# A Herschel/HIFI Legacy Survey of HF in the Galaxy:

## Diffuse Molecular Clouds at Small Scales

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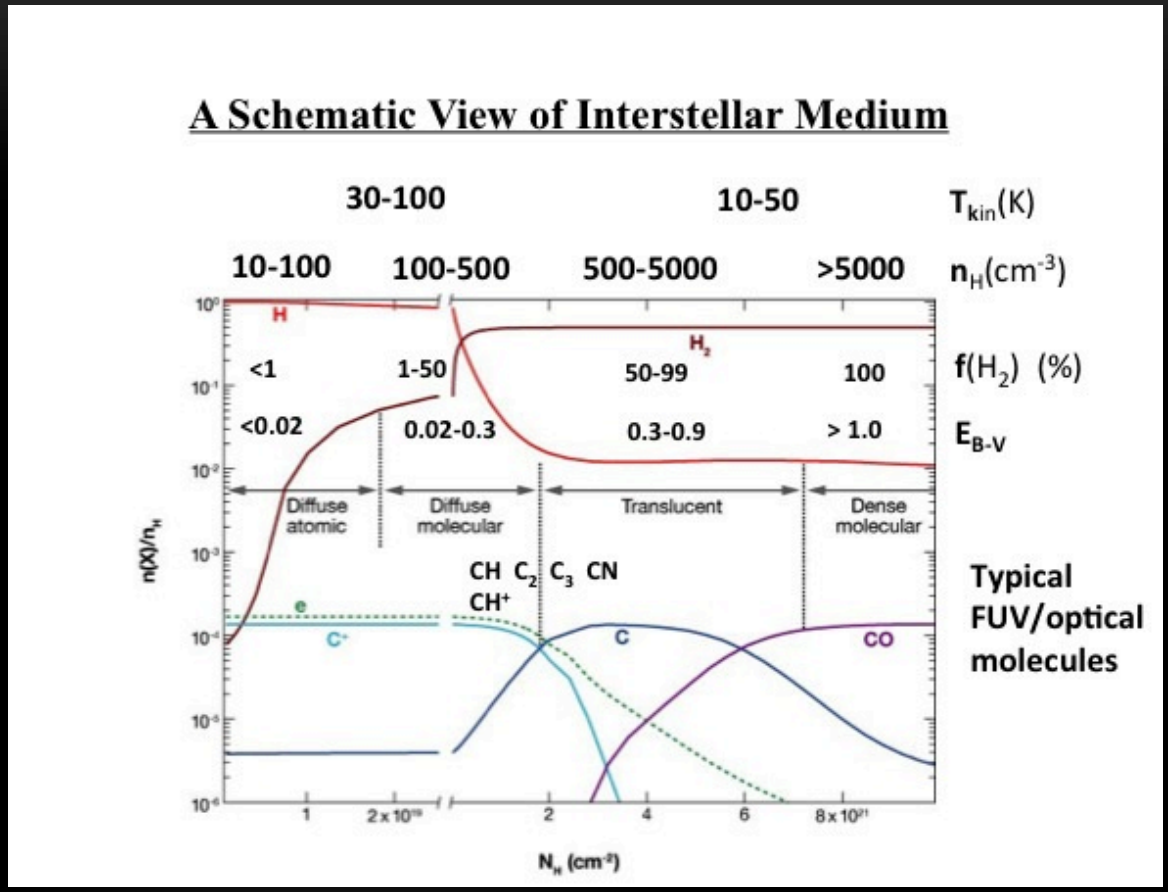
# Diffuse Molecular Clouds in a Nutshell

Traditionally observed in FUV/Optical range

BUT

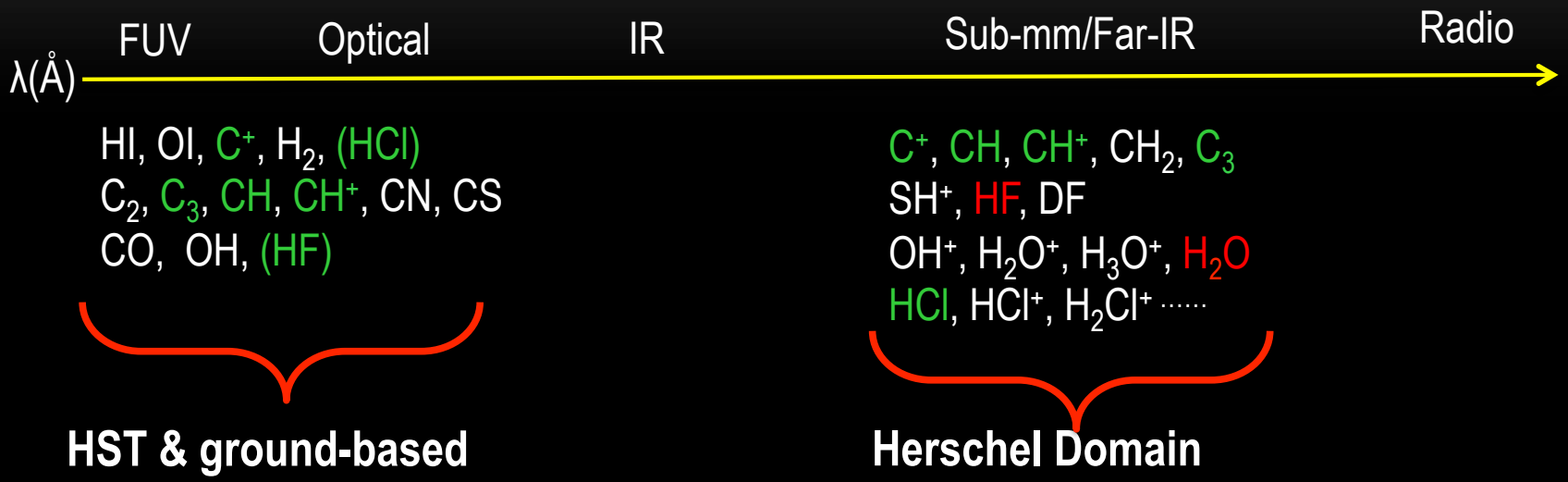
Dust scattering limits Galactic disk studies to:

- $N(H_2) < 8x10^{21}$ cm$^{-2}$
- $A_V < 3$ mag
- $R_{gal} < 2$ kpc




*Adapted from Snow & McCall (2006)*

# Diffuse Molecular Clouds in a Nutshell




**GTKP PRISMAS (PRobing the InterStellar Medium with Absorption line Studies) goal:**

Use sub-mm range to complement FUV/Optical studies and probe diffuse molecular clouds chemistry

- ✧ at larger Av
- ✧ at greater Galactic distances
- ✧ with a greater variety of (detectable) molecular tracers

# Diffuse Molecular Clouds in a Nutshell

One potential problem though:
In sub-mm we need surrogate tracer of $H_2$ to determine molecular abundances and probe chemical networks !

Traditionally, CH used to trace $H_2$

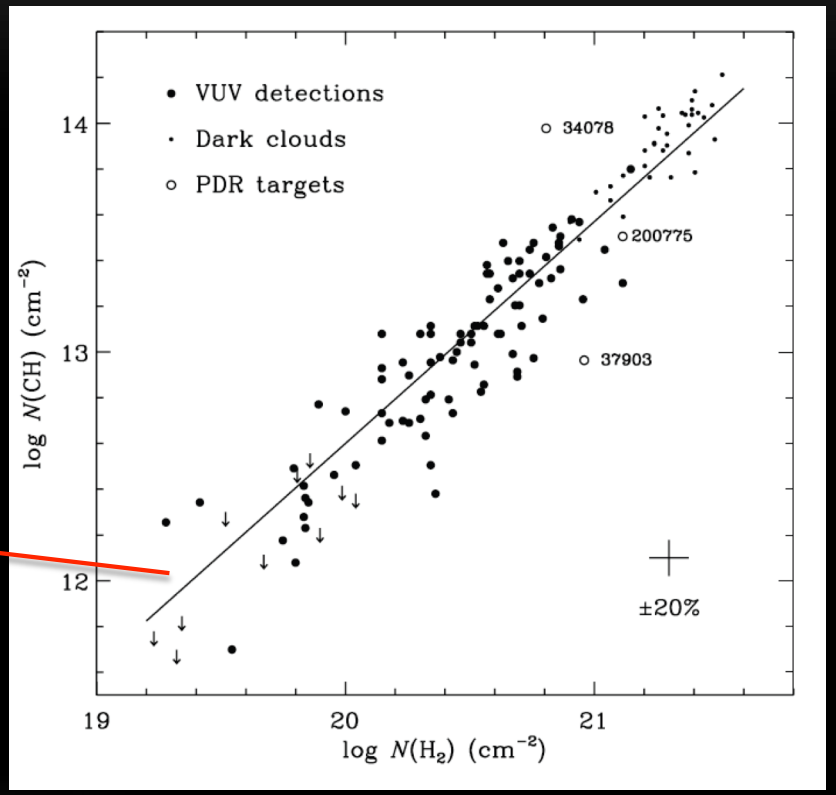
Sheffer et al. (2008) most recent results show:

$N(CH)/N(H_2)= 3.5 \times 10^{-8}$

BUT

Dispersion of factor 1.6 is real!

FUV/Optical




## Are there valuable alternatives to CH?

# PRISMAS: Is Hydrogen Fluoride (HF) an alternate tracer of $H_2$ ?

F reacts exothermically with $H_2$ thanks to reaction:

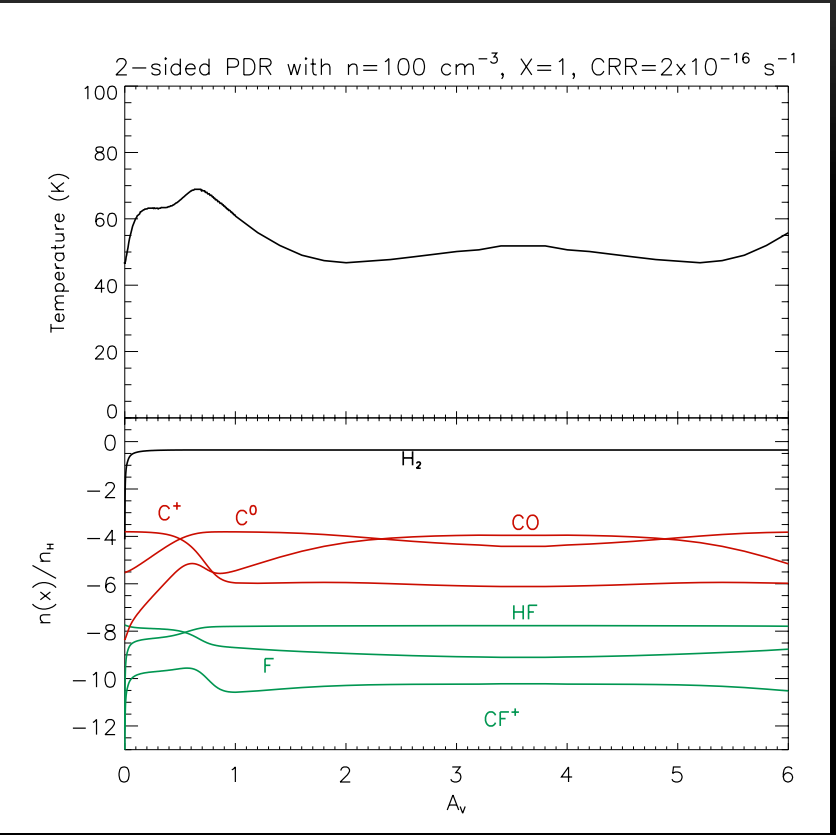
$F + H_2 \longrightarrow HF + H + 1.4eV$

Predictions:

1. HF traces $H_2$ from onset of $H_2$ formation
2. Since tau(HF) > tau(CH), HF expected to trace diffuse clouds of lower $A_V$ than CH
3. HF abundance varies with cloud depth with:

$1.0x10^{-8} \leq N(HF)/N(H_2) \leq 2 \times [F/H]_{gas} = (3.6 \pm 1.6)x10^{-8}$

wherever freeze-out is not significant yet

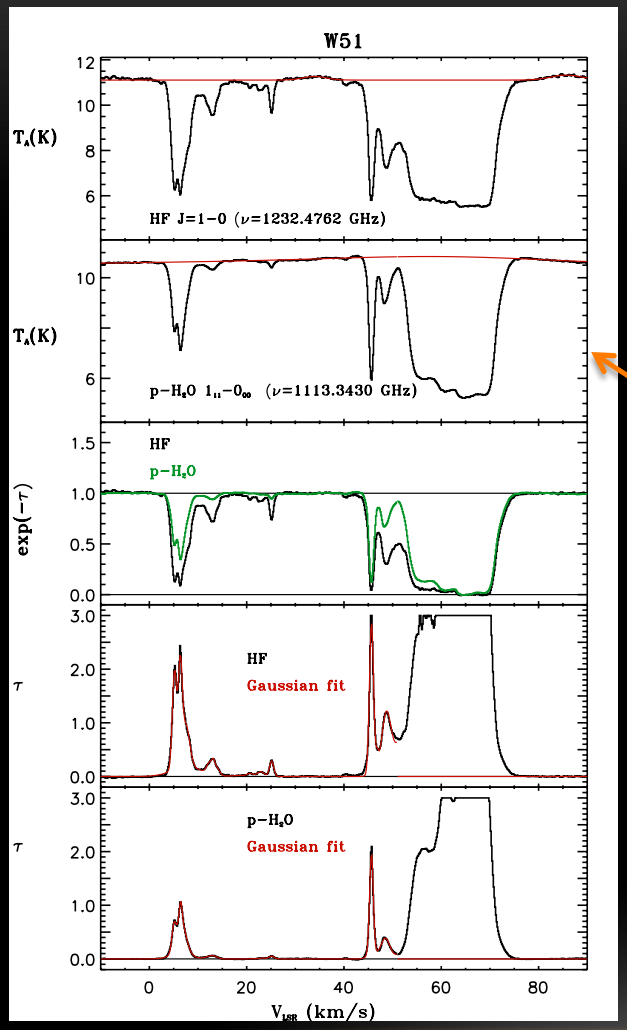


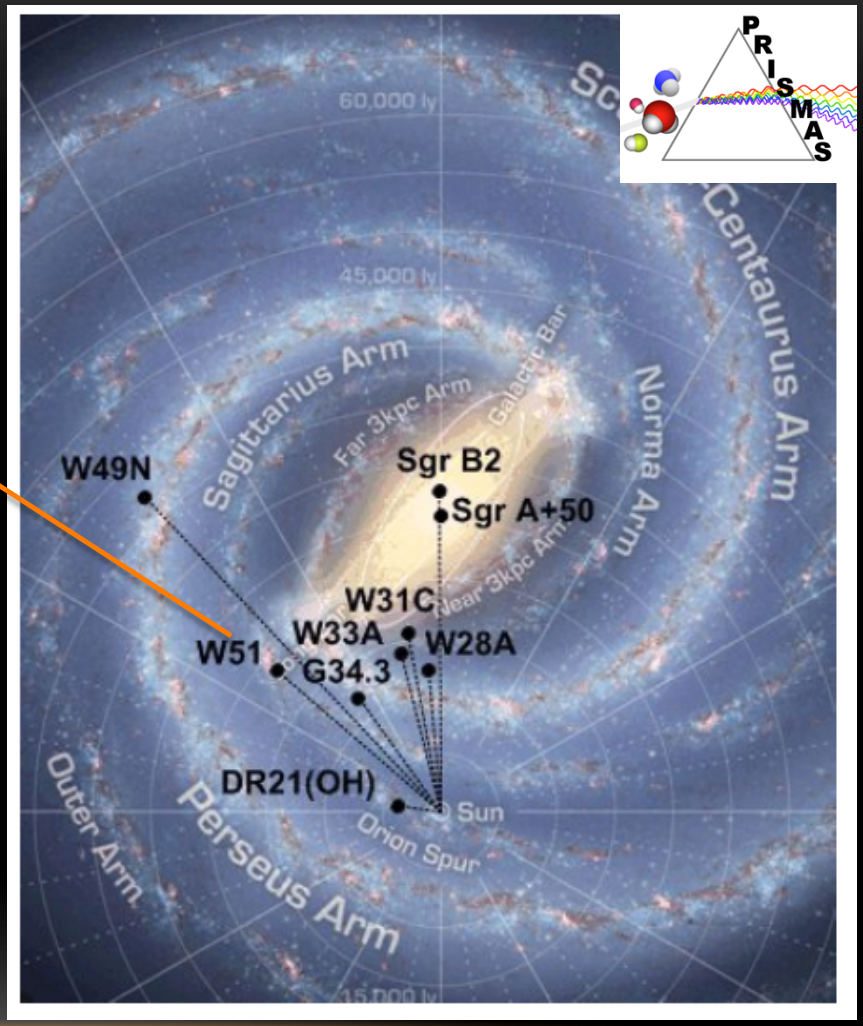

*Adapted from Neufeld & Wolfire (2009)*

## Do Herschel/HIFI observations confirm those predictions?

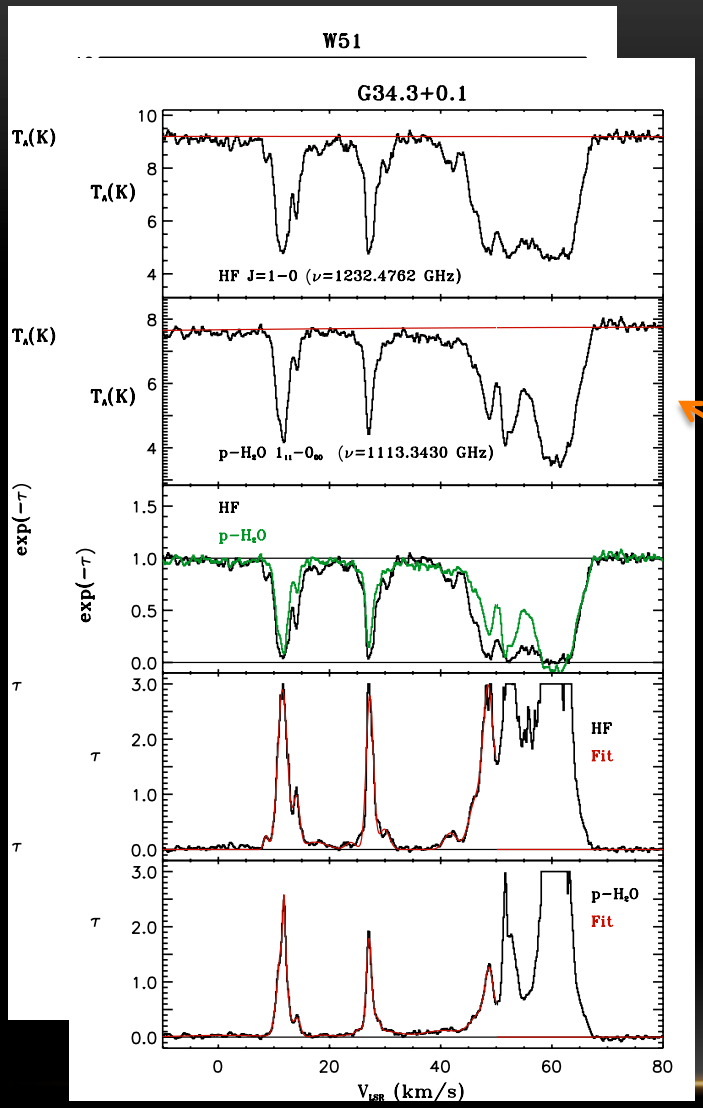
# Hydrogen Fluoride (HF) and Water ($H_2O$) in Galaxy with Herschel/HIFI

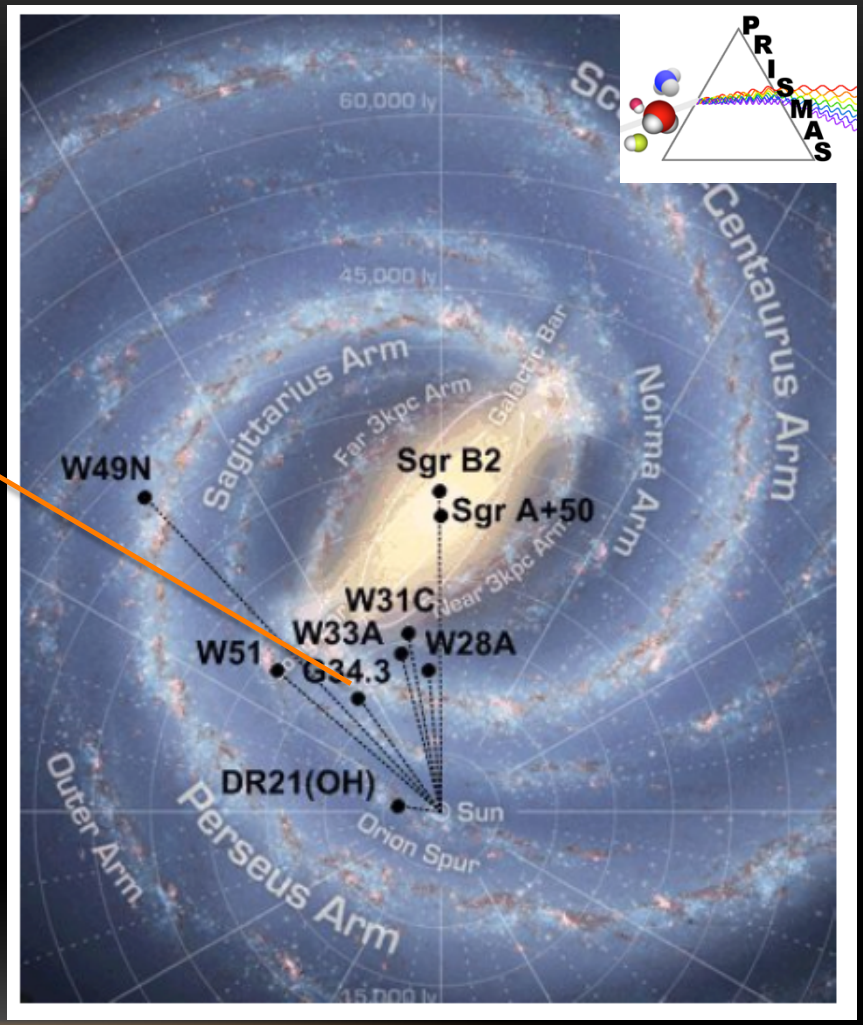
Observations combining PRISMAS, WISH and OT2 data



# Hydrogen Fluoride (HF) and Water ($H_2O$) with Herschel/HIFI



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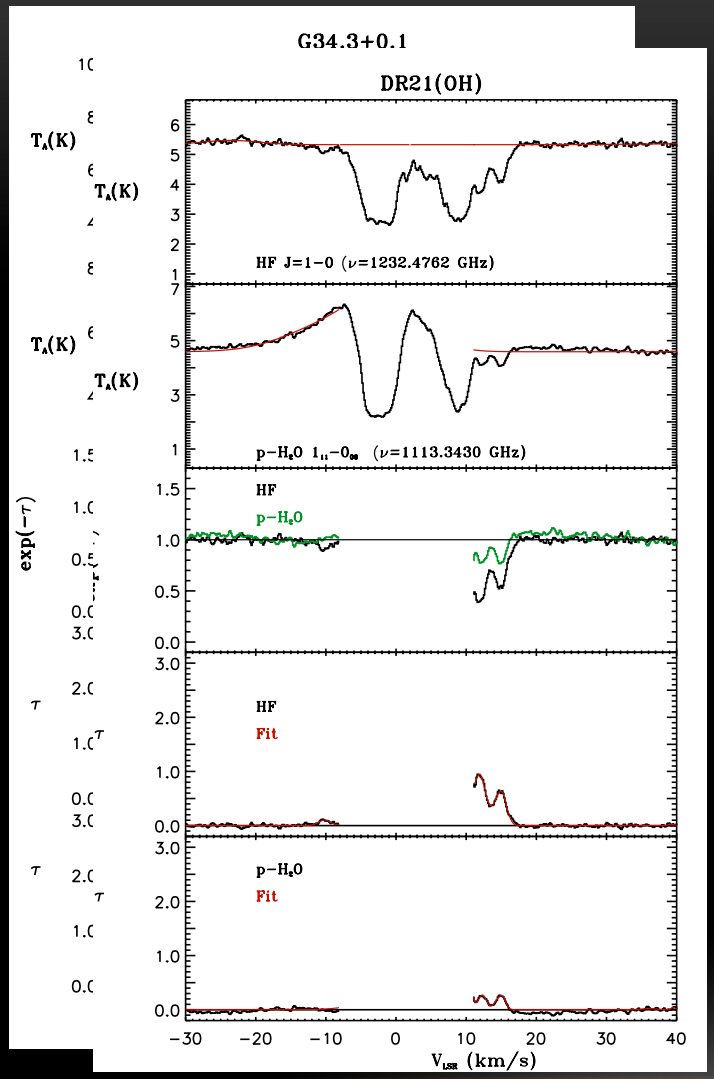


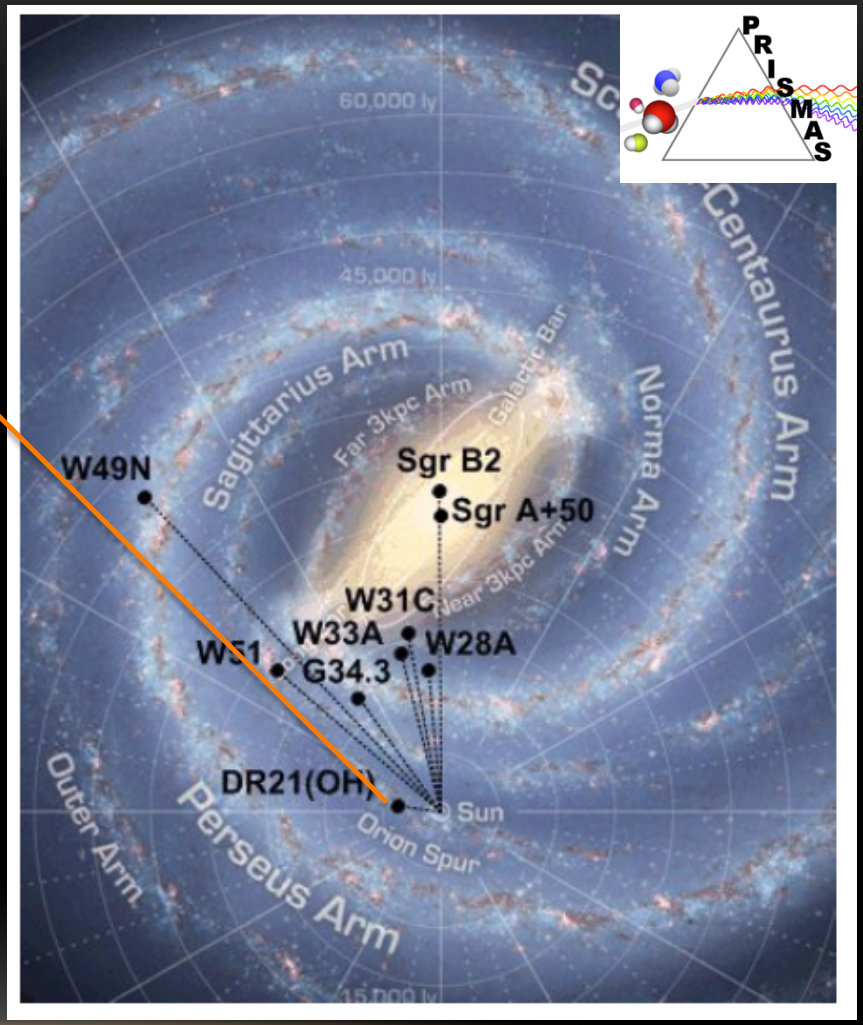

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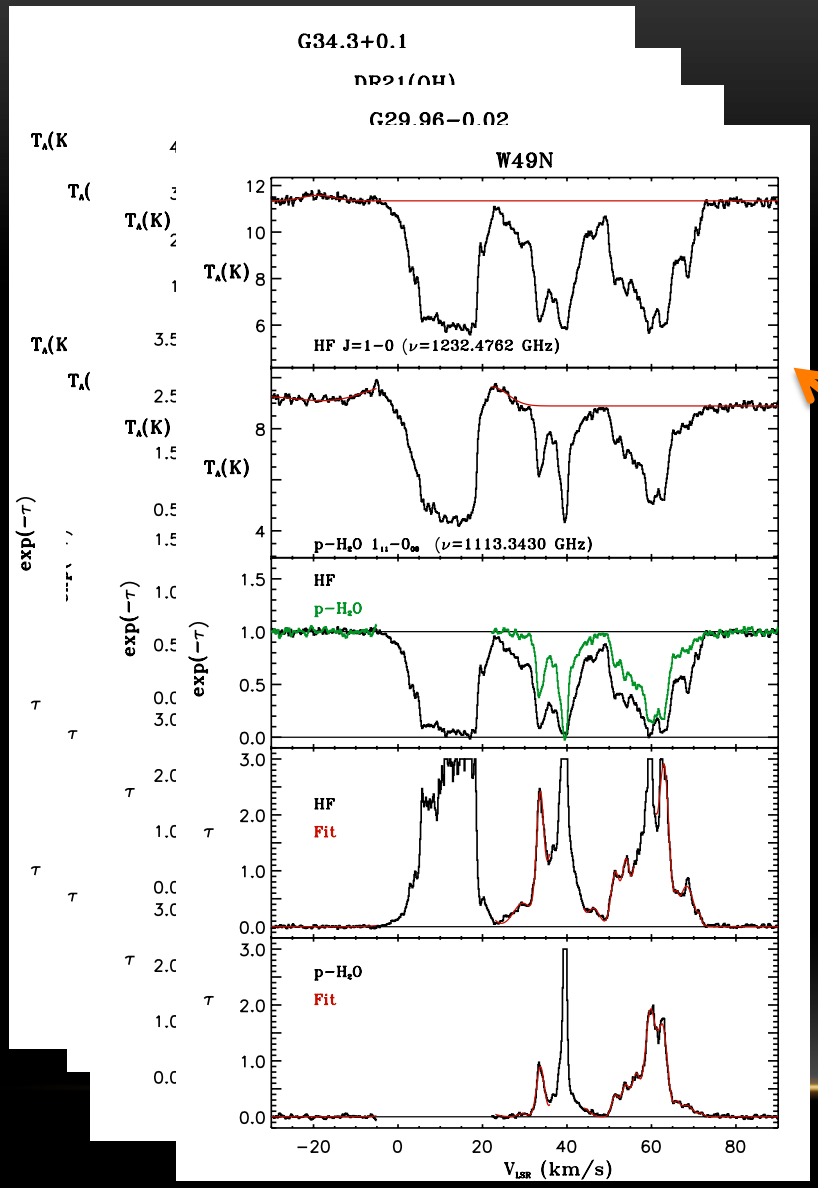


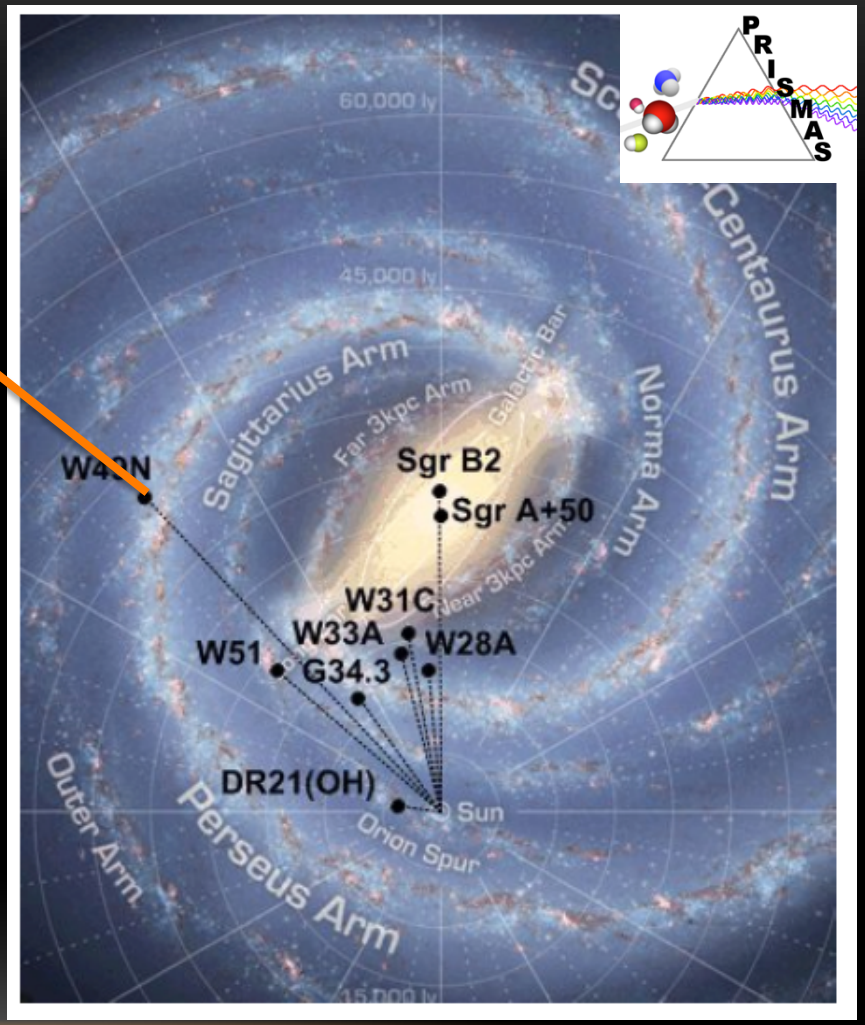

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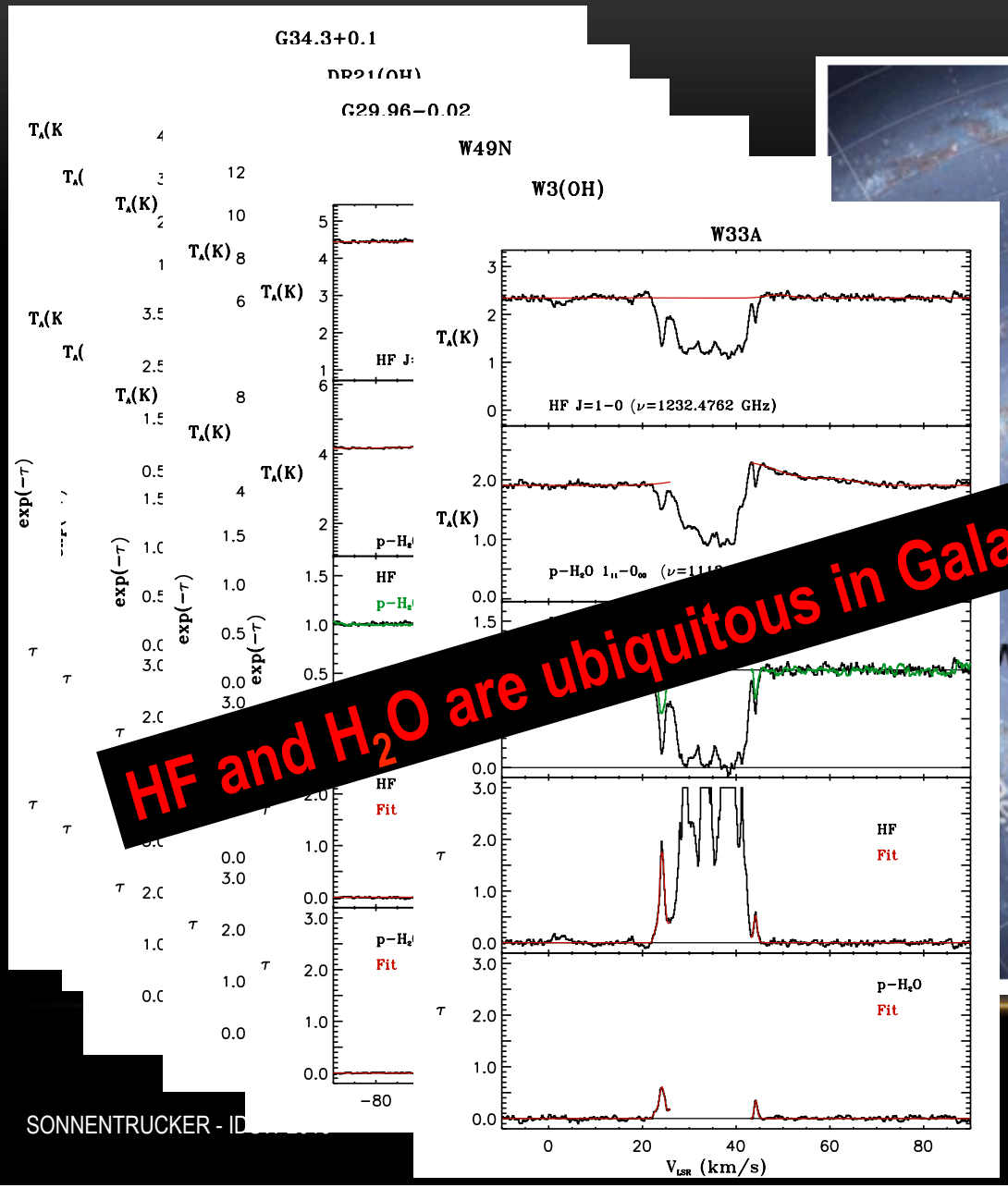
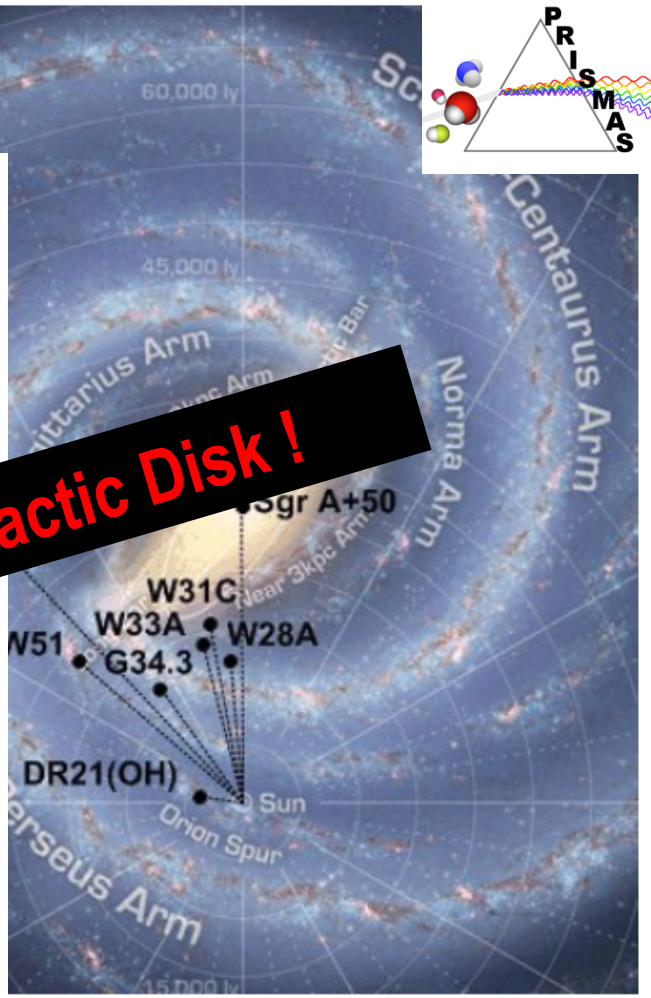






**HF and $H_2O$ are ubiquitous in Galactic Disk !**

# PRISMAS: Is Hydrogen Fluoride (HF) an alternate tracer of $H_2$ ?

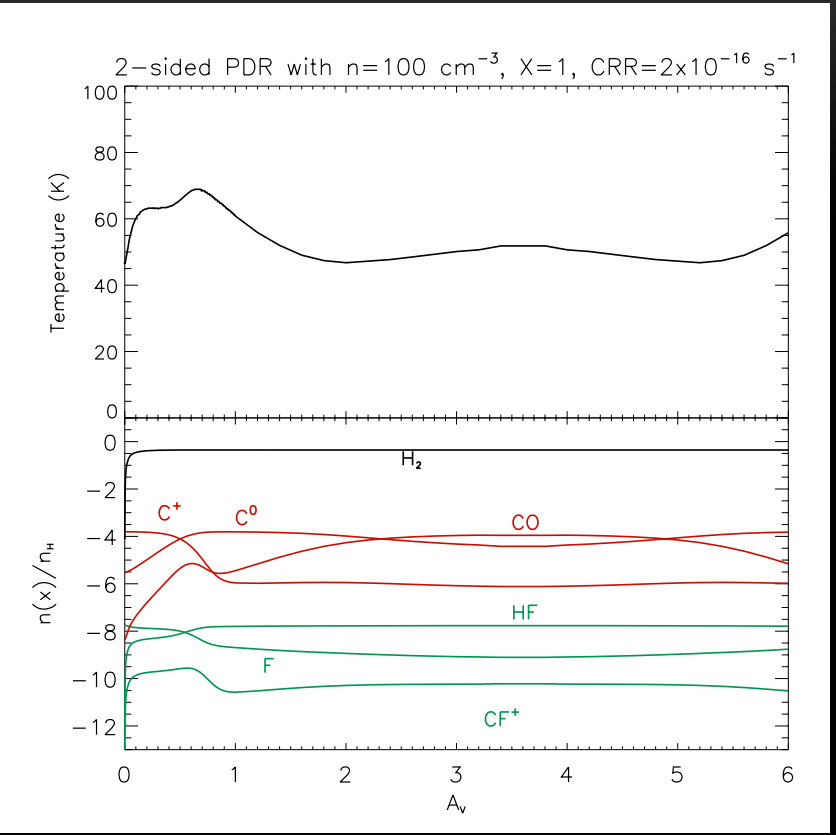
**Predictions:**

1. HF traces $H_2$ from onset of $H_2$ formation ✔

HF ubiquitous in Galactic disk which validates chemical pathways

HF is measured in clouds of molecular fractions as low as 5% (*Neufeld et al. 2010*)

HF and $H_2O$ trace each other very closely!




*Adapted from Neufeld & Wolfire (2009)*

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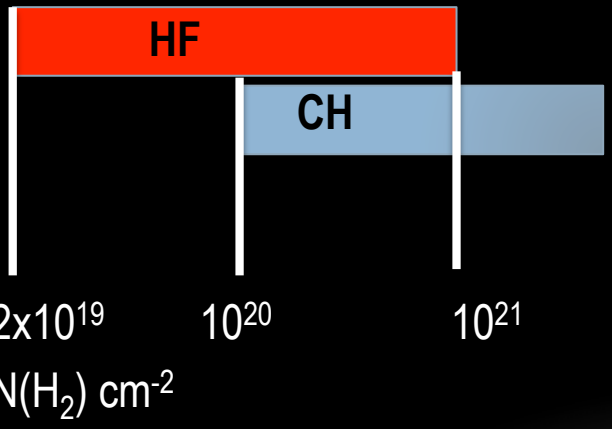
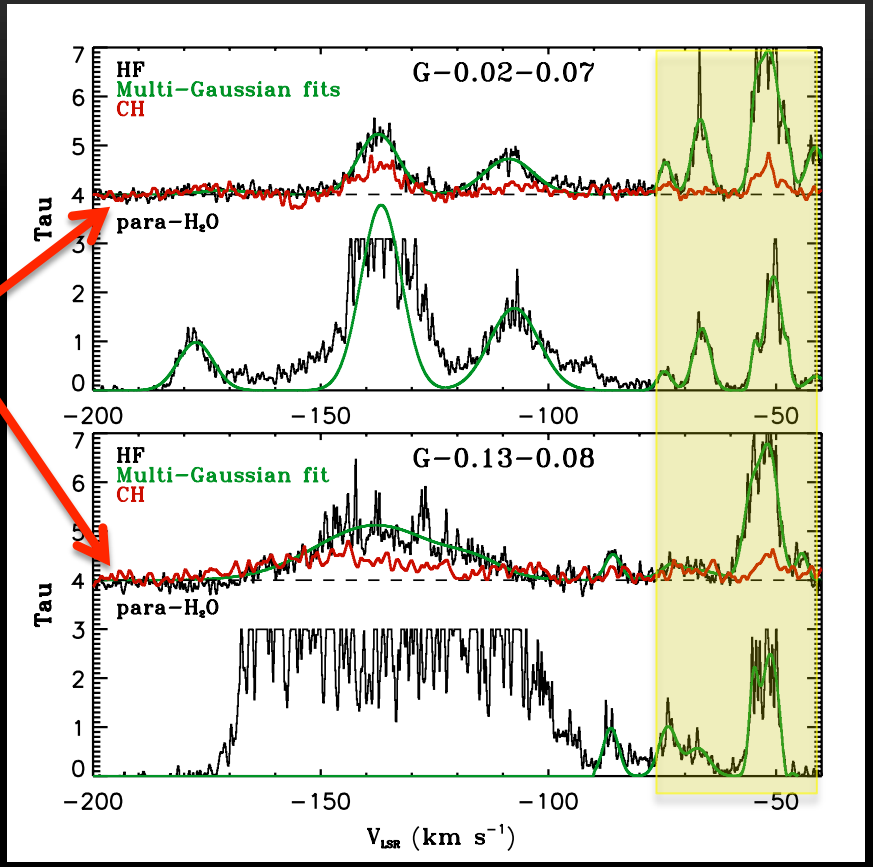
**Predictions:**

2. Since tau(HF) > tau(CH):
HF expected to trace diffuse clouds of lower $A_V$ and lower $H_2$ than CH




✔

CH with HIFI




*Sonnentrucker et al. (2013)*

**HF and CH are complementary tracers of $H_2$!**

# PRISMAS: Is Hydrogen Fluoride (HF) an alternate tracer of $H_2$ ?

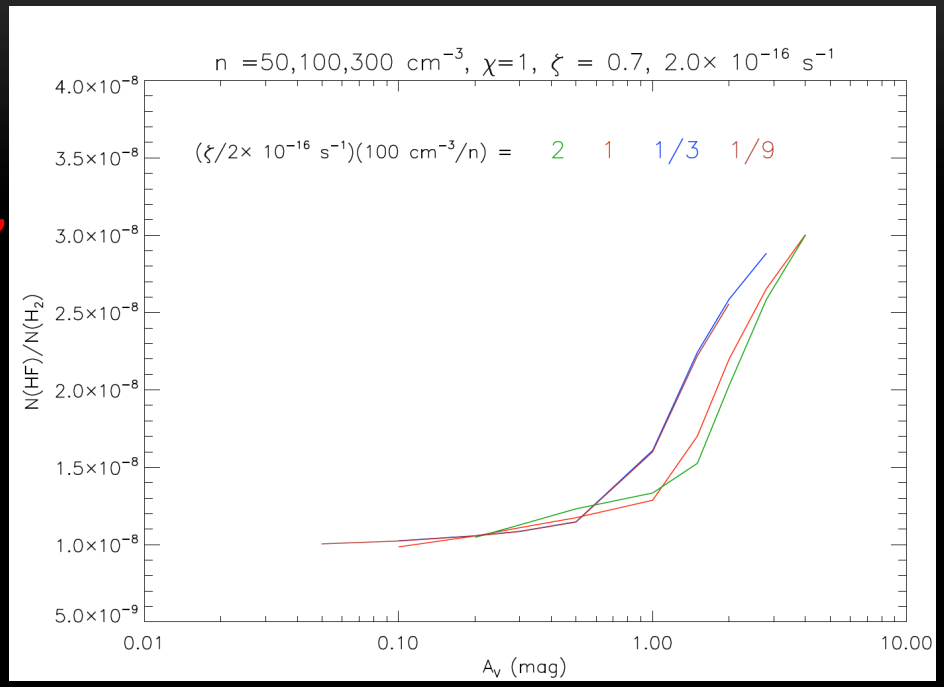
## Predictions:

3. HF abundance varies with cloud depth with:

$1.0 \times 10^{-8} \leq N(HF)/N(H_2) \leq (3.6 \pm 1.6) \times 10^{-8}$

$= 2 \times [F/H]_{gas}$

without freeze-out onto grains




*Sonnentrucker et al. (2013, in prep.)*

## HF measurements so far:

**$1.0 \times 10^{-8} < N(HF)/N(H_2) < 2.5 \times 10^{-8}$**

*(e.g. Sonnentrucker et al. (2010, 2012, 2013 in prep; Indriolo et al. (2013); Emprechtinger et al. 2012; Monje et al. 2011; Neufeld et al. 2010)*

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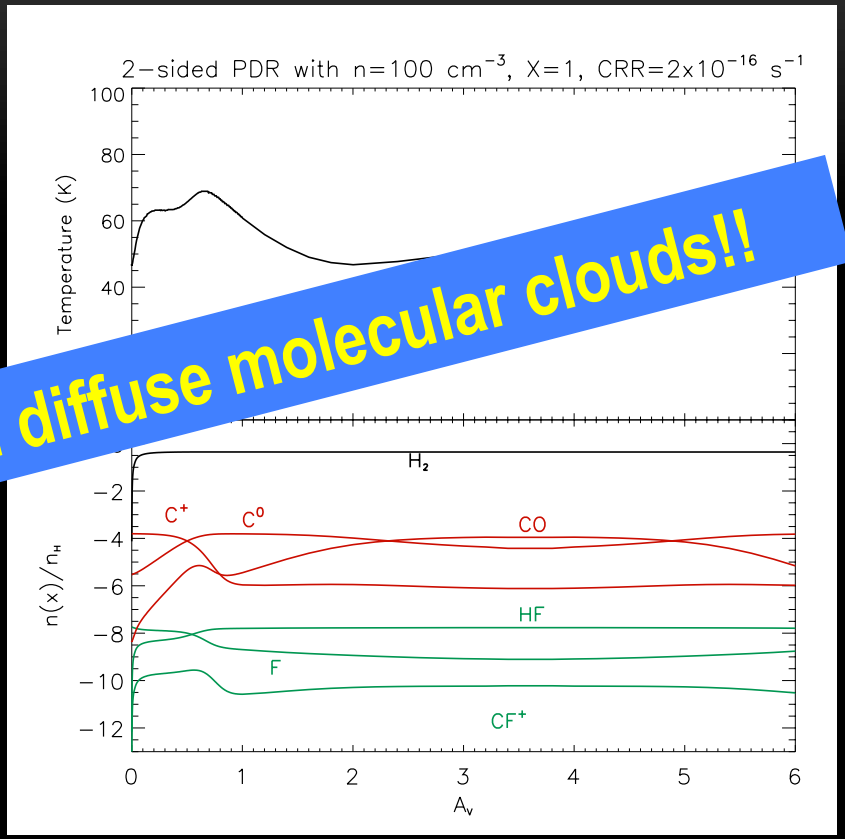
wherever freeze-out is not significant yet

**HF is very sensitive tracer of $H_2$ in diffuse molecular clouds!!**



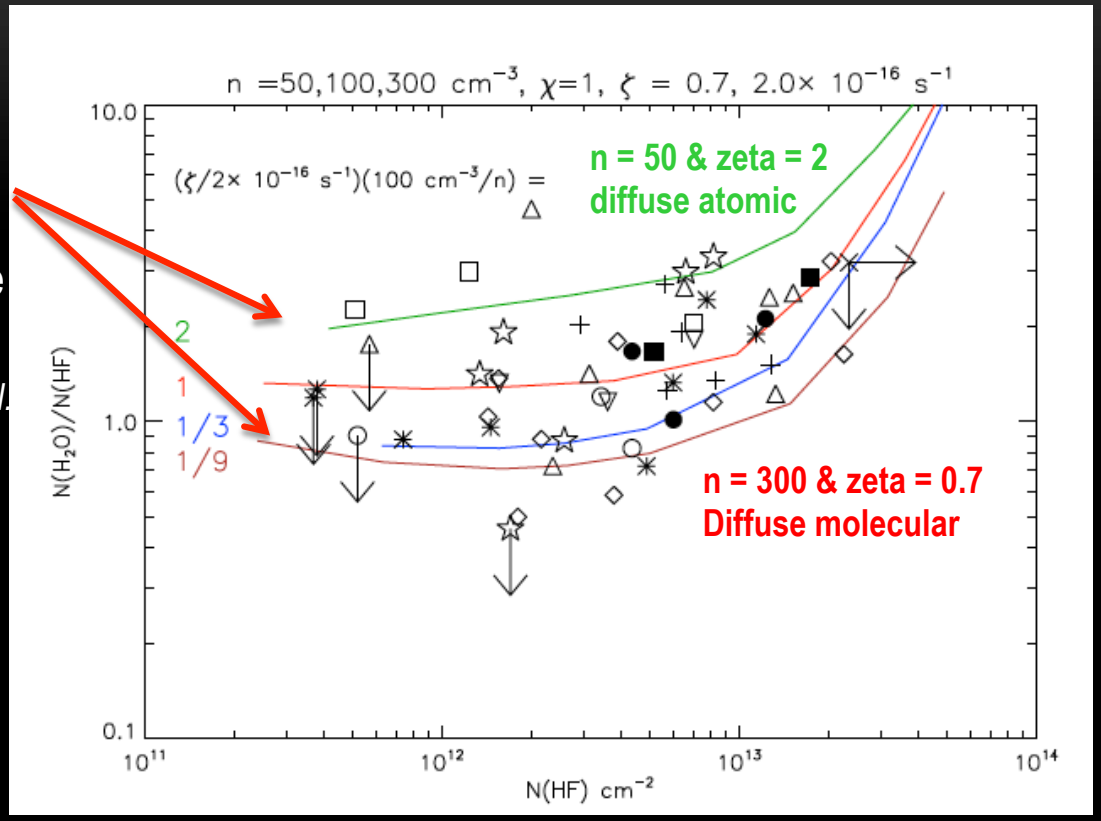

*Adapted from Neufeld & Wolfire (2009)*

## Do Herschel/HIFI observations confirm those predictions?

# $H_2O$ abundance distribution in probed Galactic Disk Diffuse Clouds

Various Model predictions for $H_2O$ abundance

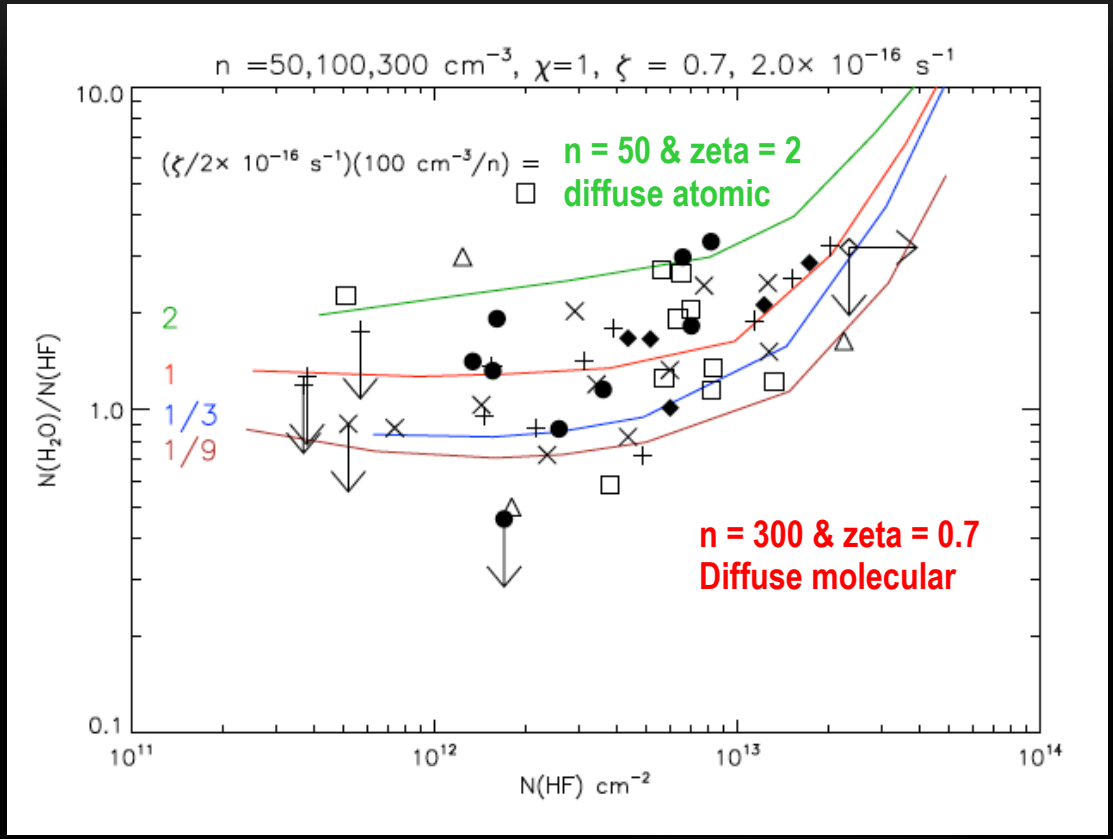
(*Sonnentrucker et al. 2013, in prep.*)




Sources:
+ : W49N
* : W51
◇ : G29.6
△ : G34.3
□ : W33A
X : W31C
O : DR21(OH)
★ : W3(OH)
▽ : W3 IRS5
▢ : G-0.02
● : G-0.13

- All measurements fitted by models with 0.7 < zeta < 2x10$^{-16}$ s$^{-1}$ and 50 < $n_H$ < 300 cm$^{-3}$
- All sight lines contain multiple foreground clouds with range of physical conditions
- $H_2O$ abundance variation driven mostly by cosmic-ray ionization variations

# $H_2O$ abundance distribution with distance in the Galaxy




- ✱ r < 4kpc
- ◇ 4 < r < 5 kpc
- △ 5 < r < 6 kpc
- □ 6 < r < 7 kpc
- X 7 < r <7 kpc
- \+ r > 8kpc

**No clear dependence in Water abundance with Galacto-centric distance**

# Herschel/HIFI Survey of HF and $H_2O$ the Galaxy Diffuse ISM: Conclusions

Herschel/HIFI Survey of HF established that:

- ✧ the measured HF abundance relative to $H_2$ is consistent with chemical model predictions
- ✧ HF provides a sensitive probe of clouds of small $H_2$ column density
- ✧ HF is a valuable tracer of $H_2$ over a large range of $H_2$ column densities

Herschel/HIFI Survey showed a striking distribution similarity between $H_2O$ and HF !

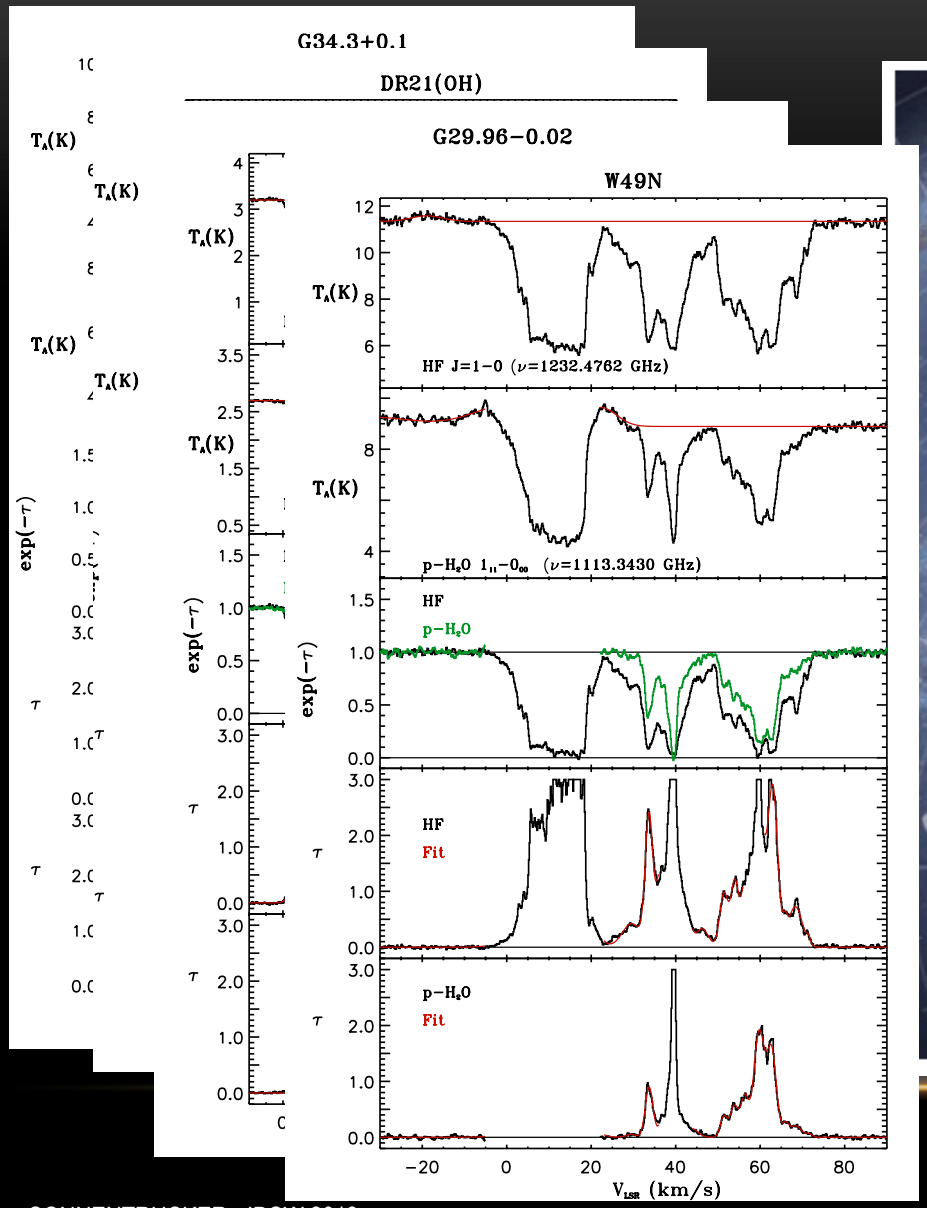
- ✧ $H_2O$ abundance relative to HF has no dependence with Galacto-centric distance
- ✧ $H_2O$ abundance relative to HF is mostly driven by cosmic-ray ionization
- ✧ allowed us to constrain physical conditions in probed diffuse Galactic Disk ISM

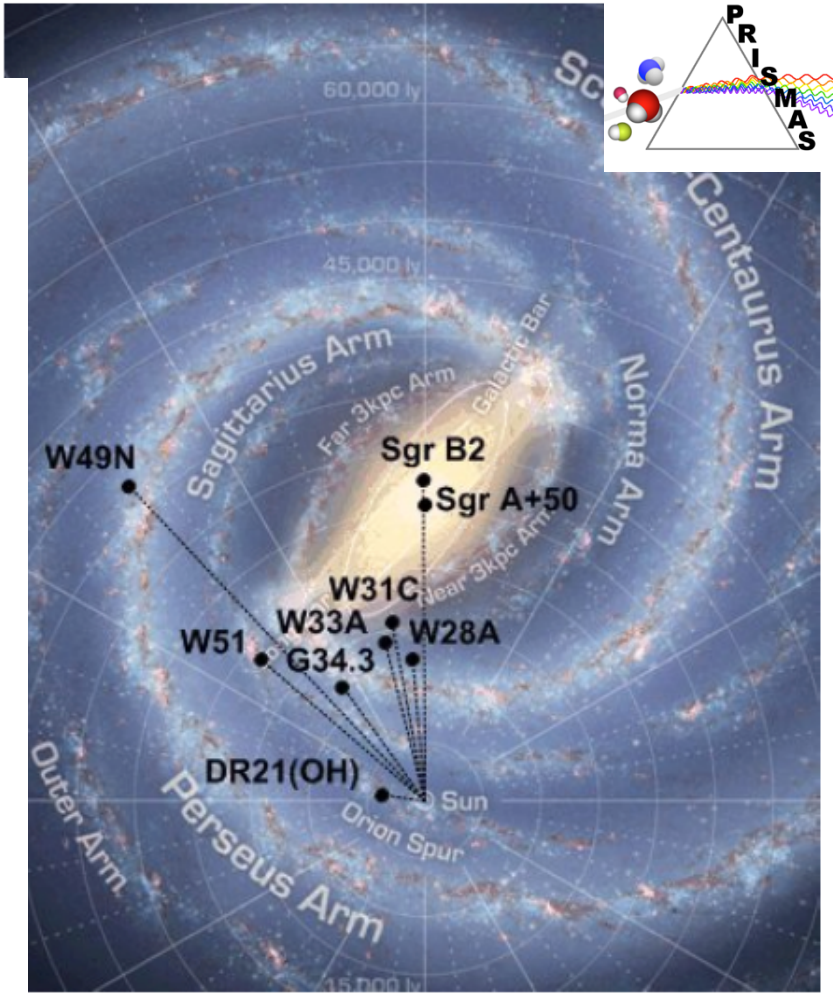
Herschel/HIFI Observations will serve as templates for studies of the ISM at high redshift now possible from the ground with ALMA

NB: HF already observed at z=2.56 using CSO (cloverleaf quasar: Monje et al. 2012)

# ADDITIONAL MATERIAL

# Hydrogen Fluoride (HF) and Water ($H_2O$) with Herschel/HIFI



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