Diffuse Molecular Clouds in a Nutshell

Traditionally observed in FUV/Optical range

BUT

Dust scattering limits Galactic disk studies to:

- $N(H_2) < 8 \times 10^{21} \text{ cm}^{-2}$
- $A_V < 3 \text{ mag}$
- $R_{\text{gal}} < 2 \text{ kpc}$

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
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:

\[ \frac{N(\text{CH})}{N(\text{H}_2)} = 3.5 \times 10^{-8} \]

BUT

Dispersion of factor 1.6 is real!

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:

\[
\text{F} + \text{H}_2 \rightarrow \text{HF} + \text{H} + 1.4\text{eV}
\]

Predictions:

1. HF traces H$_2$ from onset of H$_2$ formation

2. Since \( \tau(\text{HF}) > \tau(\text{CH}) \), HF expected to trace diffuse clouds of lower A$_V$ than CH

3. HF abundance varies with cloud depth with:
   \[
   1.0 \times 10^{-8} \leq \frac{N(\text{HF})}{N(\text{H}_2)} \leq 2 \times [\text{F/H}]_{\text{gas}} = (3.6 \pm 1.6) \times 10^{-8}
   \]
   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$_2$O) in Galaxy with Herschel/HIFI Observations combining PRISMAS, WISH and OT2 data
Hydrogen Fluoride (HF) and Water ($H_2O$) with Herschel/HIFI
Hydrogen Fluoride (HF) and Water (H$_2$O) with Herschel/HIFI
Hydrogen Fluoride (HF) and Water (H$_2$O) with Herschel/HIFI
Hydrogen Fluoride (HF) and Water (H$_2$O) 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$_2$O trace each other very closely!

Adapted from *Neufeld & Wolfire (2009)*
PRISMAS: Is Hydrogen Fluoride (HF) an alternate tracer of $\text{H}_2$?

Predictions:

2. Since $\tau(\text{HF}) > \tau(\text{CH})$: HF expected to trace diffuse clouds of lower $A_V$ and lower $\text{H}_2$ than CH

HF and CH are complementary tracers of $\text{H}_2$!
PRISMAS: Is Hydrogen Fluoride (HF) an alternate tracer of $H_2$?

Predictions:

3. HF abundance varies with cloud depth with:
   
   $1.0 \times 10^{-8} \leq \frac{N(\text{HF})}{N(H_2)} \leq (3.6 \pm 1.6) \times 10^{-8}$
   
   $= 2 \times [F/H]_{\text{gas}}$
   
   without freeze-out onto grains

HF measurements so far:

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

(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)
PRISMAS: Is Hydrogen Fluoride (HF) an alternate tracer of H$_2$?

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$$F + H_2 \rightarrow HF + H + 1.4\text{eV}$$

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   wherever freeze-out is not significant yet

Do Herschel/HIFI observations confirm those predictions?

Adapted from Neufeld & Wolfire (2009)
H$_2$O abundance distribution in probed Galactic Disk Diffuse Clouds

Various Model predictions for H$_2$O abundance

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

- All measurements fitted by models with $0.7 < \zeta < 2 \times 10^{-16}$ s$^{-1}$ and $50 < n_H < 300$ cm$^{-3}$
- All sight lines contain multiple foreground clouds with range of physical conditions
- H$_2$O abundance variation driven mostly by cosmic-ray ionization variations
H$_2$O abundance distribution with distance in the Galaxy

No clear dependence in Water abundance with Galacto-centric distance
Herschel/HIFI Survey of HF and H$_2$O 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$_2$O and HF!

✧ H$_2$O abundance relative to HF has no dependence with Galacto-centric distance
✧ H$_2$O 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$_2$O) with Herschel/HIFI
Hydrogen Fluoride (HF) and Water (H$_2$O) with Herschel/HIFI