Column density PDFs as diagnostic tool

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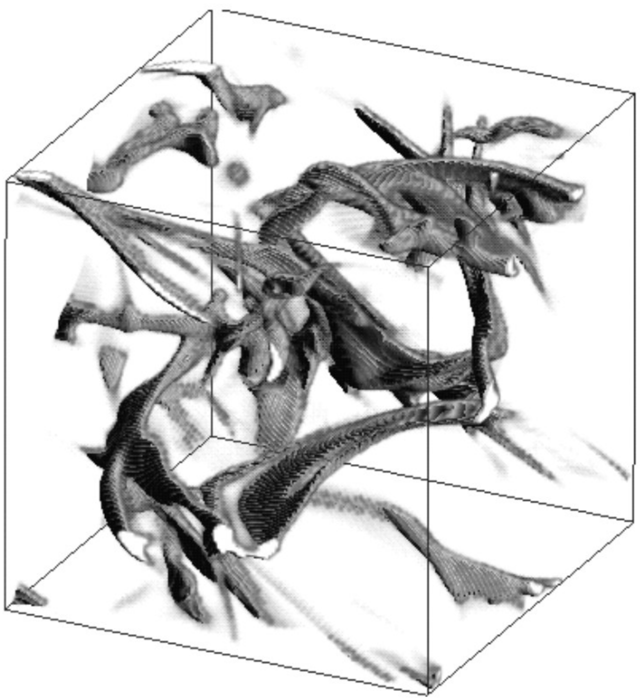
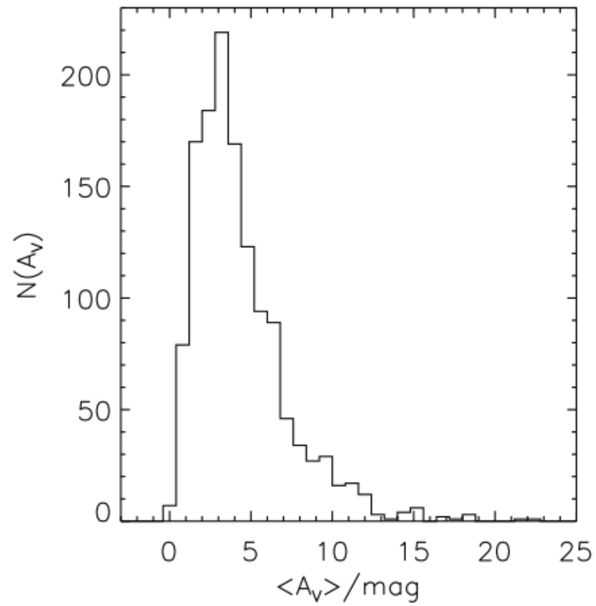
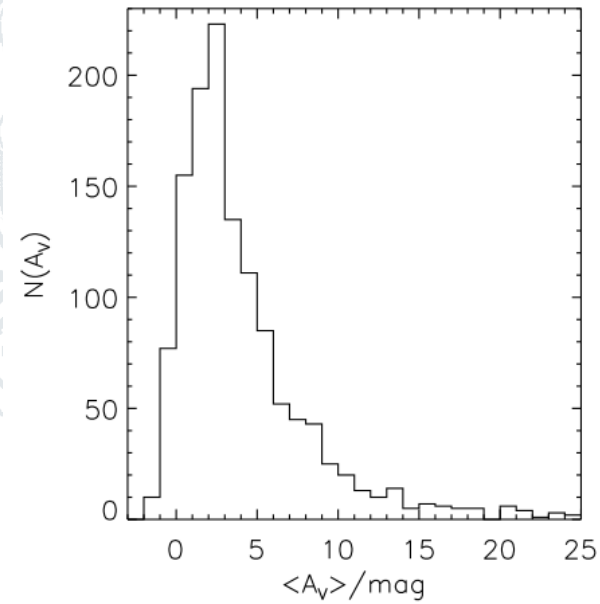
Probability distribution functions (PDFs) of column densities:

- From turbulence simulations (Padoan & Nordlund 1999)





PDF of supersonic model



Observed in IC5146 (Lada et al. 1994)

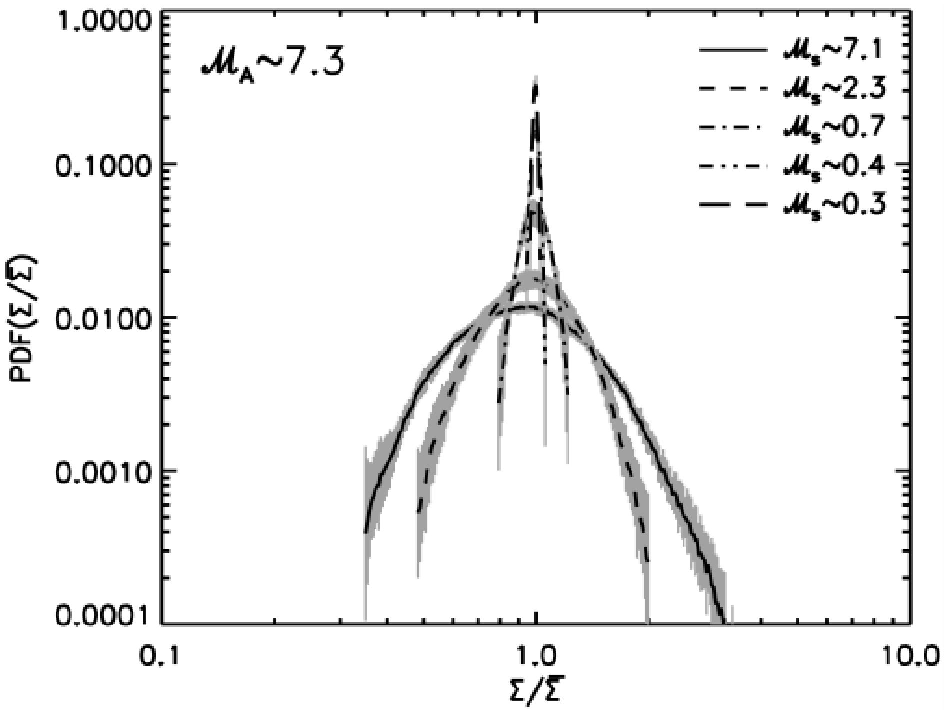
  - For logarithm of column densities: $\eta = \ln\left(\frac{N}{N_{\rm peak}}\right)$

→ Gaussian shape: $p_\eta(\eta) = \frac{1}{\sqrt{2\pi}\sigma_\eta} \exp\left(-\frac{\eta^2}{2\sigma_\eta^2}\right)$ → **log-normal**

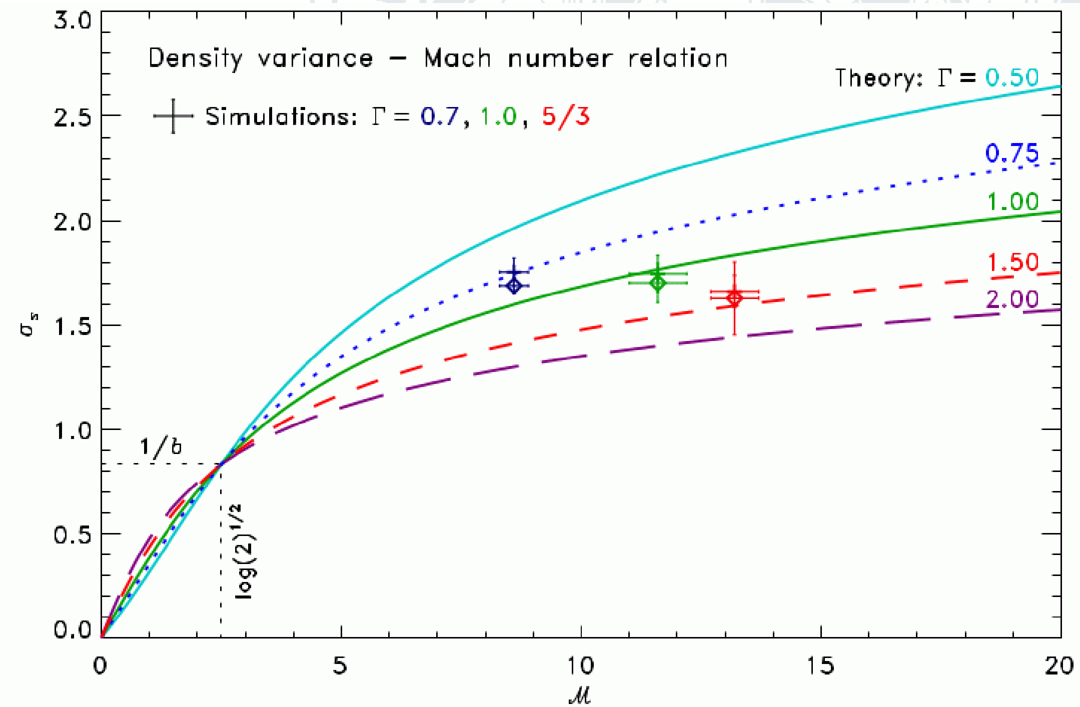
Probability distribution functions of column densities

Log-normal PDFs of turbulent media:

- PDF width σ_η determined by Mach number (Passot & Vazquez-Semadeni 1998)



Column-density PDFs from isothermal simulations with different sonic Mach numbers (Kowal et al. 2007)

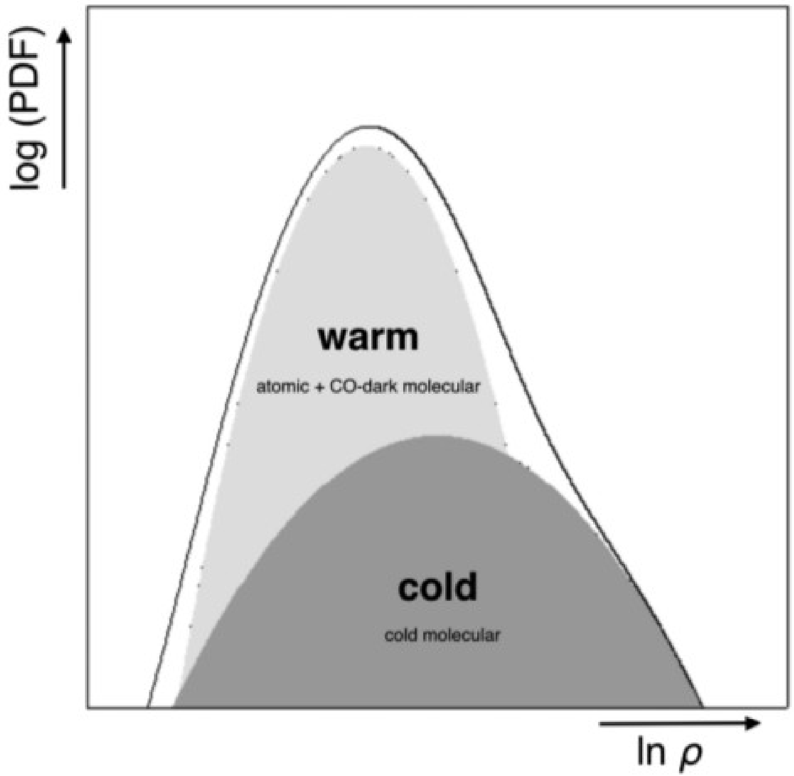


Parameter study for non-isothermal simulations gives small correction (Federrath & Banerjee 2015)

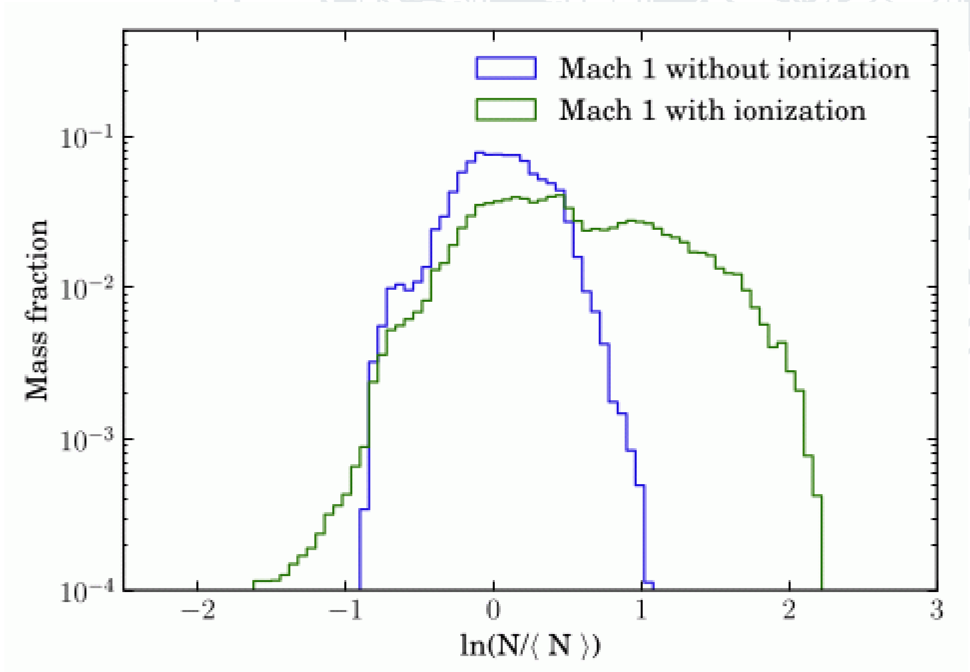
- $\sigma_\eta^2 = A \times \ln\left(1 + b^2 \mathcal{M}_s^2\right)$
- Small asymmetries depending on the magnetic field impact

Phase transitions:

- Different phases: – different equation of state
  - – different Mach numbers → double-peak PDFs



Brunt (2015)



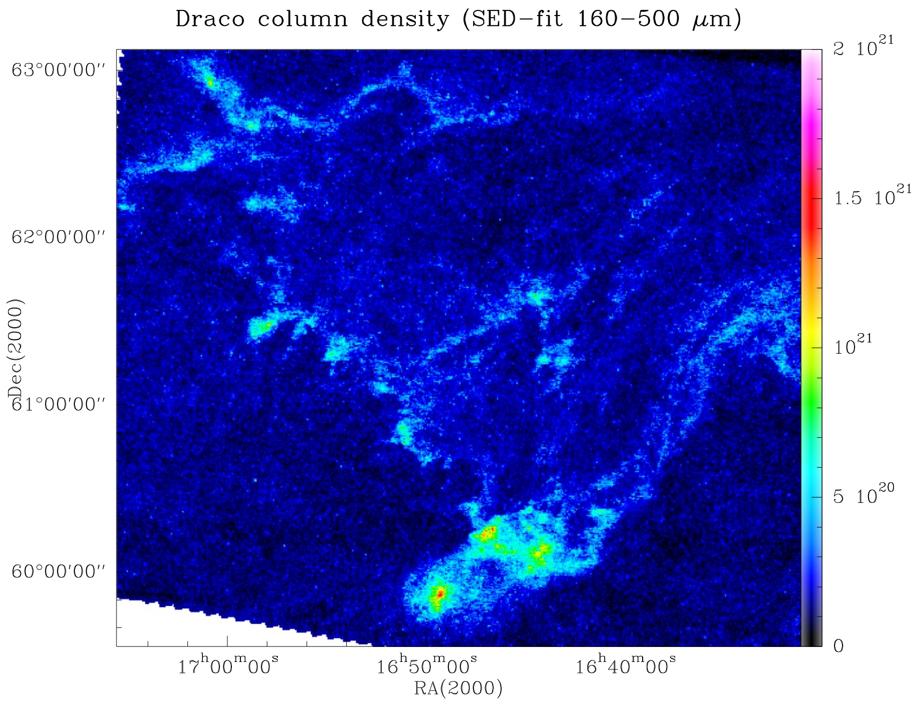
Tremblin et al. (2014)

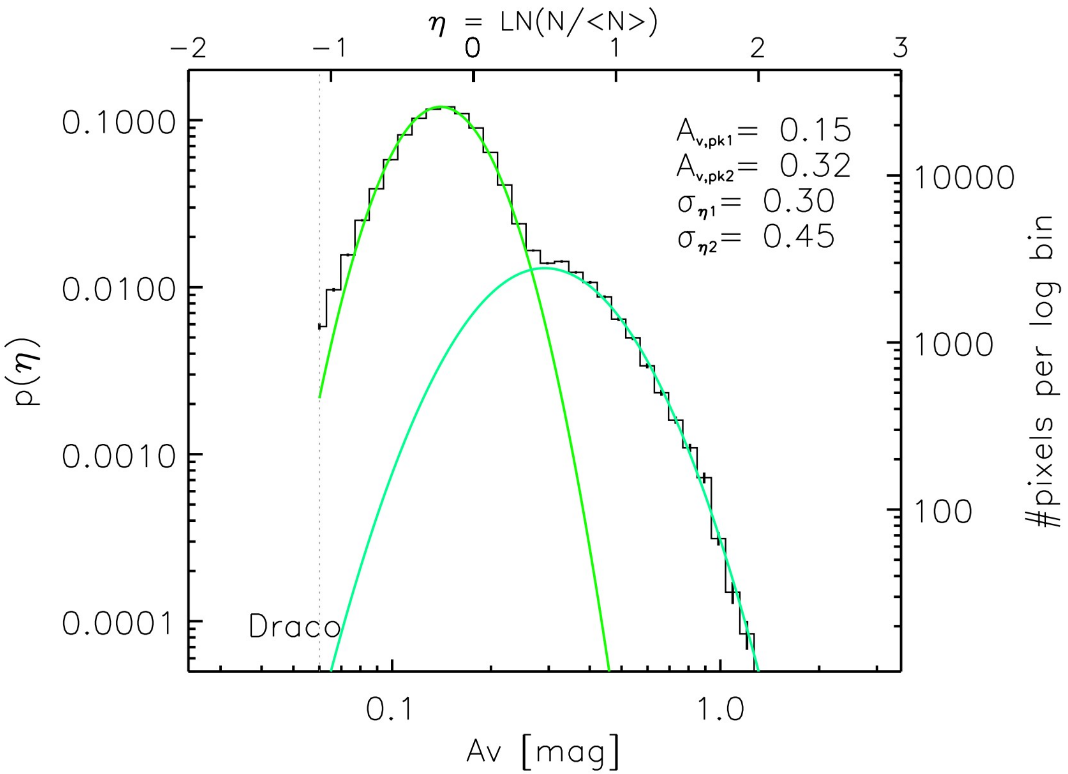
– Important transition for molecular clouds: HI – H_2

Phase transitions

Observation: Draco

- Intermediate-velocity cloud, possible template for colliding flow
- Transition of HI → H_2 and C^+ → C → CO
- Weak CO detection (Stark et al. 1997)





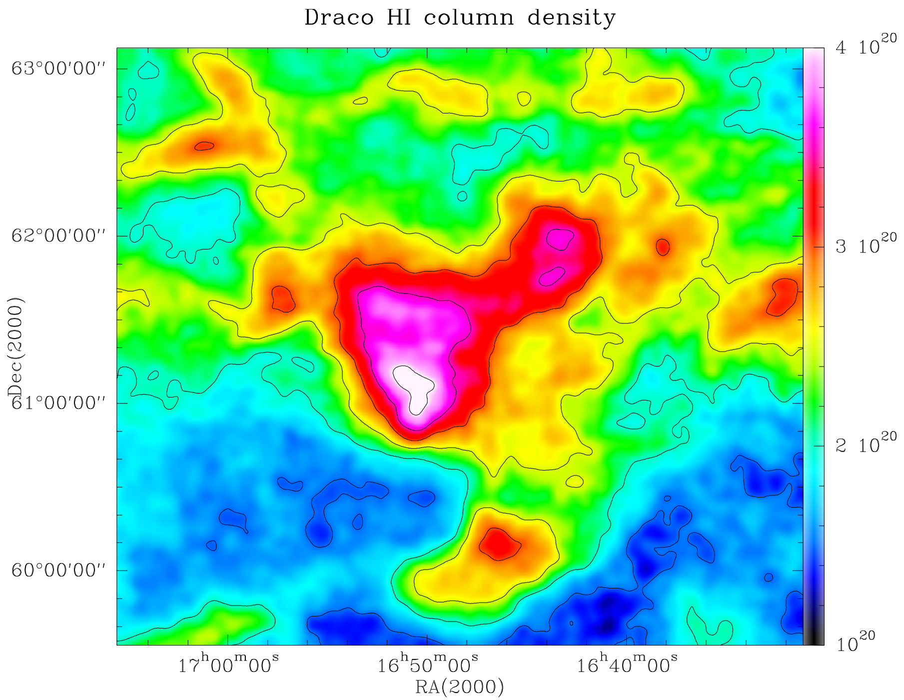
Total column density: Schneider et al. (in prep)

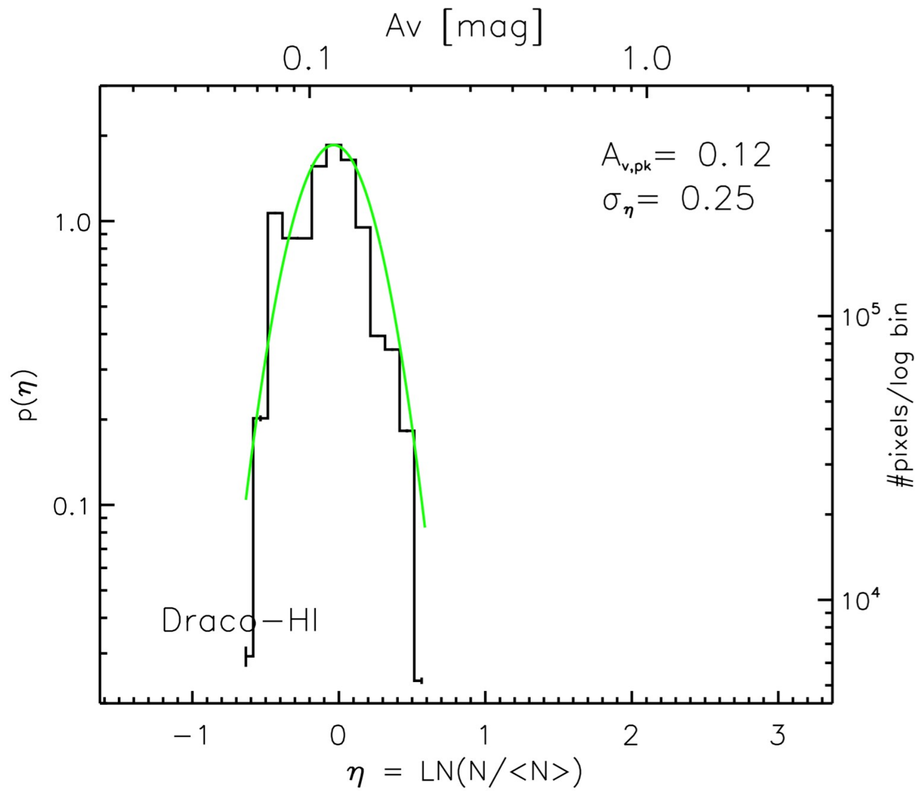
– Two peaks, separation at $A_V \approx 0.3$ → assignment to phases

Phase transitions

Observation: Draco

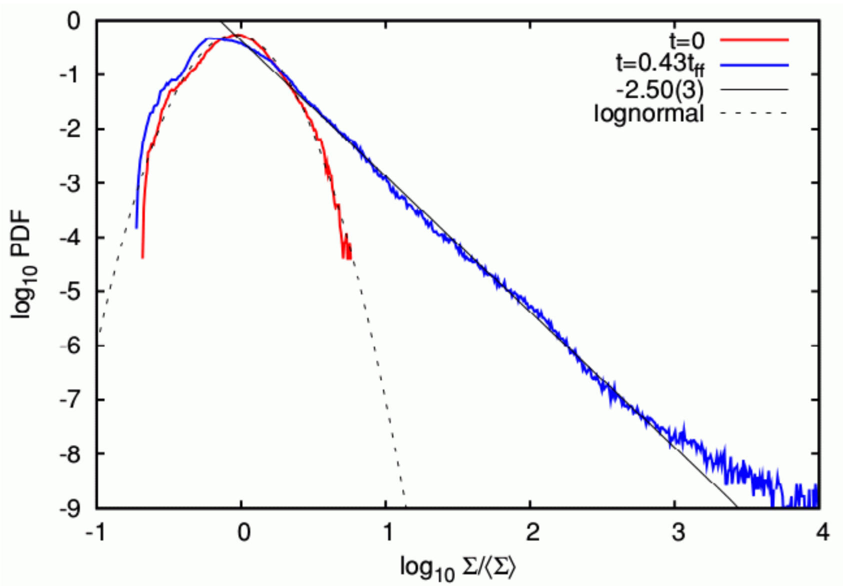
- HI gas:





- Low density peak: HI gas
  - lower Mach number for same turbulent velocities → narrow distribution
- H_2 gas: No good tracer available (CO only formed at $A_V \approx 1$)
  - Separation at $A_V \approx 0.3$ → H_2 formation depth

Power law tails in PDFs:



PDF of collapsing model (Kritsuk et al. 2011)

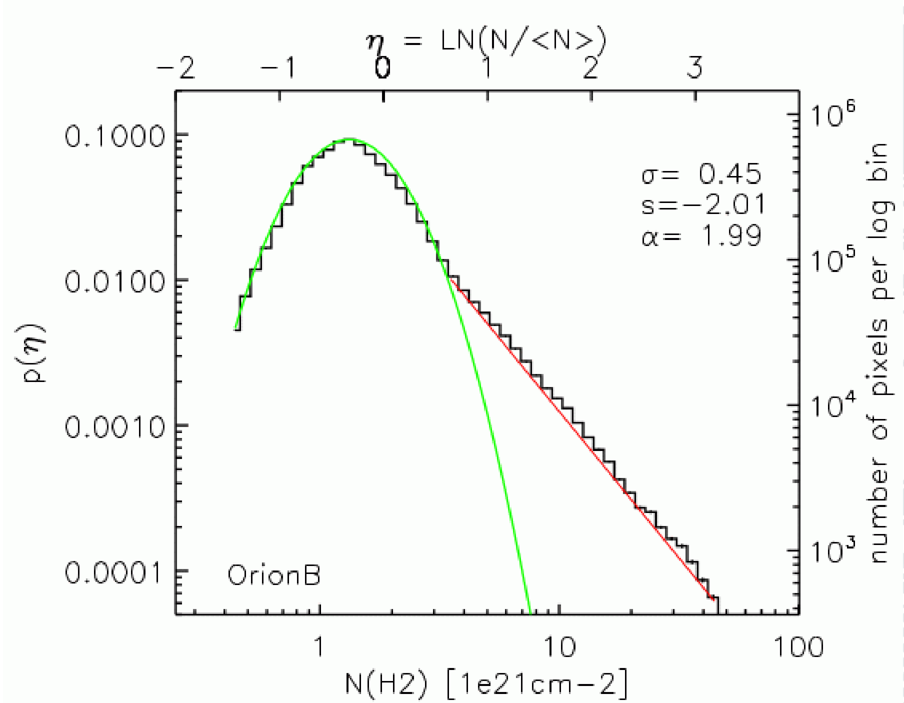
- **Self-gravity unavoidably creates power-law tails:**

Ballesteros-Paredes et al. 2011; Kritsuk et al. 2011; Girichidis et al. 2011, 2014; Federrath & Klessen (2013); Froebrich & Rowles 2010; Myers 2015; Toci & Galli 2015, Passot & Vazquez-Semadeni 1998; Kainulainen et al. 2009, 2011; Tremblin et al. 2013, 2014, ...

- Power-law tail: $p_\eta(\eta) = \left(\frac{N}{N_{\rm peak}}\right)^{-s}$
  - Exponent depends on density profile: $n(r) \propto r^{-\alpha}$
    - $s = 2/(\alpha - 1)$ for spherical symmetry (cores)
    - $s = 1/(\alpha - 1)$ for cylindrical symmetry (filaments)

Observations

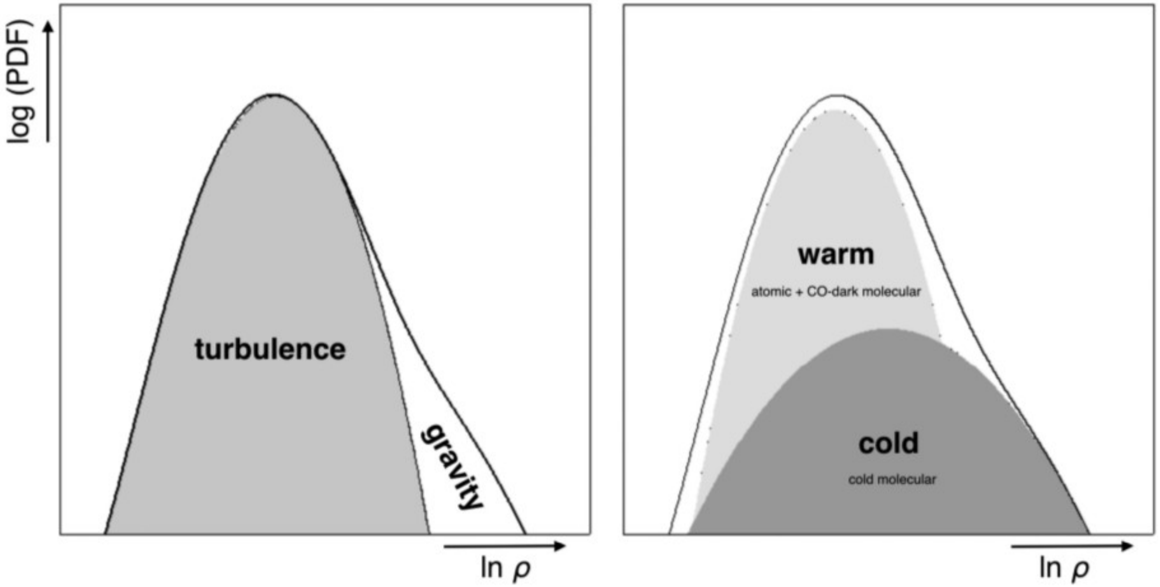
PDF in Orion B (Schneider et al. 2013)



→ Compare log-normal part and power-law tail

→ Key to quantify relative influence of turbulence and gravity

– But: very careful data analysis needed to distinguish different cases

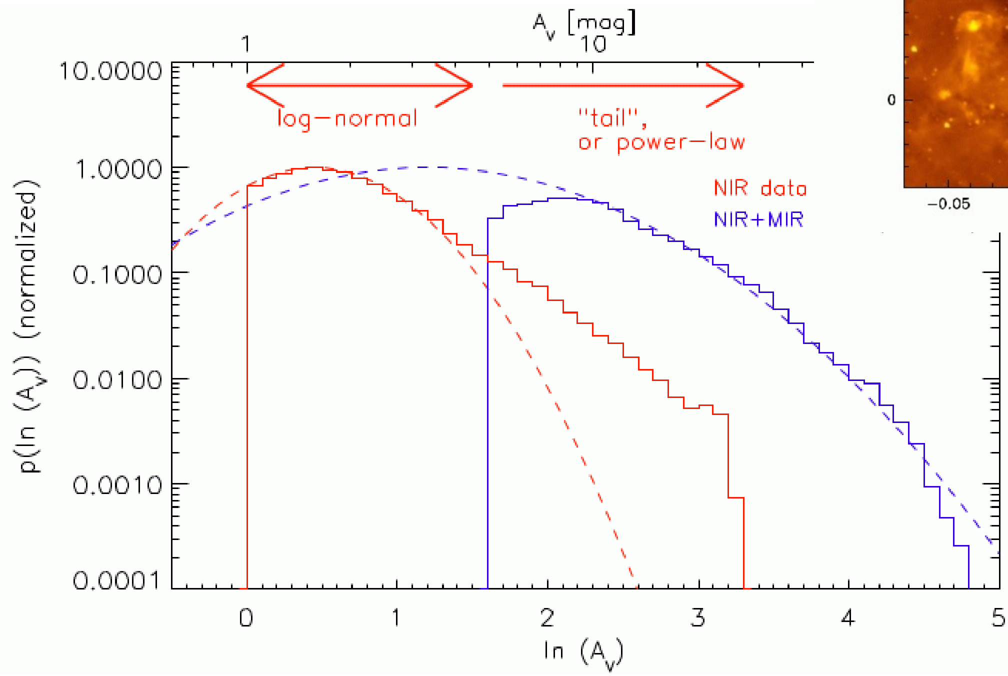


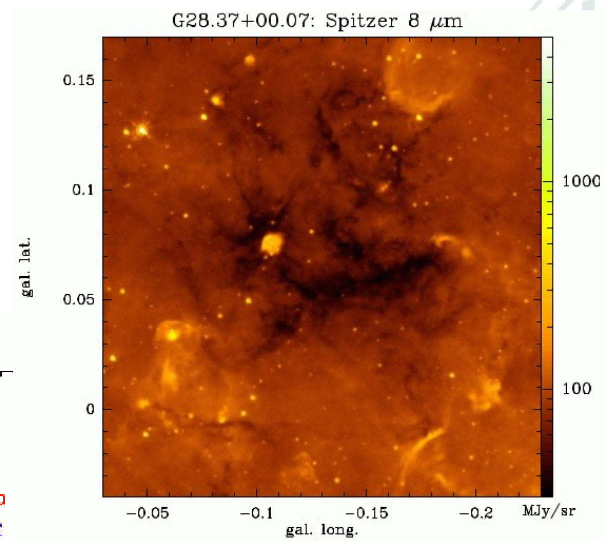
Brunt (2015)

The disputes

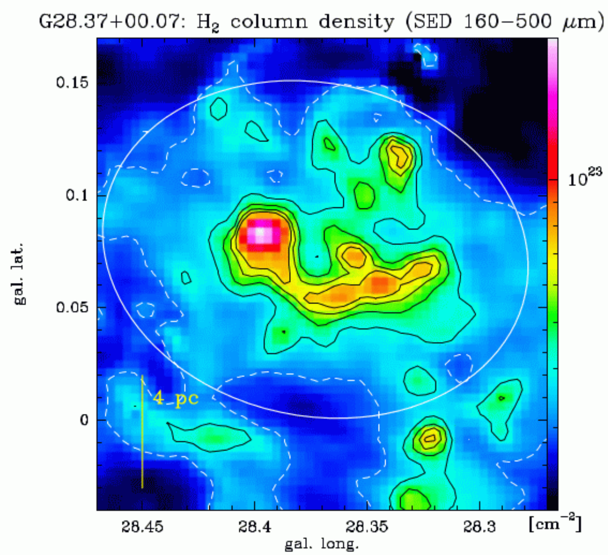
IRDC G28.37+0.07:

- Analysis of extinction data and Herschel column density maps:

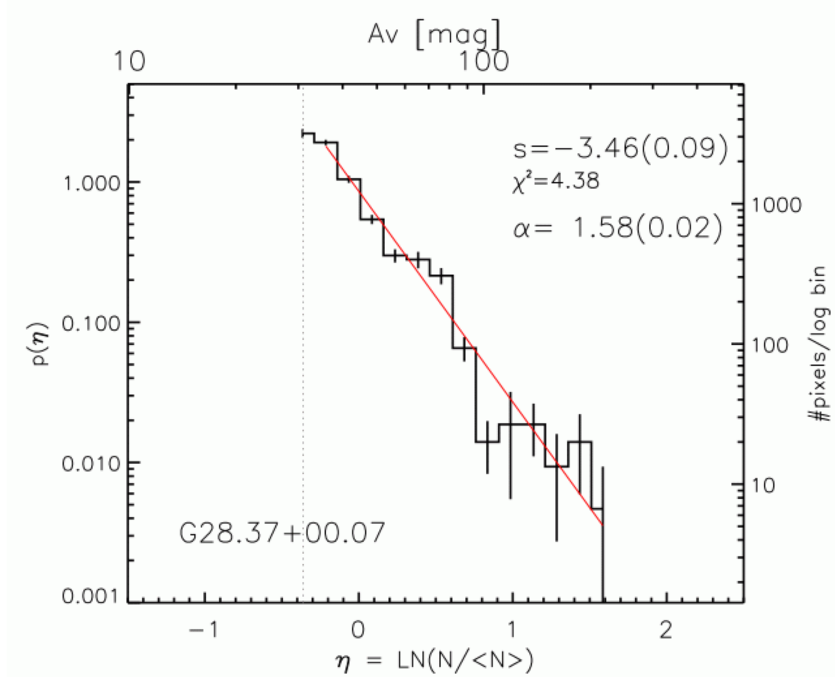




IRAC 8µm



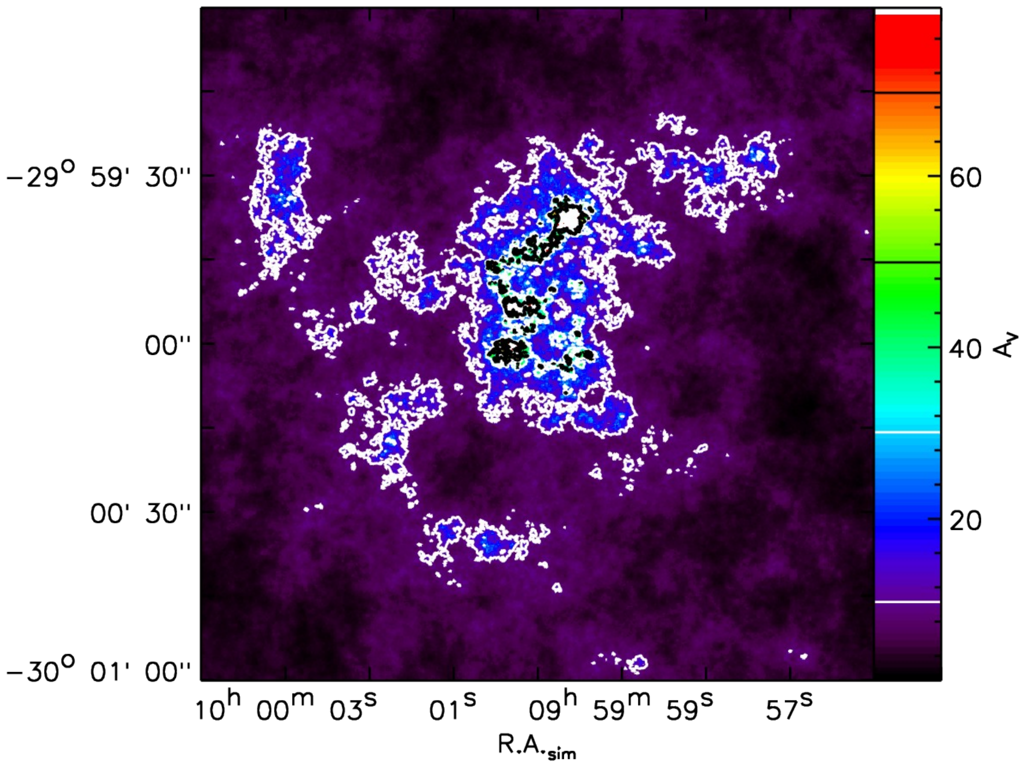
Herschel column density



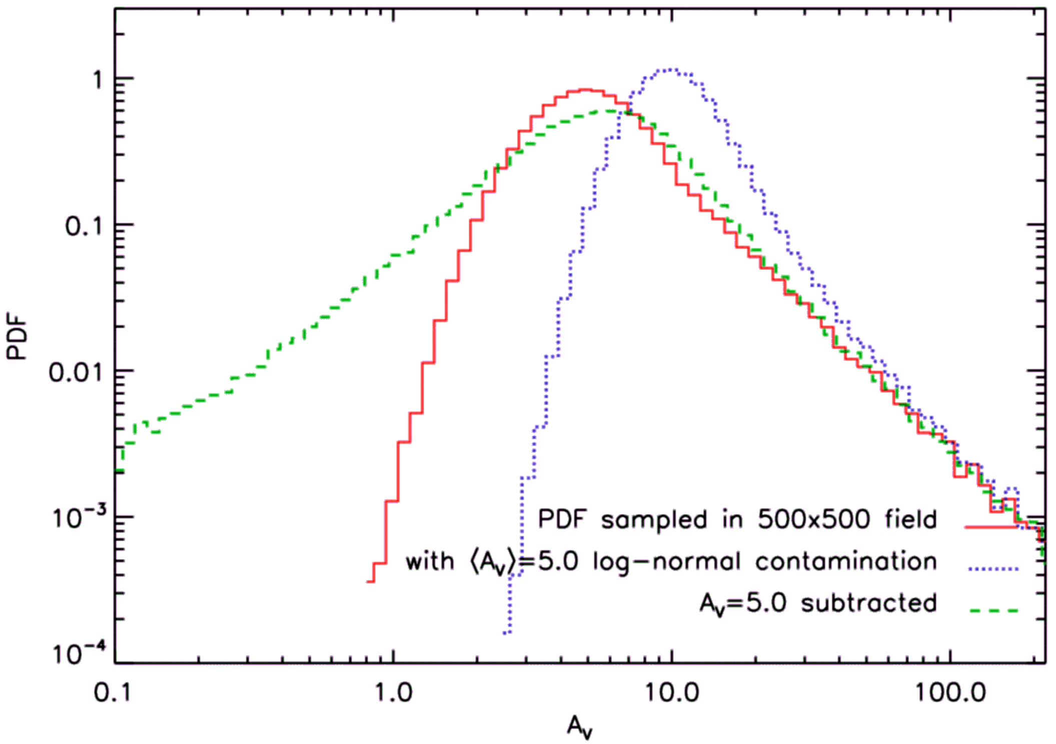
- Kainulainen & Tan (2013): purely log-normal
- Schneider et al. (2015): only power law tail
  - **For same region!**

Main problem

- Line-of-sight contamination
  - Can be easily simulated (Schneider et al. 2015a, Ossenkopf-Okada et al. 2016):
  - Constant foreground or second log-normal cloud



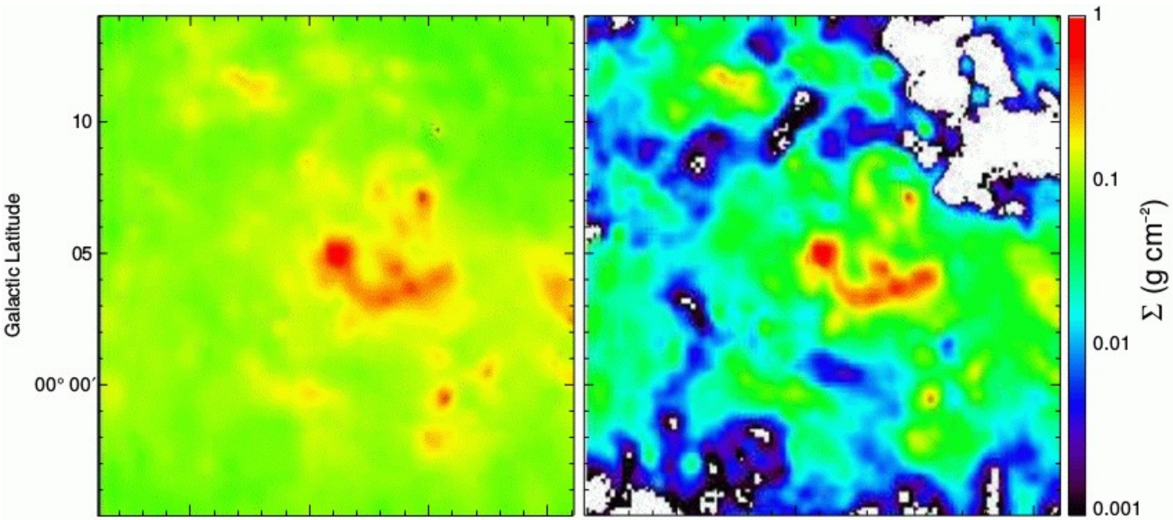
Ideal test cloud used in the simulations



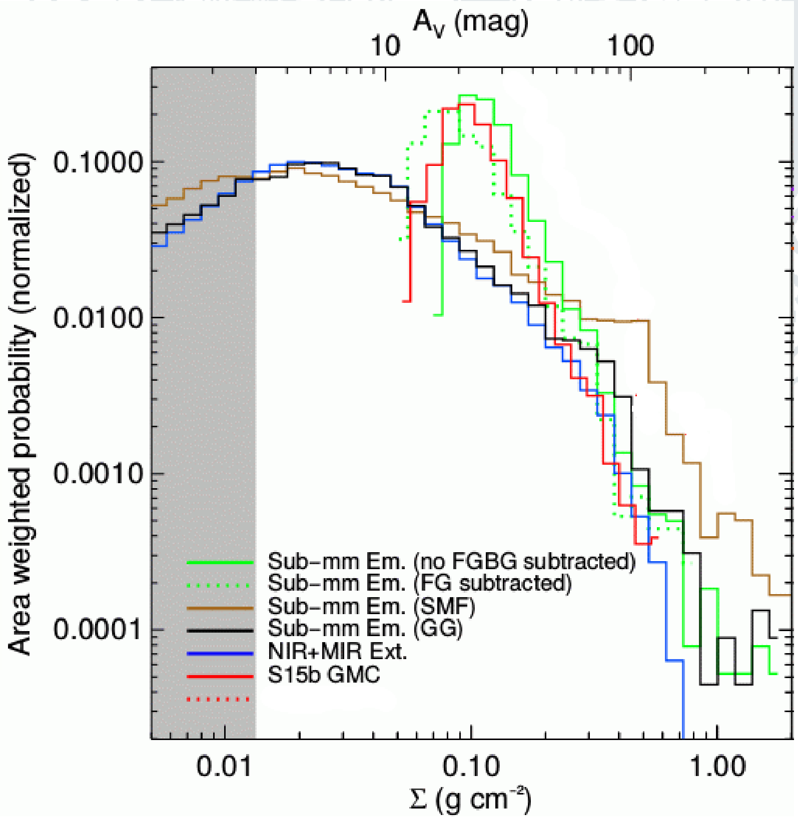
- Contamination does not create second peak
- Lognormal part of PDF is “compressed”
- Power-law tail is steepened
- Original parameters can be recovered by fit if contamination is known
  - Reasonable correction already by constant screen subtraction

Application of LOS correction

- Lim et al (2016, submitted):
  - Correcting the G28.37 data for strong line of sight contamination
  - Assumes average Galactic column density profile
    - High contamination: $A_V > 30$



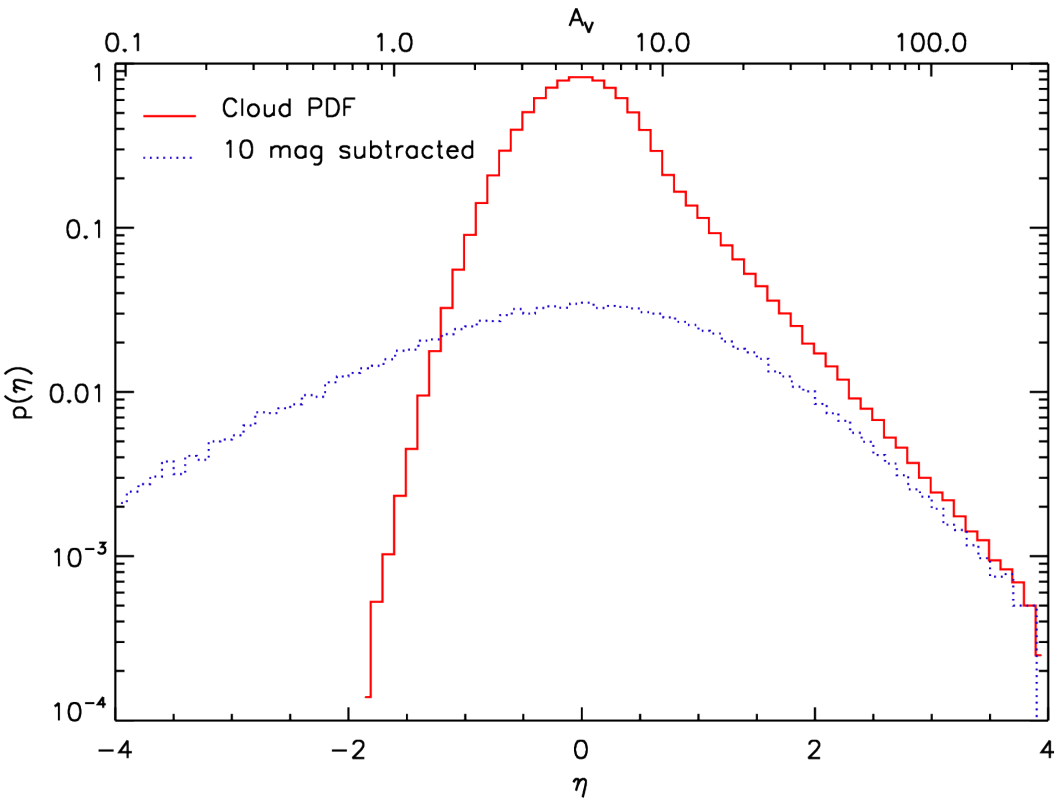
Original column density map Contamination subtracted map

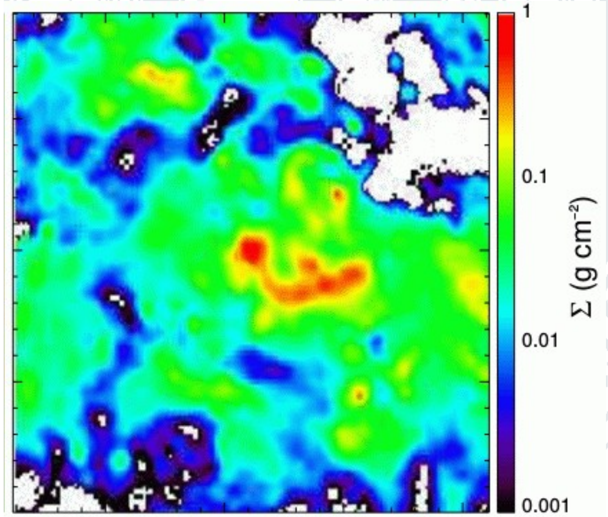


  - Again interpretation as log-normal distribution with very wide width σ_η

Alternative interpretation

- “Over-correction”:
  - Negative features in subtracted map prove over-correction:
  - Simulation of “over-correction” for the test cloud:





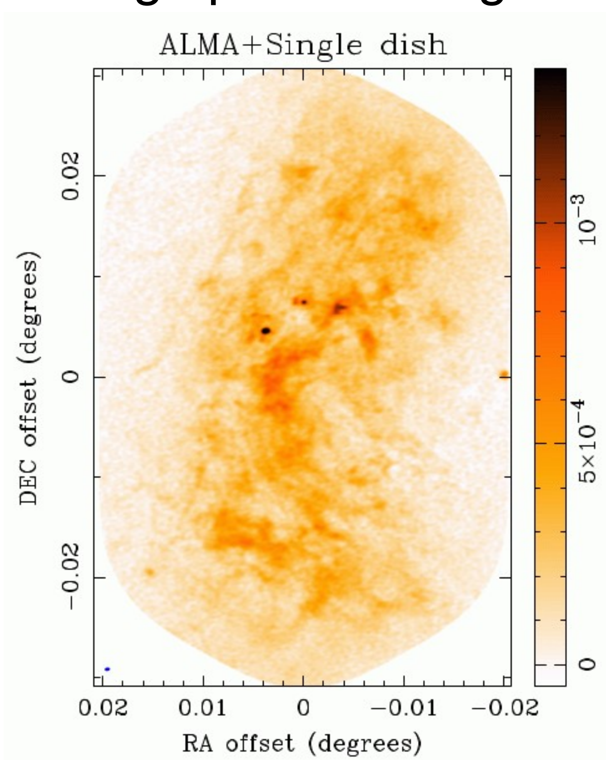
Contamination subtracted map

  - Over-correction creates PDF that seems log-normal, but has power-law tail

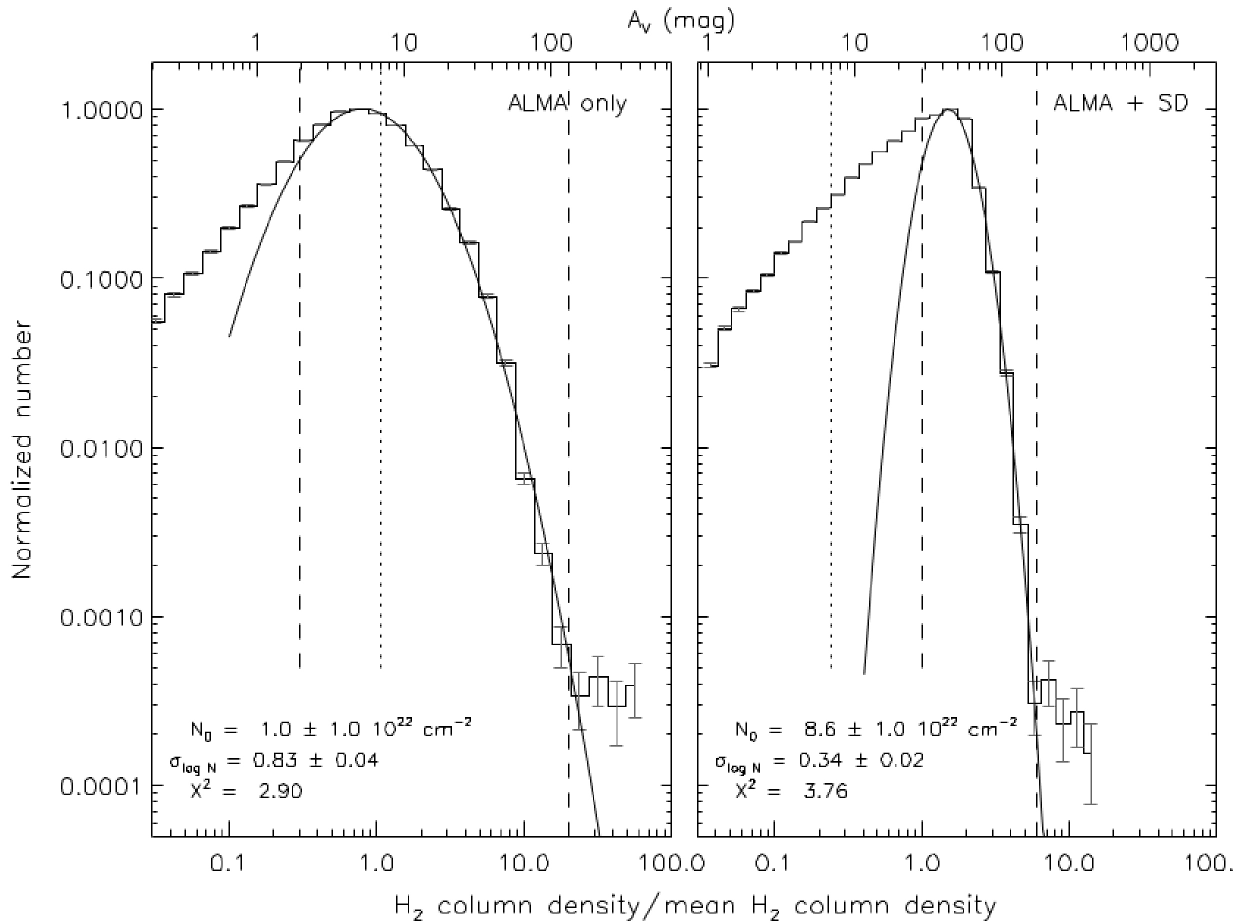
The disputes

ALMA observations of the CMZ:

- G0.253+0.016 (Rathborne et al. 2014)
  - High pressure region



- No significant power-law tail
- Low-density excess
- But: incomplete sampling of uv-plane!

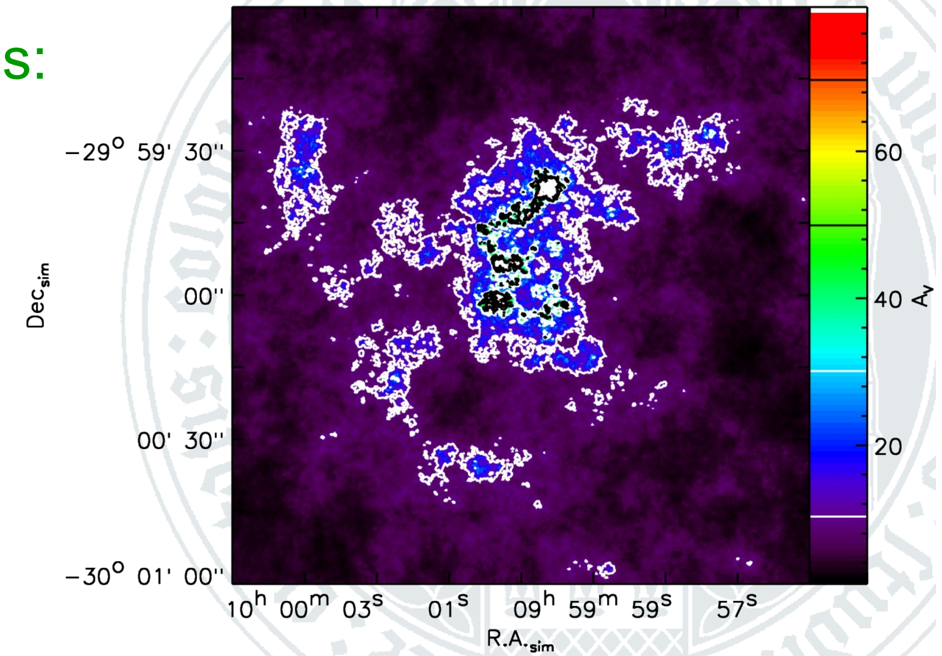


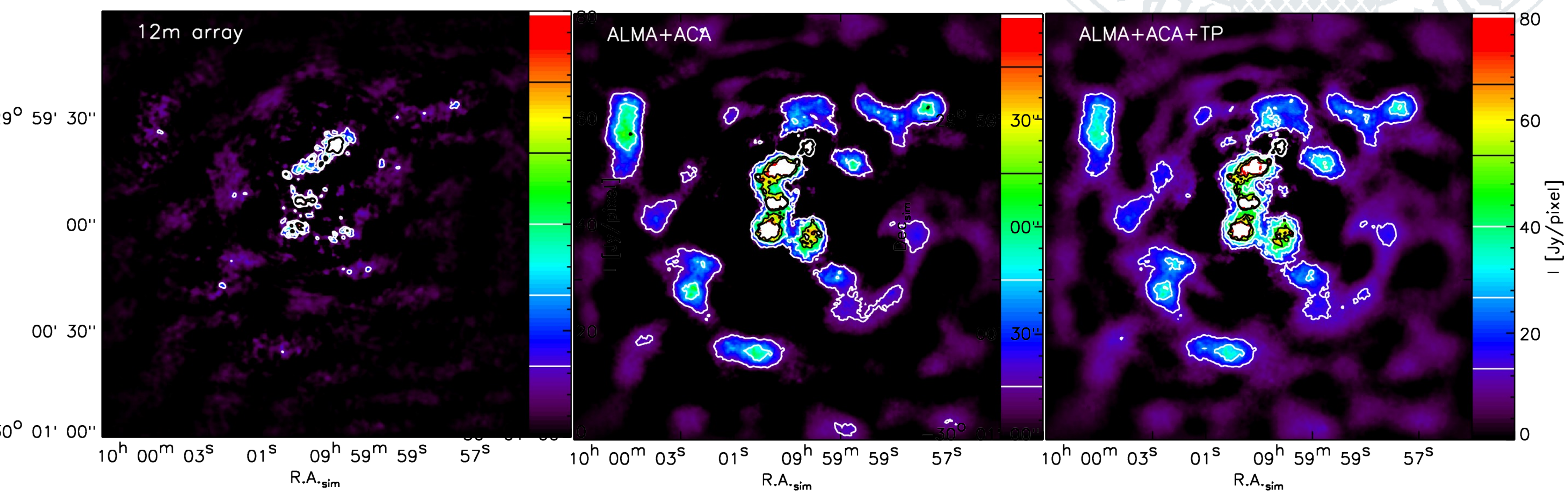
PDFs from maps with and without single-dish correction (Rathborne et al. 2014)

Statistics from interferometric observations

- CASA simulations of ALMA observations:
  - Typical ALMA mapping (2h 12m array, 4h ACA, 8h TP)
    - 0.6" resolution
    - Favourable assumptions: TP currently not offered for continuum

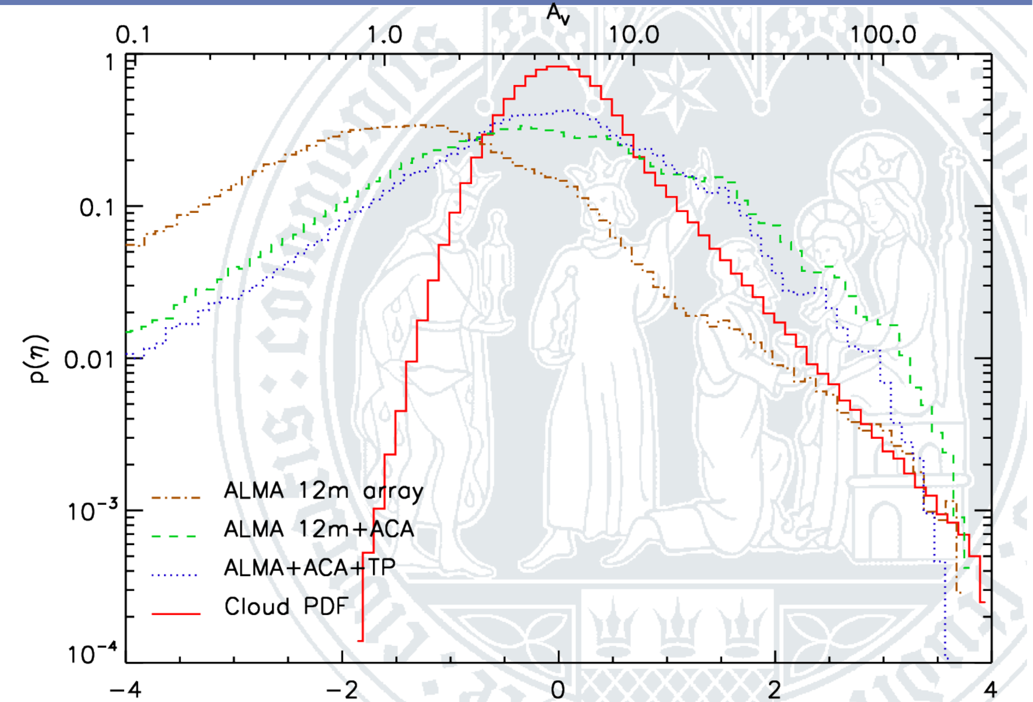
Input and recovered maps from 2h ALMA observation (Ossenkopf-Okada et al. 2016)

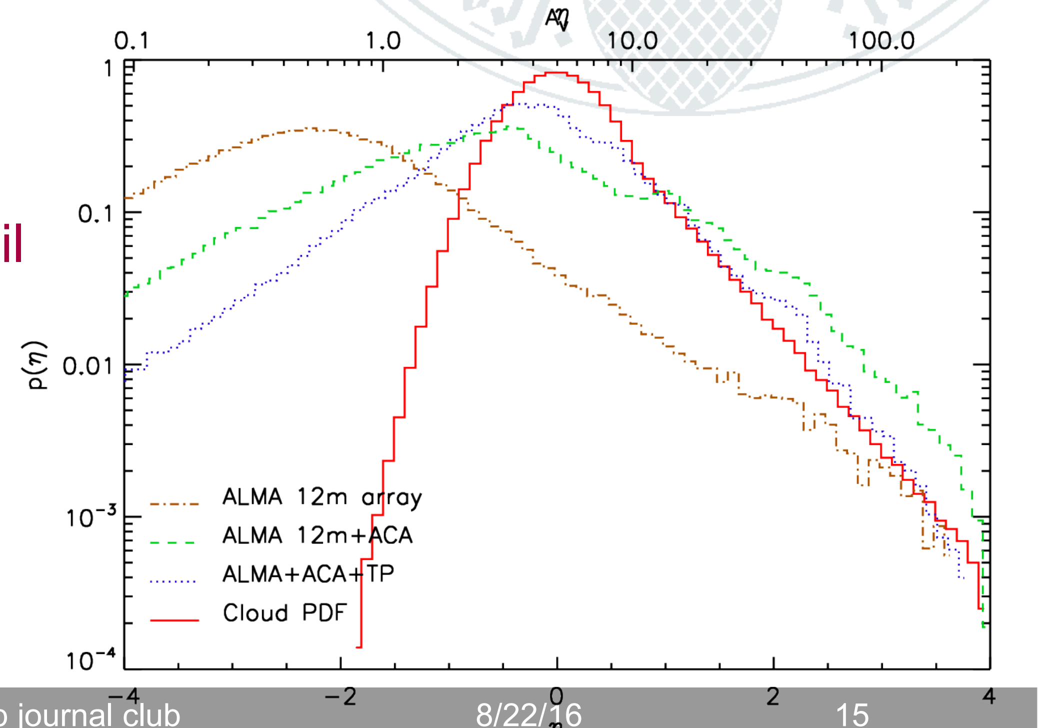




Statistics from interferometric observations

- CASA simulations:
  - Typical ALMA mapping (2h 12m array, 4h ACA, 8h TP)
  - Standard ALMA observations are unusable for PDFs!
    - Even with TP correction
- Extra-long ALMA observation:
  - Extended ALMA mapping (8h 12m array, 16h ACA, 32h TP)
  - ALMA observations beyond todays offers can recover the high density tail of the PDF
  - Additional simulations show:
    - No interferometer can recover the log-normal core of the PDFs
    - TP and short spacing is crucial

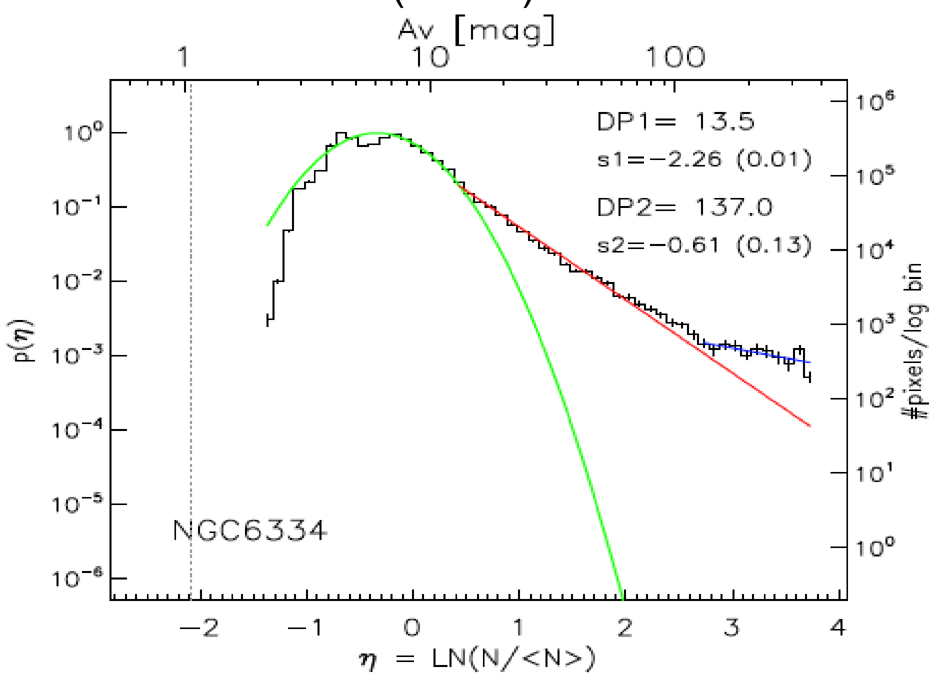


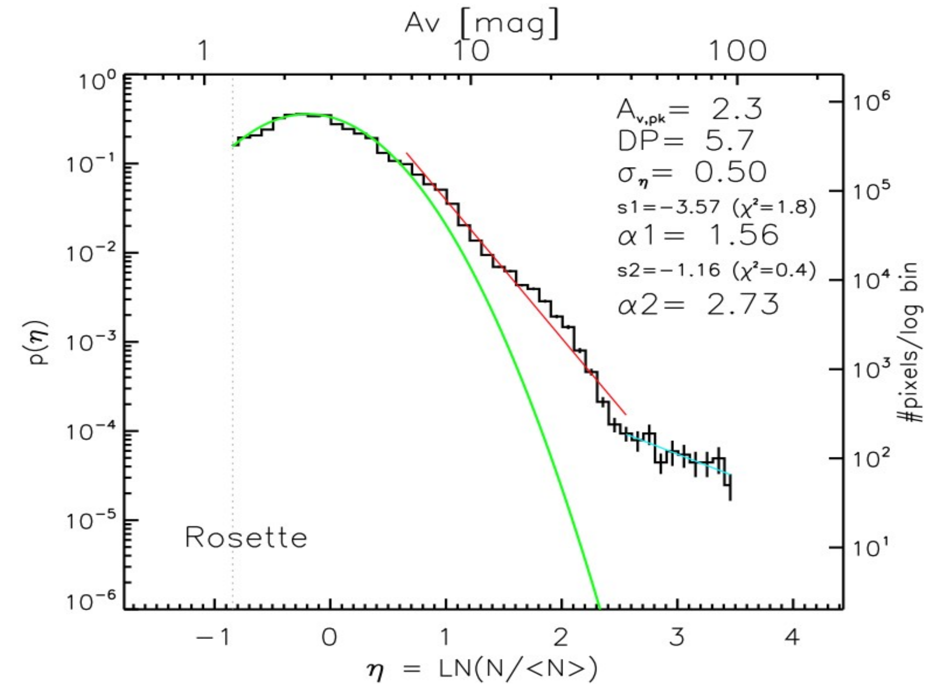


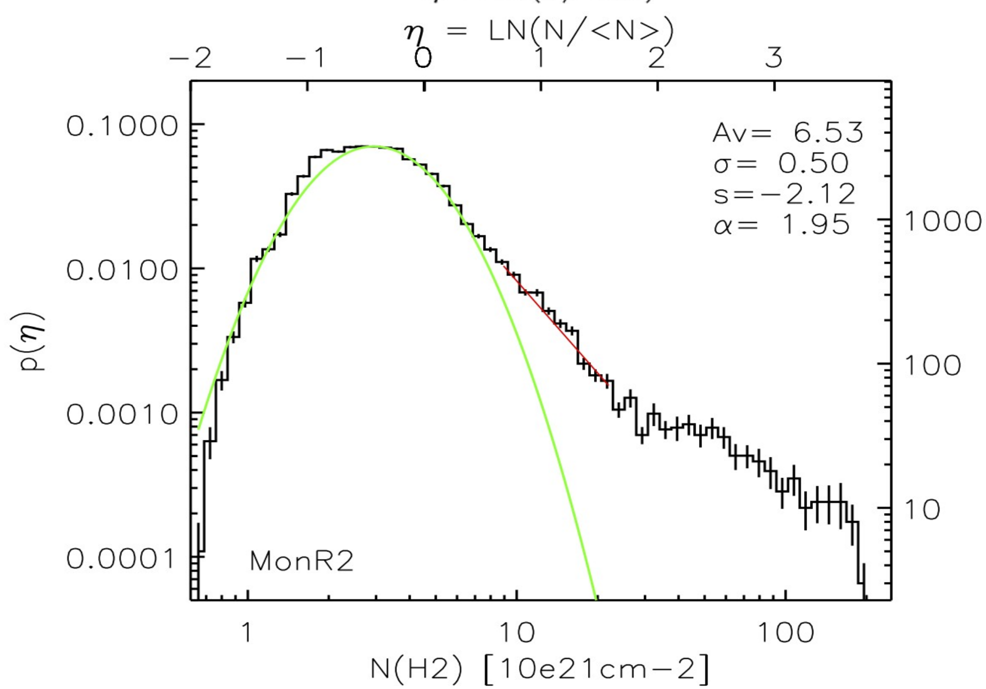
Further surprises

- Two power law tails:
  - Common, but not omnipresent in massive GMCs
  - Excess with $\alpha > 2$ must be caused by a process that reduces the flow of mass towards higher densities at $A_V \geq 50$
  - Cause: Unknown so far

Schneider et al. (2015c)







Conclusions

Column density PDFs are a sensitive tool to characterize the dynamical state of a given region.

- Measuring the PDF of a particular cloud is NOT trivial
- Careful LOS correction is key to quantify power-law tail and log-normal
  - Line observations help to distinguish multiple clouds along the LOS
- Interferometric observations are currently unusable to get a reliable PDF
  - Missing data in the uv-plane are worse than missing data in RA-Dec
  - Future extensions of ALMA capabilities may allow for a measurement of the high-density tail of the PDF, but not of the turbulent structure
- Many clouds show two power laws → indicates some collapse threshold
  - Explanation ?????