ASTROCHEMISTRY

Brett A. McGuire (NRAO)

Sixteenth Synthesis Imaging Workshop

16-23 May 2018

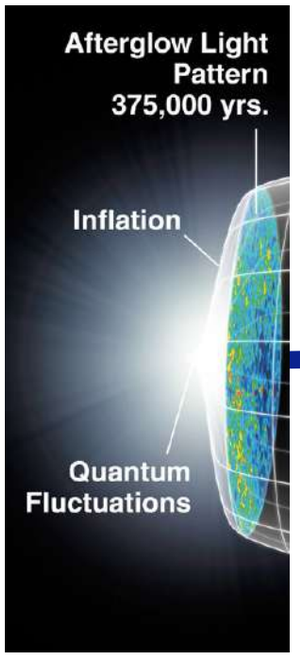
History and Context

AS • TRO • CHEM • IS • TRY

/ astrō'keməstrē /

(n) the study of molecules in space - where they are, how they got there, and what they are doing

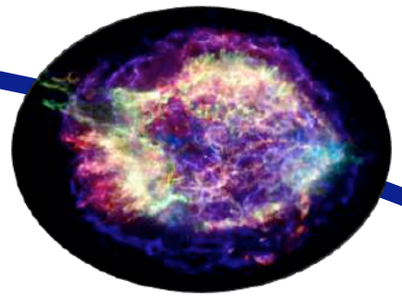
History and Context



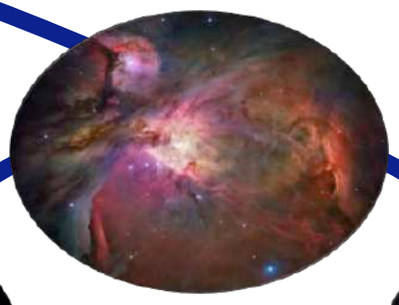
Big Bang
H, He

First Stars Born

First Stars Die
'Heavy' Element Synthesis



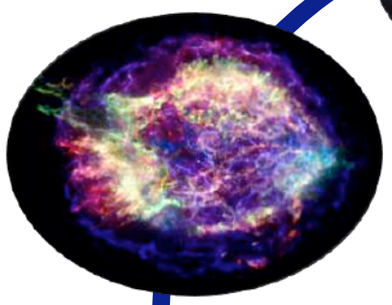
Stellar Nursery



New Stars

Planet Formation

Chemical Delivery



Fiery **Cat**aclysm
(Whomp whomp)

Life! (Awww)

Fundamental Driving Question of Astrochemistry

How do you make a cat from H and He?

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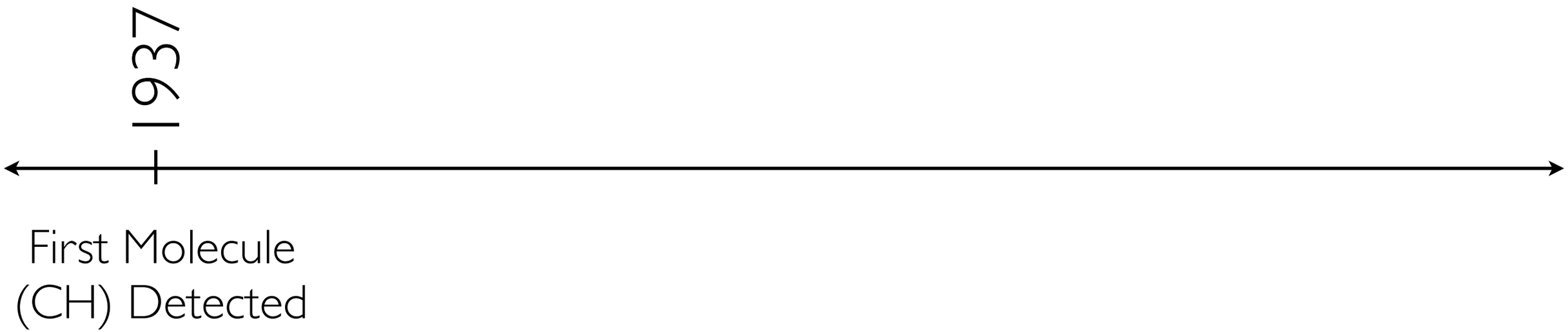

History and Context

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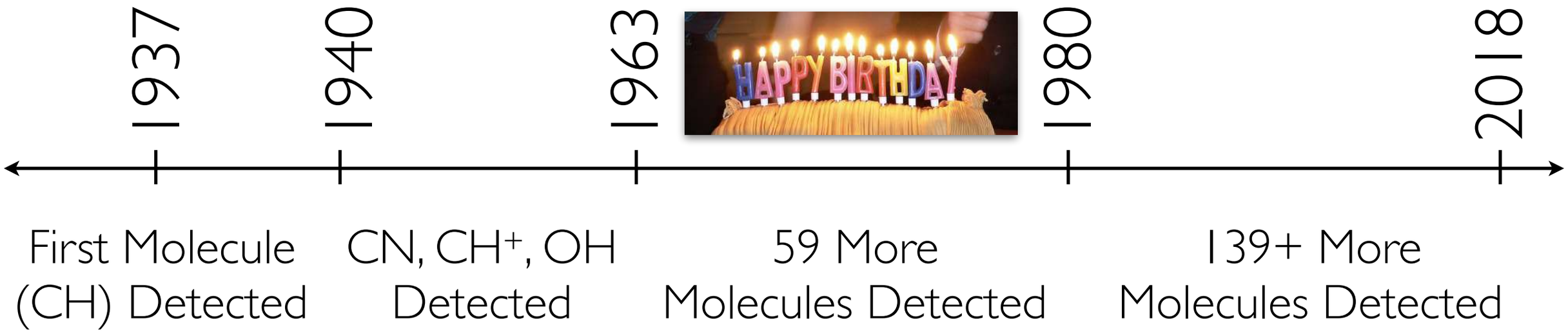
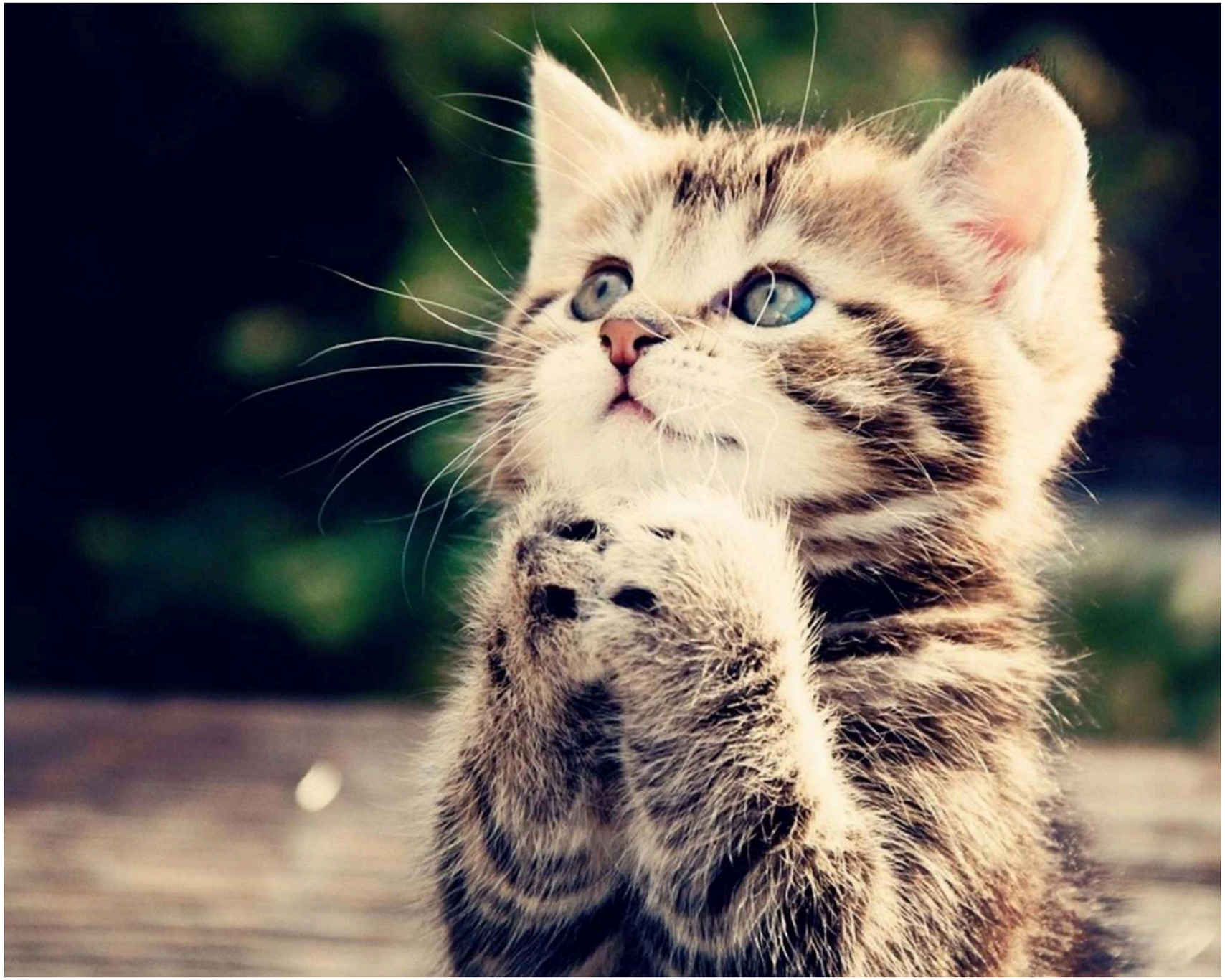
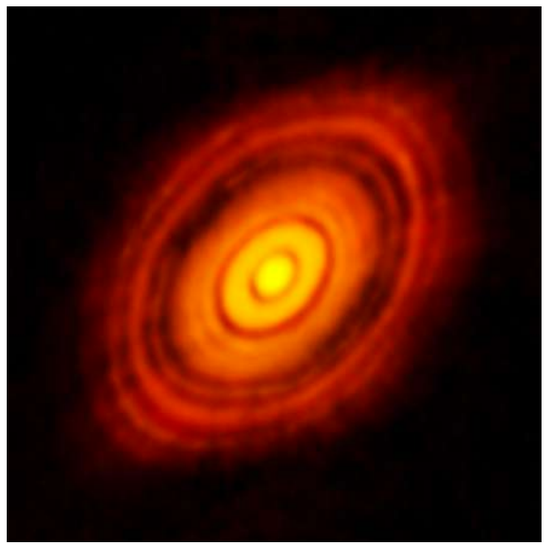


Why Do I Care?



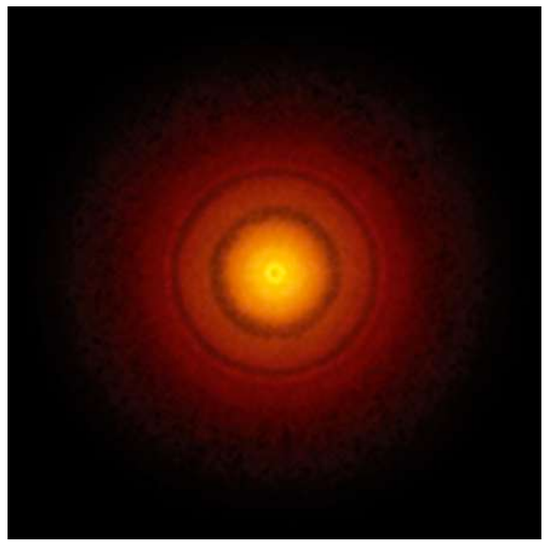
WHY SHOULD YOU CARE?

HL Tau



Brogan, ALMA et al.
(2015 *ApJL* 808, L3)

TW Hydrae



Andrews et al.
(2018 *ApJL* 820, L40)

Elias 2-27

Pérez et al.
(2016 *Science* 353, 6307)

Do these gaps correspond to snow lines?
How much H_2O is available for these planets?
What's the C/O ratio?
Can you tell me where a planet formed?
Did it move?

What Can Astrochemistry Do For You?

We can tell you why that SiO emission in your source is probably a good tracer of a shock

We can tell you whether that comet you observed was probably formed in a very cold environment, and maybe even where in the disk

We can tell you whether that CH_3OH maser you're observing is collisionally or radiatively pumped

What Can Astrochemistry Do For You?

Question

"Where can I find a table of molecules and what they trace?"

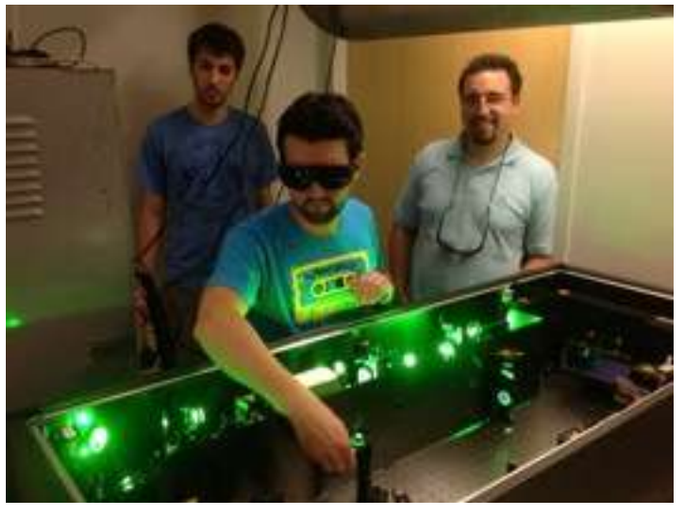
Answer

Hopefully nowhere

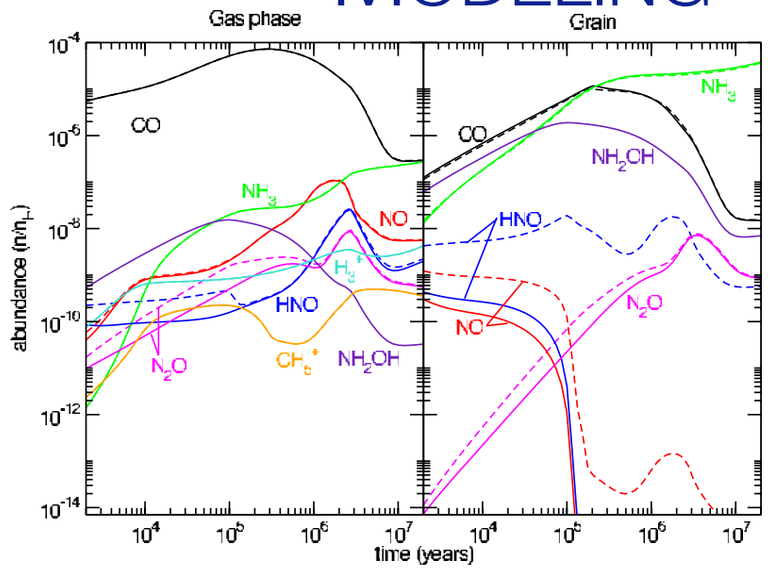
What astrochemistry can provide is the ability to draw contextualized conclusions on physical conditions and evolutionary history of an observed source based on the synthesis of laboratory, observational, and modeling studies

Astrochemistry

Laboratory Astrophysics



Astrochemical Modeling



Chemical Reactions, Kinetics, Thermodynamics

Species and Reactions of Interest

Temperatures, Abundances, and Densities

Rotational, Vibrational, and Electronic Spectra

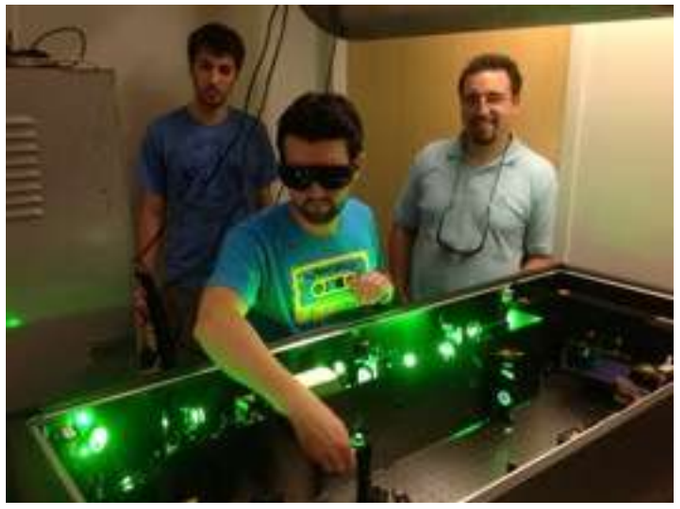
Environments and Species of Interest

Chemical Inventories Temperatures, Abundances, and Densities

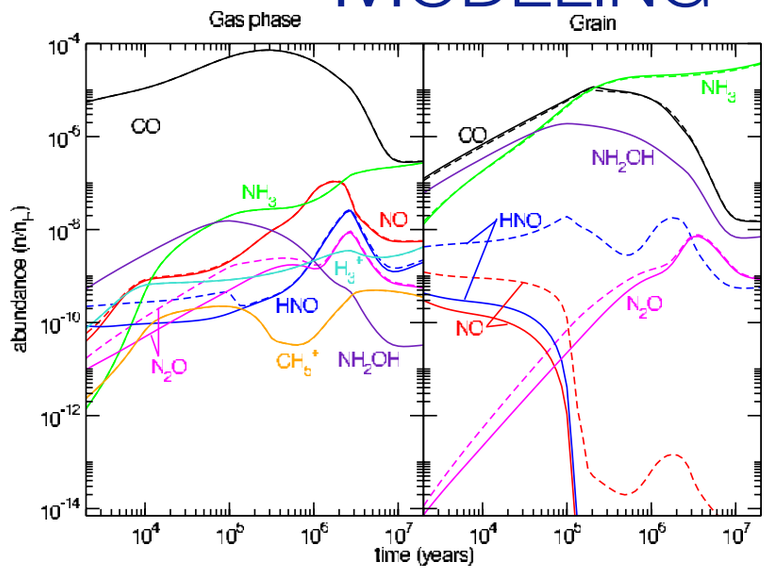
Observational Astronomy

ASTROCHEMISTRY

LABORATORY ASTROPHYSICS



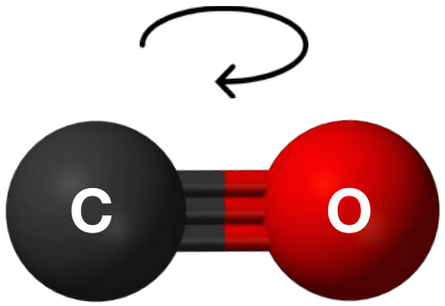
ASTROCHEMICAL MODELING



Rotational, Vibrational, and Electronic Spectra

OBSERVATIONAL ASTRONOMY

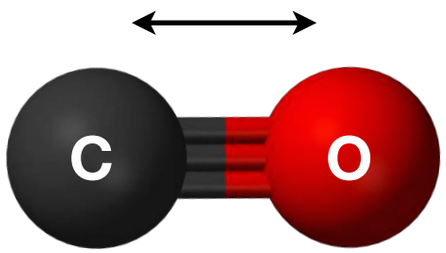
Laboratory Spectroscopy



Rotational 'Microwave' Spectroscopy

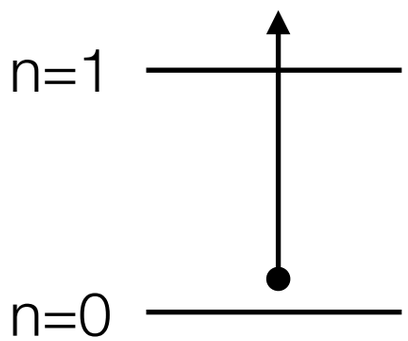
>90%

- <2000 GHz; Permanent Dipole Moment Req'd



(Ro-)Vibrational Spectroscopy

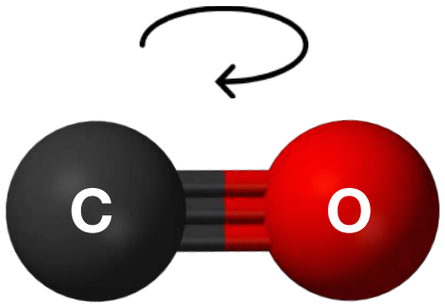
- (Far-)Infrared; Permanent Dipole Moment Not Req'd
- Each vibrational level also has rotational transitions



Electronic (Rovibronic) Spectroscopy

- UV-Visible; Permanent Dipole Moment Not Req'd
- Each electronic level also has vibrational and rotational transitions

Laboratory Spectroscopy



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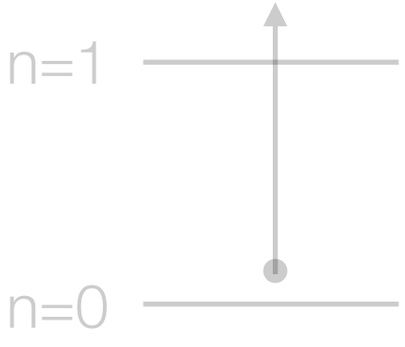

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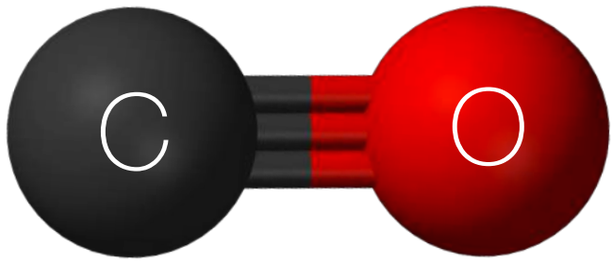
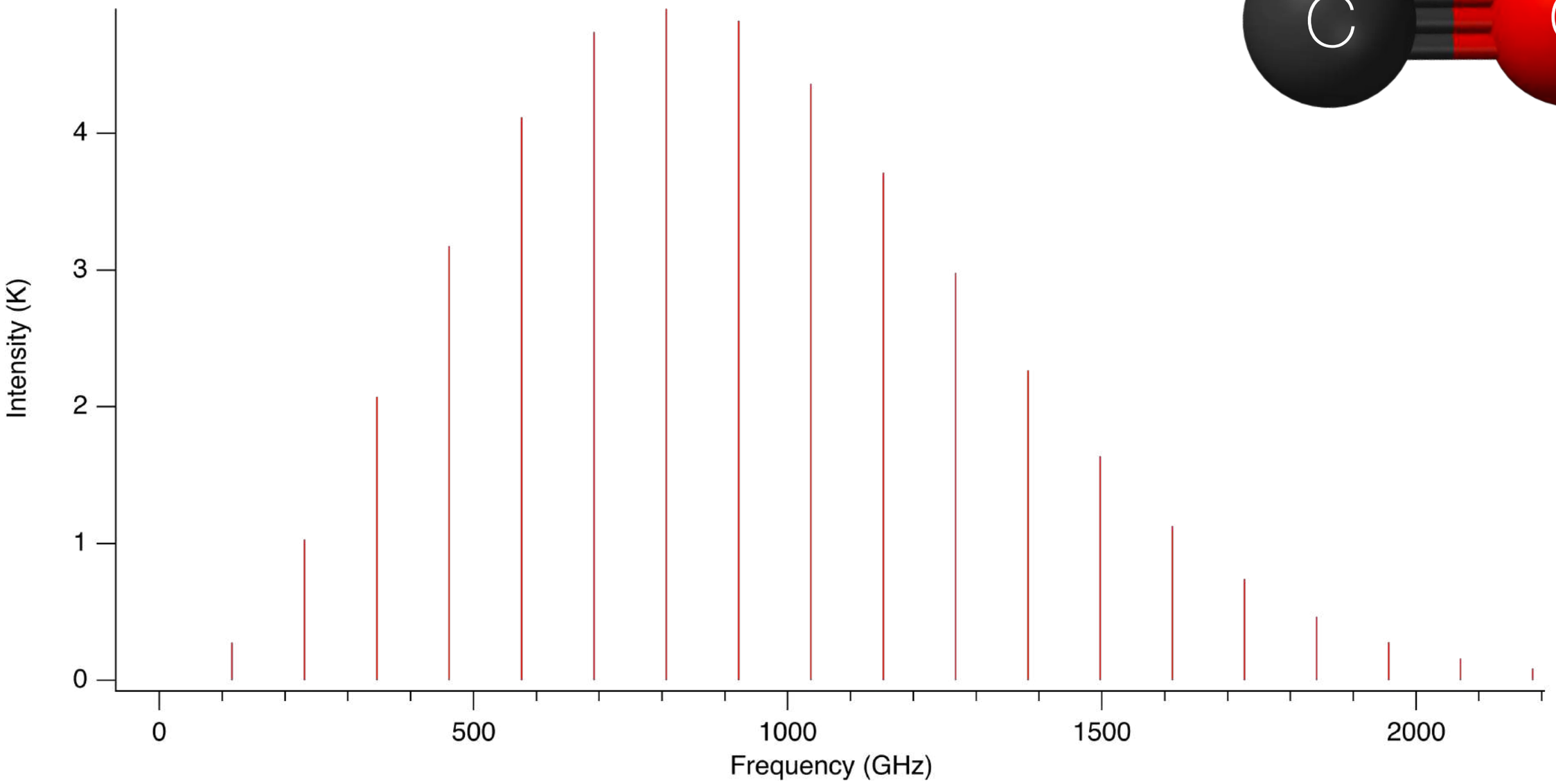
Rotational Spectroscopy

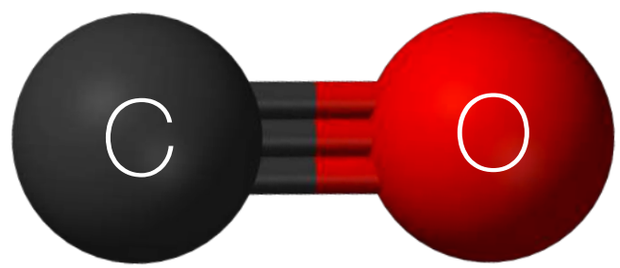




Rotational Spectroscopy

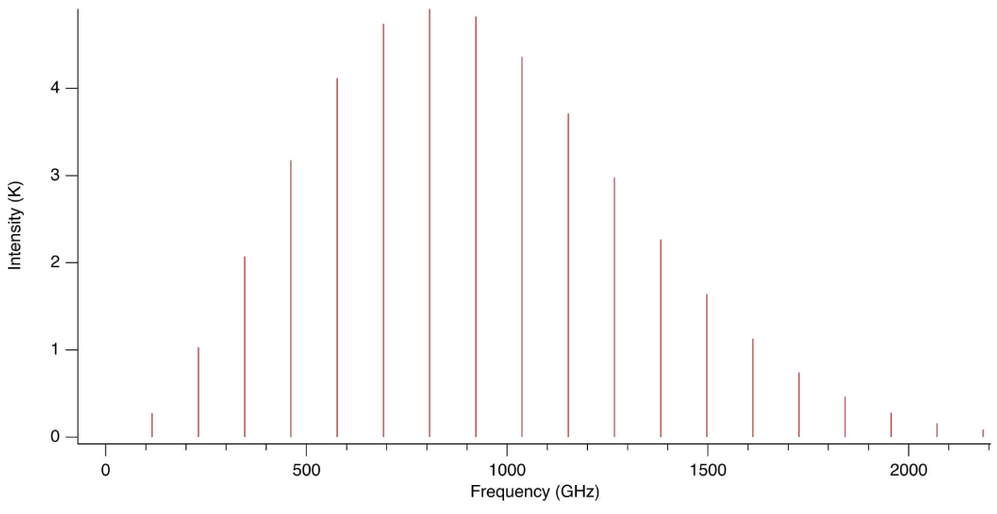
$$\nu = 2B(J+1)$$

$$B = \frac{h}{8\pi^2 cI}$$



$$I = \mu r^2$$

$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$



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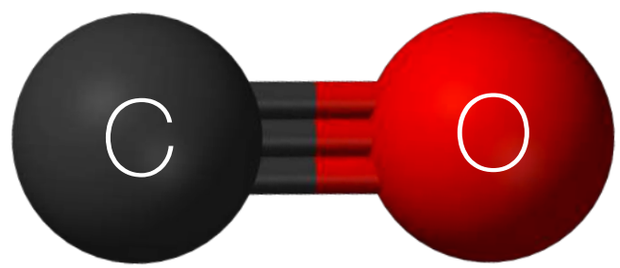
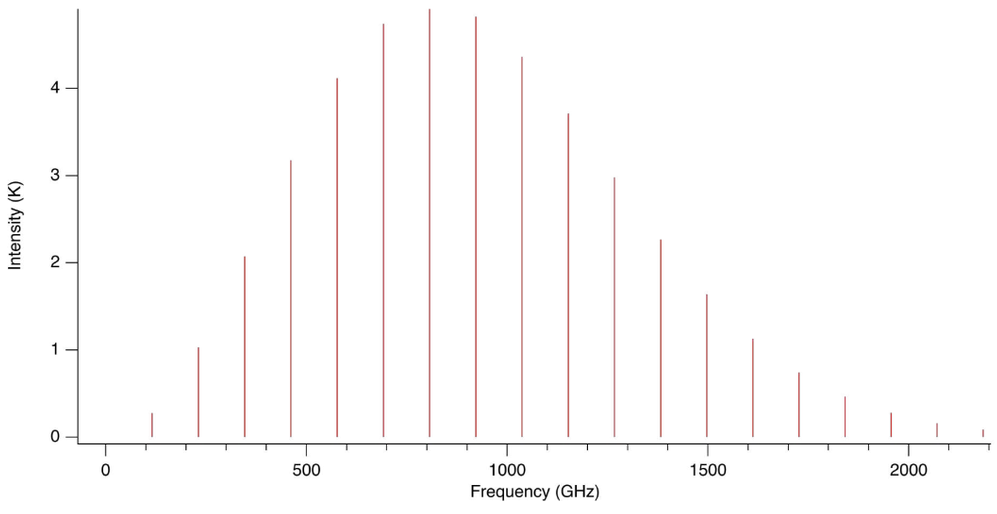
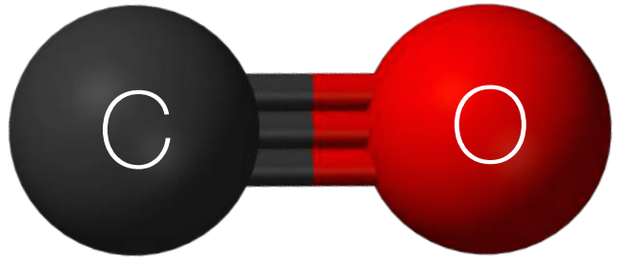




Rotational Spectroscopy

To first order, the rotational frequencies of a molecule are determined exclusively by its structure.



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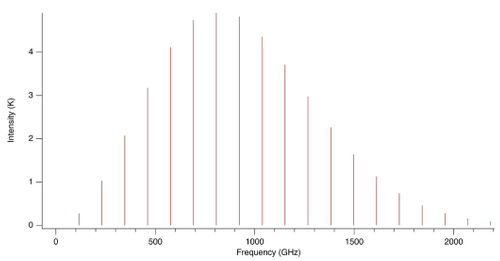
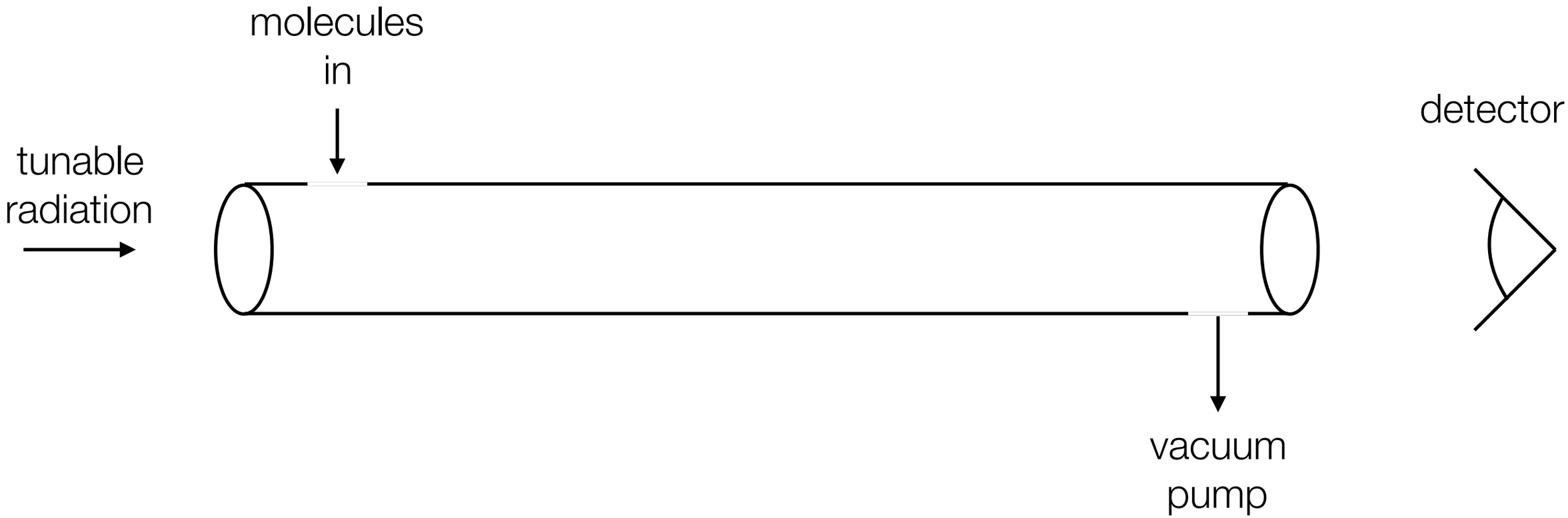


To ∞-order, no two molecules can share the same rotational spectrum. A rotational spectrum is a unique molecular fingerprint.

ROTATIONAL SPECTROSCOPY

Direct Absorption



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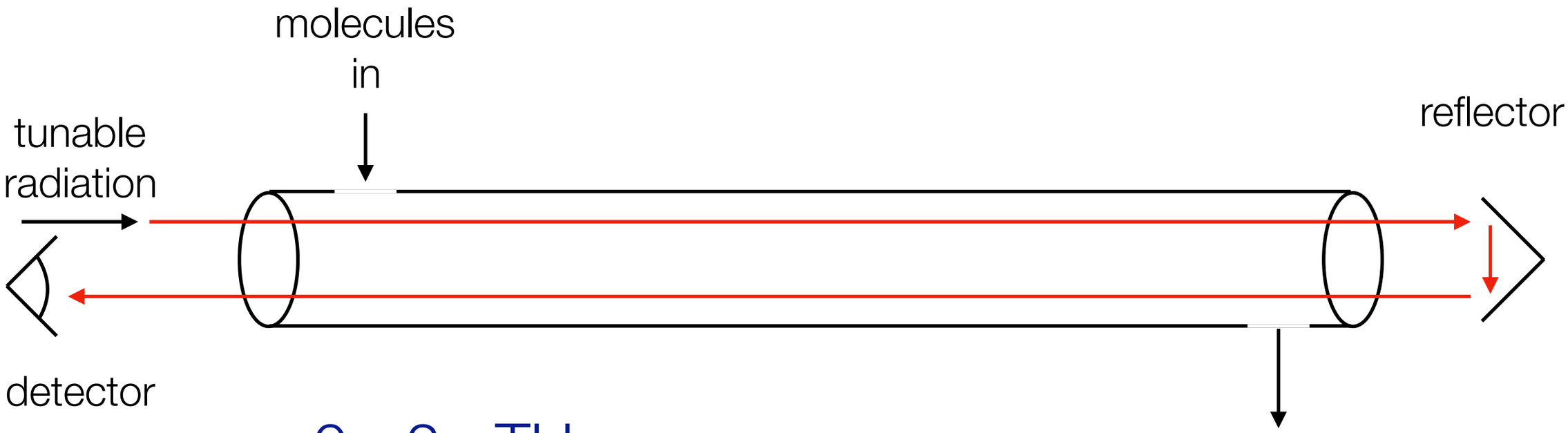
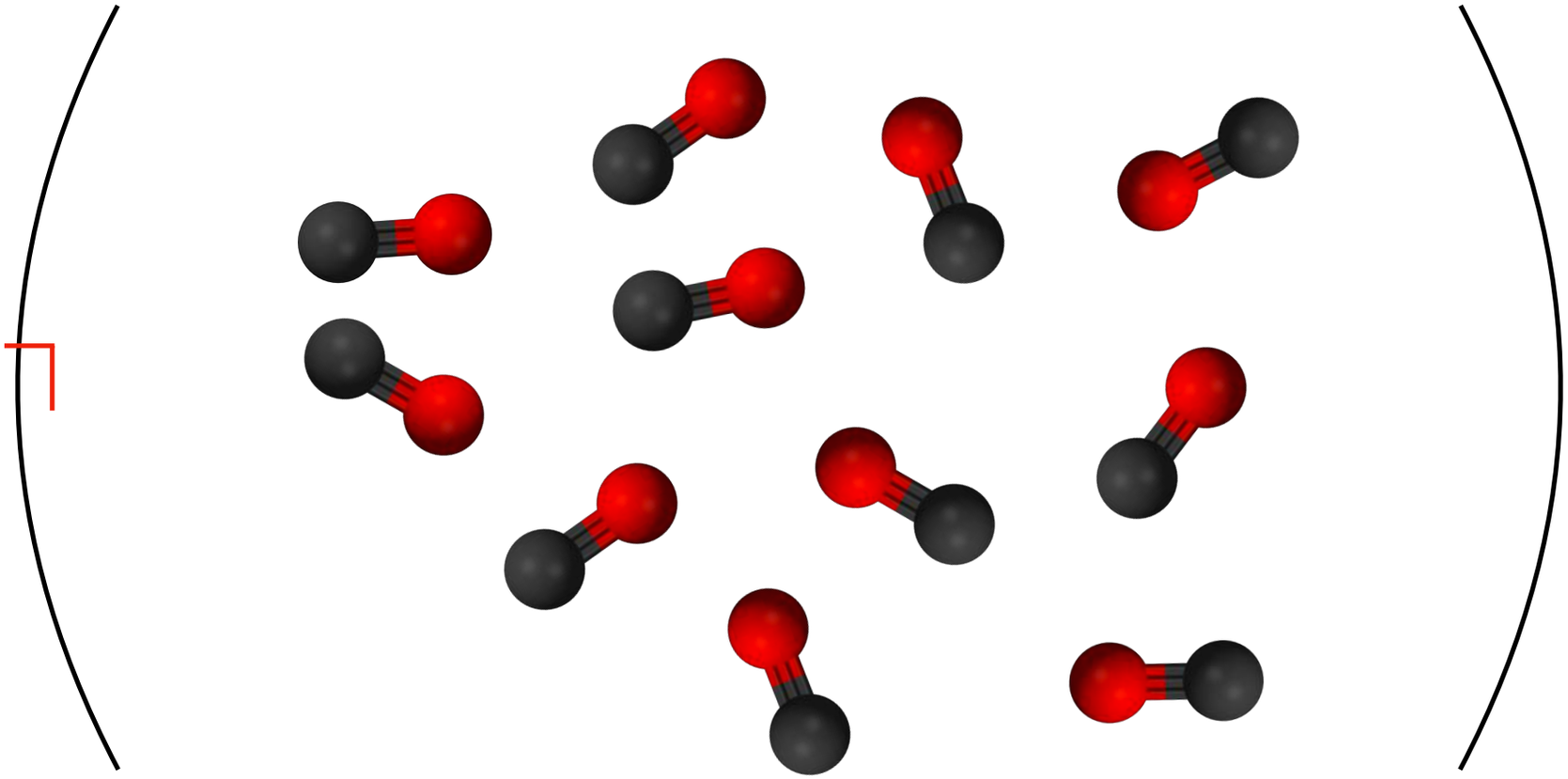


- 0 - 2+ THz
- Relatively broad lines
- 10-25 kHz accuracy
- Modest sensitivity
- Slow

Rotational Spectroscopy

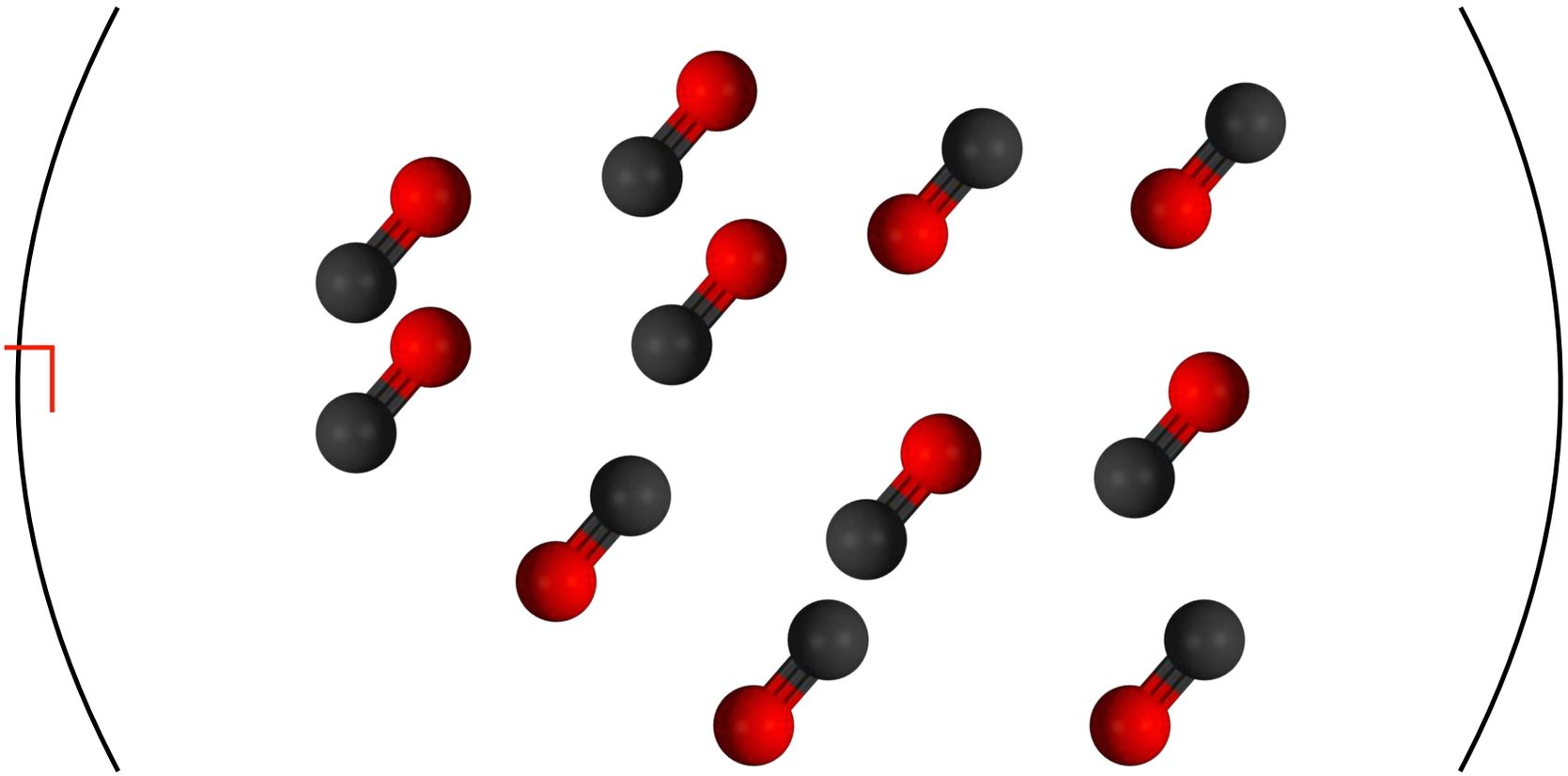
Cavity FTMW



It's an FFT. Our power is distributed over one mode, and amplified in cavity.

Rotational Spectroscopy

Cavity FTMW



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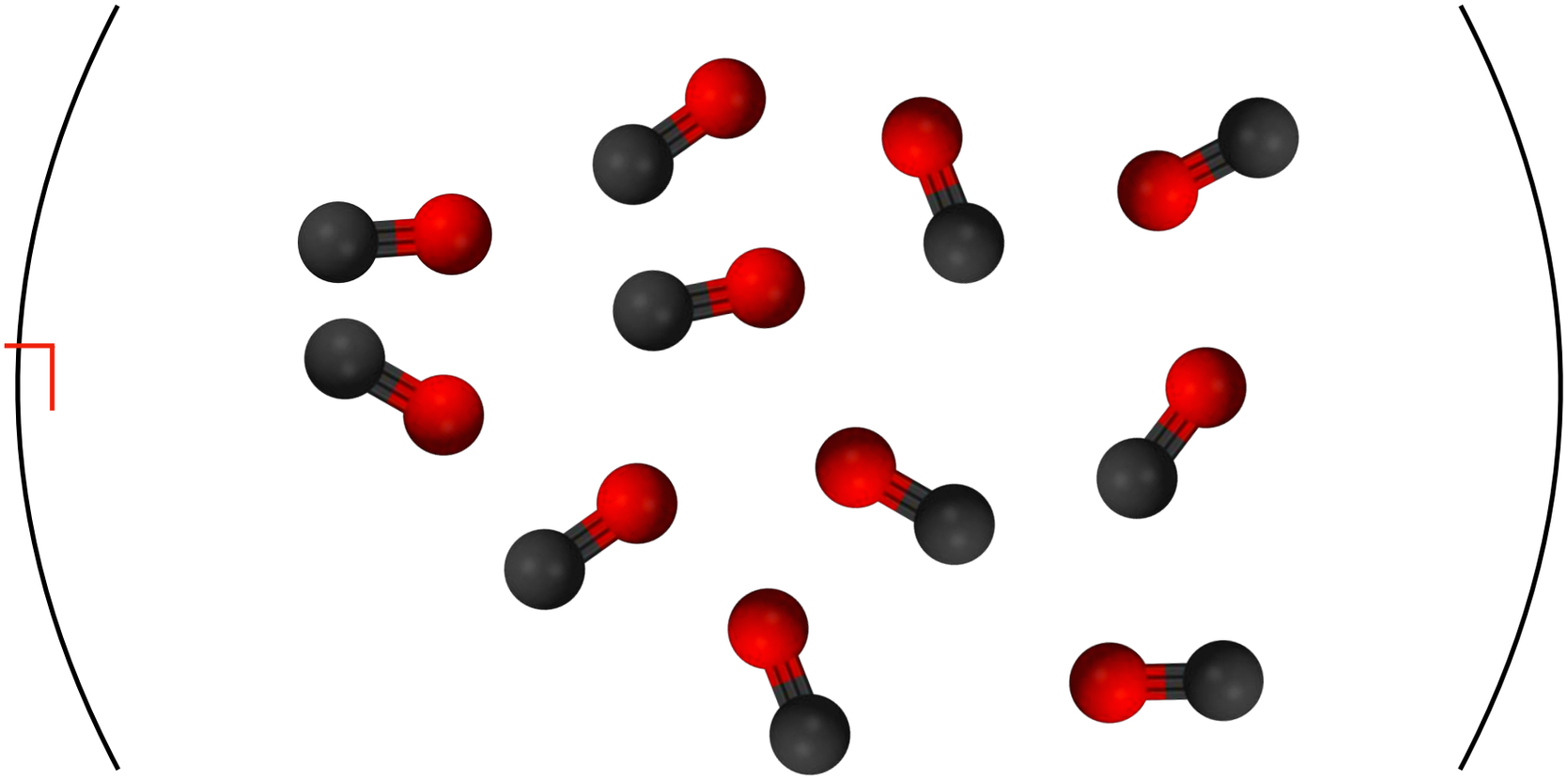

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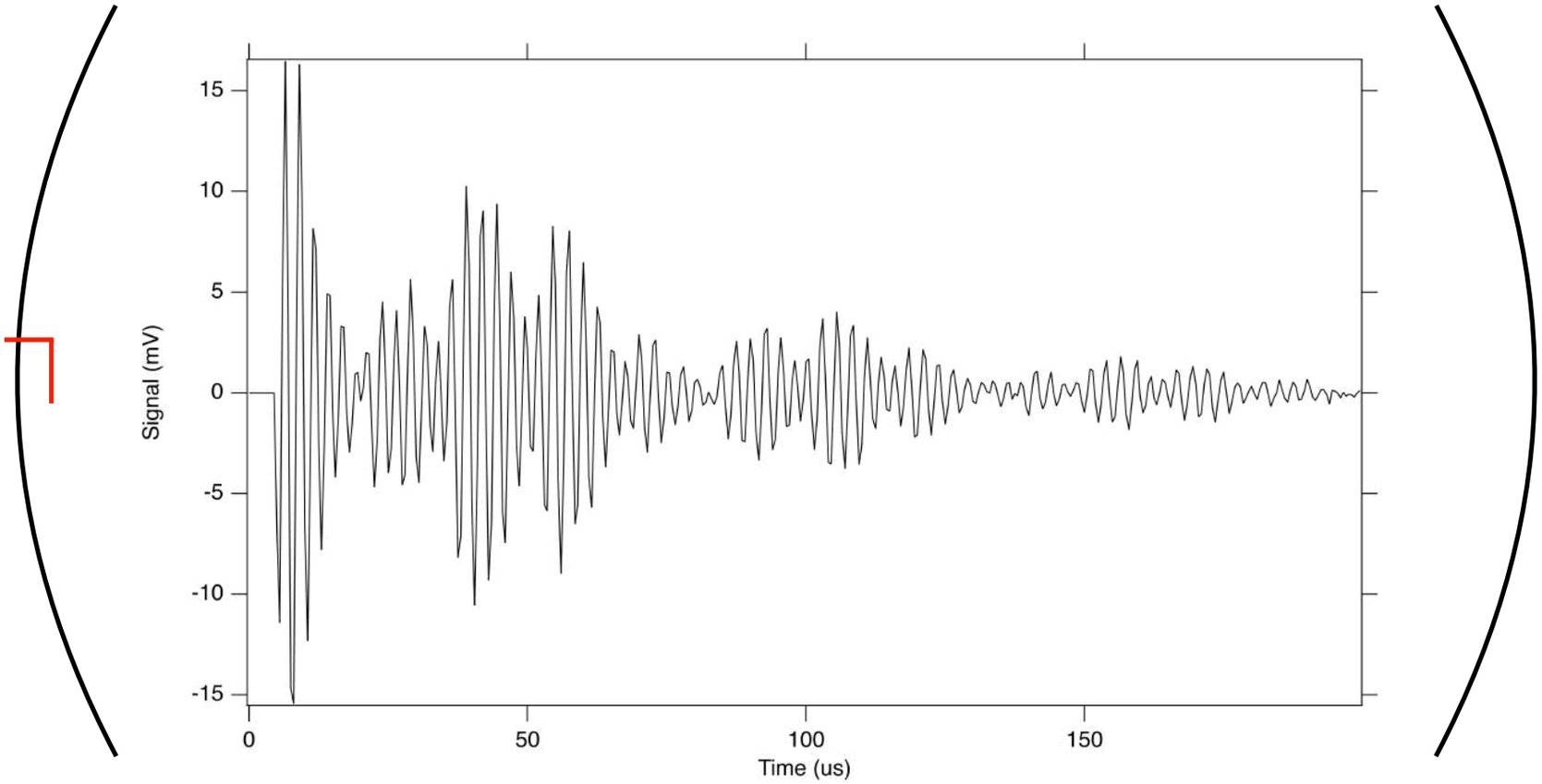

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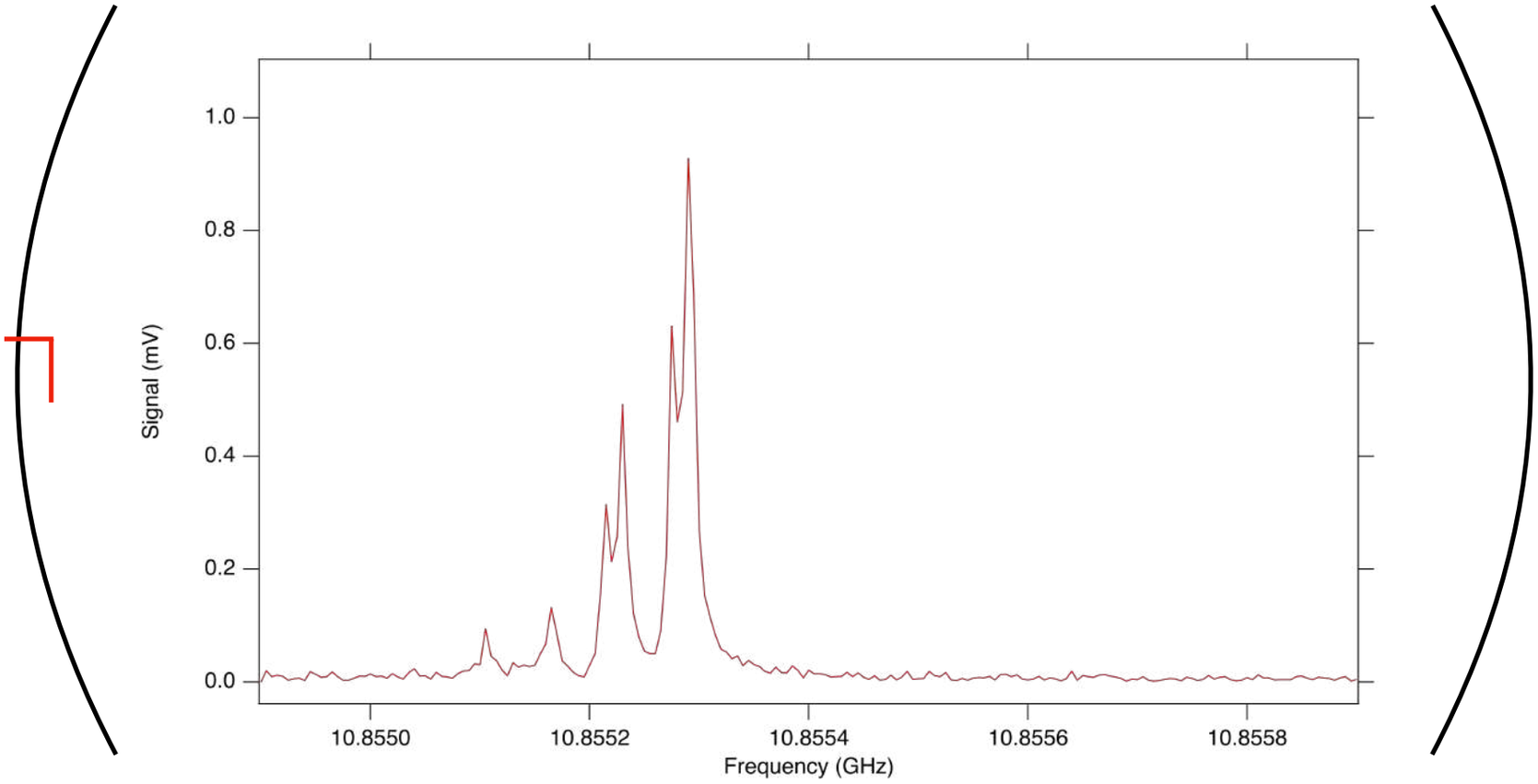


Rotational Spectroscopy

Cavity FTMW

- 0 - 45 GHz
- Extremely narrow lines
- <1 kHz accuracy
- Very high sensitivity
- Slow

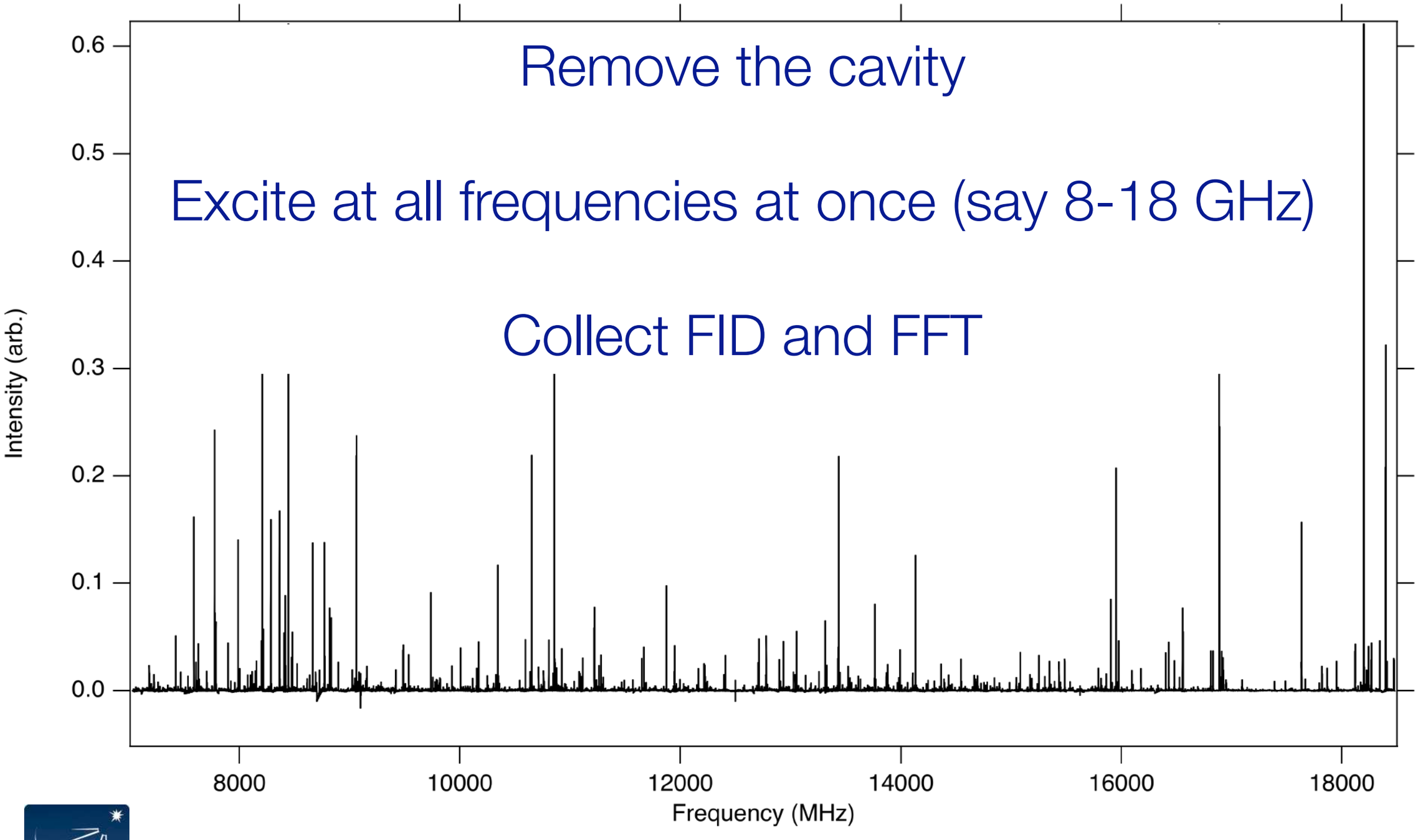
ROTATIONAL SPECTROSCOPY

CP-FTMW

Remove the cavity

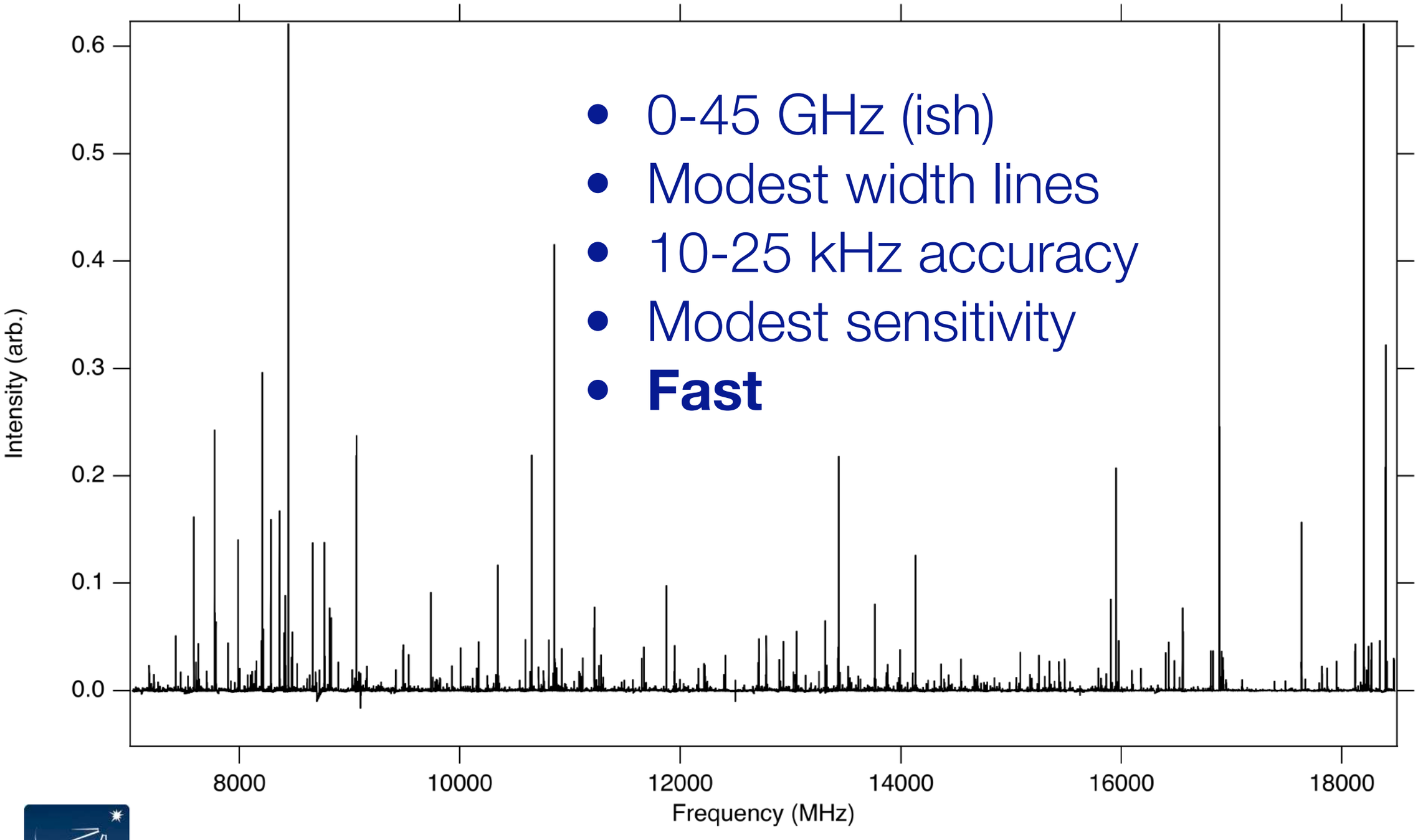
Excite at all frequencies at once (say 8-18 GHz)

Collect FID and FFT



Rotational Spectroscopy

CP-FTMW



- 0-45 GHz (ish)
- Modest width lines
- 10-25 kHz accuracy
- Modest sensitivity
- **Fast**

Deliverable Process

Measure 10^1 - 10^4 lines

$$\nu = 2B(J+1)$$

↓

Determine the rotational constants to high accuracy

↓

Use those constants to predict other unmeasured lines and construct a ‘complete’ spectrum

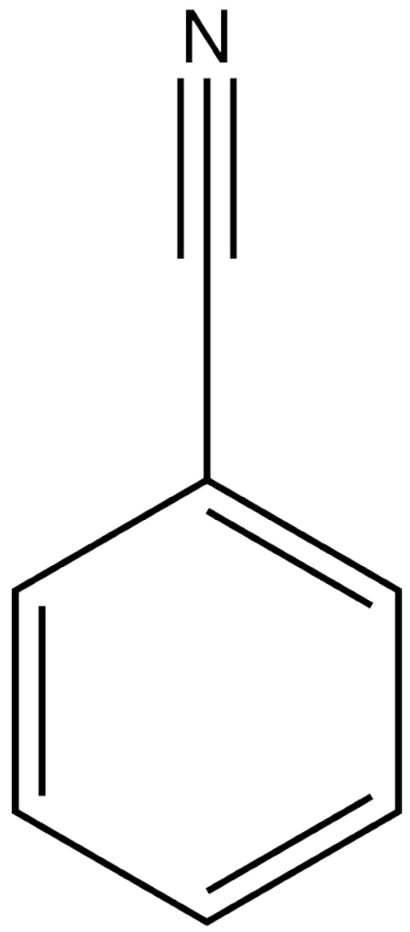
↓

Publish

ROTATIONAL SPECTROSCOPY DATABASES

$$\nu = 2B(J+1)$$

Constant	Ref. (*24*)	This work[1,2]	Global[1,3]
A (MHz)	5655.2654(72)	5655.26522(59)	5655.26519(59)
B (MHz)	1546.875864(66)	1546.875836(63)	1546.875822(54)
C (MHz)	1214.40399(10)	1214.404061(48)	1214.404047(40)
Δ_J (kHz)	0.0456(15)	0.045629(284)	0.04555(235)
Δ_{JK} (kHz)	0.9381(56)	0.93328(241)	0.93304(234)
Δ_K (kHz)	0.50(38)	0.272(64)	0.272(64)
δ_J (kHz)	0.01095(41)	0.011106(163)	0.011094(157)
δ_K (kHz)	0.628(53)	0.6136(73)	0.6141(72)
χ_{aa}(N) (MHz)	-4.23738(36)	-4.23797(89)	-4.23749(45)
χ_{bb}(N) (MHz)	2.2886(11)	2.28907(118)	2.28871(65)
Number of Measurements	78	146	175
σ (MHz)	0.00524	0.00130	0.00123
weighted average	0.709	0.622	0.628



McGuire et al. 2018 *Science* 359, 202

ROTATIONAL SPECTROSCOPY DATABASES

Splatalogue

ALMA OT

splatalogue
database for astronomical spectroscopy

Basic	Advanced		
Motivation	Notes on Observing Frequencies	Notes on Quantum Numbers	
Applications (SLAP Interface)	NRAO Homepage	NAASC/ALMA Homepage	
ALMA Science Portal	Helpdesk	Splatalogue Quick Start Guide (PDF)	Splatalogue Changelog

03006 13C17O - Carbon Monoxide
03007 H13CO+ - Formylium
03008 HC17O+ - Formylium

Enter Molecular Formula (Case sensitive) to Calculate Mass

Calculate Mass

Data Versions +/-

Version 3 (7/1/2016)

Specify Ranges +/-

Specify a Frequency Range:

From 12340 To 12370

+ Frequency - Frequency

MHz GHz

Specify an Energy Range:

From to

E_L (cm^{-1}) E_U (cm^{-1})

E_L (K) E_U (K)

Line Intensity Lower Limits +/-

Search Results

Found 145 lines from 12340 - 12370 MHz, showing 1 - 145
Click on the chemical formula below for more information about that species

	Species	Chemical Name	Freq in MHz (Err)	Meas Freq in MHz (Err)	Resolved QNs	CDMS/JPL Intensity	Lovas/AST Intensity	E_L (cm^{-1})	Linelist
1	CH_3NH_2	Methylamine	12340.01200 (0.008)		6(1)E2-1- 5(2)E2-1 , F= 7 - 6	0.00000		33.22400	SLAIM
2	H_2NCH_2COOH - II v=1	Glycine	12340.13420 (3.0698)		24(7,17)-24(7,18), F=24-24	-8.98960		1570.12040	JPL
3	$C^{13}CC_4H$	1,3,5-Hexatriynyl		12340.32800 (0.01)	J=9/2-7/2, Ω=3/2, F_1= 5- 4, F=11/2-9/2, l=f	-5.67320		0.54970	CDMS
4	CH_3NH_2	Methylamine	12340.37000 (0.008)		6(1)E2-1- 5(2)E2-1	0.00000		33.22400	SLAIM
5	$C^{13}CC_4H$	1,3,5-Hexatriynyl		12340.40300 (0.01)	J=9/2-7/2, Ω=3/2, F_1= 5- 4, F=9/2-7/2, l=f	-5.76210		0.54970	CDMS
6	CH_3NH_2	Methylamine	12340.43060 (0.0056)		J = 6 - 5, K = 1 - 2, E_2, l = -1	-7.59660		33.22350	JPL
7	$CH_3CH_2CH_2CN$-gauche	Butyronitrile	12340.43840 (0.0446)		42(6,37)-43(4,40)	-9.35220		281.10860	JPL
8	NH_3 v=0	Ammonia	12340.44520 (0.2898)		22(17)0a-22(17)0s	-11.85300		3895.89460	JPL
9	CH_3COOH v=1	Acetic Acid	12341.07000 (0.005)		6(6, 0)- 6(5, 1) +- v=1	0.00000		92.36000	SLAIM
10	CH_3NH_2	Methylamine	12341.25100 (0.008)		6(1)E2-1- 5(2)E2-1 , F= 6 - 5	0.00000		33.22400	SLAIM

Transition Filter

*

*e.g. CO*2-1* or *oxide**

Include description

Frequency Filters

ALMA Band

1 2 3 4 5 6 7 8 9 10

Sky Frequency (GHz)

Min 31.3 Max 950

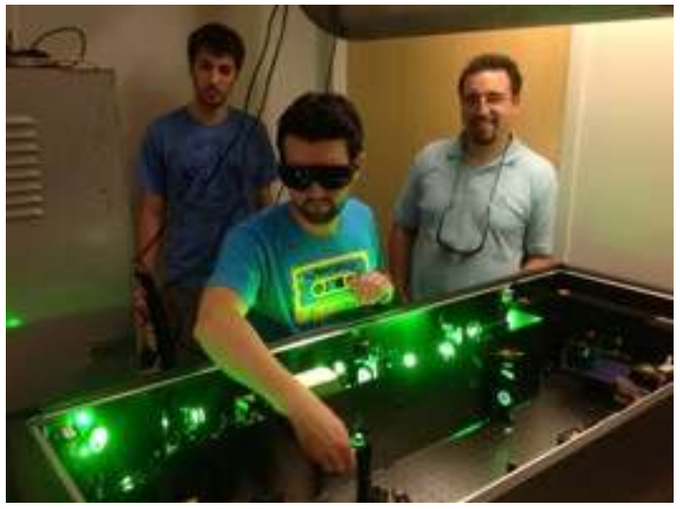
Transitions matching your filter settings:

(double-click column header for primary sort, single-click subsequent columns for secondary sorting. Single clicks will reverse sort order of already selected columns.)

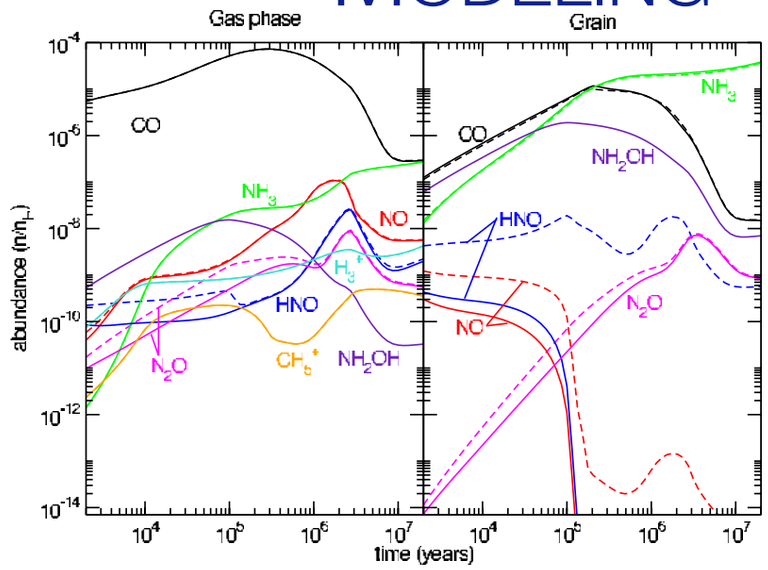
Transition	Description	Rest Freq...	Sky Frequency	Upper-state ...	Lovas Inte...	Sij μ^2	Cata...
l-C5H J=35/2-33/2, Ω=3/2, F=17-16, l=f	2,4-Pentadiynylidyne	84.108238 ...	84.108319 ...	71.861 K	4.7	401.709 D^2	Offline
l-C5H J=35/2-33/2, Ω=3/2, F=18-17, l=f	2,4-Pentadiynylidyne	84.108398 ...	84.108480 ...	71.861 K	4.7	425.314 D^2	Offline
l-C5H J=35/2-33/2, Ω=3/2, F=17-16, l=e	2,4-Pentadiynylidyne	84.110087 ...	84.110168 ...	71.862 K		401.692 D^2	Offline
l-C5H J=35/2-33/2, Ω=3/2, F=18-17, l=e	2,4-Pentadiynylidyne	84.110244 ...	84.110325 ...	71.862 K		425.395 D^2	Offline
C4H v7 = 1 J=17/2-15/2, Ω=1/2, l=f	1,3-Butadiynyl radical	84.123003 ...	84.123085 ...	211.671 K	2.1	12.771 D^2	Offline
CH3CH2CN v=0 11(0,11)-10(1,10)	Ethyl Cyanide	84.151838 ...	84.151919 ...	28.102 K	0.1	10.328 D^2	Offline
CH3OH v t=1 11(10,1)-11(11,0)	Methanol	84.158571 ...	84.158652 ...	1066.119 K		1.459 D^2	Offline
U-84163	UNIDENTIFIED	84.163000 ...	84.163081 ...		0.06		Offline
30SiO v=1 2-1	Silicon Monoxide	84.164253 ...	84.164334 ...	1753.828 K		19.441 D^2	Offline
c-H13CCCH 2(1,2)-1(0,1)	Cyclopropenylidene	84.185621 ...	84.185703 ...	6.331 K	0.13	17.24 D^2	Offline
U-84215	UNIDENTIFIED	84.215000 ...	84.215081 ...		0.08		Offline
CH3CN v8=1 J =36-36, K =3-1	Methyl Cyanide	84.271390 ...	84.271472 ...	1139.034 K		0.122 D^2	Offline
SO2 v=0 32(5,27)-31(6,26)	Sulfur dioxide	84.320876 ...	84.320958 ...	549.36 K	0.1	13.463 D^2	Offline

Astrochemistry

Laboratory Astrophysics



Astrochemical Modeling



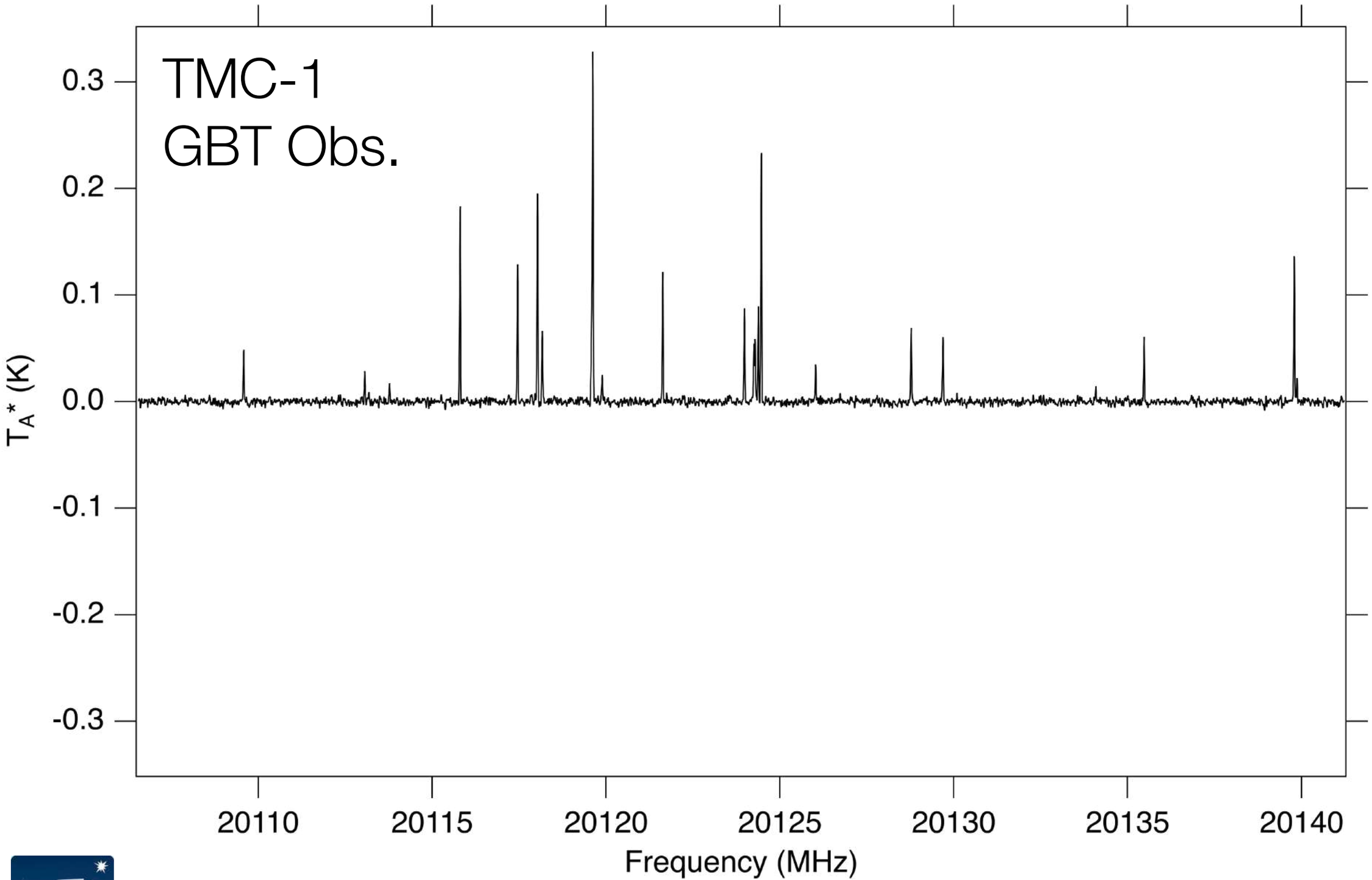
Temperatures, Abundances, and Densities

Rotational, Vibrational, and Electronic Spectra

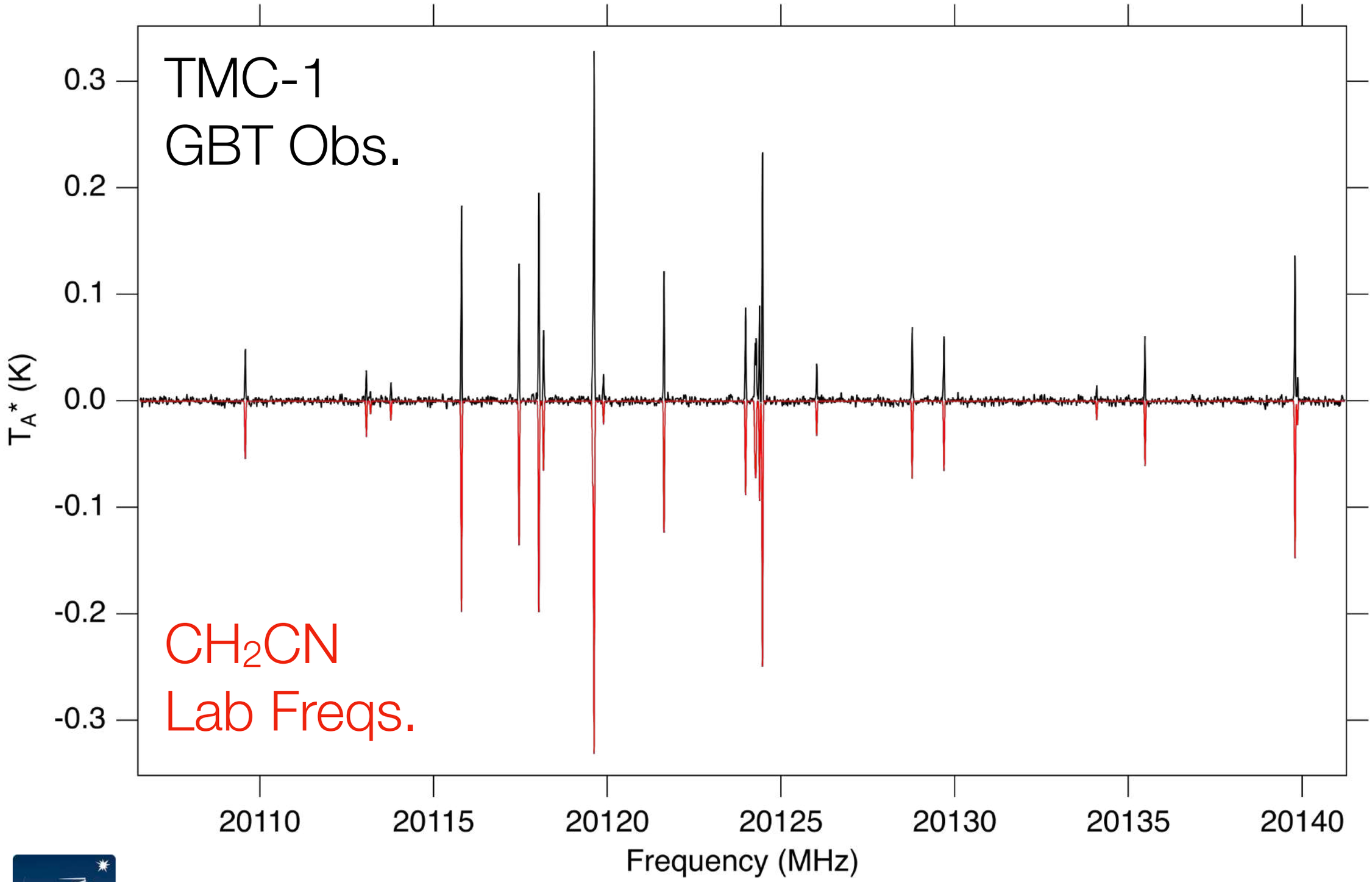
Chemical Inventories Temperatures, Abundances, and Densities

Observational Astronomy

INTERSTELLAR DETECTIONS



Interstellar Detections

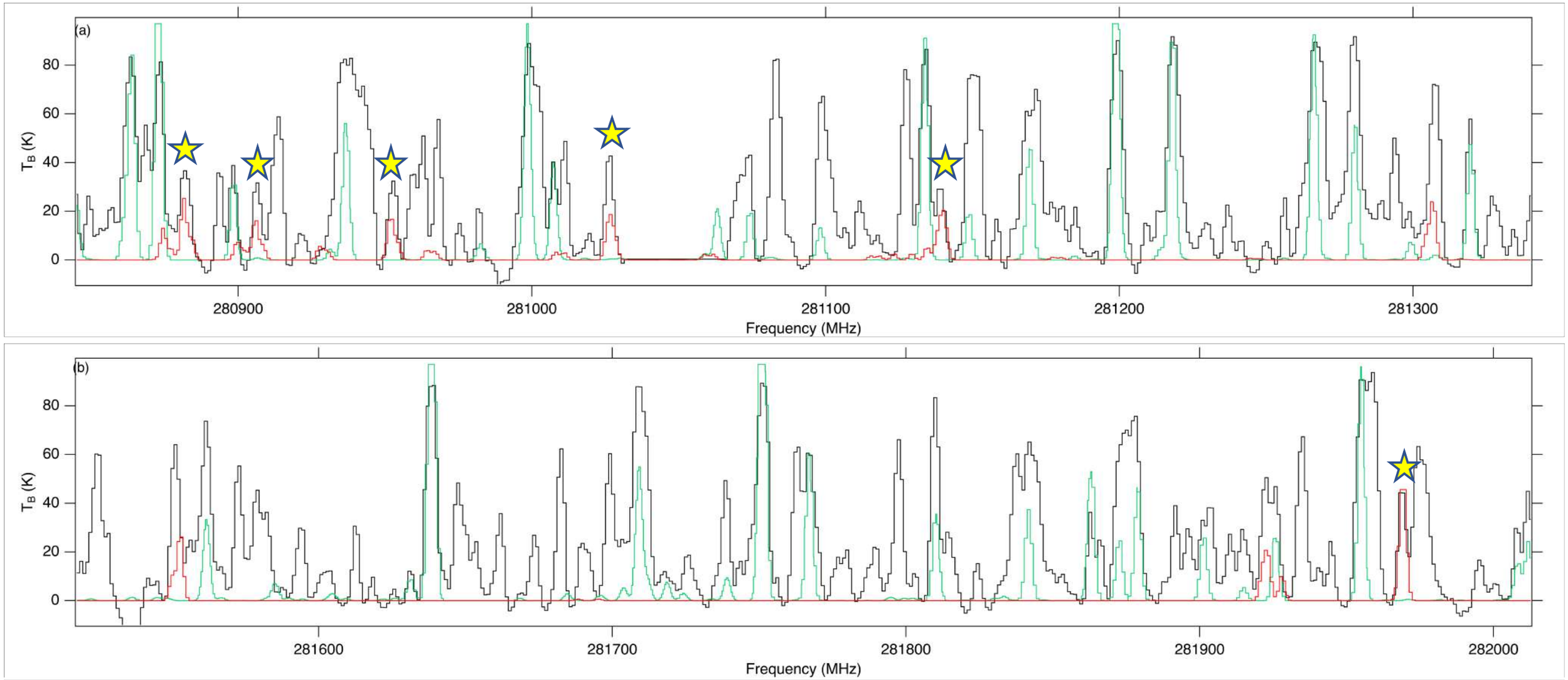


INTERSTELLAR DETECTIONS

NGC 6334I (ALMA Obs)

Common Species (Lab Freqs.)

methoxymethanol (Lab Freqs.)



McGuire et al. 2017 *ApJL* 851, L46

What Has Been Glossed Over/Ignored?

How do we predict the relative intensities of the lines in observations?

Intrinsic Line Strength
Excitation Temperature (T_{ex})
Background Continuum
Beam Size vs Source Size
Linewidth
Excitation Conditions (Radiation/Density)
Optical Depth

Interstellar Detections

2 Atoms

H_2 AlF AlCl C_2 CH CH^+ CN CO CO^+ CP SiC HCl KCl NH NO NS NaCl OH PN SO SO^+ SiN SiO SiS CS HF HD FeO O_2 CF^+ SiH PO AlO OH^+ CN^- SH^+ SH HCl^+ TiO ArH^+ N_2 NO^+ NS^+

3 Atoms

C_3 C_2H C_2O C_2S CH_2 HCN HCO HCO^+ HCS^+ HOC^+ H_2O H_2S HNC HNO MgCN MgNC N_2H^+ N_2O NaCN OCS SO_2 *c*-SiC_2 CO_2 NH_2 H_3^+ SiCN AlNC SiNC HCP CCP AlOH H_2O^+ H_2Cl^+ KCN FeCN HO_2 TiO_2 C_2N Si_2C HS_2 NCO HSC HCS

4 Atoms

c-C_3H /-C_3H C_3N C_3O C_3S C_2H_2 NH_3 HCCN $HCNH^+$ HNCO HNCS $HOCO^+$ H_2CO H_2CN H_2CS H_3O^+ c-SiC_3 CH_3 C_3N^- PH_3 HCNO HOCN HSCN H_2O_2 C_3H^+ HMgNC HCCO

5 Atoms

C_5 C_4H C_4Si /-C_3H_2 *c*-C_3H_2 H_2CCN CH_4 HC_3N HC_2NC HCOOH H_2CNH H_2C_2O H_2NCN HNC_3 SiH_4 H_2COH^+ C_4H^- HC(O)CN HNCNH CH_3O NH_4^+ H_2NCO^+ NCCNH$^+$ CH_3Cl H_2NCO^+

6 Atoms

C_5H /-H_2C_4 C_3H_4 CH_3CN CH_3NC CH_3OH CH_3SH HC_3NH^+ HC_2CHO NH_2CHO C_5N /-HC_4H /-HC_4N *c*-H_2C_3O H_2CCNH C_5N^- HNCHCN SiH_3CN

7 Atoms

C_6H CH_2CHCN CH_3C_2H HC_5N CH_3CHO CH_3NH_2 *c*-C_2H_4O H_2CCHOH C_6H^- CH_3NCO HC_5O

8 Atoms

CH_3C_3N $HC(O)OCH_3$ CH_3COOH C_7H C_6H_2 CH_2OHCHO /-HC_6H CH_2CHCHO CH_2CCHCN H_2NCH_2CN CH_3CHNH CH_3SiH_3

9 Atoms

CH_3C_4H CH_3CH_2CN $(CH_3)_2O$ CH_3CH_2OH HC_7N C_8H $CH_3C(O)NH_2$ C_8H^- C_3H_6 CH_3CH_2SH CH_3NHCHO

10 Atoms

CH_3C_5N $(CH_3)_2CO$ $(CH_2OH)_2$ CH_3CH_2CHO CH_3CHCH_2O CH_3OCH_2OH

11 Atoms

HC_9N CH_3C_6H C_2H_5OCHO $CH_3OC(O)CH_3$

12 Atoms

c-C_6H_6 $C_2H_5OCH_3$ *n*-C_3H_7CN *i*-C_3H_7CN

>12 Atoms

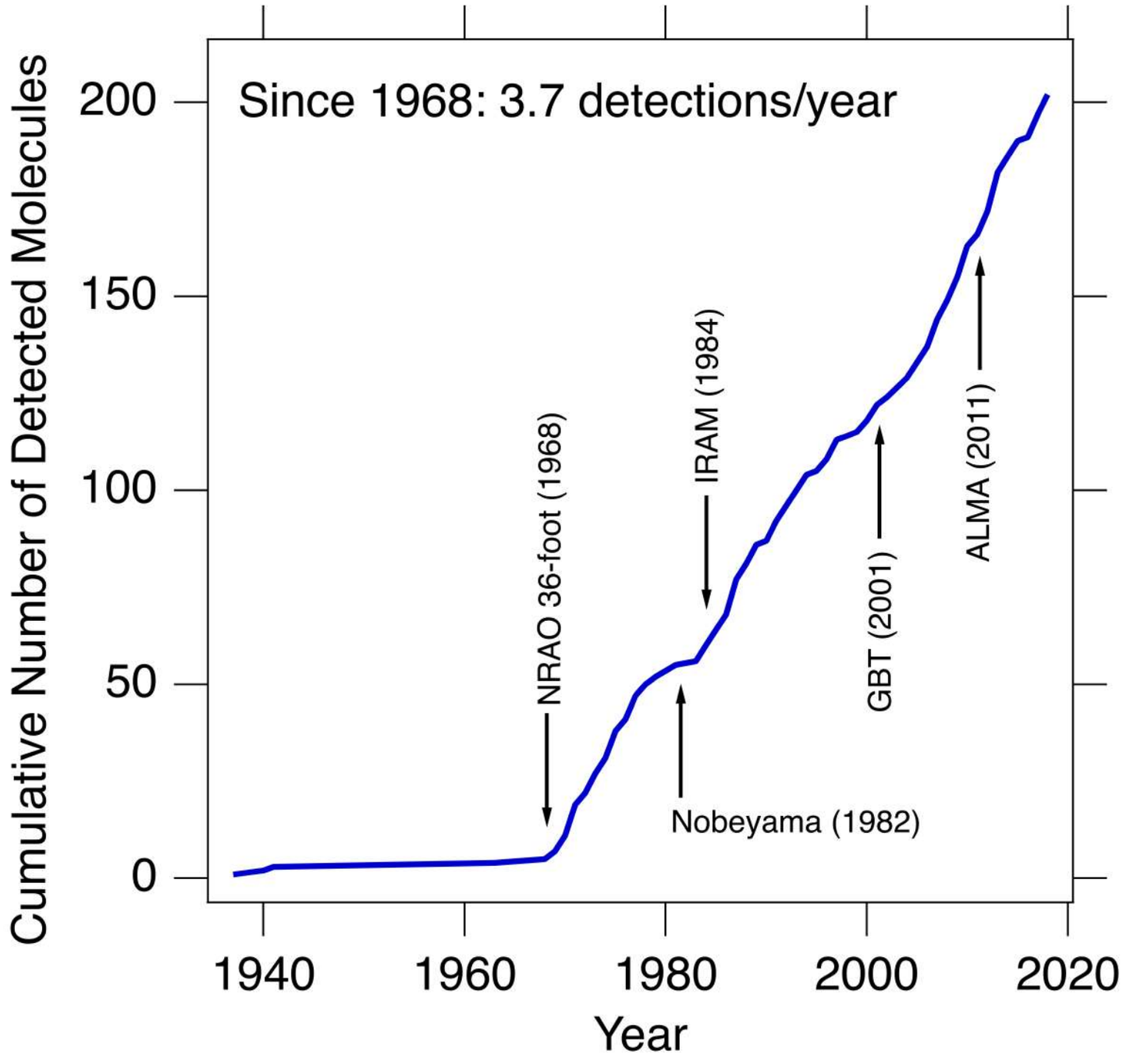
c-C_6H_5CN C_{60} C_{60}^+ C_{70}

202 Individual Species

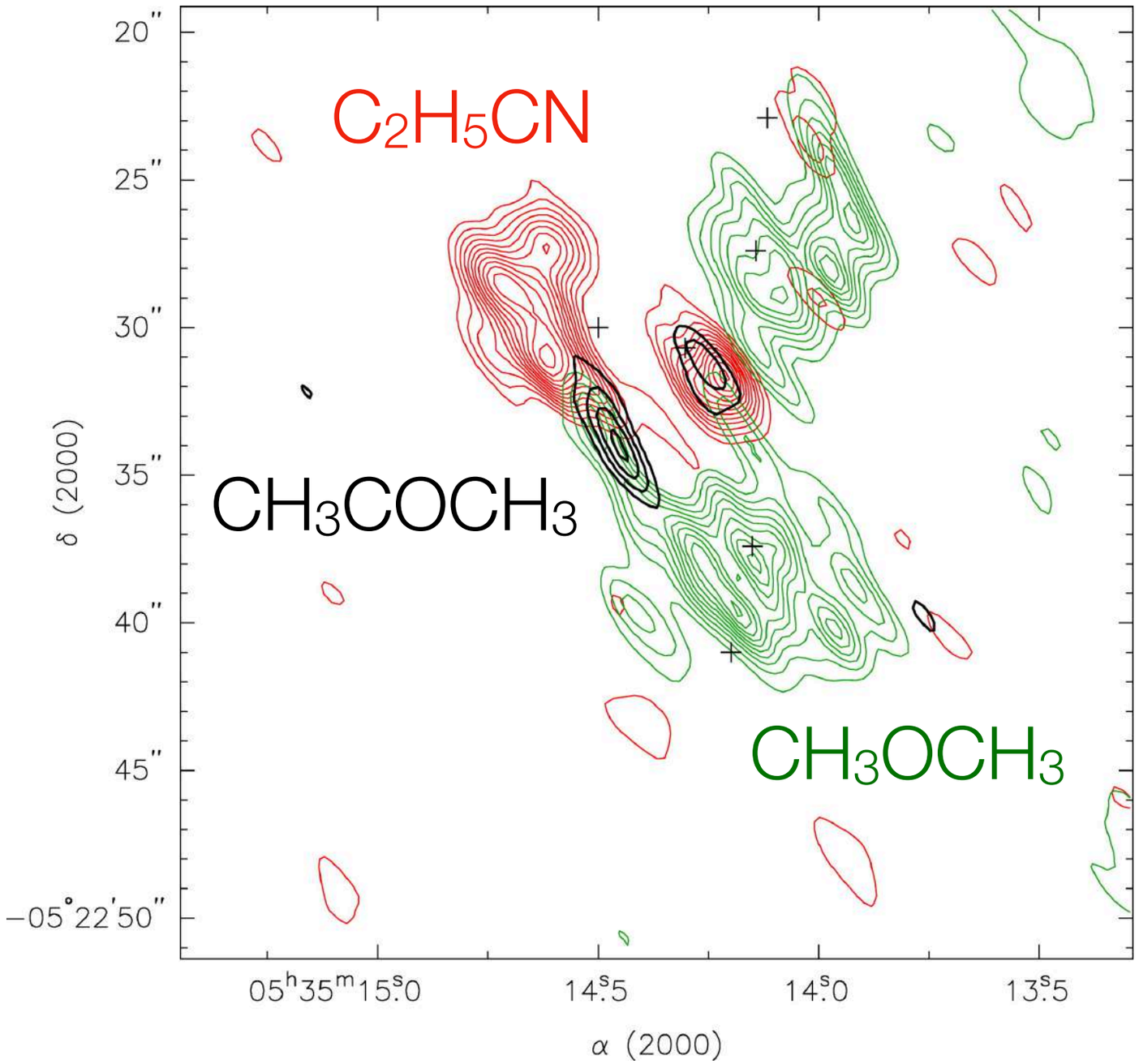
INTERSTELLAR DETECTIONS

	1																2
I	**H** 141 1.00794 Hydrogen																**He** 4.002602 Helium
	3	4											5	6	7	8	9	10
II	**Li** 6.941 Lithium	**Be** 9.012182 Beryllium											**B** 10.811 Boron	**C** 154 12.0107 Carbon	**N** 74 14.0067 Nitrogen	**O** 66 15.9994 Oxygen	**F** 3 18.9984032 Fluorine	**Ne** 20.1797 Neon
III	11 **Na** 2 22.98976928 Sodium	12 **Mg** 3 24.3050 Magnesium											13 **Al** 5 26.9815386 Aluminum	14 **Si** 13 28.0855 Silicon	15 **P** 6 30.973762 Phosphorus	16 **S** 23 32.065 Sulfur	17 **Cl** 7 35.453 Chlorine	18 **Ar** 1 39.948 Argon
IV	19 **K** 2 39.0983 Potassium	20 **Ca** 40.078 Calcium	21 **Sc** 44.955912 Scandium	22 **Ti** 2 47.867 Titanium	23 **V** 50.9415 Vanadium	24 **Cr** 51.9961 Chromium	25 **Mn** 54.938045 Manganese	26 **Fe** 1 55.845 Iron	27 **Co** 58.933195 Cobalt	28 **Ni** 58.6934 Nickel	29 **Cu** 63.546 Copper	30 **Zn** 65.38 Zinc	31 **Ga** 69.723 Gallium	32 **Ge** 72.64 Germanium	33 **As** 74.92160 Arsenic	34 **Se** 78.96 Selenium	35 **Br** 79.904 Bromine	36 **Kr** 83.798 Krypton
V	37 **Rb** 85.4678 Rubidium	38 **Sr** 87.62 Strontium	39 **Y** 88.90585 Yttrium	40 **Zr** 91.224 Zirconium	41 **Nb** 92.90638 Niobium	42 **Mo** 95.96 Molybdenum	43 **Tc** [98] Technetium	44 **Ru** 101.07 Ruthenium	45 **Rh** 102.90550 Rhodium	46 **Pd** 106.42 Palladium	47 **Ag** 107.8682 Silver	48 **Cd** 112.411 Cadmium	49 **In** 114.818 Indium	50 **Sn** 118.710 Tin	51 **Sb** 121.760 Antimony	52 **Te** 127.60 Tellurium	53 **I** 126.90447 Iodine	54 **Xe** 131.293 Xenon
VI	55 **Cs** 132.9054519 Cesium	56 **Ba** 137.327 Barium	LA	72 **Hf** 178.49 Hafnium	73 **Ta** 180.94788 Tantalum	74 **W** 183.84 Tungsten	75 **Re** 186.207 Rhenium	76 **Os** 190.23 Osmium	77 **Ir** 192.217 Iridium	78 **Pt** 195.084 Platinum	79 **Au** 196.966569 Gold	80 **Hg** 200.59 Mercury	81 **Tl** 204.3833 Thallium	82 **Pb** 207.2 Lead	83 **Bi** 208.98040 Bismuth	84 **Po** [209] Polonium	85 **At** [210] Astatine	86 **Rn** [222] Radon
VII	87 **Fr** [223] Francium	88 **Ra** [226] Radium	AC	104 **Rf** [267] Rutherfordium	105 **Db** [268] Dubnium	106 **Sg** [271] Seaborgium	107 **Bh** [272] Bohrium	108 **Hs** [270] Hassium	109 **Mt** [276] Meitnerium	110 **Ds** [281] Darmstadtium	111 **Rg** [280] Roentgenium	112 **Cn** [285] Copernicium	113 **Nh** [284] Nihomium	114 **Fl** [289] Flerovium	115 **Mc** [288] Moscovium	116 **Lv** [293] Livermorium	117 **Ts** [294] Tennessine	118 **Og** [294] Oganesson
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18

INTERSTELLAR DETECTIONS



DELIVERABLES

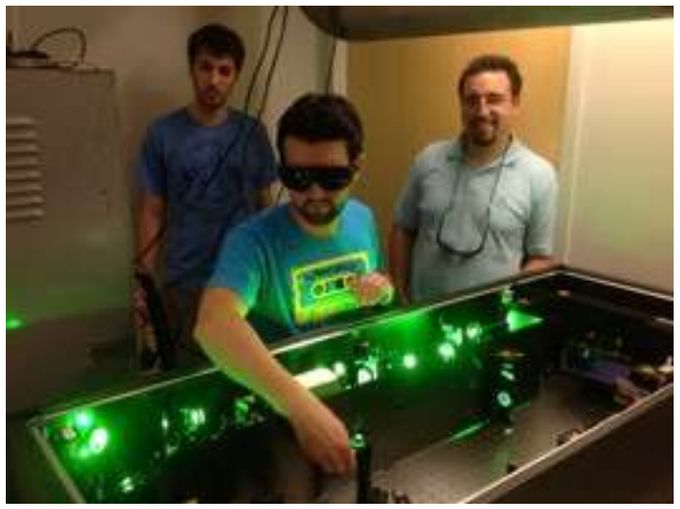


- Spatial distributions
- Excitation conditions
- Column densities

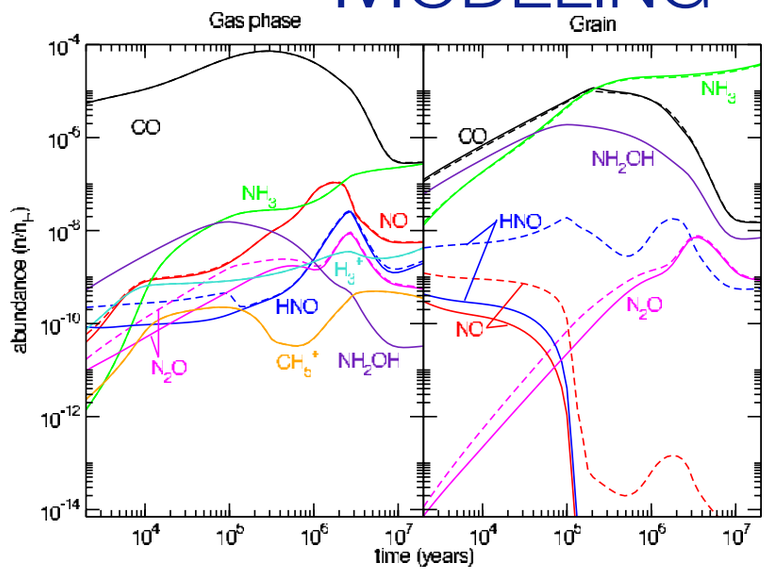
Friedel et al. 2008 *ApJ* 672, 962

Astrochemistry

Laboratory Astrophysics



Astrochemical Modeling



Chemical Reactions, Kinetics, Thermodynamics

Species and Reactions of Interest

Extraordinarily Broad Range of Research

Temperatures, Abundances, and Densities

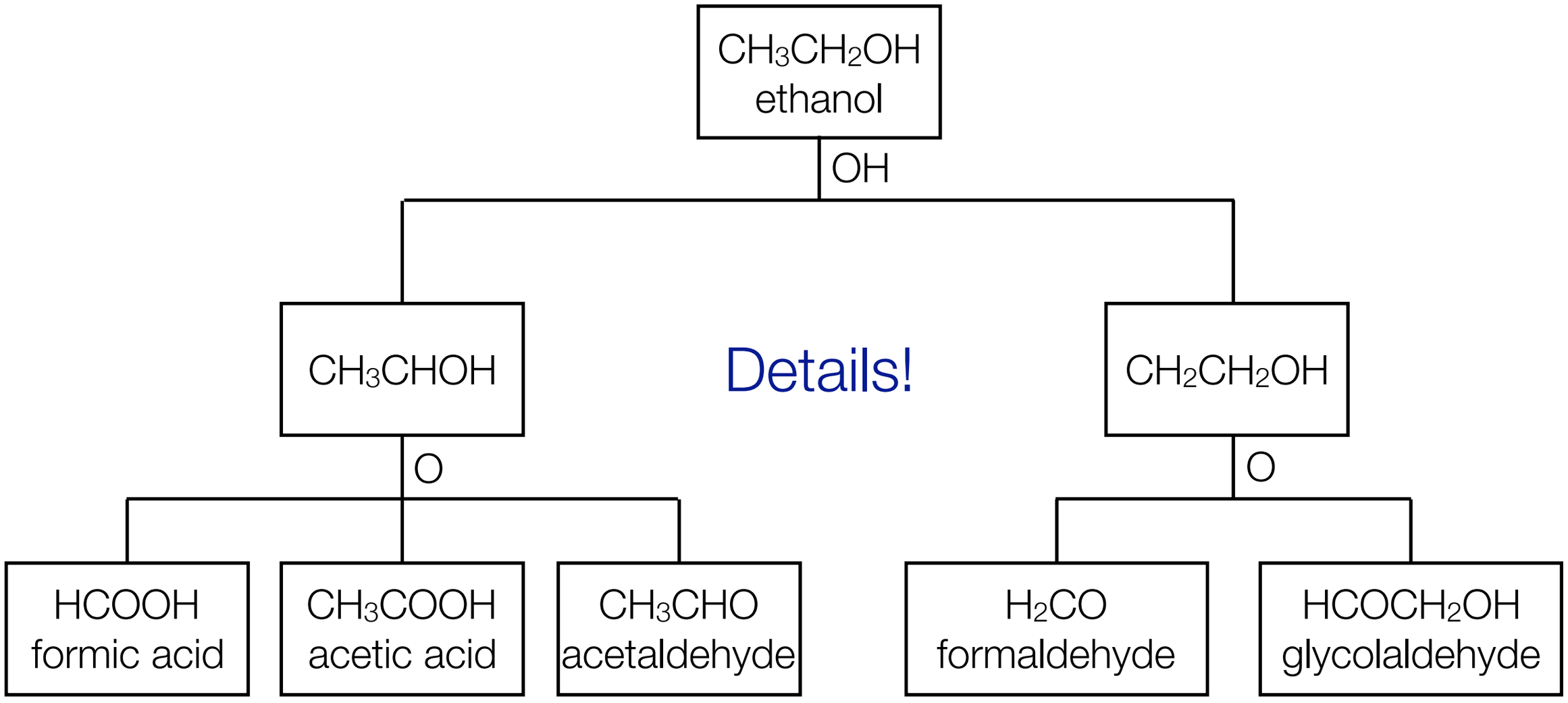
Rotational, Vibrational, and Electronic Spectra

Environments and Species of Interest

Chemical Inventories Temperatures, Abundances, and Densities

Observational Astronomy

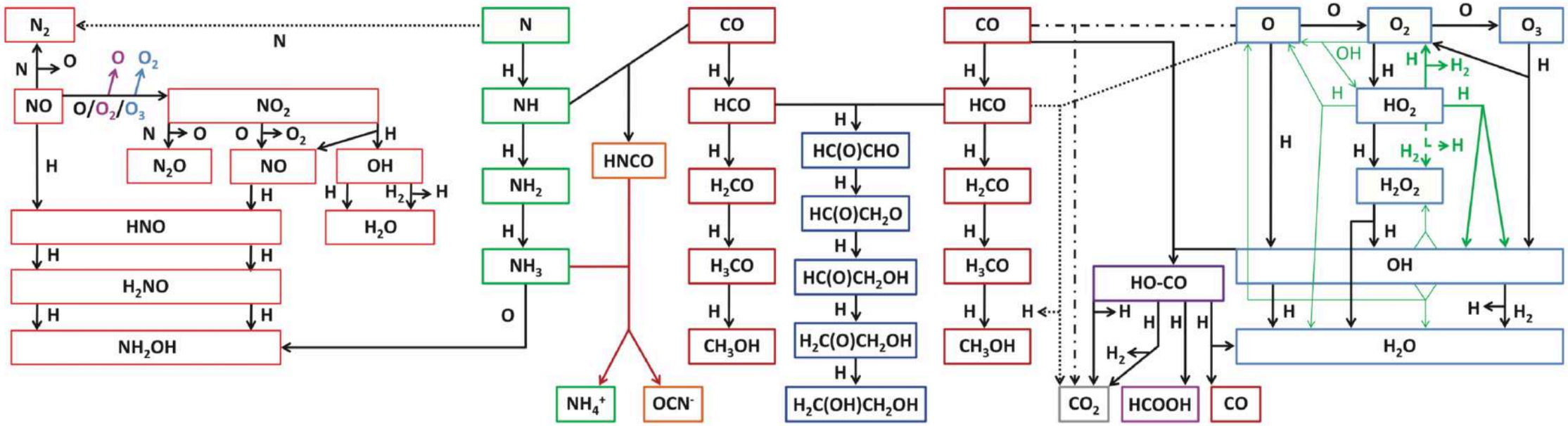
Chemical Modeling



Details!

Skouteris et al. 2018 *ApJ* 854, 135

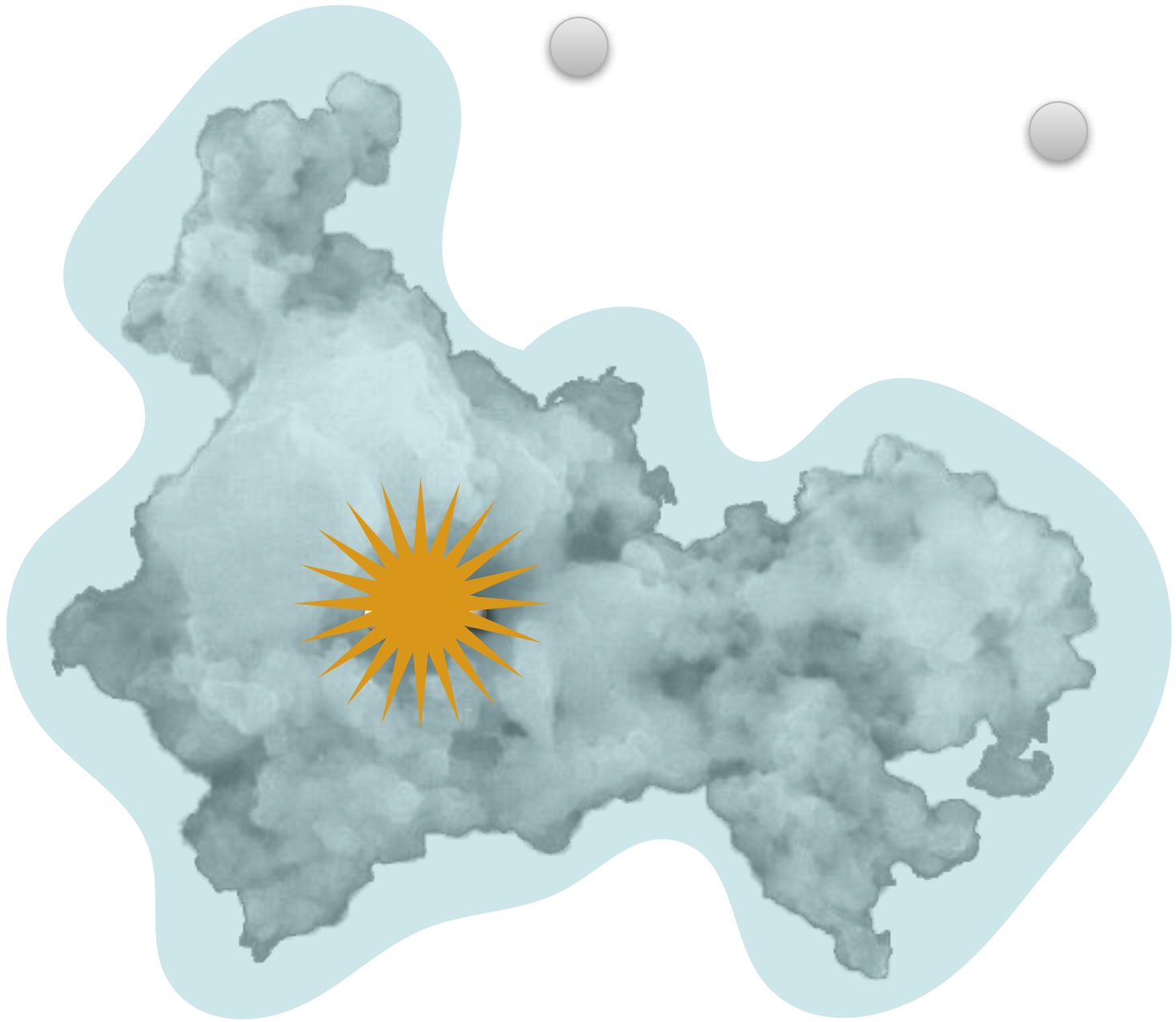
CHEMICAL MODELING



Typical networks have 800+ species and ~10,000 reactions

Linnartz et al. 2015 *Int. Rev. Phys. Chem.* 34, 205

Chemical Modeling



Chemical Modeling - Rate Equations

Formation of ***x***

Destruction of ***x***

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \sum_y \sum_z k_{yz} n(y) n(z) - n(x) \sum_y k_{xy} n(y)$$

How molecule **x** changes abundance with time ***t***

(~)Rate of the reaction between ***y*** and ***z*** to form ***x***

Abundance of species ***y*** and ***z*** that react to form ***x***

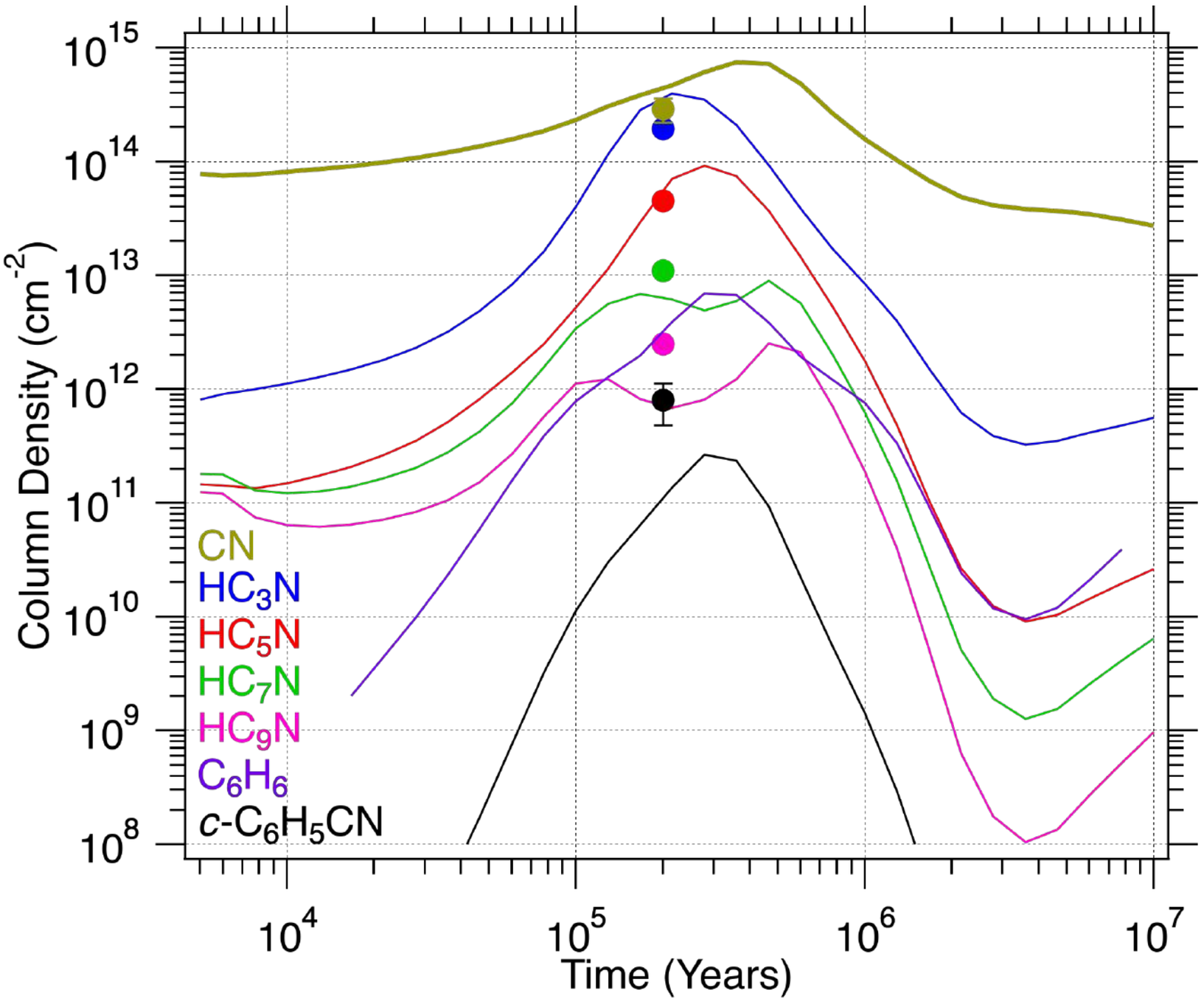
Abundance of ***x***

(~)Rate of the reaction with ***y*** to destroy ***x***

Abundance of species ***y*** that destroys ***x***

1 differential equation per molecule

Chemical Modeling - Rate Equations



McGuire et al. 2018 *Science* 359, 202

Chemical Modeling - Rate Equations

Formation of ***x***

Destruction of ***x***

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Abundance of species ***y*** and ***z*** that react to form ***x***

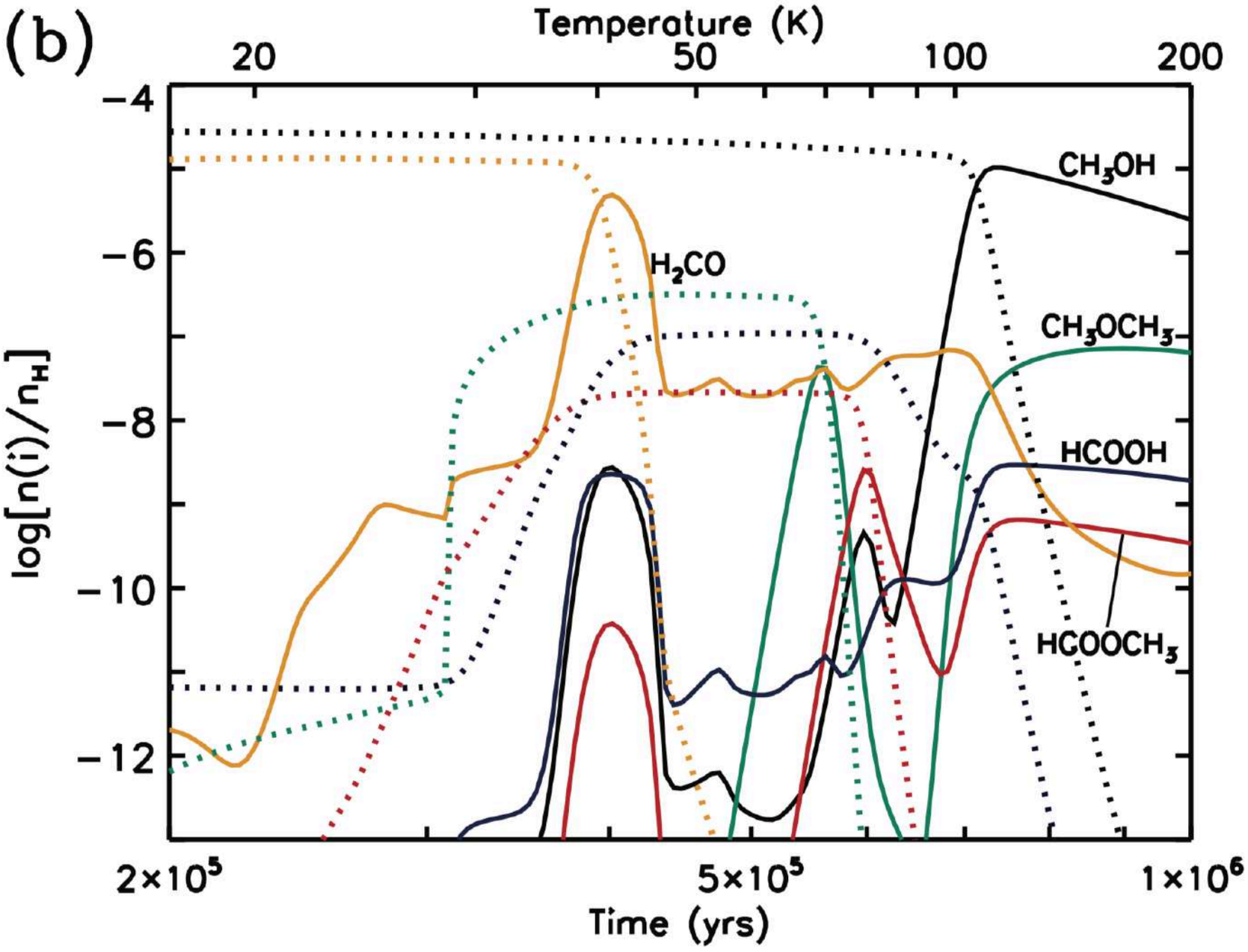
Abundance of ***x***

(~)Rate of the reaction with ***y*** to destroy ***x***

Abundance of species ***y*** that destroys ***x***

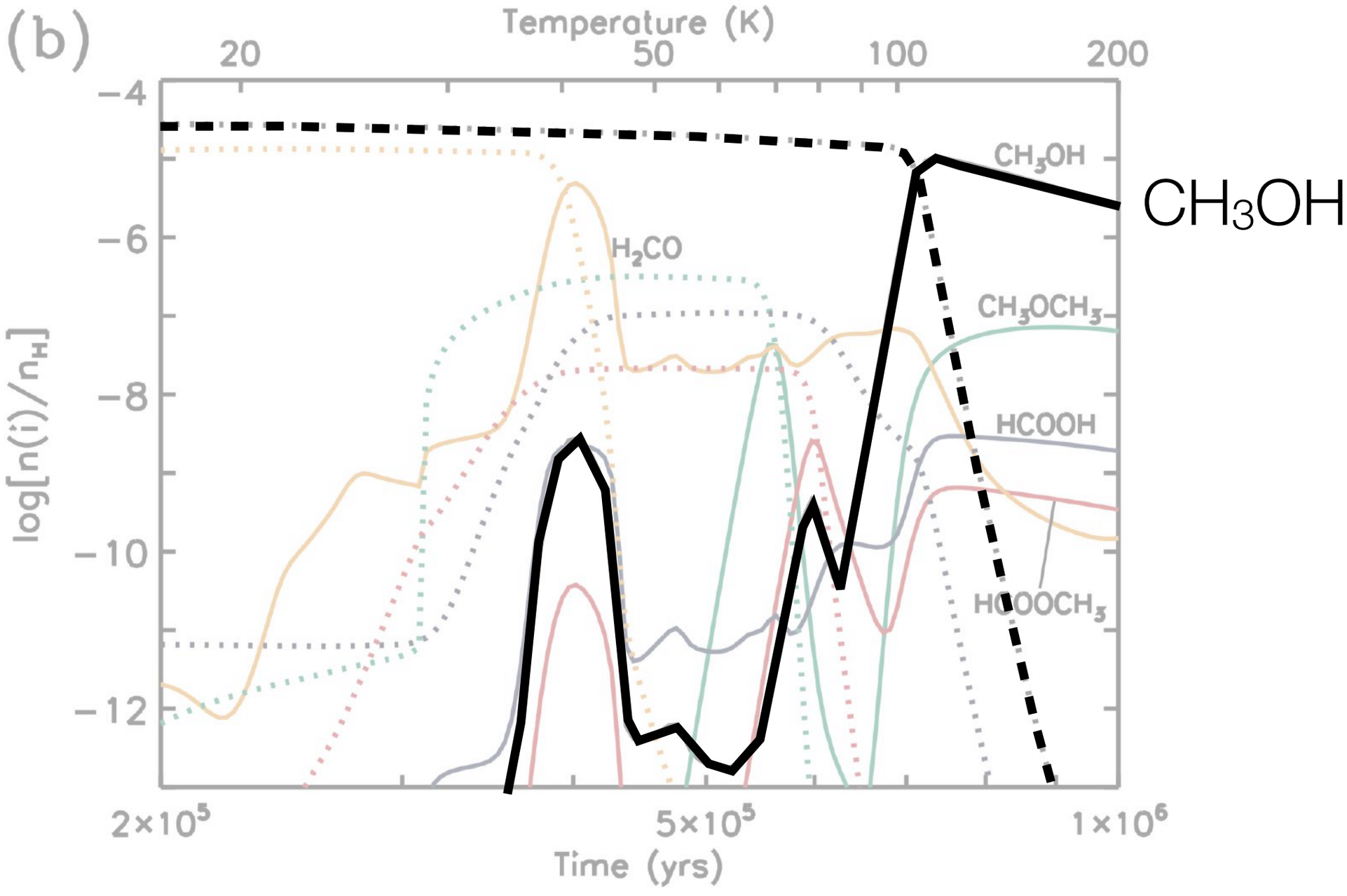
Depend on temperature, density, UV radiation field, cosmic ray ionization rate, etc.

CHEMICAL MODELING - RATE EQUATIONS



Garrod et al. 2008 *ApJ* 628, 283

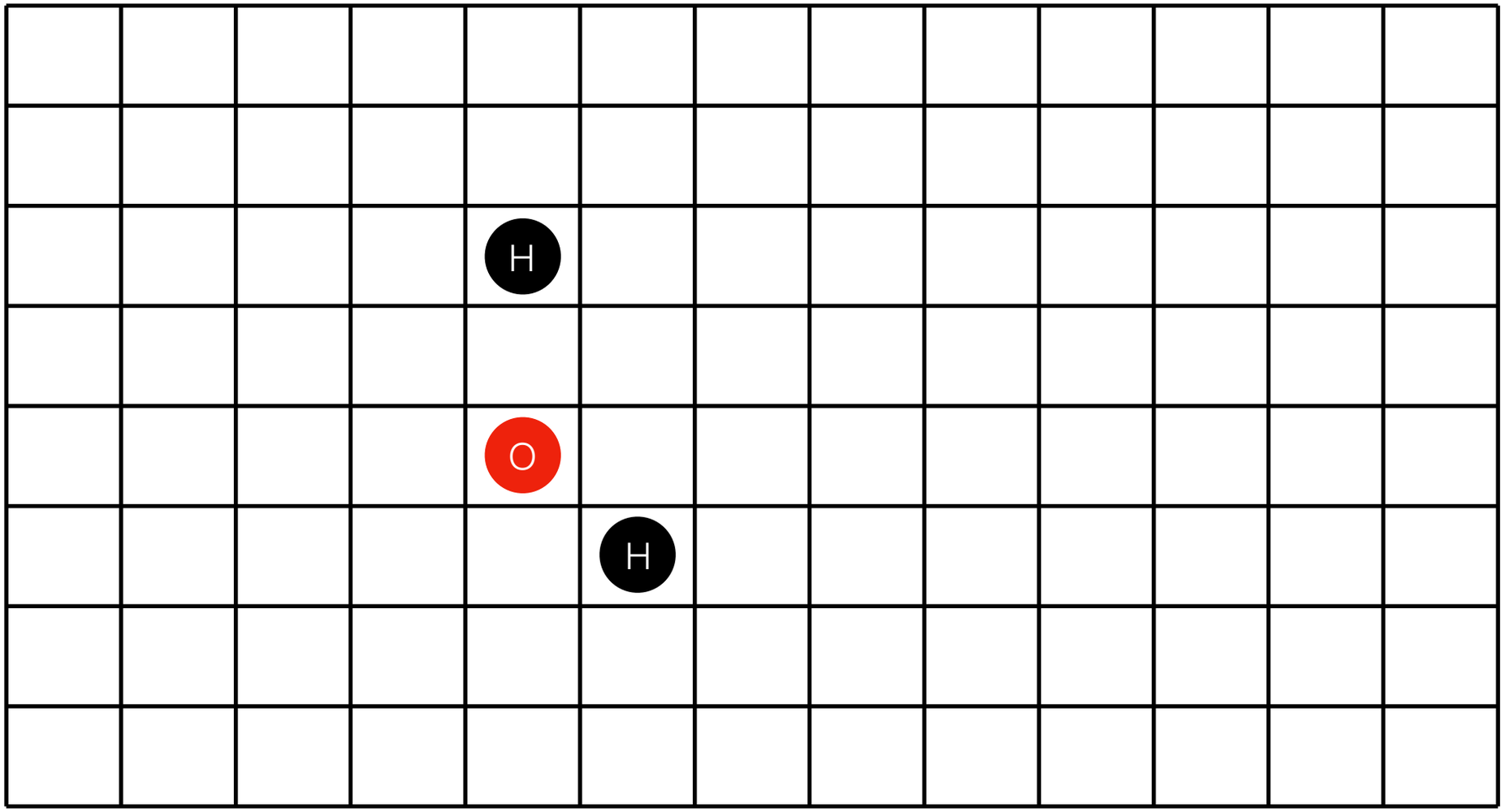
CHEMICAL MODELING - RATE EQUATIONS



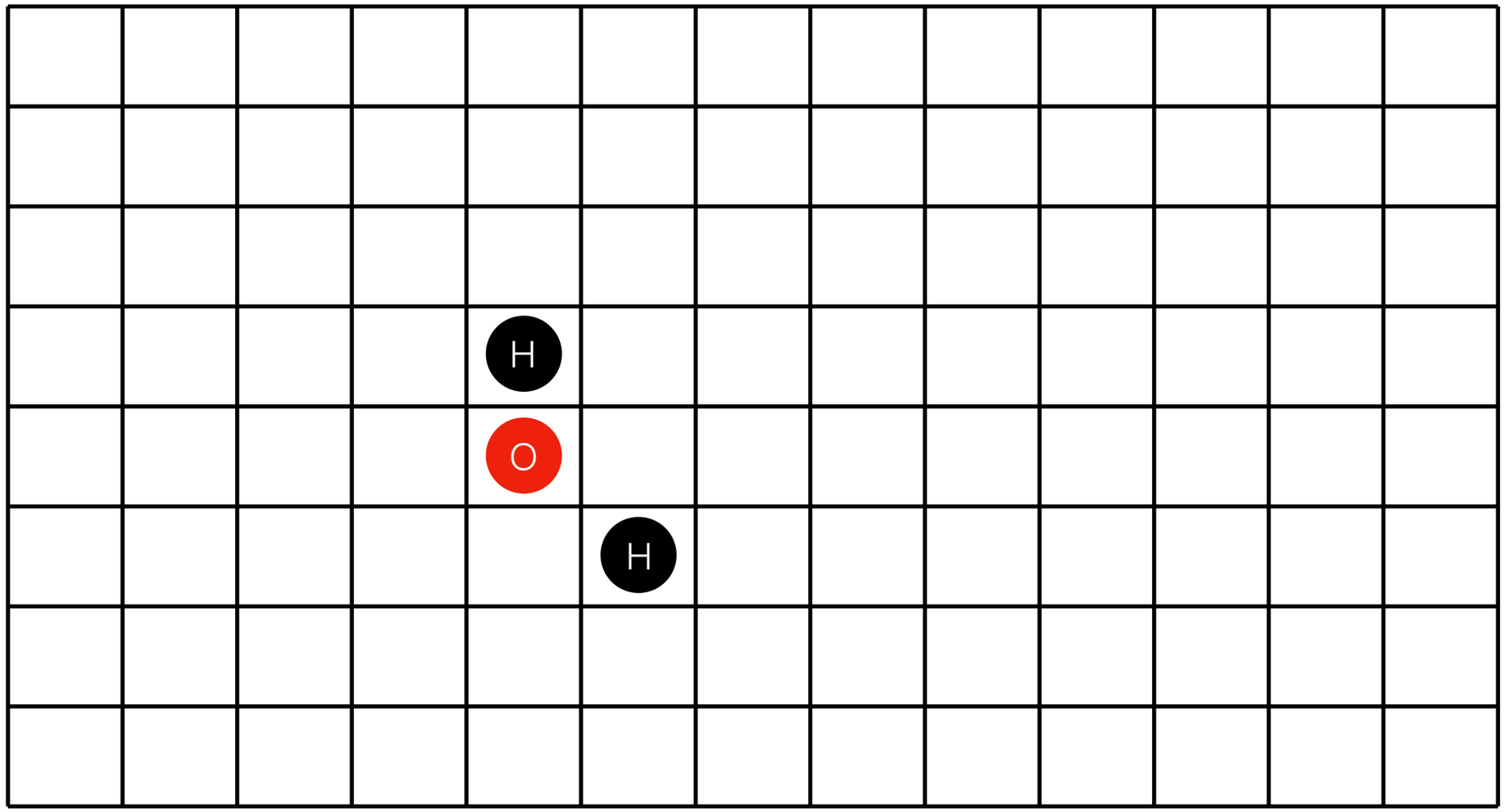
CH_3OH

Garrod et al. 2008 *ApJ* 628, 283

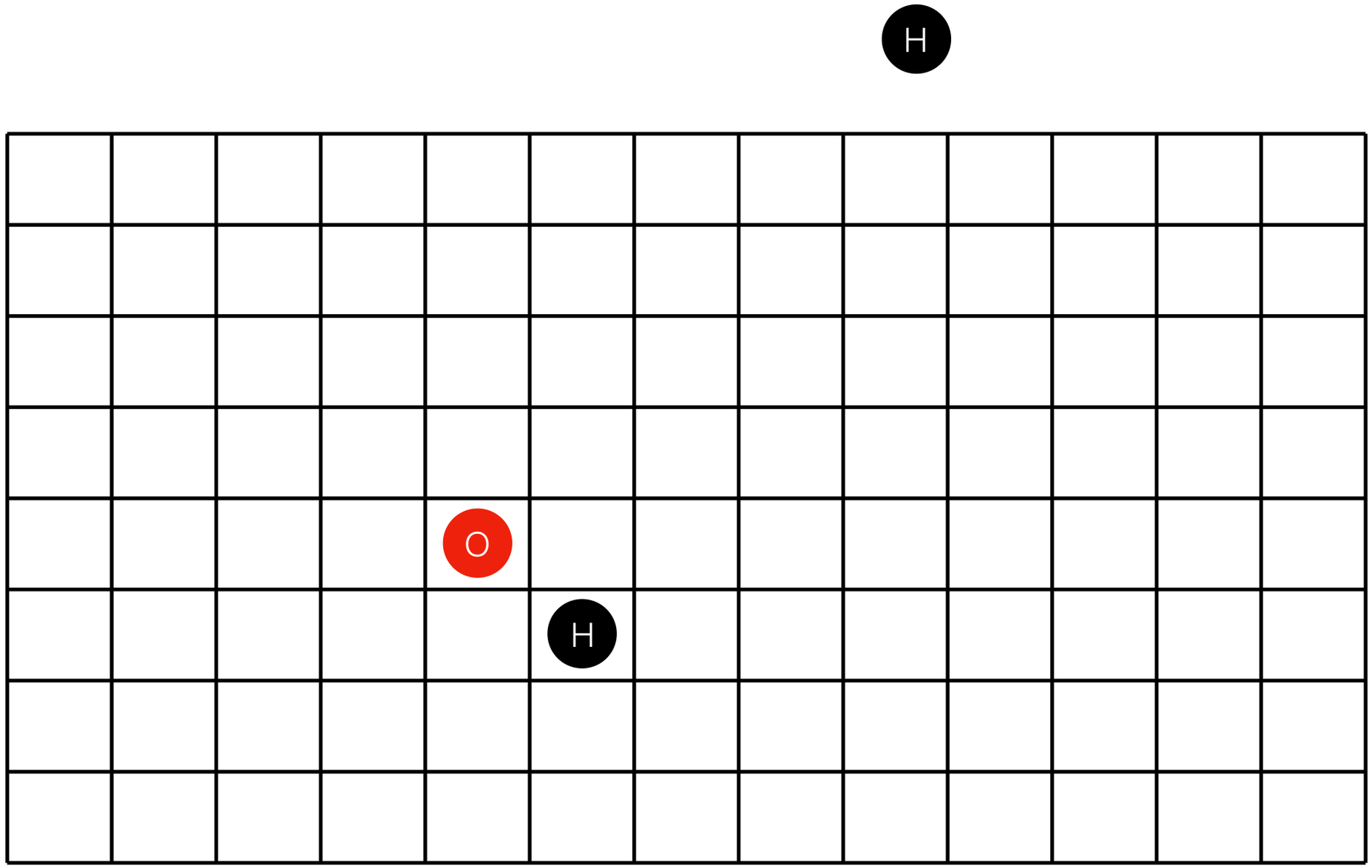
Chemical Modeling - Monte Carlo



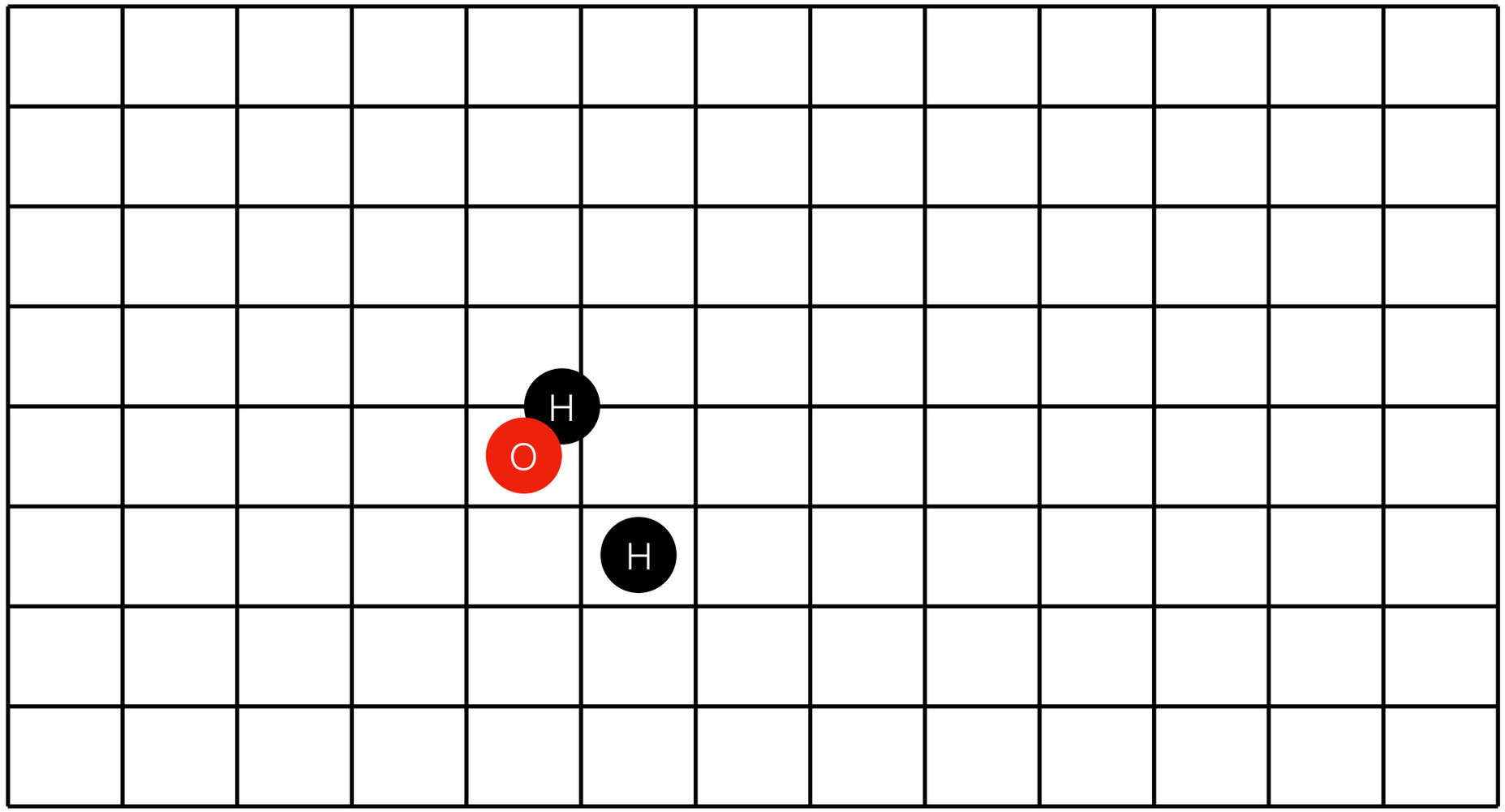
Chemical Modeling - Monte Carlo



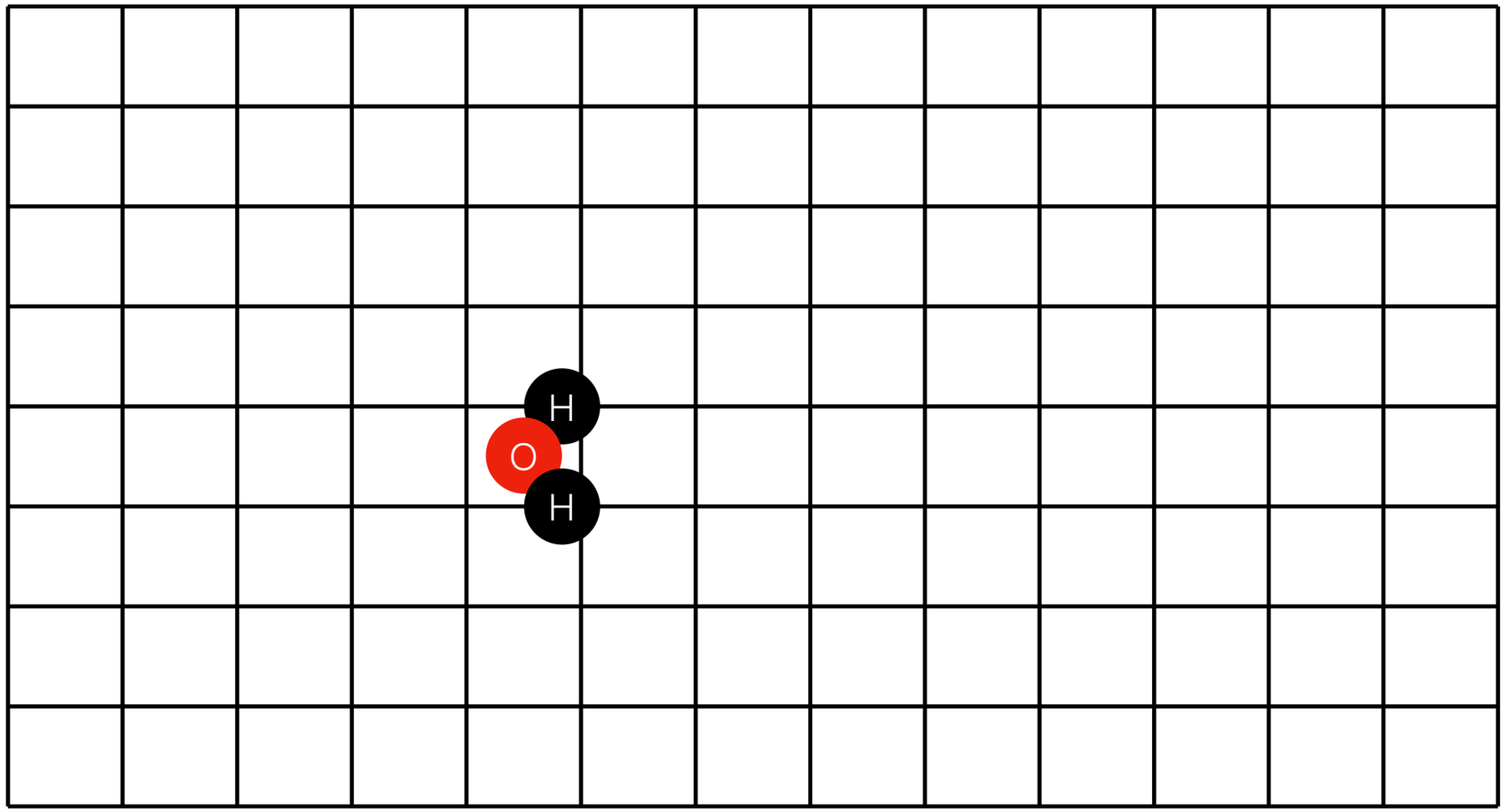
Chemical Modeling - Monte Carlo



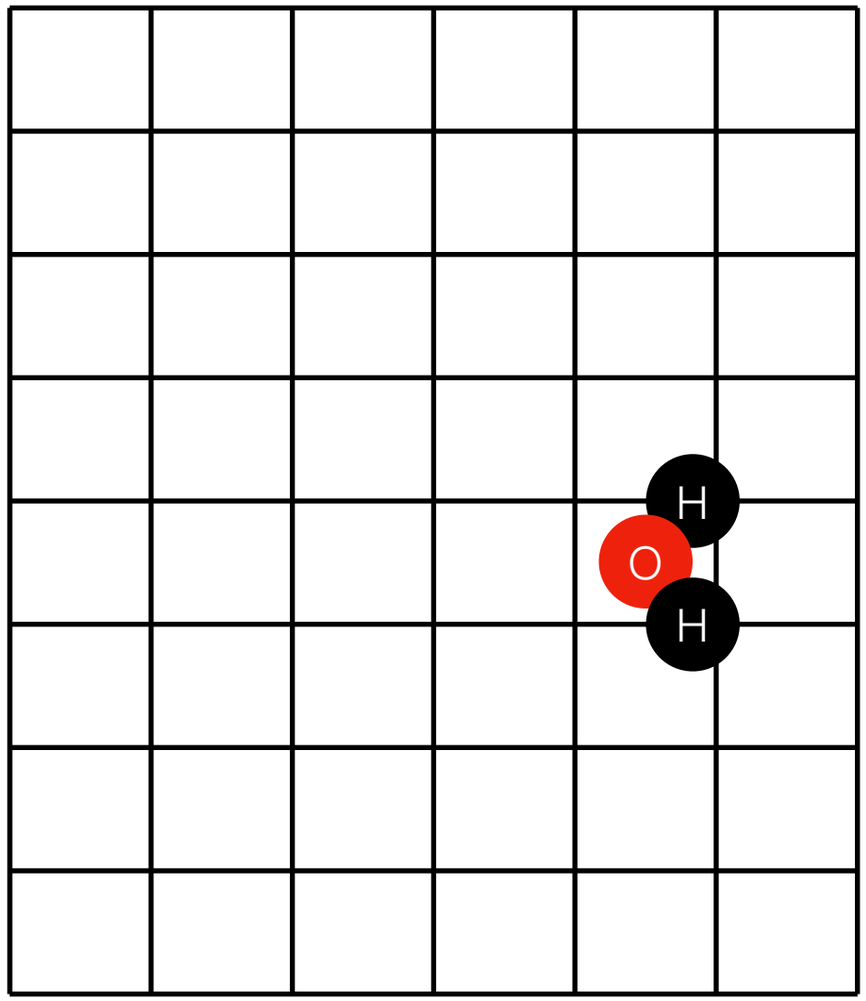
CHEMICAL MODELING - MONTE CARLO



Chemical Modeling - Monte Carlo



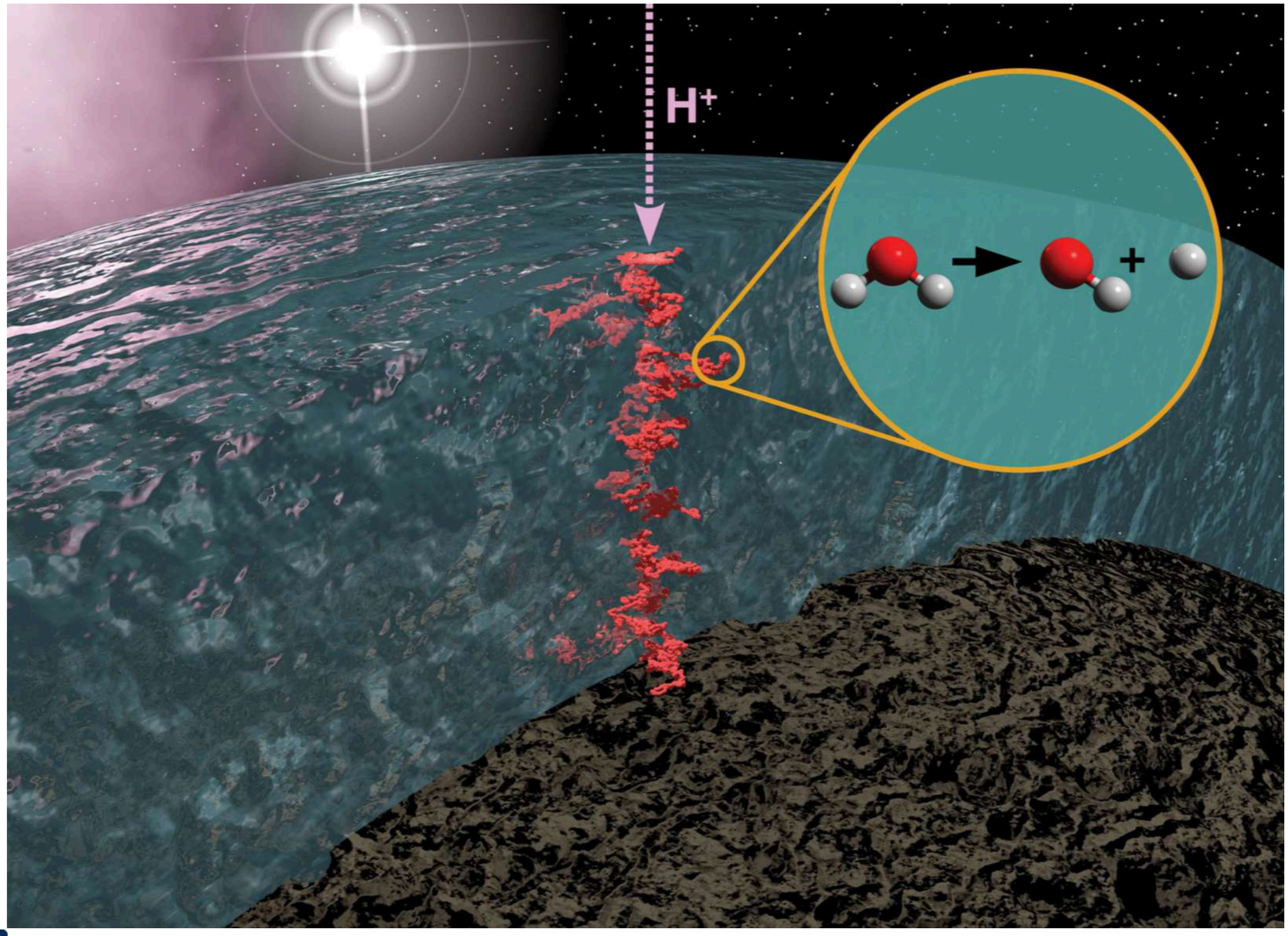
Chemical Modeling - Monte Carlo



Provides ability to trace the complete and discrete history of any individual item

Can model complex physical issues like crystallinity and porosity of ices or the extremely complex effects of a cosmic ray impact

Chemical Modeling - Monte Carlo



Chemical Modeling

Rate Equations	Monte Carlo
Computationally inexpensive	Computationally v. expensive
'Easy' to implement new chemistry, physics, rapidly adapt model	(Not so) 'easy' to implement new chemistry, physics, rapidly adapt model
Can model an arbitrarily long timescale by simply altering time step; time steps need not be linear	Can model an arbitrarily long timescale by simply altering time step; time steps need not be linear
'Hard' to implement microscopic properties - ice structure, diffusion, environment-sensitive issues	Get a 'complete' physical picture of the system. System is typically ~1 gas-grain interface
Models the entire cloud - bulk gas and bulk surface	More physically 'realistic'

Chemical Modeling - A Final note

Astrochemical models are almost always completely incapable of correctly reproducing reality

BUT

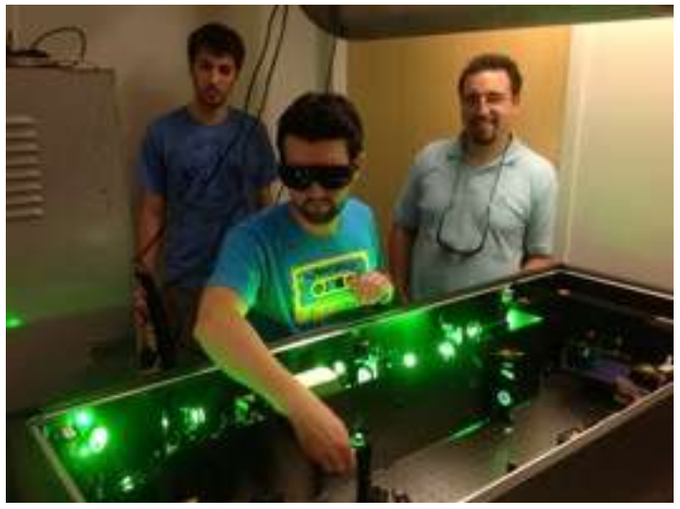
They are still incredibly useful and important for:

Identifying gaps in our understanding of pertinent reactions, species, and physical processes

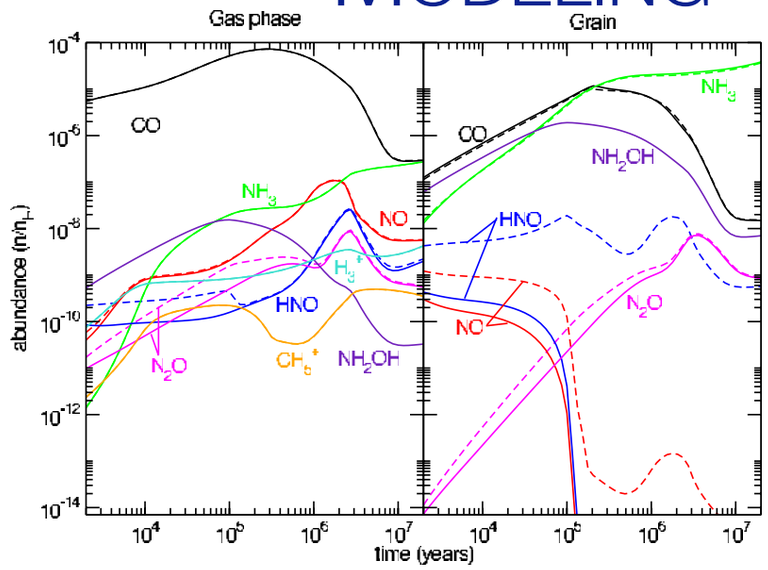
Suggesting reasonable explanations for observations, and necessary follow-up observational or laboratory tests

Astrochemistry

Laboratory Astrophysics



Astrochemical Modeling



Chemical Reactions, Kinetics, Thermodynamics

Species and Reactions of Interest

Temperatures, Abundances, and Densities

Rotational, Vibrational, and Electronic Spectra

Environments and Species of Interest

Chemical Inventories Temperatures, Abundances, and Densities

Observational Astronomy

PARTING THOUGHTS

Astrochemistry seeks to understand the evolution of molecular complexity through cosmic time and its influence on the dynamical evolution of our universe.

Molecular lines aren't noise - they're invaluable information on the current conditions and evolutionary history of the source you're studying! Don't ignore them!

Molecules can be valuable probes/tracers of physical conditions, but only when interpreted in context. If in doubt, ask an astrochemist!