Synthetic CO spectra of molecular clouds

Alexandre PERRONI (PhD, 2nde year)
Supervisor: Pierre HILY-BLANT

Context: universal properties of star formation

Main question

★ Dense Core Mass Function (DCMF) = origin of IMF ?

Dense cores

★ Form in massive filaments ($N_H > 10^{22}$ cm^{-2})
★ Formation is mediated by Gravity, Turbulence, Magnetic fields

My PhD: origin of the DCMF

- Role of turbulence in the formation of filaments and dense cores
- Formation of massive filaments in turbulent clouds
- Properties of turbulence in molecular clouds (MCs)
- Supersonic to subsonic transition

Methodology: benchmark turbulence statistical tools with numerical simulations

→ Modeling of CO emission spectra from Molecular Clouds (chemistry of CO, radiative transfer)
→ Observation of CO towards diffuse molecular clouds
→ Characterize turbulence properties: structure functions of high order

Taurus Molecular Cloud in 12CO(1-0) Goldsmith et al 2008 [1]

Turbulence in molecular clouds

Turbulent motions

- set in at high Reynolds numbers (Re > 3000):
  - U: characteristic velocity at scale L, dissipation scale η and kinematic viscosity ν
- are characterized by different aspects: chaotic and messy, unpredictable, multi-scale, mixing

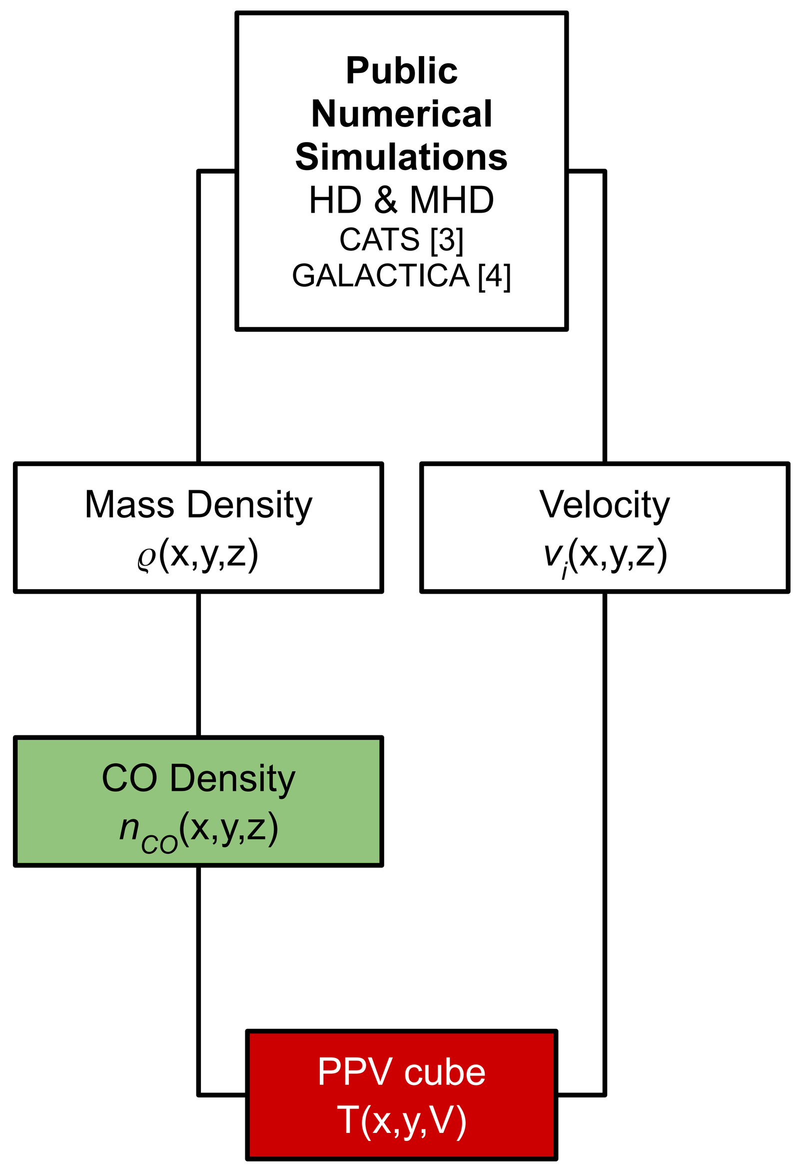
Turbulence in molecular clouds

- Reynolds number > 10^6 at 10 pc scale
- supersonic and magnetized: characterized by the sonic and Alfvénic Mach numbers M_S and M_A
- strongly supersonic (M_S ~ 10) and trans- to super-Alfvénic (M_A ~ 1-3) on large scales (~ 10 pc)
- subsonic below the sonic scale [7]

$$Re_L = \frac{U\,L}{\nu} \propto \left(\frac{L}{\eta}\right)^{4/3}$$

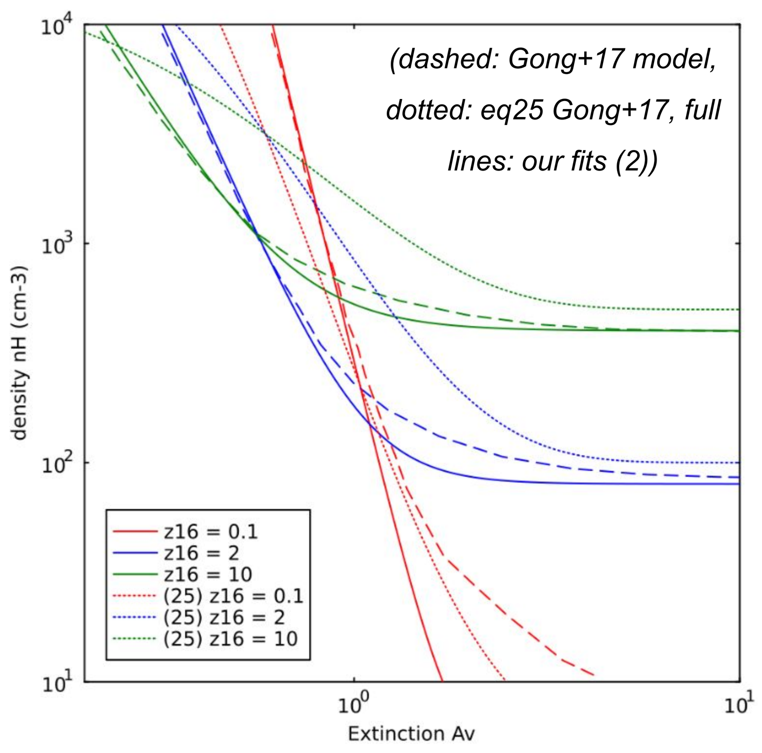
$$M_s = \sigma_v/c_s,\; M_A = \sigma_v/v_A,\; v_A = B/\sqrt{\mu_0\rho}.$$

Overall Methodology

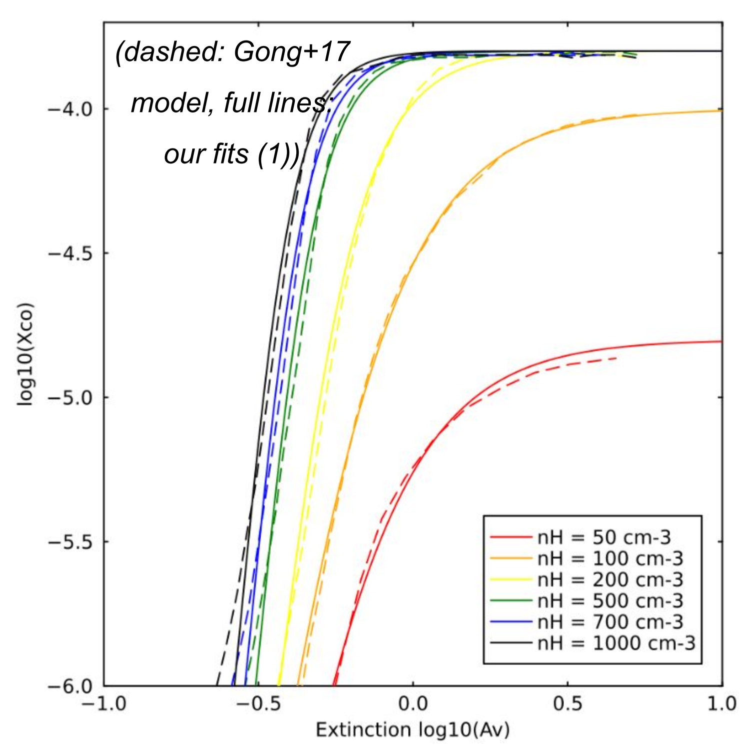


CO abundance

- X_{CO} abundance driven by C/CO transition: (F)UV photodissociation, extinction, density
  - requires following UV propagation and shielding by H_2
  - however, precise H/H2 transition not needed for bulk CO
- Adopted methodology: empirical approach to compute CO/H abundance
  - based on extensive grid calculations of Gong+17 [2]; provide analytical fit to the C/CO transition
  - present work:
    - work with log10 quantities: x=log10(X), α=log10(A_V)
    - continuous transition from xmin=-8 to xmax=-3.9 centered at α_m
    - α_m depends on density, cosmic-ray and ionization rate; expressed in terms of $\alpha_{1/2}$ (at which $X_{CO}=X_{max}/2$) as parameterized by Gong+17; in this work, alternative expression of $\alpha_{1/2}$



$$n_{1/2} = 40\zeta_{16} + 10^4\left(\frac{A_{V,1/2}}{0.37\zeta_{16}^{-0.22}}\right)^{-\beta}$$



$$x = x_m + \frac{1}{2}\Delta x\,\tanh\left(\frac{\alpha - \alpha_m}{\Delta\alpha}\right) \quad (1)$$

Spectral line

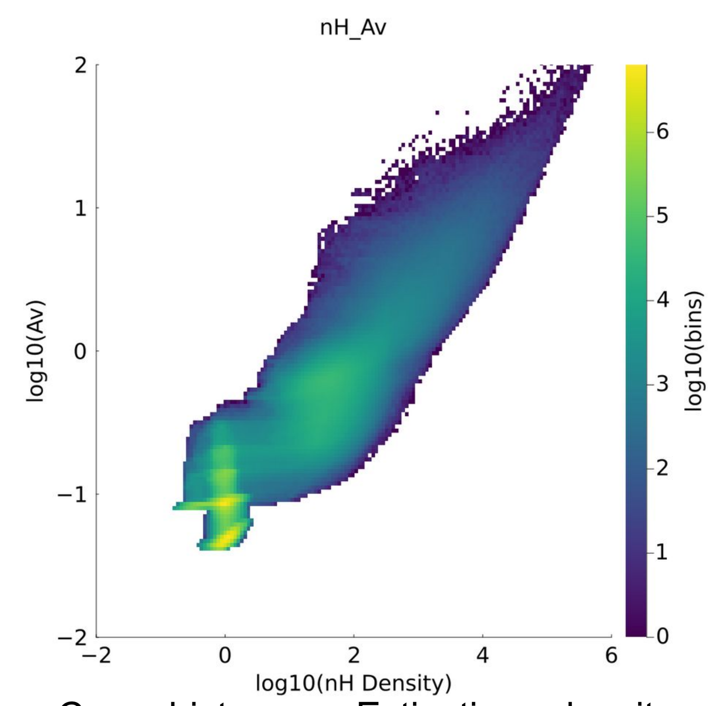
- Emergent spectrum calculated by integration of the radiative transfer equation
  - key point: each cell is treated as a uniform slab
  - use formal solution of RT equation $I_V^i = I_V^{i-1}e^{-\tau_V^i} + \left(1 - e^{-\tau_V^i}\right)B_V(T^i_{\rm kin}).$

$$\tau_V^i = \frac{c^3 A_{ul}}{8\pi\nu_0^3}\frac{3}{\mathcal{Q}(T_x^i)}\left(1 - e^{-5.5/T^i_{\rm kin}}\right)N^i_{\rm CO}\Phi(v_i, V)$$

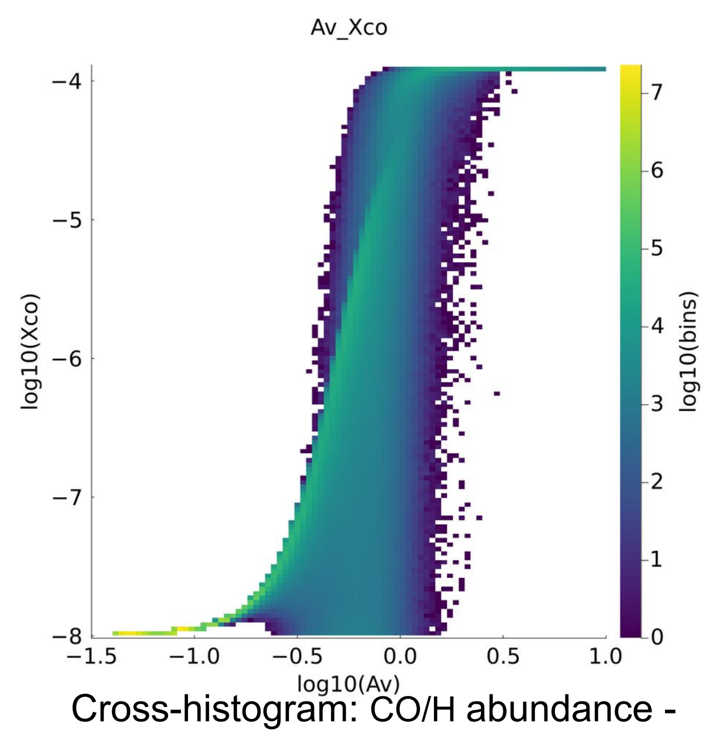
- Intrinsic line profile: Gaussian, width = (therma + local) dispersions $\Phi(v_i, V) = \frac{1}{\sqrt{2\pi\sigma_v^2}}\exp -\frac{(V - v_i)^2}{2\sigma_v^2}$

$$\sigma^2_{v,i} = (\Delta v_i/2.35)^2 + \frac{k_B T_{\rm kin}}{M}.$$

- CO level populations: LTE at local gas kinetic temperature (uniform in CATS, not in ORION)
- Computation of the excitation temperature: the excitation temperature (now set as the medium temperature field) is going be computed with radiative transfer. (GALACTICA simulation check figures)



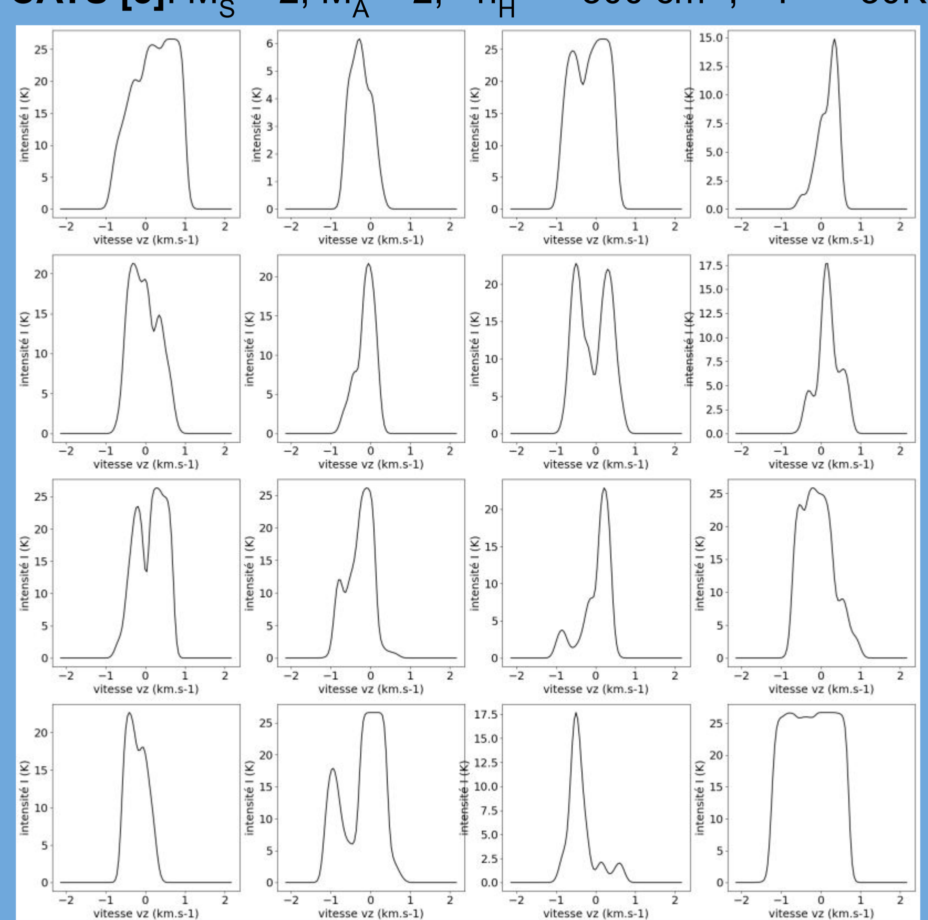
Cross-histogram: Extinction - density (see right fig right frame)

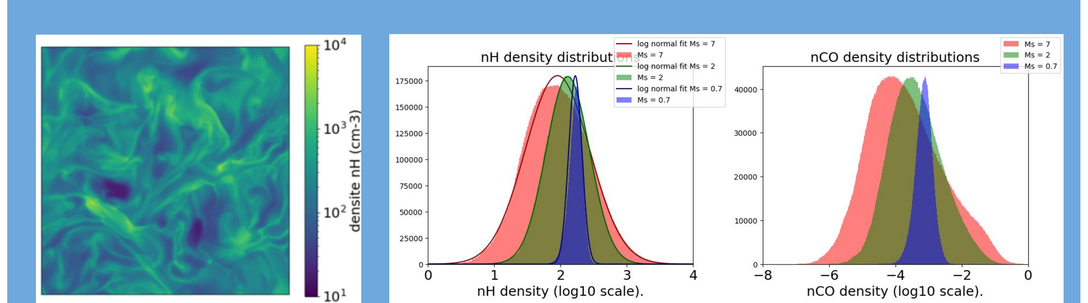


Cross-histogram: CO/H abundance - extinction (see left fig right frame)

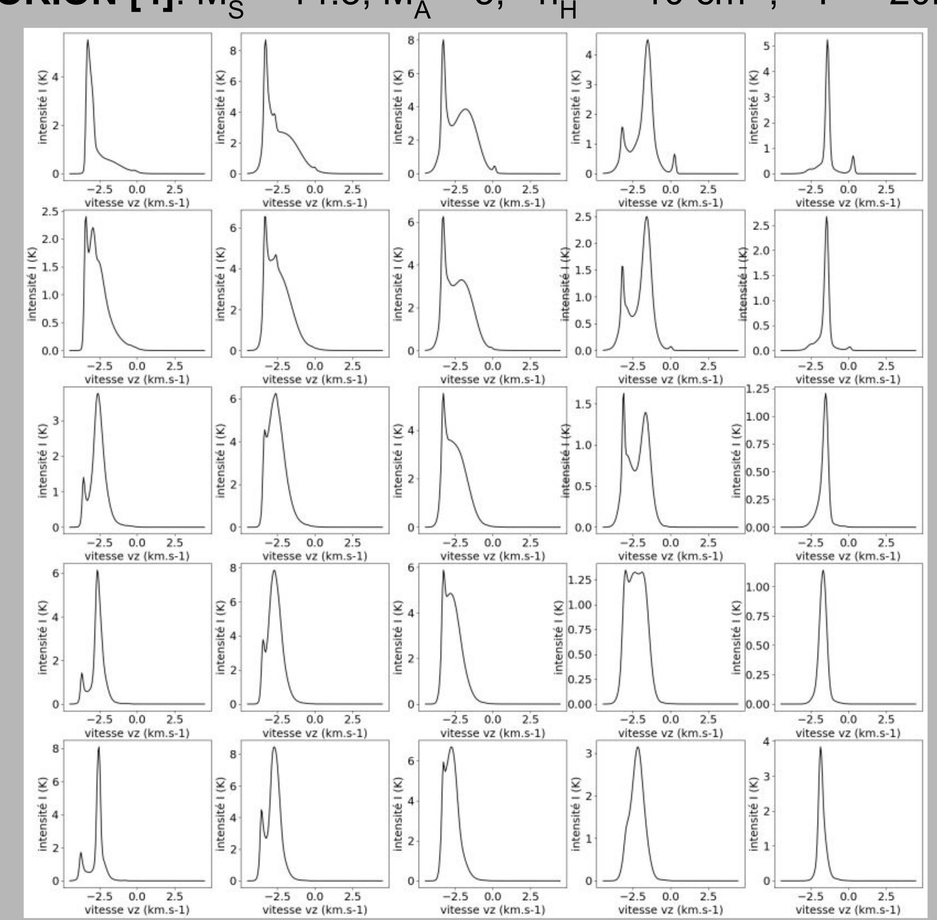
Results

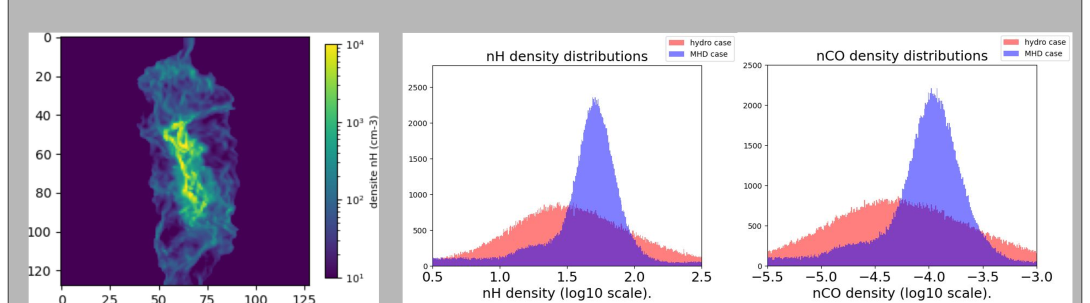
CATS [3]: M_S = 2, M_A = 2, $\langle n_H \rangle$ = 300 cm^{-3}, <T> ~ 30K



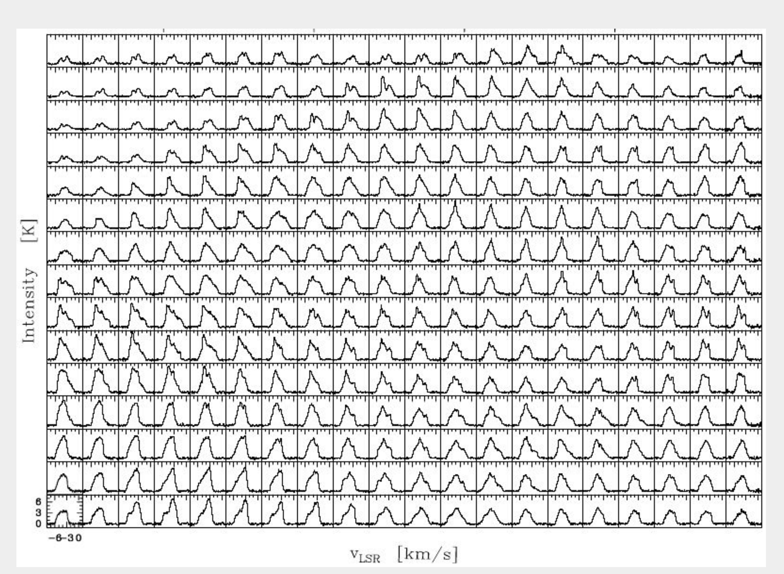


ORION [4]: M_S = 14.3, M_A = 5, $\langle n_H \rangle$ = 10 cm^{-3}, <T> ~20K

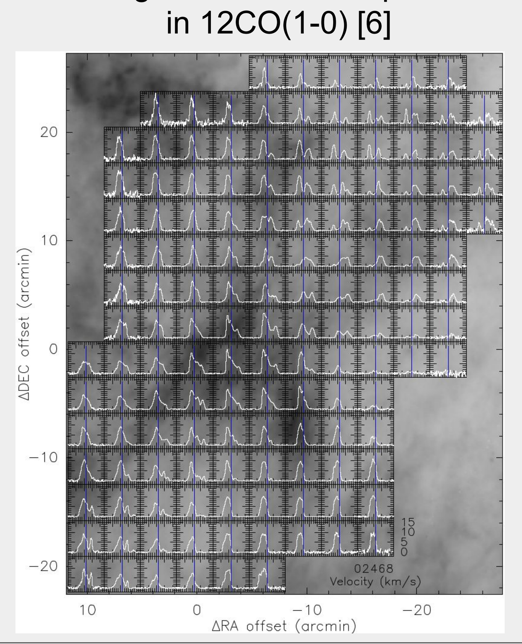




Polaris Molecular Cloud 12CO(1-0) [5]



Convergent flow in the Pipe Nebula in 12CO(1-0) [6]



- Diversity of line profiles
  - single peak, multiple peaks
  - saturated profiles
- Strong dependence on sonic Mach number
  - high Ms show two many, well separated peaks
  - high Ms unlike observations of molecular clouds

Perspectives

- CO abundance prescriptions for gas-phase depletion at high density
- CO abundance: coupling with chemical calculations; review of CO chemistry
- Radiative transfer: 3D Monte Carlo calculations

- [1] Goldsmith et al 2008
- [2] Gong, Ostriker, Wolfire 2017
- [3] Burkhart et al 2020
- [4] Ntormousi et Hennebelle 2019
- [5] Hily-Blant & Falgarone 2007
- [6] Delcamp, Hily-Blant, Falgarone *in prep.*
- [7] Federrath et al 2021