Turbulence in Interstellar Matter: one among the many tales (I)

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ESO-VLT

Outline

1 – The players
2 – Three major puzzles
3 – Why study IS turbulence?
4 – How do we study IS turbulence?
5 – Results from 1-pt statistics
6 – Results from 2-pt statistics (1)

To the reader of these slides:

The bulk of my two lectures was built on explanations that do not appear in the slides, making them difficult to understand as such. I have included many basic references that should help you recover the missing story, if needed.

I - The players

ISM: gas thermal phases, constituents and …

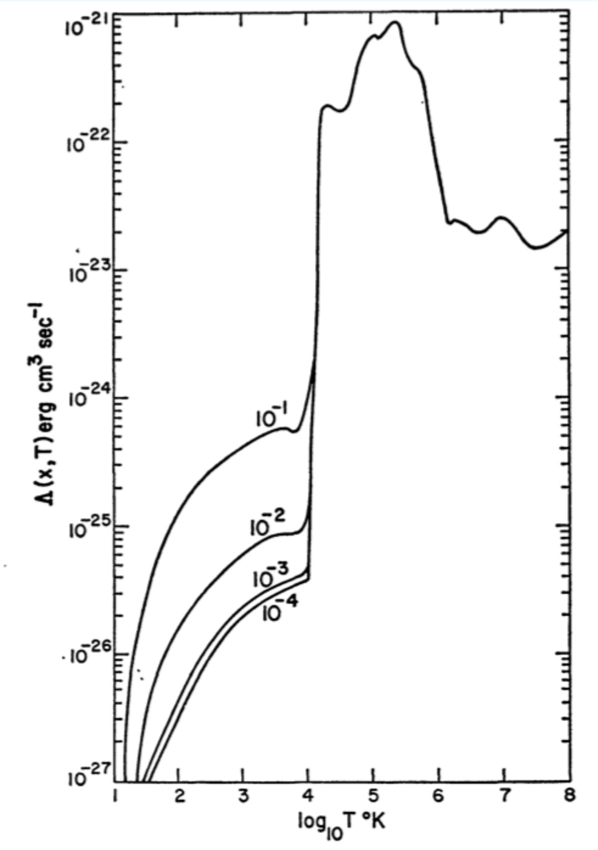
- Radiative cooling
- Two thermally stable phases:

Warm Neutral Medium T~10^4K and
Cold Neutal Medium T<100K + molecular clouds/dense cores T ~ a few 10K

- Hot Ionized Medium (T>10^5K),

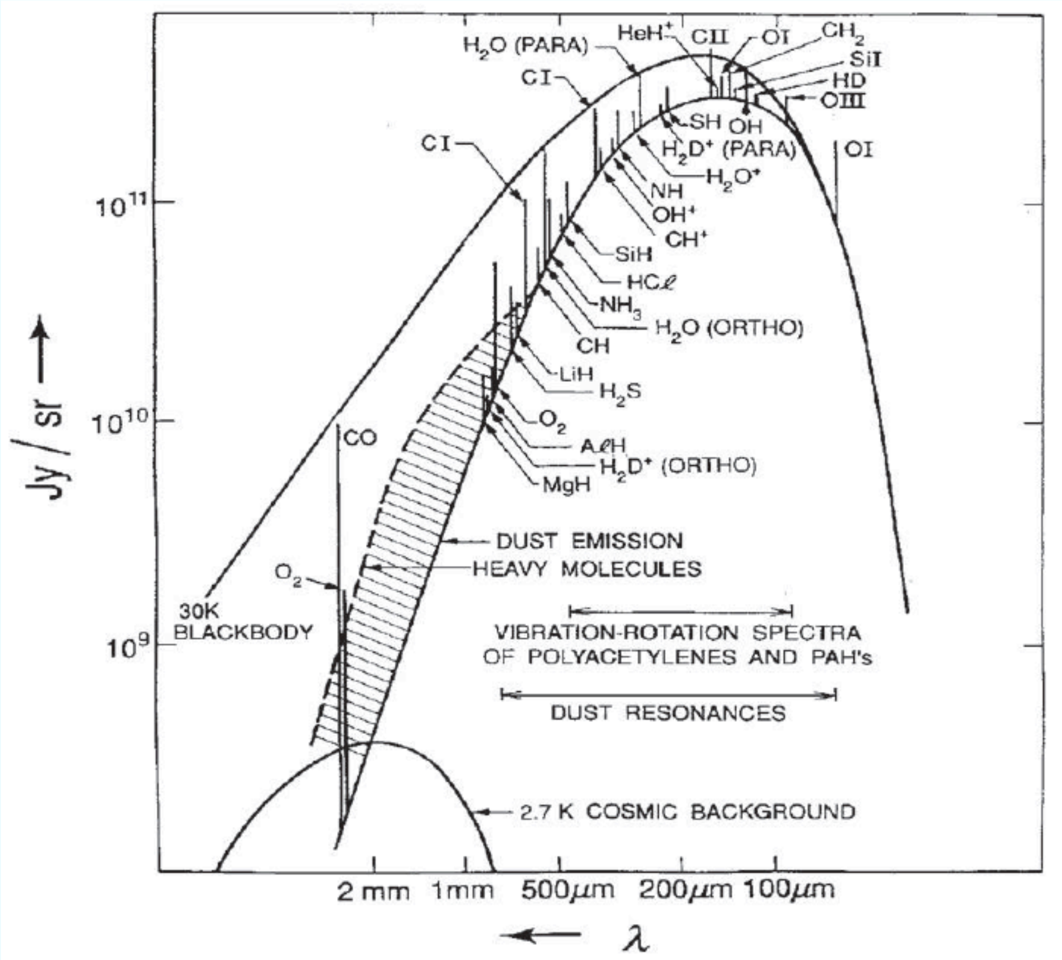
Warm Iionized Medium (fully ionized T~10^4K),

- Thermally unstable gas   T~10^3K
- Gas + dust particles + relativistic Cosmic Rays
- Heating: mostly photons (UV, X-ray) + CR
- Cooling: radiation (lines + continuum)
- Pervading magnetic field

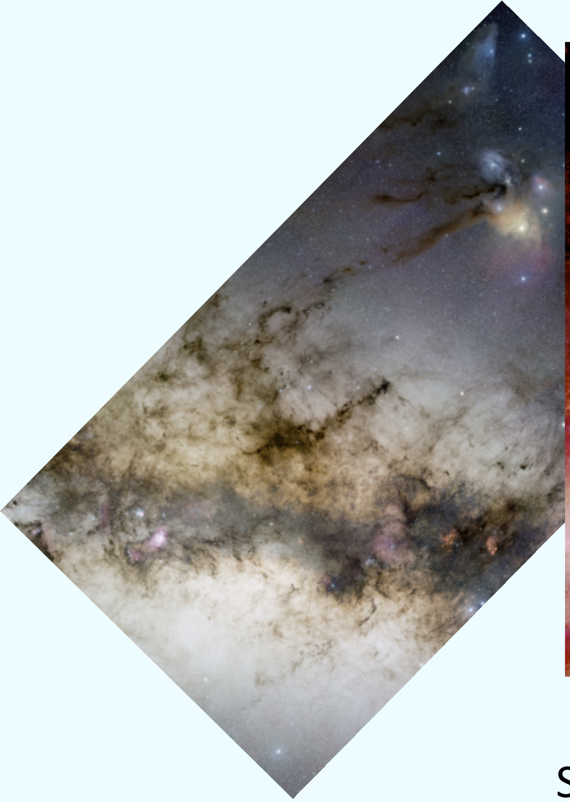


ISM cooling function,
Dalgarno & McCray 1972

Far-Infrared line and continuum emission spectrum

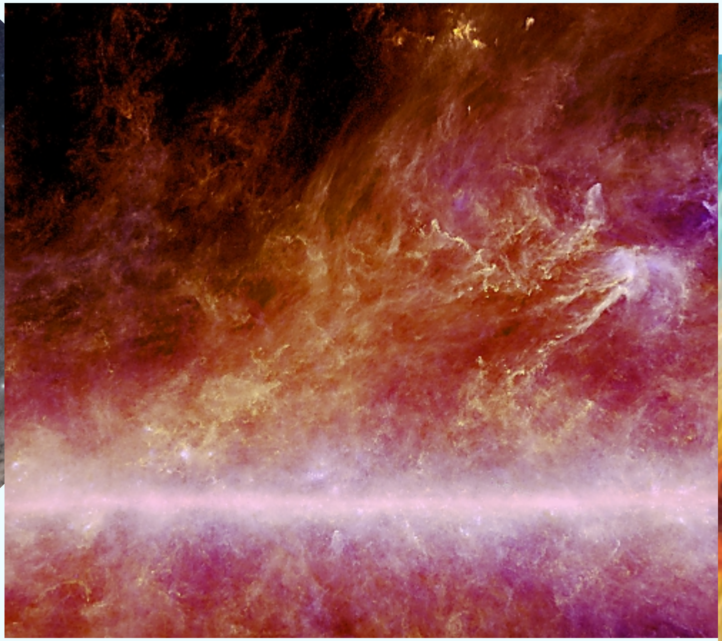


30K interstellar cloud Phillips 2009



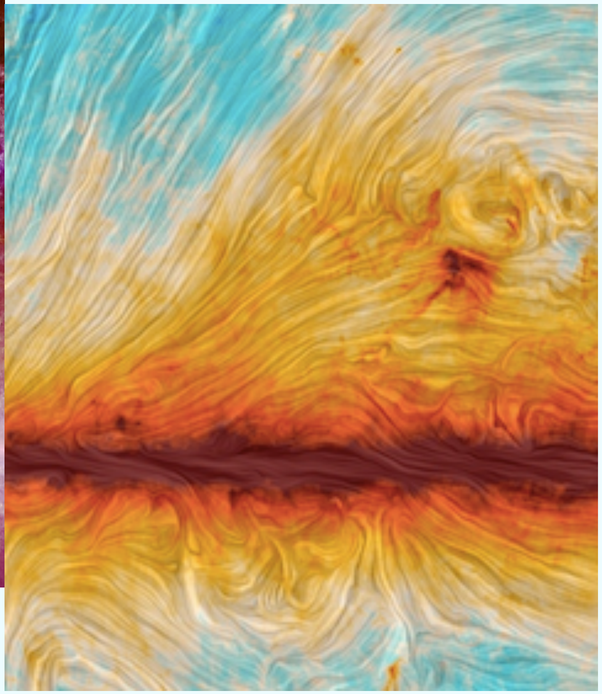
Visible observations
ESO-VLT

Shadows
= dust particles
absorb visible
stellar light



Submm emission
Planck dust thermal emission

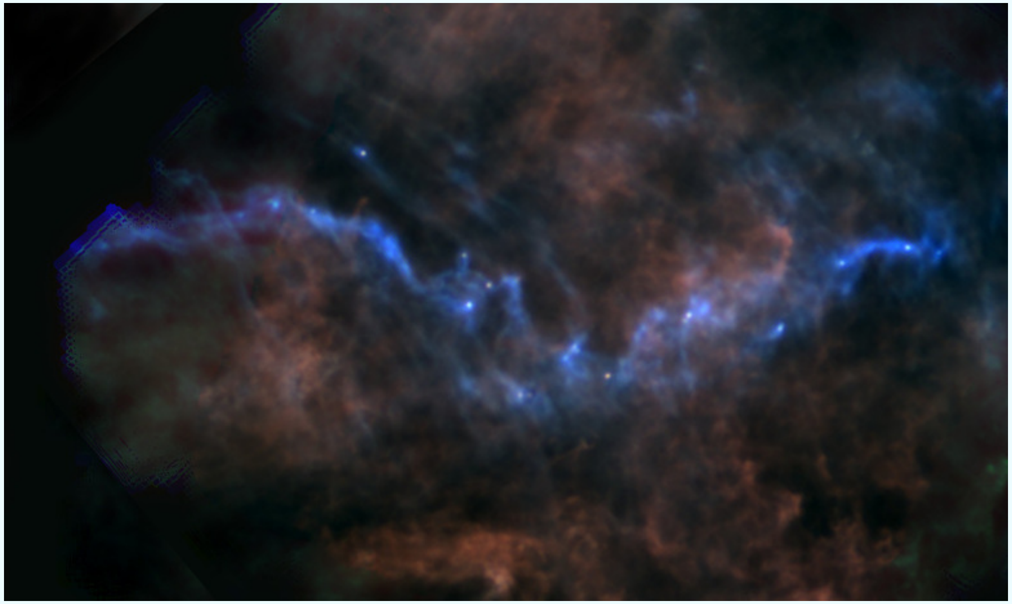
Several colors
= several observational frequencies
= several Gray Body temperatures

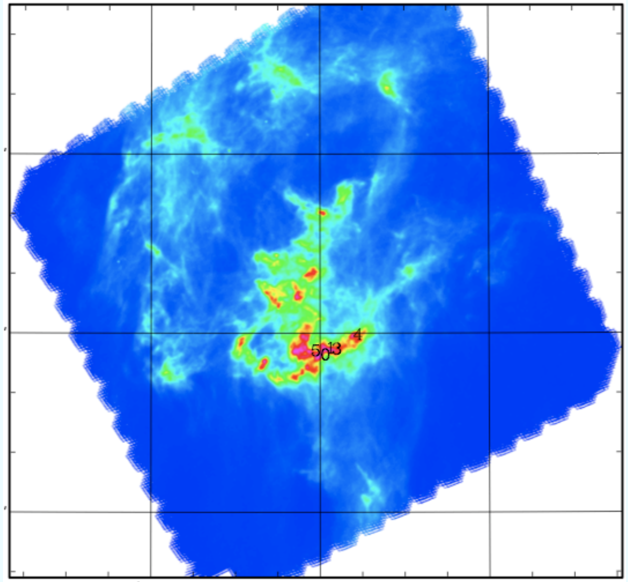


Planck polarised emission
at 353 GHz

Drapery = follows the
direction of the projected
magnetic field (after
line-of-sight
integration of polarisation
pseudo-vector)

Herschel/SPIRE at 160, 250 and 500 μm





G82.65-2.00 : in blue, very cold filaments undetected at 250 μm

Star forming
high Latitude Cloud
MBM12

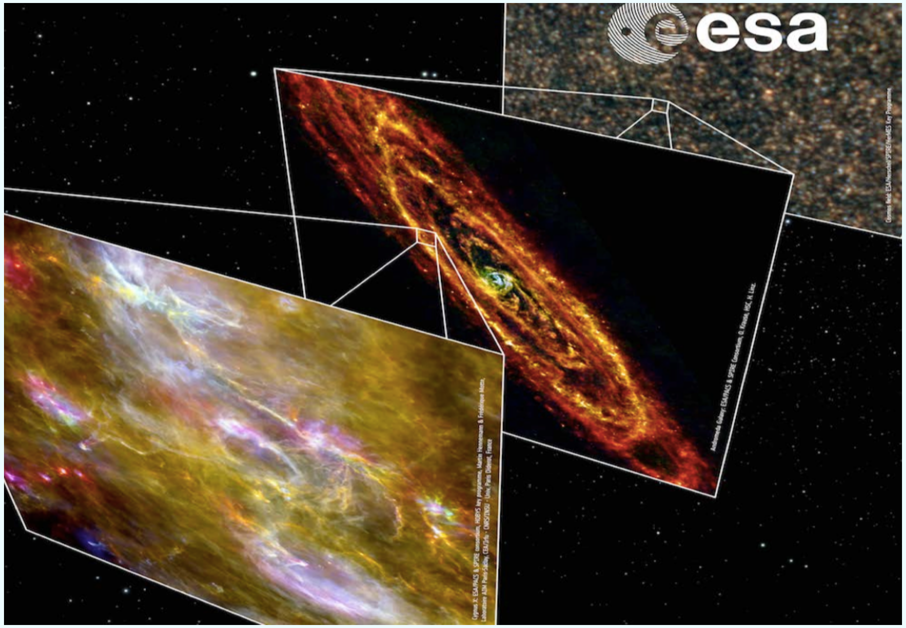
Juvela + 2010, 2011, 2012,

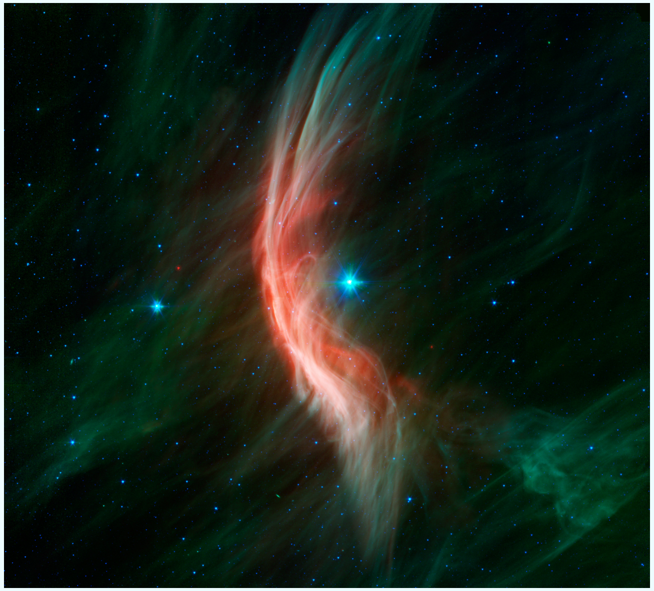
… and scales

- Galaxy : several 10kpc ~ 10^{20} m
- Cold cloud and star forming regions:
  <0.1 to 1pc ~ 10^{16} to 10^{17} m
- Protoplanetary disks
  <1000 AU ~ 10^{14} m
- Turbulence viscous dissipation scale
  in diffuse gas = a few AU ~ 10^{12} m
- Atom mean free path in diffuse gas ~ 1 AU

⇨ Validity of fluid cell concept?

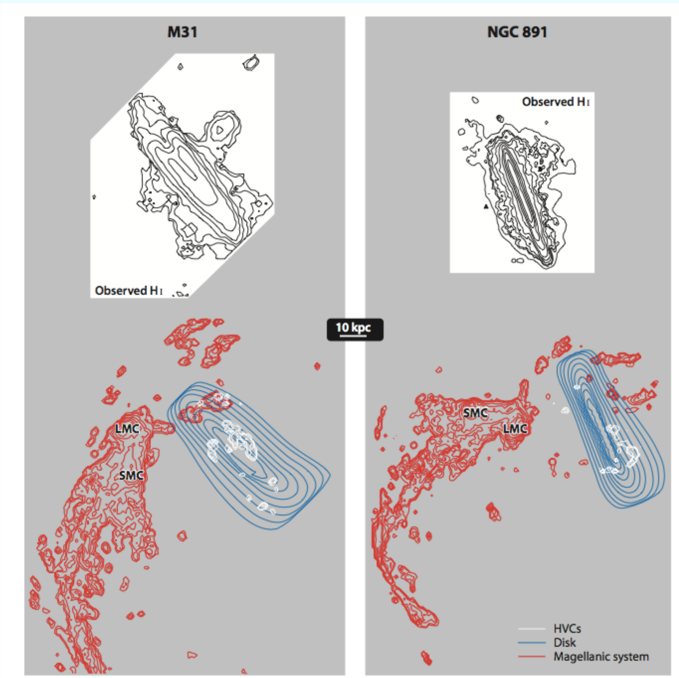
1pc about 3 light-year
1 AU = Sun-Earth distance

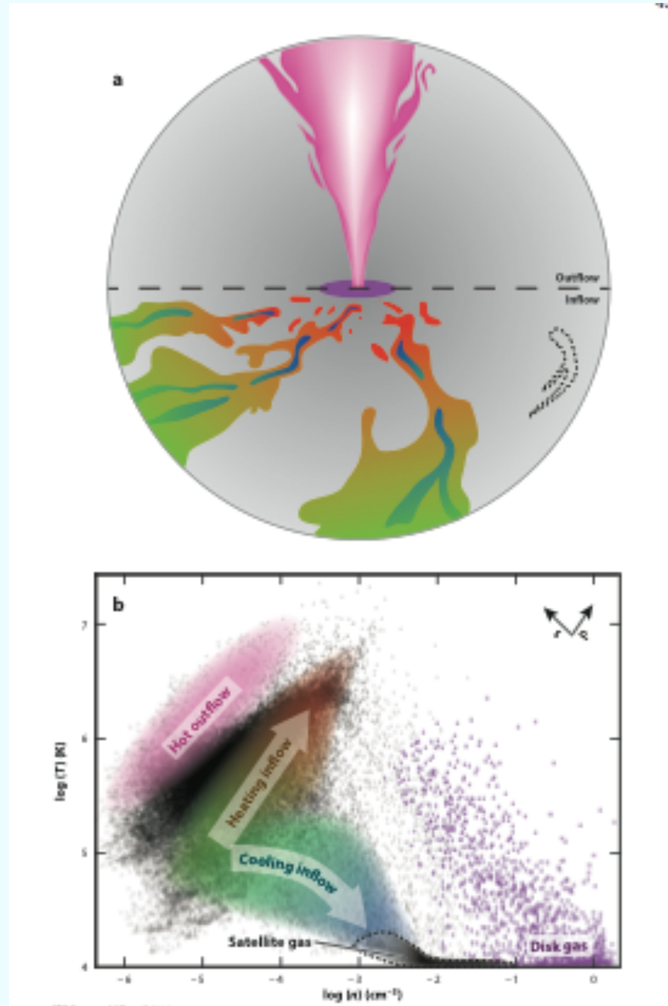


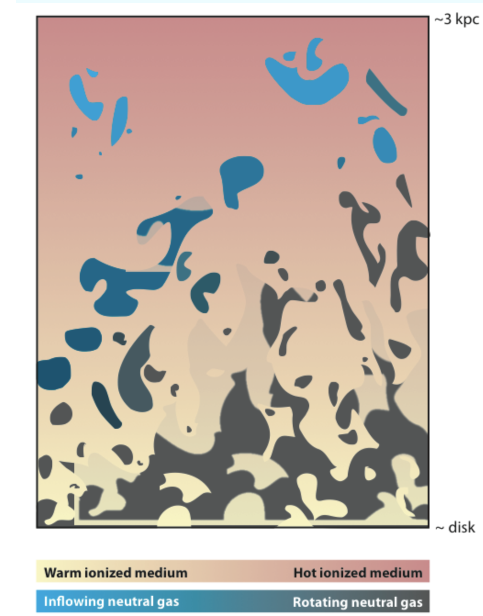


AU-scales : Mid-IR *Spitzer* image of the bow shock in front of the run-away star ζ Oph

… and thermo/dynamics coupling



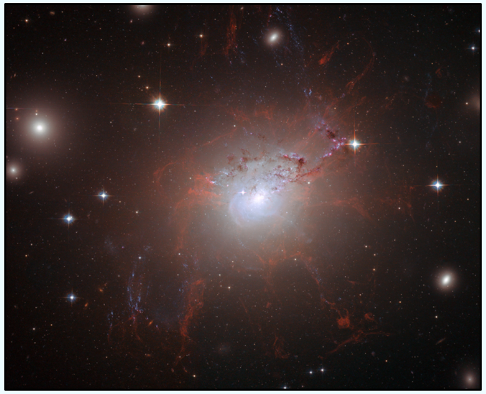




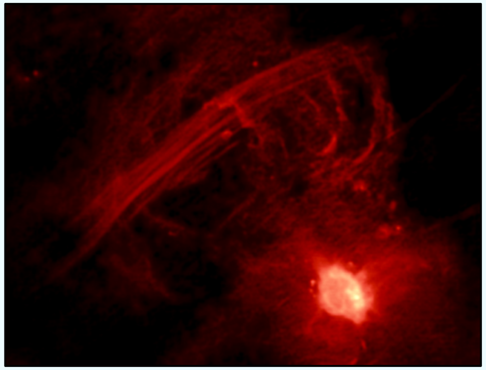
Putman et al. 2012 ARAA

Extremes of Cosmic Magnetism

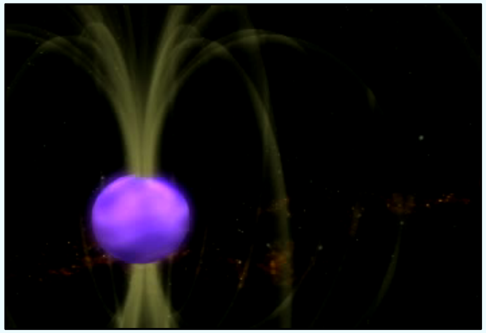
- “Seed” fields in early Universe — 10^{-30} –10^{-20} gauss
- Intergalactic gas — 1-10 nanogauss
- Gas within clusters of galaxies — 0.1-1 microgauss
- Interstellar gas — < 10 milligauss
- Centre of the Milky Way — < 1 milligauss
- Normal star: HD 215441 — 34,000 gauss
- White dwarf: PG 1031+234 — 1 billion gauss
- Pulsar: PSR J1847-0130 — 90 trillion gauss
- Magnetar: SGR 1806-20 — 2×10^{15} gauss - 1×10^{16} gauss
- Cosmic strings? — 10^{30} gauss
- Planck-mass monopoles? — 10^{55} gauss



Magnetic filaments in Perseus A (Fabian et al. 2008)

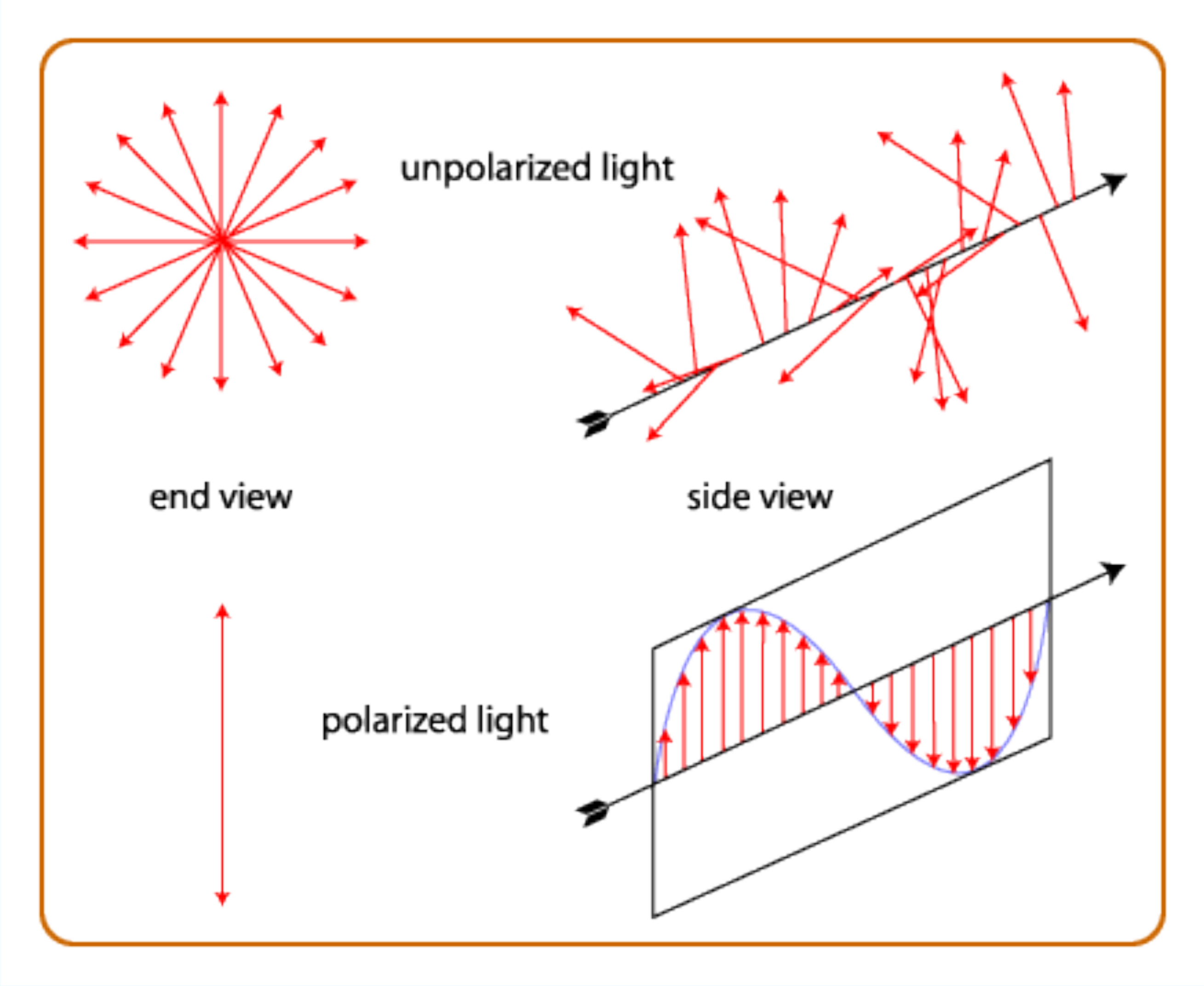


Galactic Centre (Yusef-Zadeh et al. 1984)



SGR 1806-20 giant flare (NASA)

Polarised Light

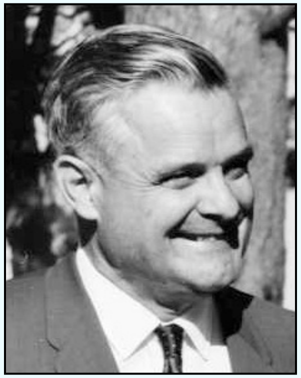


Gemological Institute of America

WARNING ON THE SKETCH: Remember that the orientation of the dust grains in the magnetic field is wrong by 90 degrees.

See references in Planck Intermediate Results XX

Magnetism in Space



Lowell Observatory Archives

166 SCIENCE February 18, 1949, Vol. 109

Observations of the Polarized Light From Stars

John S. Hall

U. S. Naval Observatory, Washington, D. C.

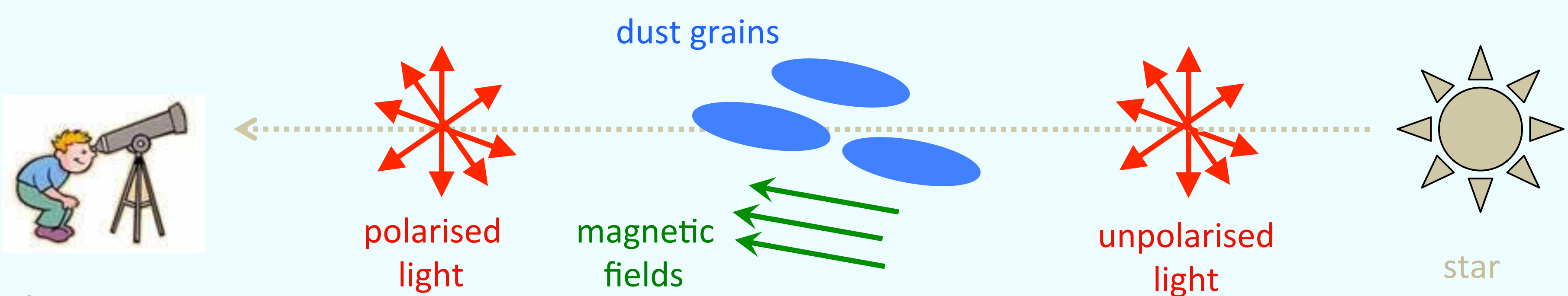
February 18, 1949, Vol. 109 SCIENCE

Polarization of Light From Distant Stars by Interstellar Medium

W. A. Hiltner

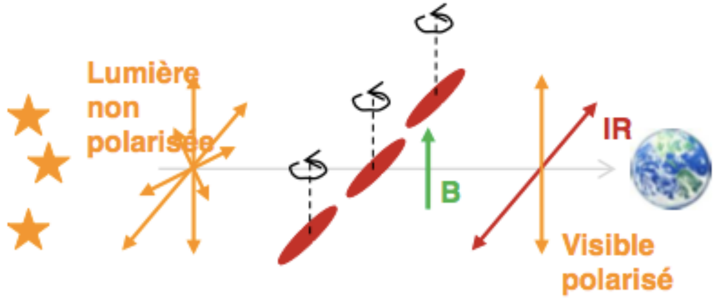
Yerkes Observatory, University of Chicago

Astronomical Society of the Pacific / Yerkes Observatory

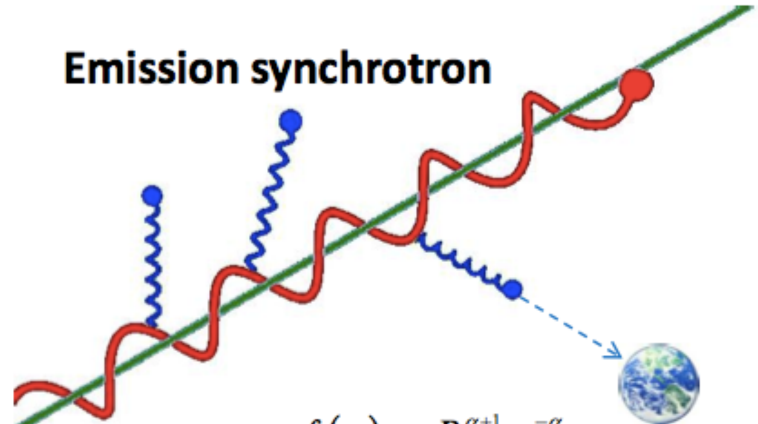


USRA

Polarisation linéaire par la poussière



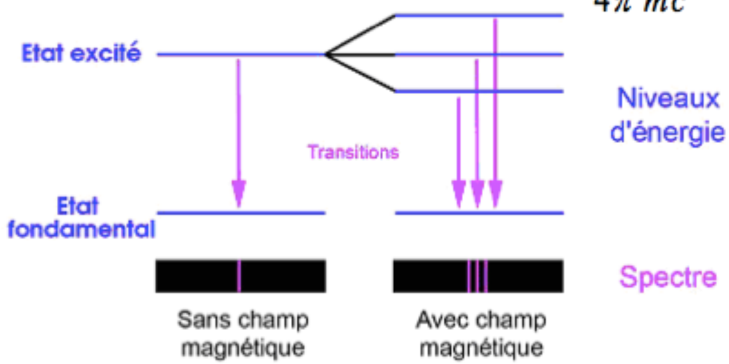
Emission synchrotron



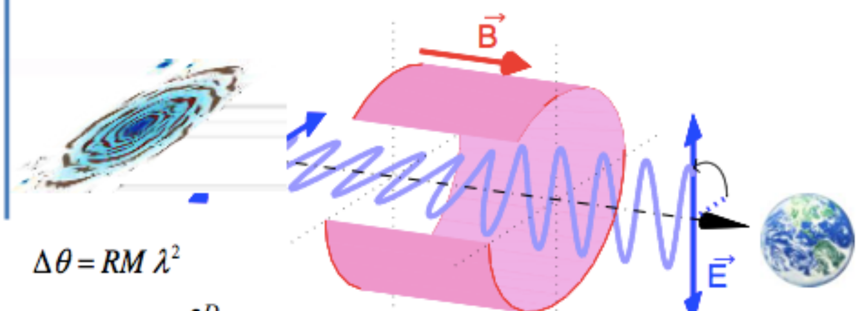
$$\varepsilon = f(\alpha)\, n_{rel}\, B_{\perp}^{\alpha+1}\, \nu^{-\alpha}$$

Effet Zeeman

$$\Delta\nu = \frac{e}{4\pi}\frac{B}{mc}$$



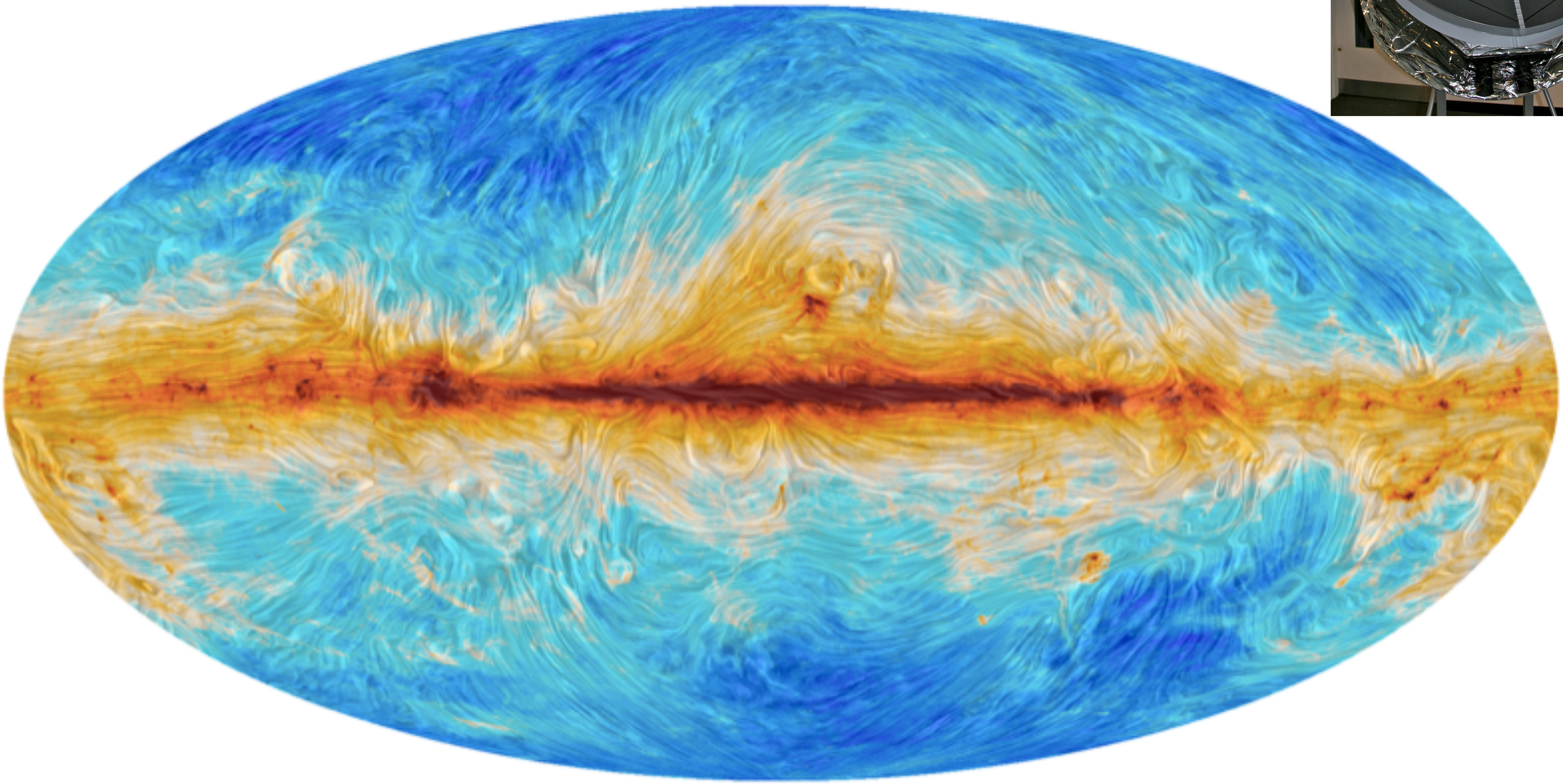
Rotation Faraday



$$\Delta\theta = RM\,\lambda^2$$

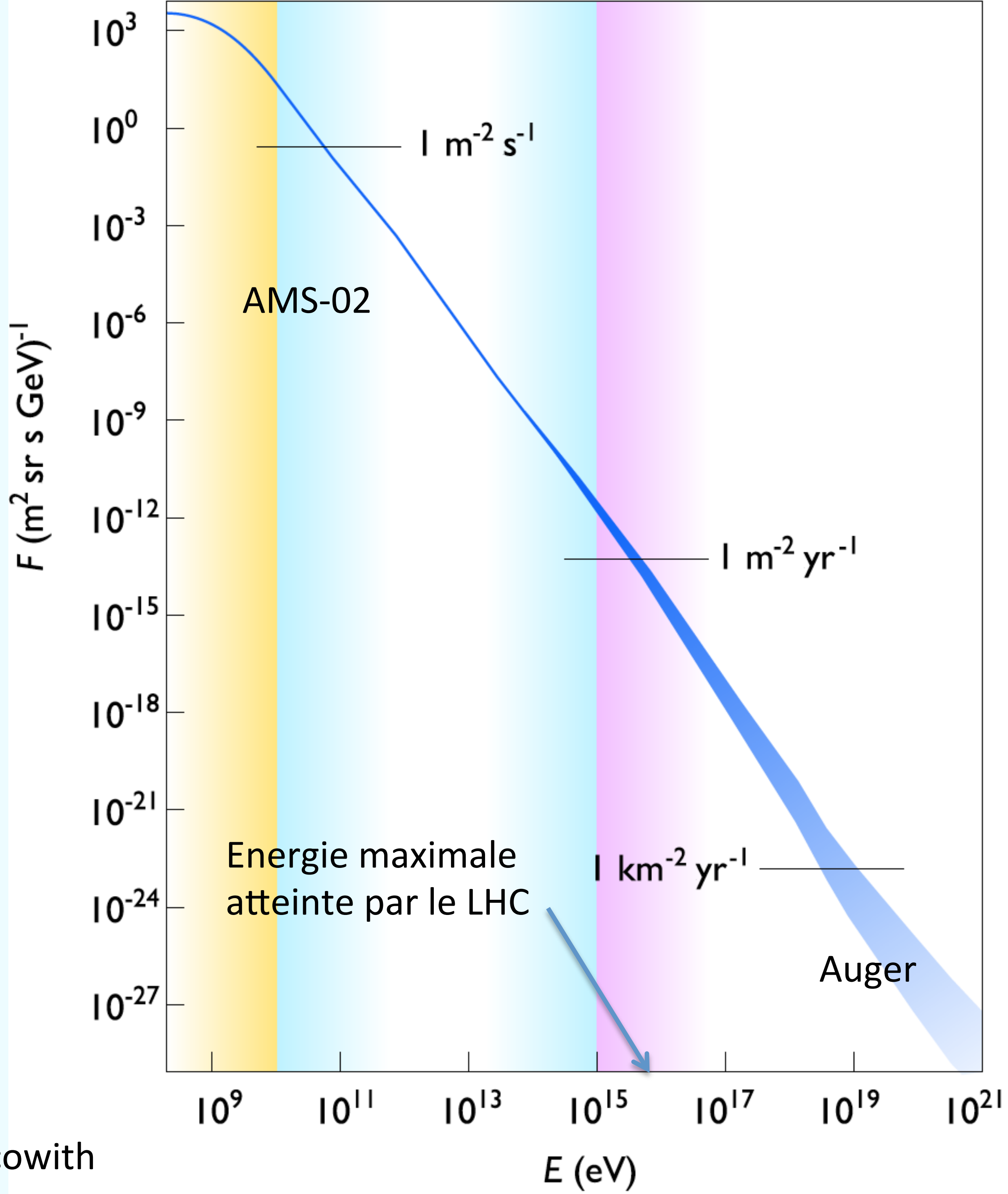
$$RM = 0.81\int_0^D n_e(s)\,B_{\parallel}(s)\,ds$$

Planck all sky 353 GHz



Color scale : 353 GHz intensity
Drapery : B field POS projection
(from polarization angle)

Le spectre du rayonnement cosmique

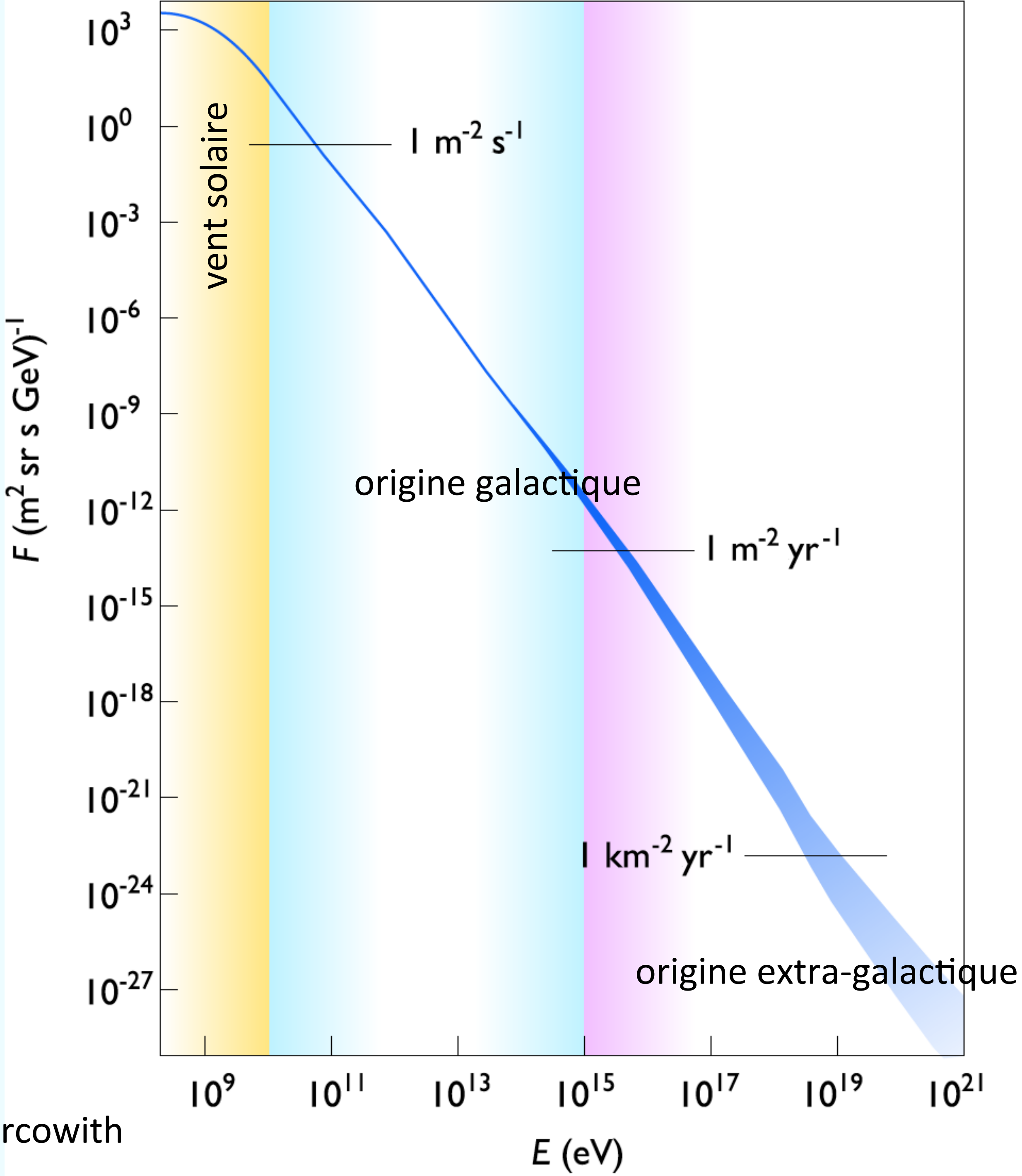


Courtesy of Alexandre Marcowith

Le spectre du rayonnement cosmique

<u>Question</u>:
où trouve t'on l'équivalent (en mieux) du LHC dans l'espace ?

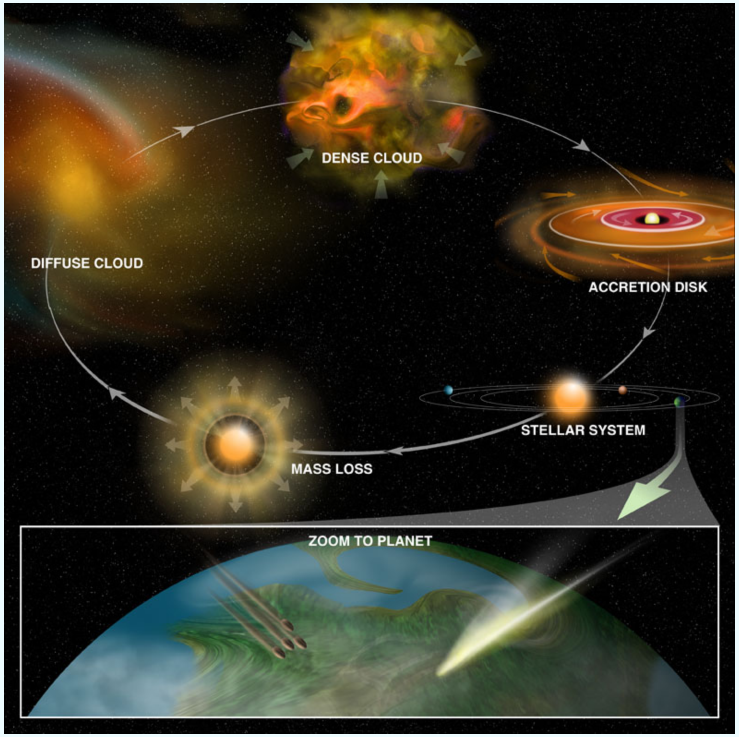
donc quelles sont les sources du rayonnement cosmique ?



Courtesy of Alexandre Marcowith

II – A few puzzles

Puzzle 1: Why ISM phases do not mix?



Because ISM is an **open system** and exchanges matter and energy with stars

No fine tuning

➪ ISM maintained **far from thermal equilibrium** by the energy of a cycle driven by star formation and feedback + extragalactic infall

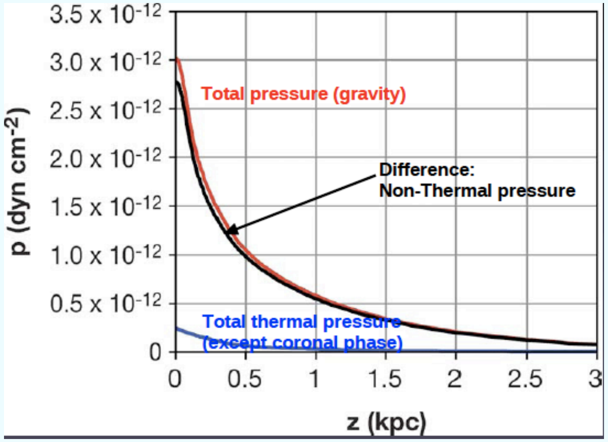
➪ Thermal phases are permanently replenished

➪ **Conversion of gravitational (and nuclear) energy** into kinetic plus thermal energy

➪ **Large galaxy scale heights** : non-thermal support

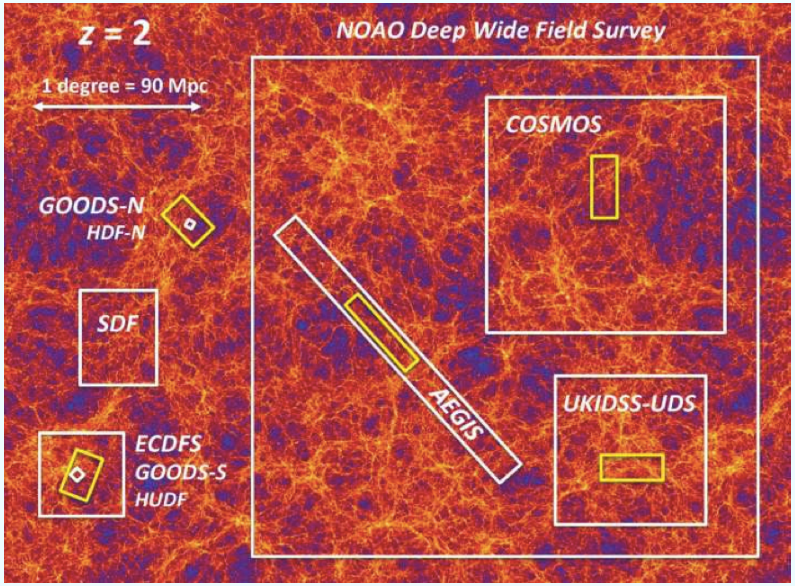
Equipartition Kinetic, Magnetic, Cosmic Rays energy densities

➪ Sustained formation of stars drives the cosmic evolution of baryonic matter

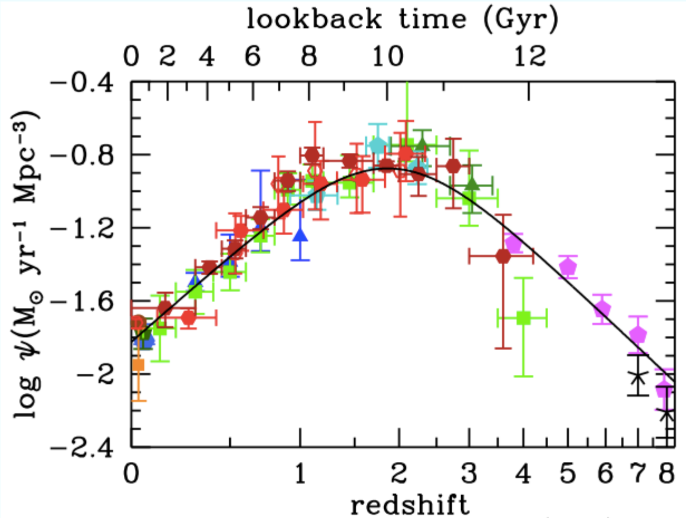


Height dependence of pressure in galactic halo
Cox 2005

Puzzle 2: Why is cosmic star formation so inefficient?

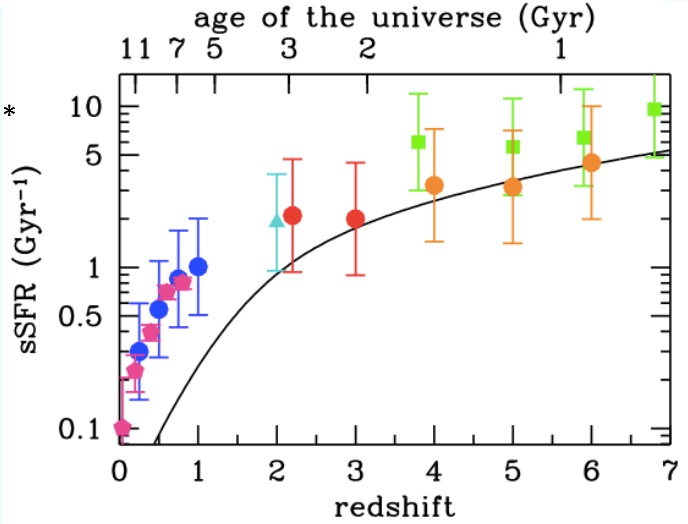


Comoving SFR



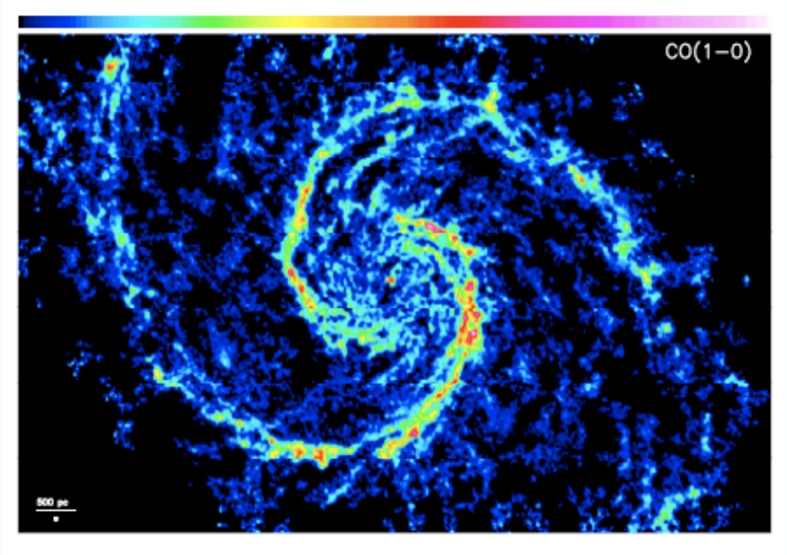
Observed Deep Fields
Rest frame UV, Vis, FIR
Background: cosmological simulations

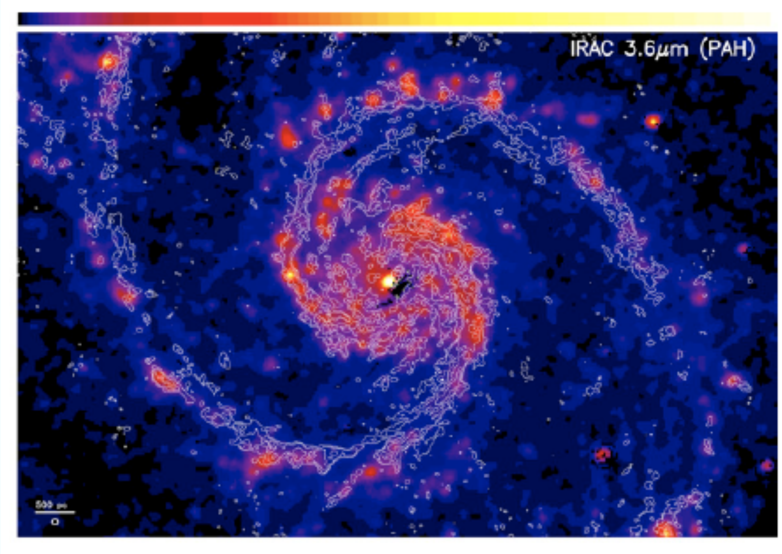
sSFR=SFR/M_*



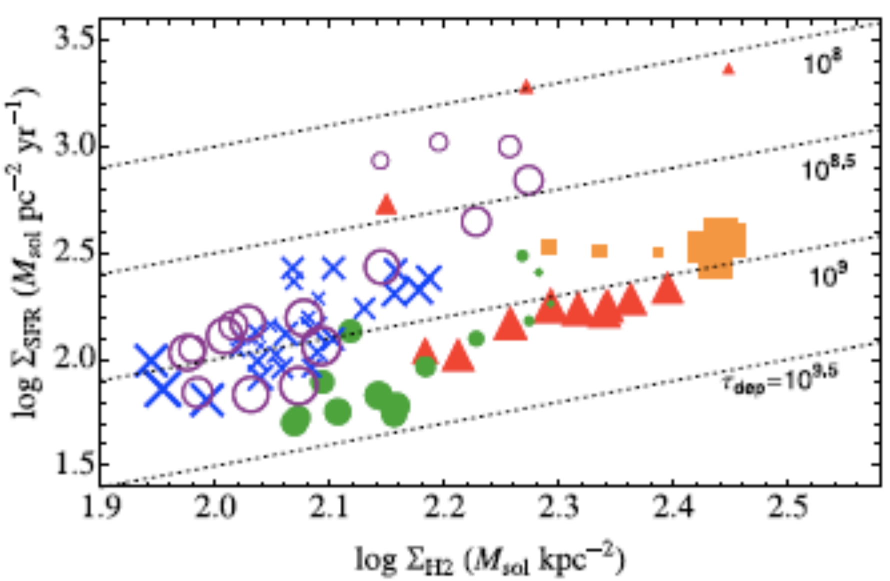
Madau & Dickinson 2014

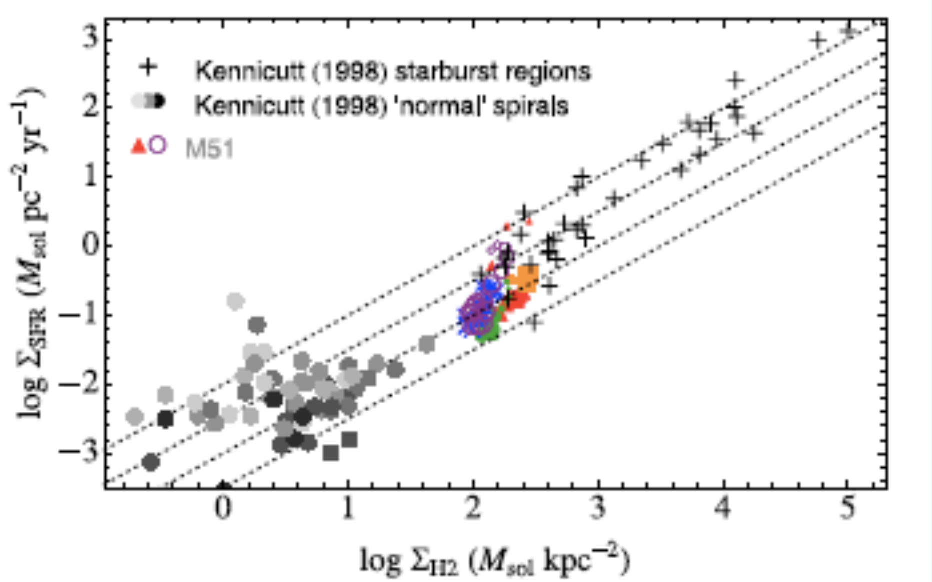
M51





IRAM- Plateau de Bure interferometer
CO(1-0) observations Schinnerer et al. 2013

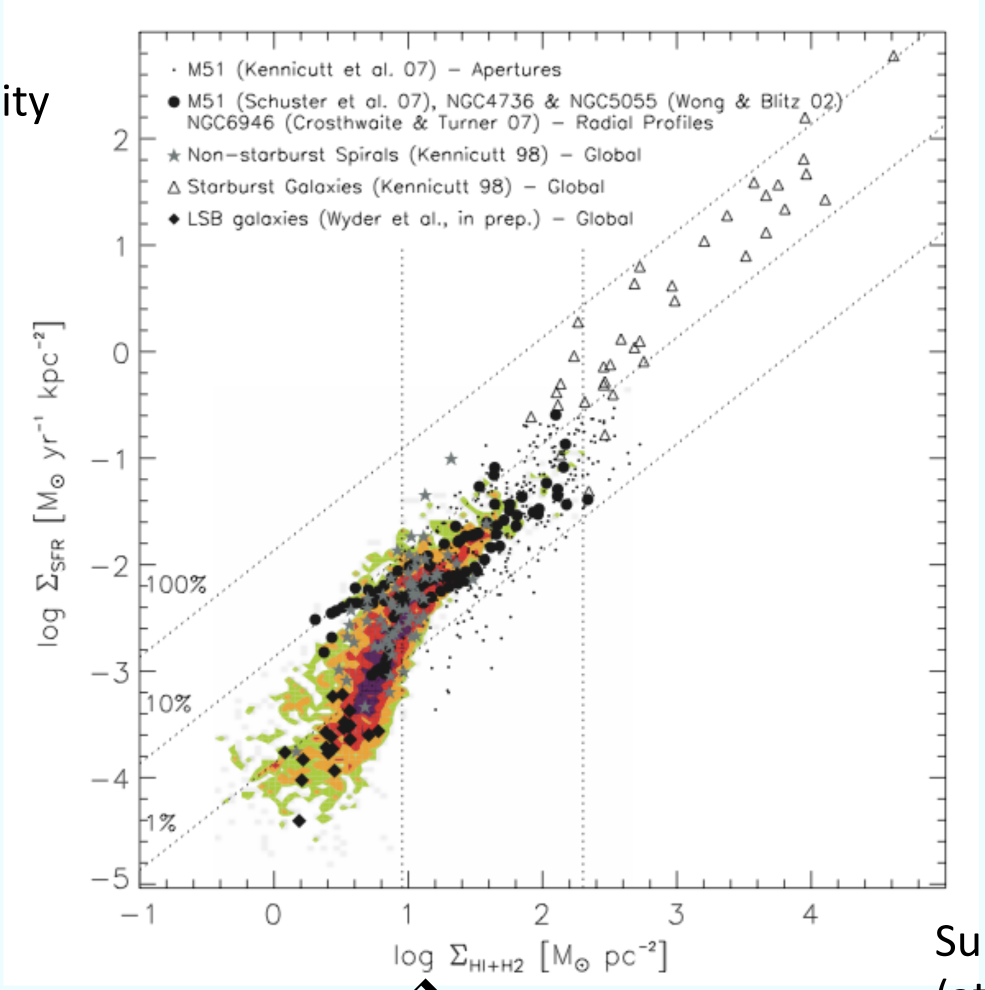




Meidt + 2013

Puzzle 3: Why is star formation linked to H_2 emergence?

SFR
surface density



Bigiel + 08

Surface density of gas
(atomic + molecular)

H/H_2 transition

III - Why study interstellar turbulence?

- **Central issue in galaxy/star formation: gravity vs. gas dissipative dynamics**
- **Dominant energy density with respect to gravity**

➪ star and galaxy formation

GMC free-fall time $t_{ff} = 48$ Myr $n^{-1/2}$ ~ GMCs dynamical time

l/σ_v = 200pc/10 km s^{-1} ~ 20 Myr (n ~ 10 cm^{-3})

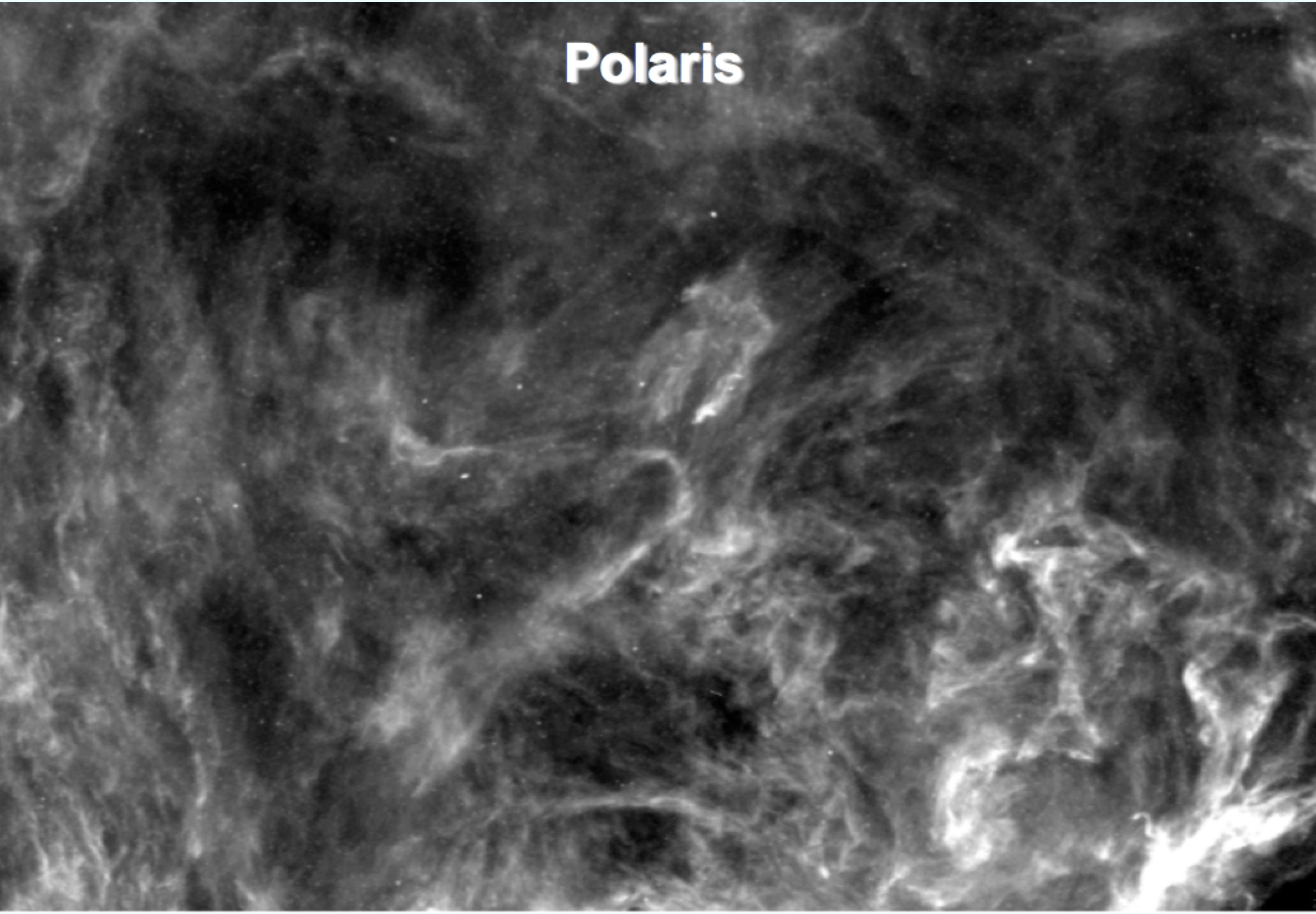
➪ SFR ~ 50 M_{sol} yr^{-1} while observed galactic average SFR ~ 3 M_{sol} yr^{-1}

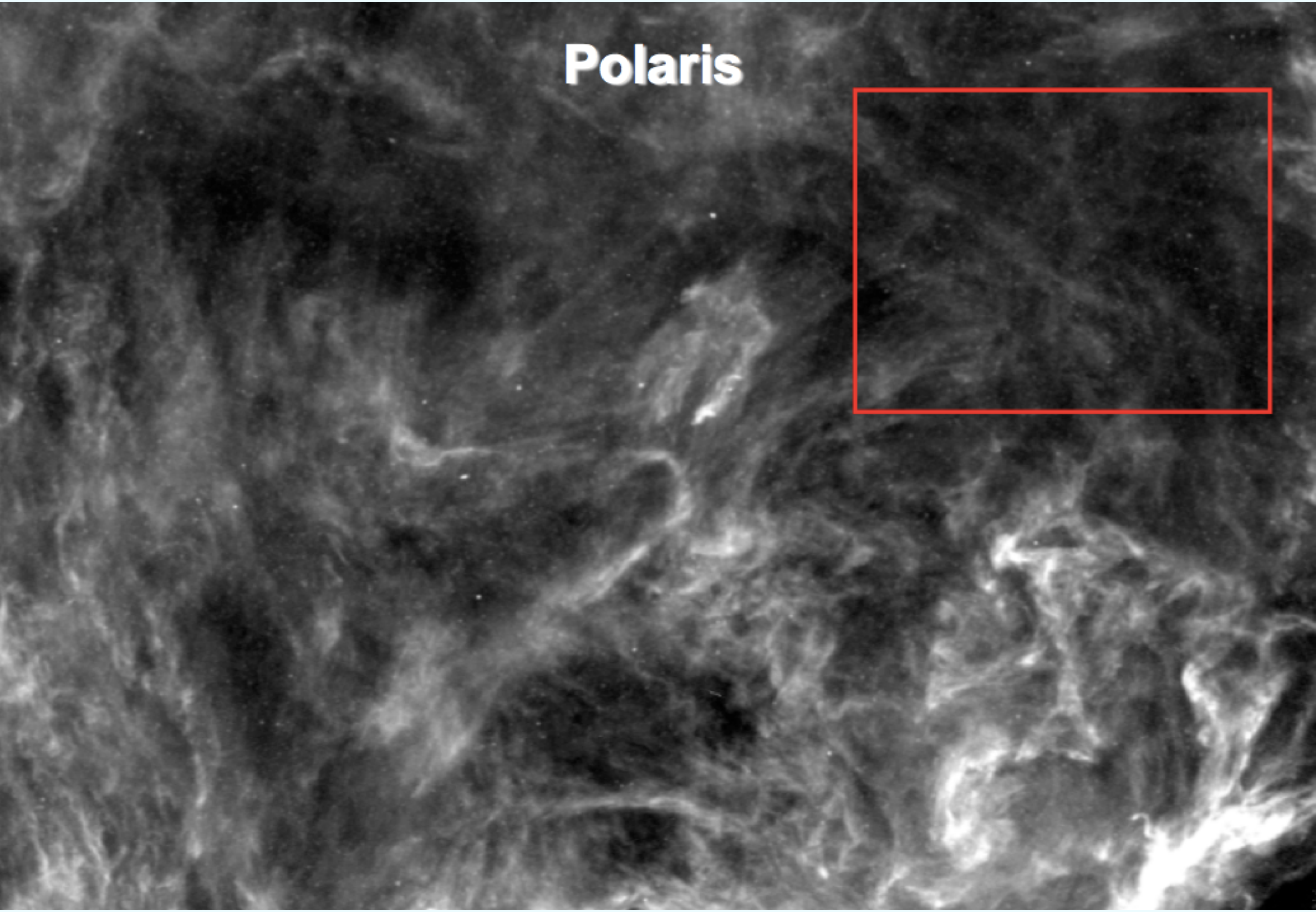
- **Dynamo :** magnetisation of the universe
- **Cosmic Rays Acceleration**
- **Dissipation scales** close to atom/molecule mean free path

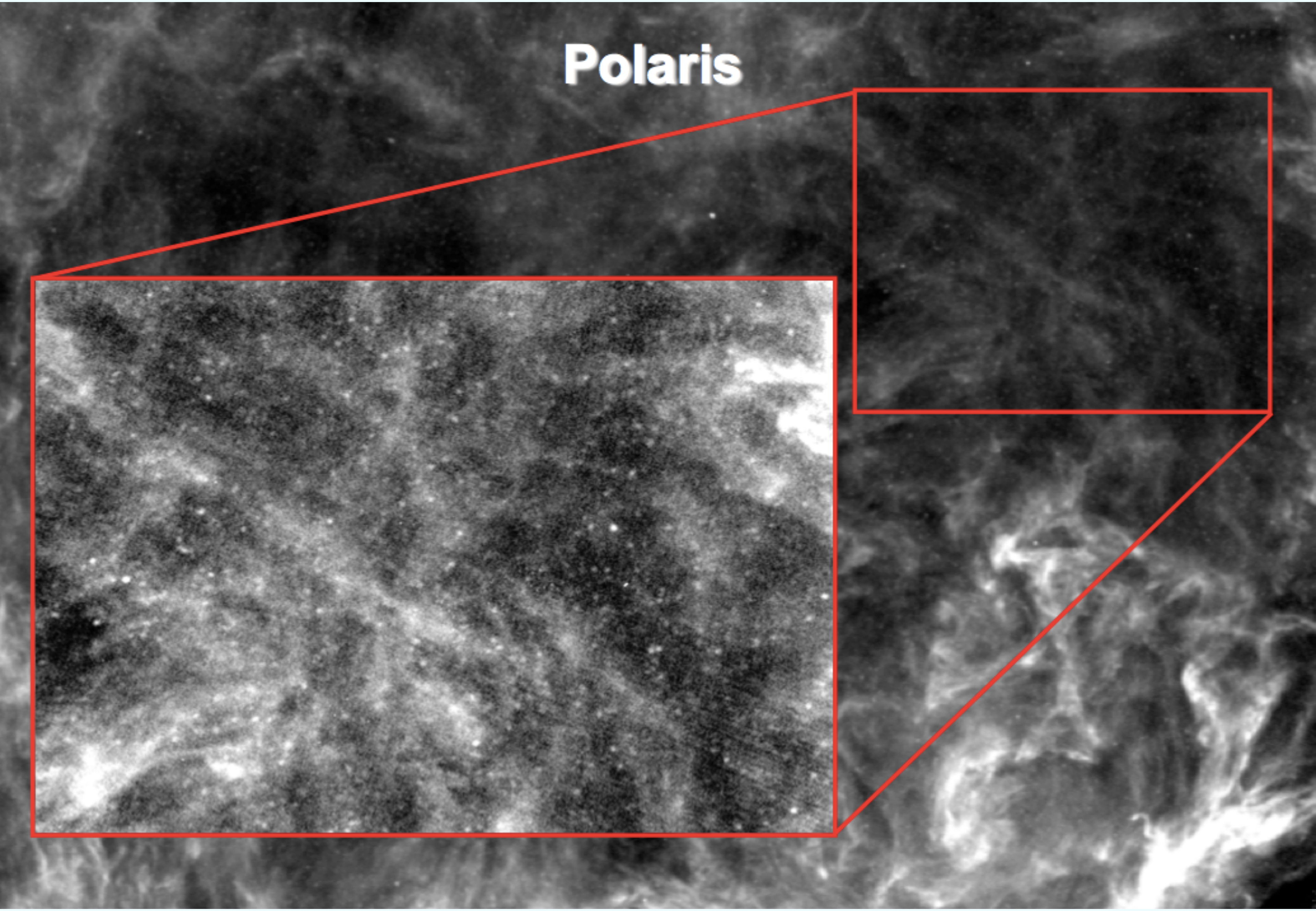
  Reynolds number Re=LV/ν > 10^7

  ➪ connects largest scales to atomic/molecular physics
- **Galactic Foregrounds to CMB:** Characterize the galactic screen to Cosmic Microwave Background ➪ dust grain physics in turbulence (see

BICEP2/Keck and Planck collaboratios 2016, Pumir & Wilkinson 2016, Falgarone & Puget 1995)


Polaris

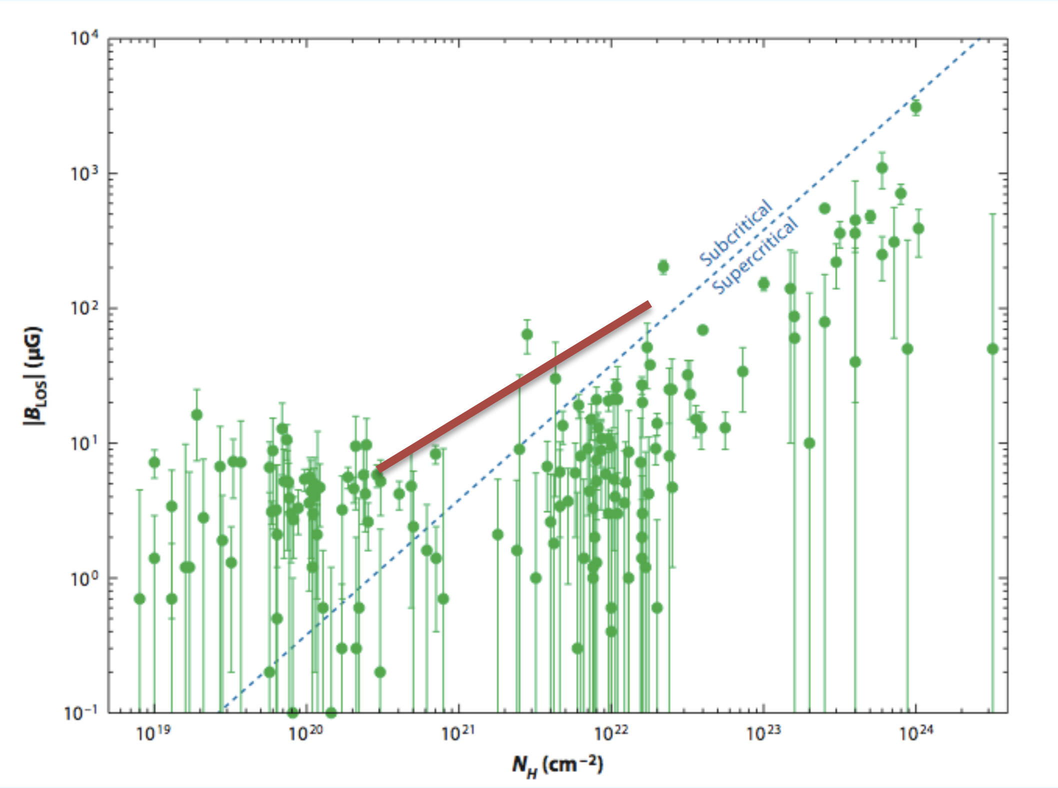

Polaris


Polaris

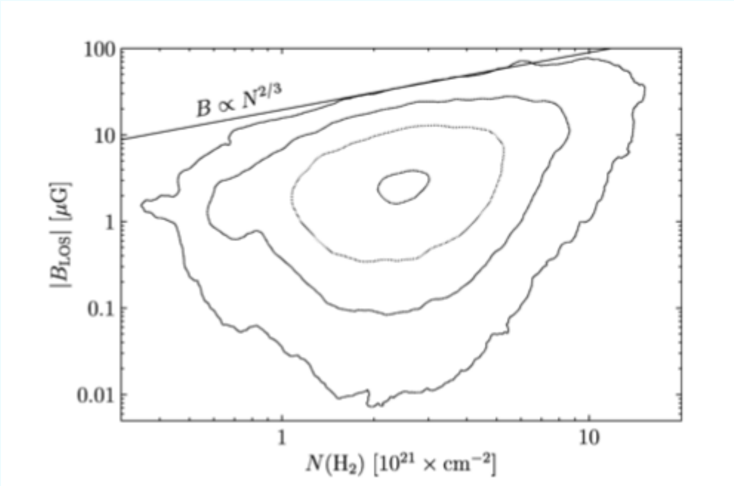
IV - How do we study turbulence?

- No time measurement (except redshift!)
- Spatial statistics: 1-, 2- and 3-point statistics
- Signatures of instabilities: observed periodic patterns (fastest growing mode?)
- Multiplicity of energy injection scales
- Multiple energy sinks
- Rarely (never?) statistically homogeneous samples
- Clearly anisotropic (e.g. Heyer + 2008, 2016)
- Projections (line-of-sight velocity, plane-of-the-sky polarisation, radiative transfer)
- Confrontation observations / numerical simulations

Comparison with simulations of super-Alfvénic MHD turbulence



Crutcher + 2010

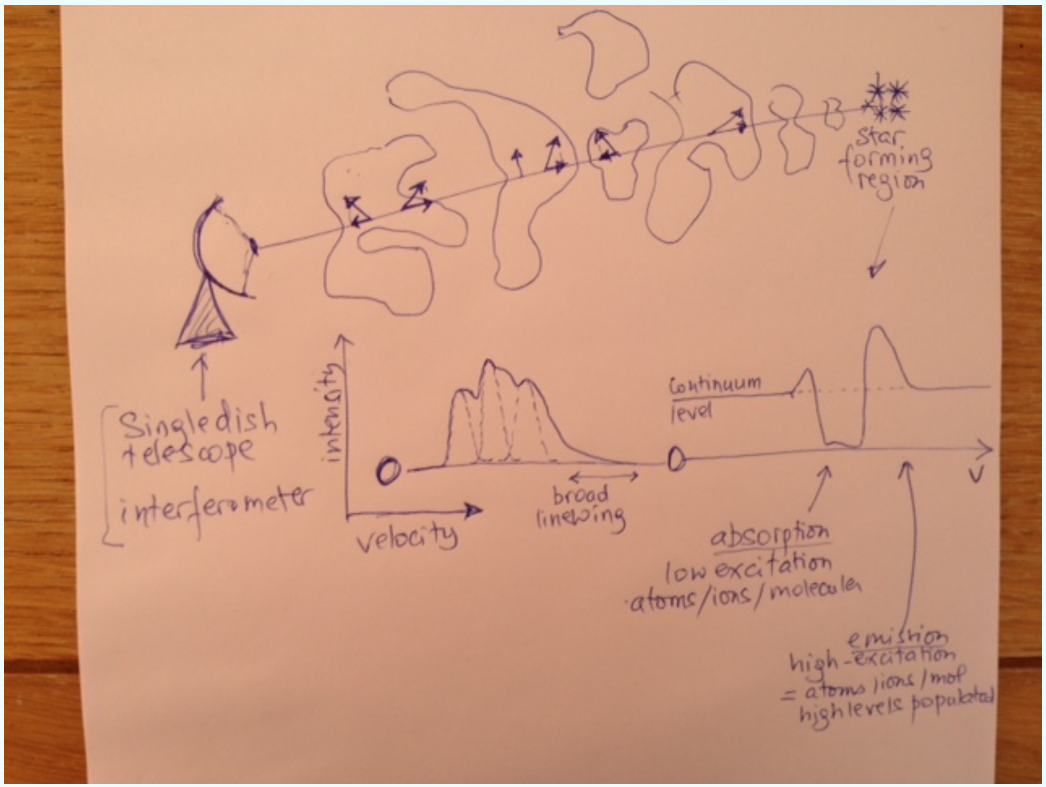


Padoan et al. 2008

Upper boundary of B_{los} distribution: $B_{los} \propto N_{H2}^{2/3}$

➯ Most of the scatter is due to intrinsic fluctuations of the B-field intensity at a given N_H, not fluctuations of the B-direction

Link of atomic and molecular line observations with gas turbulence

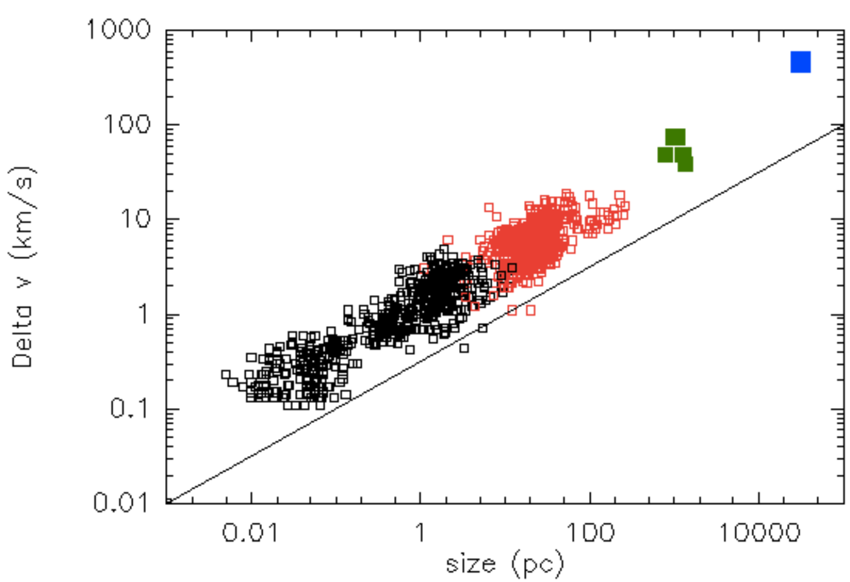


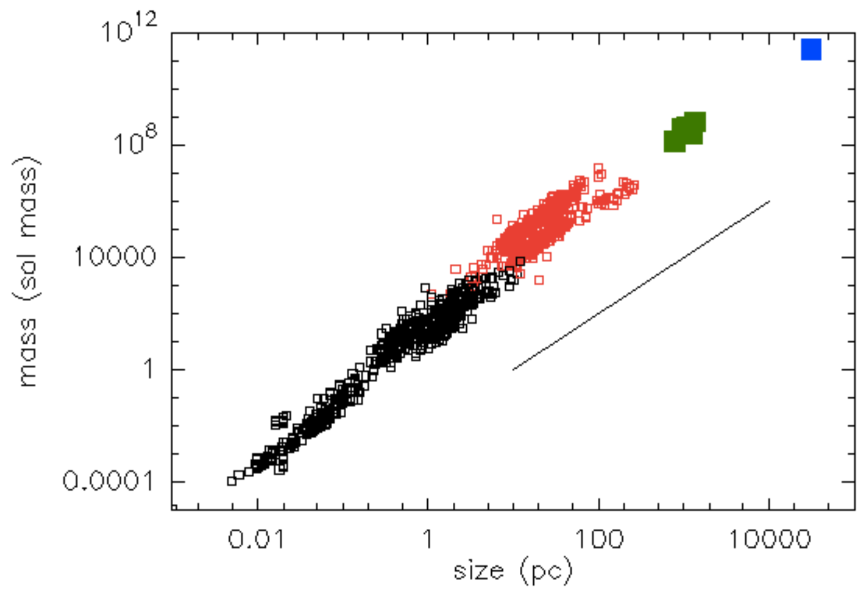
The IS gas cools radiatively
Line photons escape in velocity space

➪ line photons carry an intricate information on the velocity field

V – A few results of 1-point statistics

Scaling laws « at scales dominated by diffuse molecular gas »





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

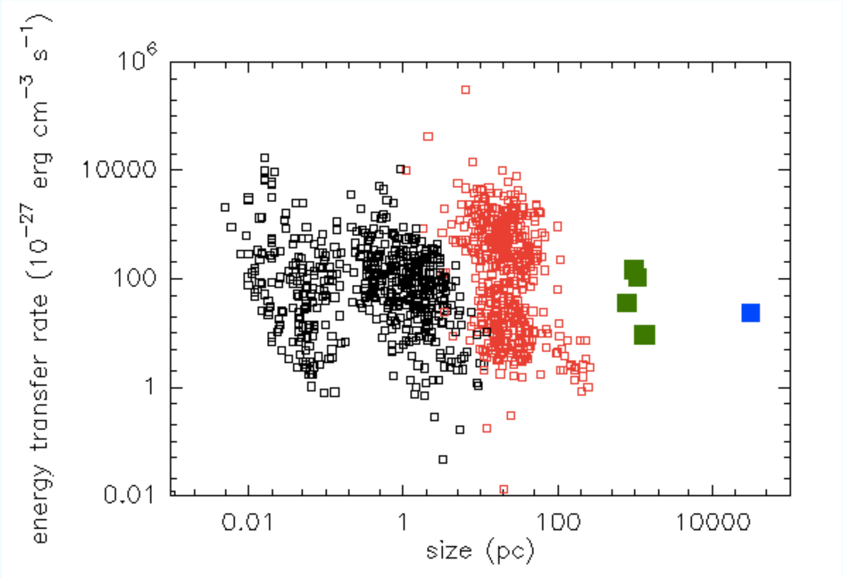
$$M \propto L^2$$

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

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

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

Kinetic energy transfer rate



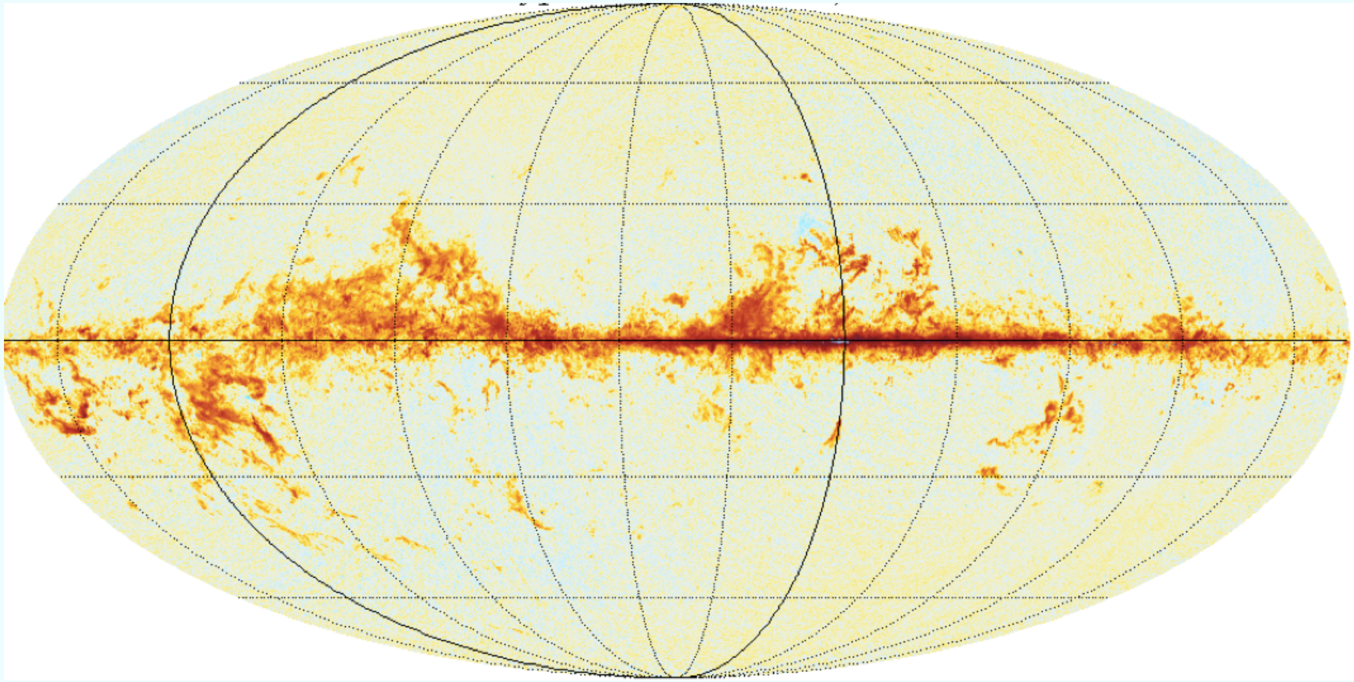
Invariant of the cascade
in the Milky Way

$$\epsilon = \rho \sigma_v^3(l)/l$$

Density, velocity dispersion and size are related by the scale invariance of the kinetic energy transfer rate.

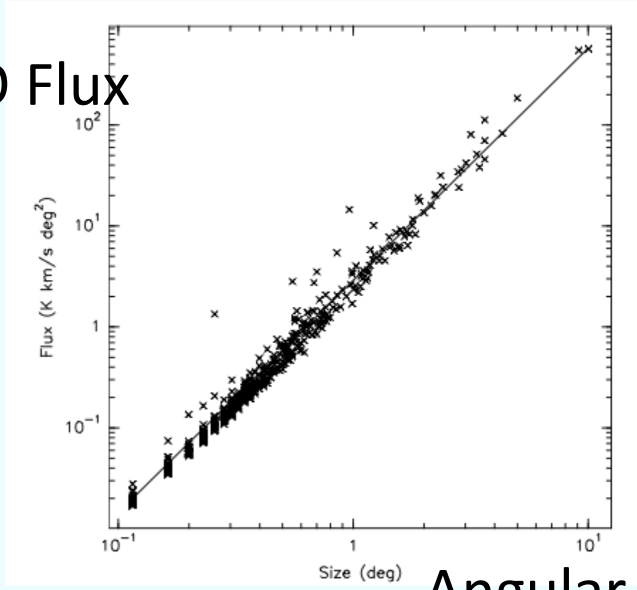
Scaling laws reproduced in simulations
of isothermal supersonic turbulence, whether gravity is present or not
Kritsuk et al. 2013

Planck : all-sky CO



CO at high galactic latitude:
power law distributions of size and flux of hundreds of « patches »
flux = CO brightness x $(\text{size})^2 \sim (\text{size})^{1.9 \text{ to } 2.5}$

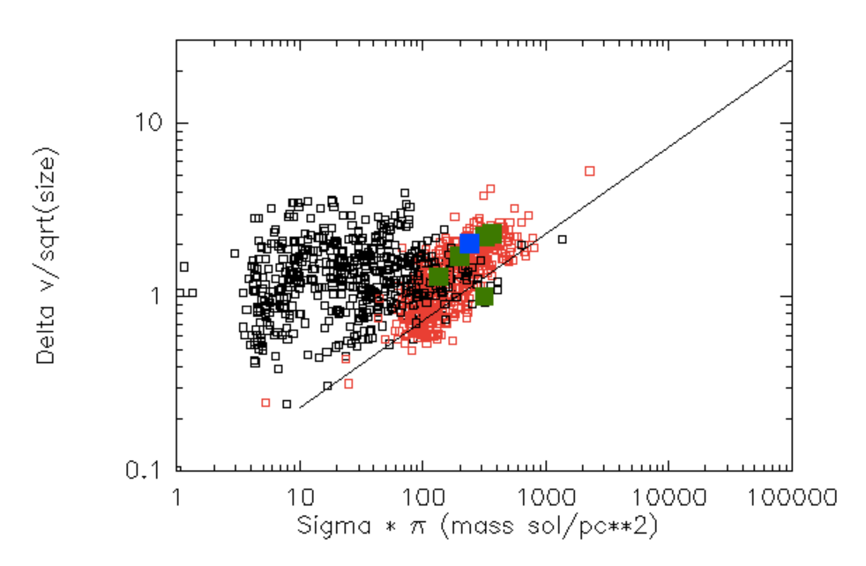
CO Flux



Angular Size

Planck Collaboration (in prep.)

Turbulent and Virialized linewidth-size relations



- Large surface densities

$$\sigma_v/\sqrt{R} \propto \Sigma^{1/2}$$

Not on the isolated-virial slope
Pressure-bounded virial equilibrium for the GMCs : external pressure scales with the disk gravitational pressure

$$P_{ext} = \Sigma^2_{\mathrm{star+DM}}$$

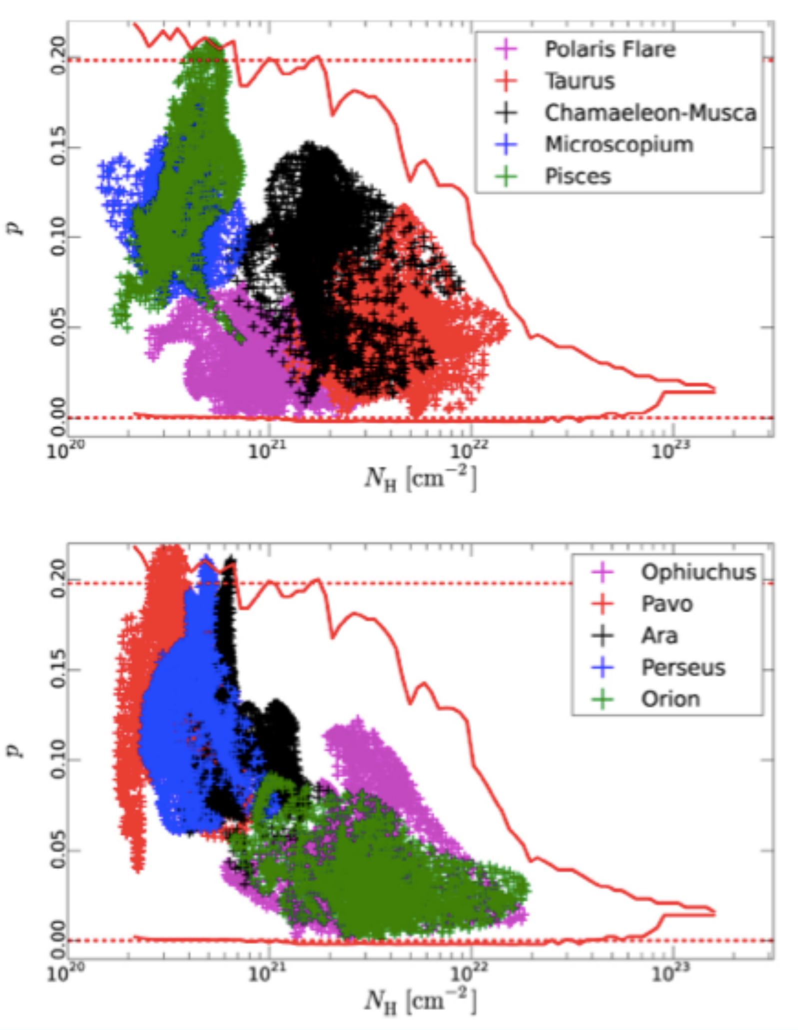
- Low surface densities

$$\sigma_v/\sqrt{R} = cste$$

➔ supersonic turbulence
➔ mean acceleration $\gamma = 2\pi G\Sigma_{tot}$

$$\Sigma_{tot} = 60\mathrm{M}_{\odot}\mathrm{pc}^{-2}$$

Polarization fraction vs HI column density

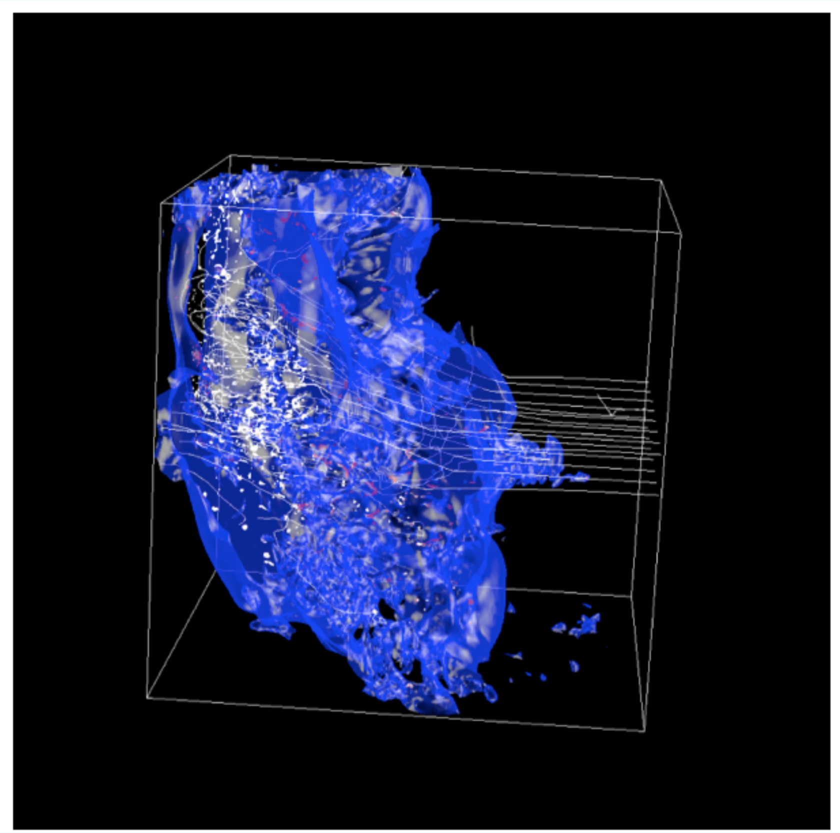


Three unexpected results :

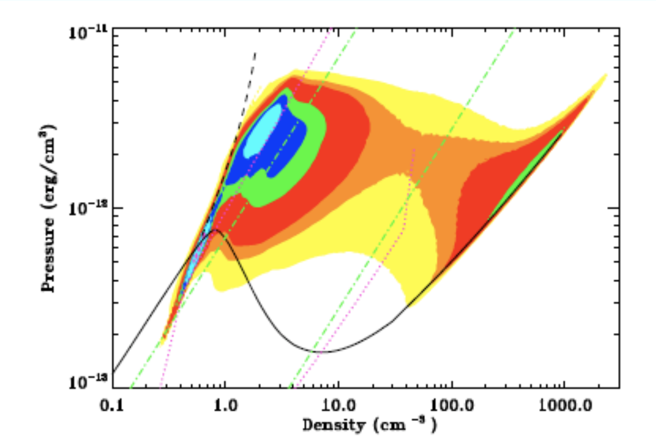
- Highest polarization fractions at low column densities
- Large max values of the polarization fraction 20%
- Large scatter of p at low column densities

Planck Collaboration XX 2015

Colliding flow simulations

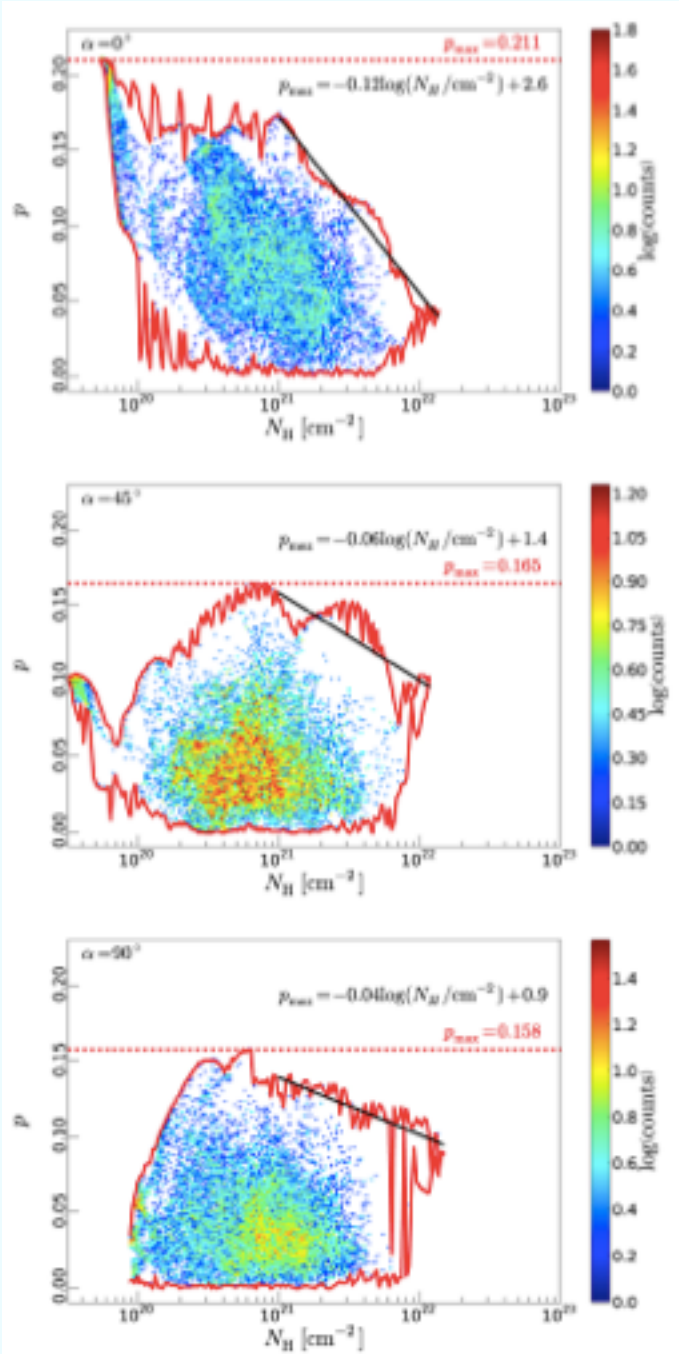


MHD simulations
Adaptive Mesh Refinement
Colliding flow: initial $v_{WNM} // B_0 > c_{s,WNM}$
WNM collision generates CNM (white)

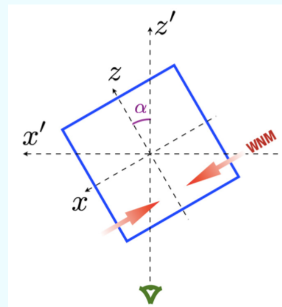


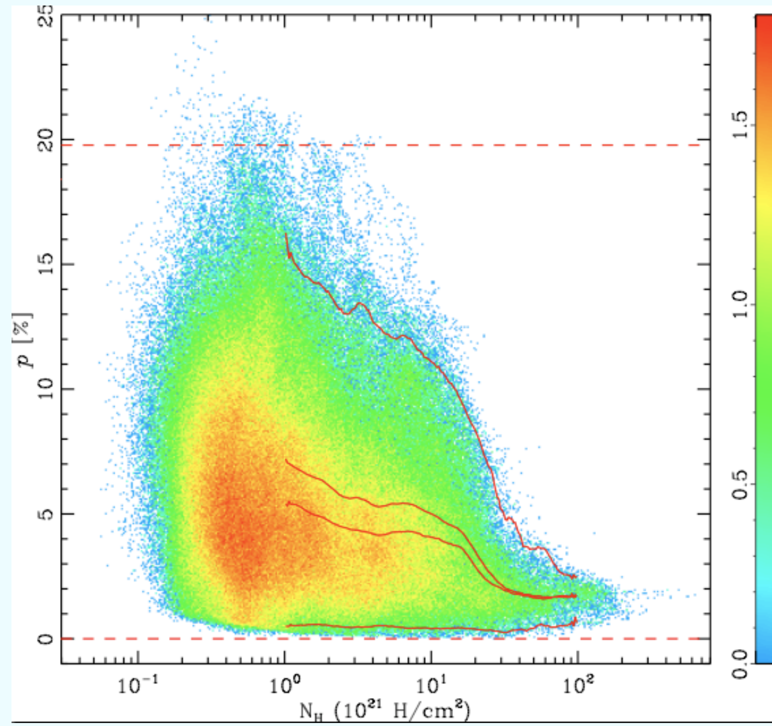
Distribution of the gas pressure and density above the curve of thermal equilibrium (black)

Audit & Hennebelle 2005, 2010



Comparison observations/simulations





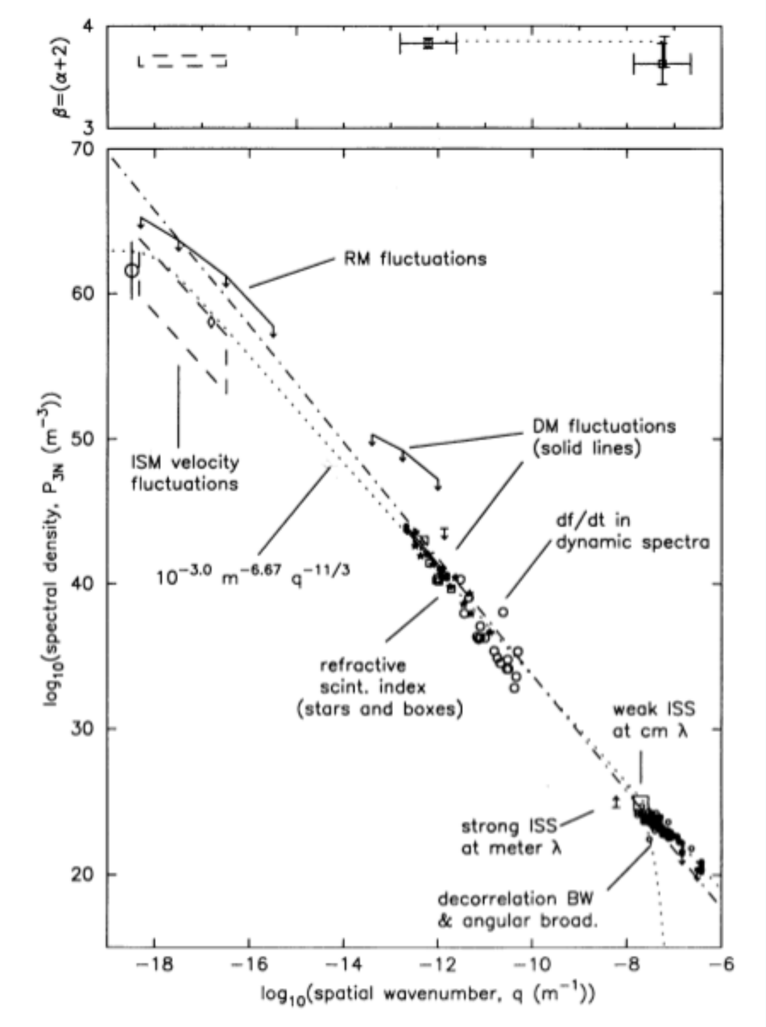
All sky polarization fraction vs NH

Planck collaboration XIX 2015

⇨ Isotropic MHD turbulence fails at reproducing the observed trends

VI – A few results of 2-point statistics

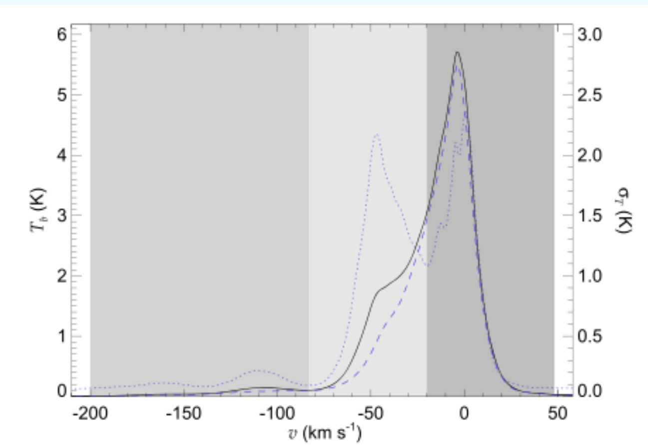
Power spectrum: Electron density fluctuations

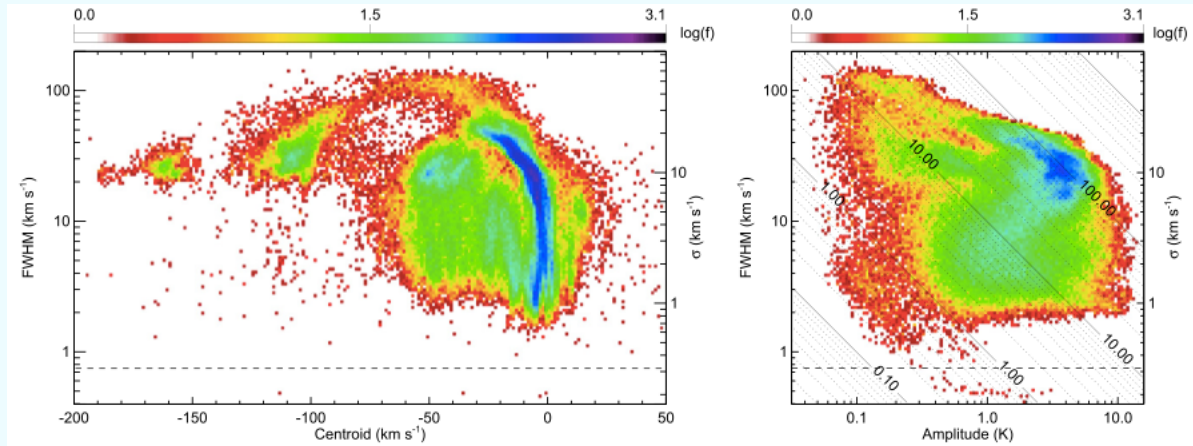


- Kolmogorov slope
- Density fluctuations advected by turbulence

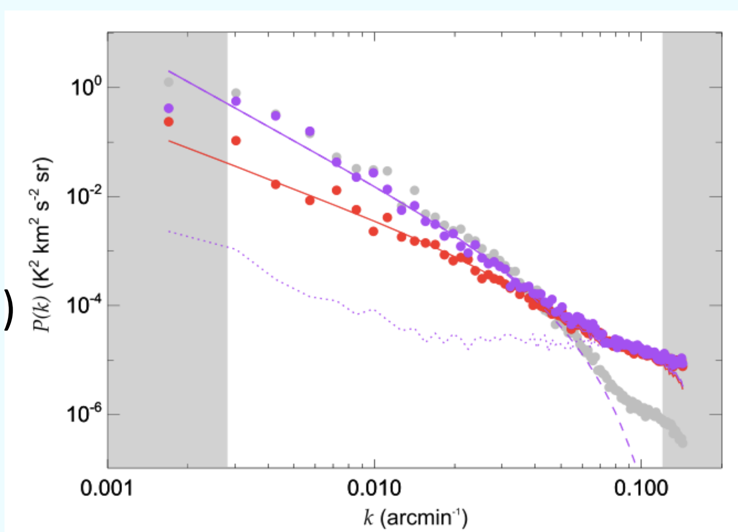
Armstrong + 1995

Power spectra of column density of atomic hydrogen





Slopes
CNM (red)
-1.9
WNM (purple)
-2.9



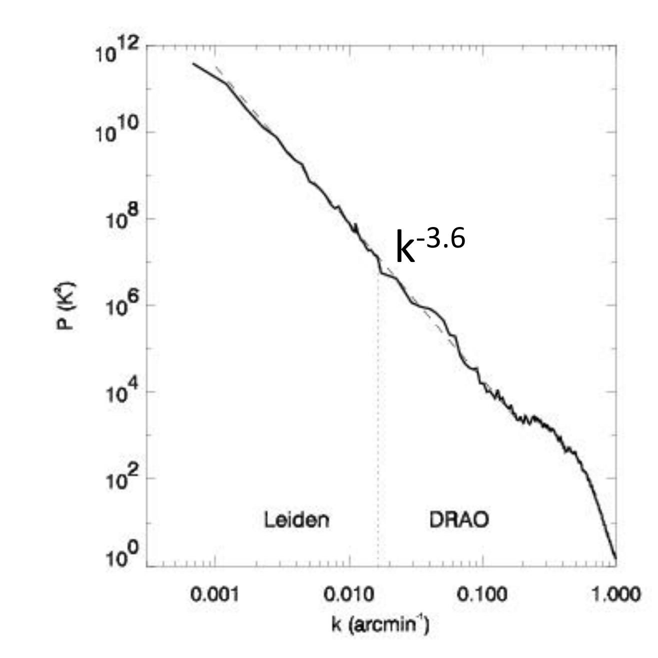
$c_S = (\gamma k_B\ T/\ \mu\ m_H)^{1/2}$

$c_S = 0.8\ \text{km s}^{-1}\ (\gamma T_{100})^{1/2}$

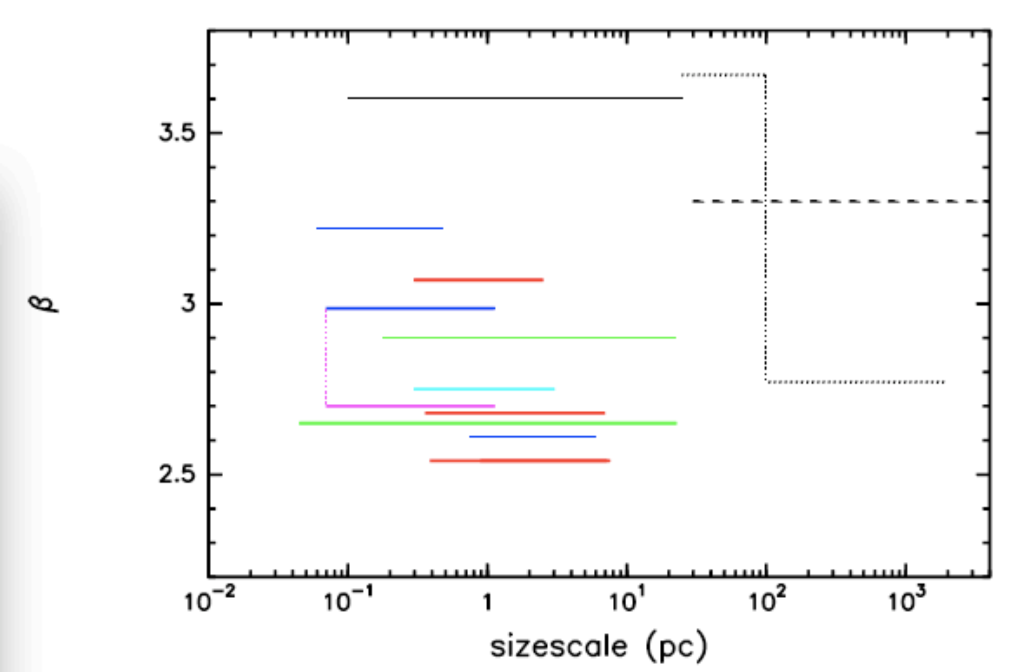
$N_{HI} = 1.8 \times 10^{18}\ \text{cm}^{-2}\ T_B\ \Delta v$

Martin P. + 2015 ApJ809 153

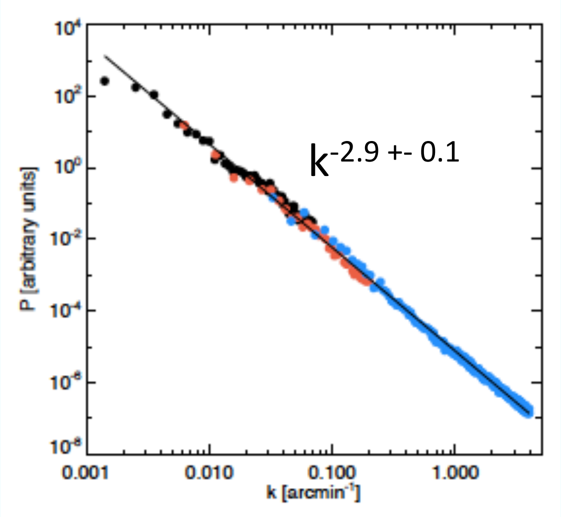
Power spectra



Energy spectrum HI 21cm emission
Miville-Deschênes + 03



HI, dust, CO power spectra
Hennebelle & Falgarone 12



Energy spectrum Planck (black), WISE (red), Visible (blue)
Miville-Deschênes + 16

Elements of answers

- Turbulence drives the gas fraction in the cold/dense phase that eventually forms stars
- Star formation takes place in molecular clouds
- The molecular clouds, sites of star formation are in virial balance between gravitational energy and turbulent energy ⇨ $2T+U=0$