The ISM : scale and phase coupling

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- *Planck* CO survey and polarized dust emission
- *Herschel*/HIFI absorption spectroscopy
- ALMA high-z absorption

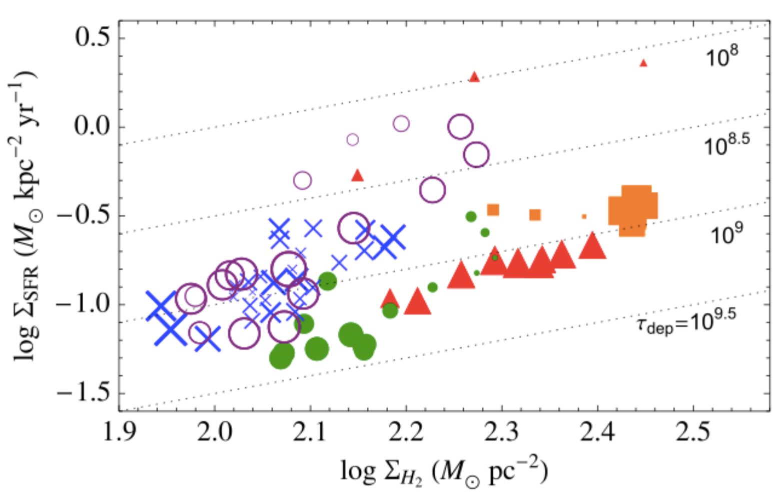
planck

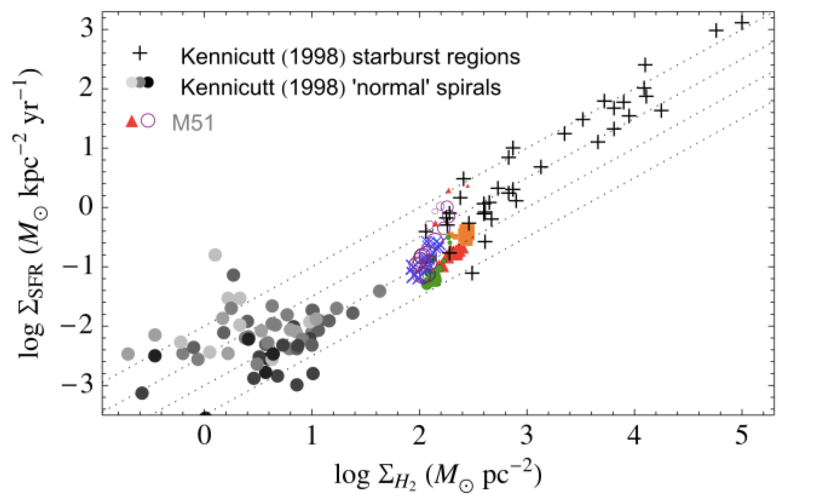
l'Observatoire de Paris

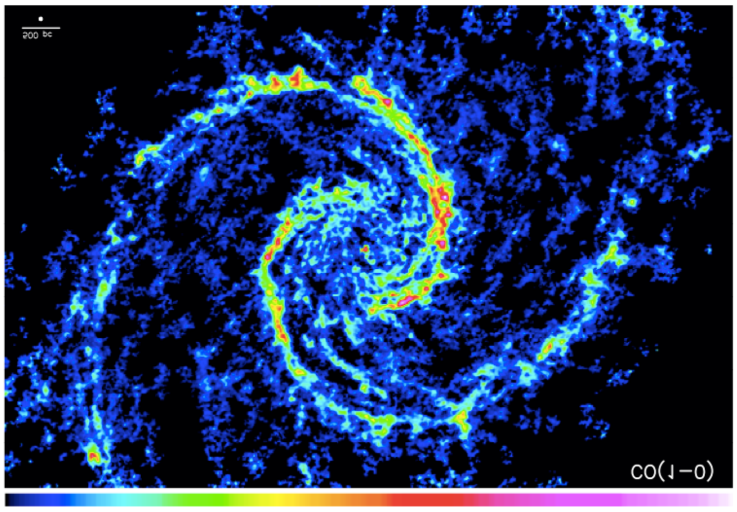
Elements of answer to …

- Where does the mass of the cold ISM lies?
- Is the CO-dark gas truely CO-dark?
- Where does the cold ISM energy come from?
- Does cold purely atomic hydrogen exist at all?
- What do the sharp changes of dust polarization angle tell us about B ? In the cold ISM? In the ionized gas?

Star Formation Rate and galactic environment





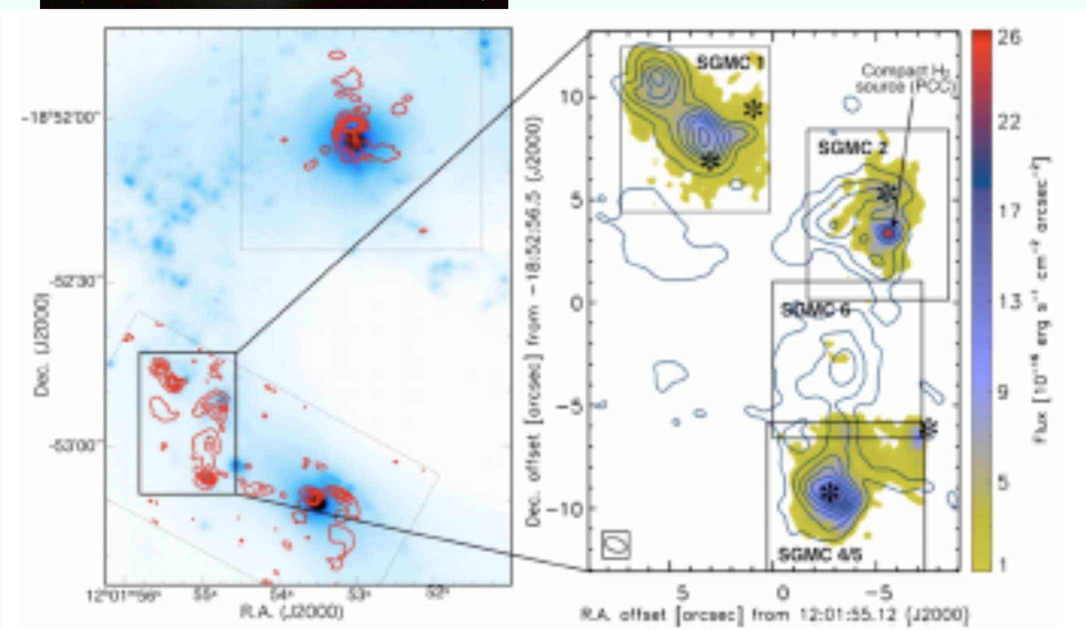


Influence of gas-streaming motions on SF activity

M51
CO(1-0)
IRAM-PdBI survey

Meidt + 2013

Stellar cluster formation in the interacting Antennae galaxies



- Gravitational encounter generates compressive tides
- Enhances turbulence but unbalance compressive over solenoidal modes
- Star formation enhanced

Renaud et al. 2014

Contours:
ALMA CO(3-2)
CFHT K band (blue)

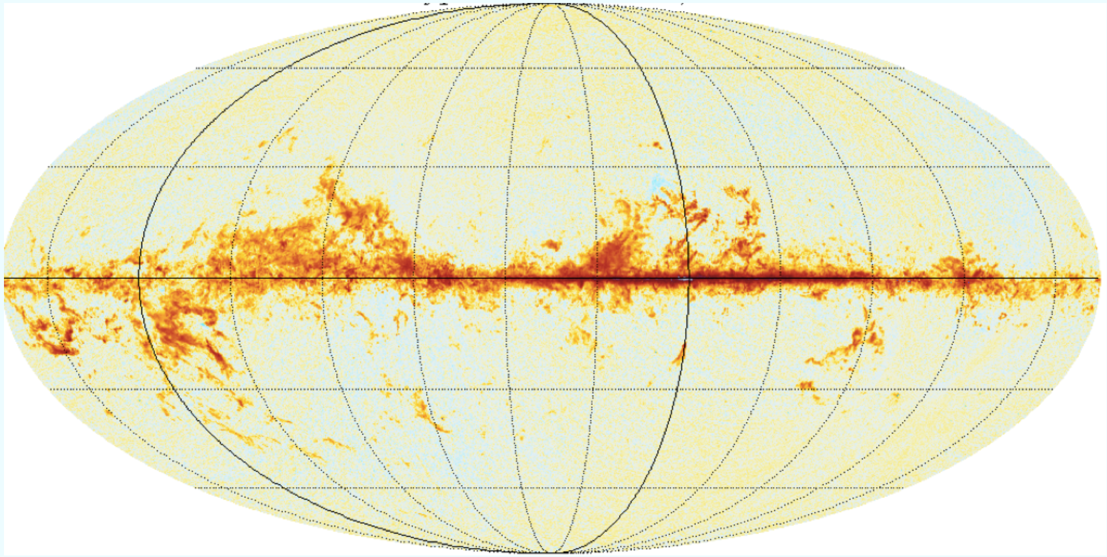
Star clusters * + H_2^*
VLT/Sinfoni emission

Hererra et al. 11, 12

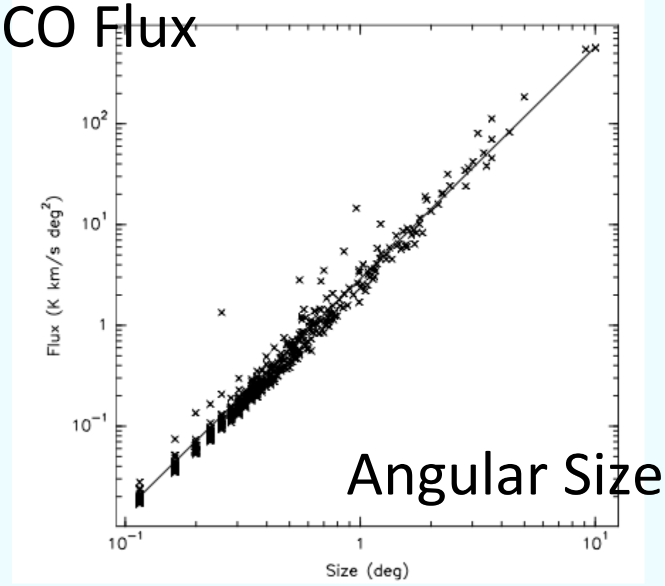
Where does the mass of the cold ISM lies?

Planck CO all-sky survey

HI Super Clouds



Planck : all-sky CO



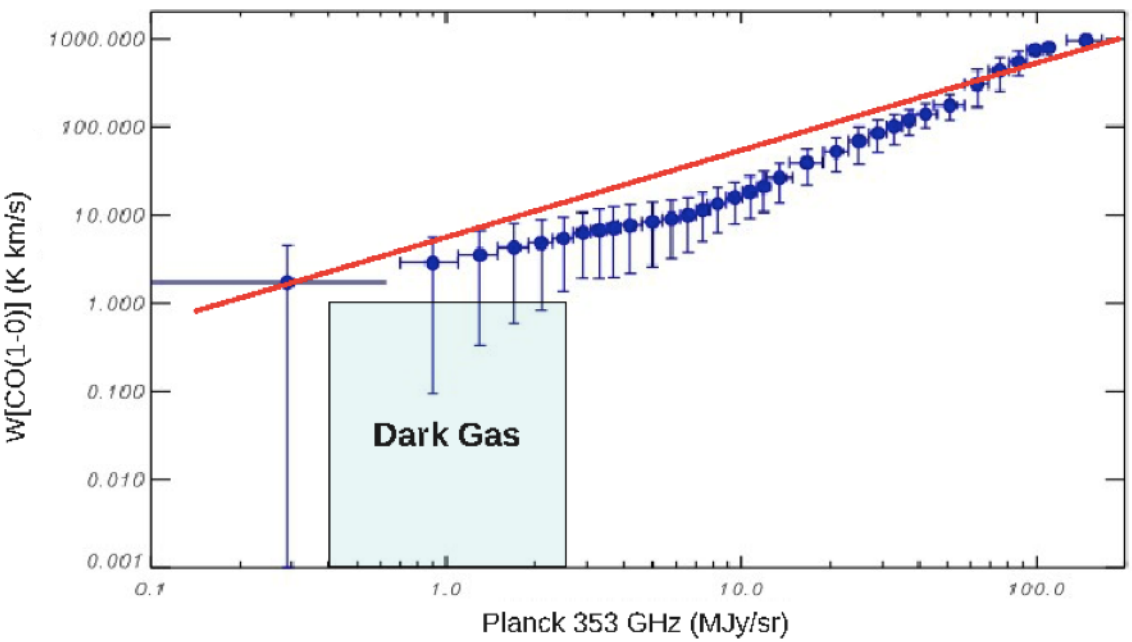
CO at high galactic latitude:
power law distributions of size and flux of hundreds of « patches »

flux = CO brightness x $(\text{size})^2 \sim (\text{size})^{1.9 \text{ to } 2.5}$

➔ CO brightness ~ $(\text{size})^{-0.1 \text{ to } 0.5}$
➔ Weak extended emission expected below the detection level

Planck Collaboration XIII (2014)
Planck Collaboration (in prep.)

CO reliable molecular gas mass tracer



Average X_{CO} factor :

$$X_{\rm CO} = N(\rm H_2)/W(\rm CO)$$

$$X_{\rm CO} = 2 \times 10^{20} \rm cm^{-2}/K\,km\,s^{-1}$$

$$f_{\rm H_2} = 1$$

➔ CO is a reliable molecular gas mass tracer within a factor of a few over 3 orders of magnitude of column densities

Mean and standard deviation of CO emission in bins of 353 GHz emission = proxy for N_H

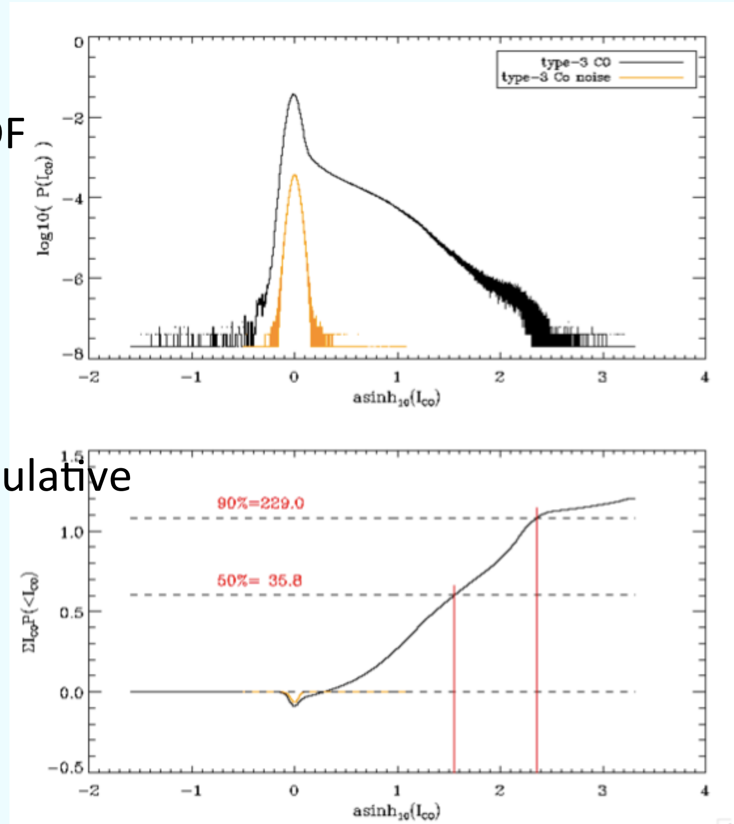
1 MJy sr^{-1} @ 353 GHz ➔ 2 x 10^{21} cm^{-2} or ≈1 mag

^{13}CO contamination at most 14%

see Bolatto + 2013

CO all-sky distribution

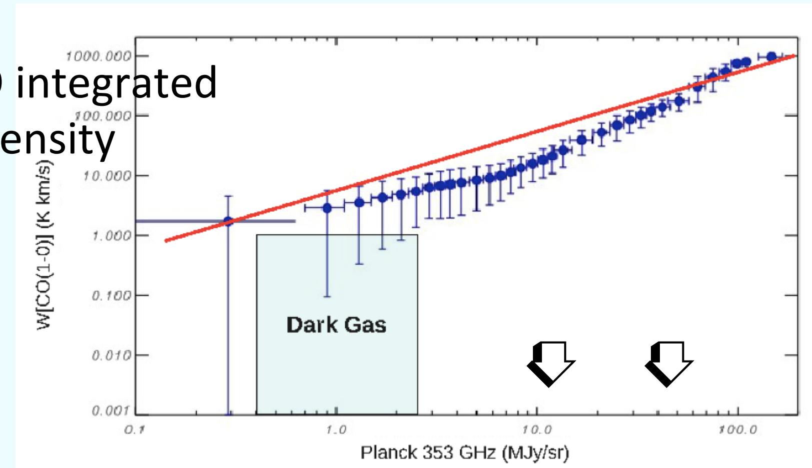
PDF



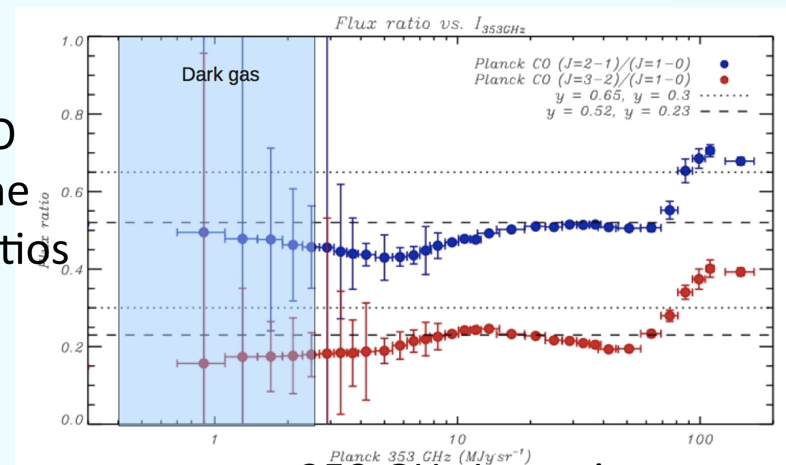
Cumulative PDF

CO integrated intensity

CO integrated intensity



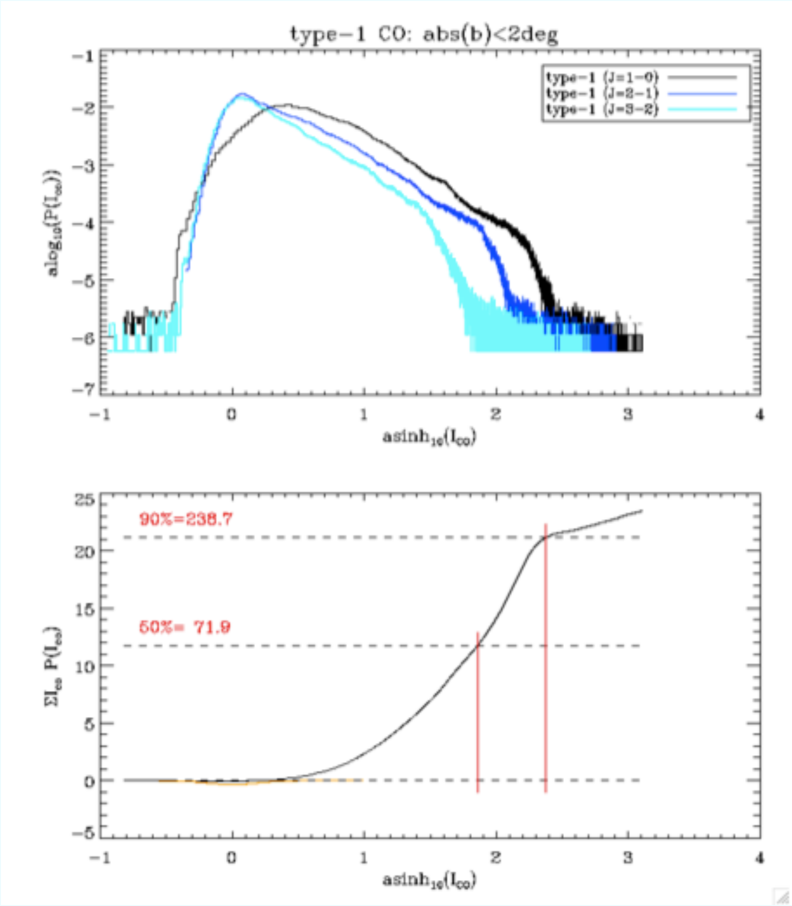
CO line ratios



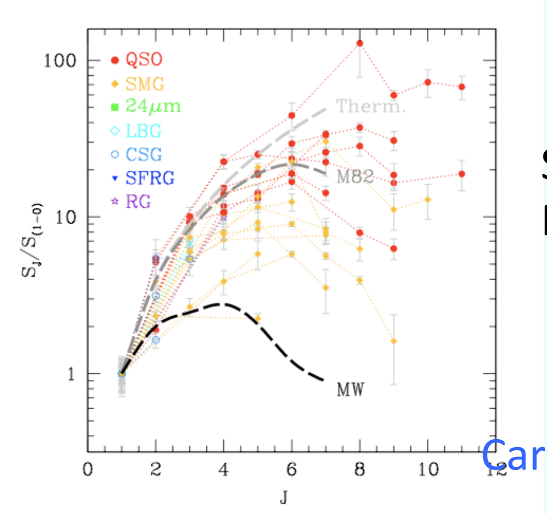
353 GHz Intensity

➔ 90% of the cumulative flux reached at W(CO)=229 K km s^{-1}

Bulk molecular mass of the Milky Way



$$R_{2-1/1-0} = 0.5 \pm 0.1$$
$$R_{3-2/1-0} = 0.23 \pm 0.05$$



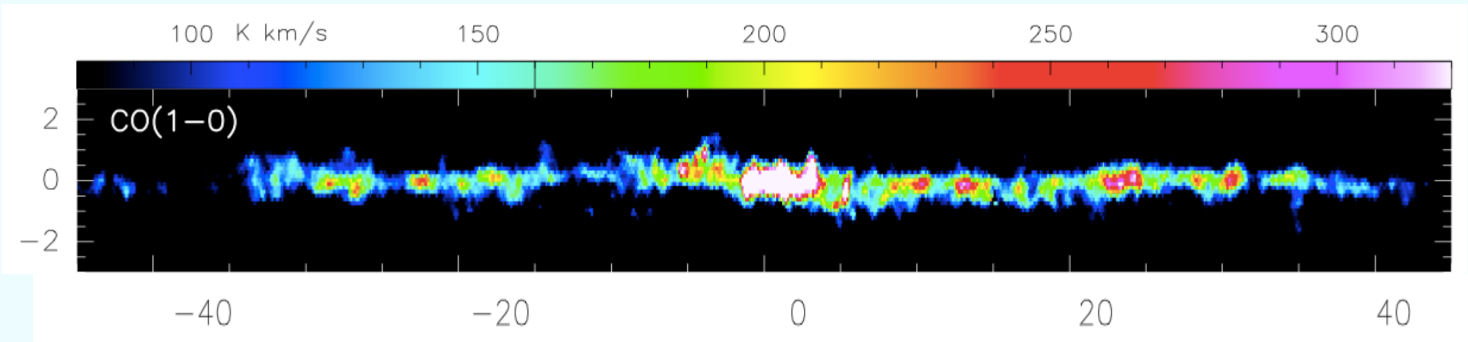
SLEDs of galaxies
Milky Way model

Carilli & Walter 2013

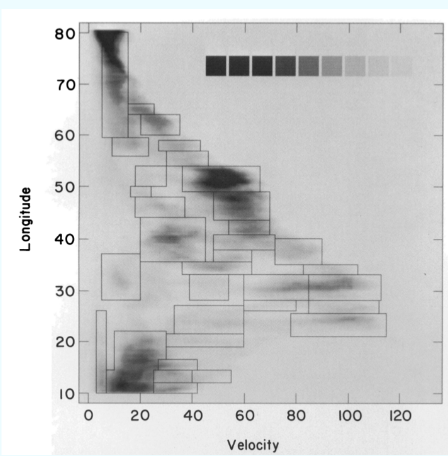
Non-LTE analysis: density, temperature degeneracy

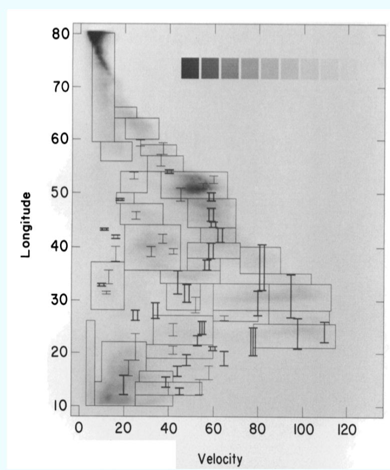
➔ H_2 density < 600 cm^{-3} and T_k > 20K

Bulk of mass seen in CO : edges of GMCs in Inner Galaxy



First Quadrant





HI super clouds + CO GMCs Dame + 1986
Elmegreen & Elmegreen 1987

HI Super Clouds

Same average density as CO GMCs

$M = 10^6 – 4 \times 10^7 M_{sol}$

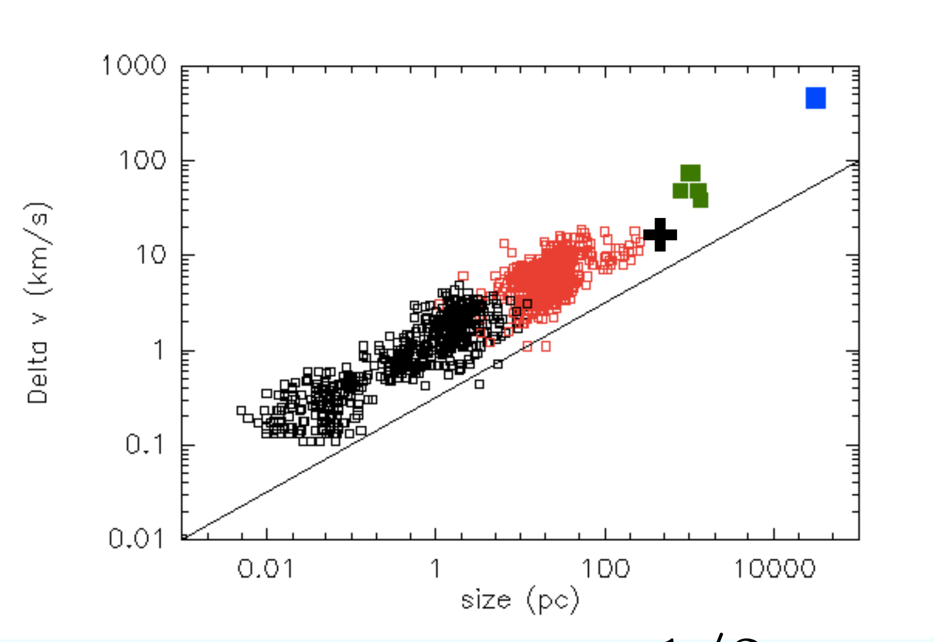
40 to 70% total HI

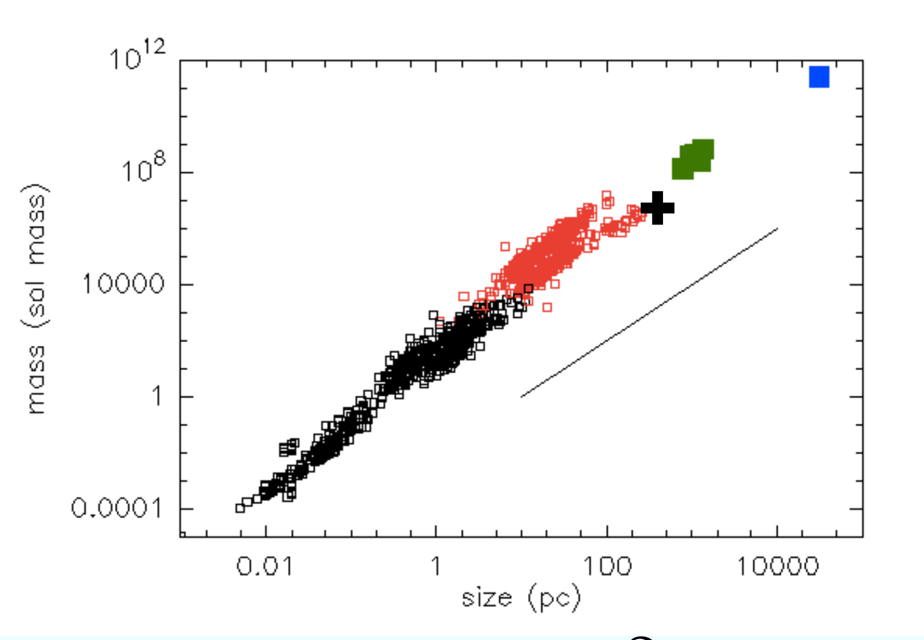
Gravitationally bound

Declining f_{H2} with R_G

➔ Fundamental units for SF

Scaling laws « at scales dominated by diffuse molecular gas »





$$\Delta v \propto L^{1/2}$$

$$M \propto L^2$$

$^{12}CO(1\text{-}0)$ galactic molecular clouds Hennebelle & Falgarone 2012

$^{12}CO(3\text{-}2)$ Super GMCs in Antennae Interaction region (green squares) Wilson 2000

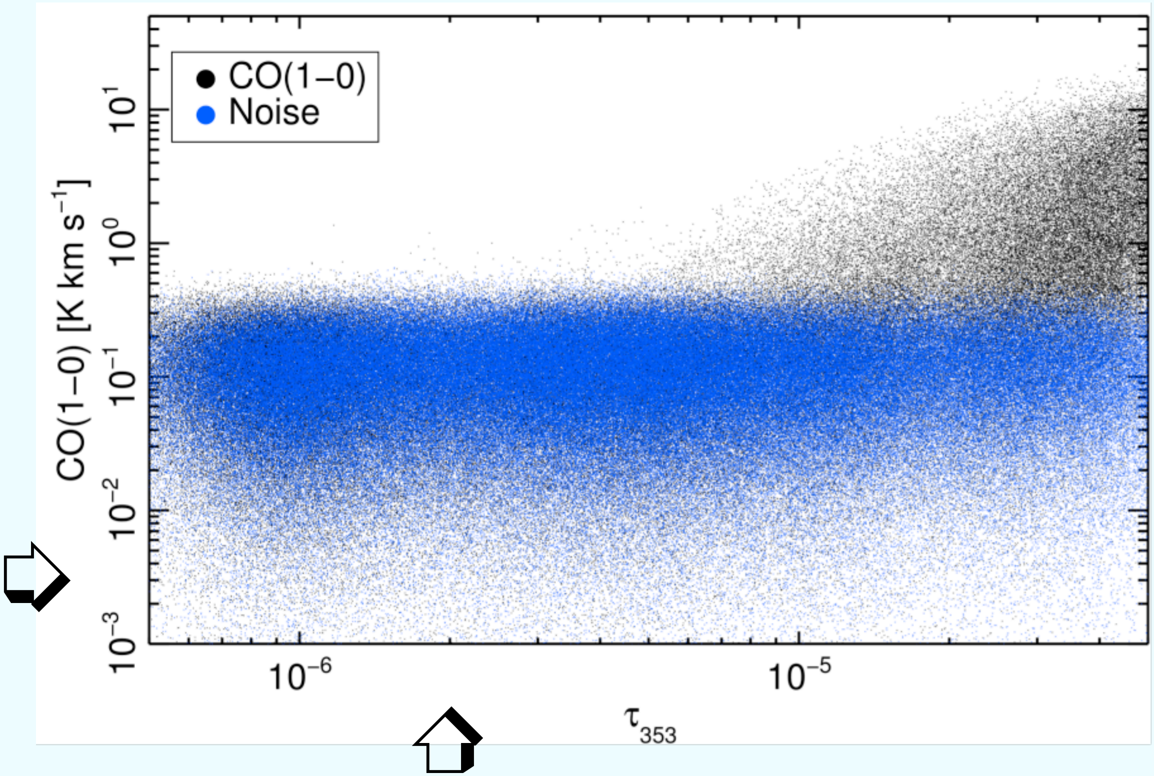
Massive diffuse halo in SDP17b at z=2.3 (blue square) Falgarone + 2015

Average HI Super cloud (cross) Elmegreen & Elmegreen 1987

Is the CO-dark gas truely CO-dark?

Or rather CO-faint?

Noise-limited threshold for CO emergence

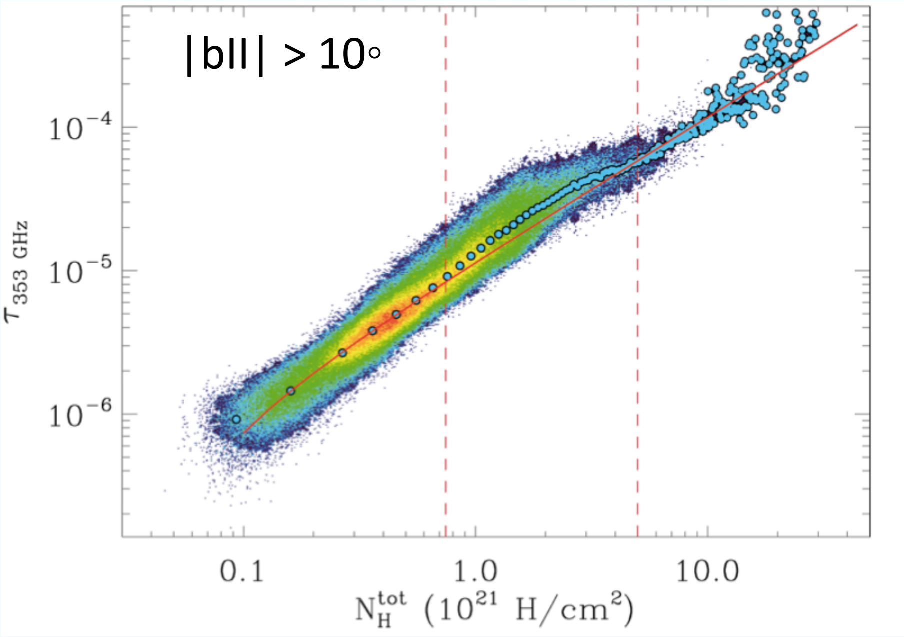


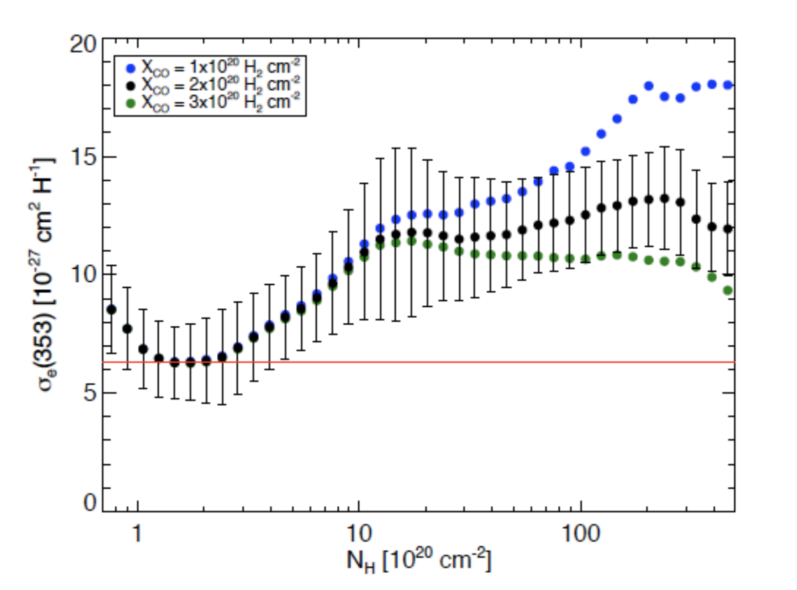
Expected threshold: $N_{CO} = 3 \times 10^{12}$ cm^{-2} (HST visible absorption)

⇨ $W(CO_{1\text{-}0}) = 3$ mK km s^{-1} (low density gas)

at $N_H = 2 \times 10^{20}$ cm^{-2} (threshold for H_2 emergence) ⇨ $\tau_{353} = 2 \times 10^{-6}$

CO-dark gas in Solar Neighbourhood



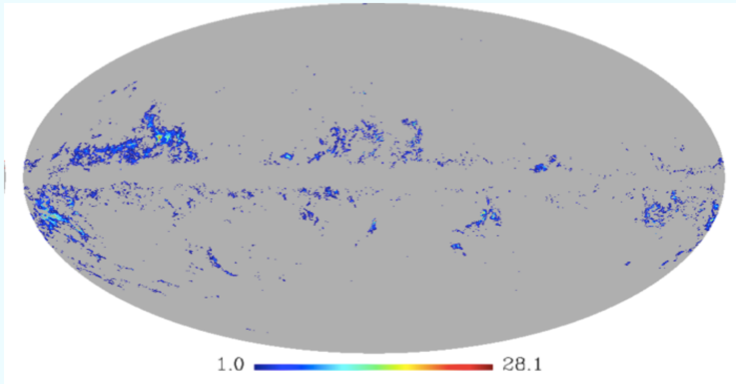


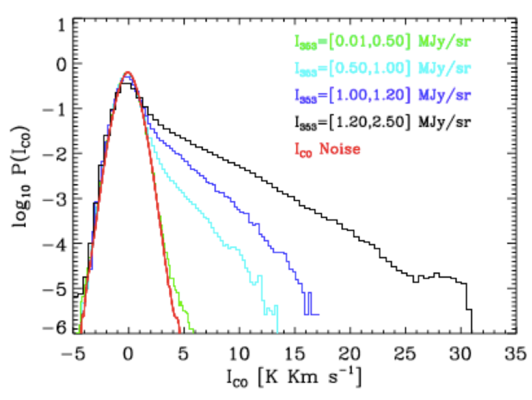
N_H^{tot} – dust optical depth correlation at 353 GHz
Red line: best linear correlation derived at low N_H^{tot}
Assumption: the dust opacity per unit gas column is the same in atomic and molecular phases

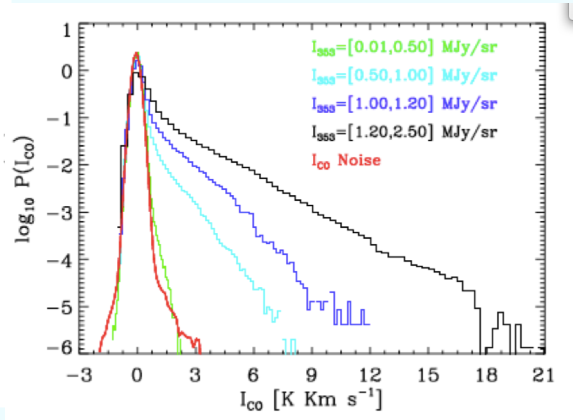
Degeneracy : dust properties, HI optical depth

Planck Early Results 2011:
Dark Gas: 28% of atomic component
118% of CO emitting gas

CO emission of the CO-dark gas







CO emission in 353 GHz bins dominated by CO-dark gas

Dynamic of the CO emission above noise level exceeds that of I_{353}

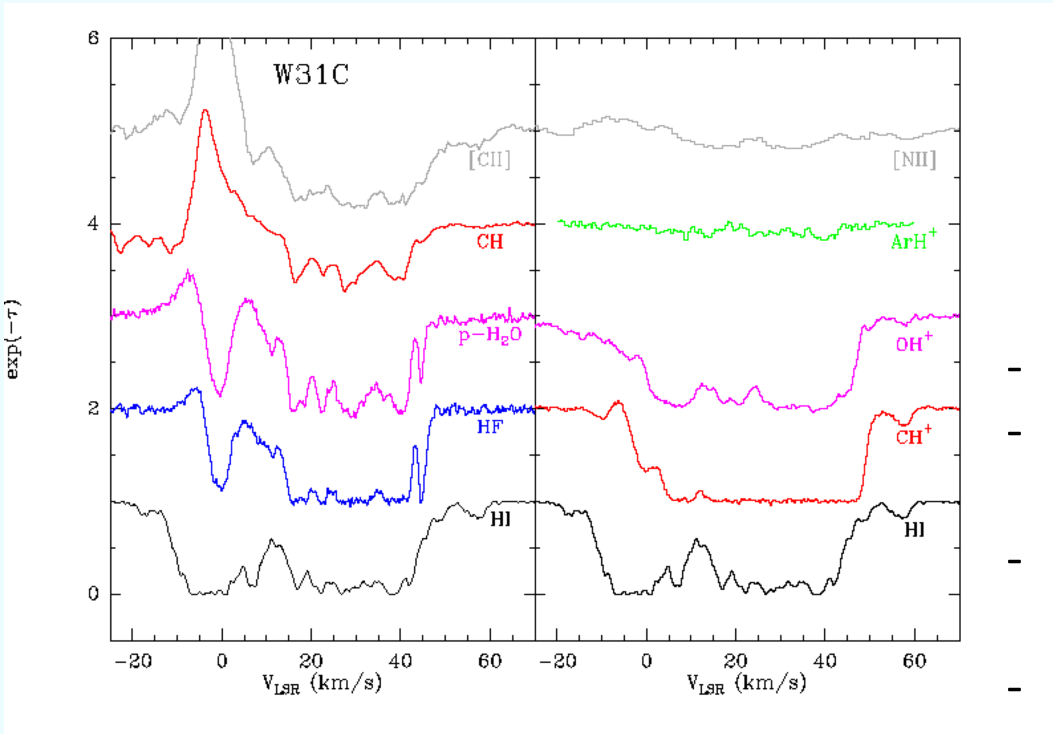
Large fluctuations of CO emission at low column densities ➔ chemical fluctuations
Locally CO-overluminous gas
see Liszt & Pety 2012

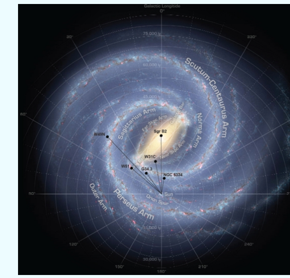
Powerful non-equilibrium chemistry driven by turbulence dissipation and/or ty magnetized shocks in unshielded regions
Godard + 2009, 2014

Does cold purely atomic hydrogen exist at all?

Herschel absorption spectroscopy of diffuse molecular gas

Herschel/HIFI absorption spectroscopy

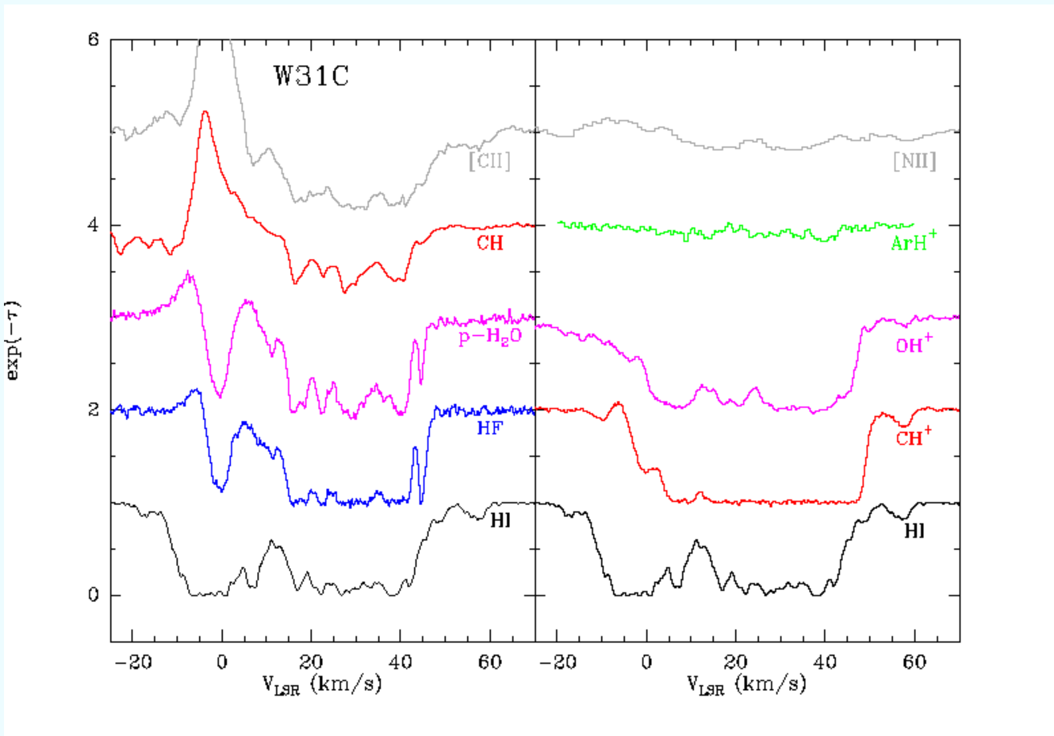




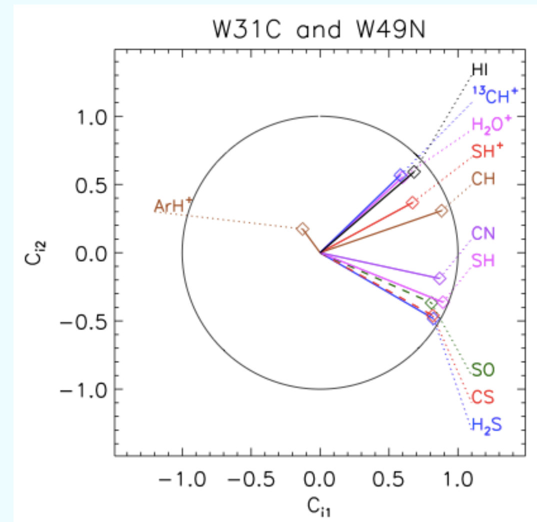
- HF : tracer of H_2 , exothermic F + H_2
- CH : tracer of H_2 (density larger than 100 cm^{-3})
- OH^+ : tracer of CR, destroyed by collisions with H and H_2
- CH^+ : tracer of energy dissipation, destroyed by collisions H and H_2
- ArH^+ : tracer of HI, $f_{H2}<10^{-3}$ and CR

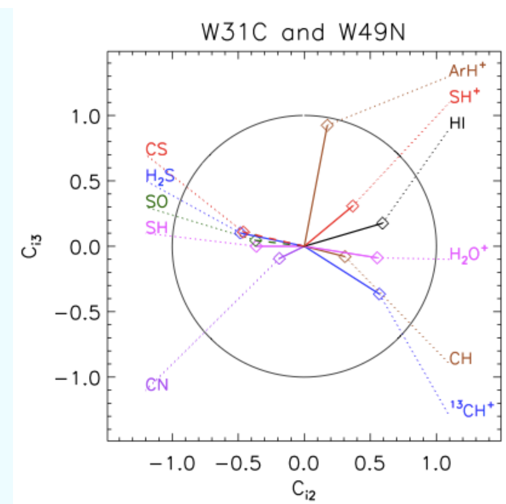
HI : EVLA, Brunthaler + in prep
CII : Gerin + 2015
NII : Persson + 2014
CH : Gerin + 2010a
HF and H_2O : Neufeld + 2010
ArH^+ : Schilke + 2014
OH^+ : Gerin + 2010b
CH^+ : Falgarone + 2010, Godard + 2012

Herschel/HIFI absorption spectroscopy



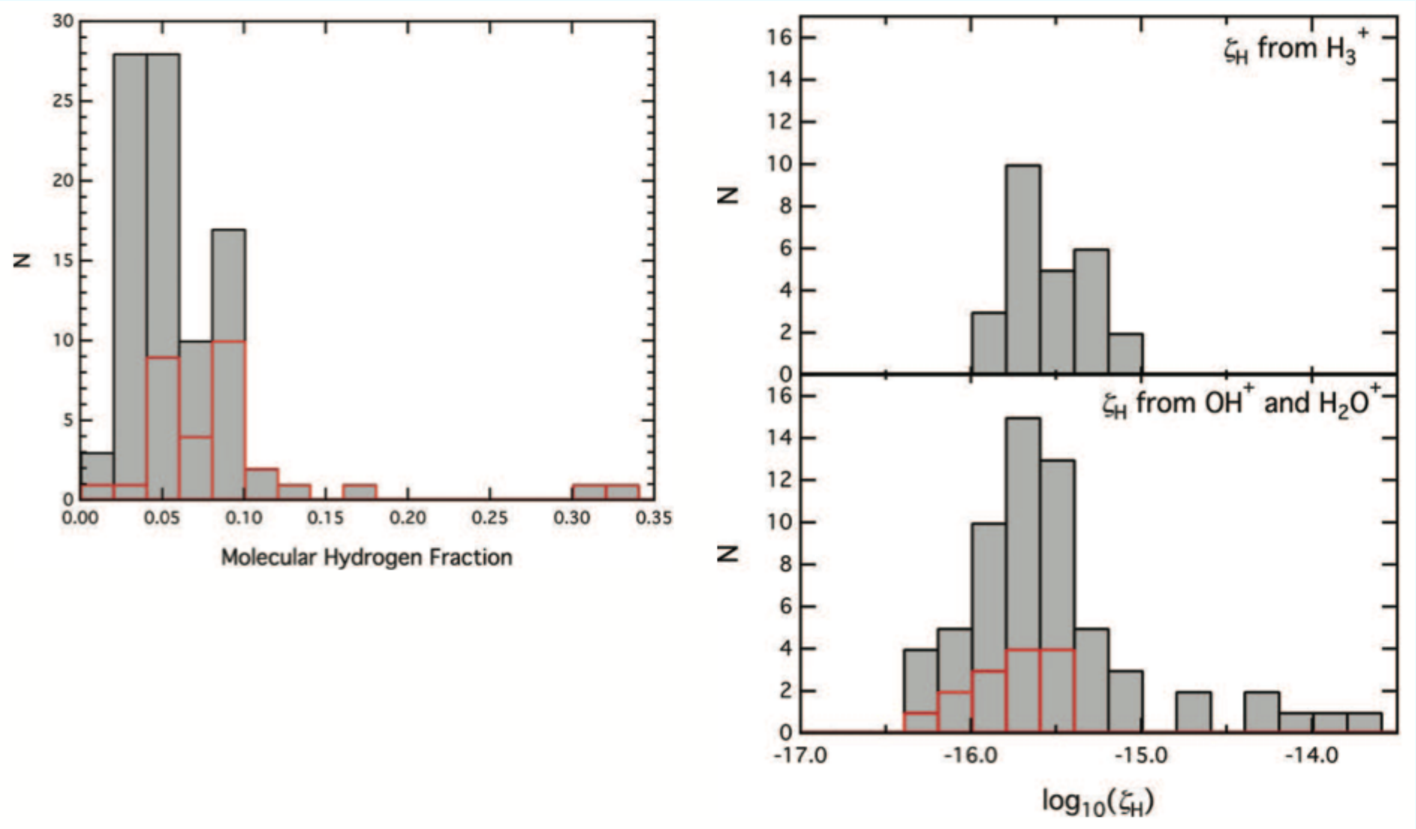
See Gerin, Neufeld, Goicoechea, ARAA, 2016





PCA analysis Neufeld + 2015

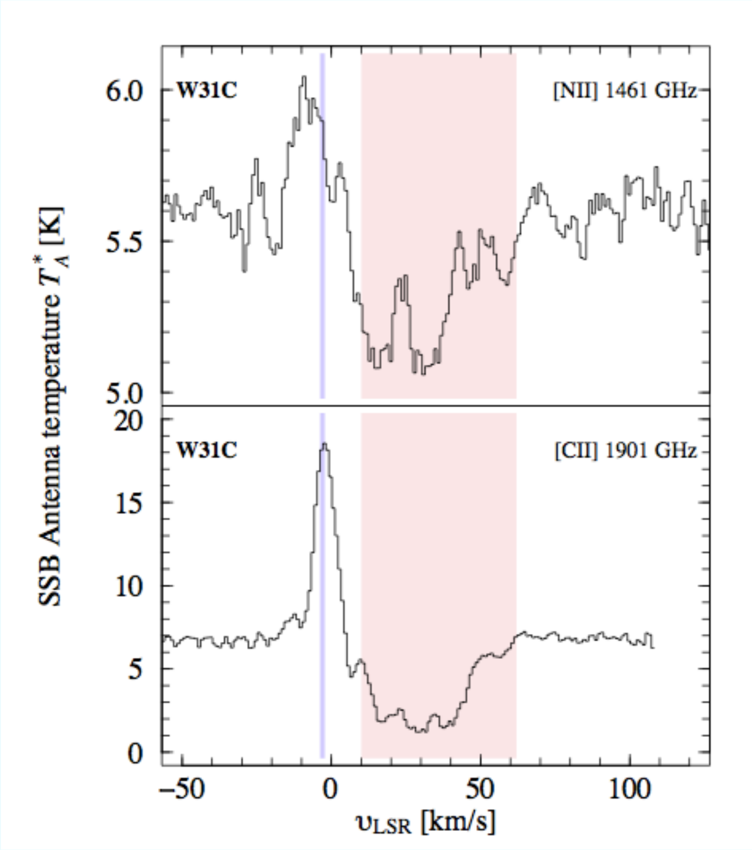
H_2 fraction and CR ionisation rates in diffuse molecular gas



Indriolo + 2015

- ➯ H_2 fractions are very low, down to < 10^{-3}
- ➯ CR ionisation rates are much larger than upper limits provided by low temperatures in dense cores

NII and CII absorption in diffuse gas

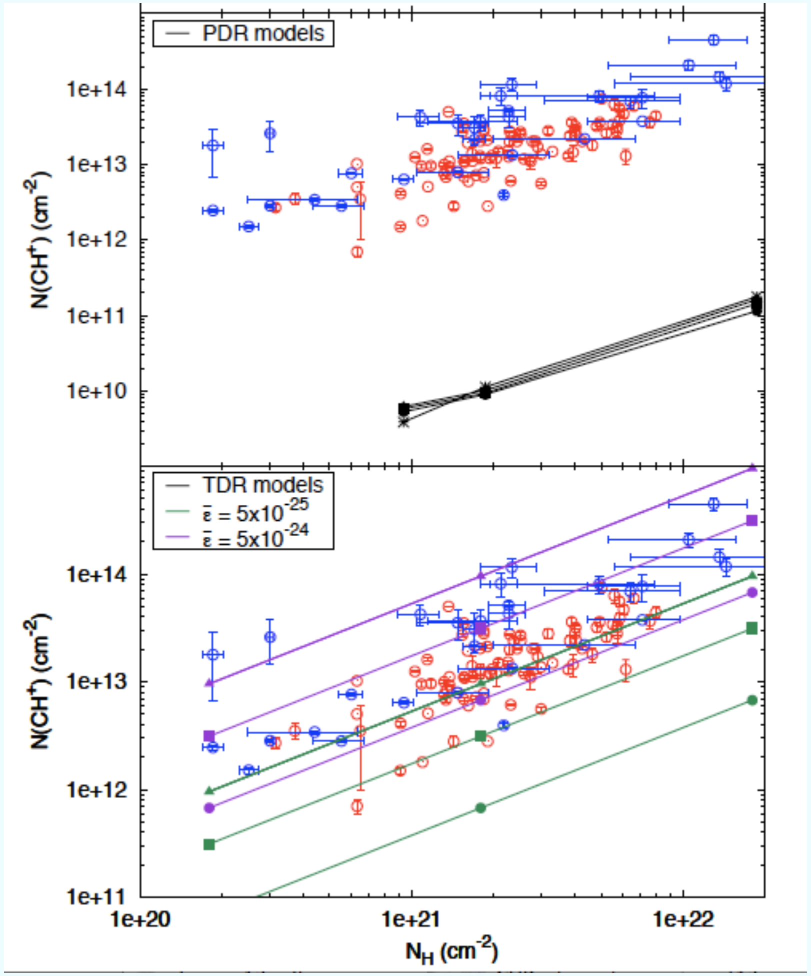


NII emission line : HII regions
in SF regions

NII absorption line from the WIM :
Mean n_e = 0.1 to 0.3 cm^{-3}
for LOS filling factor 0.5 to 0.7

CII and NII comparison:
➔ 7 – 10 % of all C^+ in the WIM

Turbulent dissipation in diffuse gas : CH^+ formation



TDR models for n_H= 30, 50, 100 cm^{-3}

Godard et al. 2014

- ➪ $N(CH^+)$ increases with UV-field
- ➪ $N(CH^+)$ proportional to **turbulent injection rate**

Lifetime

$$t = 1\mathrm{yr}/f_{\mathrm{H_2}}(n_{\mathrm{H}}/50\,\mathrm{cm}^{-3})^{-1}$$

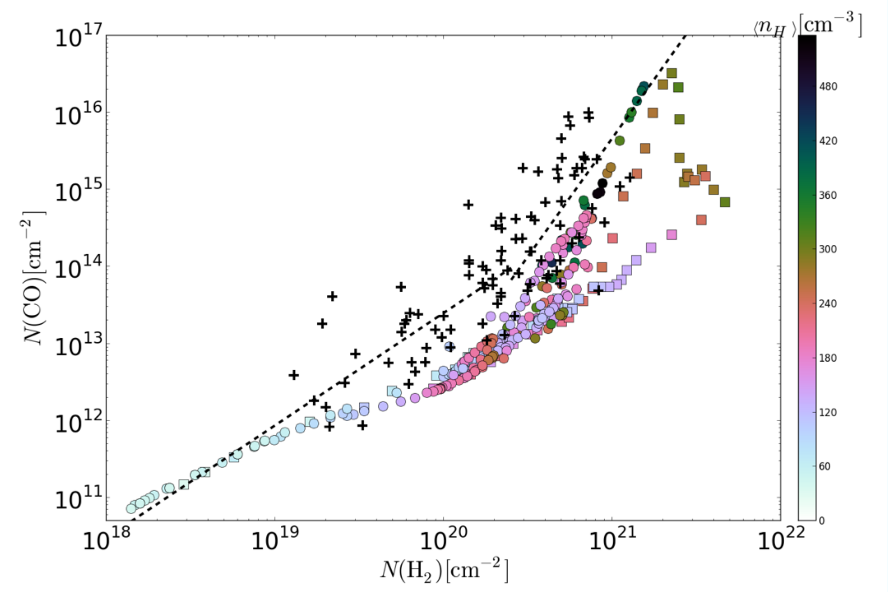
Energy formation $E_{form}=0.5\mathrm{eV}$

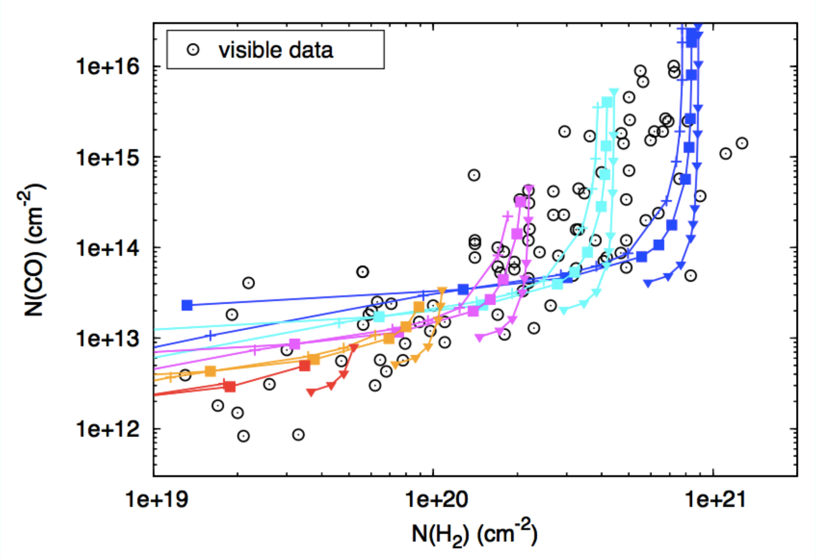
➪ Direct measure of the energy flux:

$$\dot{E} = \mathcal{N}(\mathrm{CH}^+)E_{form}/t$$

Turbulent dissipation in difuse gas: CO formation

CO : visible data (absorption lines against nearby stars)
Sheffer + 08, Pan + 05, Rachford + 09, Snow + 08



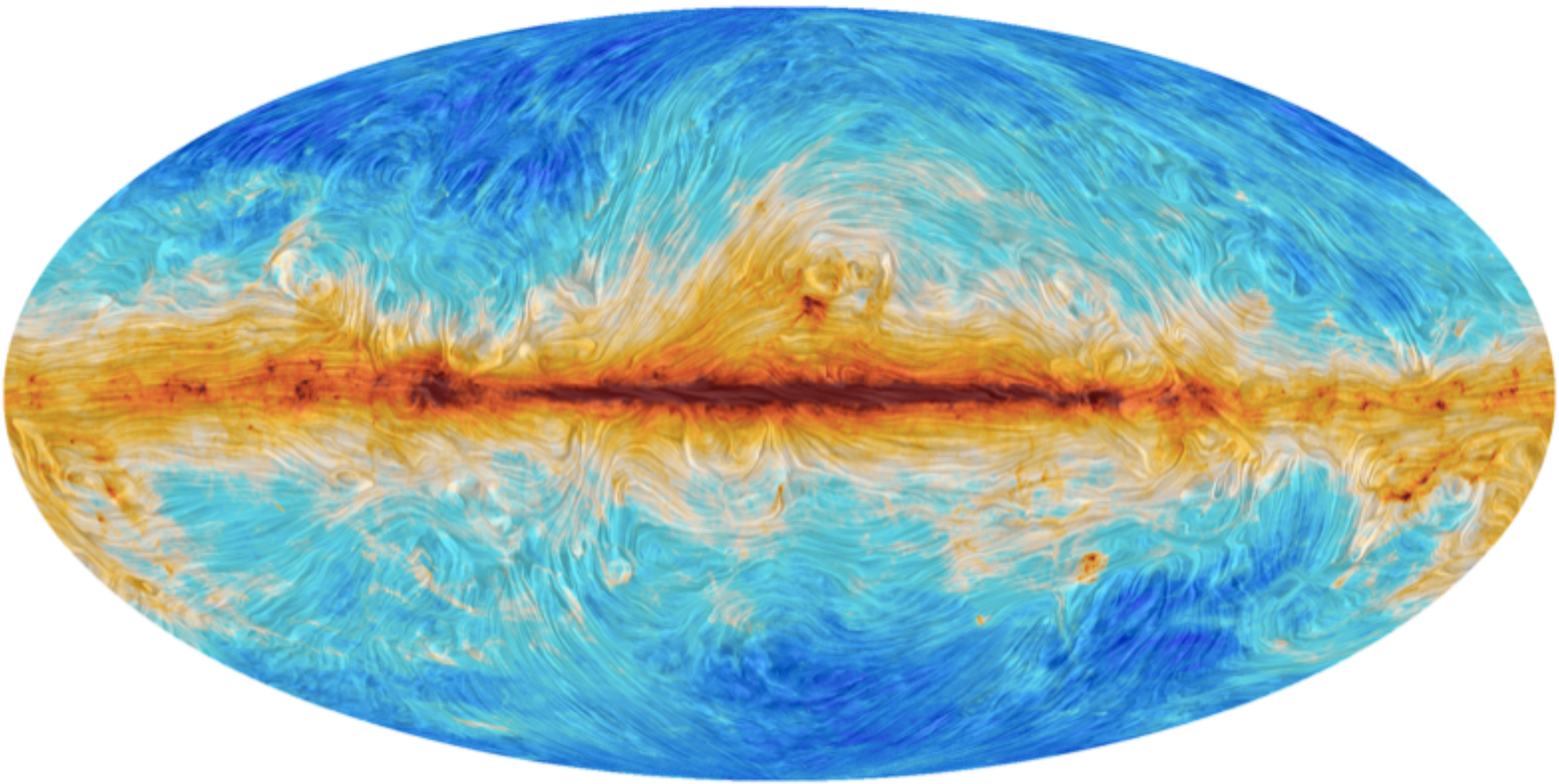


Post-treatment:
PDR models in MHD colliding flow simulations
Levrier + 2012

Turbulent dissipation regions: model predictions for low densities
Godard + 2014

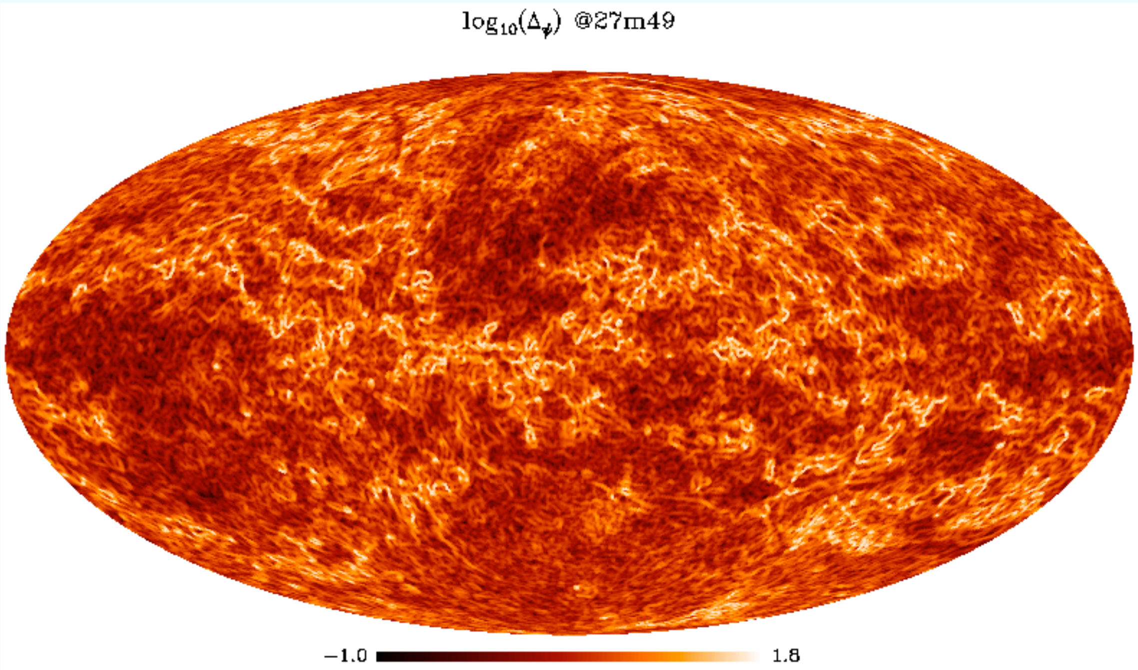
What do the sharp changes of dust polarization angle tell us about B ?

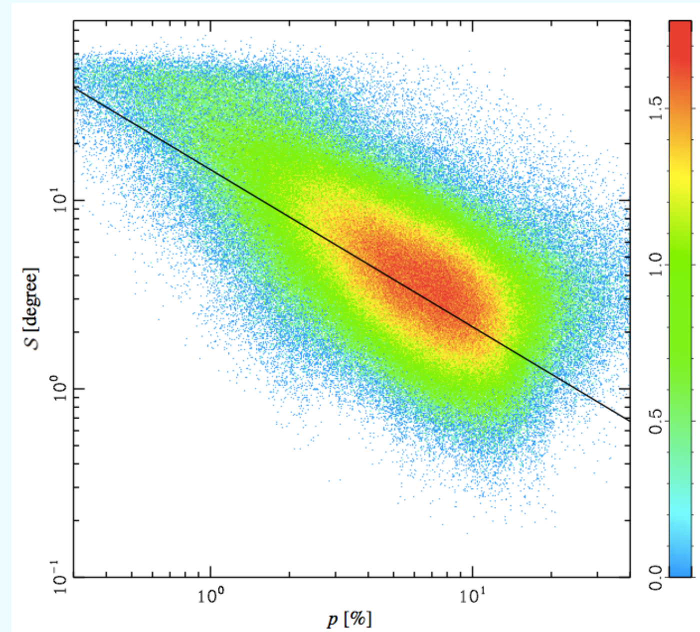
Planck all sky 353 GHz



Color scale : 353 GHz intensity
Drapery : B field POS projection

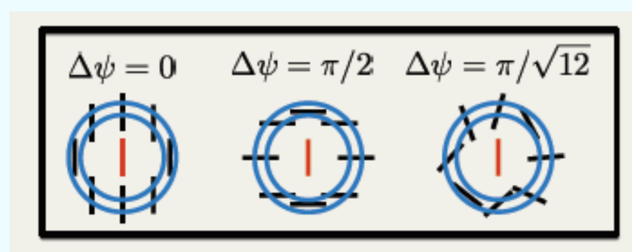
Polarization angle dispersion function





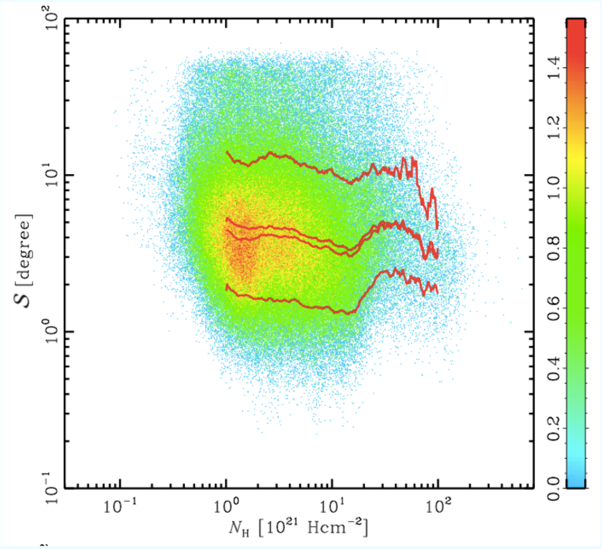
p = polarization fraction

$$\Delta\psi^2(l) = \frac{1}{N}\sum_{i=1}^{N}\left[\psi\left(\mathbf{r}\right) - \psi\left(\mathbf{r} + \mathbf{l}_i\right)\right]^2$$

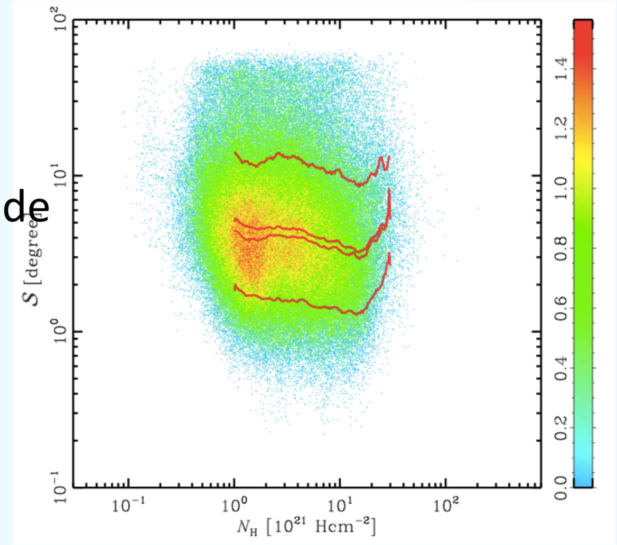


Planck Intermediate Results XIX 2015

All sky



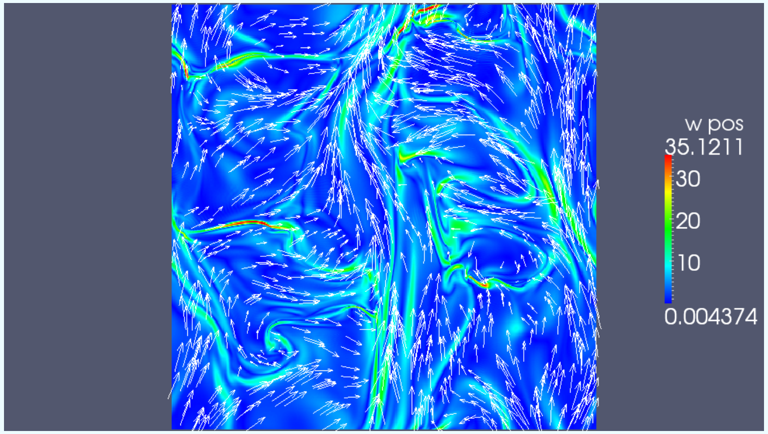
High Latitude



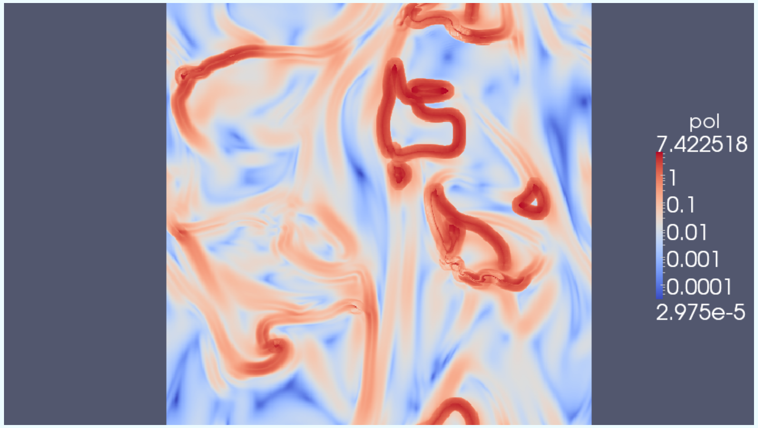
No correlation of the fluctuations of polarization angle with N_H

Planck Intermediate Results XIX 2015

Vorticity (POS projection) + B POS



Fluctuations of polarization angle



Spectral simulations

Incompressible Magnetized AD turbulence

➔Fundamental property of magnetized turbulence?

Momferratos + 2014, Falgarone + 2015

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