A Brief History of Chemistry in the Cosmos

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Columbia University

Outline

Let there be light

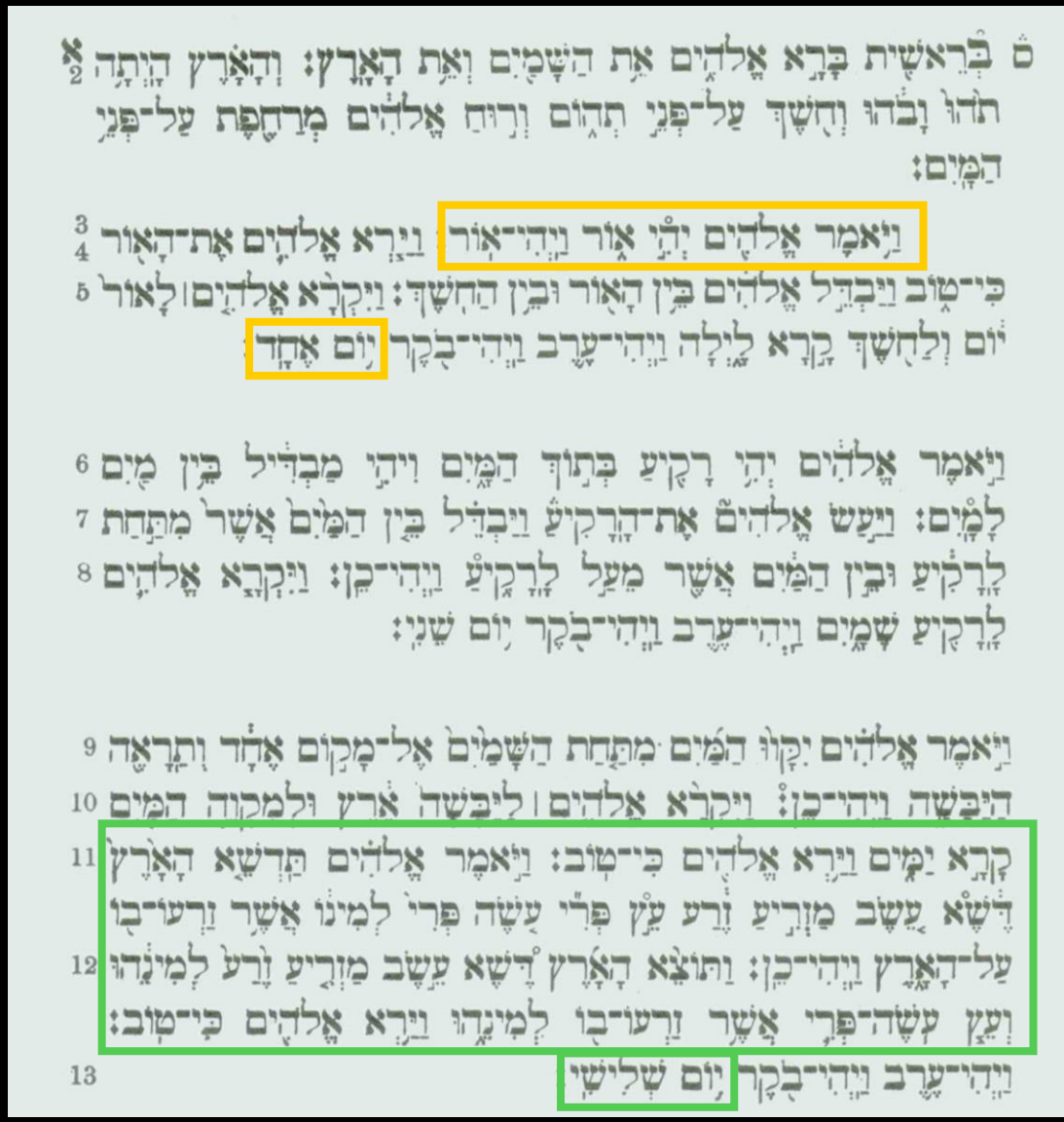
$H^- + H \rightarrow H_2 + e^-$

- Motivation
- D1 Experiment
- Results

Let there be life

$C + H_3^+ \rightarrow COMs$

- Motivation
- D3 Experiment
- Results



Science is answering questions that humanity has pondered for millennia.

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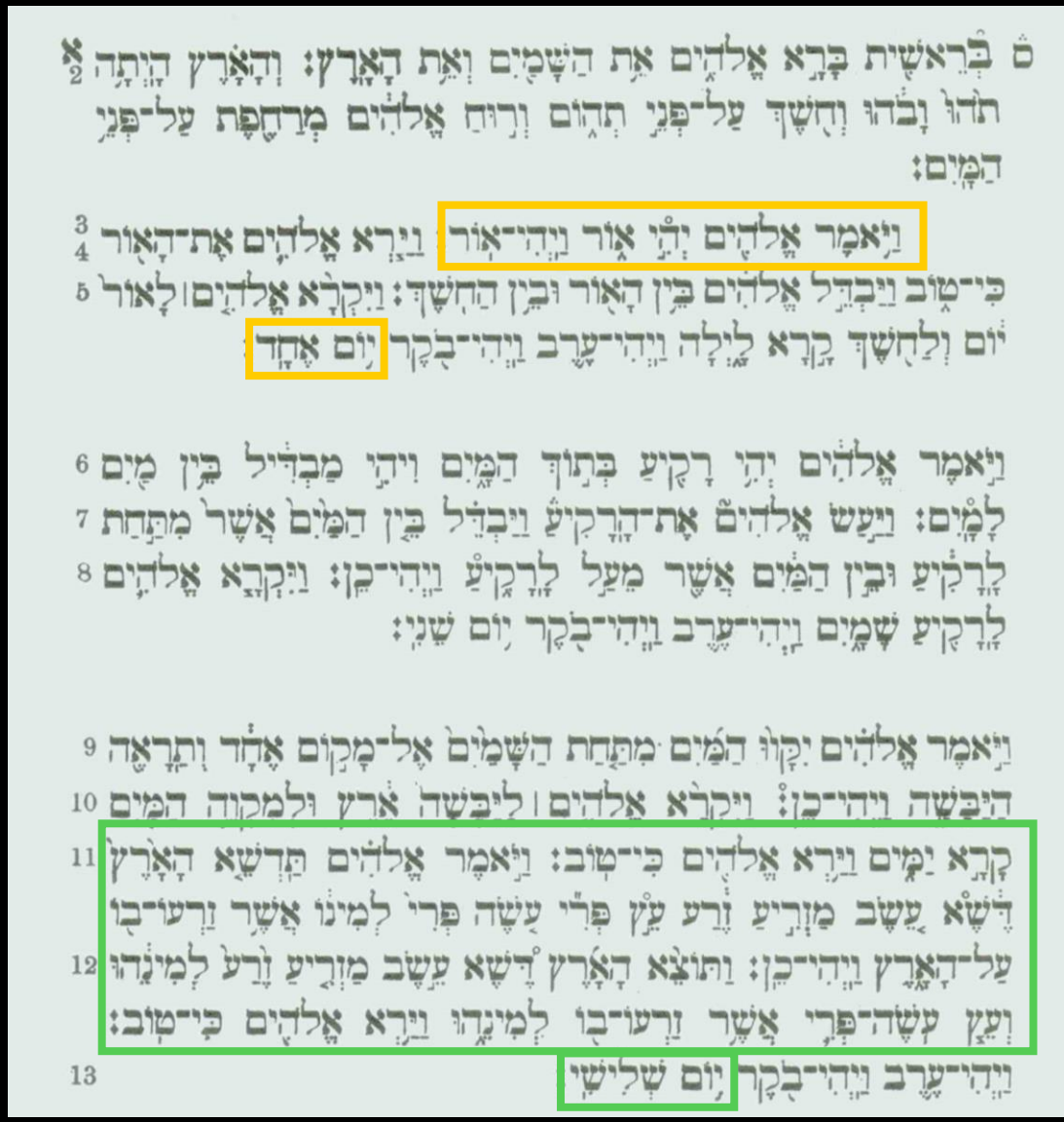
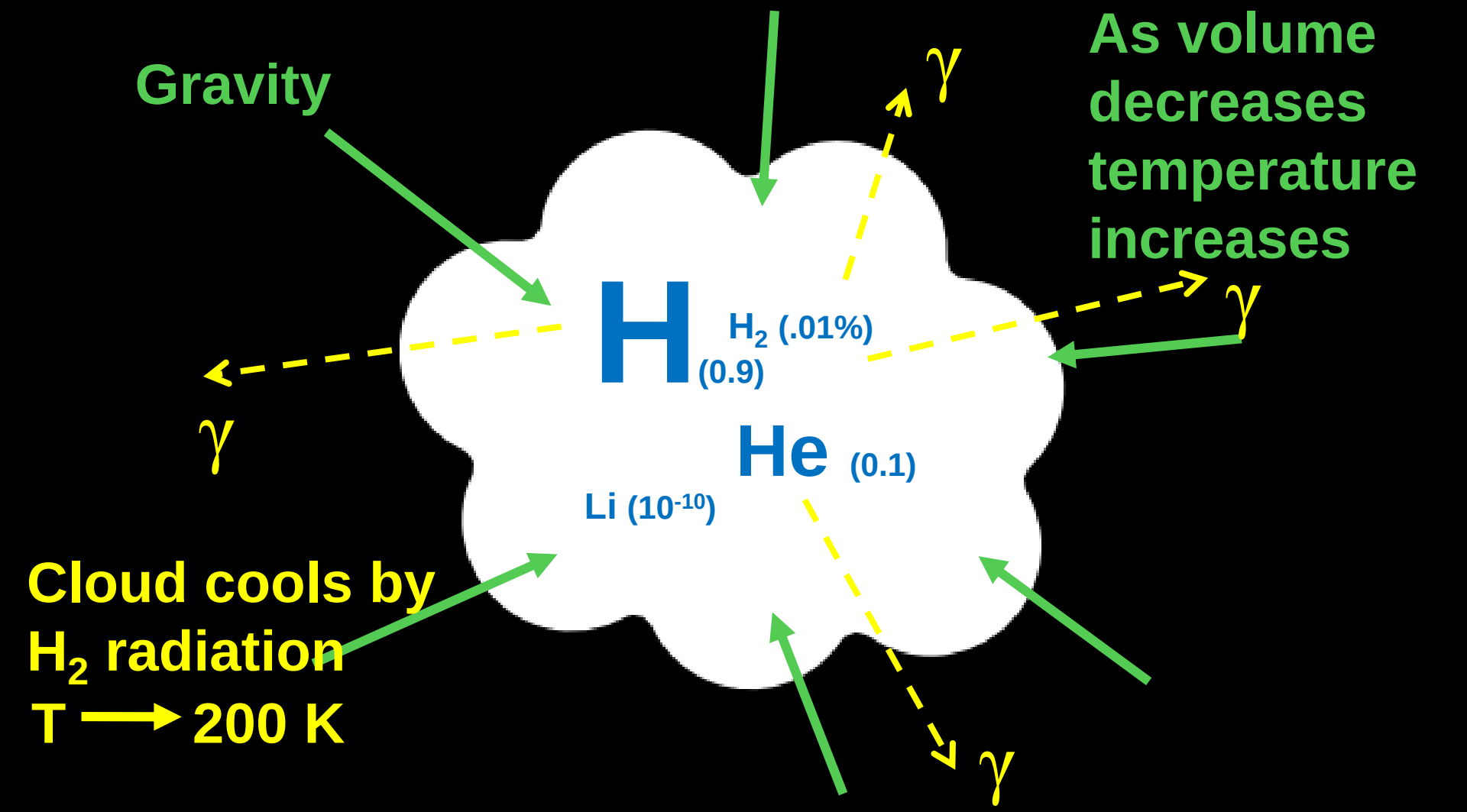
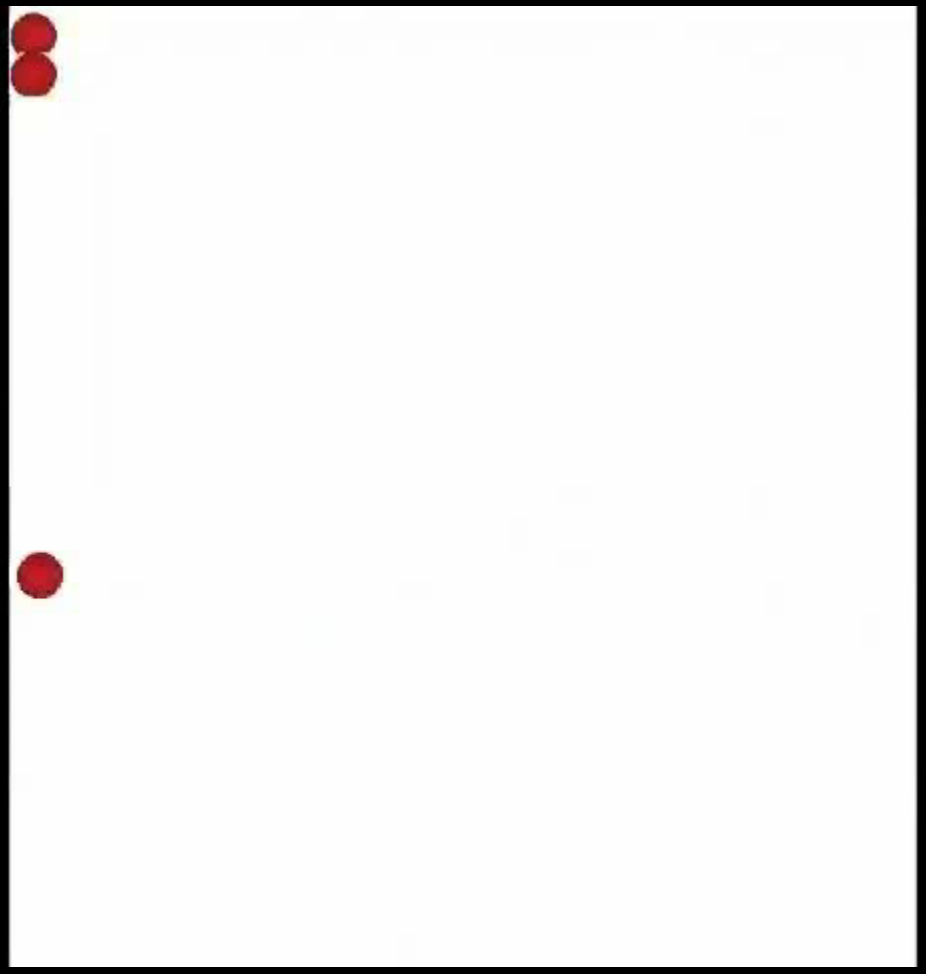


Structure formation in the early universe



How H_2 radiatively cools the gas down to temperature of T ~ 200 K



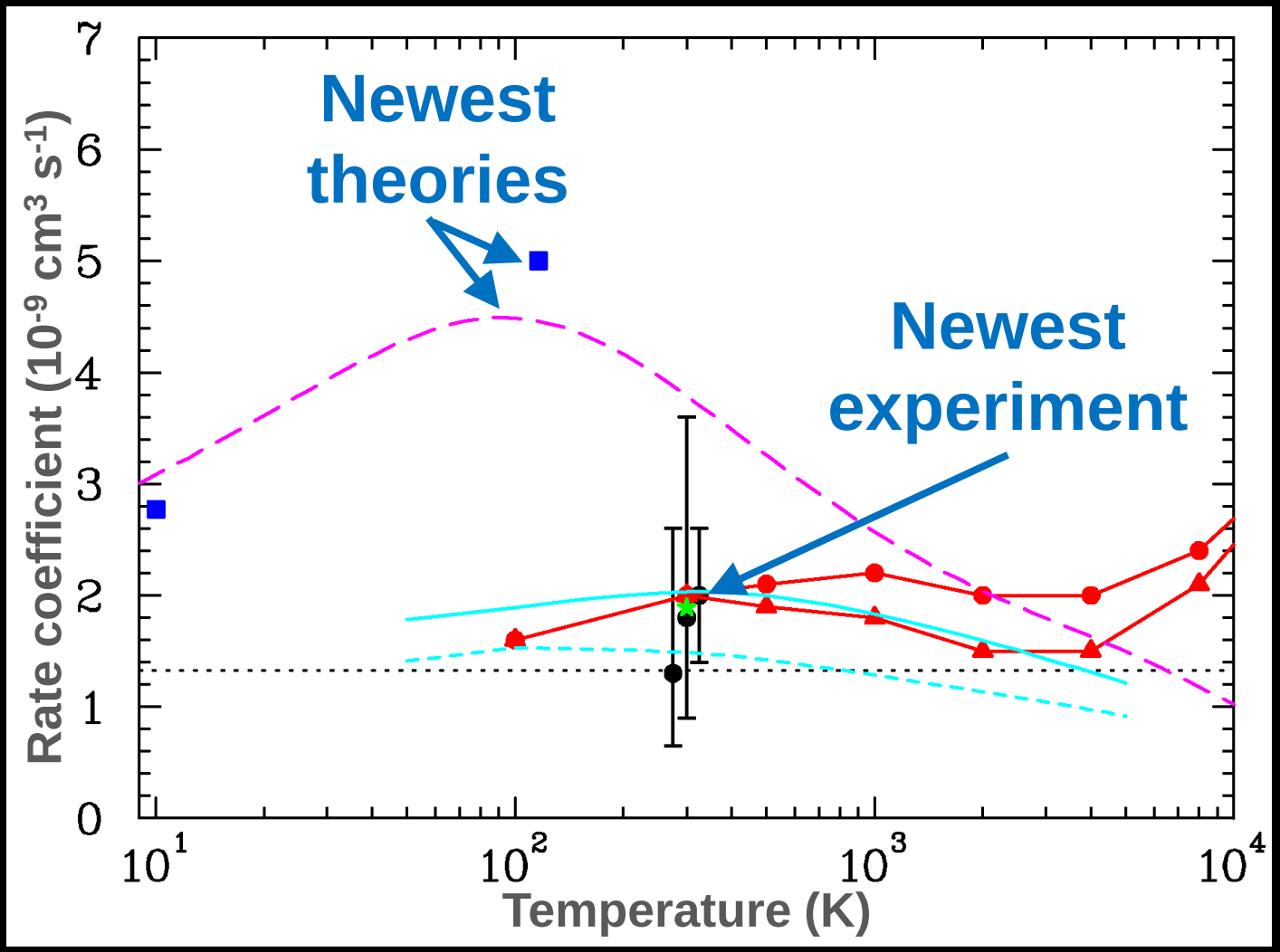
H_2 Formation during Epoch of Protogalaxy and First Star Formation

Associative detachment (AD)

$$H^- + H \rightarrow H_2 + e^-$$

This was not well understood before we started.

Published kinetics for $H^- + H \rightarrow H_2 + e^-$



There is nearly an order of magnitude spread.

This has significant cosmological implications!

First Star Formation

Upper limit for stellar mass set by balance of outward pressure and inward gravitational force.

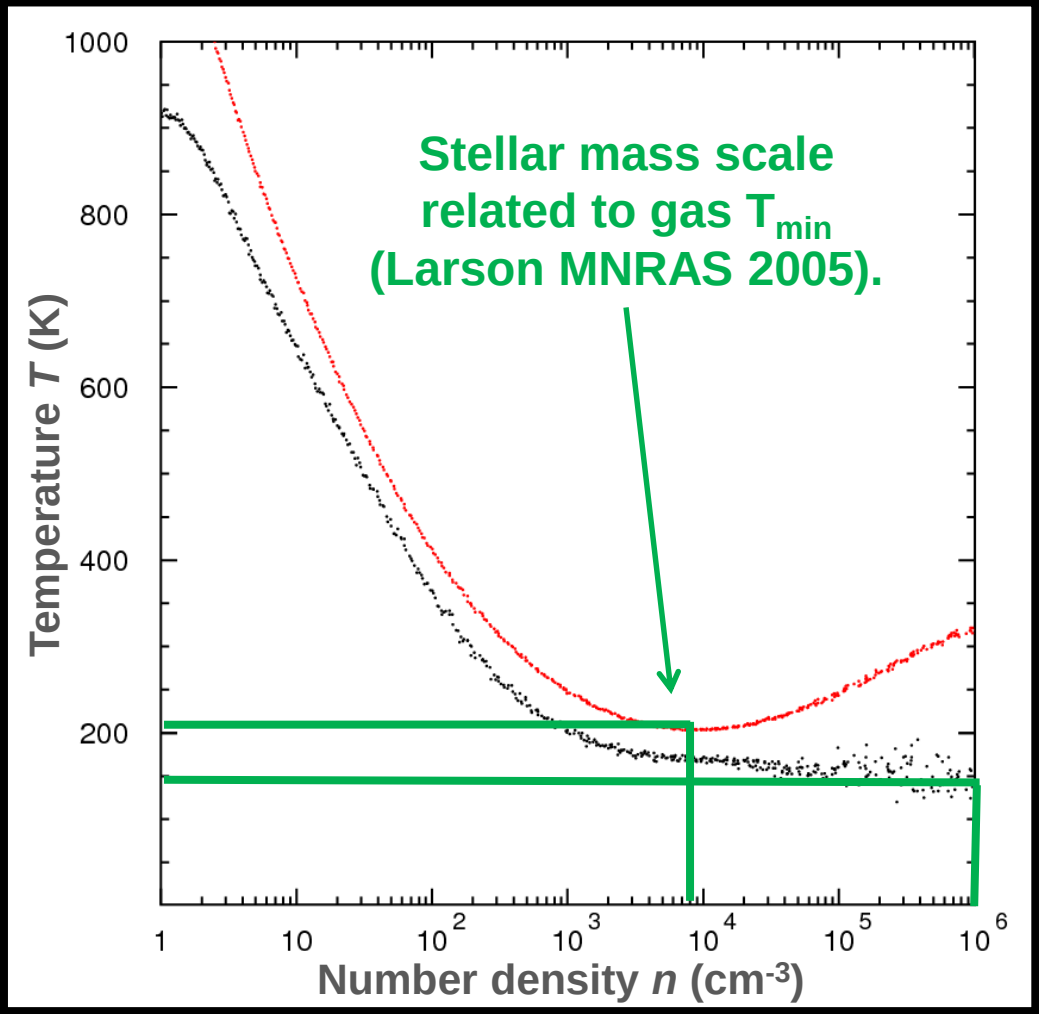
This hydrostatic equilibrium limit is commonly called the Jeans mass:

$$M_{\mathrm{J}} \propto \frac{T^{3/2}}{\sqrt{n}}$$

Uncertainties in M_{J} translate into uncertainties in predicted elemental yield from nucleosynthesis.

Implications for First Star Formation

- Initially ionized gas
- 3D simulation.
- Curves is for limits of $H^- + H \rightarrow H_2 + e^-$ rate coefficient.
- $M_J \propto T^{3/2} n^{-1/2}$
- M_J uncertain by factor of 20.



(Kreckel et al. 2010, Science, 329, 69)

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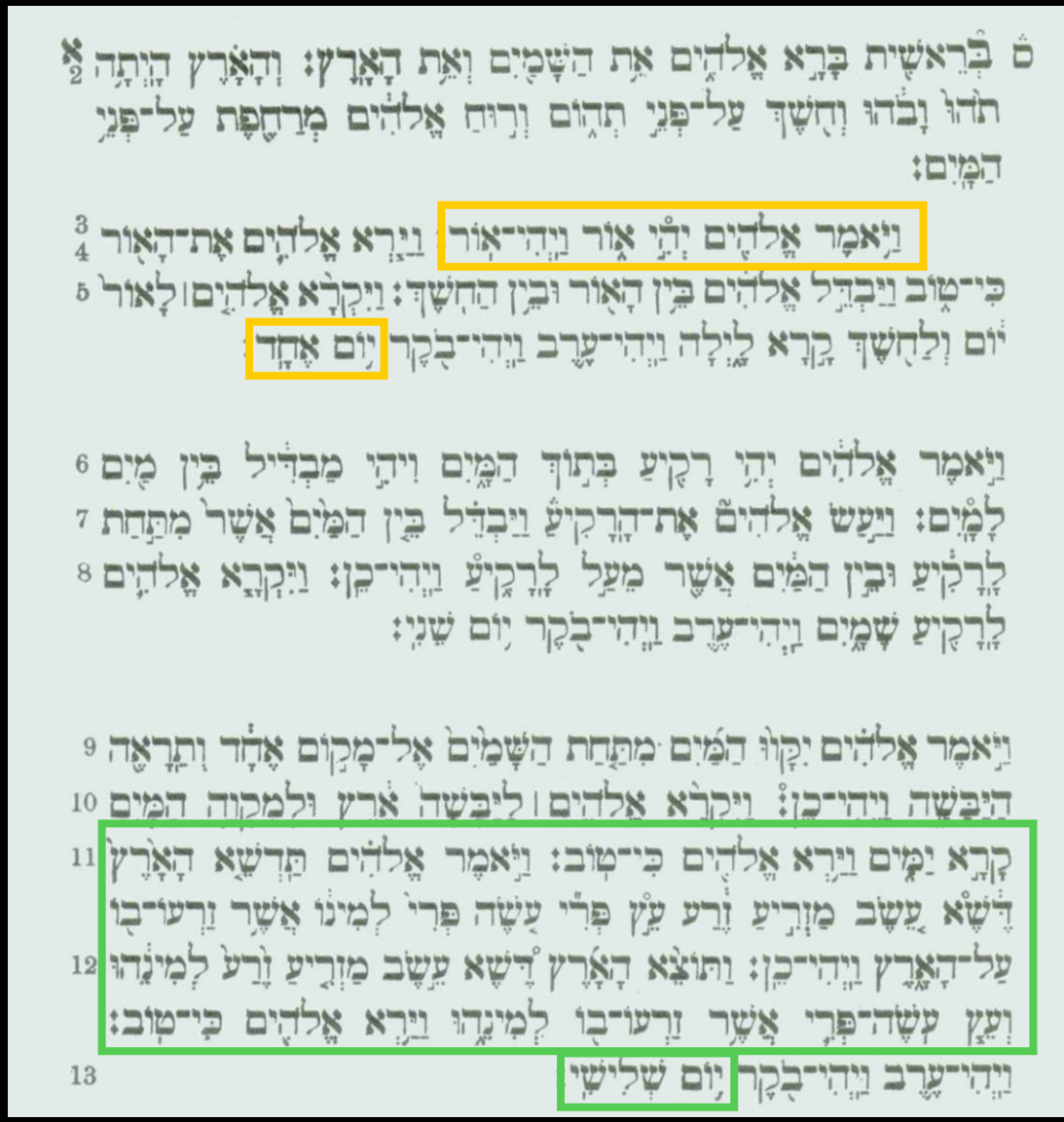
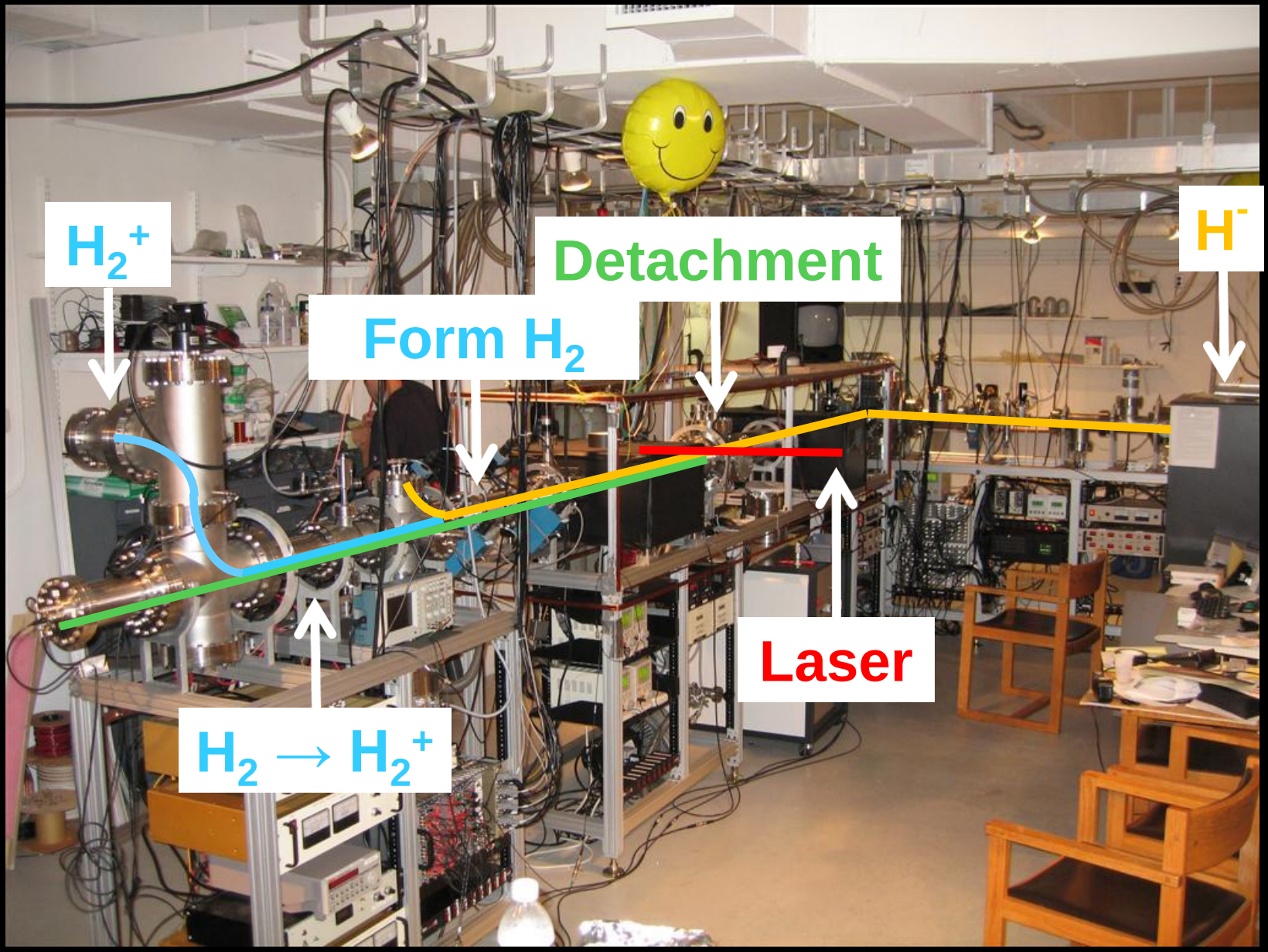
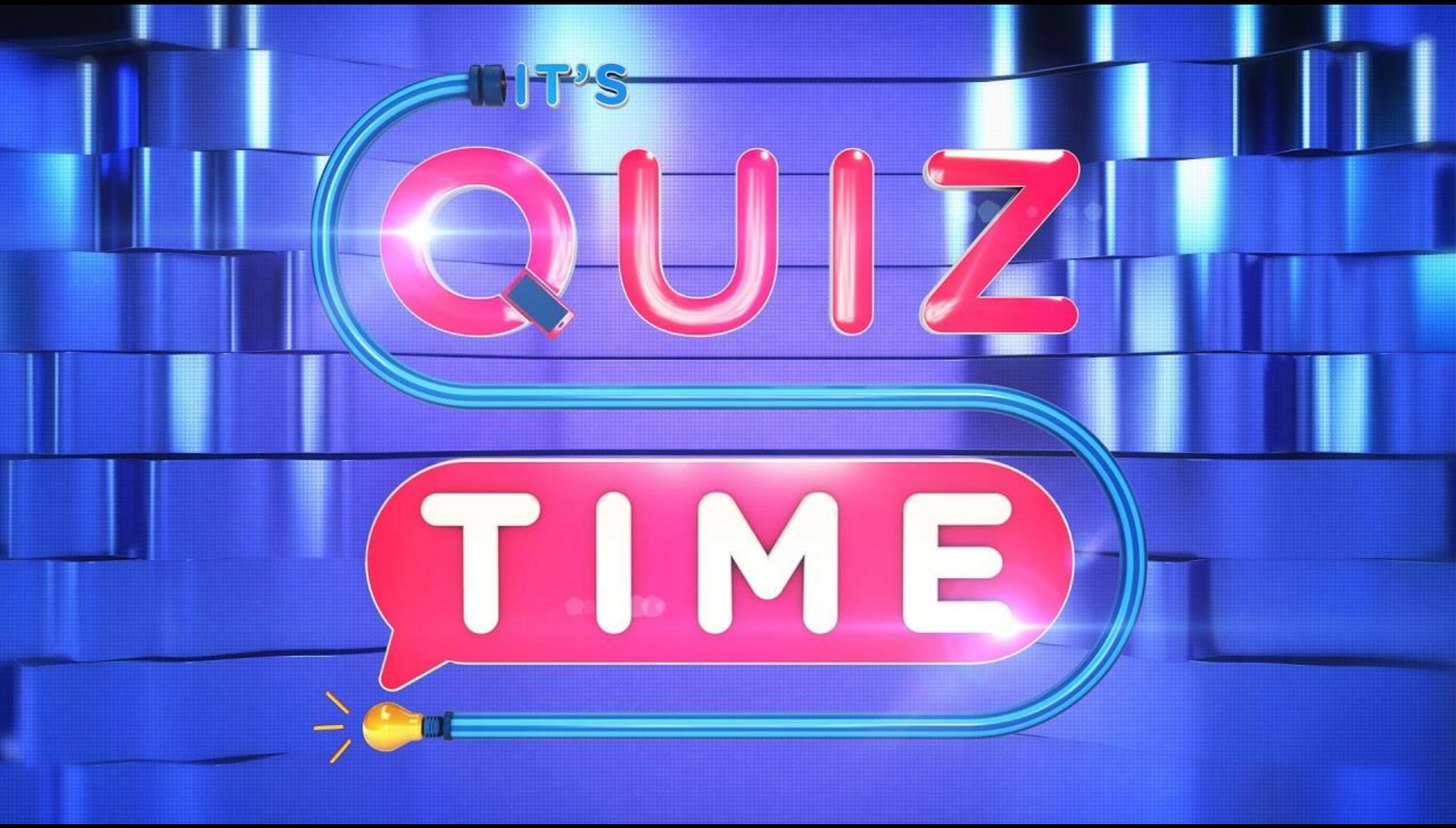
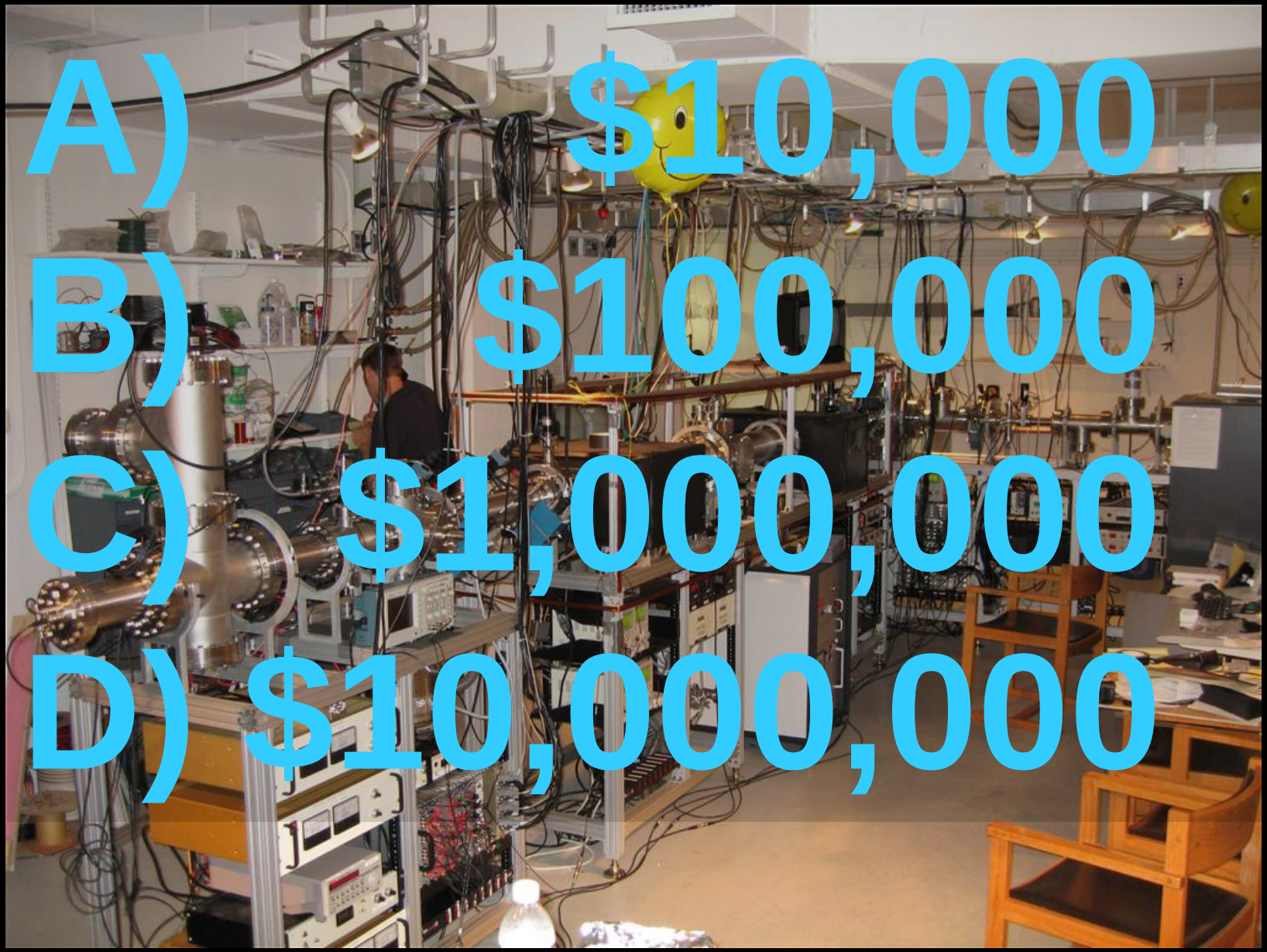


The apparatus the day after first signal




IT'S
QUIZ
TIME

How much did this cost?



A) $10,000

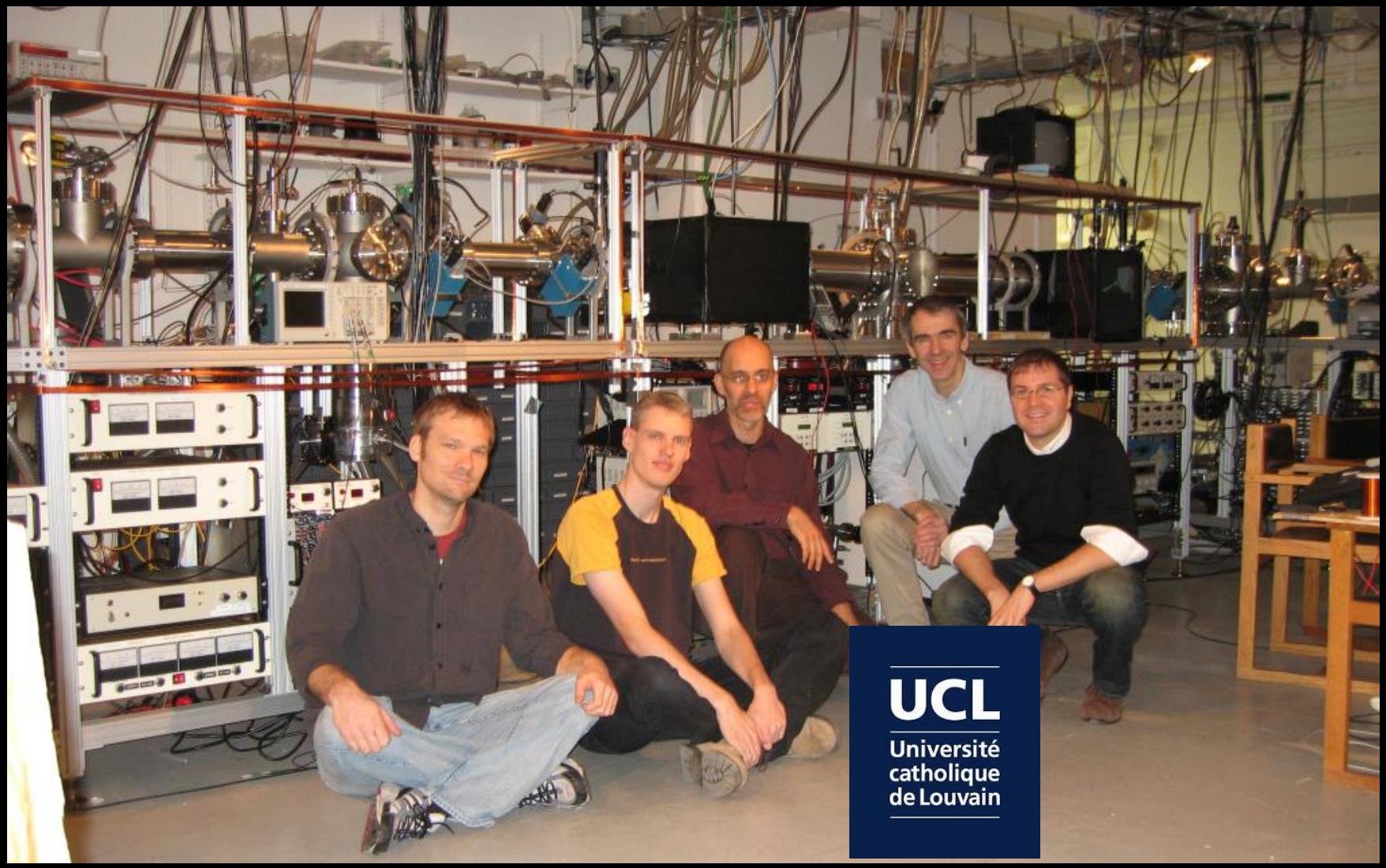
B) $100,000

C) $1,000,000

D) $10,000,000

How much did this cost?

The Team Members



K. A. Miller, H. Bruhns, DWS, X. Urbain, H. Kreckel

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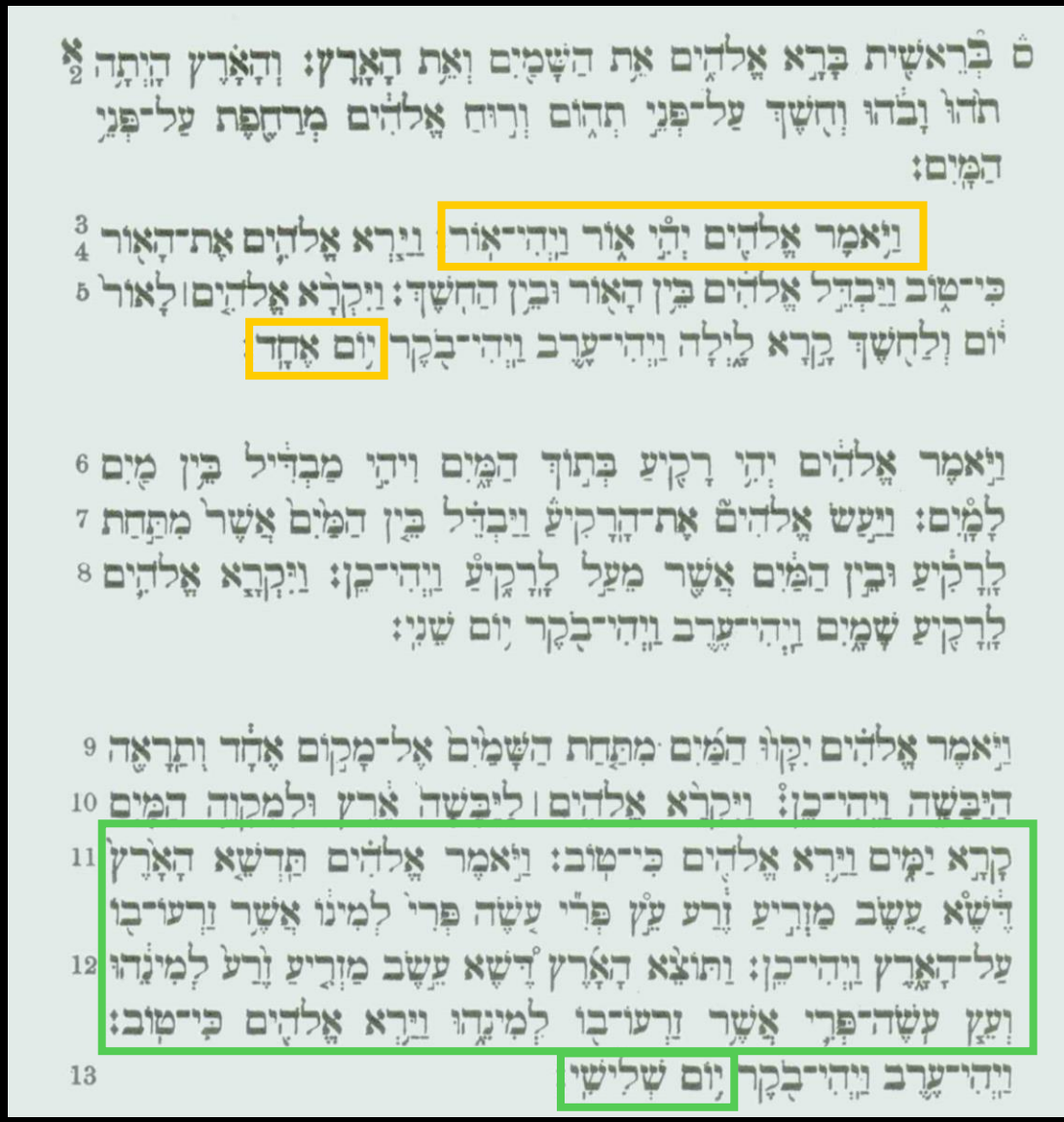
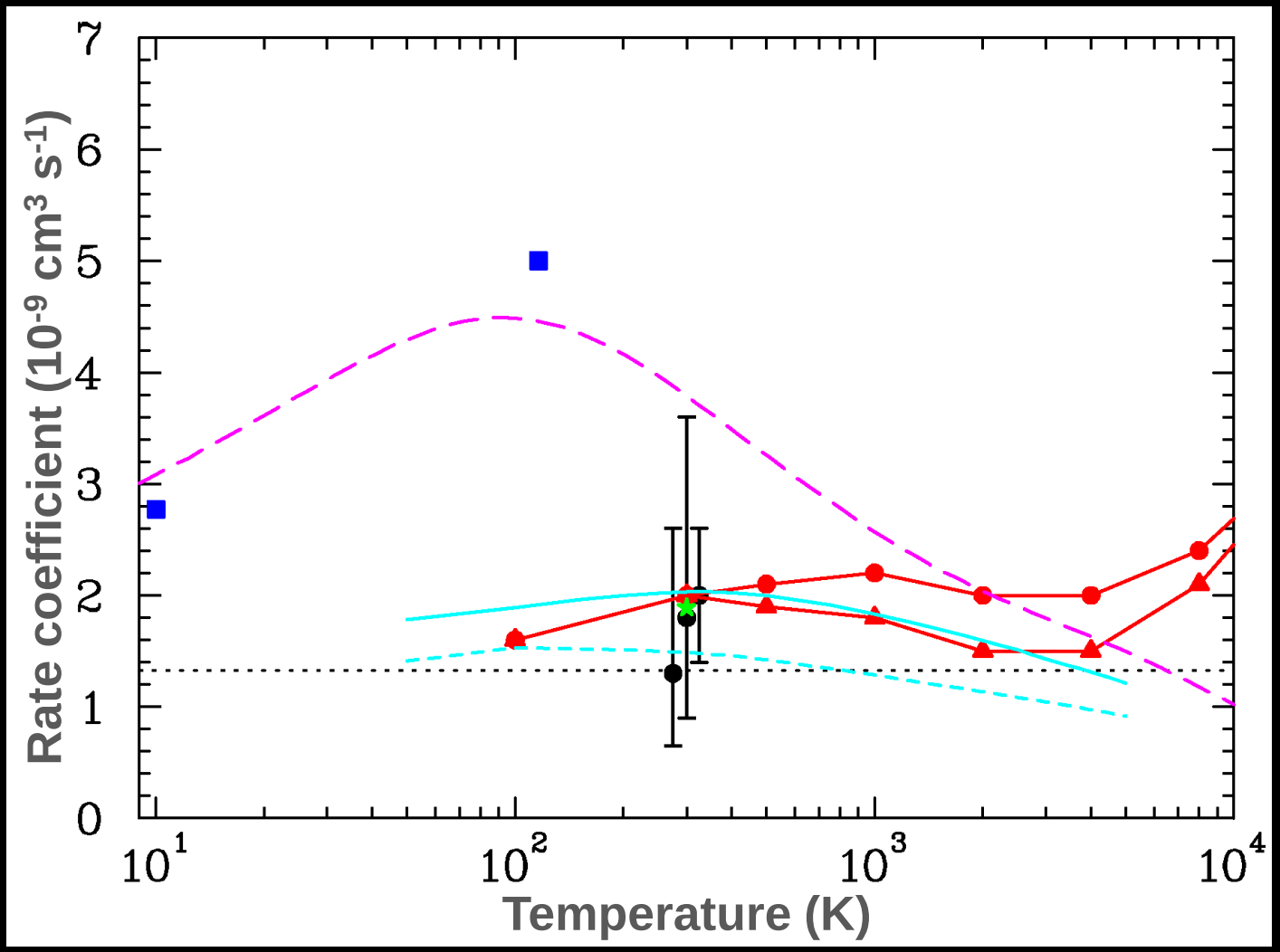
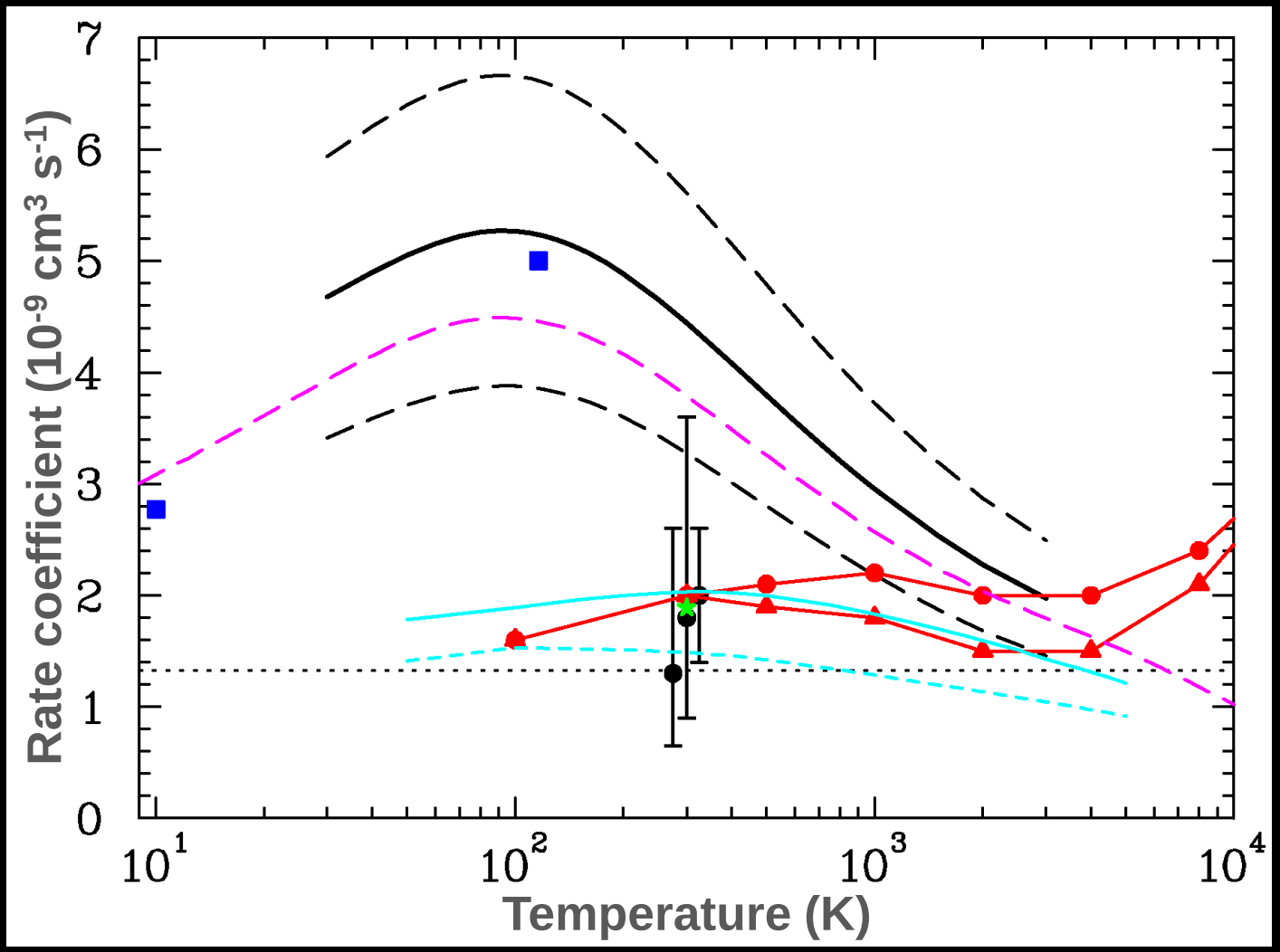


Kinetics data for $H^- + H \rightarrow H_2 + e^-$



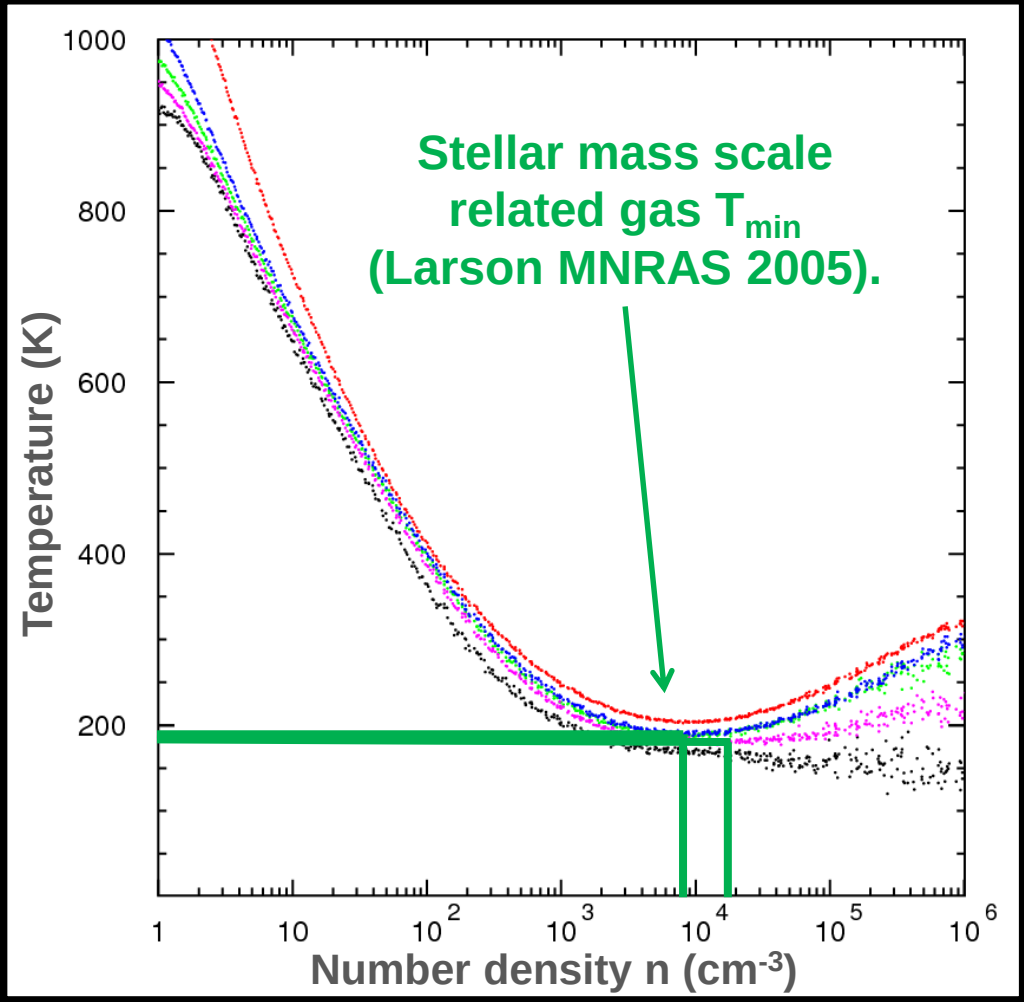
Adding in our results



Theory and experiment have finally converged.

Implications for First Star Formation

- Initially ionized gas
- 3D simulation.
- Red & black due to previous AD uncert.
- Other points show new ±25% uncert.
- M_J uncertainty goes from 20 to 2!



(Kreckel et al. 2010, Science, 329, 69)

Questions on First Half of Talk?

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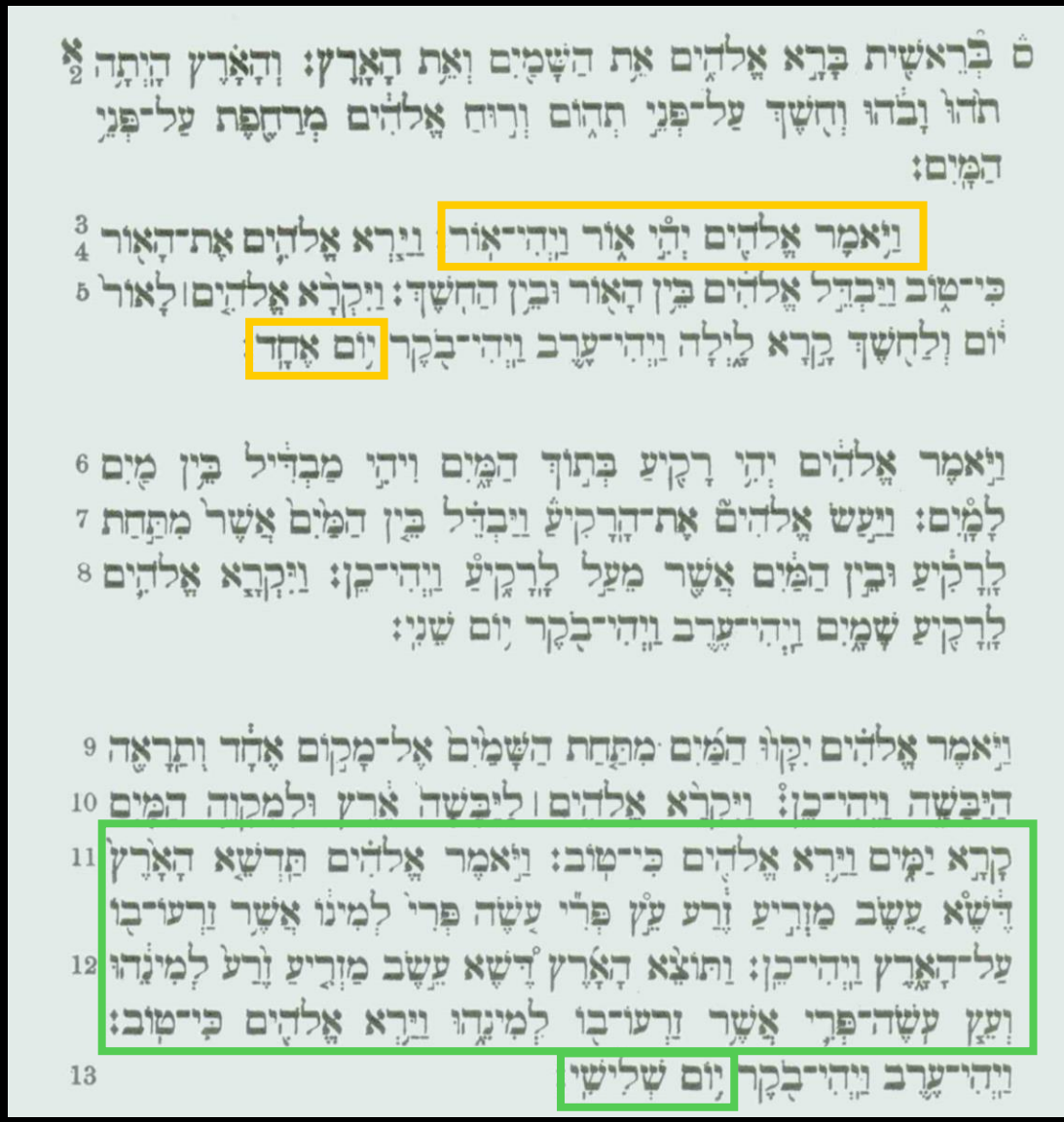
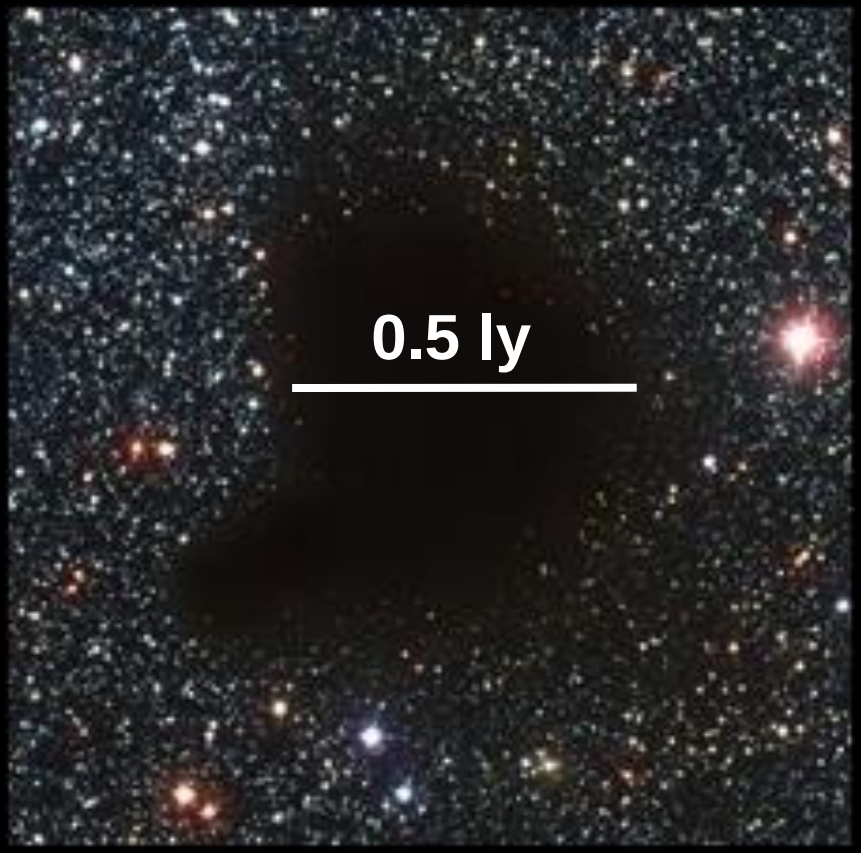


Pathway from atoms in space to life on Earth is full of unknowns



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How far did interstellar chemistry take us on this pathway towards life?

The interstellar medium exhibits a rich chemistry

200+ molecules have been found.

3/4^{ths} contain carbon (C).

Interstellar chemistry is organic in nature.

There's water there too.

Species	Mass	Species	Mass	Species	Mass	Species	Mass
H_2	2	NO	30	$HOCO^+$	45	CH_3CONH_2	59
H_3^+	3	CF^+	31	NH_2CHO	45	HNCS	59
CH	13	CH_3NH_2	31	PN	45	C_5	60
CH^+	13	H_3CO^+	31	AlF	46	CH_2OHCHO	60
CH_2	14	HNO	31	C_2H_5OH	46	CH_3COOH	60
CH_3	15	CH_3OH	32	CH_3OCH_3	46	$HCOOCH_3$	60
NH	15	SiH_4	32	H_2CS	46	OCS	60
CH_4	16	HS	33	HCOOH	46	SiS	60
NH_2	16	HS^+	33	NS	46	C_5H	61
NH_3	17	H_2S	34	CH_3SH	48	AlCl	62
OH	17	H_2S^+	34	SO	48	$HOCH_2CH_2OH$	62
OH^+	17	C_3	36	SO^+	48	HC_4N	63
H_2O	18	HCl	36	C_4H	49	CH_3C_4H	64
H_2O^+	18	c-C_3H	37	C_4H^-	49	S_2	64
NH_4^+	18	l-C_3H	37	NaCN	49	SiC_3	64
H_3O^+	19	c-C_3H_2	38	C_3N	50	SO_2	64
HF	20	H_2CCC	38	H_2CCCC	50	CH_2CCHCN	65
C_2	24	HCCN	39	HCCCCH	50	CH_3C_3N	65
C_2H	25	C_2O	40	MgCN	50	C_3S	68
C_2H_2	26	CH_2CN	40	MgNC	50	FeO	72
CN	26	CH_3CCH	40	HC_3N	51	C_6H	73
CN^+	26	SiC	40	HCCNC	51	C_6H^-	73
HCN	27	CH_3CN	41	HNCCC	51	C_5N	74
HNC	27	CH_3NC	41	c-SiC_2	52	C_6H_2	74
C_2H_4	28	H_2CCO	42	C_3O	52	HCCCCCCH	74
CO	28	NH_2CN	42	$H_2C_3N^+$	52	HC_5N	75
CO^+	28	SiN	42	AlNC	53	KCl	75
H_2CN	28	CP	43	CH_2CHCN	53	NH_2CH_2COOH	75
$HCNH^+$	28	HNCO	43	c-H_2C_3O	54	SiC_4	76
N_2^+	28	$HNCO^-$	43	HC_2CHO	54	C_6H_6	78
CH_2NH	29	c-C_2H_4O	44	SiCN	54	C_7H	85
HCO	29	CH_3CHO	44	SiNC	54	CH_3C_6H	88
HCO^+	29	CO_2	44	CH_3CH_2CN	55	C_8H	97
HN_2^+	29	CO_2^+	44	C_2S	56	C_8H^-	97
HOC^+	29	CS	44	C_3H_4O	56	HC_7N	99
SiH	29	N_2O	44	CH_3CH_2CHO	58	HC_9N	123
CH_3CH_3	30	SiO	44	CH_3COCH_3	58	$HC_{11}N$	147
H_2CO	30	HCS^+	45	NaCl	58		

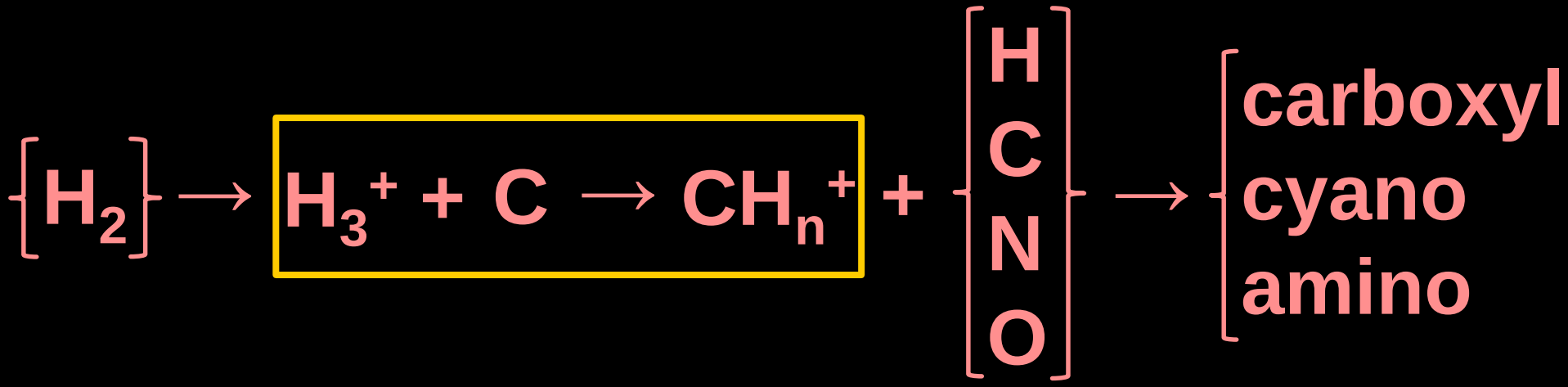
Source: astrochemistry.net

Some gas-phase pathways for forming the chemicals needed for life

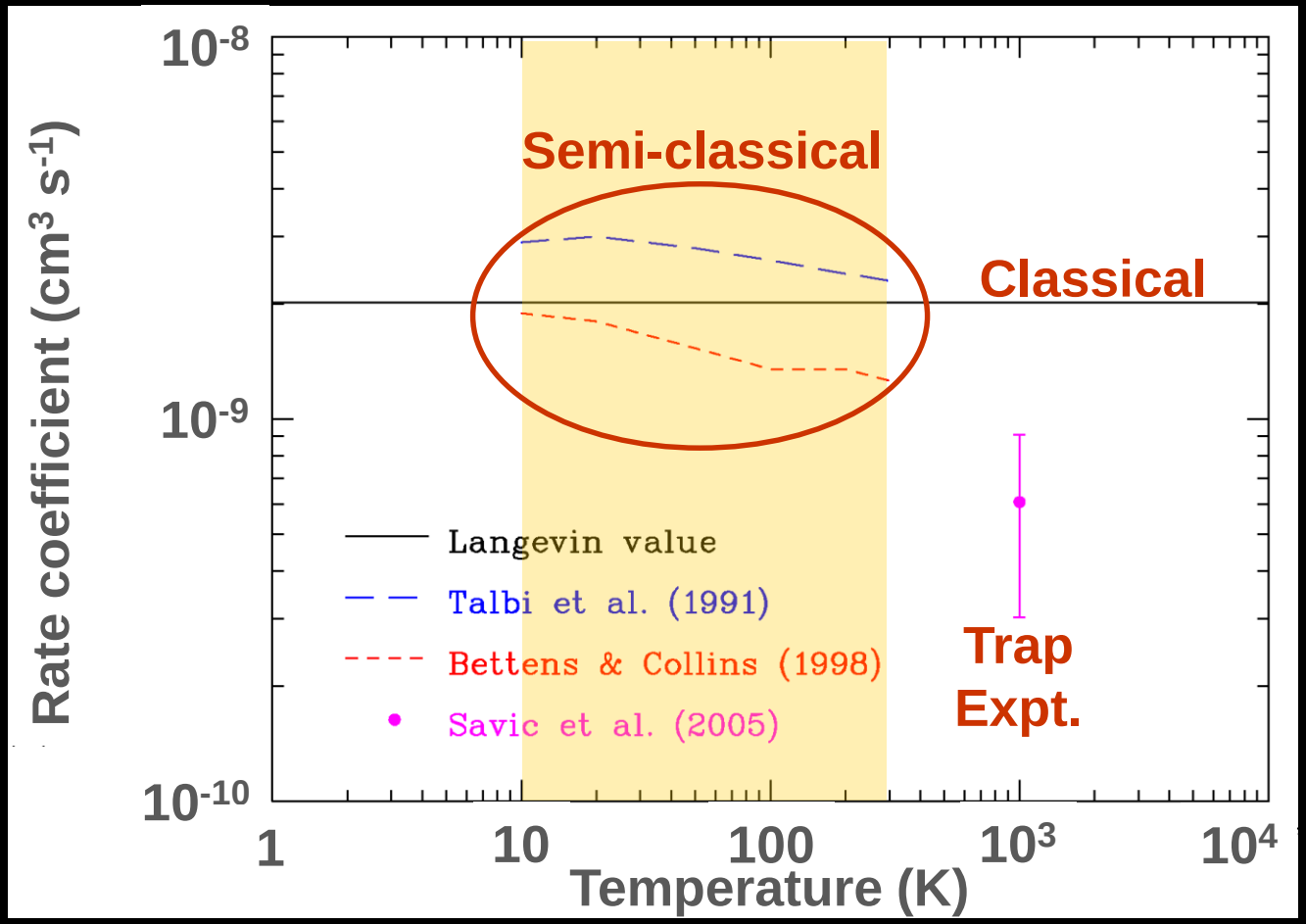
Conditions in dense molecular clouds:

$n \sim 10^4$ cm^{-3}

$T_{gas} \sim 10$ K



Published kinetics of $C + H_3^+ \rightarrow CH^+ + H_2$



QM calc's beyond current theoretical abilities.

No lab data exist at molecular cloud temperatures.

Over factor of 2 uncertainty in the rate coefficient.

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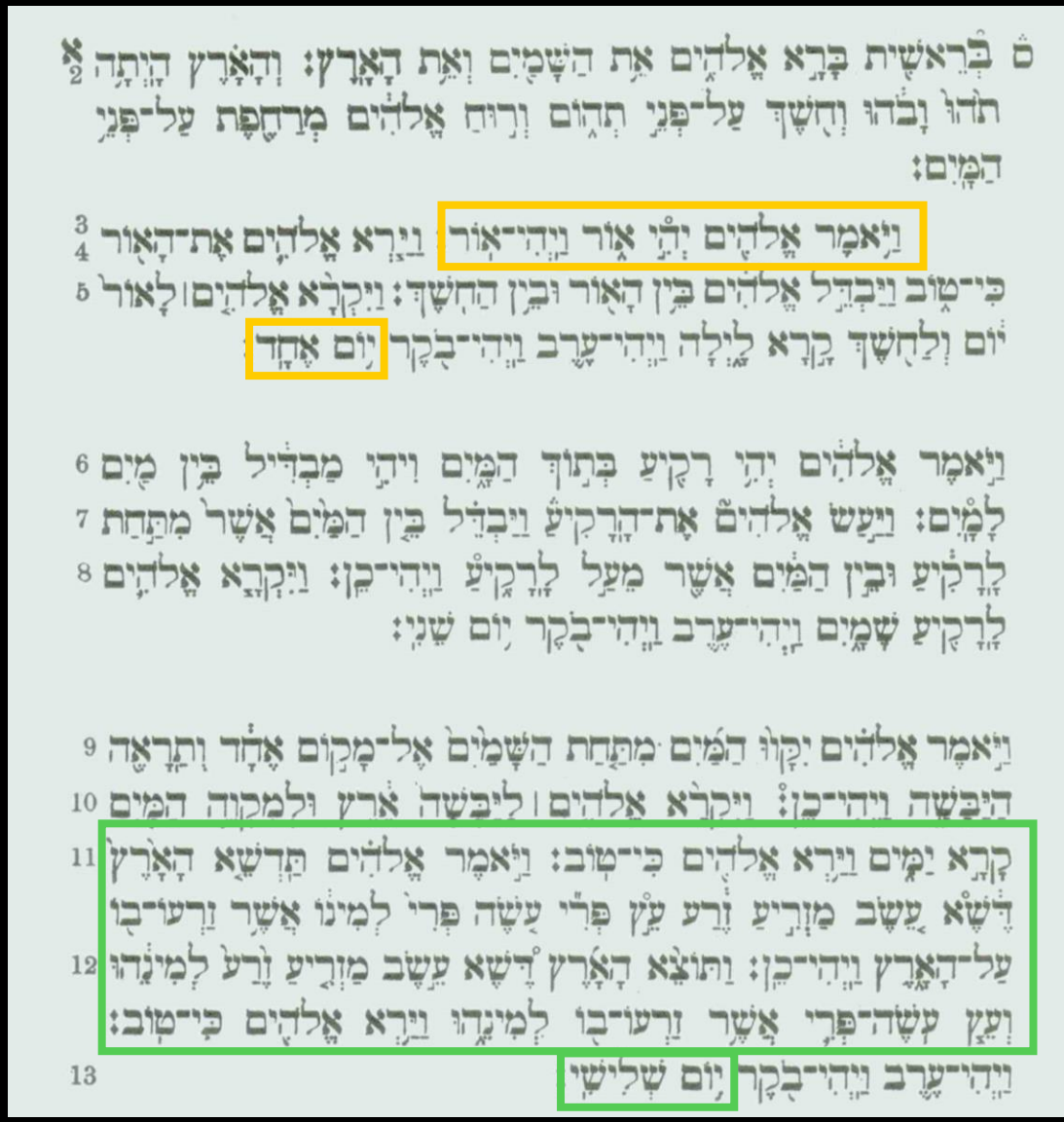
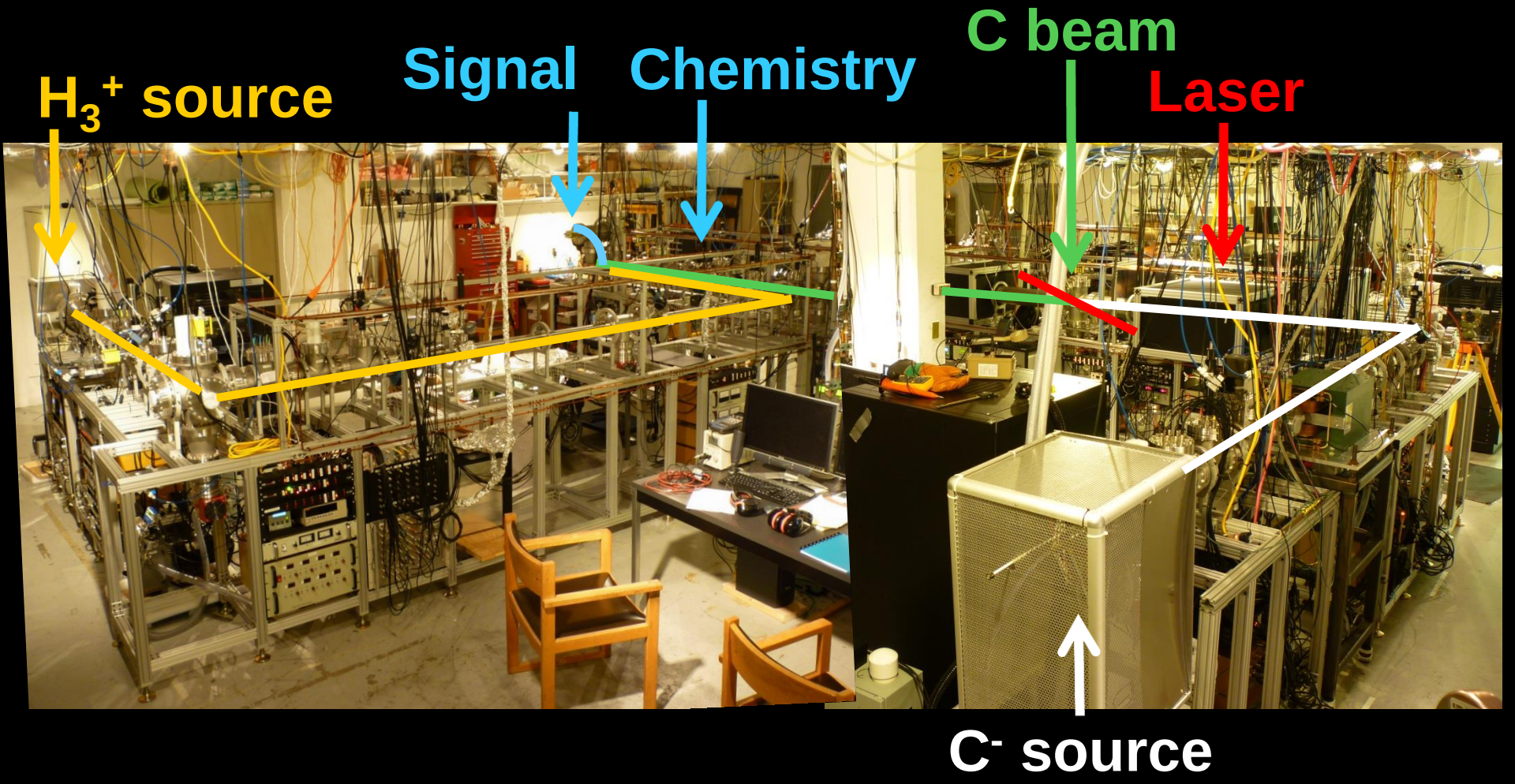
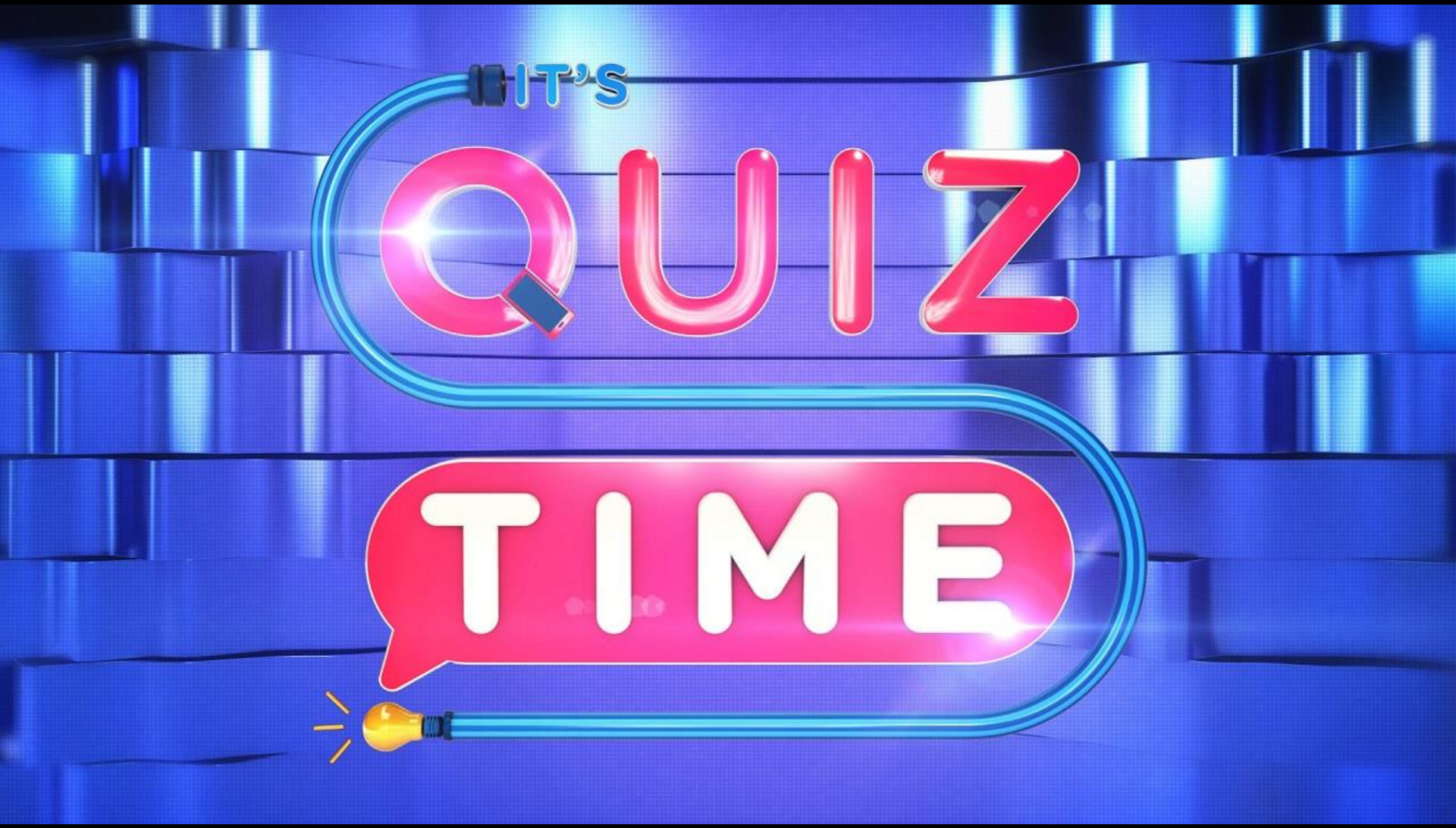


We have built an apparatus to study

$$C + H_3^+ \rightarrow CH_n^+ + H_{3-n}$$




IT'S
QUIZ
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How much did this cost?

A) $1,000,000

B) $2,000,000

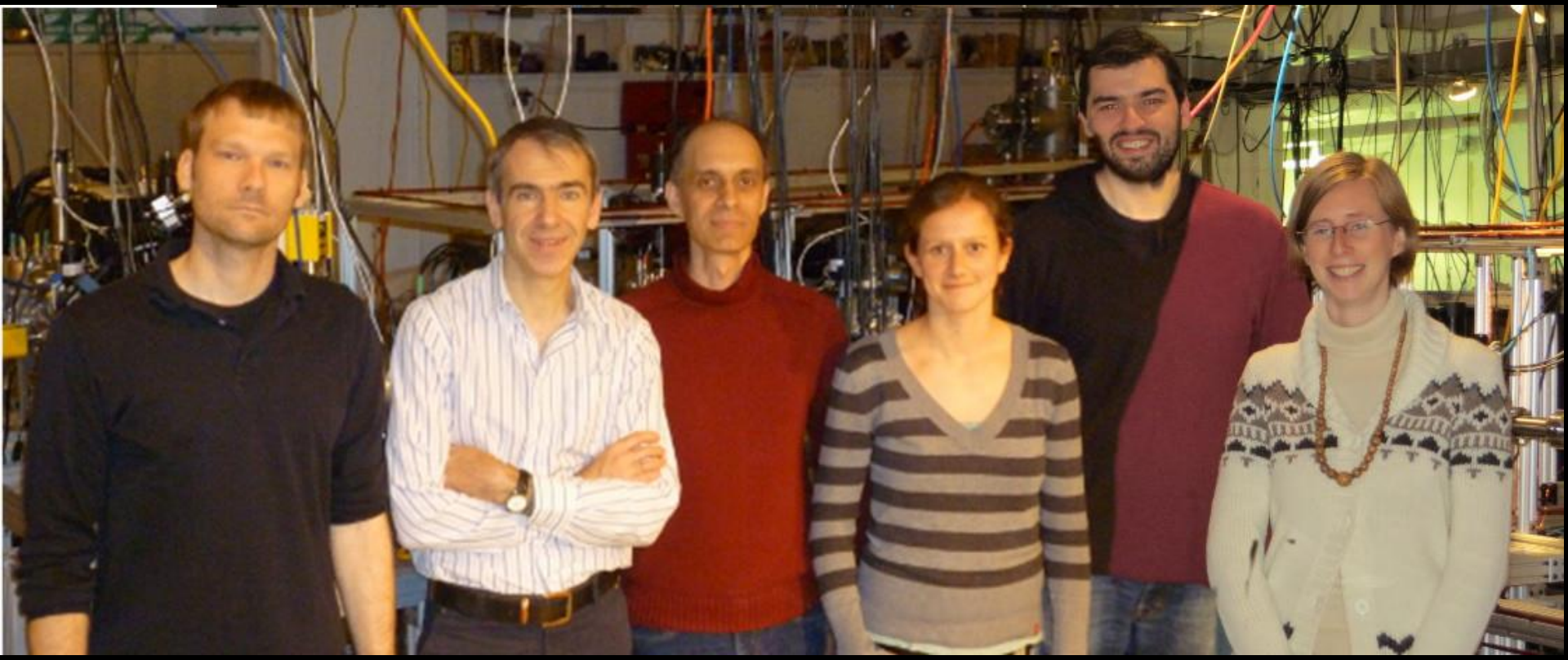
C) $4,000,000

D) $8,000,000

How much did this cost?

B) $1,999,242

The Team Members



Ken Miller, X. Urbain, DWS, Jule Stützel, A. O'Connor, Nathalie de Ruette

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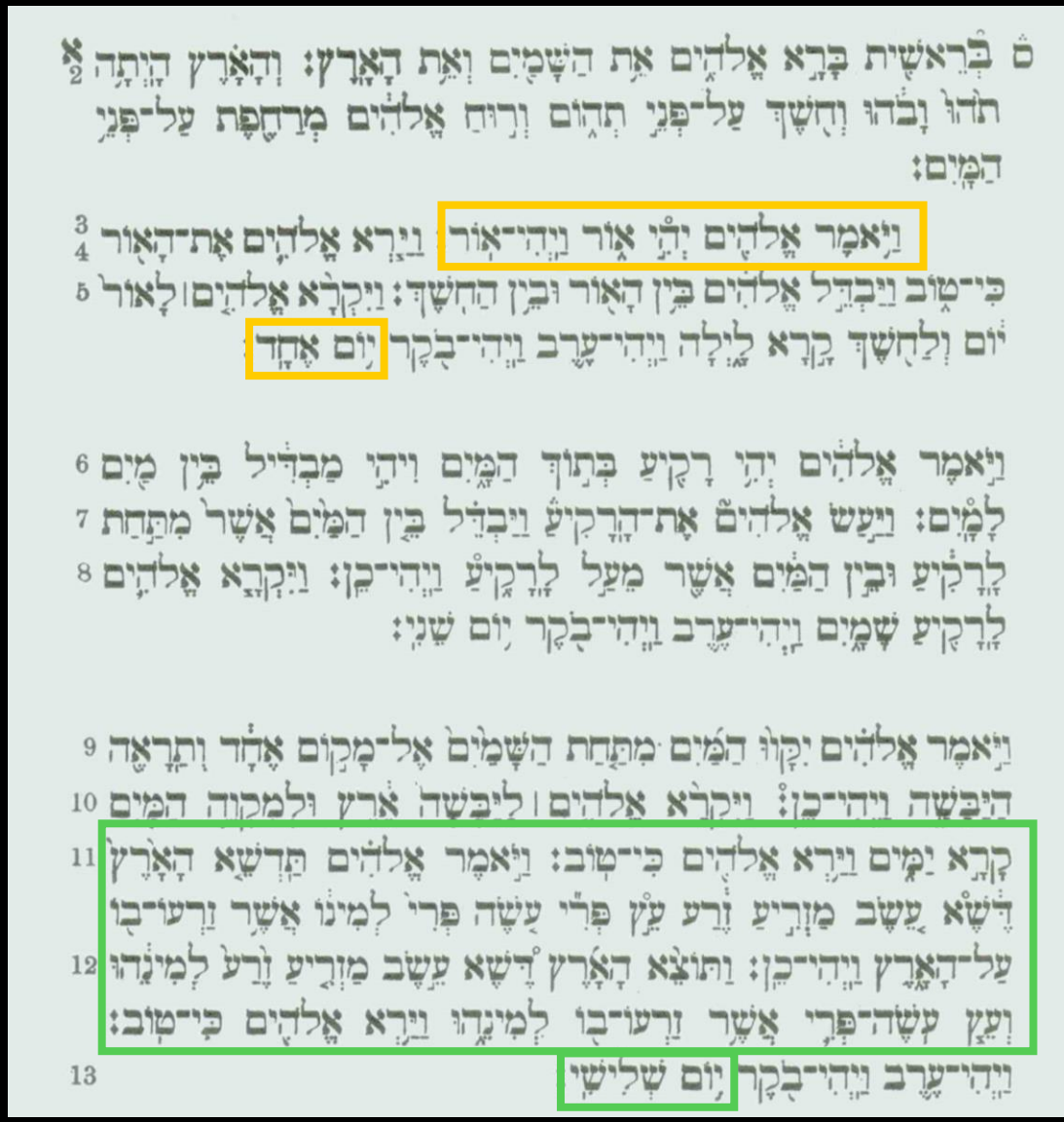
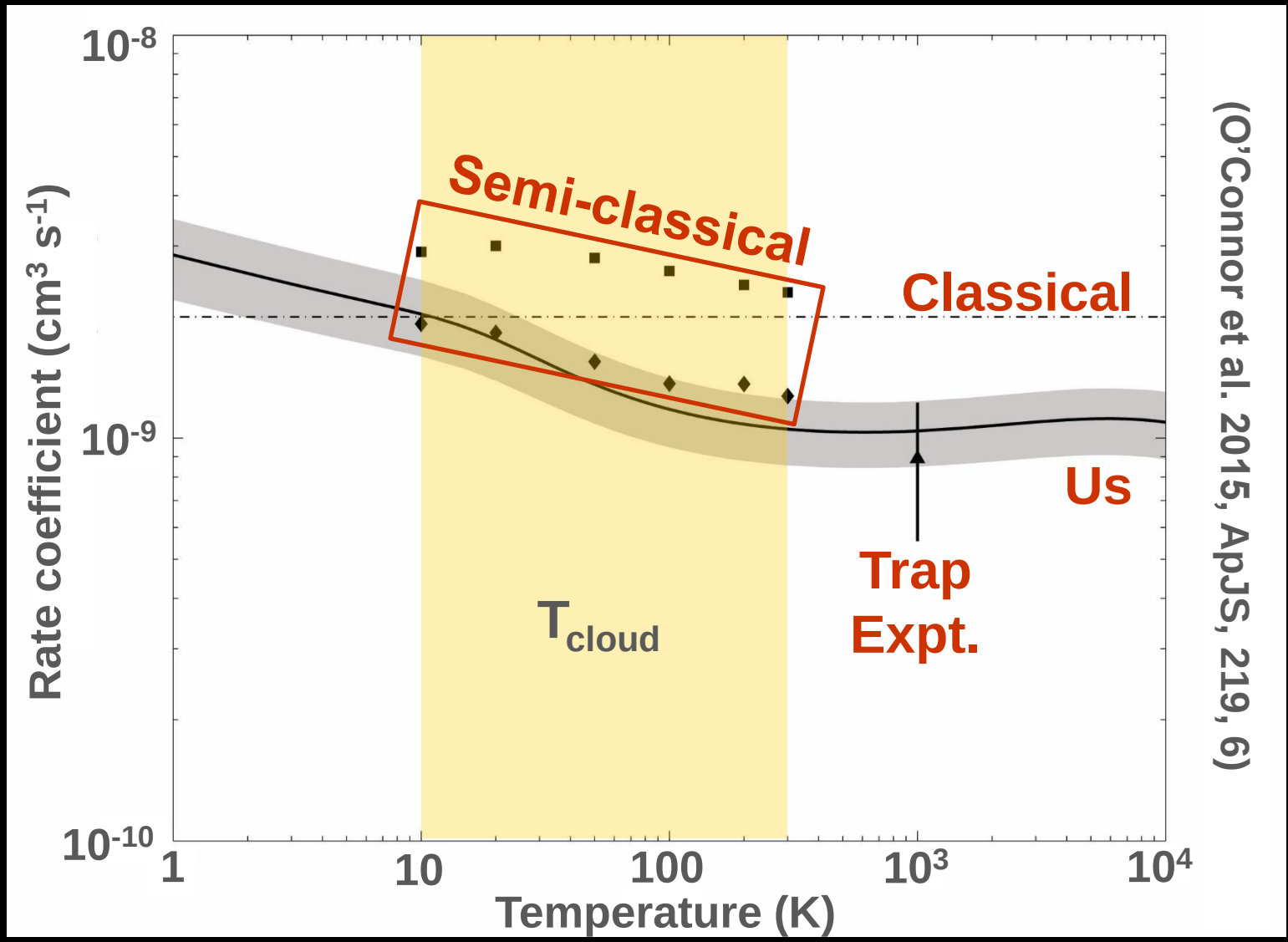
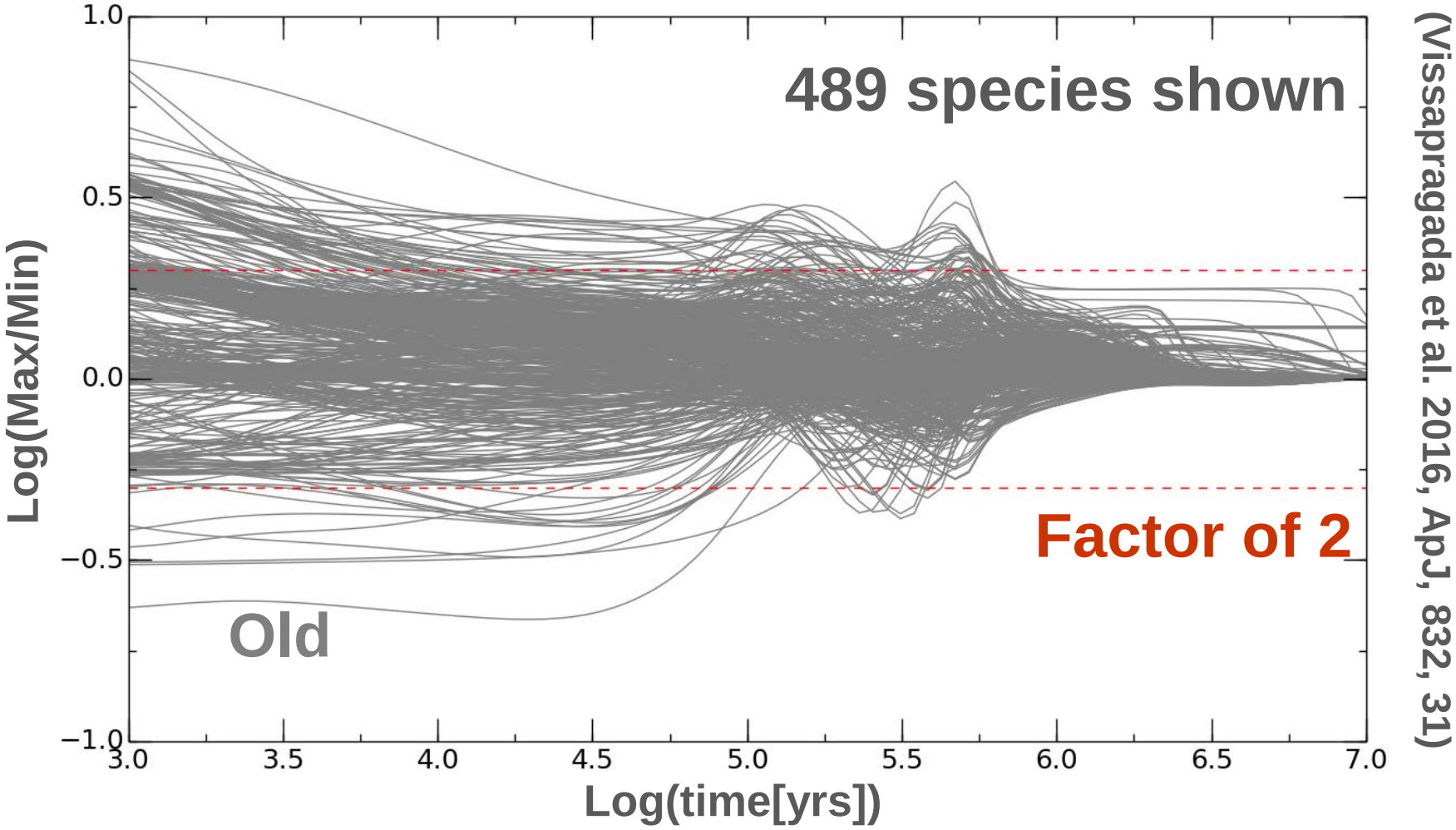


C + H_3^+ summed thermal rate coefficients



Reduced uncertainty from factor of >2 to <20%.

New C + H_3^+ data reduces abundance uncertainties in astrochemical models



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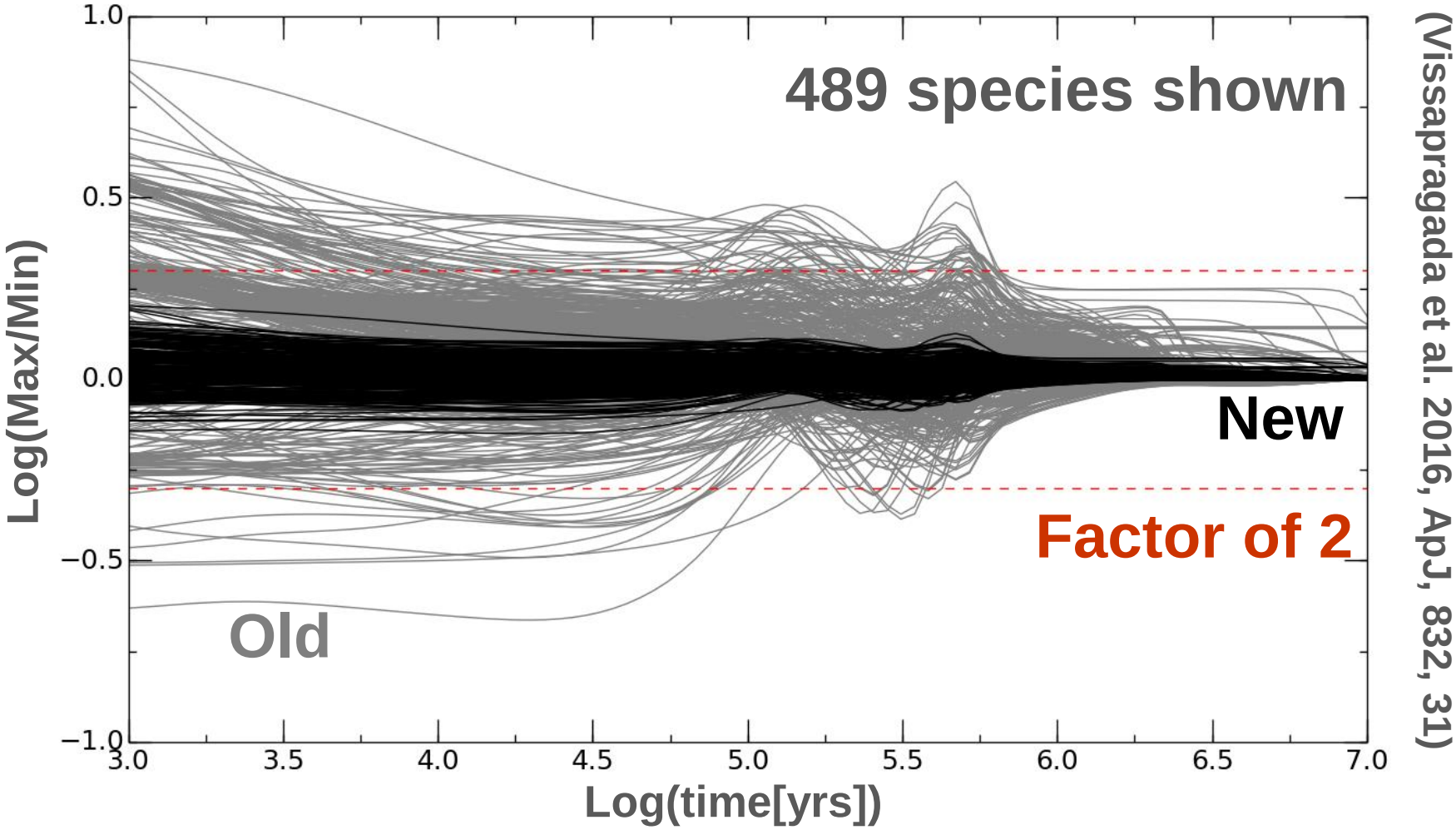

Conclusions

- We have performed the first energy dependent measurements for the $H^- + H \rightarrow H_2 + e^-$ reaction.
- Our results will improve cosmological models for protogalaxy and first star formation.
- Have developed a new apparatus to study astrochemical reactions with atomic D, C, and O.
- We have measured $C + H_3^+$, $O + H_3^+$, as well as $D + H_3^+/H_2D^+/D_2H^+$.
- Results improve our understanding of the chemical evolution of the cosmos.

Thanks for your attention.