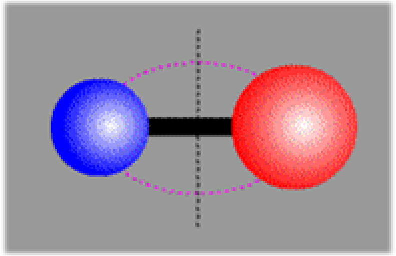
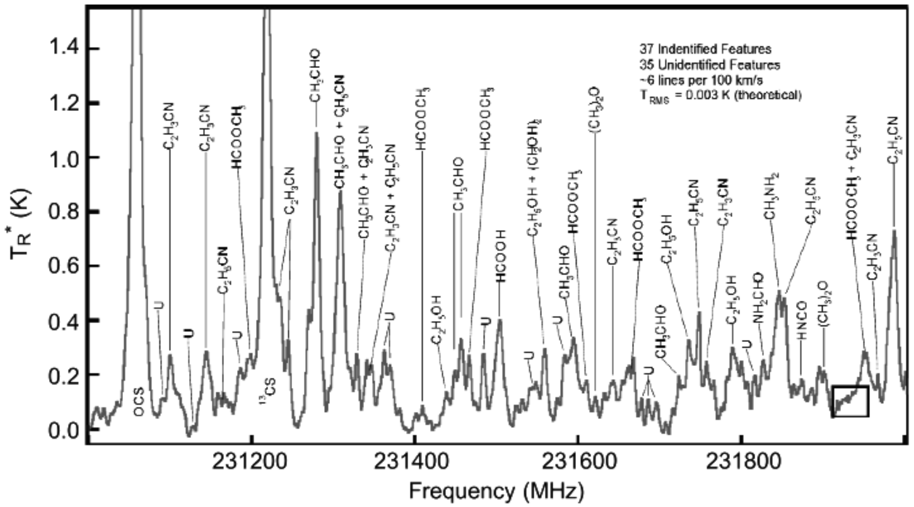
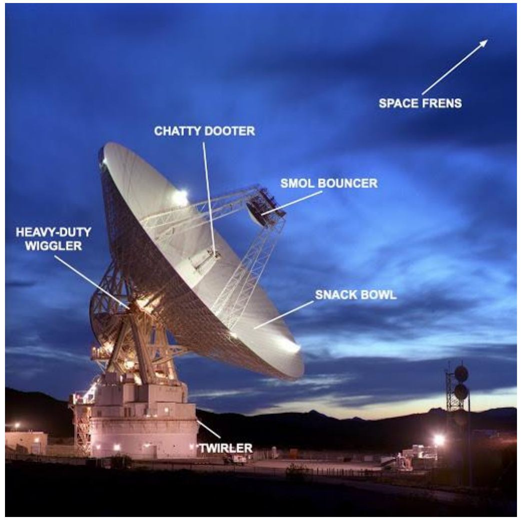






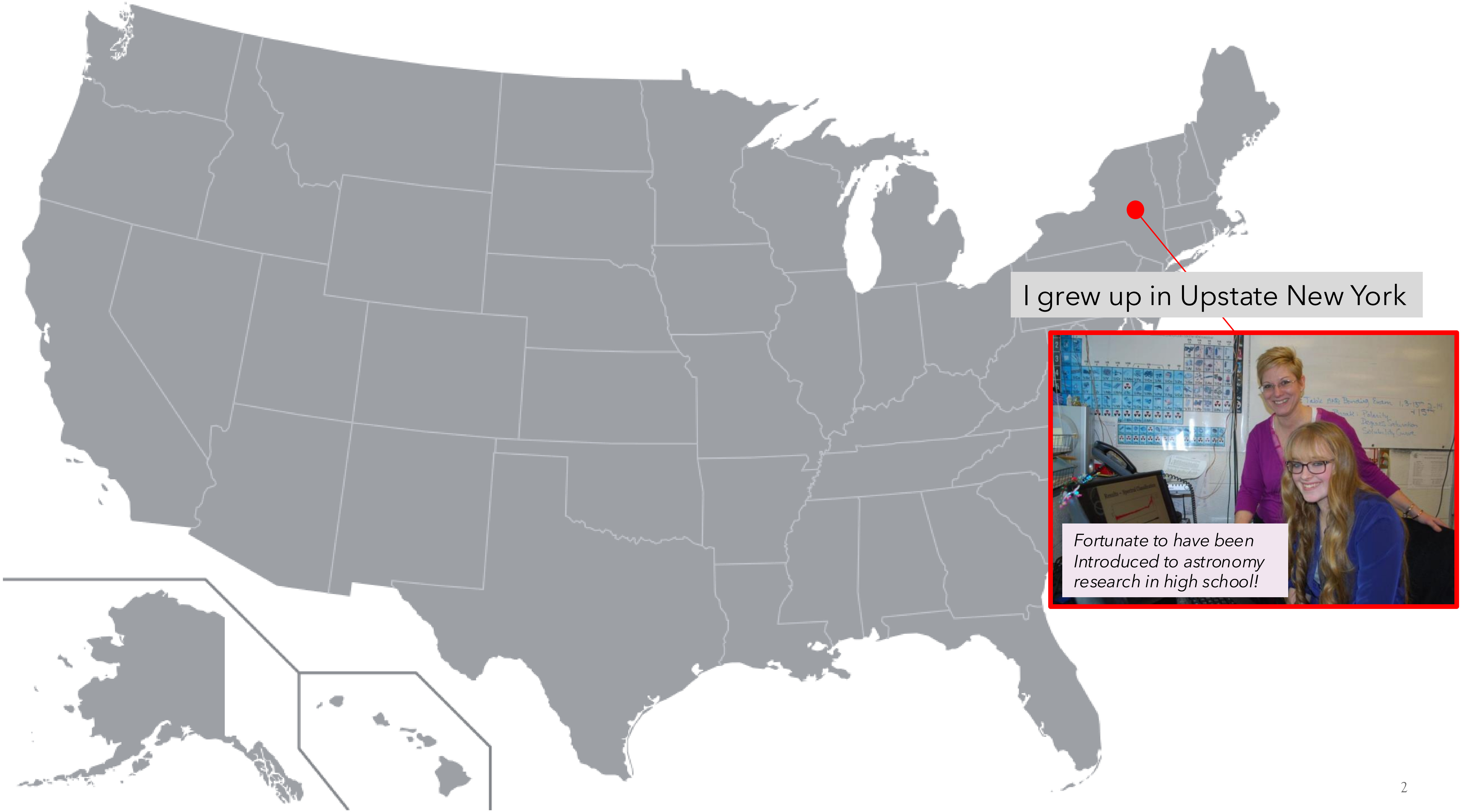
Introduction to Astrochemistry **Part 1:**

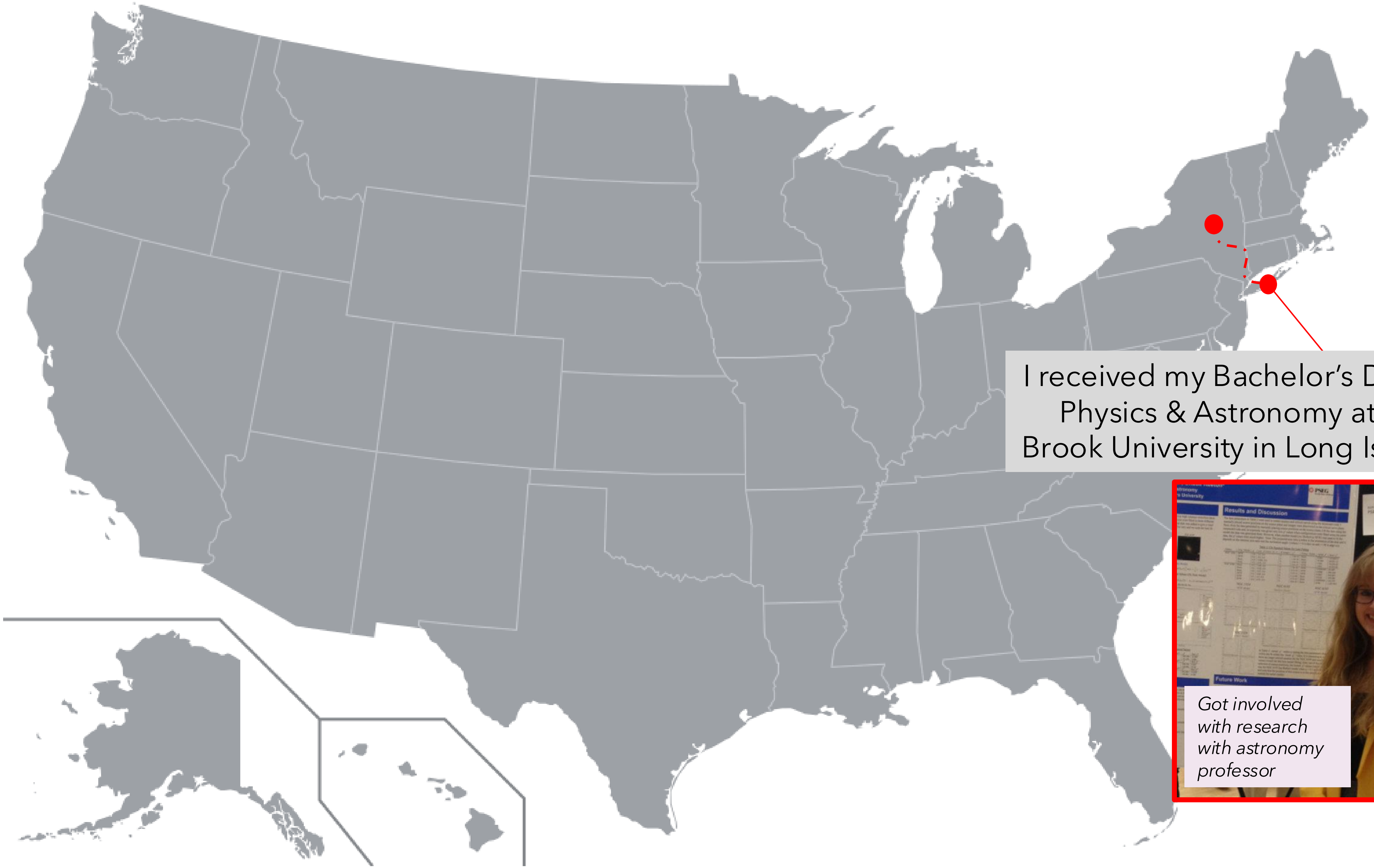
Molecular Spectroscopy & Millimeter Radio Telescopes

Dr. Samantha Scibelli

Jansky Fellow at the National Radio Astronomy Observatory (NRAO)

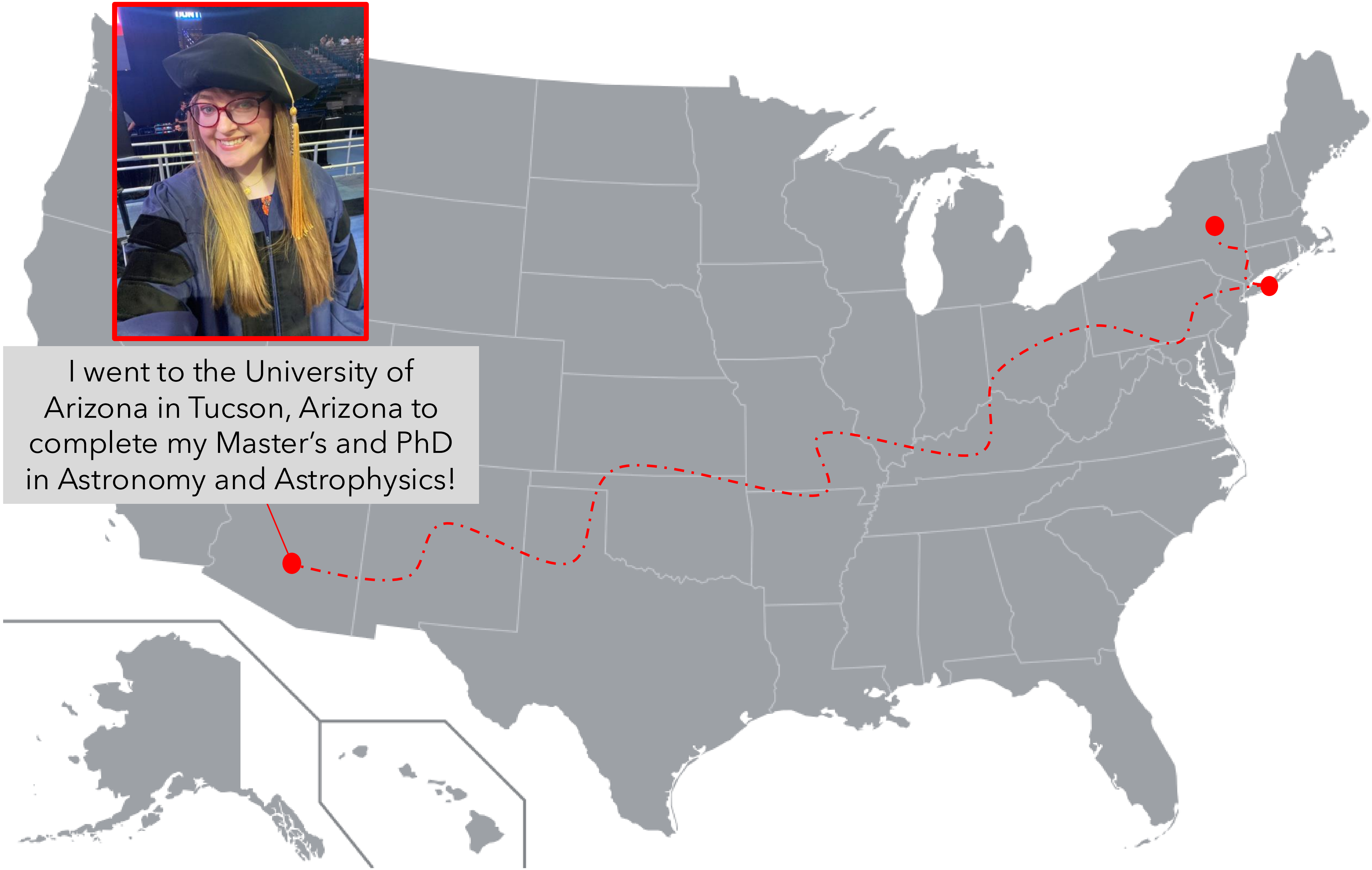
AAA.org Lecture, May 21st, 2024


I grew up in Upstate New York
Fortunate to have been
Introduced to astronomy
research in high school!



I received my Bachelor's Degree in Physics & Astronomy at Stony Brook University in Long Island, NY

Got involved with research with astronomy professor



I went to the University of Arizona in Tucson, Arizona to complete my Master's and PhD in Astronomy and Astrophysics!

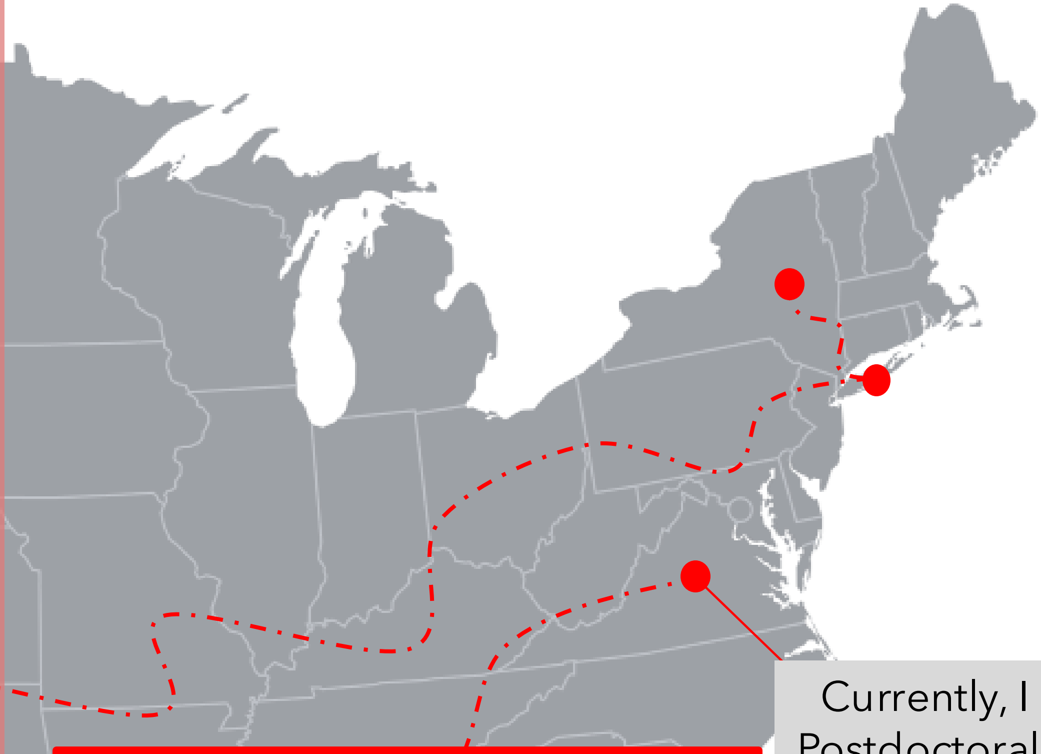
Currently, I am a Jansky Postdoctoral Fellow at the National Radio Astronomy Observatory (NRAO) here in Charlottesville, VA!

12m Radio Telescope, Kitt Peak, AZ

Control Room @ SMT, Mt. Graham, AZ

IRAM 30m Radio Telescope, Granada, Spain

Green Bank Radio Telescope, 100m, in West Virginia



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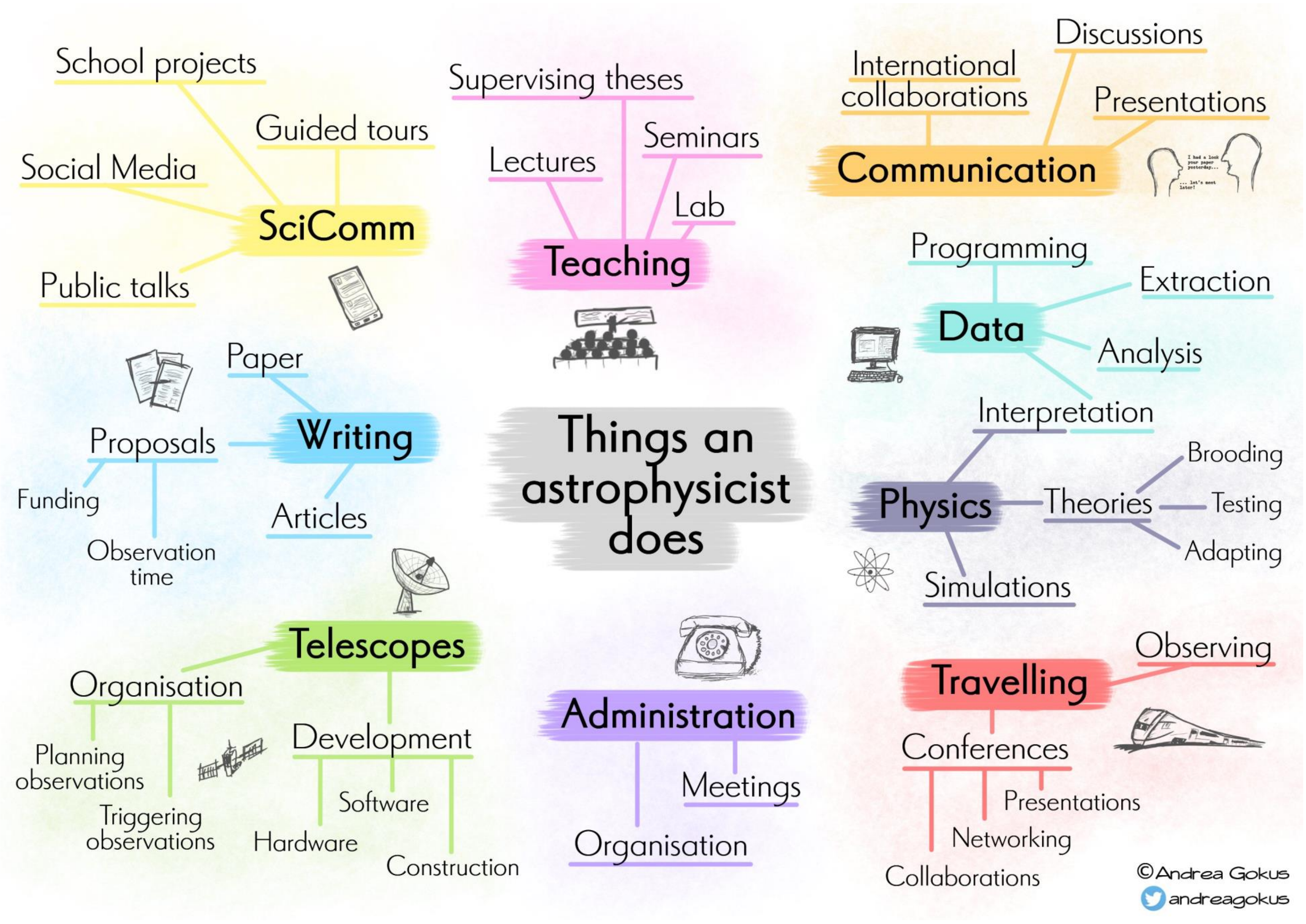
Things an astrophysicist does
SciComm
School projects
Guided tours
Social Media
Public talks
Teaching
Supervising theses
Lectures
Seminars
Lab
Communication
International collaborations
Discussions
Presentations
Data
Programming
Extraction
Analysis
Interpretation
Writing
Paper
Proposals
Funding
Observation time
Articles
Physics
Theories
Brooding
Testing
Adapting
Simulations
Telescopes
Organisation
Planning observations
Triggering observations
Development
Software
Hardware
Construction
Administration
Meetings
Organisation
Travelling
Observing
Conferences
Presentations
Networking
Collaborations
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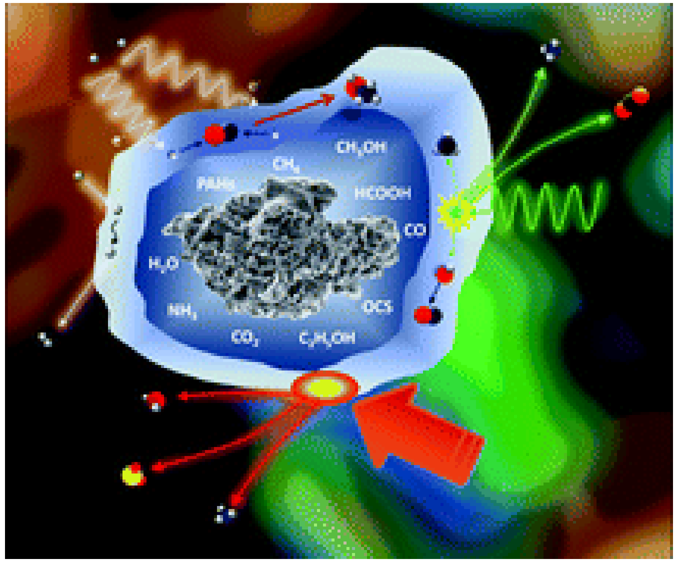
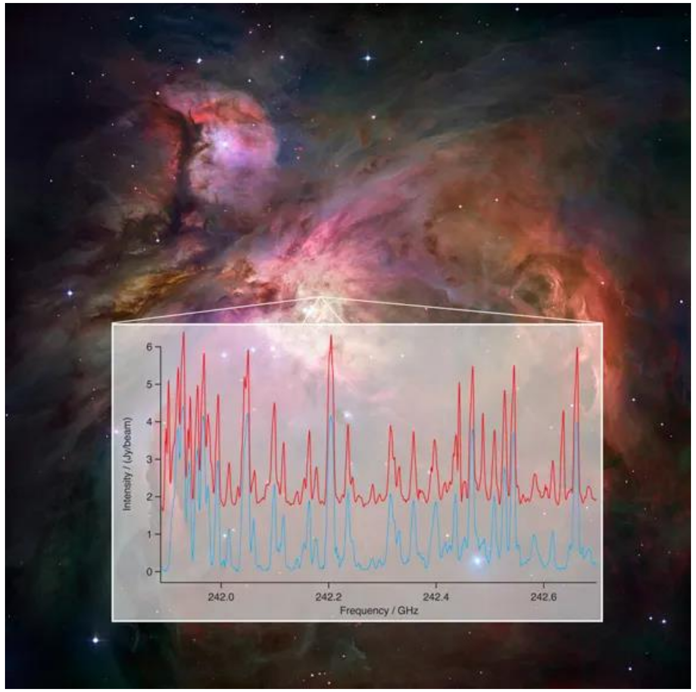
andreagokus

Astrochemistry is an interdisciplinary field! Including, chemistry, physics, astronomy, biology, etc.,

Modeling



Observations

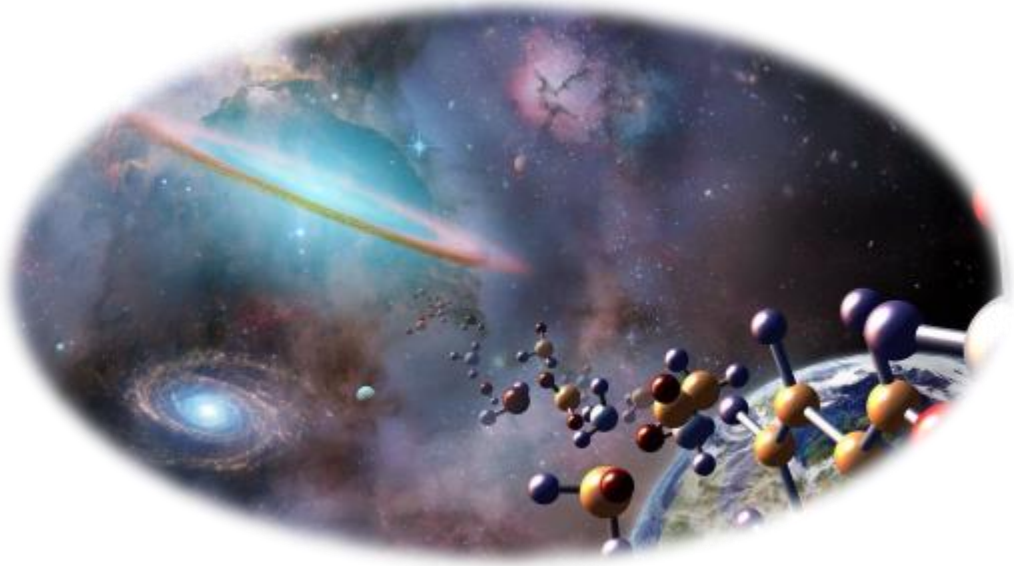


Things an astro**chemist** does

Laboratory

Astrochemistry, or "Molecular Astrophysics"

Definition: The study of the formation and destruction of molecules in the Universe, their interaction with radiation, and their feedback on physics of the environments



*I write about molecules with great diffidence, having not yet rid myself of the tradition that **atoms are physics, but molecules are chemistry**, but the new conclusions that hydrogen is abundant seems to make it likely that the above mentioned elements H, O, and N will frequency form molecules*

- *Sir A. Eddington, 1937*

What is a molecule?

- The smallest particle of a substance that retains the chemical and physical properties of that substance
- They are composed of two or more atoms, a group of like or different atoms held together by chemical forces

What molecules can you think of?

What is a molecule?

- The smallest particle of a substance that retains the chemical and physical properties of that substance
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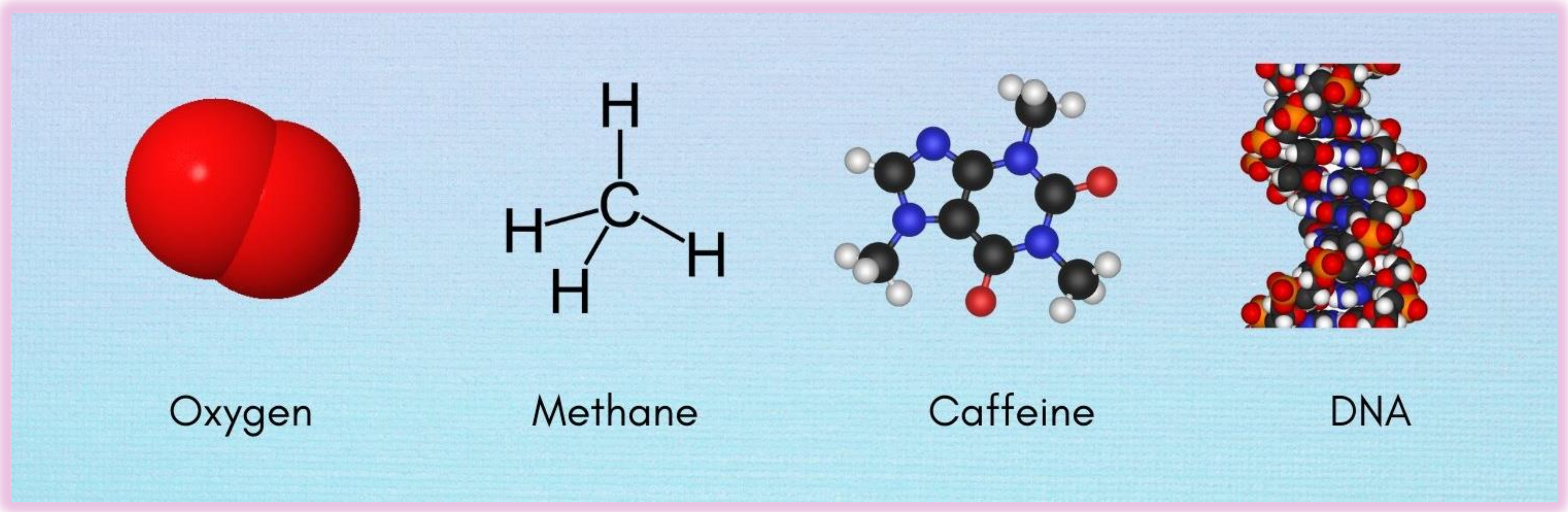
What molecules can you think of?



What is a molecule?

- The smallest particle of a substance that retains the chemical and physical properties of that substance
- They are composed of two or more atoms, a group of like or different atoms held together by chemical forces

How many molecules do you think have been detected in space?

A Molecular Universe!

2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	7 Atoms
CH	NH	H_2O	MgCN	NH_3	SiC_3	HC_3N	C_4H^-	CH_3OH	CH_3CHO
CN	SiN	HCO^+	H_3^+	H_2CO	CH_3	HCOOH	CNCHO	CH_3CN	CH_3CCH
CH^+	SO^+	HCN	SiCN	HNCO	C_3N^-	CH_2NH	HNCNH	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	AlNC	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	SiNC	C_2H_2	HCNO	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	HOCN	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	HNCS	HSCN	SiH_4	$NCCNH^+$	CH_3NC	c-C_2H_4O
CS	PO	C_2H	AlOH	$HOCO^+$	HOOH	c-C_3H_2	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	l-C_3H^+	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	l-C_3H	HMgNC	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	HCCO	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	FeCN	H_3O^+	CNCN	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	HONO	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	c-C_3H	MgCCH	HCCNC	C_4S	HC_4N	HC_3HNH
NaCl	SH	C_2S	CCN	HC_2N	HCCS	HNCCC	CHOSH	c-H_2C_3O	c-C_3HCCH
AlCl	TiO	C_3	SiCSi	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					HNCHCN	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	MgNC	NCO					MgC_4H	
CP		NH_2	CaNC					CH_3CO^+	
		NaCN	NCS					H_2CCCS	
		N_2O						CH_2CCH	

8 Atoms	9 Atoms	10 Atoms	11 Atoms	12 Atoms	13 Atoms	PAHs	Fullerenes
$HCOOCH_3$	CH_3OCH_3	CH_3COCH_3	HC_9N	C_6H_6	C_6H_5CN	1-$C_{10}H_7CN$	C_{60}
CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	n-C_3H_7CN	$HC_{11}N$	2-$C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	1-C_5H_5CN			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	2-C_5H_5CN			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_2CHCH_3						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
$HCCCH_2CN$	HCCCHCHCN						
CH_2CHCCH	H_2CCHC_3N						

>300 Molecules

McGuire 2022; https://arxiv.org/pdf/2109.13848

A Molecular Universe!

2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	7 Atoms
CH	NH	H_2O	MgCN	NH_3	SiC_3	HC_3N	C_4H^-	CH_3OH	CH_3CHO
CN	SiN	HCO^+	H_3^+	H_2CO	CH_3	HCOOH	CNCHO	CH_3CN	CH_3CCH
CH^+	SO^+	HCN	SiCN	HNCO	C_3N^-	CH_2NH	HNCNH	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	AlNC	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	SiNC	C_2H_2	HCNO	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	HOCN	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	HNCS	HSCN	SiH_4	$NCCNH^+$	CH_3NC	c-C_2H_4O
CS	PO	C_2H	AlOH	$HOCO^+$	HOOH	c-C_3H_2	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	l-C_3H^+	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	l-C_3H	HMgNC	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	HCCO	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	FeCN	H_3O^+	CNCN	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	HONO	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	c-C_3H	MgCCH	HCCNC	C_4S	HC_4N	HC_3HNH
NaCl	SH	C_2S	CCN	HC_2N	HCCS	HNCCC	CHOSH	c-H_2C_3O	c-C_3HCCH
AlCl	TiO	C_3	SiCSi	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					HNCHCN	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	MgNC	NCO					MgC_4H	
CP		NH_2	CaNC					CH_3CO^+	
		NaCN	NCS					H_2CCCS	
		N_2O						CH_2CCH	

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CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	n-C_3H_7CN	$HC_{11}N$	2-$C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	1-C_5H_5CN			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	2-C_5H_5CN			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_3CHCH_2						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
$HCCCH_2CN$	HCCCHCHCN						
CH_2CHCCH	H_2CCHC_3N						

>300 Molecules

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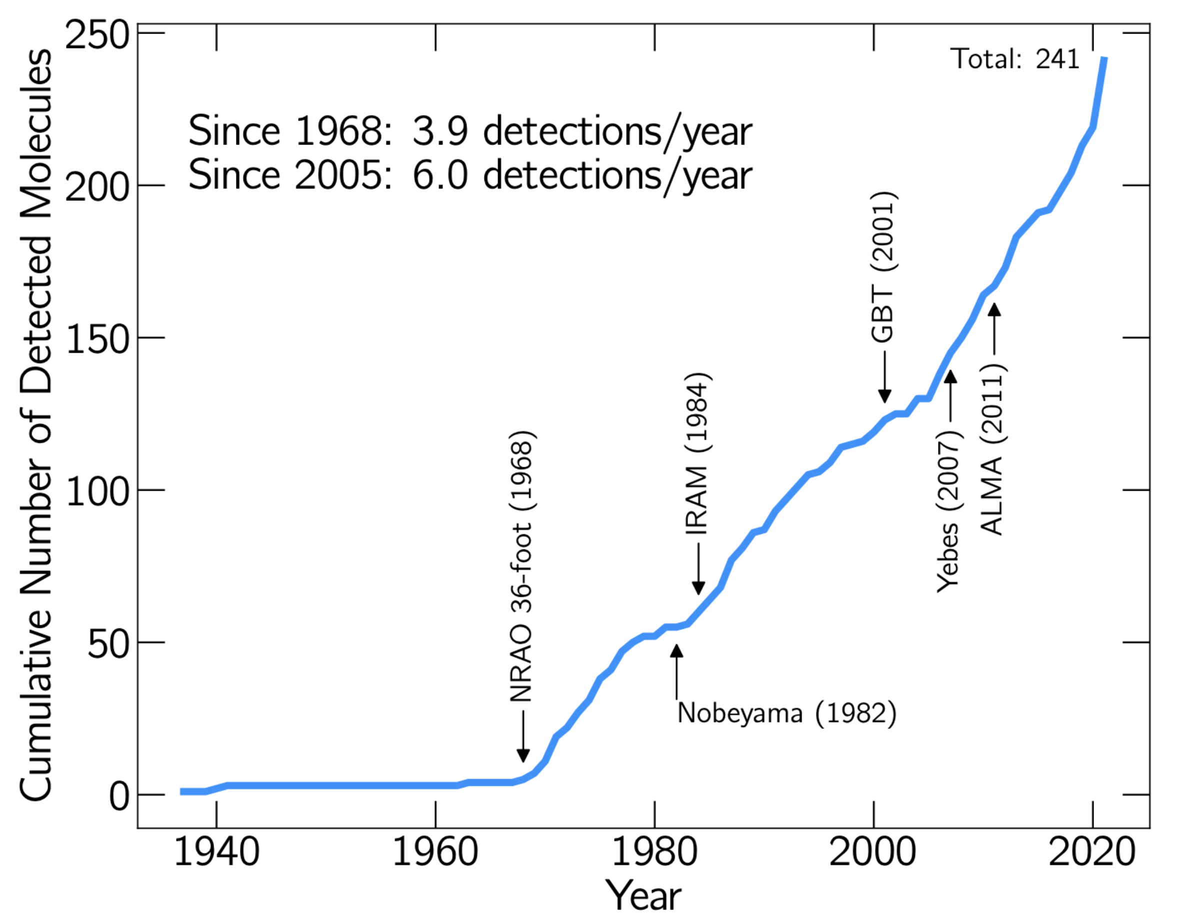

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CH^+	SO^+	HCN	SiCN	HNCO	C_3N^-	CH_2NH	HNCNH	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	AlNC	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	SiNC	C_2H_2	HCNO	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	HOCN	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	HNCS	HSCN	SiH_4	$NCCNH^+$	CH_3NC	c-C_2H_4O
CS	PO	C_2H	AlOH	$HOCO^+$	HOOH	c-C_3H_2	CH_3Cl	HC_2CHO	CH_2CHOH
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NS	CN^-	HNO	KCN	$HCNH^+$	HCCO	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	FeCN	H_3O^+	CNCN	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	HONO	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	c-C_3H	MgCCH	HCCNC	C_4S	HC_4N	HC_3HNH
NaCl	SH	C_2S	CCN	HC_2N	HCCS	HNCCC	CHOSH	c-H_2C_3O	c-C_3HCCH
AlCl	TiO	C_3	SiCSi	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					HNCHCN	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	MgNC	NCO					MgC_4H	
CP		NH_2	CaNC					CH_3CO^+	
		NaCN	NCS					H_2CCCS	
		N_2O						CH_2CCH	

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CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	n-C_3H_7CN	$HC_{11}N$	2-$C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	1-C_5H_5CN			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	2-C_5H_5CN			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_2CHCH_3						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
$HCCCH_2CN$	HCCCHCHCN						
CH_2CHCCH	H_2CCHC_3N						

>300 Molecules

McGuire 2022; https://arxiv.org/pdf/2109.13848

# of molecule discoveries per observatory

Facility	#	Facility	#
IRAM 30-m	64	SMA	2
NRAO 36-ft	33	SEST	2
GBT 100-m	28	SOFIA	2
NRAO/ARO 12-m	27	Hat Creek 20-ft	2
Yebes 40-m	19	IRTF	2
Nobeyama 45-m	15	PdBI	2
NRAO 140-ft	13	OVRO	2
Bell 7-m	8	MWO 4.9-m	2
ALMA	8	Hubble	1
SMT	7	IRAS	1
Herschel	7	BIMA	1
Parkes	5	NRL 85-ft	1
FCRAO 14-m	5	ATCA	1
ISO	5	Mitaka 6-m	1
APEX	4	McMath Solar Telescope	1
Onsala 20-m	4	UKIRT	1
KPNO 4-m	4	Odin	1
Effelsberg 100-m	4	FUSE	1
Algonquin 46-m	3	KAO	1
Mt. Wilson	3	Mt. Hopkins 60-in	1
Spitzer	3	Aerobee-150 Rocket	1
Haystack	3	Millstone Hill 84-ft	1
CSO	2	Goldstone	1

A Molecular Universe!

2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	7 Atoms
CH	NH	H_2O	MgCN	NH_3	SiC_3	HC_3N	C_4H^-	CH_3OH	CH_3CHO
CN	SiN	HCO^+	H_3^+	H_2CO	CH_3	HCOOH	CNCHO	CH_3CN	CH_3CCH
CH^+	SO^+	HCN	SiCN	HNCO	C_3N^-	CH_2NH	HNCNH	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	AlNC	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	SiNC	C_2H_2	HCNO	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	HOCN	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	HNCS	HSCN	SiH_4	$NCCNH^+$	CH_3NC	$c\text{-}C_2H_4O$
CS	PO	C_2H	AlOH	$HOCO^+$	HOOH	$c\text{-}C_3H_2$	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	$l\text{-}C_3H^+$	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	$l\text{-}C_3H$	HMgNC	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	HCCO	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	FeCN	H_3O^+	CNCN	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	HONO	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	$c\text{-}C_3H$	MgCCH	HCCNC	C_4S	HC_4N	HC_3HNH
NaCl	SH	C_2S	CCN	HC_2N	HCCS	HNCCC	CHOSH	$c\text{-}H_2C_3O$	$c\text{-}C_3HCCH$
AlCl	TiO	C_3	SiCSi	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					HNCHCN	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	MgNC	NCO					MgC_4H	
CP		NH_2	CaNC					CH_3CO^+	
		NaCN	NCS					H_2CCCS	
		N_2O						CH_2CCH	

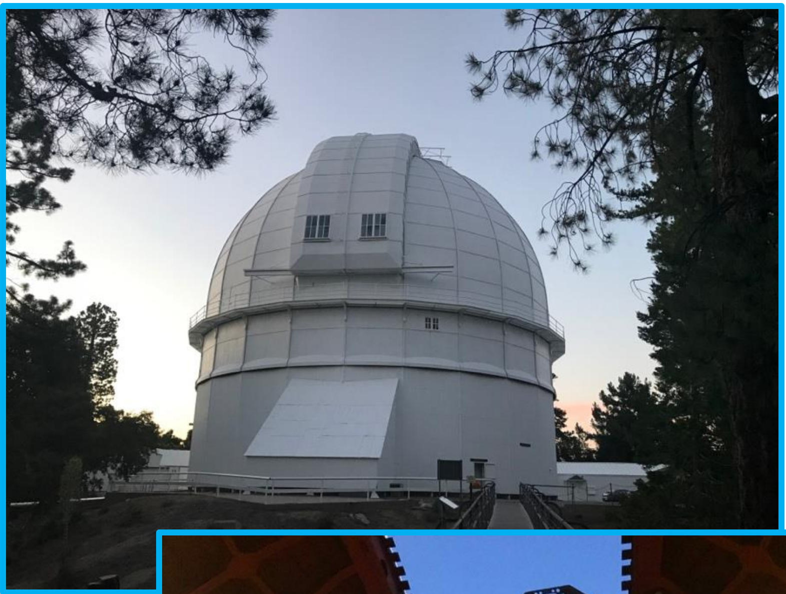
8 Atoms	9 Atoms	10 Atoms	11 Atoms	12 Atoms	13 Atoms	PAHs	Fullerenes
$HCOOCH_3$	CH_3OCH_3	CH_3COCH_3	HC_9N	C_6H_6	C_6H_5CN	$1\text{-}C_{10}H_7CN$	C_{60}
CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	$n\text{-}C_3H_7CN$	$HC_{11}N$	$2\text{-}C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	$i\text{-}C_3H_7CN$		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	$1\text{-}C_5H_5CN$			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	$2\text{-}C_5H_5CN$			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_2CHCH_3						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
$HCCCH_2CN$	$HCCCHCHCN$						
CH_2CHCCH	H_2CCHC_3N						

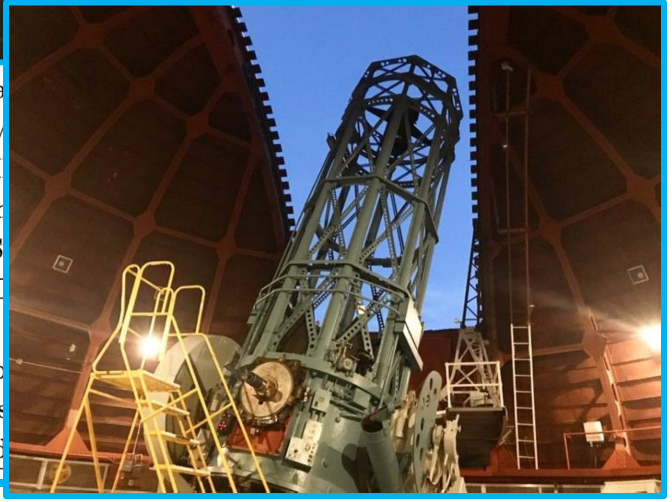
>300 Molecules

McGuire 2022; https://arxiv.org/pdf/2109.13848

of molecule discoveries per observatory

Facility		
IRAM 30-m		
NRAO 36-ft		
GBT 100-m		
NRAO/ARO 12-m		
Yebes 40-m		
Nobeyama 45-m		
NRAO 140-ft		
Bell 7-m		
ALMA		
SMT		
Herschel		
Parkes		
FCRAO 14-m		
ISO	5	Mita
APEX	4	McM
Onsala 20-m	4	UKI
KPNO 4-m	4	Odin
Effelsberg 100-m	4	FUS
Algonquin 46-m	3	KAO
Mt. Wilson	3	Mt.
Spitzer	3	Aero
Haystack	3	Mills
CSO	2	Gold





The first molecules detected in the ISM were CH, CN and CH^+ during the mid- twentieth century via an **optical** absorption spectroscopy (McKellar, 1940)

A Molecular Universe!

2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	7 Atoms
CH	NH	H_2O	MgCN	NH_3	SiC_3	HC_3N	C_4H^-	CH_3OH	CH_3CHO
CN	SiN	HCO^+	H_3^+	H_2CO	CH_3	HCOOH	CNCHO	CH_3CN	CH_3CCH
CH^+	SO^+	HCN	SiCN	HNCO	C_3N^-	CH_2NH	HNCNH	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	AlNC	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	SiNC	C_2H_2	HCNO	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	HOCN	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	HNCS	HSCN	SiH_4	$NCCNH^+$	CH_3NC	c-C_2H_4O
CS	PO	C_2H	AlOH	$HOCO^+$	HOOH	c-C_3H_2	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	l-C_3H^+	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	l-C_3H	HMgNC	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	HCCO	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	FeCN	H_3O^+	CNCN	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	HONO	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	c-C_3H	MgCCH	HCCNC	C_4S	HC_4N	HC_3HNH
NaCl	SH	C_2S	CCN	HC_2N	HCCS	HNCCC	CHOSH	c-H_2C_3O	c-C_3HCCH
AlCl	TiO	C_3	SiCSi	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					HNCHCN	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	MgNC	NCO					MgC_4H	
CP		NH_2	CaNC					CH_3CO^+	
		NaCN	NCS					H_2CCCS	
		N_2O						CH_2CCH	

8 Atoms	9 Atoms	10 Atoms	11 Atoms	12 Atoms	13 Atoms	PAHs	Fullerenes
$HCOOCH_3$	CH_3OCH_3	CH_3COCH_3	HC_9N	C_6H_6	C_6H_5CN	1-$C_{10}H_7CN$	C_{60}
CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	n-C_3H_7CN	$HC_{11}N$	2-$C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	1-C_5H_5CN			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	2-C_5H_5CN			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_2CHCH_3						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
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CH_2CHCCH	H_2CCHC_3N						

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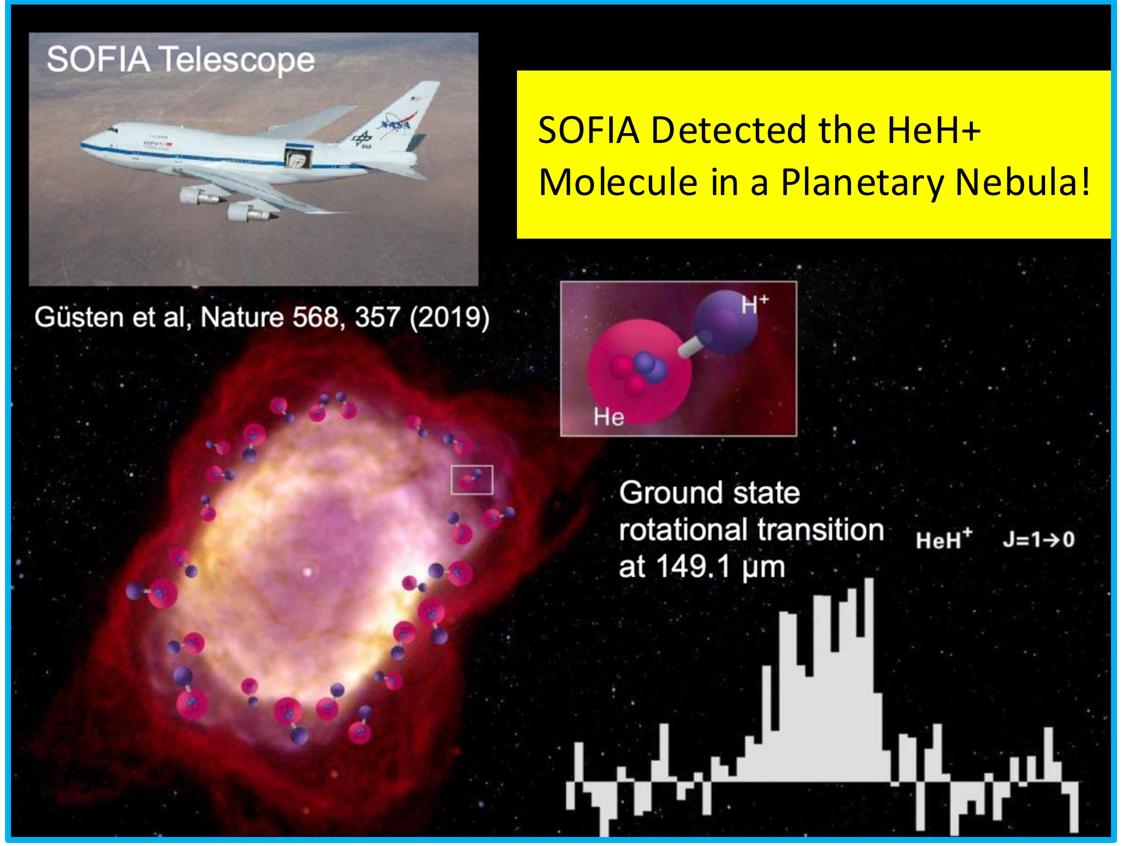

A Molecular Universe!

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CN	SiN	HCO^+	H_3^+	H_2CO	CH_3	HCOOH	CNCHO	CH_3CN	CH_3CCH
CH^+	SO^+	HCN	SiCN	HNCO	C_3N^-	CH_2NH	HNCNH	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	AlNC	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	SiNC	C_2H_2	HCNO	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	HOCN	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	HNCS	HSCN	SiH_4	$NCCNH^+$	CH_3NC	$c\text{-}C_2H_4O$
CS	PO	C_2H	AlOH	$HOCO^+$	HOOH	$c\text{-}C_3H_2$	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	$l\text{-}C_3H^+$	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	$l\text{-}C_3H$	HMgNC	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	HCCO	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	FeCN	H_3O^+	CNCN	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	HONO	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	$c\text{-}C_3H$	MgCCH	HCCNC	C_4S	HC_4N	HC_3HNH
NaCl	SH	C_2S	CCN	HC_2N	HCCS	HNCCC	CHOSH	$c\text{-}H_2C_3O$	$c\text{-}C_3HCCH$
AlCl	TiO	C_3	SiCSi	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					HNCHCN	
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CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	$n\text{-}C_3H_7CN$	$HC_{11}N$	$2\text{-}C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	$i\text{-}C_3H_7CN$		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	$1\text{-}C_5H_5CN$			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	$2\text{-}C_5H_5CN$			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_2CHCH_3						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
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CH_2CHCCH	H_2CCHC_3N						

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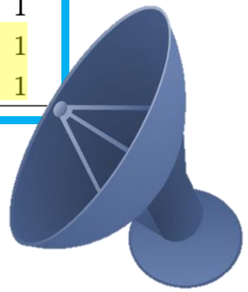
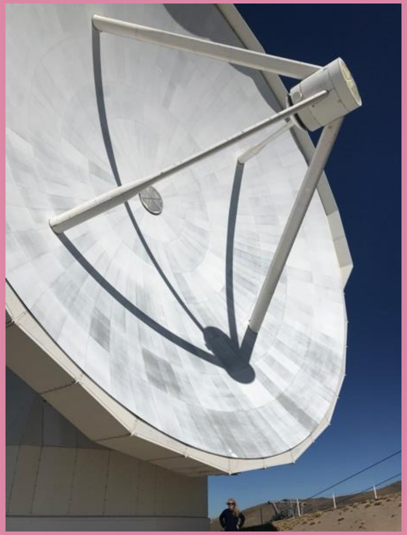
Yebes 40-m	19	IRTF	2
Nobeyama 45-m	15	PdBI	2
NRAO 140-ft	13	OVRO	2
Bell 7-m	8	MWO 4.9-m	2
ALMA	8	Hubble	1
SMT	7	IRAS	1
Herschel	7	BIMA	1
Parkes	5	NRL 85-ft	1
FCRAO 14-m	5	ATCA	1
ISO	5	Mitaka 6-m	1
APEX	4	McMath Solar Telescope	1
Onsala 20-m	4	UKIRT	1
KPNO 4-m	4	Odin	1
Effelsberg 100-m	4	FUSE	1
Algonquin 46-m	3	KAO	1
Mt. Wilson	3	Mt. Hopkins 60-in	1
Spitzer	3	Aerobee-150 Rocket	1
Haystack	3	Millstone Hill 84-ft	1
CSO	2	Goldstone	1

> 90% Identified by Radio Astronomy!



12m Radio Telescope, Kitt Peak, AZ

Control Room @ SMT, Mt. Graham, AZ



IRAM 30m Radio Telescope, Granada, Spain

Green Bank Radio Telescope, 100m, in West Virginia

of molecule discoveries per observatory

Facility	#	Facility	#
IRAM 30-m	64	SMA	2
NRAO 36-ft	33	SEST	2
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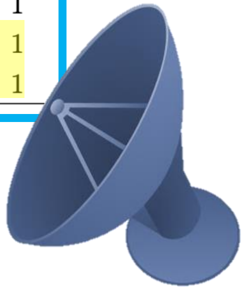
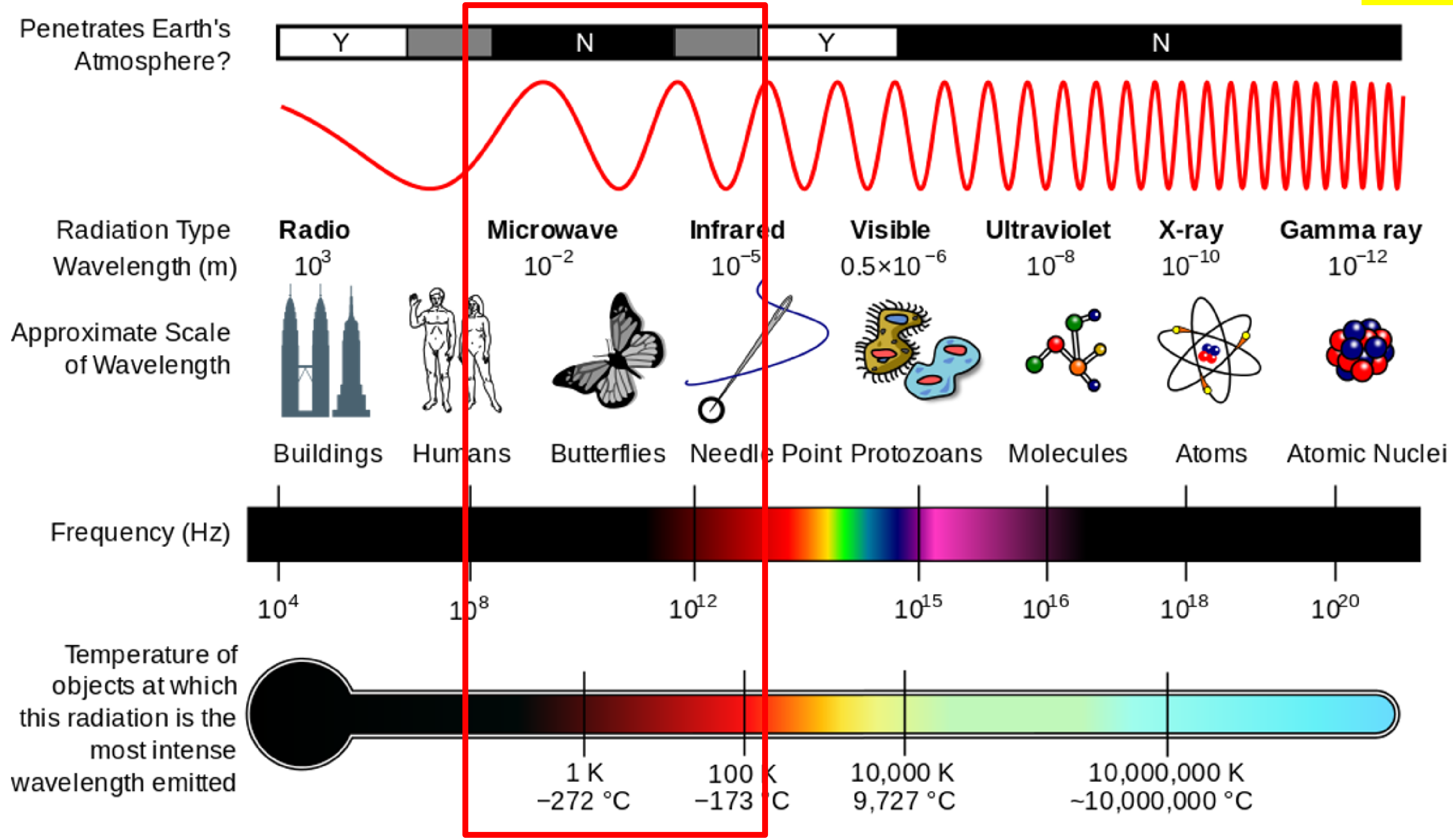


The Electromagnetic Spectrum

$E = \frac{hc}{\lambda} = h\nu$

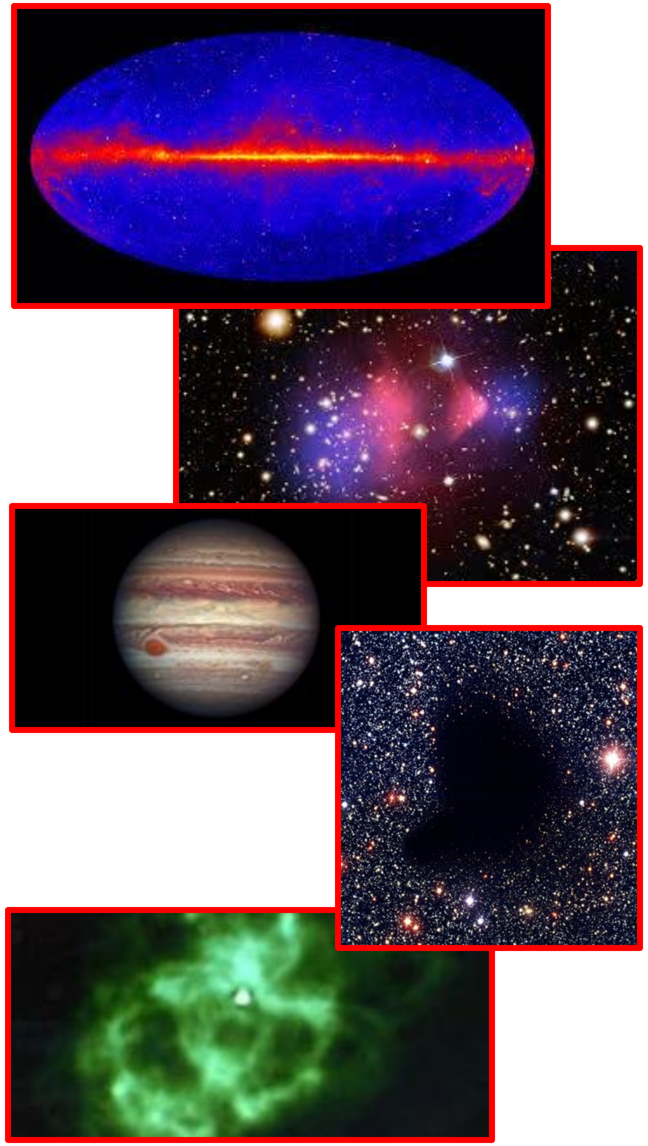


Submillimeter and millimeter (or Terahertz) radio astronomy ~ cm to a few mm wavelengths (10^{12} Hz)

Emission of E&M Radiation Deeply Connected to the Temperature of the Source!

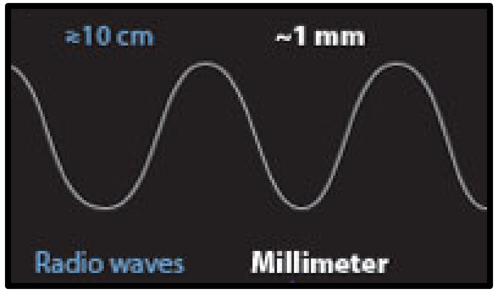
Types of Radiation	Radiated by Objects at this Temperature	Typical Sources
Gamma-rays	> 10^8 Kelvin (K)	accretion disks around black holes
X-rays	10^6-10^8 K	Gas in clusters of galaxies; supernova remnants; stellar corona
Ultraviolet	10^4-10^6 K	Supernova remnants; very hot stars
Visible	10^3-10^4 K	Planets, stars, some satellites
Infrared	10-10^3 K	**cool clouds of dust and gas**; planets
Microwave	1-10 K	**Cool clouds of gas**; newly formed stars; cosmic microwave background
Radio	< 1 K	Radio emission produced by electrons moving in magnetic fields

*1 K = - 457.87 °F, 10^6 K ~ 10^6 °F



Submillimeter and Millimeter Radio Telescopes Probe Cool Molecular Gas!

Most Interstellar gas is cold! Radio telescopes let us see objects we can't see in visible light – such as the dust and gas inside dense molecular clouds that will form stars like our Sun!



This is the type of object I study! →

Starless Core B68

Visible light image

Starless Core: Birthplace of low-mass stars ($M \leq$ a few $M_{\odot}$)
Dense (10^4 - 10^5 cm^{-3}) & cold ($\leq$ 10K)

10K = - 441.67° F!
Low temp. at poles of Mars −243 °F

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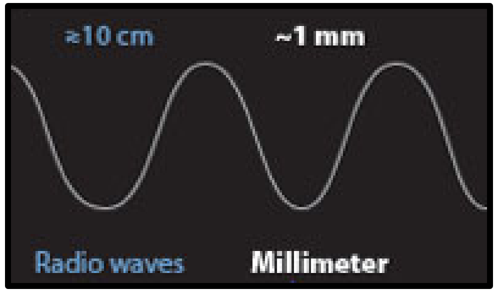

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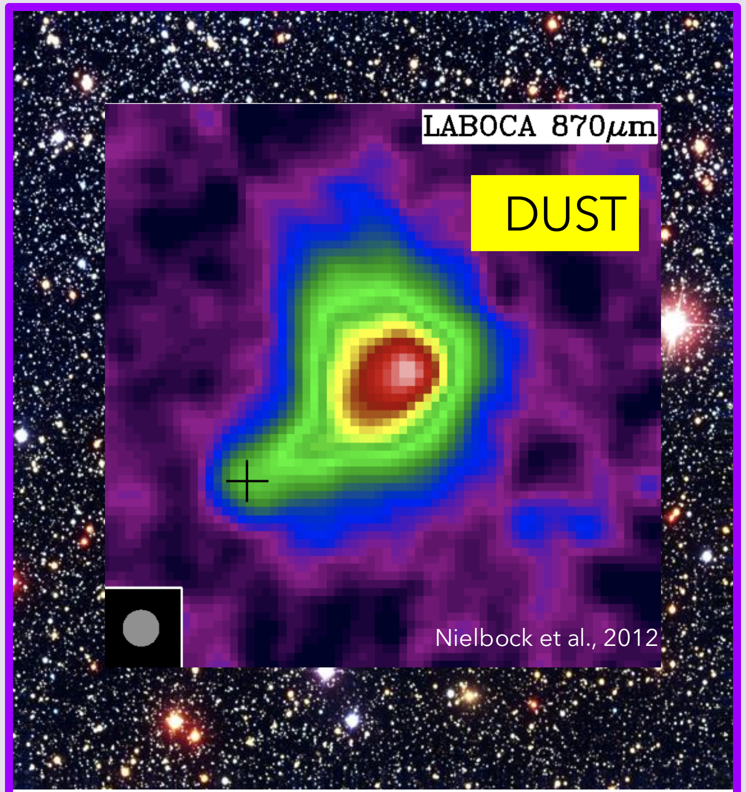
Starless Core B68

Radio light image



Starless Core: Birthplace of low-mass stars (M ≤ a few $M_\odot$)
Dense (10^4 - 10^5 cm^{-3}) & cold (≤ 10K)

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Low temp. at poles of Mars –243 °F

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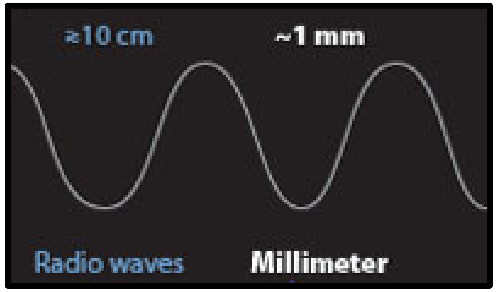

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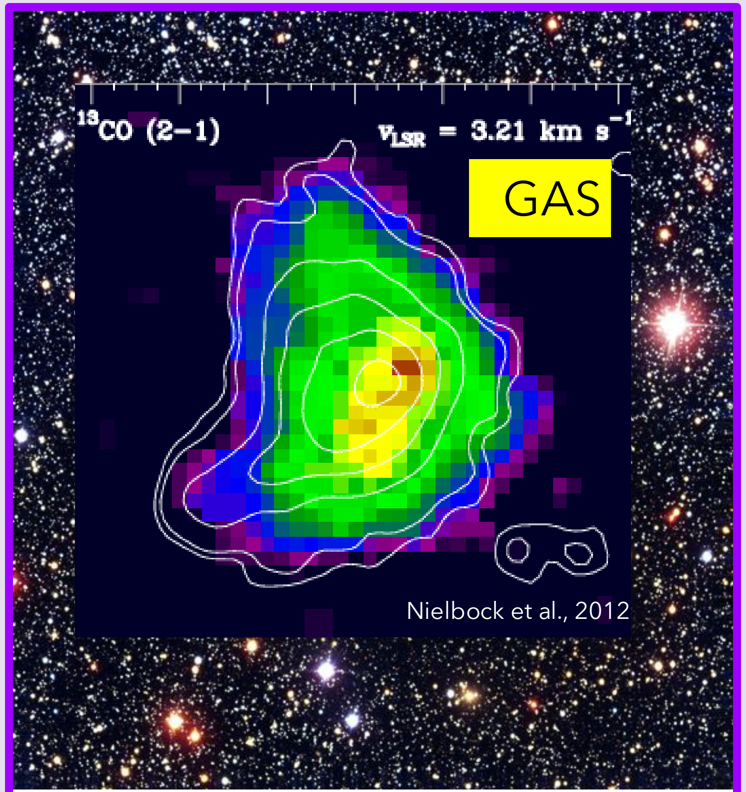

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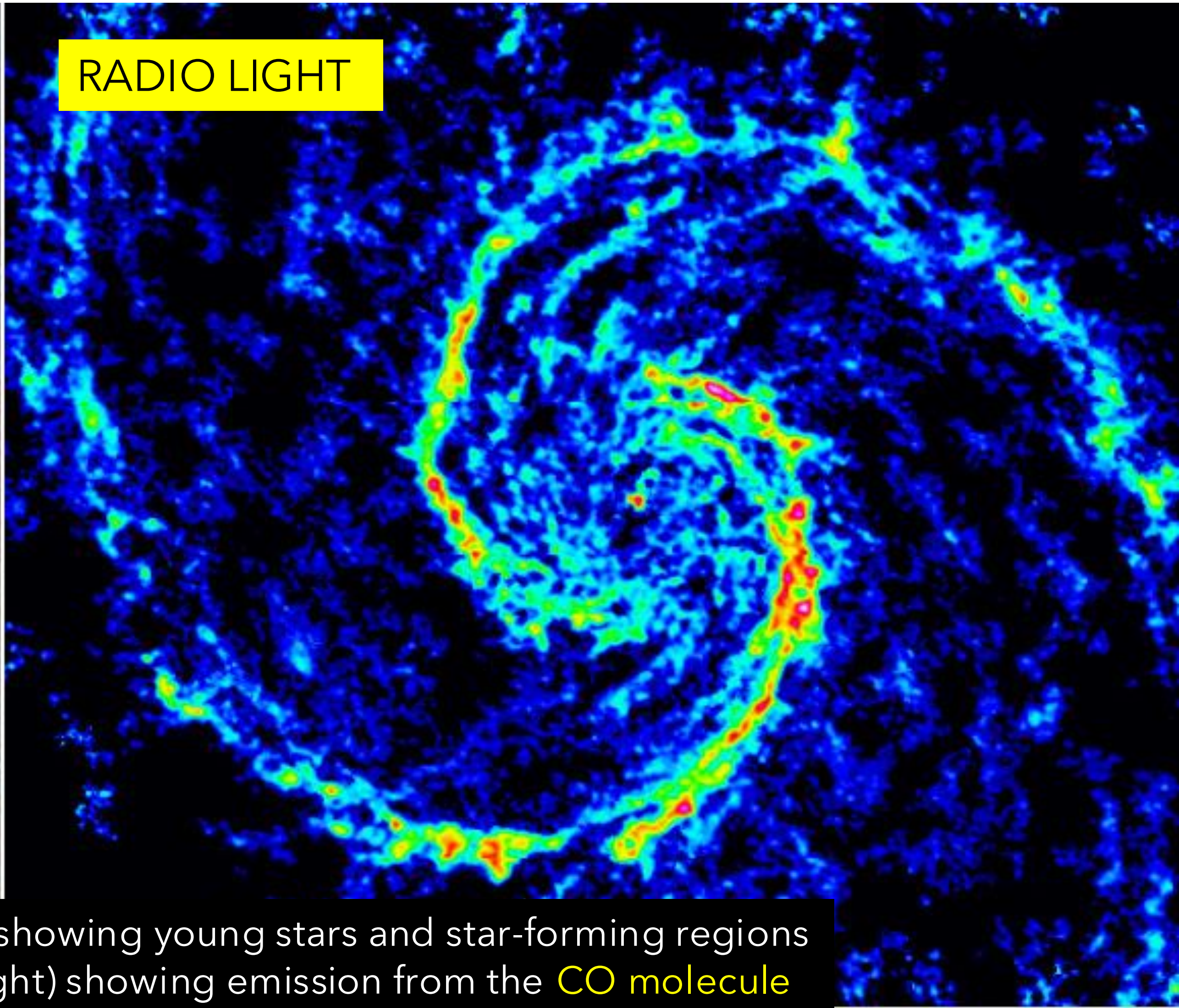

The Whirlpool galaxy imaged in visible light (left) showing young stars and star-forming regions delineating the spiral arms and a radio image (right) showing emission from the CO molecule tracing the molecular clouds in which stars form (Credit: NASA / PAWS)

Importance of molecules in space!

Probes of a variety of **physical** (temperature, density, ionization, gas kinematics) and **environmental** (heating and cooling gas) **conditions**!

Diffuse Clouds:
- densities ~ 1- 10 cm^{-3}
- T ~ 100 K
- Starlight (UV radiation) can penetrate

Dense Clouds:
- densities ~ 10^3 - 10^6 cm^{-3}
- T ~ 10 - 100 K
- Starlight cannot penetrate

"Hot Cores":
- densities ~ 10^3 - 10^6 cm^{-3}
- T ~ 10 - 300 K
- An embedded forming star

Importance of molecules in space!

Probes of a variety of **chemical conditions** (chemical processes, "Age" indicators, prebiotic chemistry (origin of life?)

2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	7 Atoms
CH	NH	H_2O	MgCN	NH_3	SiC_3	HC_3N	C_4H^-	CH_3OH	CH_3CHO
CN	SiN	HCO^+	H_3^+	H_2CO	CH_3	HCOOH	CNCHO	CH_3CN	CH_3CCH
CH^+	SO^+	HCN	SiCN	HNCO	C_3N^-	CH_2NH	HNCNH	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	AlNC	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	SiNC	C_2H_2	HCNO	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	HOCN	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	HNCS	HSCN	SiH_4	$NCCNH^+$	CH_3NC	c-C_2H_4O
CS	PO	C_2H	AlOH	$HOCO^+$	HOOH	c-C_3H_2	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	l-C_3H^+	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	l-C_3H	HMgNC	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	HCCO	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	FeCN	H_3O^+	CNCN	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	HONO	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	c-C_3H	MgCCH	HCCNC	C_4S	HC_4N	HC_3HNH
NaCl	SH	C_2S	CCN	HC_2N	HCCS	HNCCC	CHOSH	c-H_2C_3O	c-C_3HCCH
AlCl	TiO	C_3	SiCSi	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					HNCHCN	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	MgNC	NCO					MgC_4H	
CP		NH_2	CaNC					CH_3CO^+	
		NaCN	NCS					H_2CCCS	
		N_2O						CH_2CCH	

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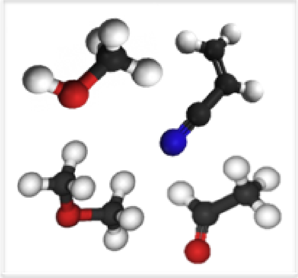
CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	n-C_3H_7CN	$HC_{11}N$	2-$C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	1-C_5H_5CN			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	2-C_5H_5CN			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_2CHCH_3						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
$HCCCH_2CN$	$HCCCHCHCN$						
CH_2CHCCH	H_2CCHC_3N						

McGuire 2022; https://arxiv.org/pdf/2109.13848

Complex **O**rganic **M**olecules

- Contains at least 6 or more atoms
- Contains at least one carbon atom



Herbst & van Dishoeck 2009

- Of interest to astrochemists and astrobiologists, COMs are the **precursor molecules of prebiotic chemistry**
- Understanding the formation of COMs in the various physical conditions throughout our universe is an active area of research!

Importance of molecules in space!

Probes of a variety of **chemical conditions** (chemical processes, "Age" indicators, prebiotic chemistry (origin of life?)

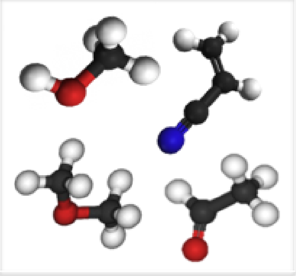
2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	7 Atoms
CH	NH	H_2O	$MgCN$	NH_3	SiC_3	HC_3N	C_4H^-	CH_3OH	CH_3CHO
CN	SiN	HCO^+	H_3^+	H_2CO	CH_3	$HCOOH$	$CNCHO$	CH_3CN	CH_3CCH
CH^+	SO^+	HCN	$SiCN$	$HNCO$	C_3N^-	CH_2NH	$HNCNH$	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	$AlNC$	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	$SiNC$	C_2H_2	$HCNO$	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	$HOCN$	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	$HNCS$	$HSCN$	SiH_4	$NCCNH^+$	CH_3NC	c-C_2H_4O
CS	PO	C_2H	$AlOH$	$HOCO^+$	$HOOH$	c-C_3H_2	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	l-C_3H^+	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	l-C_3H	$HMgNC$	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	$HCCO$	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	$FeCN$	H_3O^+	$CNCN$	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	$HONO$	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	c-C_3H	$MgCCH$	$HCCNC$	C_4S	HC_4N	HC_3HNH
$NaCl$	SH	C_2S	CCN	HC_2N	$HCCS$	$HNCCC$	$CHOSH$	c-H_2C_3O	c-C_3HCCH
$AlCl$	TiO	C_3	$SiCSi$	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					$HNCHCN$	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	$MgNC$	NCO					MgC_4H	
CP		NH_2	$CaNC$					CH_3CO^+	
		$NaCN$	NCS					H_2CCCS	
		N_2O						CH_2CCH	

8 Atoms	9 Atoms	10 Atoms	11 Atoms	12 Atoms	13 Atoms	PAHs	Fullerenes
$HCOOCH_3$	CH_3OCH_3	CH_3COCH_3	HC_9N	C_6H_6	C_6H_5CN	1-$C_{10}H_7CN$	C_{60}
CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	n-C_3H_7CN	$HC_{11}N$	2-$C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	1-C_5H_5CN			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	2-C_5H_5CN			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_2CHCH_3						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
$HCCCH_2CN$	$HCCCHCHCN$						
CH_2CHCCH	H_2CCHC_3N						

McGuire 2022; https://arxiv.org/pdf/2109.13848

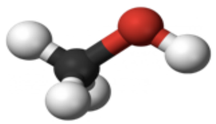
Complex Organic Molecules

- Contains at least 6 or more atoms
- Contains at least one carbon atom



Herbst & van Dishoeck 2009

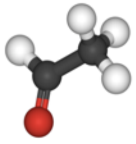
Methyl or wood alcohol, is extremely toxic!



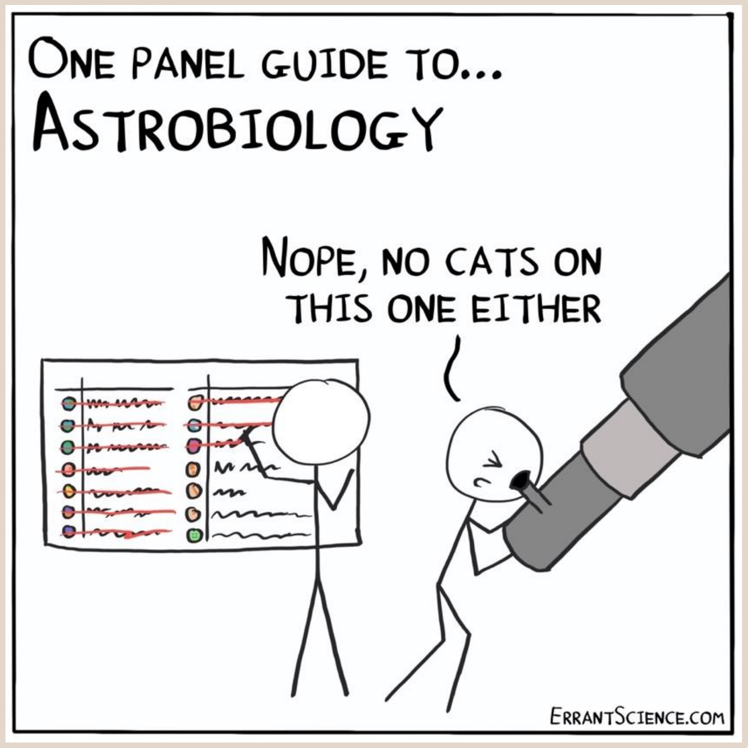
Methanol
CH_3OH

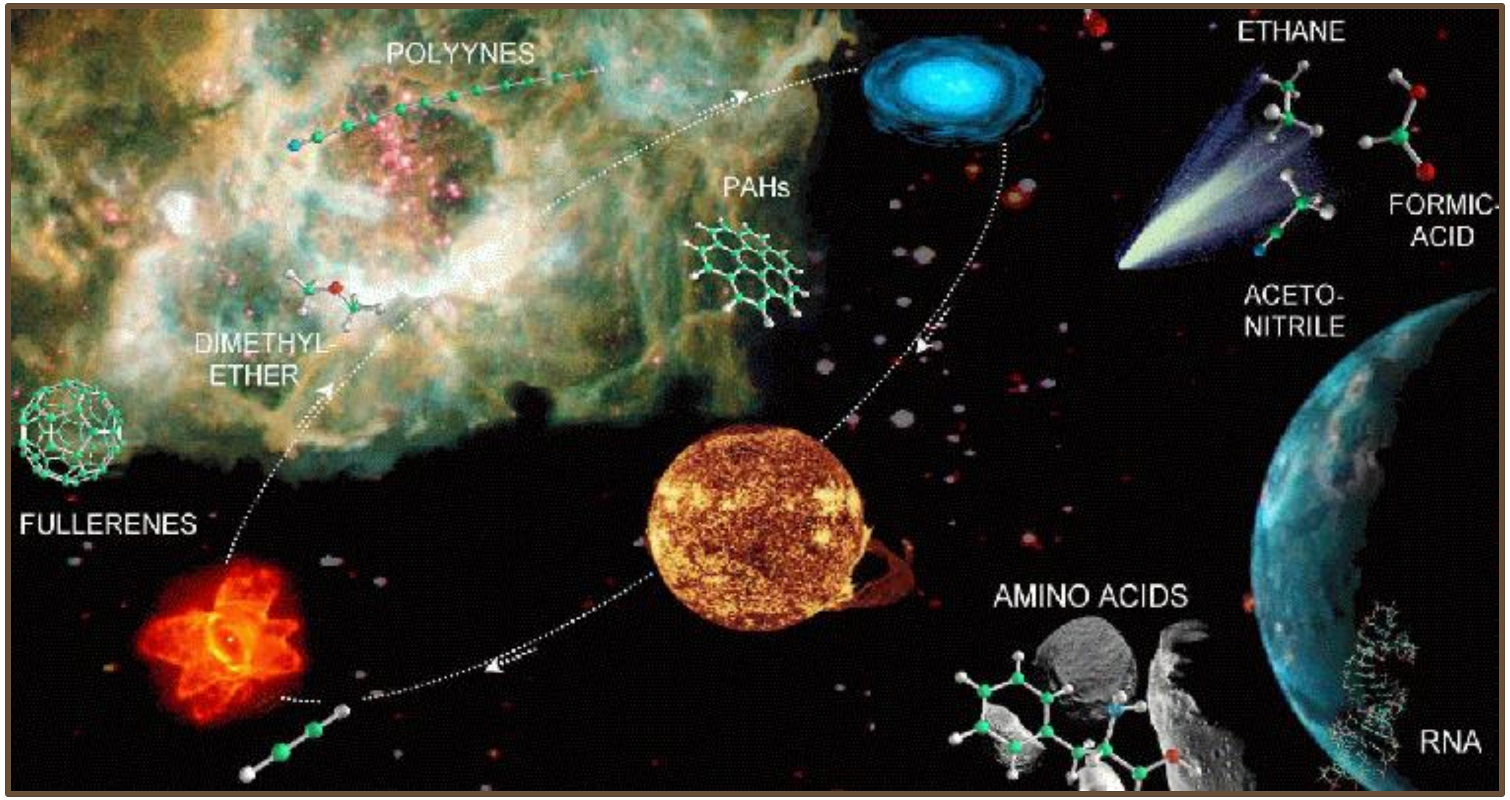
Green apple smell! Found in fermented foods, including yogurt and aged wines

Acetaldehyde
CH_3CHO



Big Questions in Astrochemistry: COMs as Prebiotic Precursors?

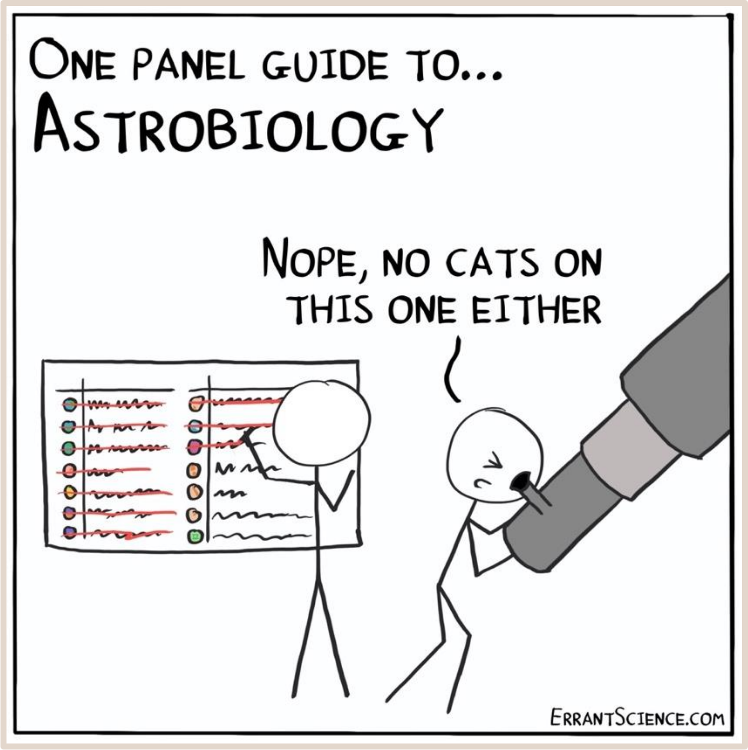




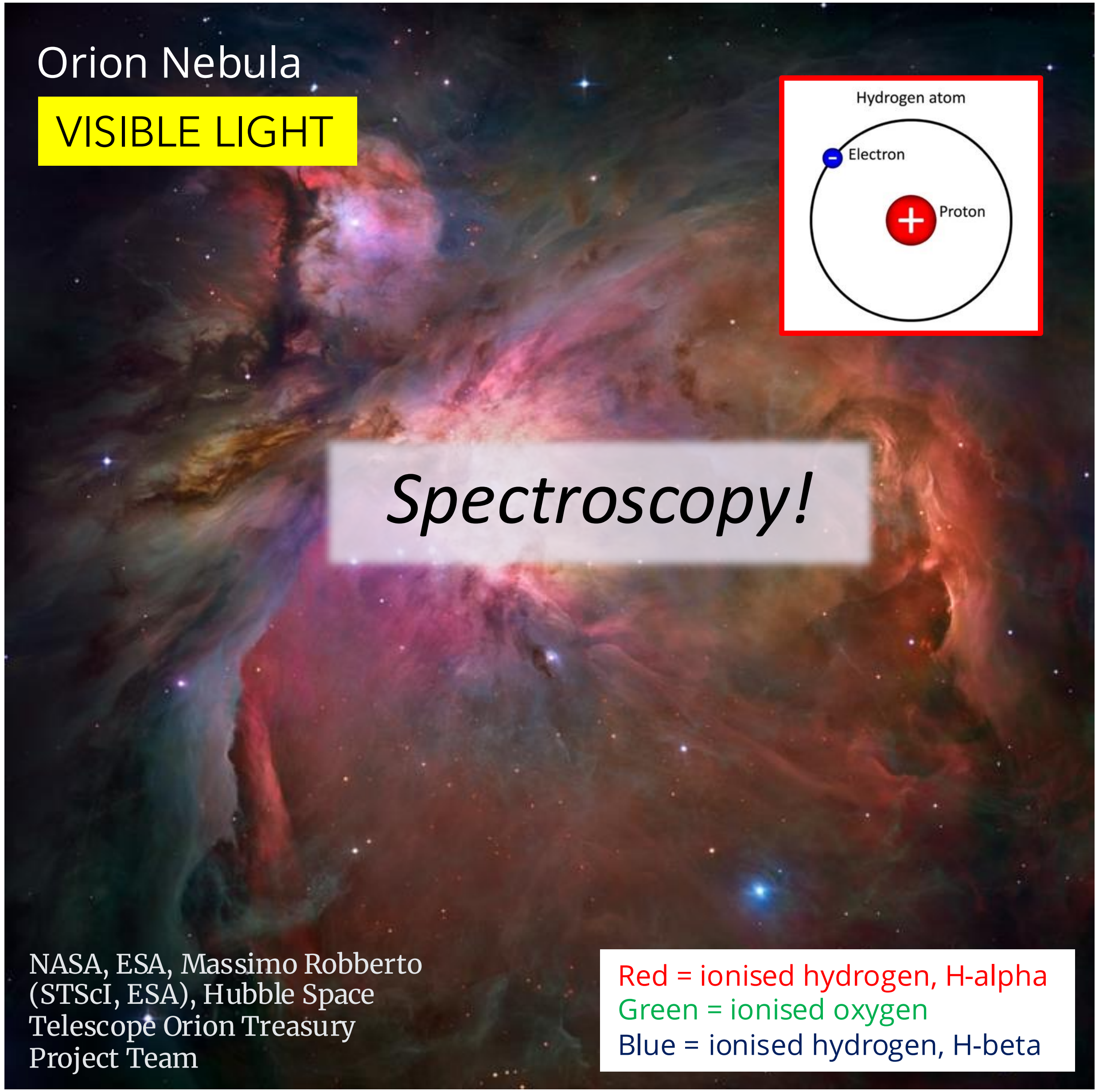
http://www.esa.int/spaceinimages/Images/2001/05/Astrobiology

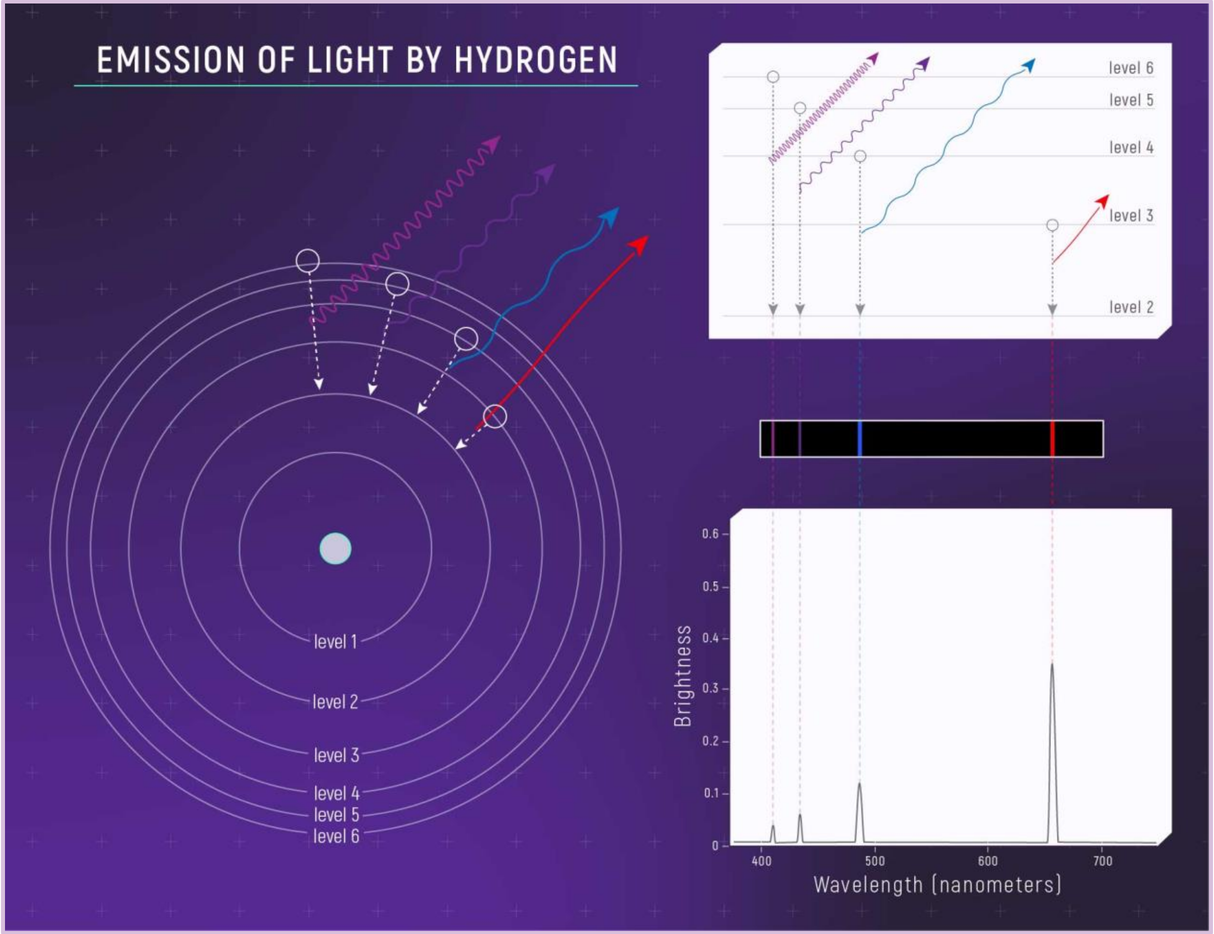
Do organic molecules synthesized in space contribute to the chemical evolution needed for the ***emergence of life on Earth***?

How do we investigate the vast chemical inventory in the universe?

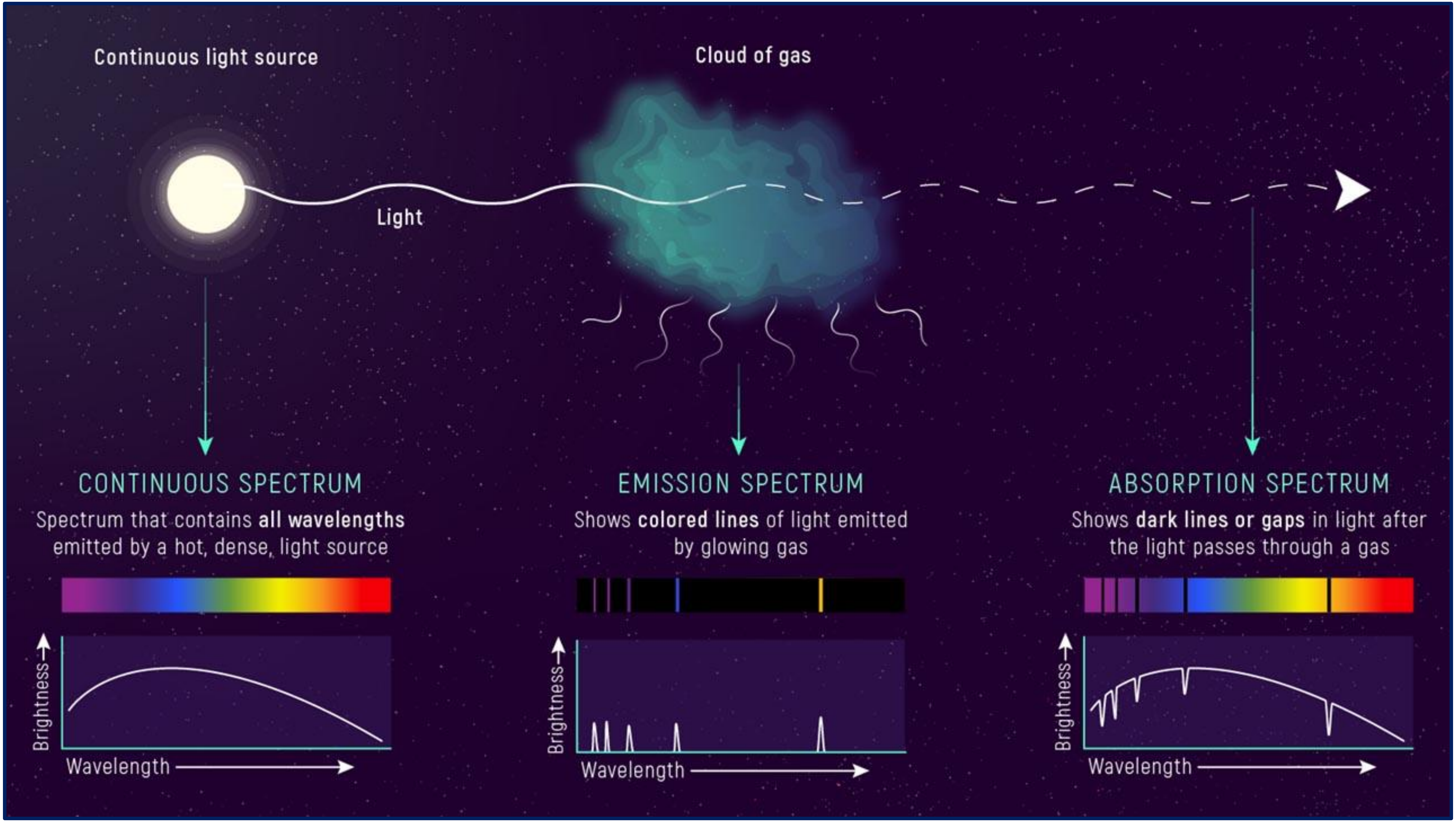


How do we investigate the vast chemical inventory in the universe?

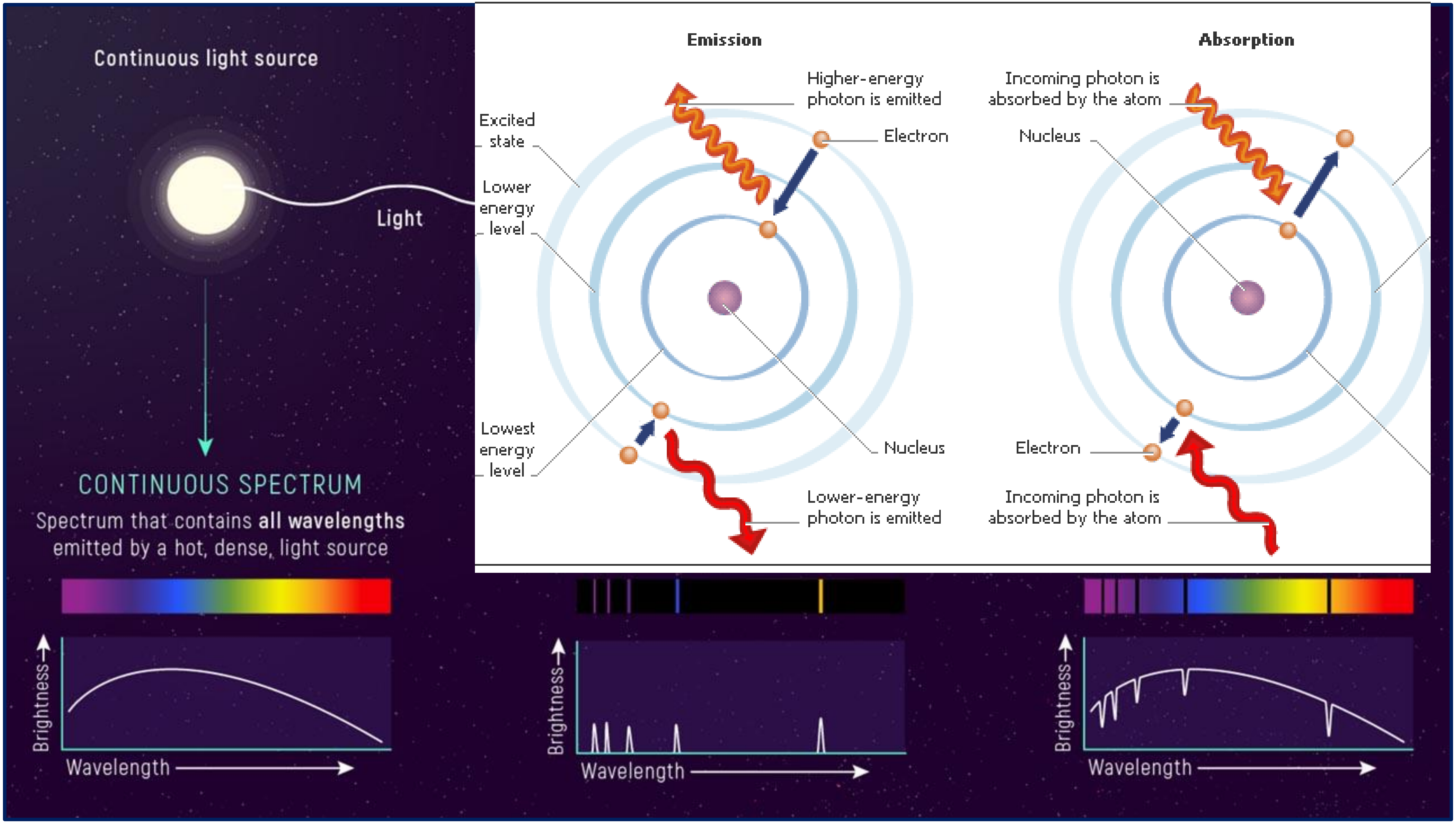




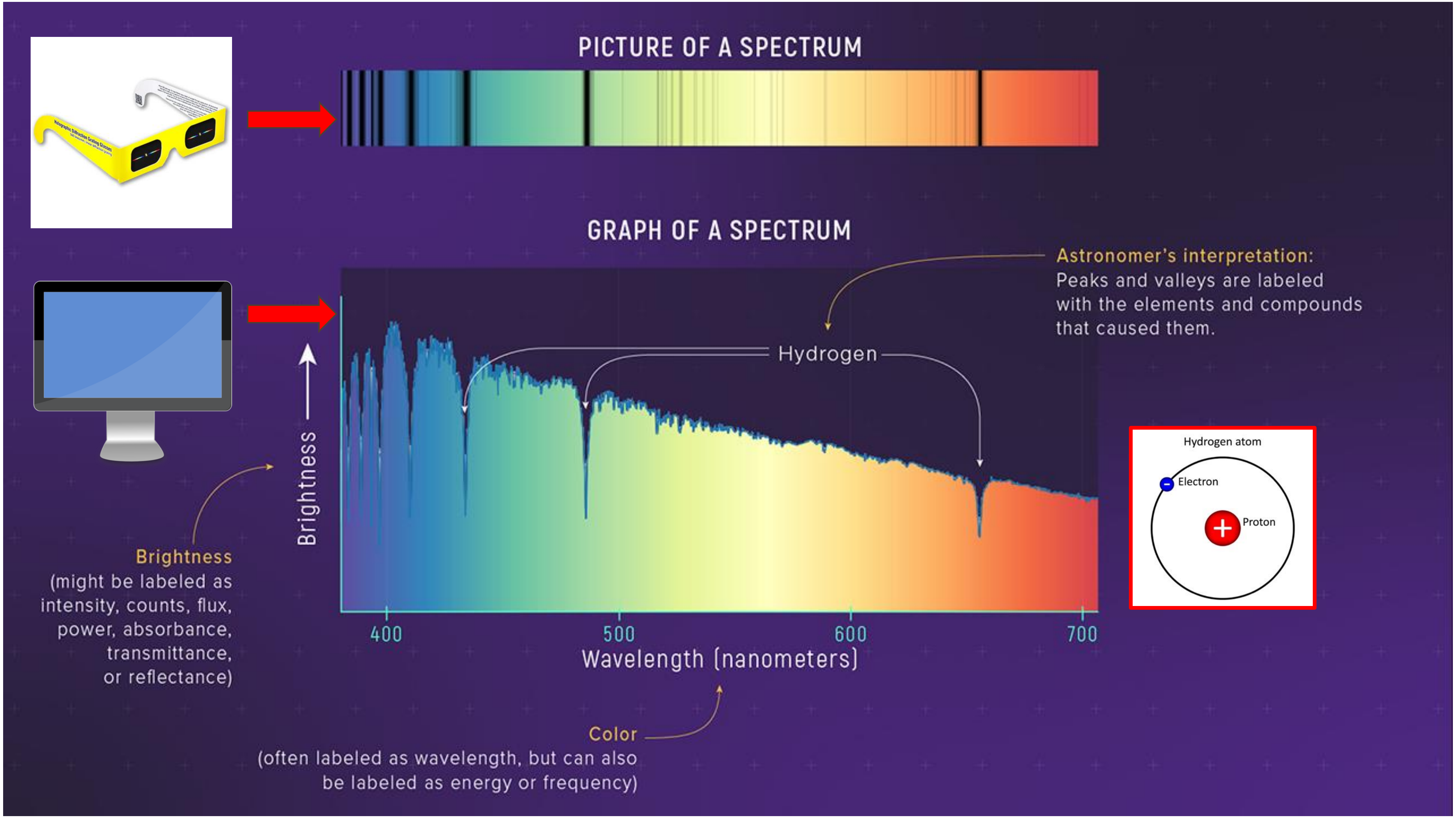
Clouds of gas will emit spectral lines at specific wavelengths corresponding to energy transitions of certain atoms and/or molecules!

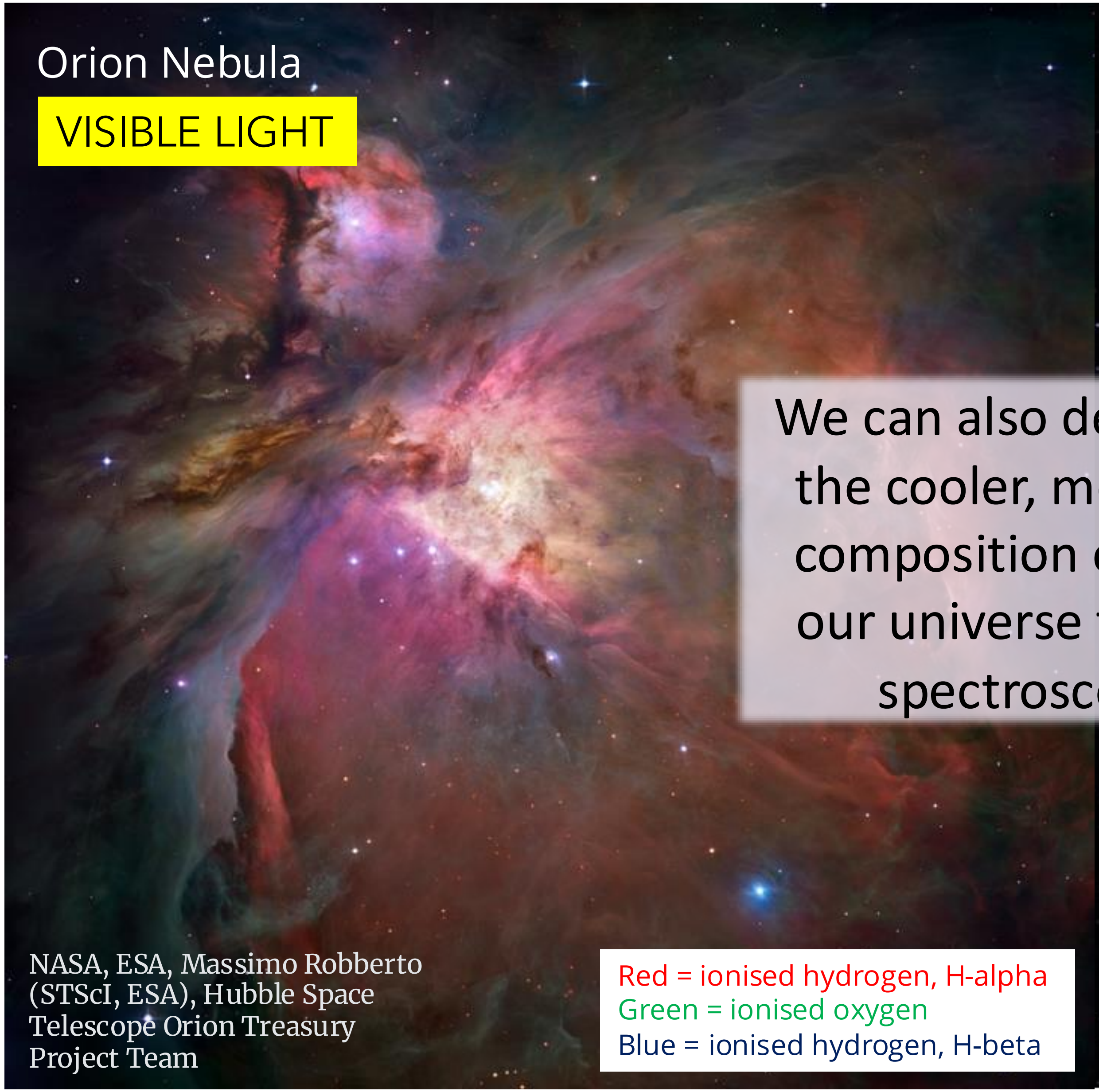


Continuous light source
Cloud of gas
Light
CONTINUOUS SPECTRUM
Spectrum that contains all wavelengths emitted by a hot, dense, light source
Brightness
Wavelength
EMISSION SPECTRUM
Shows colored lines of light emitted by glowing gas
Brightness
Wavelength
ABSORPTION SPECTRUM
Shows dark lines or gaps in light after the light passes through a gas
Brightness
Wavelength

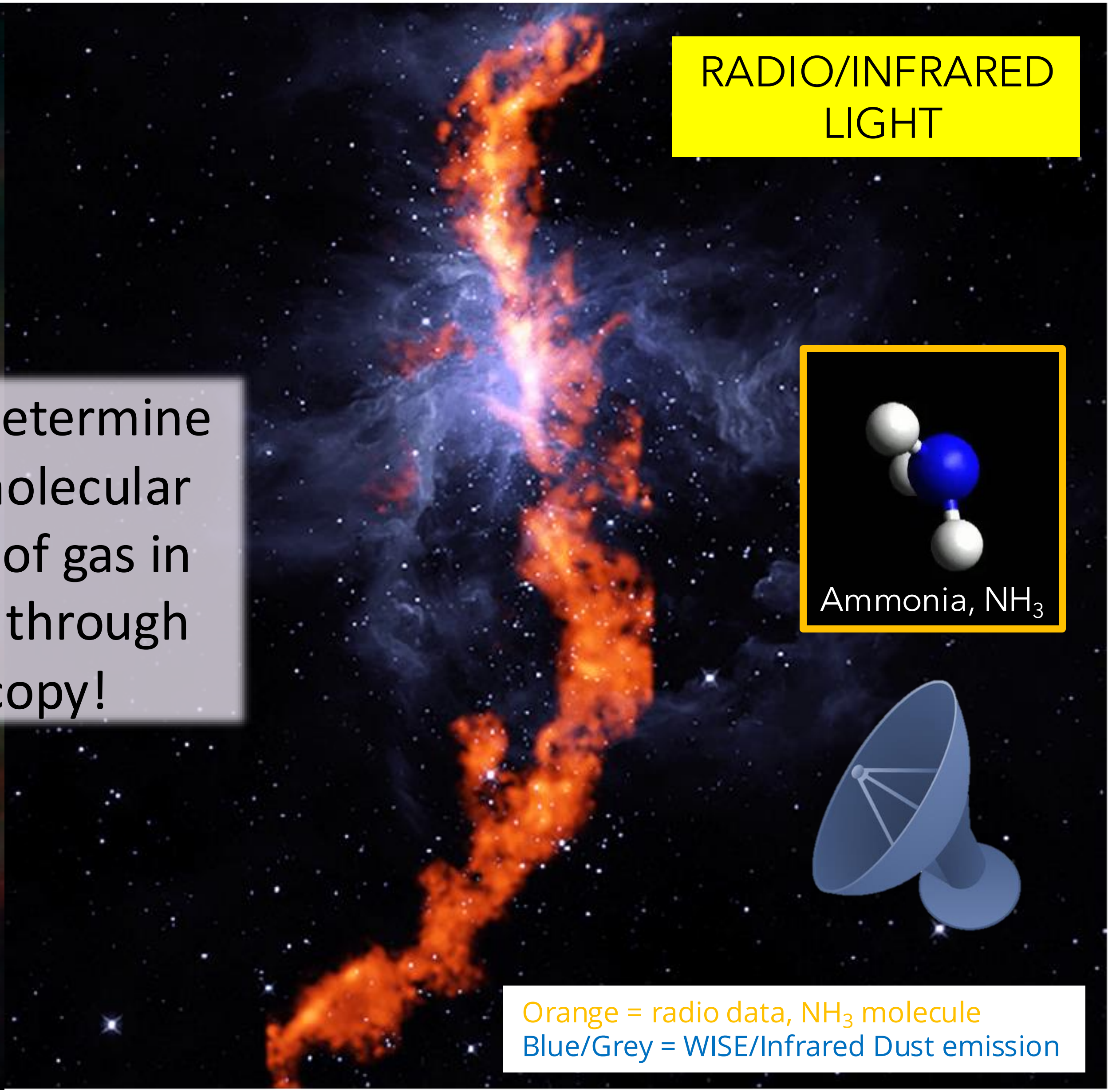


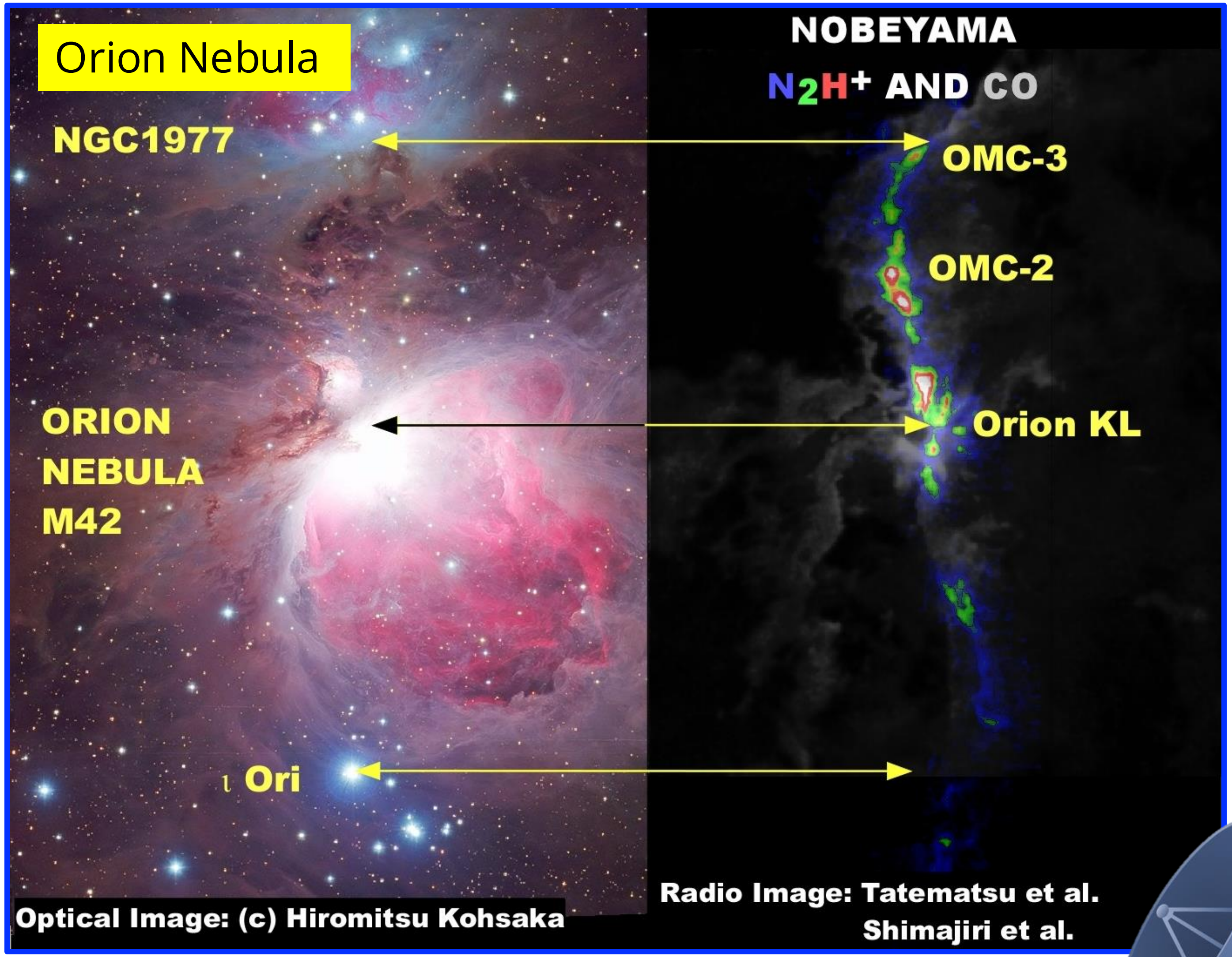
Continuous light source
Light
CONTINUOUS SPECTRUM
Spectrum that contains **all wavelengths** emitted by a hot, dense, light source
Emission
Absorption
Higher-energy photon is emitted
Incoming photon is absorbed by the atom
Excited state
Electron
Nucleus
Lower energy level
Lowest energy level
Nucleus
Electron
Lower-energy photon is emitted
Incoming photon is absorbed by the atom
Brightness
Wavelength
Brightness
Wavelength
Brightness
Wavelength


PICTURE OF A SPECTRUM
GRAPH OF A SPECTRUM
Astronomer's interpretation:
Peaks and valleys are labeled with the elements and compounds that caused them.
Hydrogen
Brightness
400
500
600
700
Wavelength (nanometers)
Hydrogen atom
Electron
Proton
Brightness
(might be labeled as intensity, counts, flux, power, absorbance, transmittance, or reflectance)
Color
(often labeled as wavelength, but can also be labeled as energy or frequency)

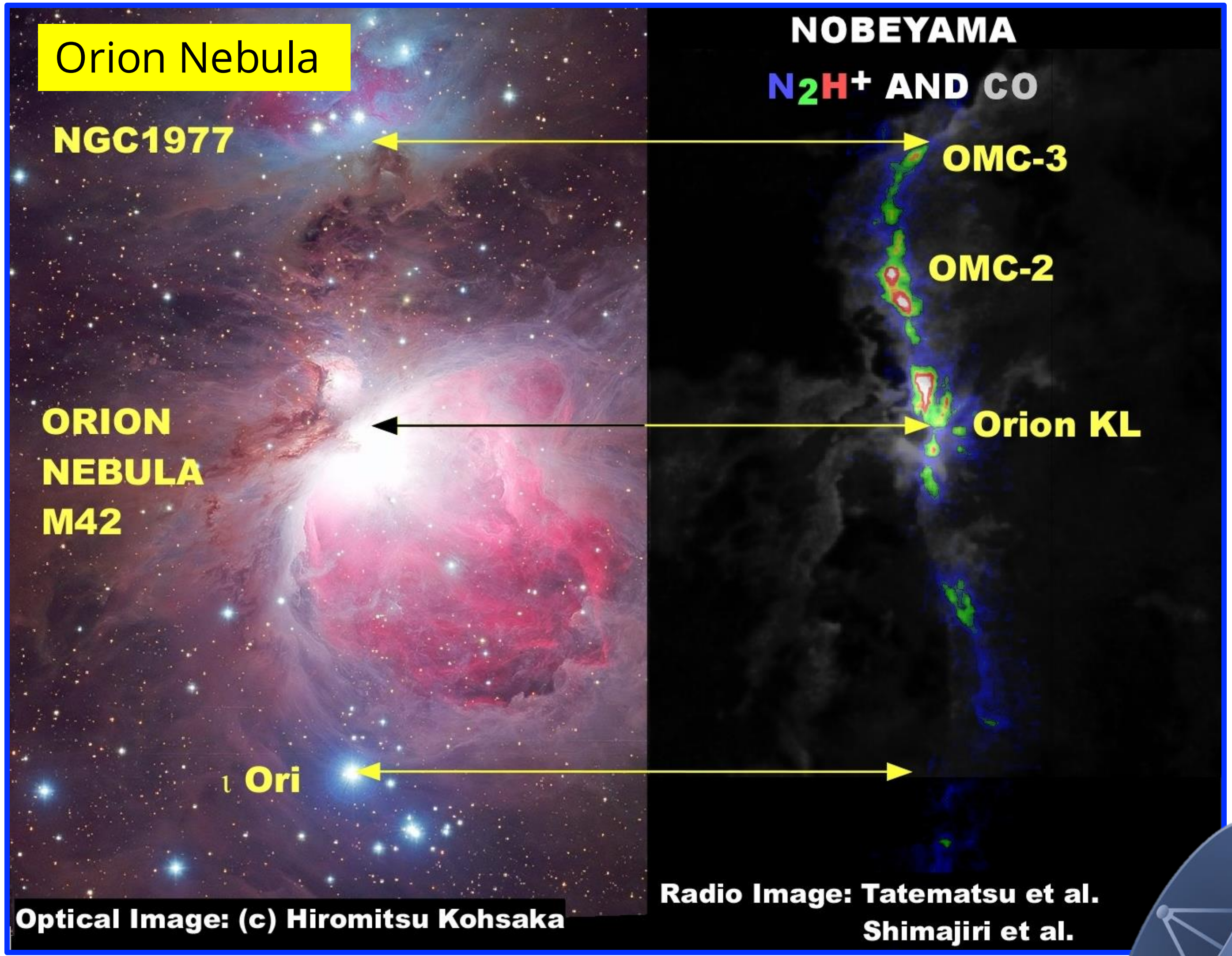


We can also determine the cooler, molecular composition of gas in our universe through spectroscopy!





https://www.nro.nao.ac.jp/~kt/html/kt-e.html



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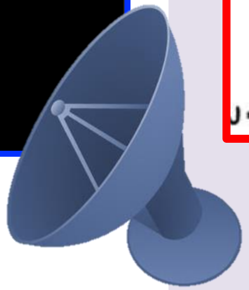
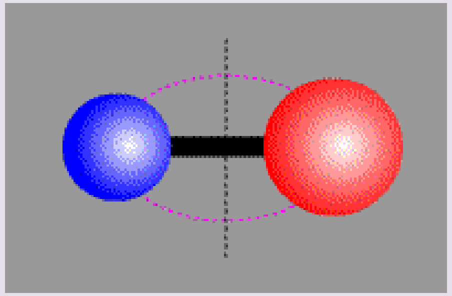
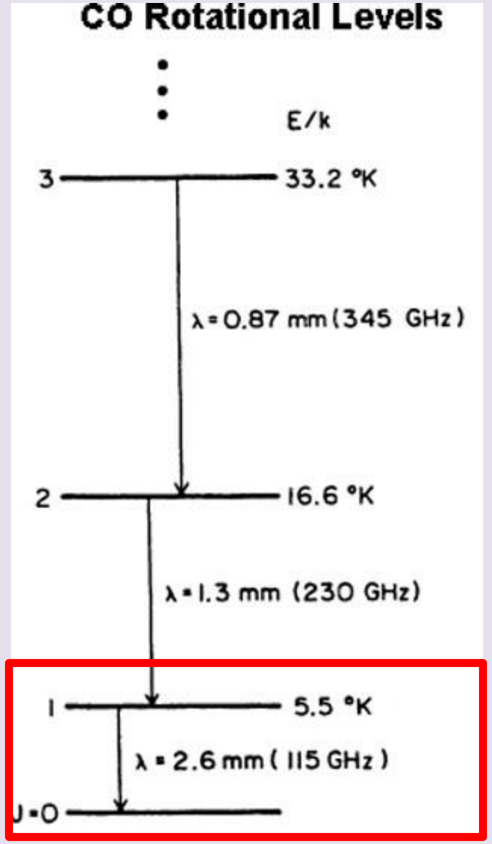
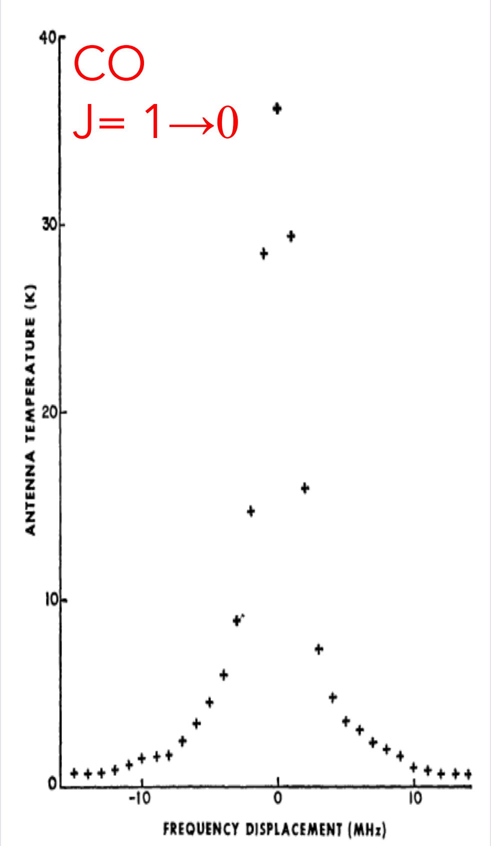


Discovery of CO
in the Star Forming Region,
Orion KL at 115 GHz
($J = 1 \rightarrow 0$ transition)
in 1970 at **Kitt Peak, Arizona!**



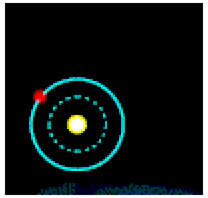




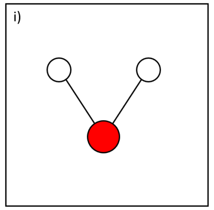
Wilson et al., 1970

Spectroscopy: Primary Molecule Identification Method!

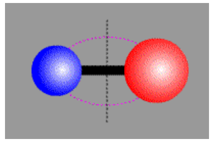
- Molecular Energy Levels consist of:



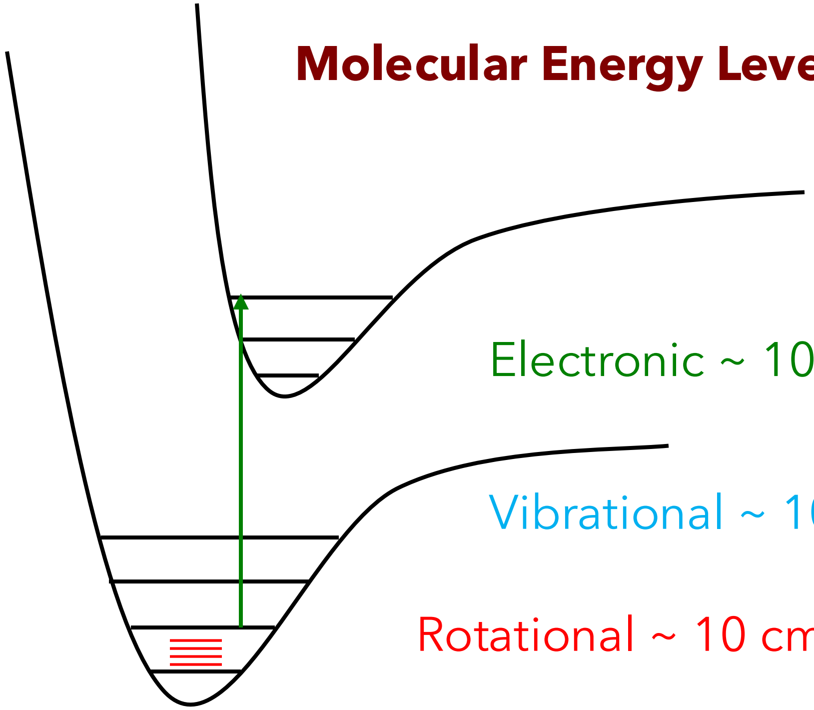
1) ELECTRONIC STATES
   - electrons change levels
   - energies in visible, UV



2) VIBRATIONAL STATES
   - normal modes of nuclear motions
   - occur in infrared region



3) ROTATIONAL STATES
   - end-on-end motion of nuclei
   - energies in microwave/millimeter-wave regions



Credit: L. Ziurys

Spectroscopy: Primary Molecule Identification Method!

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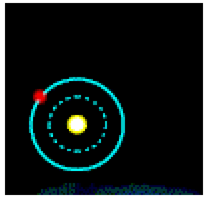

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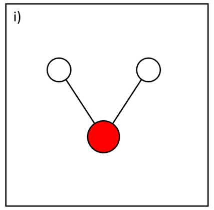

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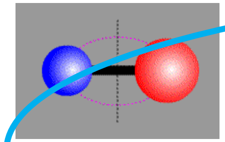

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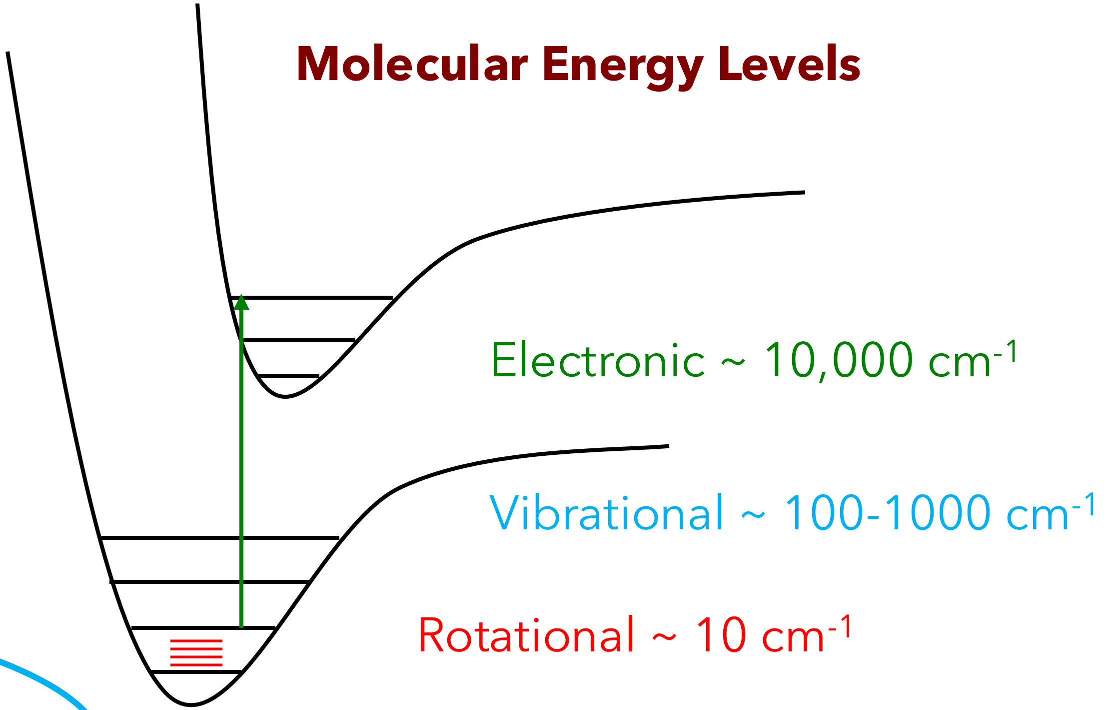


- Electronic states have **vibrational/rotational structure**
- Vibrational states have **rotational structure**

Credit: L. Ziurys

Spectroscopy: Primary Molecule Identification Method!

ELECTRONIC STATES

• Need energies ~ 0.5 – 1 eV to excite molecules (~ 5,000 – 10,000 K)

• Need a **UV/optical "pump"** to excite levels, provided by background star

• Molecular material in front of source cannot be dense (< 100 cm^{-2})

⇒ used in Diffuse Clouds

• Diffuse clouds contain primarily diatomic species

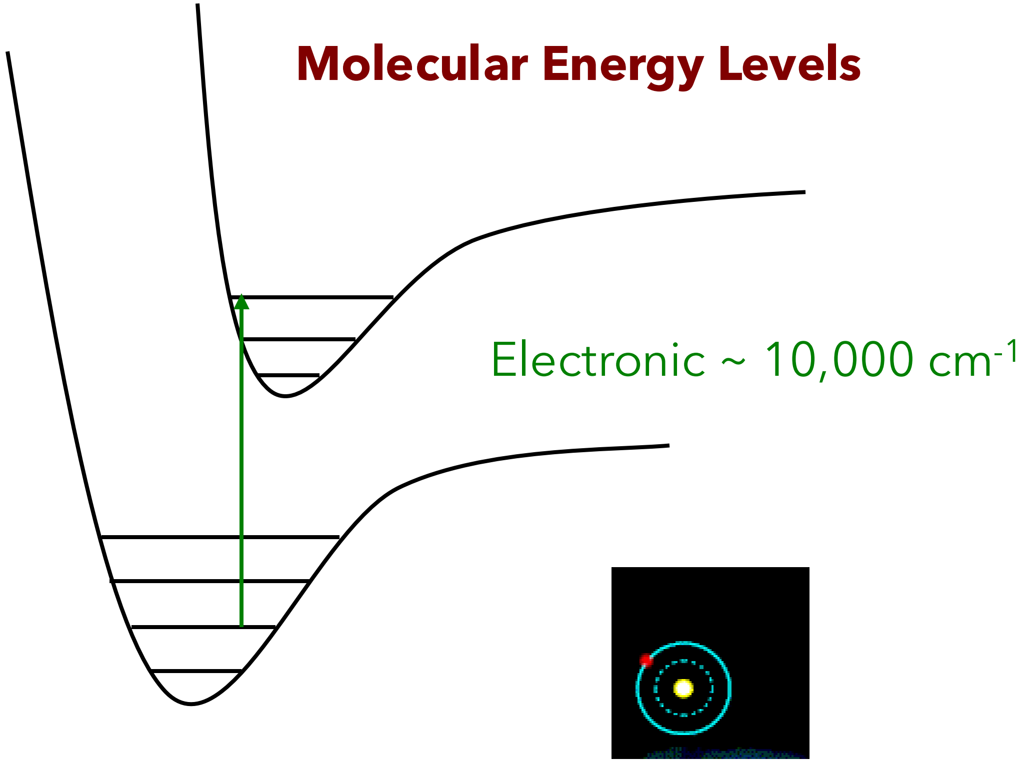
⇒ UV radiation photo-dissociates molecules readily

• Almost always **2-3 atom species**

- relatively simple spectra observed in **ABSORPTION**

• Also important in stellar photospheres of cool stars

- molecules can survive radiation field



Credit: L. Ziurys

Spectroscopy: Primary Molecule Identification Method!

ELECTRONIC STATES

Photospheric Spectra (Stars)

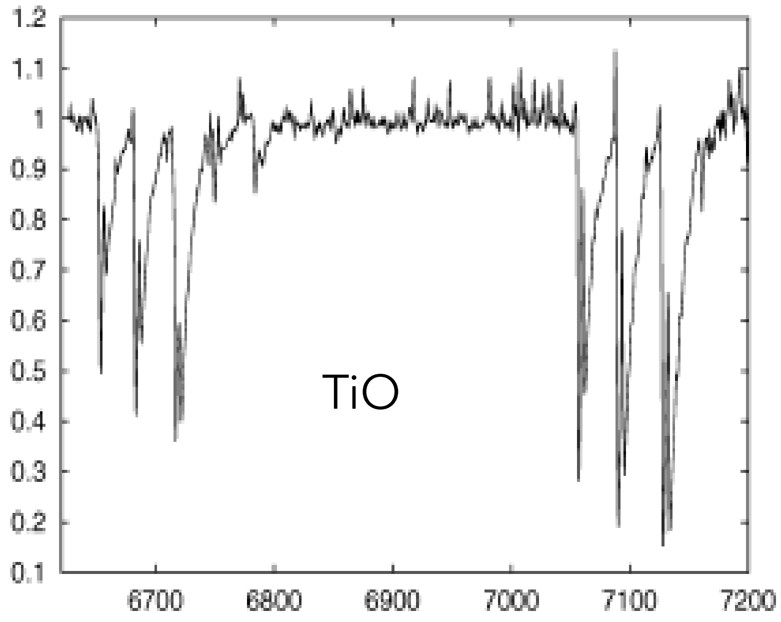


Figure 5. The 6630–7200 Å region of the JD 245 1221 optical spectrum of IRAS 08182−6000, showing the γ (1, 0), (2,1) and (0, 0) bands of TiO and some of the atomic emission lines recorded in Table 4.

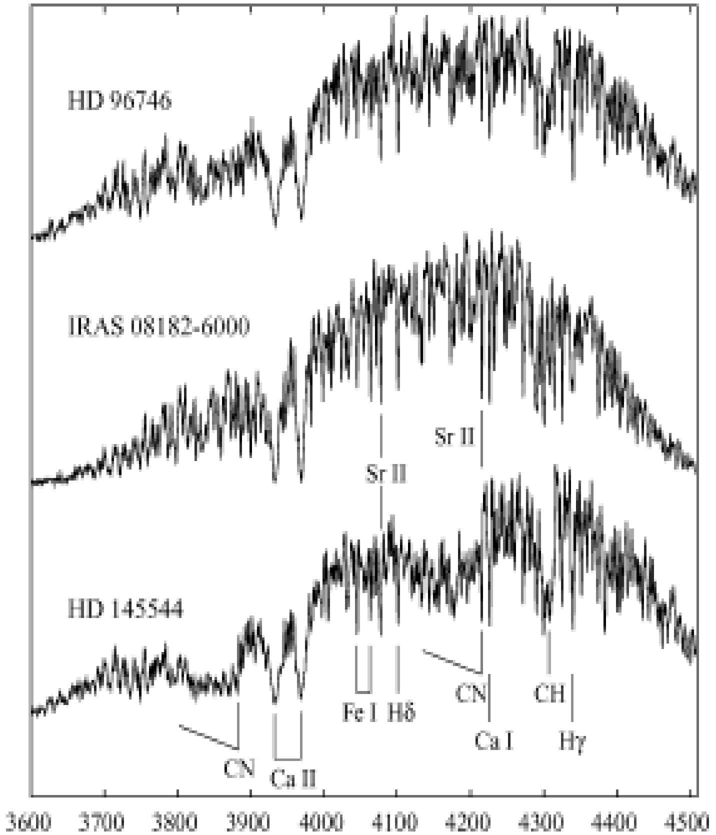


Figure 4. The spectrum of IRAS 08182−6000 (JD 244 9426) compared with those of HD 96746, G2Iab (above) and HD 145544, G2Ib-II (below).

CN
&
CH

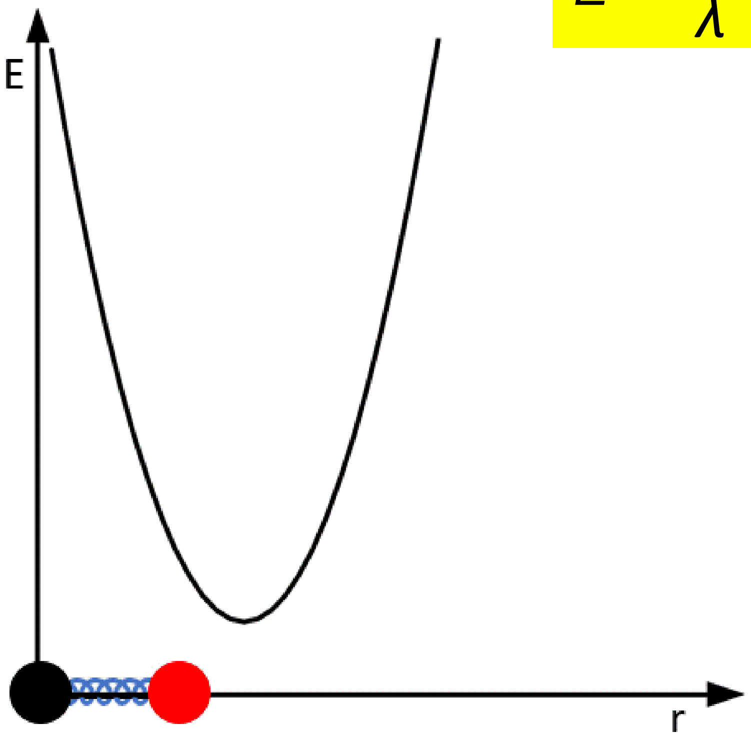
Credit: L. Ziurys

Spectroscopy: Primary Molecule Identification Method!

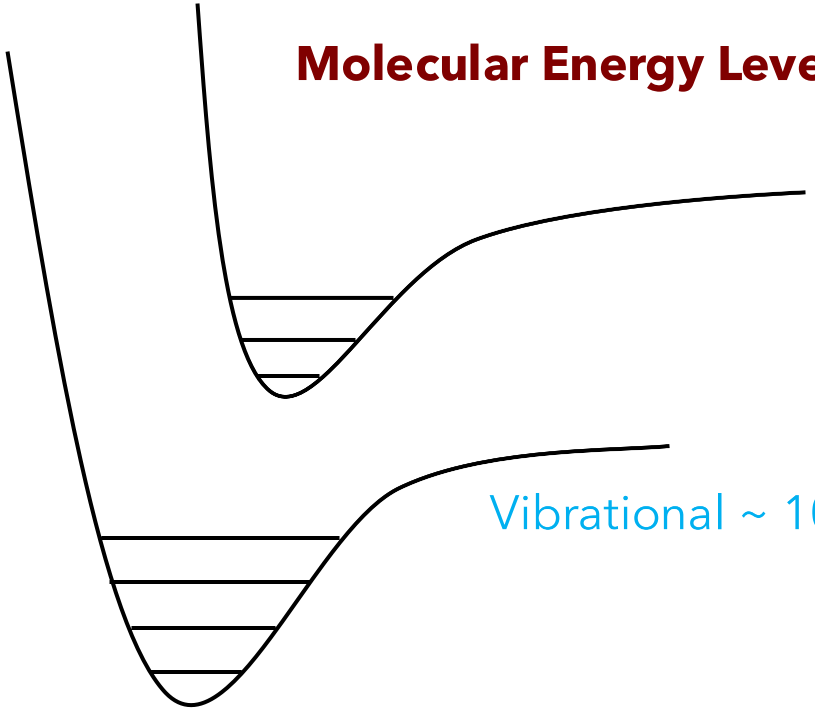
VIBRATIONAL STATES

- For a simple two-atom molecule, think back to your 'simple harmonic oscillator' whose energy can be quantized!

$$E = \frac{hc}{\lambda} = h\nu$$



Molecular Energy Levels



Vibrational ~ 100-1000 cm^{-1}

Spectroscopy: Primary Molecule Identification Method!

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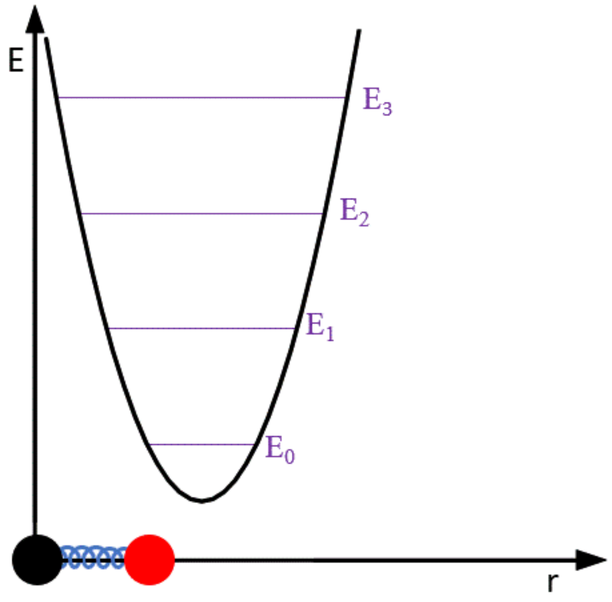
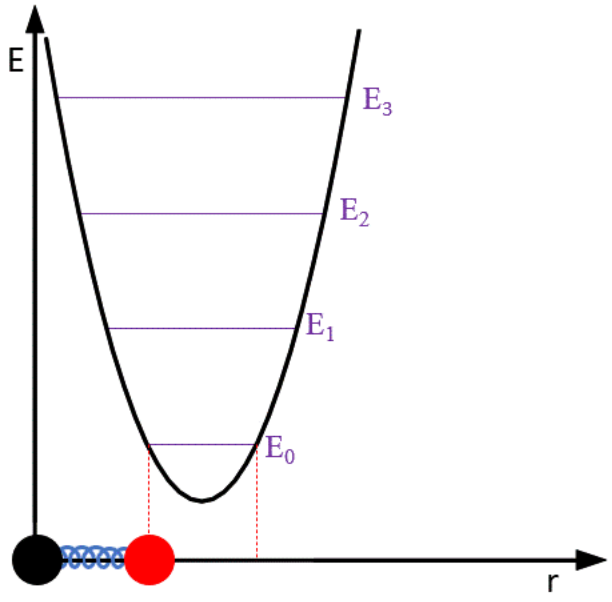
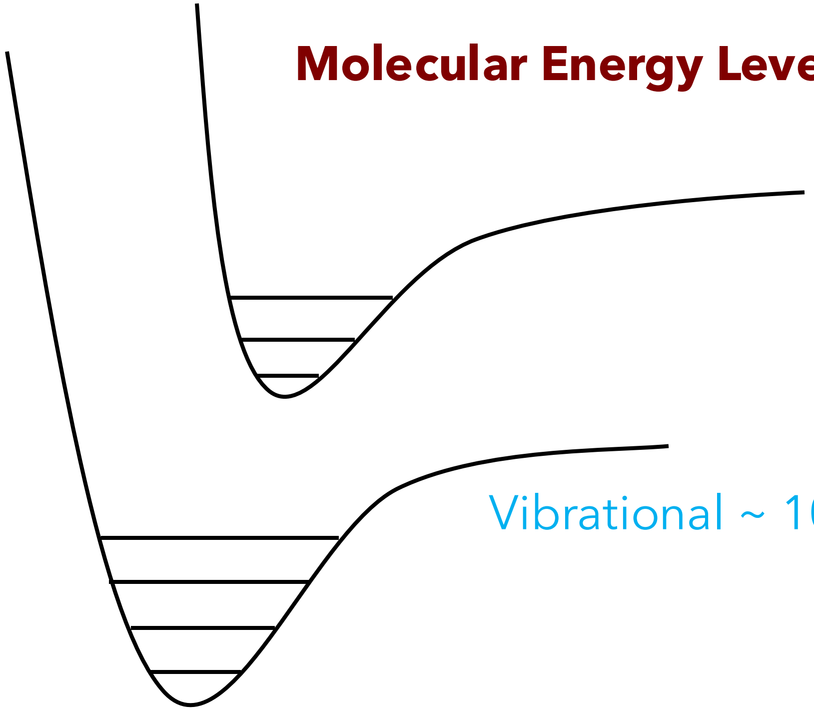




Molecular Energy Levels

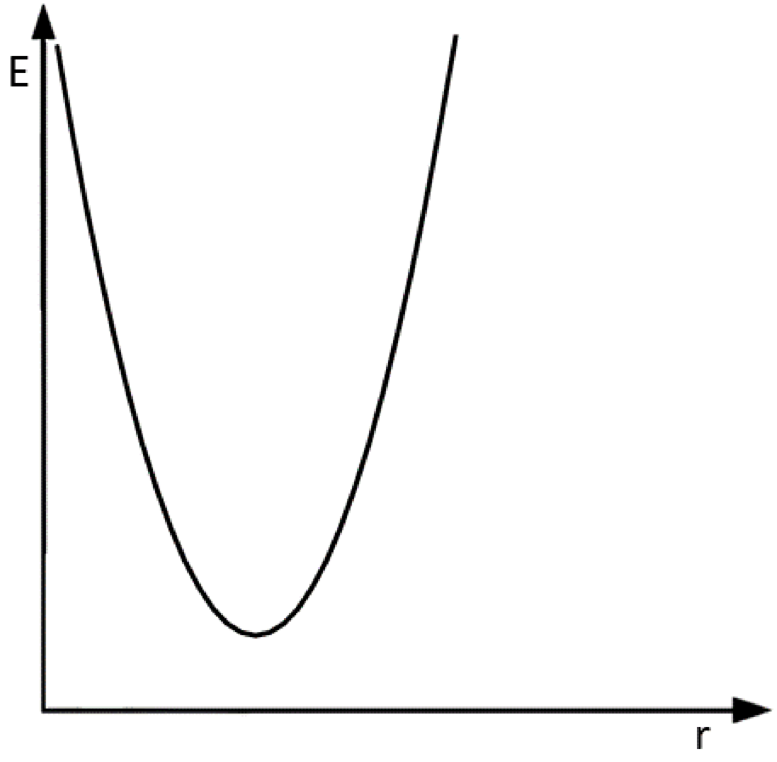


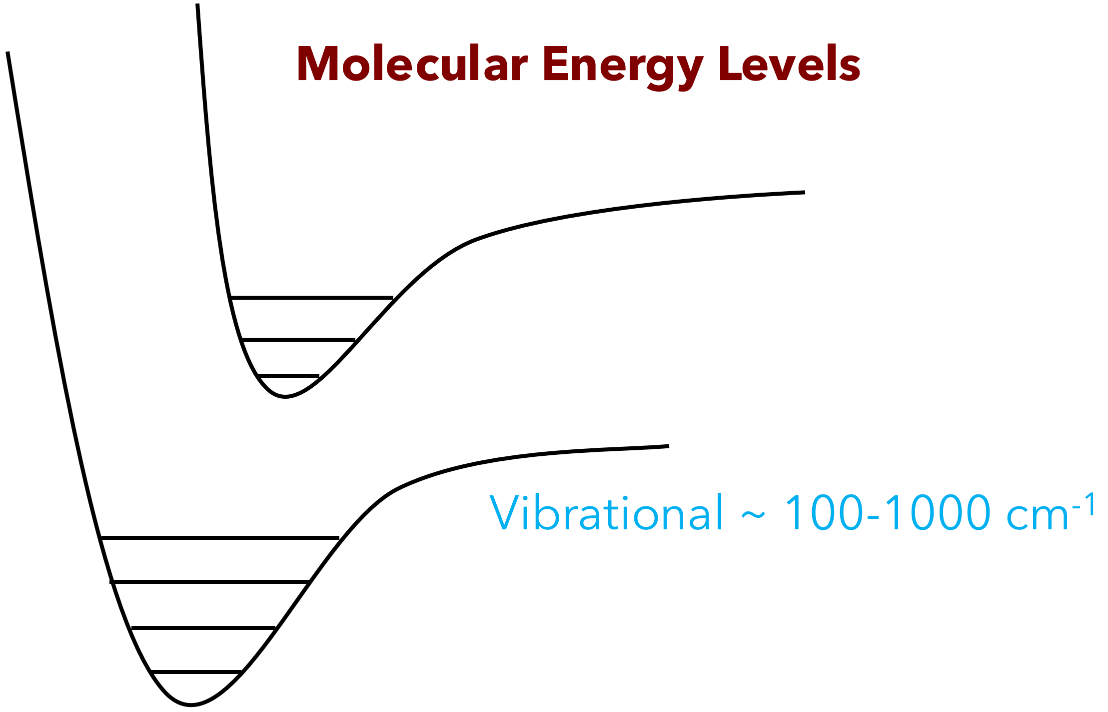
Vibrational ~ 100-1000 cm^{-1}

Spectroscopy: Primary Molecule Identification Method!

VIBRATIONAL STATES

- In the real world, eventually your 'spring snaps'
- The gap between higher excited states thus begins to narrow

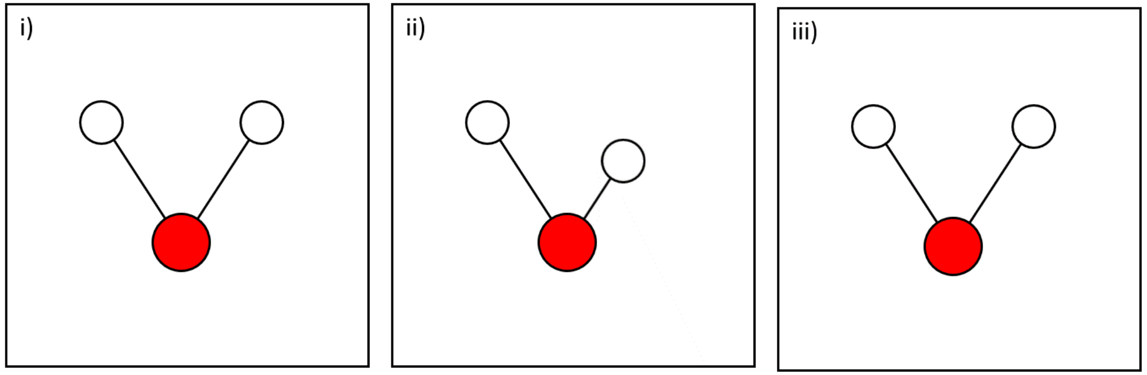




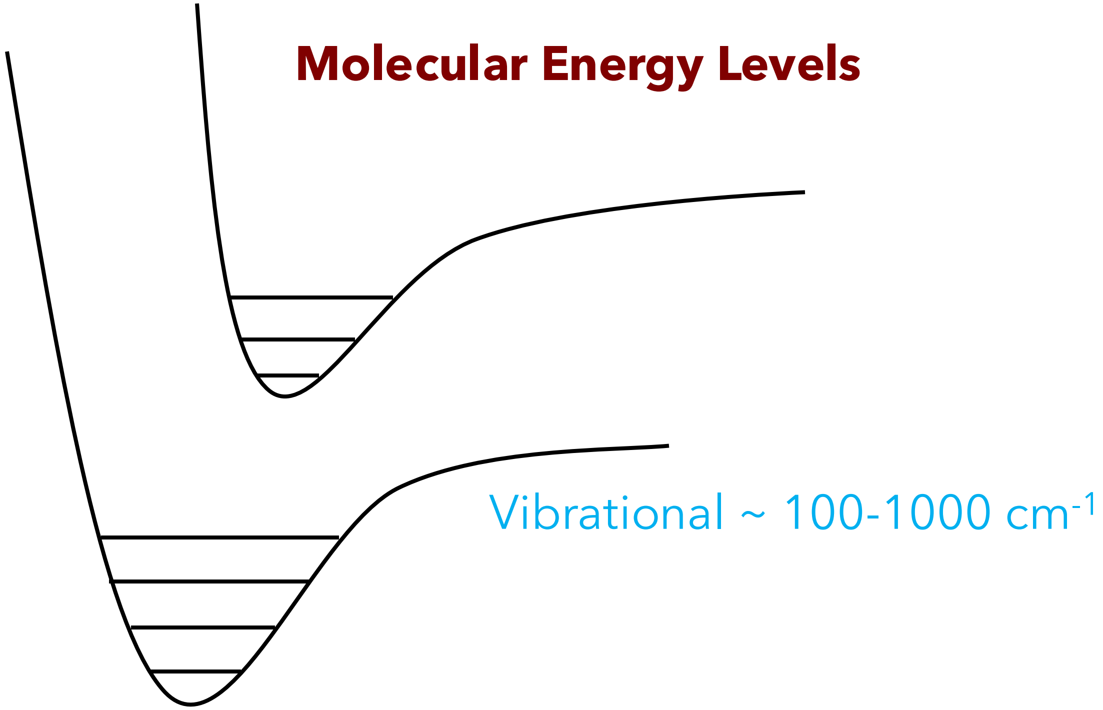
Spectroscopy: Primary Molecule Identification Method!

VIBRATIONAL STATES

- For molecules with several atoms, the type of possible vibrations increases, and more fundamental bands observed!
- The total number of possible vibrations for a molecule is equal to 3N-6 where N is the # of atoms in the molecule
    - E.g., water, H_2O, has 3!



i) symmetric stretch, (ii) asymmetric stretch and (iii) bending modes.



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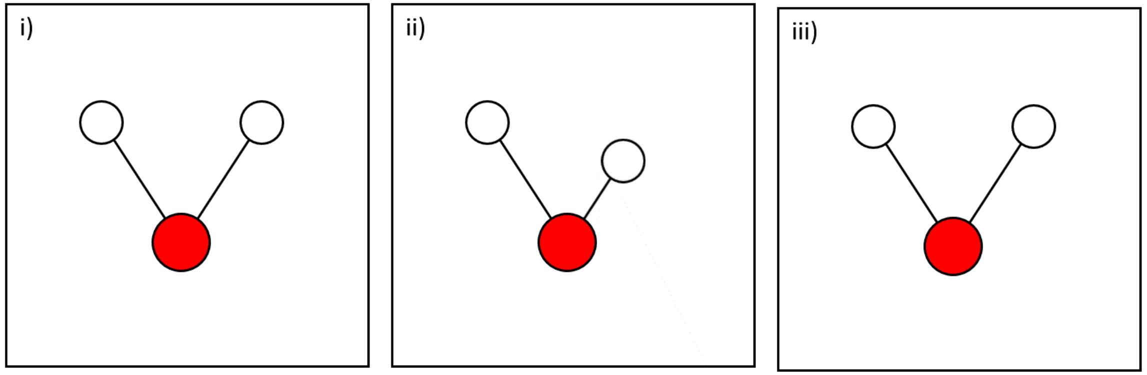

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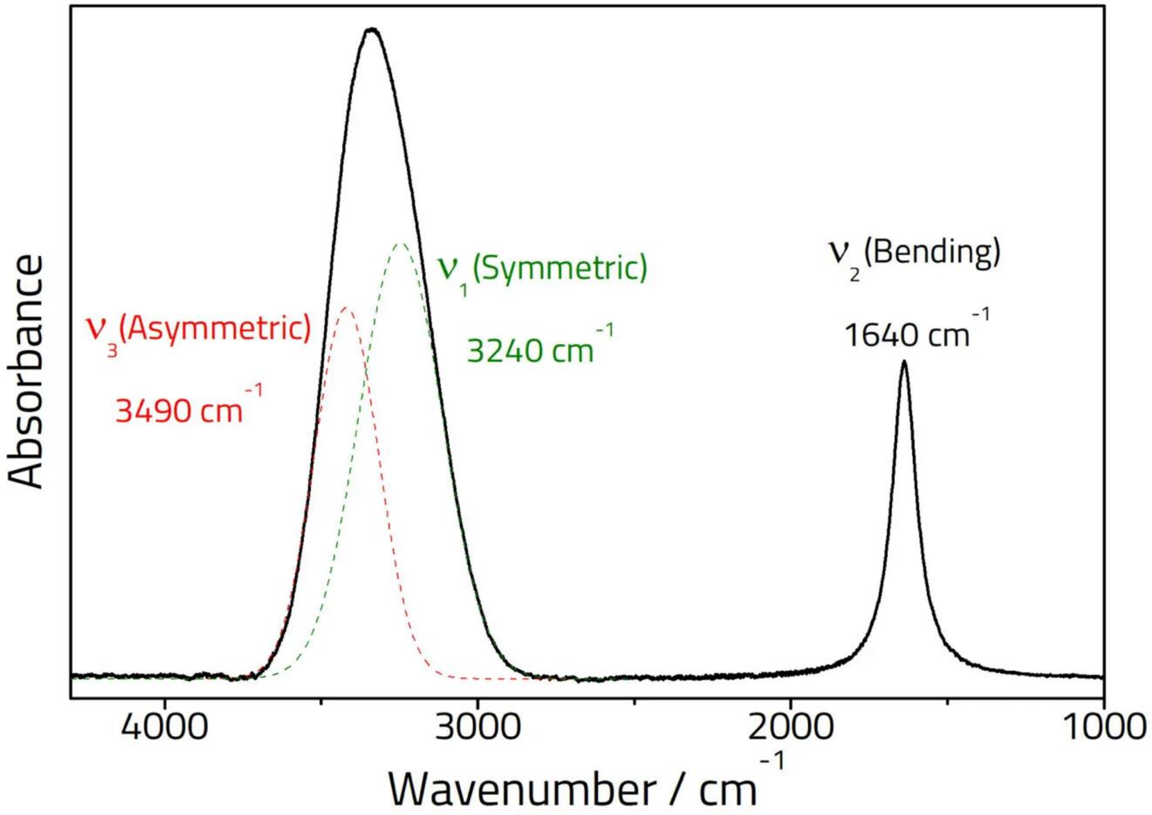


Spectroscopy: Primary Molecule Identification Method!

VIBRATIONAL STATES

• Need **energies** ~ 200 – 2000 cm^{-1} to excite molecules (300 - 3000 K)

• Need an **IR "pump"** to excite levels: background source

• Provided by **DUST from Circumstellar Envelopes**: strong IR emission background

• Young Protostar as background: **IR source**

• Density restrictions not as high as in optical region

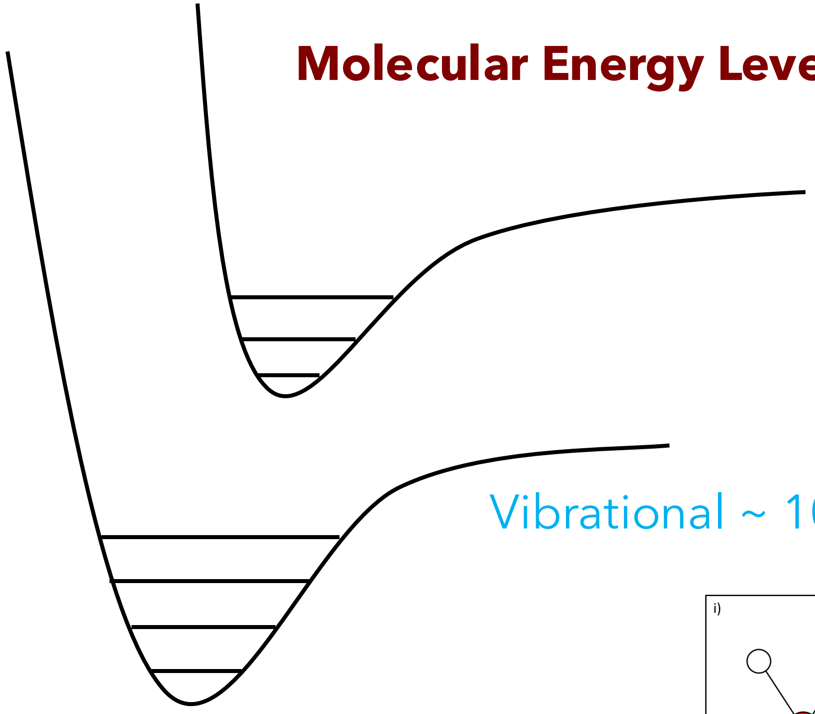
• Used to study *chemical composition* of ***circumstellar shells*** close to stellar photosphere

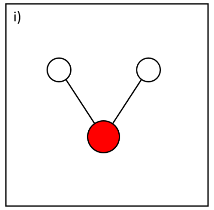
• Molecules in denser material near **cloud cores**

• Spectra primarily observed **in absorption, except H_2**

• Useful for symmetric molecules

- HCCH, H_3^+, CCC, H_2CCH_2



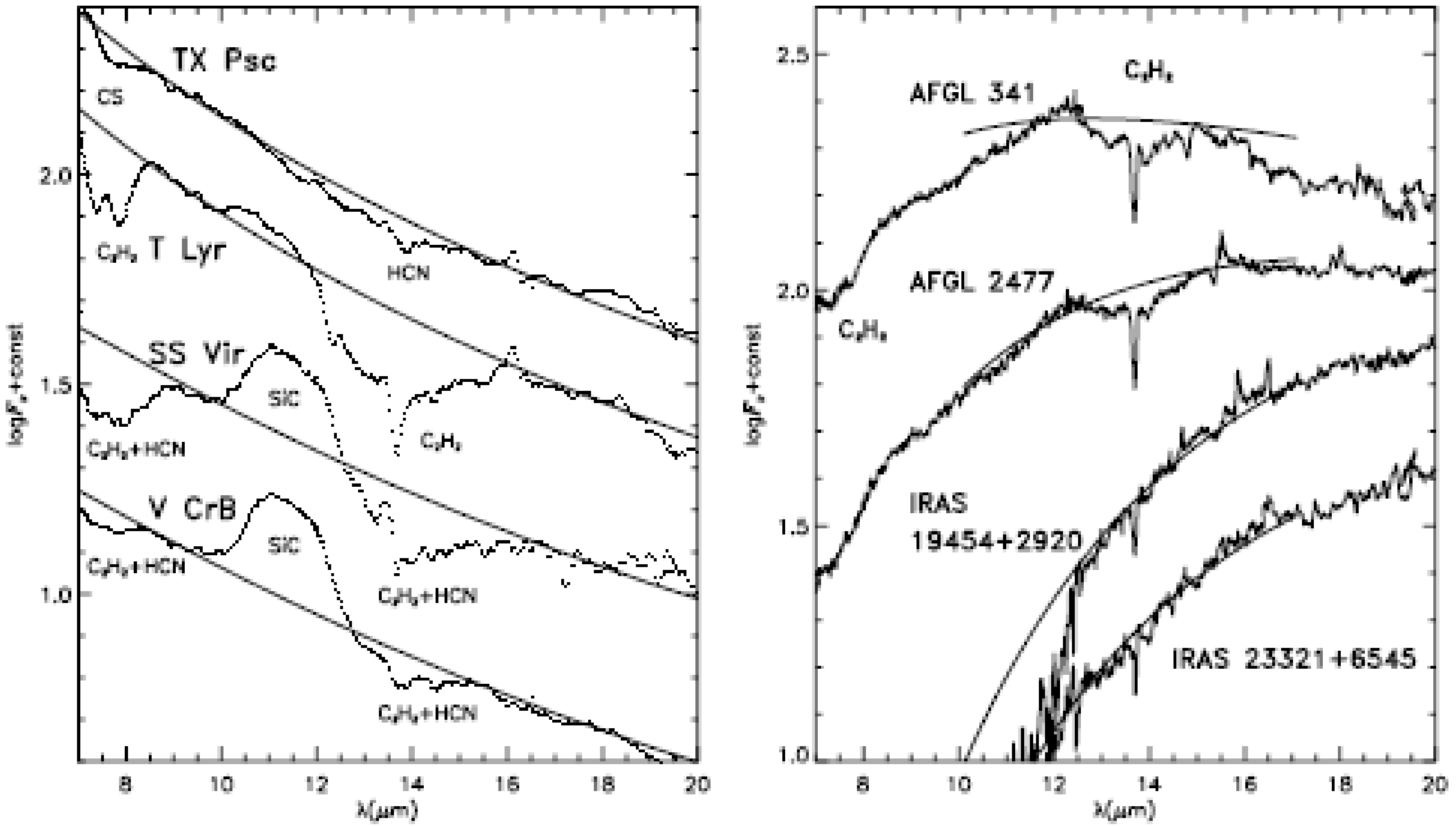


Credit: L. Ziurys

Spectroscopy: Primary Molecule Identification Method!

VIBRATIONAL STATES

C_2H_2 & HCN Vibrational Spectra around Evolved Stars



Credit: L. Ziurys

Spectroscopy: Primary Molecule Identification Method!

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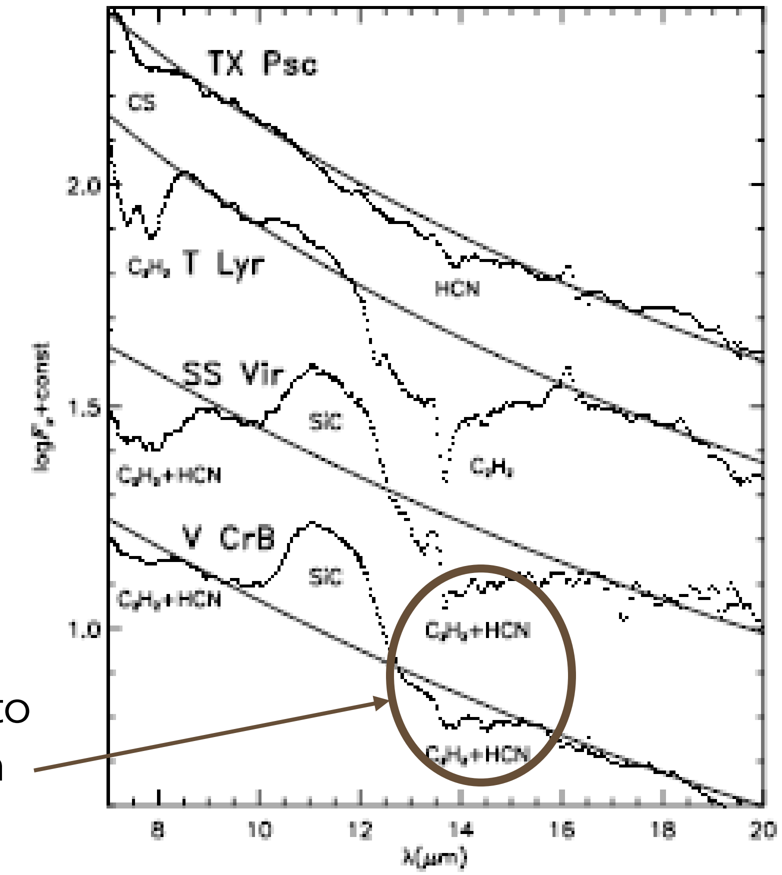
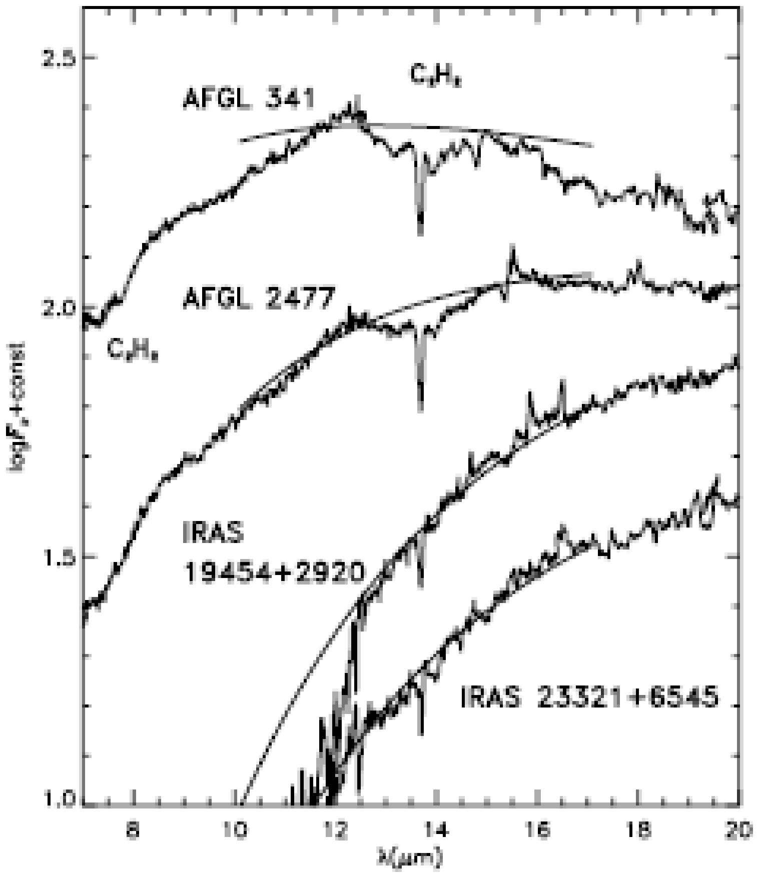


Often hard to distinguish individual modes!



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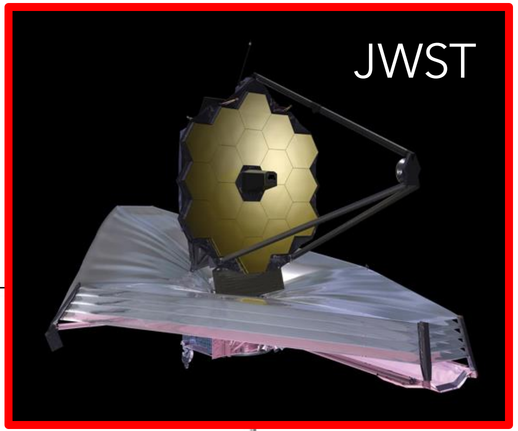
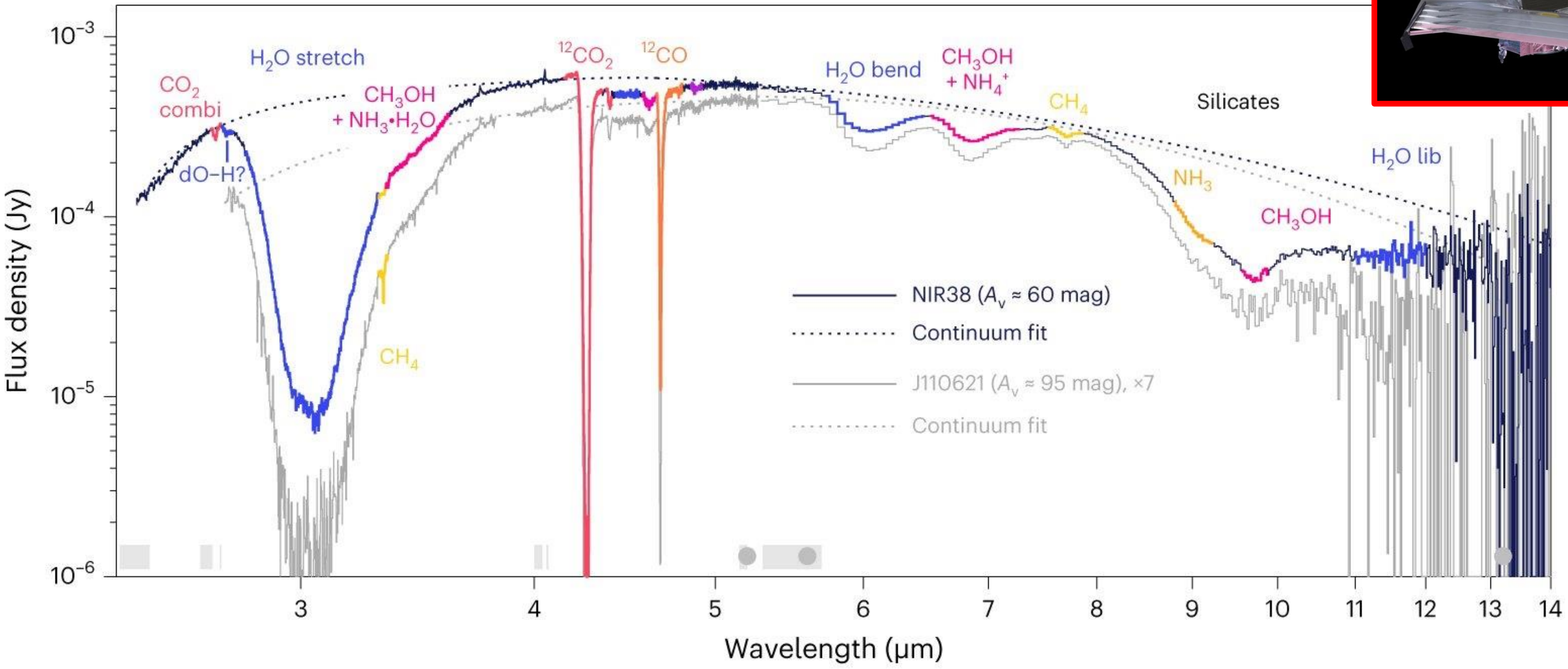


VIBRATIONAL STATES

IR Spectra of Star-Forming Core



NIRSpec FS (NIRCam WFSS) and MIRI LRS spectra of NIR38 and J110621. Credit: *Nature Astronomy* (2023). DOI: 10.1038/s41550-022-01875-w

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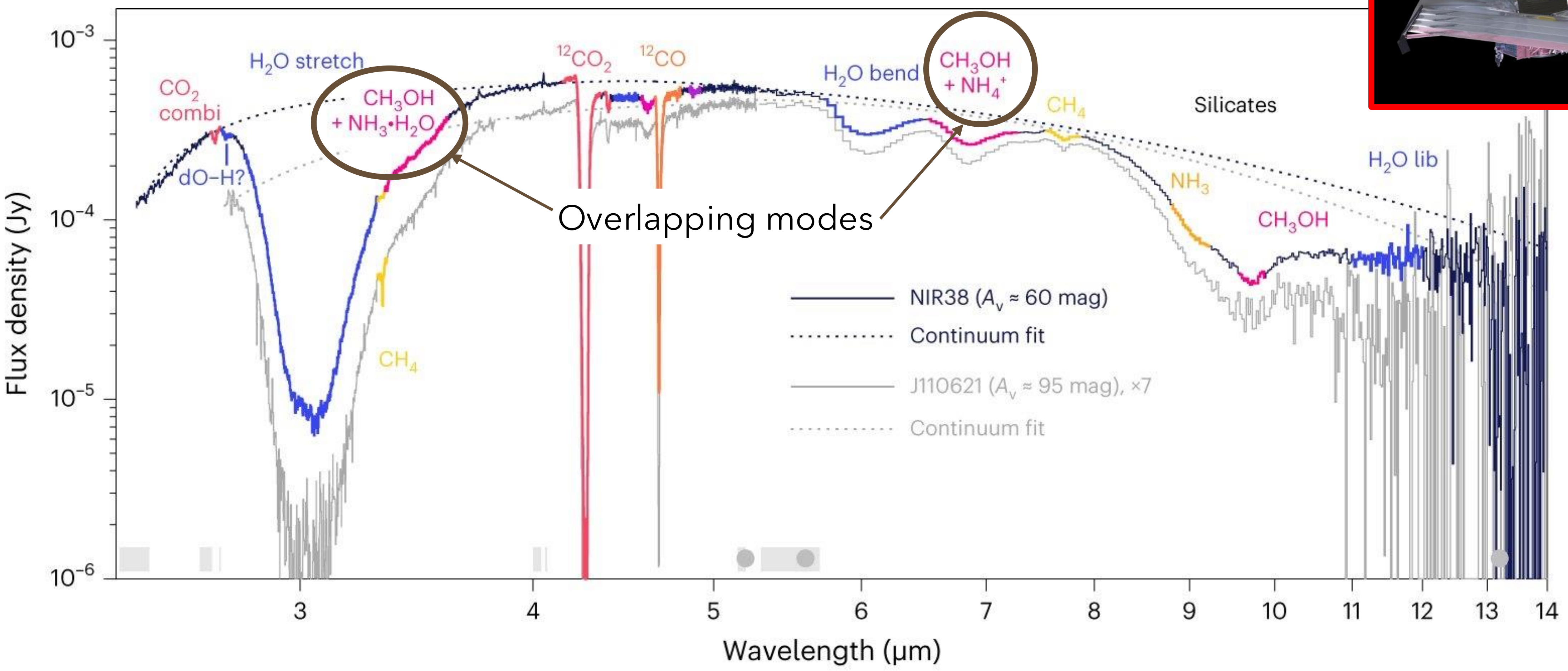

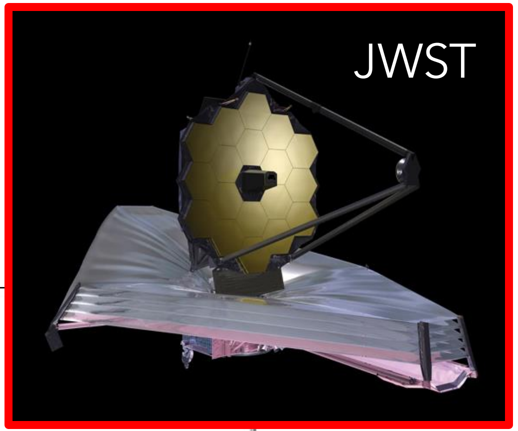

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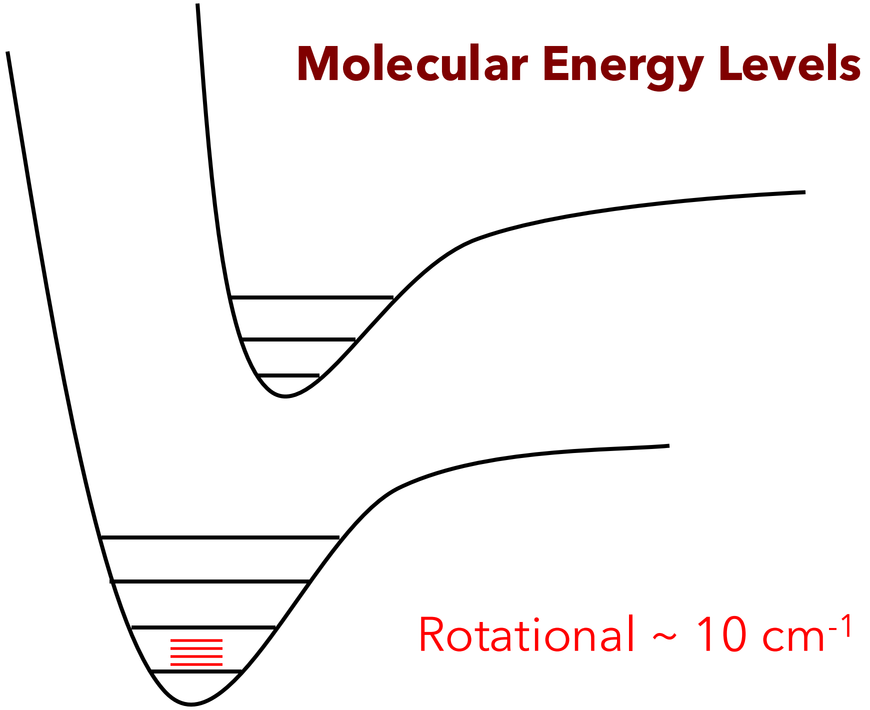
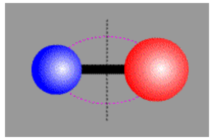
Spectroscopy: Primary Molecule Identification Method!

ROTATIONAL STATES

- Submillimeter and millimeter observations!
- Interstellar Molecular Gas is primarily **COLD**
  (T ~ 10 -100 K)
- **Rotational Levels** predominantly populated
  ⇒ two-body **collisions** with H_2
- No background source needed
- **Spontaneous Decay** results in **narrow emission lines**
- Rotational Spectrum is "Fingerprint" Pattern
- Unique to a Given Chemical Compound!
- Allows for ***unambiguous*** identification
- Rotational Transition Frequencies
  ⇒ **quantized** and proportional to ***moments of inertia***





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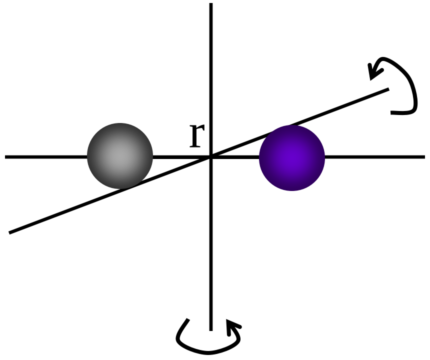
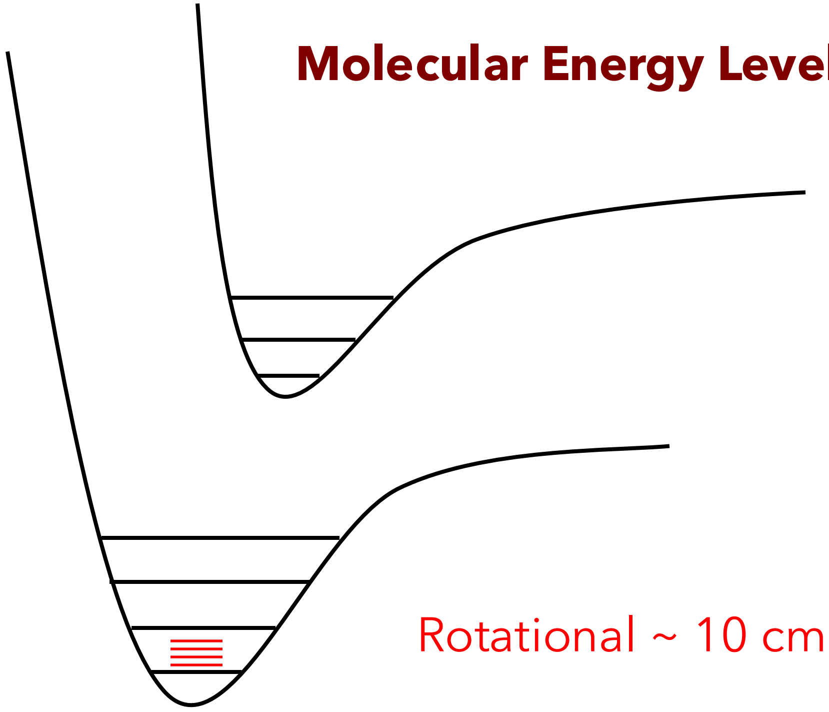
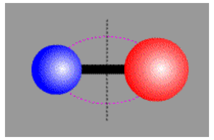


$$I = \mu r^2$$

Molecular Energy Levels



Rotational ~ 10 cm^{-1}



Credit: L. Ziurys

Rotational Spectroscopy

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

Frequency

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

Rotational Constant

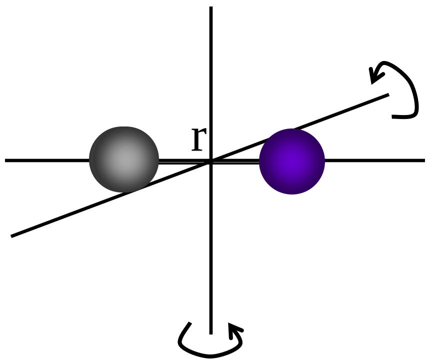
$$I = \mu r^2$$

Moment of Inertia

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

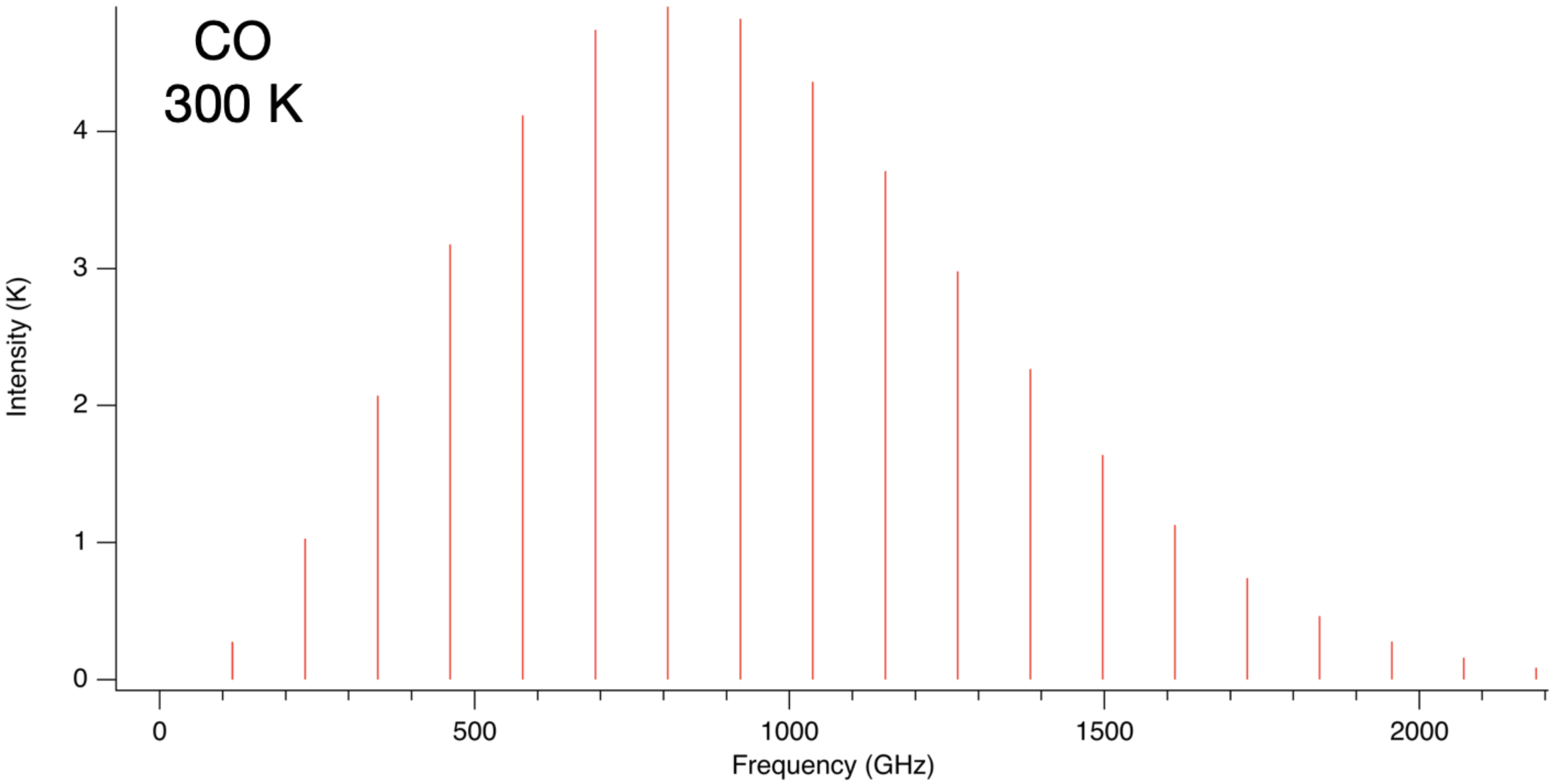
Reduced Mass

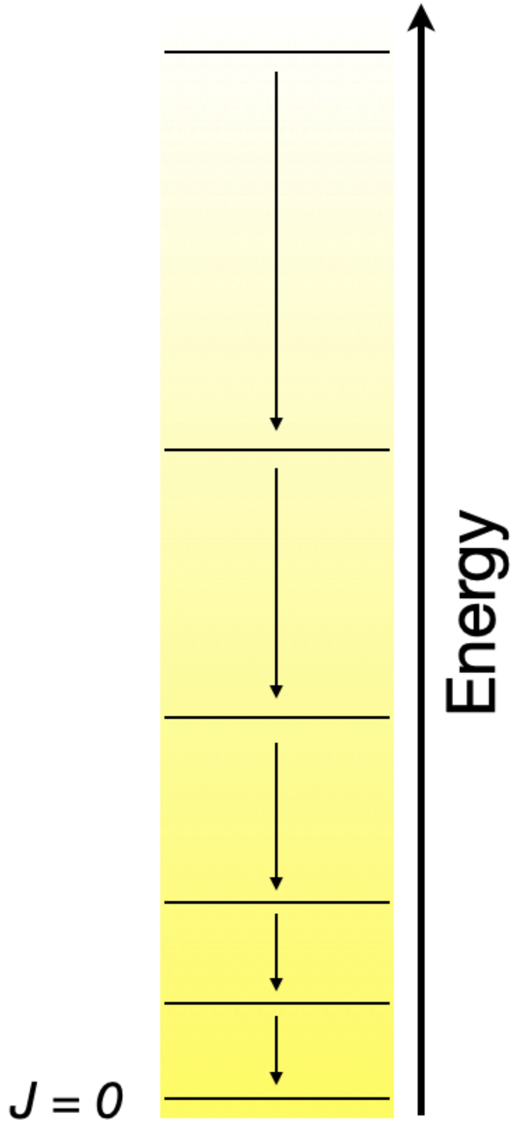
Increasing the size/mass of a molecule shifts transitions to lower frequencies!



Credit: B. McGuire

Rotational Spectroscopy





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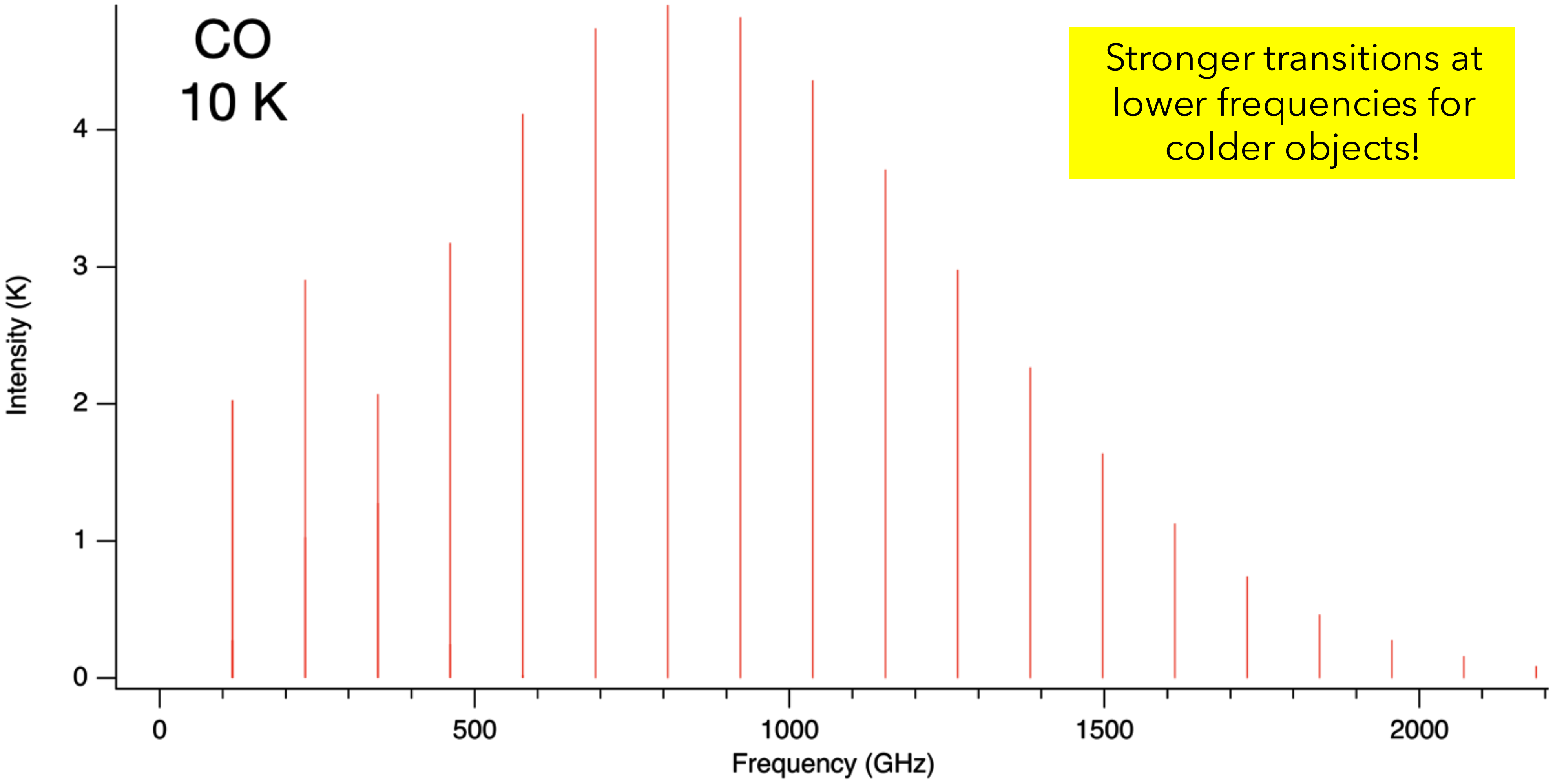
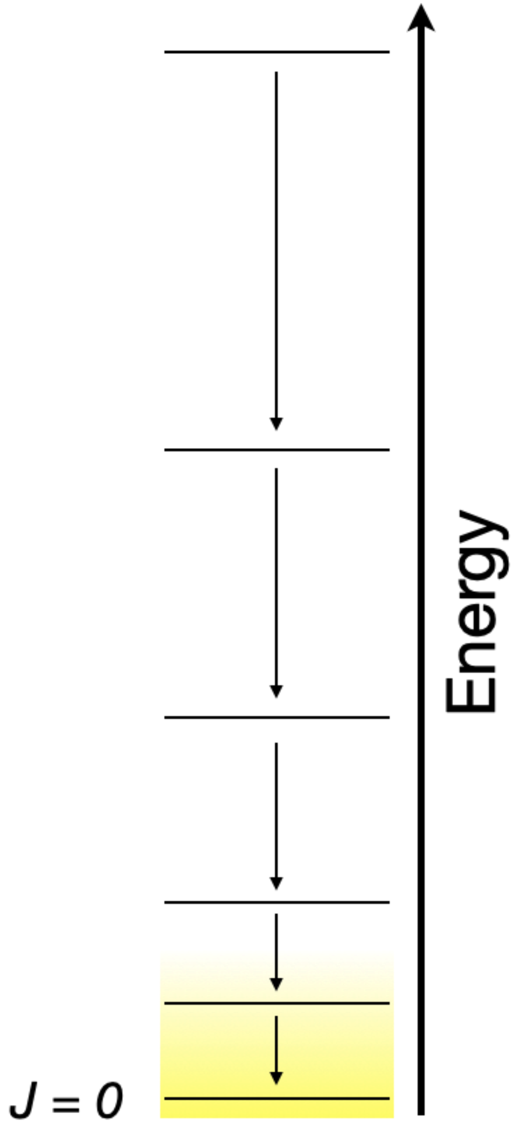
Rotational Spectroscopy

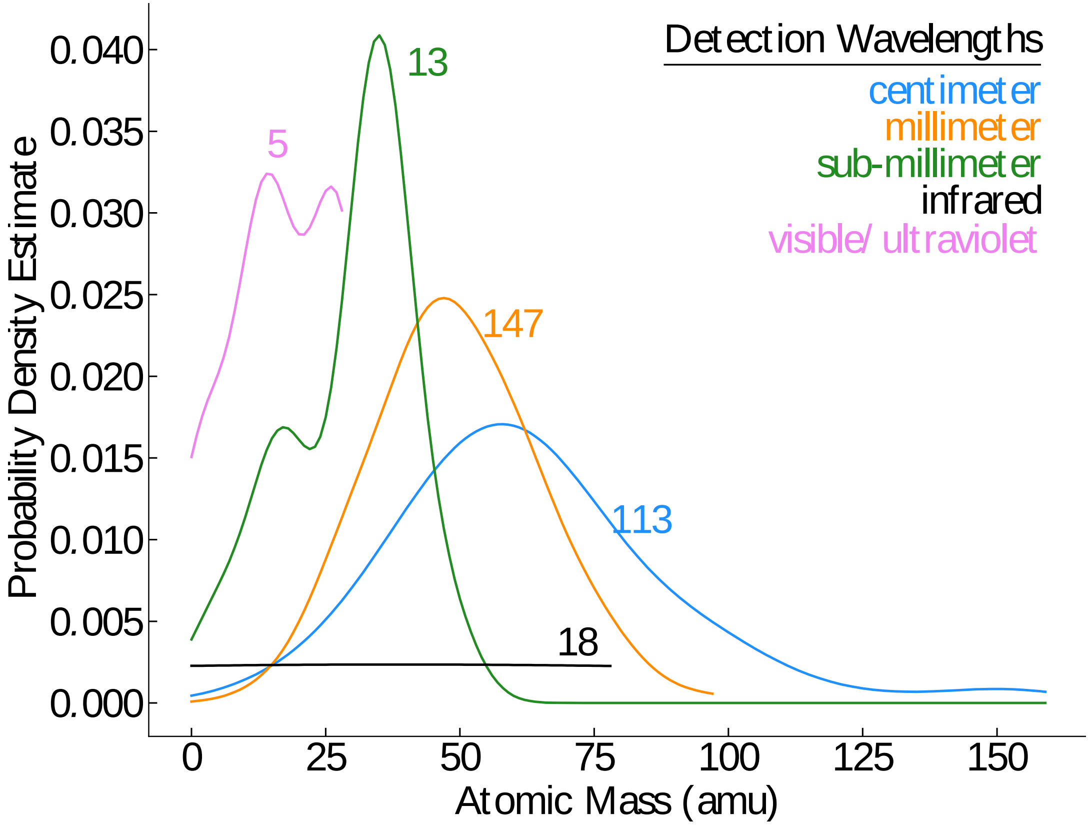


Stronger transitions at lower frequencies for colder objects!



Credit: B. McGuire

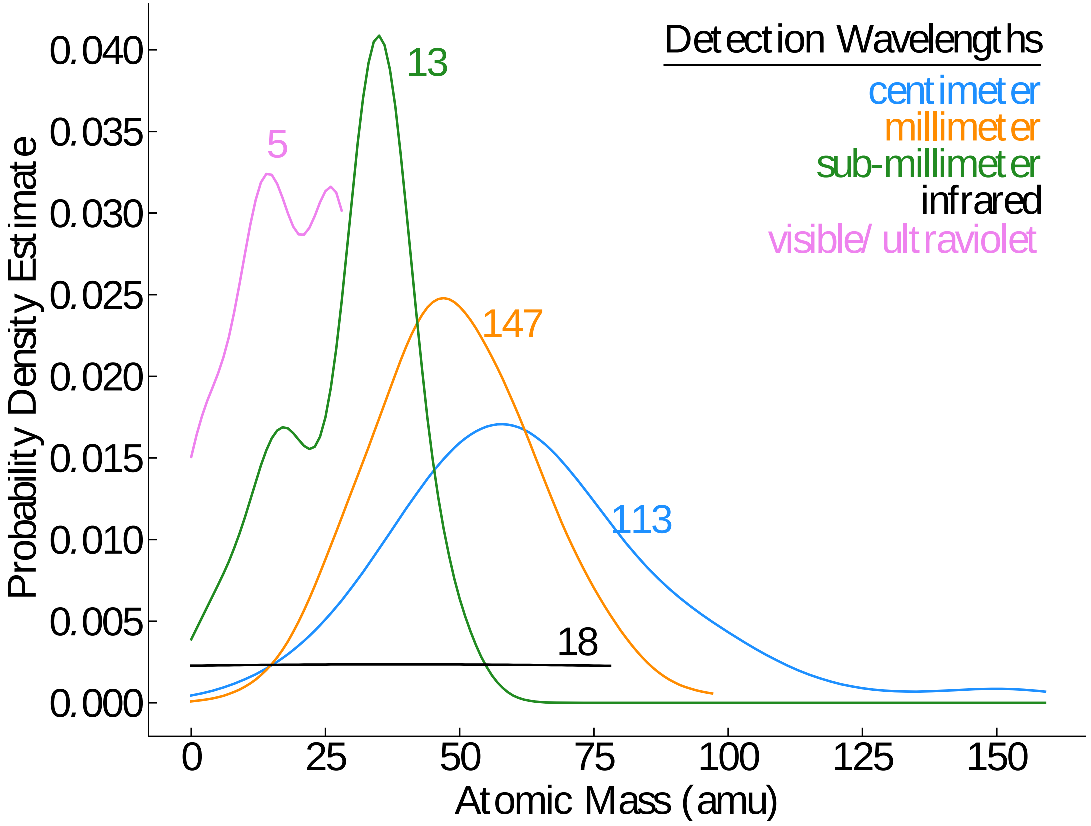
Rotational Lines at Radio Wavelengths: The Best Probe of *Complex* Molecules



The **heavier a molecule/ more complex**, the more likely it is to be first detected at longer wavelengths.

McGuire 2022; https://arxiv.org/pdf/2109.13848

Rotational Lines at Radio Wavelengths: The Best Probe of *Complex* Molecules



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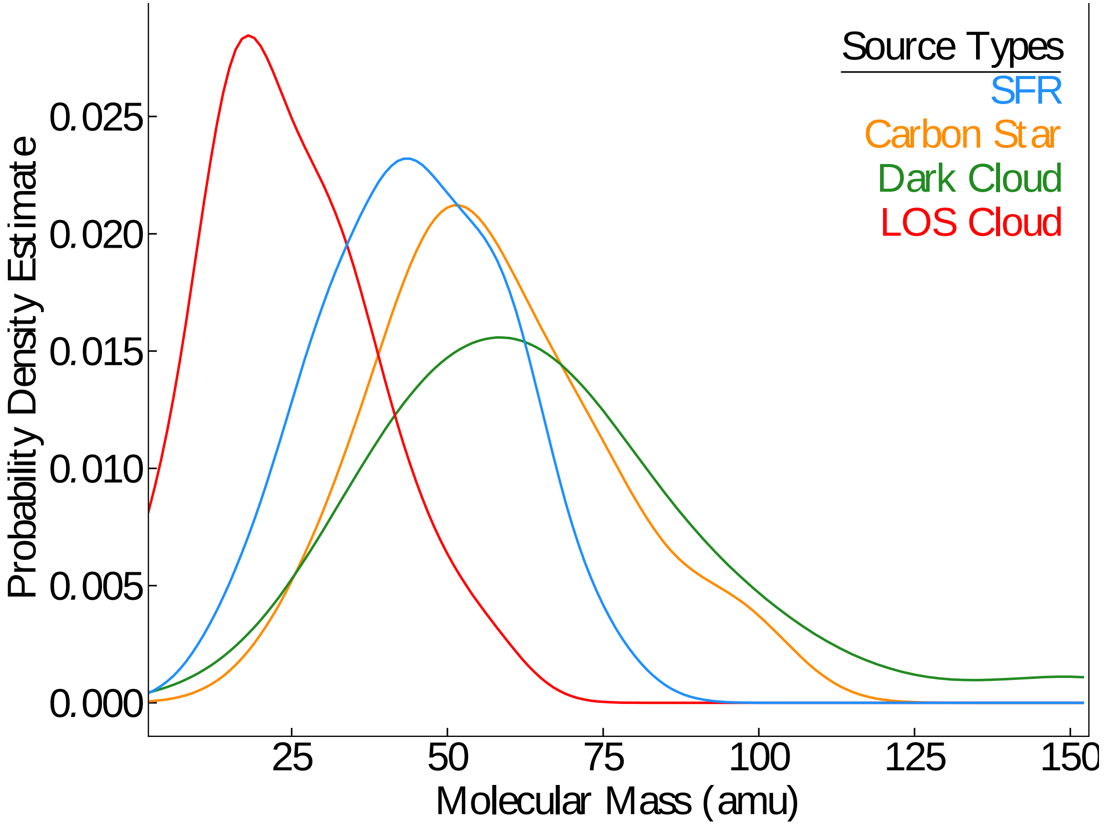


The **heavier a molecule/more complex**, the more likely it is to be first detected in a **dark cloud** or carbon star.

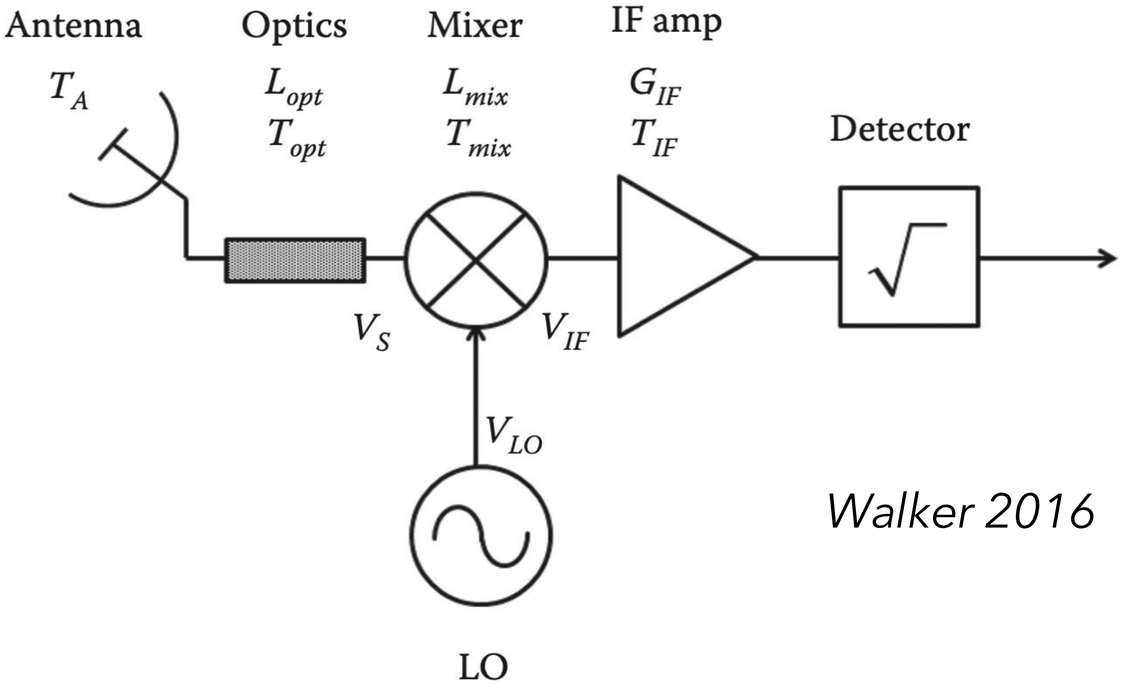
McGuire 2022; https://arxiv.org/pdf/2109.13848

Rotation Spectroscopy/Molecular Spectroscopy via Radio Telescopes

ROTATIONAL STATES

- Interstellar rotational spectra are obtained with
  Radio Telescopes
- Employ **Heterodyne SIS Mixer** detectors with
  Multiplexing Spectrometers
  ⇒ ***High spectral resolution data*** (1 part in 10^8)
  ⇒ vis Optical/IR resolutions ~ 1 part in 10^3 -10^4
- At higher frequencies electronics can not handle incoming signal, it needs to be **translated to a lower frequency** where it can be amplified and processed!

Heterodyne Receiver Layout



Walker 2016

Rotation Spectroscopy/Molecular Spectroscopy via Radio Telescopes

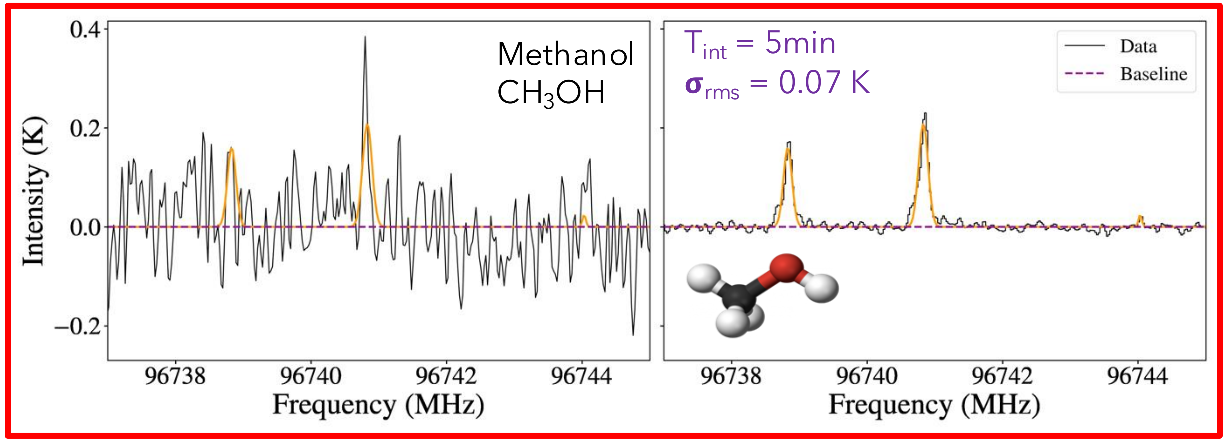
ROTATIONAL STATES

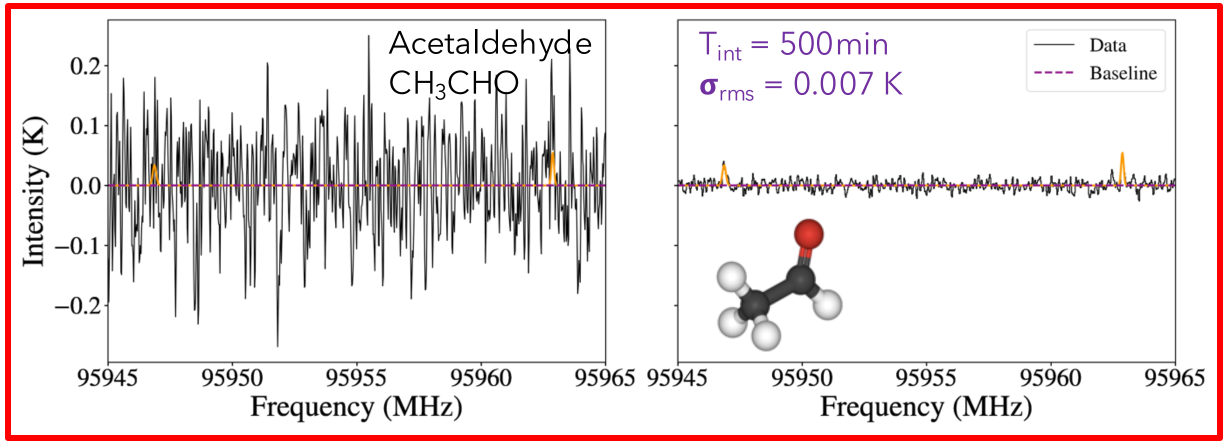
For a 10x better signal-to-noise, need to integrate 100x longer!

- Radio spectrometers measure the **spectral pattern** of individual rotational transitions!
- The time to integrate is defined by the radiometer equation, where the **signal-to- noise level, σ_{rms}, is proportional to the square root of the integration time, t_{int}**

$$t_{int} = \frac{T_{sys}^2 C}{\sigma_{rms}^2 R}$$

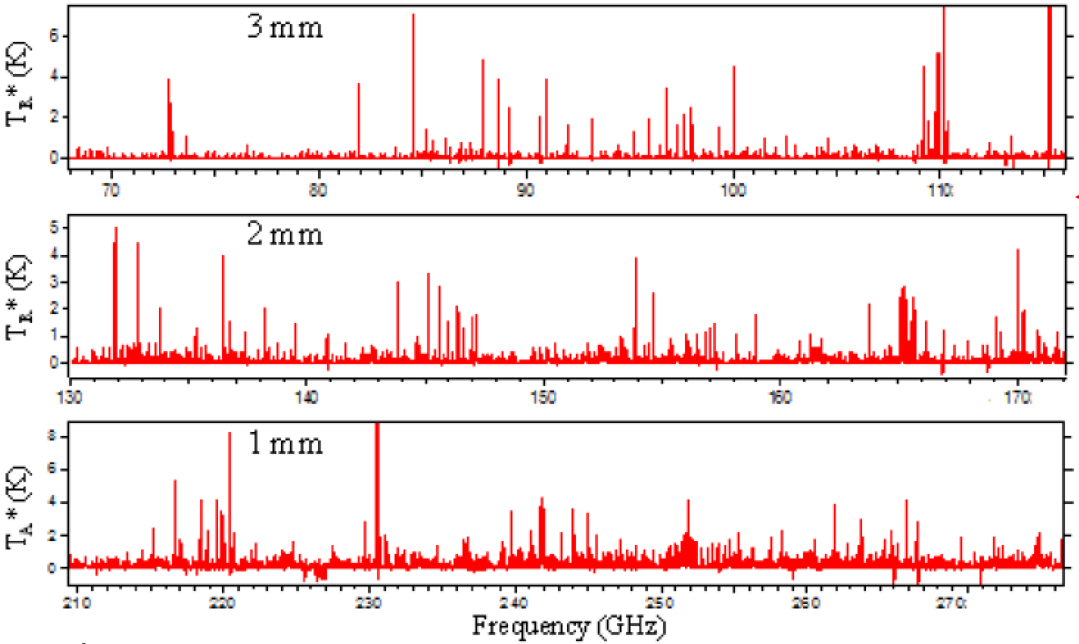
- σ_{rms} = rms noise in observation
- C is sensitivity constant ~x2 because half of the time is spent off the source
    - off-source = position switch
    - off-frequency = frequency switch
- T_{sys} = system temperature (contributes to 'noise')
- R = bandwidth, i.e., frequency range observed



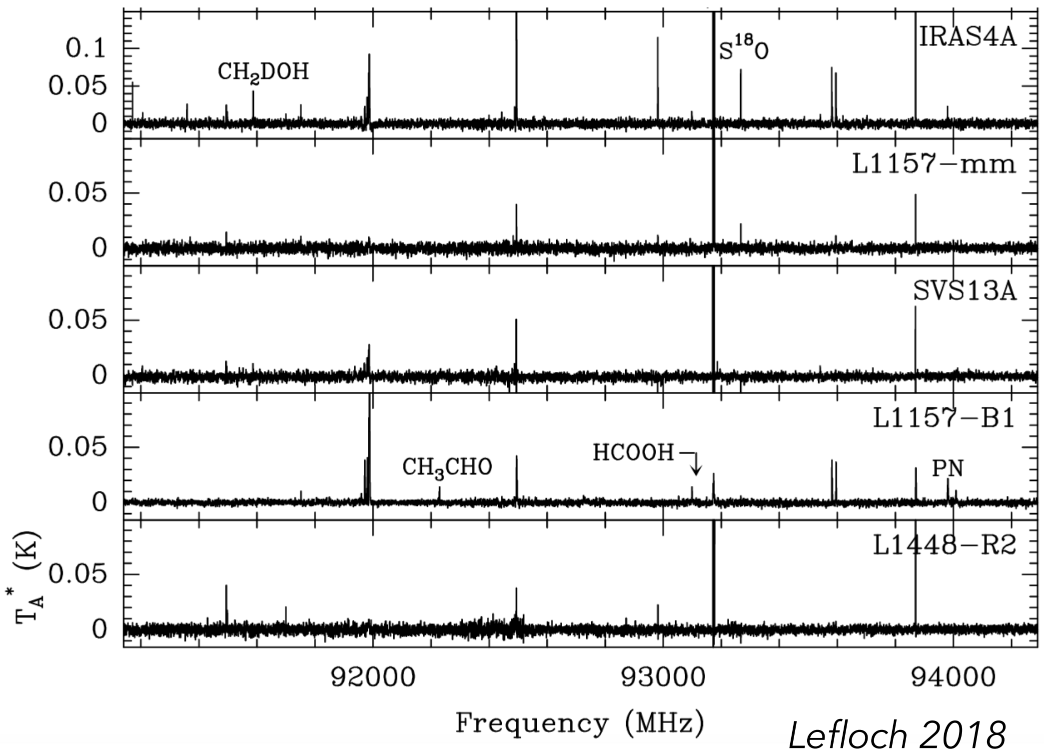


Scibelli & Shirley 2020

Rotation Spectroscopy/Molecular Spectroscopy via Radio Telescopes

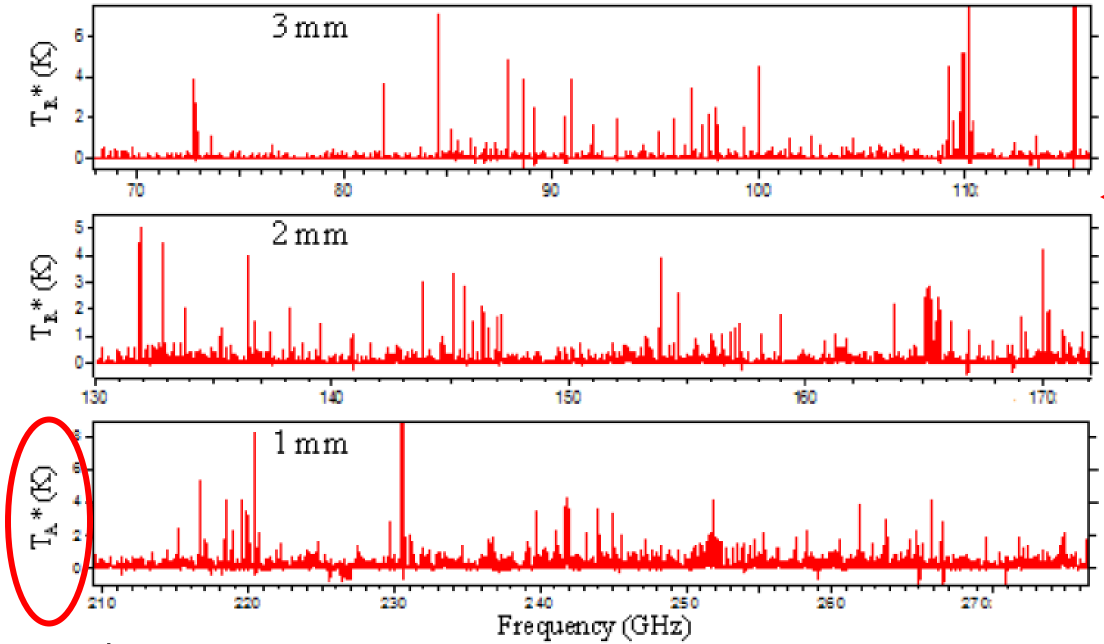


Credit: L. Ziurys



Lefloch 2018

Rotation Spectroscopy/Molecular Spectroscopy via Radio Telescopes



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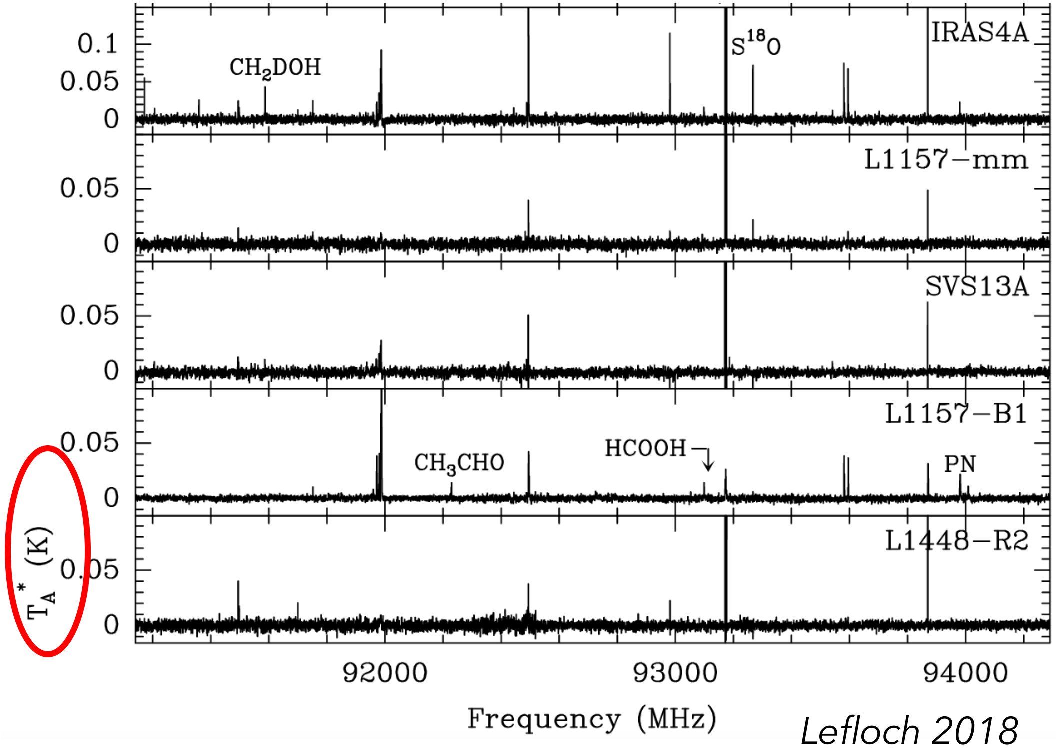


Lefloch 2018

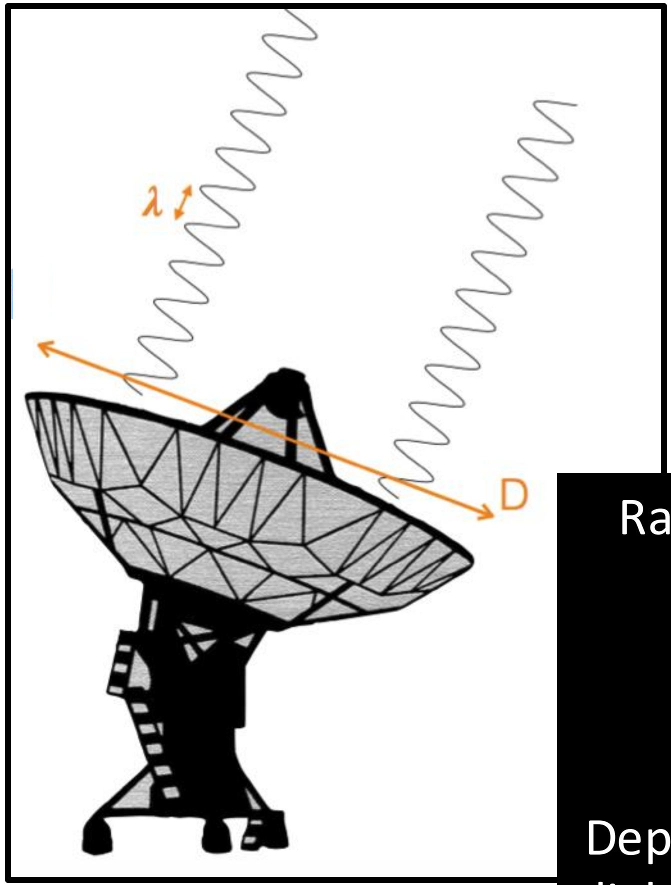
Unit for the power output per unit frequency of a receiving antenna is the 'Antenna temperature', T_A^*. It is the temperature of a resistor whose thermal power per unit frequency would be the same as that produced by the antenna:

$$T_A^* = P_\nu / k$$

$T_A^* = 1$ K corresponds to $P_\nu = kT_A^* = 1.38 \times 10^{-23}$ W Hz^{-1} (where k = boltzmann constant [W Hz^{-1} / K])

Rotation Spectroscopy/Molecular Spectroscopy via Radio Telescopes

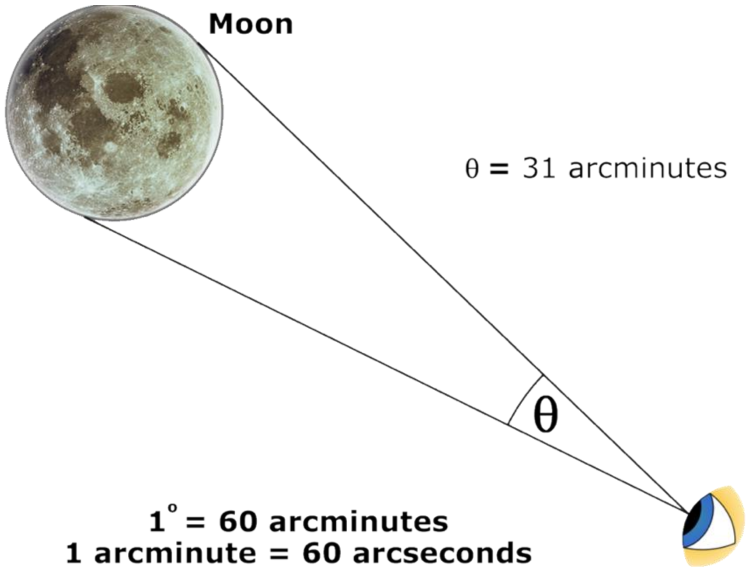
The collecting area of these radio telescopes is dependent on the wavelength of incoming light and the size of the telescope!



Radio telescopes have a ***resolution***:

$\theta \sim \lambda / D$

Depends on **wavelength** of light and **size of telescope**

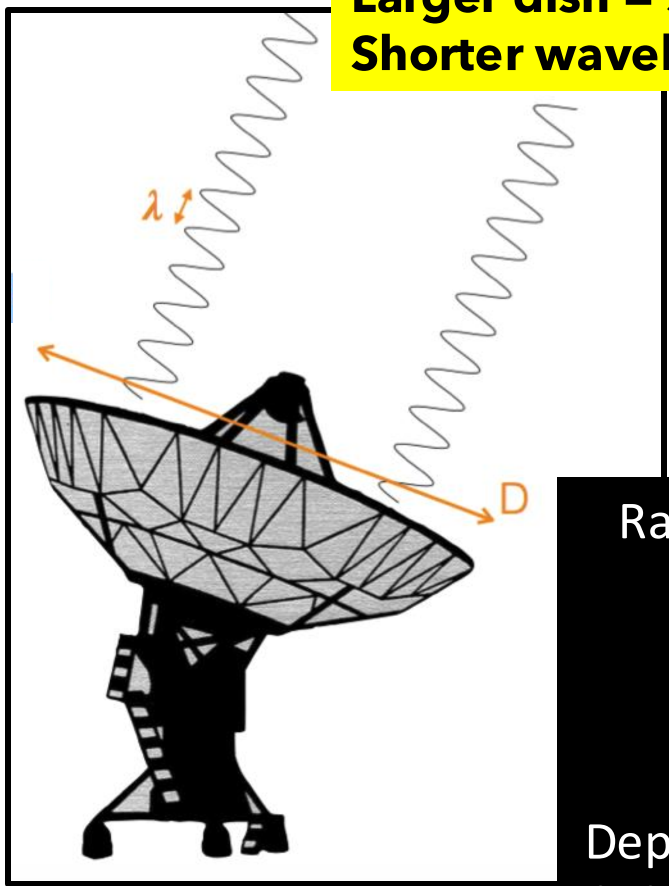


Note: 1 radian = (3600 × 180)/π = 206265"

Rotation Spectroscopy/Molecular Spectroscopy via Radio Telescopes

The collecting area of these radio telescopes is dependent on the wavelength of incoming light and the size of the telescope!

Larger dish = smaller beam
Shorter wavelength = smaller beam



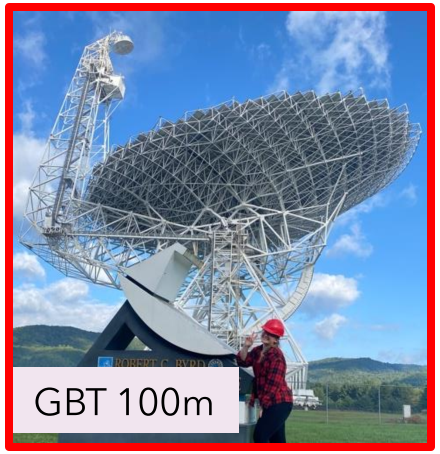
Radio telescopes have a ***resolution***:

$$\theta \sim \lambda / D$$

Depends on **wavelength** of light and **size of telescope**

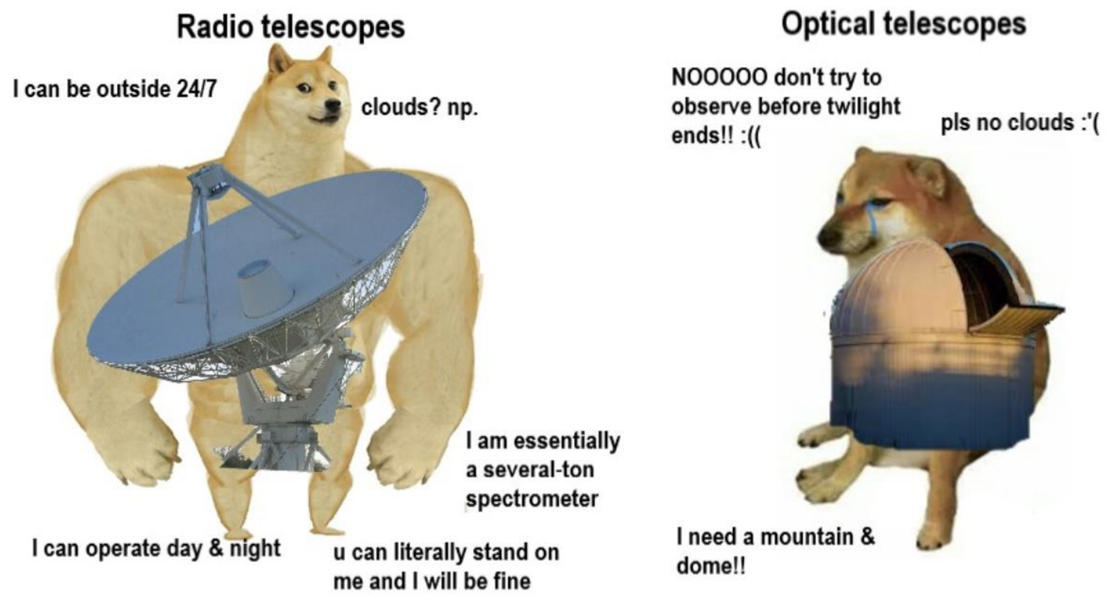
@ 3mm

@ 3mm

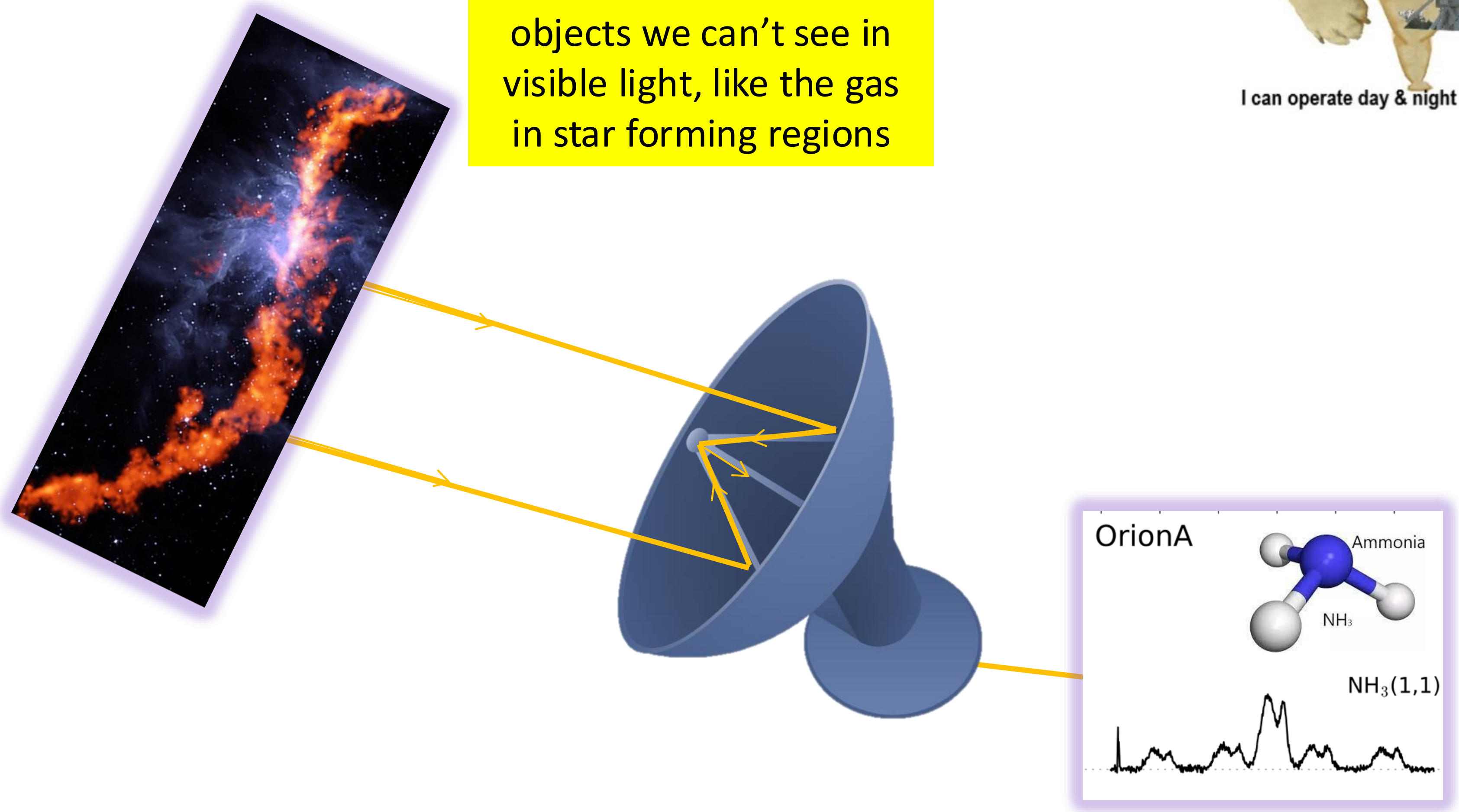


@ 3mm

Submillimeter and Millimeter Radio Telescopes Identify Molecules via Rotational Spectroscopy!



Radio waves let us see objects we can't see in visible light, like the gas in star forming regions



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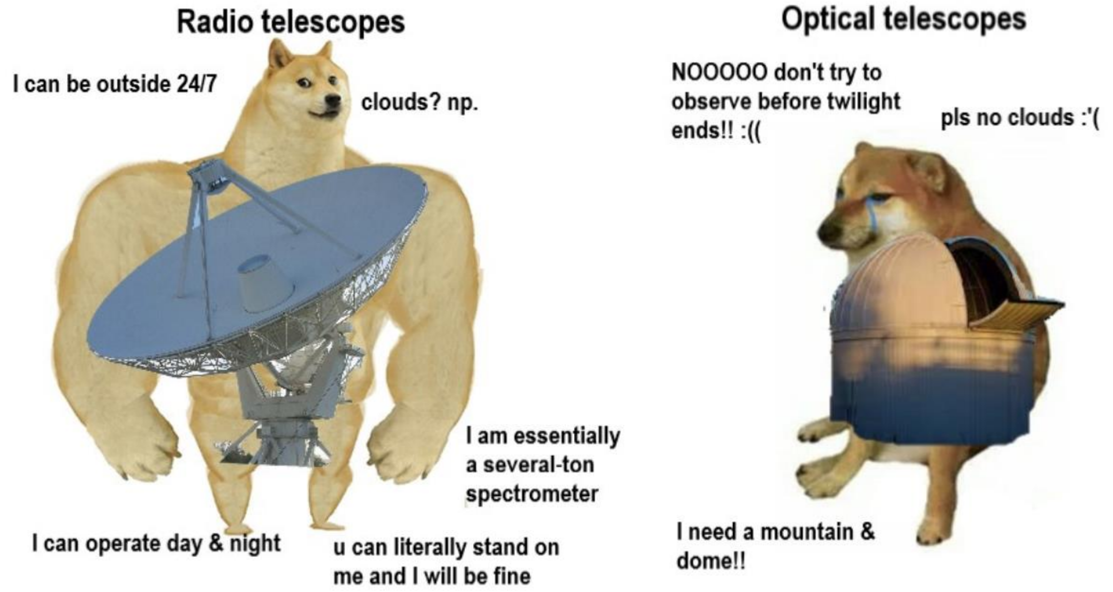

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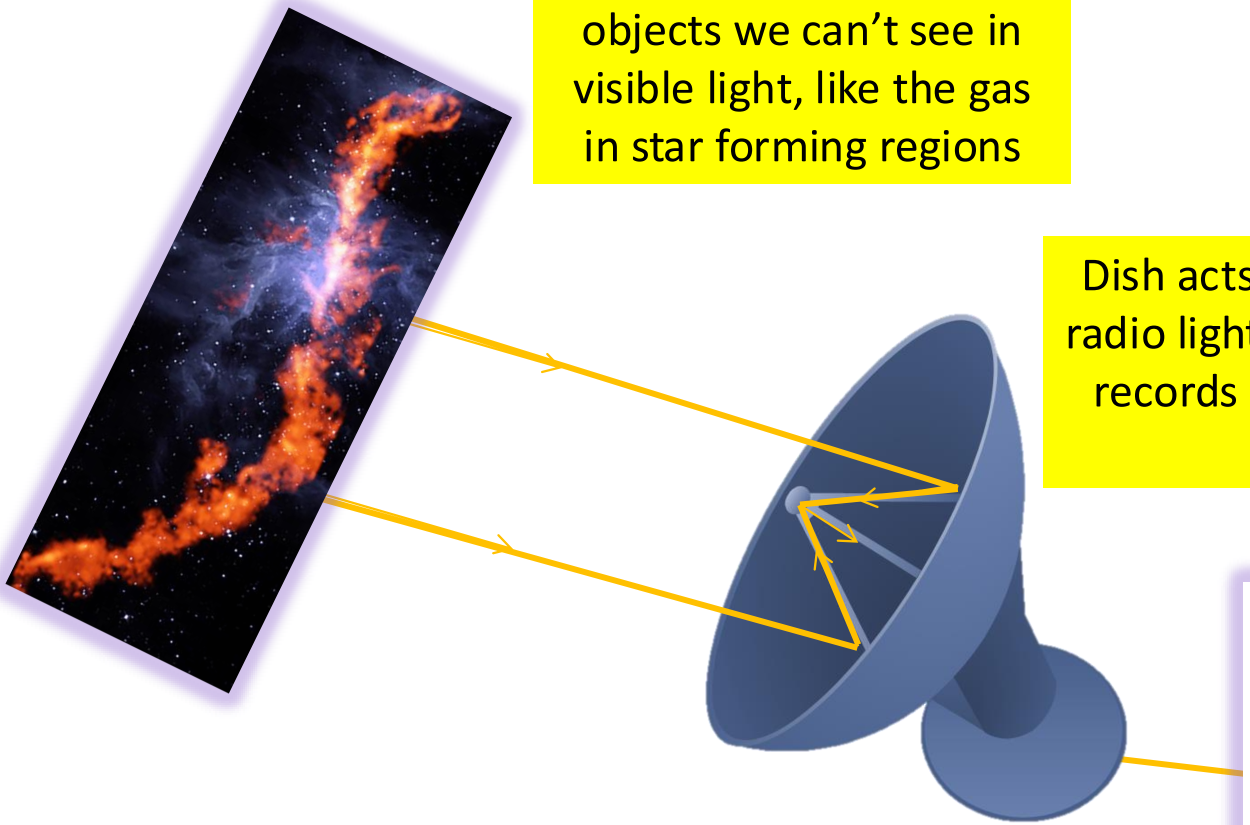
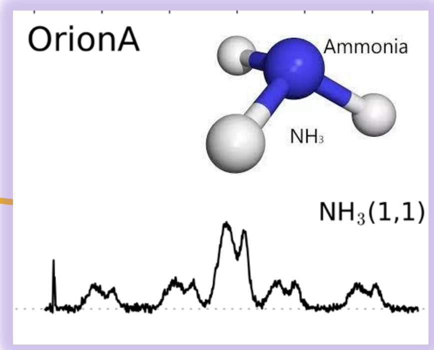
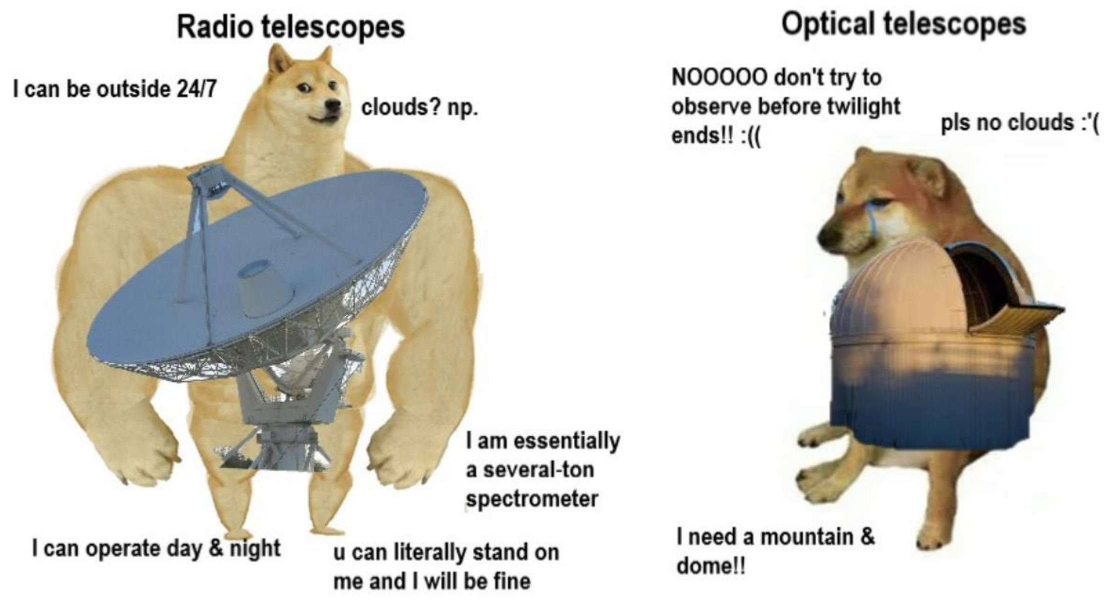


Dish acts like a mirror and focuses long wavelength radio light onto electronic device that receives it and records an objects' ***spectrum***, i.e., it's intensity vs. frequency (or wavelength)



Submillimeter and Millimeter Radio Telescopes Identify Molecules via <u>Rotational Spectroscopy</u>!



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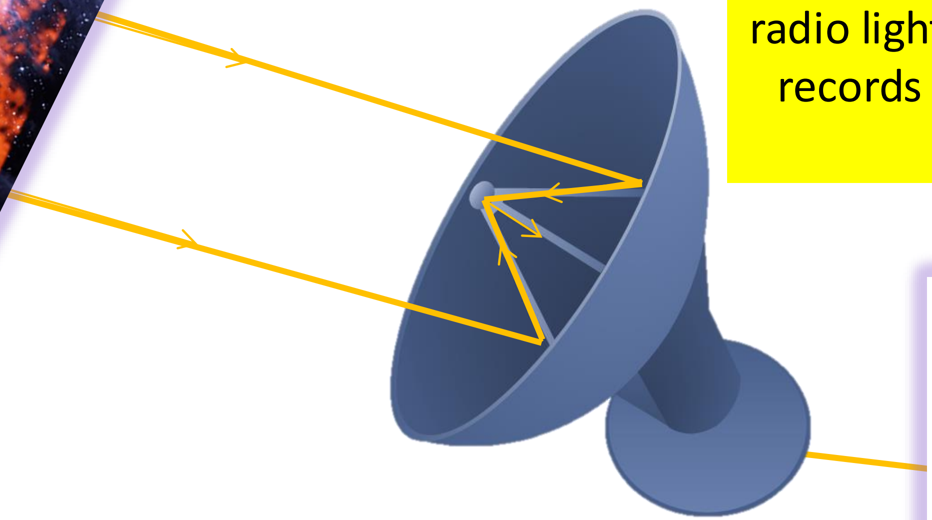

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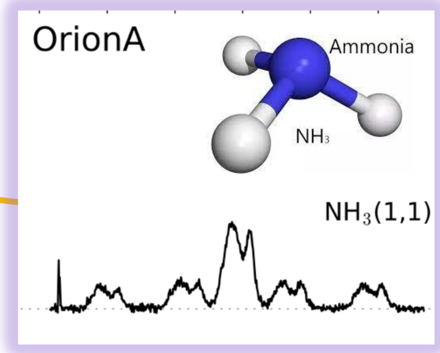
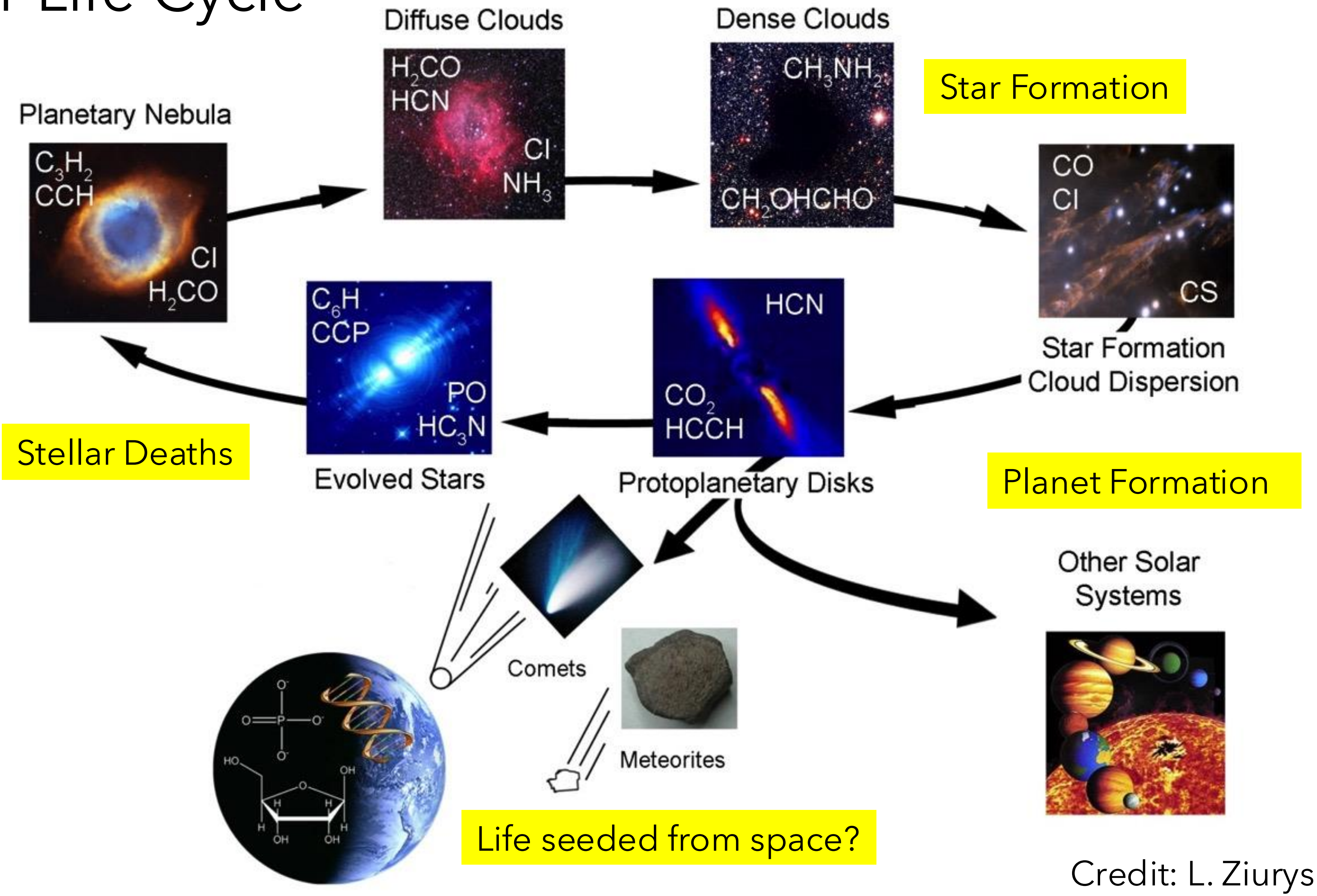


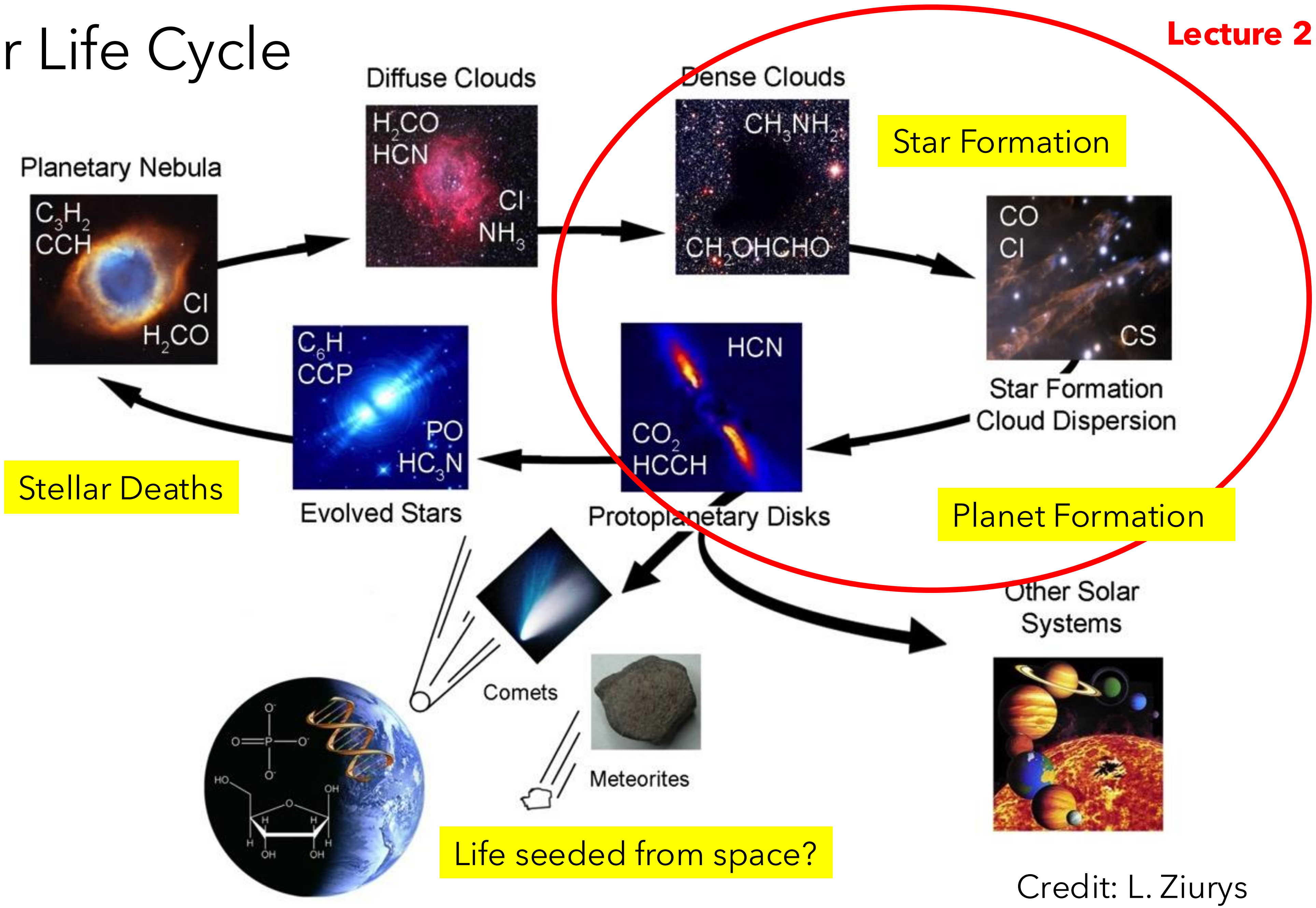
We know if a bright line occurs where a certain molecule is predicted to emit at, **we have identified that molecule**!

Molecular Life Cycle



Credit: L. Ziurys

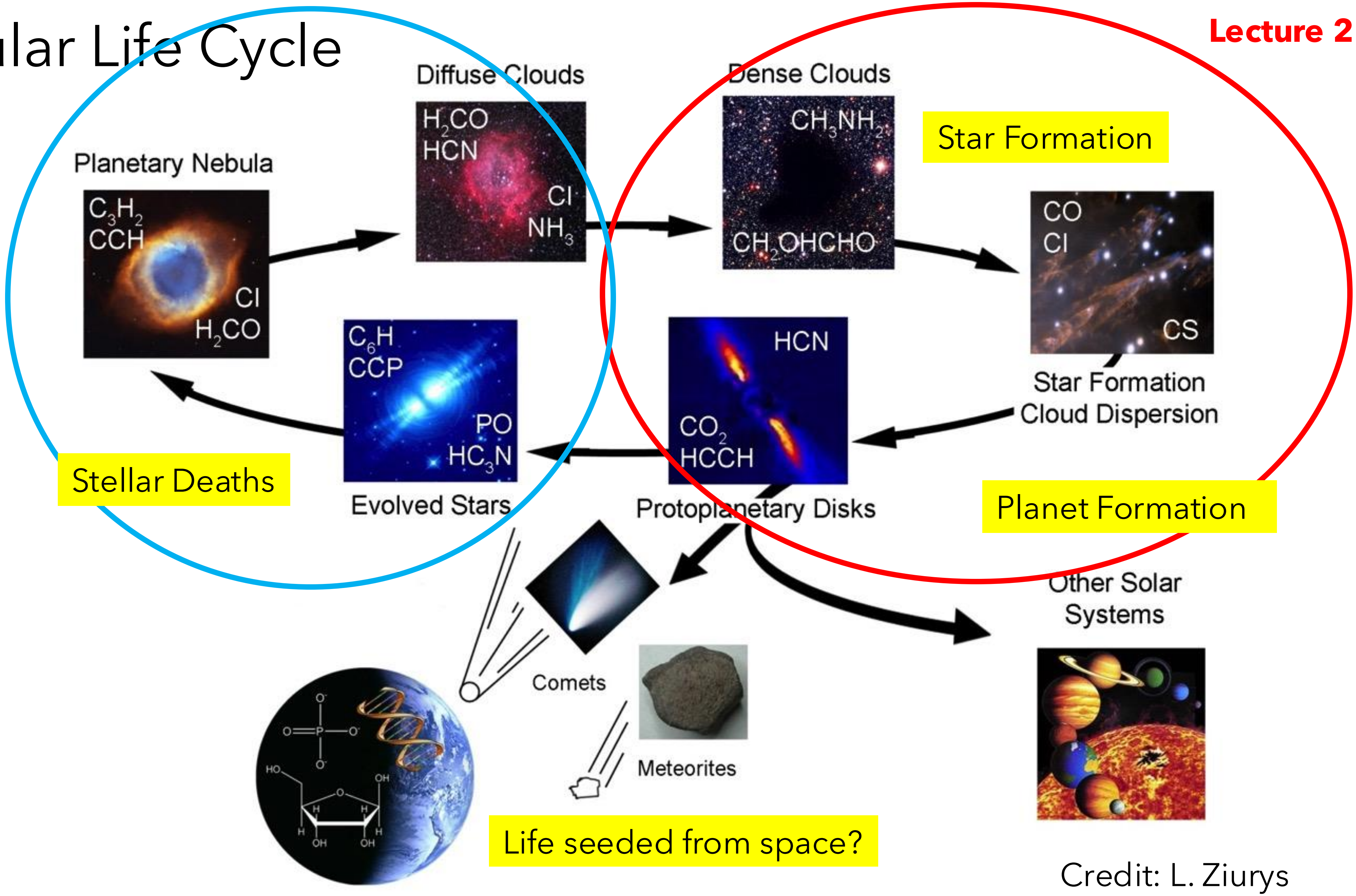
Molecular Life Cycle



Credit: L. Ziurys

Molecular Life Cycle

Lecture 3



Credit: L. Ziurys

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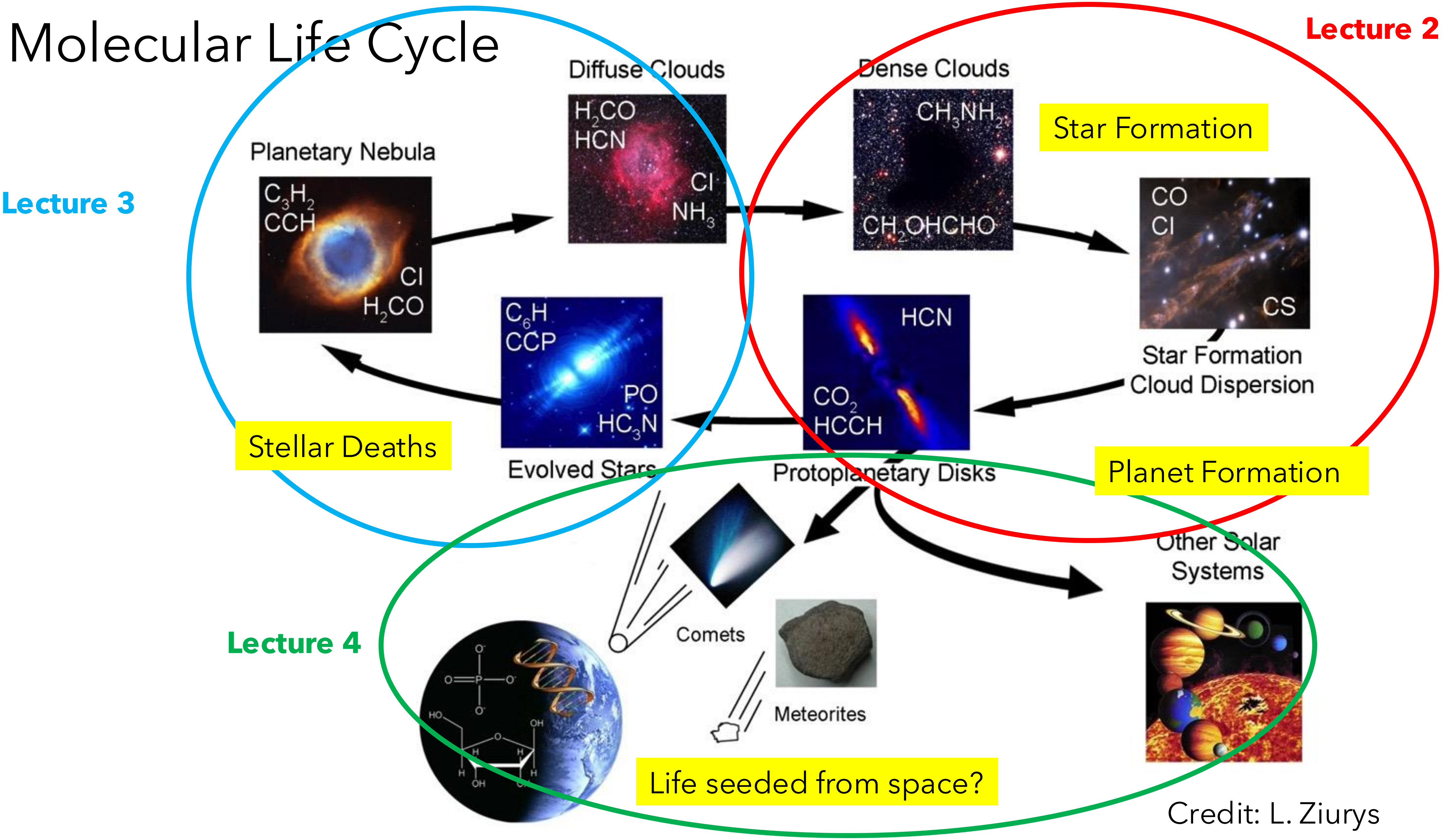

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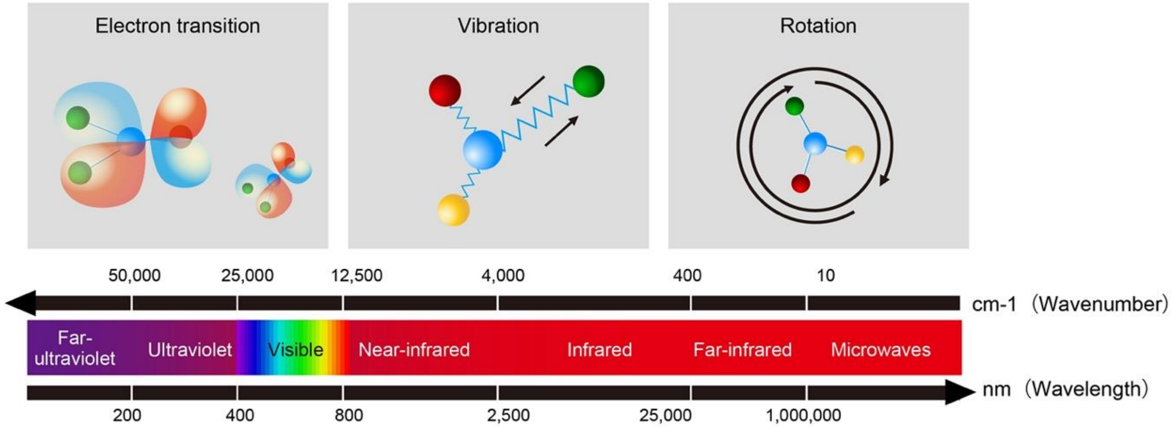
SUMMARY:



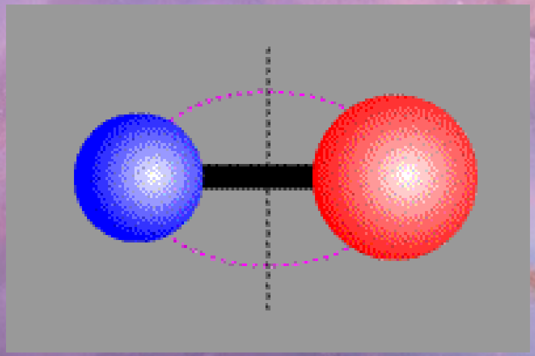
- **Astrochemistry is an interdisciplinary field** that studies "the formation and destruction of **molecules** in the Universe, their interaction with radiation and their feedback on the physics of the environments"

- More than 300 molecules have been detected in space so far, and **> 90% of molecular detections are from radio astronomy observations!**

- In addition to allowing us to probe different physical conditions across our universe, **it is possible to study the increasing complexity of different molecules in various environments,** letting astrochemists better understand, for example, the *formation of complex organic molecules (COMs) that may be precursor to molecules important for the emergence of life on Earth*

- It is through spectroscopy that we can observe these large molecule in space, and it is **rotational spectroscopy**, or molecular spectroscopy, at submillimeter and millimeter wavelengths that allow us to **detect these heavier/larger molecules in cold interstellar gas**

- **Submillimeter and millimeter radio telescopes are powerful instruments** that let observational astrochemists (like myself) study the properties of interstellar molecules in high detail!



Questions?


ROBERT C. BYRD
GREEN BANK TELESCOPE
Dedicated August 25, 2000 Green Bank, West Virginia