The origin of the Dense Core Mass Function

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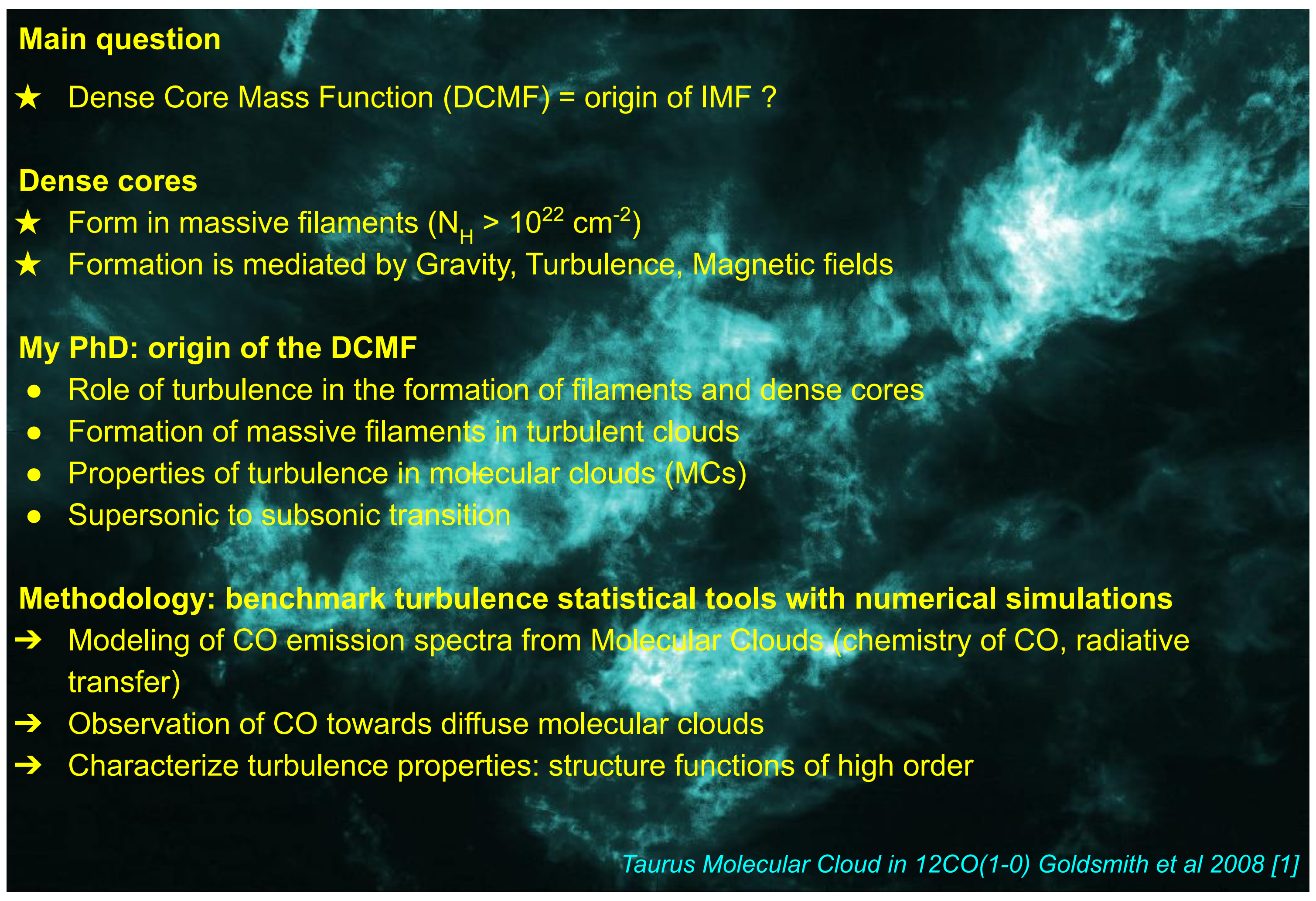
Context: universal properties of star formation



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

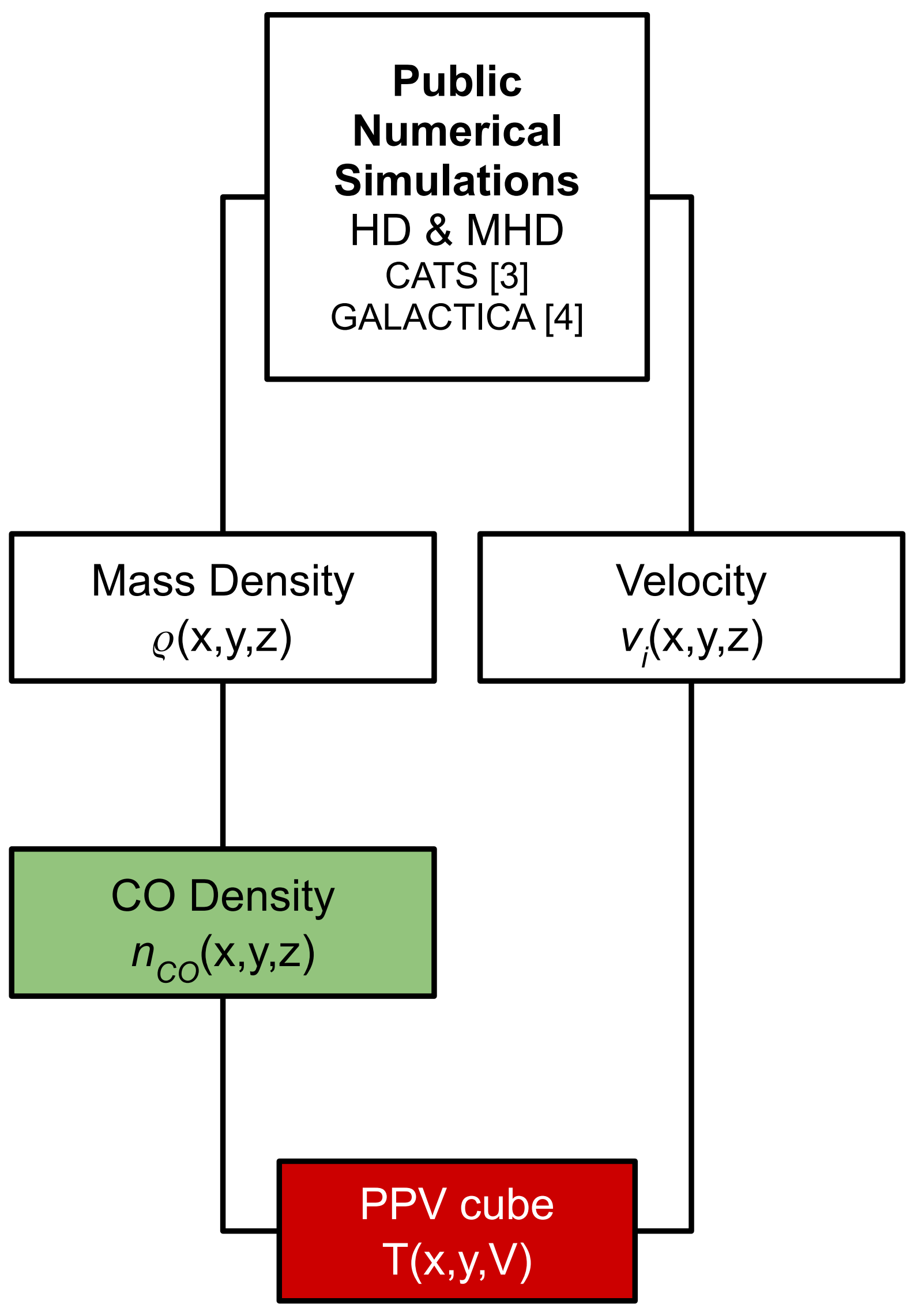
Turbulence in molecular clouds

- 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 [5]

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

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

Overall Methodology



Public Numerical Simulations
HD & MHD
CATS [3]
GALACTICA [4]

Mass Density
$\varrho(x,y,z)$

Velocity
$v_i(x,y,z)$

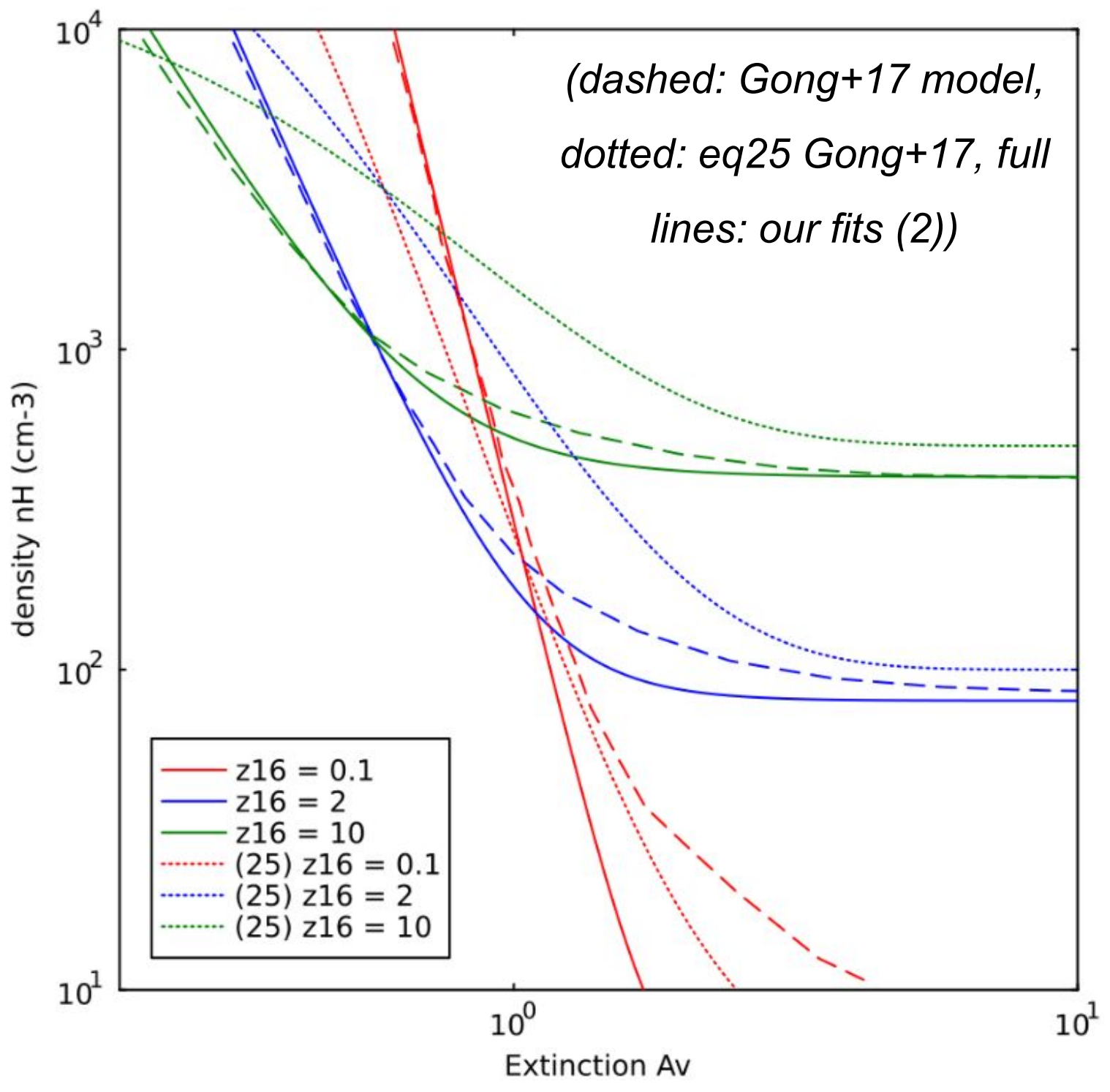
CO Density
$n_{CO}(x,y,z)$

PPV cube
T(x,y,V)

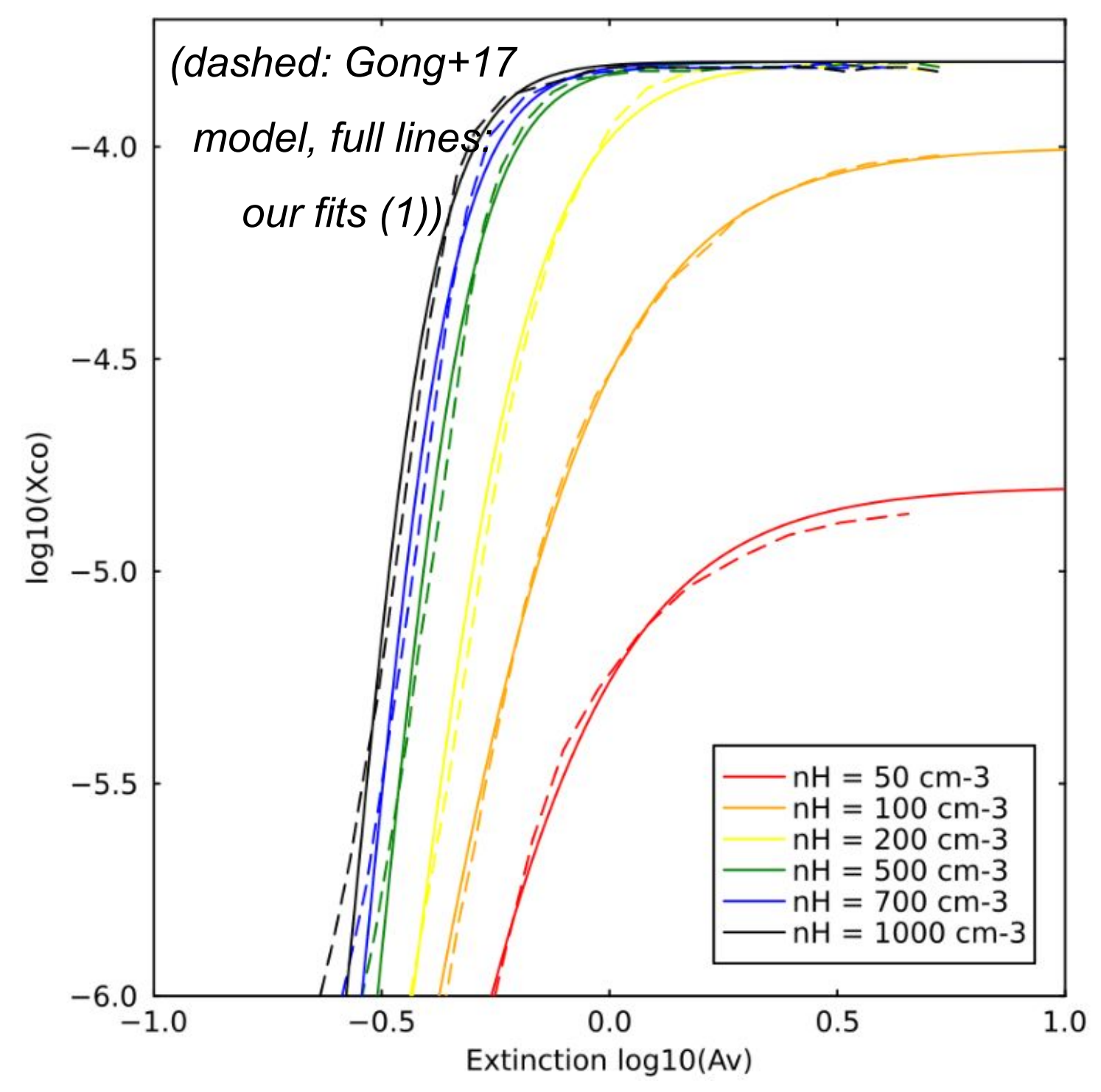
CO abundance

- 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 $\alpha_{1/2}$



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



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

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 $I_V^i = I_V^{i-1}e^{-\tau_V^i} + \left(1 - e^{-\tau_V^i}\right)B_\nu(T_{ex}^i)$

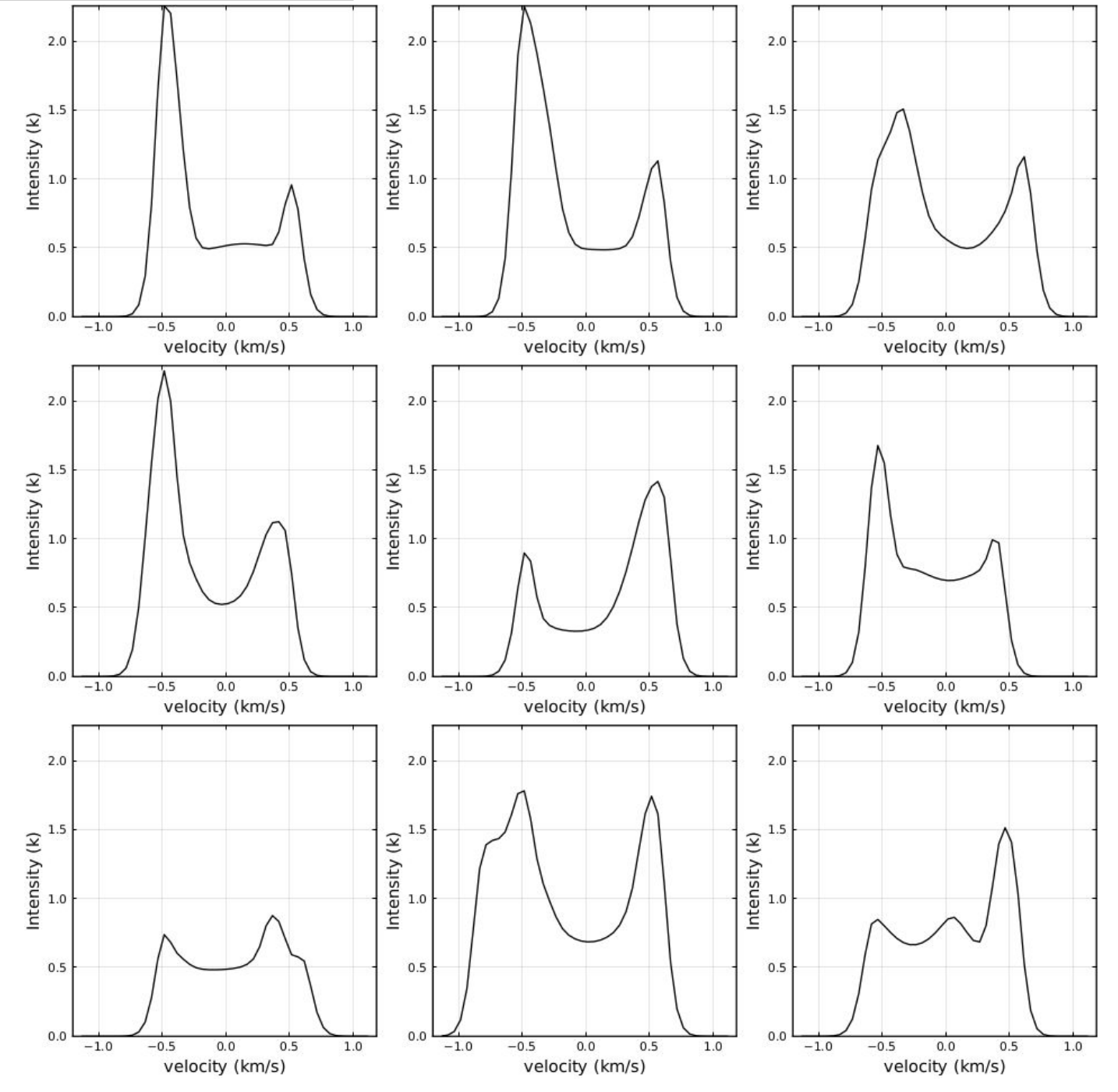
$$\tau_V^i = \frac{c^3 A_{ul}}{8\pi\nu_0^3}\frac{3}{\mathcal{Q}(T_{ex}^i)}\left(1 - e^{-5.5/T_{ex}^i}\right)N_{CO}^i\Phi(v_i, V)$$

- Intrinsic line profile: Gaussian, width = thermal dispersions $\Phi(v_i, V) = \frac{1}{\sqrt{2\pi\sigma_v^2}}\exp -\frac{(V - v_i)^2}{2\sigma_v^2}$
- CO levels populations out of LTE: analytical computation of the excitation temperature with radiative transfer including CO rotational levels until J=5.
- The increment velocity centroids (CVI) are then computed to establish structures functions of high order to characterize turbulence properties: $CVI(\boldsymbol{r}) = CV(\boldsymbol{r} + \boldsymbol{\ell}) - CV(\boldsymbol{r}), \quad \boldsymbol{r} = (x, y)$

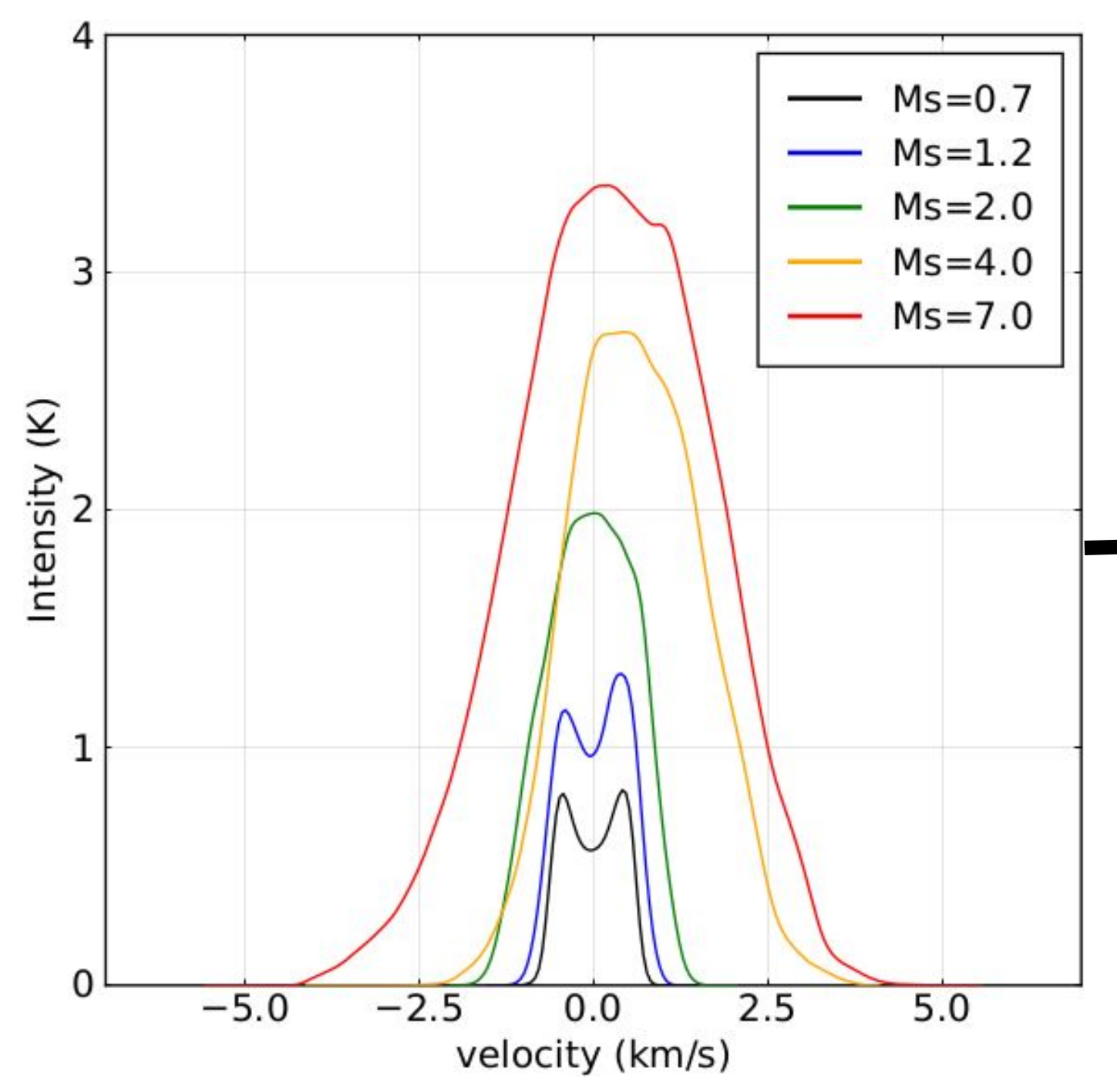
$$CV(x, y) = \frac{1}{\sum_{i=1}^N I(x, y, v_i)}\sum_{i=1}^N I(x, y, v_i)\, v_i$$

Results

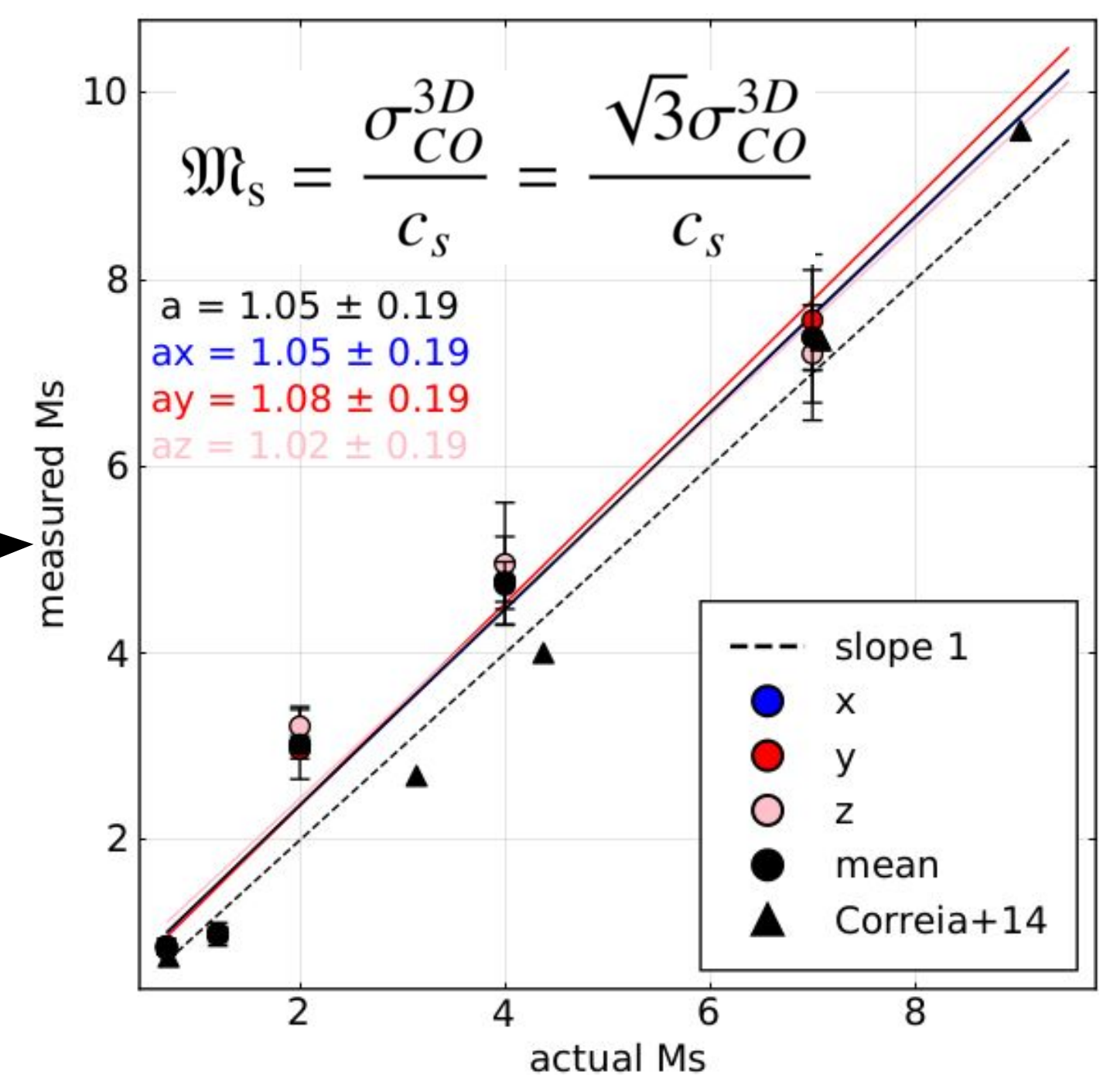
Models



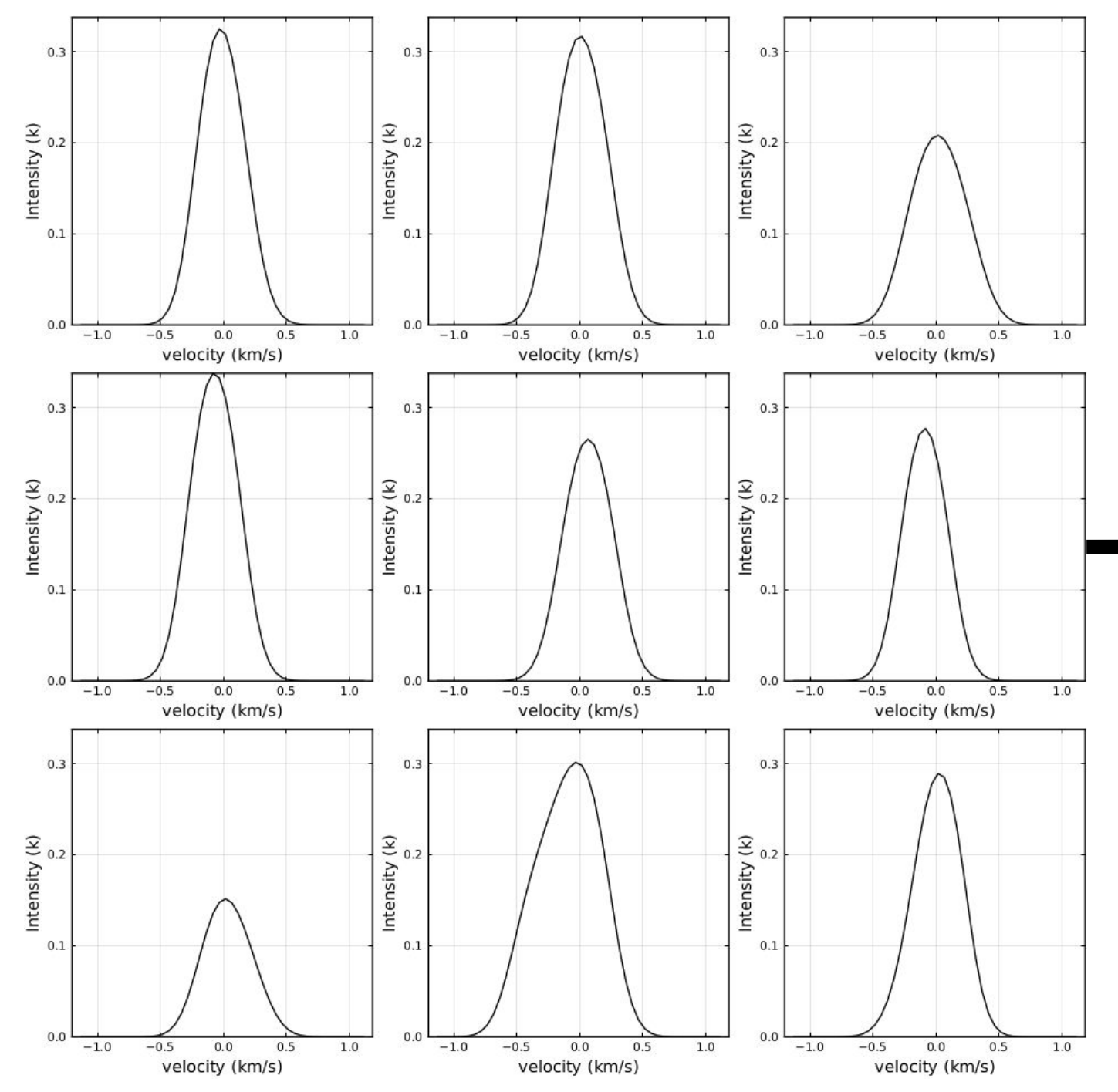
12CO synthetic spectra from **CATS** simulation with Ma = 2, Ms = 0.7



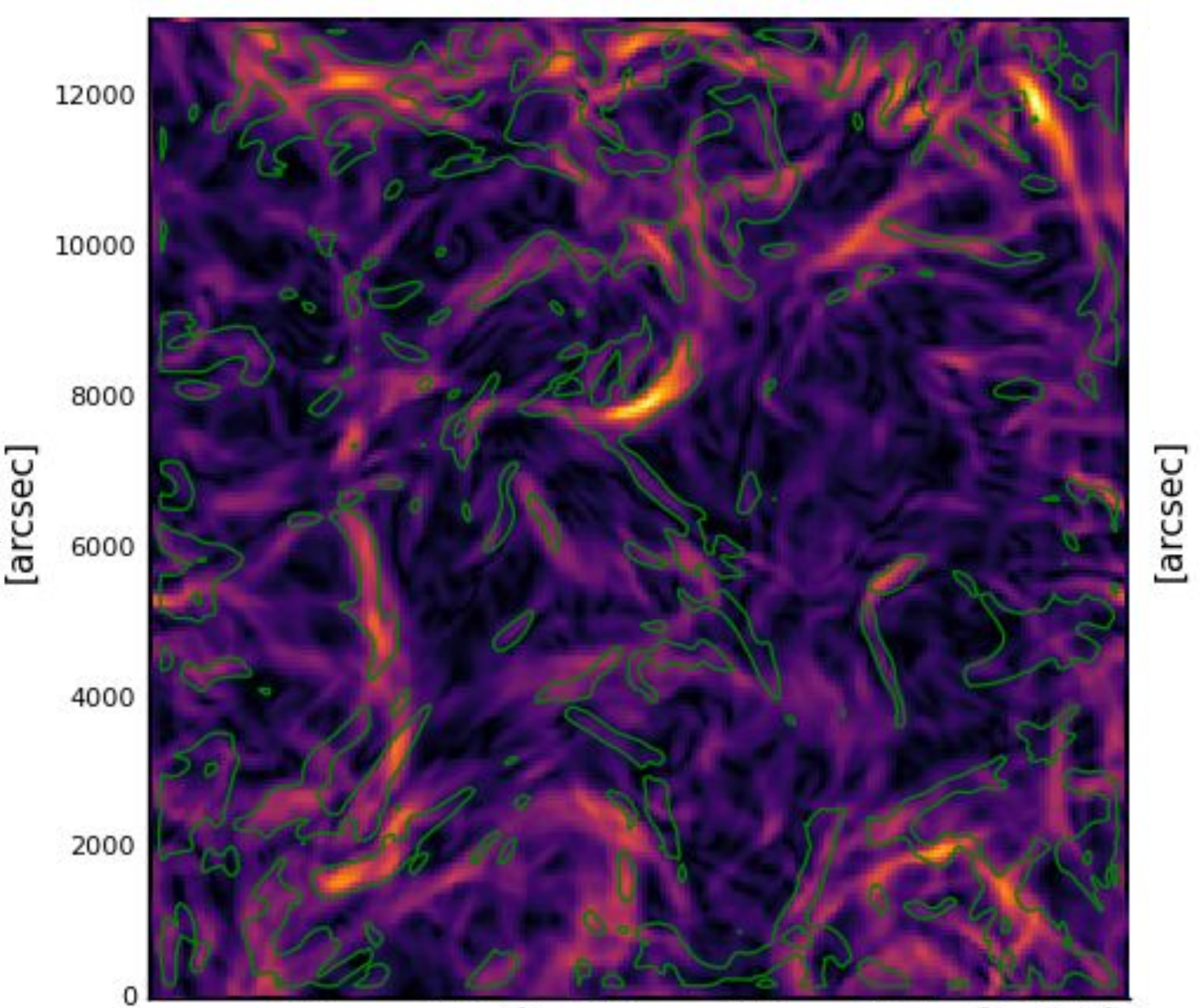
CATS simulation 12CO mean spectra for Ma =2 and every range of Ms



A quite good estimation of Ms is obtained thanks to spectra width [6]

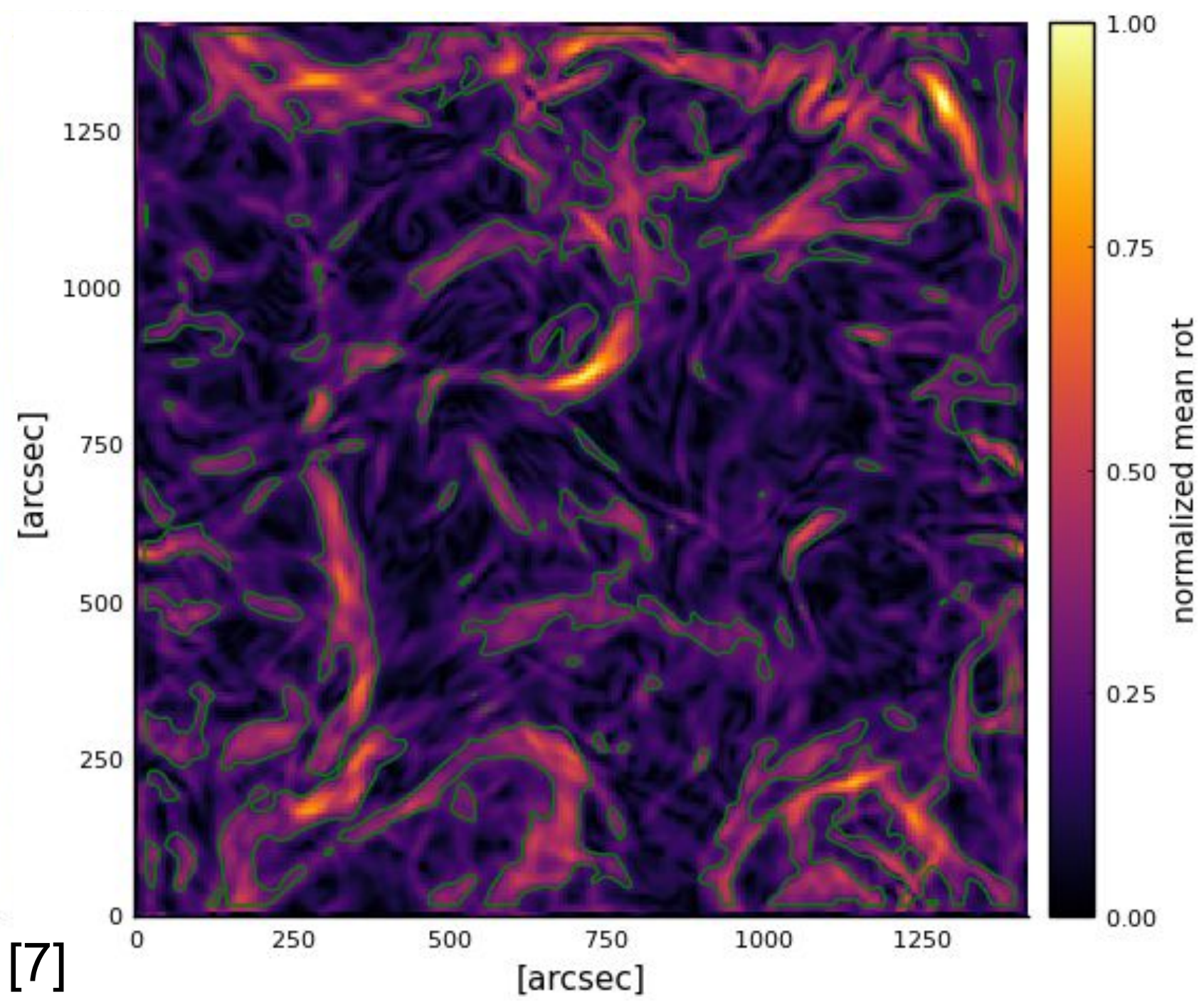


C18O synthetic spectra from **CATS** simulation with Ma = 2, Ms = 0.7



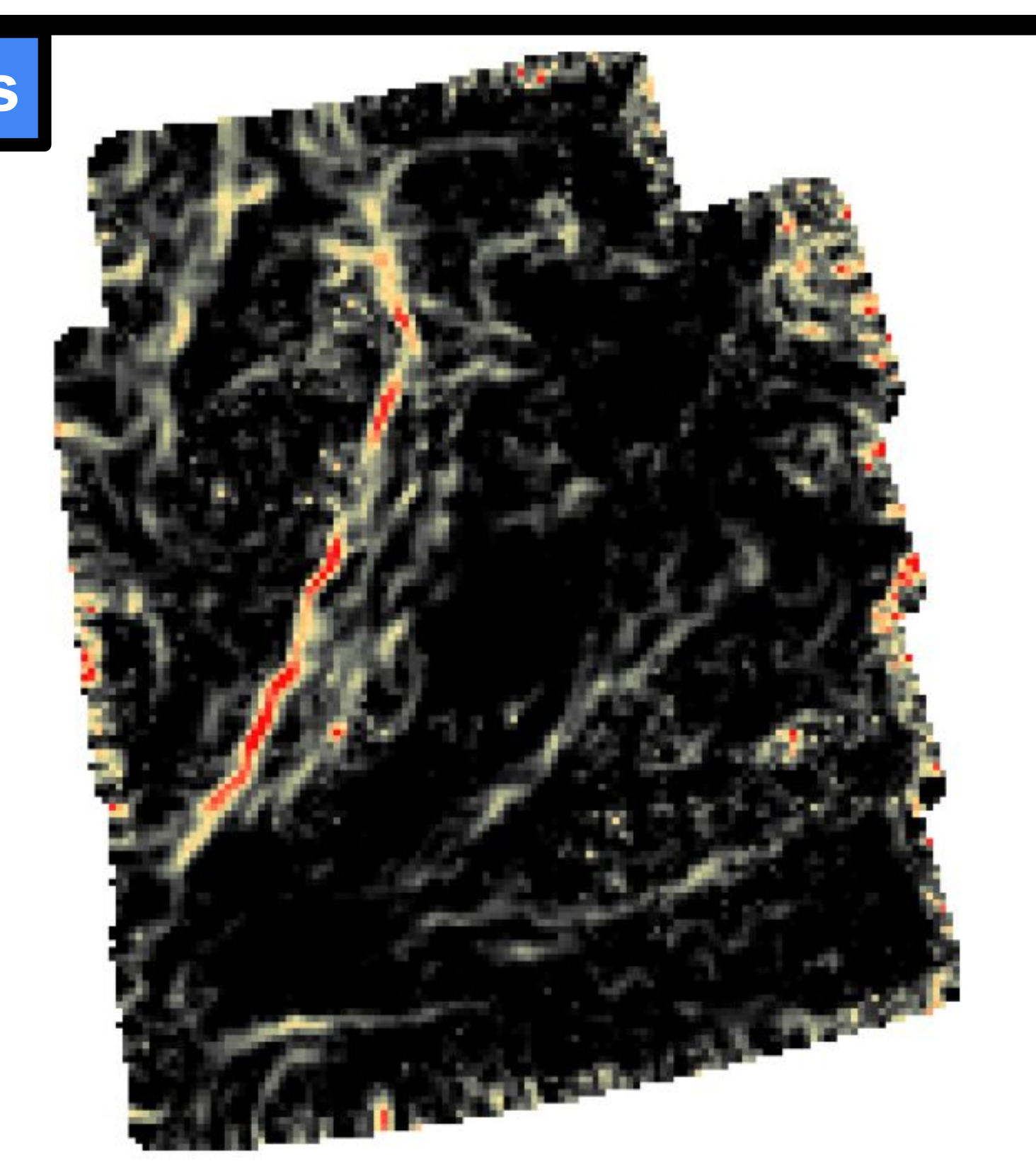
$$\left[\langle(\mathrm{rot}\,\boldsymbol{v})_y\rangle^2 + \langle(\mathrm{rot}\,\boldsymbol{v})_z\rangle^2\right]^{1/2}$$ [7]

CVI contours (high CVI) of C18O (optically thin) in green show a relative correlation with the rotational filed

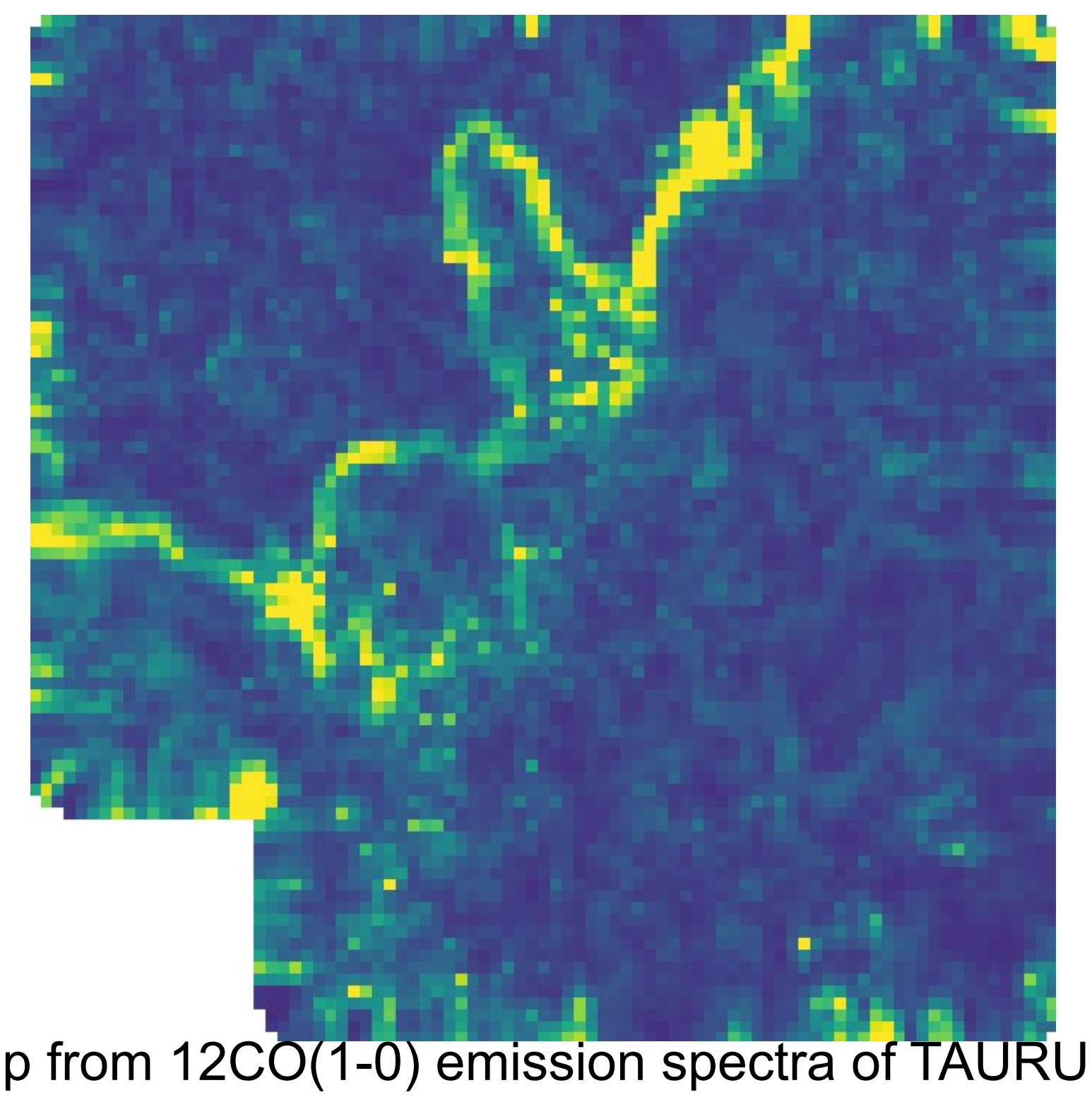


CVI contours of Hydrogen in green show a direct correlation with the rotational field [7]

Observations



CVI map from 12CO(1-0) emission spectra of POLARIS (from IRAM's 30m)



CVI map from 12CO(1-0) emission spectra of TAURUS (from IRAM's 30m)

Conclusion and perspectives

- A good approximation of Ms can be measured from the spectra width (with a supposed sound speed)
- The 13CO or C18O (optically thin) CVI contours can partially rectrace the dissipation shown by the rotational field [7]
- The filamentary structures formed in CVI maps from observations look likes the ones formed in modeled CVI

=> structure functions of high order thus obtained will help us to characterise the turbulence properties of the observed molecular clouds

- [1] Goldsmith et al 2008
- [2] Gong, Ostriker, Wolfire 2017
- [3] Burkhart et al 2020
- [4] Ntormousi et Hennebelle 2019
- [5] Federrath et al 2021
- [6] Correia et al 2014
- [7] Lis et al 1996