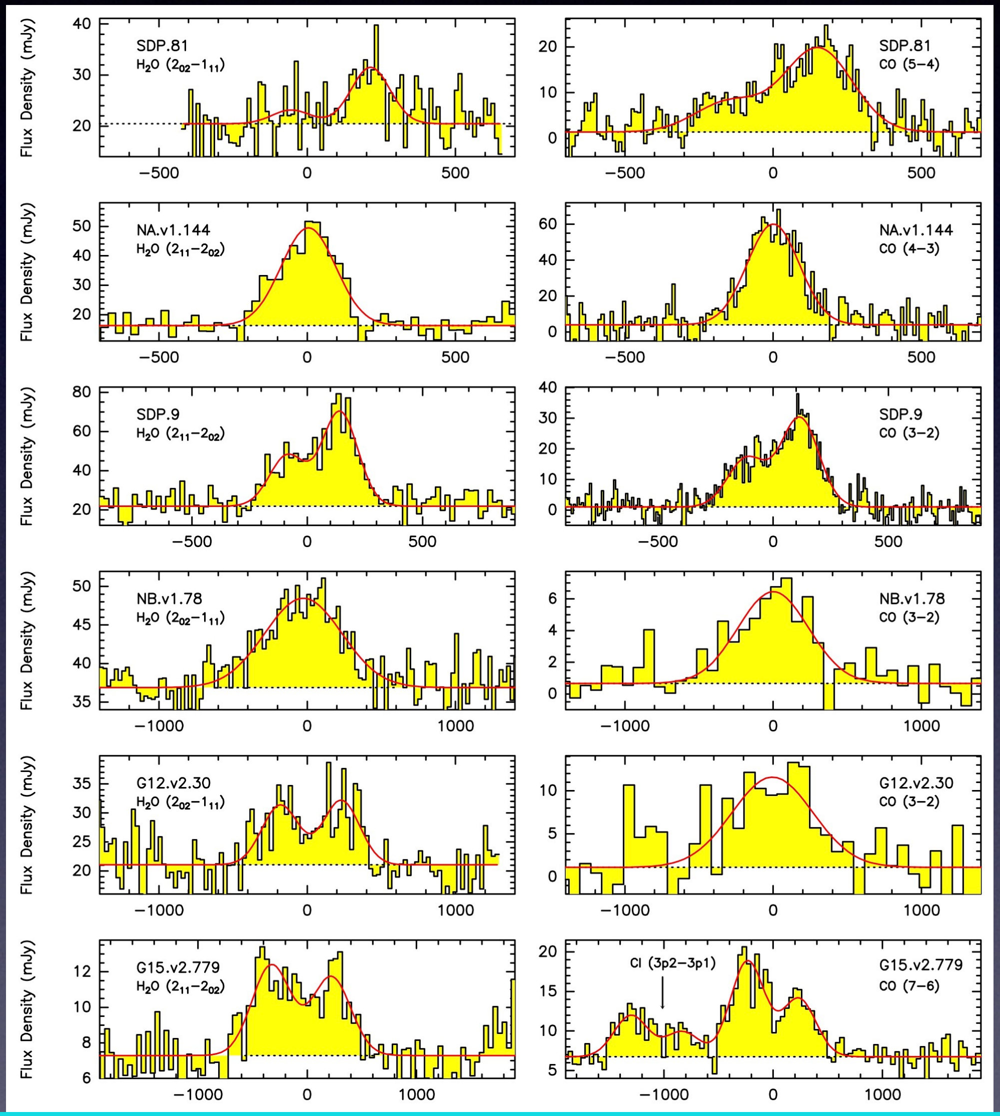
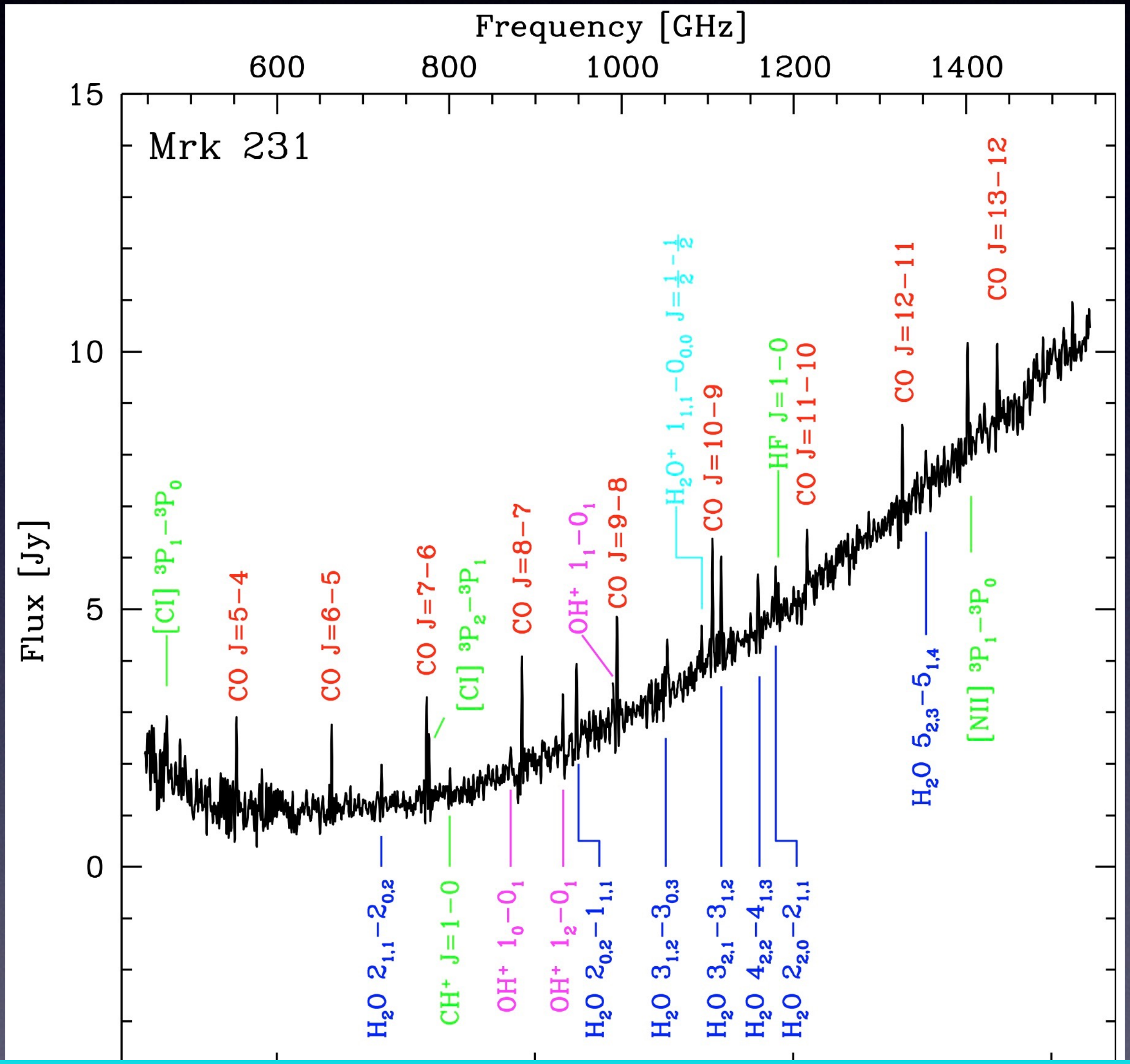
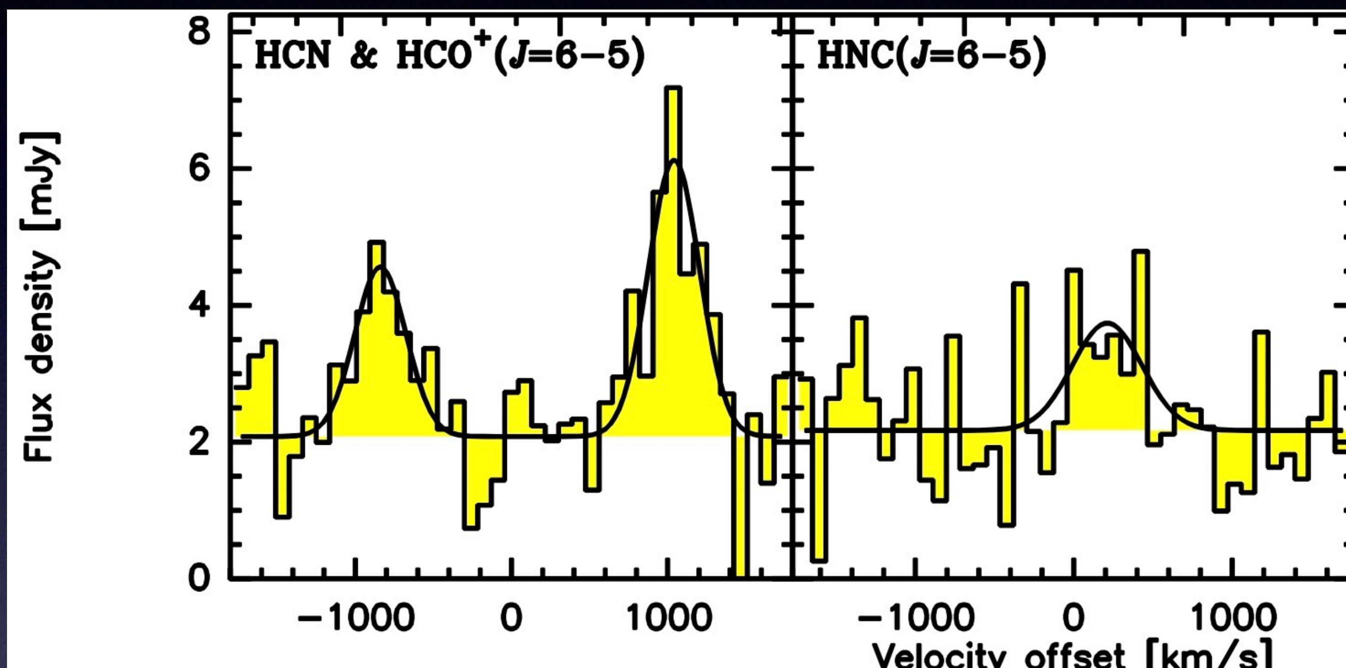




- H_2O luminosity comparable CO luminosity ,1-2 orders of mag larger than in Orion bar
- Requires strong FIR radiation pumping by dust and X-ray heating.
- May also be related to shocks

The second billion years: HCN, HCO^+

Most complex molecules (3 athoms) in luminous quasar APM 08279 when the universe was only 10% of its age



HCN/HCO^+

- **massive dense gas reservoirs**
- **HCN energetic molecule**
- **HCO+ reactive ion**

Riechers+2010

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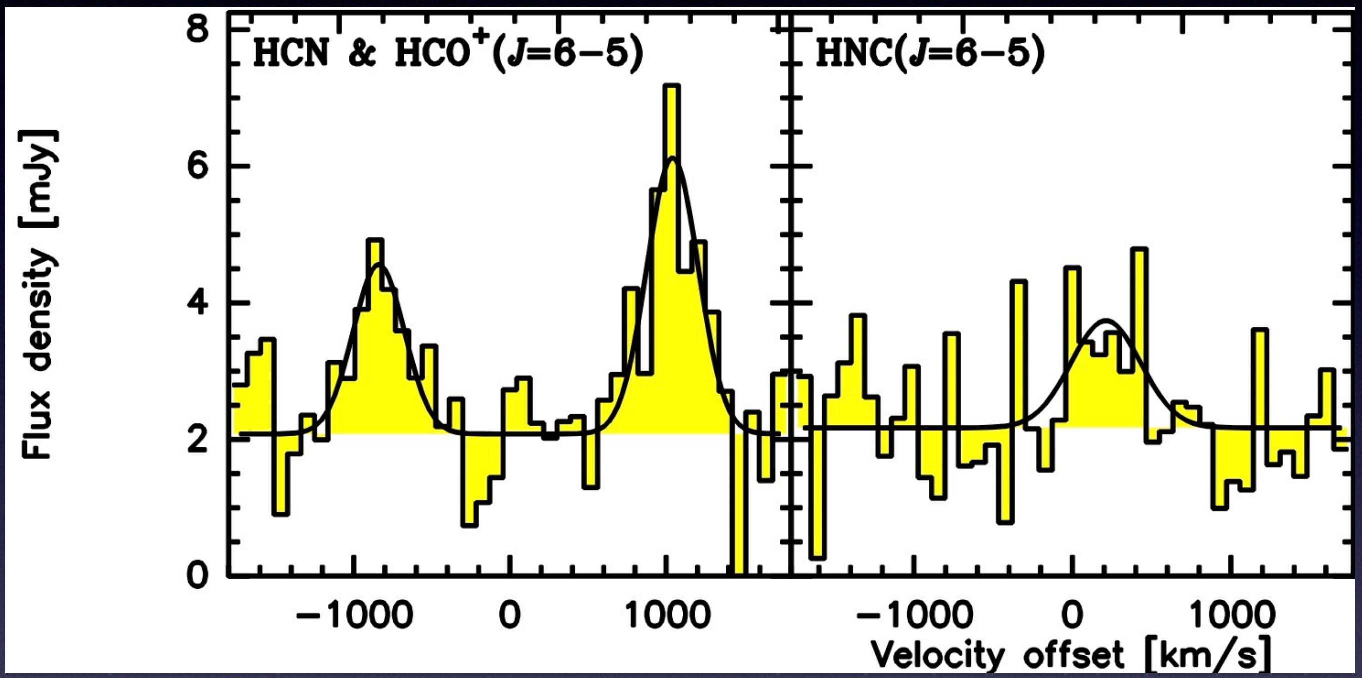

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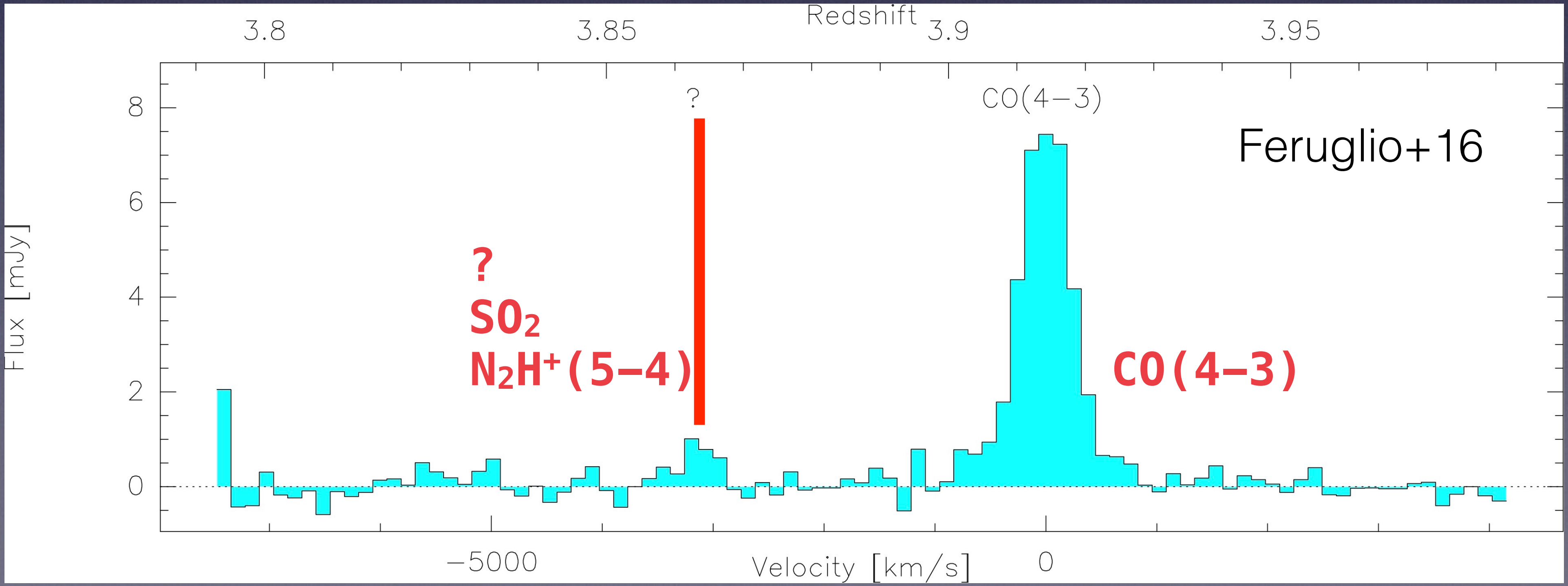
Identification problem:
- **Sulfur-bearing molecule**
- **N_2H^+ ion**

Shock and Cosmic Ray ionisation

BOTH possible since we have fast molecular outflows there



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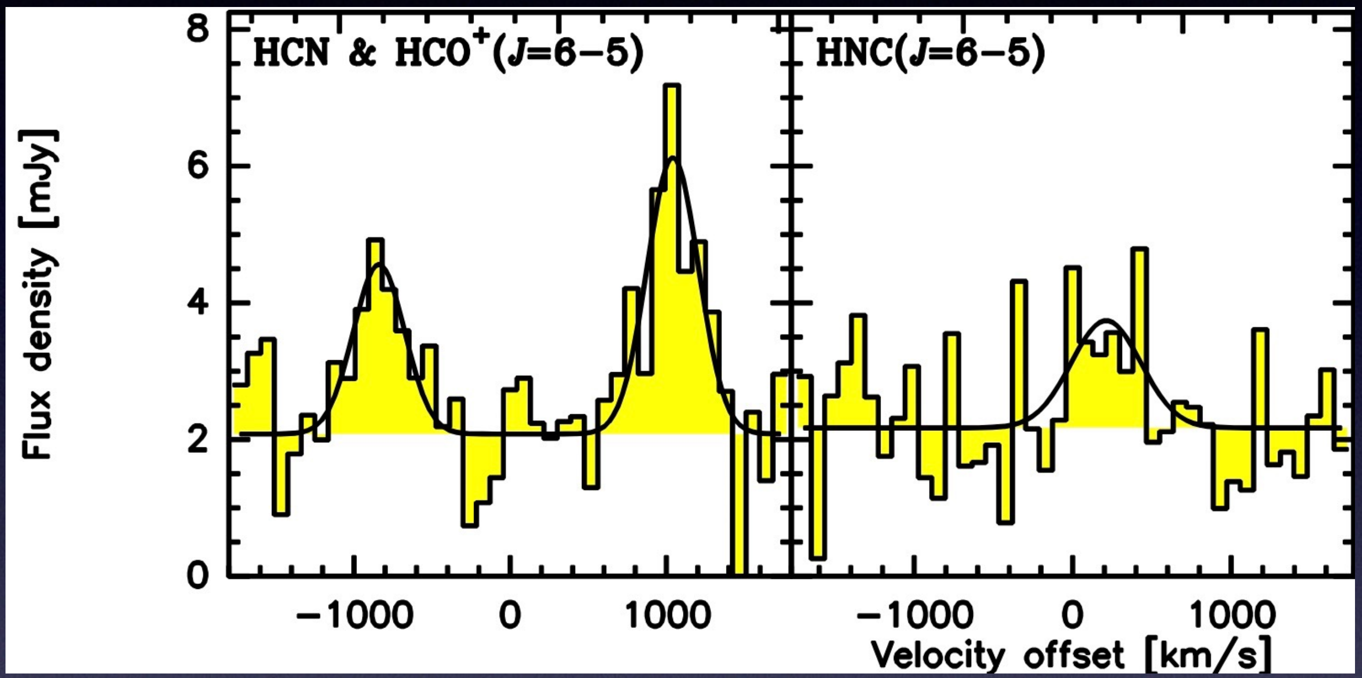

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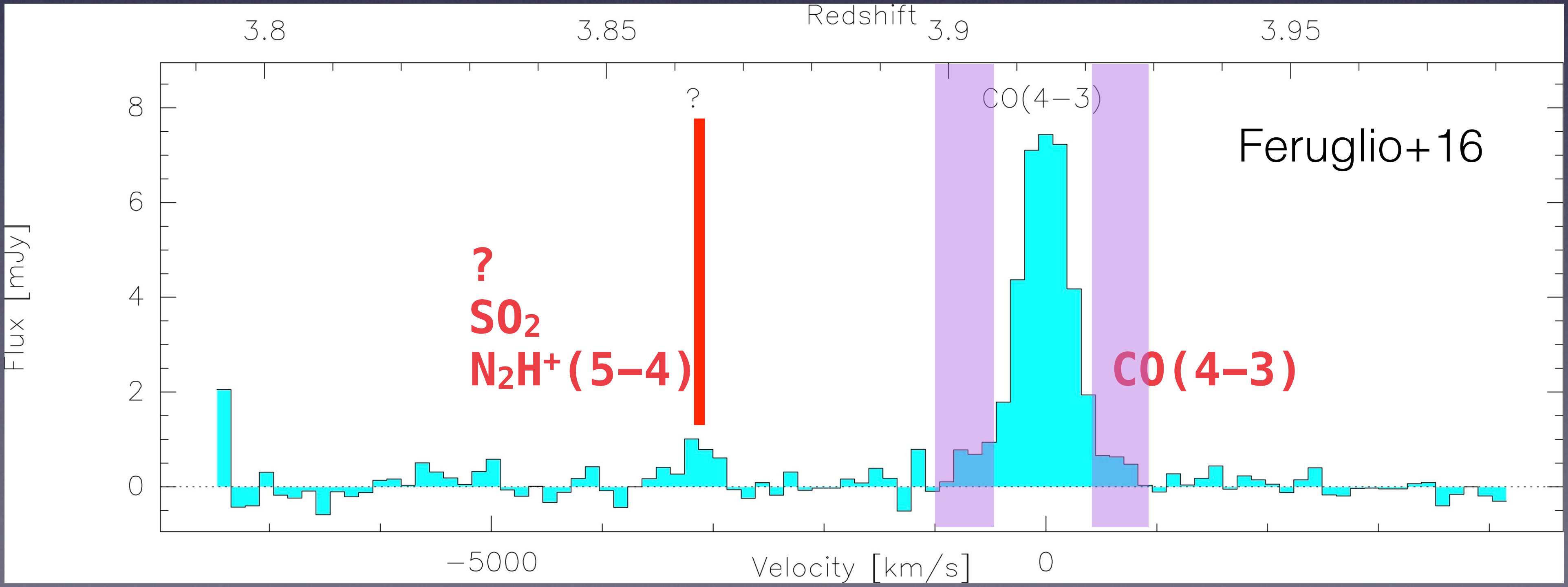


Mid age universe: PAHs

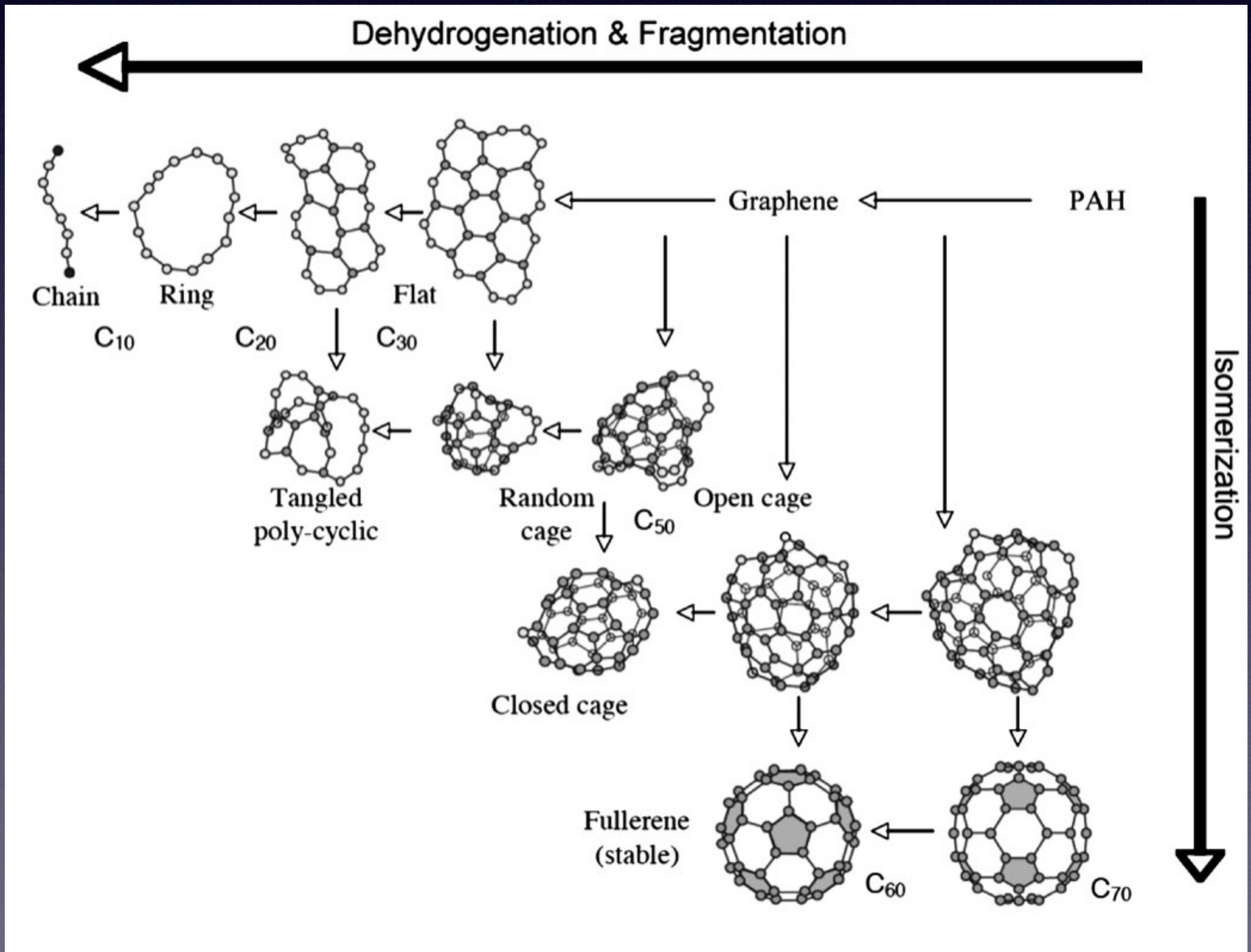
Infrared fluorecence of UV-pumped 50-100 C atoms compounds formed in stellar outflows

No specific spectral signature, broad emission bands

Abundant and ubiquitous ISM component, Lock ~10% of C

TOP-DOWN CHEMISTRY

PAHs are building blocks of ISM dust grains, mediate chemical processes



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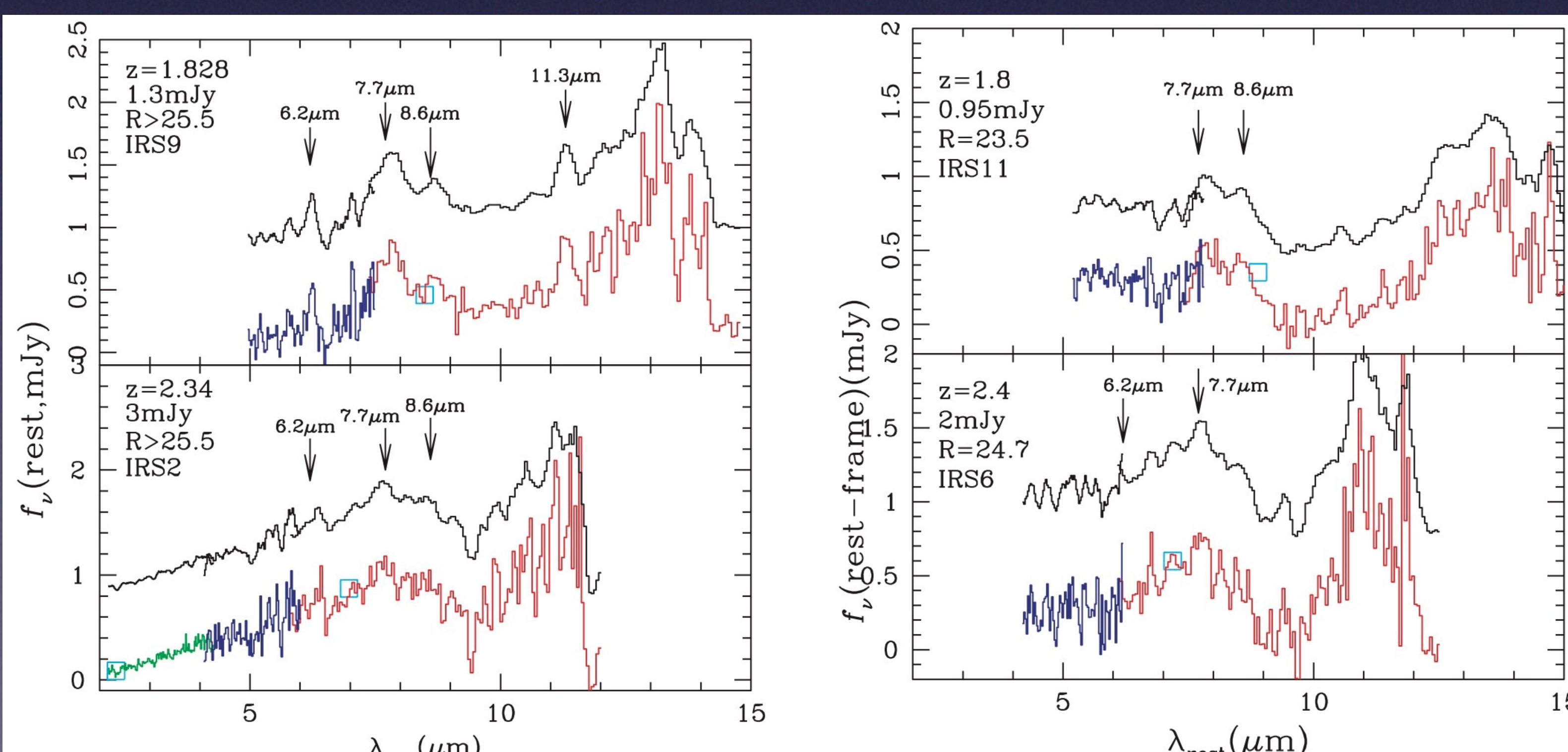
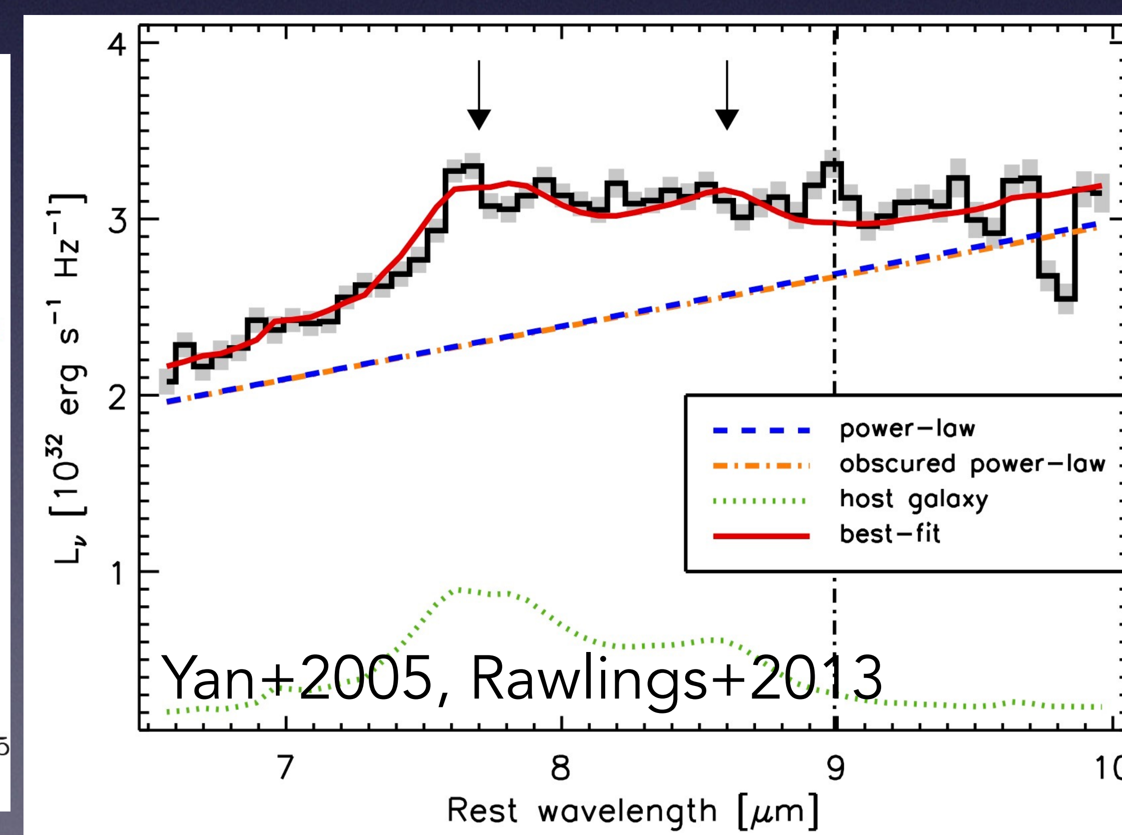
Aromatic infrared bands at
6.2 to 11.3 micron widely detected in luminous galaxies out to z~3
less in AGN (destroyed by X-rays)

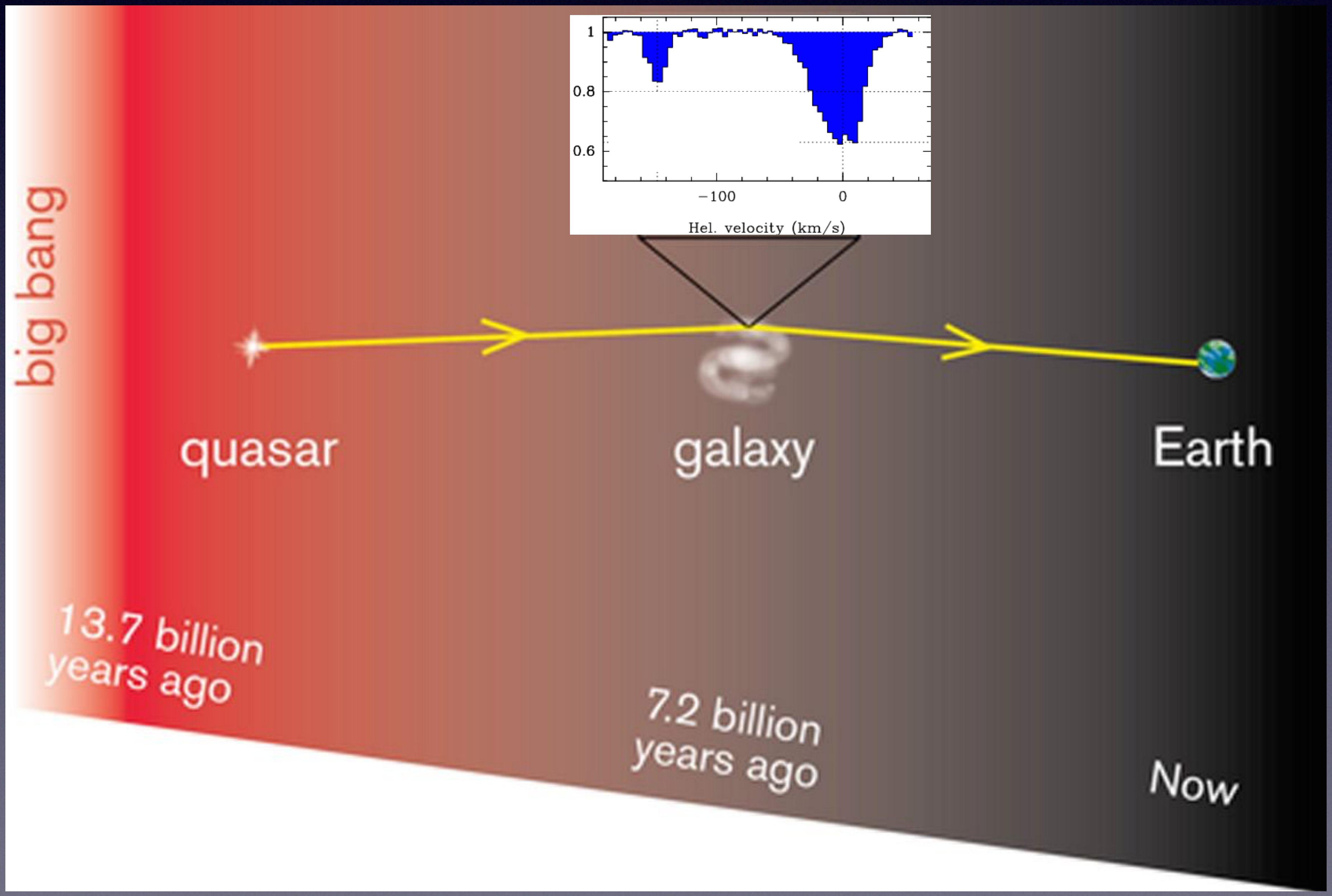




well before Earth formation

Mid age universe: molecular absorption lines

MW-like Galaxy at z~0.9 towards bright quasar PKS1830



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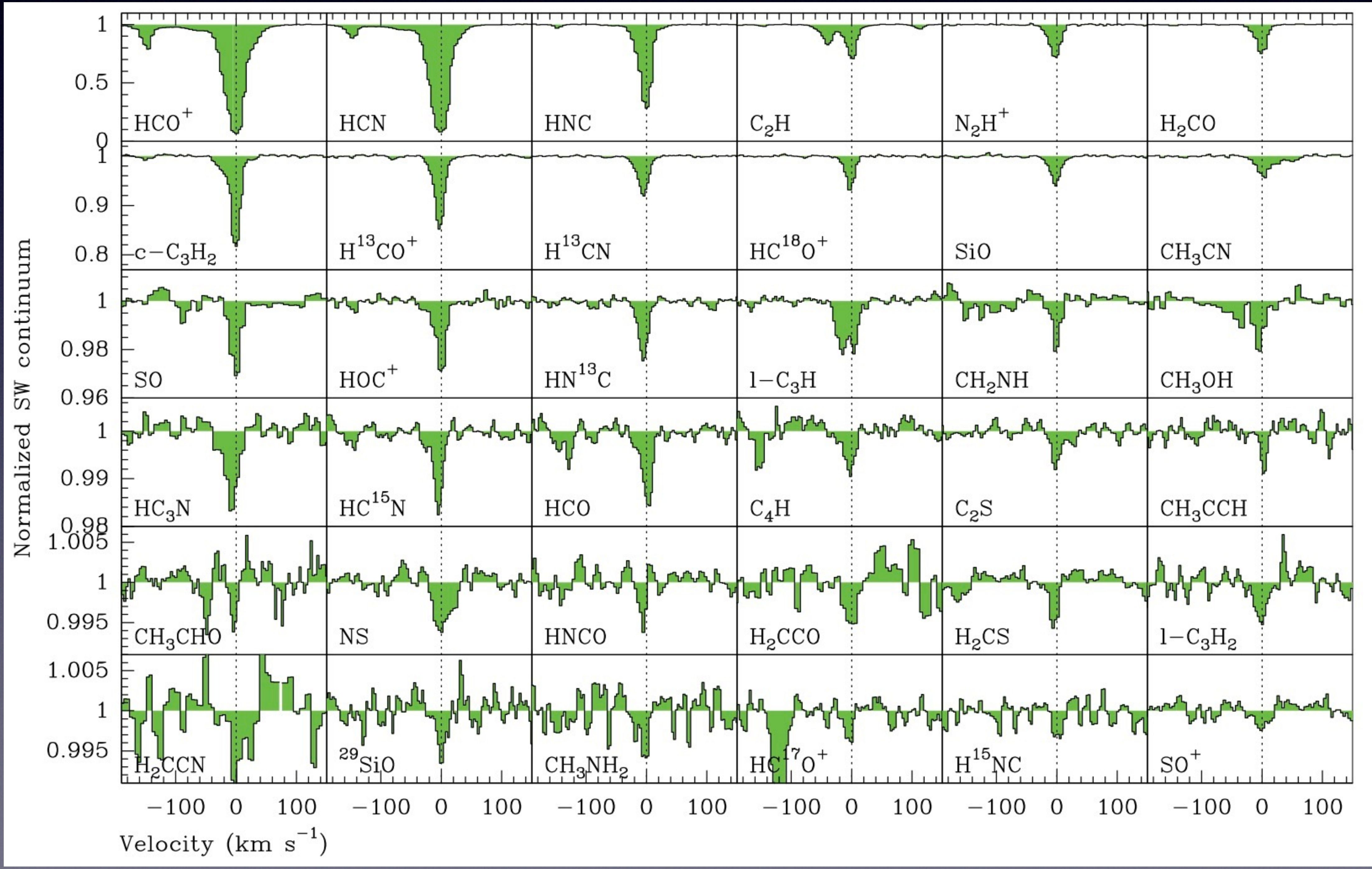
> 40 molecular species detected (Muller+2011,2014)



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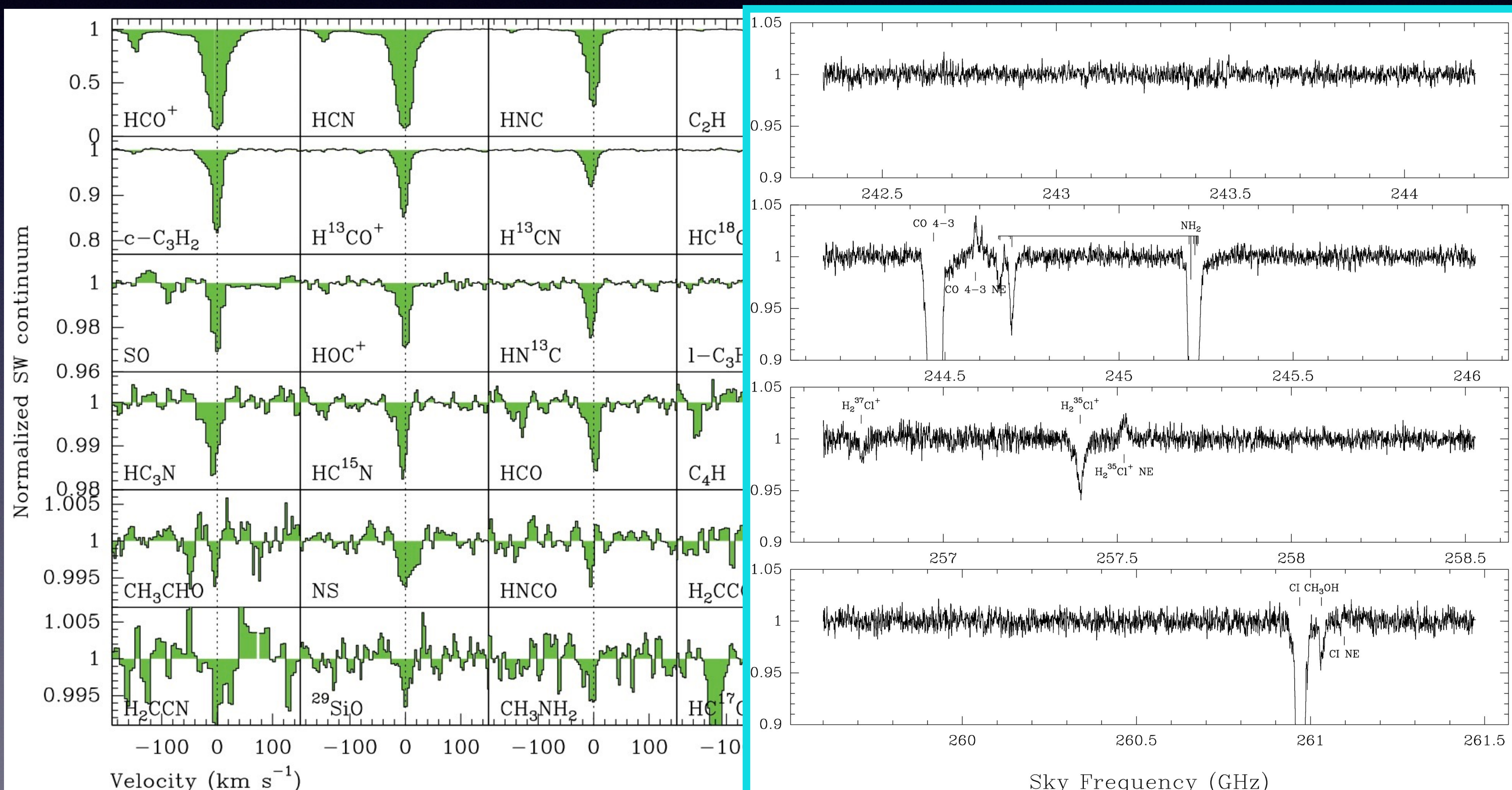

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Muller+2011, 2014

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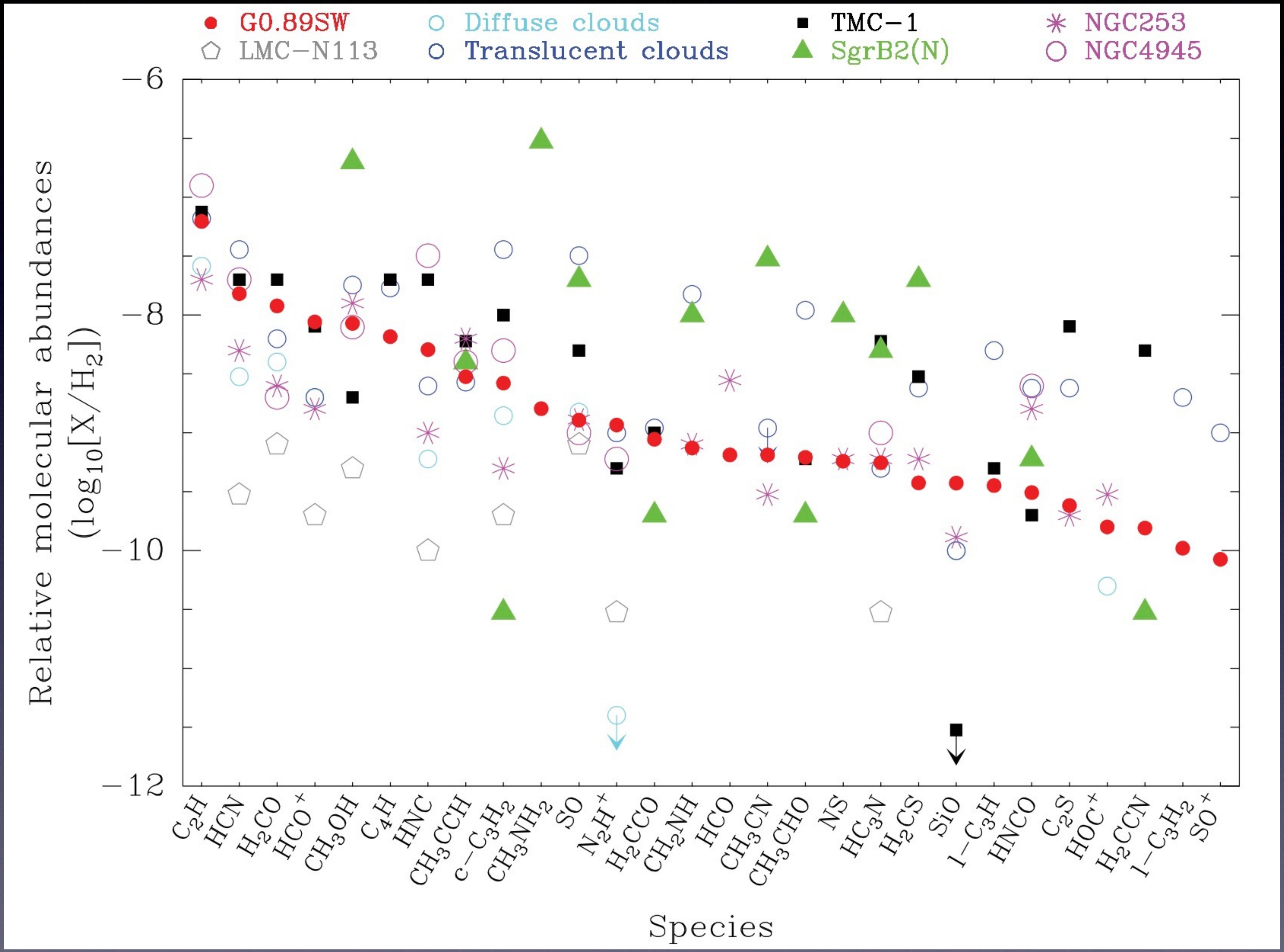
(CO) [bci]	C_2H [e]	H_2CO [ce]	$c\text{-}C_3H_2$ [e]	$\mathbf{CH_3CN}$	$\mathbf{CH_3C_2H}$
(CS) [af]	HCN [aef] △	$\underline{\mathbf{l\text{-}C_3H}}$	$\underline{\mathbf{l\text{-}C_3H_2}}$		$\underline{\mathbf{CH_3CHO}}$
SiO [j] †	HNC [aef] ◇	$\mathbf{HNCO}$	$\underline{\mathbf{H_2CCN}}$		
$\mathbf{NS}$	N_2H^+ [a]	$\mathbf{H_2CS}$	$\underline{\mathbf{H_2CCO}}$		
$\mathbf{SO}$	HCO^+ [aef] ○		$\underline{\mathbf{C_4H}}$		
$\underline{\mathbf{SO^+}}$	$\mathbf{HCO}$		HC_3N [ej]		
	$\mathbf{HOC^+}$				
	(H_2S) [f]				
	$\mathbf{C_2S}$				

Mid age universe: molecular absorption lines

Muller+2011, 2014



Despite look-back time ~7 Gyr, chemical composition not wildly different from Milky Way's

Today's universe: nearby luminous galaxies

Most studied but… they do not look at all like the Milky Way!

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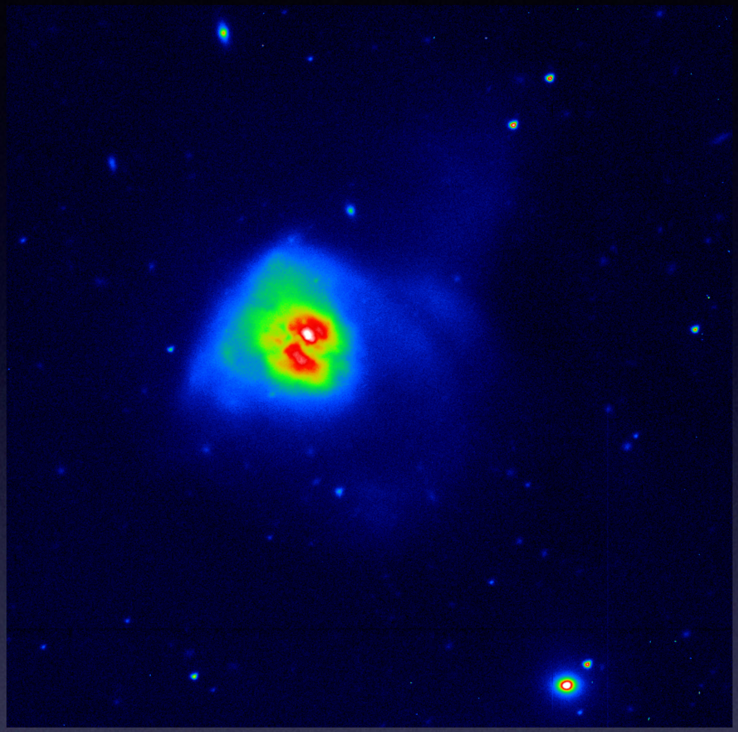

Today's universe: nearby luminous galaxies

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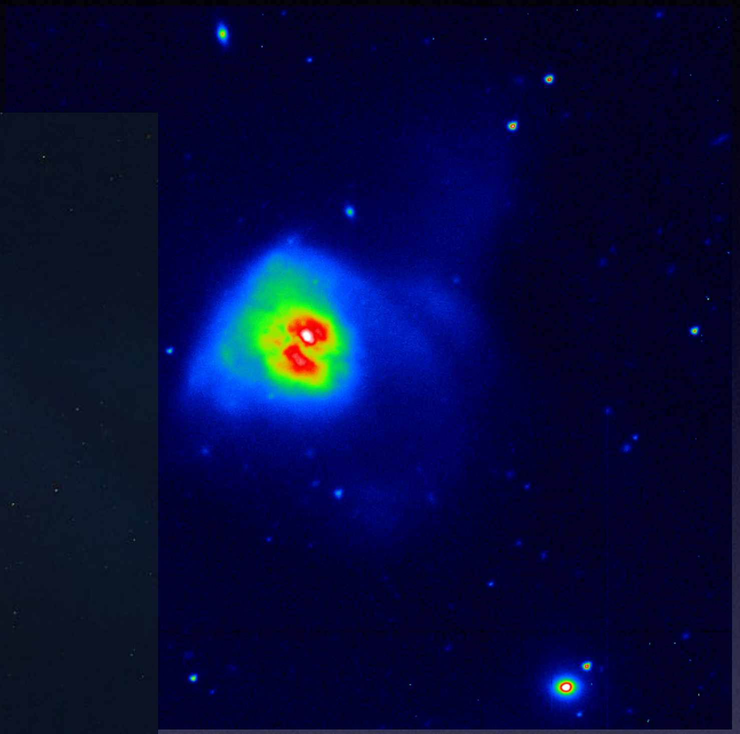

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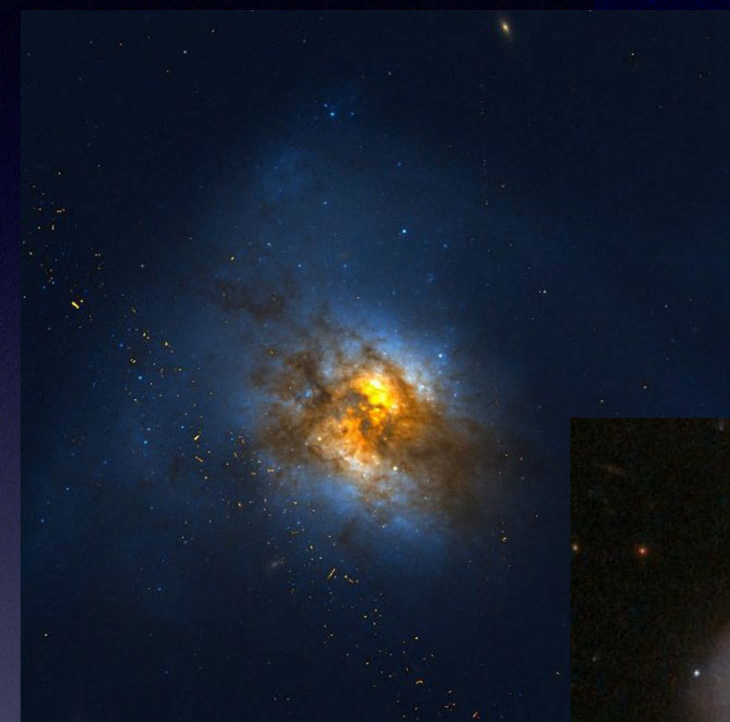

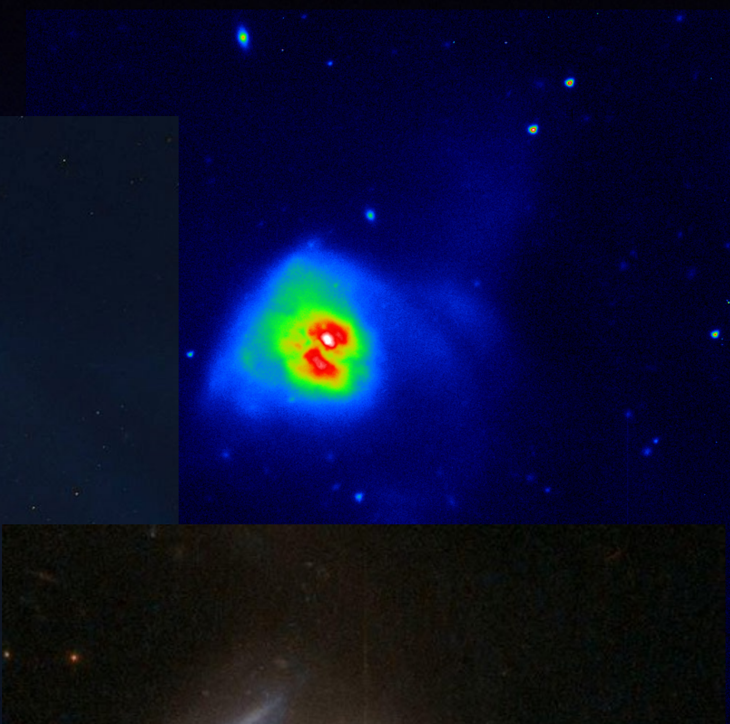

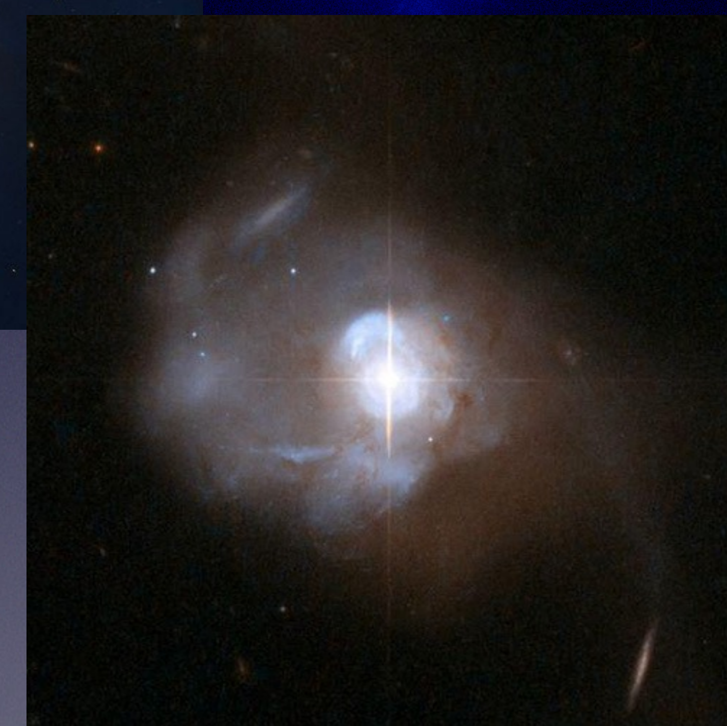

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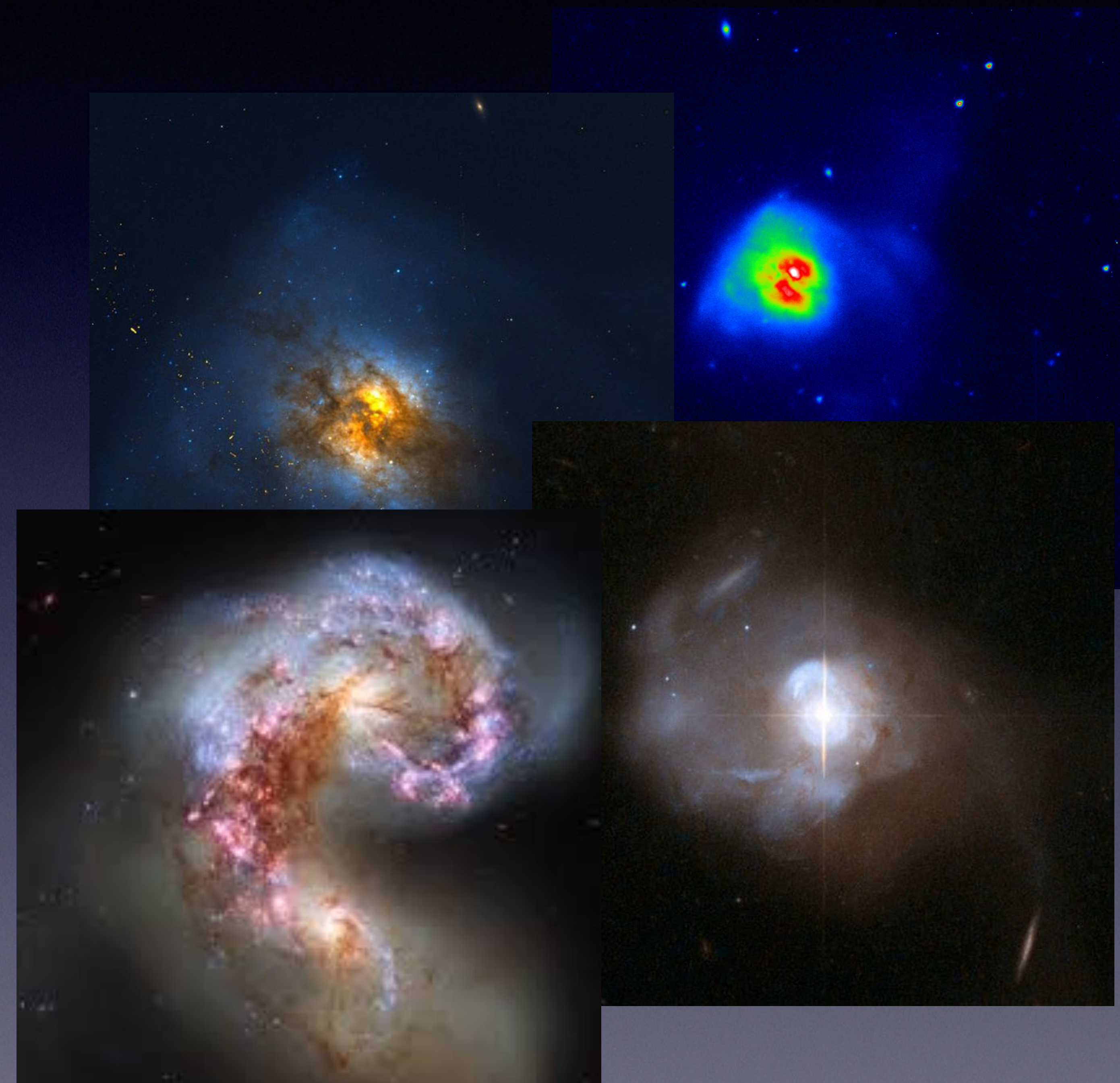

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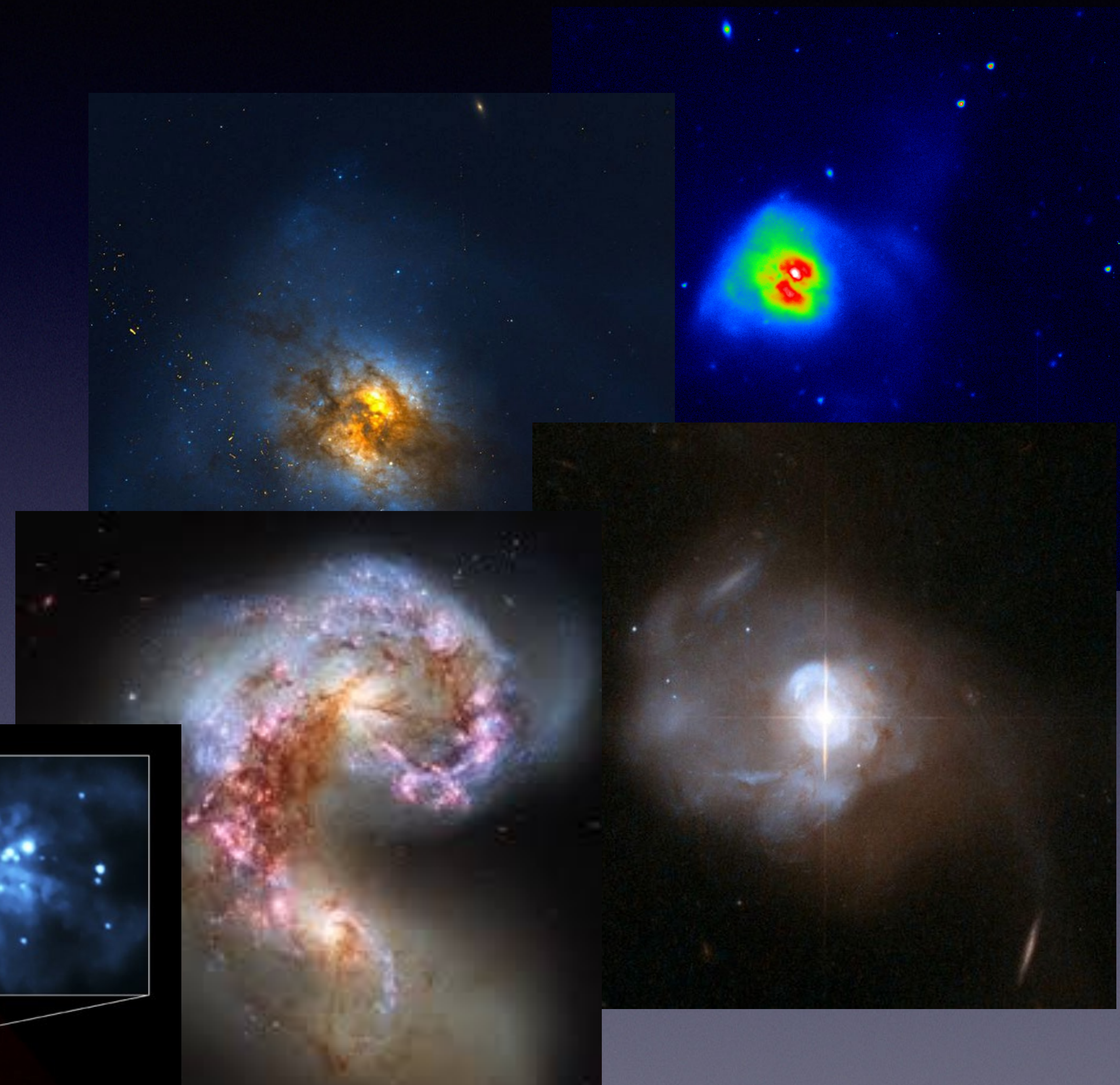

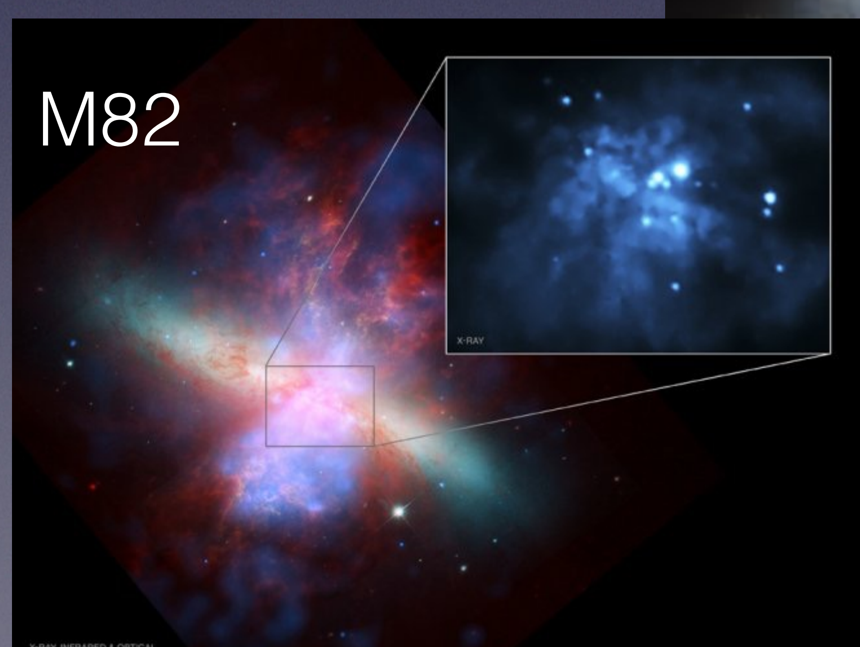

Luminosity ~10-100 larger

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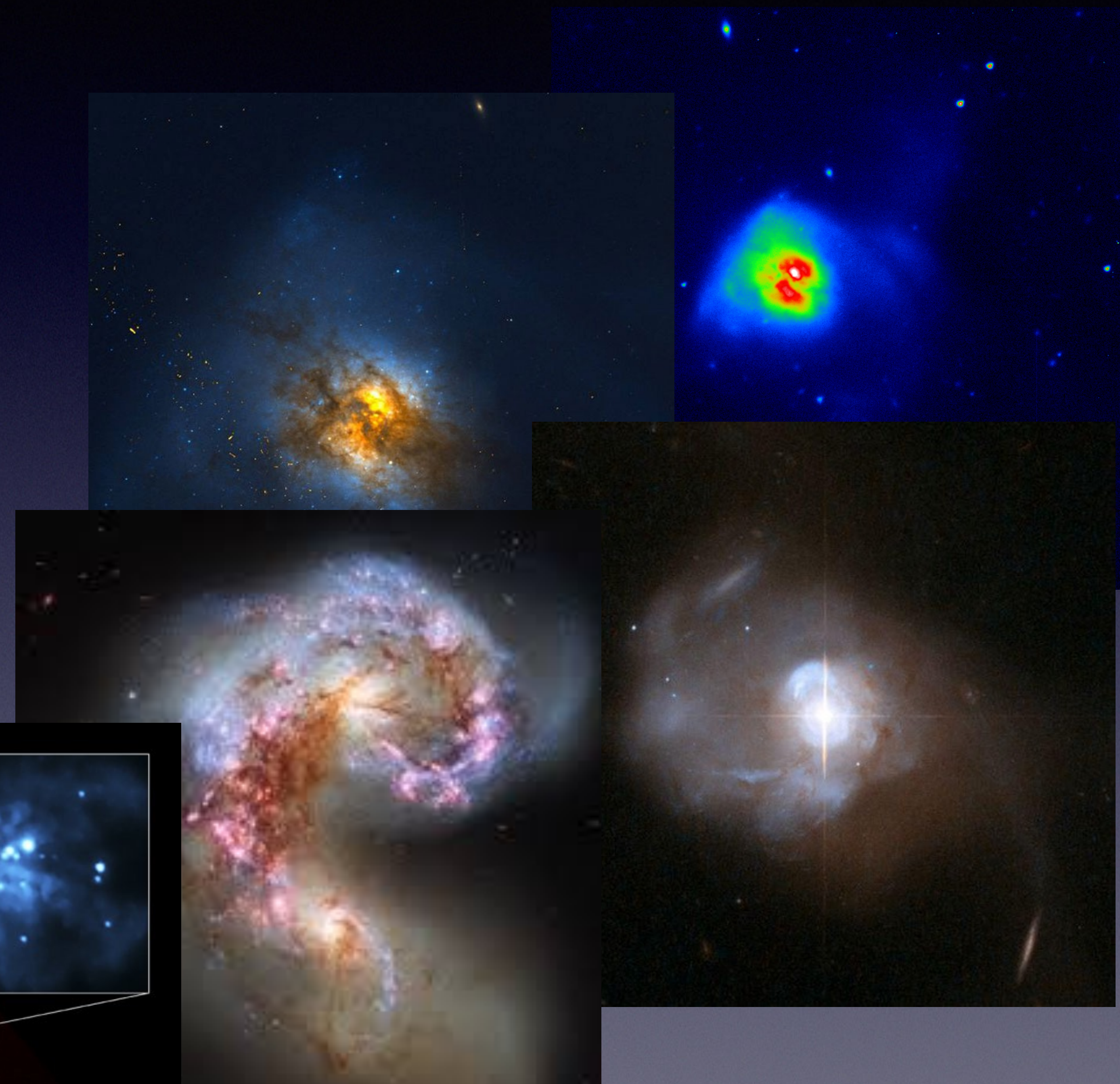
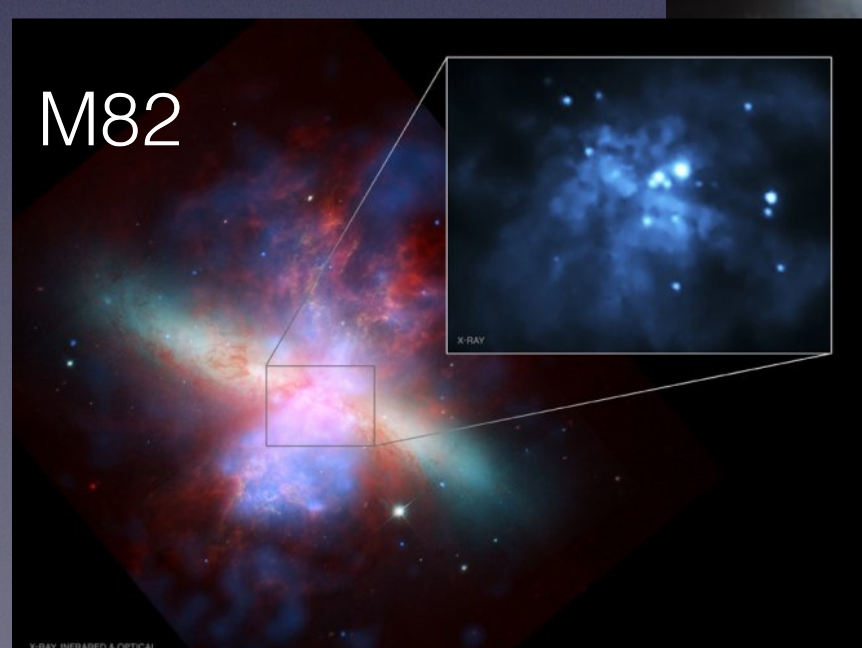
Forms stars at rate 1 MSun/yr



tens-hundreds MSun/yr
Often Super-massive BH
Superwinds



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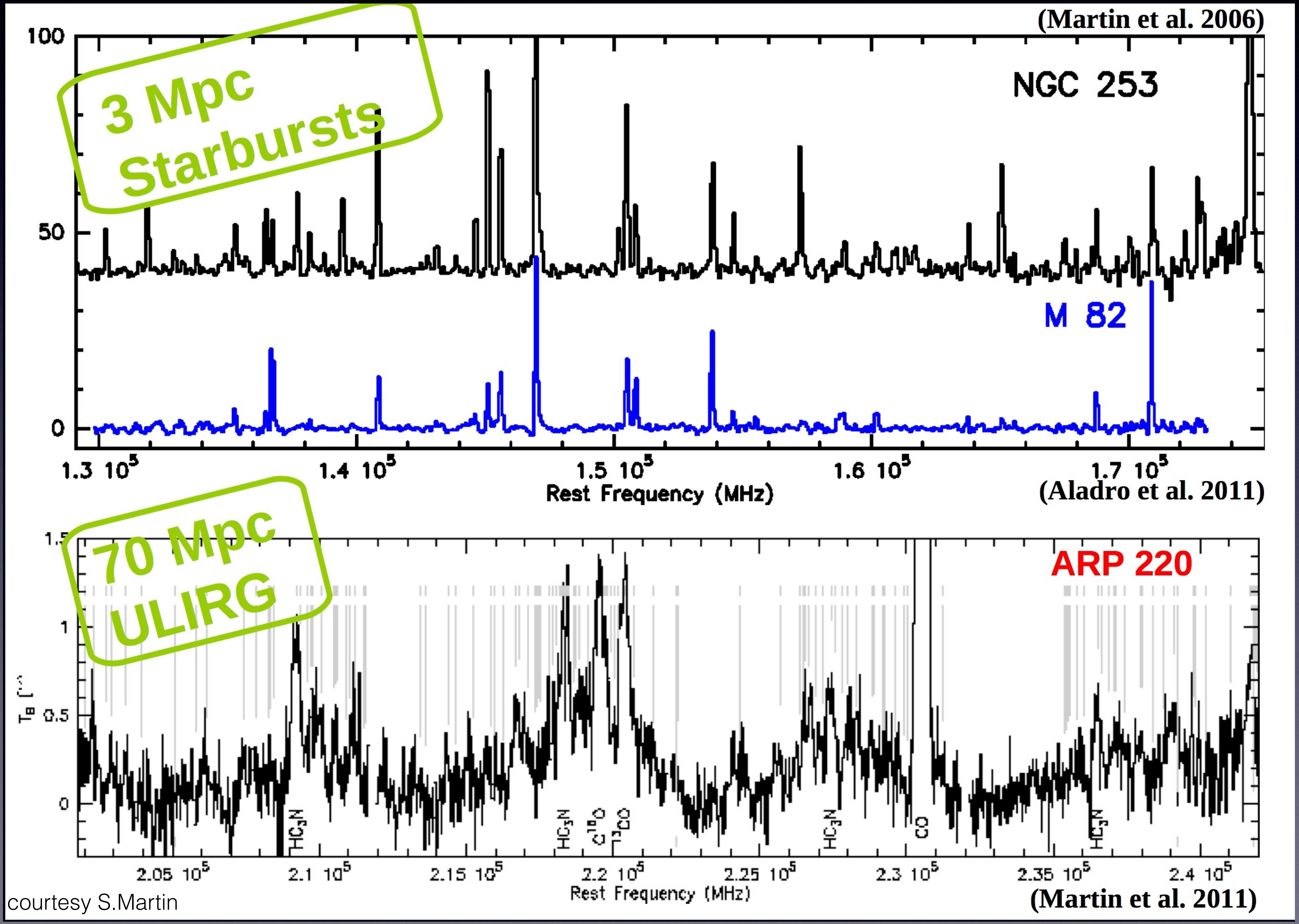
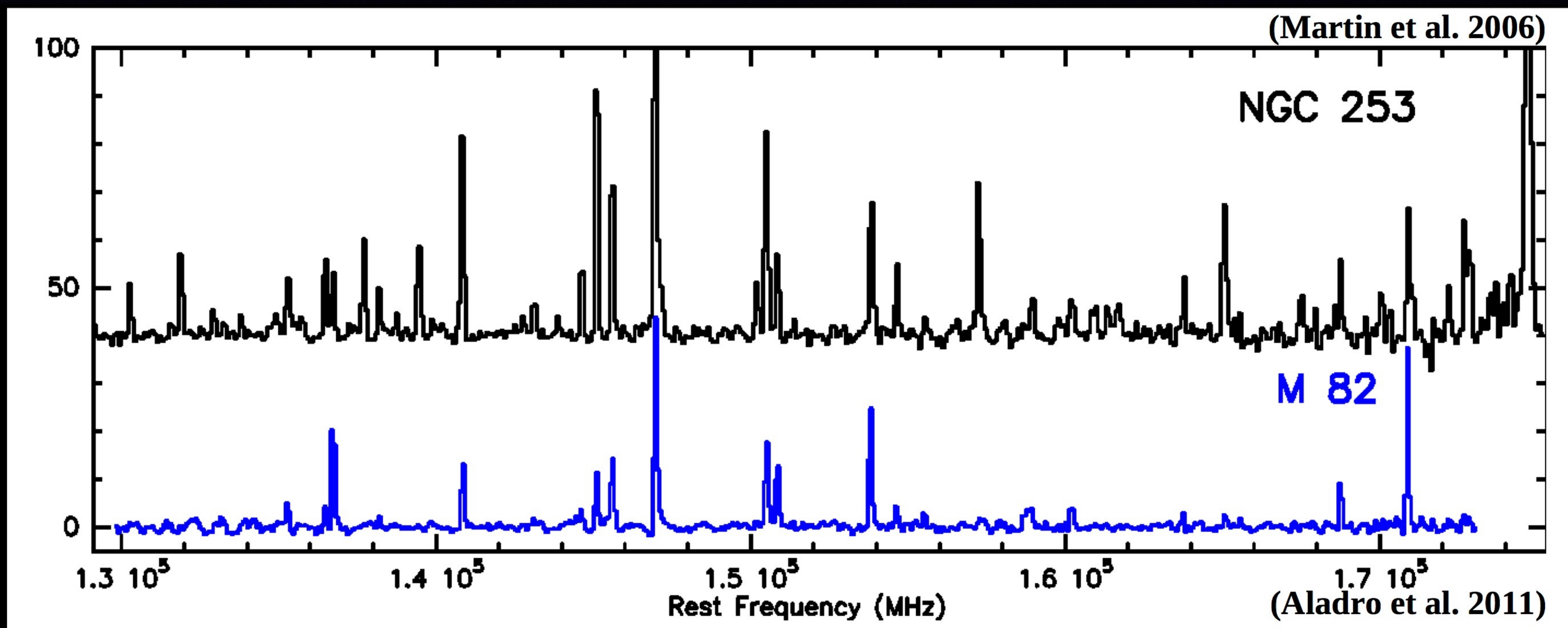
Beginning to explore the tip of the iceberg of chemical complexity of the extragalactic ISM

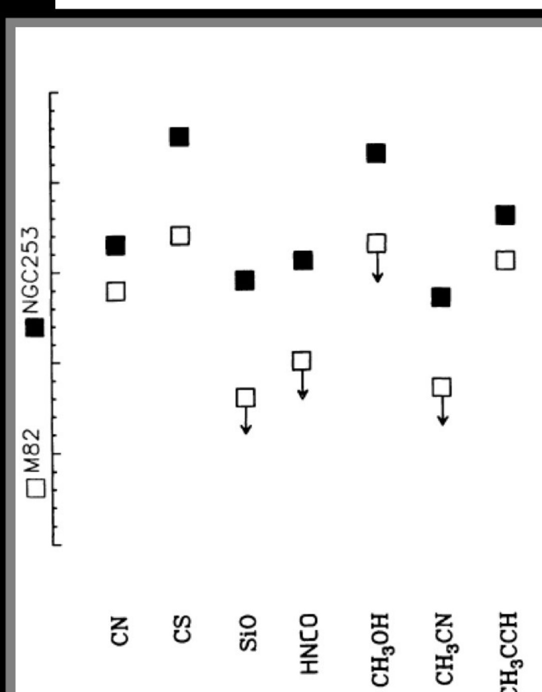


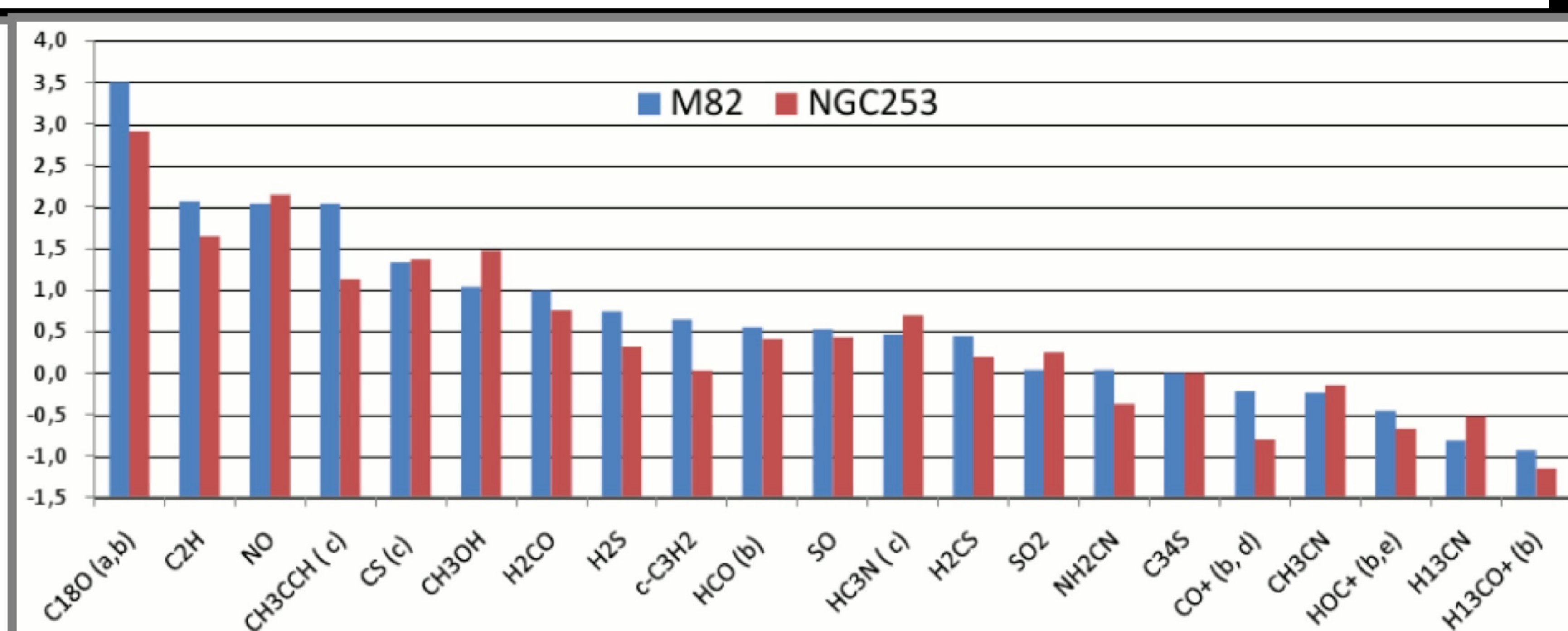
Today's universe: starburst galaxies

Molecular abundances to trace starburst evolution

courtesy S. Martin







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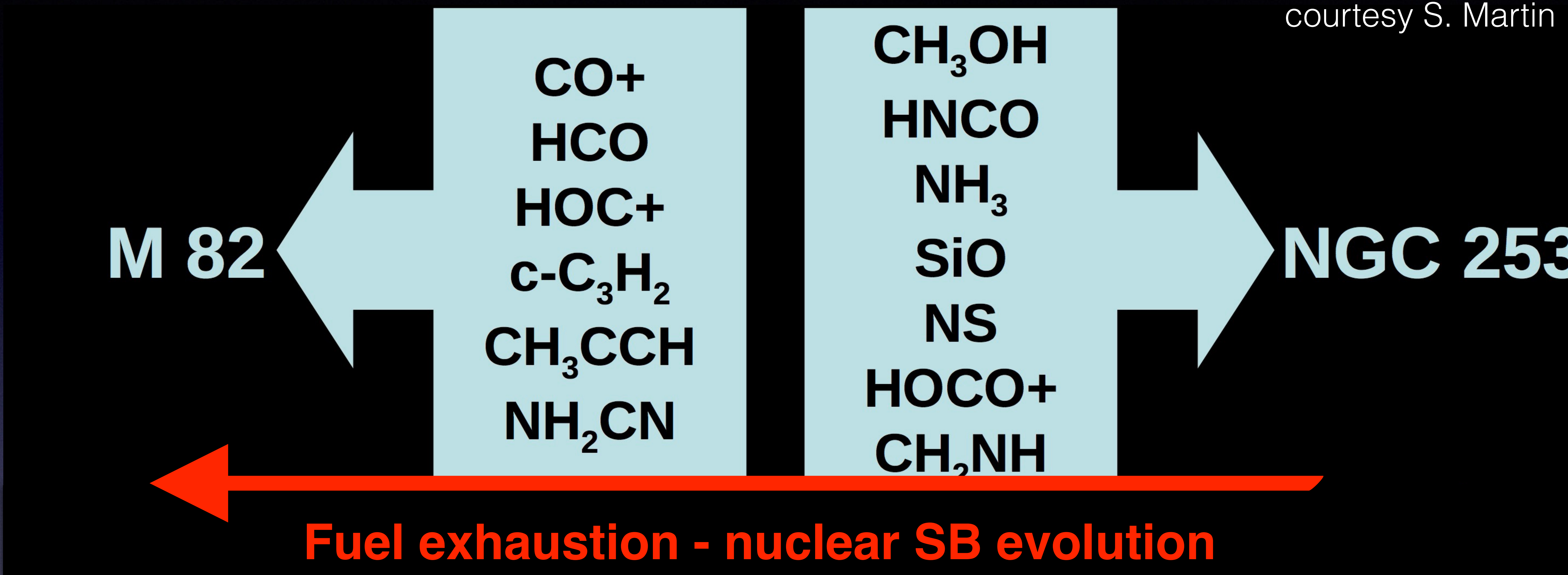
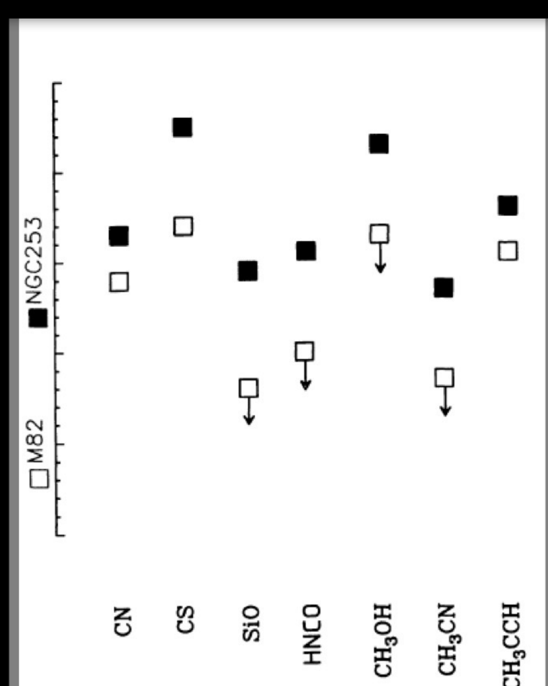
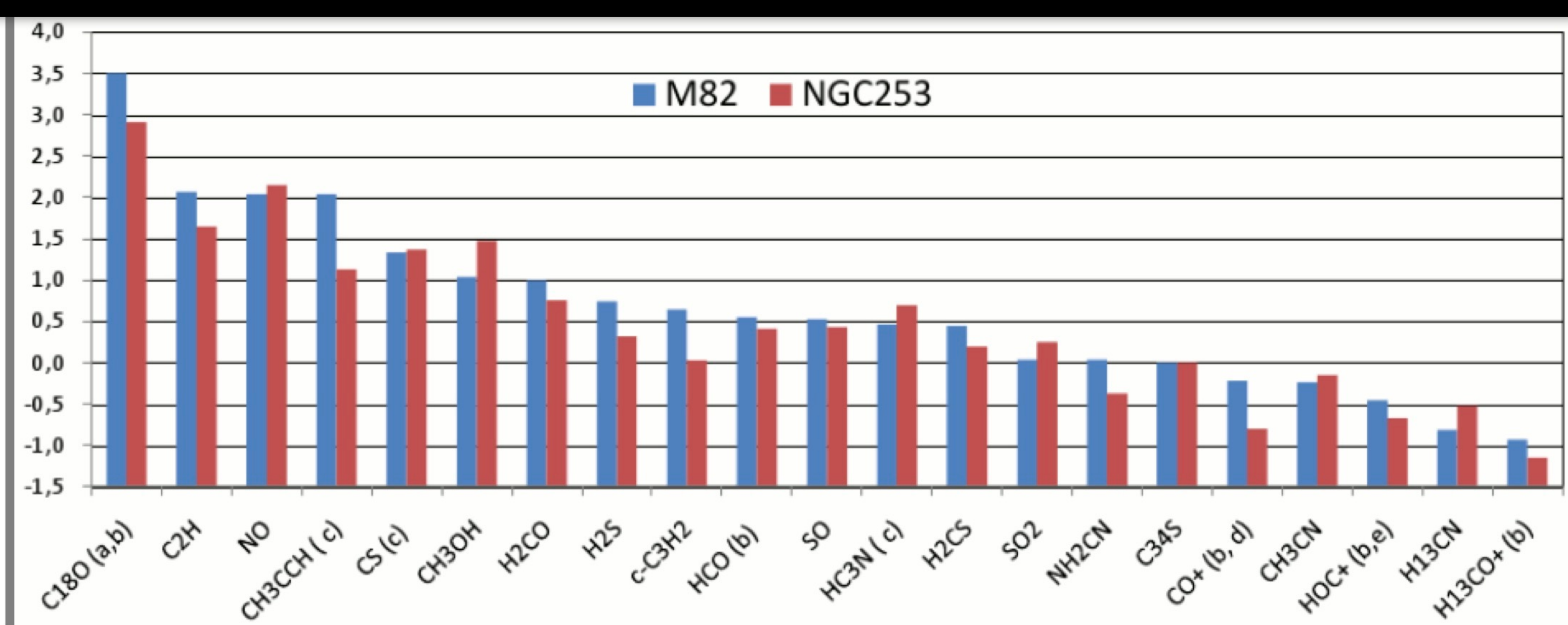






Today's universe: nearby active galaxies

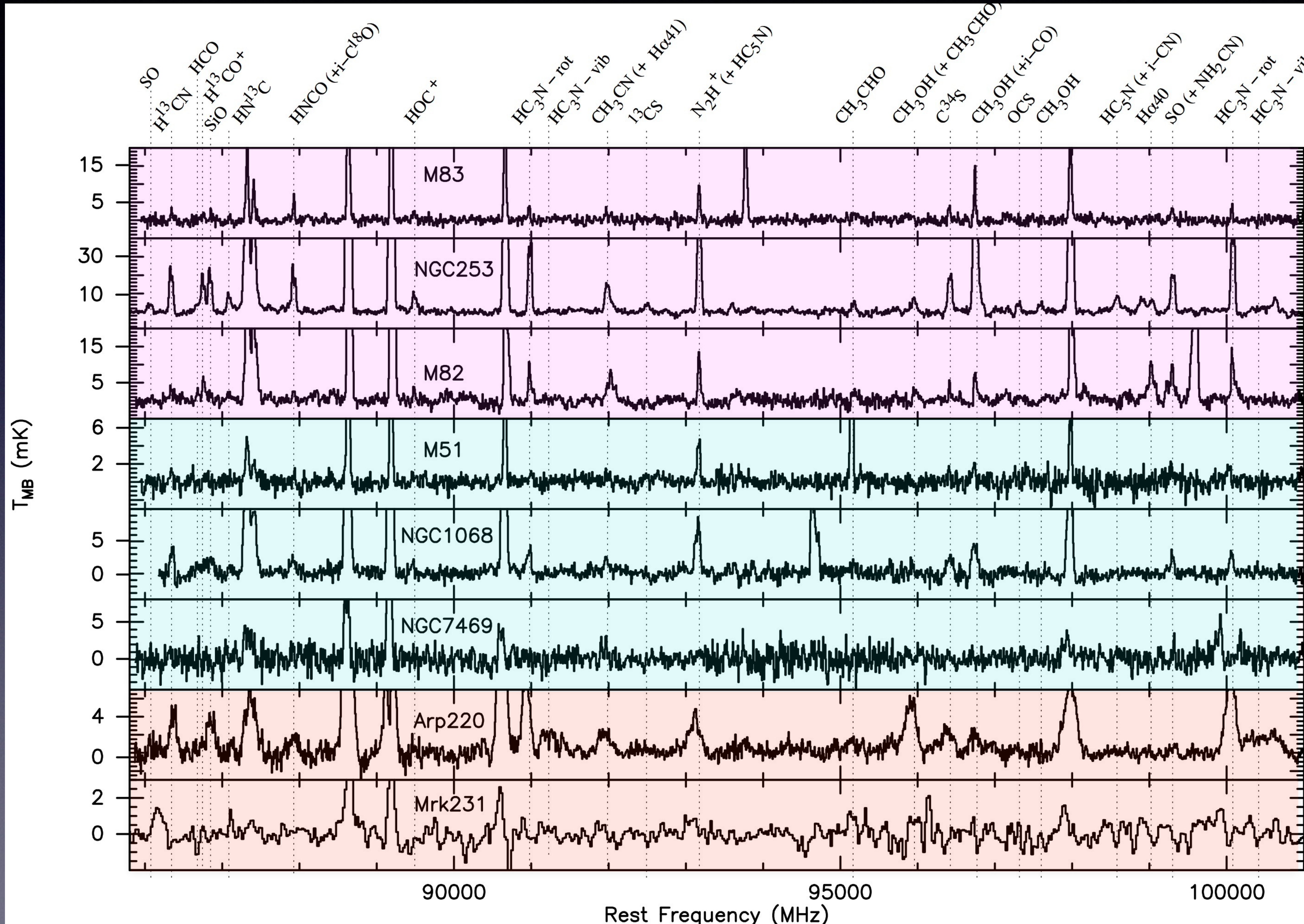
Chemical differentiation: evolutionary stage, physical processes

Aladro+2015

Nuclear starburst

Active nucleus AGN

ULIRGs



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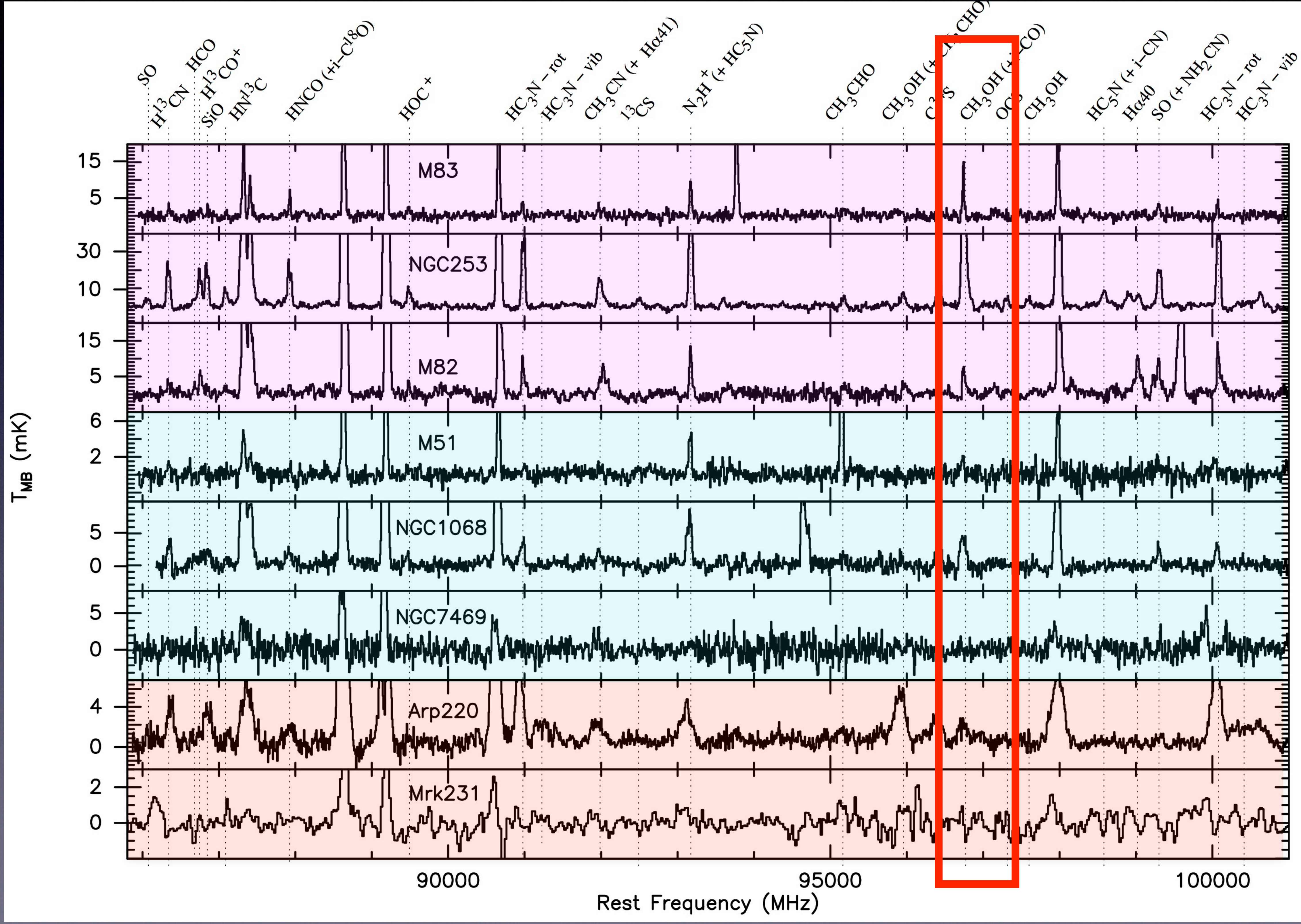
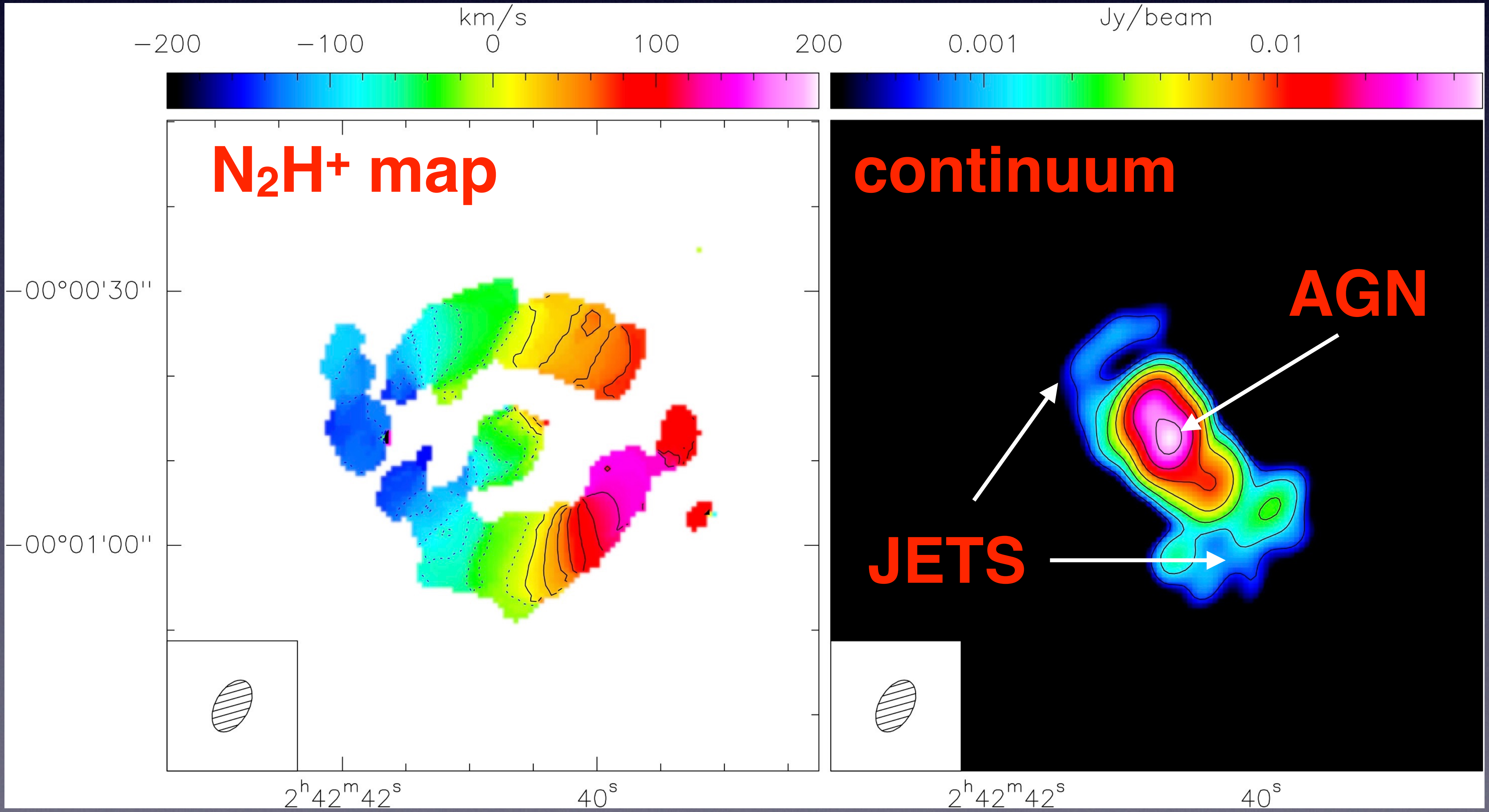


Today's universe: Cosmic Ray Ionisation

COSMIC RAYS rule chemistry in dense/obcured/UV opaque regions

N_2H^+ probe Cosmic Ray/ X-ray ionisation and chemistry in ULIRG/AGN NGC1068



NOEMA map by Ceccarelli in prep.

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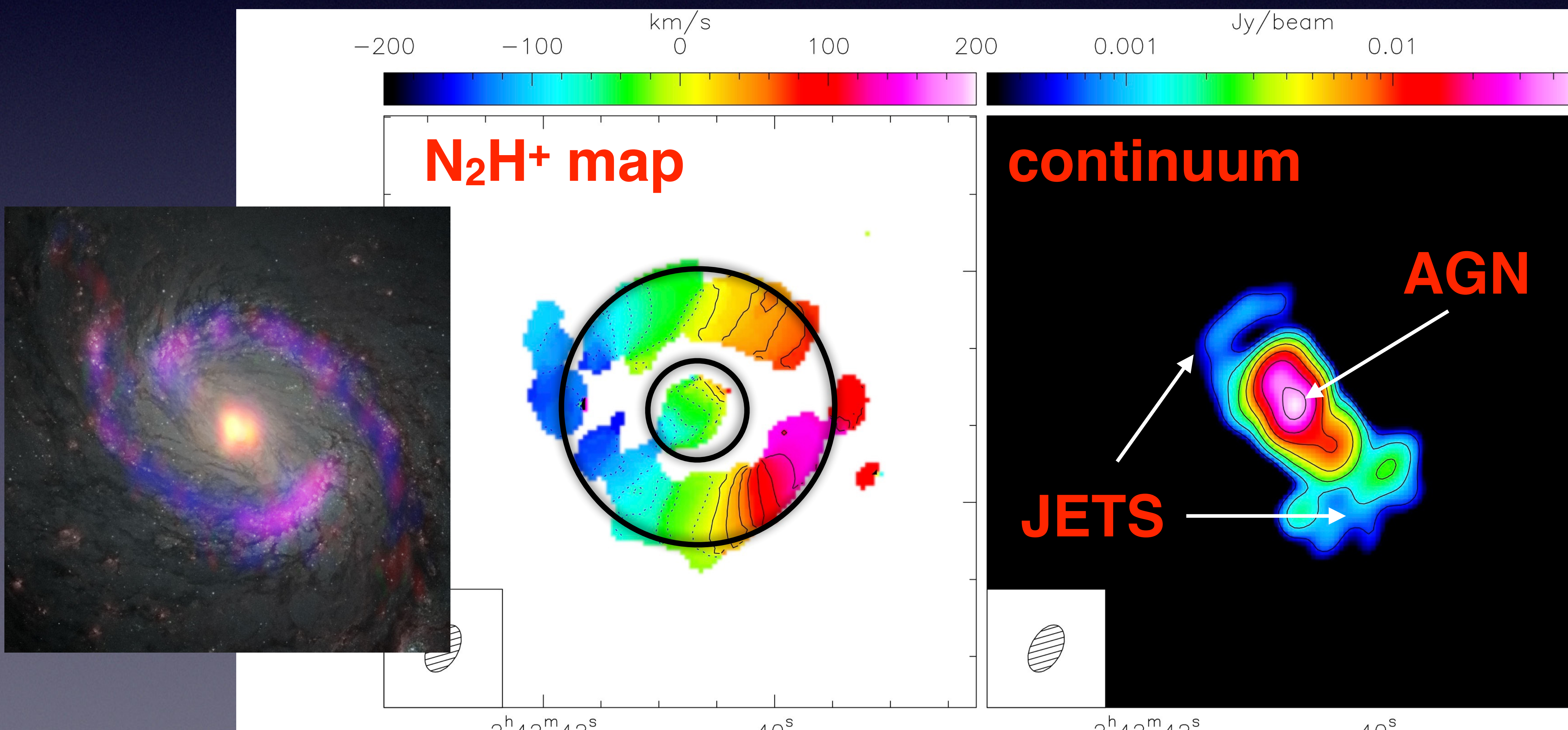

NOEMA map by Ceccarelli in prep.

Summary

- Exploration of chemical complexity at early cosmic epochs ***started…***
    - ***Complex molecules likely present***
    - ***News expected from ALMA, NOEMA, EVLA***
    - ***Species identification problem***

- Learning of extragal ISM physics from COM chemistry ***started***
    - ***nature of gas not significantly different from MW***
    - new tools/diagnostics being tested/developed
    - tighter synergy astrophysicist/cosmologist, chemistry/astro

- Need theoretical models, predictions to interpret observed complexity
    - Angular resolution is key element, but limited compared to MW
    - Need to adapt diagnostics/techniques to galaxy wide environment