Chemical probes of the turbulent diffuse ISM

B. Godard, E. Falgarone, G. Pineau des Forêts, P. Lesaffre,
V. Valdivia, M. Gerin, and P. Hennebelle

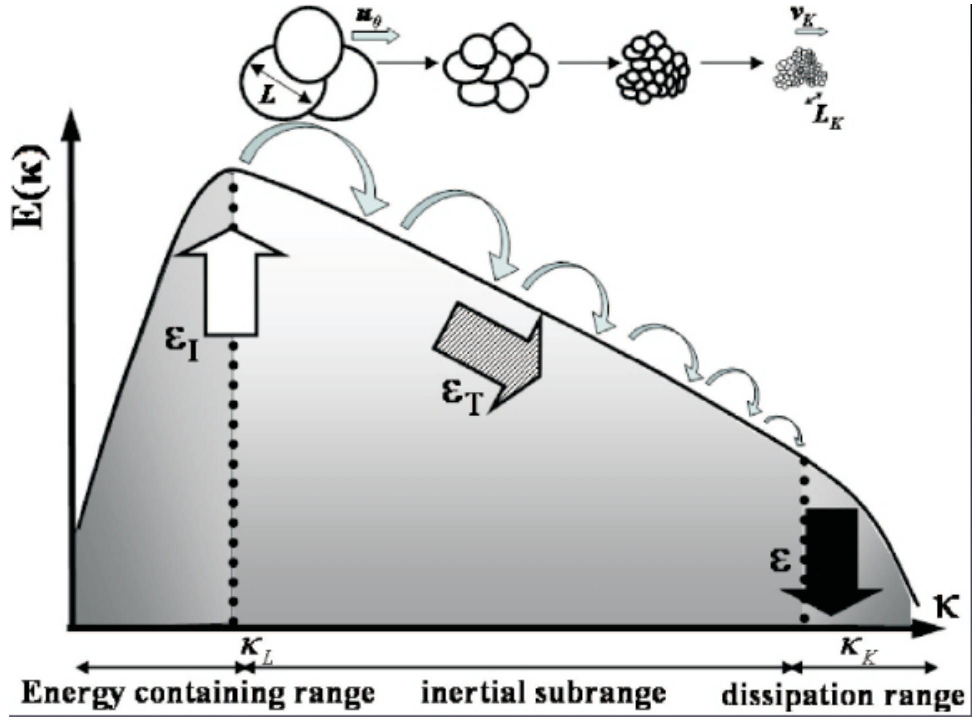
The hydride toolbox, Paris, 2016

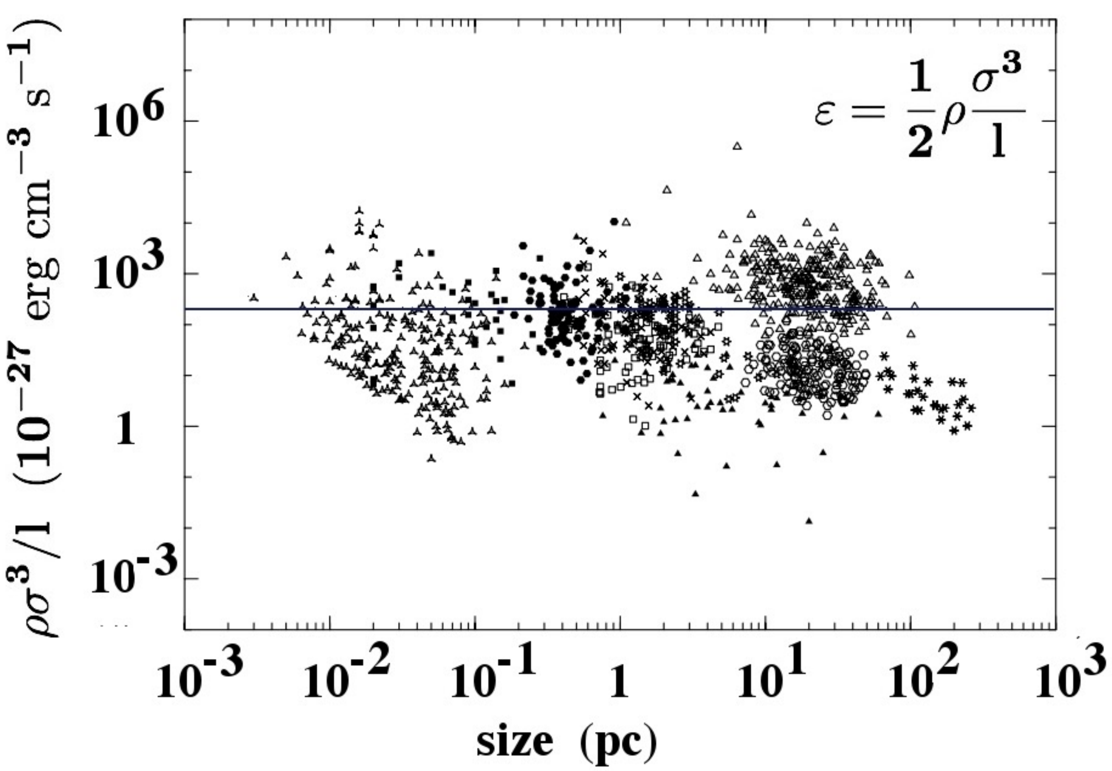
1. Overview of turbulence and its unknowns
2. Tracers of turbulence and deduction of its properties in the framework of the TDR model
3. Limitations of 1D models and future prospects

Turbulent cascade

- advection force $\mathbf{u} \cdot \nabla \mathbf{u}$
- dissipation forces
  - ✓ friction $\nu \nabla^2 \mathbf{u}$
  - ✓ compression $\nu \nabla [\nabla \cdot \mathbf{u}]$
  - ✓ ion-neutral diff. $\gamma_{in}(\mathbf{u}_i - \mathbf{u}_n)$
  - ✓ magnetic diff. $\mu \nabla^2 \mathbf{b}$
- transfer rate

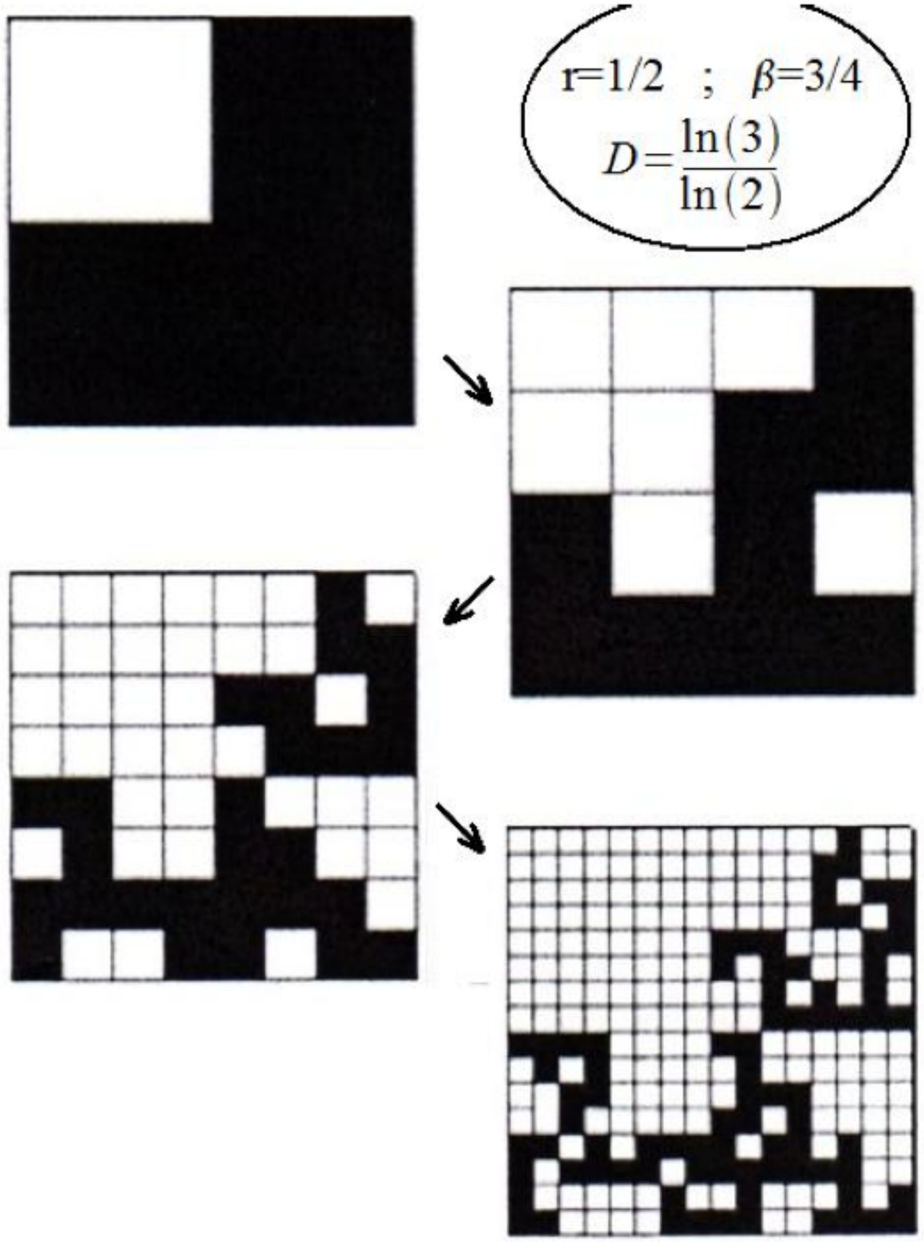
$$\overline{\varepsilon} \sim 2 \times 10^{-25} \quad \mathrm{erg\ cm^{-3}\ s^{-1}}$$



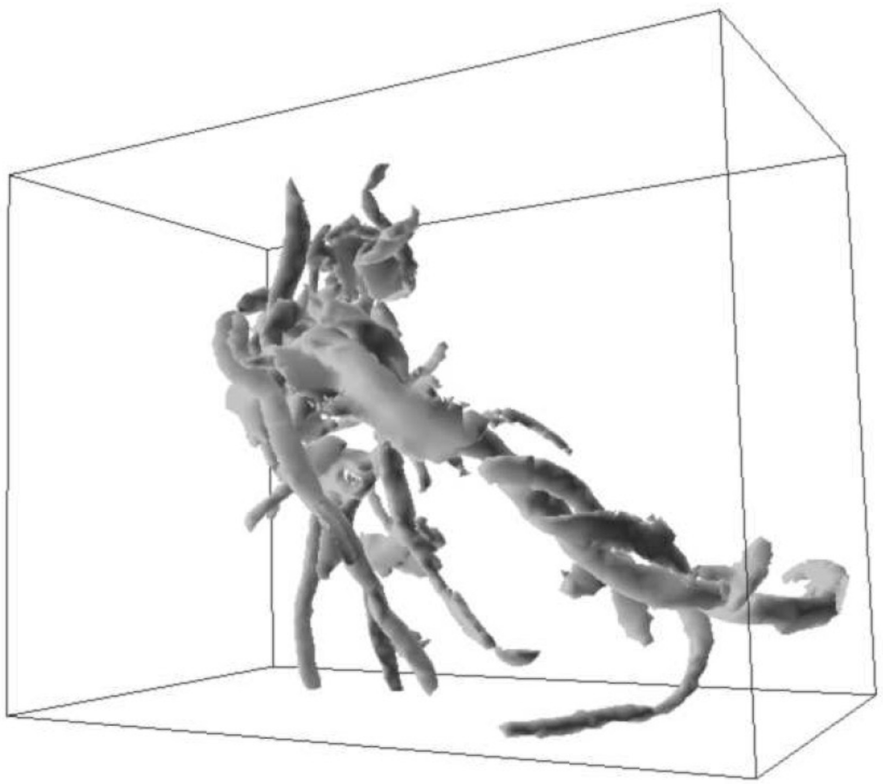


Hennebelle & Falgarone (2012)

Intermittency



Frish (1995)



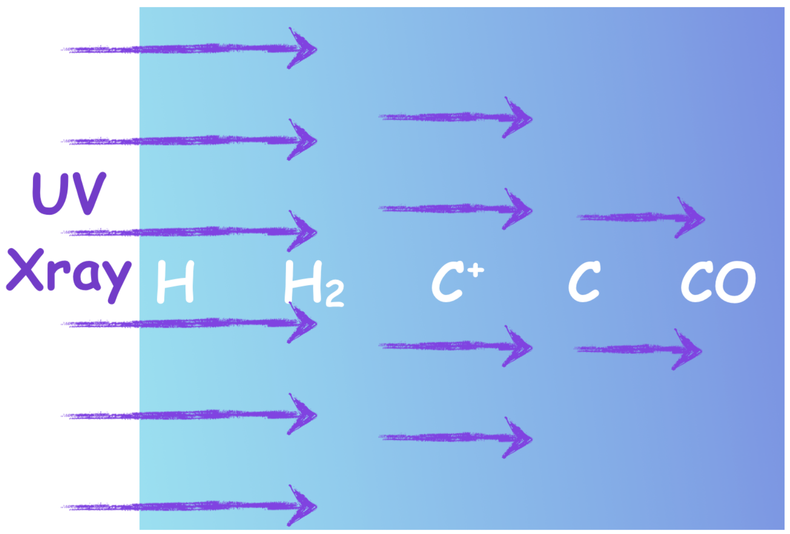
Moisy & Jimenez (2004)

Open questions

- dissipative scales ? structures ?
- physical processes involved ?
- local dissipation rate ?
- link with the magnetic field ?

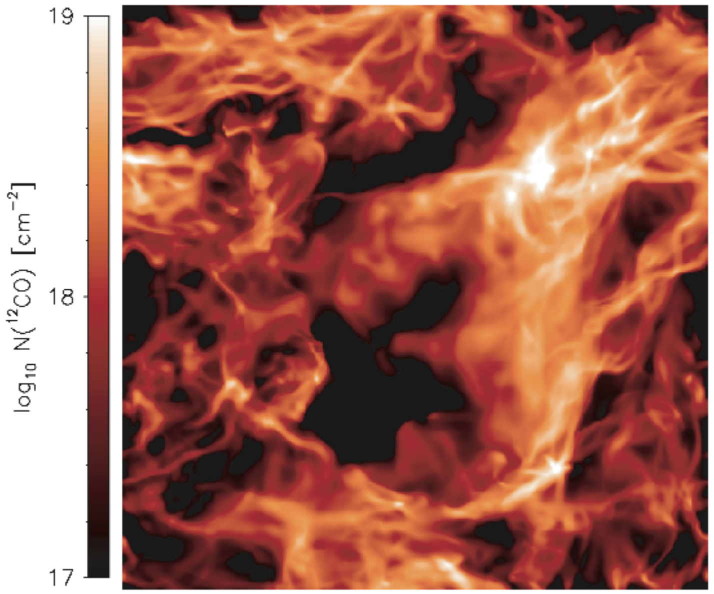
average heating rates (erg cm^{-3} s^{-1})			
photons	cosmic rays	turbulence	magnetic
5×10^{-24}	3×10^{-25}	2×10^{-25}	2×10^{-25}

photo dom. medium



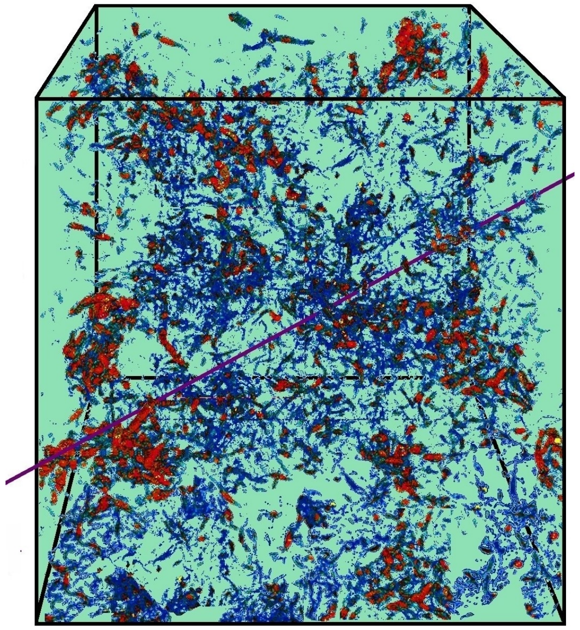
Le Petit et al. (2006)
Röllig et al. (2007)
Ferland et al. (2013)

turbulent mixing

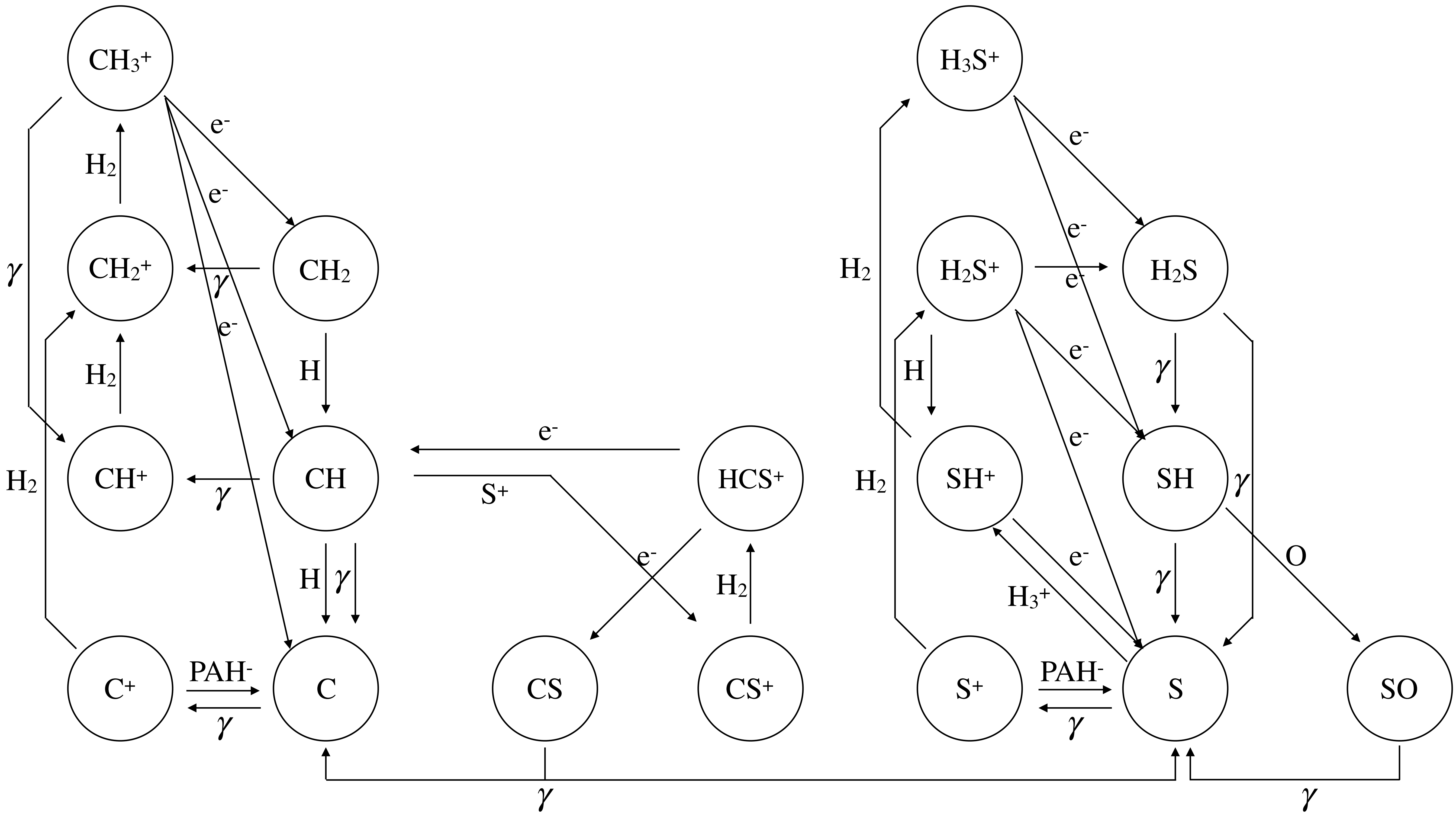


Glover et al. (2010)
Levrier et al. (2012)
Valdivia et al. (2016)

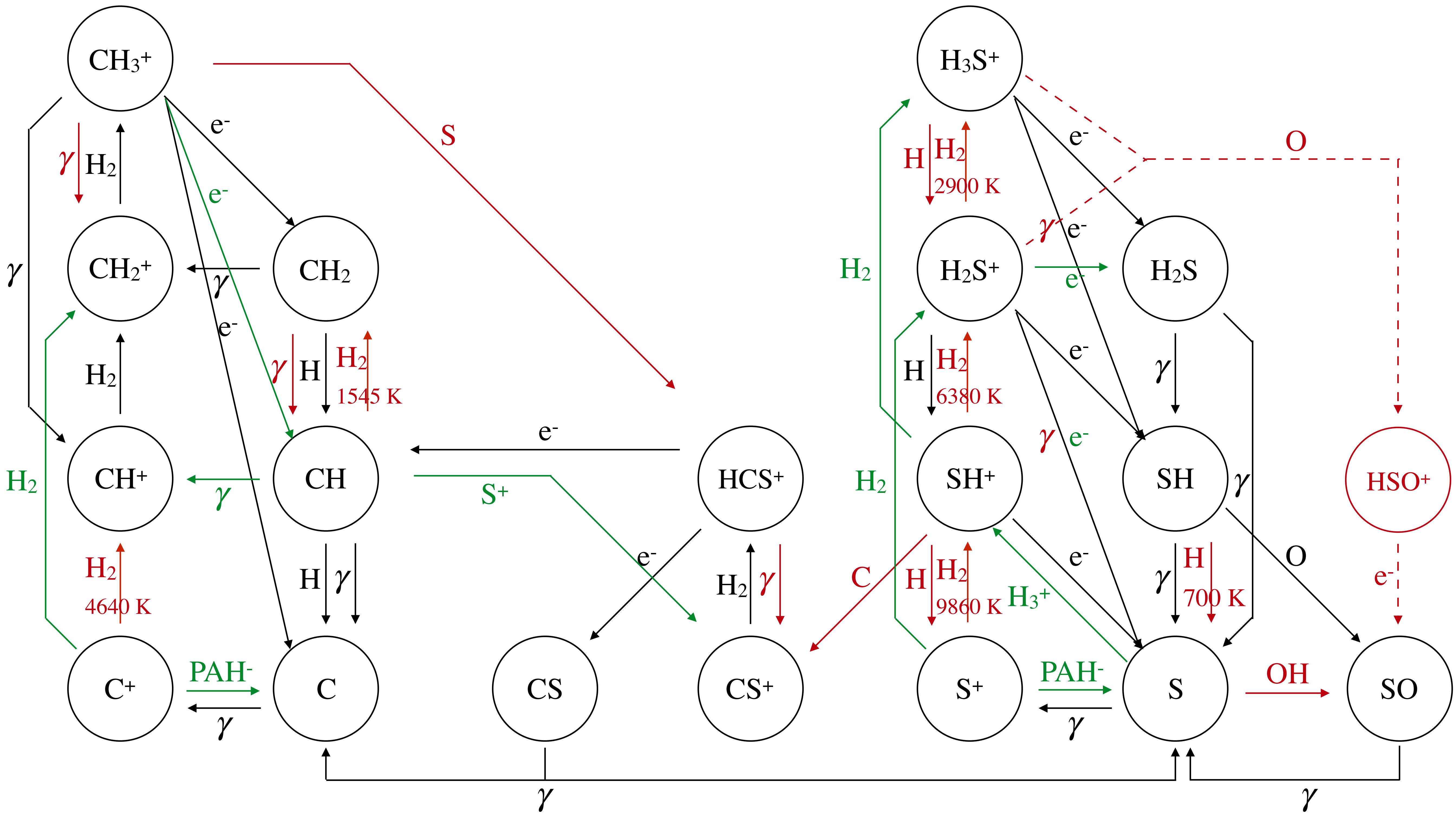
dissipation



Lazarian & Vishniac (1999)
Lesaffre et al. (2013)
Godard et al. (2014)



Neufeld et al. (2015)



Neufeld et al. (2015)

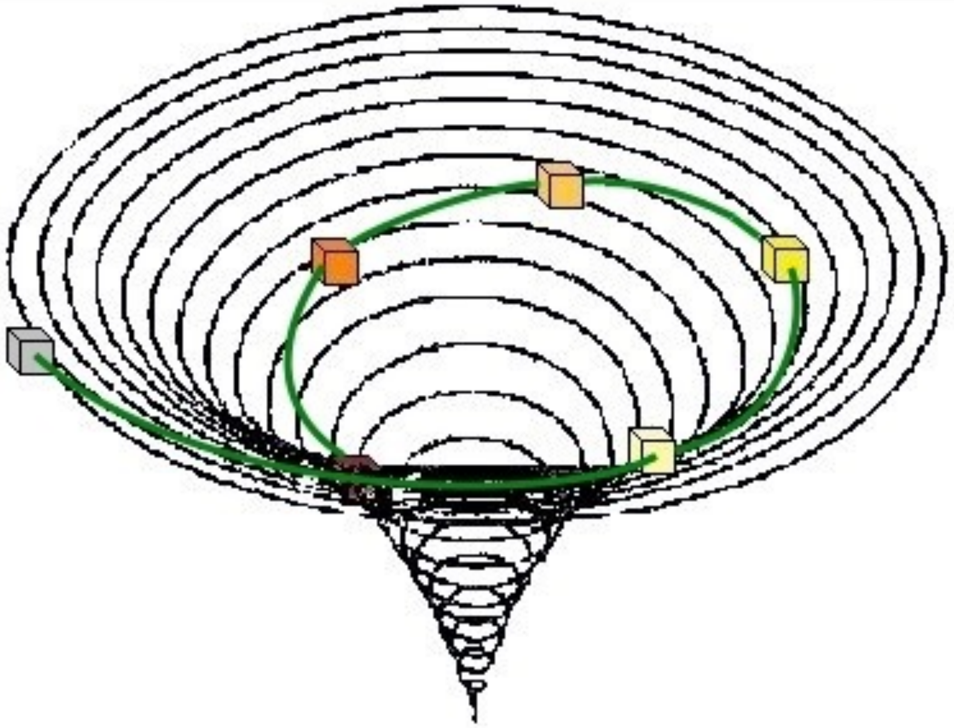
Chemistry of turbulent dissipation

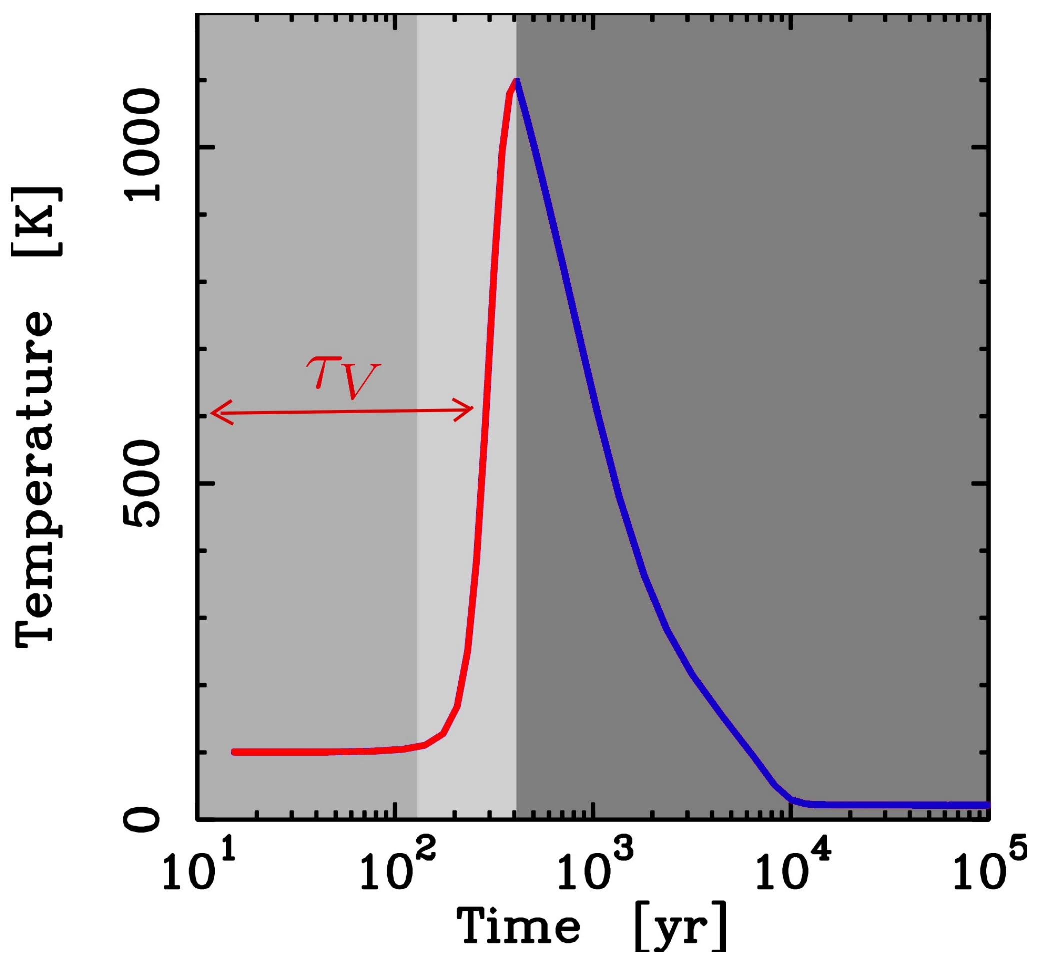
Dissipation phase

- magnetized vortices
- Lagrangian approach
- non equilibrium chemistry
- turbulent heating process
  - ✓ viscous friction
  - ✓ ion-neutral friction

Relaxation phase

- Eulerian approach
- no turbulent heating

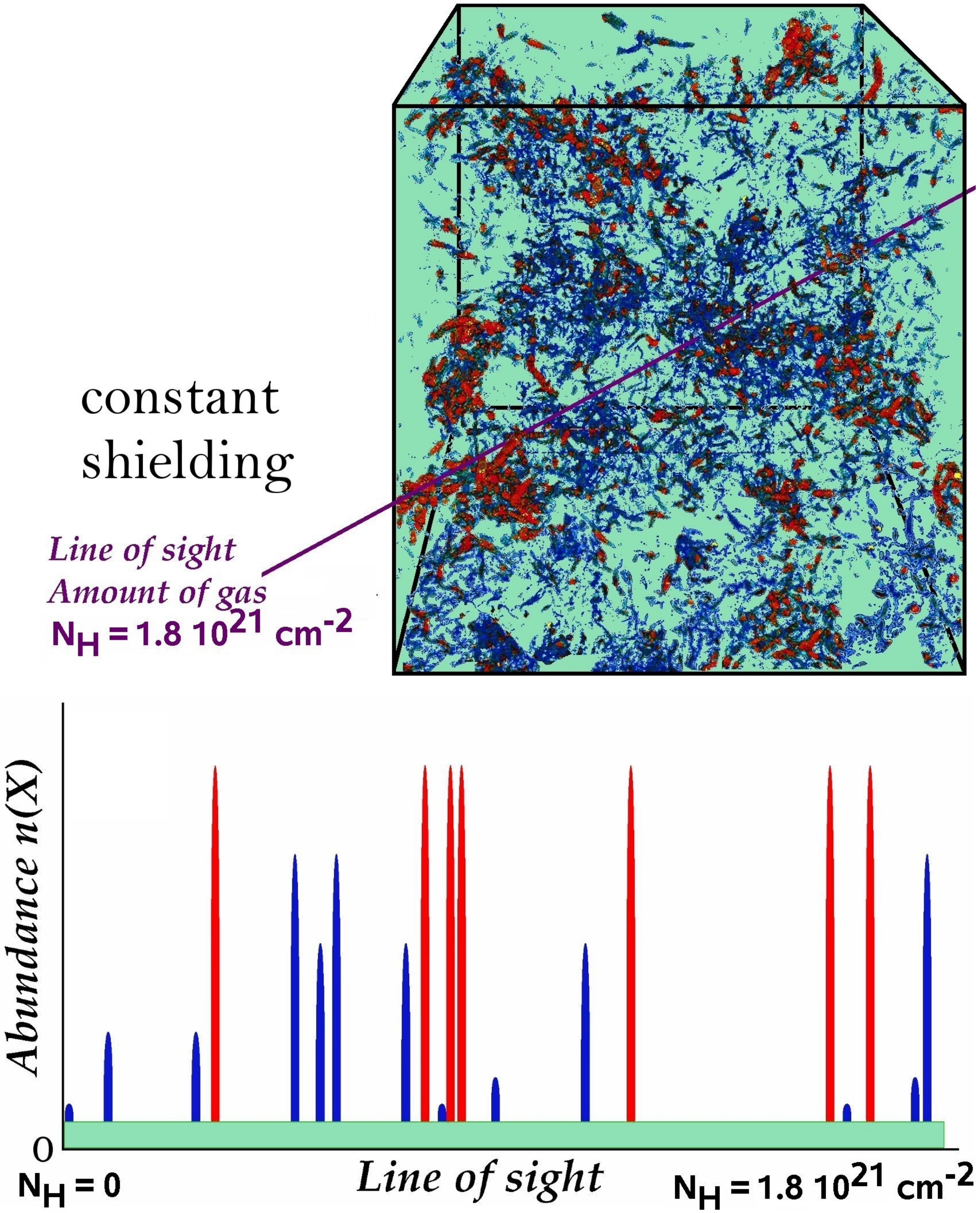




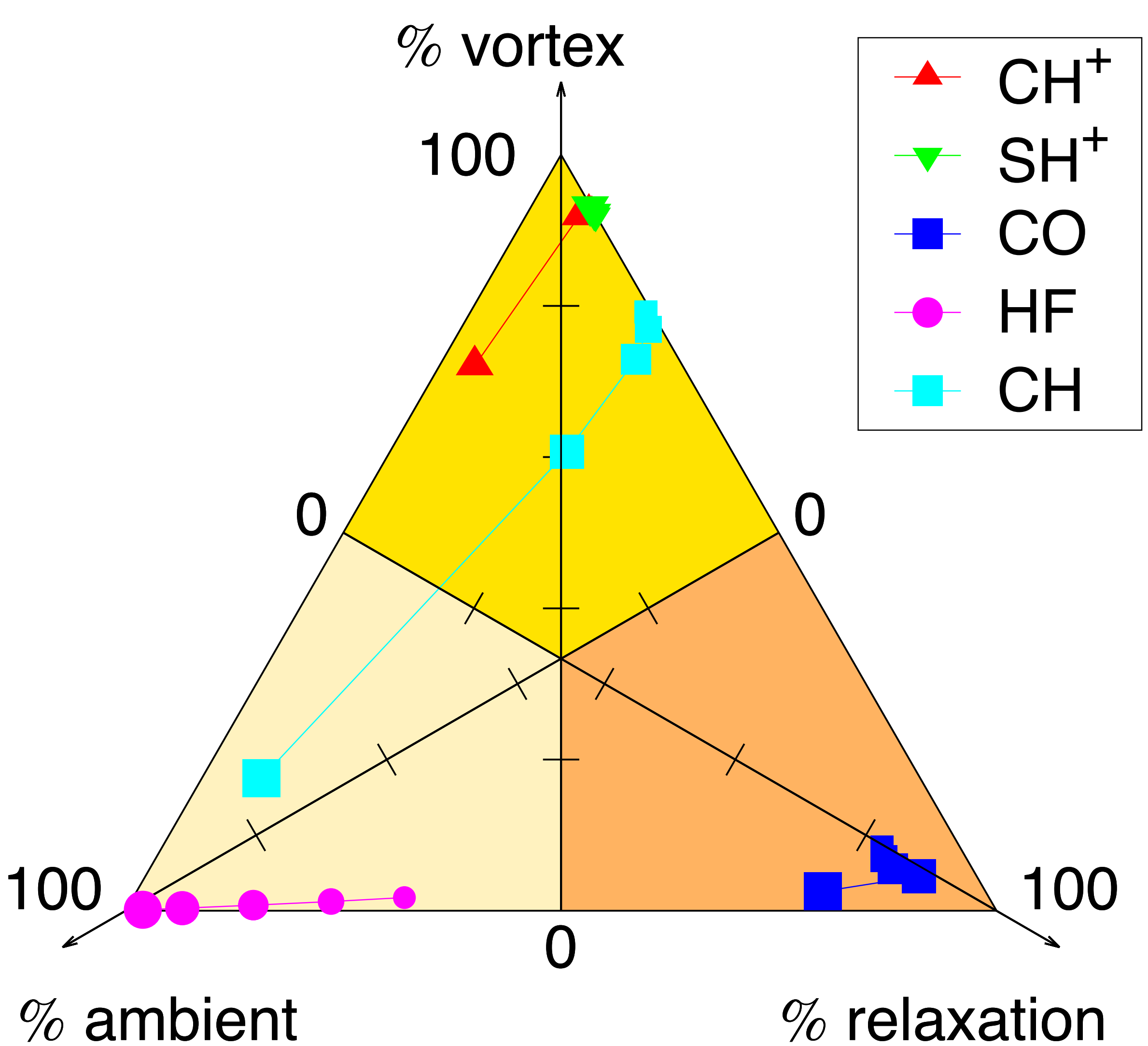
Model parameters

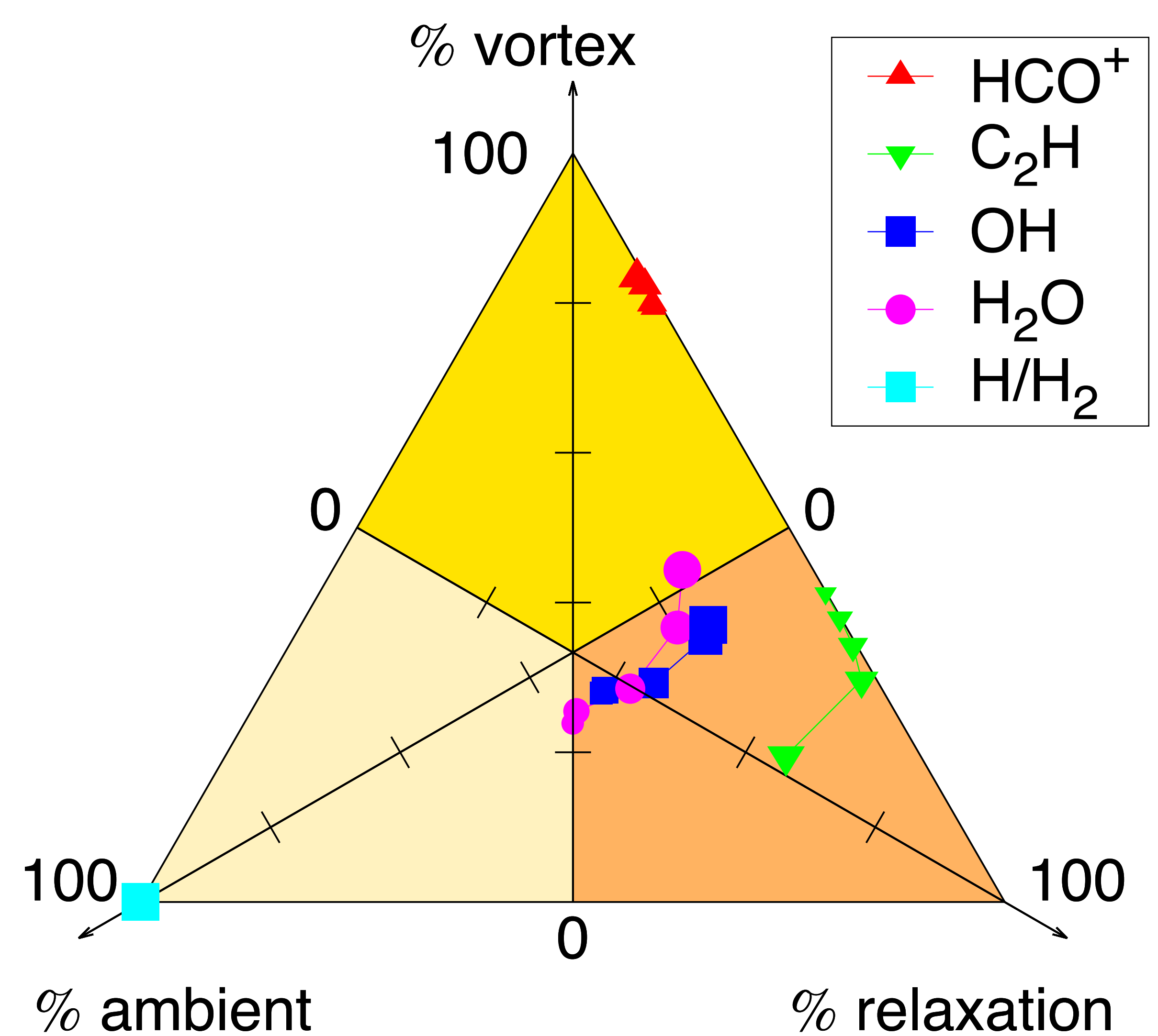
- density $n_{\rm H}$
- shielding A_V
- CR ionization ζ

- stretching $a \rightarrow l$
- max. rot. vel. $u_{\theta m} \rightarrow u_{in}$
- transfer rate $\bar{\varepsilon} \rightarrow N_V$
- lifetime $\tau_V \rightarrow N_R$



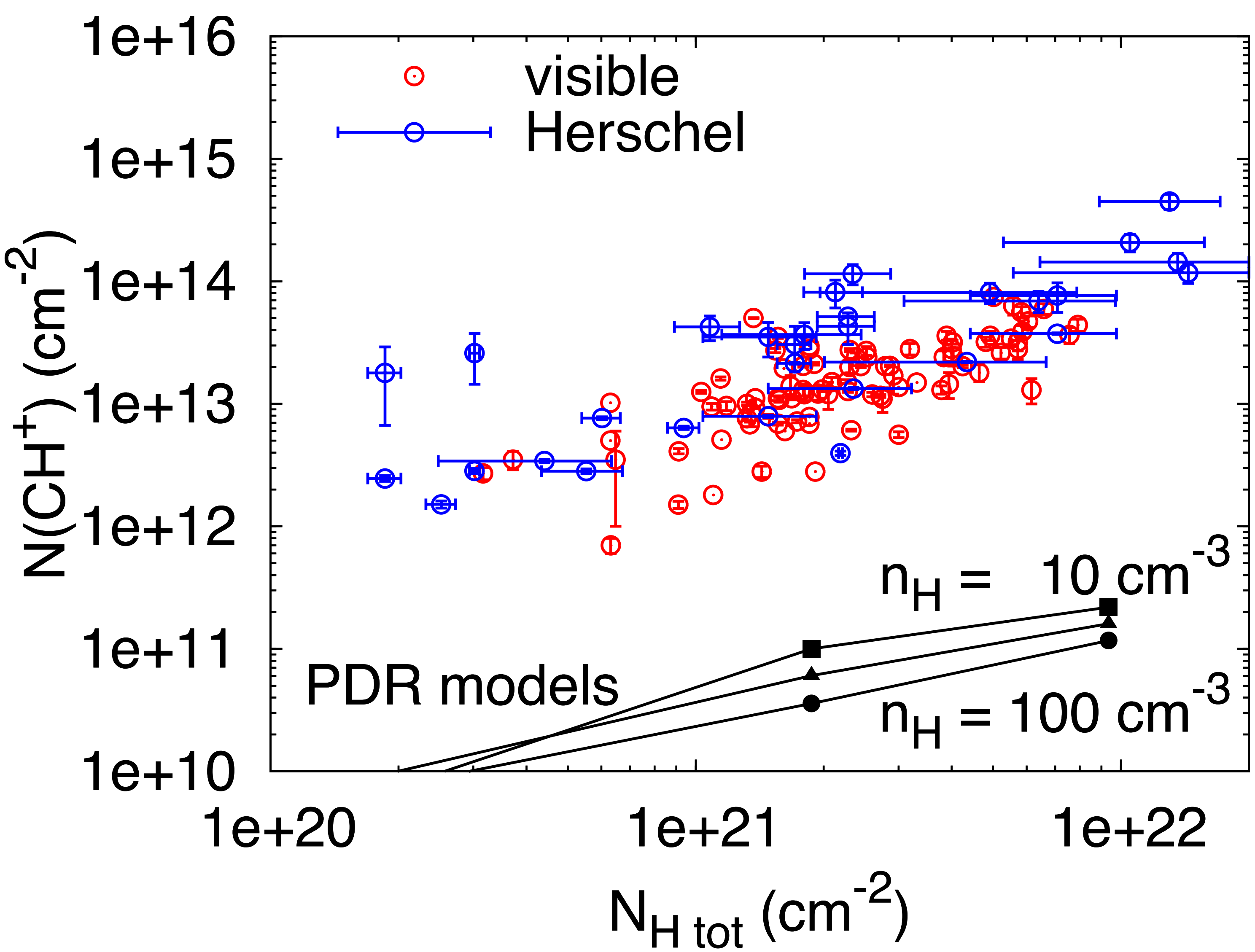
strategy to derive turbulent properties





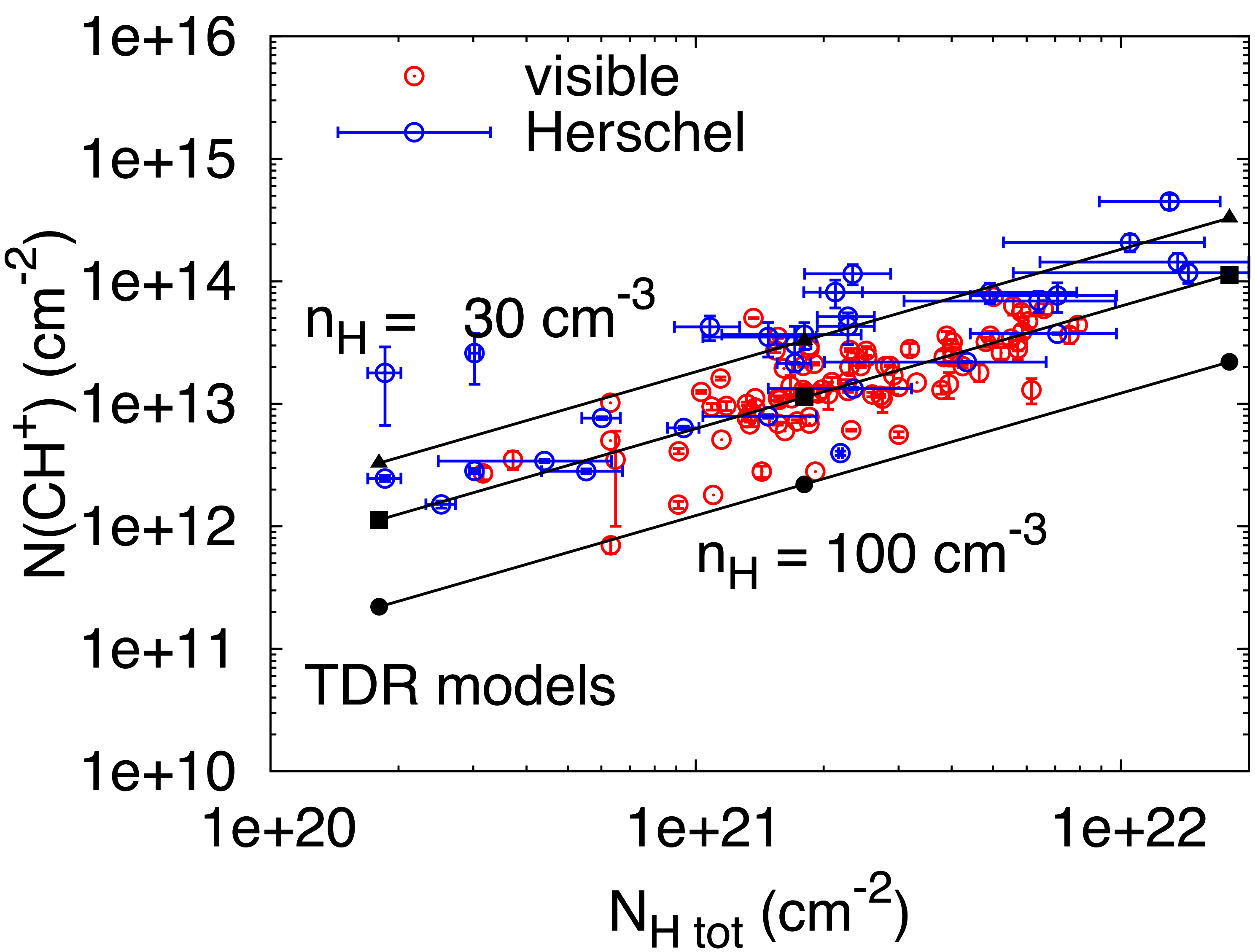
- n_H increases with symbol size
- $A_V = 0.4$ $\zeta = 3 \times 10^{-16}\ s^{-1}$

CH^+ vs N_H



$C^+ + H_2 \rightarrow CH^+ + H \quad (\Delta E/k = 4640\ K)$

CH^+ vs N_H

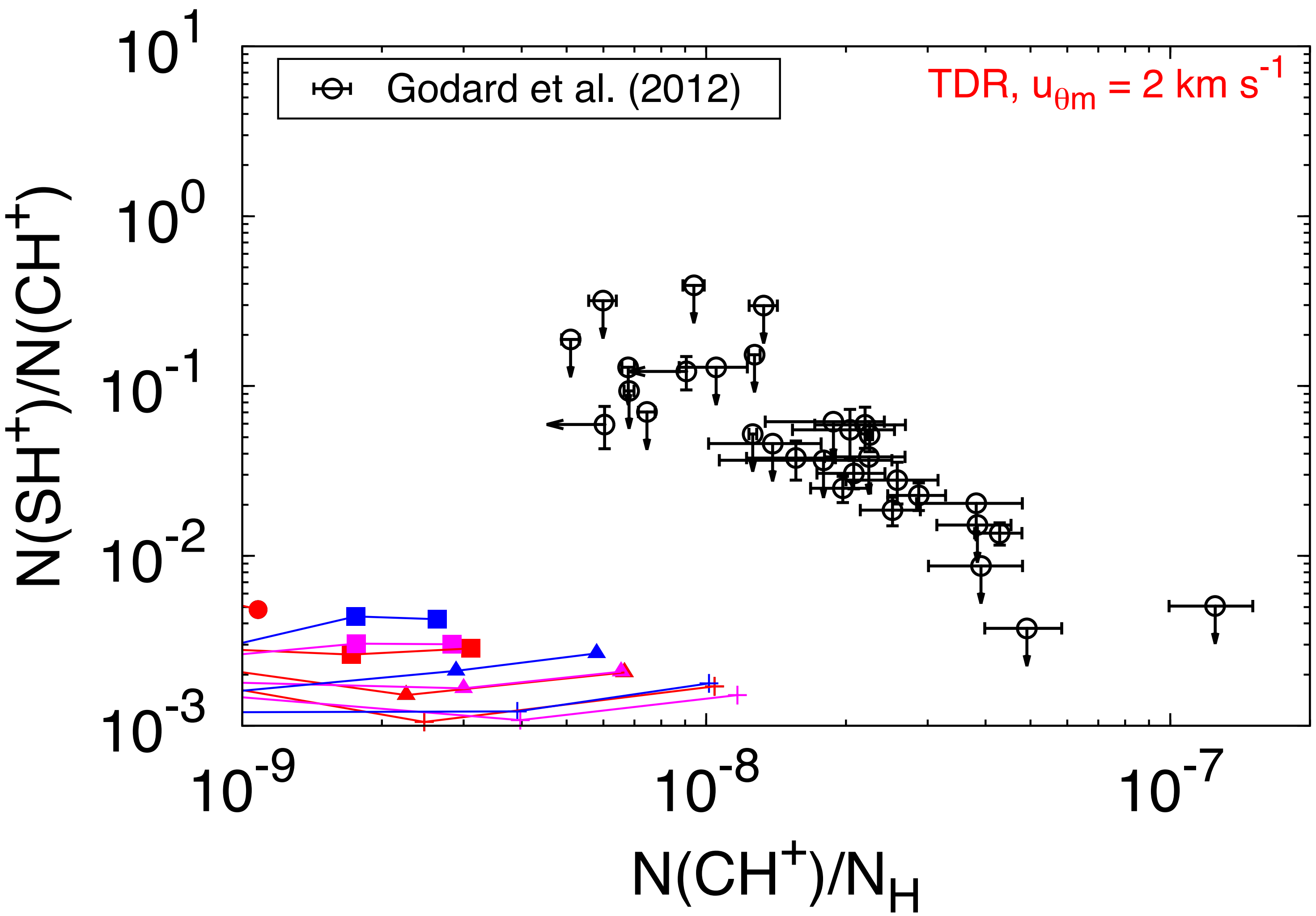


$C^+ + H_2 \rightarrow CH^+ + H$ ($\Delta E/k = 4640$ K)

dissipation rate

- $$\frac{N(\mathrm{CH}^+)}{N_\mathrm{H}} = \bar{\varepsilon}\; n_\mathrm{H}^{-2.2}\; A_V^{-0.32}\; a^{-0.5}$$
- $n_\mathrm{H} \leqslant 100\ \mathrm{cm}^{-3}$
- $$0.2 \leqslant \frac{\bar{\varepsilon}}{10^{-24}\,\mathrm{erg\,cm^{-3}\,s^{-1}}} \leqslant 5$$

CH^+ vs SH^+



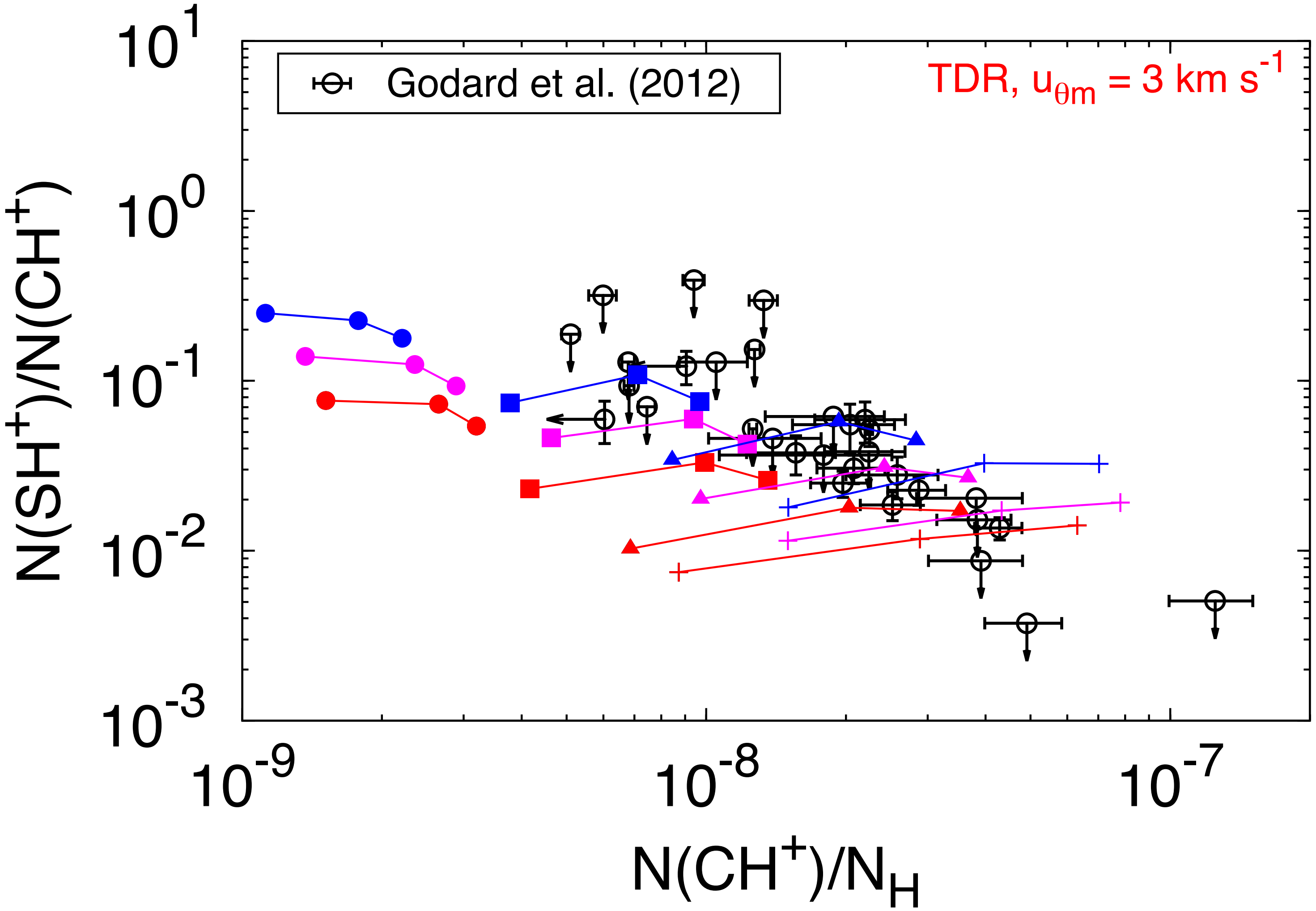
ion-neutral drift

- $$\frac{N(\mathrm{SH}^+)}{N(\mathrm{CH}^+)} \propto \exp(5220/T_{\mathrm{eff}})$$
- indep. of other param

$C^+ + H_2 \rightarrow CH^+ + H$ ($\Delta E/k$ = 4640 K)

$S^+ + H_2 \rightarrow SH^+ + H$ ($\Delta E/k$ = 9860 K)

CH^+ vs SH^+



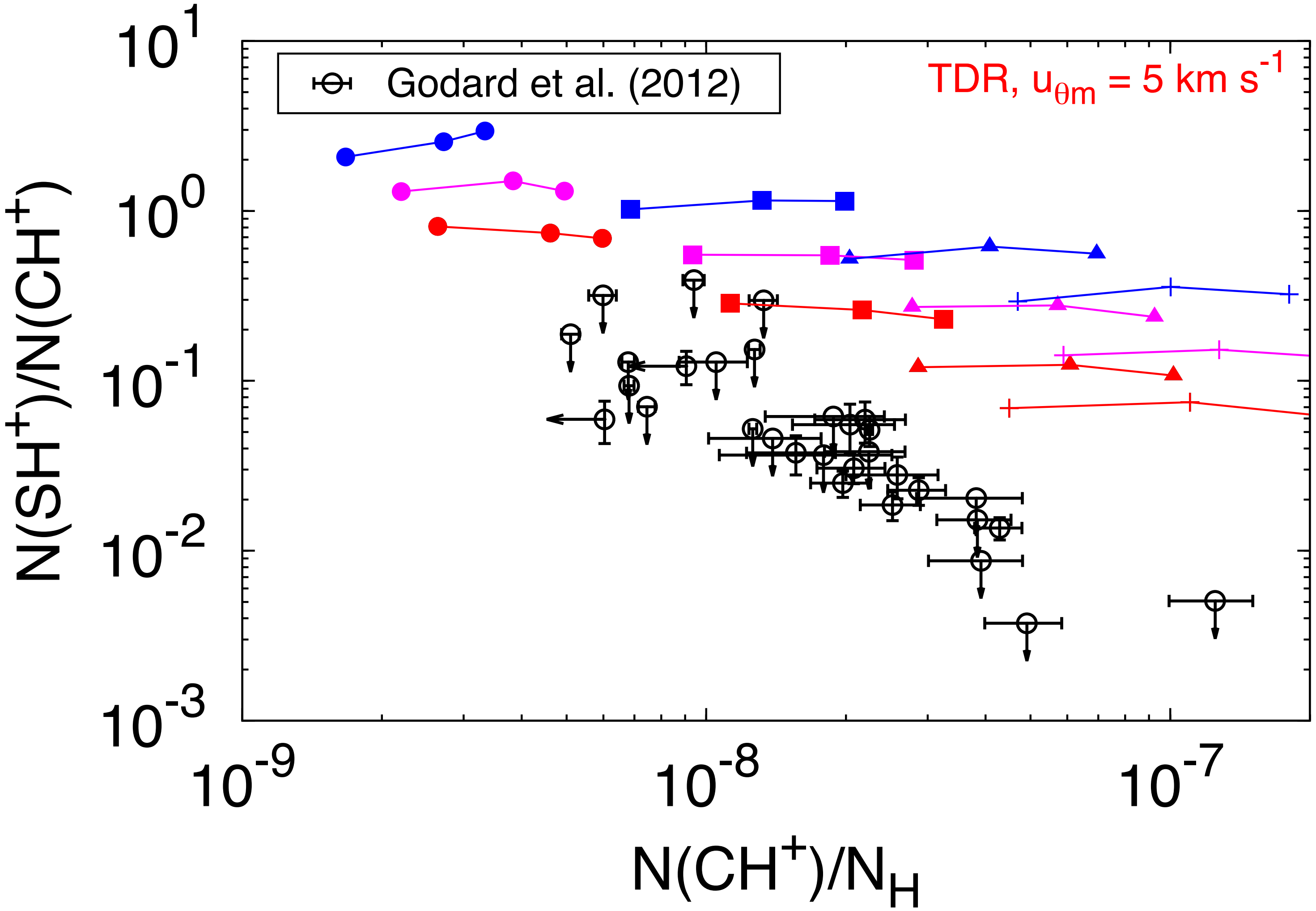
ion-neutral drift

- $\frac{N(\mathrm{SH}^+)}{N(\mathrm{CH}^+)} \propto \exp(5220/T_{\mathrm{eff}})$
- indep. of other param

$C^+ + H_2 \rightarrow CH^+ + H$ ($\Delta E/k$ = 4640 K)

$S^+ + H_2 \rightarrow SH^+ + H$ ($\Delta E/k$ = 9860 K)

CH^+ vs SH^+



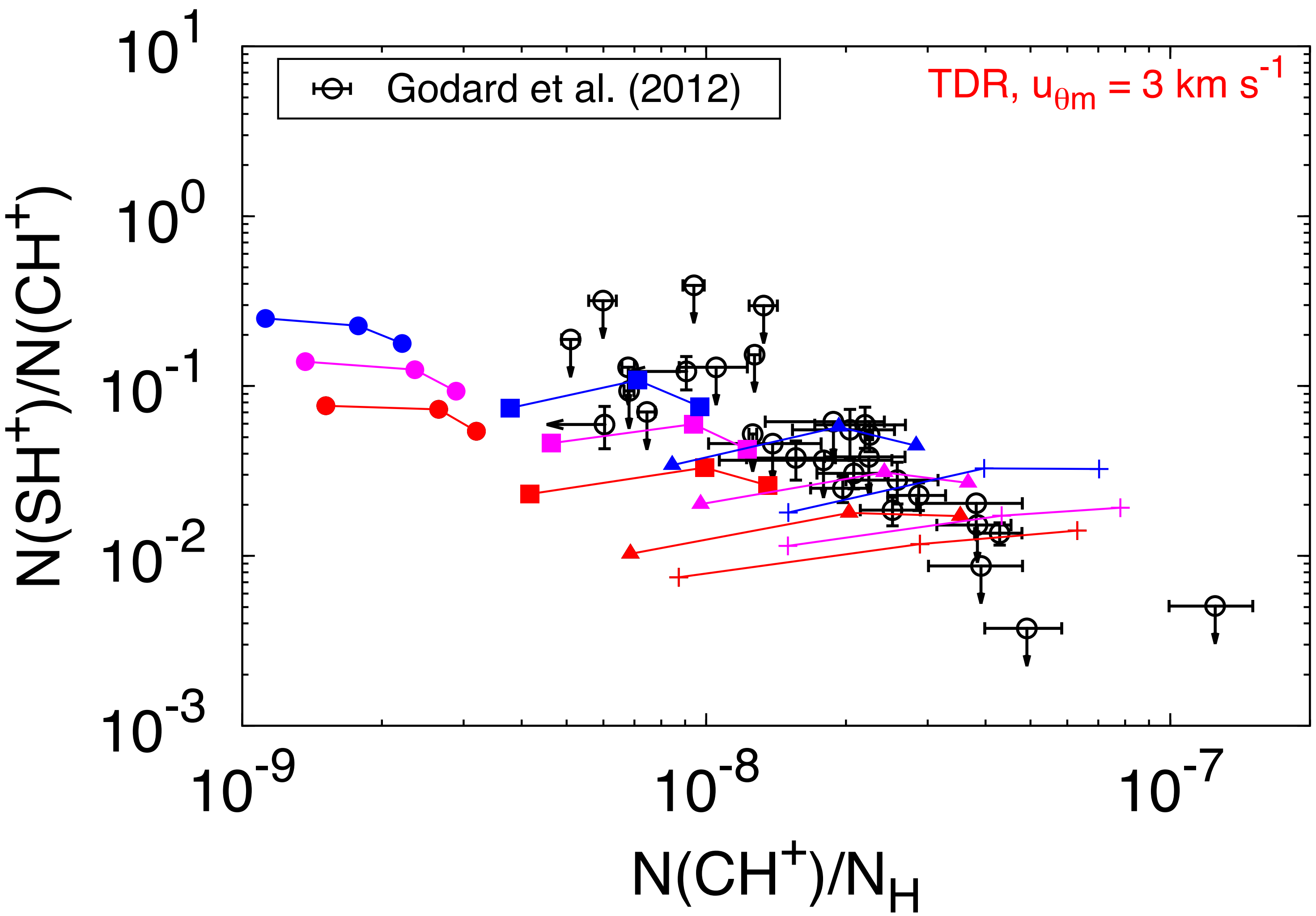
<u>ion-neutral drift</u>

- $\frac{N(\mathrm{SH}^+)}{N(\mathrm{CH}^+)} \propto \exp(5220/T_{\mathrm{eff}})$
- indep. of other param

$C^+ + H_2 \rightarrow CH^+ + H$ ($\Delta E/k$ = 4640 K)

$S^+ + H_2 \rightarrow SH^+ + H$ ($\Delta E/k$ = 9860 K)

CH^+ vs SH^+



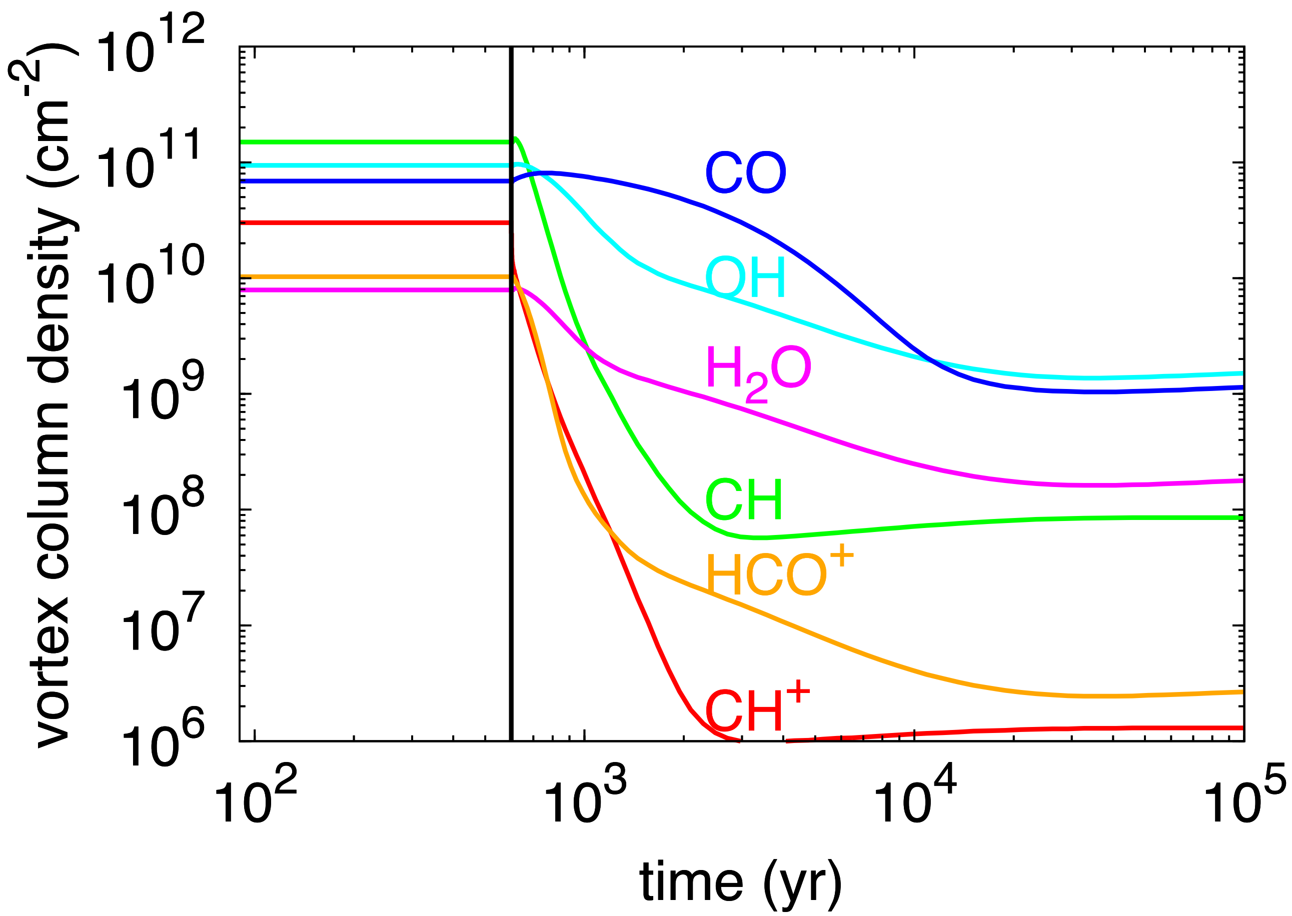
<u>ion-neutral drift</u>

- $\dfrac{N(\mathrm{SH}^+)}{N(\mathrm{CH}^+)} \propto \exp(5220/T_{\mathrm{eff}})$
- indep. of other param
- $2.5 \leqslant u_{\theta m} \leqslant 3.5 \text{ km s}^{-1}$
- correlation reproduced

$C^+ + H_2 \rightarrow CH^+ + H$ ($\Delta E/k$ = 4640 K)

$S^+ + H_2 \rightarrow SH^+ + H$ ($\Delta E/k$ = 9860 K)

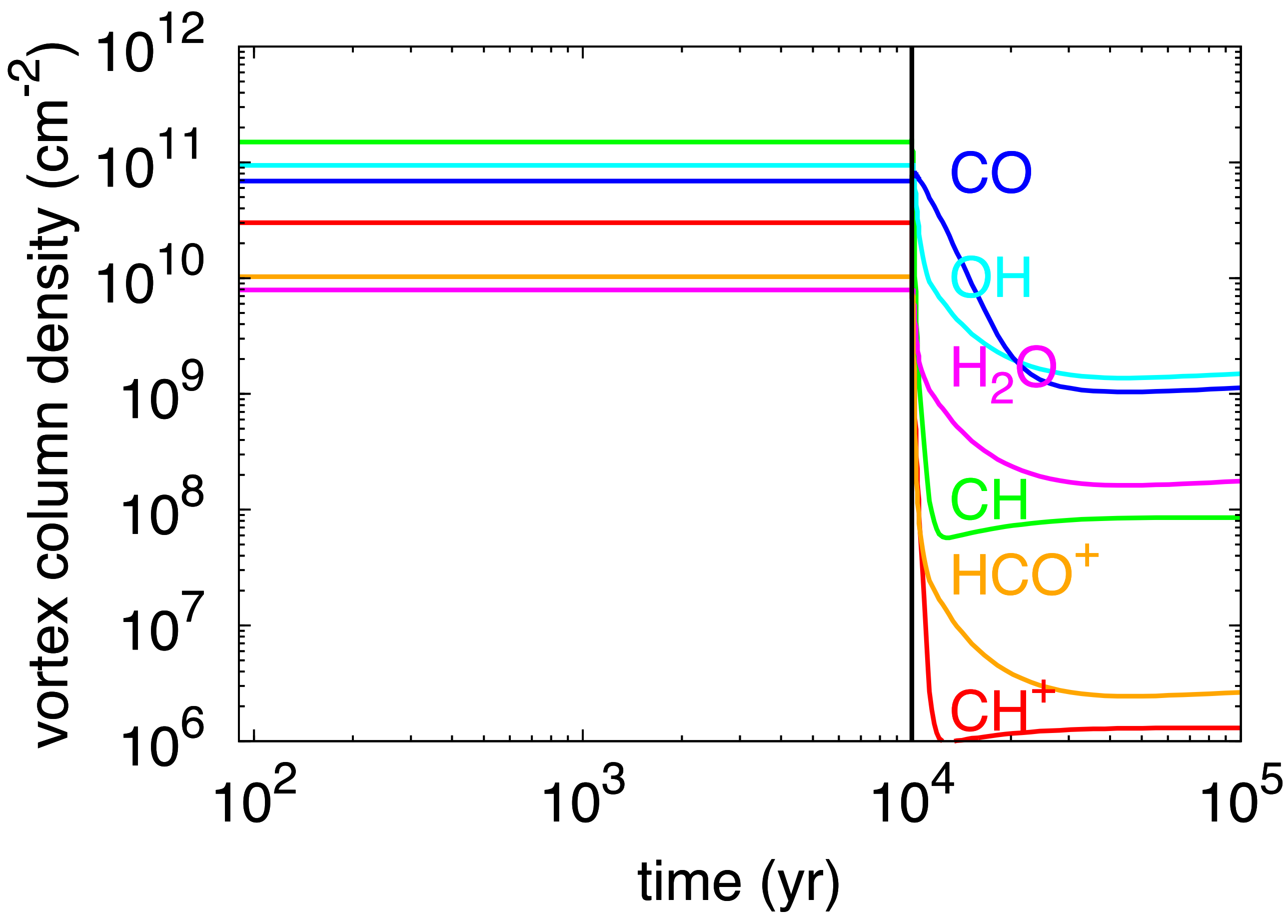
CO vs HCO+

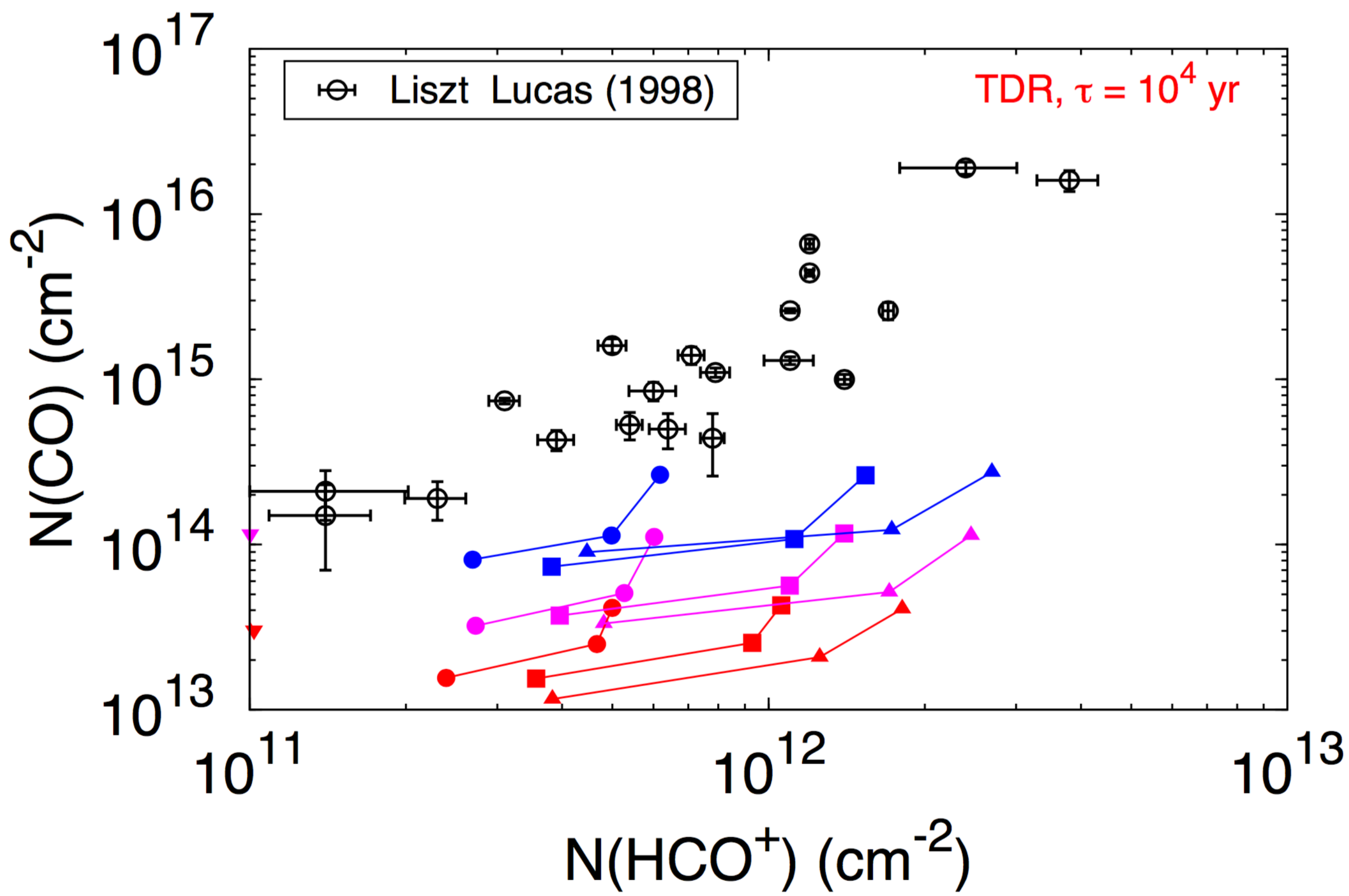


<u>dissipation timescale</u>

- $\tau_R(\mathrm{CO}) \sim 100 \times \tau_R(\mathrm{CH}^+) \sim 100 \times \tau_R(\mathrm{HCO}^+)$

CO vs HCO+

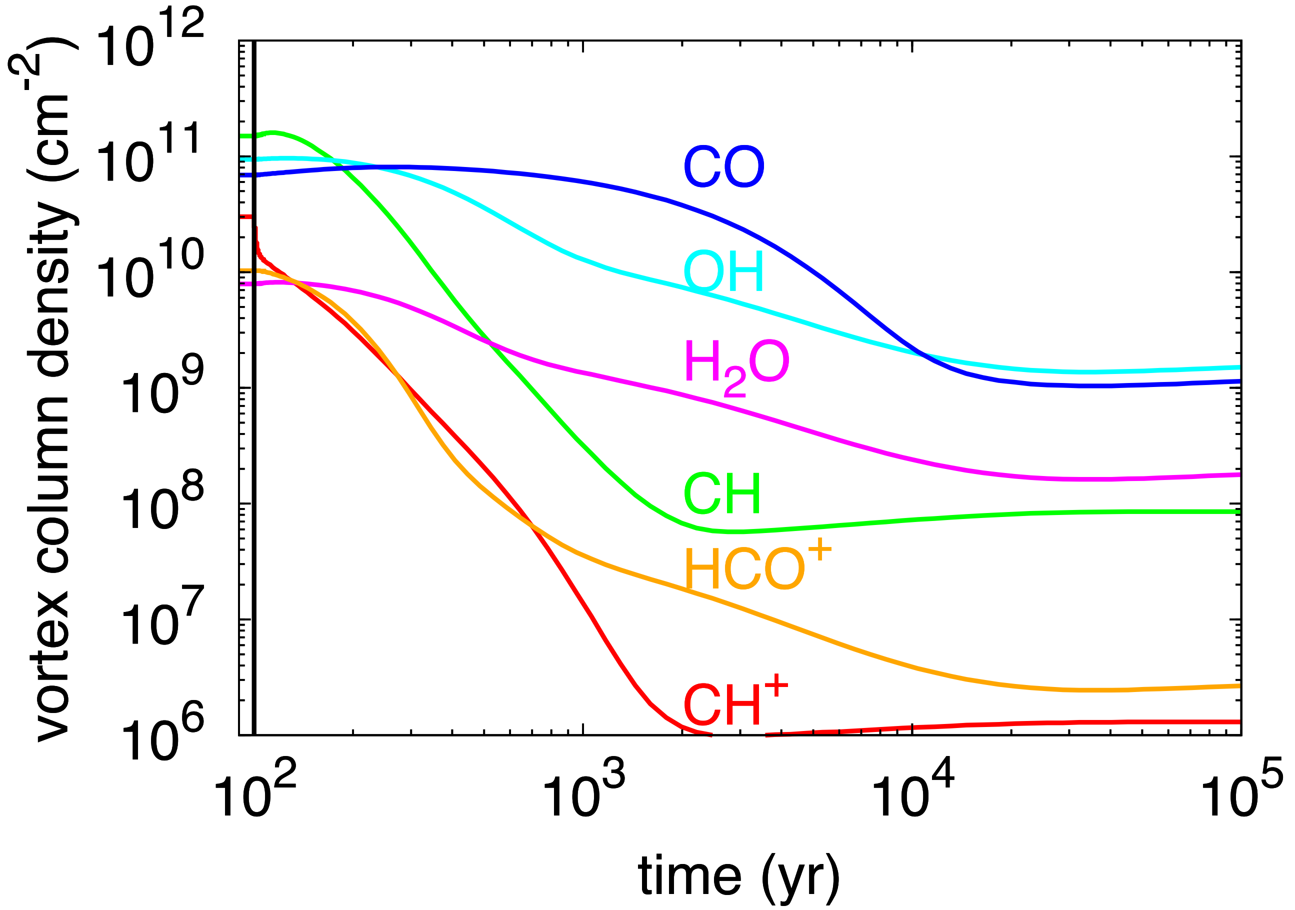


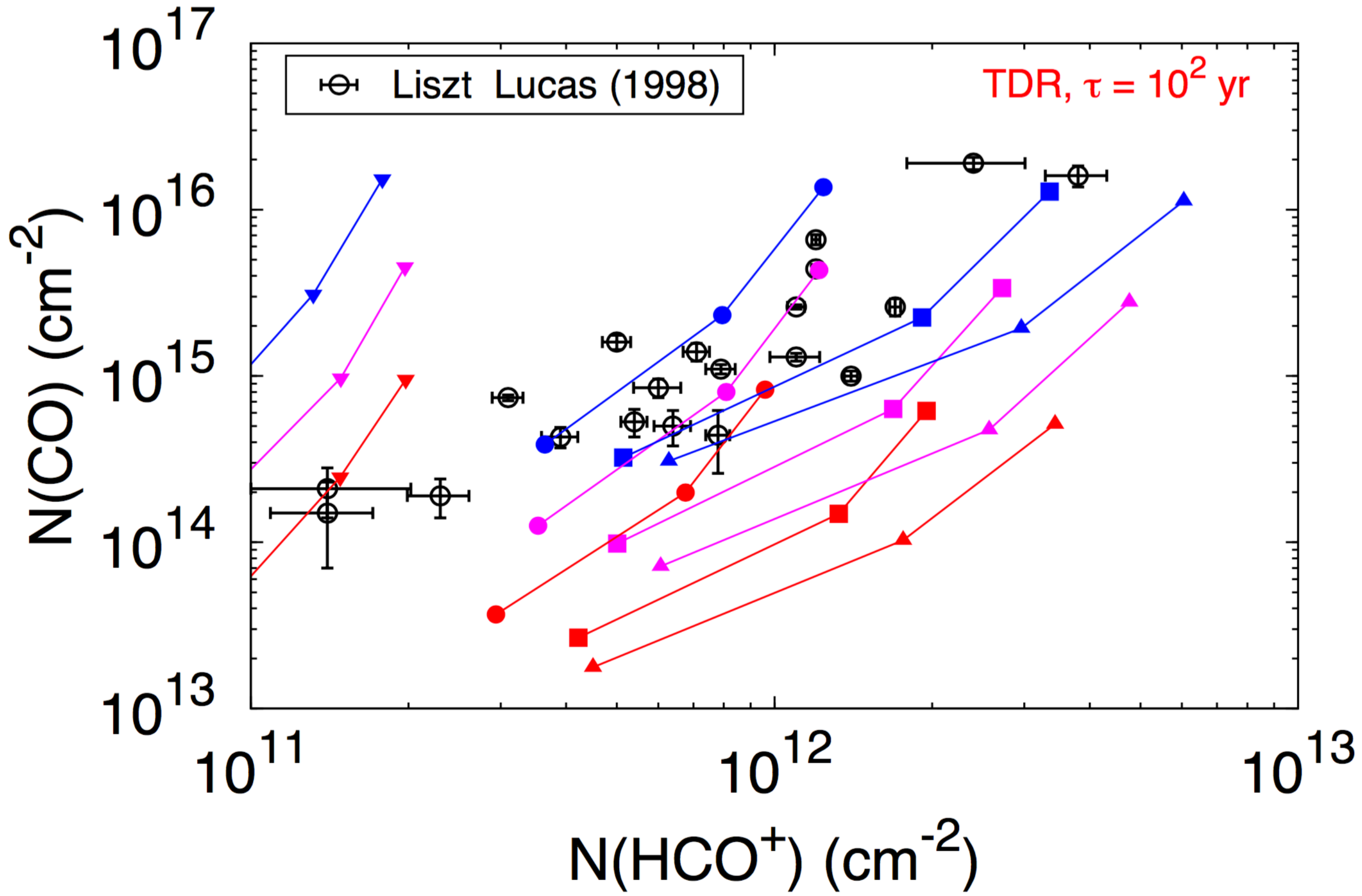


dissipation timescale

- $\tau_R(\mathrm{CO}) \sim 100 \times \tau_R(\mathrm{CH}^+) \sim 100 \times \tau_R(\mathrm{HCO}^+)$

CO vs HCO+



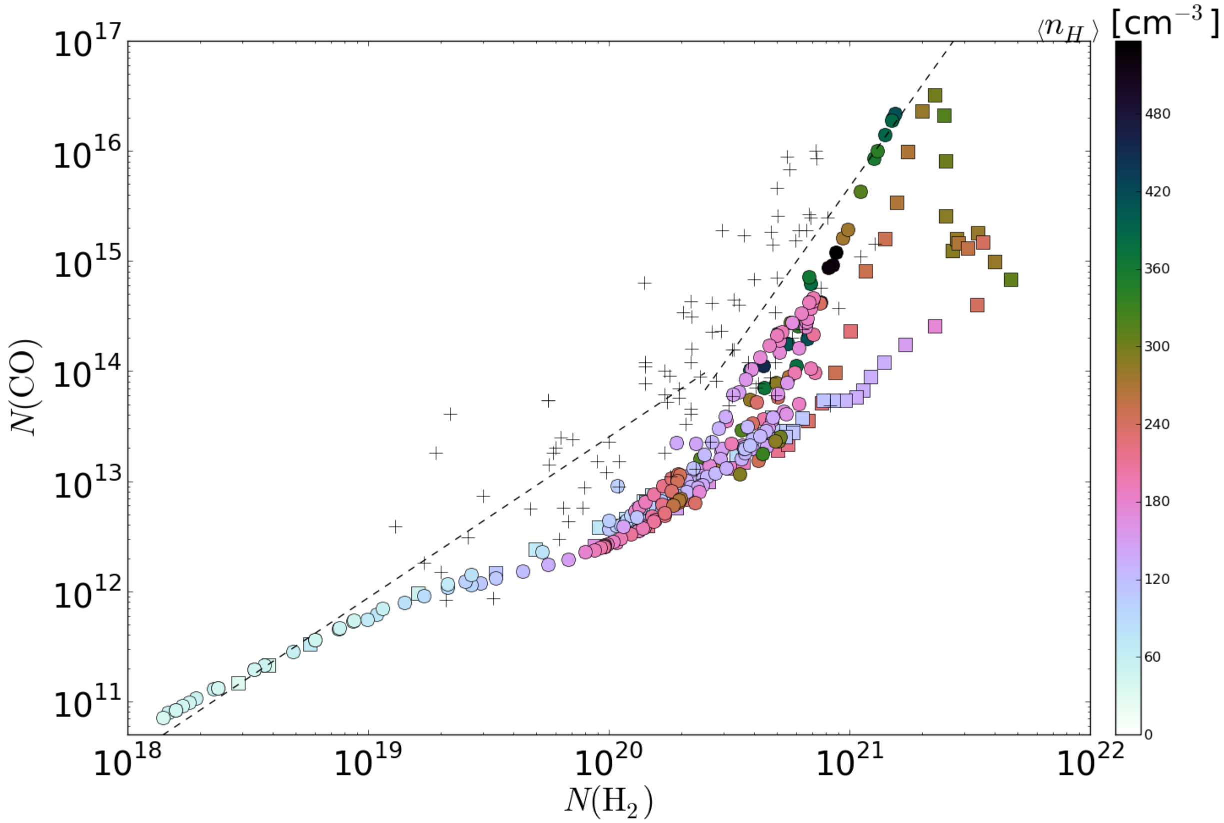


dissipation timescale

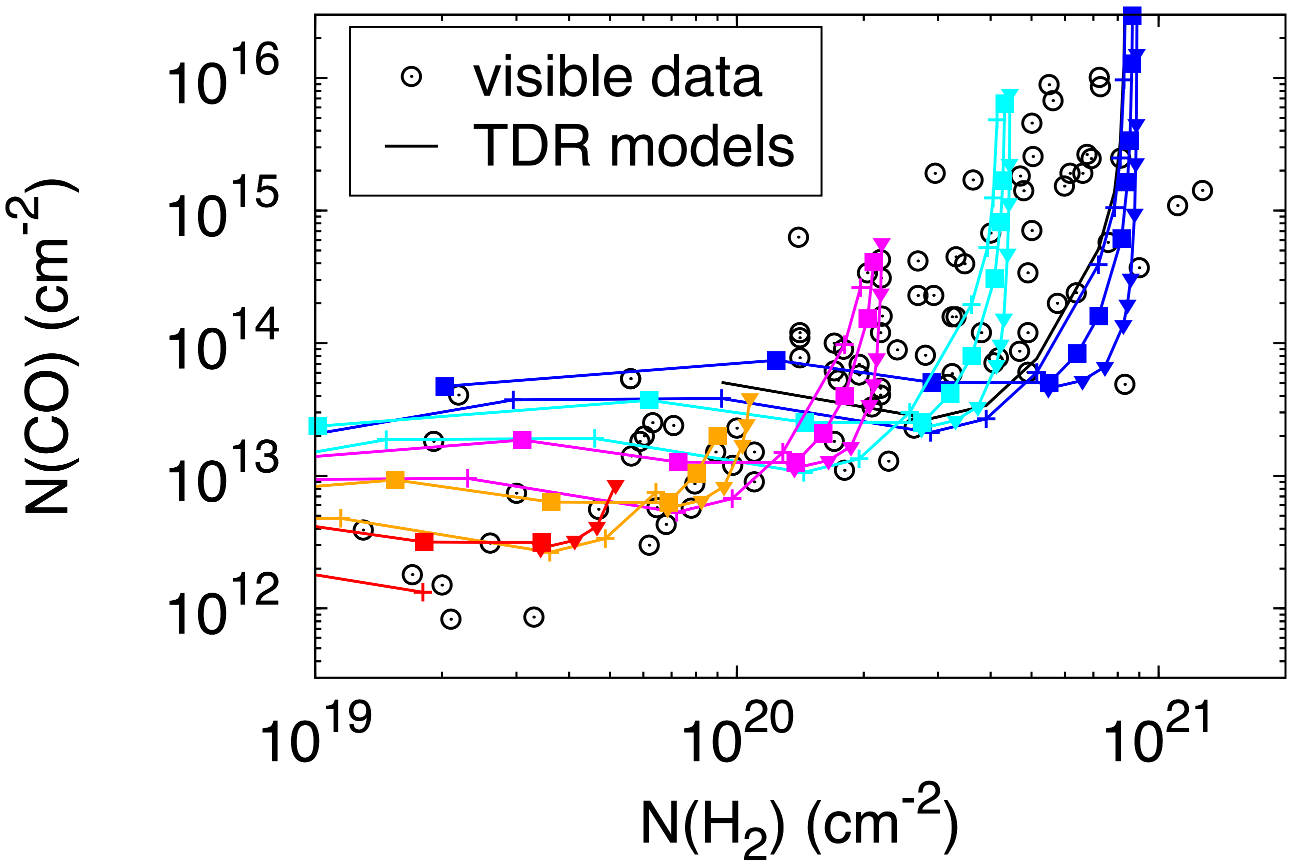
- $\tau_R(\mathrm{CO}) \sim 100 \times \tau_R(\mathrm{CH^+}) \sim 100 \times \tau_R(\mathrm{HCO^+})$

  $N(\mathrm{CO}) \propto \tau_R/\tau_V \quad \rightarrow \quad 10^2 \leqslant \tau_V \leqslant 10^3 \text{ yr}$

CO vs H_2



Levrier et al. (2012)



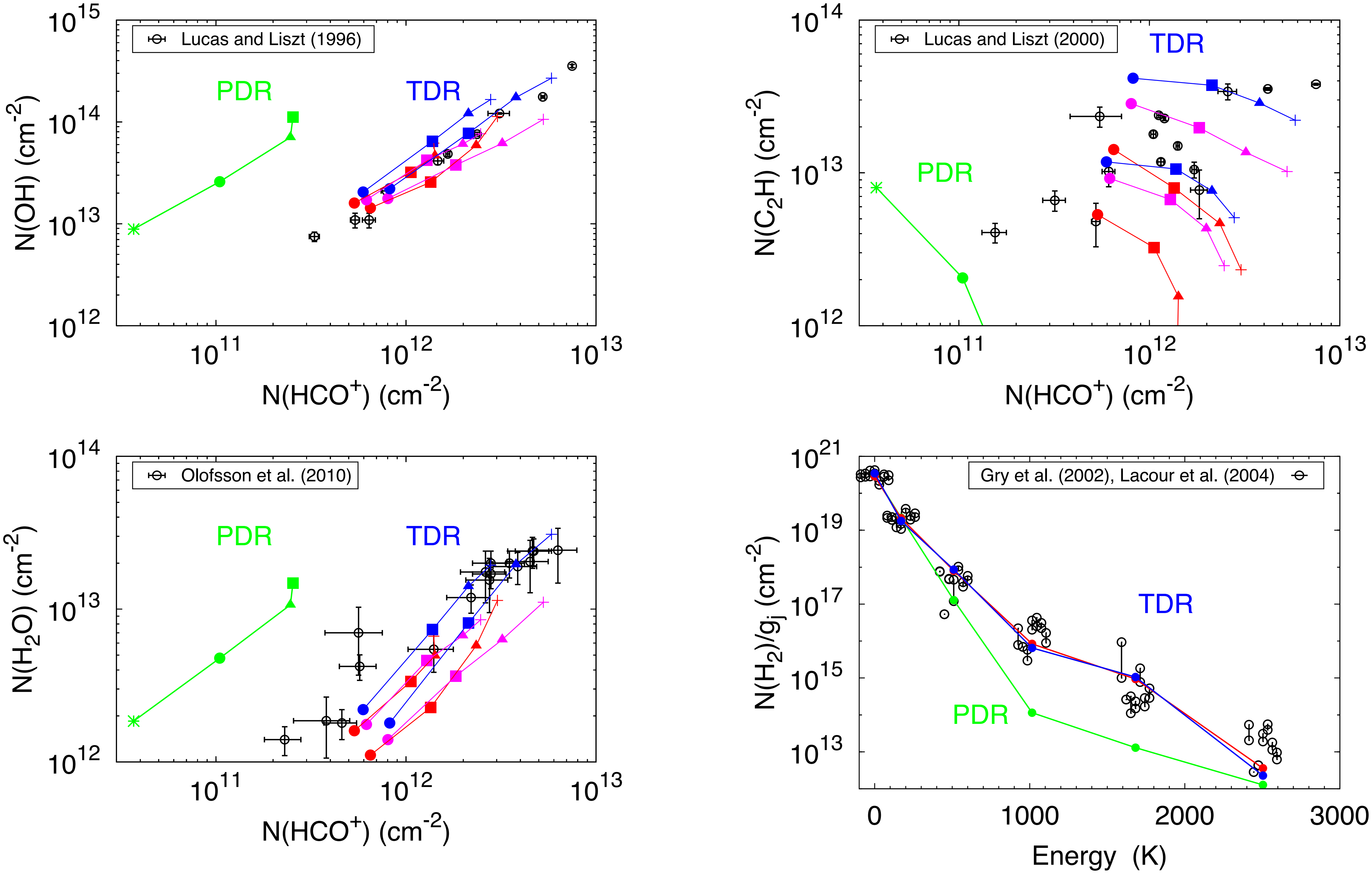
realistic fragmentation + PDR

- $N(CO)_{obs}/N(CO)_{PDR} > 10$
- bending explained

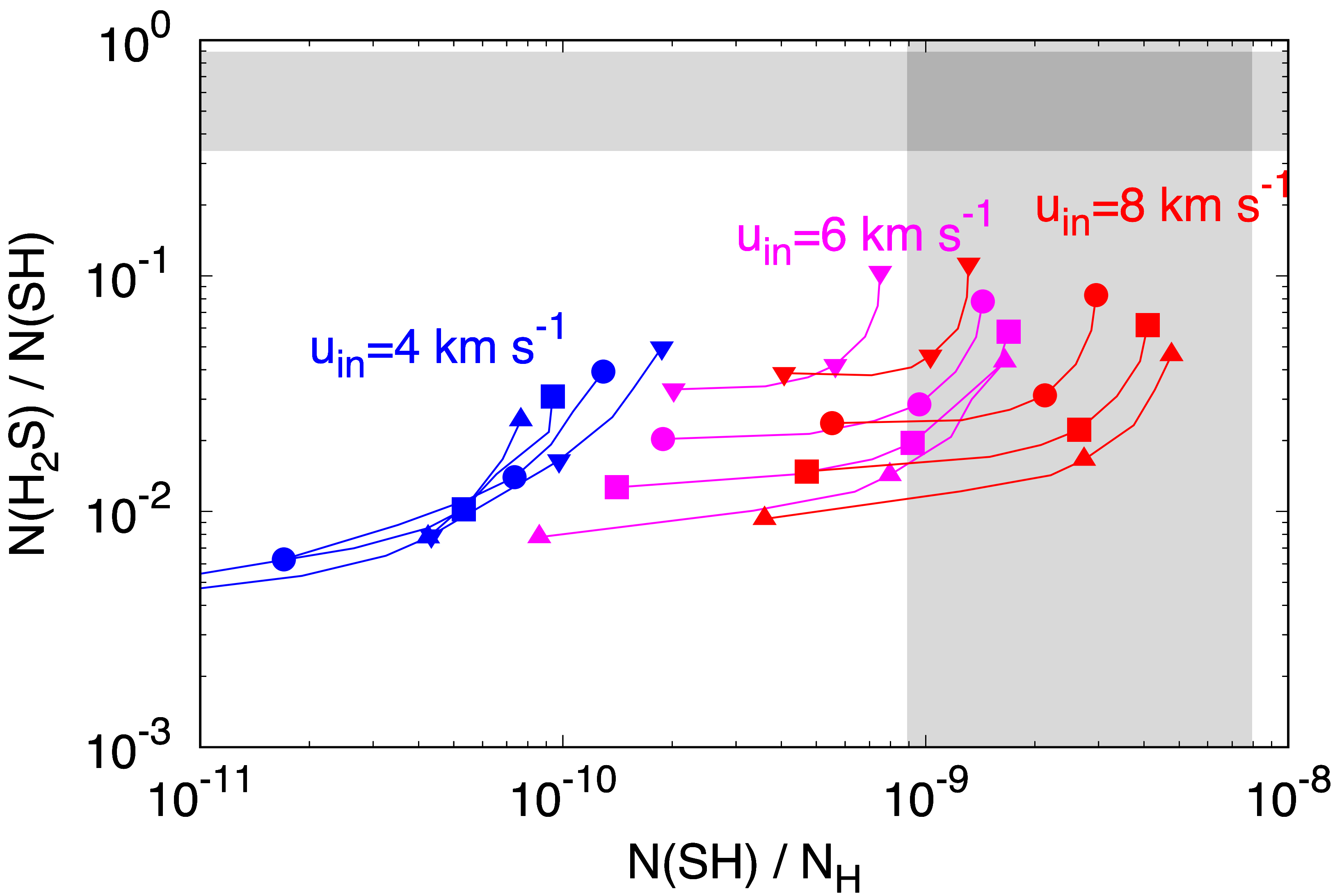
Turbulent dissipation regions

- if full fragmentation, no bending

other tracers



Limitations of 1D modeling



chemical discrepancies

- SH require high velocity drift
- H_2S, SO underestimated by a factor of 10

↓

- distribution of events
- missing physical and chemical processes ?

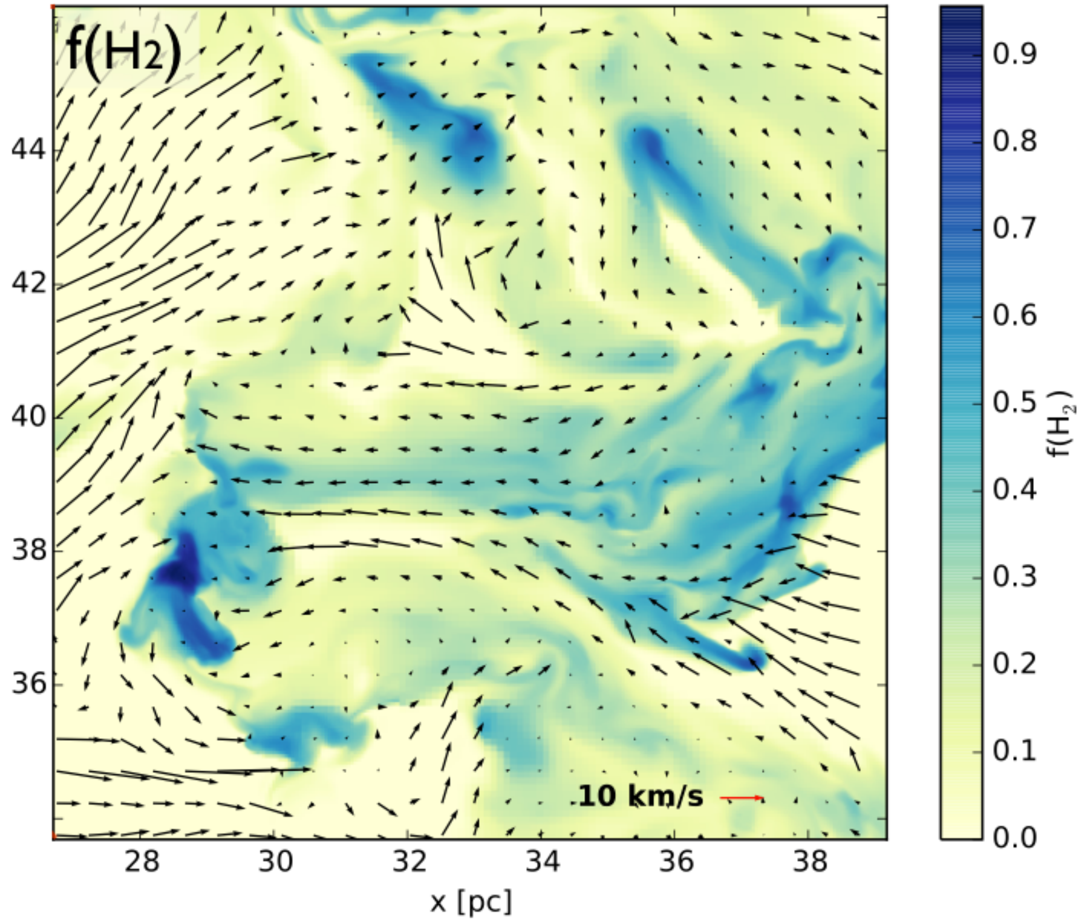
theoretical limitations

- 1D idealized structures
- stationary model (see talk by P. Lesaffre)
- no realistic distribution of events — Lesaffre et al. (2013)
- line profile not predicted
- fluid cells history not included — Joulain et al. (1998)
- lack realistic radiative conditions — Levrier et al. (2012)
- lack of coupling between scales — Momferratos et al. (2014)

  & coherence with turbulent cascade

need for a more realistic framework

Valdivia et al. (2016a, 2016b)



3D colliding flow

ideal MHD

partially static chemistry

- implementation of chemistry
  - ✓ computational time
  - ✓ timescales / out-of-equilibrium effects
- biphasic / monophasic
- impact of turbulent mixing
- dissipative scales / processes

Summary

- species influenced by turbulence (mixing or dissipation)

strongly	moderately	mildly
CH^+ H_2^* H_2S	HCO^+ CO	CH C_2H
SH^+ SH	SO	$I(C^+)$

- extract turbulent properties in the framework of TDRs
  - CH^+ / H ⟶ dissipation rate and density
  - SH^+ / CH^+ ⟶ ion neutral decoupling
  - CO / HCO^+ ⟶ dissipation timescale
- open issues and future prospects
  - formation of S-bearing species (H_2S, SO, SH, ...)
  - lack of realistic distribution & line profiles in 1D models
  - need for chemistry in simulation of MHD turbulence