I. Physikalisches Institut, Köln ITA, Heidelberg ISM SPP 1573/2

Scales and thresholds in molecular cloud turbulence

Volker Ossenkopf, Ralf Klessen, Stefanie Walch

Context

- In the first 3 years, we tested **statistical tools** to **compare simulations of the turbulent multi-phase ISM with recent observations**.
- These tools are able to **identify characteristic scales and parameters** of the different physical processes that govern the dynamic evolution of the ISM.
- We started to apply them to data sets from large surveys and compare the results with the outcome of sophisticated (M)HD simulations.

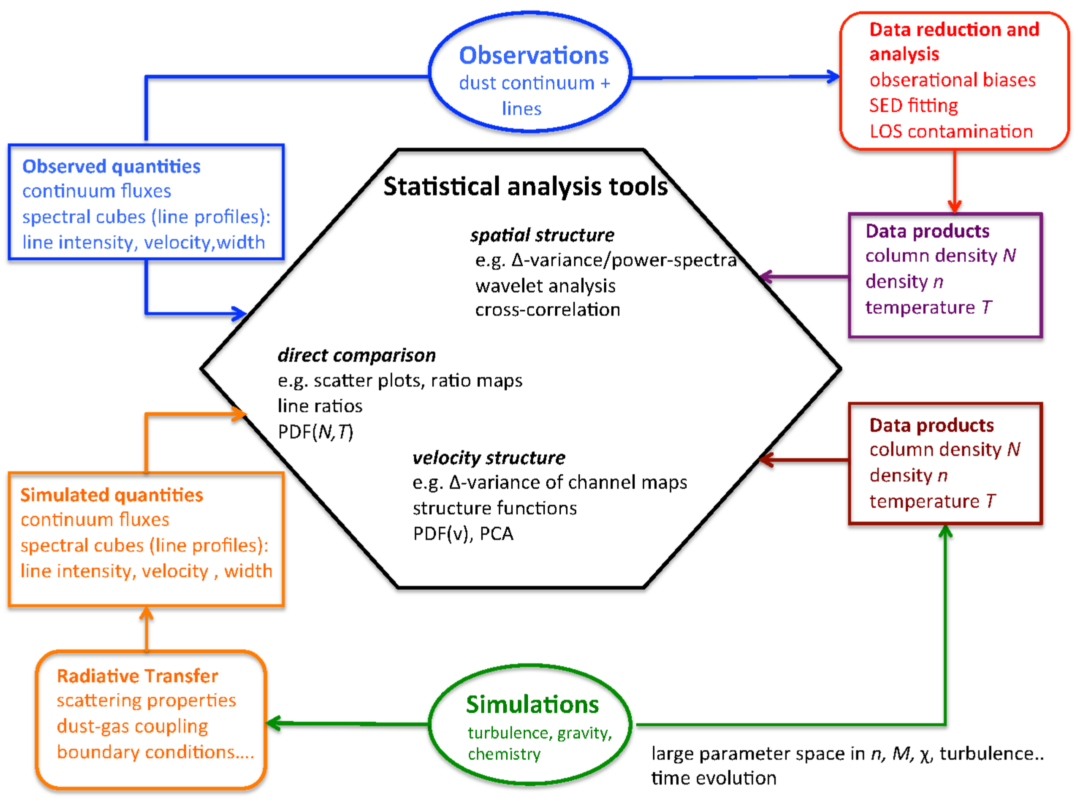

Figure 1: Work flow in the project. The central tool for comparing simulations and observations are the statistical measures that will be applied both in the direct comparison of actual and simulated observations and in the comparison of characteristic parameters.

Column density PDFs

Probability distribution functions (PDFs) of column density are one of the best tools to disentangle the **relative importance of turbulence and gravity** in a molecular cloud. Observed PDFs first need to be corrected for observational biases (Fig. 1). This is critical for deriving the properties of the underlying turbulence.

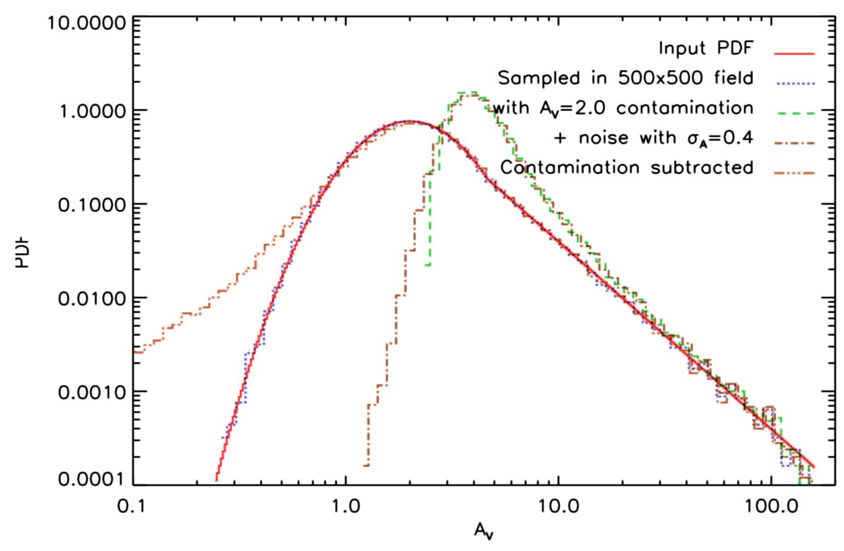

Figure 2: Simulation of contamination effects on a measured column density PDF representative for the observations of the Maddalena molecular cloud. Ignoring foreground contamination leads to an underestimate of the width of the log-normal part and an overestimate of the power-law exponent (Schneider, Ossenkopf, Csengeri, Klessen, et al. 2014, A&A submitted, arXiv 1403.2996)

We showed that double-peaks in the PDF can arise from **radiative feedback** and that low- and high-mass star-forming regions share similar PDF properties. The scales of the **transition from turbulence-dominated to gravitationally dominated** structures determine the collapse scenarios.

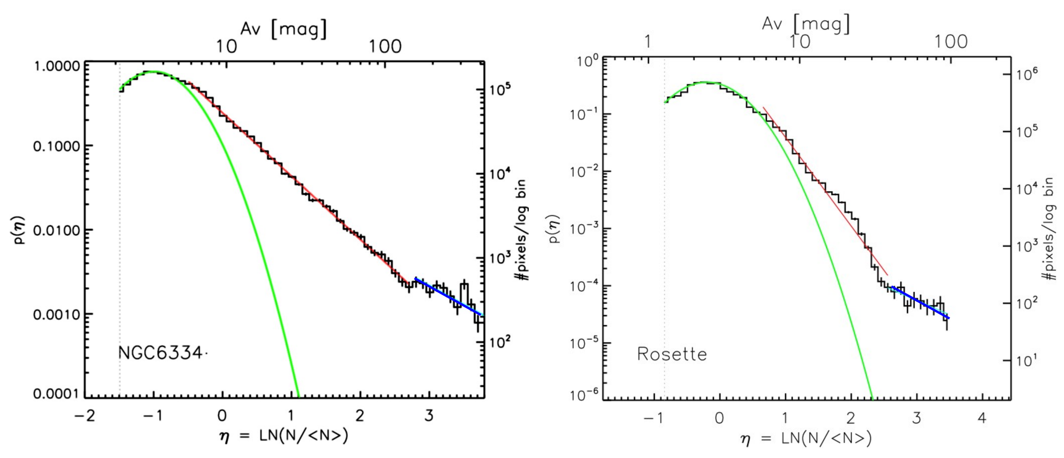

Figure 3: Column density PDFs from various high-mass star-forming clouds. They are all characterized by a log-normal contribution from the turbulent large-scale structure and two power law tails indicating gravitational collapse. Not all clouds show two tails and the transitional density between them also varies between different clouds (Russeil et al. 2013, Schneider, Csengeri, Ossenkopf, Klessen in prep.).

We often find **two power-law tails** from self-gravity (Fig. 2). The transition between the two power laws may indicate a transition between spherically symmetric and filamentary collapse.

Cross correlation

With the **wavelet-based cross correlation** (WWCC) we developed a tool to compare the mutual scaling of turbulent structures in a pair of maps. It measures the degree of correlation and systematic offsets as a function of the size scale and includes an inherent weighting for observational uncertainties.

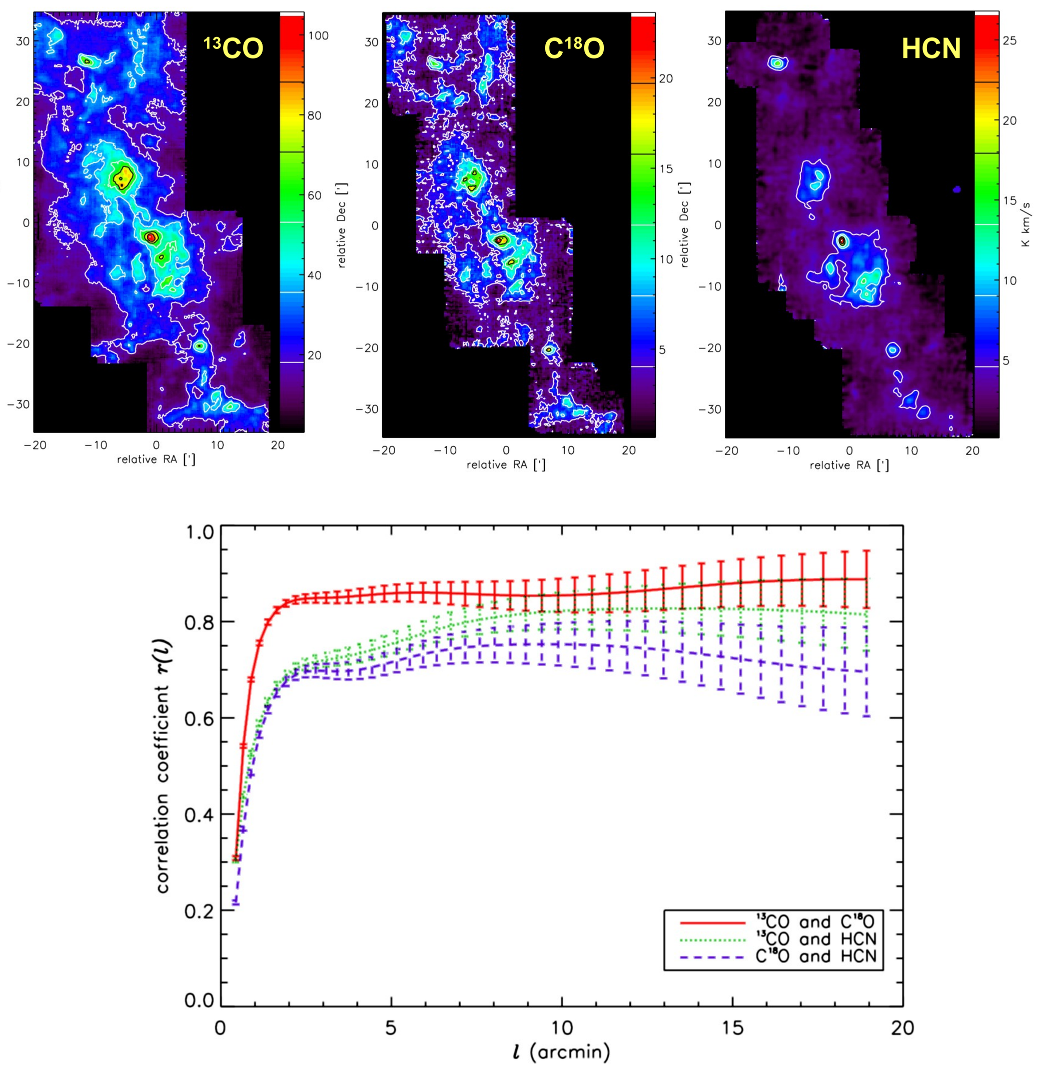

Figure 4: Integrated line maps of G333 (Lo et al. 2009) and wavelet cross correlation function as a function of spatial scale for the three pairs of maps. ^{13}CO - $C^{18}O$ are perfectly correlated above the noise scale. HCN indicates a chemical differentiation at scales < 7´ (Arshakian & Ossenkopf in prep.).

The similarity of ^{13}CO and $C^{18}O$ maps on all scales shows that **optical depth and excitation effects** play no significant role. The difference in the structures seen in HCN below 7' indicates a chemical transition scale of about 8 pc.

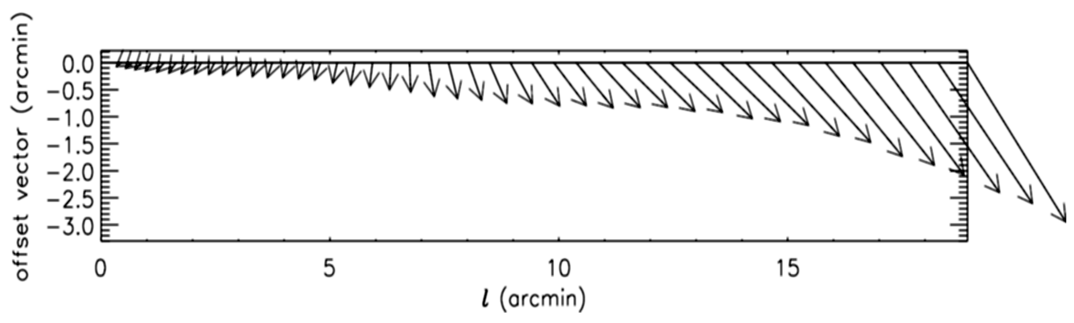

Figure 5: Offset vectors of characteristic structures in HCN relative to the characteristic structures in ^{13}CO for the G333 maps in Fig. 3. The increase with size scale and follow the direction of the overall filament to the south-west. Larger, low-density structures are further displaced.

The growing offset at larger scales probably indicates a **cometary density structure** pointing to the south-west. Alternatively it could be produced by an anisotropic large scale-radiation field.

The method can also be used to measure heating lengths, IR and UV penetration depths, and to analyze the scaling of velocity structures.

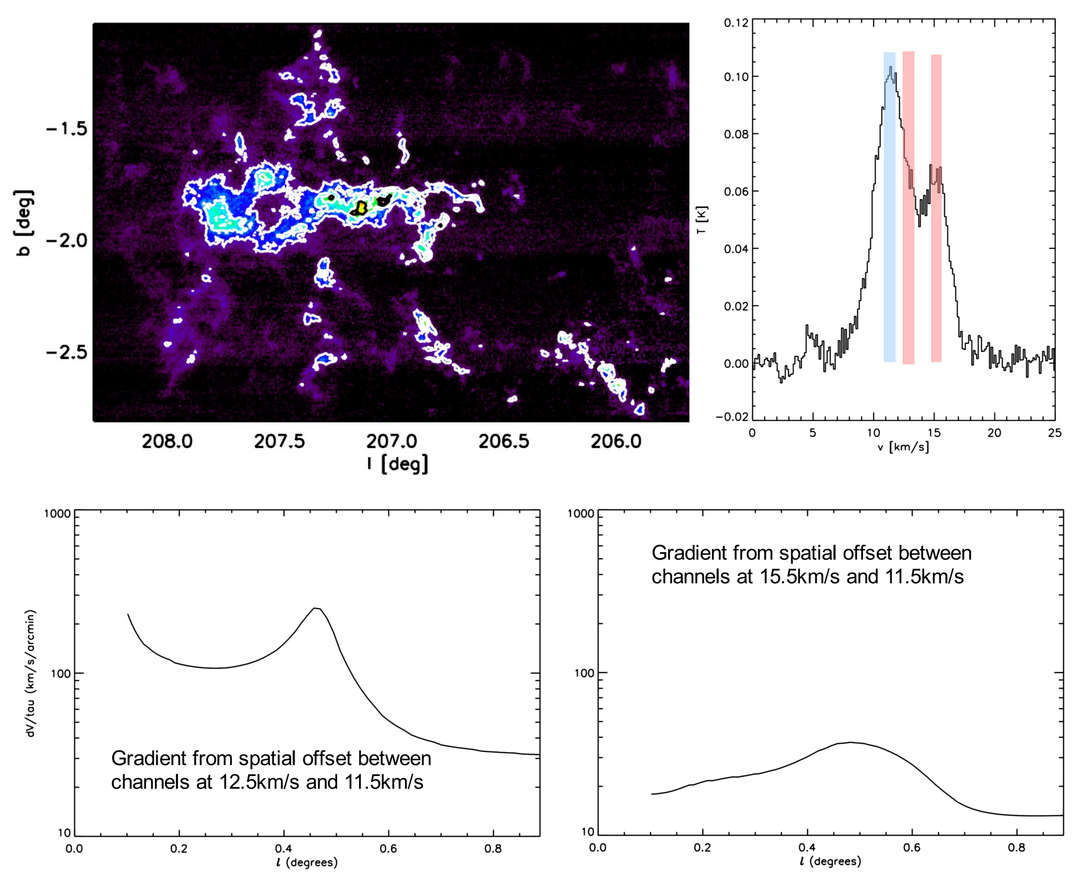

*Figure 6: ^{13}CO 1-0 observations of the Rosette molecular cloud (Heyer et al. 2006). **Top:** Integrated line map and average line profile. **Bottom:** Scale-dependent velocity gradients measured between the reference channel at 11.5 km/s and the channels at 12.5 km/s and 15.5 km/s. Within the main component, there is a systematic gradient composed from a contribution following constant gradient and a shear component at 27'. The small, constant gradient between the two velocity components indicates two independent clouds.*

Measuring the scale-dependent shear velocity distribution allows to address the **injection scale of interstellar turbulence**.

(M)HD and radiative transfer

With Gadget2, FLASH4 and AREPO we now have a full suite of simulation tools that include the effects of **gravitation, radiative transfer, dust-coupling, and fully time-dependent chemical networks**.

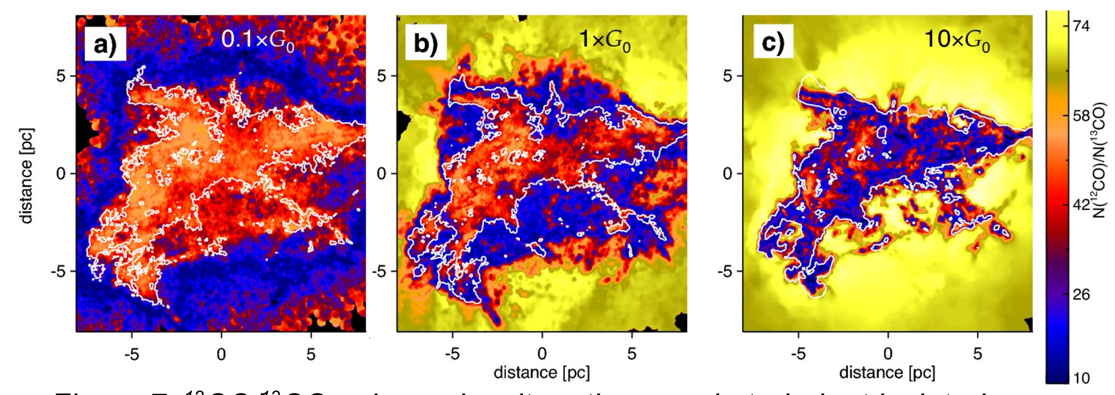

Figure 7: $^{12}CO/^{13}CO$ column density ratio maps in turbulent isolated molecular clouds for varying strength of the interstellar radiation fields: a) 0.1 G_0, b) 1 G_0, and c) 10 G_0 (Szucs, Glover, Klessen 2014, MNRAS submitted)

We already studied the impact of:

- H_2 formation
- Radiative and dynamical feedback
- Radiative transfer, including self-shielding, dust attenuation, ...

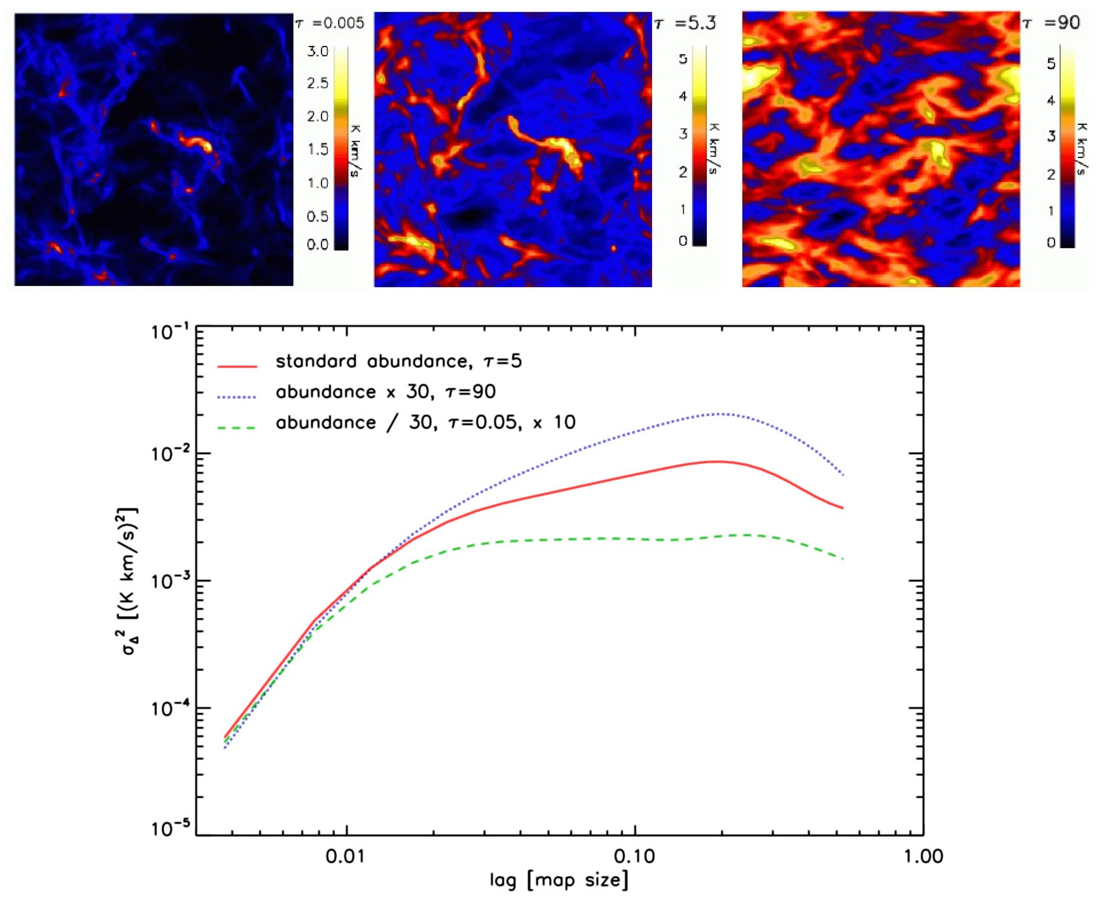

Figure 8: Maps of the ^{13}CO 2-1 line computed in a supersonic MHD simulation (M_S=7, M_A=0.7) for varying abundances to investigate optical depth effects. The lower plot shows the impact on the Δ-variance spectra. The scaling in the integrated line maps is dominated by radiative transfer effects instead of the underlying density structure (Burkhart et al. 2013a,b)

No single tracer is suitable to recover the density and velocity structure in turbulent clouds. We have to combine the information from **multiple species, transitions, and the dust continuum**.

Work program

We propose to **exploit our new tools** to identify physical scales and thresholds where the properties of the turbulent cascade change.

Key goals:

- Identify the best observational tracer for each threshold.
- Quantify the role of filamentary structures in the dynamical evolution.
- Refine the numerical simulations to include stellar feedback processes (ionizing radiation, winds, and outflows)
- Measure the scales of
  - chemical mixing
  - UV and IR penetration in filamentary clouds
  - characteristic velocity patterns
  - turbulence dissipation.
- Measure the density thresholds for
  - onset of gravitational collapse in various geometries
  - excitation of particular cooling processes
  - chemical phase transitions.

Outlook:

- Predict the cloud fate based on the measured scaling properties.