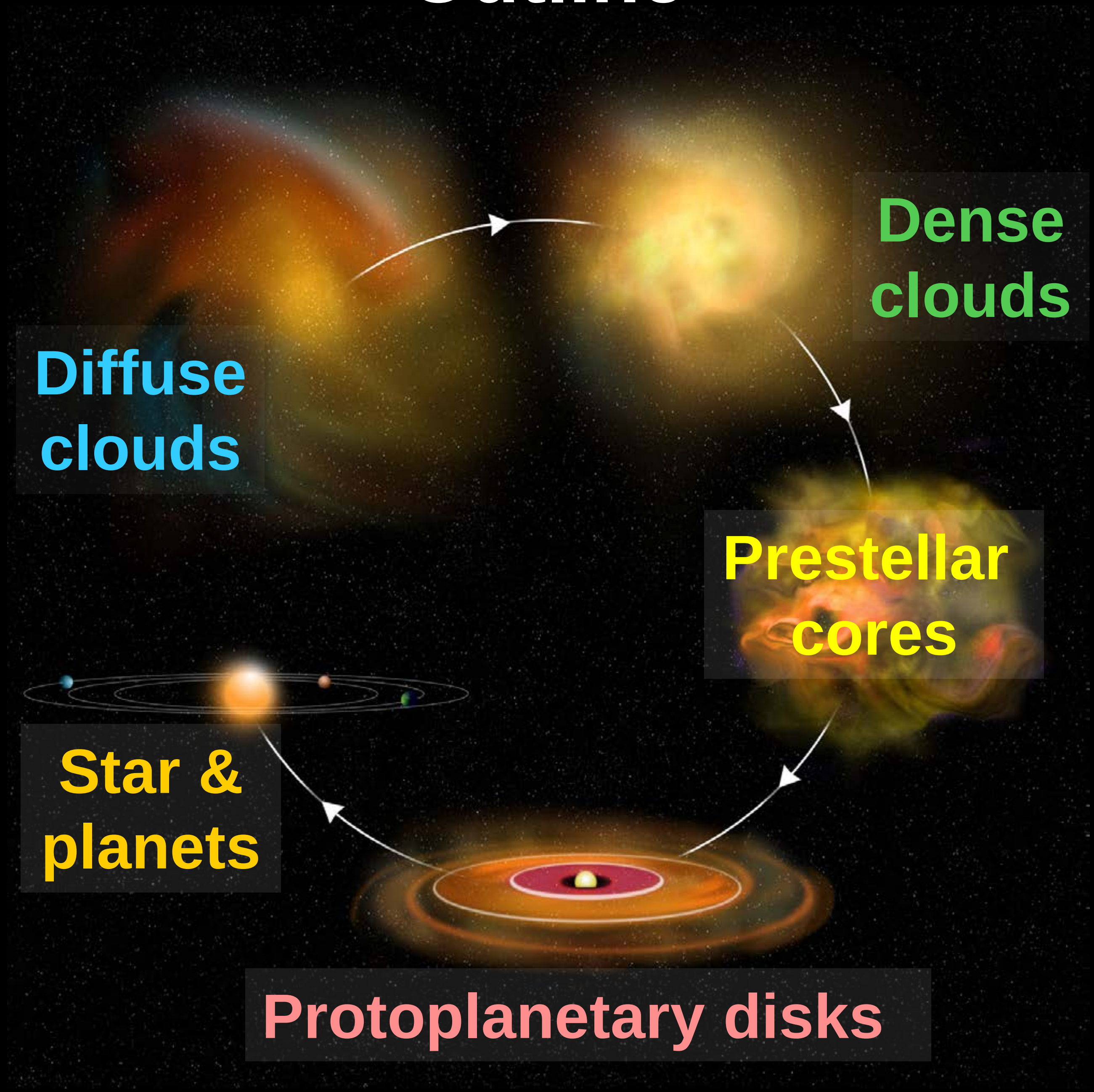
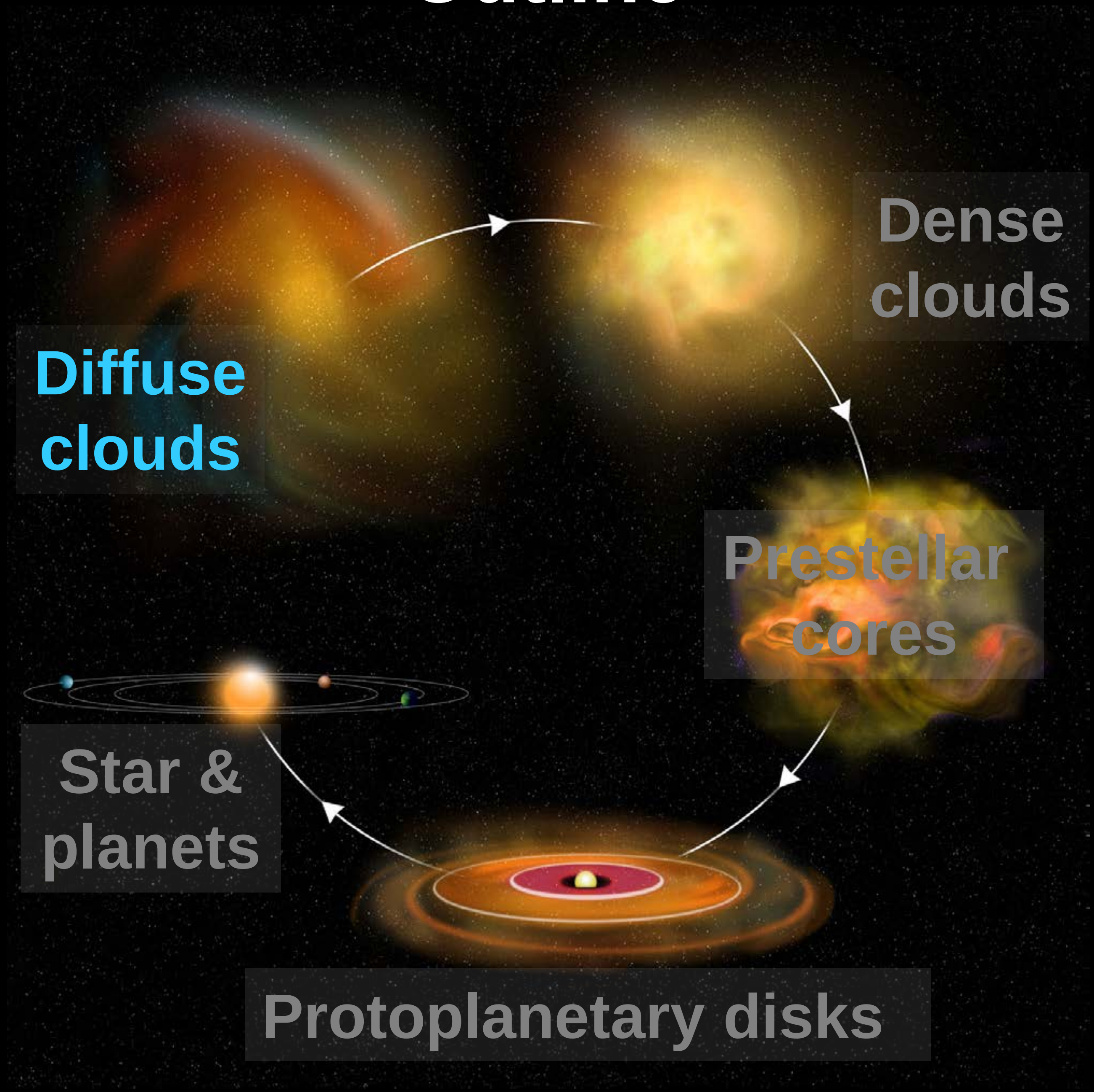
Laboratory Astrophysics along the Cosmic Cycle of Gas

Daniel Wolf Savin
Columbia University

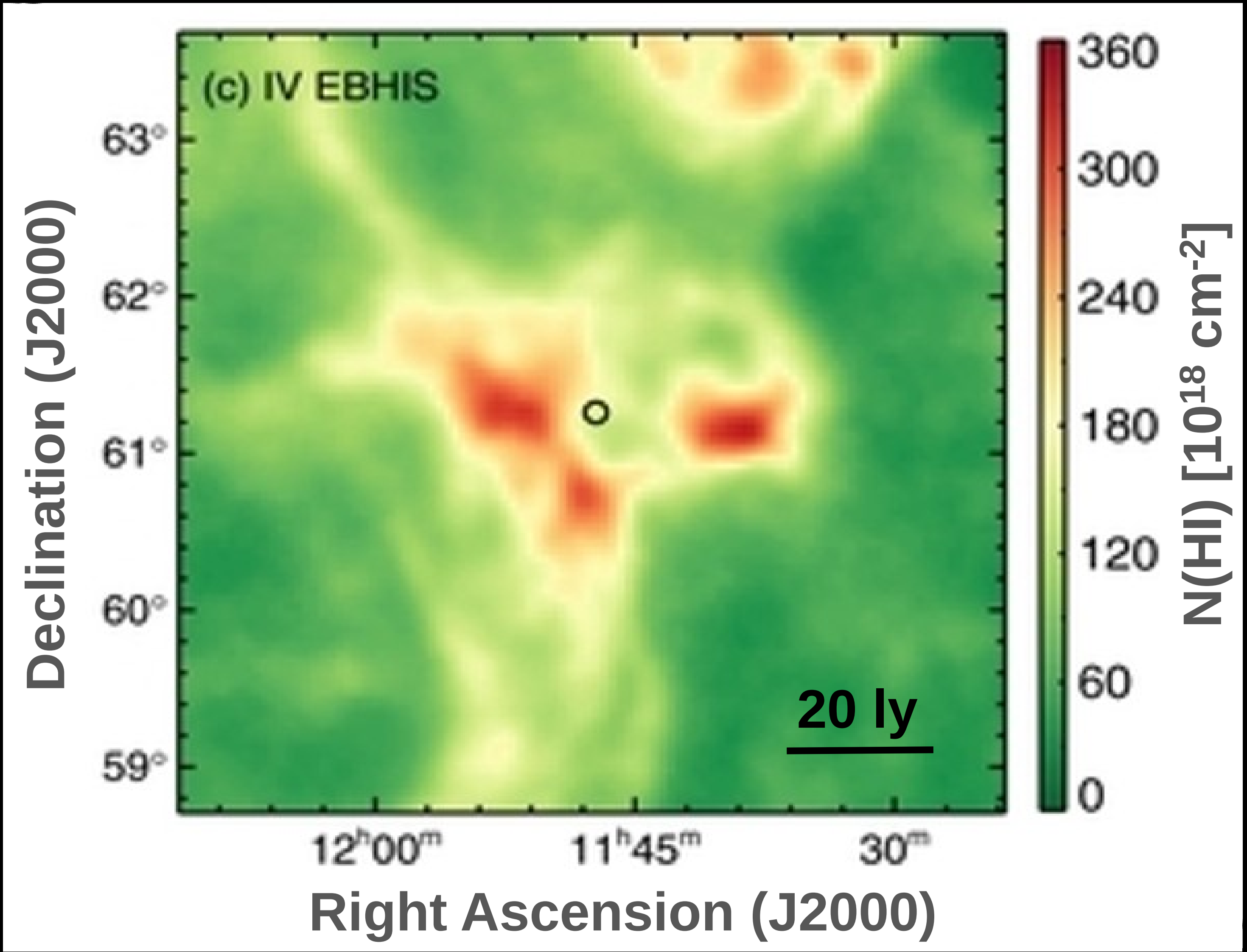
Outline


Dense clouds
Prestellar cores
Protoplanetary disks
Star & planets
Diffuse clouds

Outline


Dense clouds
Prestellar cores
Protoplanetary disks
Star & planets
Diffuse clouds

Diffuse clouds are a first step in present day star formation process



Chemistry plays an important role in the evolution of diffuse clouds (H, He O, C)

$n_H \sim$ 10-100 cm^{-3}

Binary Reactions

$T_{gas} \sim$ 50-100 K

Ion-neutral chemistry

So what ionizes the gas and initiates the chemistry?

H atoms shield cloud interiors from ionizing radiation → **Ionization is by cosmic rays (MeV protons)**

Cosmic ray ionization rate (CRIR) helps drive the evolution of diffuse clouds

- CRIR of H (ζ_H) initiates the chemistry and thereby affects the cooling of the cloud.
- ζ_H sets the ionization fraction of the cloud, which couples the gas dynamics to ambient B field.
- This affects the transfer of angular momentum, dissipation of turbulence, and collapse of cloud.

Determining CRIR (ζ_H) in diffuse clouds using the OH^+ abundance

Formation

$$CR + H \rightarrow CR' + H^+ + e^-$$

$$H^+ + O \rightarrow H + O^+$$

$$O^+ + H_2 \rightarrow OH^+ + H$$

Determining CRIR (ζ_H) in diffuse clouds using the OH^+ abundance

Formation

$$CR + H \rightarrow CR' + H^+ + e^-$$

$$H^+ + O \rightarrow H + O^+$$

$$O^+ + H_2 \rightarrow OH^+ + H$$

Determining CRIR (ζ_H) in diffuse clouds using the OH^+ abundance

Formation

$CR + H \rightarrow CR' + H^+ + e^-$

$H^+ + O \rightarrow H + O^+$

$O^+ + H_2 \rightarrow OH^+ + H$

Rate ~ $\zeta_H n_H$

Determining CRIR (ζ_H) in diffuse clouds using the OH^+ abundance

Formation

$CR + H \rightarrow CR' + H^+ + e^-$

$H^+ + O \rightarrow H + O^+$

$O^+ + H_2 \rightarrow OH^+ + H$

Rate ~ $\zeta_H n_H$

Destruction

$e^- + OH^+ \rightarrow O + H$

Dissociative Recombination (DR)

Rate ~ $k_{DR} n_{e-} n_{OH+}$

Determining CRIR (ζ_H) in diffuse clouds using the OH^+ abundance

Assuming quasi-steady state

Formation ~ Destruction

$$\zeta_H \sim k_{DR}\, n_{e-}\, n_{OH+} / n_H$$

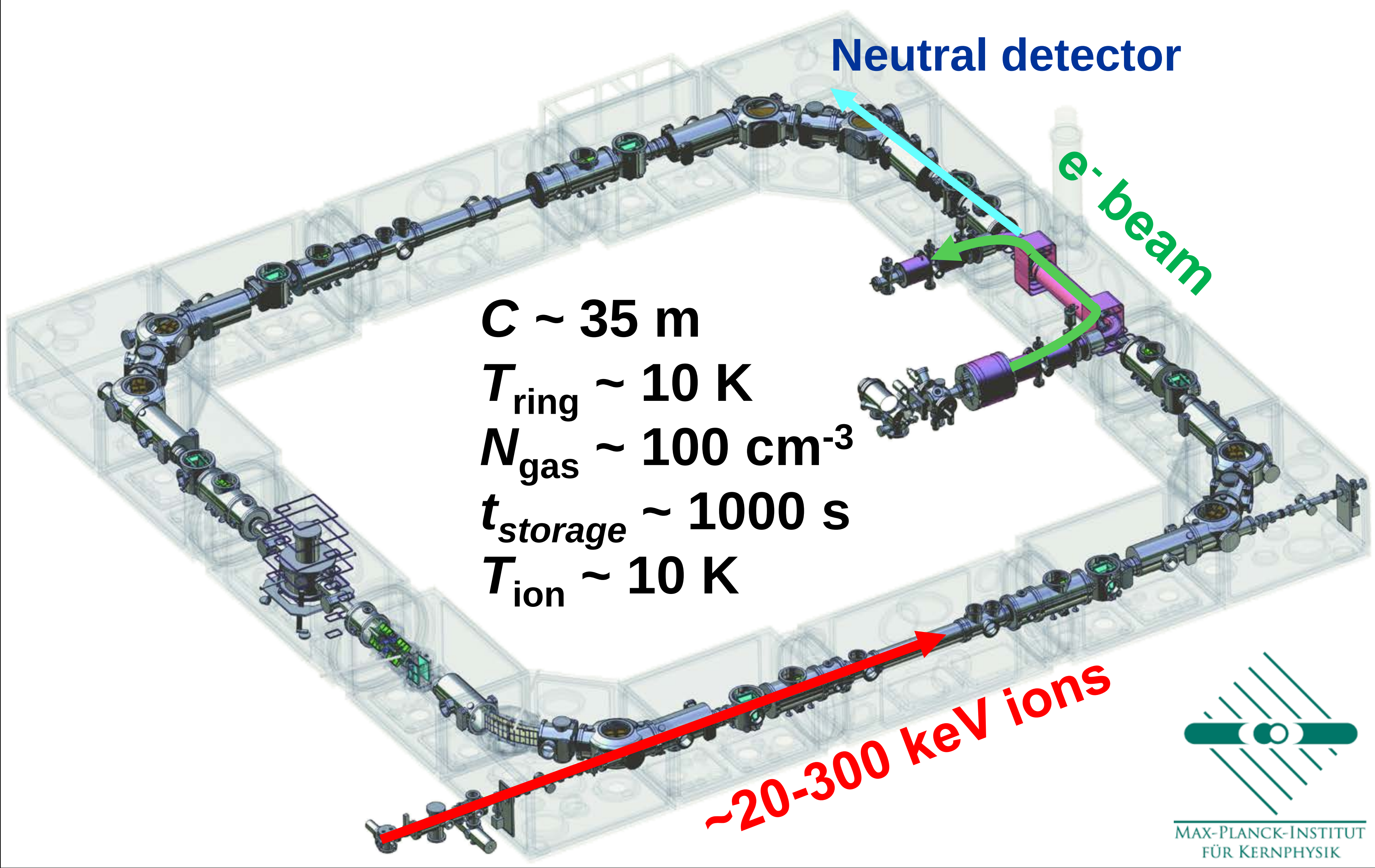
Observations yield n_{e-}, n_{OH+}, and n_H

How well do we know k_{DR}?

What are the challenges in generating reliable DR data for OH^+

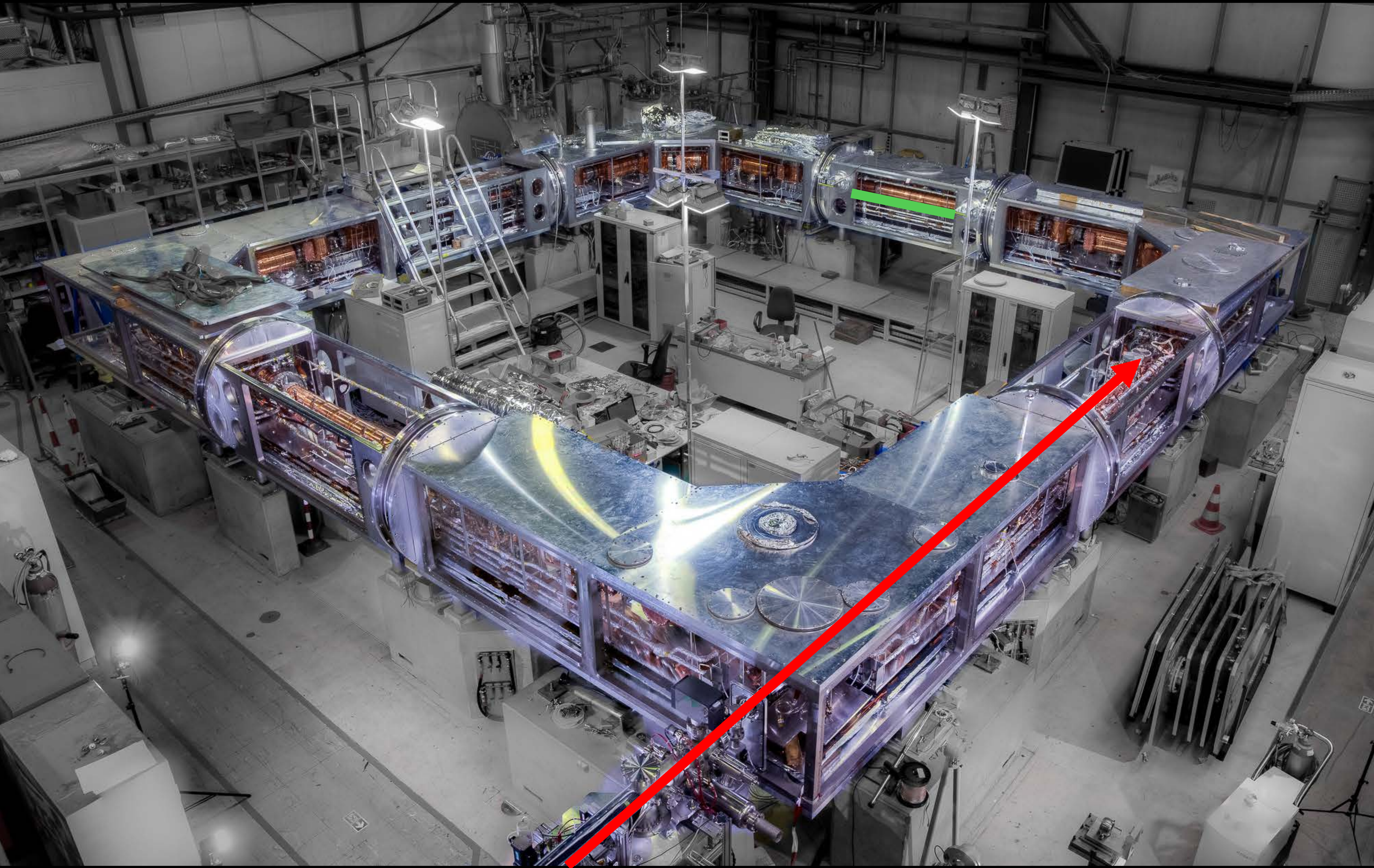
- QM calculations for multi-electron systems are theoretically and computationally challenging.
- Past lab studies used highly excited OH^+ not appropriate for diffuse cloud temperatures.
- How can one create internally cold OH^+ and interact it with electrons?

The Cryogenic Storage Ring (CSR)

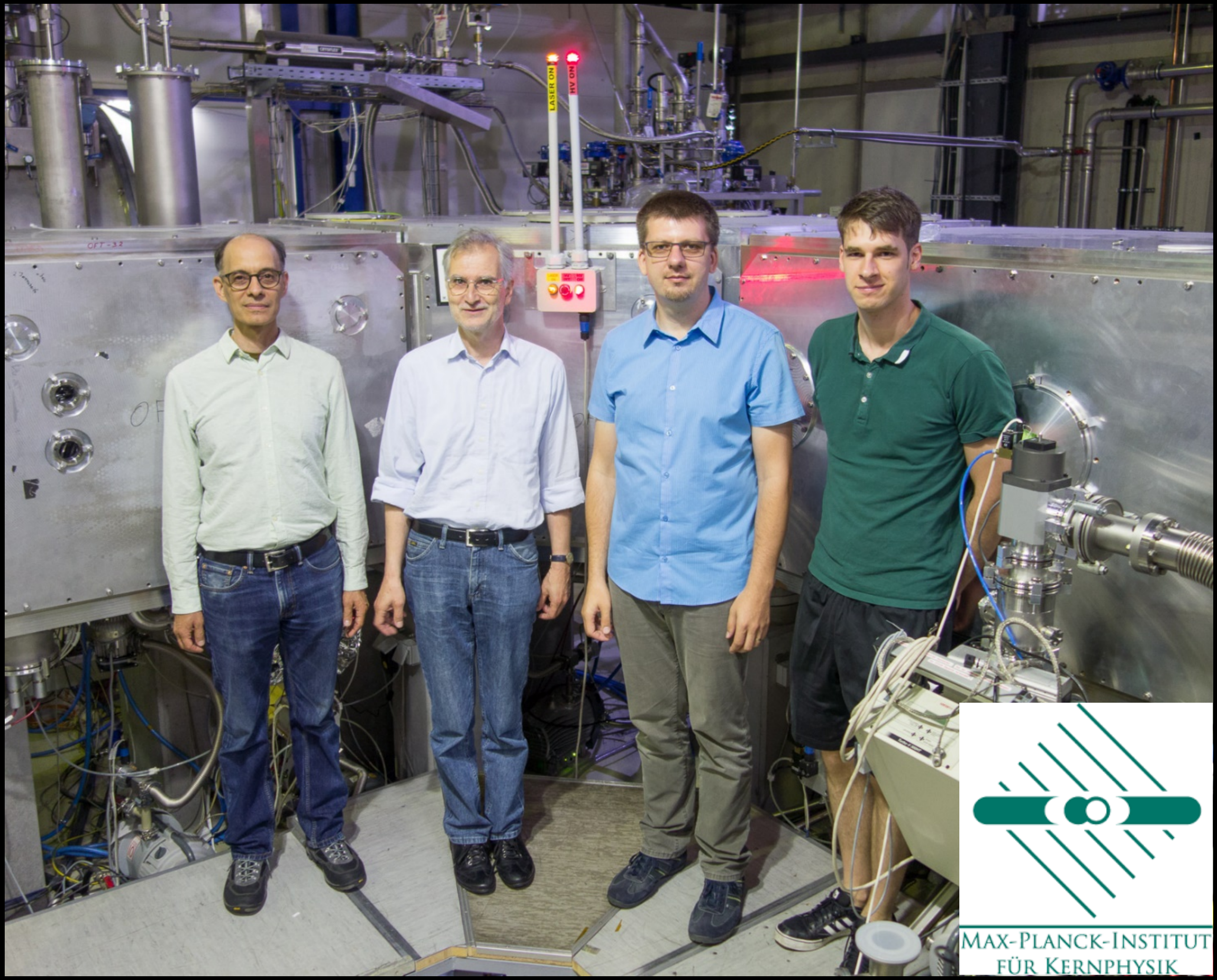


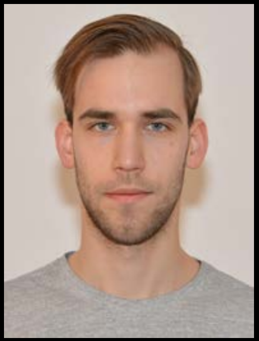
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

The Cryogenic Storage Ring (CSR)



The Team Members

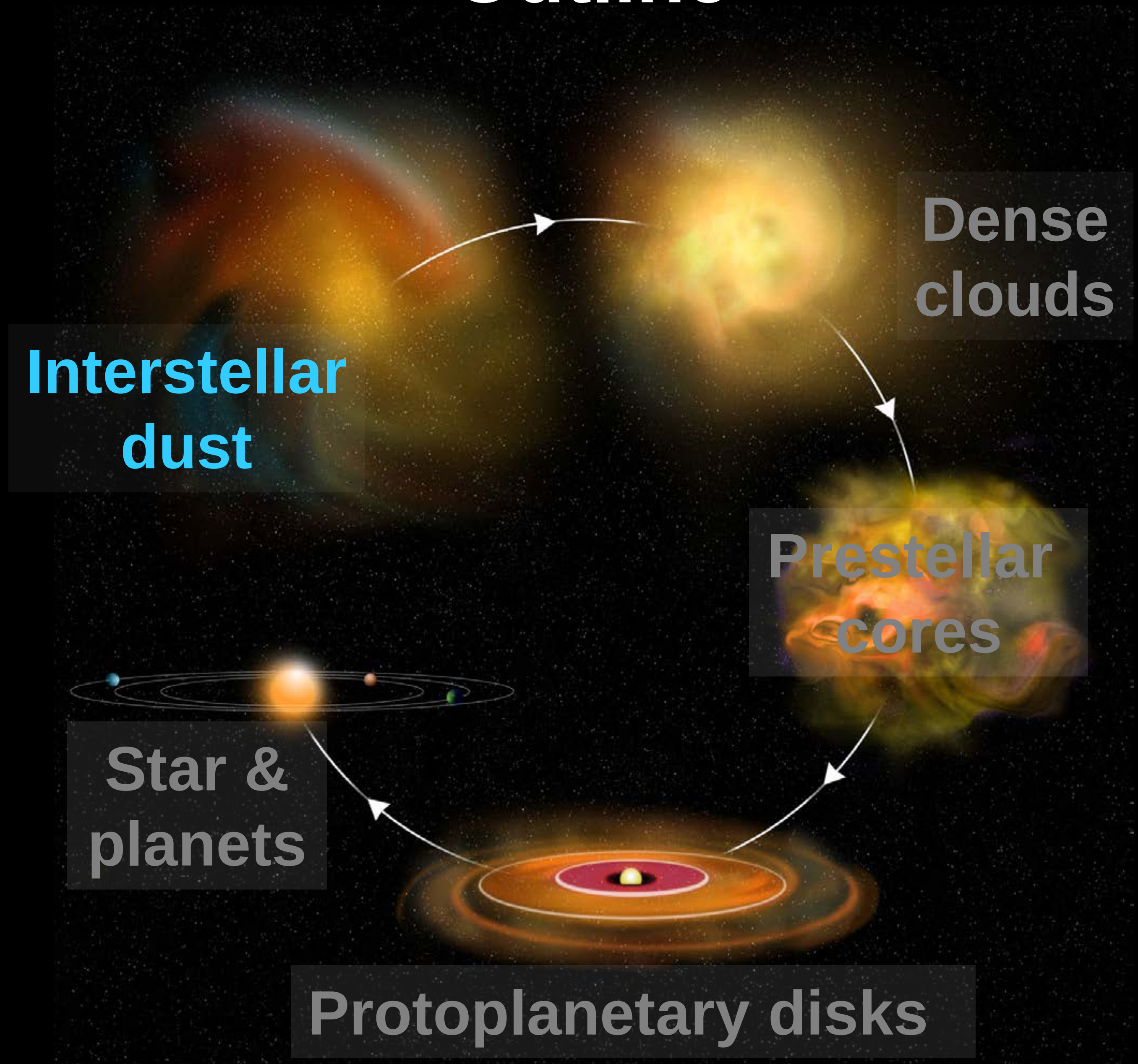




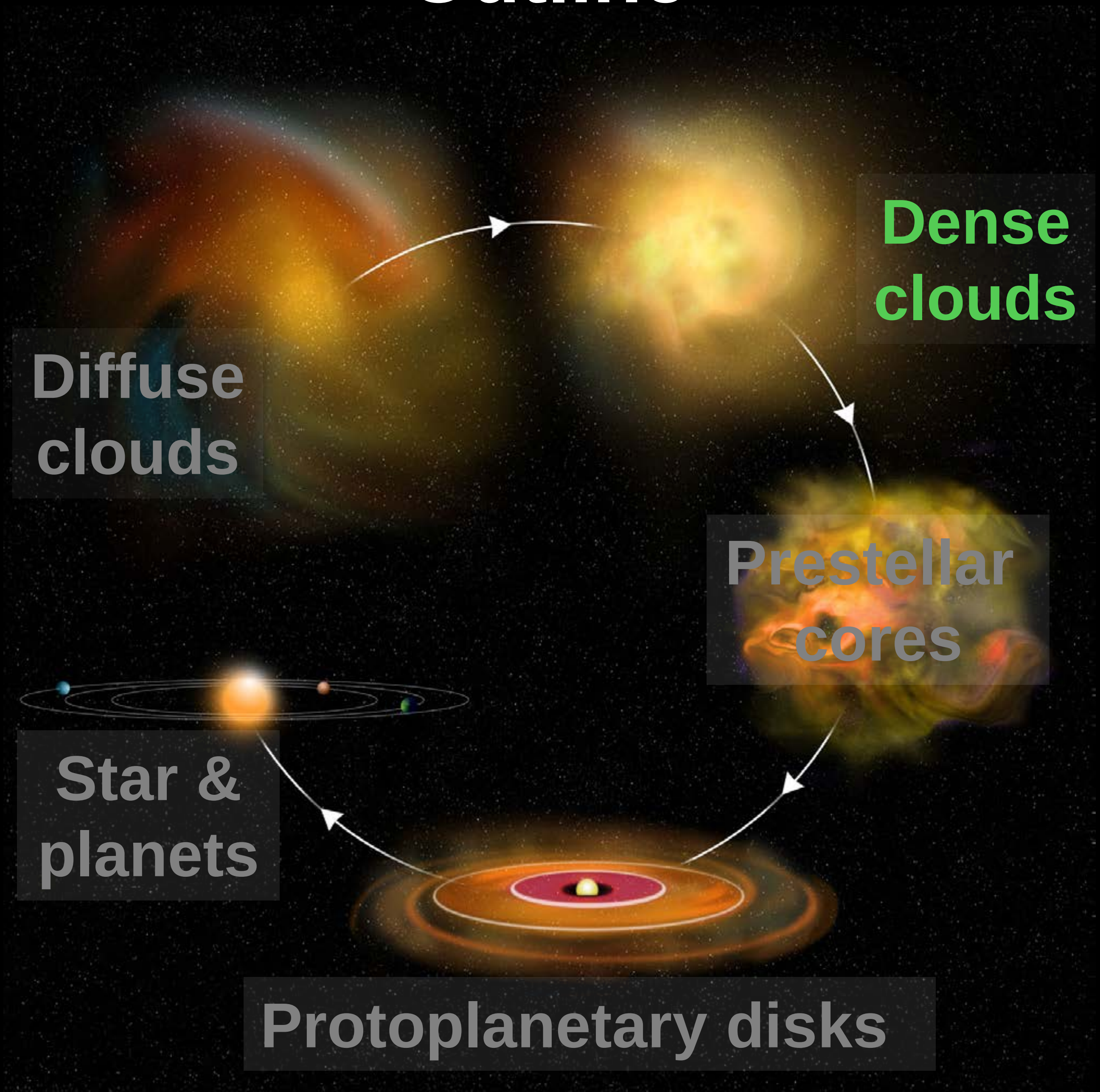
DWS, Andreas Wolf, OldA Novotny, Patrick Wilhelm, Ábel Kálosi, Daniel Paul, and Sunny Saurabh

Stay tuned for future results.

Outline


Dense clouds
Interstellar dust
Prestellar cores
Star & planets
Protoplanetary disks

Outline



Dense clouds
Diffuse clouds
Prestellar cores
Star & planets
Protoplanetary disks

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

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

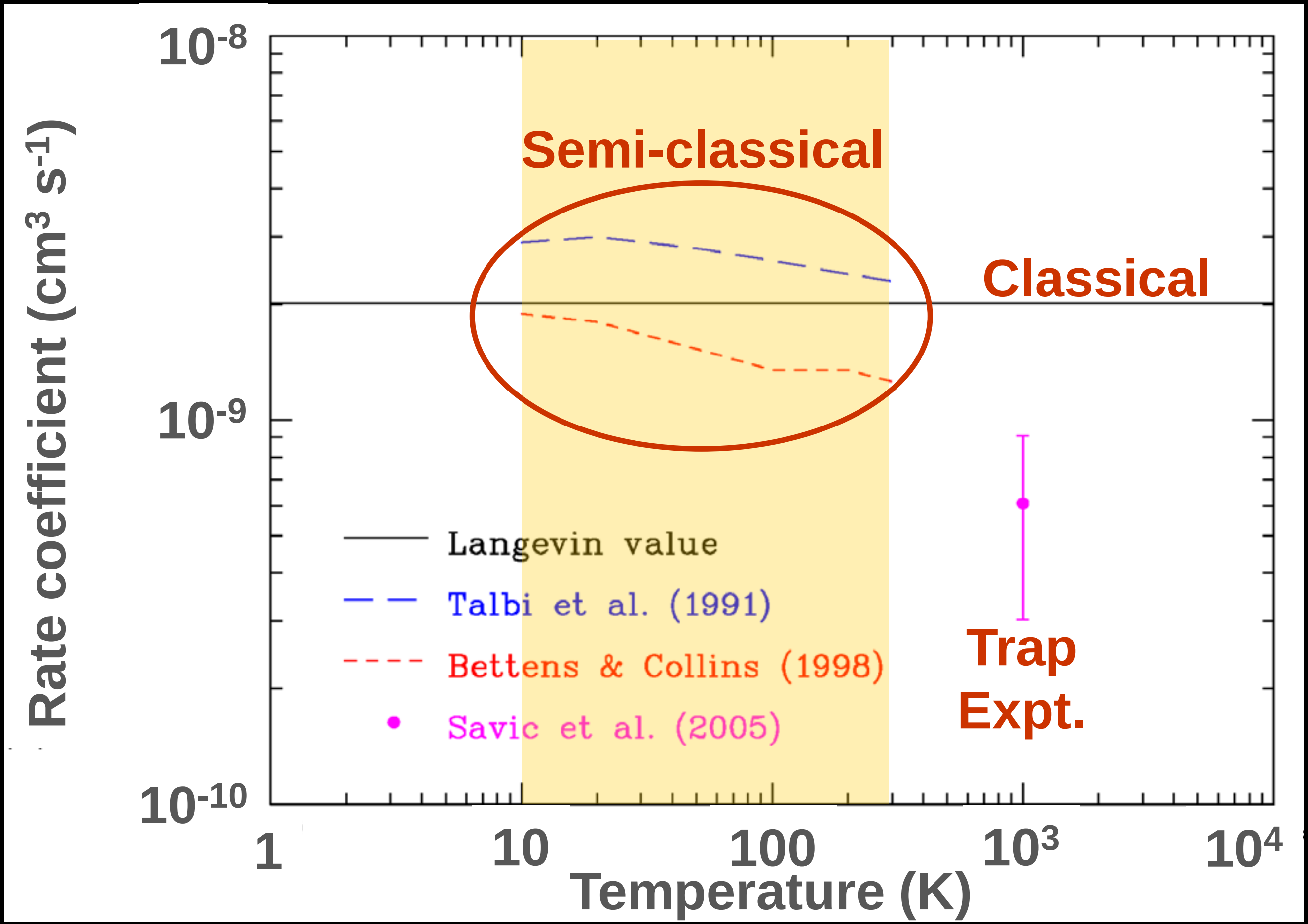
Conditions in dense molecular clouds:

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

$T_{gas} \sim 10\ \mathrm{K}$

$$\left\{\mathrm{H_2}\right\} \rightarrow \boxed{\mathrm{H_3^+ + C \rightarrow CH_n^+}} + \left\{\begin{matrix}\mathrm{H}\\ \mathrm{C}\\ \mathrm{N}\\ \mathrm{O}\end{matrix}\right\} \rightarrow \left\{\begin{matrix}\text{carboxyl}\\ \text{cyano}\\ \text{amino}\end{matrix}\right.$$

Published data for $C + H_3^+ \rightarrow CH^+ + H_2$



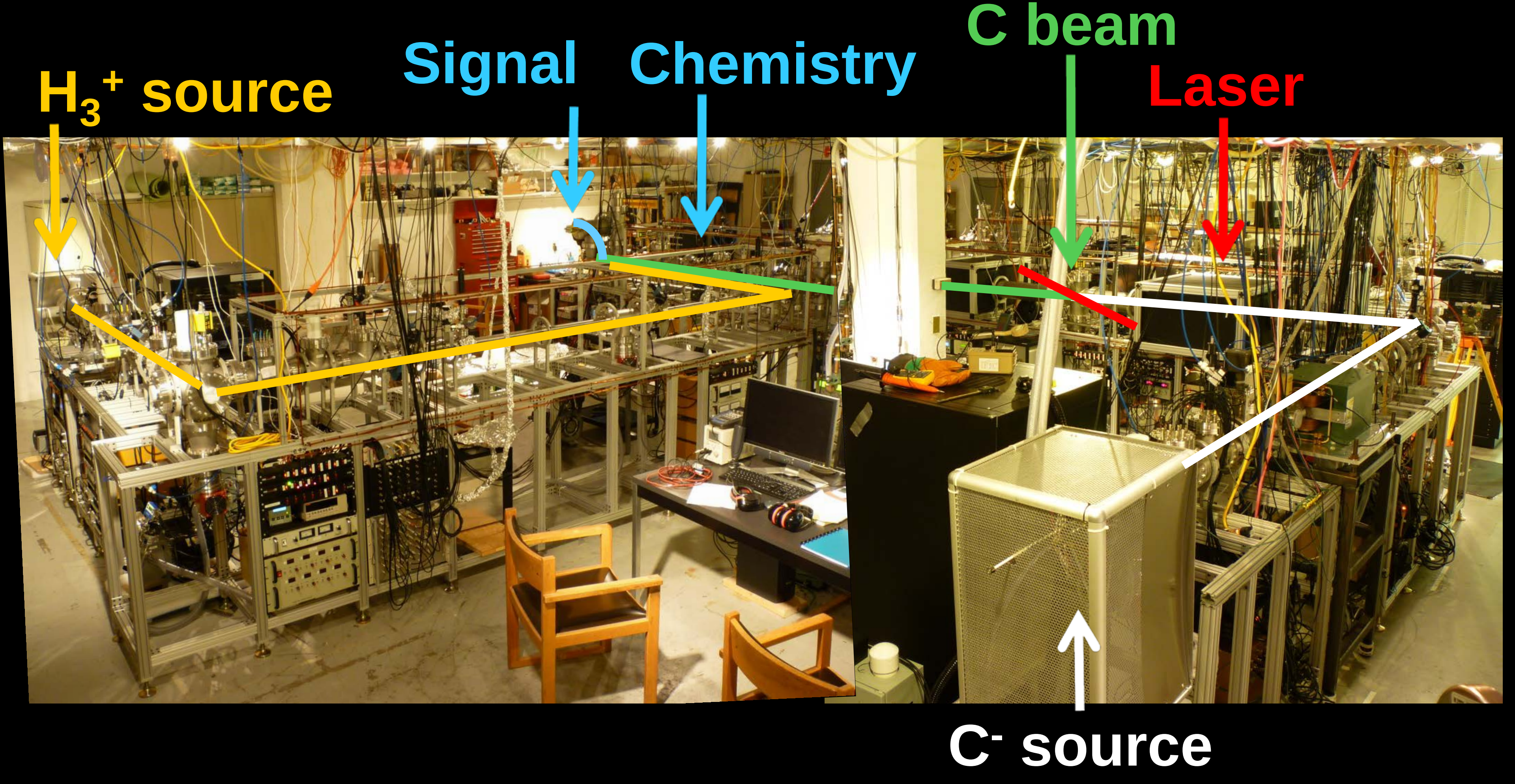
QM calc's beyond current theoretical abilities.

No lab data exist at molecular cloud temperatures.

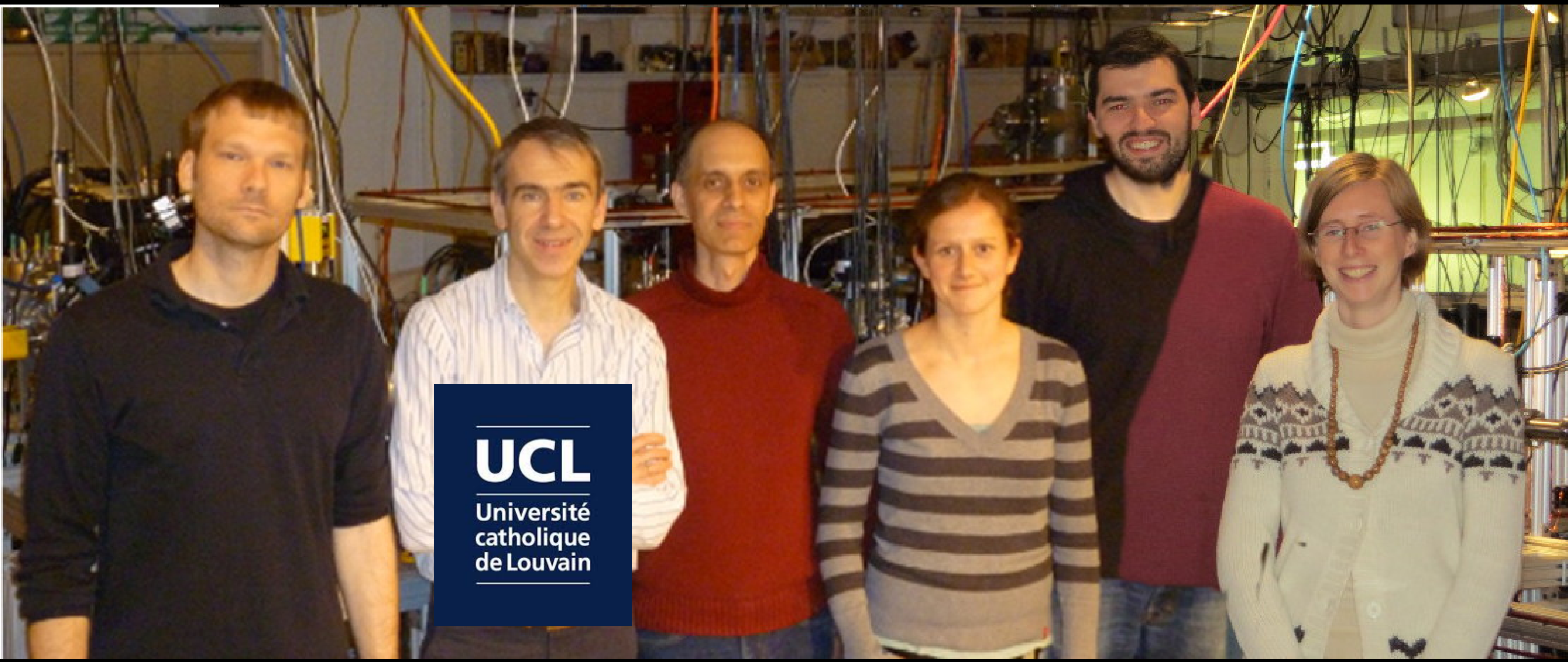
Over factor of 2 uncertainty in the rate coefficient.

We have built an apparatus to study

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

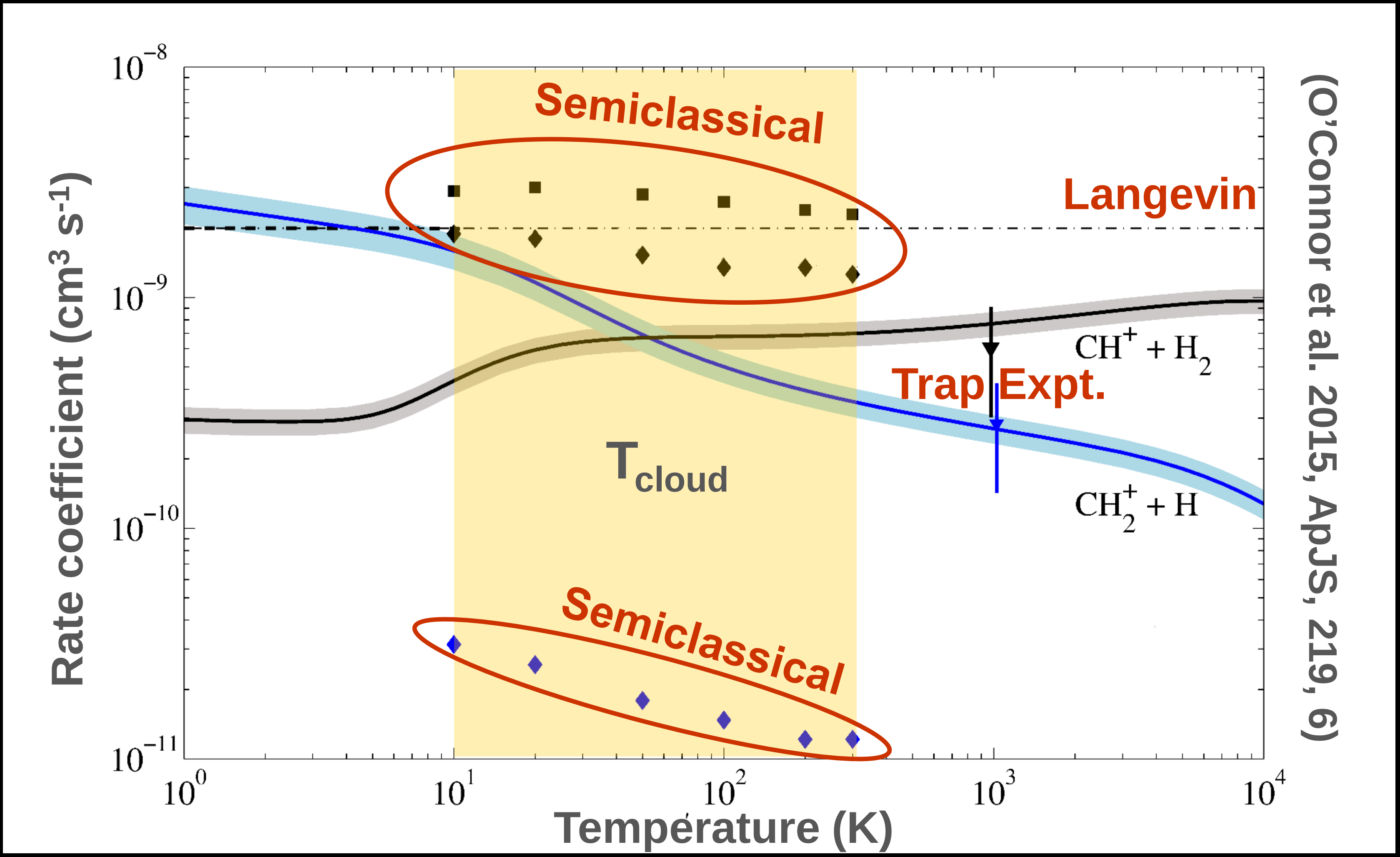


The Team Members



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

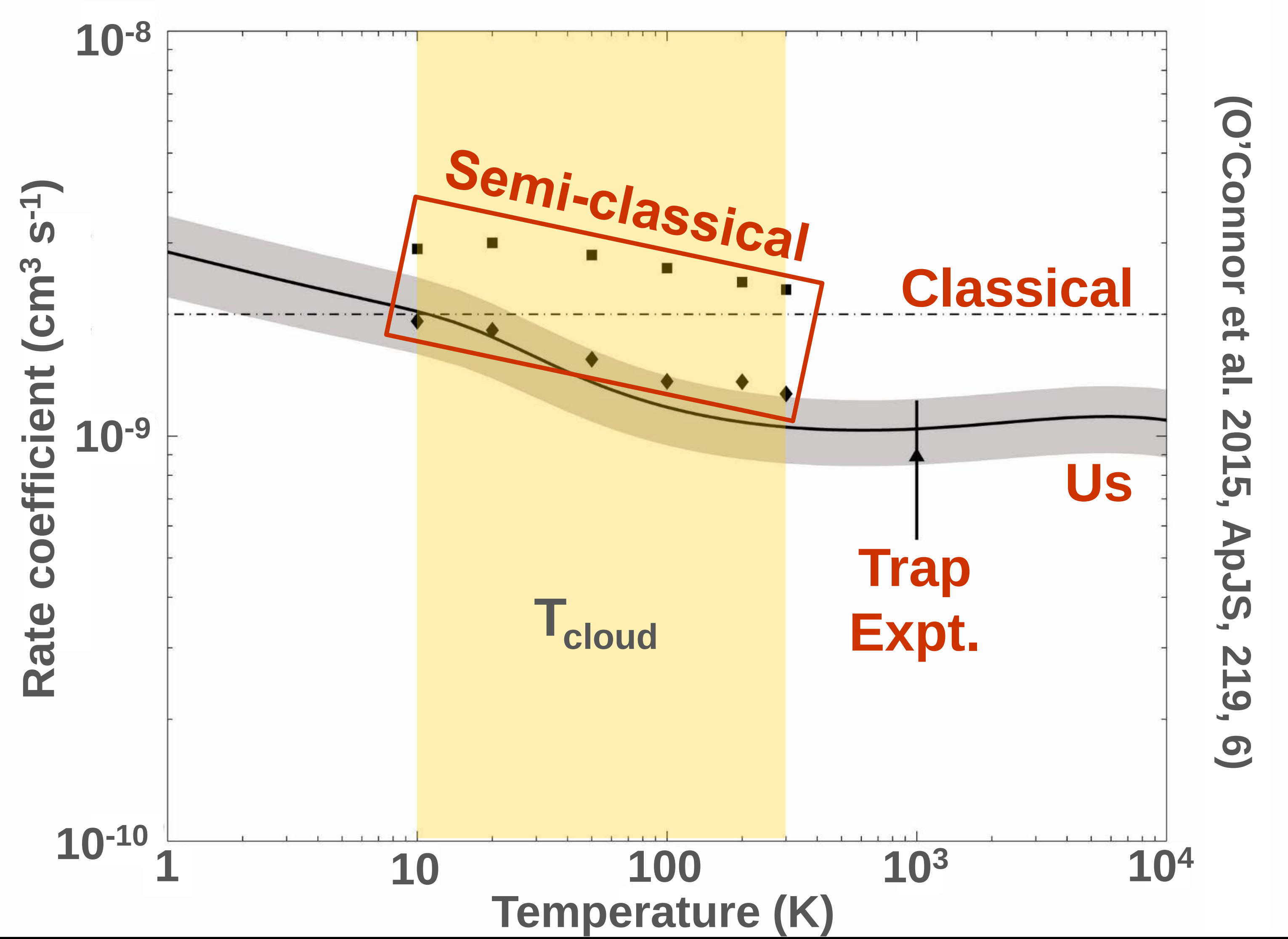
C + H_3^+ thermal rate coefficients



Good agreement with previous measurement.

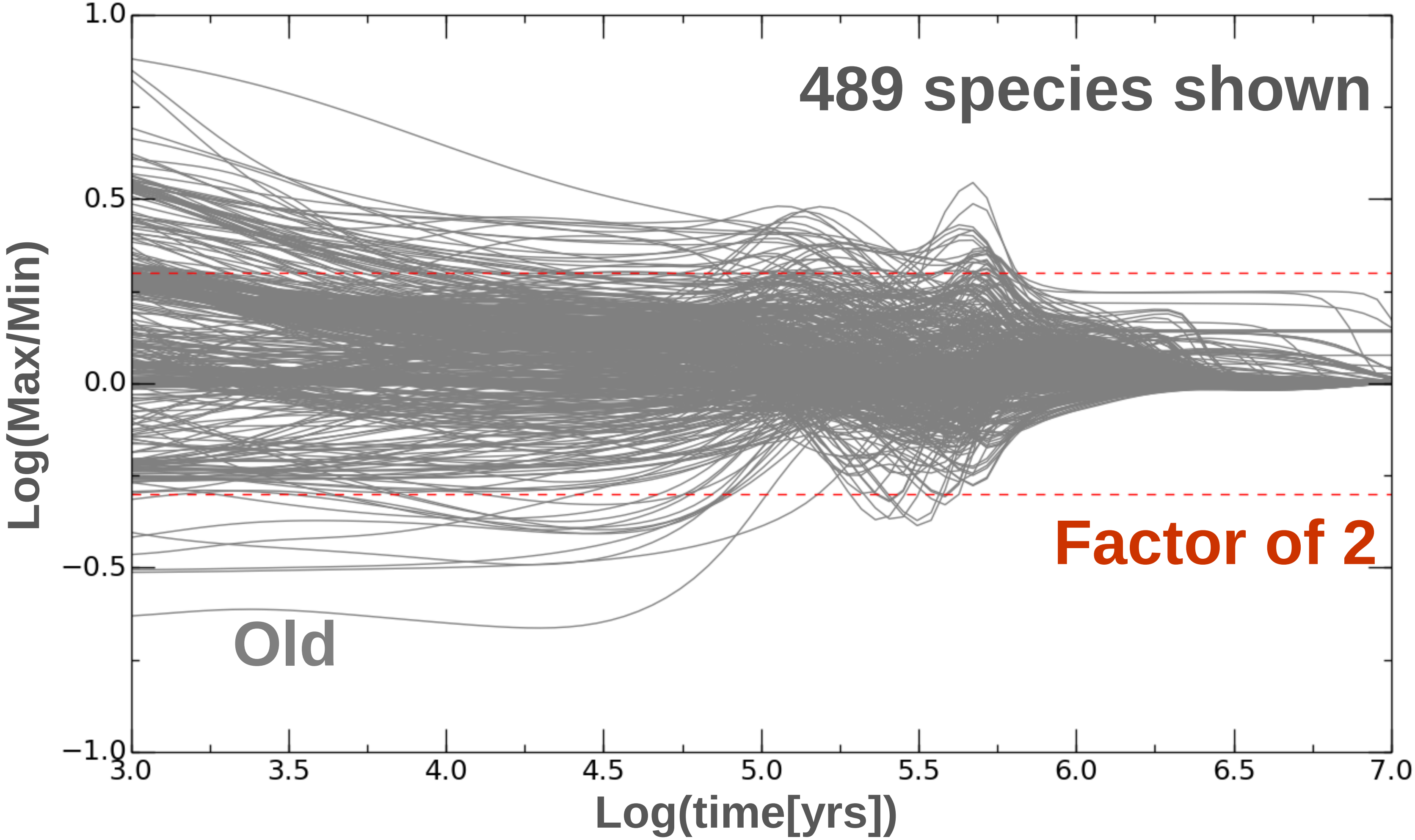
Cause for discrepancy with theory is not clear.

C + H_3^+ summed thermal rate coefficients



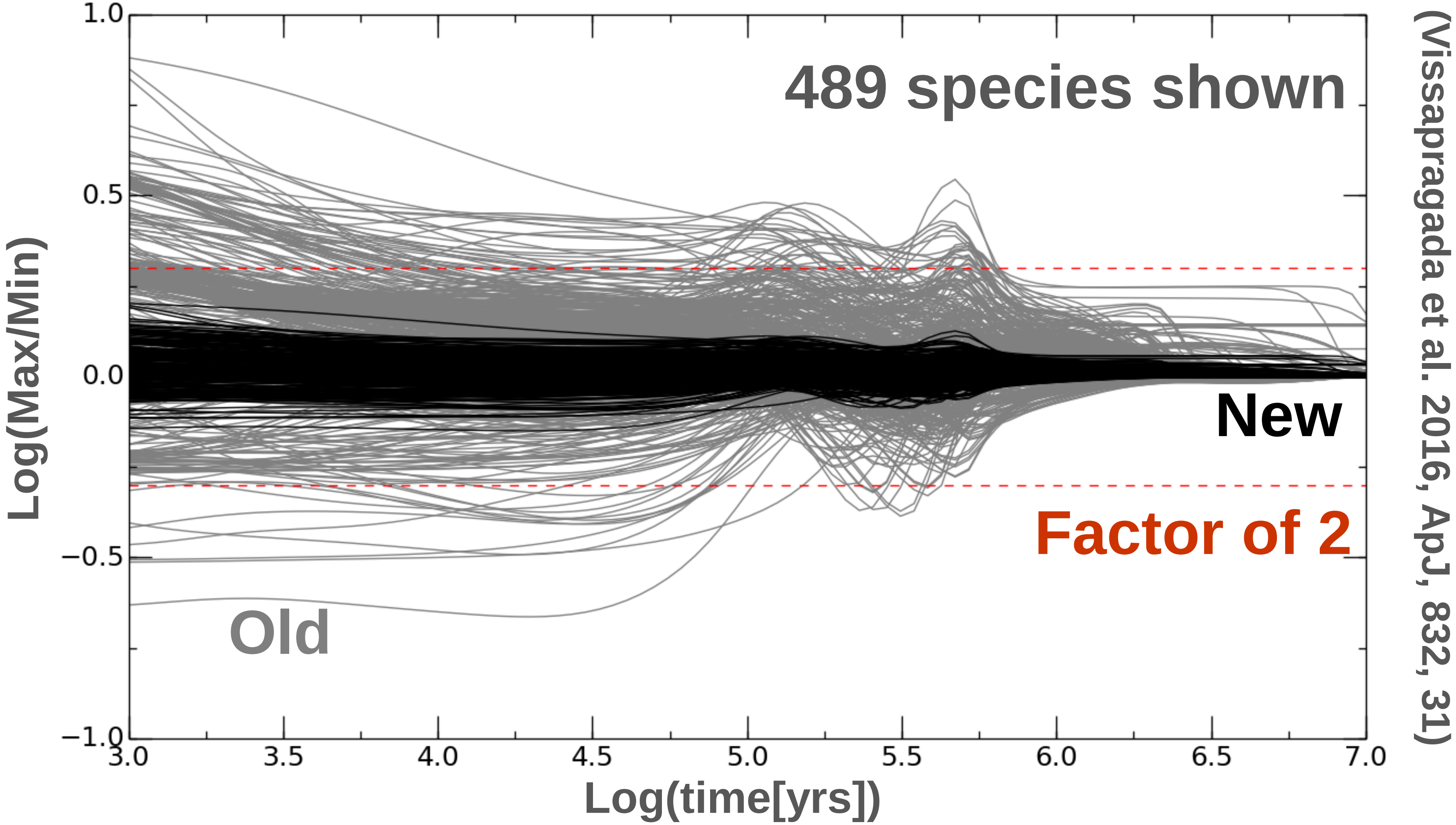
Reduced uncertainty from factor of >2 to <20%.

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

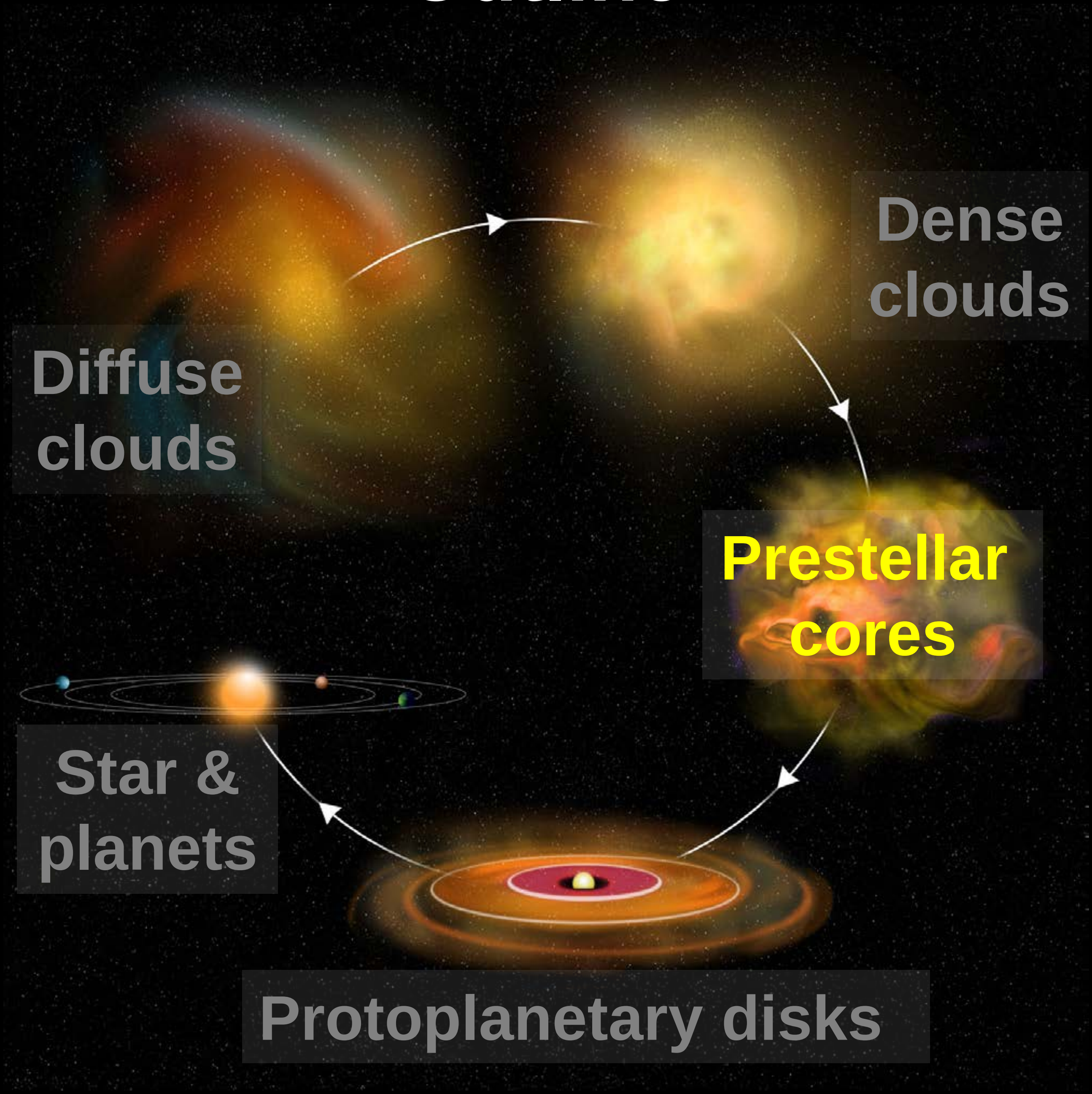


(Vissapragada et al. 2016, ApJ, 832, 31)

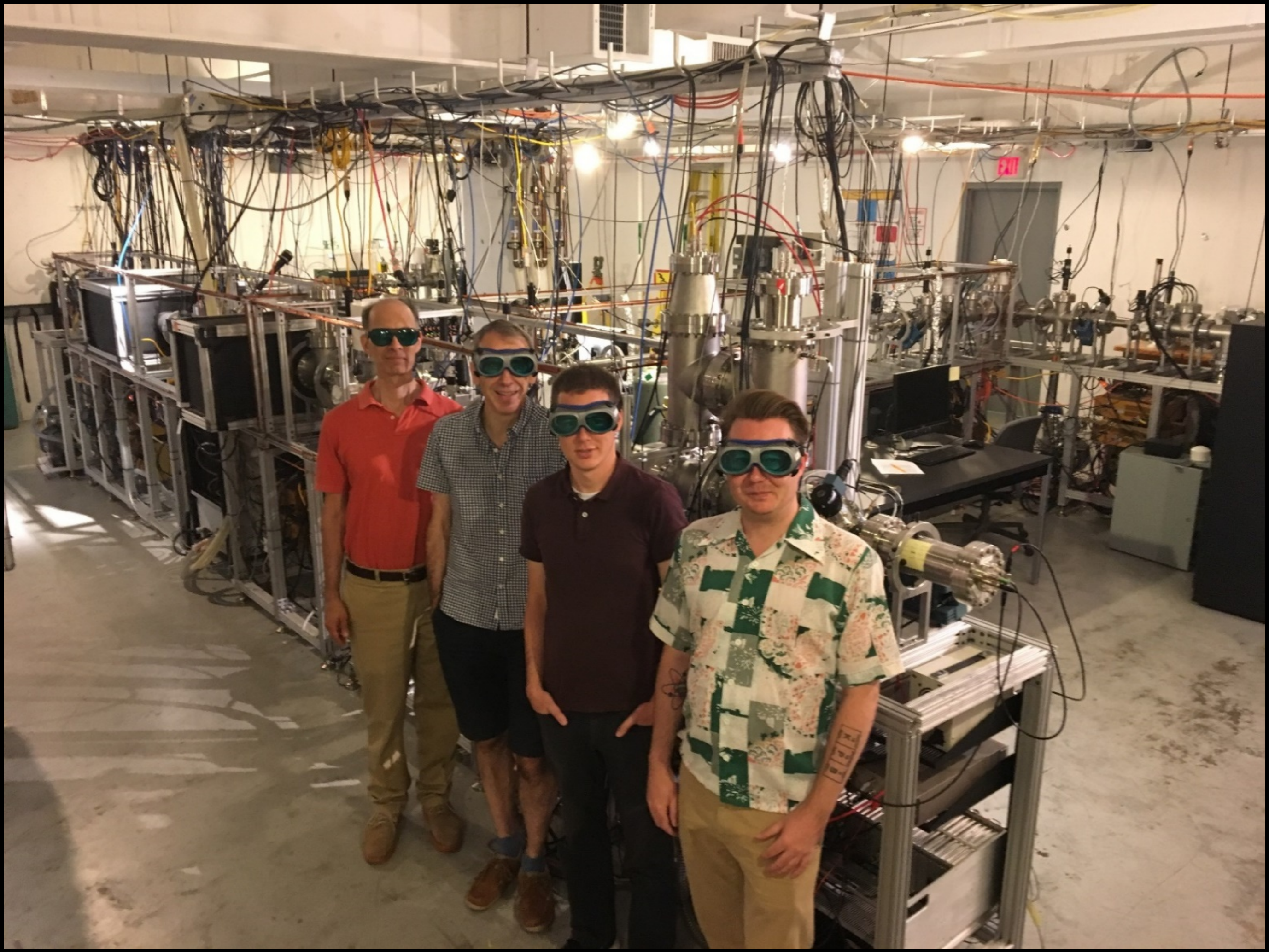
New C + H_3^+ data reduces abundance uncertainties in astrochemical models



Outline

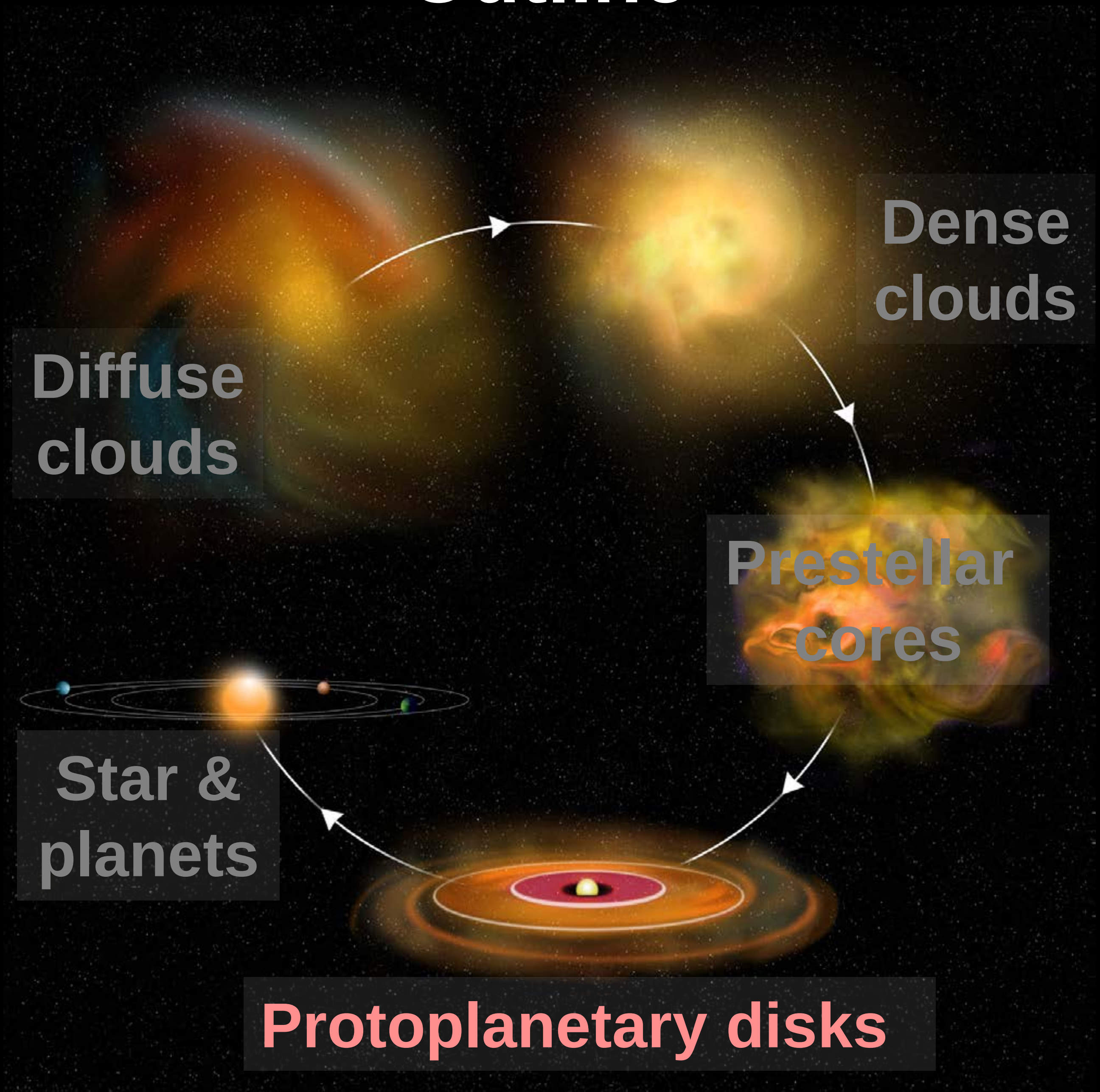

Dense clouds
Diffuse clouds
Prestellar cores
Star & planets
Protoplanetary disks

The Team Members

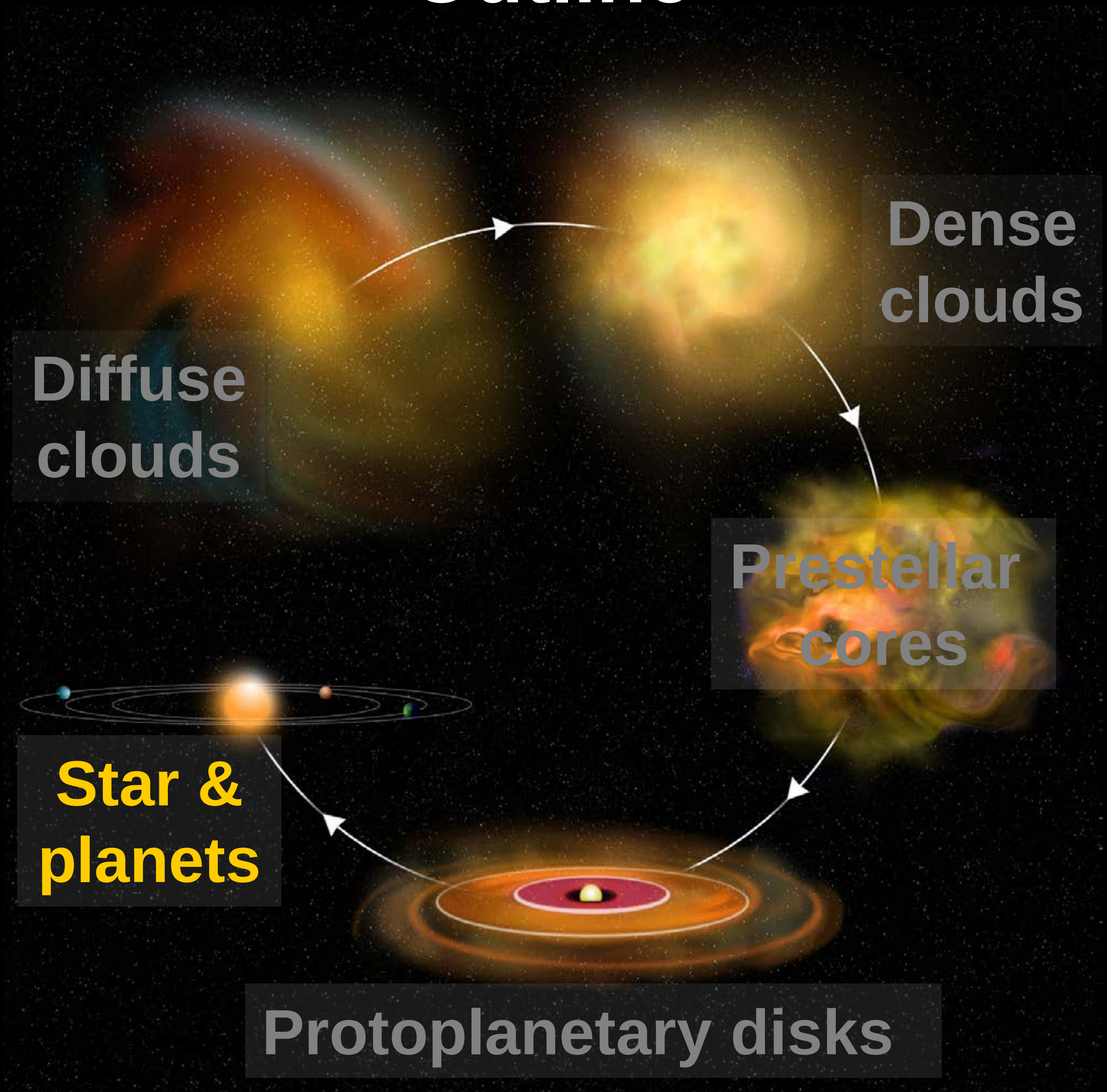


DWS, Xavier Urbain, Pierre-Michel Hillenbrand, & Kyle Bowen
Not shown – Jacky Liévin

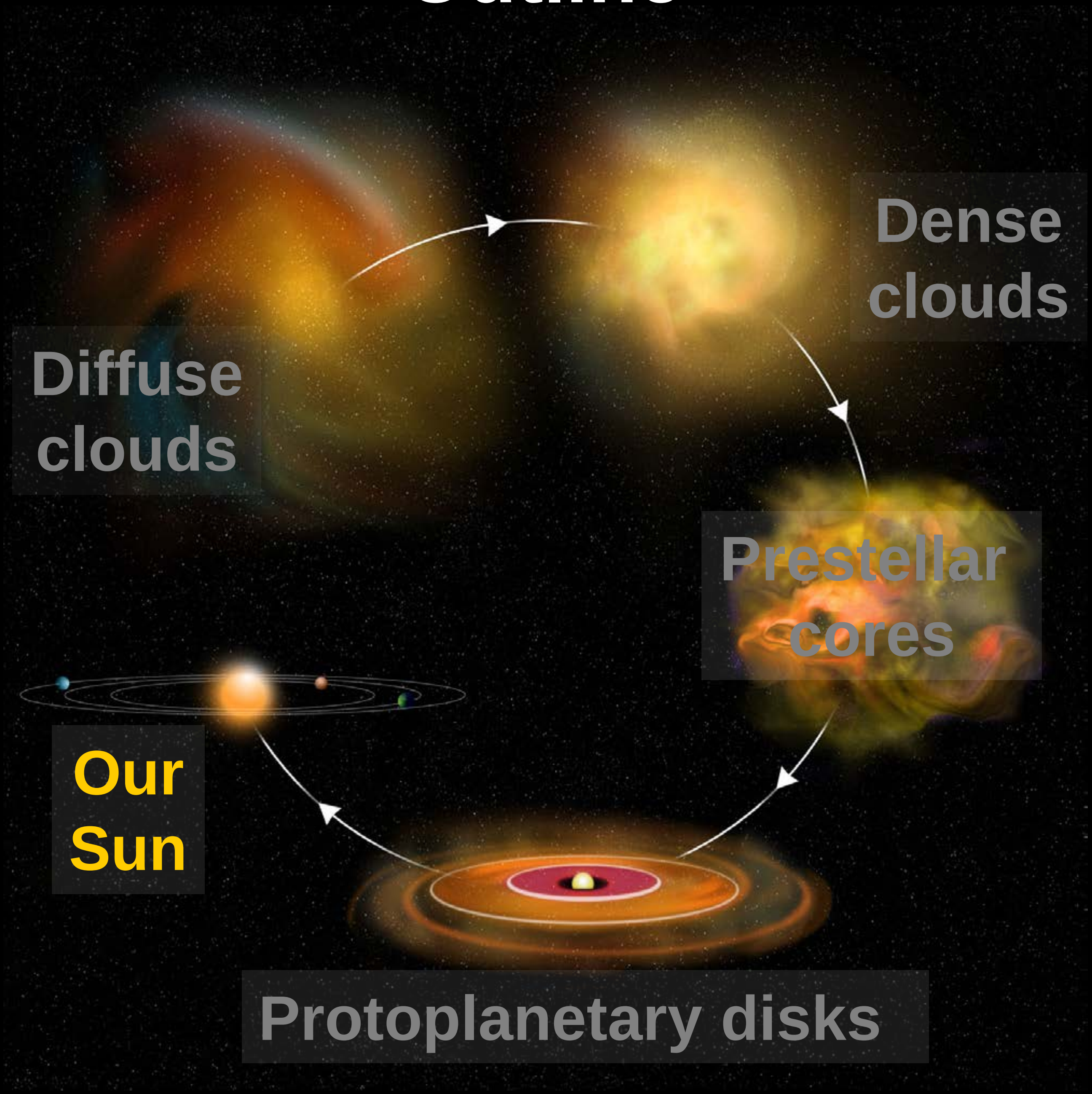
Outline


Dense clouds
Diffuse clouds
Prestellar cores
Star & planets
Protoplanetary disks

Outline

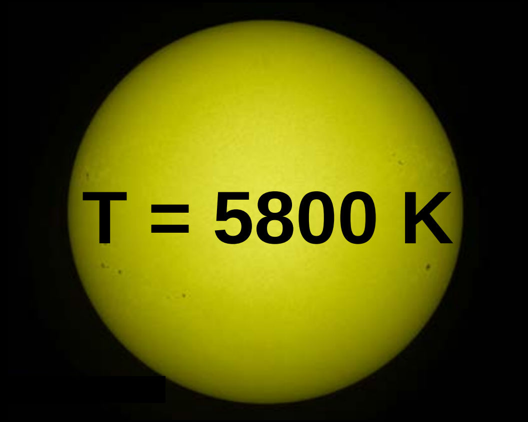

Dense clouds
Diffuse clouds
Prestellar cores
Star & planets
Protoplanetary disks

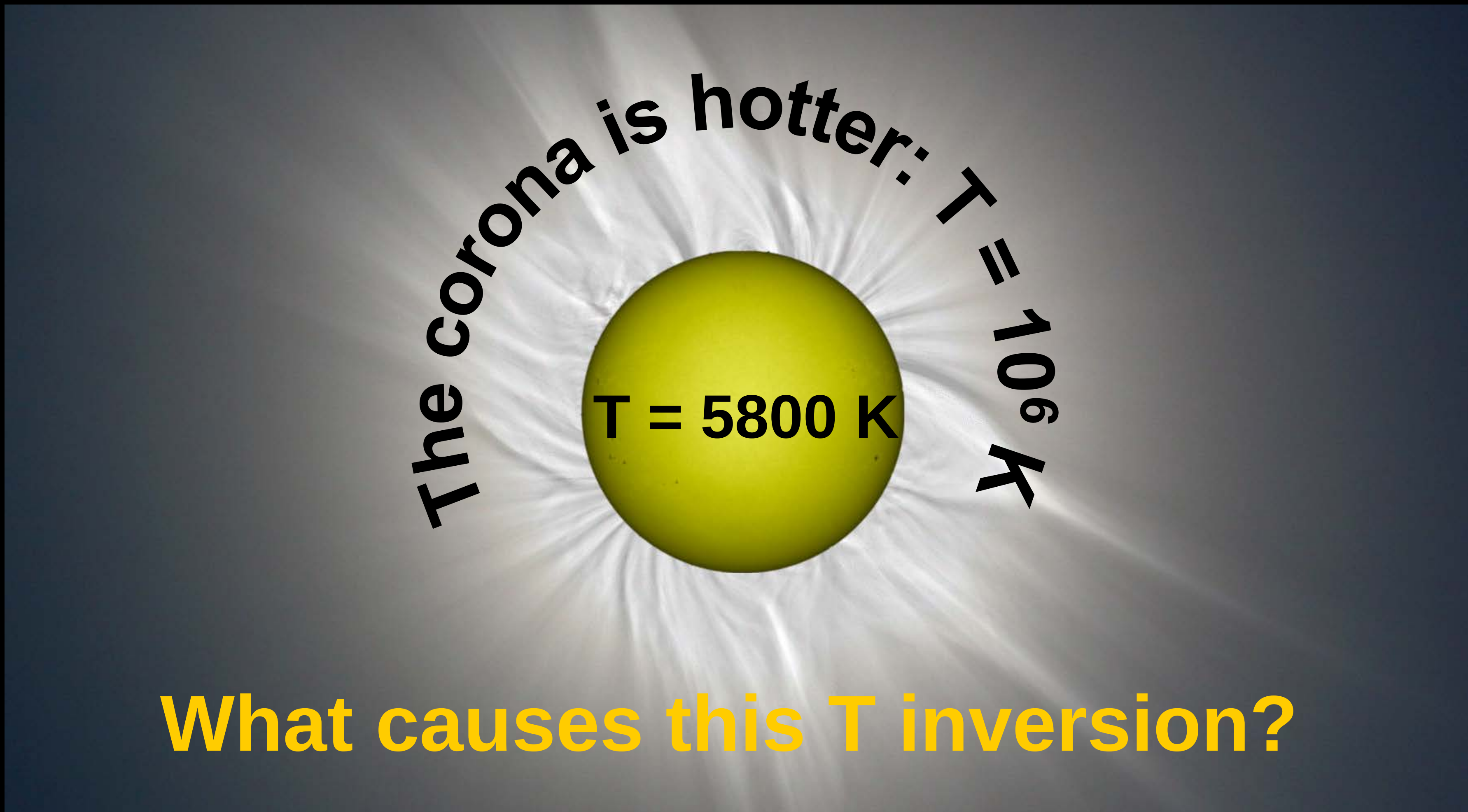
Outline



Dense clouds
Diffuse clouds
Prestellar cores
Our Sun
Protoplanetary disks

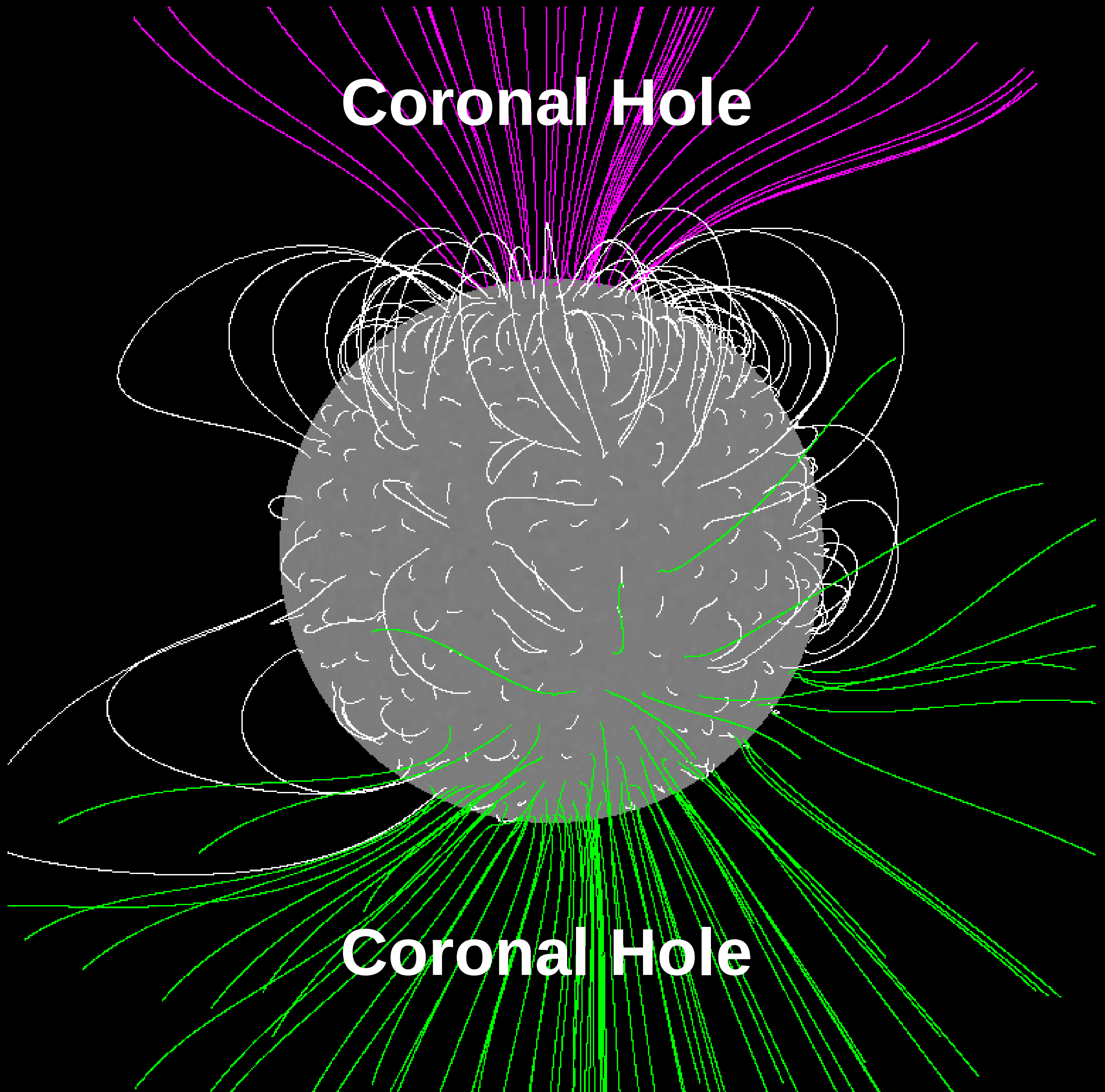
The Sun is hot





An unsolved problem since 1939

Are magnetic fields the heat source?



Magnetic reconnection
(Flares)

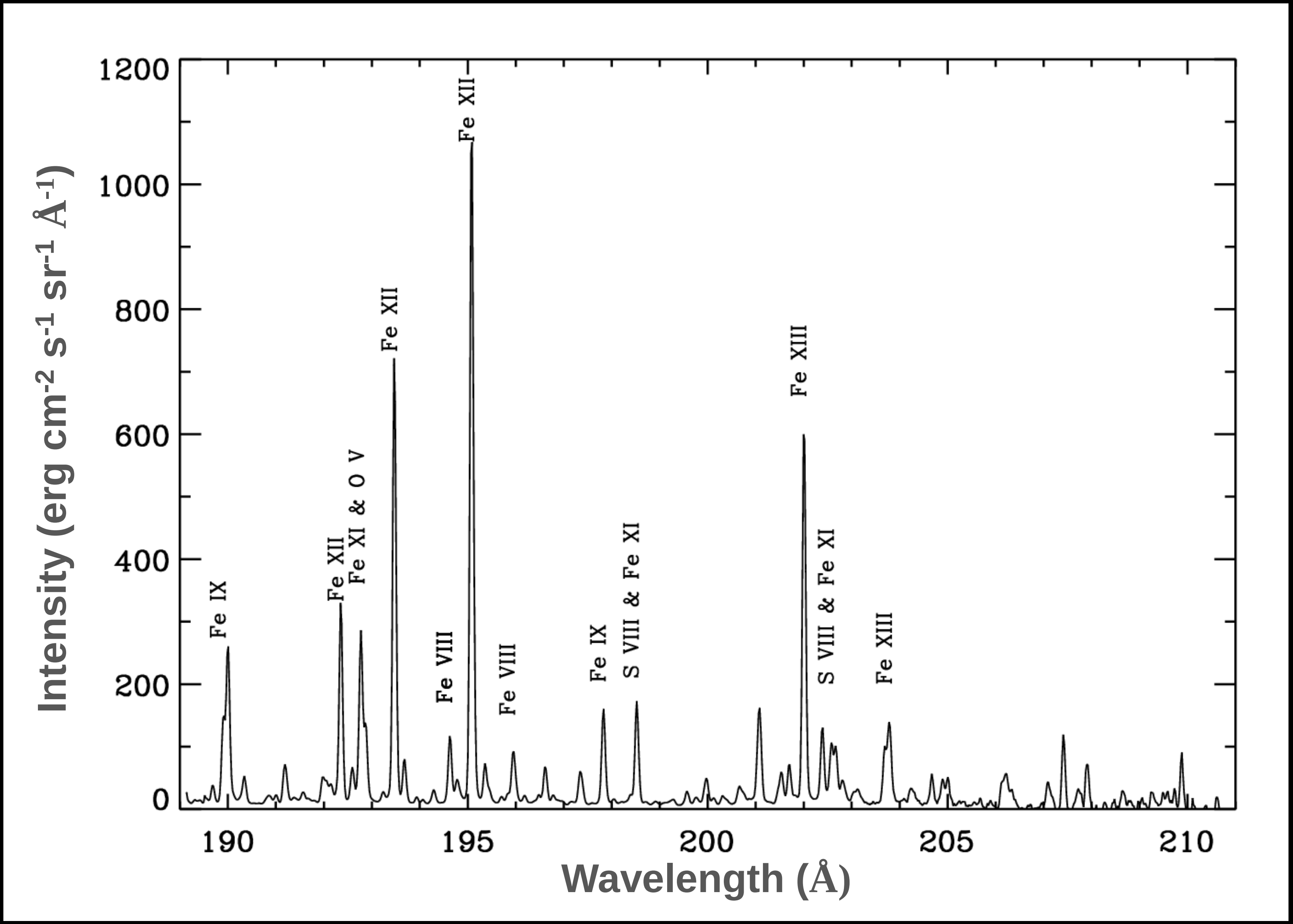
Magnetohydrodynamic
(MHD) waves

What do solar observations tell us?

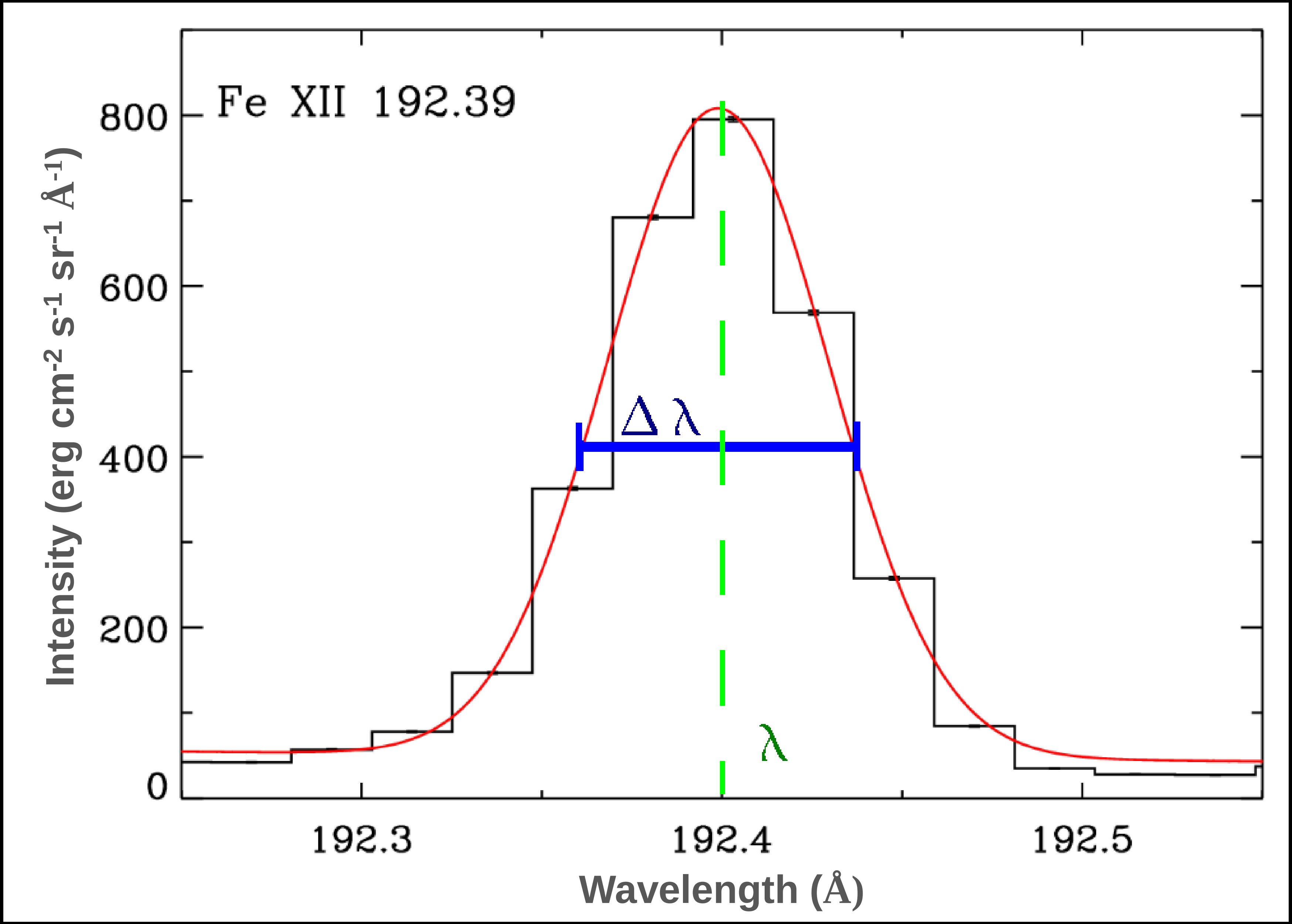
We used Extreme Ultraviolet Imaging Spectrometer (EIS) onboard Hinode, launched in 2006

We looked at a polar coronal hole

And analyzed the collected spectra



Spectroscopic evidence for MHD waves



Spectroscopic evidence for MHD waves

$$\Delta\lambda \propto \left(v_{\mathrm{nt}}^2 + \frac{2k_{\mathrm{B}}T_{\mathrm{i}}}{M_{\mathrm{i}}} \right)^{1/2}$$

v_{nt} – Nonthermal velocity

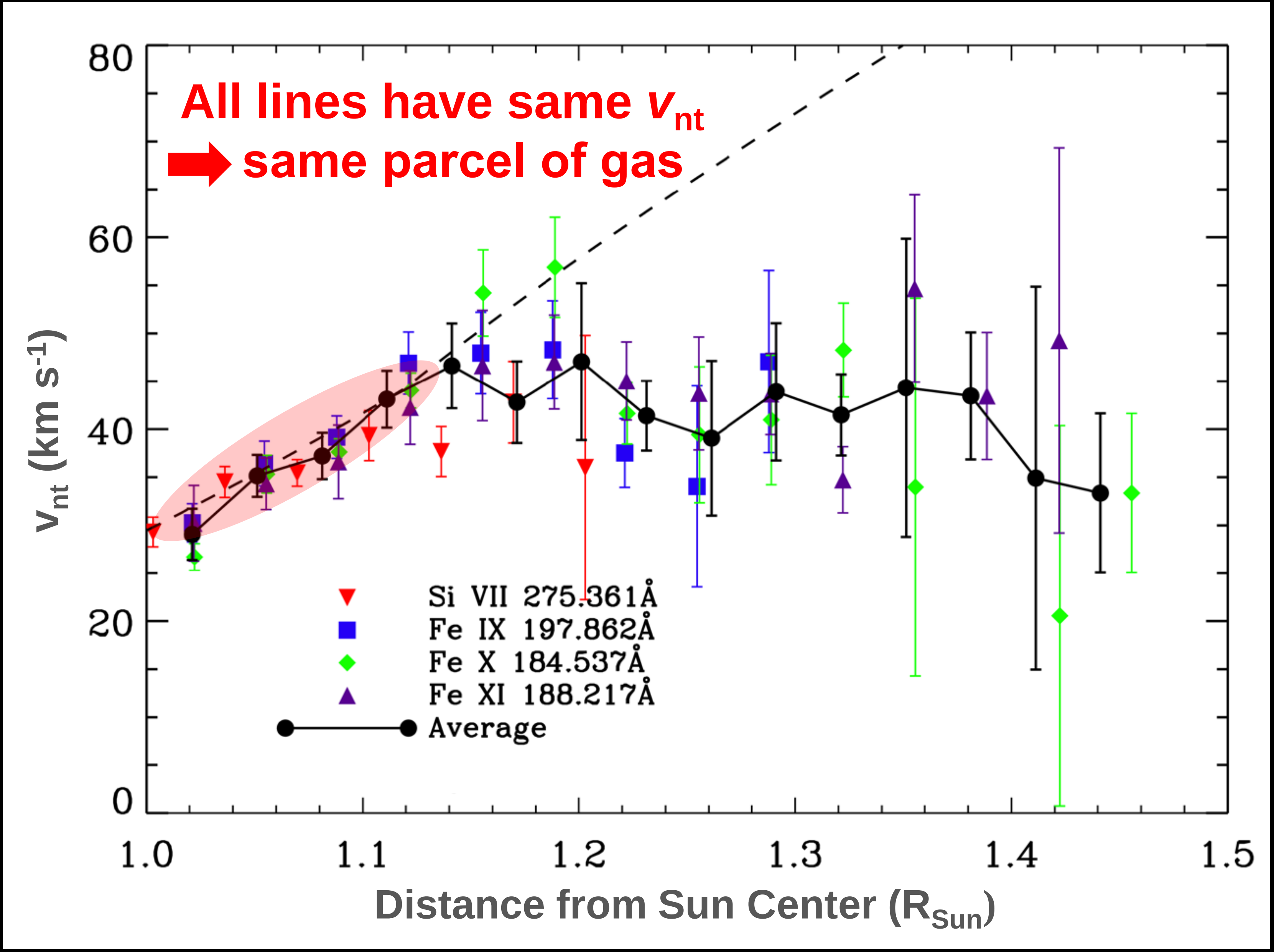
k_B – Boltzmann's constant

T_i – Ion temperature

M_i – Ion Mass

Wave amplitude δv given by $\langle \delta v^2 \rangle = 2v_{nt}^2$

Wave amplitudes expressed as v_{nt}



Is the MHD wave energy conserved?

Wave power (energy/time) be expressed as

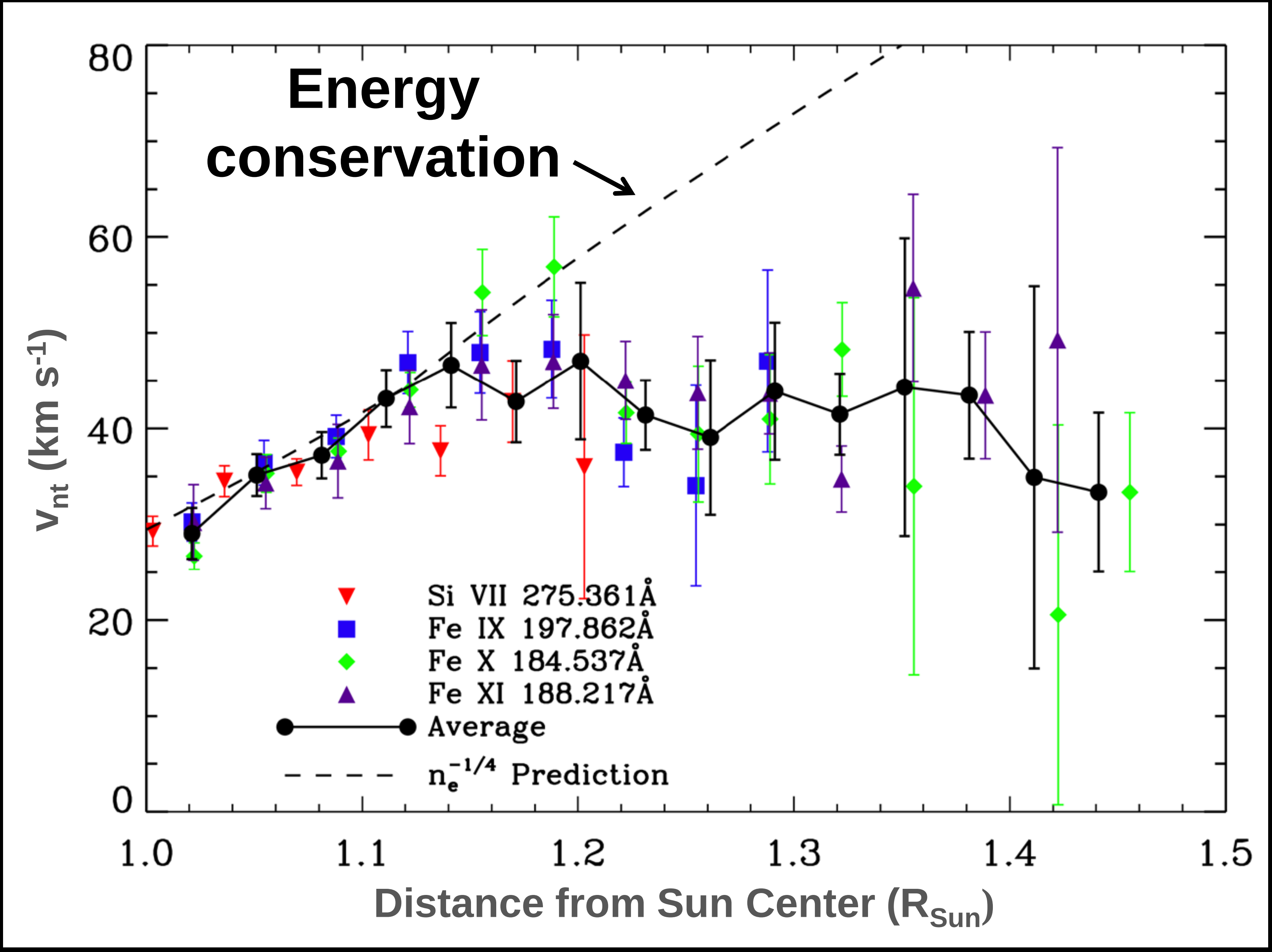
$$FA = \frac{1}{\sqrt{\pi}} \rho^{1/2} v_{\mathrm{nt}}^2 BA$$

In coronal holes, *B-field*Area* is constant.
For undamped waves *Flux*Area* is constant giving

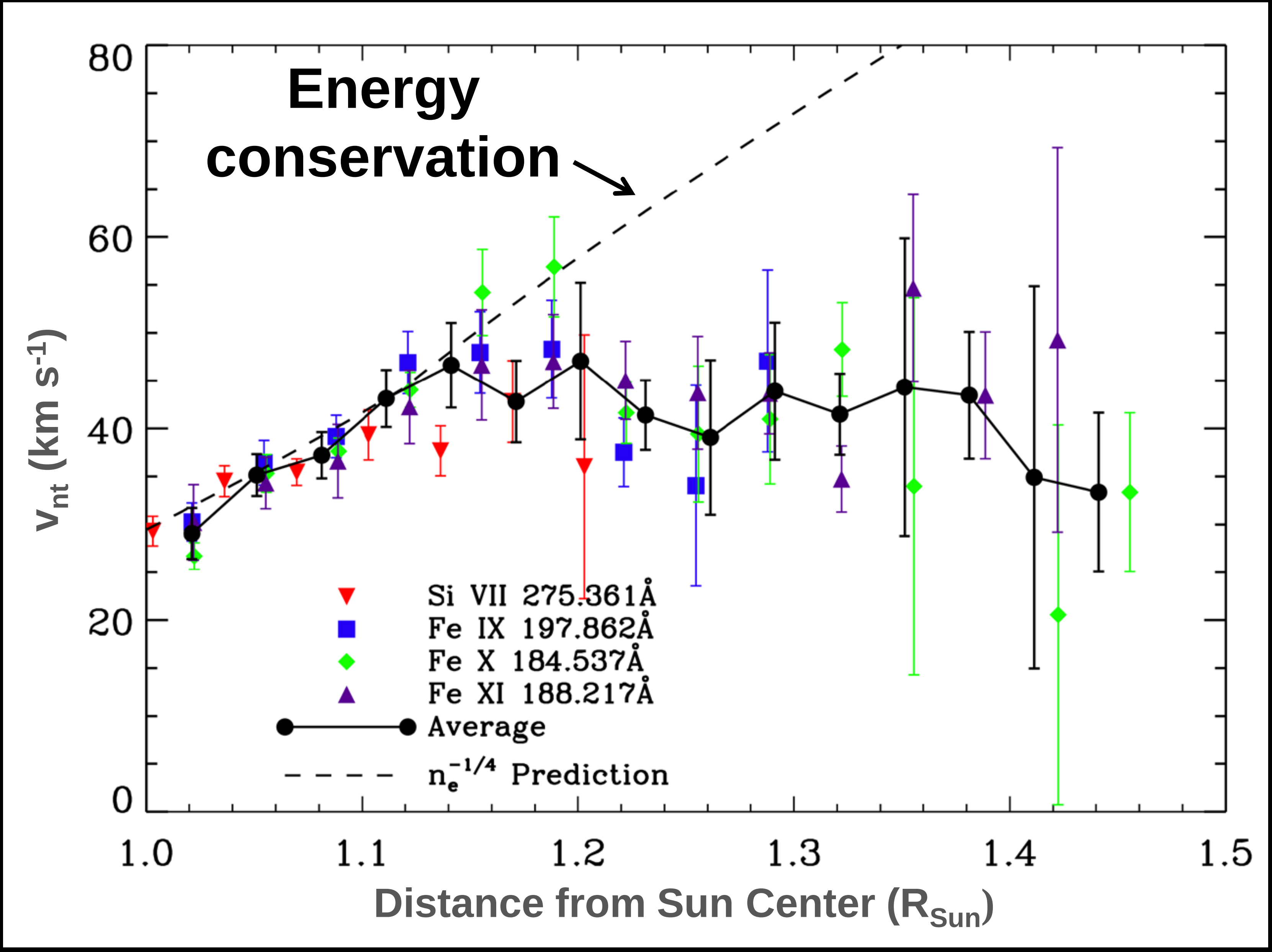
$$v_{\mathrm{nt}} \propto \rho^{-1/4}$$

Does v_{nt} increase with height as ρ decreases?

Wave damping begins about 1.15 $R_\odot$



Wave energy is not conserved



MICHAEL HAHN

2012 REGIONAL AWARD WINNER — POST-DOC

Current Position:
Associate Research Scientist

Institution:
Columbia University

Discipline:
Astrophysics & Cosmology

Recognized for: Advancing our knowledge of the extreme temperature of the Sun's corona

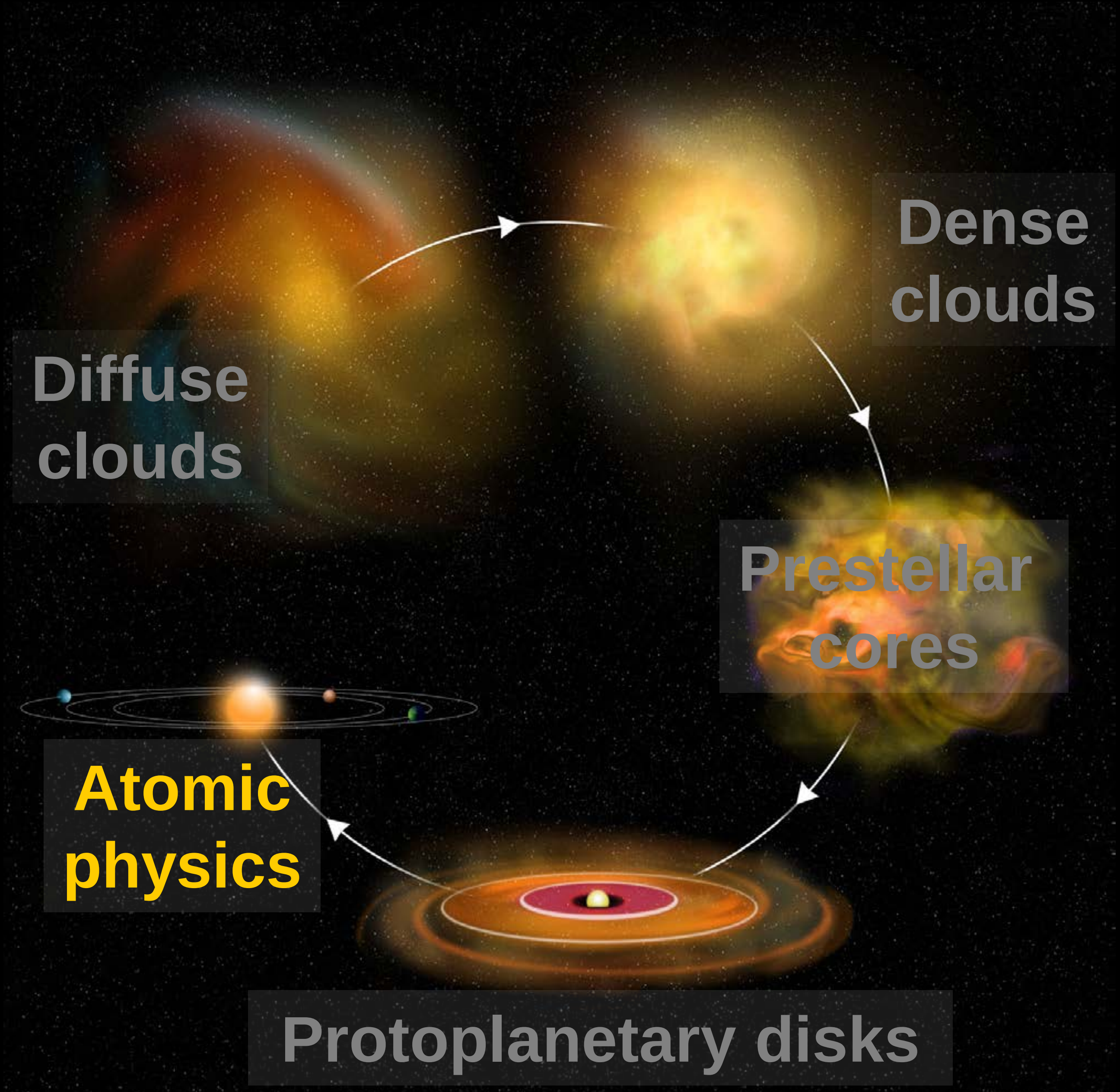
Areas of Research Interest and Expertise: Solar physics, especially to determine the sources of coronal heating and the acceleration of the solar wind; plasma waves and damping processes; experimental measurements of atomic properties needed to interpret astrophysical spectra.

Our findings raise several questions that we are now trying to answer

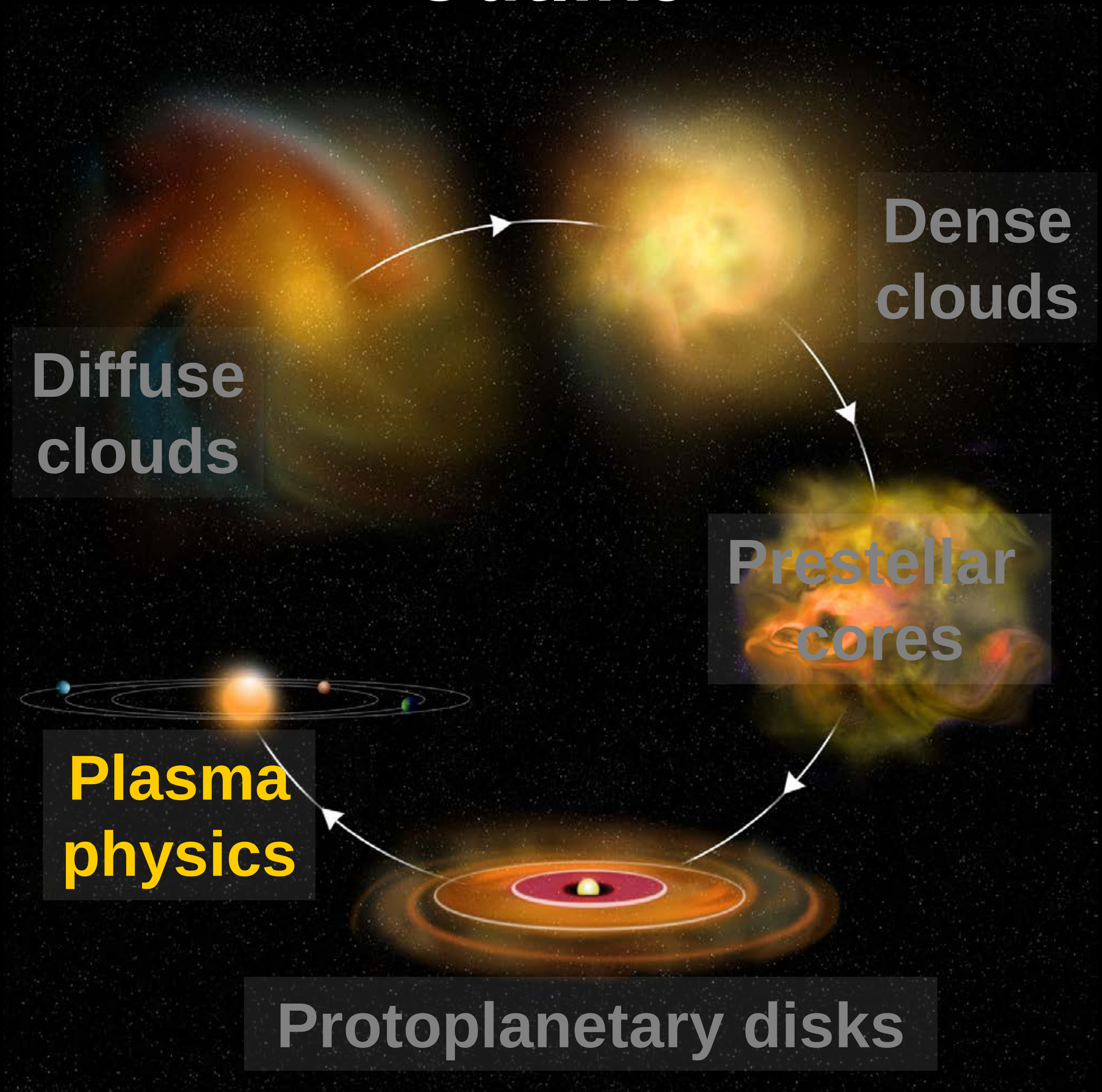
$$FA = \frac{1}{\sqrt{\pi}} \rho^{1/2} v_{nt}^{2} BA$$

- How well do we know the electron density used to infer the energy flux?
- What is the plasma physics mechanism that causes the wave damping?
- We are conducting laboratory studies to address both of these issues.

Outline

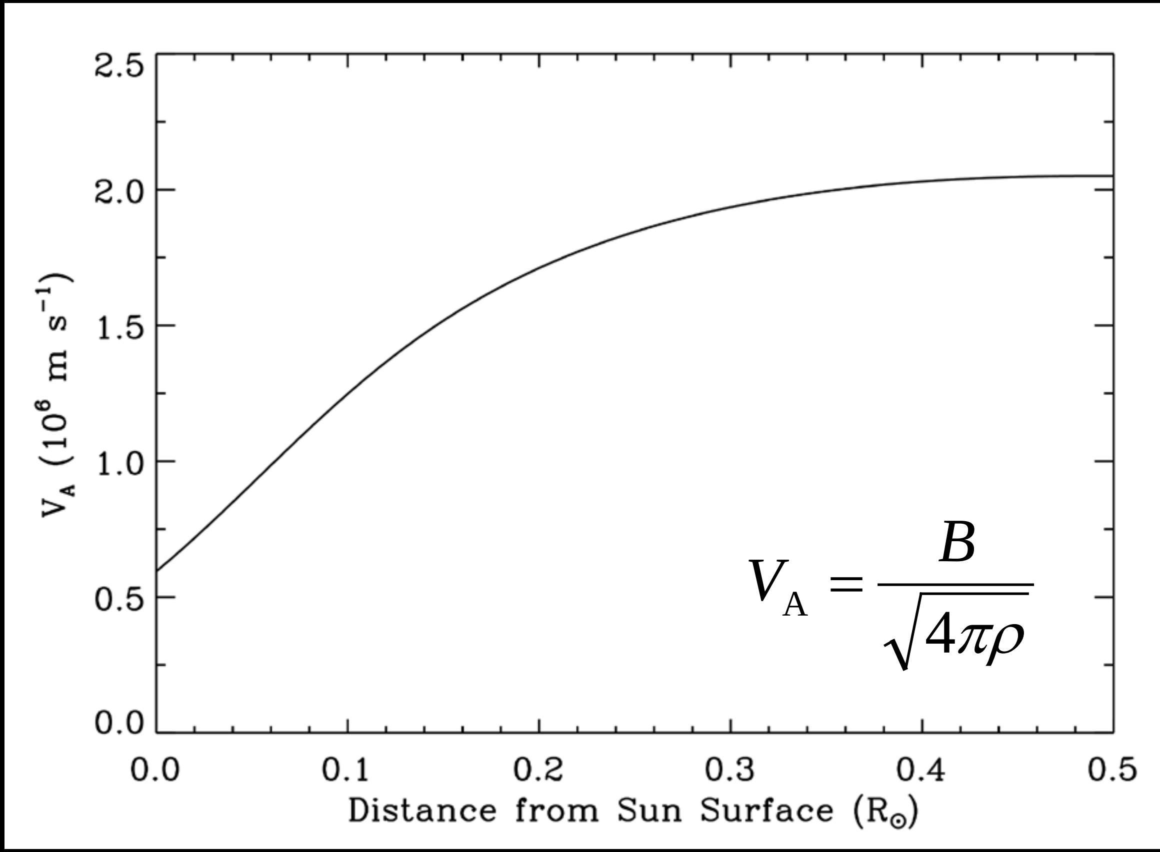

Dense clouds
Diffuse clouds
Prestellar cores
Atomic physics
Protoplanetary disks

Outline


Dense clouds
Diffuse clouds
Prestellar cores
Plasma physics
Protoplanetary disks

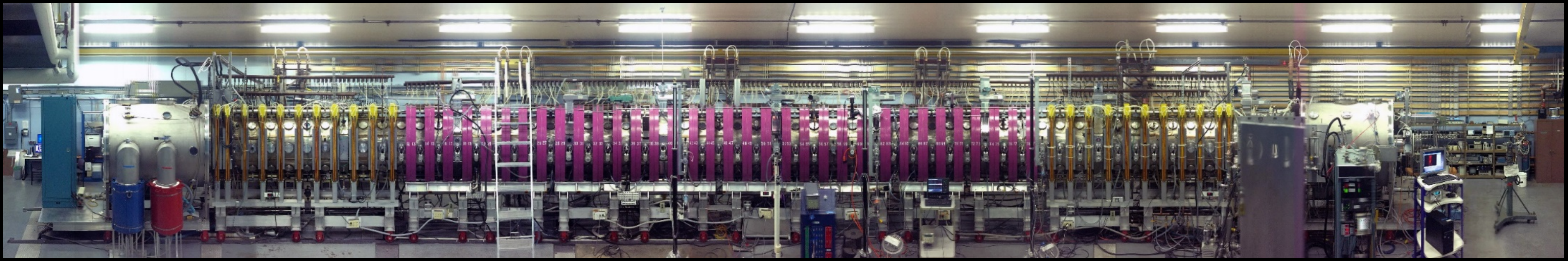
What plasma physics causes damping?

Longitudinal gradients: *B* and *ρ* fall off with *R*



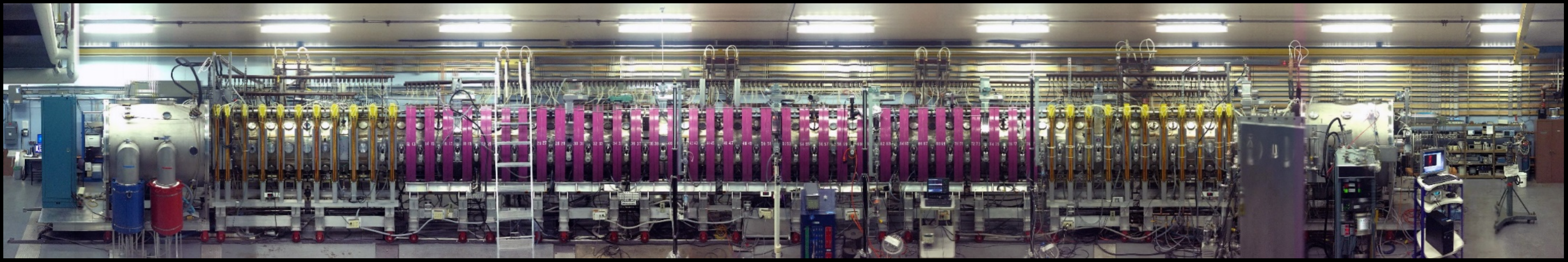
Gradients in V_A can cause reflection and turbulence

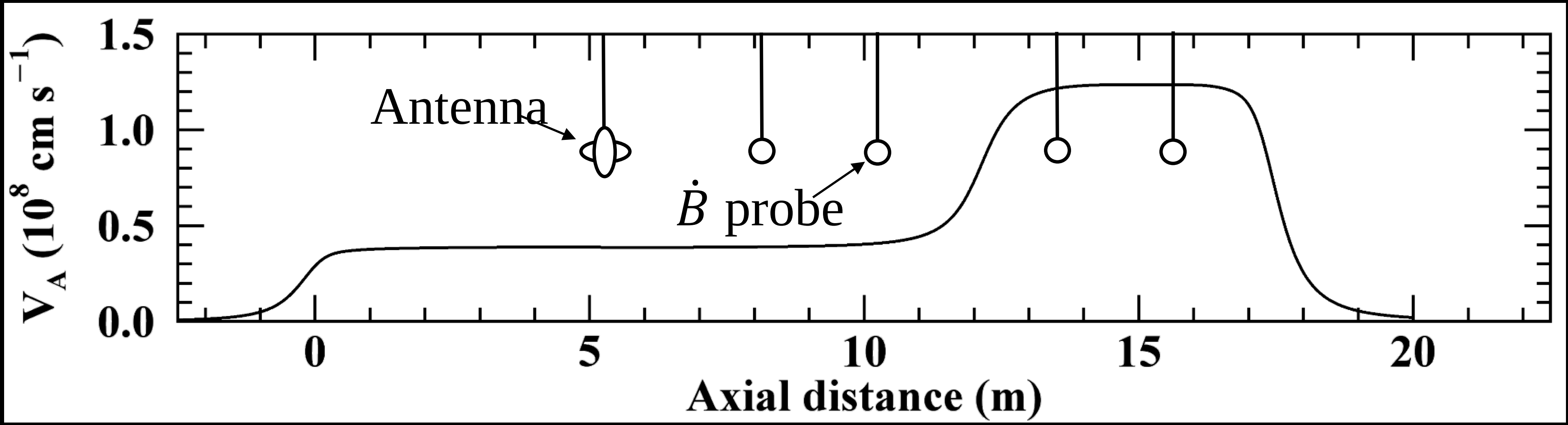
Using the Large Plasma Device (LAPD), we are exploring this question



LAPD is an ~ 20 m long discharge tube surrounded by solenoid coils

Using the Large Plasma Device (LAPD), we are exploring this question





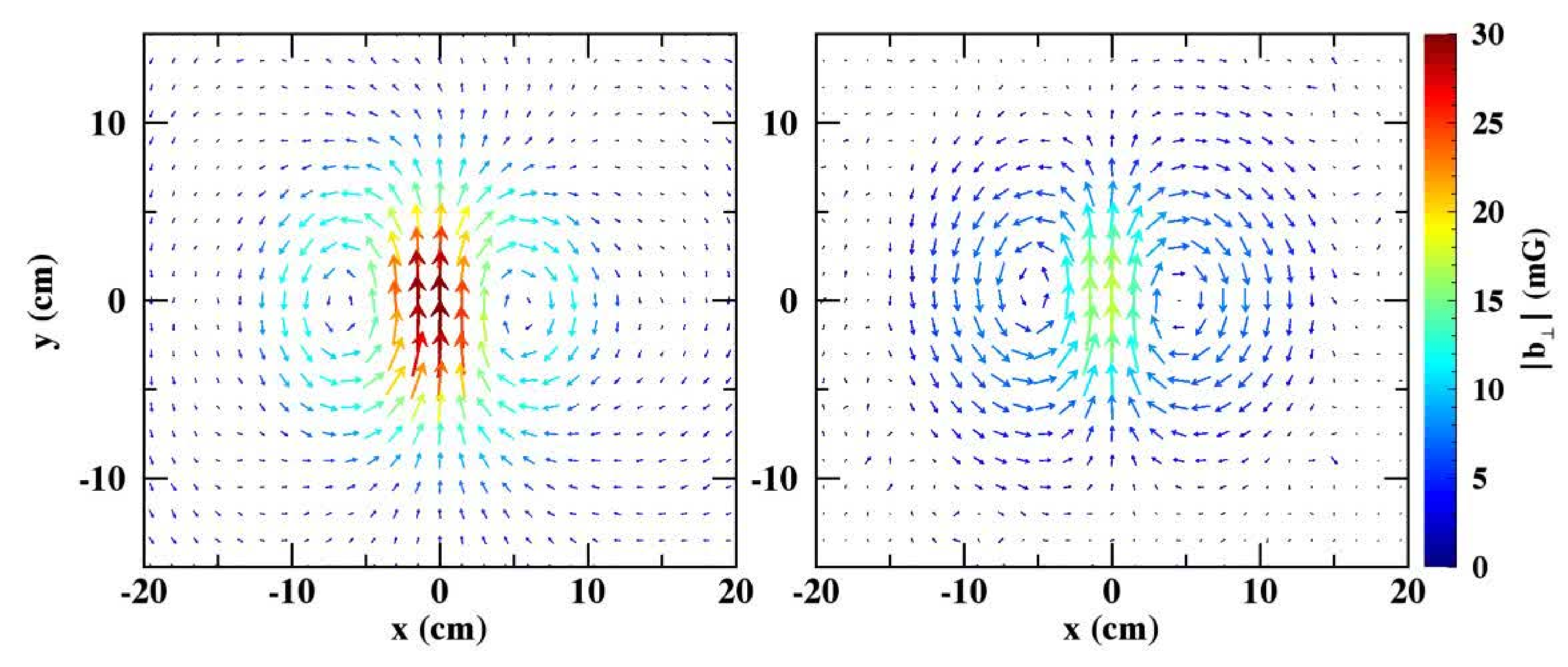
The Team Members

Sayak Bose, Mike Hahn, Walter Gekelman, and Steve Vincena
(missing from photo: Troy Carter and Shreekrishna Tripathi)

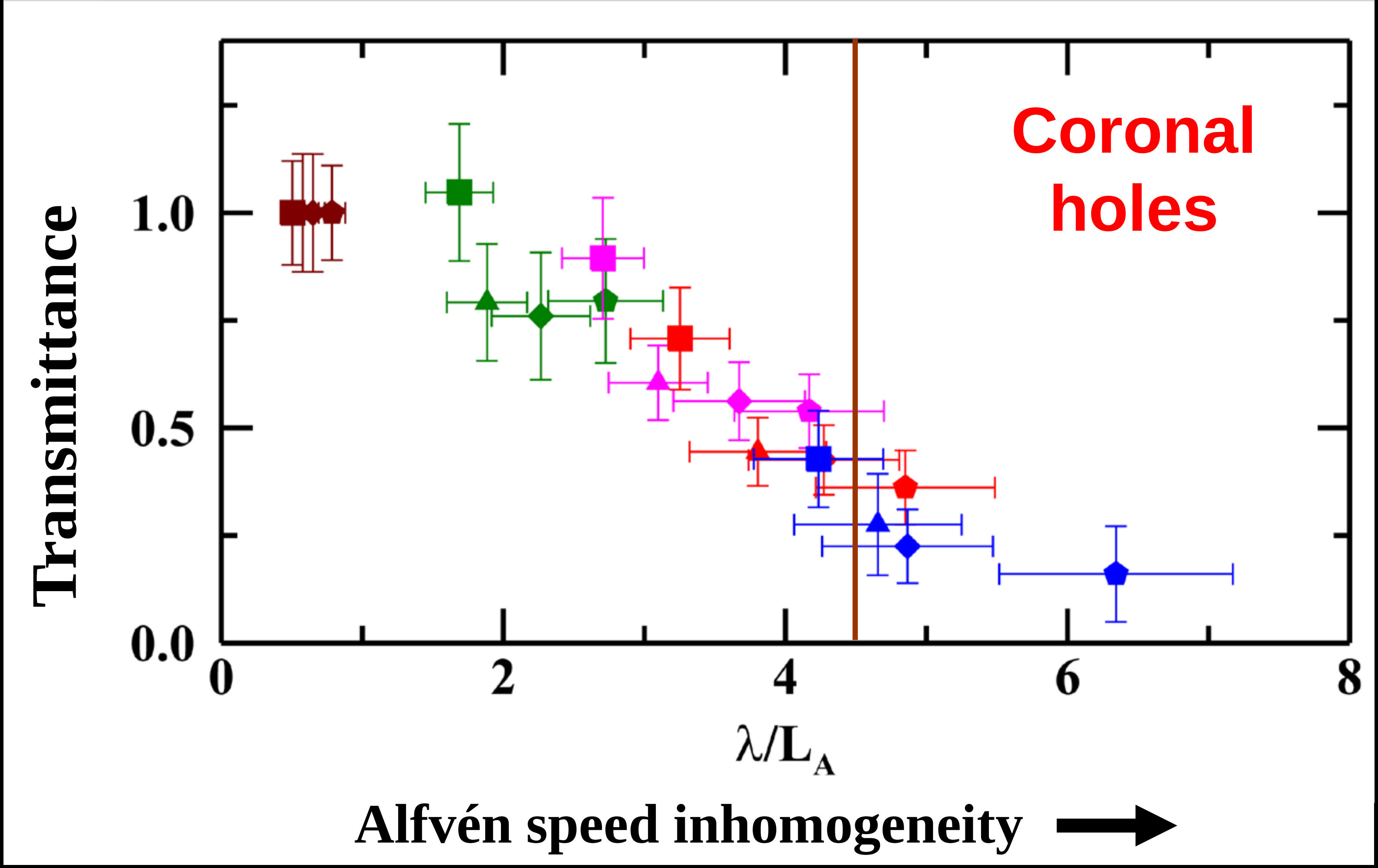
Alfvén Waves in LAPD

Before gradient

After gradient

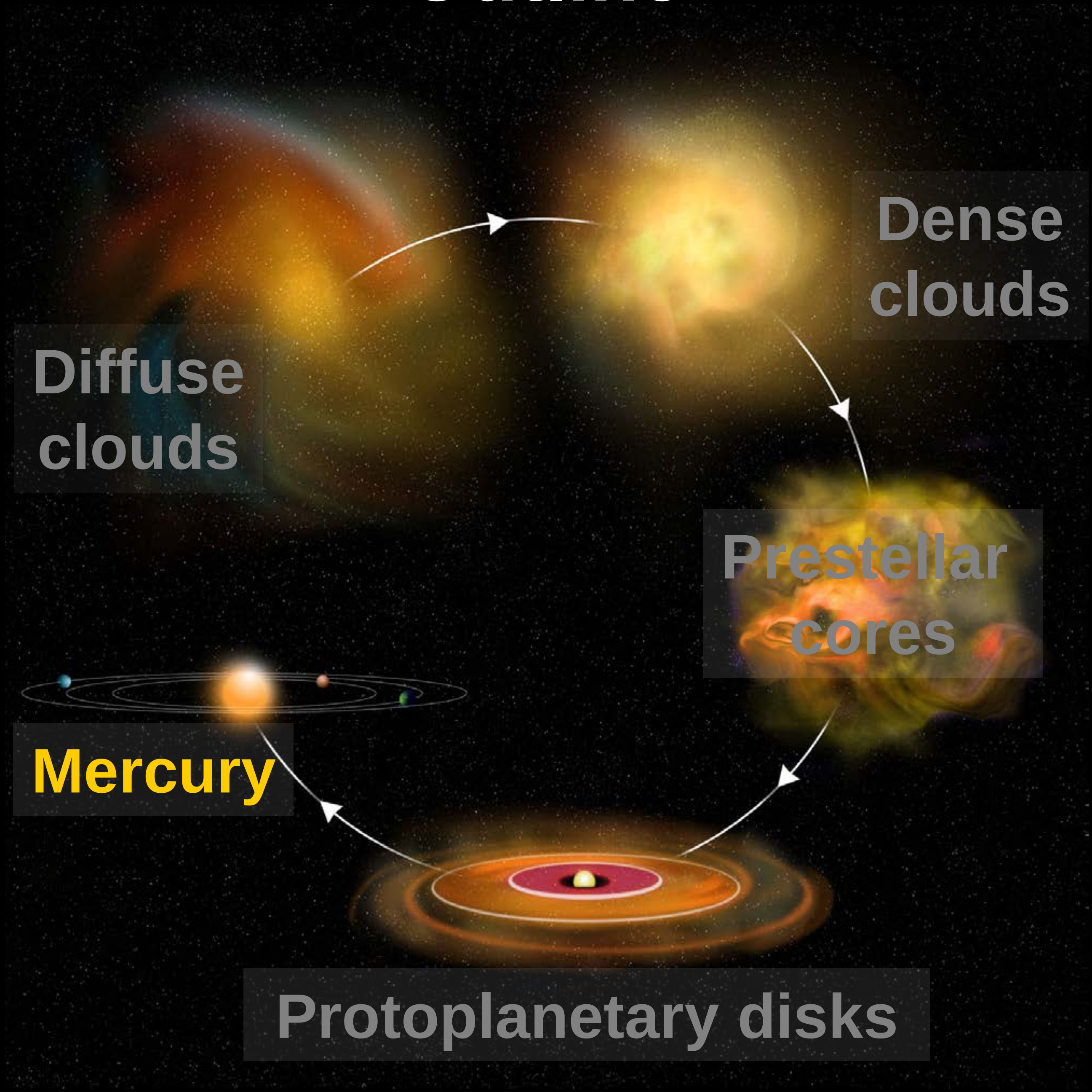


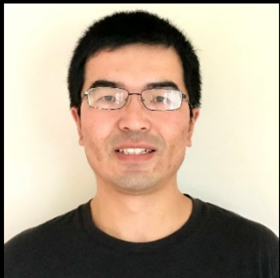
Transmittance through the Gradient



What are the plasma & solar physics implications?

Outline


Dense clouds
Prestellar cores
Protoplanetary disks
Mercury
Diffuse clouds



Ruitian Zhang
Kyle Bowen
Benjamin Bostick

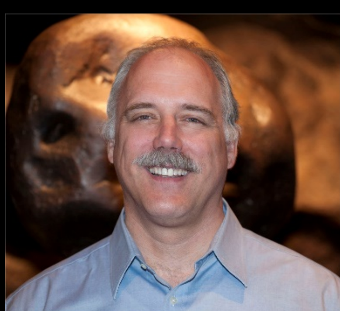
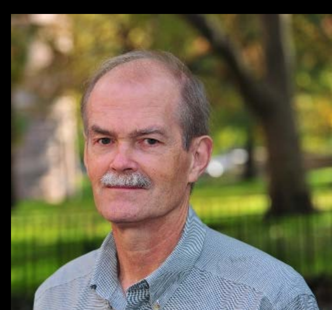
COLUMBIA

Deborah Domingue

PLANETARY SCIENCE INSTITUTE
EST. 1972

Rosemary Killen

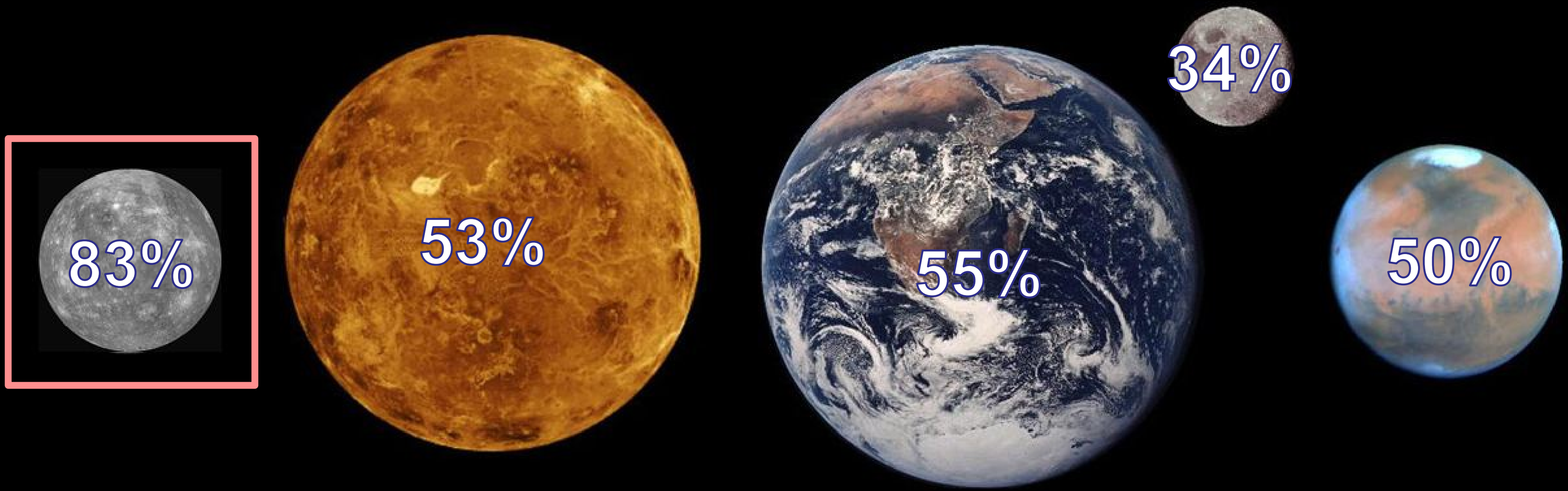
Goddard
SPACE FLIGHT CENTER

Denton Ebel, George Harlow

AMERICAN MUSEUM OF NATURAL HISTORY

One of these planets is unlike the others

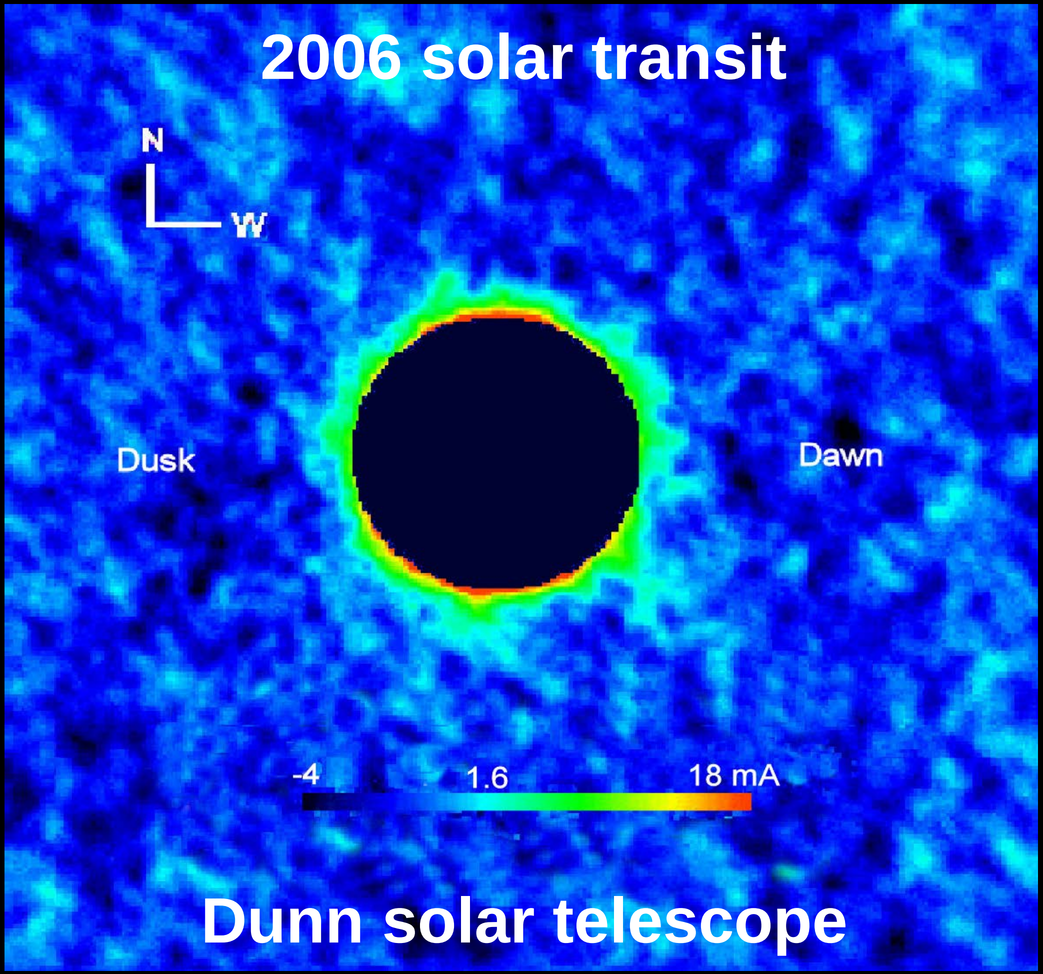


Mercury Venus Earth Moon Mars

- All are rocky
- All have Fe cores
- Most have abundant surface Fe

- Mercury's surface is Fe poor
- Why?

Planet formation constrained by surface mineralogy inferred from the exosphere



(Killen, private communication)

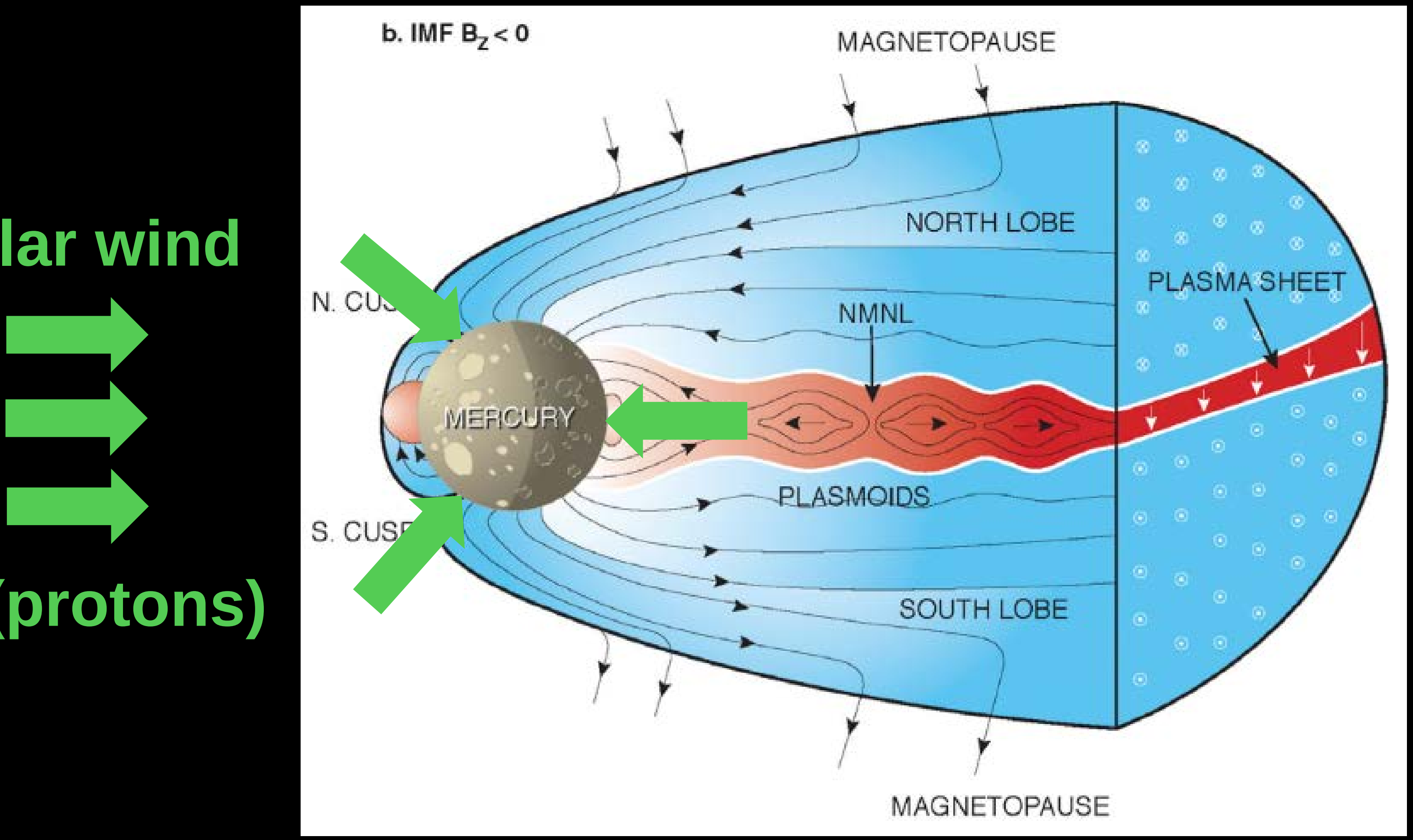
Mercury has a tenuous Na exosphere

Is this coming from rocks on the surface of the planet?

Ion sputtering, impact vaporization, photo-desorption,…?

Solar wind ion impacting the surface may explain the Na exosphere

Solar wind



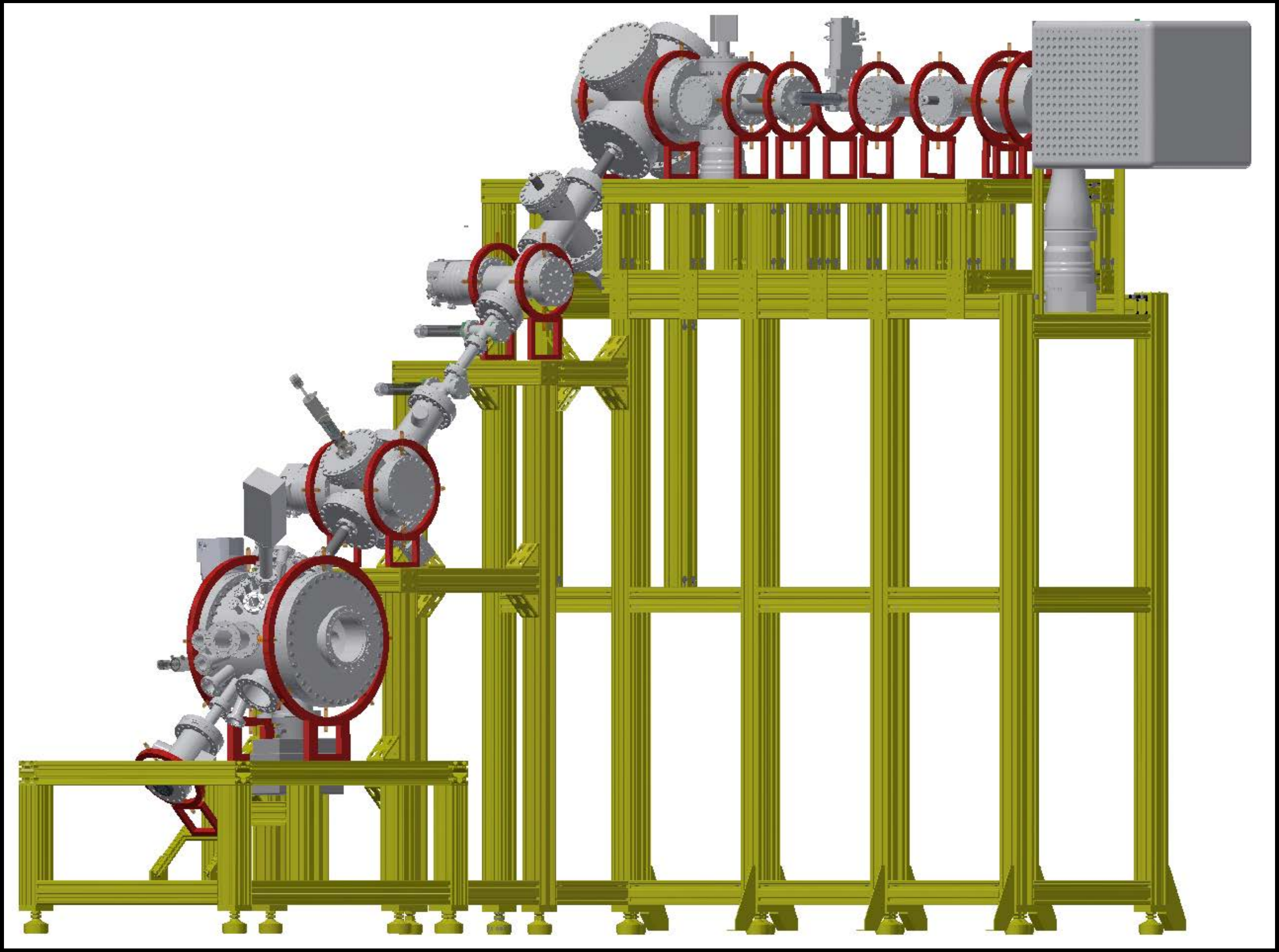
H$^+$ (protons)

(Slavin et al. 2012, J. Geophys. Res. Space Sci., 117, A 01215)

But sputtering of regolith-like loose powders by ions is poorly understood

- Regolith-like loose powders are difficulty to study experimentally
- All samples to date have been generated in atmosphere, unlike the vacuum of space
- Most studies have used ion beam energies much greater than the 1 keV/amu of the solar wind
- *In-situ* and *in-vacuo* diagnostics are needed to prevent contamination of the activated surfaces

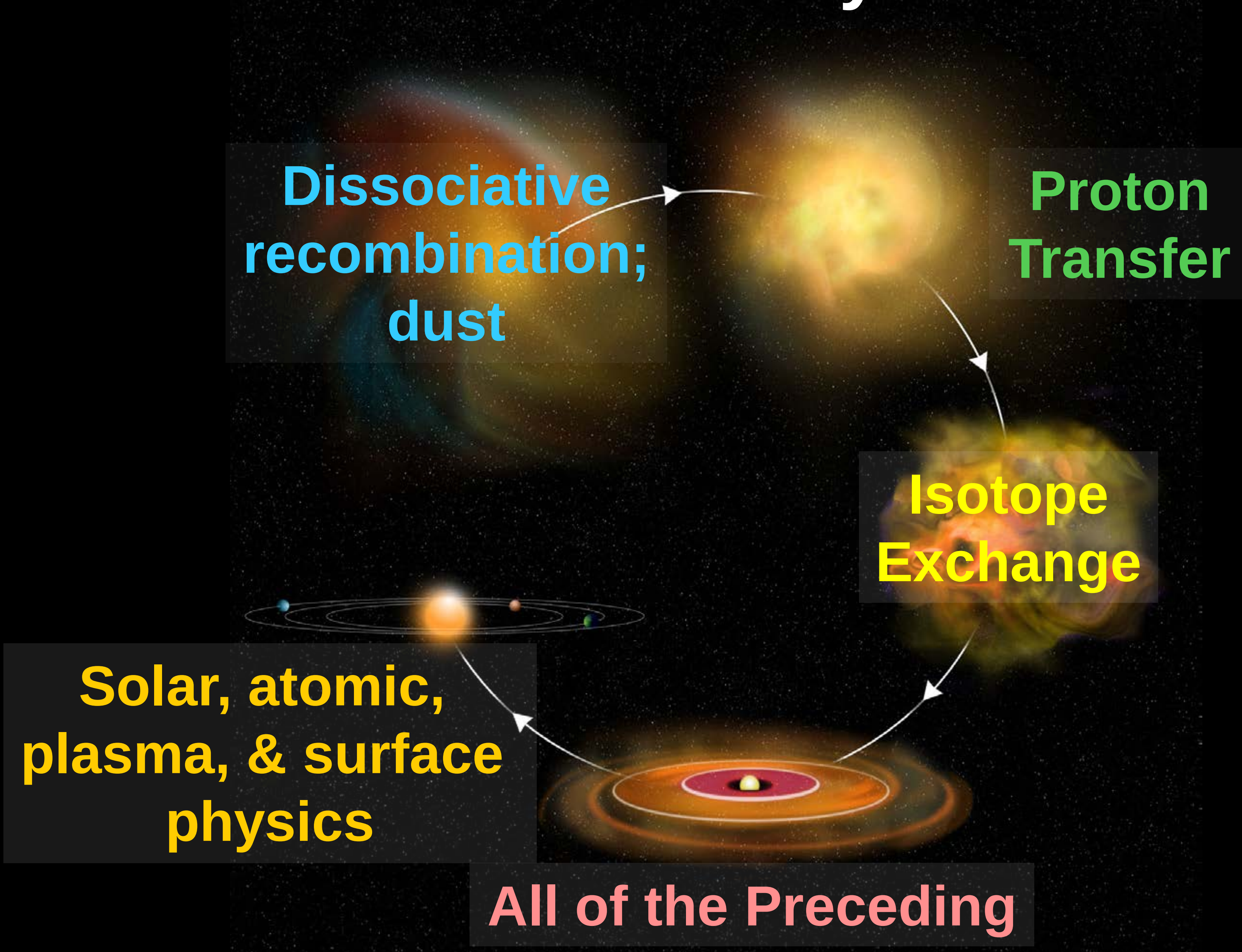
We are building a novel apparatus to study ion sputtering of loose powders



We are building a novel apparatus to study ion sputtering of loose powders

Stay tuned for future results.

Summary


Dissociative recombination; dust
Proton Transfer
Isotope Exchange
All of the Preceding
Solar, atomic, plasma, & surface physics

And thanks for your attention