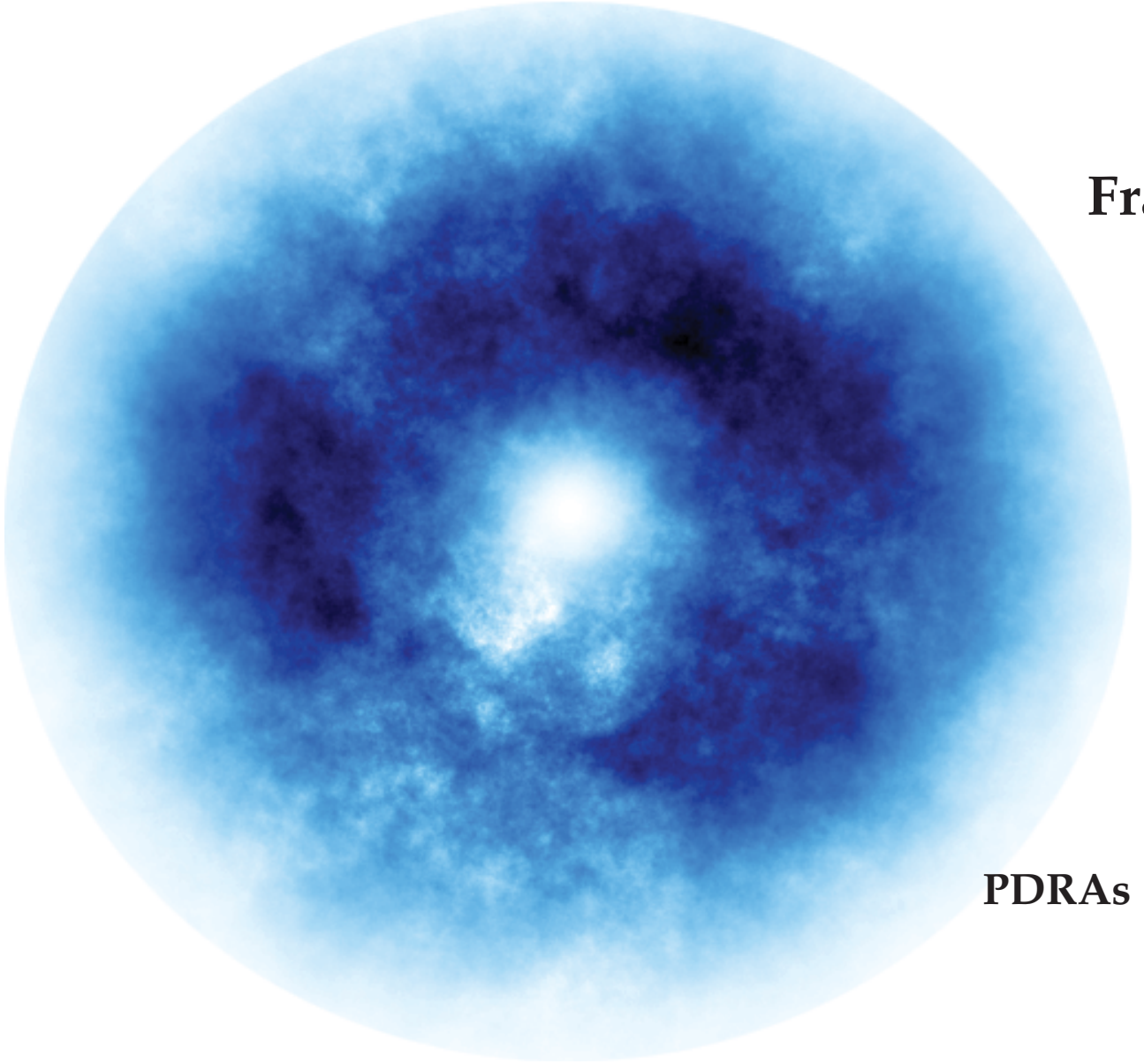
ANALYSIS OF COMPLEX STRUCTURES IN RADIO-INTERFEROMETRY

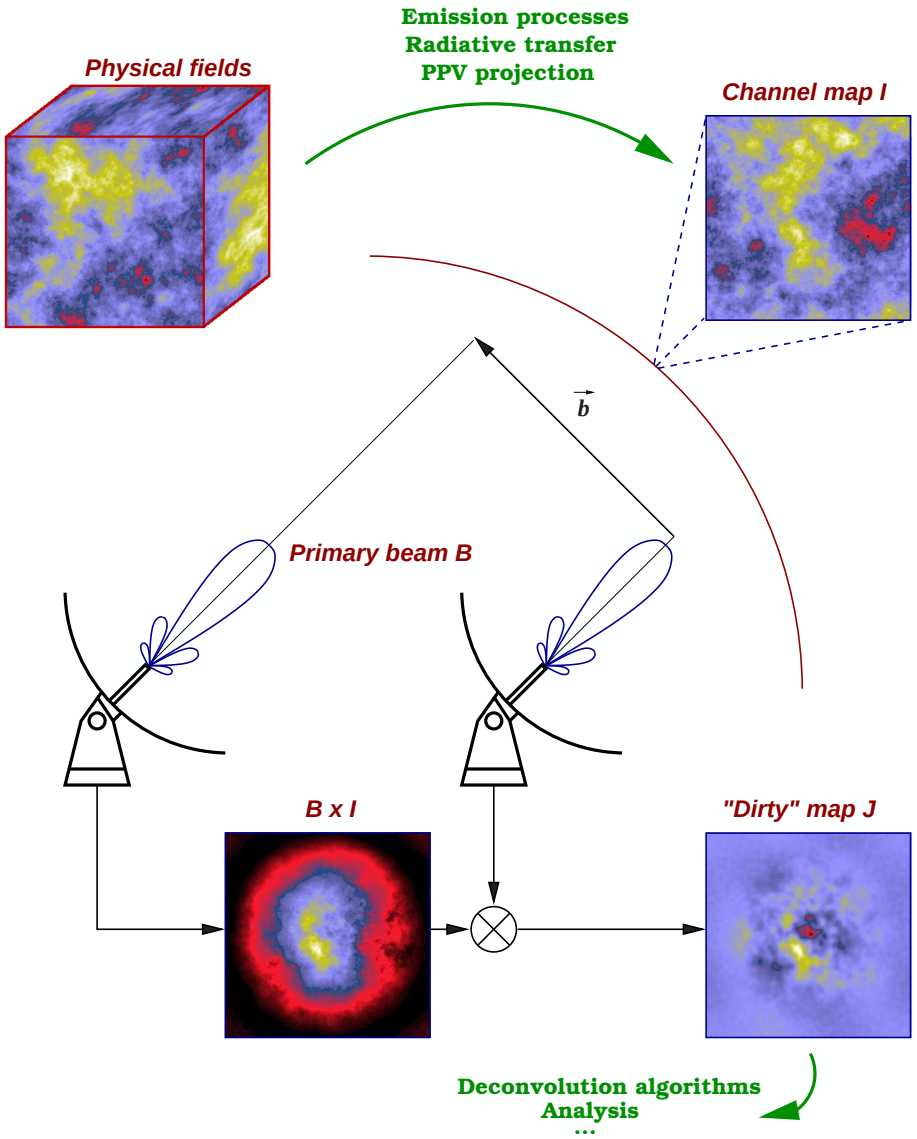


François Levrier

PDRAs SKADS Interview, Oxford

January 30, 2007

Interferometry in a nutshell

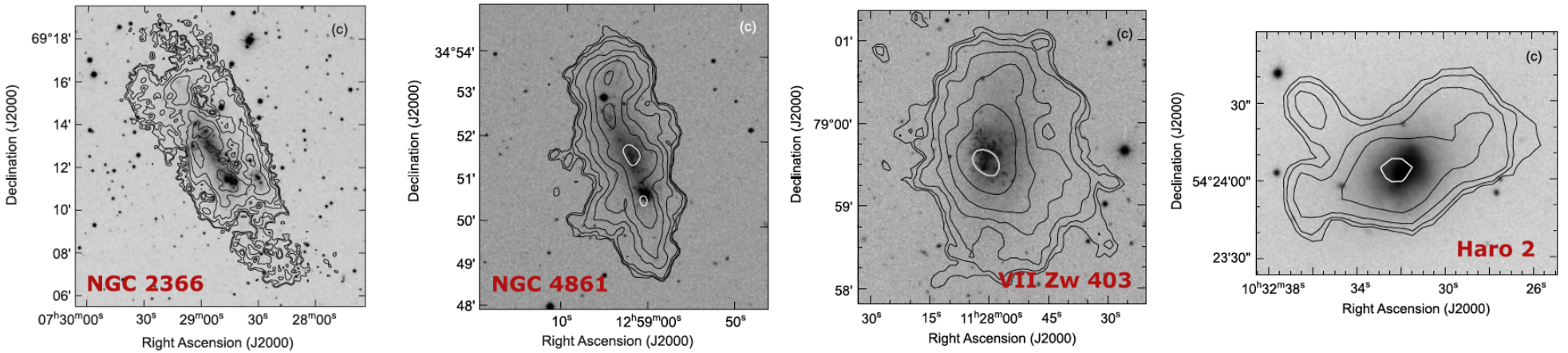


- Projection on a PPV hybrid space
- Antenna pairs measure correlations
- Primary beam attenuation : B
- Incomplete sampling : C

$$J = T_F^{-1}[C.T_F[B.I]] = T_F^{-1}[V]$$

How does all this alter structure ?

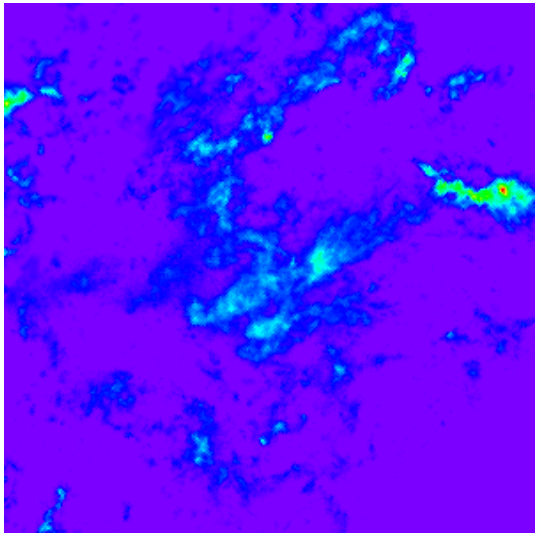
Examples of interferometric observations



HI integrated emission overlaid on DSS *(Thuan, Hibbard & Levrier, 2004)*

- **VLA 21 cm data for 4 Blue Compact Dwarfs (reduction with AIPS)**
- **NGC 2366 / NGC 4861 : cometary-like, multiple HI peaks, regular kinematics**
- **VII Zw 403 / Haro 2 : Centrally-peaked HI, irregular kinematics**
- **Regions of active star formation correspond to HI peaks**
- **High velocity dispersion ⇔ Low density : two-phased ISM**
- **Discovery of HI Clouds with no optical counterparts**

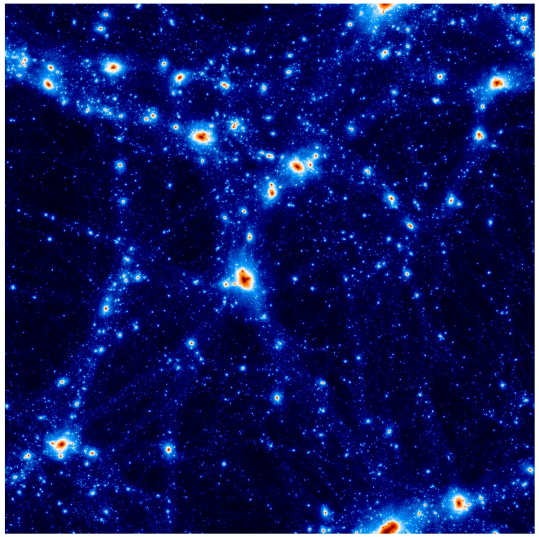
Complex structures



Interstellar medium

CO emission, Taurus Molecular Cloud, *(Dame et al. 87)*

- Galactic scales 0.01 pc to 100 pc
- Turbulence / Gravitation
- Star Formation, CMB Foreground, ...

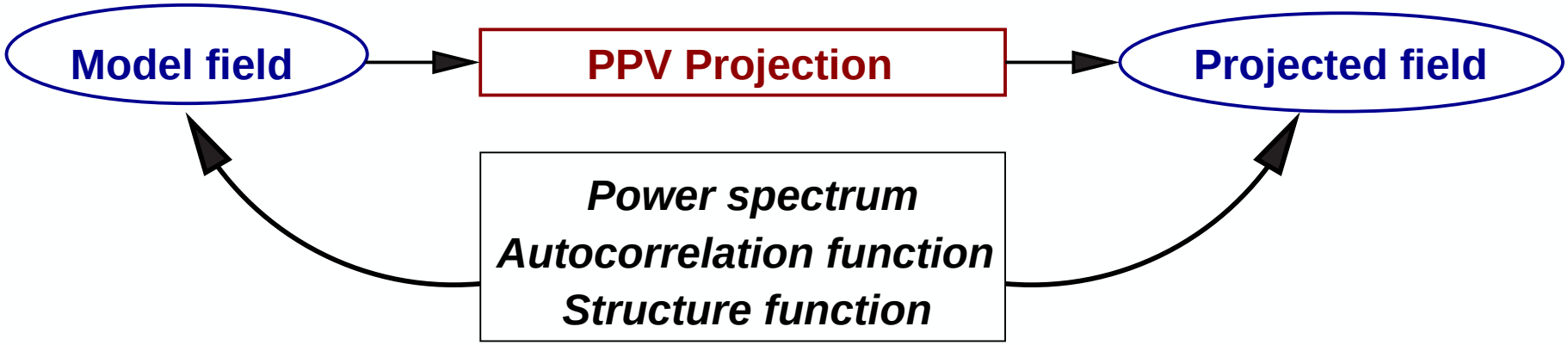


Large-scale structures

Dark Matter distribution, Horizon project, *(Aubert & Pichon)*

- Extragalactic scales above 1 Mpc
- Gravitation / Dark energy (?)
- Galaxy formation, Reionization, ...

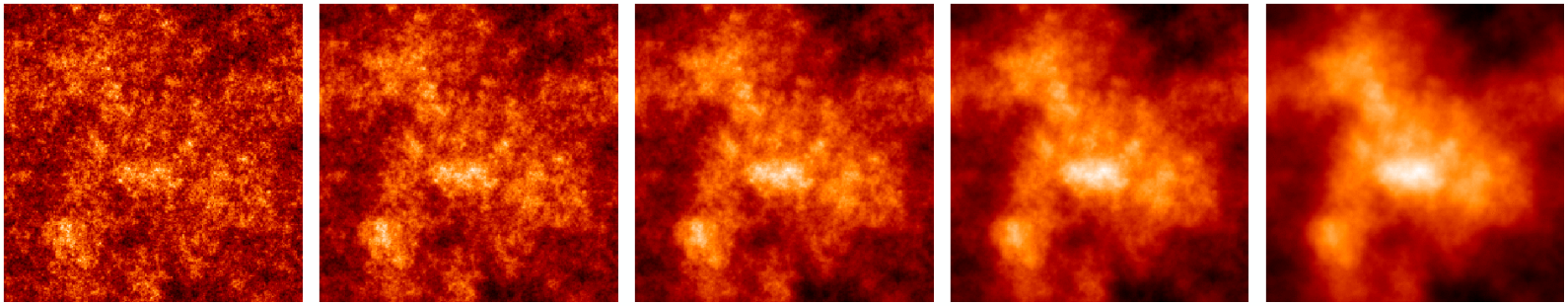
Studying the effects of projection



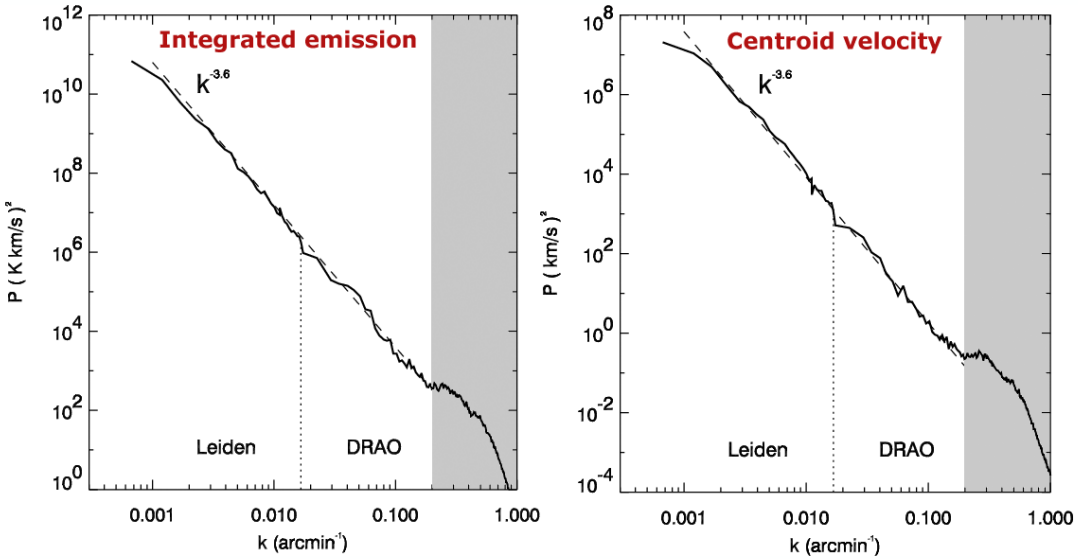
Model fields : Fractional Brownian motions

- Power spectrum $P(\vec{k}) \propto |\vec{k}|^{-\beta}$, structure function $S(\vec{r}) \propto |\vec{r}|^{H}$
- Random Fourier phases
- Models of the diffuse ISM *(Stutzki et al., 1998; Brunt & Heyer, 2002; Levrier, 2004)*

$\beta = 2$ $\beta = 2,5$ $\beta = 3$ $\beta = 3,5$ $\beta = 4$



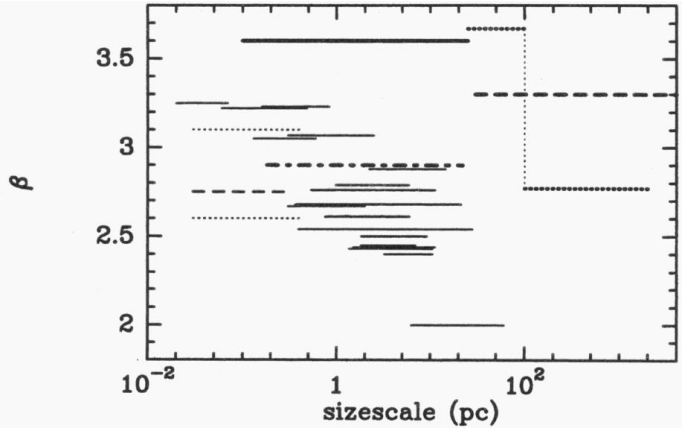
Observational results



High-latitude HI cirrus

(Miville-Deschênes et al., 2003)

➤ $\beta_C = \beta_I = 3.6$ (Kolmogorov)



Spectral indices of brightness distributions

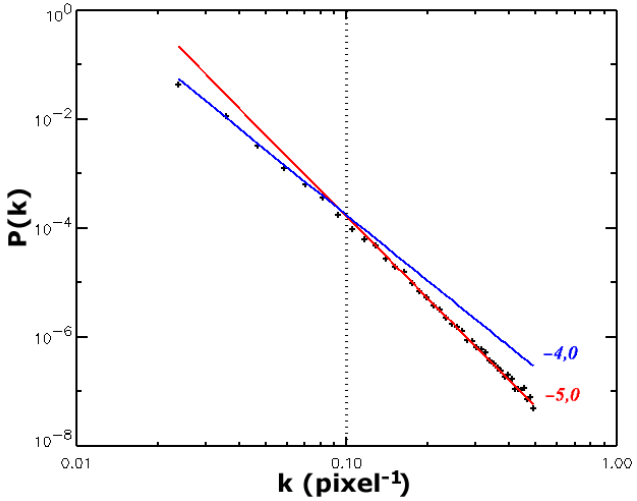
Galactic CO, Galactic and extragalactic HI, thermal dust

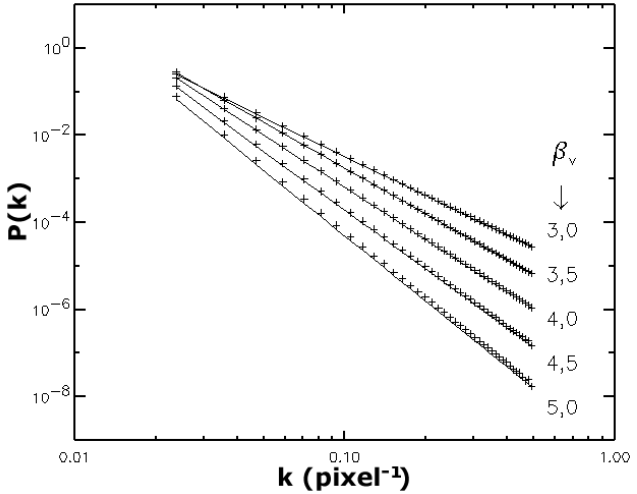
(Falgarone, Hily-Blant & Levrier, 2004)

➤ Multifractal medium ?

Linking moments to physical fields

Homogeneous isotropic turbulence / Optically thin line / Uniform excitation / Low density fluctuations





Integrated emission

R : Transverse scale / D : Depth of cloud

$\beta_I = \beta_\rho$ for $R \ll D$

$\beta_I = \beta_\rho - 1$ for $R \gg D$ *(Goldman, 2000)*

Transition for $k \propto 1/D$ *(Elmegreen et al., 2001)*

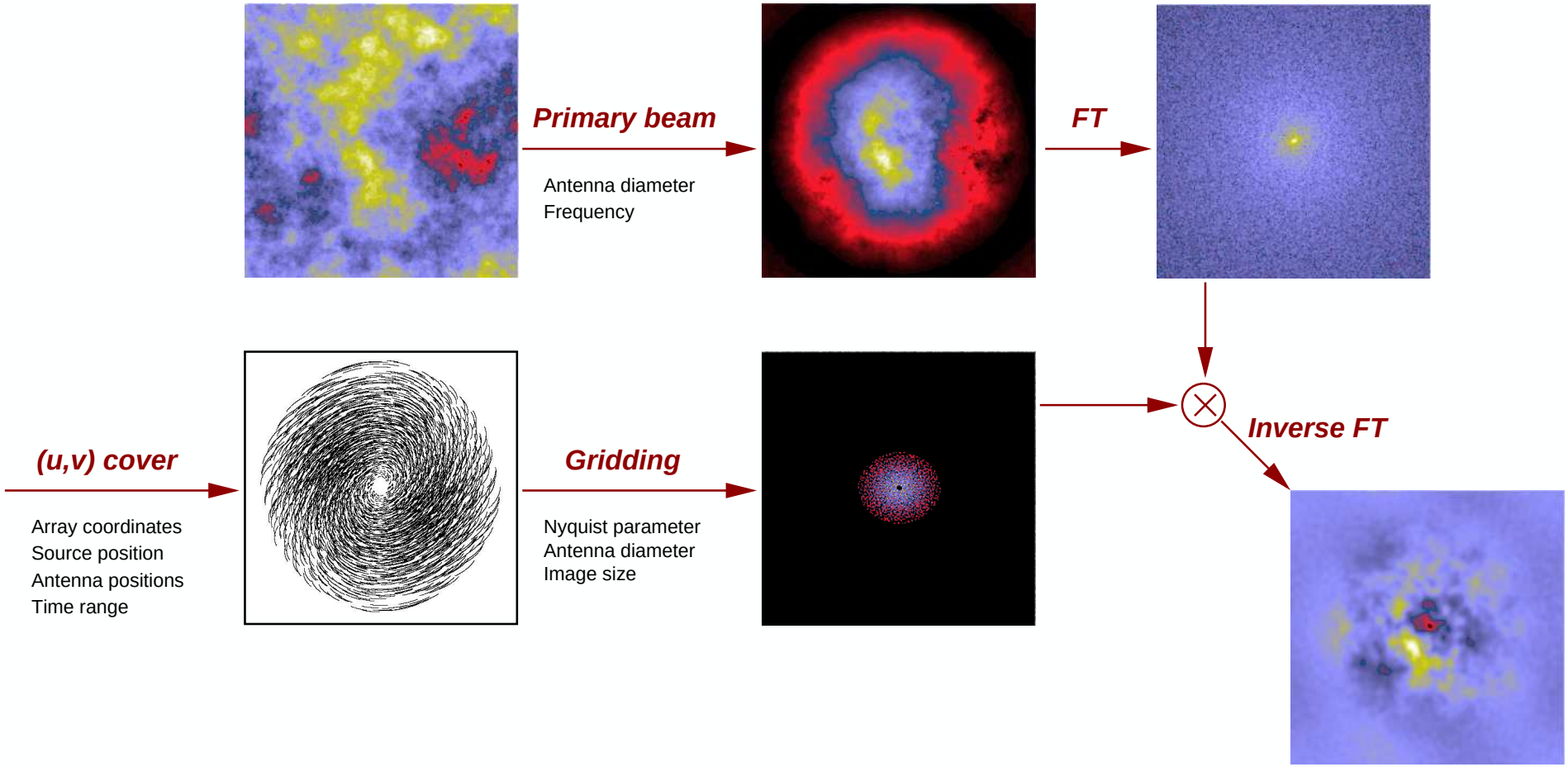
Centroid velocity

$\beta_C = \beta_v$ for $R \ll D$

Low density fluctuations essential $\sigma_\rho/\rho_0 < 0,3$

(Miville-Deschênes, Levrier & Falgarone, 2003; Levrier, 2004)

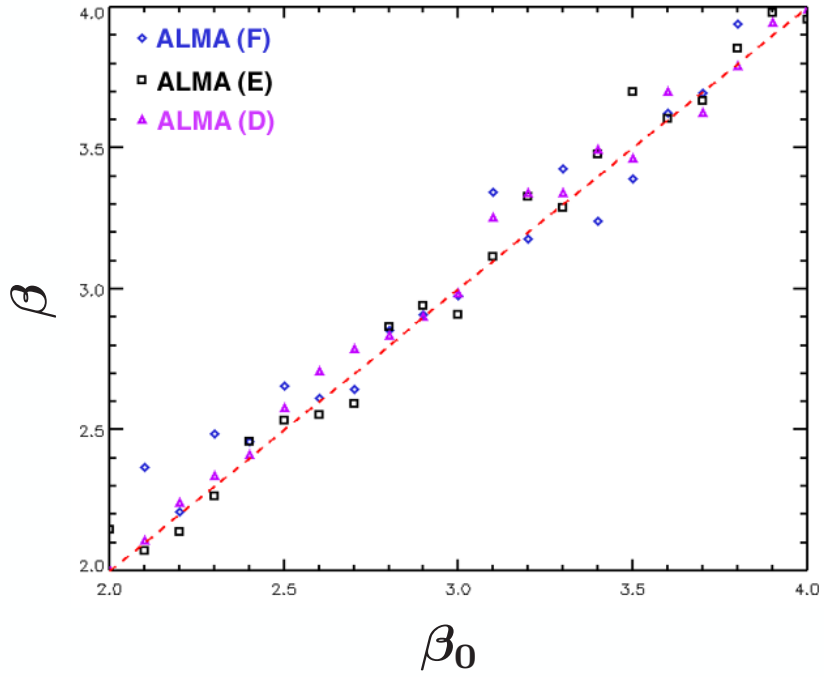
Studying the effects of interferometric filtering



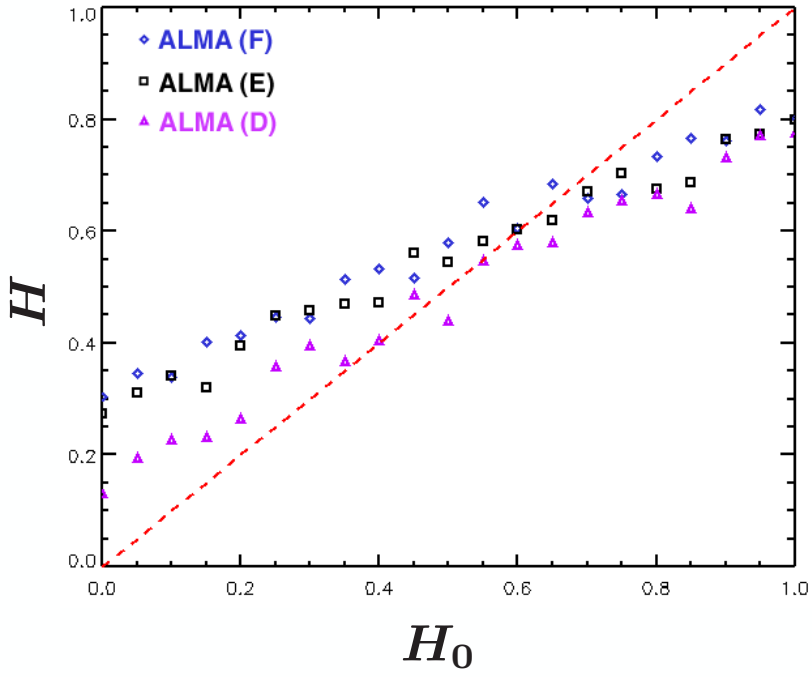
- Interferometer simulator written in IDL (my own private MeqTrees)
- Visibility based / Homogeneous arrays / Flexible configurations
- ALMA / VLA / PdBI / ...

Robustness of statistical tools

Power Spectrum



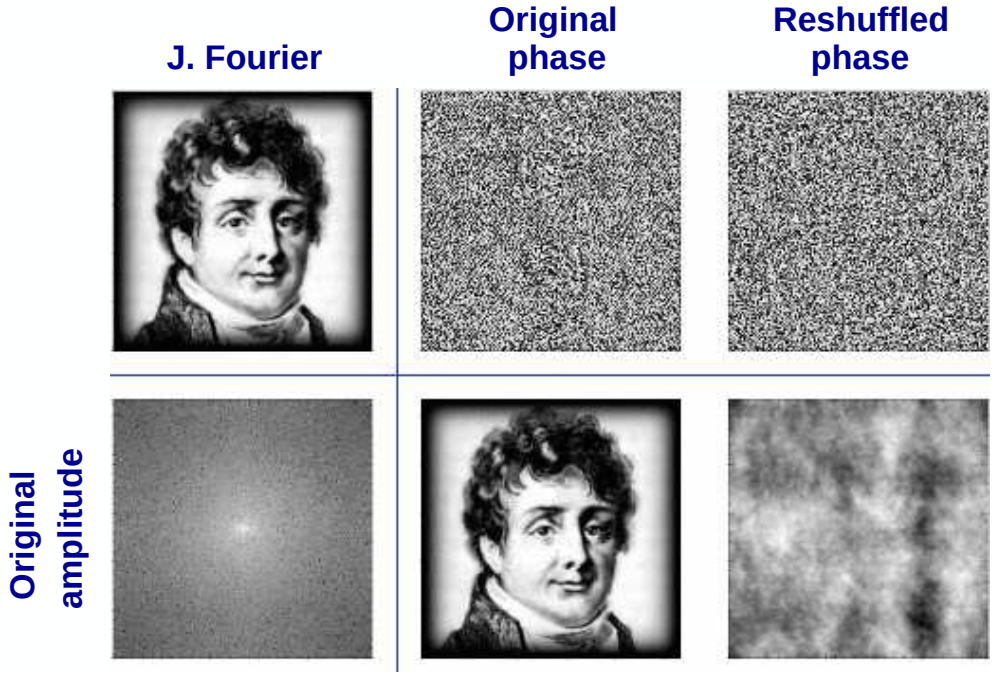
Structure function



Adaptation of statistical tools to the measurement space

- Structure function ⇔ *Direct space* ⇔ Single dish *(Bensch et al., 2001)*
- Power spectrum ⇔ *Fourier space* ⇔ Aperture synthesis *(Levrier, Ph.D.T., 2004)*
- But power spectra only make use of Fourier amplitudes, not phases...

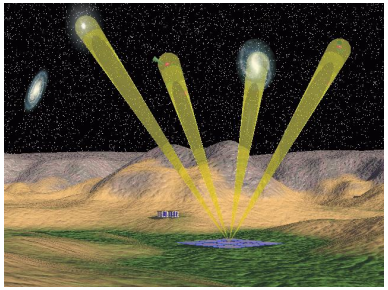
On the importance of Fourier phases



Reshuffling of the Fourier phases

▼

Loss of structural information



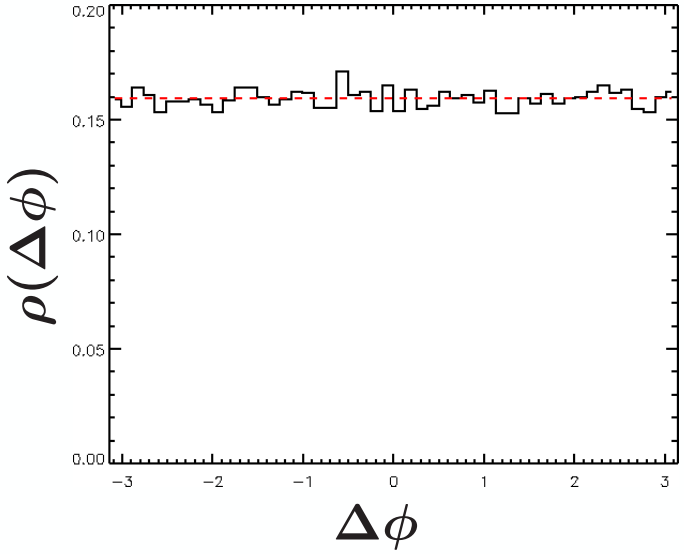
Carefully designed phased planar arrays

▼

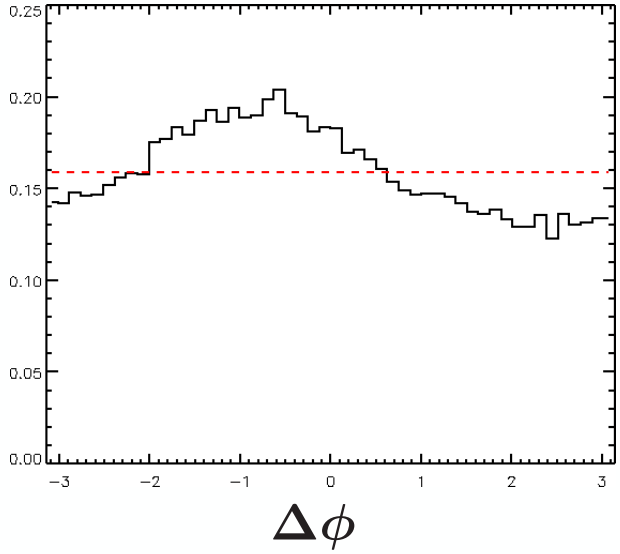
Multibeaming

Distribution of phase increments

Distribution $\rho(\Delta\phi)$ of $\Delta\phi(\vec{k},\vec{\delta}) = \phi(\vec{k}+\vec{\delta}) - \phi(\vec{k})$ for a given lag vector $\vec{\delta}$

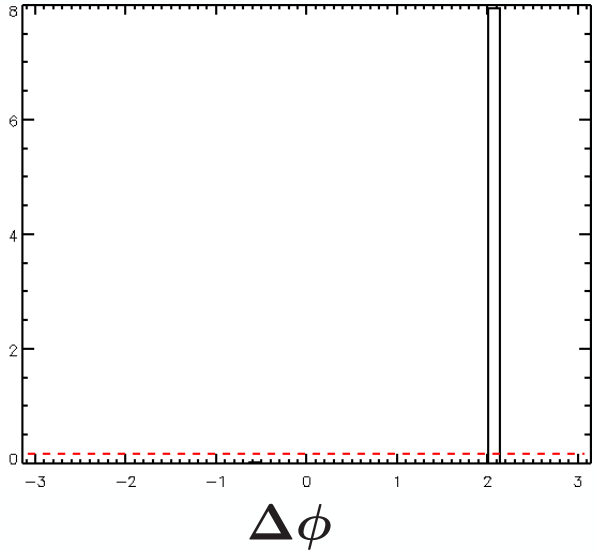


Fractional Brownian motion



Turbulence simulation

(Porter et al., 1994)



Single point source

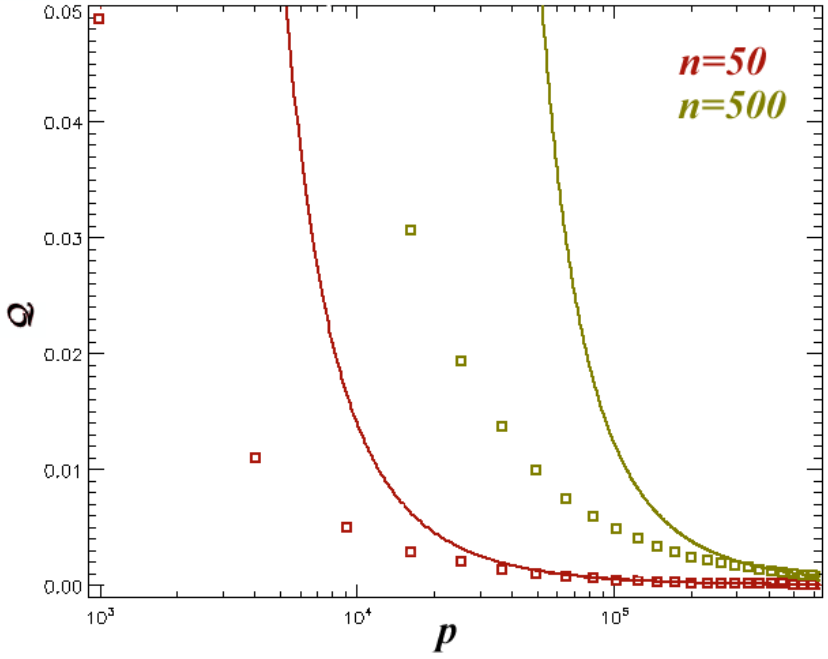
Characterizations of non-uniformity

- Phase entropy : $\mathcal{S}(\vec{\delta}) = -\int_{-\pi}^{\pi} \rho(\Delta\phi)\, ln[\rho(\Delta\phi)] d\Delta\phi$ *(Polygiannakis & Moussas, 1995)*
- "Phase structure quantity" : $\mathcal{Q}(\vec{\delta}) = ln\,(2\pi) - \mathcal{S}(\vec{\delta}) \geq 0$

The trouble with estimators

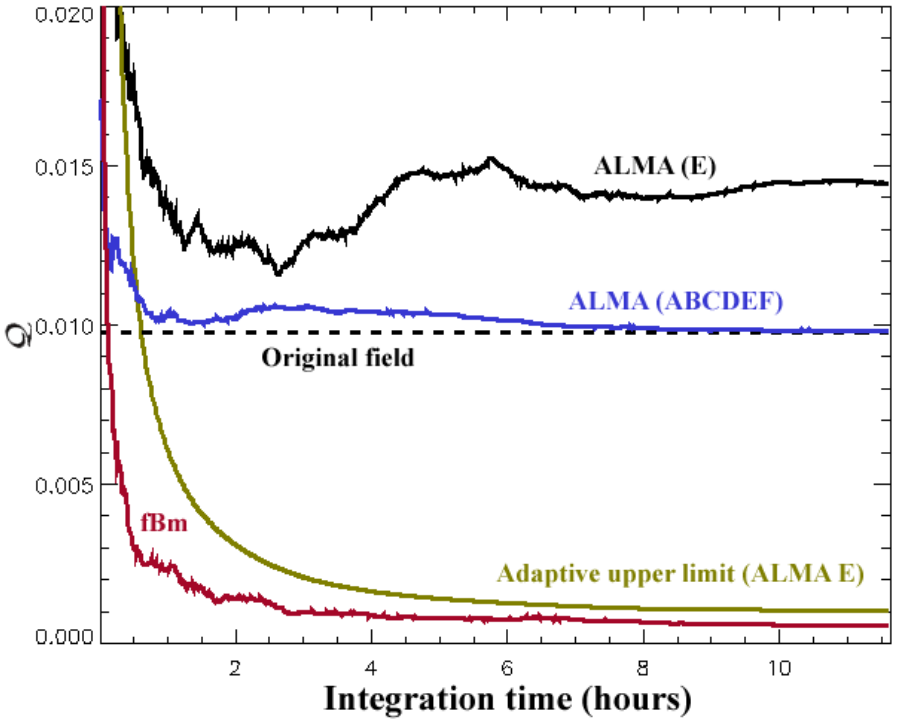
Statistical noise on finite-sized images

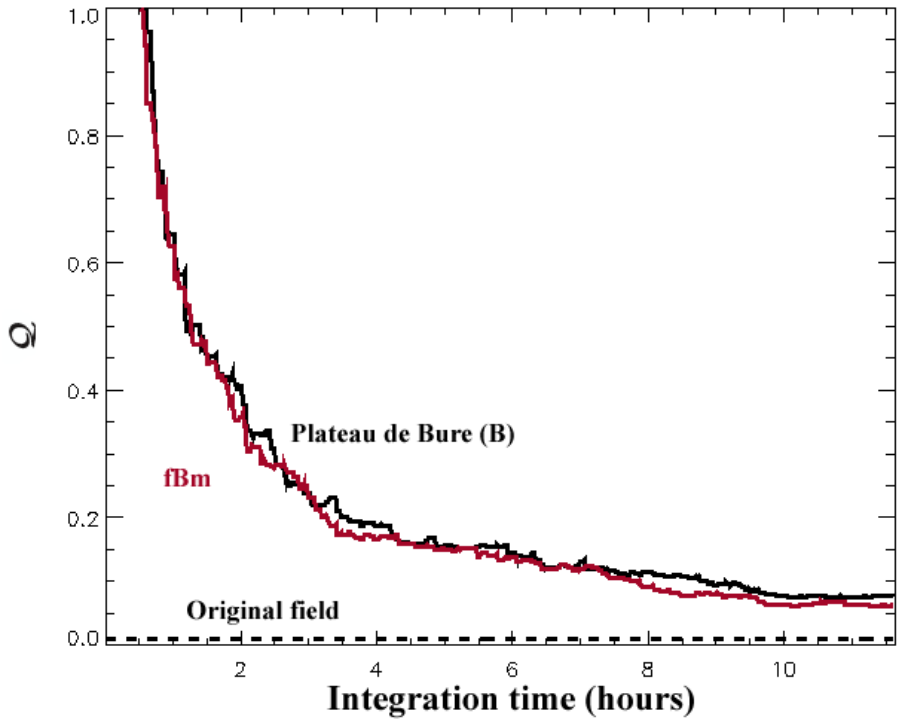
- May lead to **false detection** of phase structure
- Requires an estimate of x so that no phase structure implies $\mathcal{Q} < x$
- Depends on number of phase increments p and number of bins n
- Theoretical upper limit x computed from χ^2 statistics *(Levrier, Falgarone & Viallefond, 2006)*



Phase structure quantity in noise-free observations

- Input field : Column density of a turbulence simulation ($\mathcal{Q} \simeq 0.01$)
- Measured phase structure quantity on dirty maps as a function of integration time



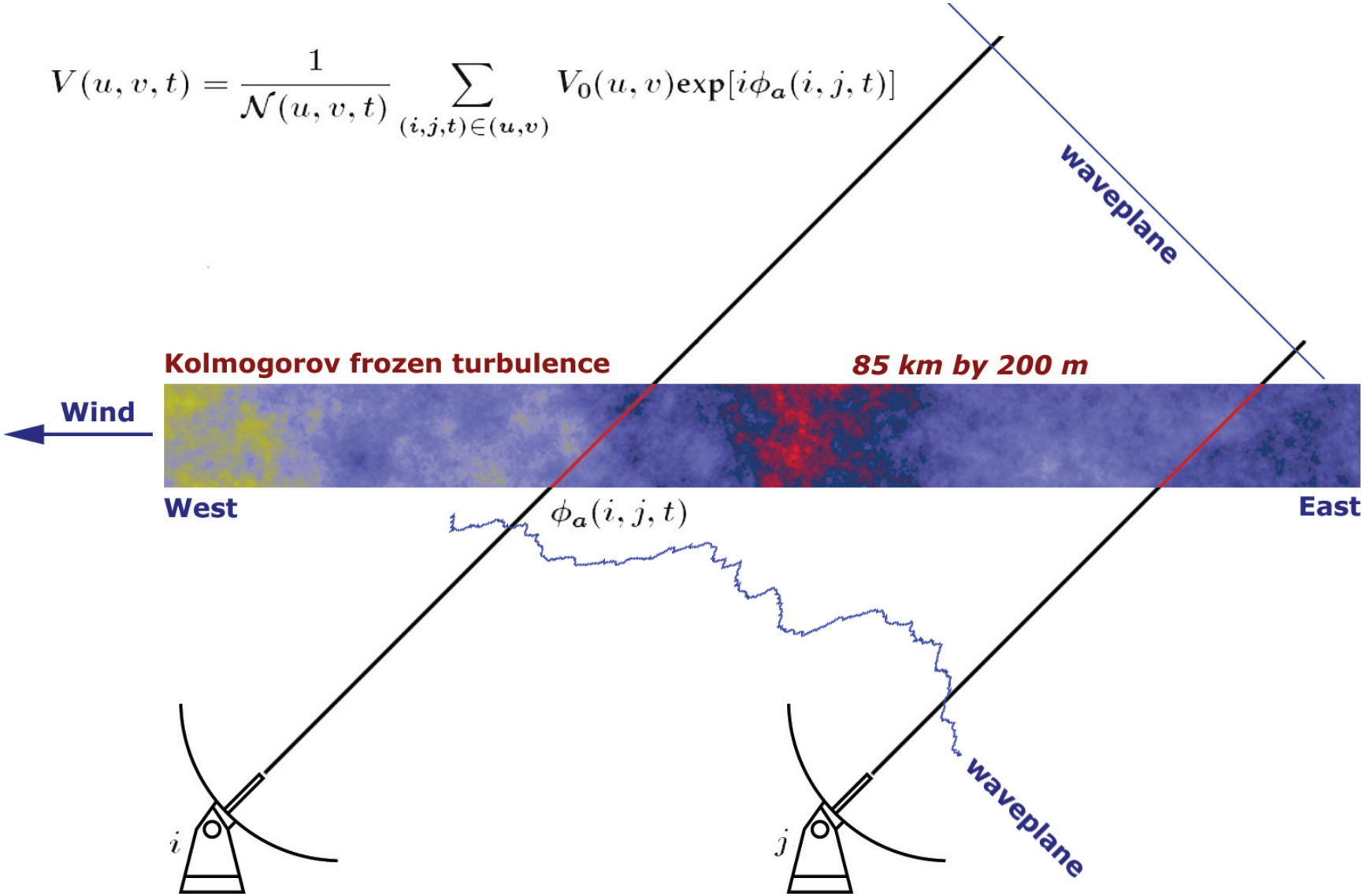


(Levrier, Falgarone & Viallefond, 2006)

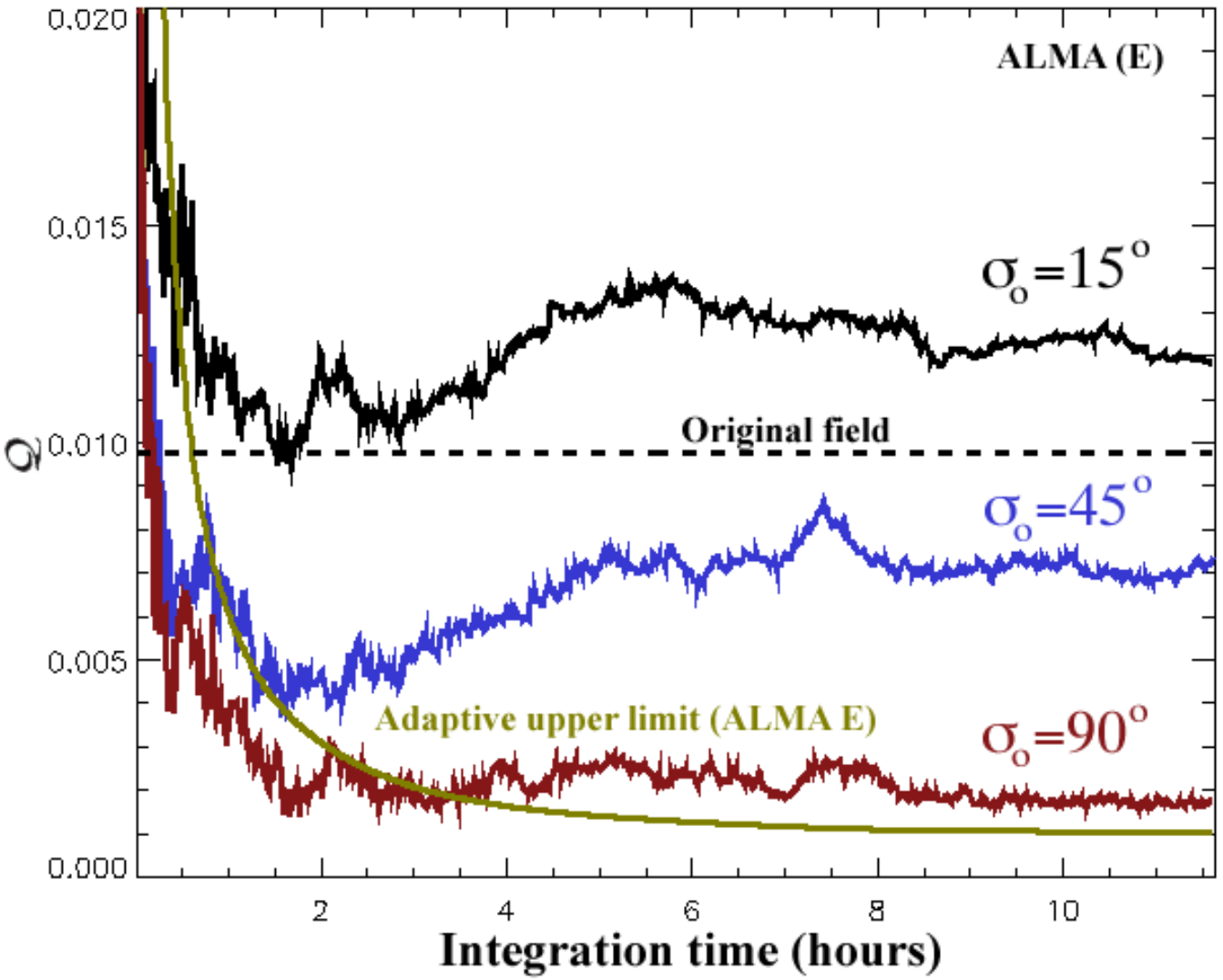
- **ALMA**: Detection (single configuration) + Measurement (multiple configurations)
- **PdBI**: No detection

Atmospheric phase noise

$$V(u,v,t) = \frac{1}{\mathcal{N}(u,v,t)} \sum_{(i,j,t)\in(u,v)} V_0(u,v)\exp[i\phi_a(i,j,t)]$$



Phase structure quantity in noisy observations



rms phase delay σ_0

- 100m baseline
- 1.3 mm wavelength
- Zenith observation

Chajnantor: 15° to 60°

Detection possible with single configuration

Conclusions and perspectives

PPV Projection effects

- Statistics of velocity fields may be recovered for small density fluctuations
- Large fluctuations require iterative scheme and accurate value of σ_ρ / ρ_0

Detection and measurement of phase structure

- High dynamic range and excellent sampling in spatial frequencies needed
- Atmospheric phase noise not critical

Future developments

- Baseline-based approach : Allow for variations of $\vec{\delta}$
- Interpretation of phase structure quantities $\Longleftrightarrow$ Physical processes