Water Abundance in Protostellar Envelopes
-
The Relation Between Water Gas and Ice

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T. Albertsson	MPIA Heidelberg
C. Walsh	Leiden University
J. Mottram	Leiden University
L. Kristensen	CfA Cambridge
and the WISH team	

WISH

Water in Star-Forming Regions with Herschel

The abundance of **volatile oxygen** in the ISM is $X_\mathrm{O} = \mathbf{3.2\ 10^{-4}}$

Meyer+ (1998), ApJ...493..222

In the *cold environment*, basically all the **volatile oxygen** should be driven into **water ice**

e.g., **Hollenbach+ (2009),** ApJ...690.1497H

INTRODUCTION

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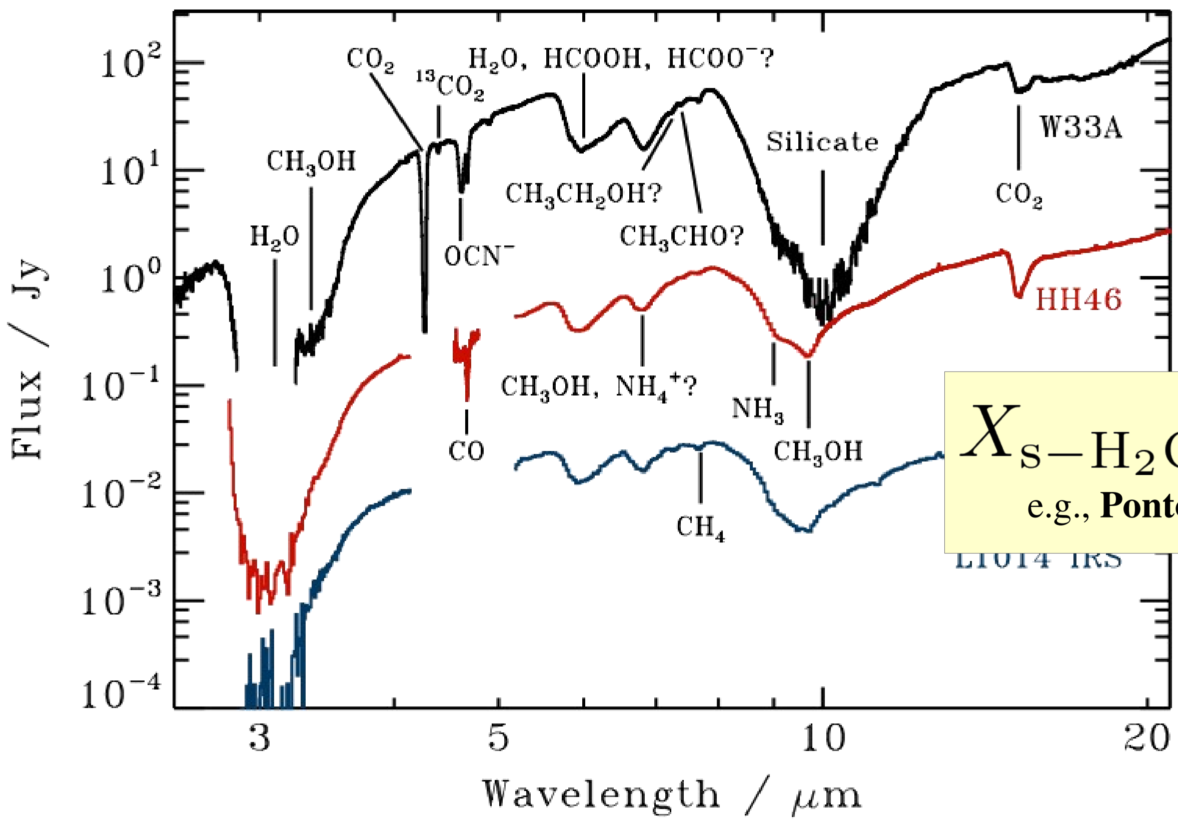
In the *cold environment*, basically all the **volatile oxygen** should be driven into **water ice** e.g., **Hollenbach+ (2009),** ApJ...690.1497H

Öberg+ (2011), ApJ...740..109



$$X_{\rm s-H_2O} \sim 5\ 10^{-5}$$

e.g., **Pontoppidan+ (2004)**, A&A...426..925

THE GOAL OF THIS PROJECT:

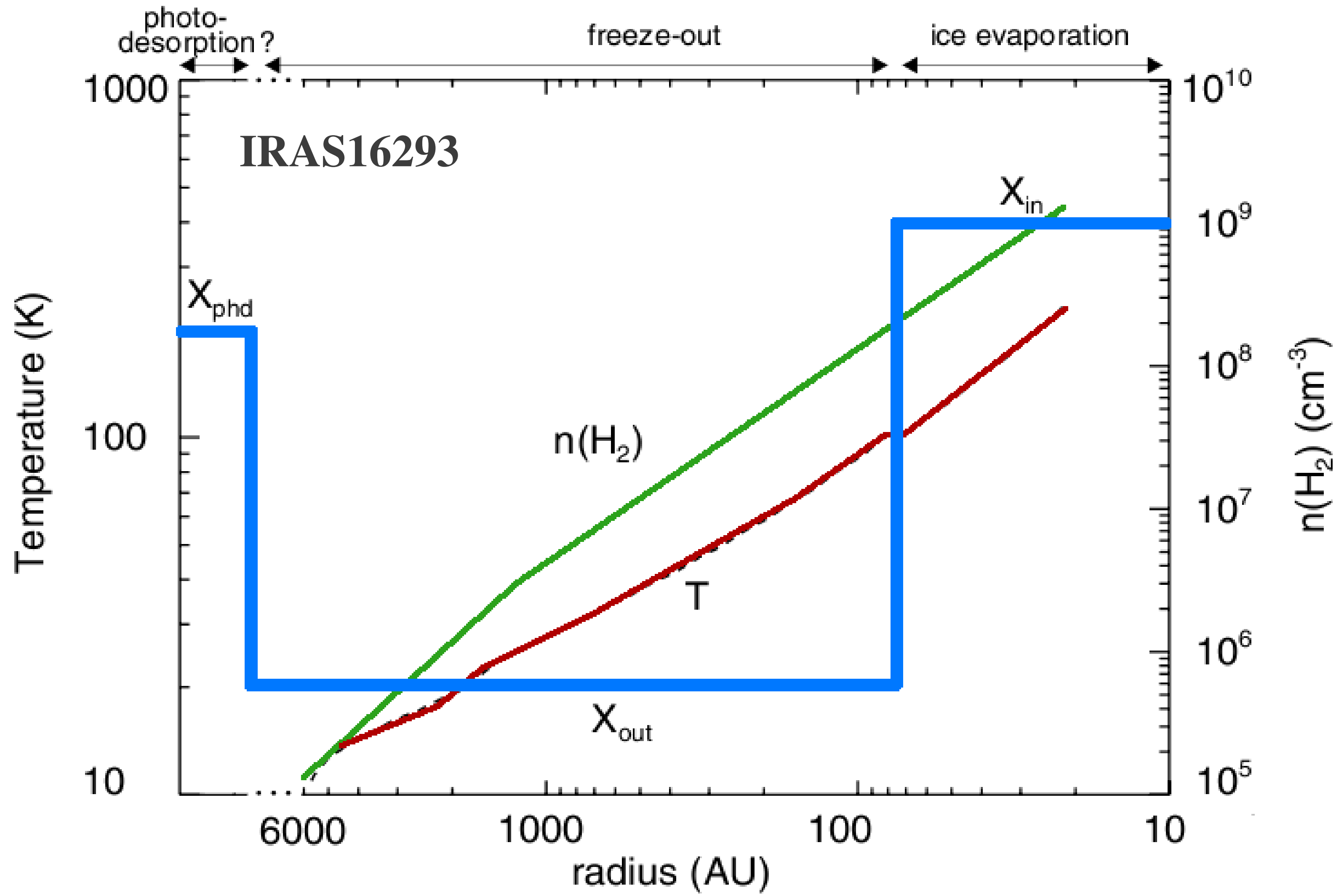
- Understand the key processes that shape the **water vapour** line profiles and **water ice** abundances in protostellar envelopes

THE SCIENCE TARGETS:

- **9 protostellar cores** with *Herschel* observations of **water vapour,** and measured **water ice** column densities

INTRODUCTION

Parameterised **drop abundance profiles** are a fast way to determine the **water vapour** abundance structure



adapted from **Coutens+ (2012),** A&A...539A.132

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INTRODUCTION

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But, ...

- … they cannot consistently reproduce all the **water vapour** lines as observed by *Herschel*

Mottram+ (2013), A&A, accepted for publication

- … they do not reveal the **physical processes** leading to that profile
- … they are not able to determine the abundance structure of **water ice**

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- … they are not able to determine the abundance structure of **water ice**

OUR ANALYSIS TOOL:

- A dedicated ***physics-motivated*** **simplified chemical network**

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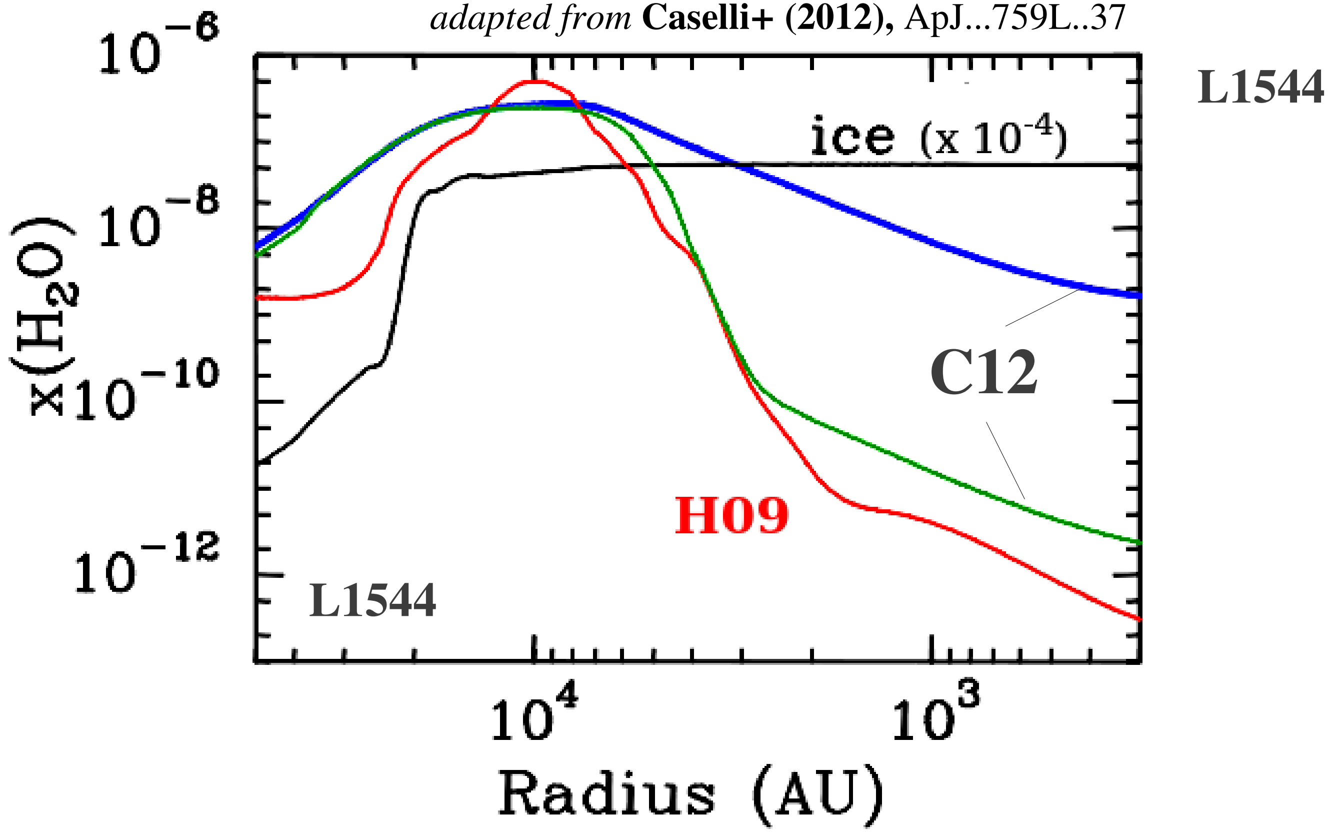
WATER VAPOUR

Simple water chemistry network does work for **water vapour** profiles in *pre-stellar cores*

adapted from **Caselli+ (2012),** ApJ...759L..37



H09 - Hollenbach+ (2009), ApJ...690.1497H

C12 - Caselli+ (2012), ApJ...759L..37

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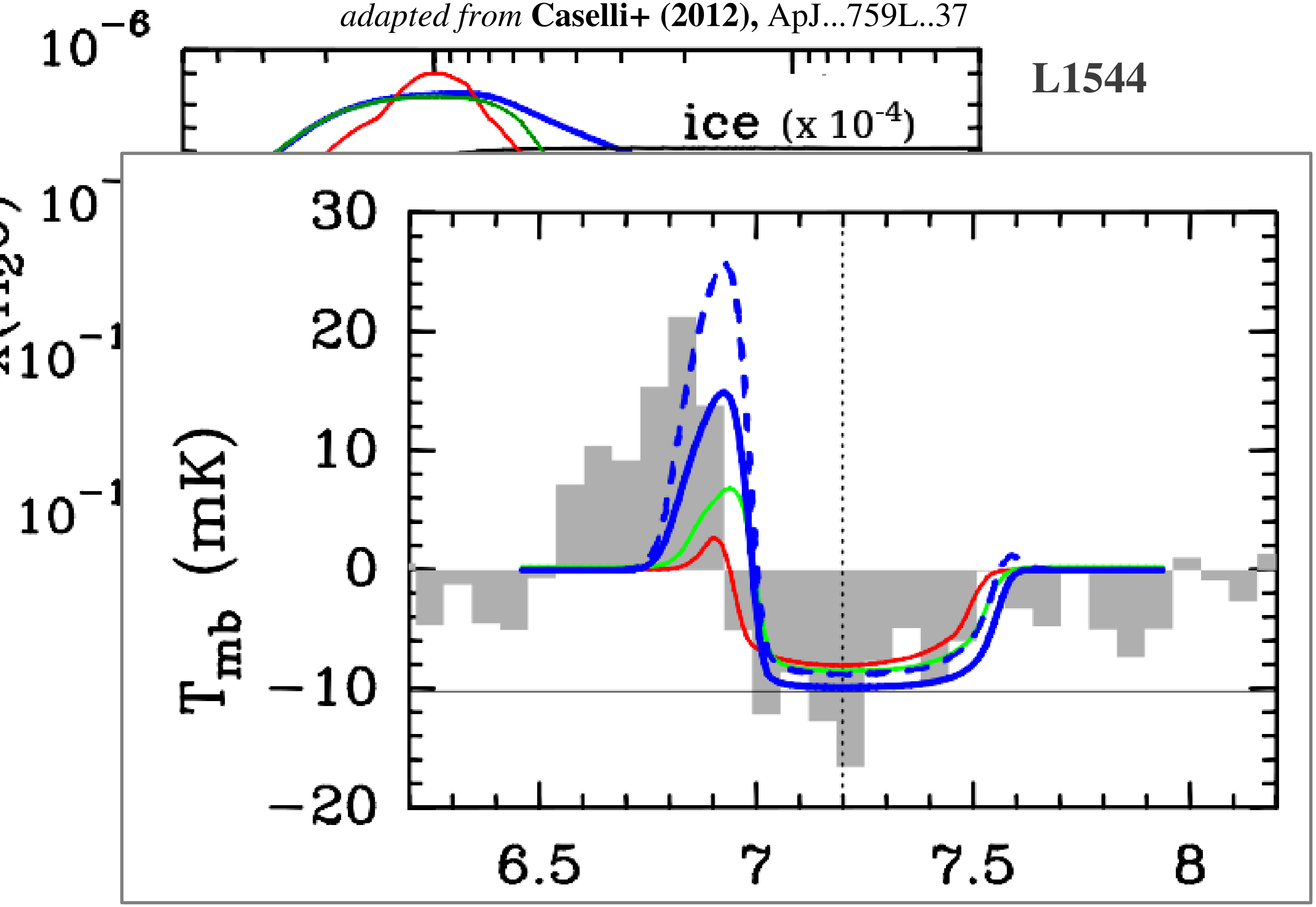

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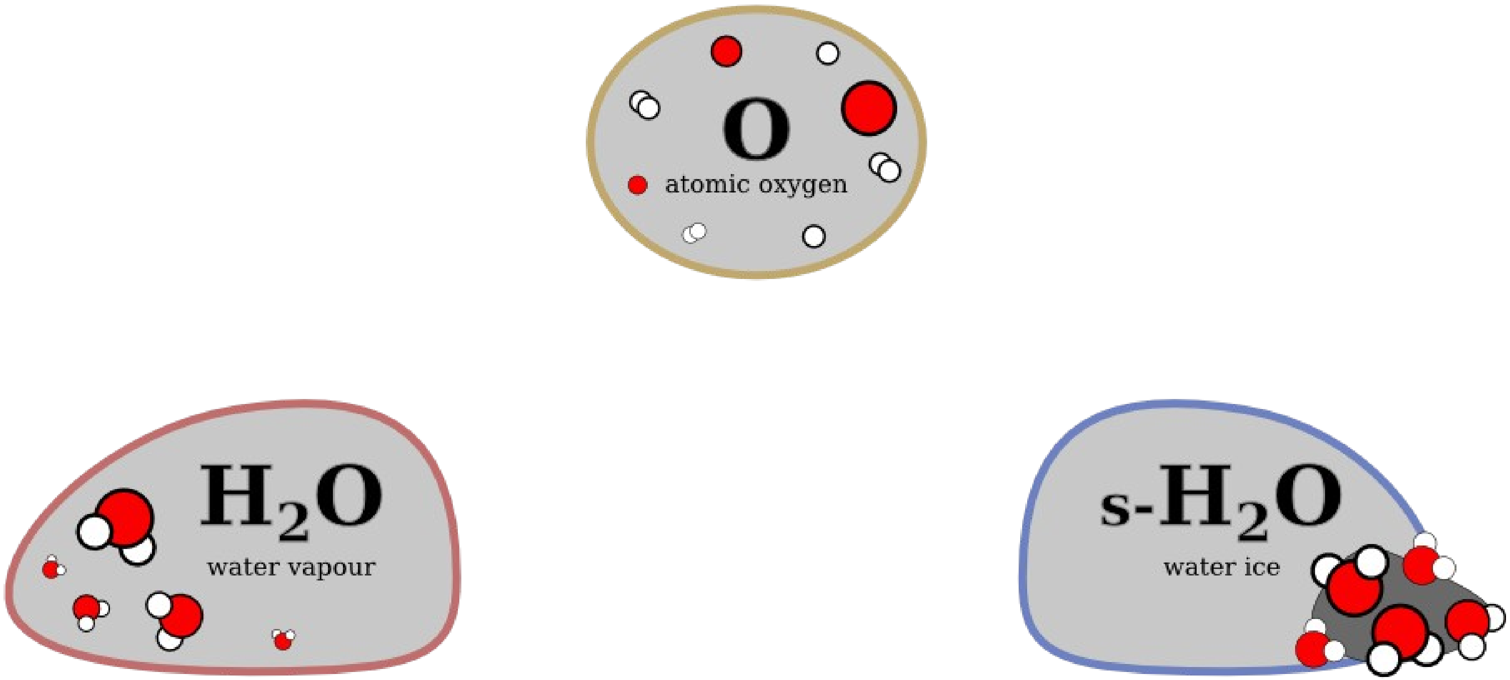
The **Simplifed Water Network (SWaN)** is an attempt to reliably determine the abundance profiles of **water vapour** and **water ice** in **cold protostellar envelopes**.



Schmalzl+, in prep.

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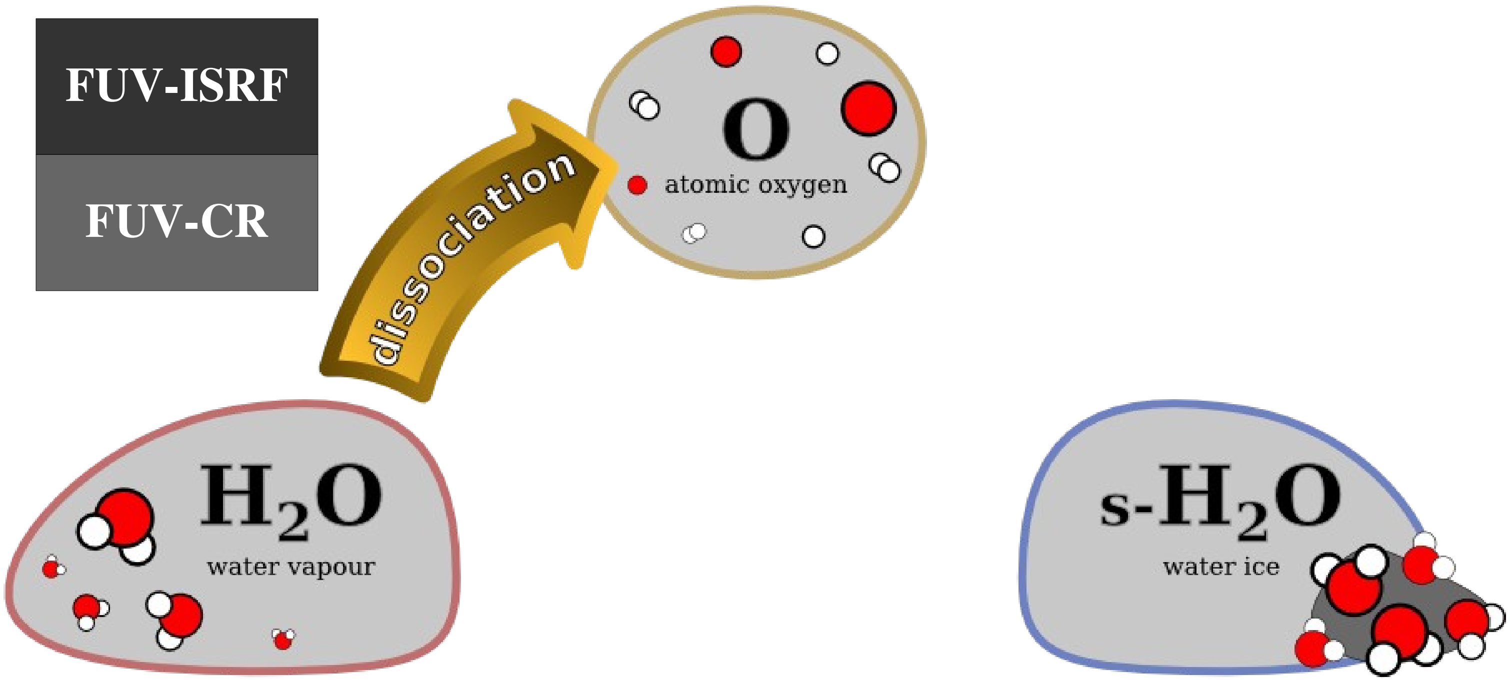

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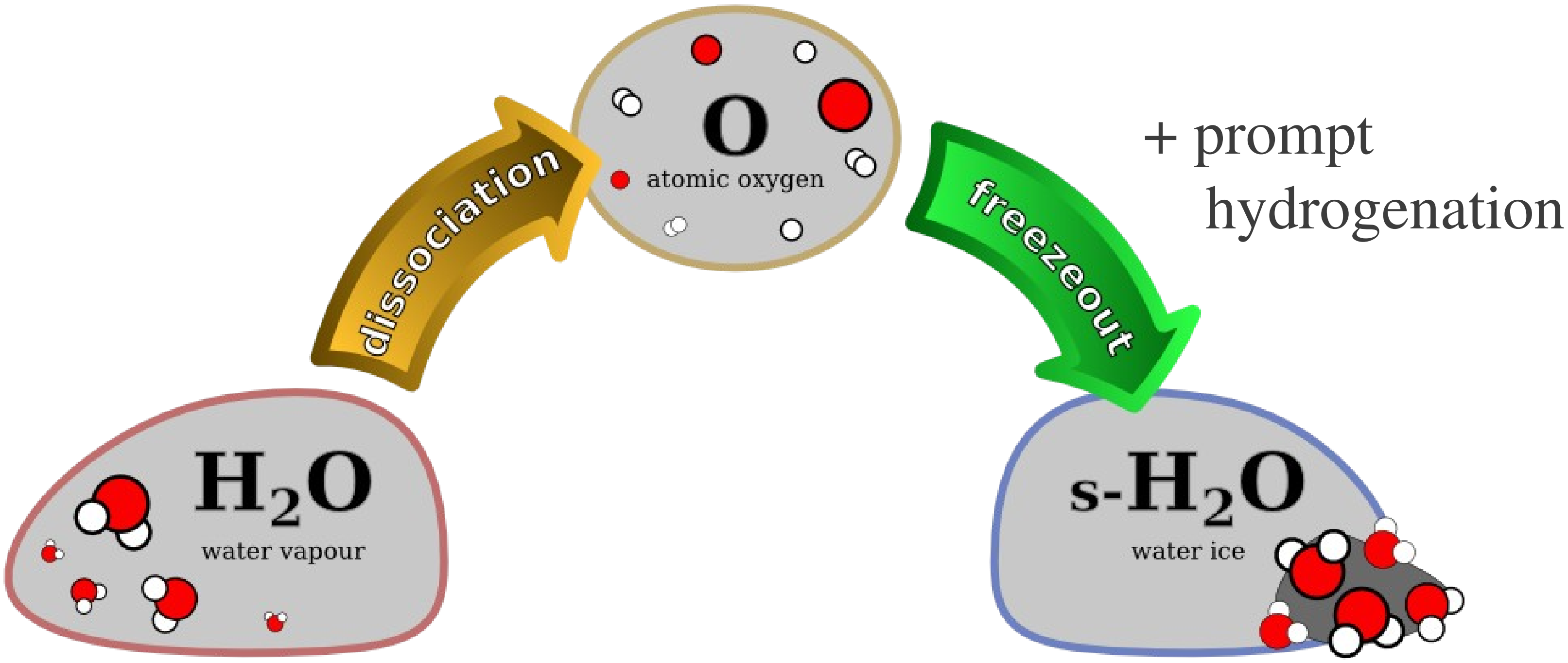

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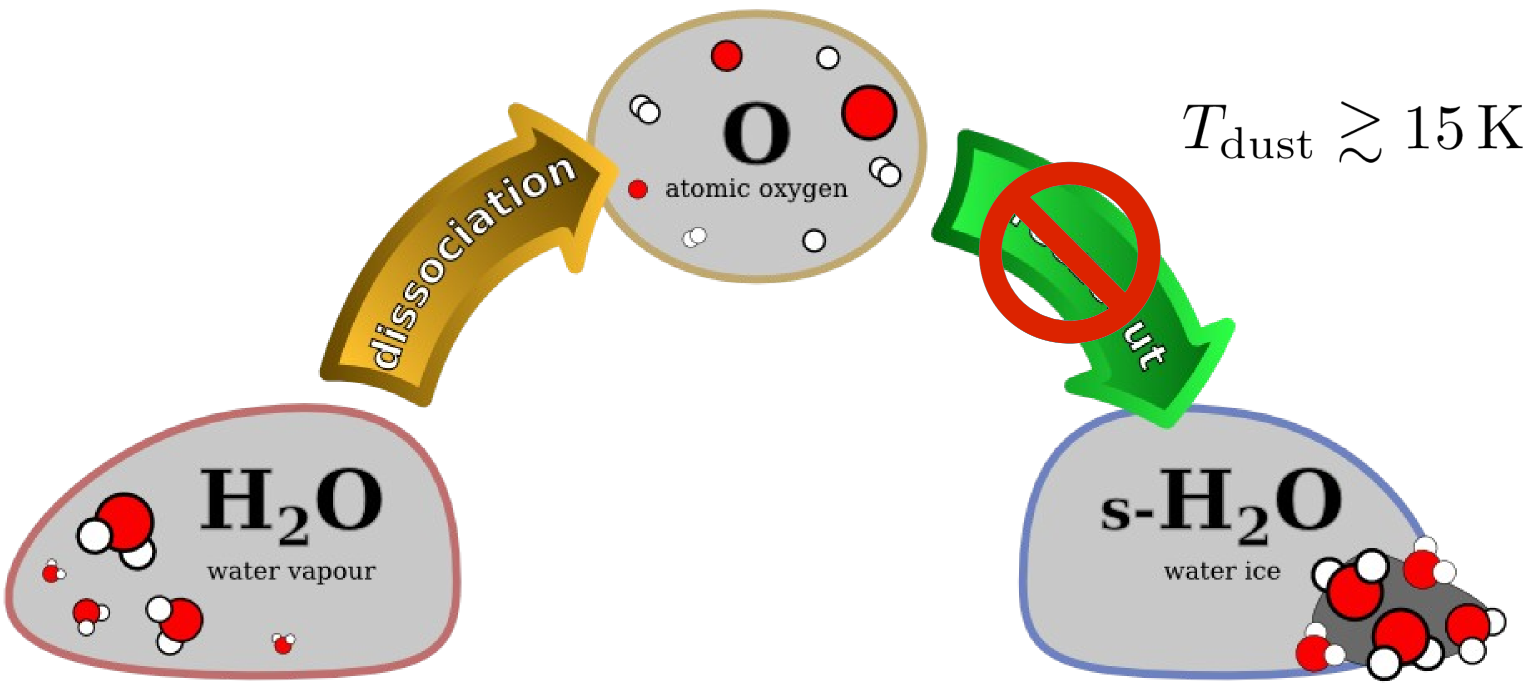

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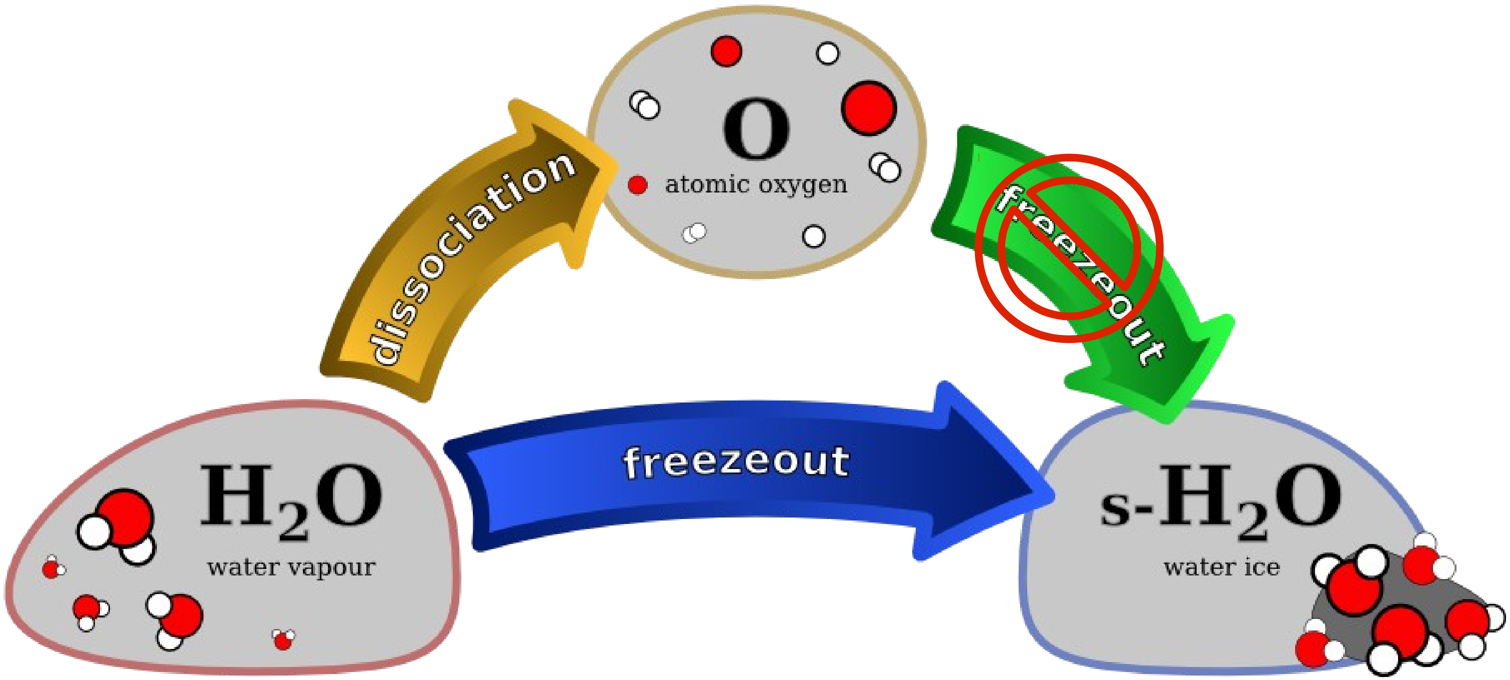

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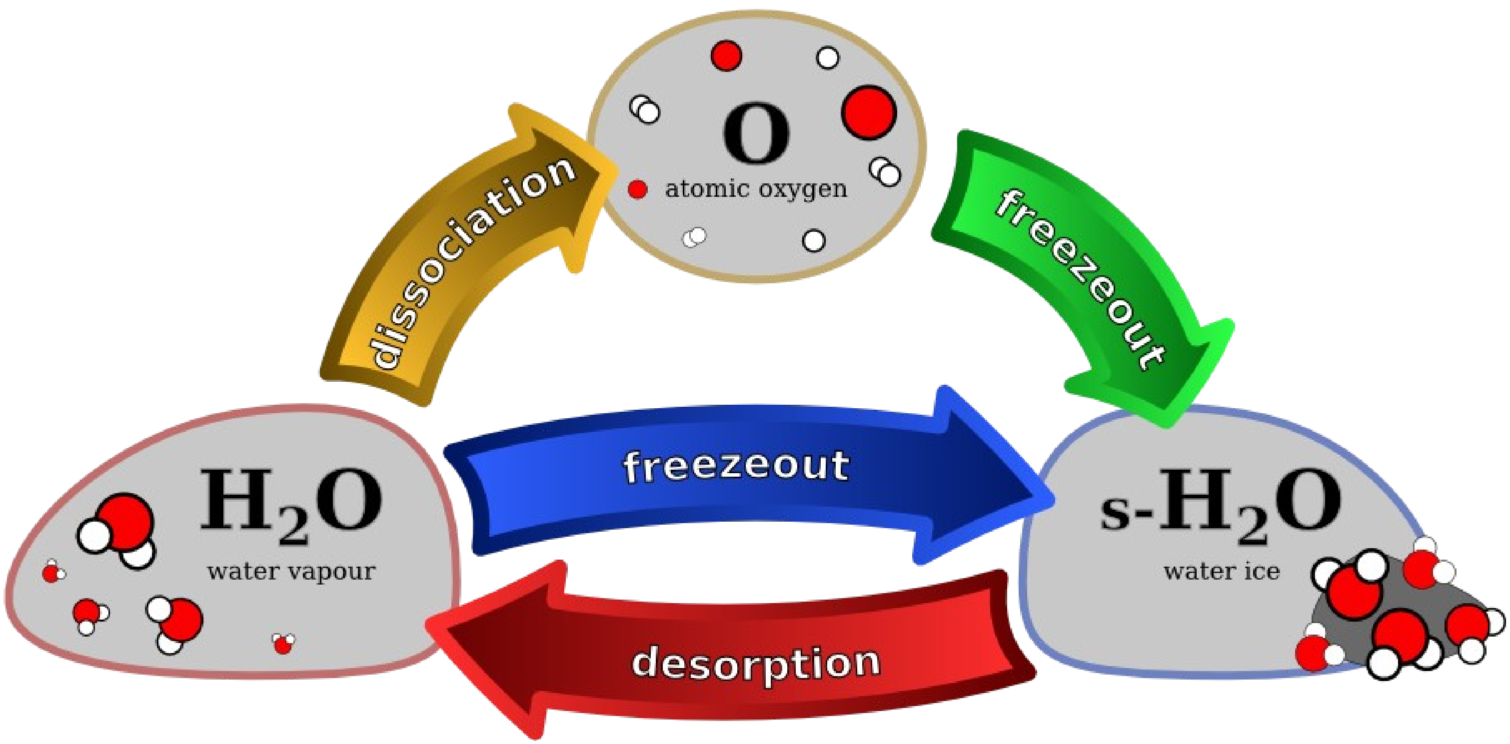
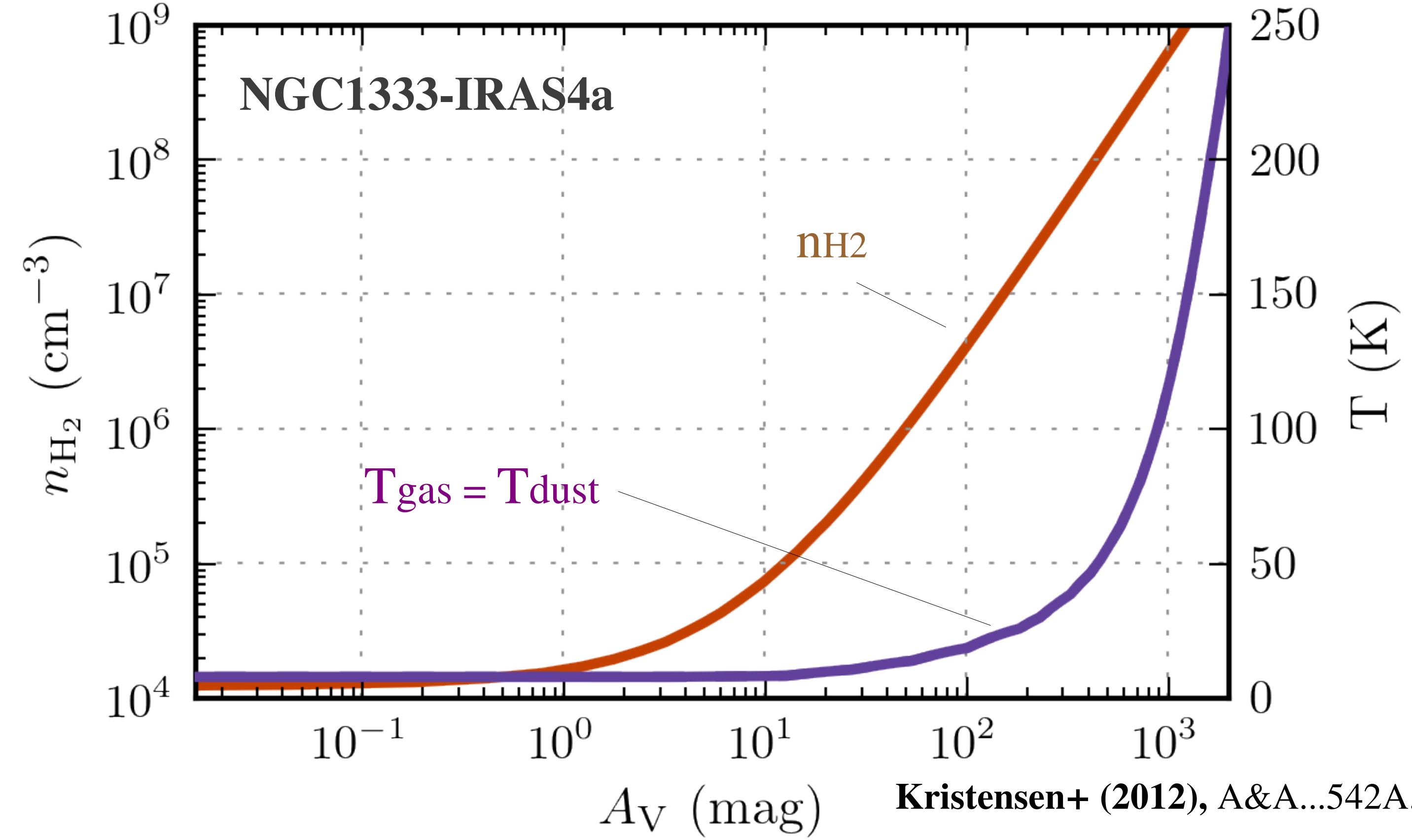


FUV-ISRF	**FUV-CR**	***T***

Schmalzl+, in prep.

Water vapour and **water ice** abundance profiles of **cold protostellar envelopes** with SWaN:



Kristensen+ (2012), A&A...542A...8

$$N_{H_2} = 1.9\ 10^{24}\,\mathrm{cm}^{-2} \qquad G_{\mathrm{isrf}} = 1.0$$

$$M_{\mathrm{env}} = 5.6\,\mathrm{M}_\odot \qquad G_{\mathrm{cr}} = 10^{-4}$$

$$L_{\mathrm{bol}} = 7.7\,\mathrm{L}_\odot$$

Schmalzl+, in prep.

SWaN - SIMPLE CHEMISTRY

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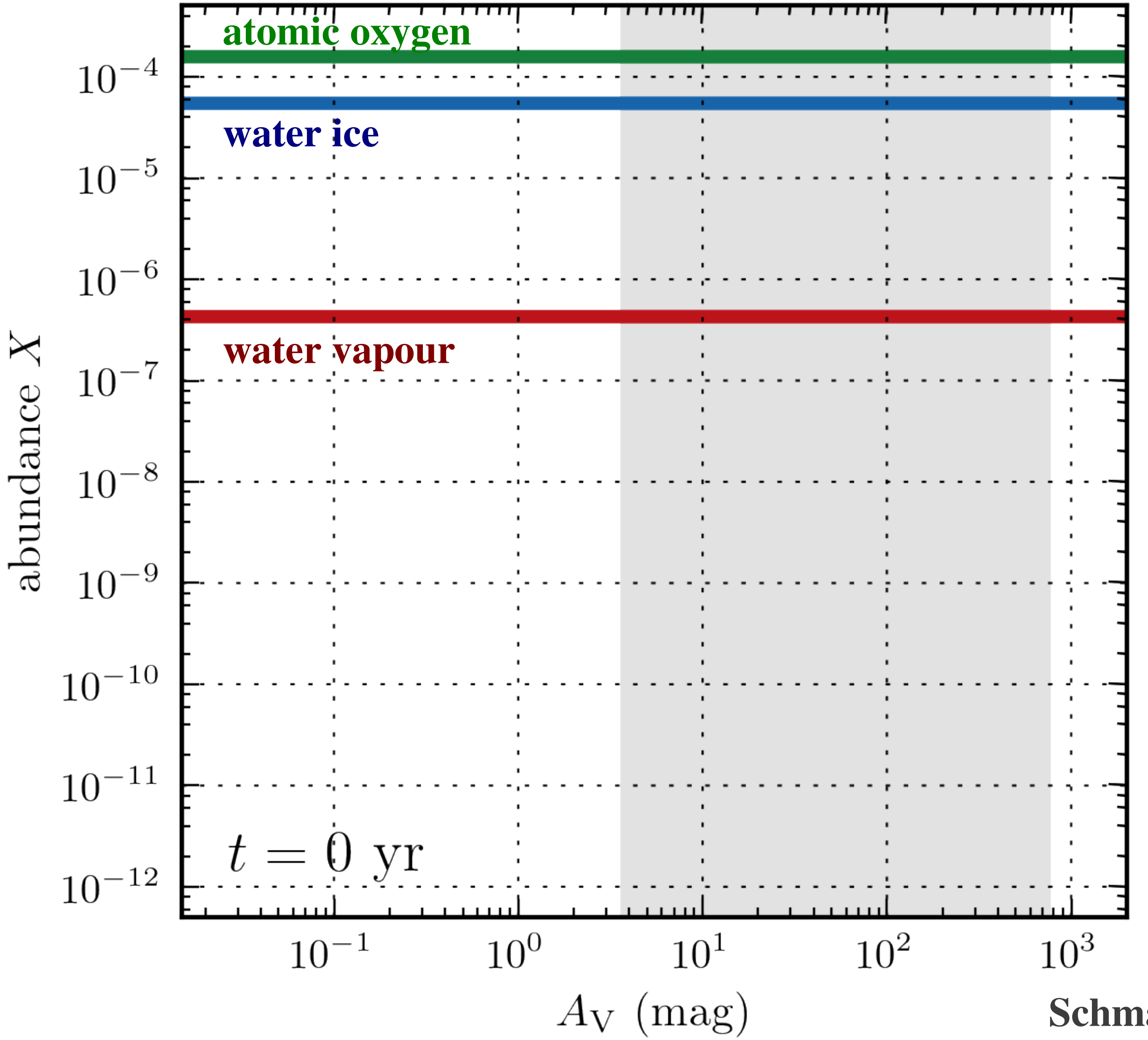

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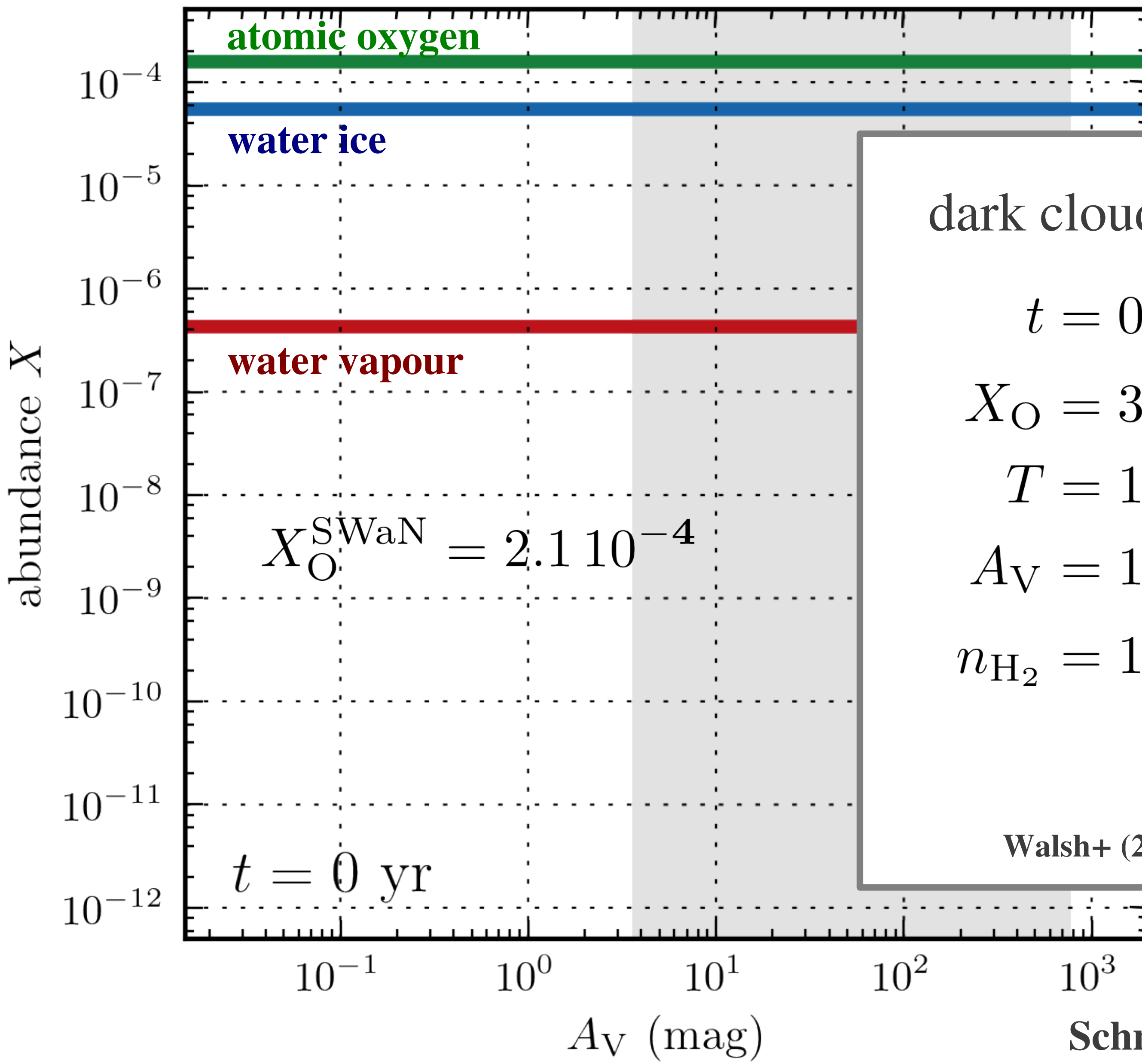

dark cloud model:

$$t = 0.1\,\mathrm{Myr}$$
$$X_{\mathrm{O}} = 3.2\ 10^{-4}$$
$$T = 10\,\mathrm{K}$$
$$A_{\mathrm{V}} = 10\,\mathrm{mag}$$
$$n_{\mathrm{H_2}} = 10^{4}\,\mathrm{cm}^{-3}$$

Walsh+ (2013), ApJ...766L..23

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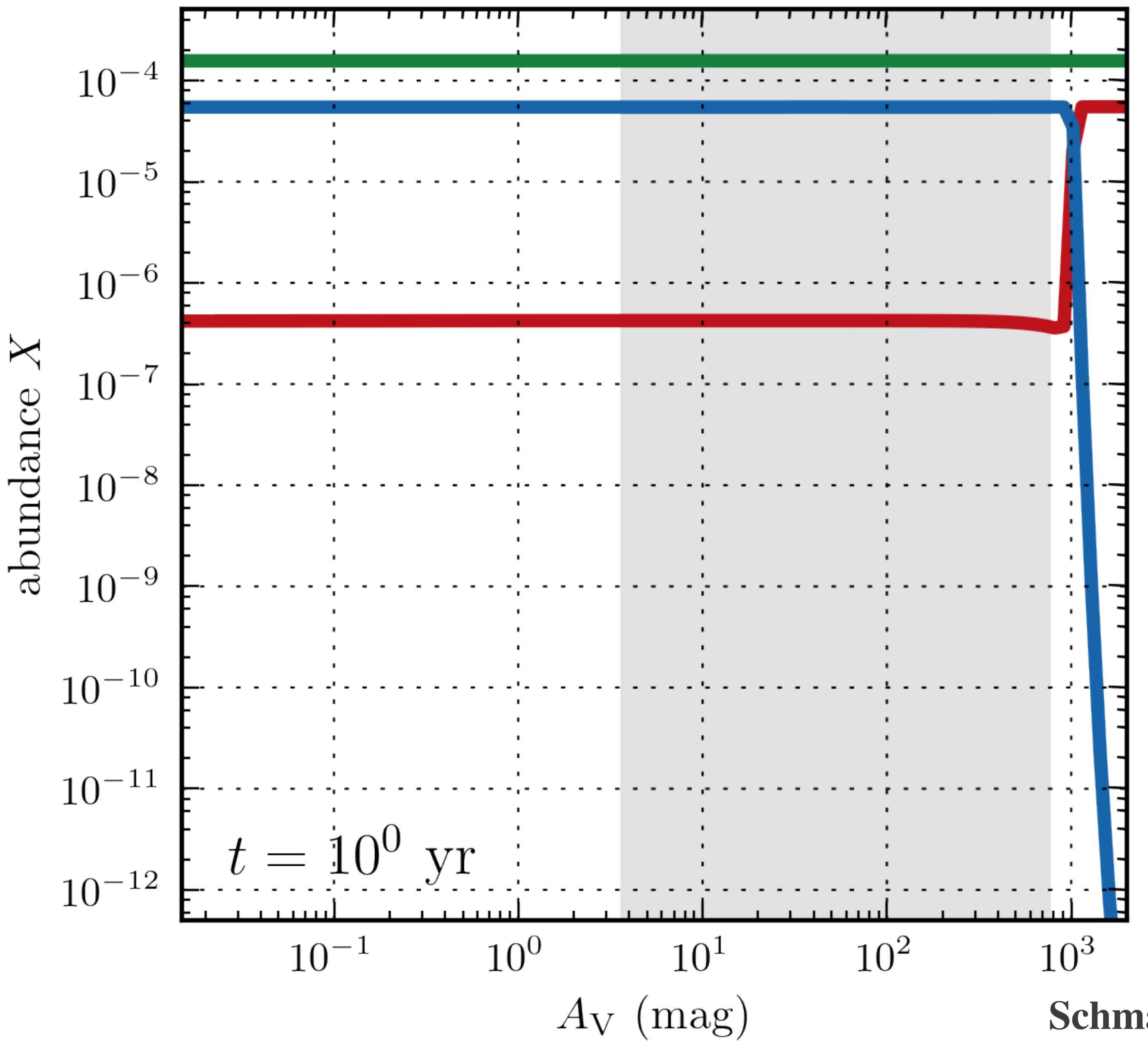

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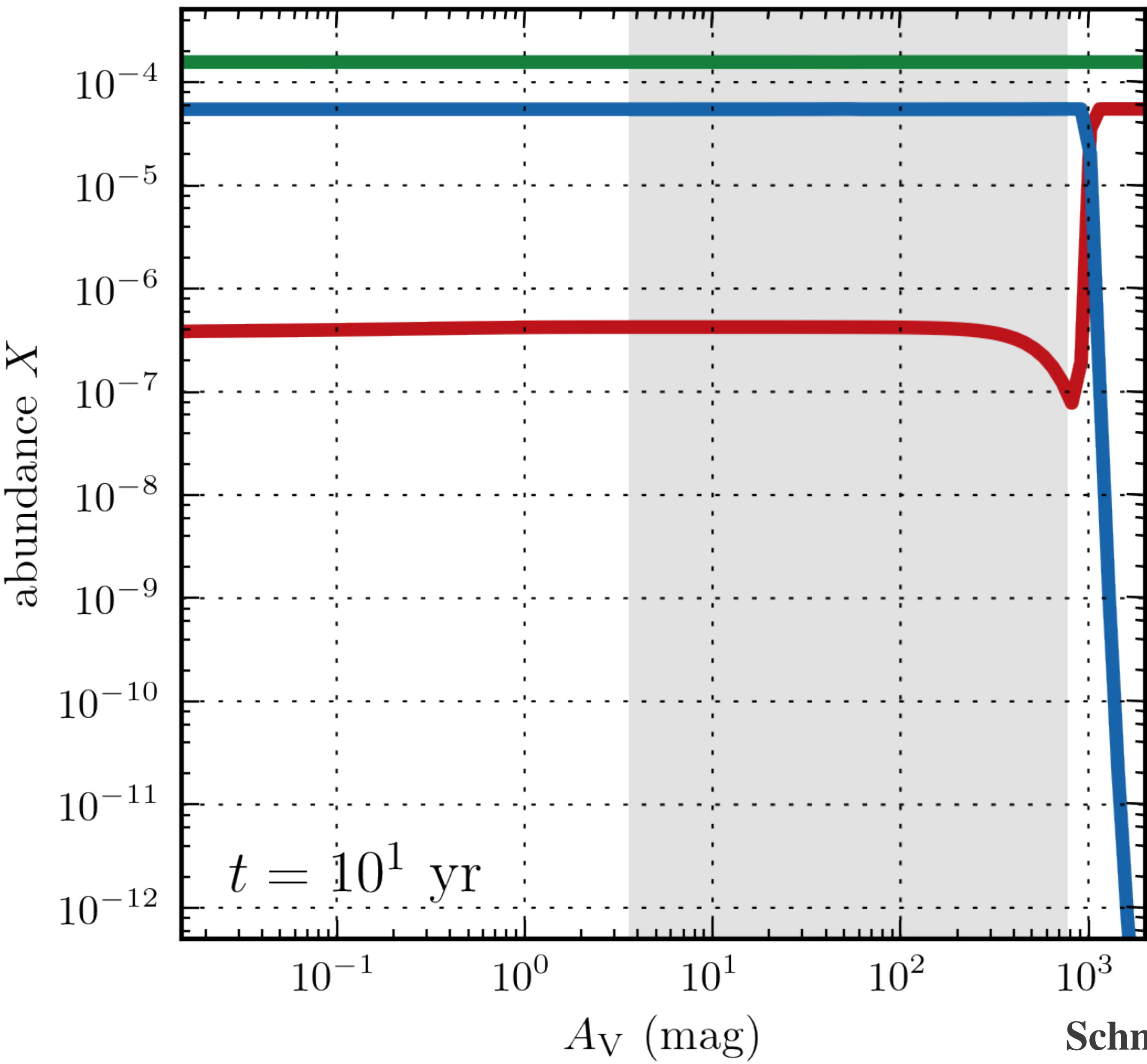

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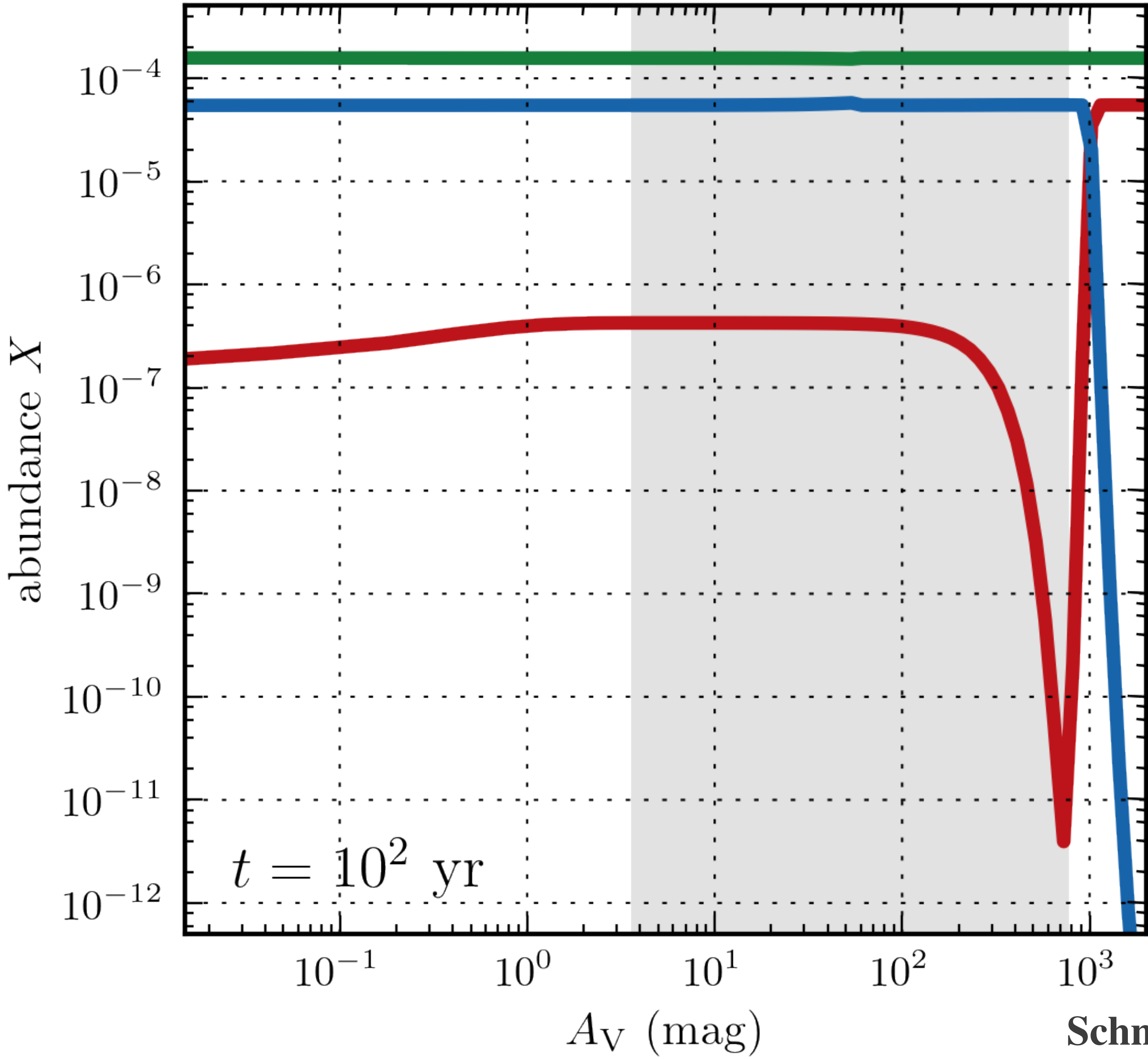

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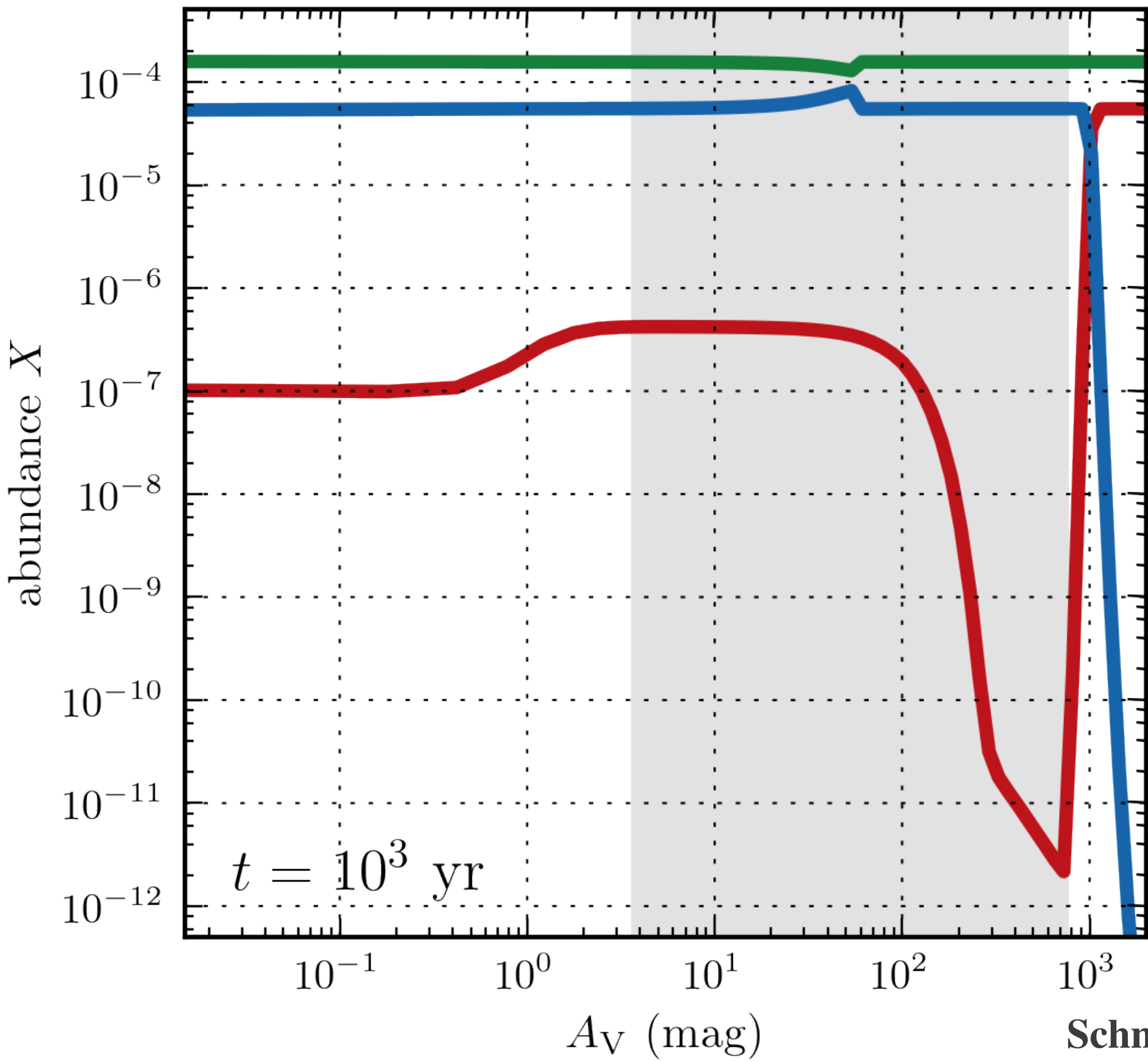

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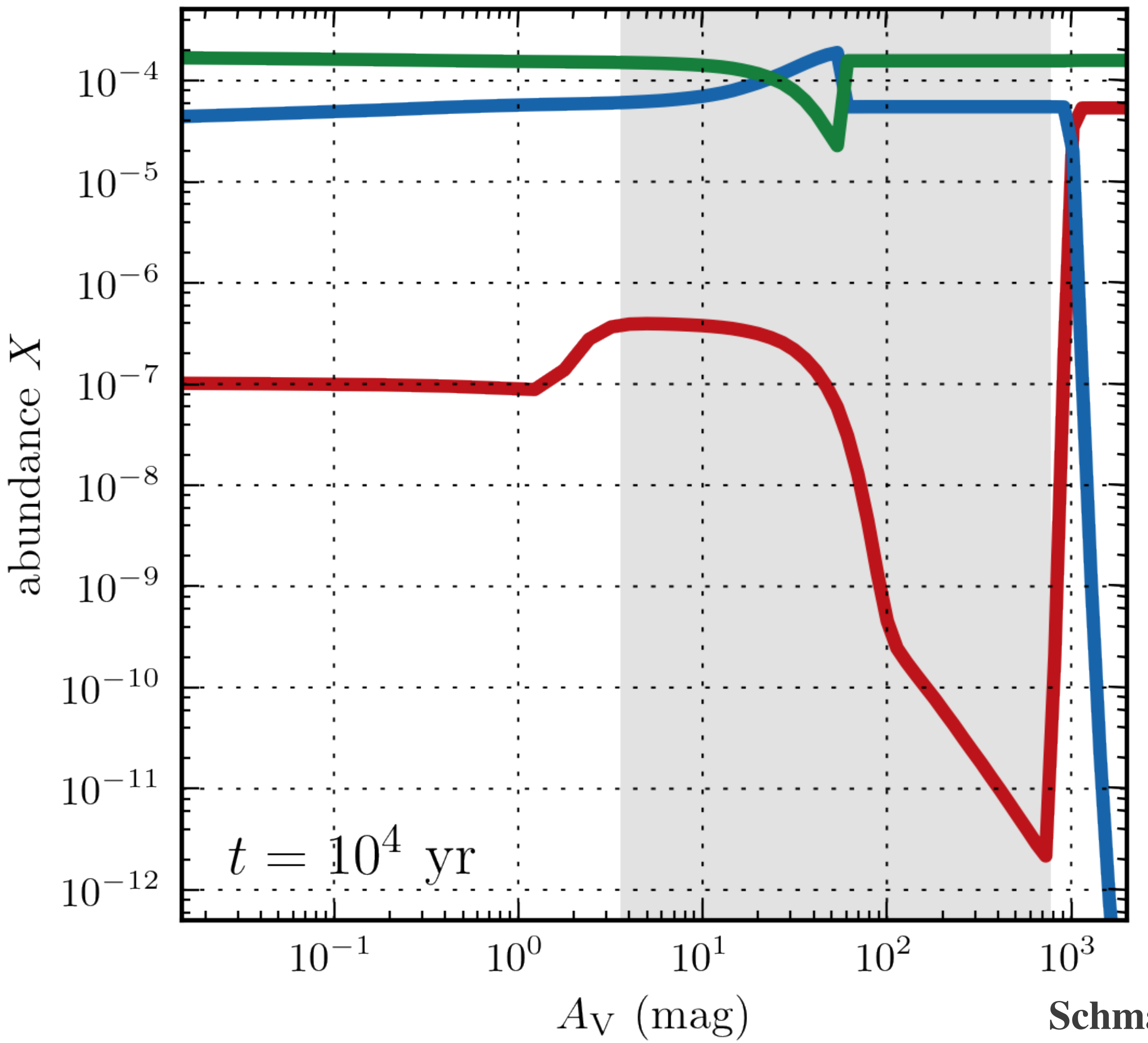

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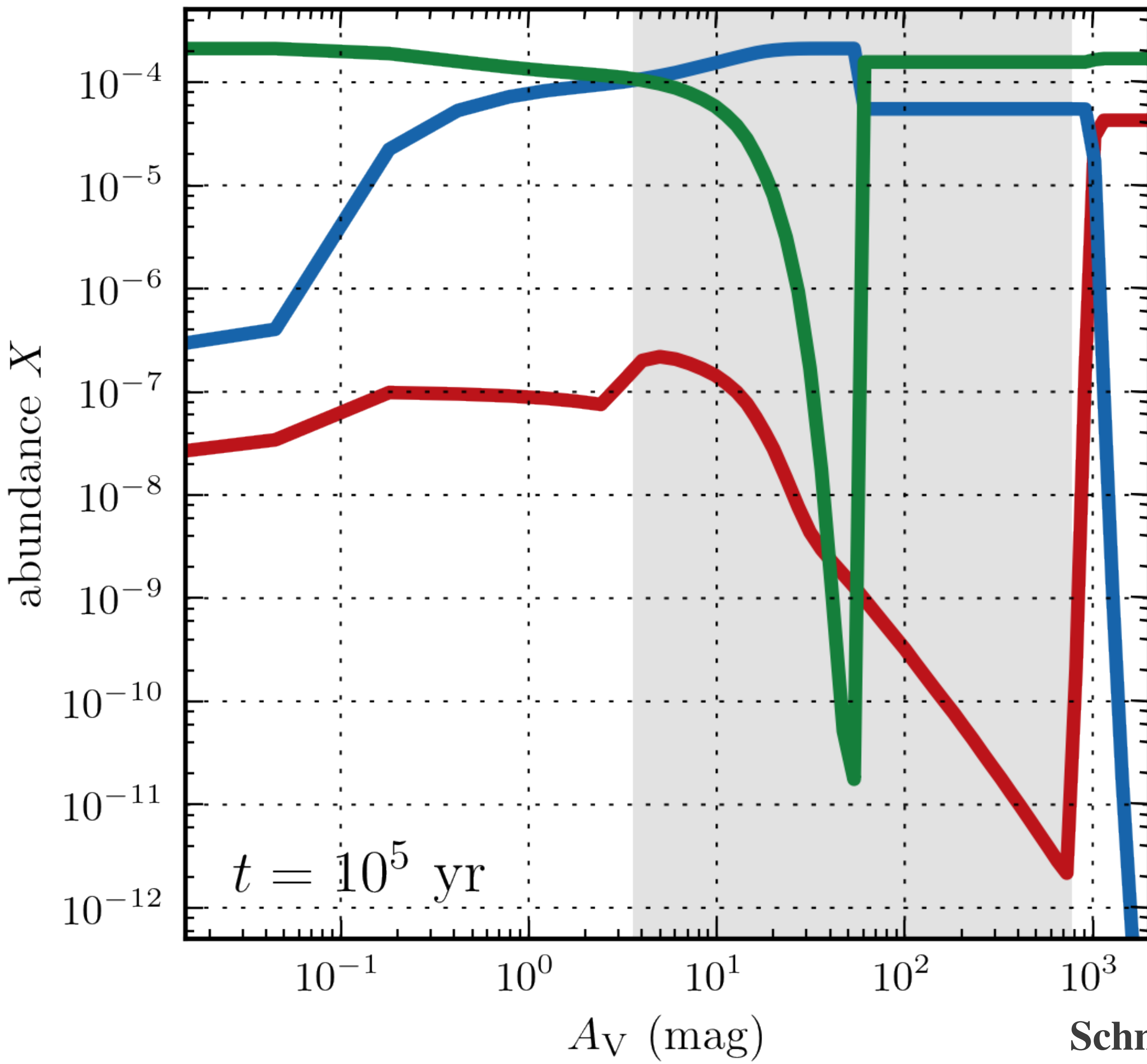

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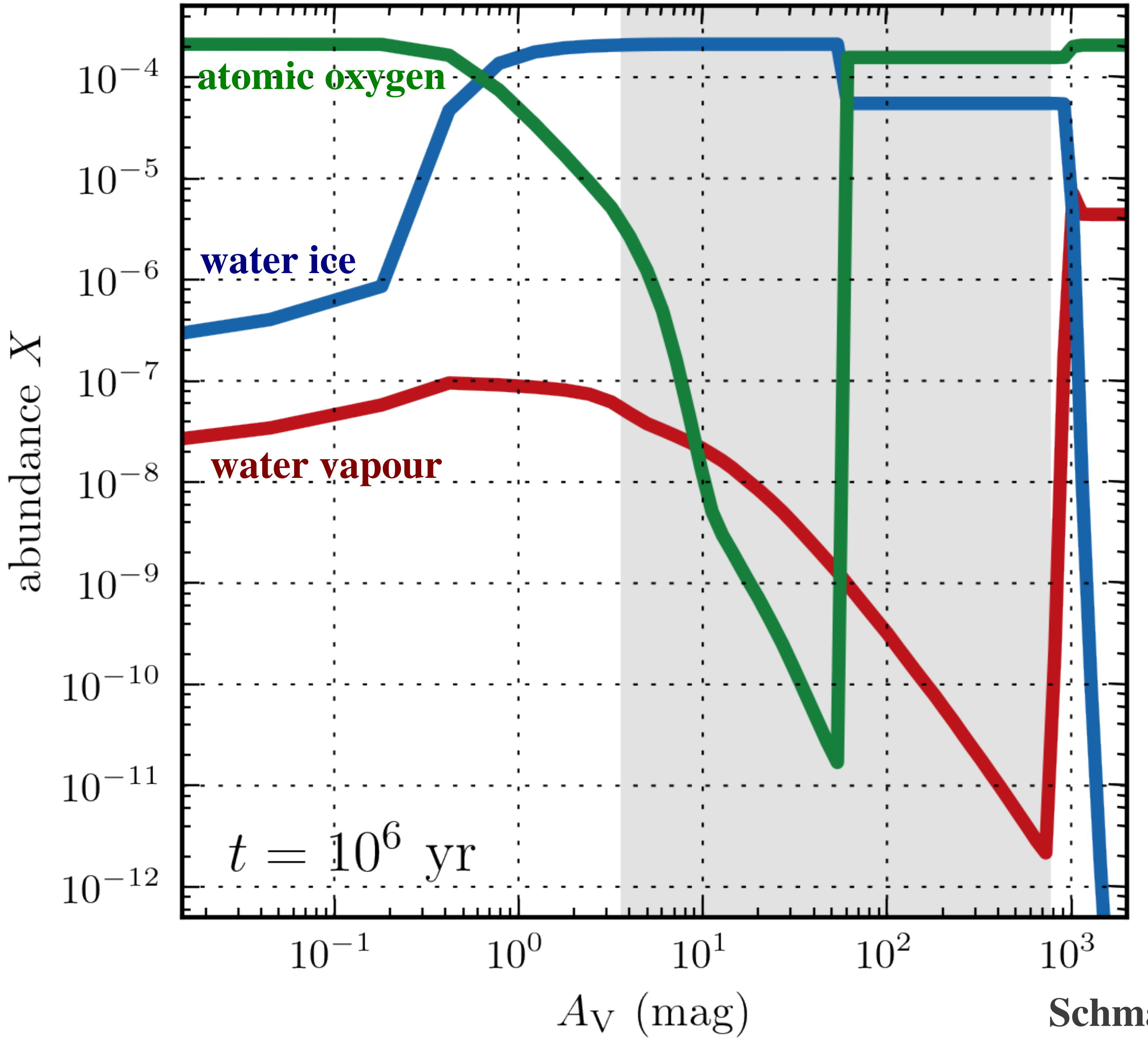

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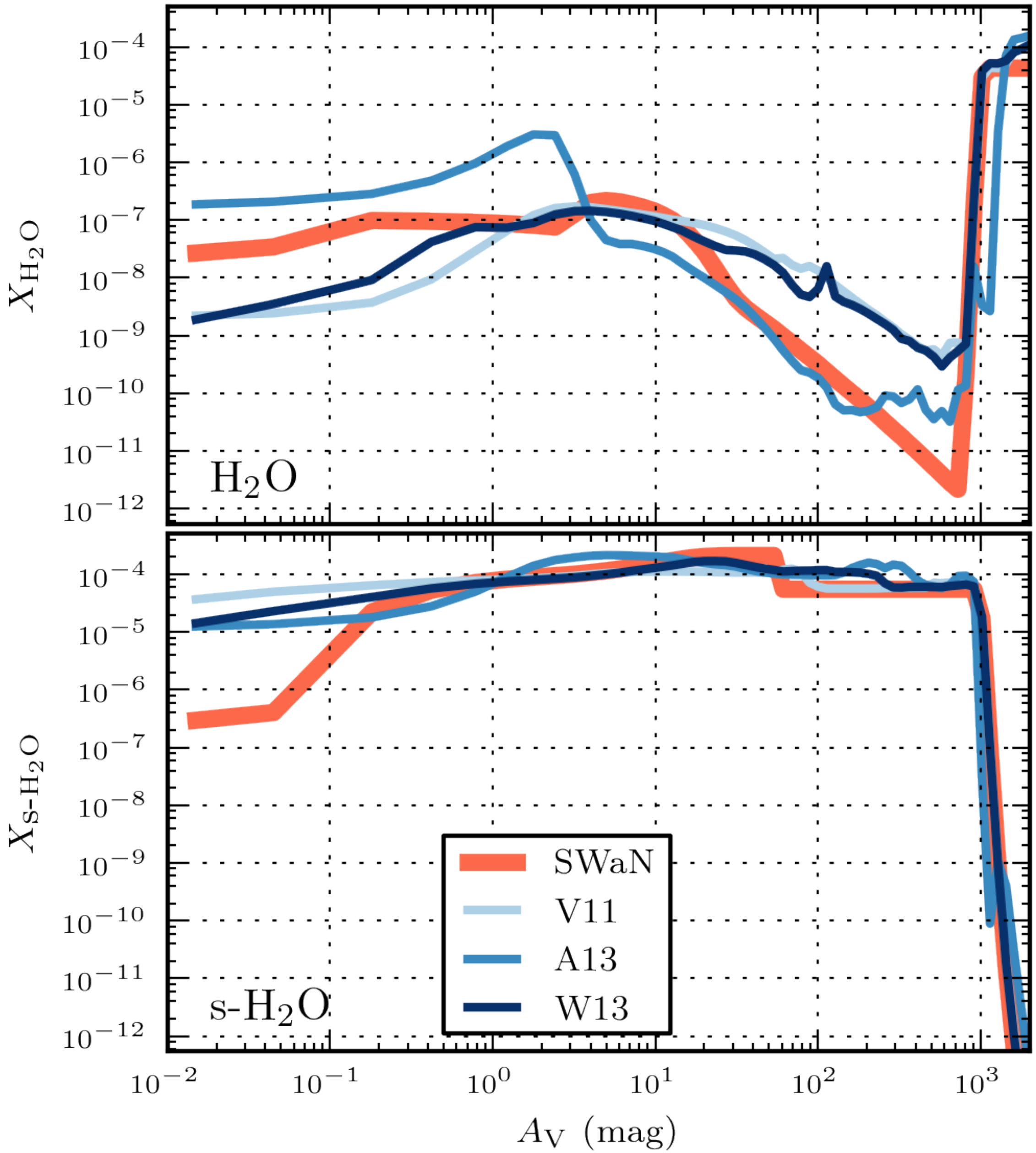
SWaN BENCHMARKING

Benchmarking the abundance profiles from **SWaN** with **other chemical networks**:



$t = 0.1\,\mathrm{Myr}$

V11 **Visser+ (2011)**, A&A...534A.132
A13 **Albertsson+ (2013),** ApJS..207...27
W13 **Walsh+ (2013),** ApJ...766L..23

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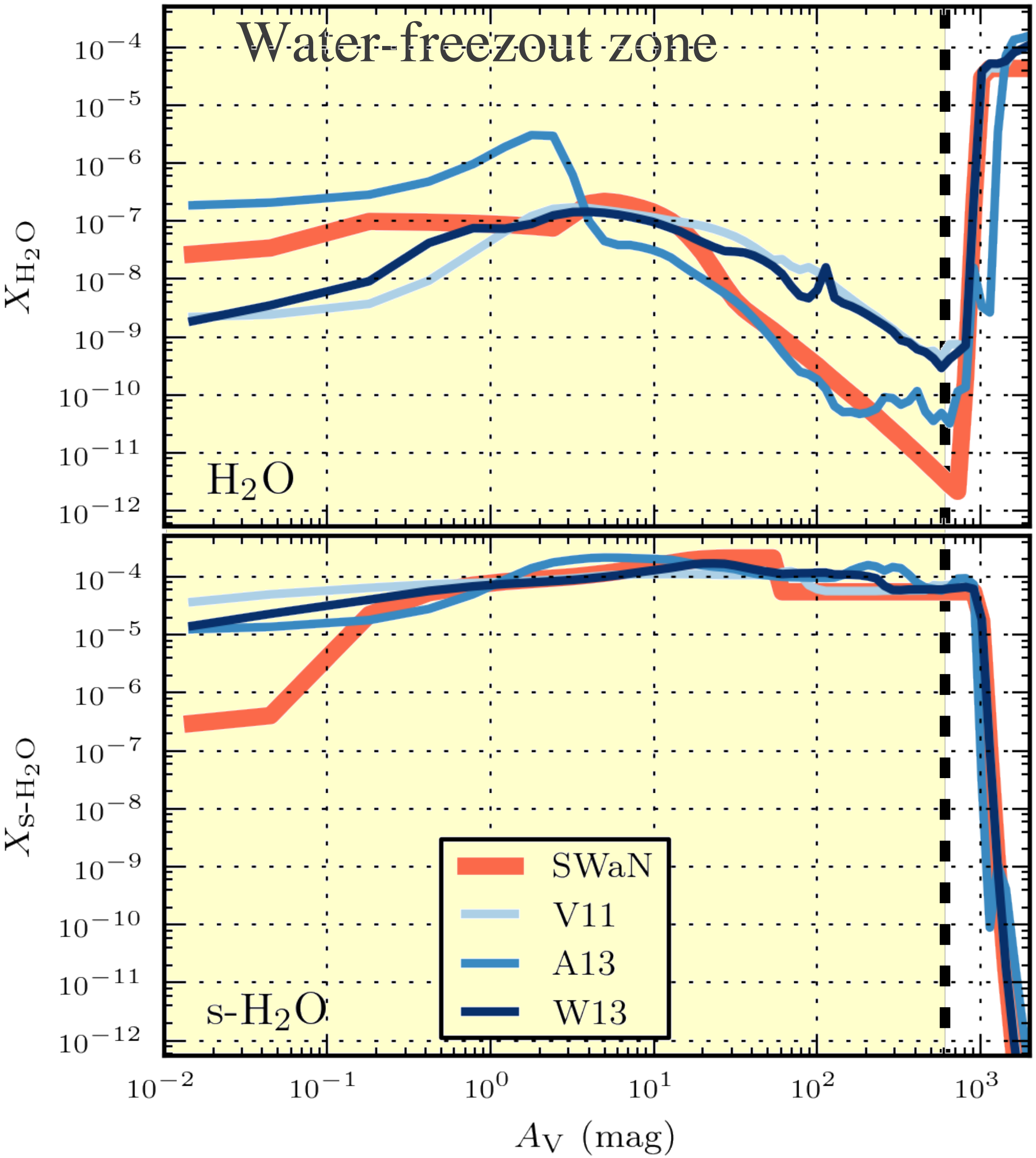

model	X_{H_2O} (10^{-9})	$X_{s\text{-}H_2O}$ (10^{-5})
SWaN	3.1	6.4
V11	7.0	7.0
A13	8.0	10.0
W13	4.9	7.8

Schmalzl+, in prep.

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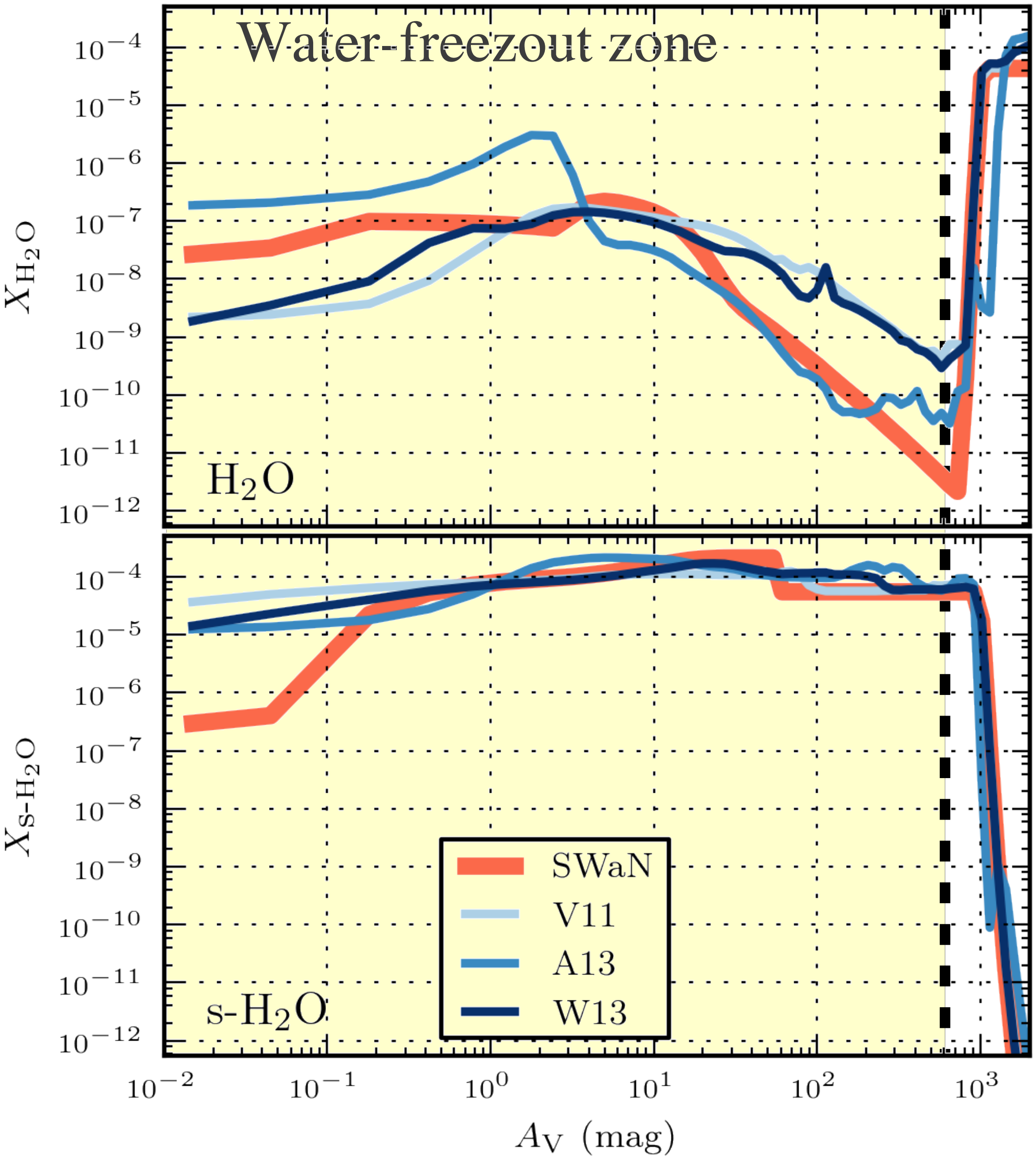

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SWaN	3.1	6.4
V11	7.0	7.0
A13	8.0	10.0
W13	4.9	7.8

Recall:
Abundance of **volatile oxygen**

$$X_O = \mathbf{3.2\ 10^{-4}}$$

Schmalzl+, in prep.

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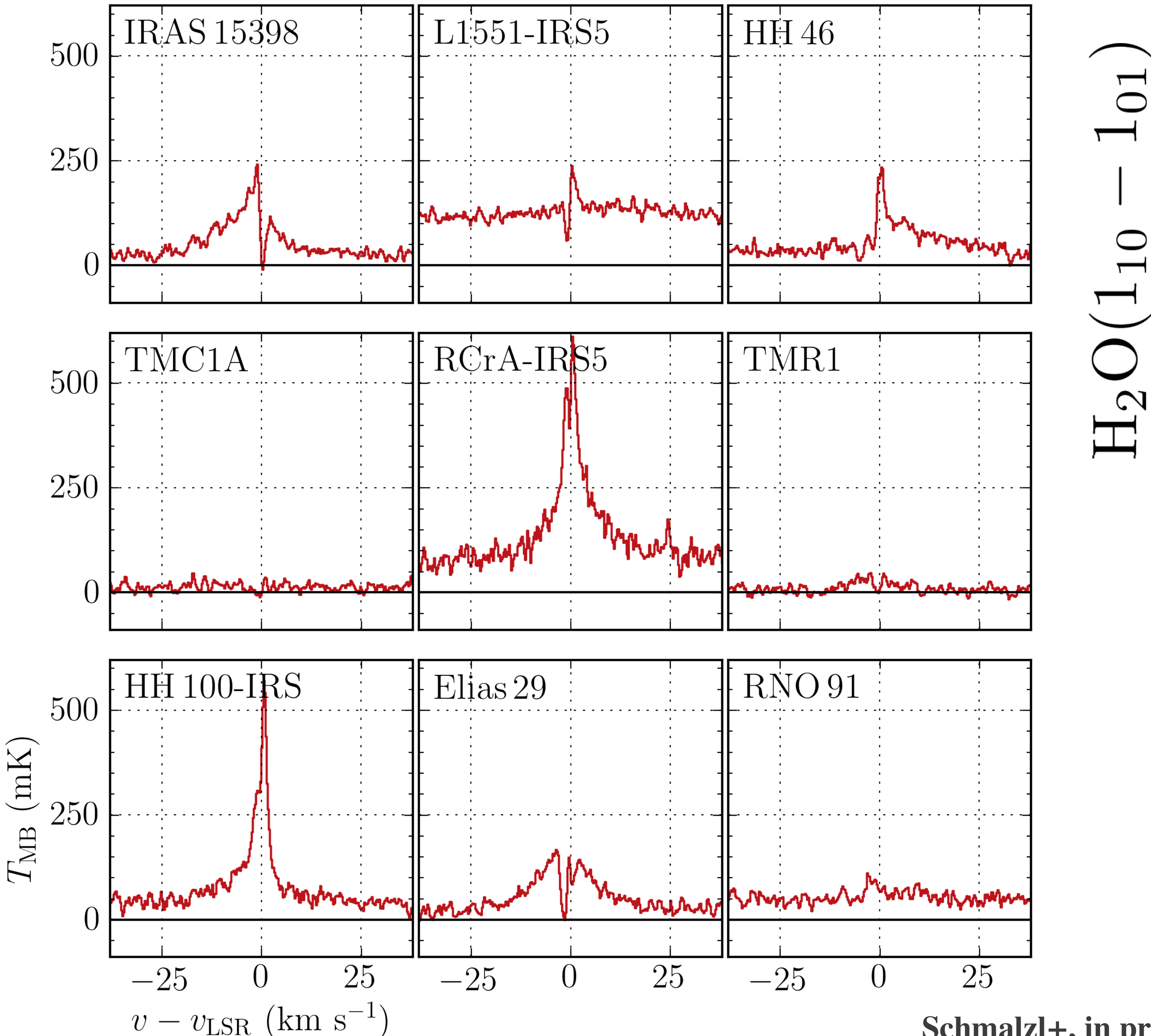
WATER GALLERY



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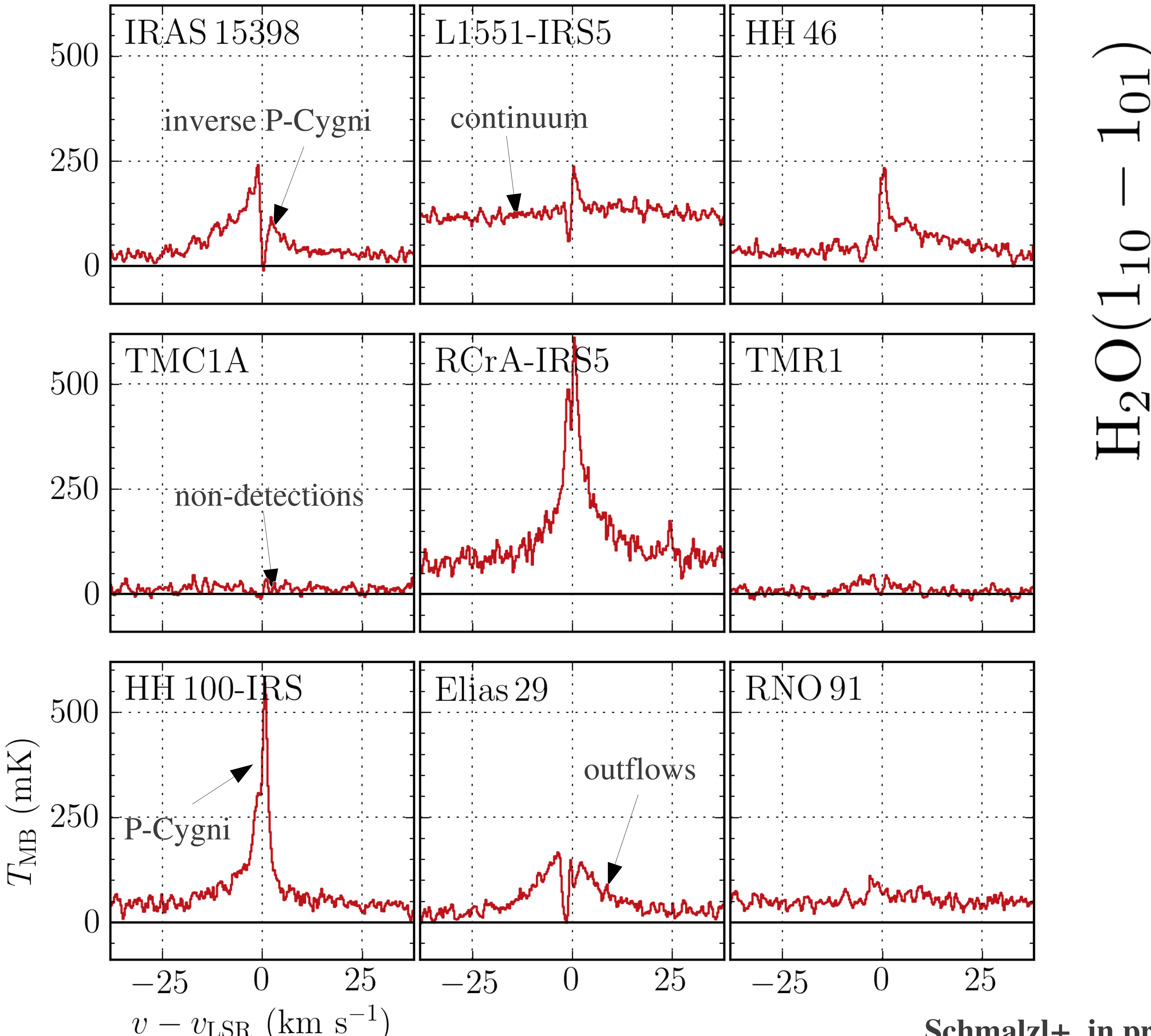

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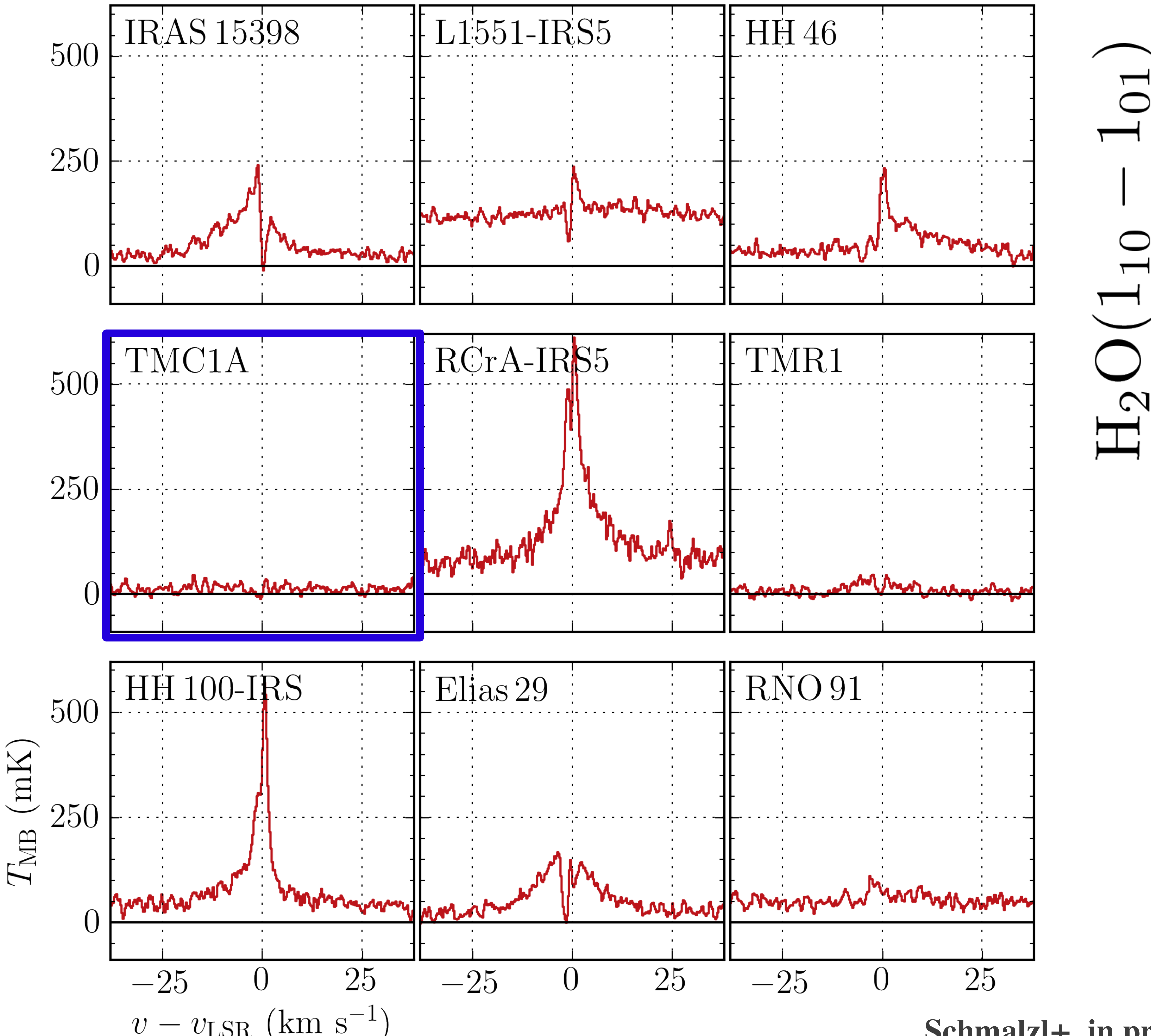
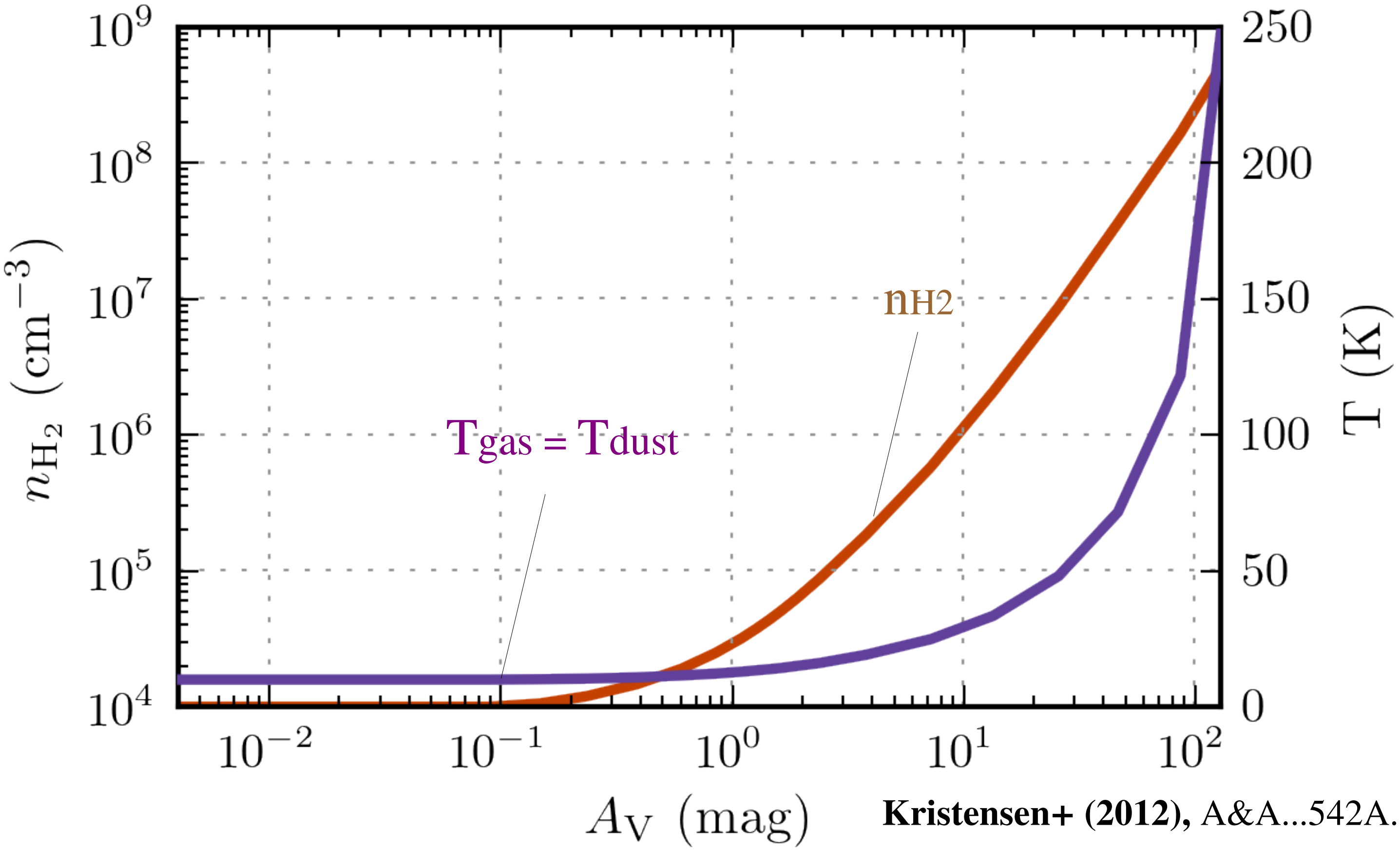


Schmalzl+, in prep.

TARGET #1: TMC1A



Kristensen+ (2012), A&A...542A...8

$$N_{H_2} = 9.9\ 10^{22}\,\mathrm{cm}^{-2} \qquad t = 0.1\,\mathrm{Myr}$$

$$M_{env} = 0.2\,\mathrm{M}_\odot \qquad G_{isrf} = 1.0$$

$$L_{bol} = 2.2\,\mathrm{L}_\odot \qquad G_{cr} = 10^{-4}$$

WISH

Schmalzl+, in prep.

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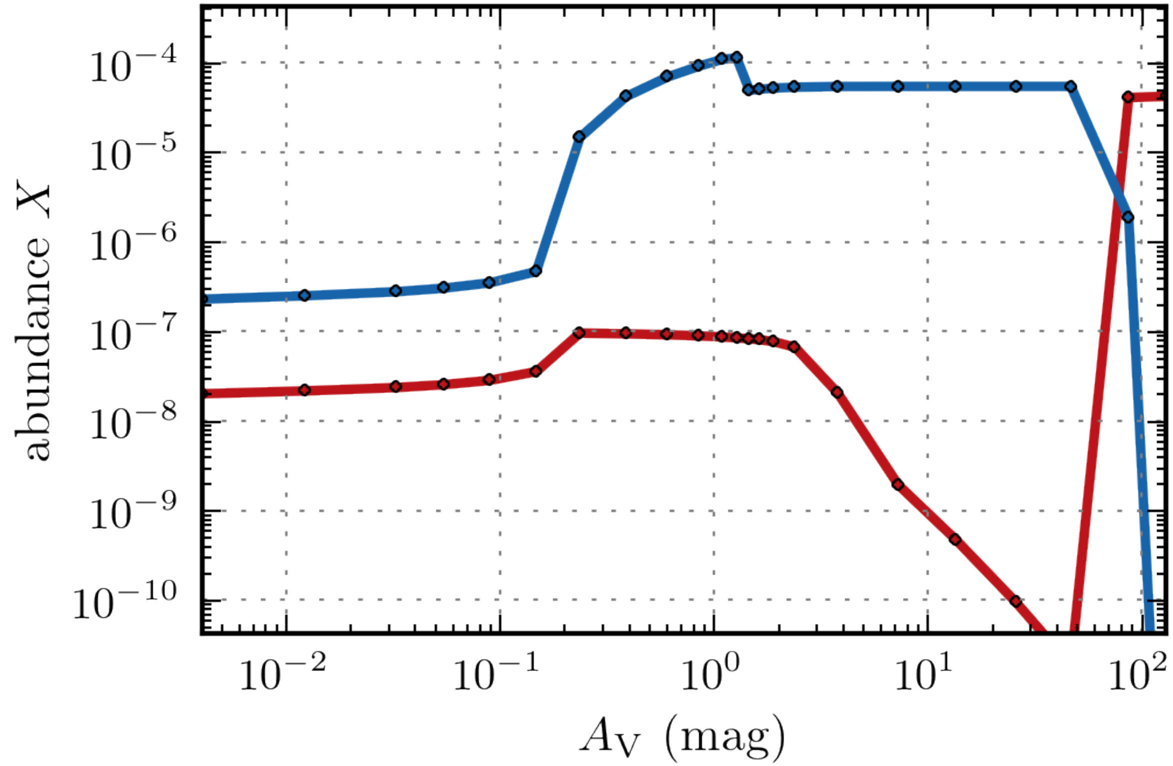

$X_{\mathrm{s-H_2O}}$: $5.5\,10^{-5}$

$X_{\mathrm{H_2O}}$: $5.8\,10^{-9}$

$t = 0.1\,\mathrm{Myr}$

$G_{\mathrm{isrf}} = 1.0$

$G_{\mathrm{cr}} = 10^{-4}$

Schmalzl+, in prep.

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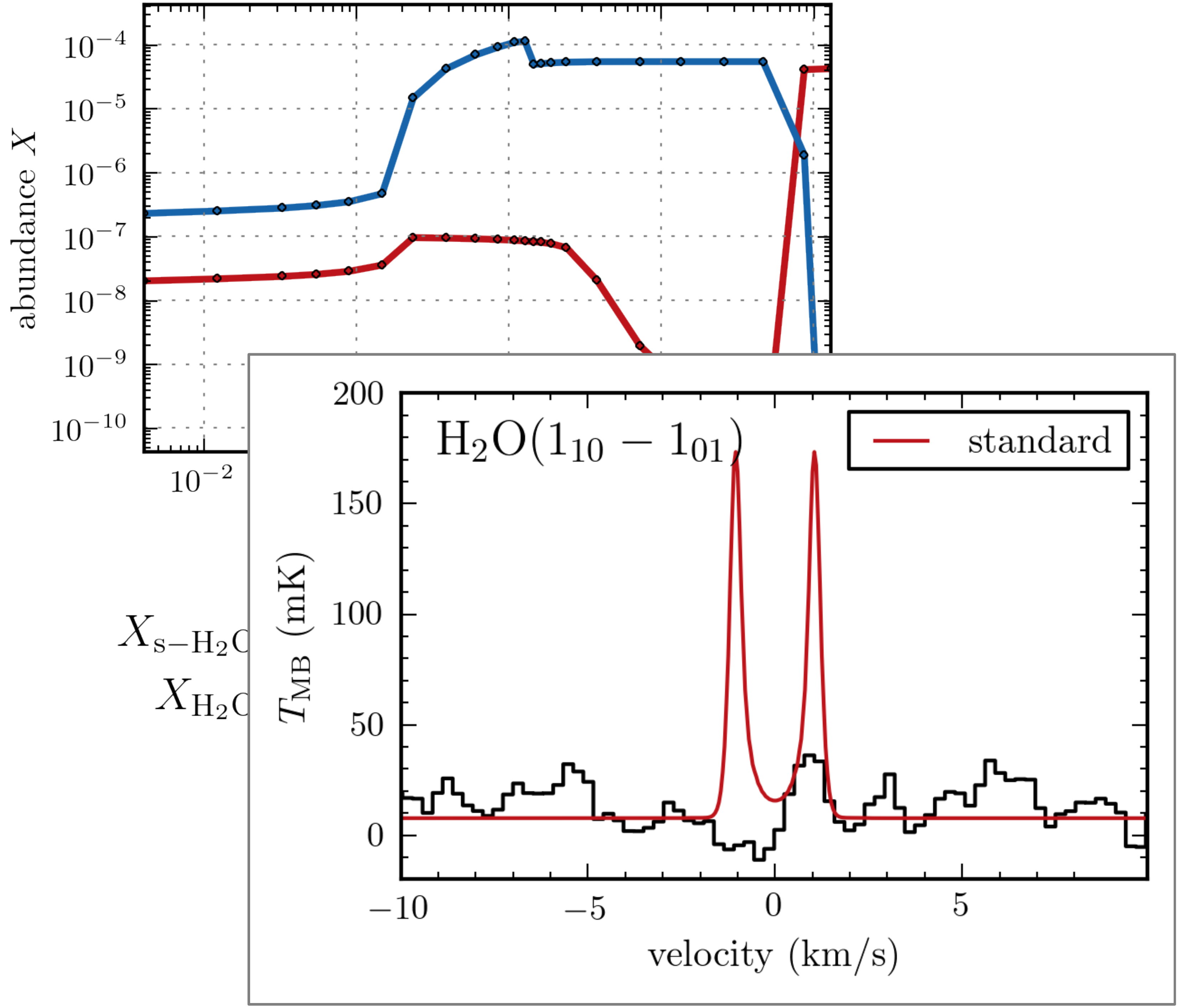

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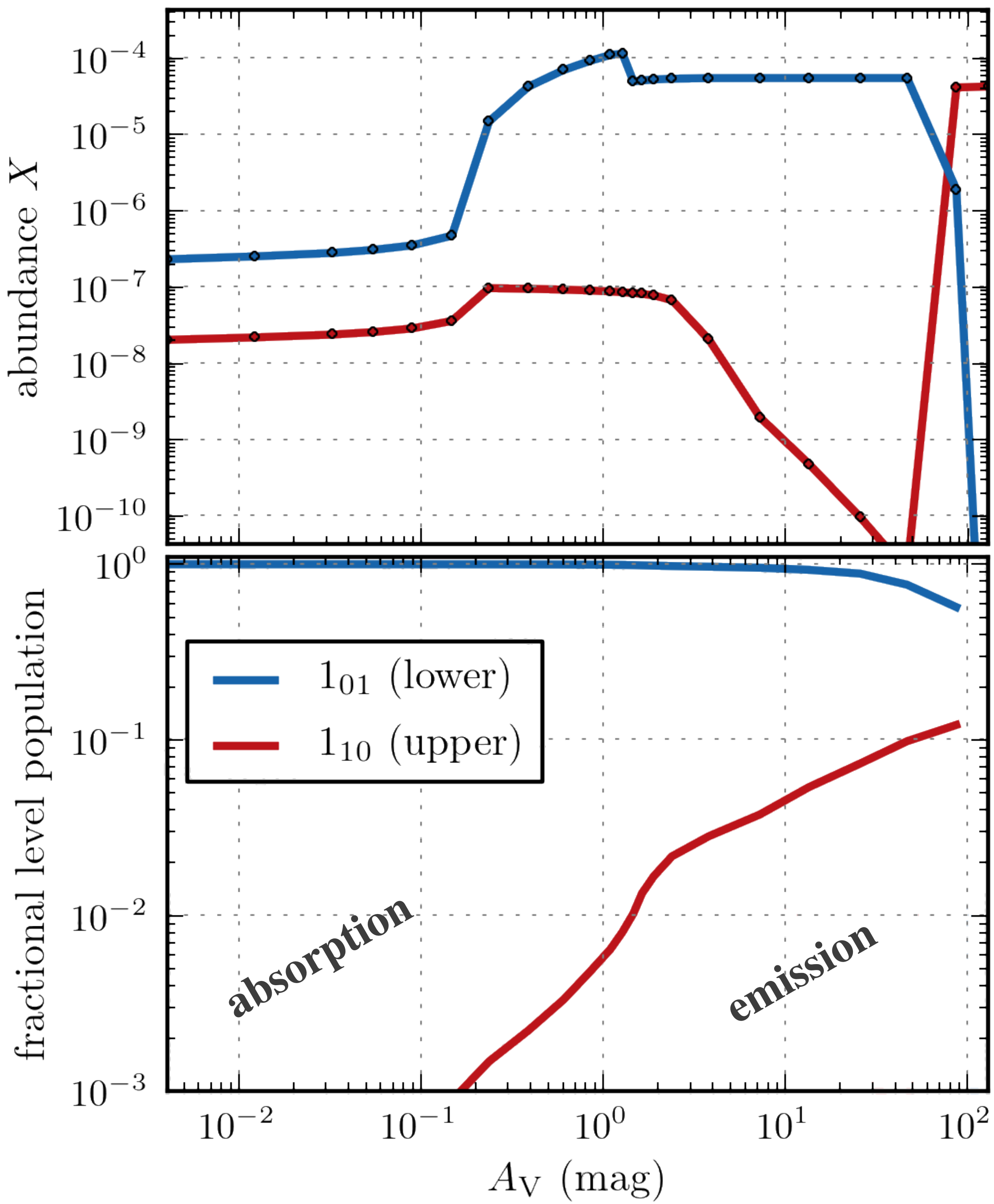

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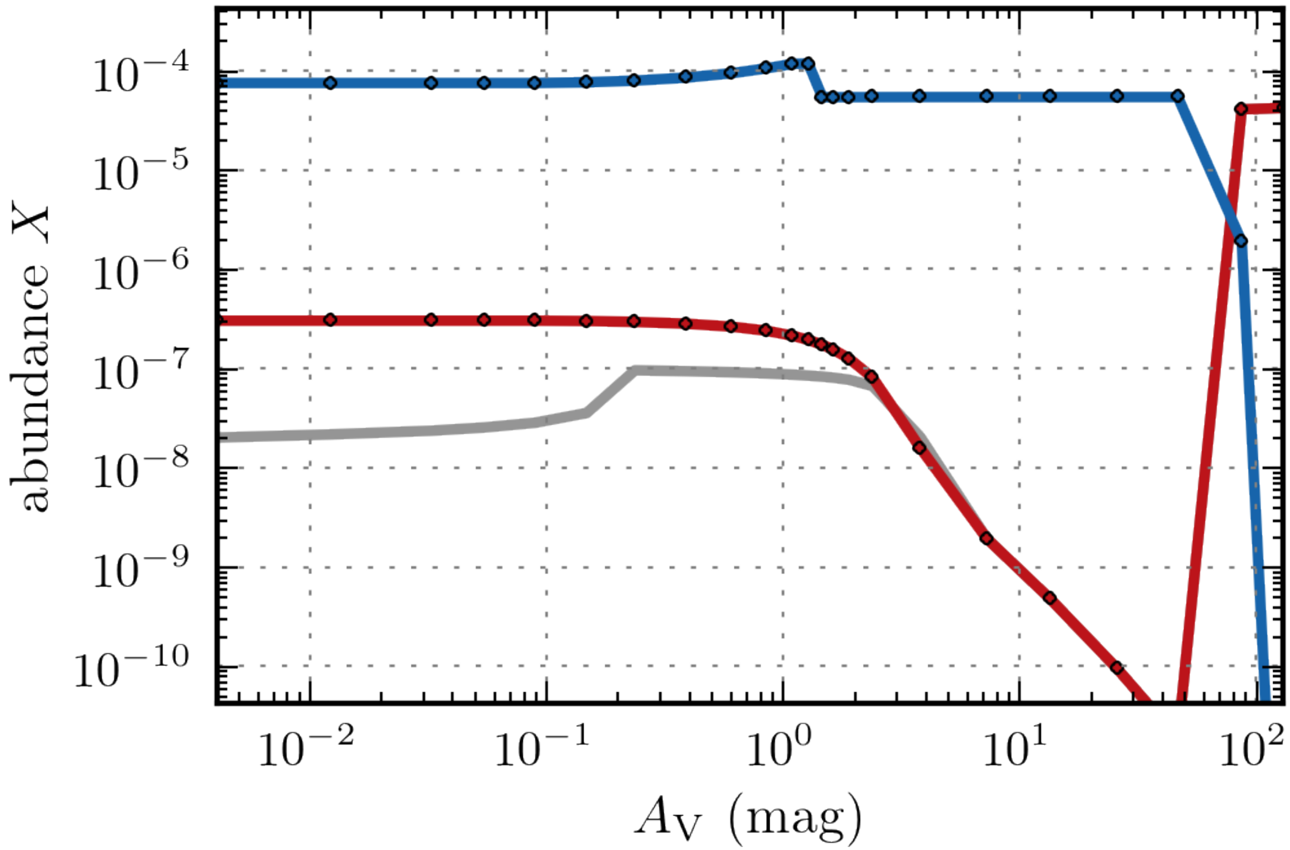

$$X_{s-H_2O}: \quad \uparrow 1.02$$
$$X_{H_2O}: \quad \uparrow 2.06$$

$$t = 0.1\,\mathrm{Myr}$$
$$G_{isrf} = 0$$
$$G_{cr} = 10^{-4}$$

Schmalzl+, in prep.

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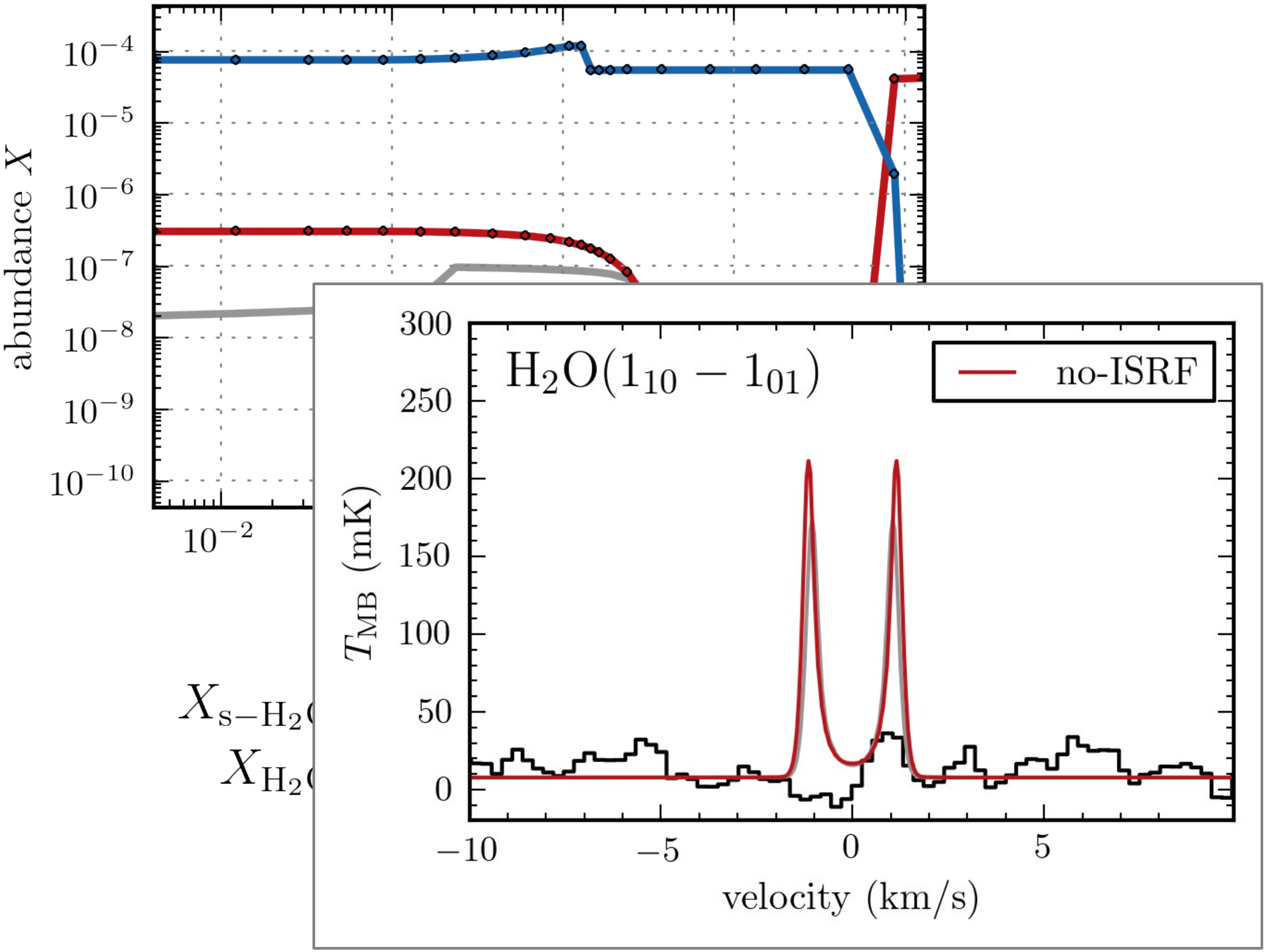

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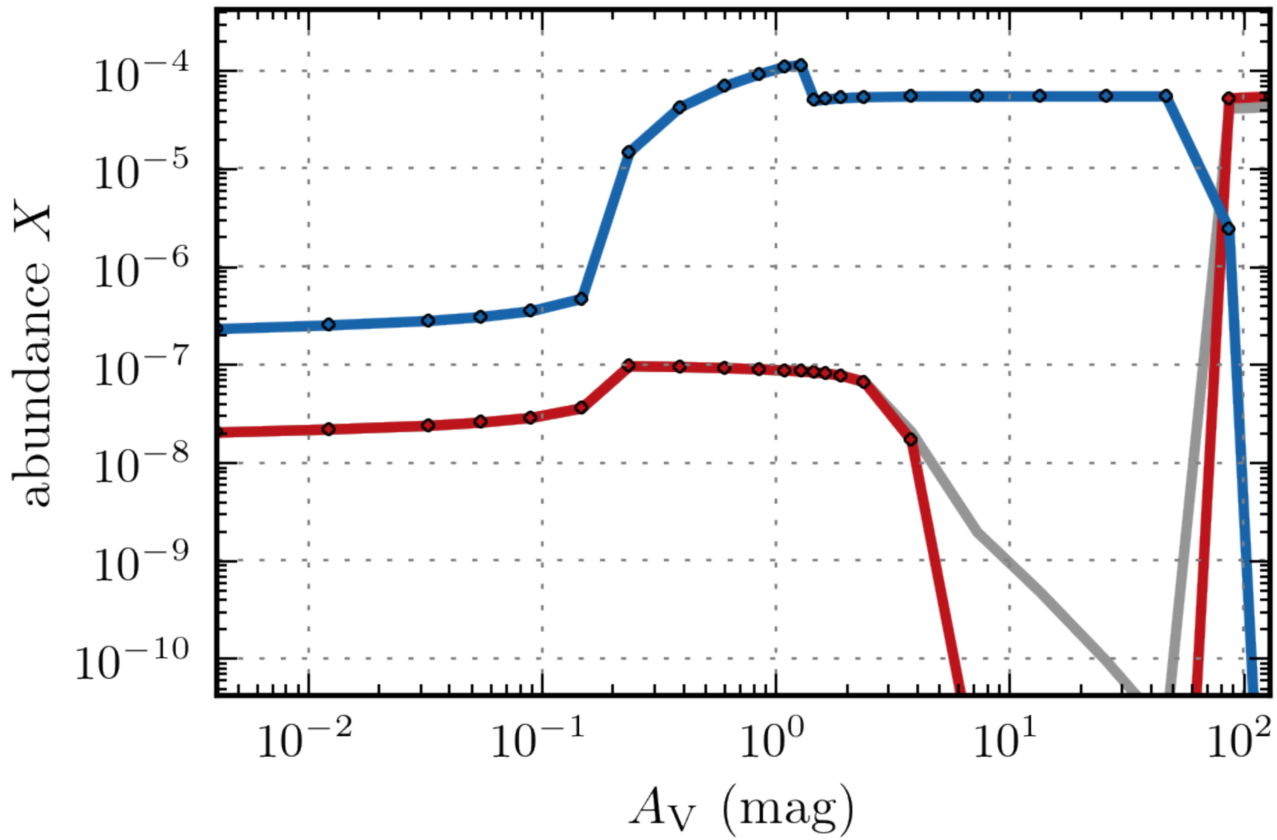

$$X_{\mathrm{s-H_2O}} : \quad \rightarrow 1.00$$

$$X_{\mathrm{H_2O}} : \quad \downarrow 1.08$$

$$t = 0.1\,\mathrm{Myr}$$

$$G_\mathrm{isrf} = 0$$

$$G_\mathrm{cr} = 10^{-4}$$

Schmalzl+, in prep.

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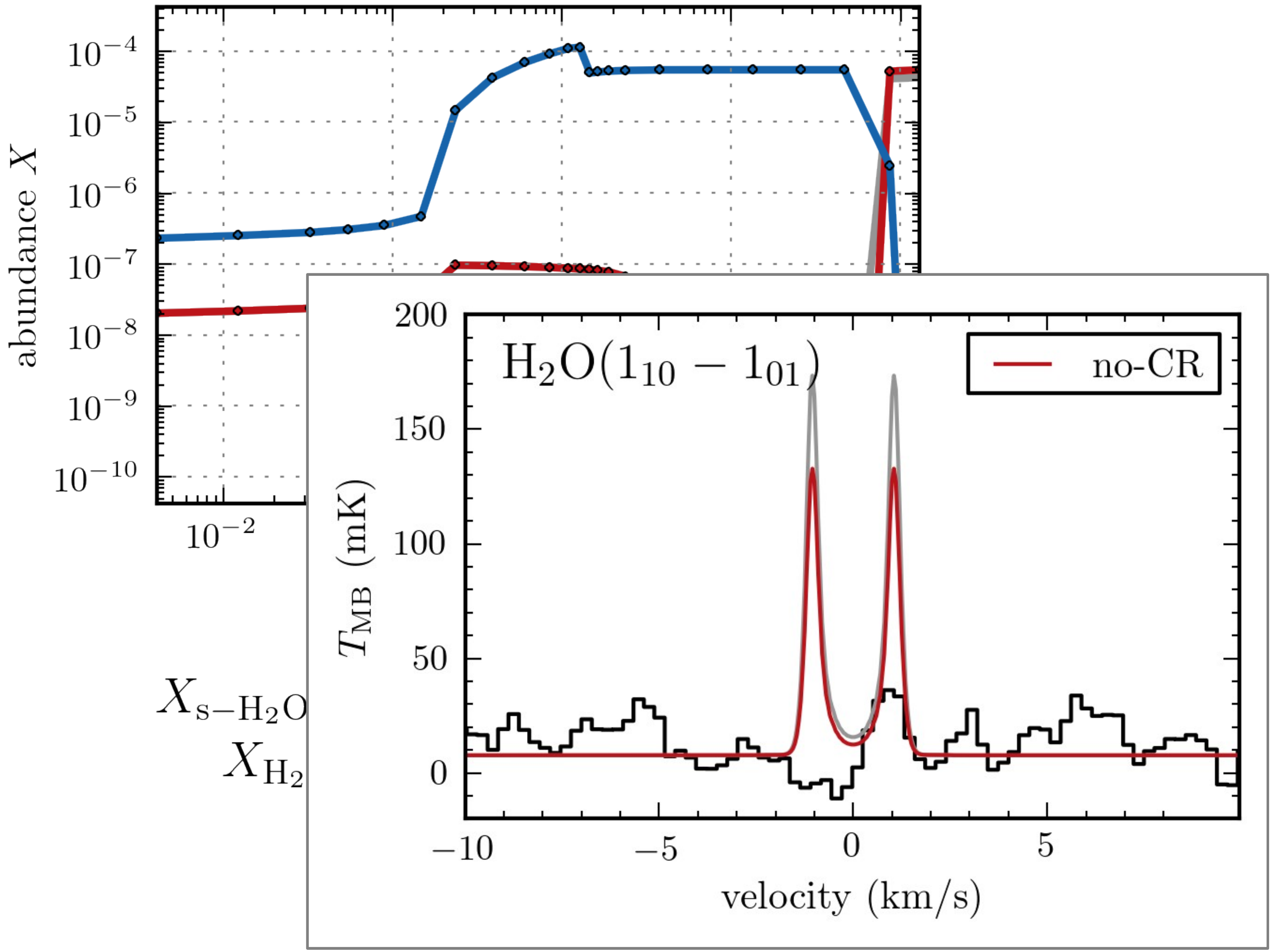

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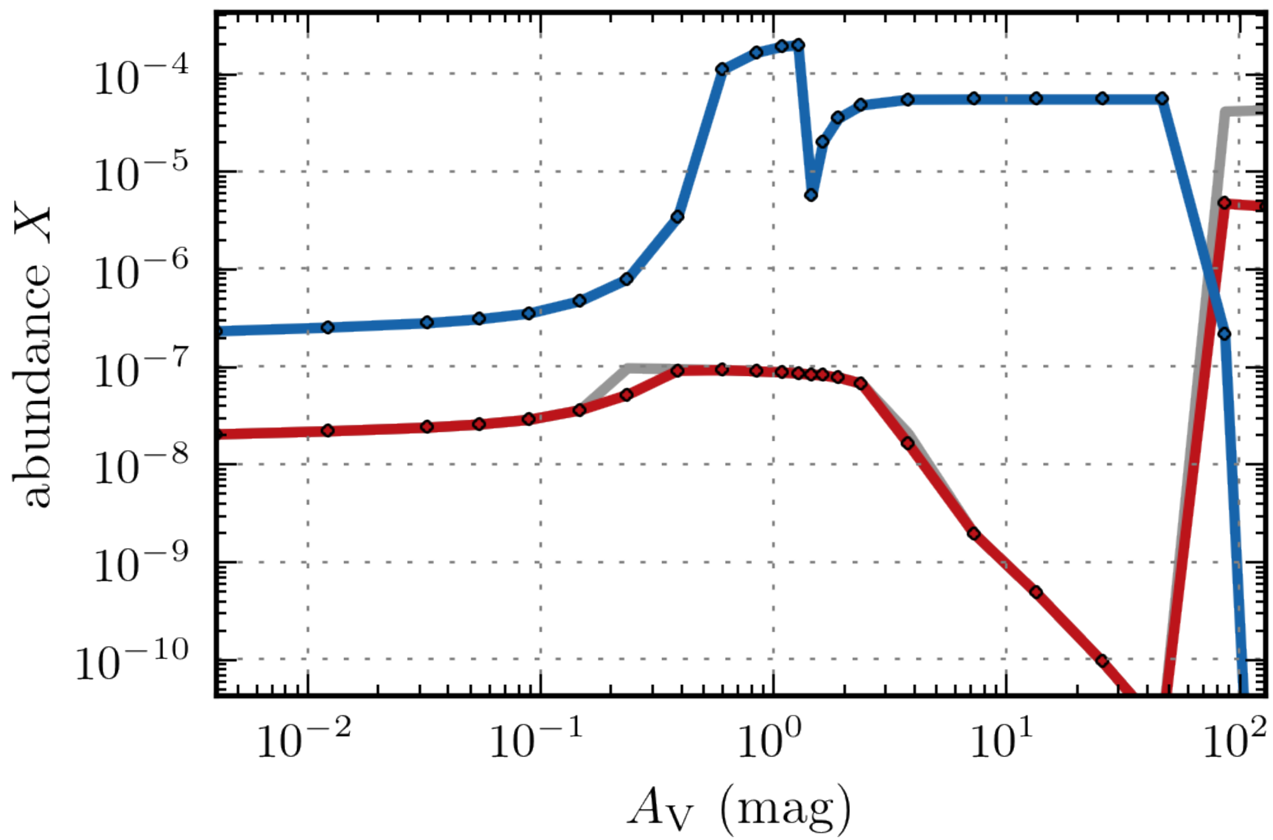

$$X_{\mathrm{s-H_2O}}: \quad \uparrow 1.01$$
$$X_{\mathrm{H_2O}}: \quad \downarrow 1.05$$

$$t = 1.0\,\mathrm{Myr}$$
$$G_{\mathrm{isrf}} = 1.0$$
$$G_{\mathrm{cr}} = 10^{-4}$$

Schmalzl+, in prep.

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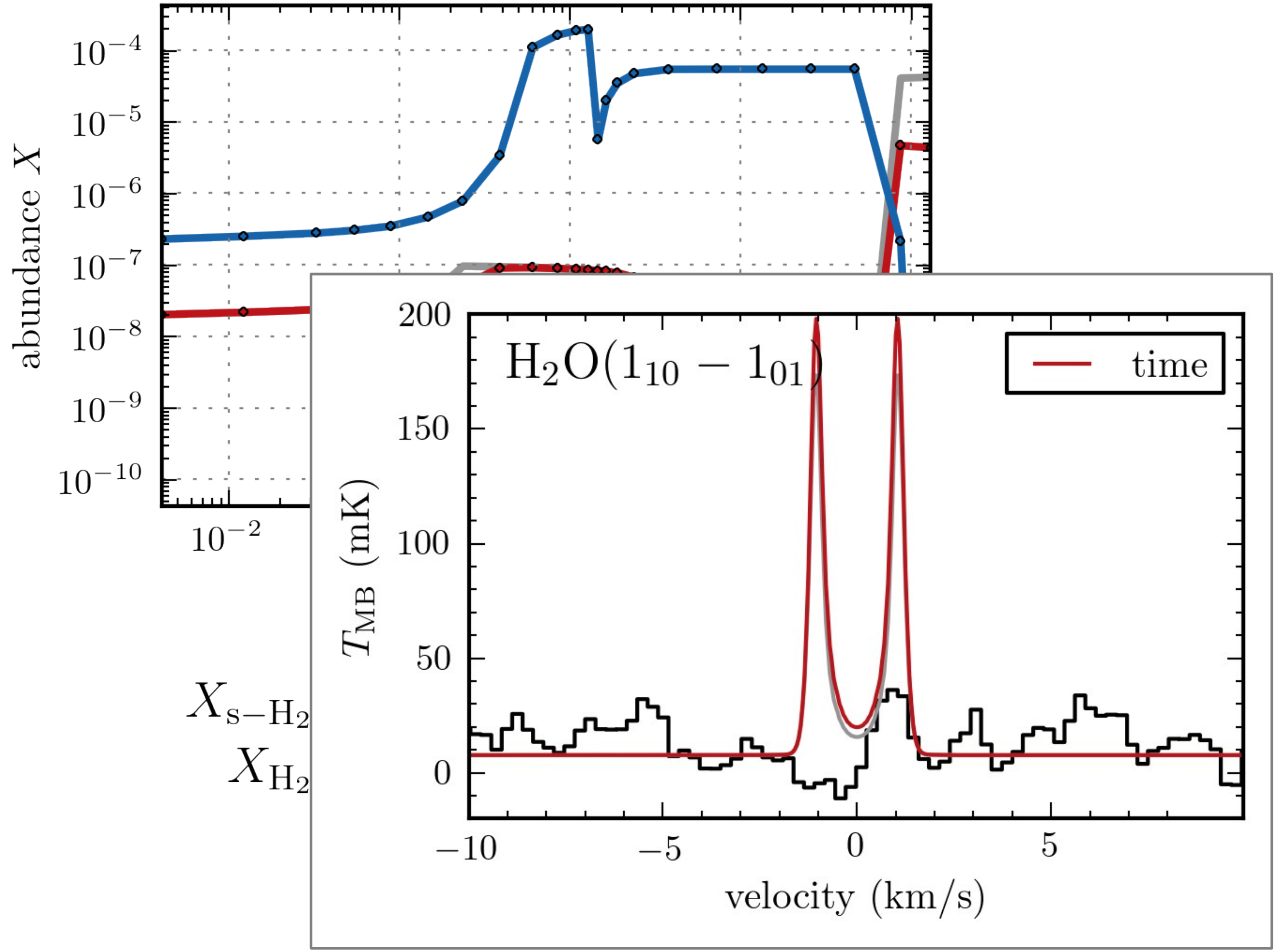

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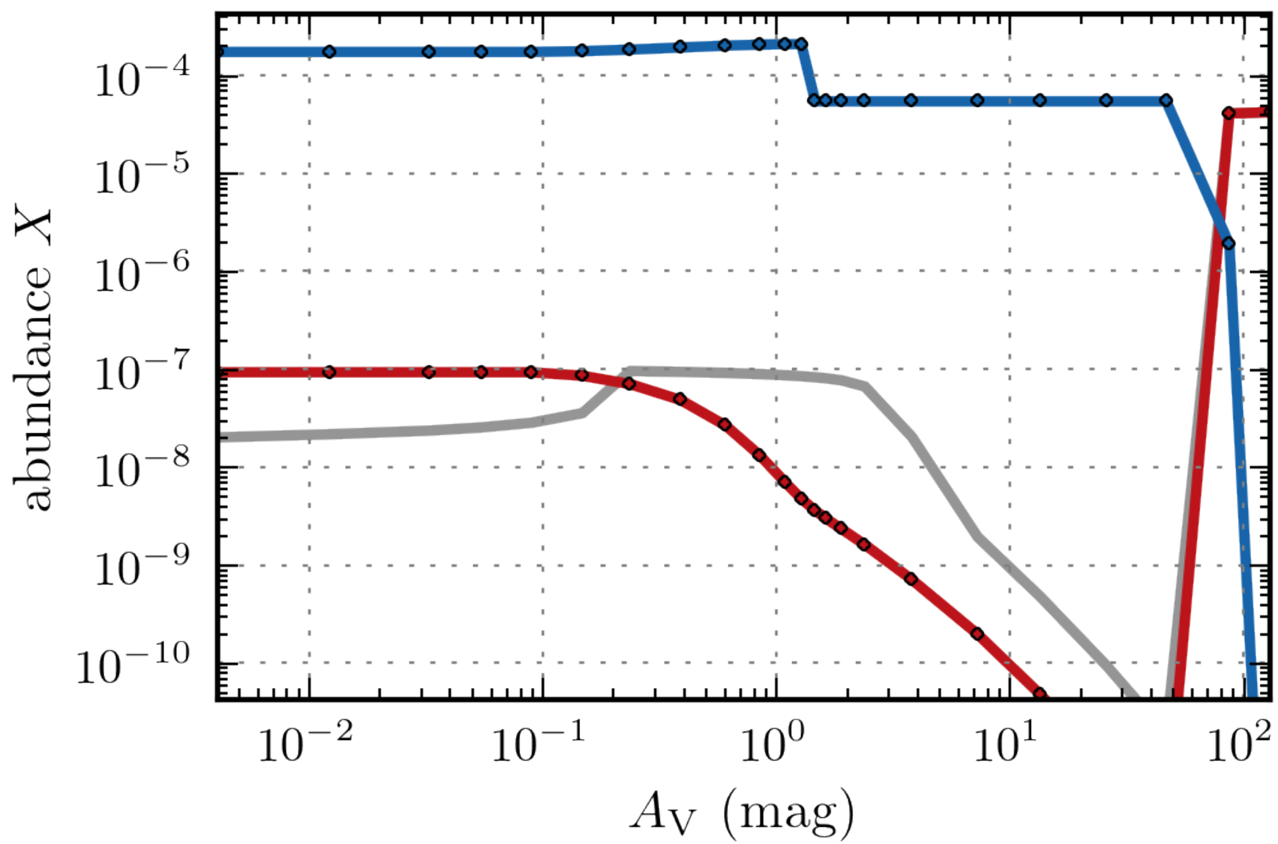

$$X_{s-H_2O}: \uparrow 1.07$$

$$X_{H_2O}: \downarrow 5.22$$

$$t = 1.0\,\mathrm{Myr}$$

$$G_{isrf} = 0$$

$$G_{cr} = 10^{-5}$$

Schmalzl+, in prep.

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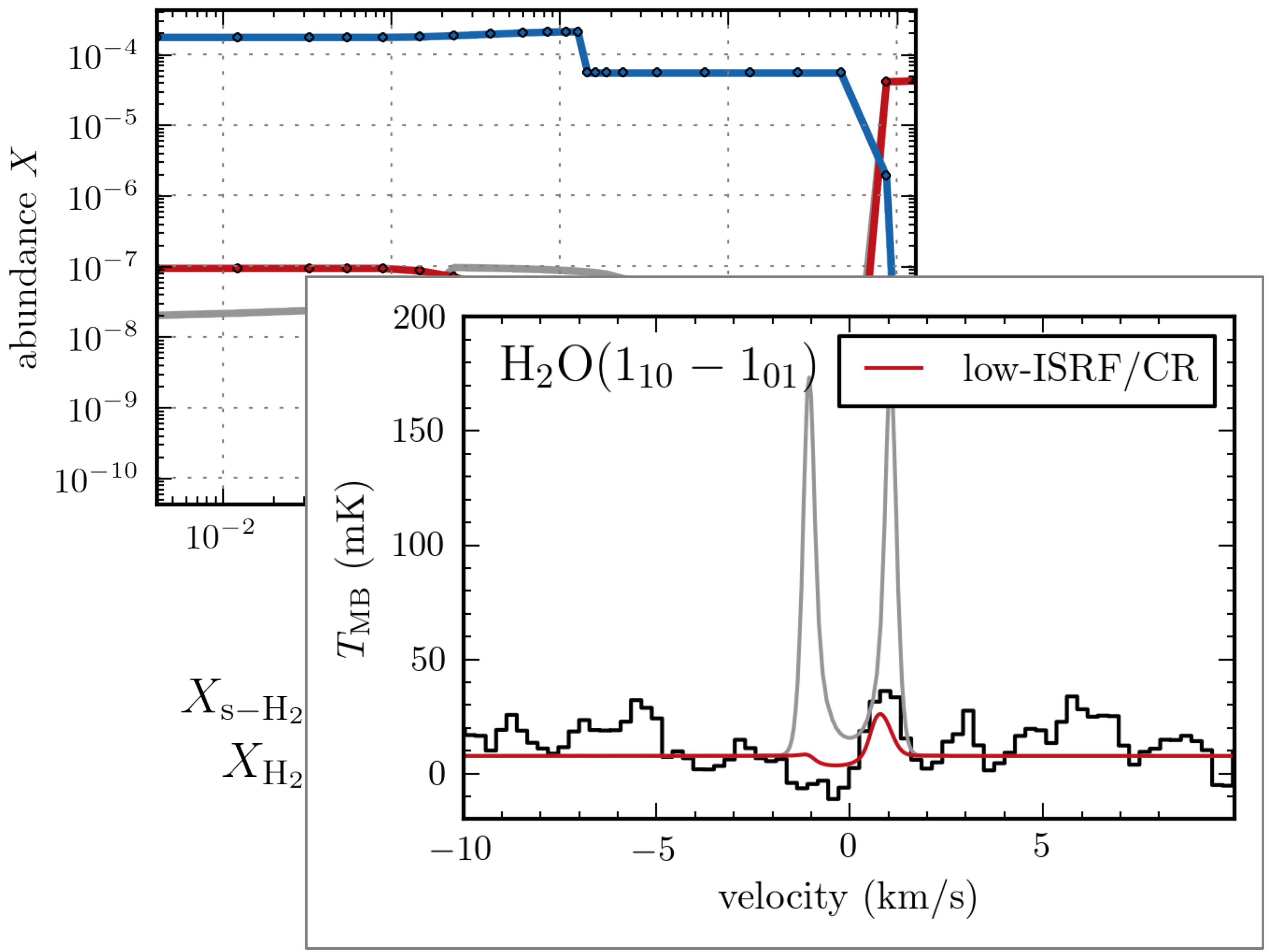

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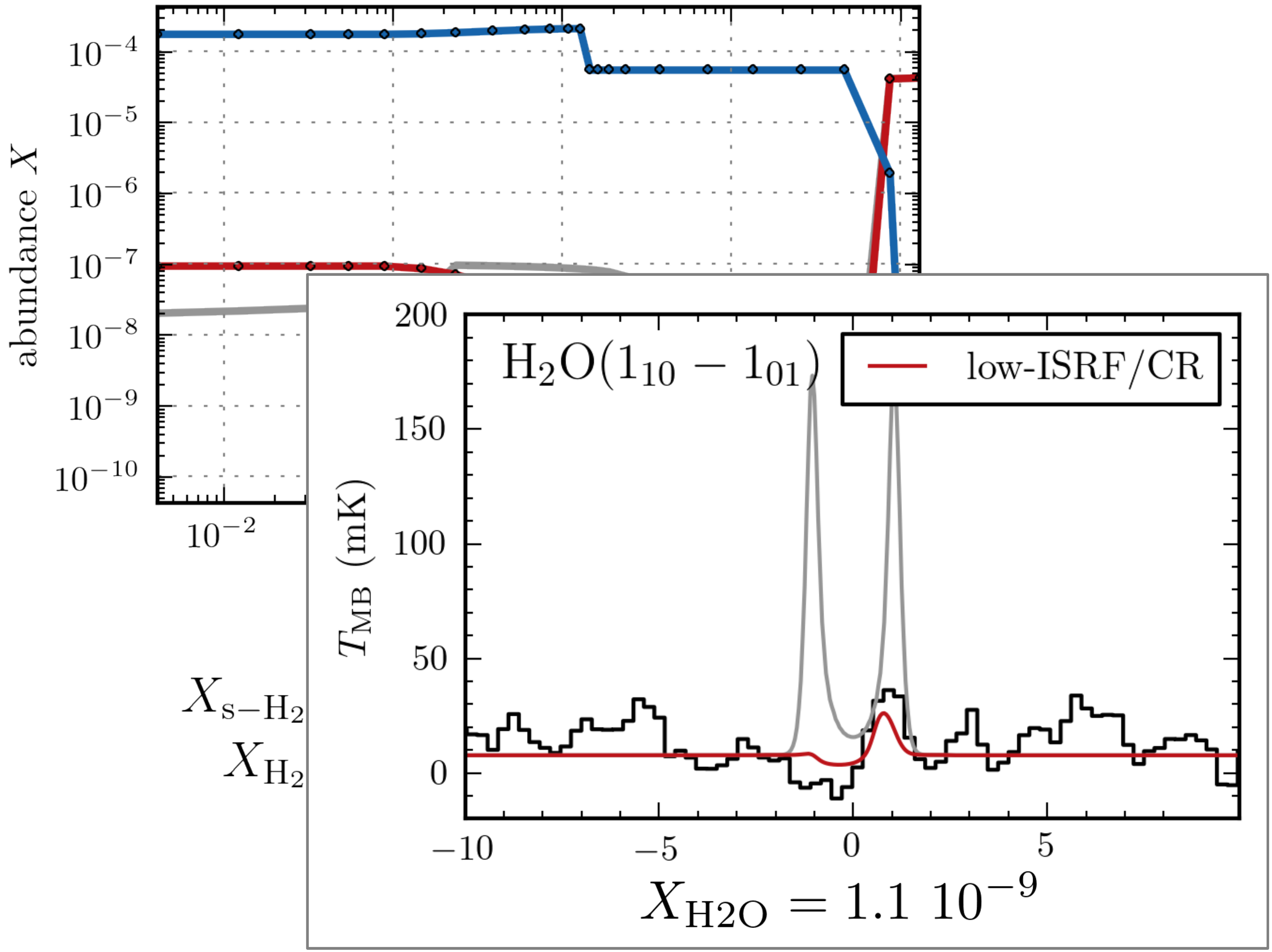

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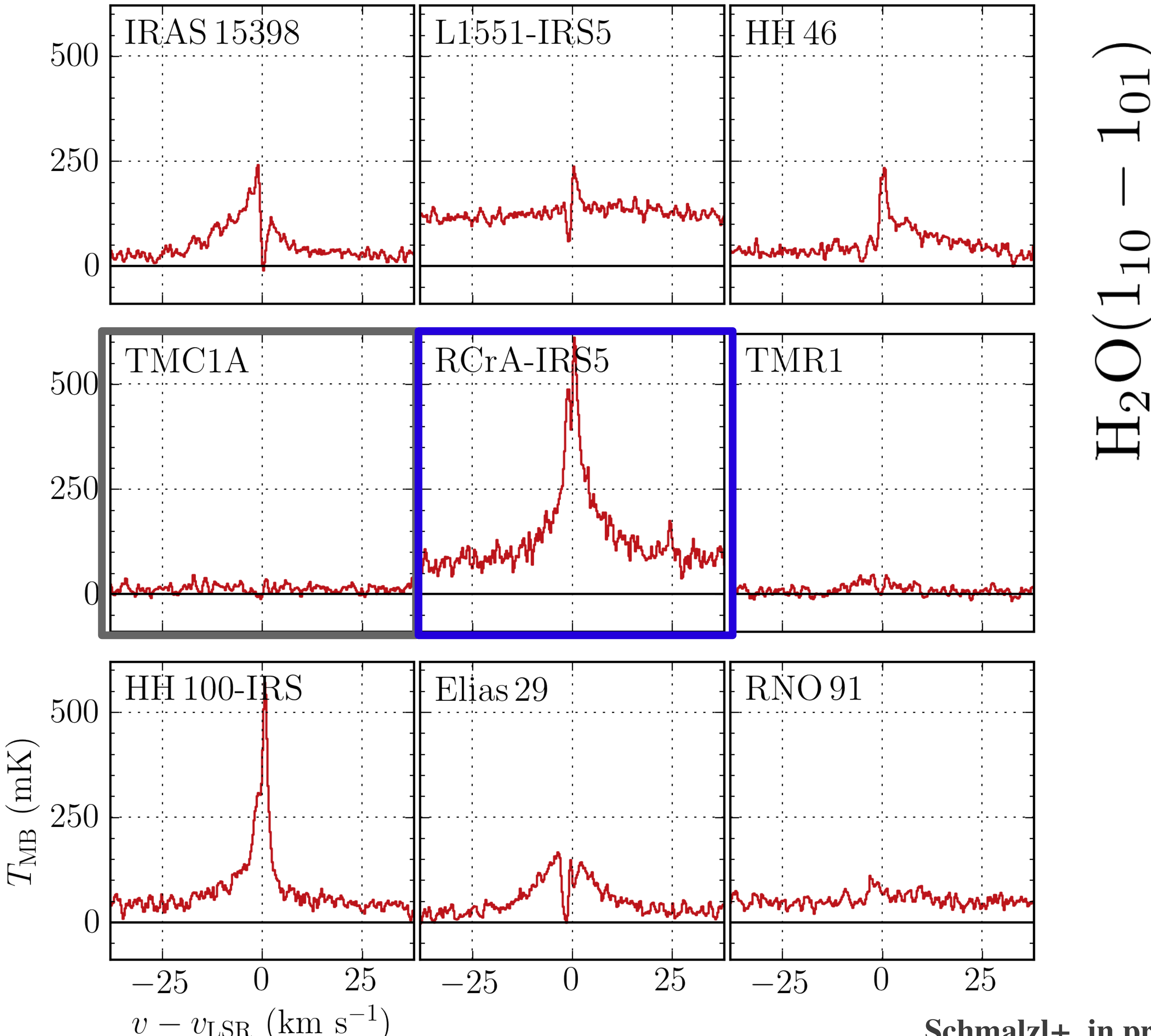

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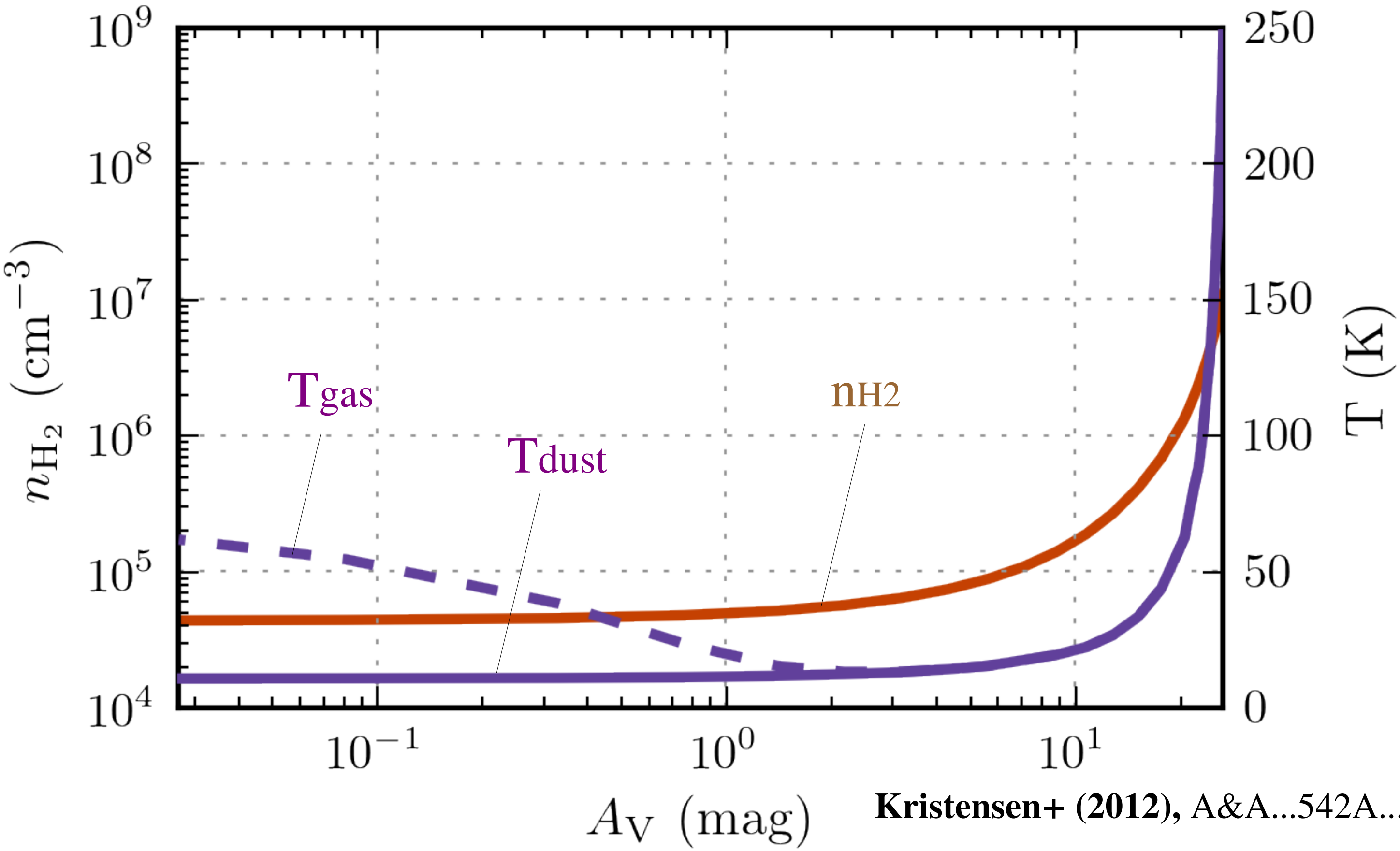
Schmalzl+, in prep.

TARGET #2: RCrA IRS5



Kristensen+ (2012), A&A...542A...8

$$N_{\mathrm{H_2}} = 2.5\ 10^{22}\,\mathrm{cm^{-2}} \qquad t = 0.1\,\mathrm{Myr}$$

$$M_{\mathrm{env}} = 2.0\,\mathrm{M_\odot} \qquad G_{\mathrm{isrf}} = 100$$

$$L_{\mathrm{bol}} = 3\,\mathrm{L_\odot} \qquad G_{\mathrm{cr}} = 10^{-4}$$

Schmalzl+, in prep.

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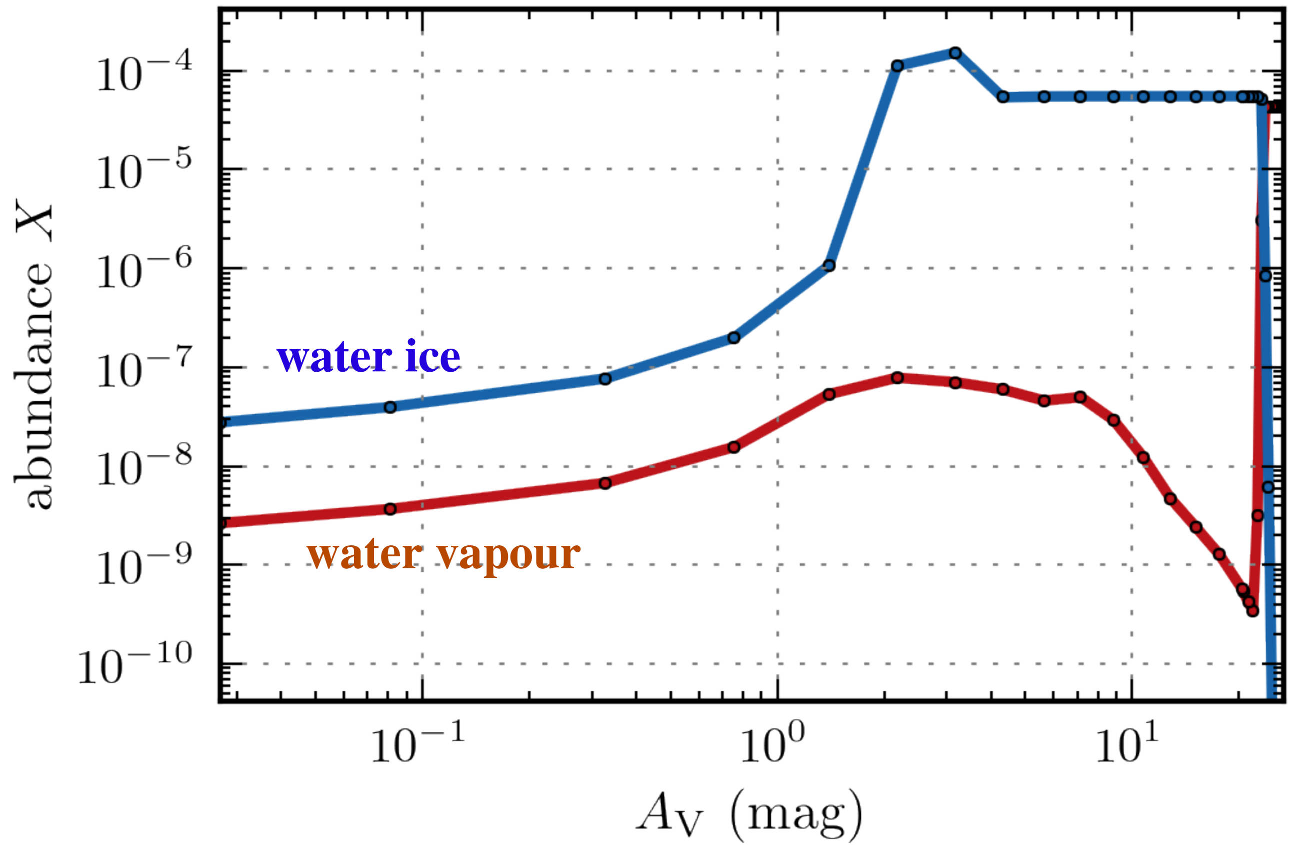

$$X_{s-H_2O}: \quad 5.7\,10^{-5}$$

$$X_{H_2O}: \quad 2.2\,10^{-8}$$

$$t = 0.1\,\mathrm{Myr}$$

$$G_{isrf} = 100$$

$$G_{cr} = 10^{-4}$$

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Schmalzl+, in prep.

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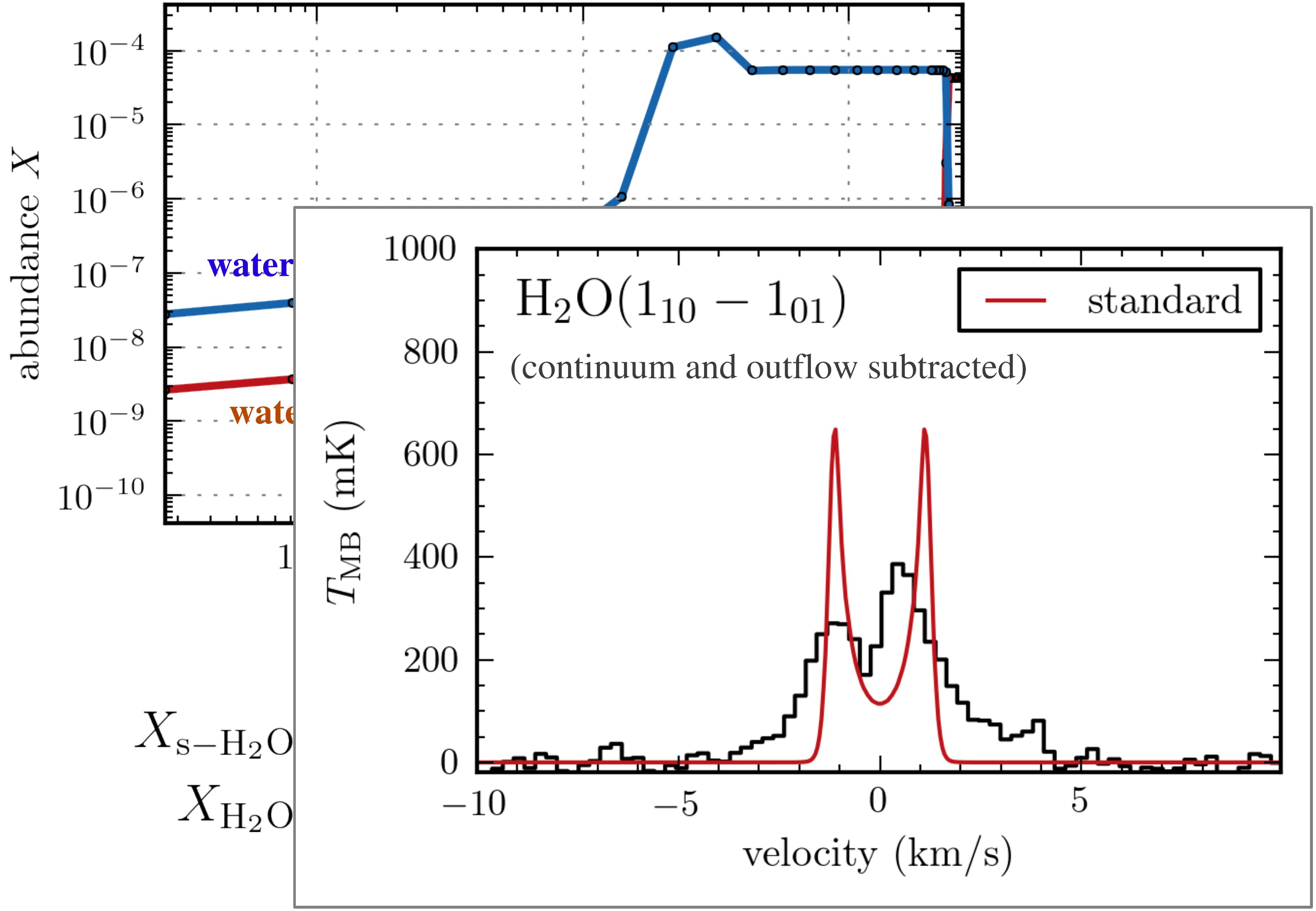

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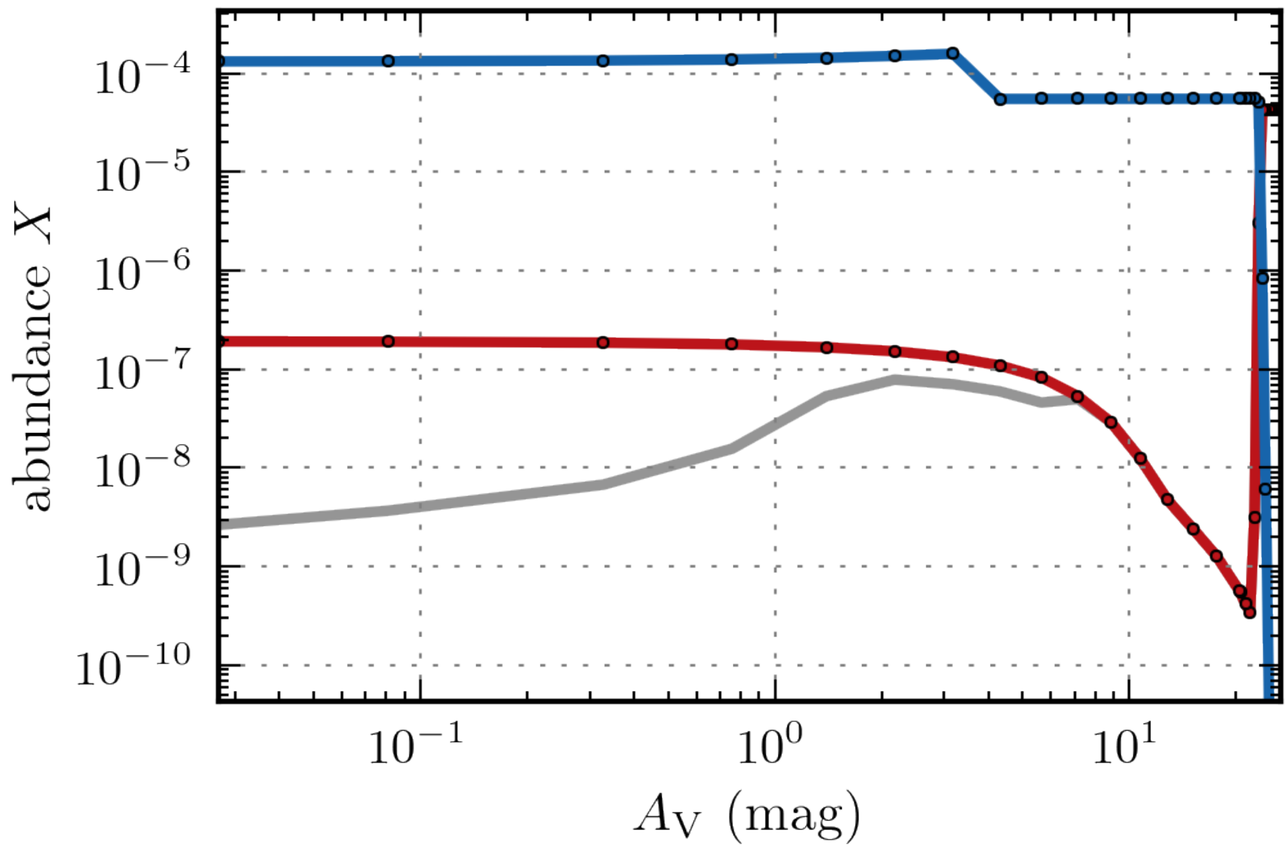

X_{s-H_2O} : $\uparrow 1.22$

X_{H_2O} : $\uparrow 2.01$

$t = 0.1\,\mathrm{Myr}$

$G_{isrf} = 0$

$G_{cr} = 10^{-4}$

Schmalzl+, in prep.

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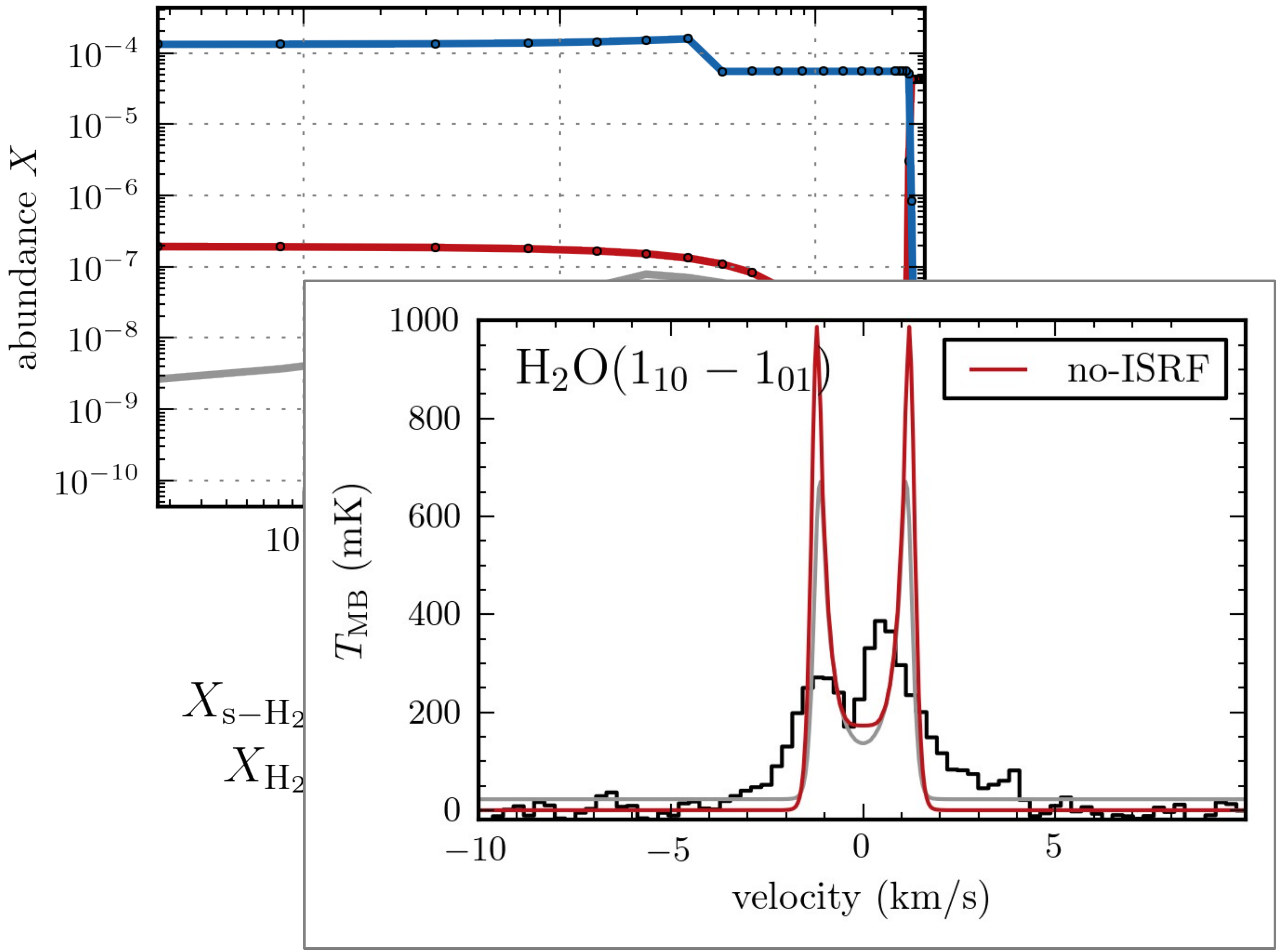
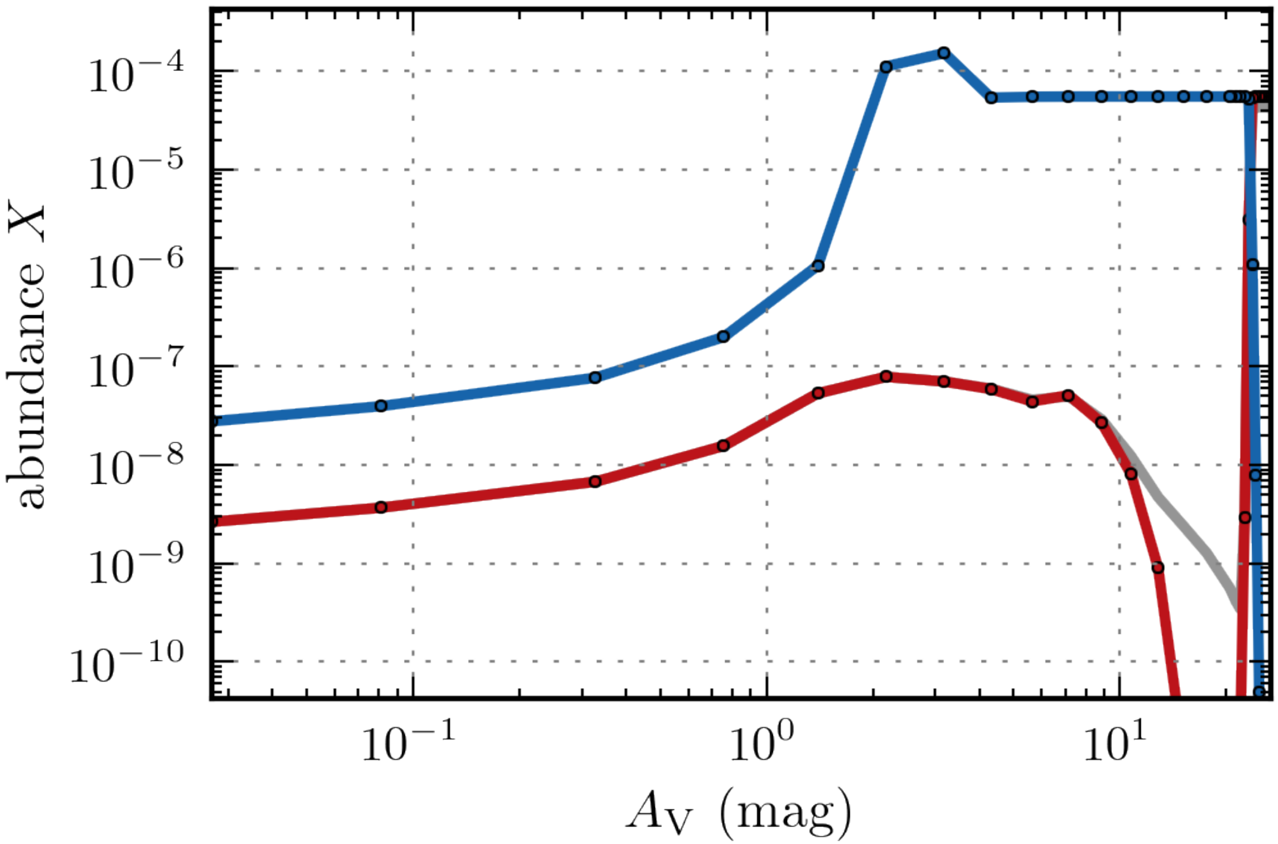


Schmalzl+, in prep.

TARGET #2: RCrA IRS5



$X_{s-H_2O}: \quad \rightarrow 1.00$

$X_{H_2O}: \quad \downarrow 1.07$

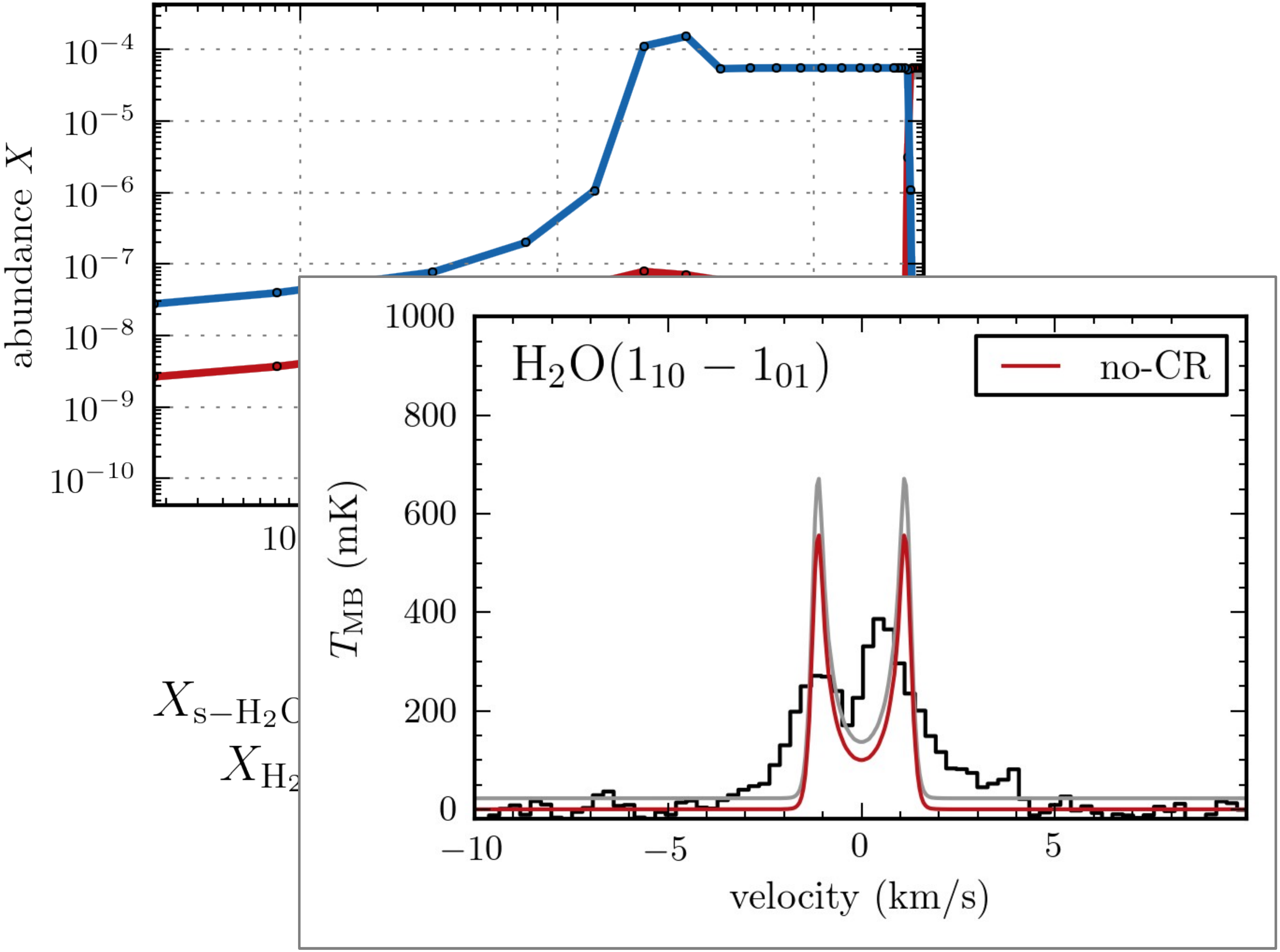
$t = 0.1\,\mathrm{Myr}$

$G_{isrf} = 100$

$G_{cr} = 0$

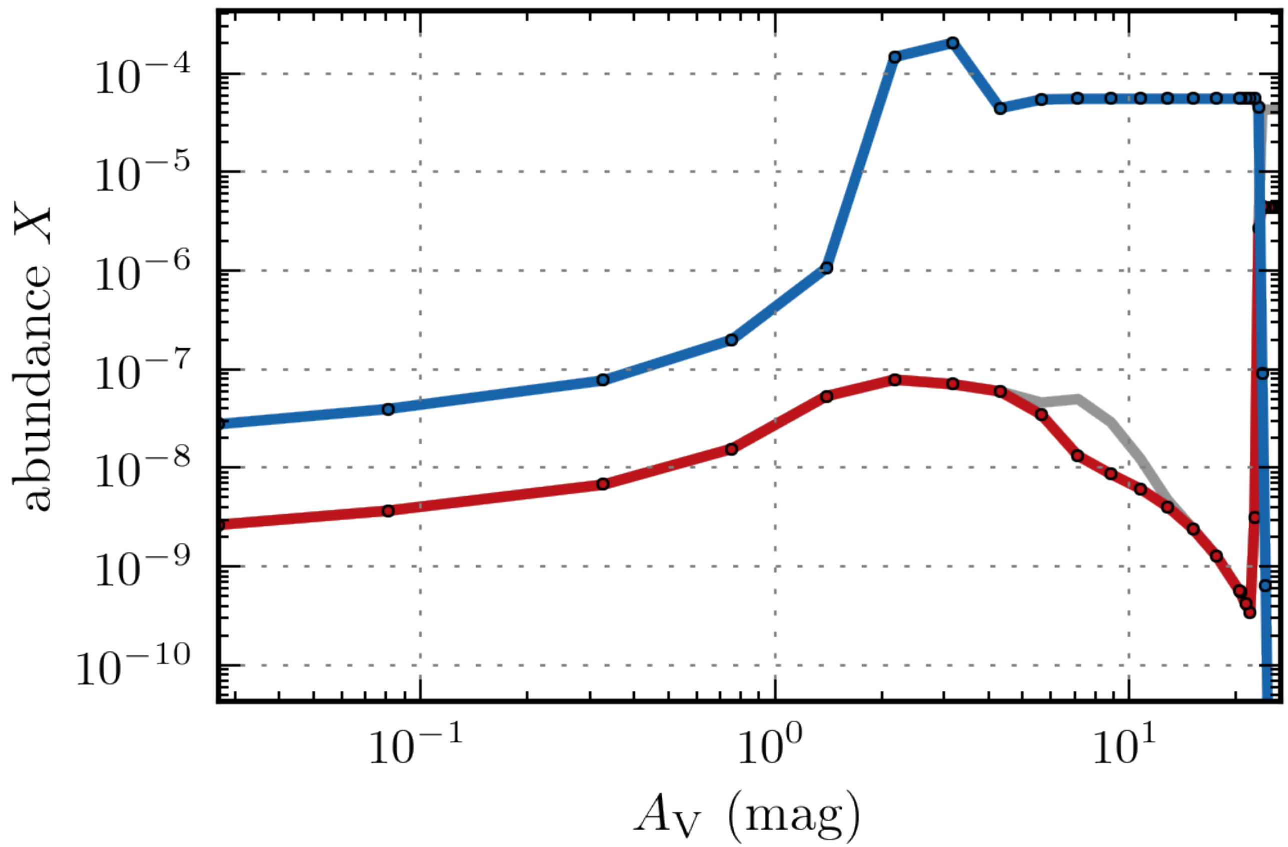
Schmalzl+, in prep.

TARGET #2: RCrA IRS5



Schmalzl+, in prep.

TARGET #2: RCrA IRS5

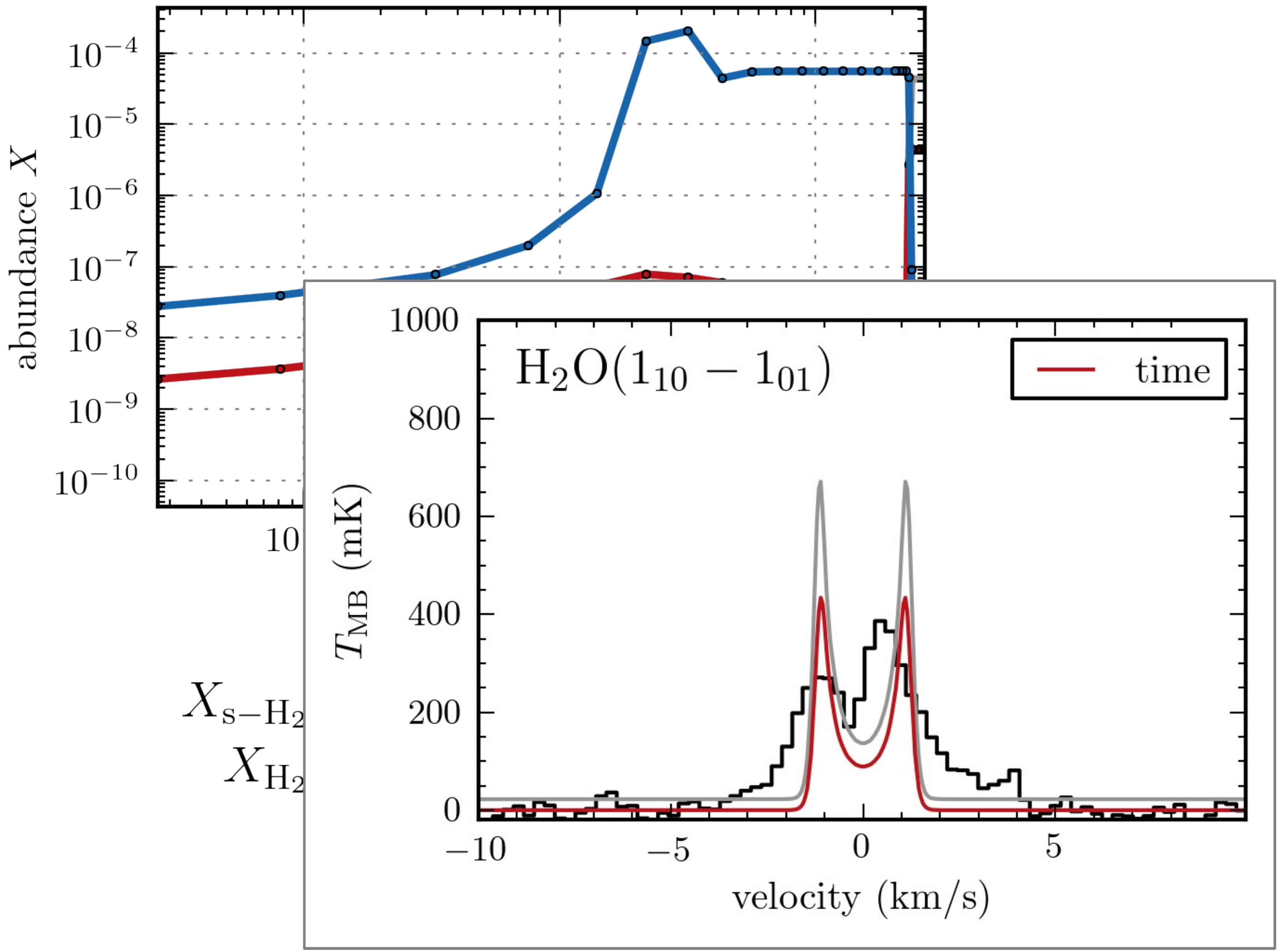


$$X_{\mathrm{s-H_2O}} : \quad \uparrow 1.06$$
$$X_{\mathrm{H_2O}} : \quad \downarrow 1.32$$

$$t = 1.0\,\mathrm{Myr}$$
$$G_{\mathrm{isrf}} = 100$$
$$G_{\mathrm{cr}} = 10^{-4}$$

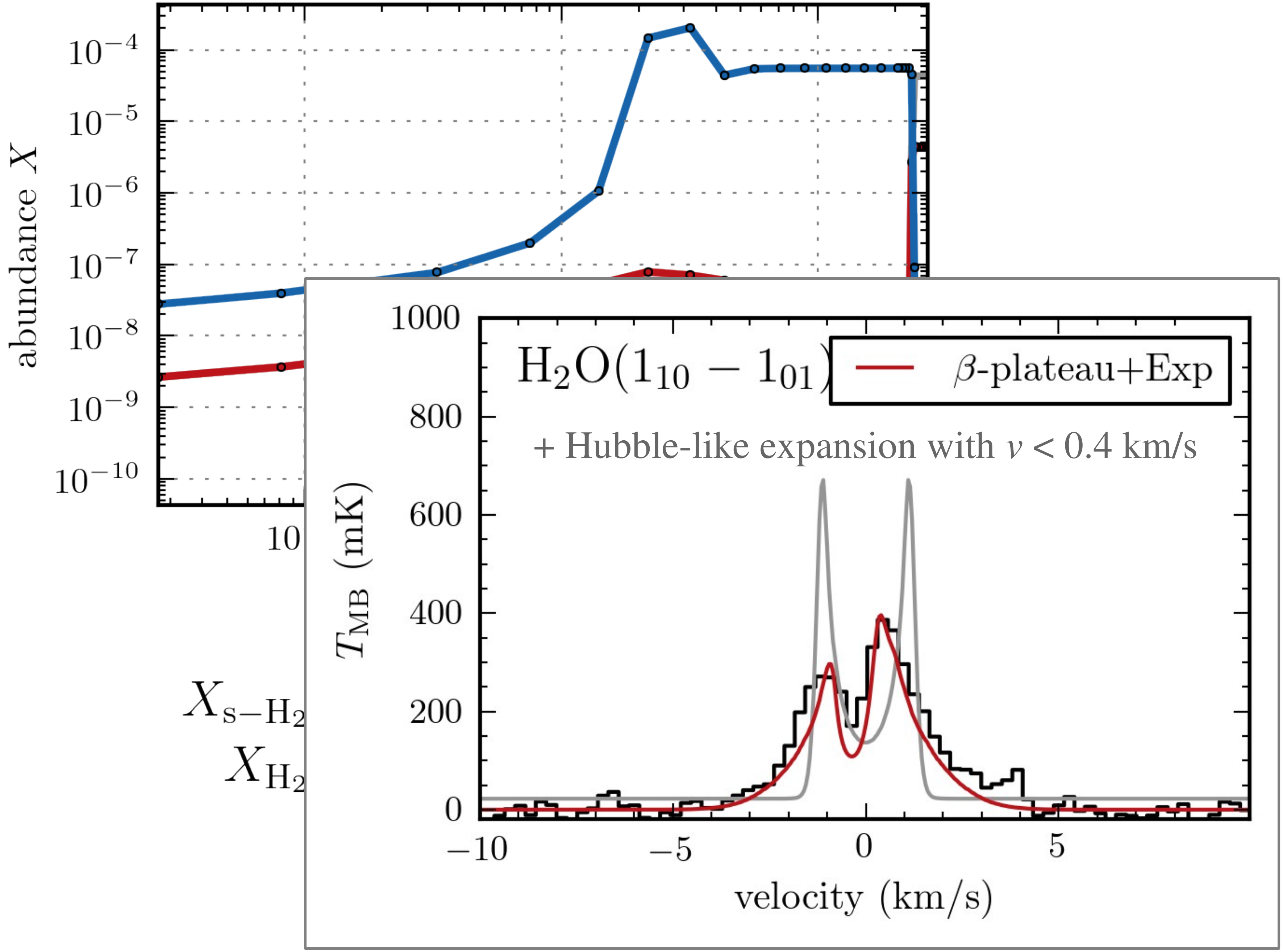
Schmalzl+, in prep.

TARGET #2: RCrA IRS5



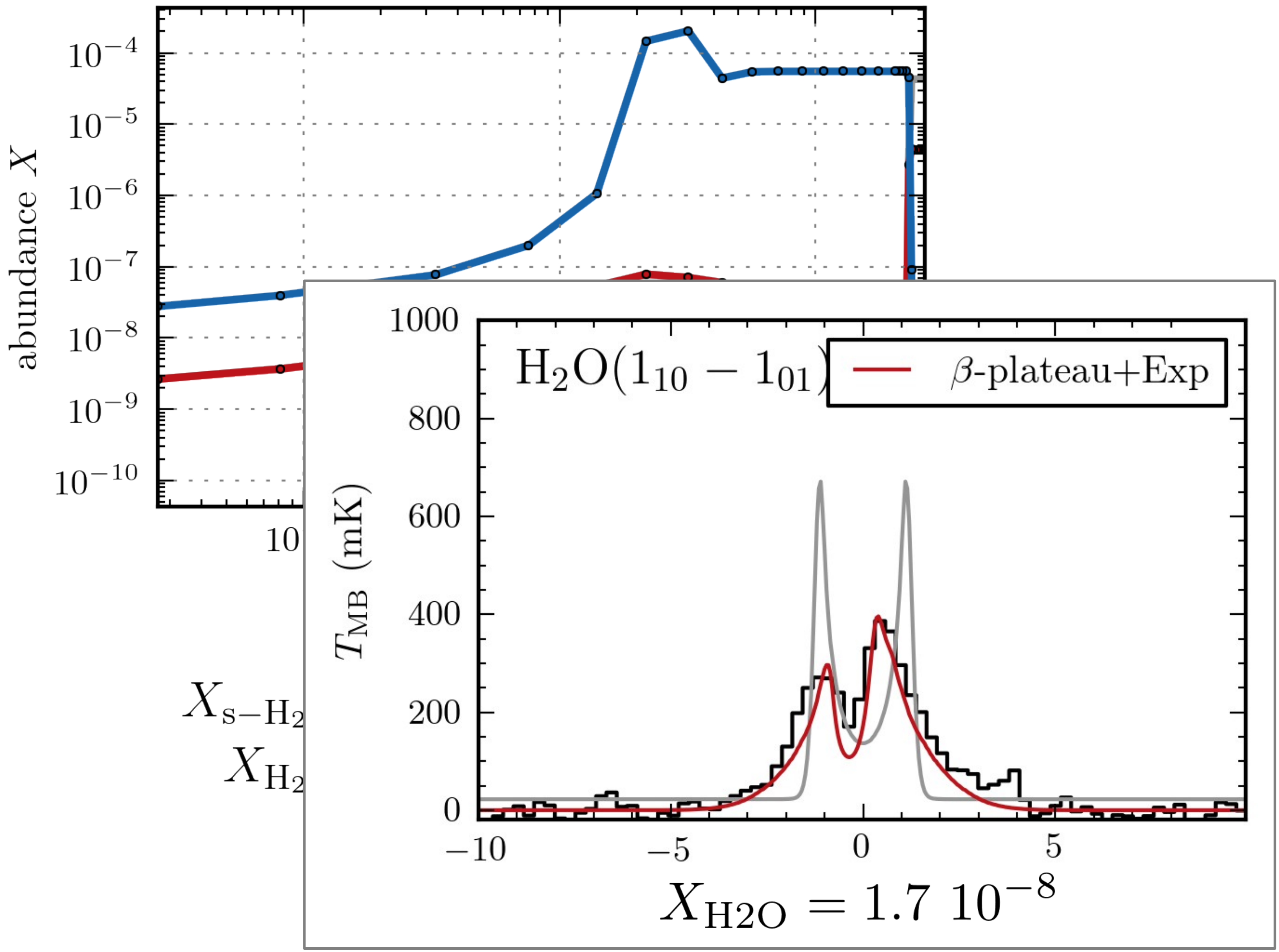
Schmalzl+, in prep.

TARGET #2: RCrA IRS5



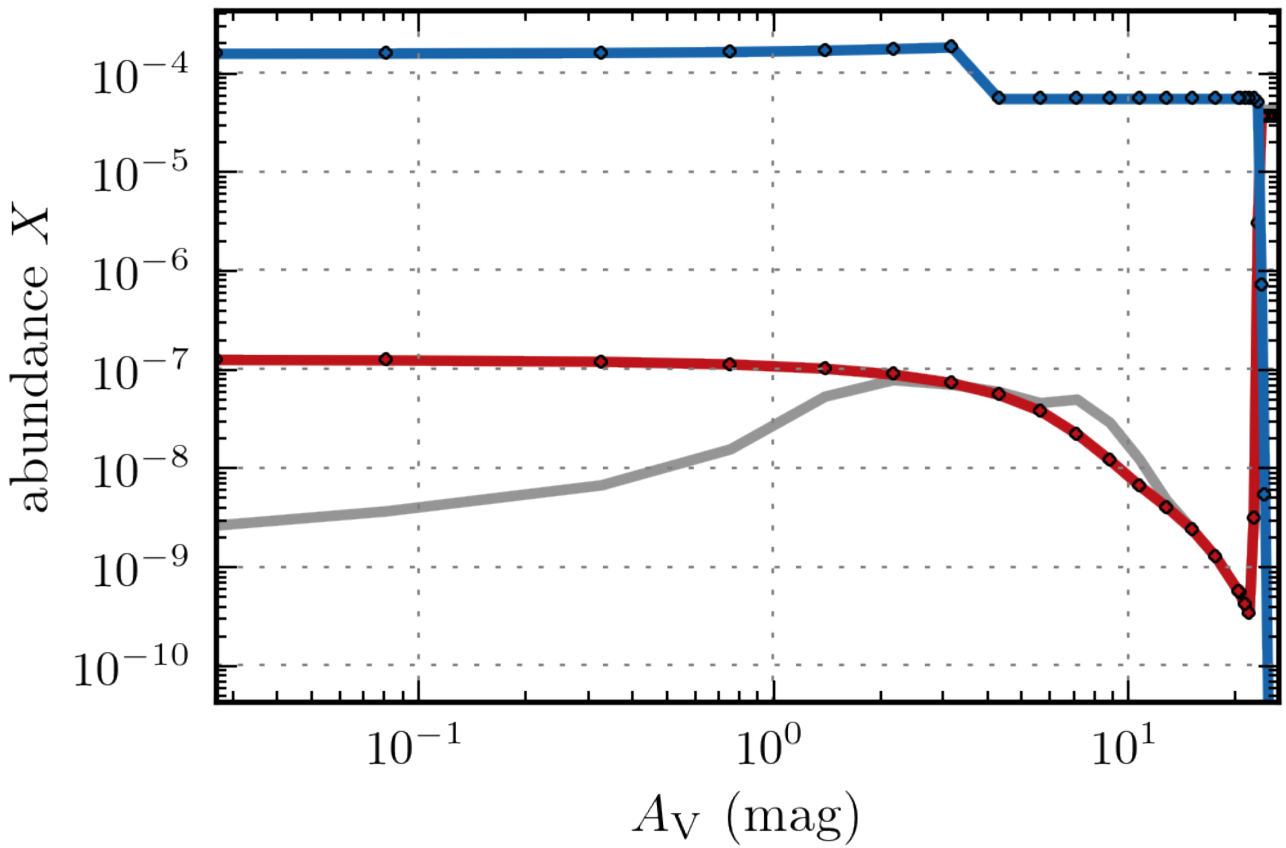
Schmalzl+, in prep.

TARGET #2: RCrA IRS5



Schmalzl+, in prep.

TARGET #2: RCrA IRS5



$$X_{s-H_2O}: \quad \uparrow 1.30$$

$$X_{H_2O}: \quad \uparrow 1.12$$

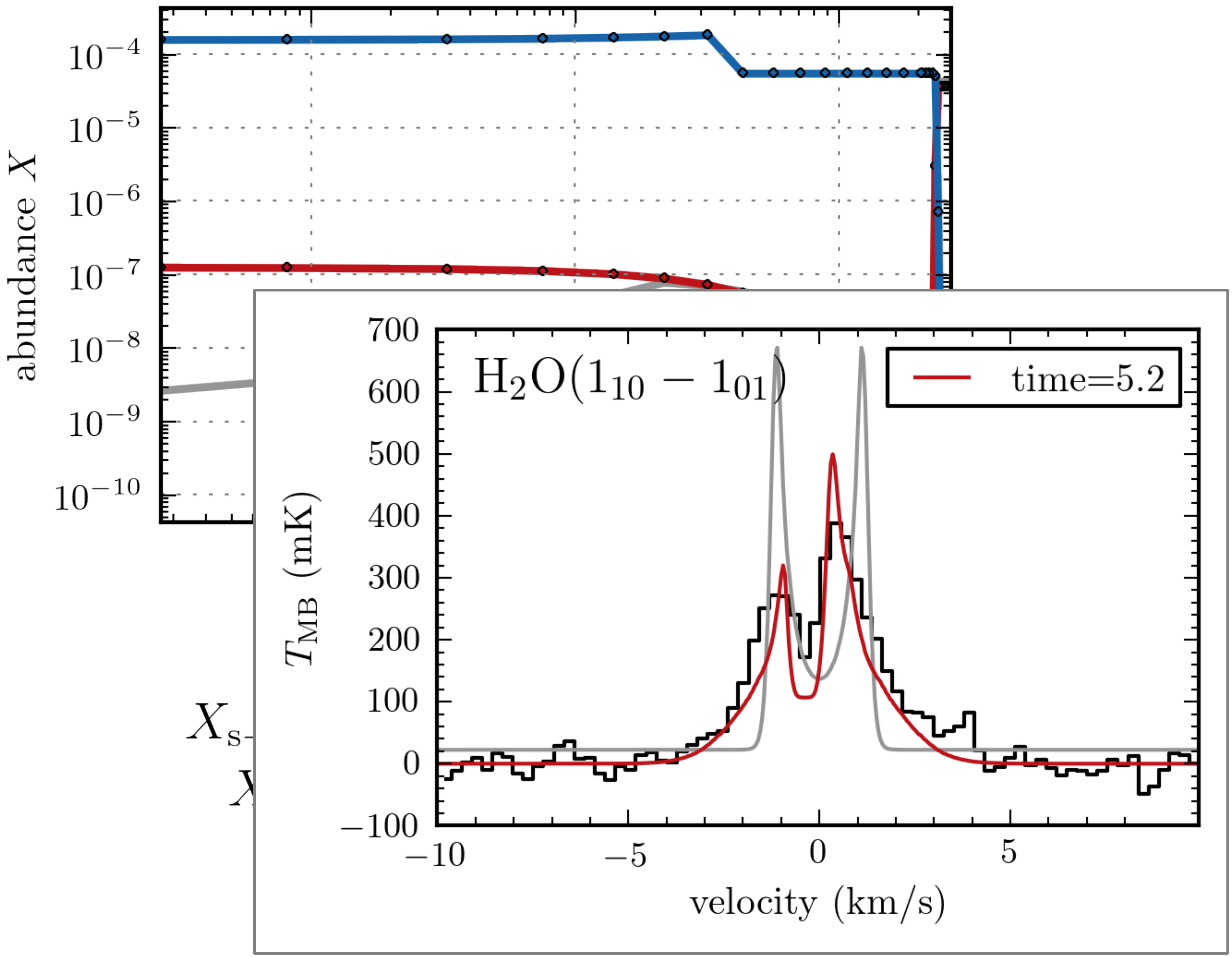
$$t = 1.6\,\mathrm{Myr}$$

$$G_{\mathrm{isrf}} = 0$$

$$G_{\mathrm{cr}} = 10^{-4}$$

Schmalzl+, in prep.

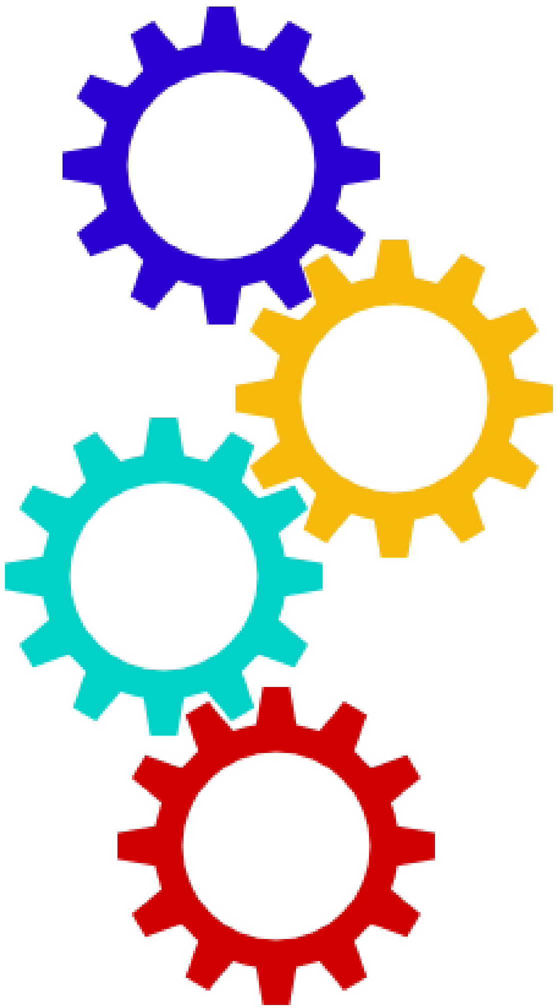
TARGET #2: RCrA IRS5



Schmalzl+, in prep.

WATER VAPOUR

The **water vapour emission profiles** of ground-state transitions can be tweaked by changing …



- … **Doppler-β** to modify the width of emission/absorption features
- … the **radial velocity** to modify the position of emission/absorption features

- … **FUV-ISRF** to modify the abundance at the core edge
- … **FUV-CR** to modify the abundance at intermediate depth
- … the **time** to decrease the abundance (as a function of density)

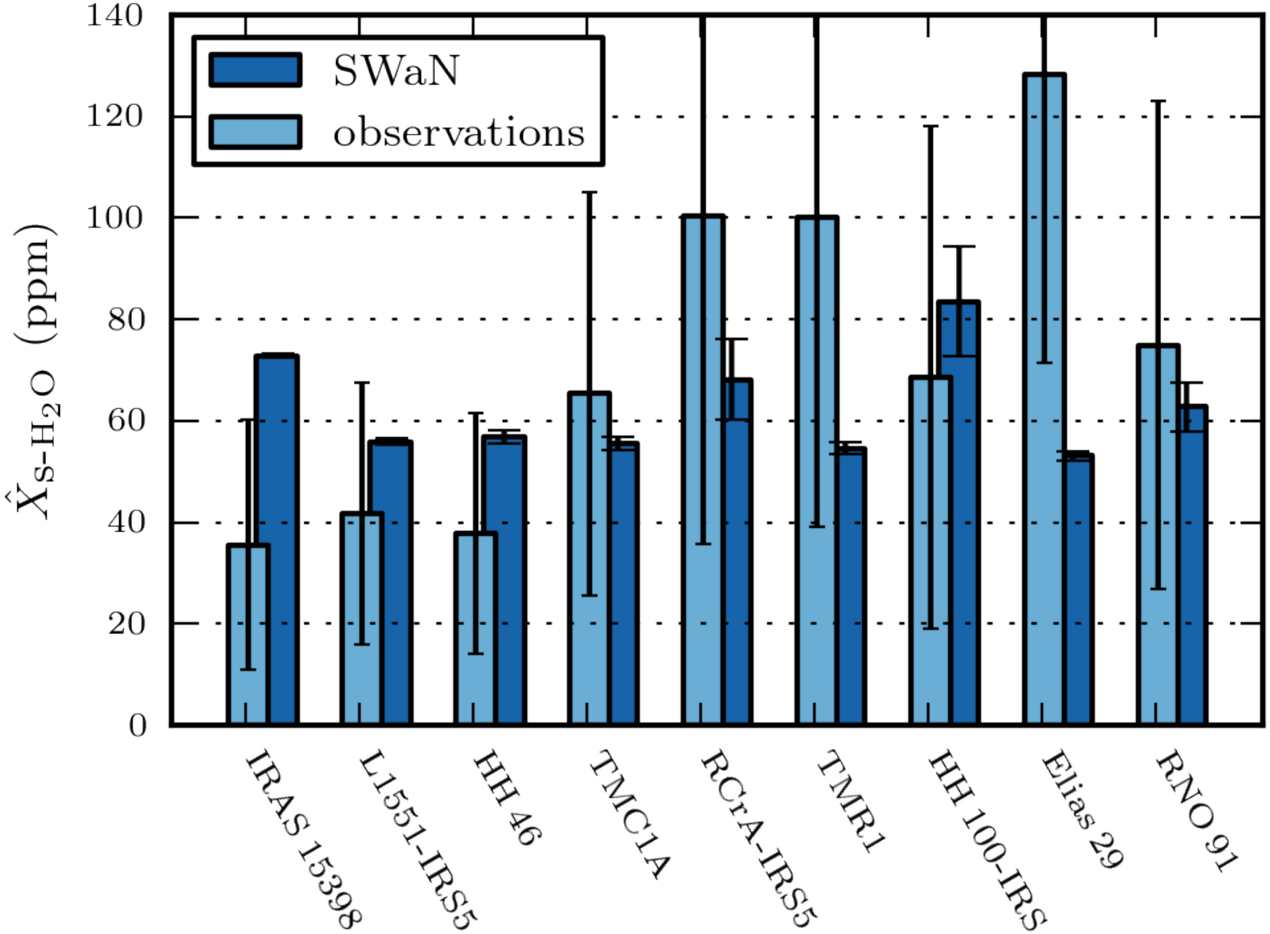
Schmalzl+, in prep.

In contrast to the **water vapour**, the **water ice** abundances are rather insensitive to FUV field and/or time

WATER ICE

In contrast to the **water vapour**, the **water ice** abundances are rather insensitive to FUV field and/or time

$$X_{\mathrm{s-H_2O}} = (6.3 \pm 1.0)\ 10^{-5}$$



Ice Column Densities from: **Zasowski+ (2009)**, ApJ...694..459; **Boogert+ (2008)**, ApJ...678..985
Temperature and Hydrogen Density Profiles from **Kristensen+ (2012)** A&A...542A...8

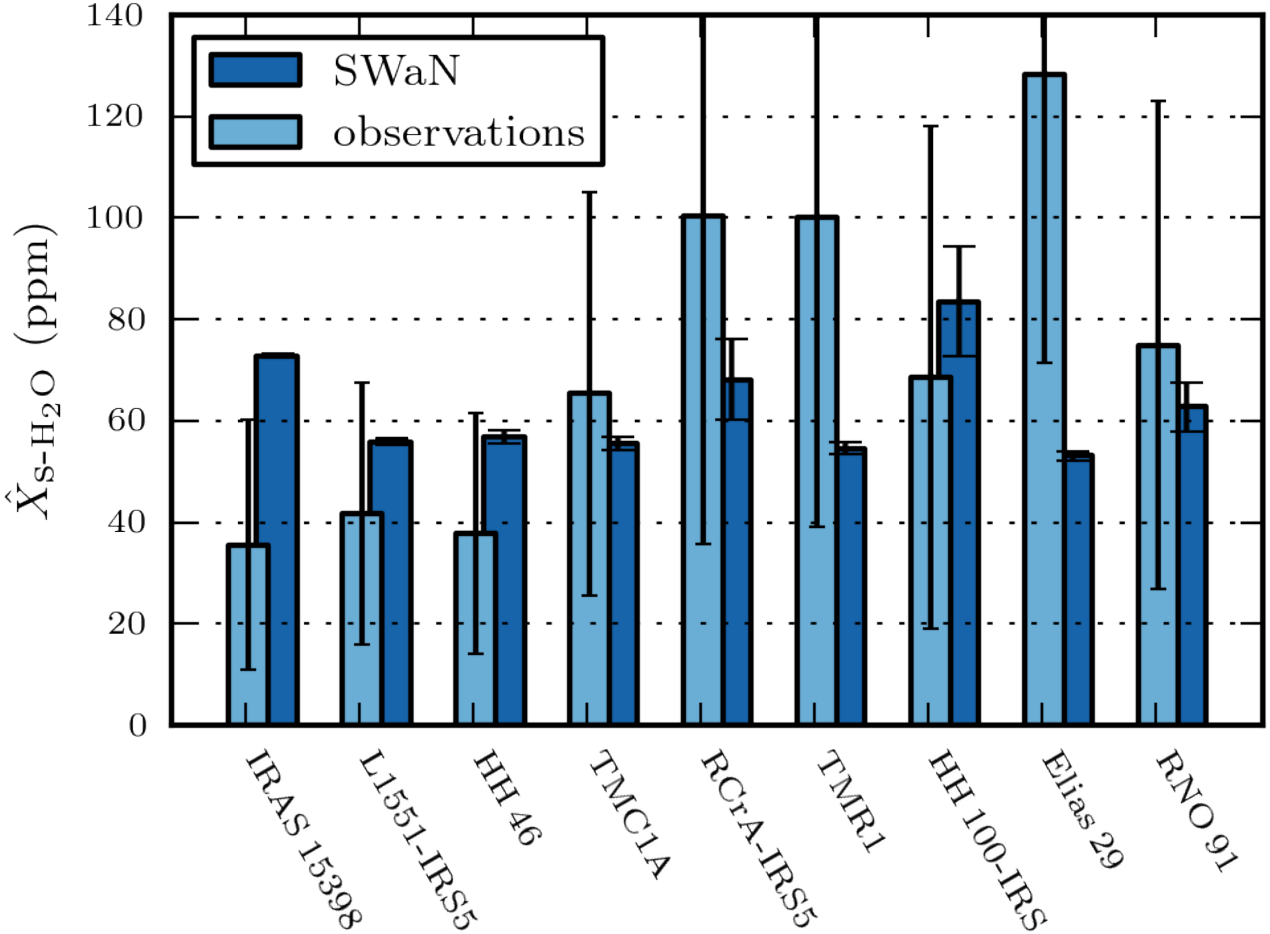
Schmalzl+, in prep.

WISH

WATER ICE

In contrast to the **water vapour**, the **water ice** abundances are rather insensitive to FUV field and/or time

$$X_{\mathrm{s-H_2O}} = (6.3 \pm 1.0)\ 10^{-5}$$



Recall:
Abundance of
volatile oxygen

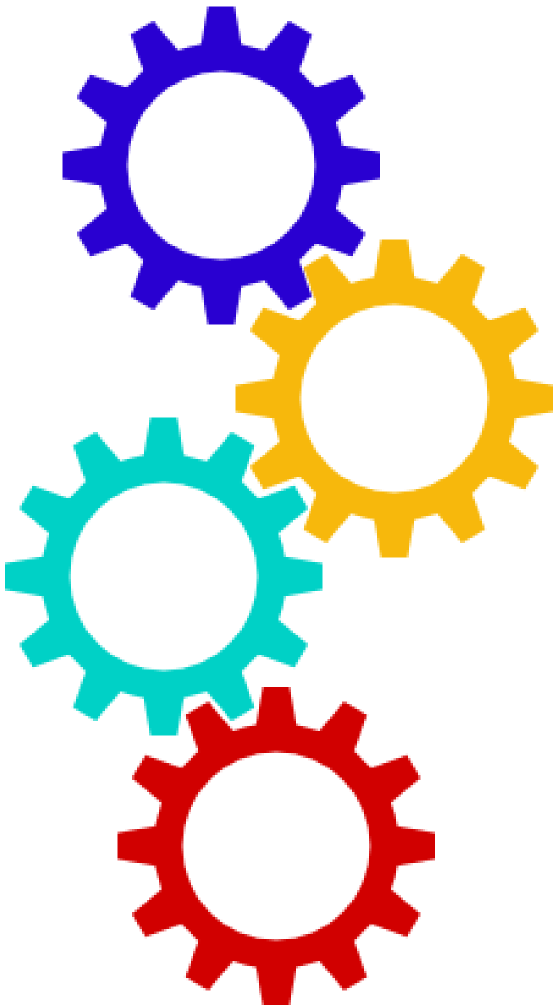
$$X_{\mathrm{O}} = 3.2\ 10^{-4}$$

Ice Column Densities from: **Zasowski+ (2009)**, ApJ...694..459; **Boogert+ (2008)**, ApJ...678..985
Temperature and Hydrogen Density Profiles from **Kristensen+ (2012)** A&A...542A...8

Schmalzl+, in prep.

WATER ICE

The **water ice column densities** can be reproduced if …



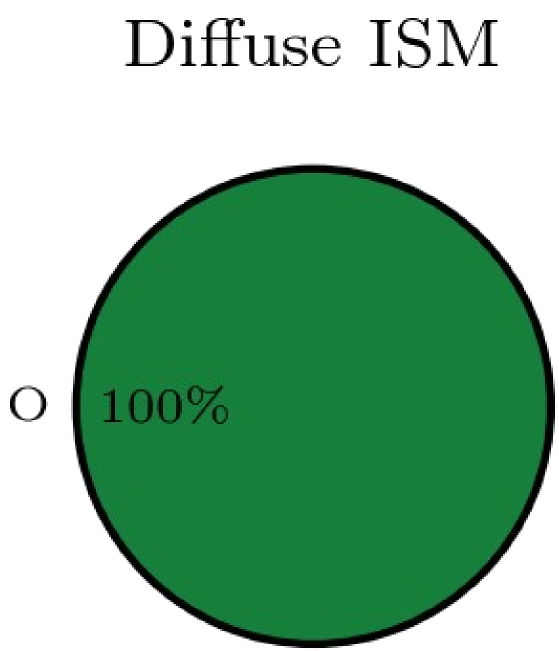
- … not more than ~25% of the **oxygen** is initially in the form of **water ice**
- … **oxygen freezeout** in regions T > 15 K is inhibited

Schmalzl+, in prep.

OXYGEN BUDGET

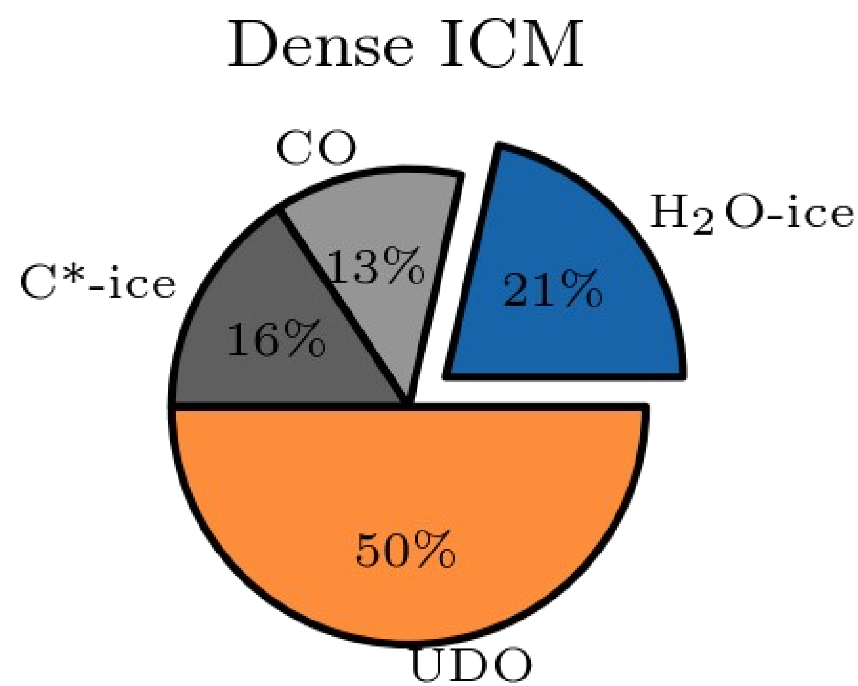
The **oxygen budget** in the dense intra-cloud medium (ICM) is apparently incomplete, with ~50% being in the form **Unidentified Depleted Oxygen (UDO)**

Whittet (2010), ApJ...710.1009



$$X_{\rm O} = 3.2\ 10^{-4}$$

Meyer+ (1998), ApJ...493..222

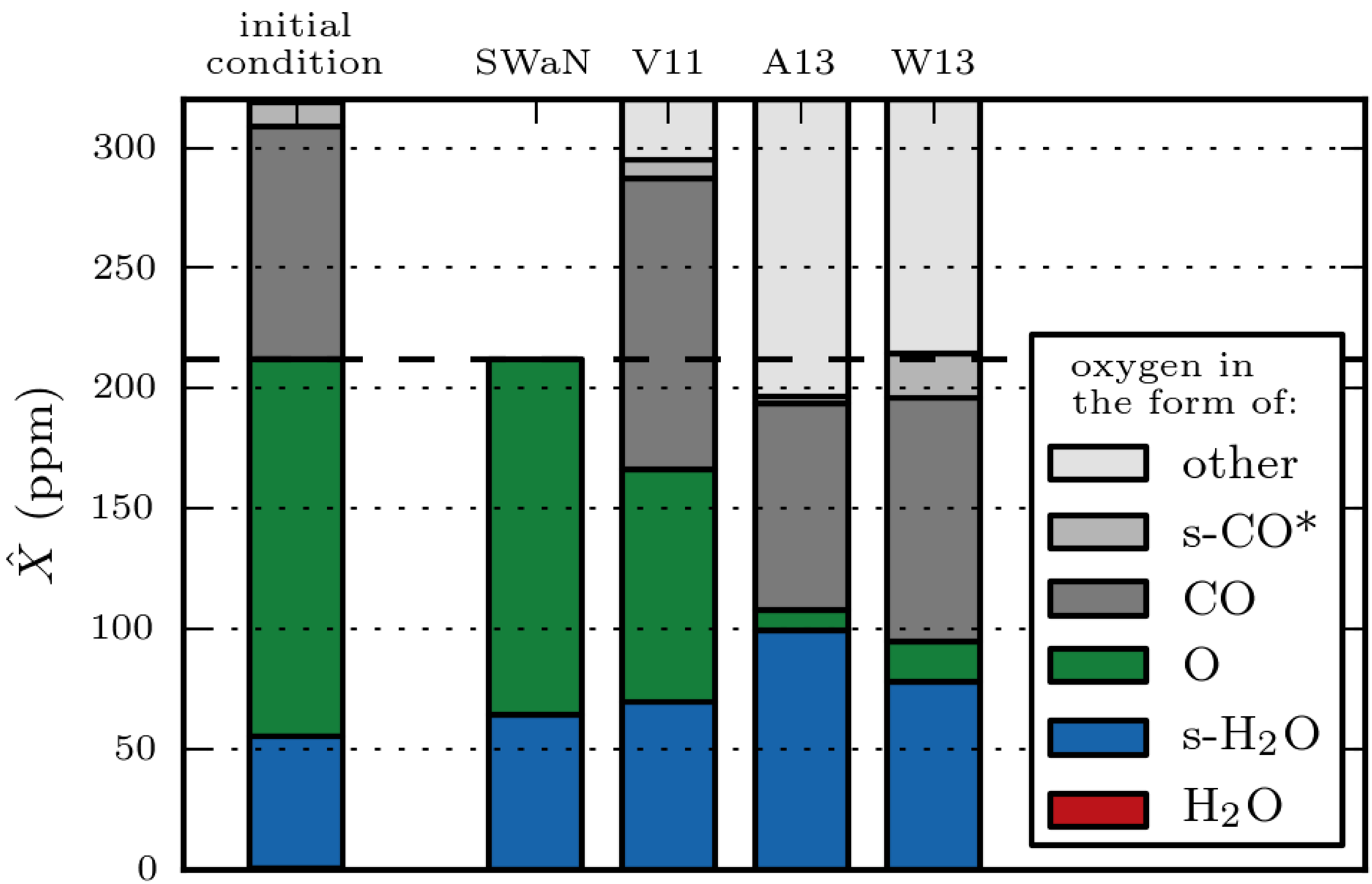


$$X_{\rm s-H_2O} = 0.68\ 10^{-4}$$

Whittet+ (2007), ApJ...655..332

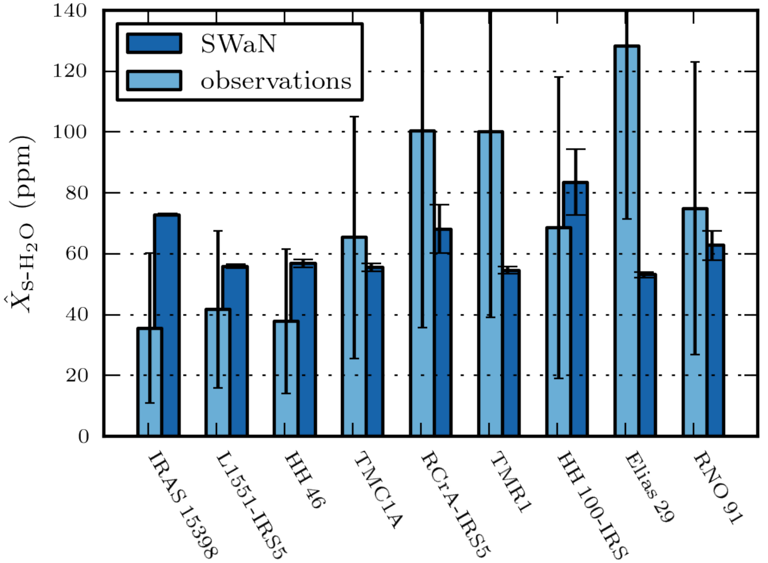
WHERE IS UDO?

From the **benchmarking of the chemical networks** we can identify where the **oxygen** went

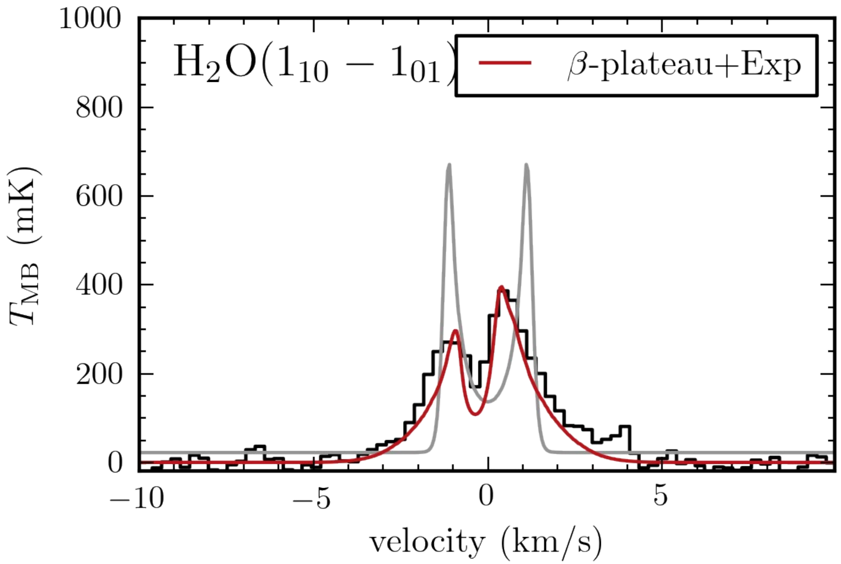


SUMMARY

- We understand why in protostellar cores **volatile oxygen** is not fully driven into **water ice**



- The **water gas/ice** ratio is changing along the line-of-sight, and depends on the **source structure & FUV field**



- We see that the **water vapour** emission profiles are an invaluable tracer for **FUV field** strengths (both CR-induced and ISRF)