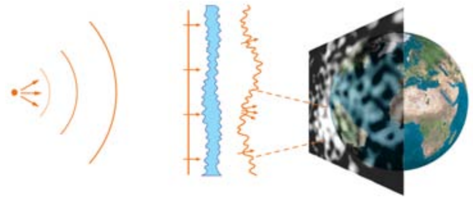


Search for galactic turbulent gas – visible or hidden - through interstellar scintillation

A&A 412, 105-120 (2003):
Does Transparent Hidden Matter Generate Optical Scintillation?
A&A 525, A108 (2011):
Results from a test with the NTT-SOFI detector
A&A 552, A93 (2013) :
Simulation of Optical Interstellar Scintillation

Marc MONIEZ, IN2P3, CNRS

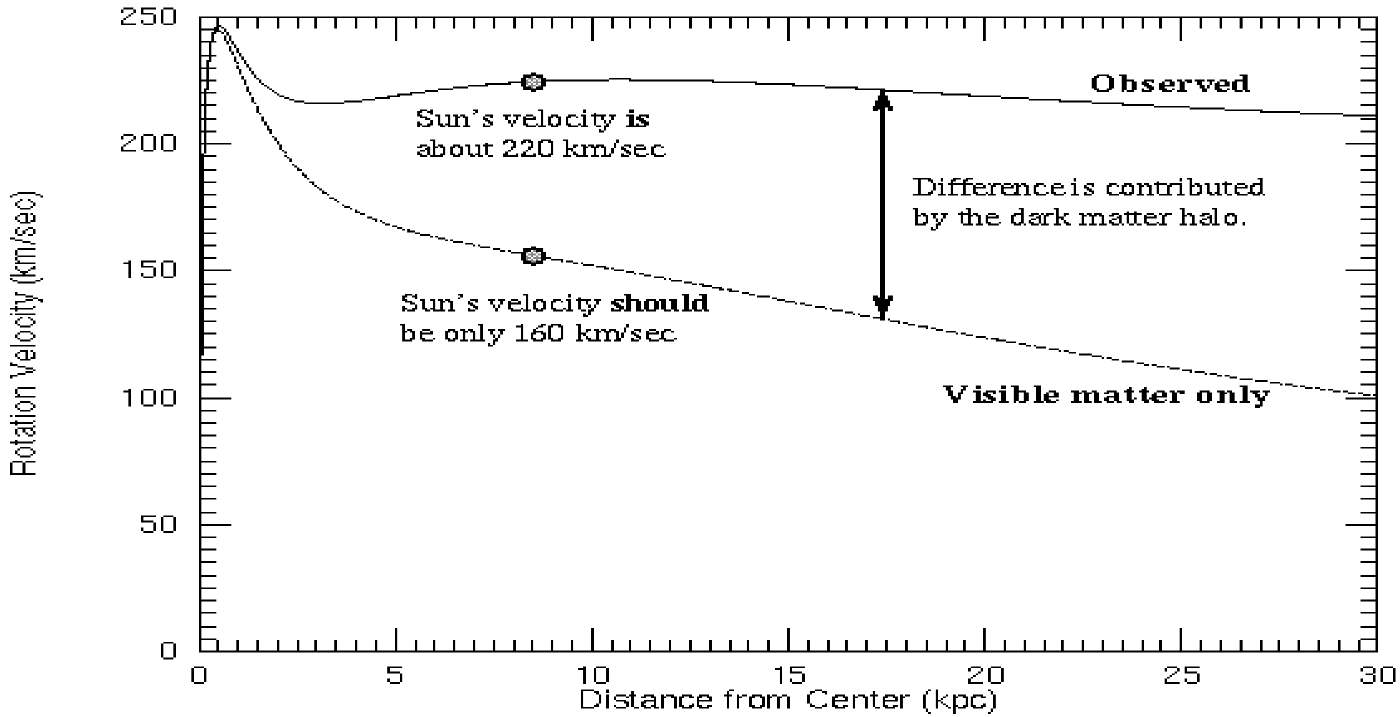
La Palma 19 juin 2014

Not an easy seminar...

- **Hidden matter problematics** are known by cosmologists and particle physicists
- **variable objects and light-curves** are known by astronomers
- **scintillation process** is known by Radio-astronomers
- **Fractal objects** are known by mathematicians
- **Fresnel diffraction** is known by opticians

The Milky Way rotation curve

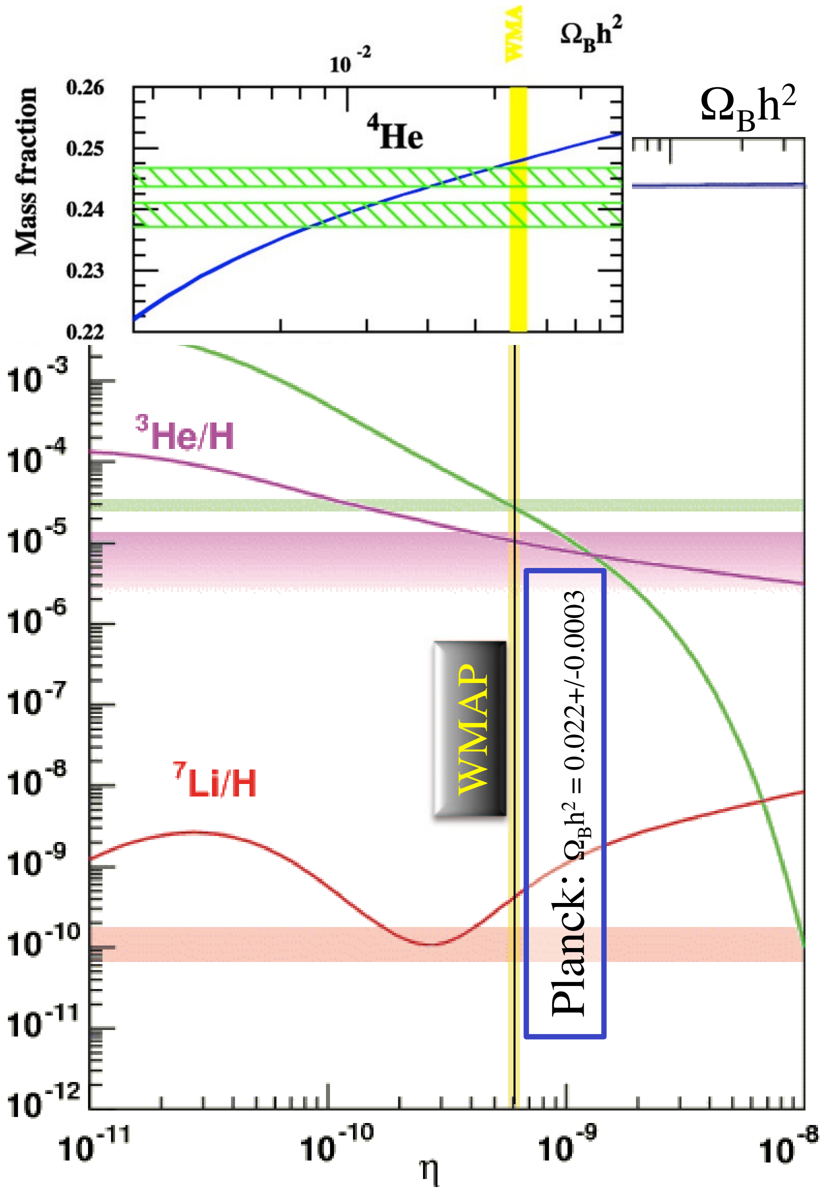
An evidence for hidden matter



The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

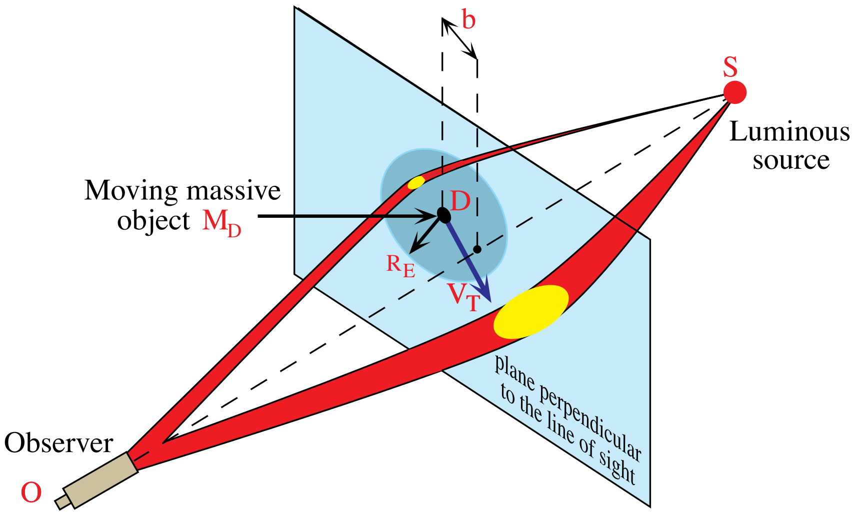
Hidden Baryons

- $\boldsymbol{\Omega_{visible}}$ **= 0.006** (unit Ω_c)
- Primordial nucleo-synthesis => $\boldsymbol{\Omega_b}$ **= 0.04**
- Planck results : $\Omega_b h^2 = 0.0224$ => $\boldsymbol{\Omega_b}$ **= 0.048**
- A factor 8 missing: fits with the galactic missing mass
- Mainly made of H + 25% He in mass

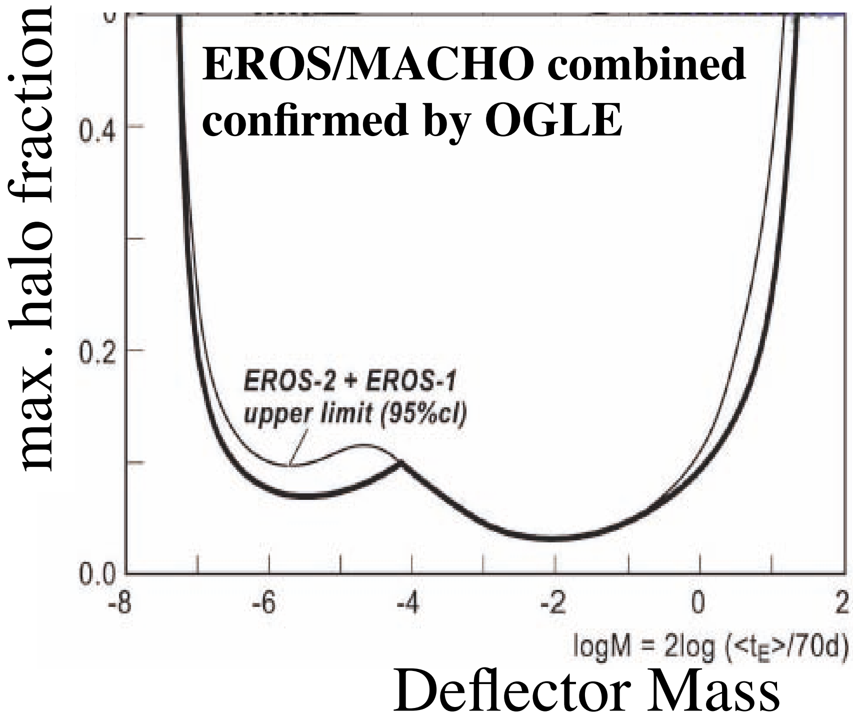


Where are these baryons?

- Not in MACHOs
  => EROS results



GRAVITATIONAL MICROLENSING EFFECT



Where are these baryons?

- **Compact Objects? ===> NO (microlensing)**
- **Gas**?
  - Atomic H well known (21cm hyperfine emission)
  - Poorly known contribution: **molecular H_2** (+25% He)
    - Cold (**10K**) => no emission. Very transparent medium.
    - In fractal structure covering **1%** of the sky.

      Clumpuscules ~10 AU (Pfenniger & Combes 1994)
    - In the **thick disc** or/and in the **halo**
    - Thermal stability with a liquid/solid hydrogen core
    - **Detection of molecular clouds** with quasars (Jenkins et al. 2003, Richter et al. 2003) and **indication of the fractal structure** with clumpuscules from CO lines in the galactic plane (Heithausen, 2004).

H_2 contribution is hard to evaluate

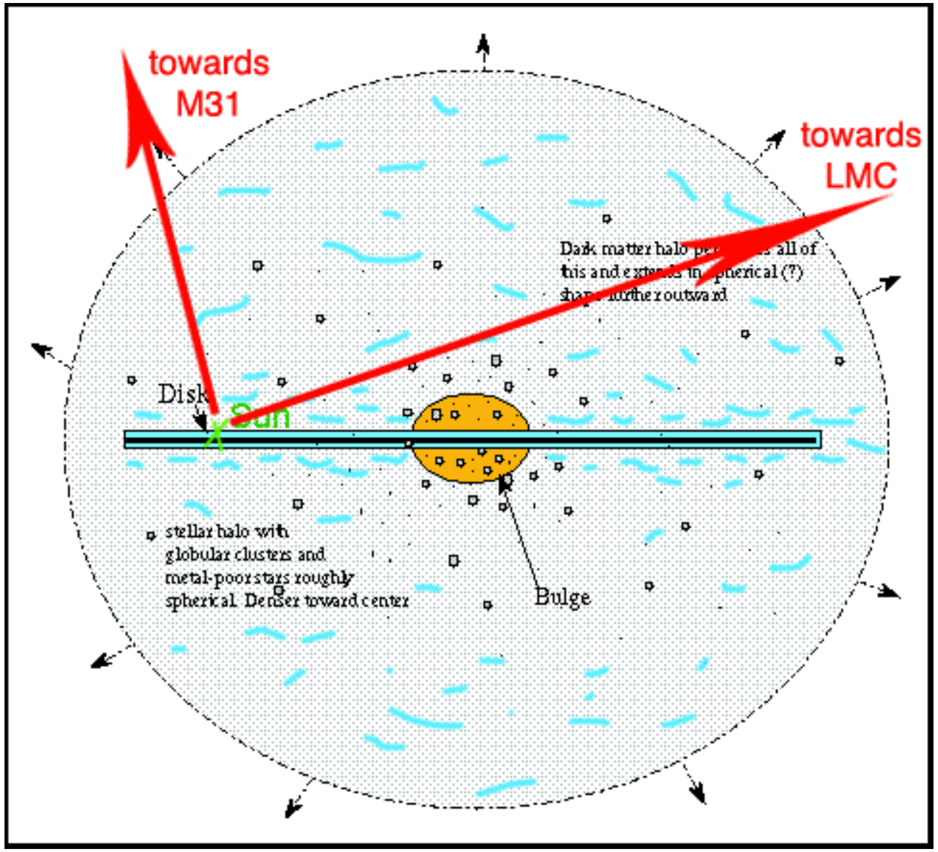
- H_2 symmetrical molecule => electric dipolar transitions forbidden
  - ✓No emission in cold medium
  - ✓No absorption at λ >110 nm

No resonant process

- Usually H_2 is estimated from CO tracer or from dust. Depend on metallicity hypothesis…

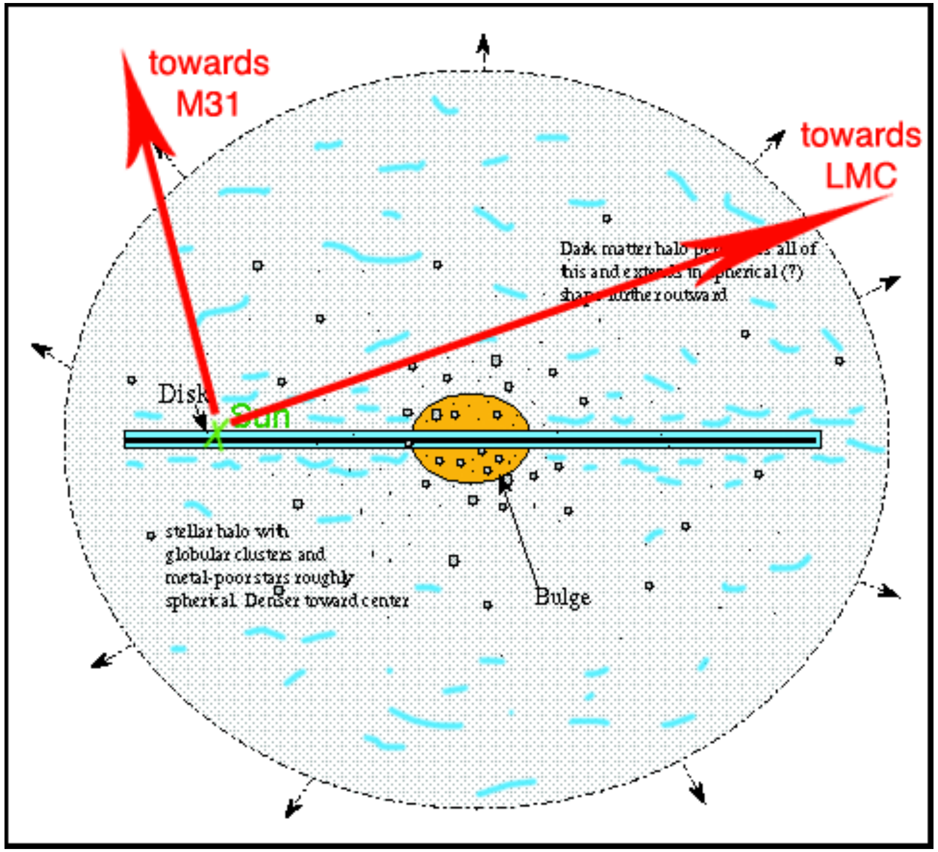
Orders of magnitude

- Assume a spherical isothermal halo



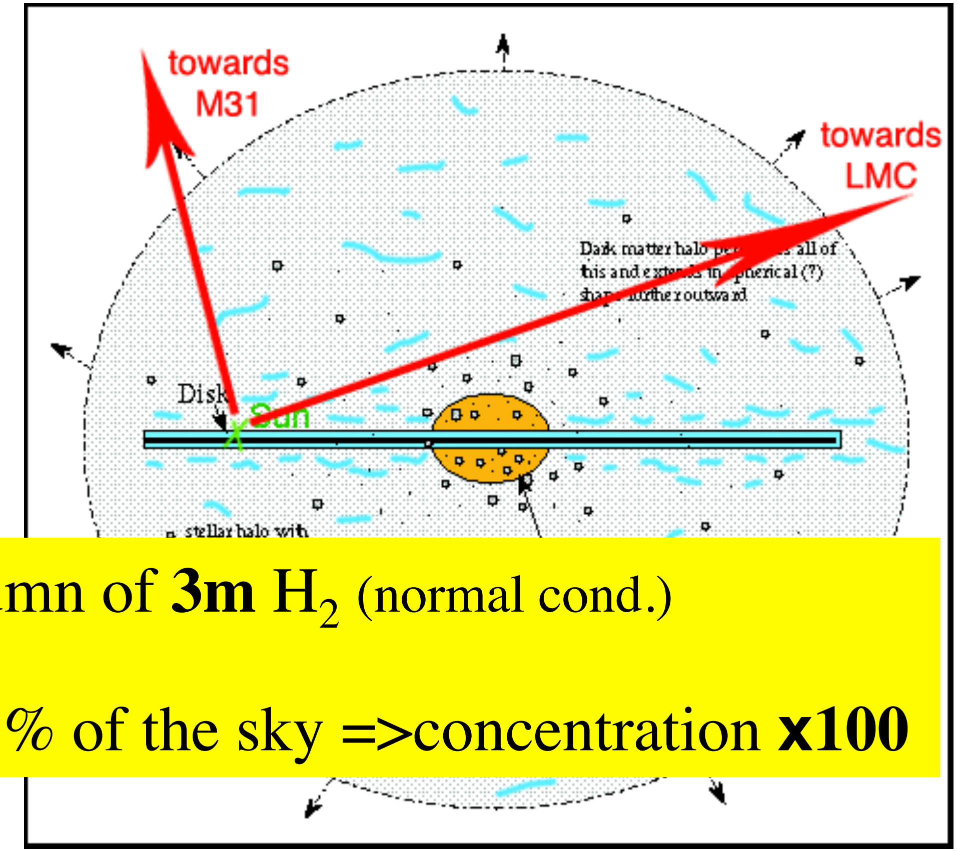
Orders of magnitude

- Assume a spherical isothermal halo
- Made of H_2 clouds
- **Question:** column-density toward LMC?

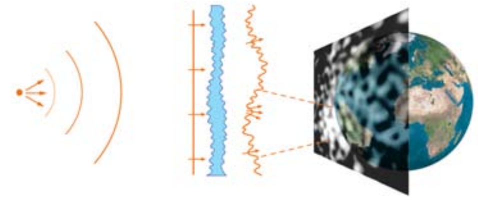


Orders of magnitude

- Assume a spherical isothermal halo
- Made of H_2 clouds
- **Average** column-density toward LMC



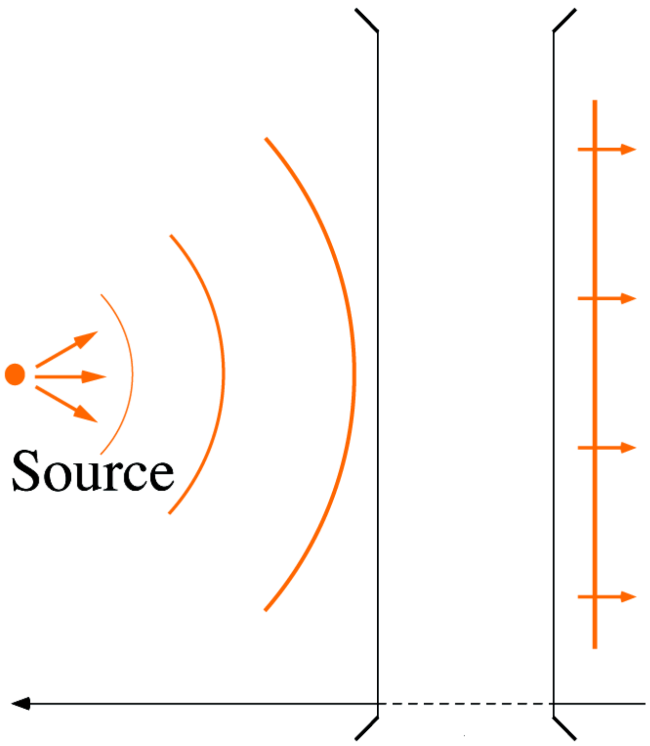
- **250g/m²** <=> column of **3m** H_2 (normal cond.)
- These clouds fill 1% of the sky =>concentration **x100**



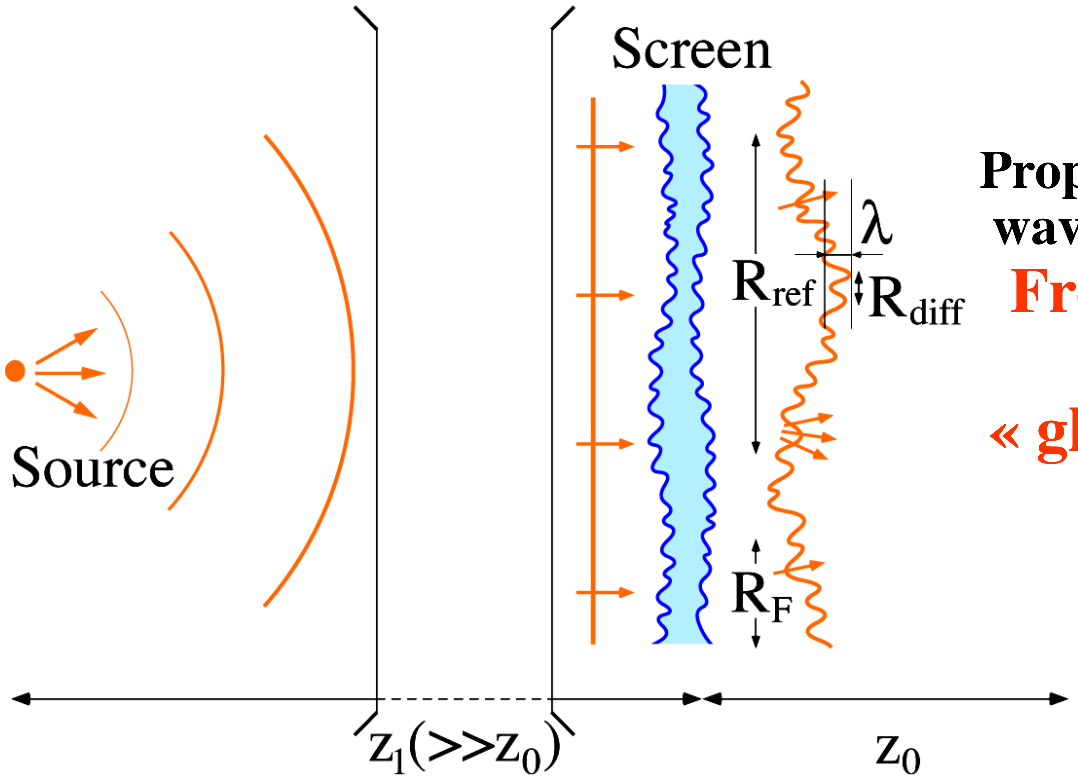
These clumpuscules refract light

- Elementary process involved: **polarizability α**
  - far from resonance
    => classical forced oscillator formalism
  - close to initial propagation direction
    => collective effect even with low molecular density ~ 10^9 cm^{-3} ($<1/\lambda^3$)
- Supplement of phase ϕ when crossing H_2 medium
  - $\Rightarrow$ typically **80,000 x2π** (for 1% of the sky) @ λ=500nm
  - $\Rightarrow$ Column density fluctuations (turbulences) in the medium **as small as 10^{-6}** are sufficient to produce detectable wavefront distorsions

Scintillation through a strongly diffusive screen



Scintillation through a strongly diffusive screen



Propagation of distorted wave surface driven by:

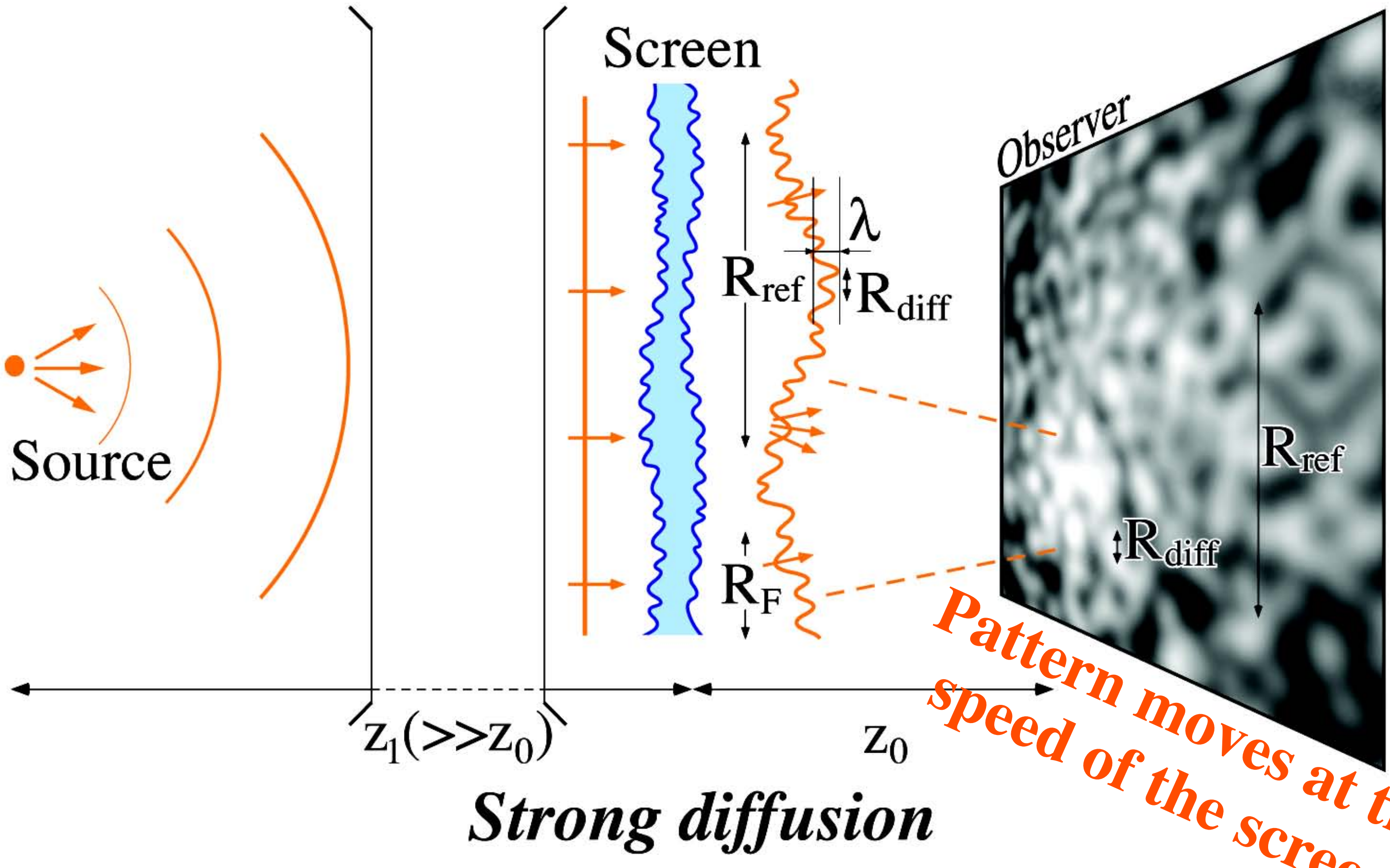
Fresnel diffraction

+

« global » refraction

Strong diffusion

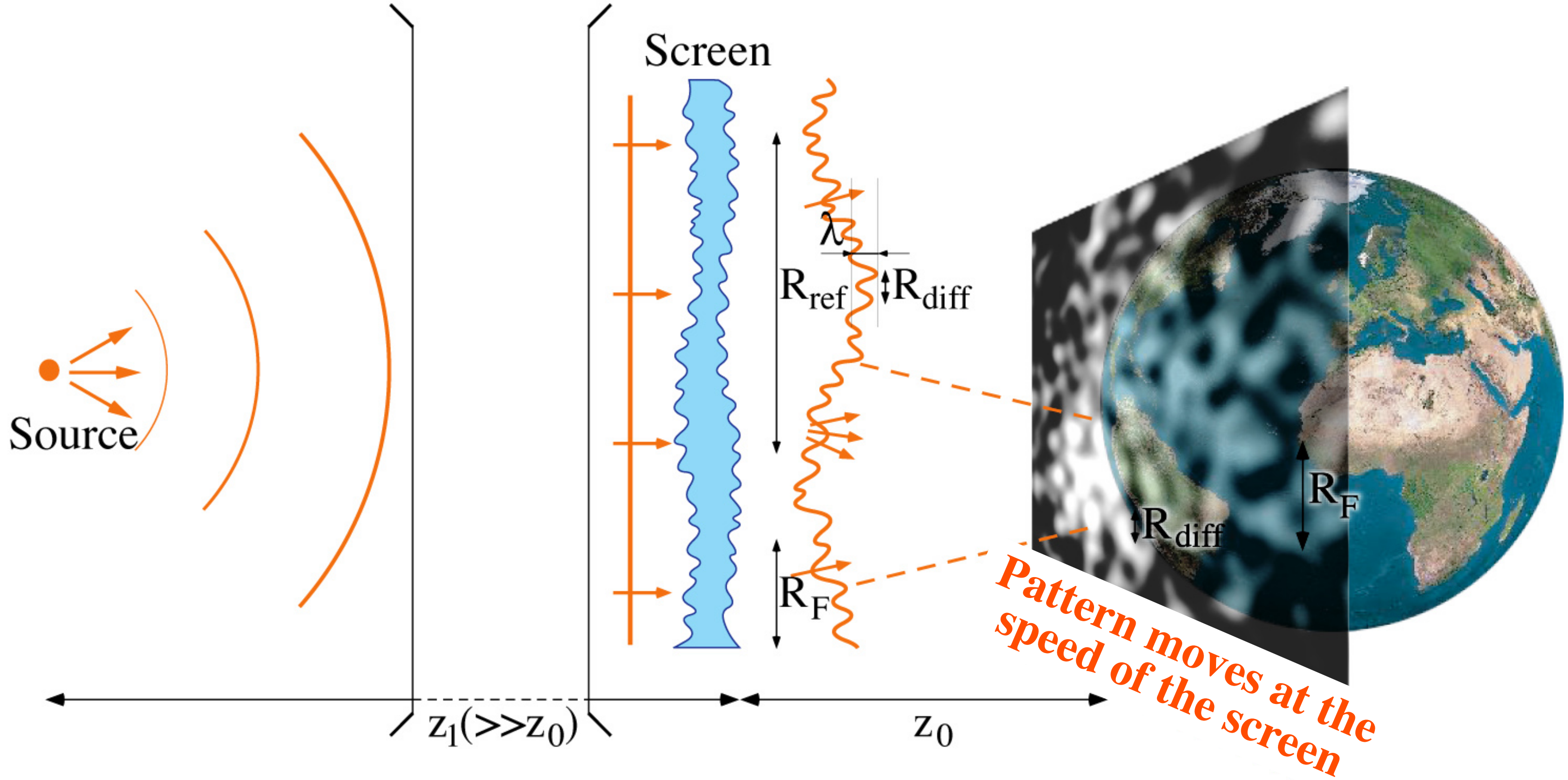
Scintillation through a strongly diffusive screen



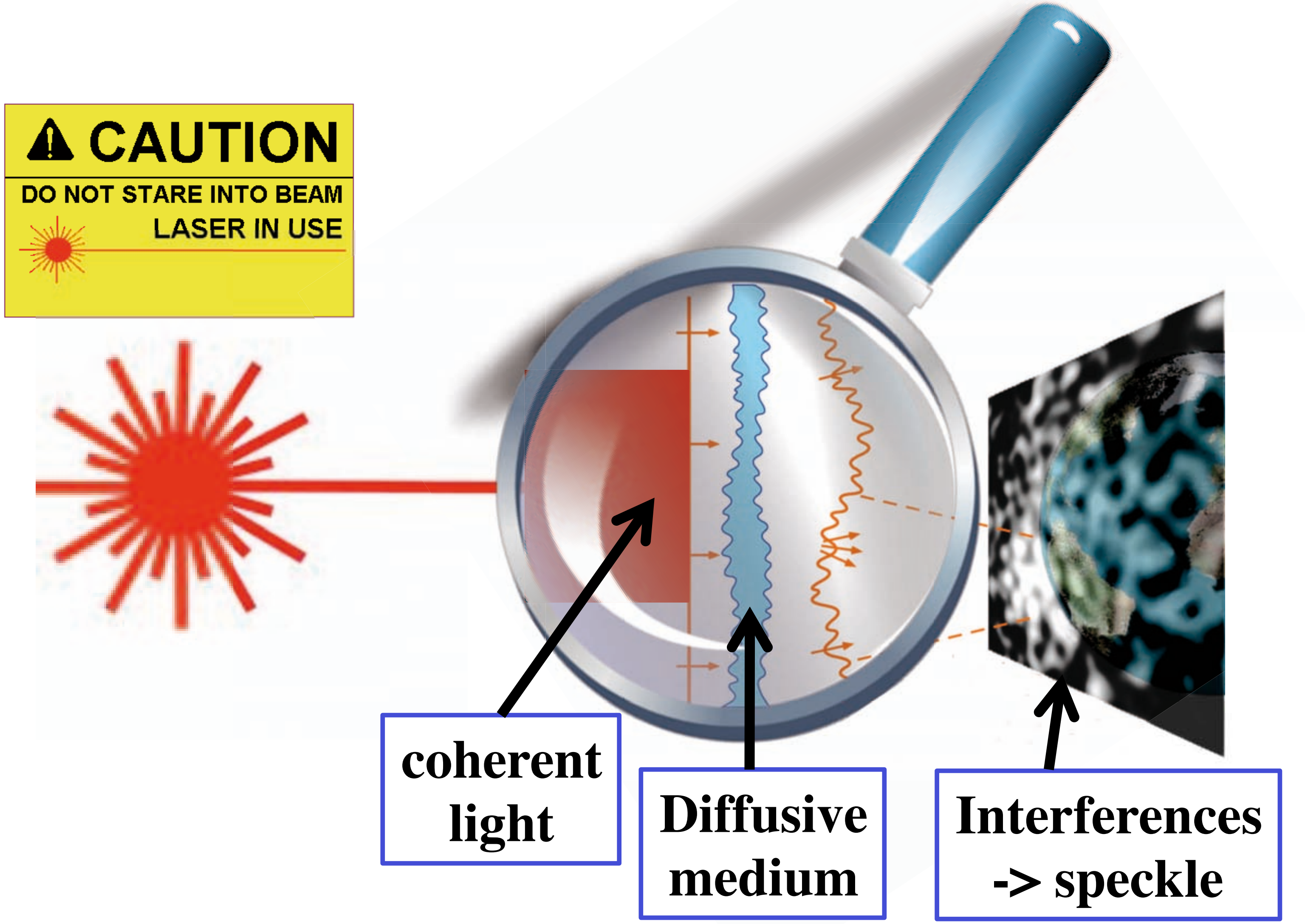
Pattern moves at the speed of the screen

Scintillation through a diffusive screen

After refraction, propagation of distorted wave surface is driven by Fresnel diffraction that produces speckle

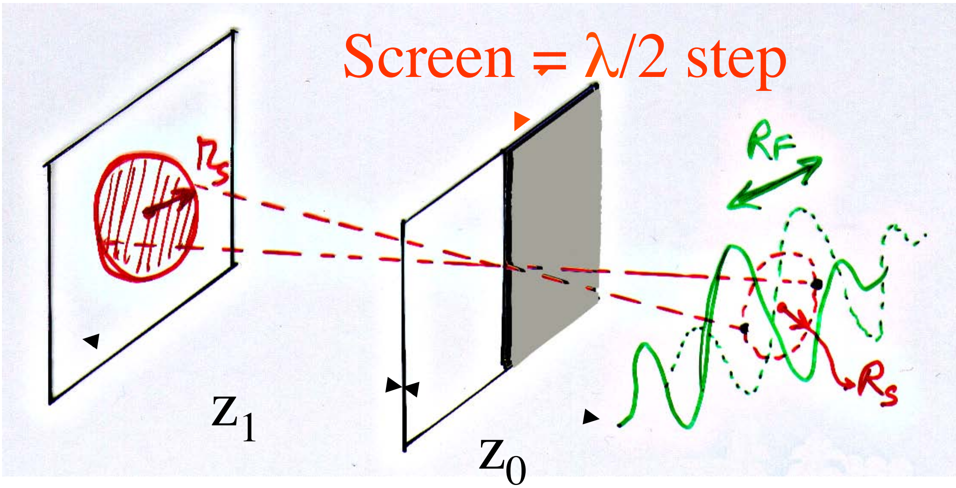


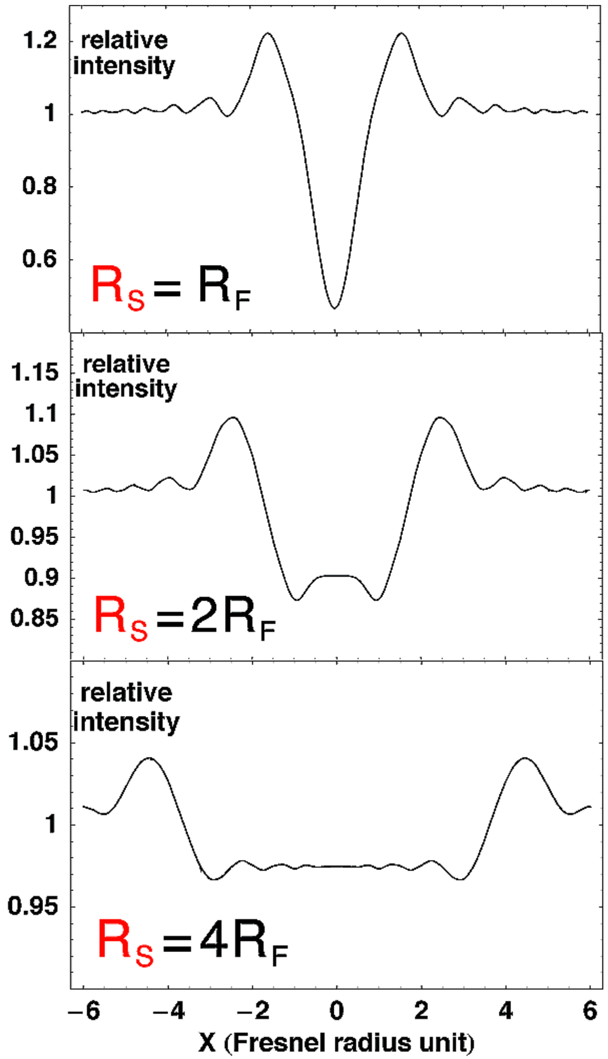
Demonstrator



[redacted]

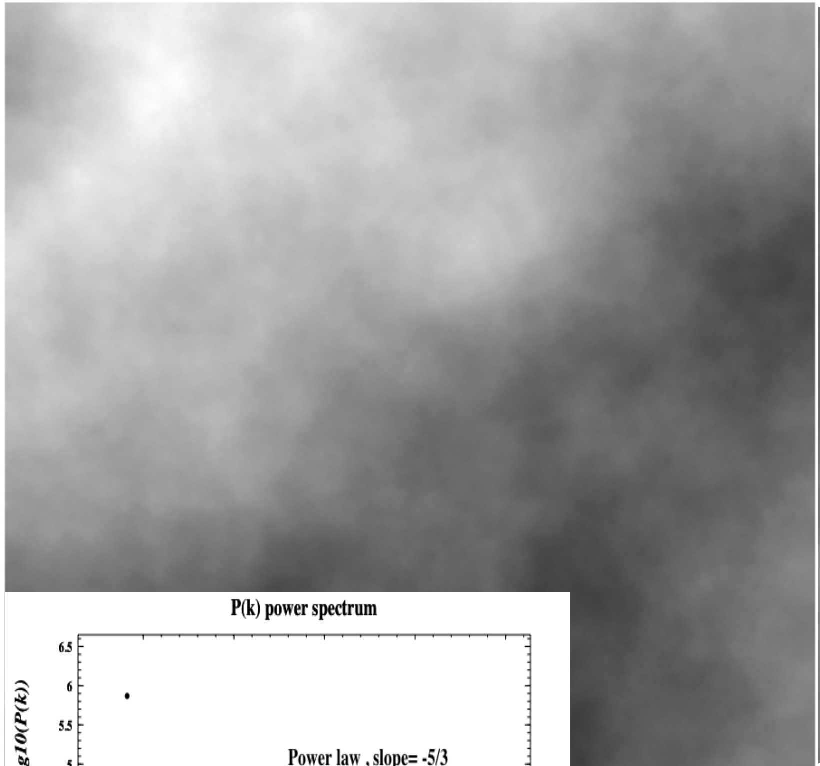
Contrast is severely limited by the source size
=> spatial coherence

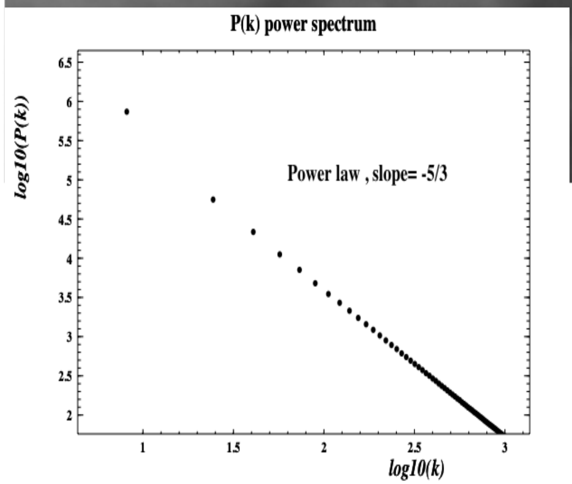




- Depression width ~ $\mathbf{R_S}$
  => Info on source size
- Contrast ~ $\mathbf{R_F}$/ $\mathbf{R_S}$
- Also depends on **Δλ** (time coherence), but not critically: $\Delta\lambda/\lambda<0.1 \Rightarrow \Delta R_F/R_F<0.05$

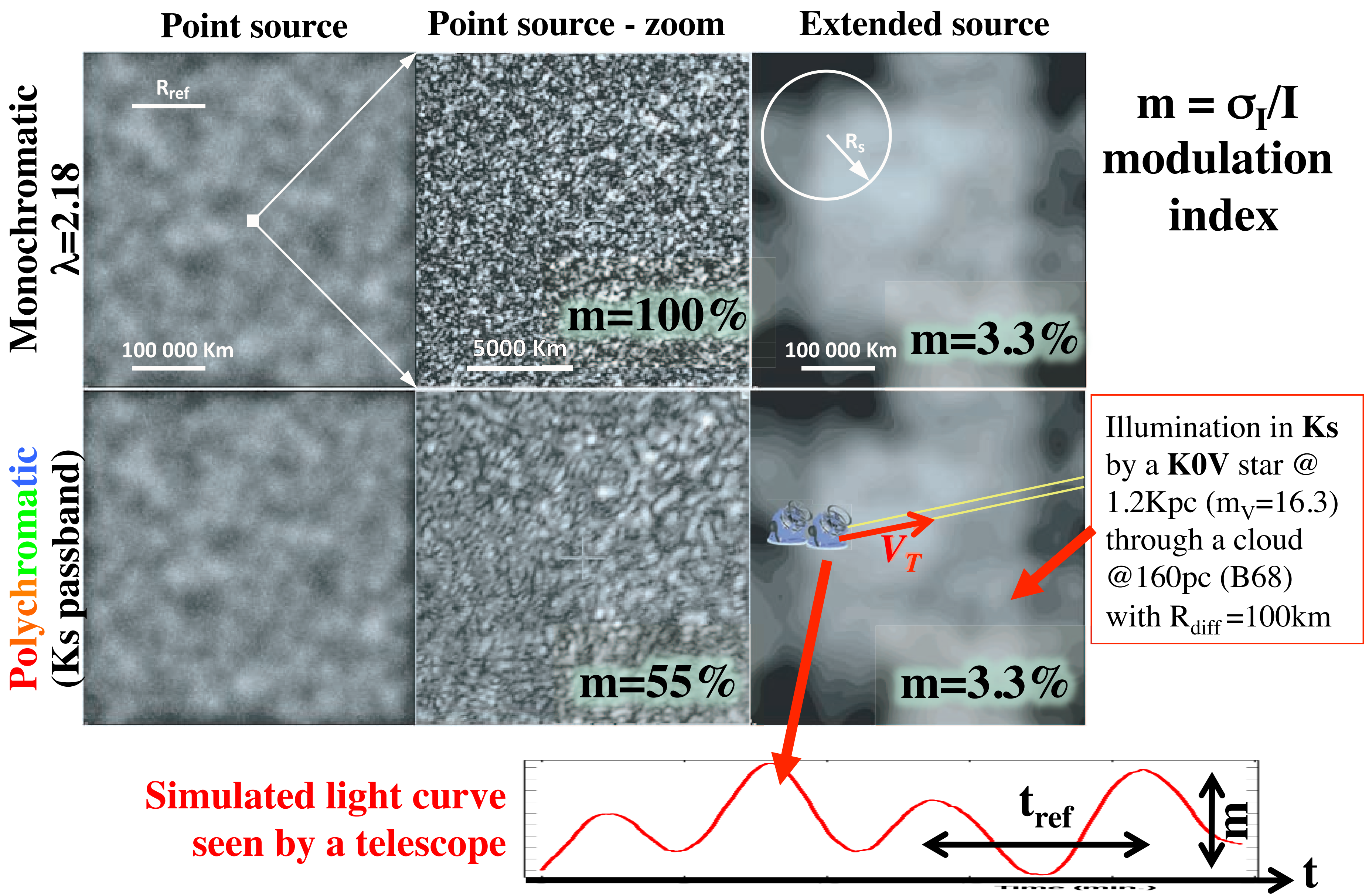
Simulation: Fractal phase screen

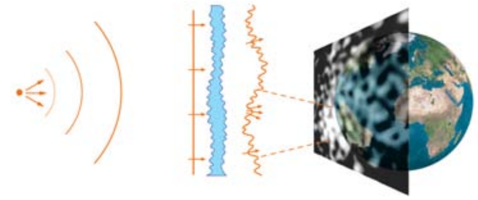




- Kolmogorov turbulence -> realistic
- Other power laws have been studied

Simulation for a polychromatic extended source





Distance scales

4 distance scales characterize the speckle pattern

- **Diffusion radius R_{diff}**
  - **separation such that:** $\sigma[\phi(\mathbf{r}+R_{diff})-\phi(\mathbf{r})] = 1$ radian
  - Characterizes the turbulence

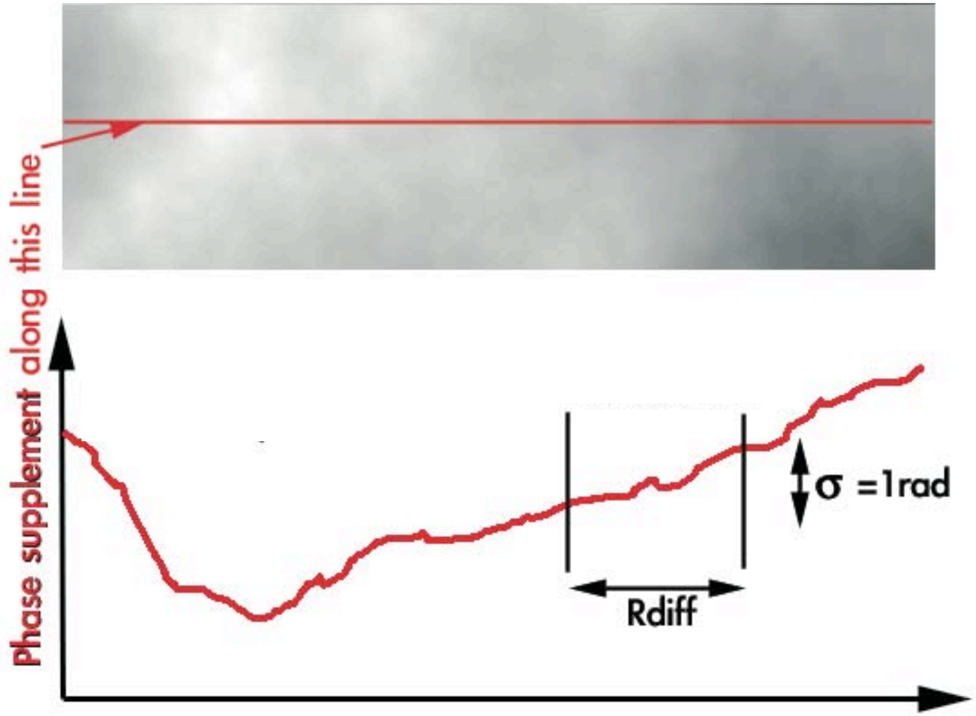
R_{diff} : Statistical characterization of a stochastic screen

R_{diff} = size of domain where

$\Delta\phi$ = 1 radian

or equivalently (@ λ = 500 nm)

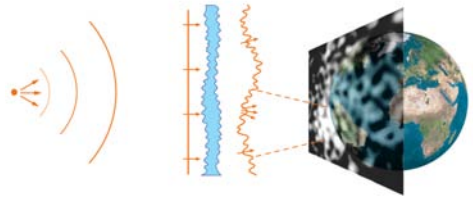
$\Delta N_l = 1.8 \times 10^{18}$ molecules/cm^2



- This corresponds to
  - **$\Delta N_l / N_l \sim 10^{-6}$**
    for disk/halo clumpuscule
  - **$\Delta N_l / N_l \sim 10^{-4}$**
    for Bok globule (NTT search)

$$R_{diff}(\lambda) = 263km \left[\frac{\lambda}{1\mu m}\right]^{\frac{6}{5}} \left[\frac{L_z}{10AU}\right]^{-\frac{3}{5}} \left[\frac{L_{out}}{10AU}\right]^{\frac{2}{5}} \left[\frac{\sigma_{3n}}{10^9 cm^{-3}}\right]^{-\frac{6}{5}},$$

L_z : Cloud size $\qquad$ L_{out} : Turbulence outer scale

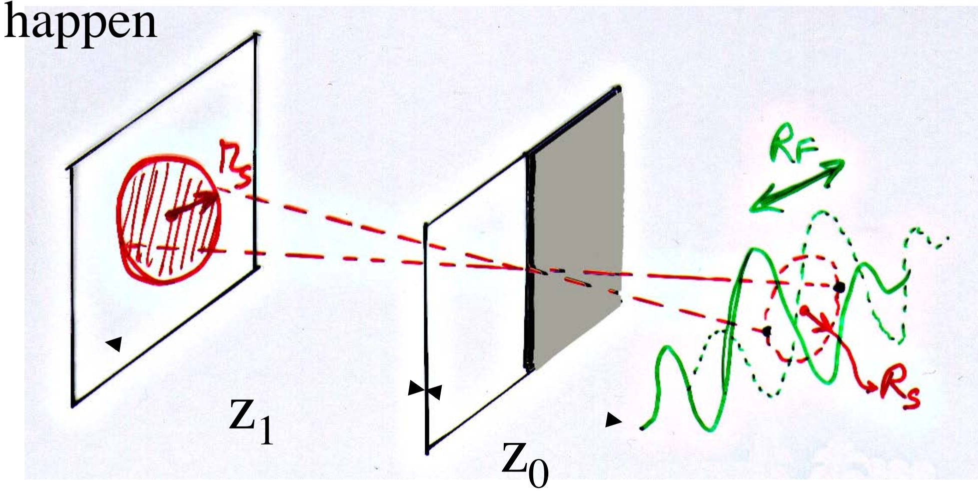


Distance scales

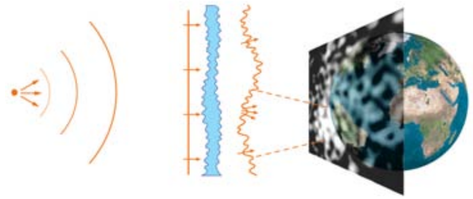
4 distance scales characterize the speckle pattern

- **Diffusion radius R_{diff}**
  - **separation such that:** $\sigma[\phi(\mathbf{r}+\mathbf{R_{diff}})-\phi(\mathbf{r})] = 1$ radian
  - Characterizes the turbulence
- **Refraction radius R_{ref}**
  - size of the region from which most of the scattered signal, seen by a single point observer, originates $\sim z_0\lambda/R_{diff}$
- **Larger scale structures** of the diffusive gas can play a role if focusing/defocusing configurations happen
- **Projected source size R_S**

speckle from a pointlike source is convoluted by the source projected profile. -> impacts the contrast of the illumination pattern



Time scale (observable)



If R_{ref} is the largest scale :

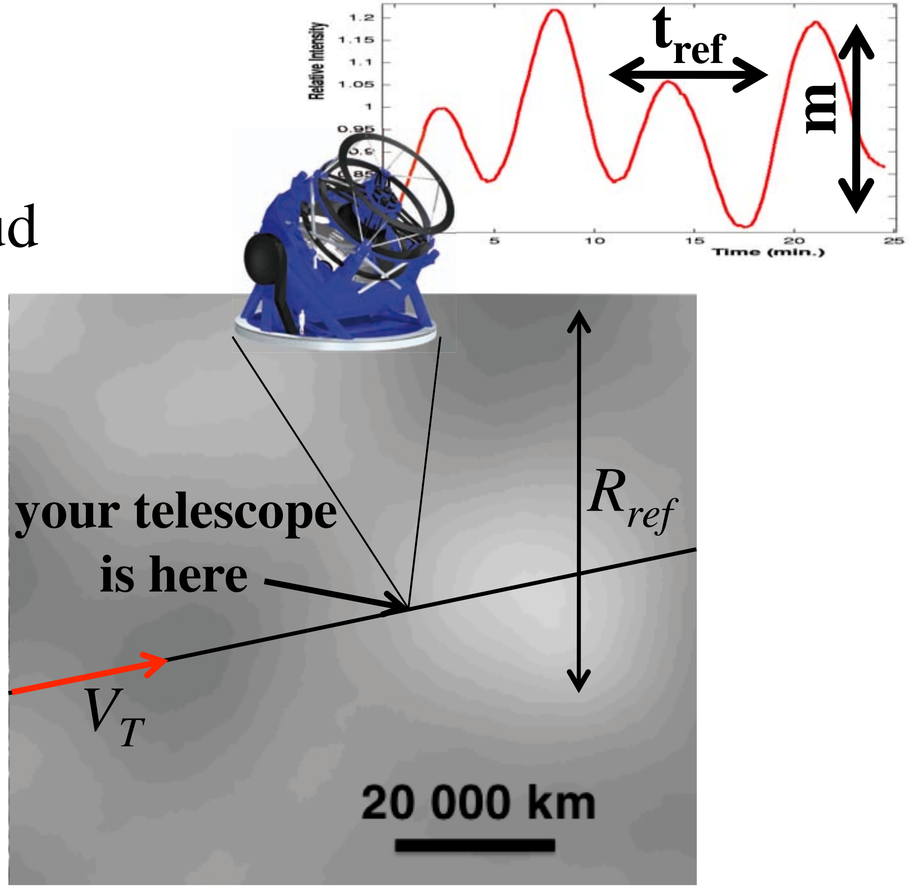
$$t_{ref}(\lambda) = \frac{R_{ref}}{V_T} \sim 5.2\,minutes \left[\frac{\lambda}{1\mu m}\right]\left[\frac{z_0}{1\,kpc}\right]\left[\frac{R_{diff}}{1000\,km}\right]^{-1}\left[\frac{V_T}{100\,km/s}\right]^{-1}$$

Where

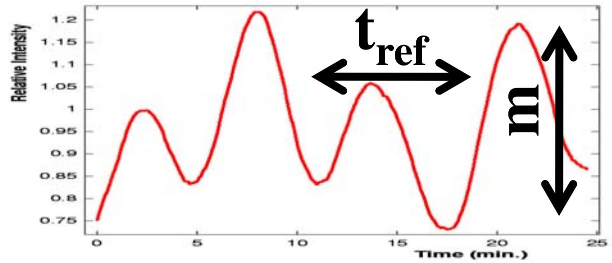
z_0 is the distance to the cloud

V_T is the relative speed of the cloud with respect to the line of sight

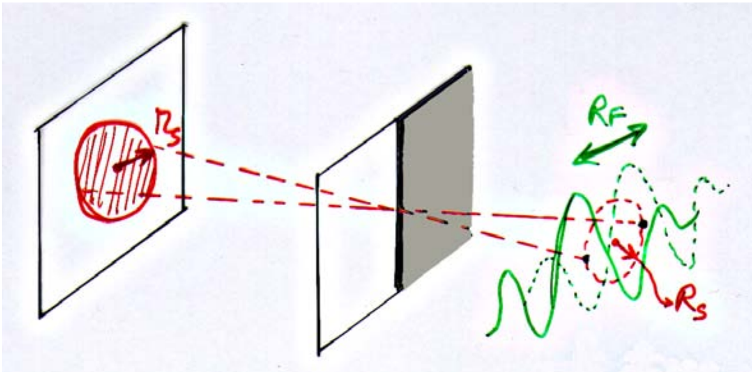
-> V_T is also the speed of the illumination pattern in front of the telescope

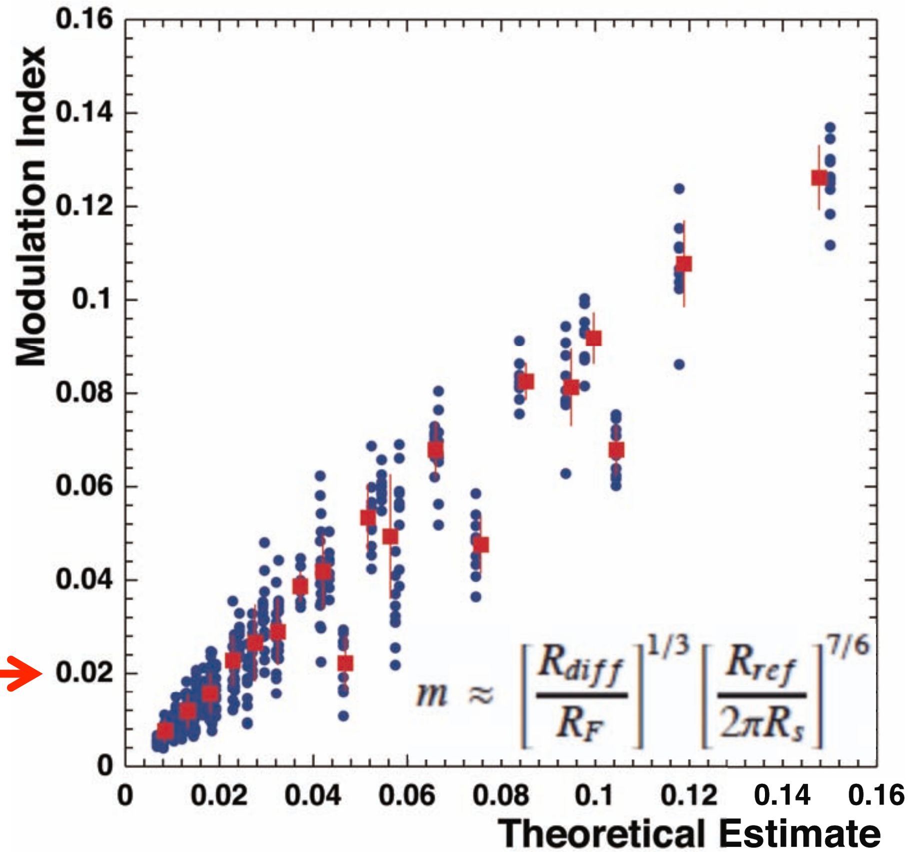


Modulation Index
(observable)



Essentially depends on $\mathbf{R_S}$ and $\mathbf{R_{ref}}$
-> not on the details of the power spectrum of the fluctuations

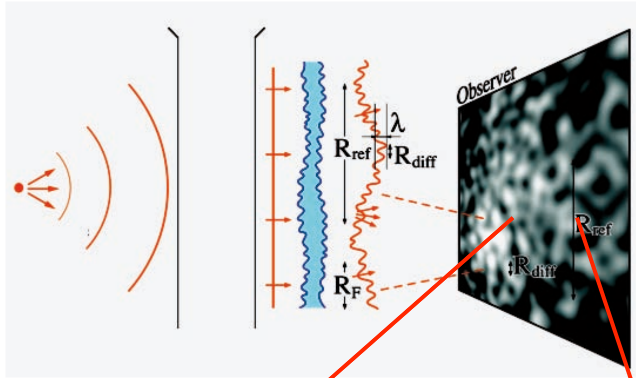




Scintillation@λ = 1 μm of Sun@10kpc (V~20) through a cloud@160pc with R_{diff}=1000km

Signature of scintillation

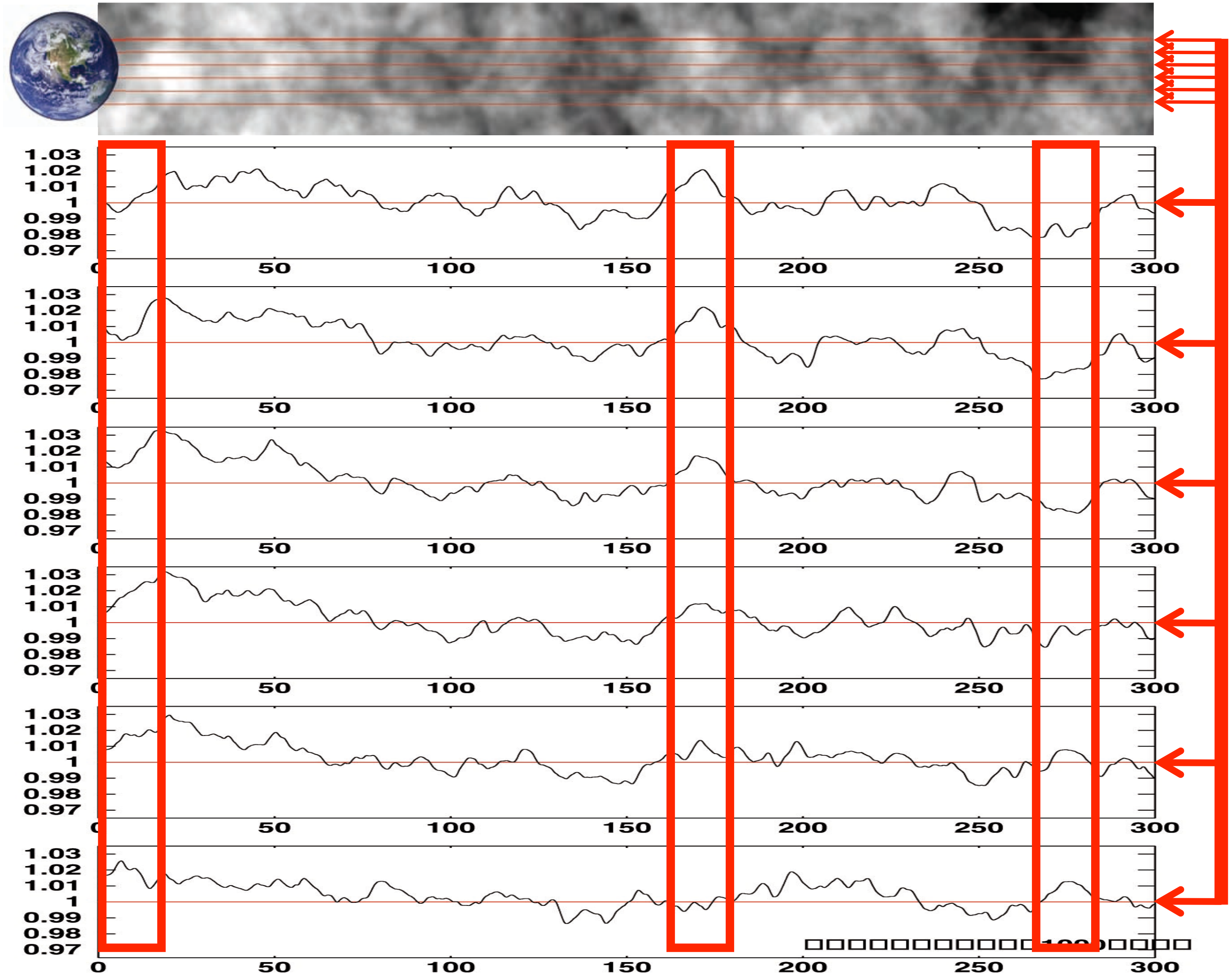
- **Stochastic light-curve** (not random)
  - Autocorrelation (power spectrum)
  - Characteristic time (few minutes)
  - Modulation index can be as high as 5%
    - decreases with increasing star radius
    - depends on cloud structure
- **Signatures of a propagation effect**
  - Chromaticity (optical wavelengths)
    - Long time-scale variations (few min.) ~ achromatic $\lambda^{-1/5}$
    - Short time-scale variations (sub-min.) varies with $\lambda^{6/5}$
  - **Correlation between light-curves measured by 2 telescopes decreases with their distance**

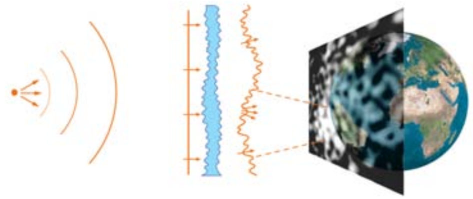


Illumination from a $0.5xR_{sun}$ star@1Kpc

through a diffusor@160pc with R_{diff} = 1000km

Series of light curves sampled by telescopes 2000 km far from each other



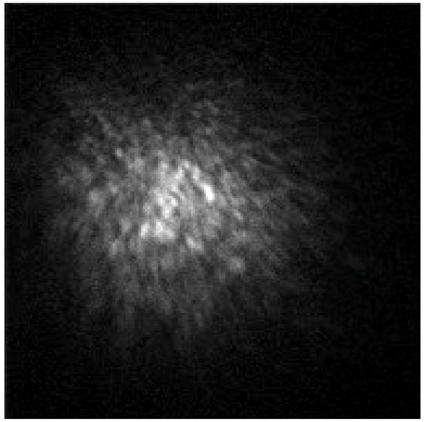


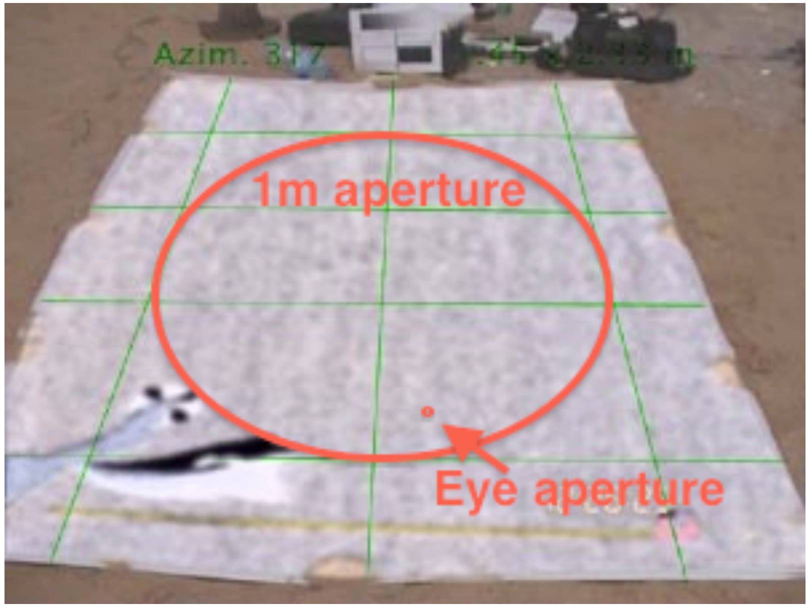
Fore and backgrounds

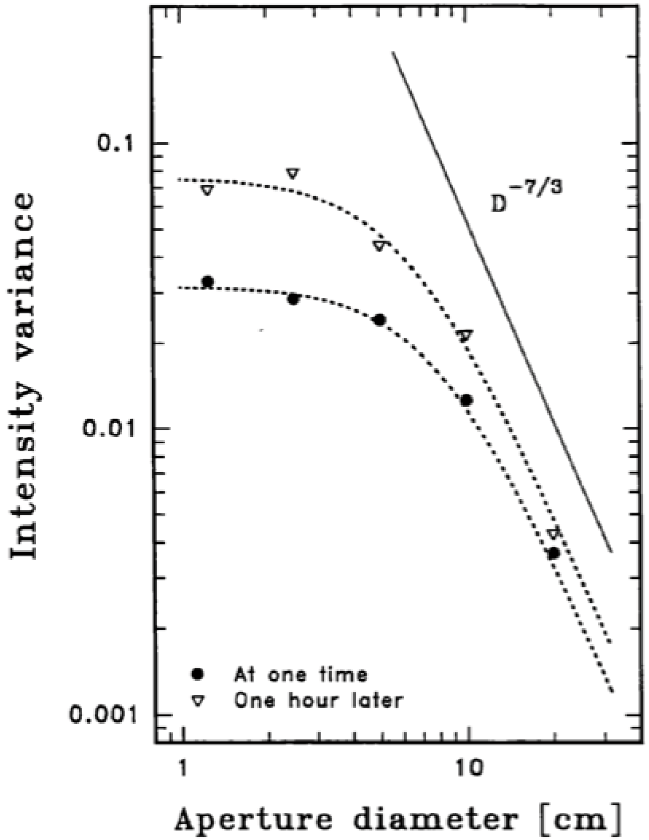
- **High altitude cirruses**
  - Would induce easy-to-detect **collective** effects on neighbour stars, whereas scintillation by a 10AU object affects only one star.
- **« nearby » gas (at ~ 10pc)**
  - Scintillation would also occur on the biggest stars
- **Intrinsic variability**
  - Rare at this time scale and only with special stars (UV Ceti, flaring Wolf-Rayet)

Atmosphere, atmosphere?

- Blurs PSF, but doesn't affect the intensity collected by a large telescope
- ~ 5cm size speckle due to turbulent layers at ~ 10km
- Observable during total solar eclipses: « shadow bands »



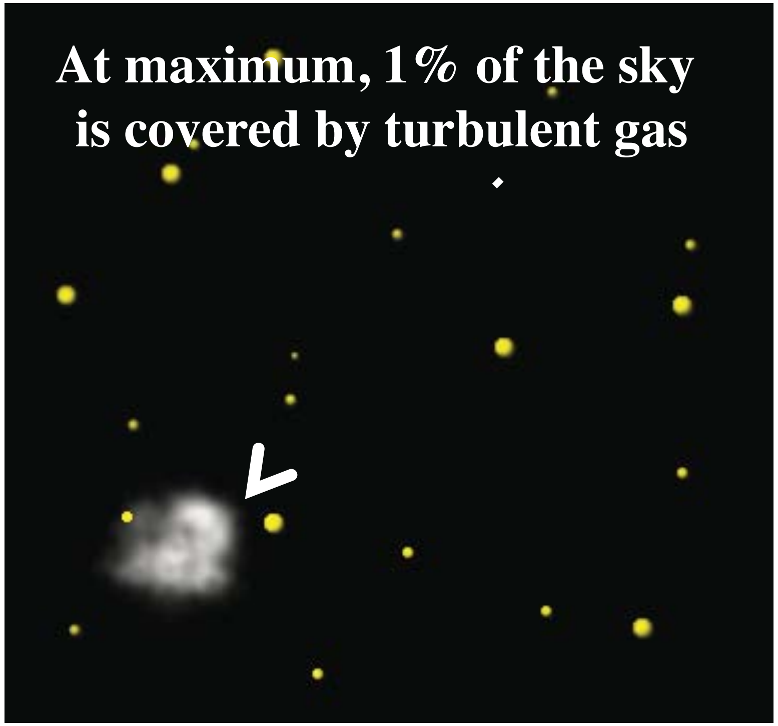




Aperture dependence of the intensity variance (2 series of measurements)

Maximum fraction of LMC/SMC scintillating stars

$$\tau(m > m_{threshold}) = 10^{-2} \times f(m_{threshold})$$



Where

- **m** is the modulation index
- **f** is the fraction of gas turbulent enough to have $m > m_{threshold}$

Expected difficulties, cures

- **Blending** (crowded field)=> differential photometry
- **Delicate analysis**
  - Detect and Subtract collective effects
  - Search for a not well defined signal
    - VIRGO robust filtering techniques (short duration signal)
    - Autocorrelation function (long duration signal)
    - **Time power spectrum**, essential tool for the inversion problem (as in radio-astronomy)
- **If interesting event** => complementary observations (large telescope photometry, spectroscopy, synchronized telescopes…)

Requirements to detect scintillation towards LMC

- Assuming R_{diff} = 1000km (fits 10 AU clumpuscules)
- Expect **5% modulation@500nm** if $r_s < r_{A5}$ ($10^5/deg^2$)

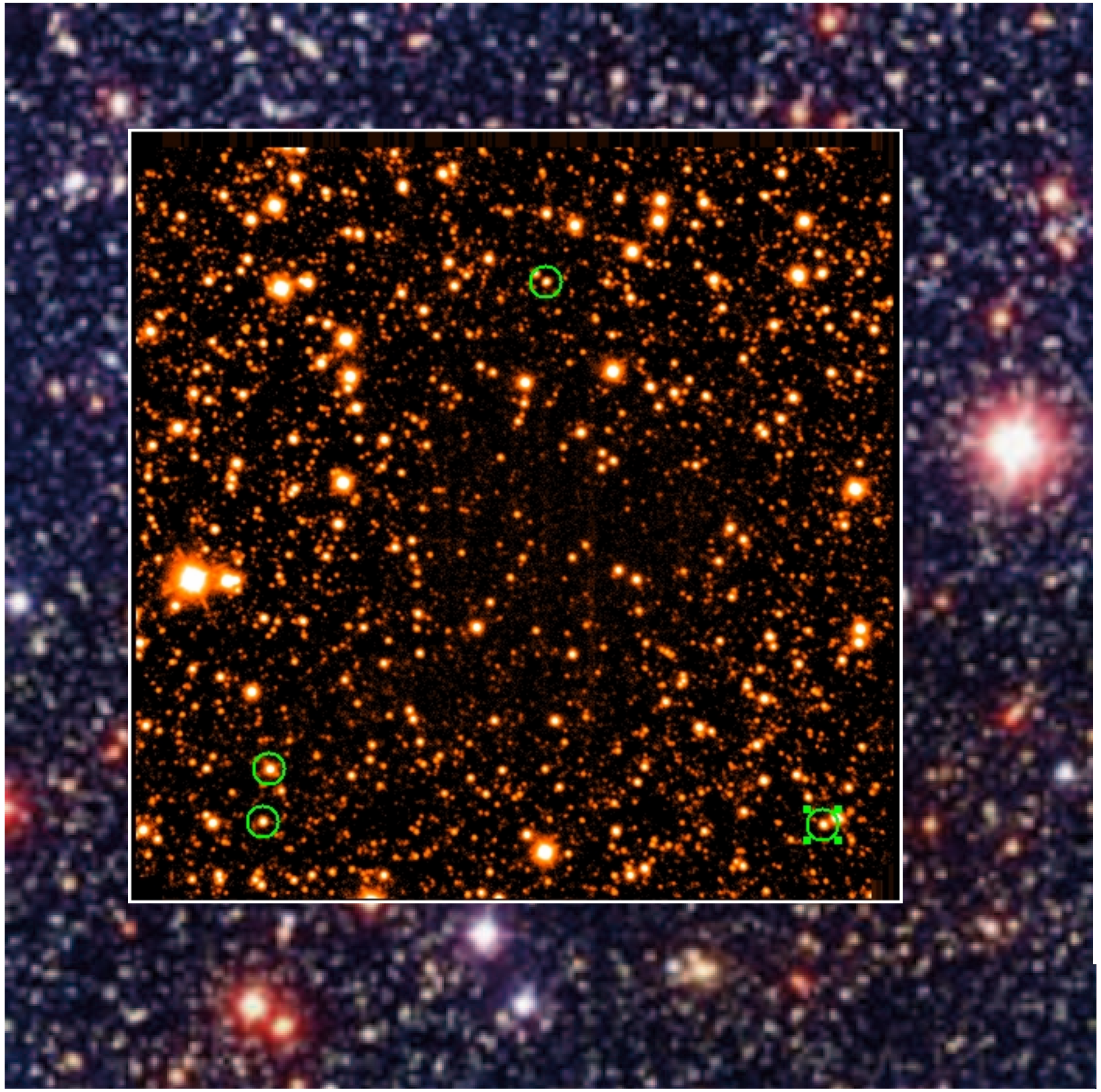
✓ Smaller than **A5** type in LMC =>
✓ Characteristic time ~ few min. =>
✓ Photometric precision required

$M_V \sim 20.5$
sub-minute exposures
~1%

✓ Dead-time < few sec. =>
✓ **B** and **R** partially correlated =>
✓ Optical depth probably small =>

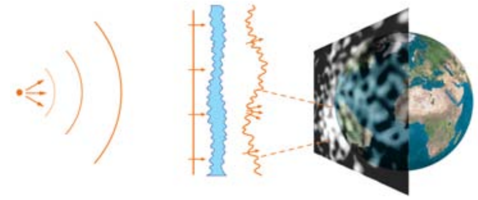
Telescope > 2 meters
Fast readout Camera
2 cameras desirable
Wide field

Test towards Bok globule B68, Circinus, cb131, and SMC



- **ESO-NTT telescope**
  - *3.6m*
  - *2 nights*
- **Infrared**
  - *monitor 1000's stars through gas/dust*
  - *allows 10s exposures with small dead-time*
- **Search for fluctuating stars**
  - *other than known artifacts*
  - *at a few % level*
  - *with light curves of 1000's samples*

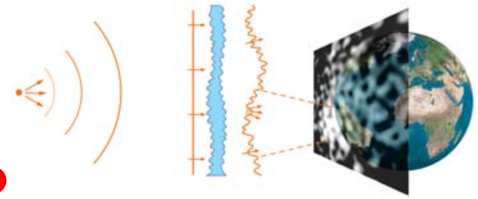
Test towards Bok globule B68 and SMC
NTT IR (2 nights)

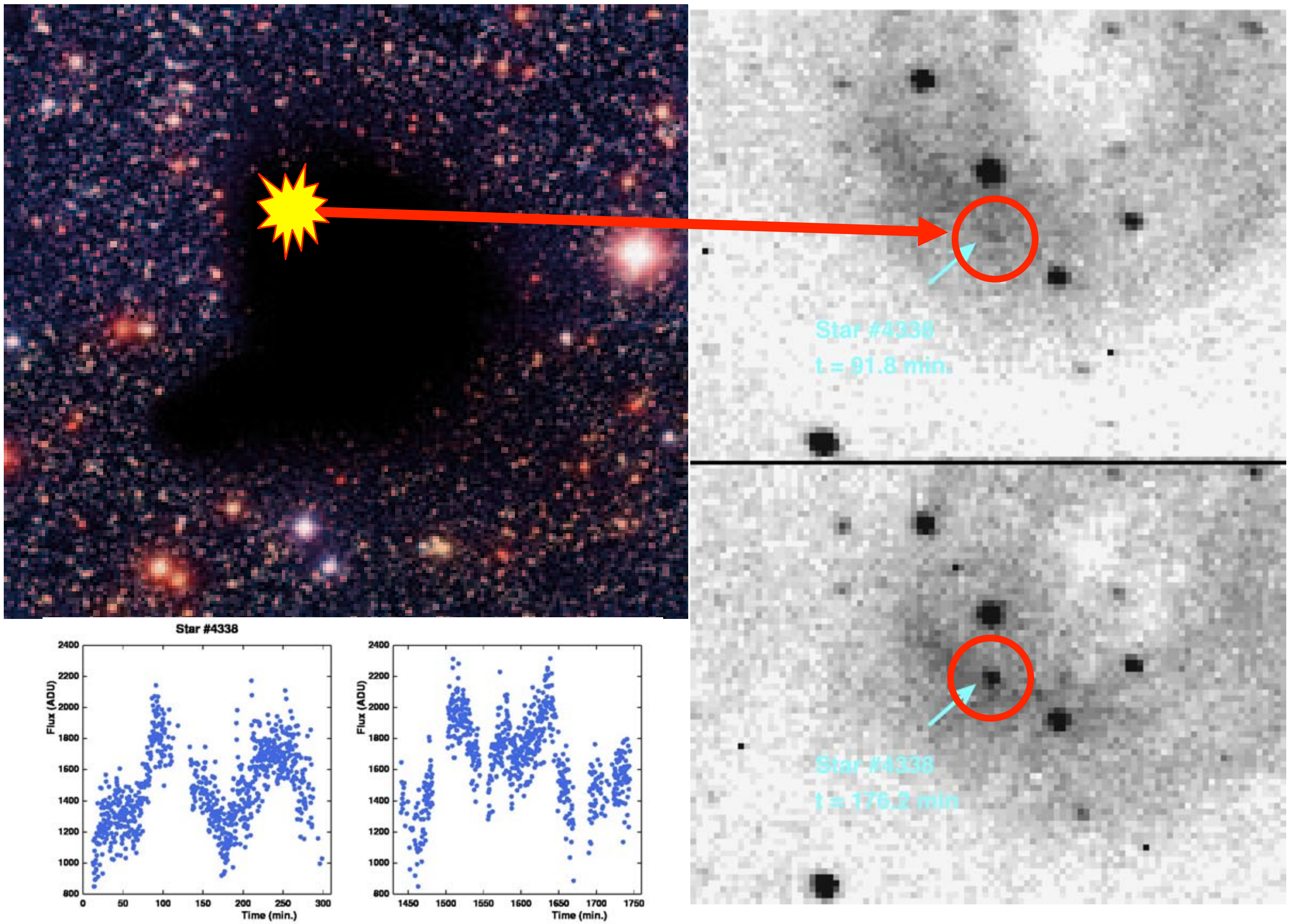


Mainly a test for background estimates and feasibility

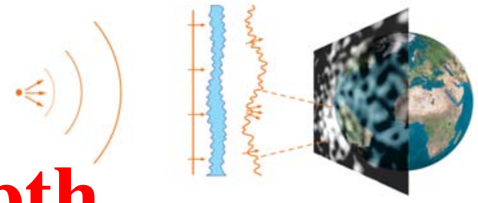
- **B68 (& cb131, Circinus nebula)**
  - **dust + existing gas at $z_0 \sim 160$ pc**
  - Column density $Nl \sim 2.6 \times 10^{22} cm^{-2}$
  - Signal if $\Delta N_l/N_l \sim 10^{-4}$ per 1000 km
  - **1114 stars monitored at $z_1 \sim 7$ kpc**
  - **50% are behind the nebula, 50% make a control sample**
  - **2000 exposures of 10s in 2 nights**
- **SMC**
  - **blind search for invisible gas**
  - **980 stars monitored at $z_1 \sim 64$ kpc**
  - **1000 exposures of 10s in 2 nights**
- **Search for few % variability**

Results toward B68:
A star scintillating through visible gas?





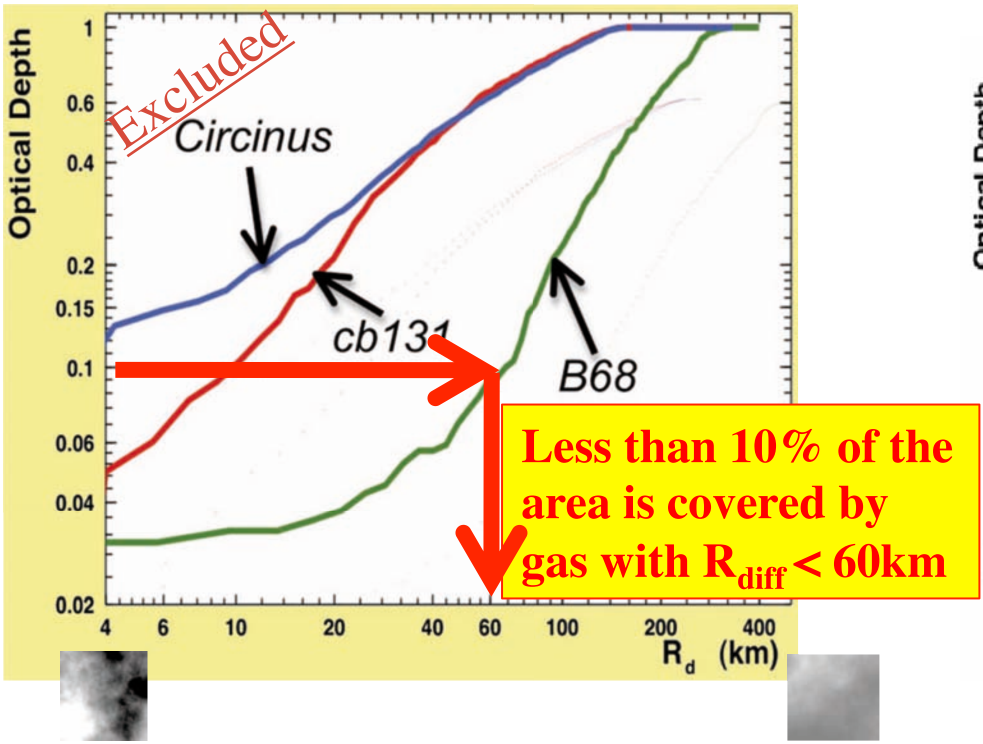
Results from faisibility studies:
upper limits on scintillation optical depth



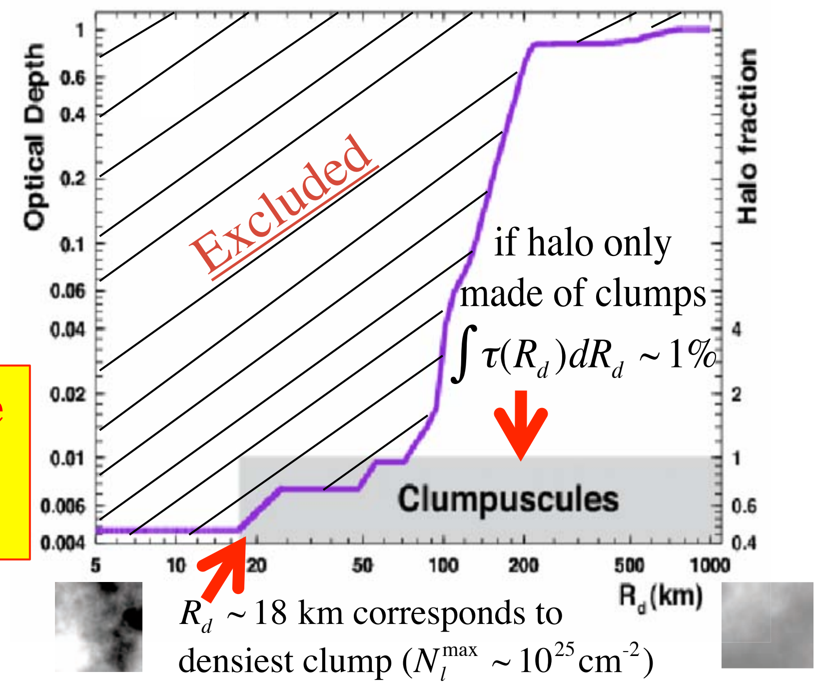
First fundamental result : **no overwhelming unexpected background**

Upper limits on scintillation probability => **constrain the turbulent gas abundance**

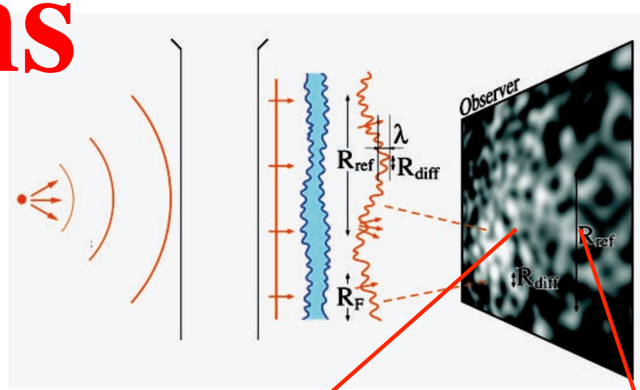
stars behind visible gas (B68 and other nebulae)



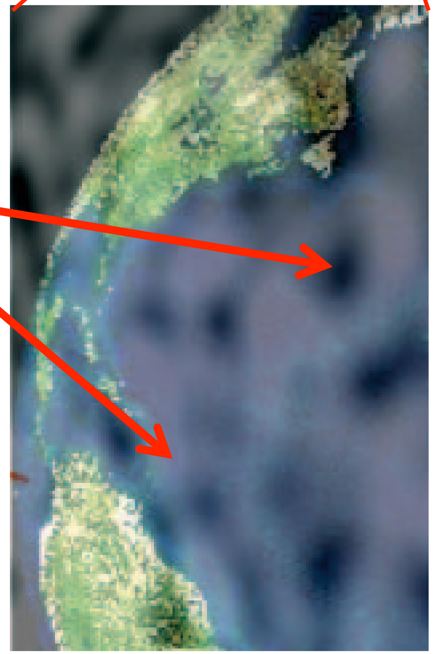
blind search with stars behind invisible gas (SMC)



short term plans



synchronized observations
through > **4m** class telescopes
to probe the strongest signature
-> ***fluctuations are not correlated at large distance***



- Obtain synchronous observations from 2 **very** distant telescopes
-> **GEMINI** telescopes?
- And/or « standard » telescope observations with complementary observations on candidates

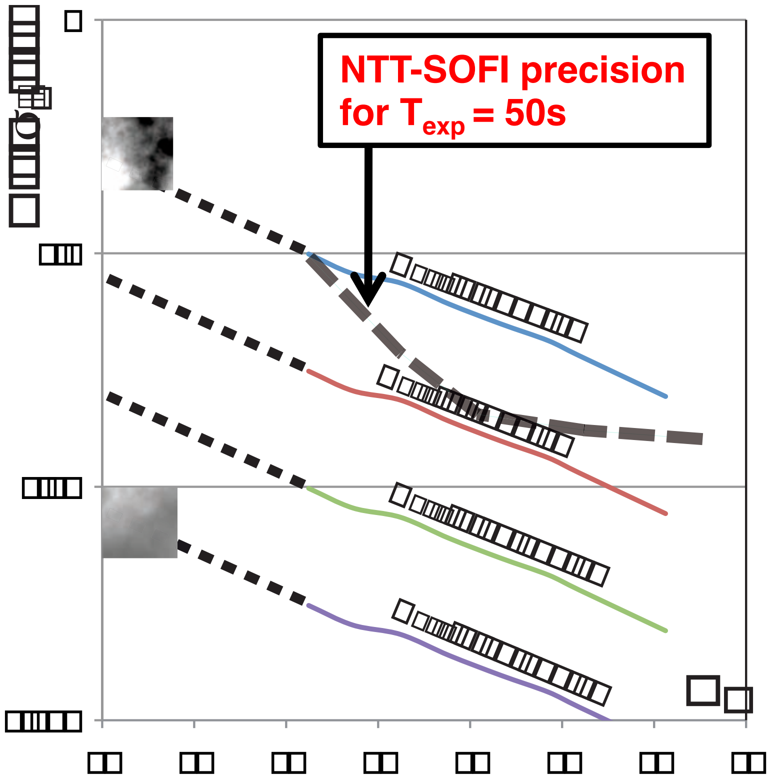
Scintillation with GAIA ?

- photometric precision in the per-CCD G band is estimated to be 6% at G=20 -> OK for the best cases
- But limited sampling (1h46 or per-CCD 4.4s) not adapted for an autocorrelation study
- GAIA can select scintillating candidates for follow-up, to search for a decisive signature
  - Stochastic variations (not periodic)
  - Small time scale (frequent change of the derivative)
  - Select stars with small angular radiae
- Working Package WP 710-02000
  - Ref.: GAIA-C7-SP-GEN-LE-009

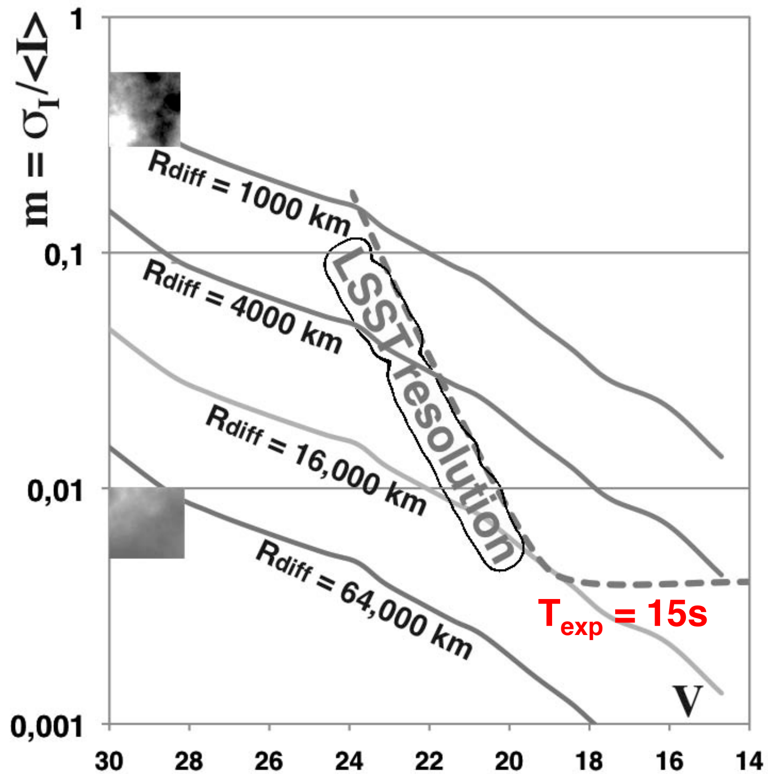
Scintillation with LSST (15s exp.) or your telescope

For given R_{diff}, the modulation $\mathbf{m = \sigma_I/<I>}$ depends on the sources' magnitude through the apparent stellar radius (here MS star)

- Source@7Kpc (gal. plane) in $\mathbf{K_S}$
- Screen@160pc : B68- **visible gas**



- Source@55Kpc (LMC) in **V**
- Screen@1Kpc : halo- **hidden gas**



Scintillation with LSST (15s exp.) or your telescope

For given R_{diff}, the modulation $\mathbf{m = \sigma_I/<I>}$ depends on the sources' magnitude through the apparent stellar radius (here MS star)

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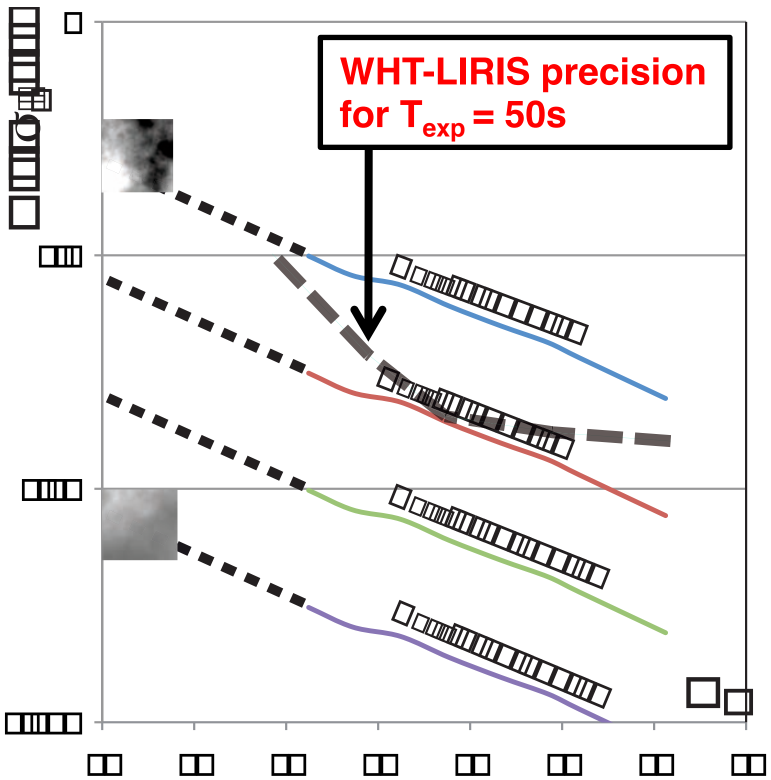

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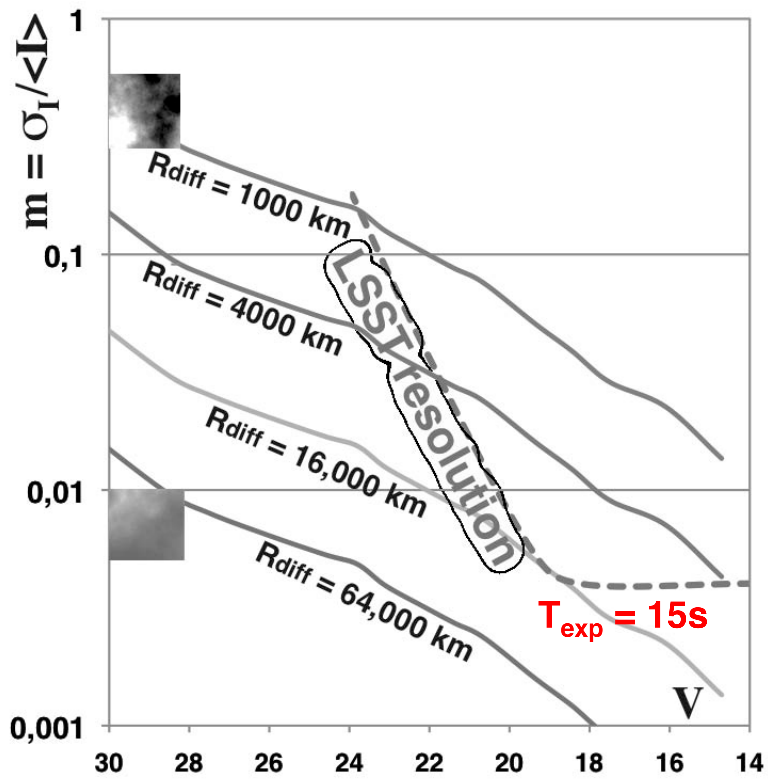

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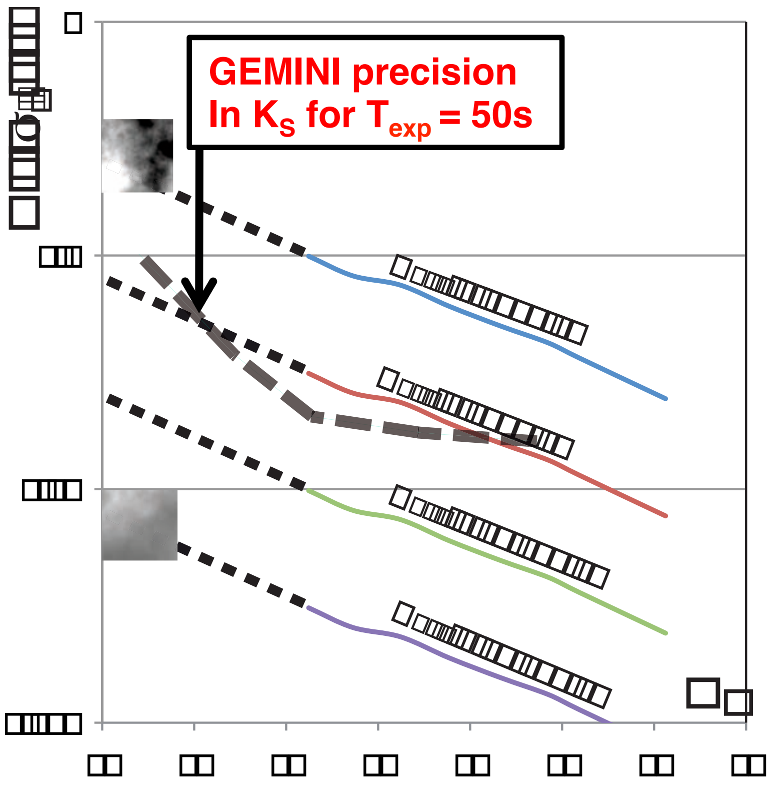

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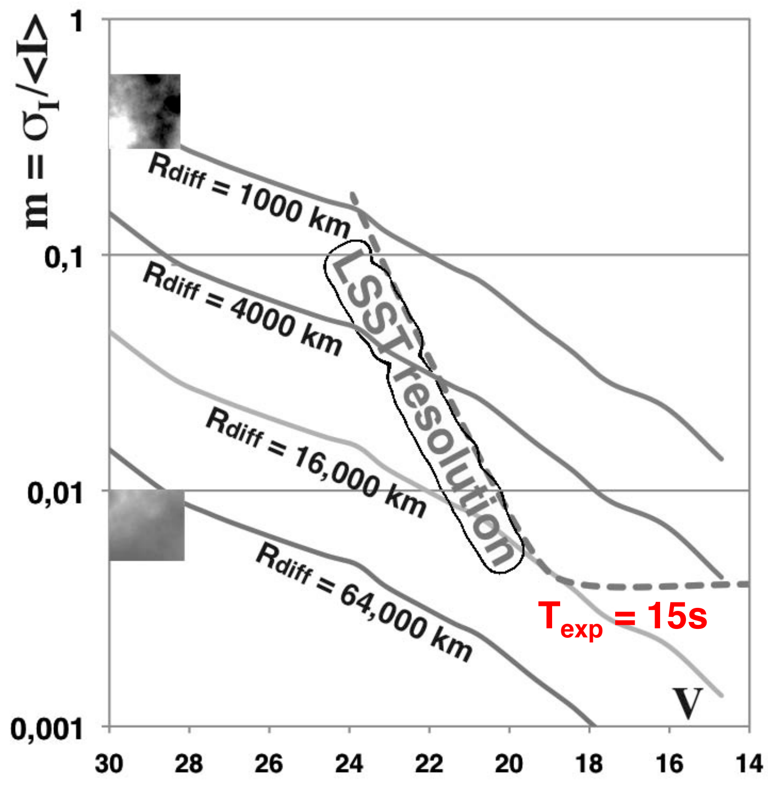
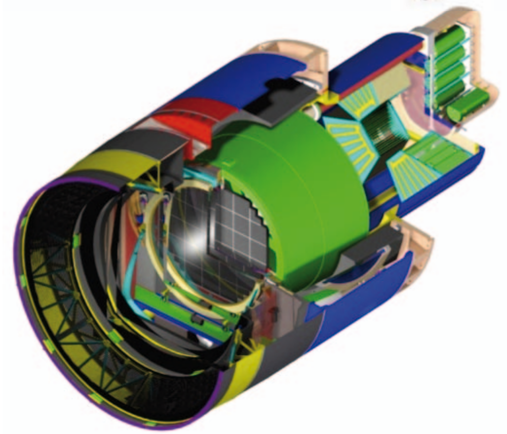


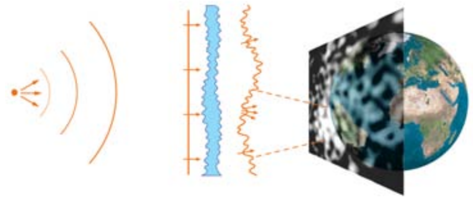
LSST : Large Synoptic Survey Telescope

- Optical telescope of 8.4 m diameter
- In Chile (Cerro Pachon)
- With wide field camera (3.5°) of 3.2 Gpixels
- 6 filters ugrizy
- Exposures 15s, readout 2s
- Total field monitored 20 000 deg^2
- Repeted every ~ 4 nights
- 10 years survey
- Galaxies: r_{lim}=27 after coaddition
- Weak Lensing up to z ~ 3
- SNIa up to z ~ 1
- BAO: 3.10^9 galaxies un to z ~ 3
- Galaxies et galaxy clusters
- Transients…



http://www.lsst.org/

Scintillation with LSST



Need for long series (hours)

of short exposures (15s)

from the same wide field

to precisely (< 1%) monitor faint stars (M > 20-21)

Movie mode 1 passband (the one with highest photon flux)

sub-minute -> during commissioning? deep drilling?

>> Other communities should be interested in this mode (transits, flares...)

– **Targets** (remember: detectable scintillating stars have V > 20):

- stars from the Galactic plane behind **visible nebulae**
- stars from LMC/SMC behind **invisible gas** **(blind search)**

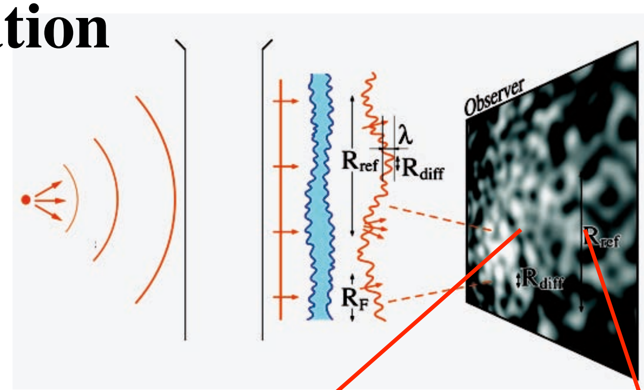
For the (very) long term future…

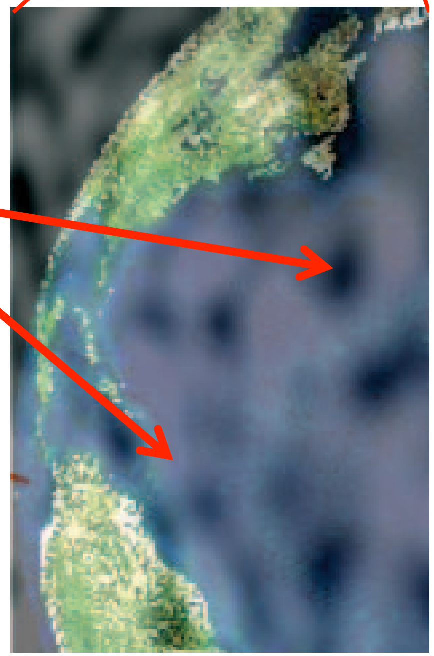
A network of distant telescopes

- Would allow to distinguish scintillation from intrinsic variabilities
- Snapshot of interferometric pattern + follow-up
  - ✓ Simultaneous R_{ref} and V_T measurements
  - ✓ => positions and dynamics of the clouds
  - ✓ Plus structuration of the clouds (inverse problem)

Conclusions - perspectives

- **Searching turbulent gas through scintillation is technically possible right now**
- **To discover scintillation effects, we need:**
  - > 2m class telescope(s)
  - Wide field camera (visible) with fast readout
  - Start with 10-100 nights with microlensing-like networks
  - Preferably **synchronized** observations through **4m** class telescopes to probe the best signature
    -> ***fluctuations are not correlated at large distance***





- Technique sensitive to clumpuscules with structuration inducing column relative density fluctuations $\geq 10^{-7}$ (10^{17}molecules/cm^2) per few 1000*km*
- Long term (halo studies): **GAIA, LSST**

Biblio : A&A 412, 105-120 (2003); A&A 525, A108 (2011); A&A 552, A93 (2013)

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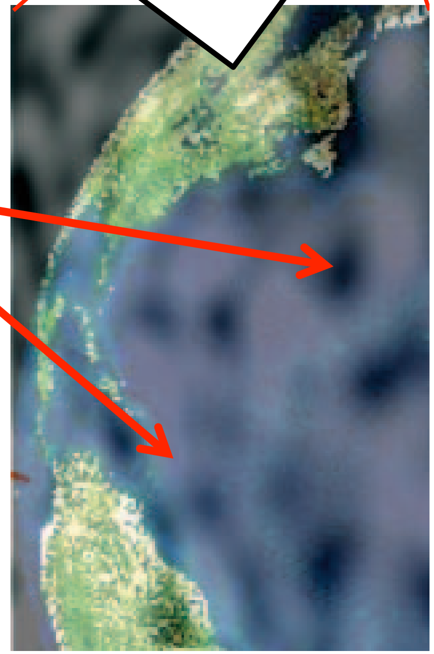

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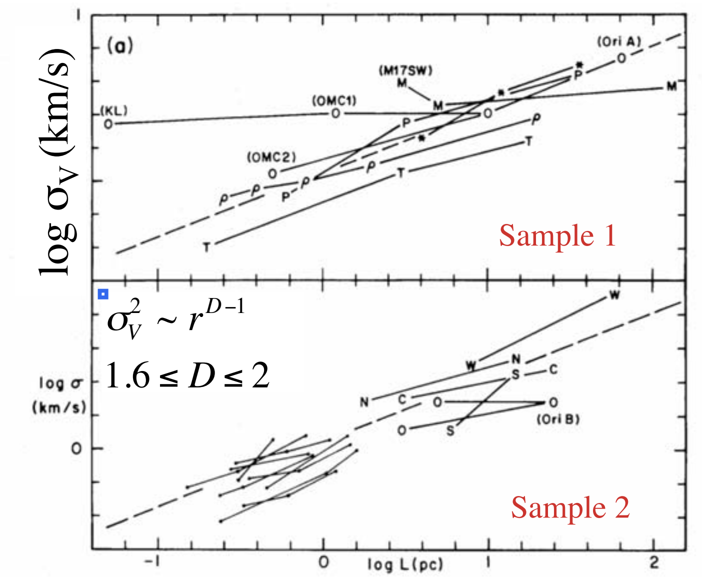
complements

Transparent molecular clouds

ISM turbulence and fractal dimension

Large cloud is gravitationally unstable,
it fragments into smaller sub-clouds and
produce a self-similar hierarchy structure.

Velocity dispersion σ$_{ς}$ ϖσ. region size *r*
in composite clouds from Milky Way
(Larson 1981)

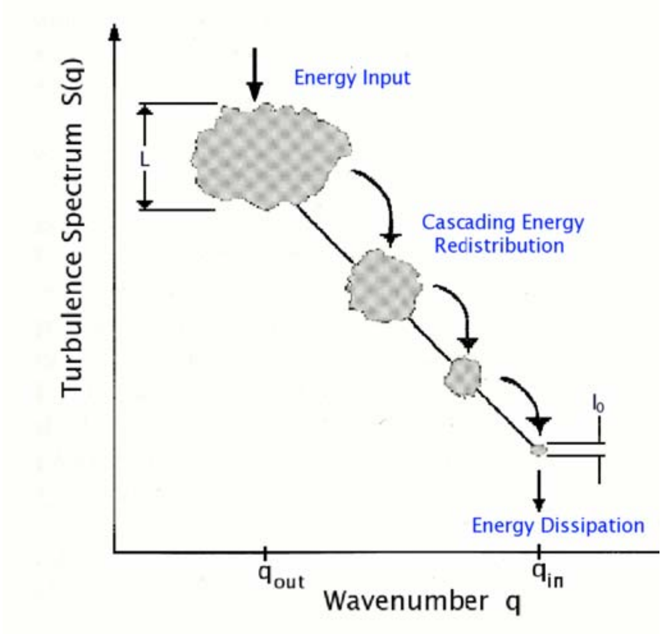


log *r* (pc)

Clouds are bound (virialized systems):

$$\sigma_V^2 \sim \frac{\text{Mass}}{r} \Rightarrow \text{Mass} \sim r^{D}$$

▸ Fractal dimension



Turbulence kinetic energy spectrum
(spatial frequencies):

$$S(q_x, q_y, q_z) \sim q^{-\beta} \qquad L_{out}^{-1} < q < L_{in}^{-1}$$

$$\beta = \frac{11}{3} \quad \text{Kolmogorov turbulence}$$

Transparent molecular clouds

Building blocks of the fractal cloud

At some scale the cooling time equals the free-fall time and the fragmentation stops. These smallest cloudlets are called *clumpuscules*.

Pfenniger & Combes Model

At $T \sim 3$ K :

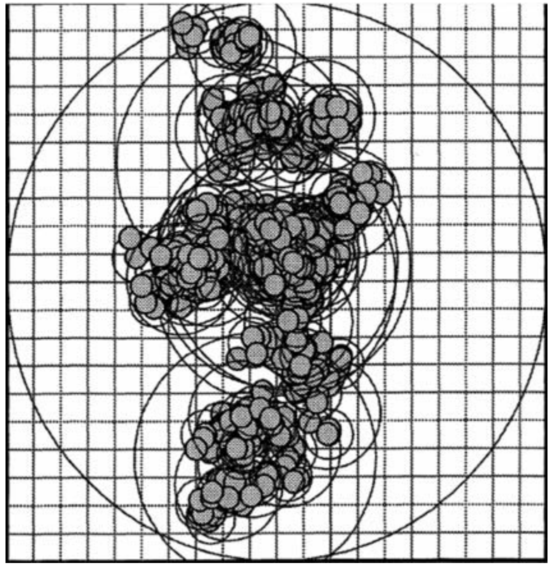
$\text{Mass} \sim 0.8 - 2.3 \times 10^{-3}\ M_{sun}$

$\text{Size} \sim 23 - 73$ A.U.

$\text{Density} \sim 0.6 - 6 \times 10^{9}\ \text{H}_2\ \text{cm}^{-3}$

$\text{Column density} \sim 0.8 - 2.7 \times 10^{24}\ \ \text{H}_2\ \text{cm}^{-2}$

$\text{Free-fall time} \sim 1.2 - 3.9 \times 10^{3}\ \text{year}$



Despite their short free-fall time, because of low temperature (T < 10 K) and the fractal structure (1.6 <D< 2)

frequent collisions:
no gravitational collapse

The turbulence energy transferred from galactic rotation to the hierarchy takes ~ 3.7 Gyr to dissipate through the structure.