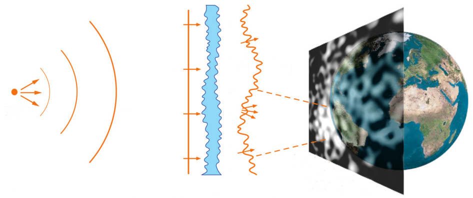


Recherche de matière baryonique cachée par effet de scintillation

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
Habibi F. *et al.* (2012, A&A accepted, on arXiv soon):
Simulation of Optical Interstellar Scintillation

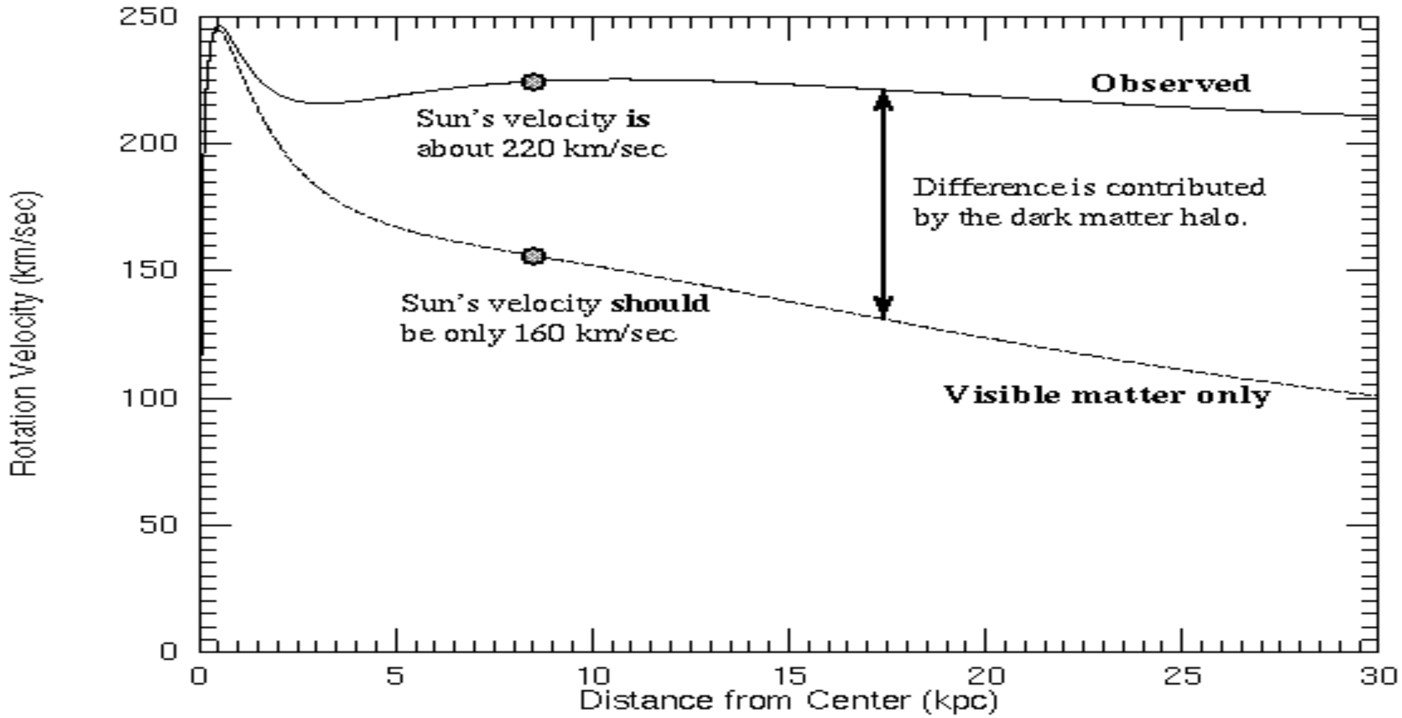
Marc MONIEZ, IN2P3, CNRS

Clermont Ferrand 7 décembre 2012

Une présentation pas facile...

- les cosmologistes et physiciens des particules sont familiers avec la question de la matière cachée
- les astronomes savent ce qu'est un objet variable et une courbe de lumière
- Les radio-astronomes connaissent le processus de scintillation
- Les mathématiciens maîtrisent les objets fractals
- Les opticiens connaissent la diffraction de Fresnel

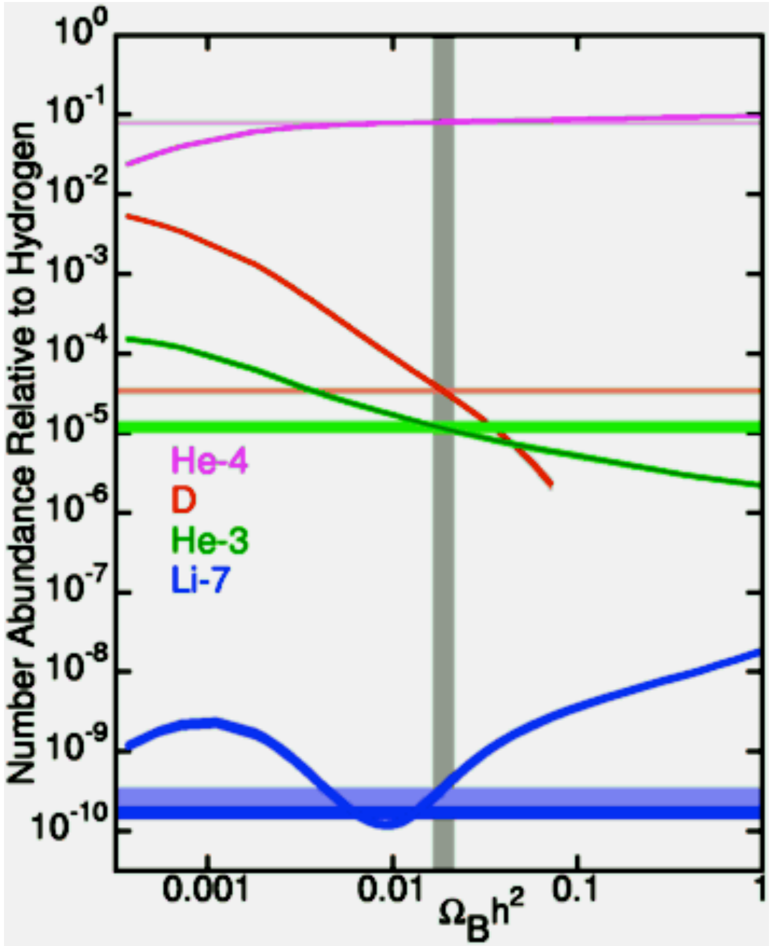
La courbe de rotation de la Voie Lactée
une preuve de l'existence de matière cachée



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.**

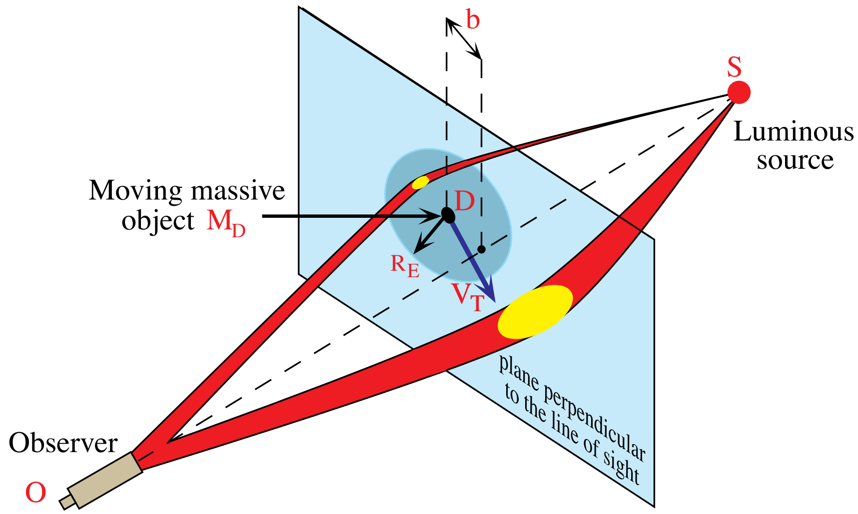
Baryons cachés

- $\mathbf{\Omega_{visible} = 0.006}$ (unité Ω_c)
- Nucléosynthèse primordiale=> $\mathbf{\Omega_b = 0.04}$
- Résultats de WMAP: $\Omega_b h^2 = 0.0224$ => $\mathbf{\Omega_b = 0.044}$
- Manque un facteur 8: Coïncide avec facteur de masse manquante Galactique
- Essentiellement formé de H + 25% He en masse

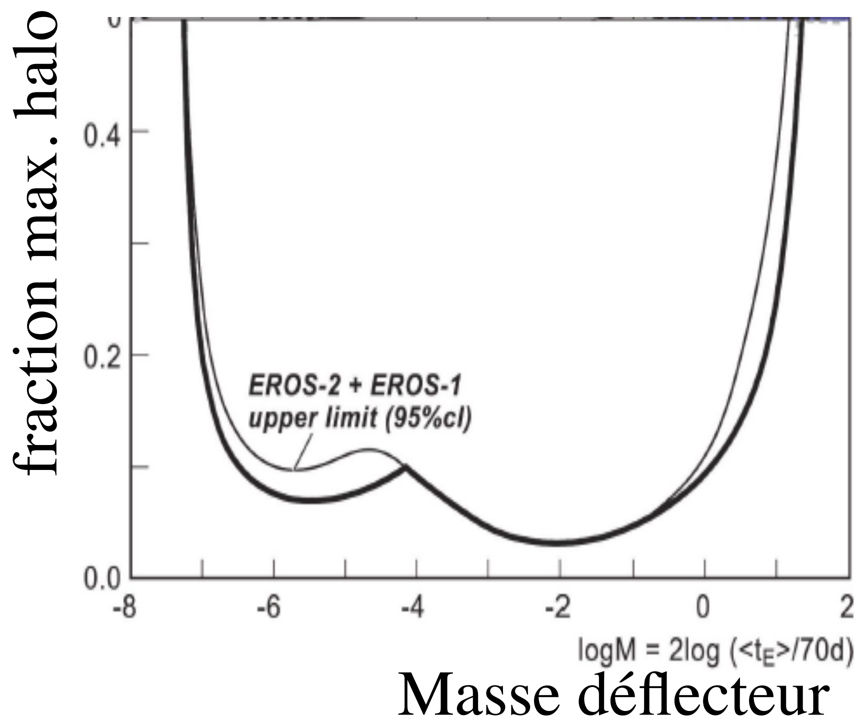


Comment sont structurés ces baryons?

- Pas des MACHOs
  => résultats EROS



GRAVITATIONAL MICROLENSING EFFECT



Comment sont structurés ces baryons?

- **Objets compacts? ===> NON (microlensing)**
- **Gaz?**
  - H atomique bien connu (en principe: mesures à 21cm)
  - Dernière contribution mal connue: $\mathbf{H_2}$ moléculaire (+25% He)
    - Froid (**10K**) => pas d'émission. Milieu très transparent.
    - Structure fractale : couvre ~**1%** du ciel.
      Clumpuscules ~10 AU (Pfenniger & Combes 1994)
    - Dans le **disque épais** ou/et dans le **halo**
    - **Longévité**: stabilité thermique grâce à un cœur de particules d'hydrogène liquide/solide
    - **Detection de nuages moléculaires** avec des quasars (Jenkins et al. 2003, Richter et al. 2003) et **indication de structure fractale** à partir de lignes d'émission de CO dans le plan galactique (Heithausen, 2004).

La contribution de H_2 est difficile à estimer

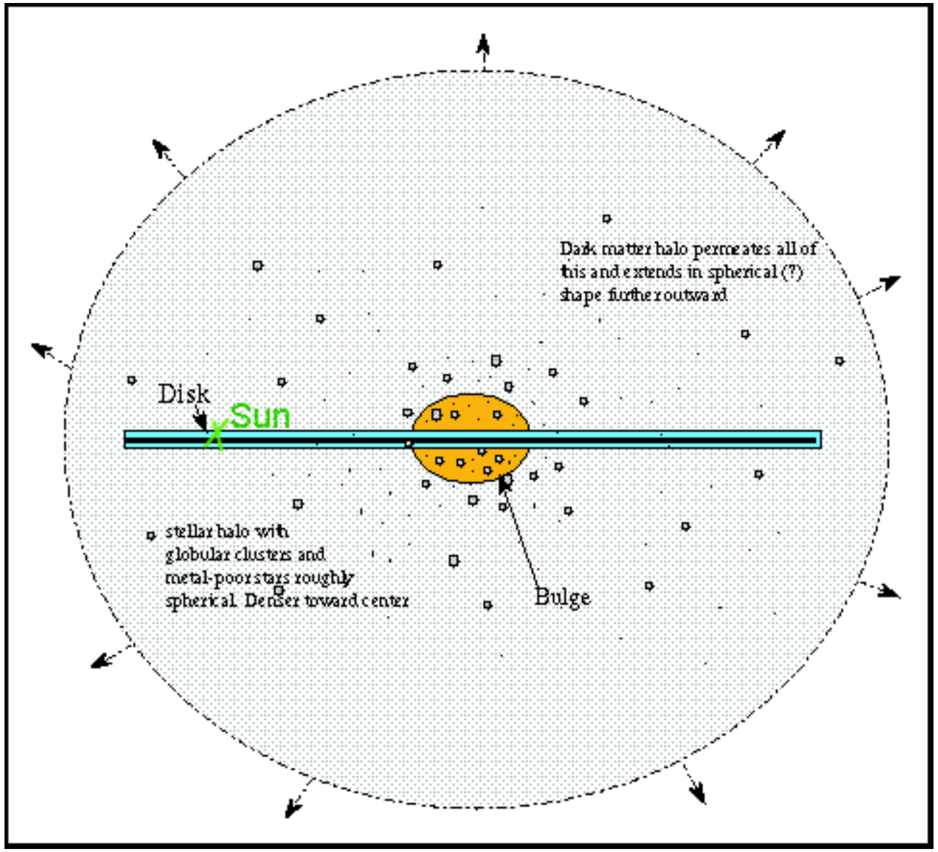
- H_2 molécule symétrique => transitions dipolaires électriques interdites
  - ✓Milieu froid n'émet pas
  - ✓Pas d'absorption à λ>110 nm

  } *Pas de processus résonant*

- H_2 est ordinairement estimé à partir de CO ou de la poussière. Mais ces estimations utilisent des hypothèses sur la métallicité…

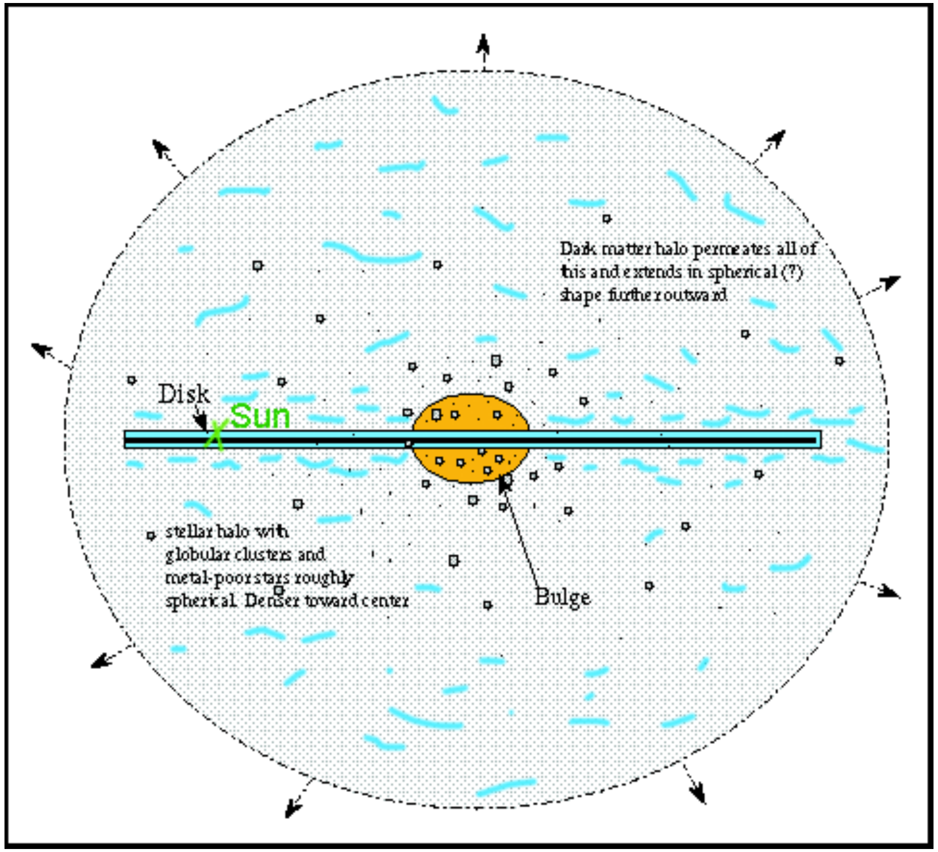
Ordres de grandeur

- Supposant un halo sphérique isotherme



Ordres de grandeur

- Supposant un halo sphérique isotherme
- Fait de nuages H_2
- Question: densité de colonne vers le LMC?

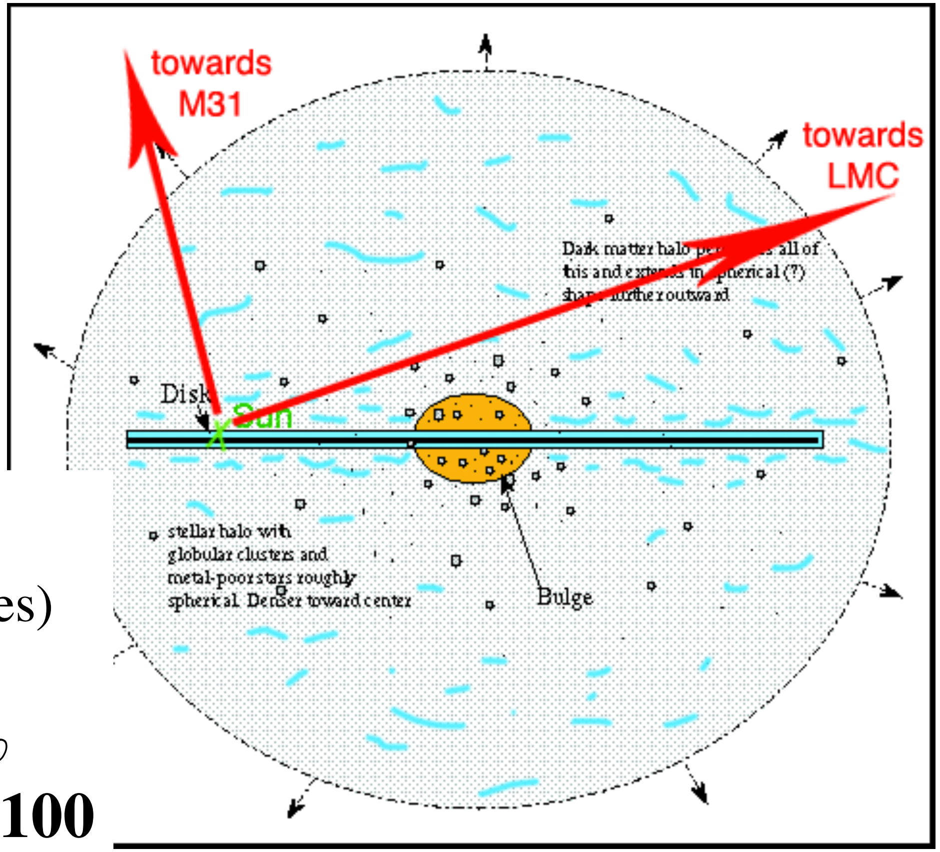


Ordres de grandeur

- Supposant un halo sphérique isotherme
- Fait de nuages H_2
- Densité de colonne Moyenne vers LMC

▪**250g/m²** <=> colonne de **3m** de H_2 (cond. normales)

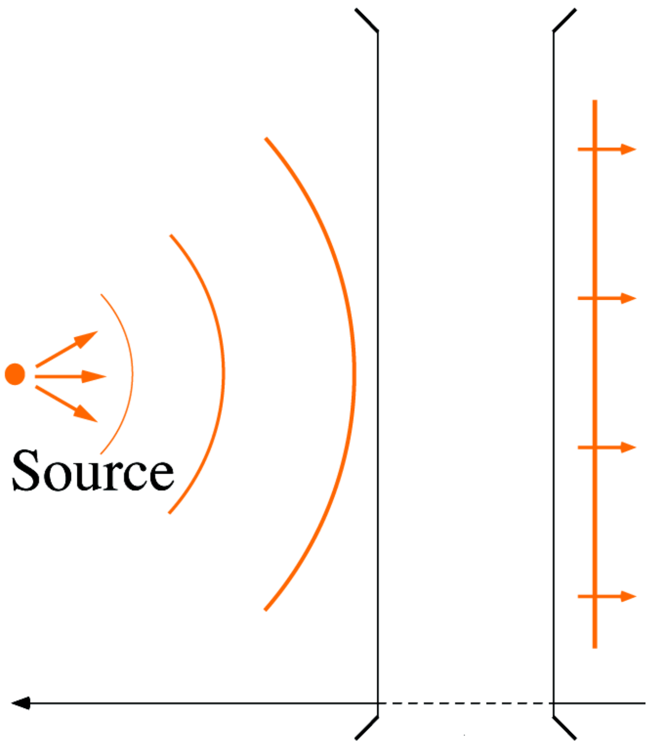
▪Les nuages couvrent 1% du ciel=>concentration **x100**



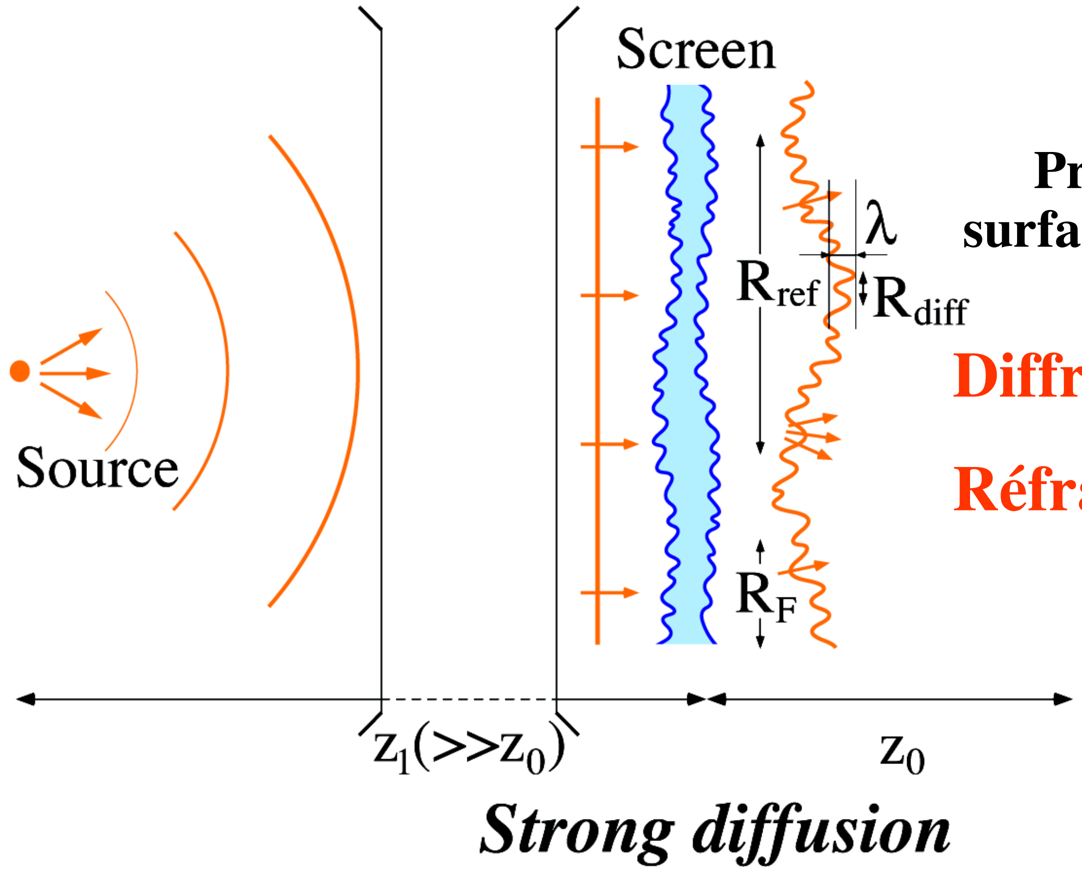
These clouds refract light

- 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} ($<1/\lambda^3$)
- Extra optical path due to H_2 medium
  - On average ~800λ @ λ=500nm
    => varies from **0** (99% of the sky) to **80,000λ** (1%)
- If the medium has column density fluctuations (turbulences) **of order of a few 10^{-6}** then wavefront distorsions may be detectable

Scintillation due à un écran fortement diffusant



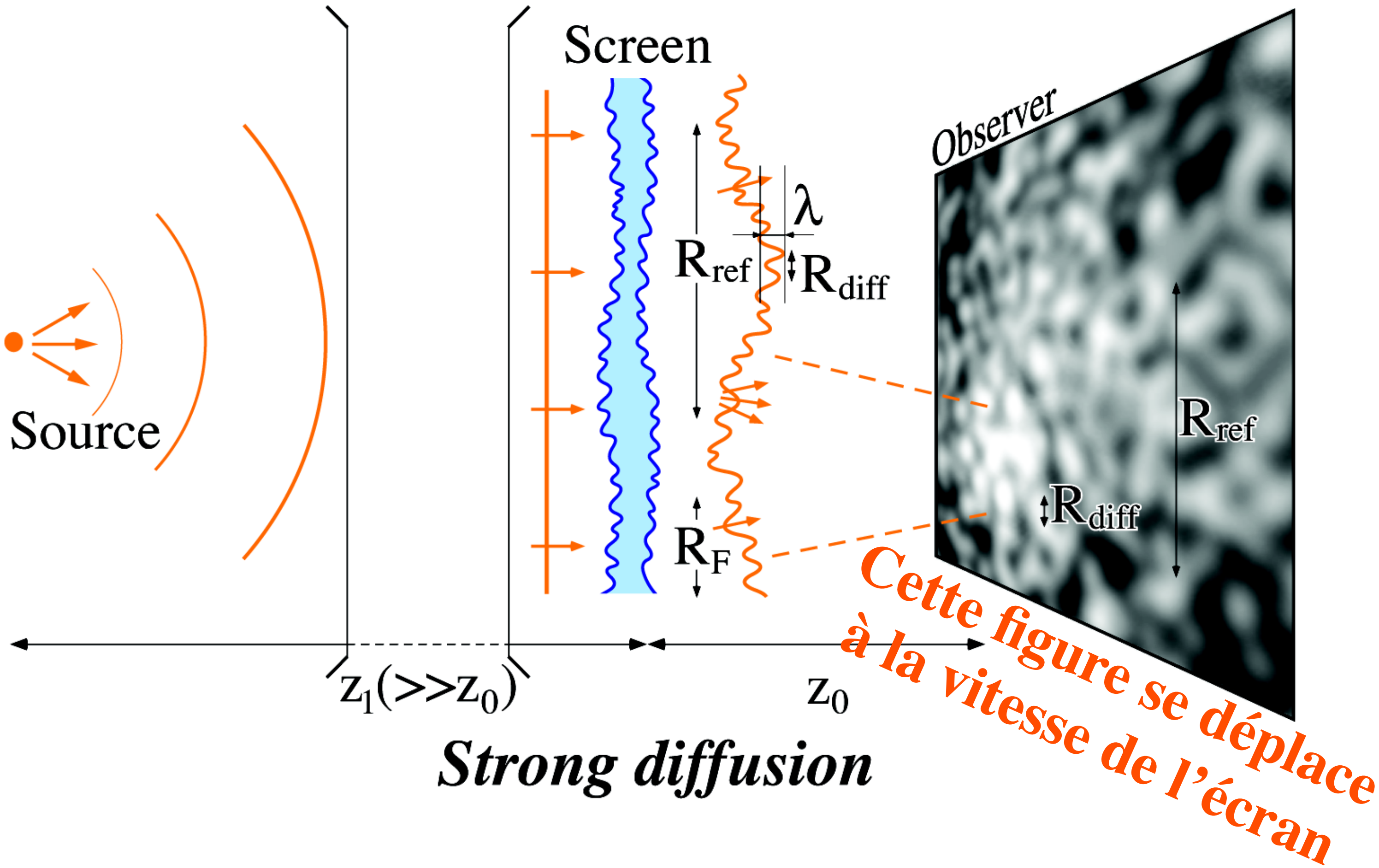
Scintillation due à un écran fortement diffusant



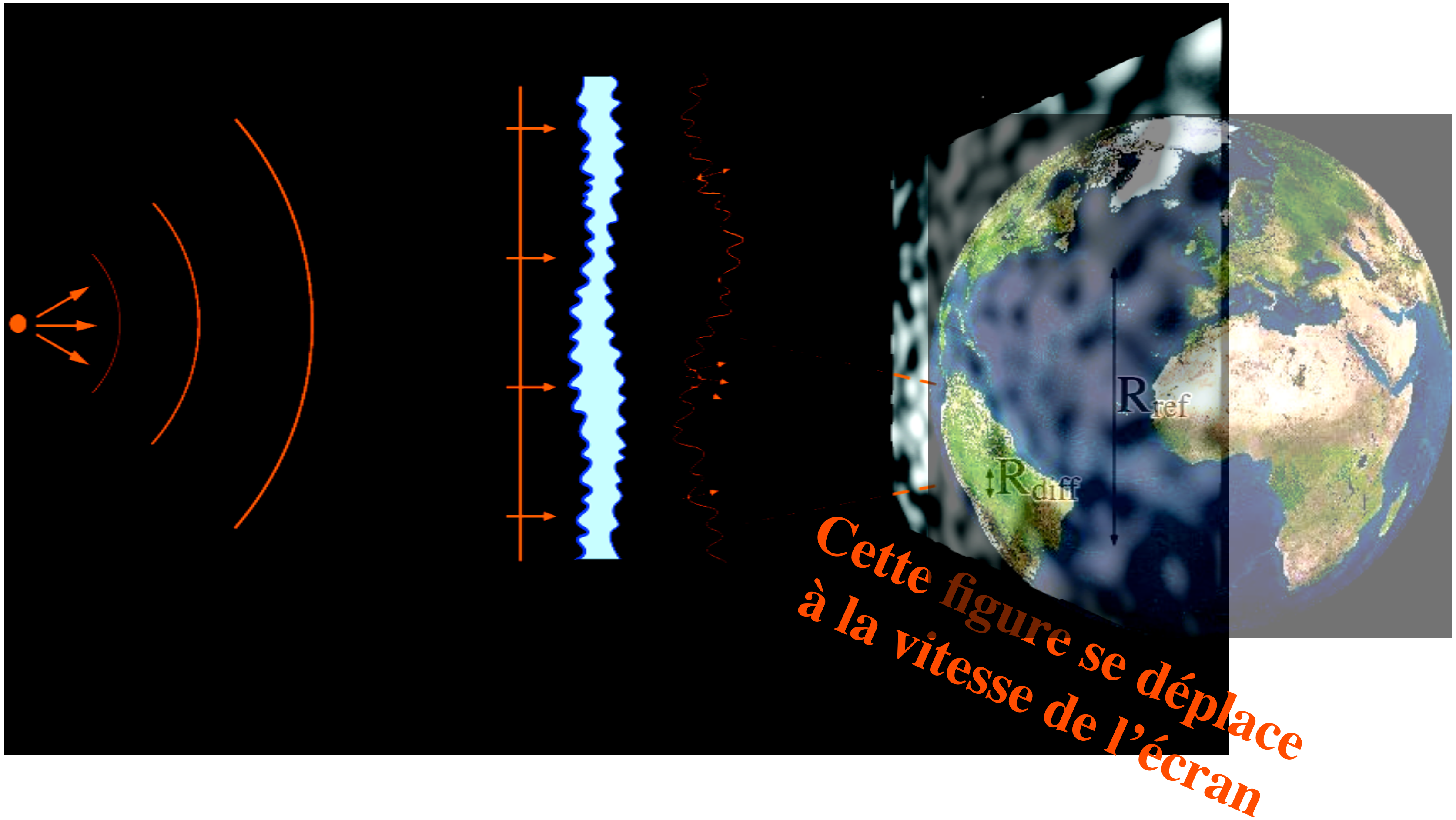
Propagation d'une surface d'onde distordue décrite par :

Diffraction de Fresnel
+
Réfraction « globale »

Scintillation due à un écran fortement diffusant

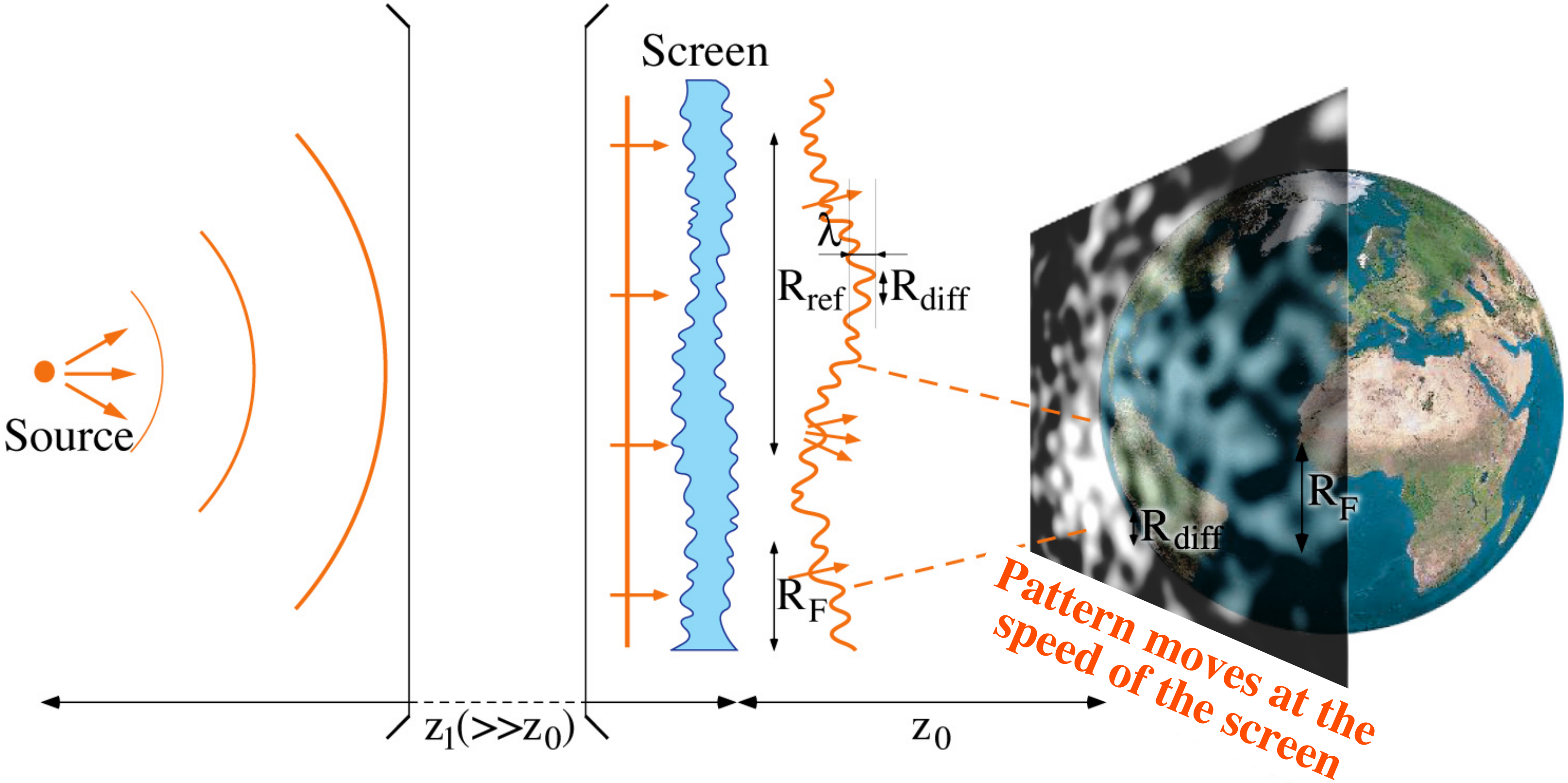


Scintillation due à un écran fortement diffusant



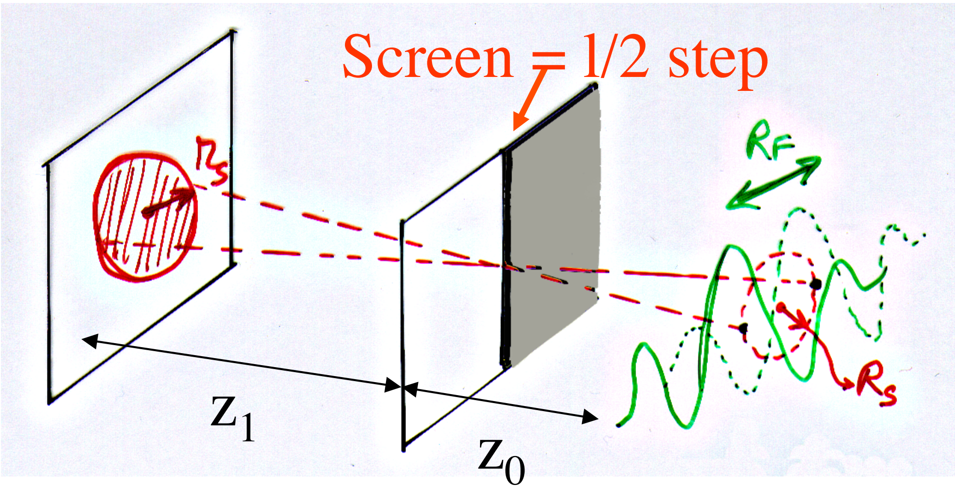
Scintillation through a diffusive screen

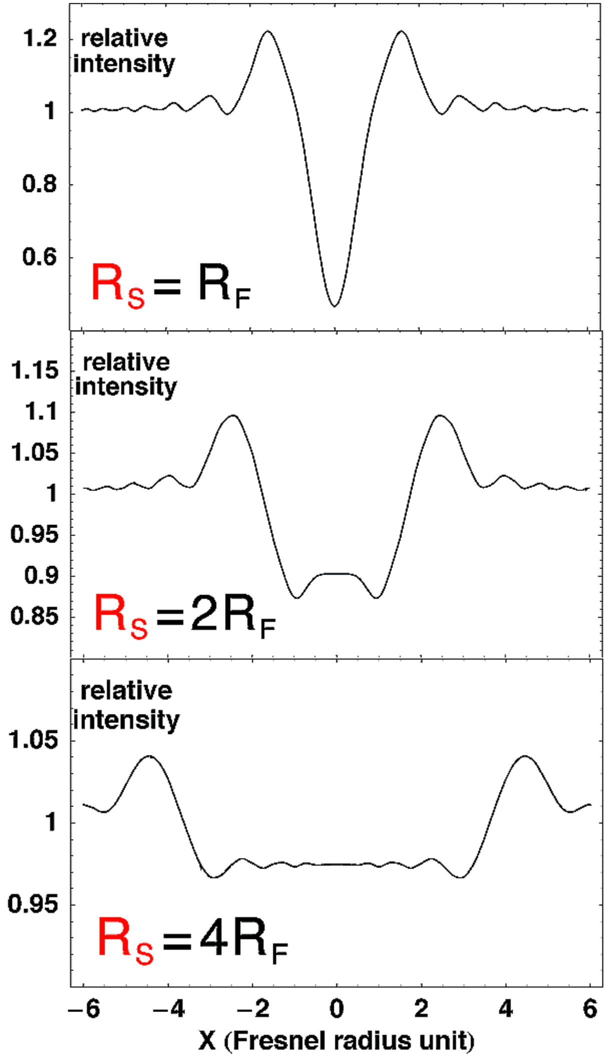
After refraction, propagation of distorted wave surface is driven by Fresnel diffraction that produces speckle



Contrast is severely limited by the source size

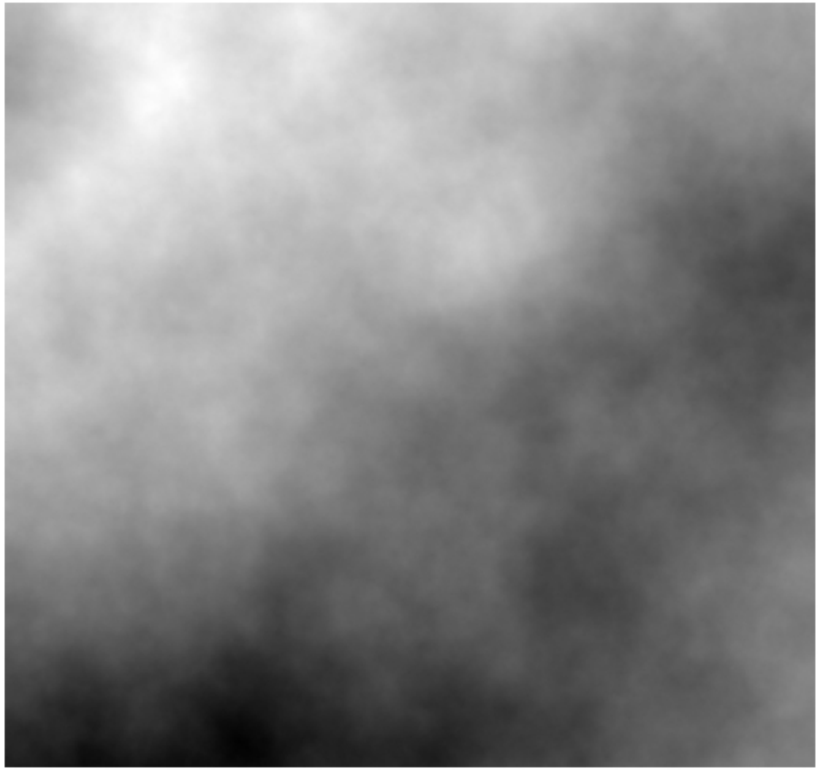
=> spatial coherence

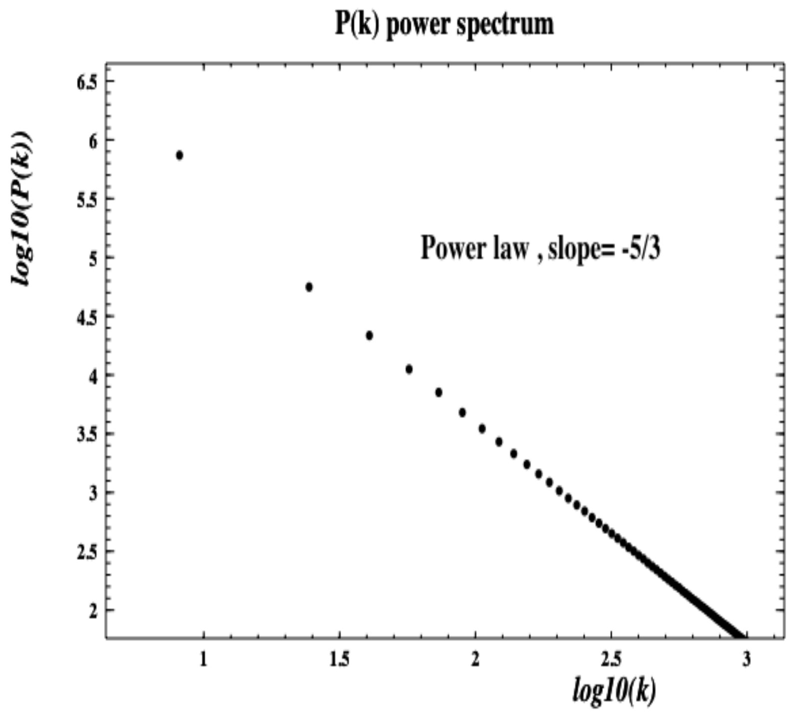




- Depression width ~ R_S
  => Info on source size
- Contrast ~ R_F/ R_S
- Also depends on $\Delta\lambda$ (time coherence), but not critically: $\Delta\lambda/\lambda<0.1 \Rightarrow \Delta R_F/R_F<0.05$

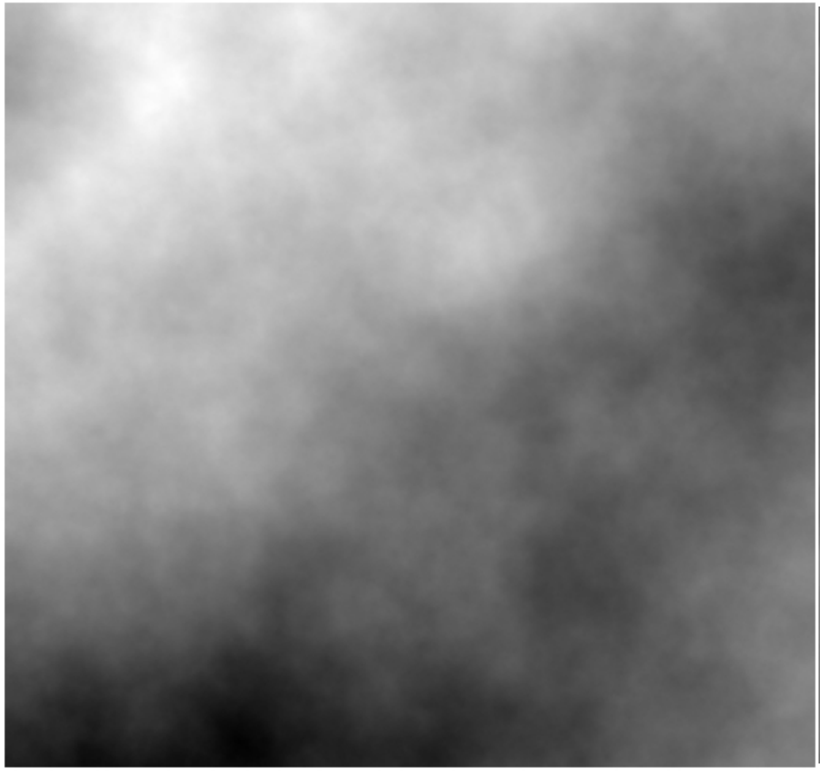
Simulation: Fractal phase screen



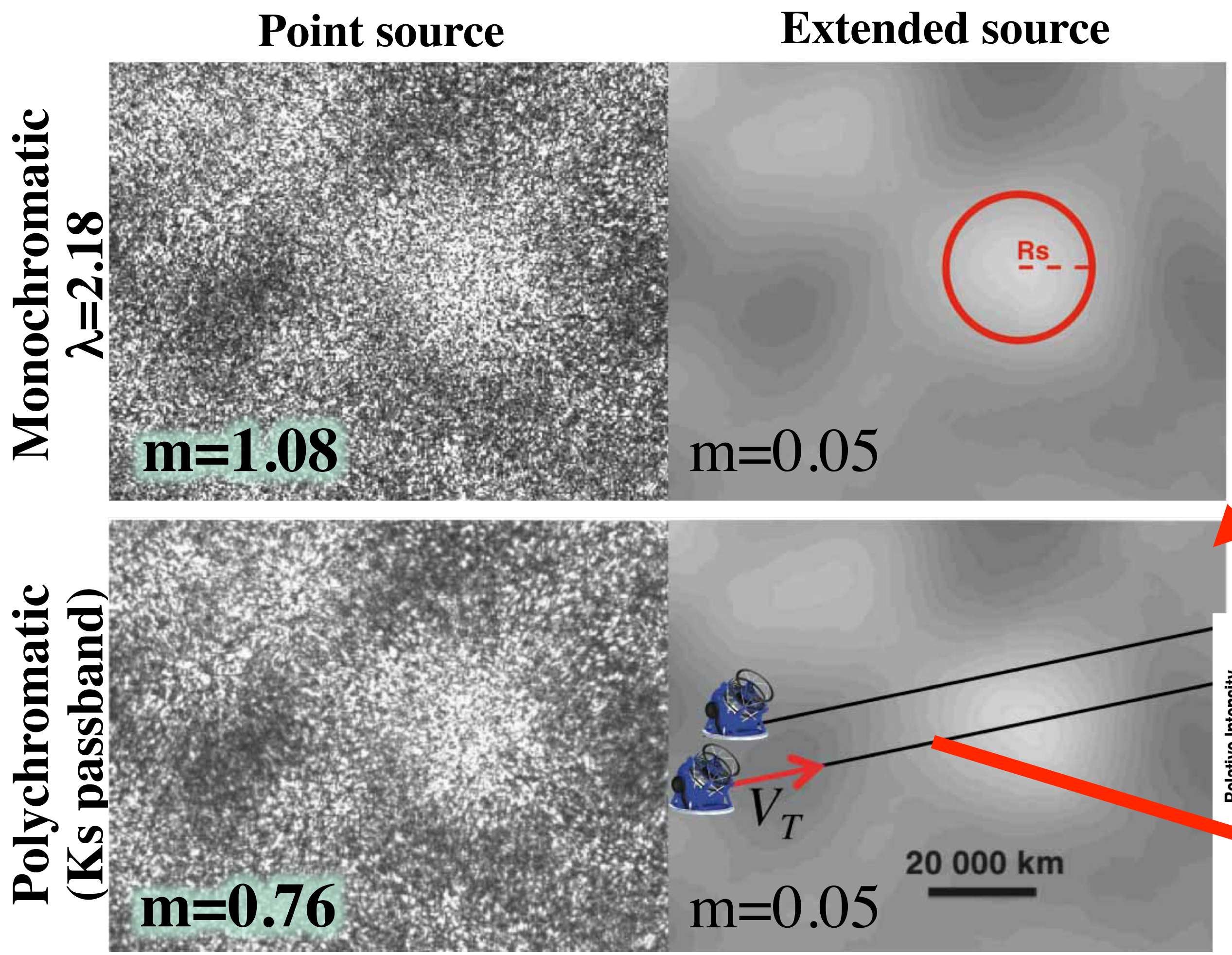


- Kolmogorov turbulence -> realistic
- Other power laws considered in paper on simulation (*in press*)

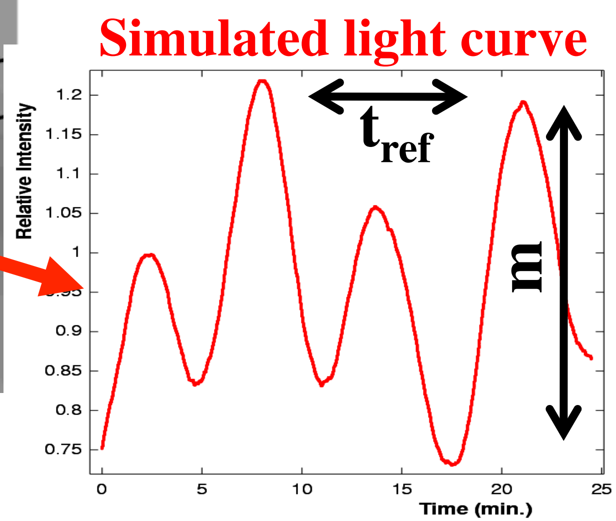
Simulation: Fractal phase screen



Simulation for a polychromatic extended source

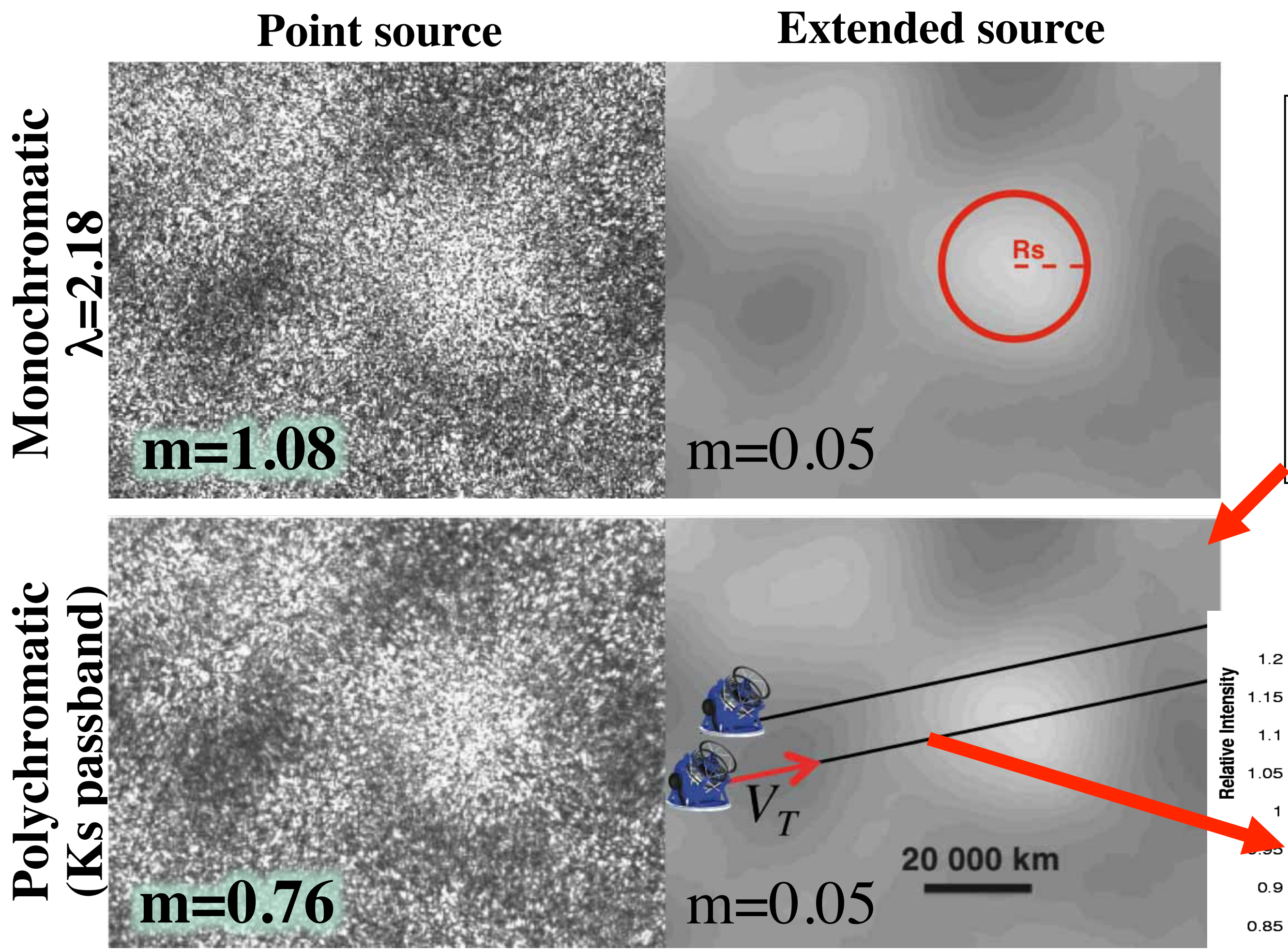


Illumination in **Ks** by a **K0V** star@8kpc (m_V=20.4) through a cloud@160pc (B68) with R_{diff}=150km

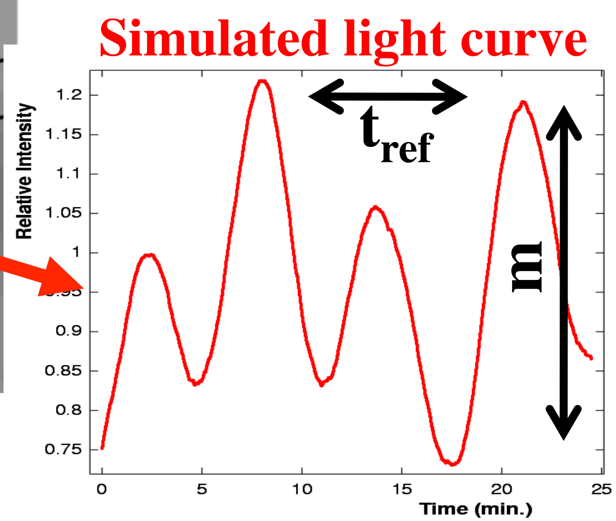


m = σ_I/I = modulation index

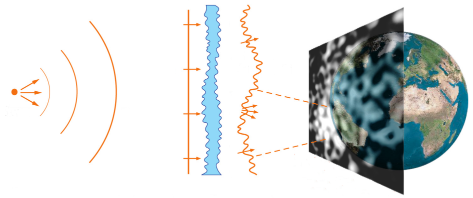
Simulation for a polychromatic extended source



Illumination in **Ks** by a bright **main sequence** star@8kpc (m_V~14) through a cloud@160pc (B68) with R_{diff}=150km



$m = \sigma_I / I$ = modulation index



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

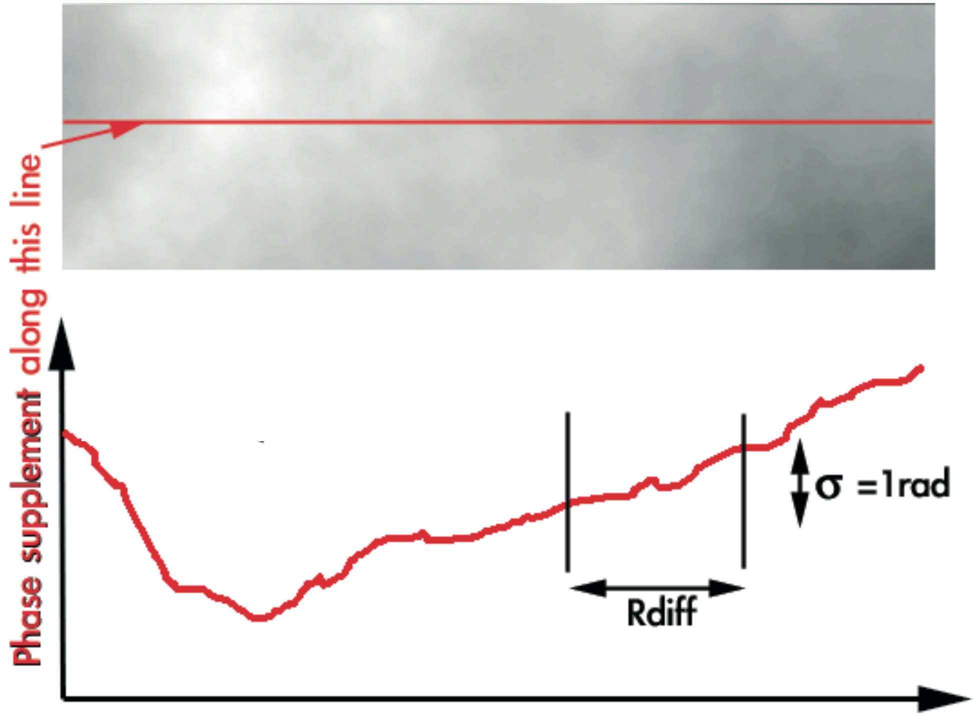
R_{diff} : Statistical characterization of a stochastic screen

R_{diff} = size of domain where

$\Delta\phi$ = 1 radian

or equivalently (@ λ = 500 nm)

ΔN_l = 1.8 x10^{18} molecules/cm^2

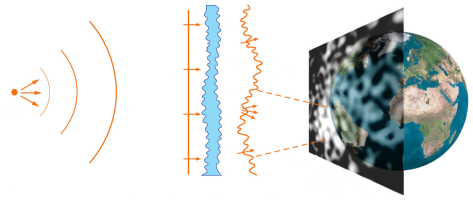


- This corresponds to

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

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

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

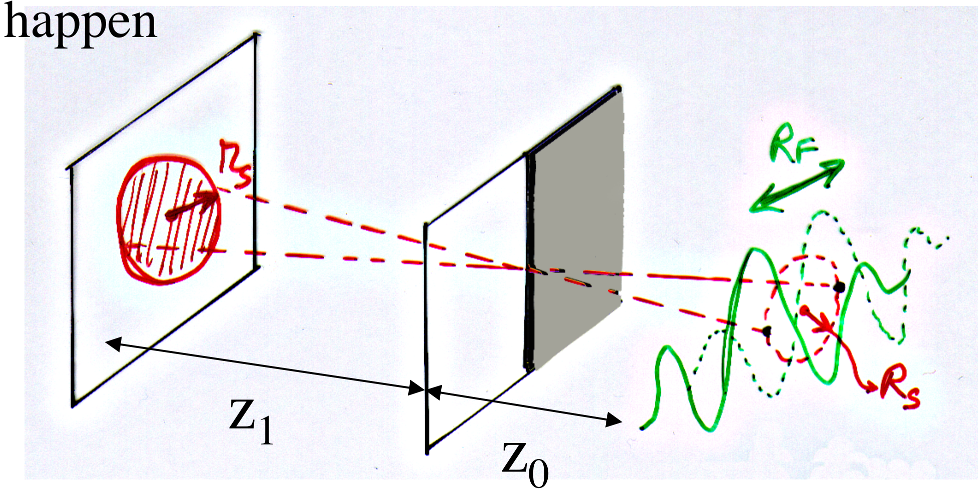


Distance scales

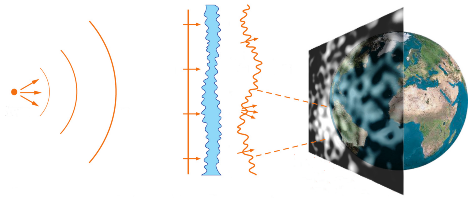
4 distance scales characterize the speckle pattern

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



If R_{ref} is the largest scale :

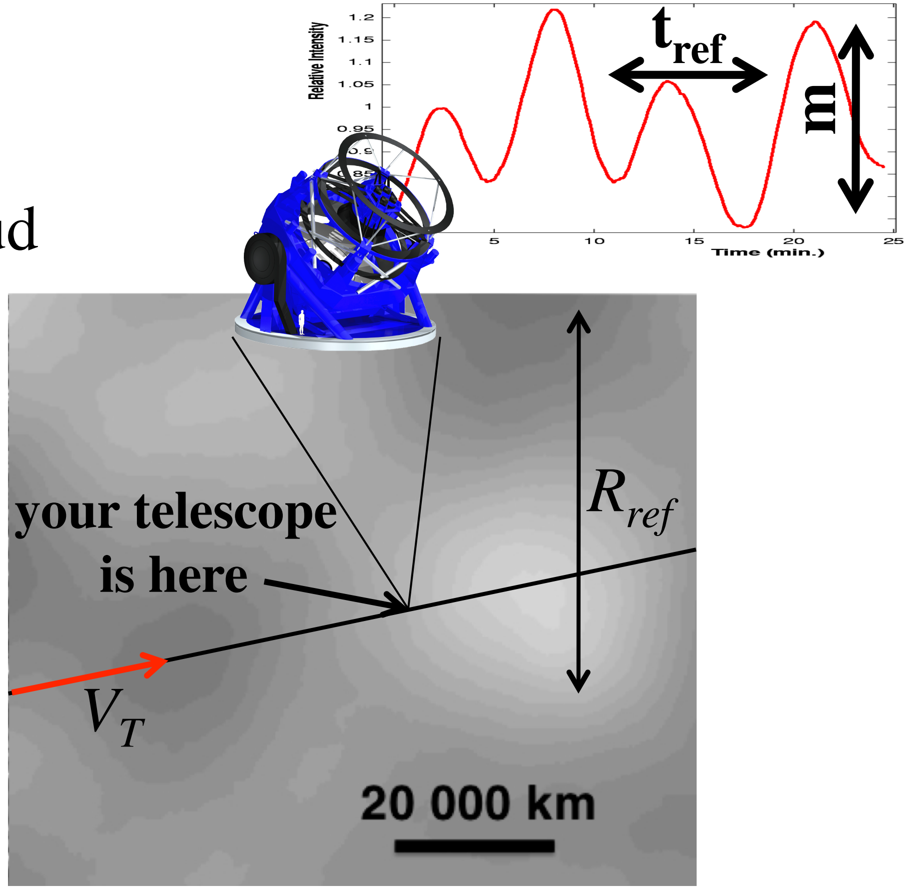
$$t_{ref}(\lambda) = \frac{R_{ref}}{V_T} \sim 5.2\,minutes \left[\frac{\lambda}{1\mu m}\right]\left[\frac{z_0}{1\,kpc}\right]\left[\frac{R_{diff}}{1000\,km}\right]^{-1}\left[\frac{V_T}{100\,km/s}\right]^{-1}$$

Where

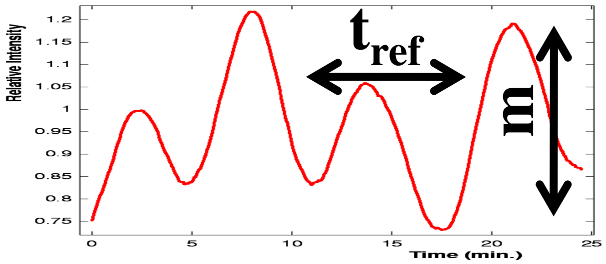
z_0 is the distance to the cloud

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

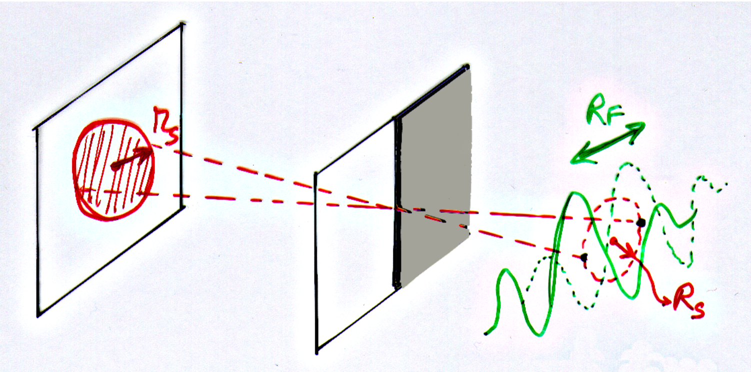
-> V_T is also the speed of the illumination pattern in front of the telescope



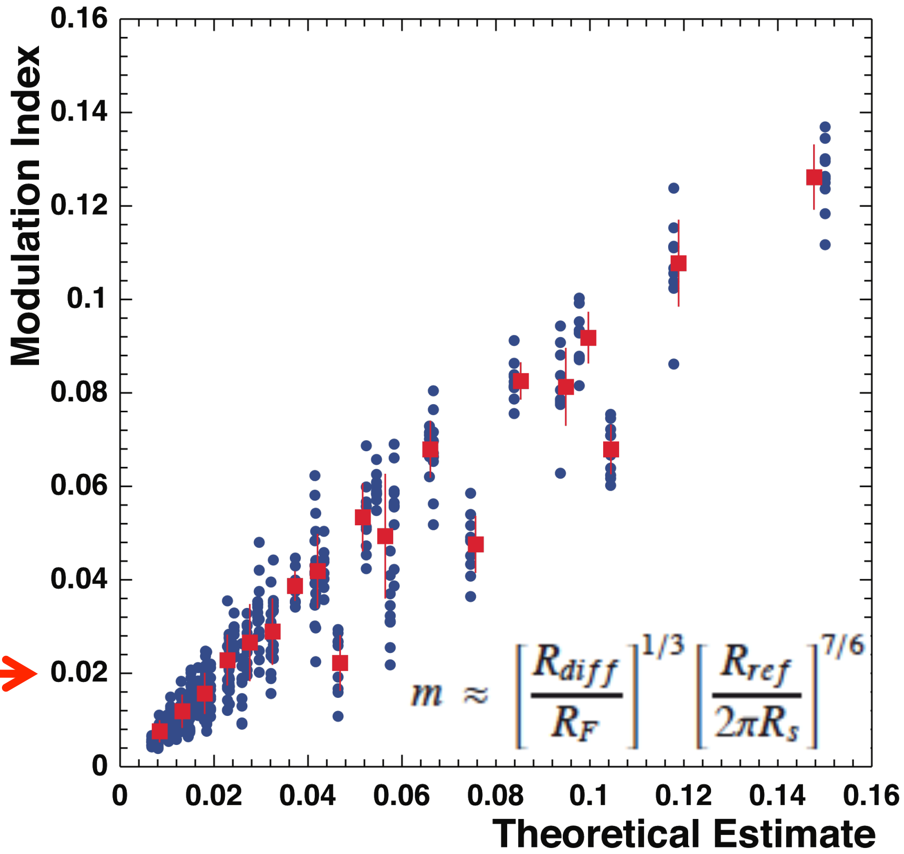
Modulation Index



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

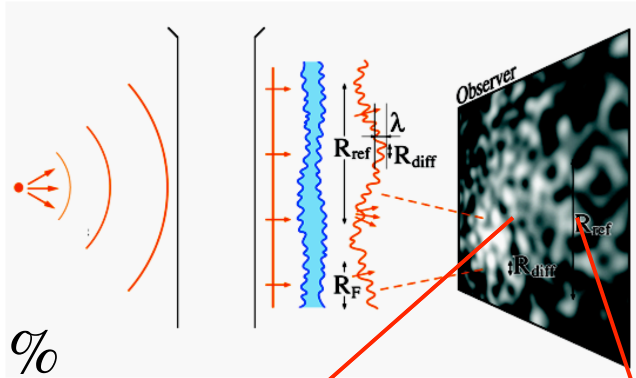


Scintillation@λ = 1 μm of Sun@10kpc (V~20) through a cloud@160pc with R_{diff}=1000km

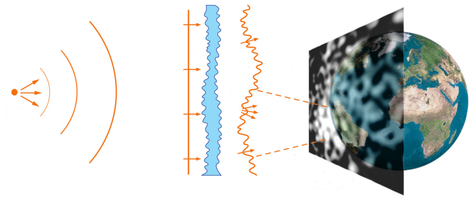


Signature of scintillation

- **Stochastic light-curve** (not random)
  - Autocorrelation (power spectrum)
  - Characteristic time (few minutes)
  - Modulation index can be as high as a few %
    - decreases with 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**

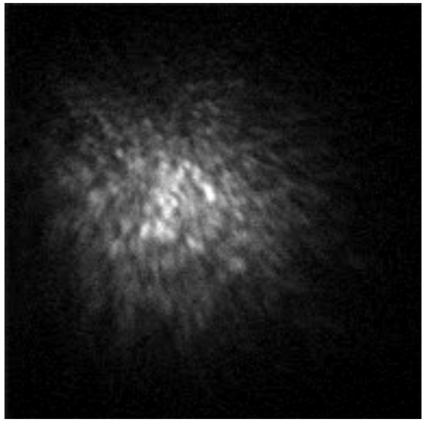


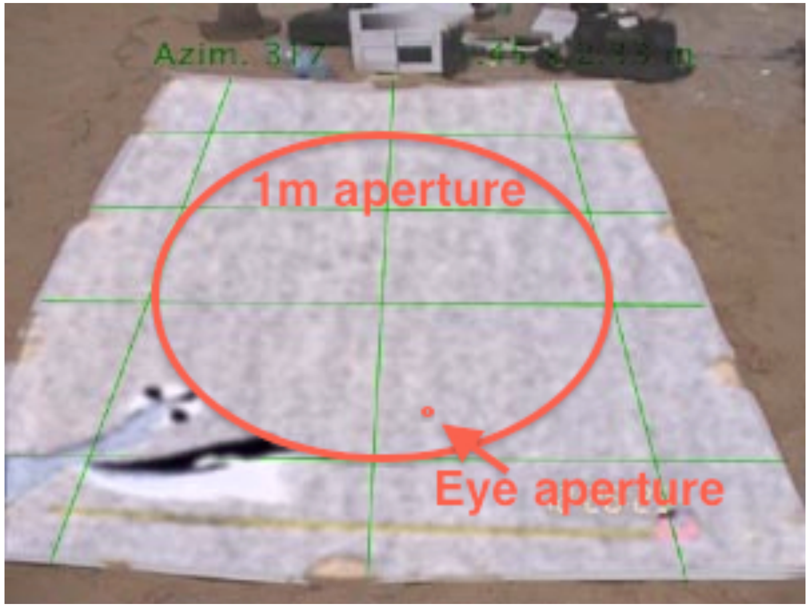
Fore and backgrounds

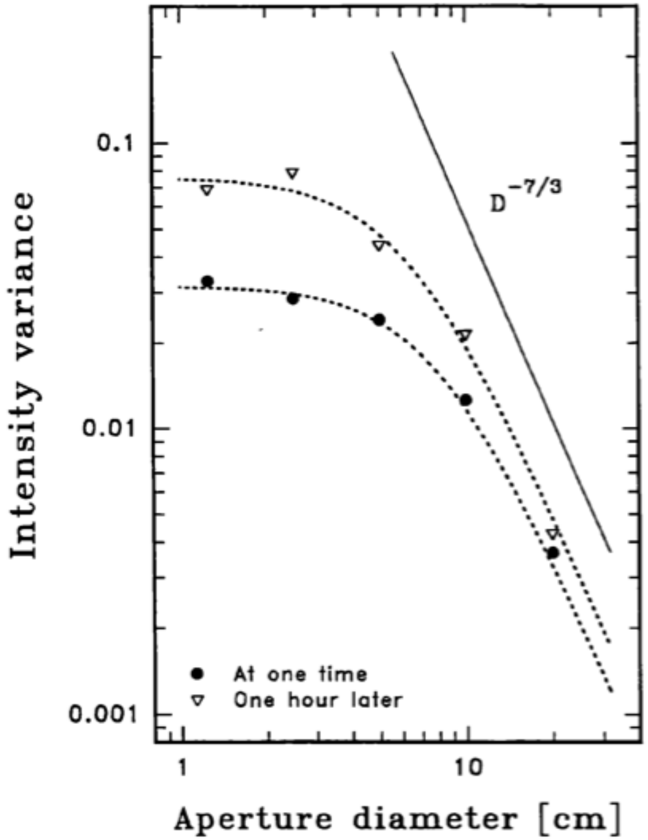
- **High altitude cirruses**
  - Would induce easy-to-detect **collective** effects on neighbour stars. But Scintillation by a 10AU object affects only one star.
- **« nearby » gas (at ~ 10pc)**
  - Scintillation would also occur on the biggest stars
- **Intrinsic variability**
  - Rare at this time 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 »



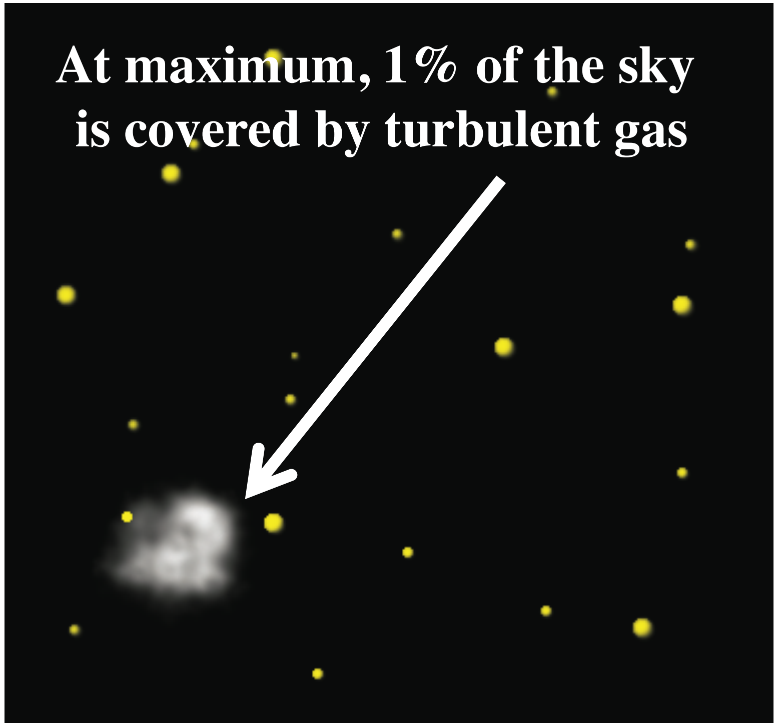




Aperture dependence of the intensity variance (2 series of measurements)

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 (10 AU clumpuscules)
- **5% modulation@500nm** => $r_s < r_{A5}$ ($10^5/deg^2$)

✓ Smaller than **A5** type in LMC => **$M_V \sim 20.5$**

✓ Characteristic time ~ few min. => **sub-minute exposures**

✓ Photometric precision required **~1%**

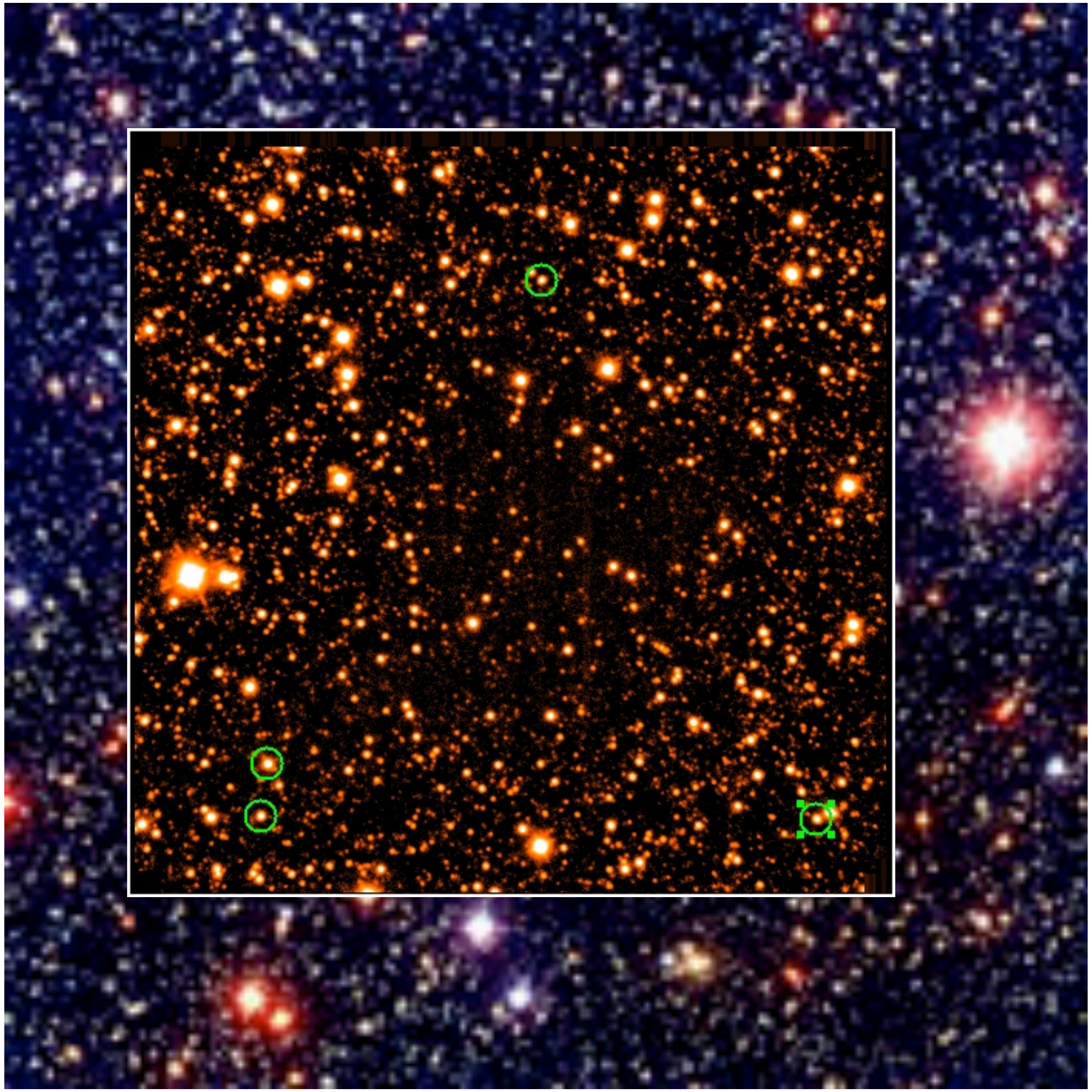
Telescope > 2 meters

✓ Dead-time < few sec. => **Fast readout Camera**

✓ **B** and **R** partially correlated => **2 cameras desirable**

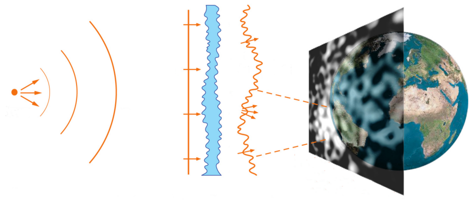
✓ Optical depth probably small => **Wide field**

Test towards Bok globule B68 and SMC

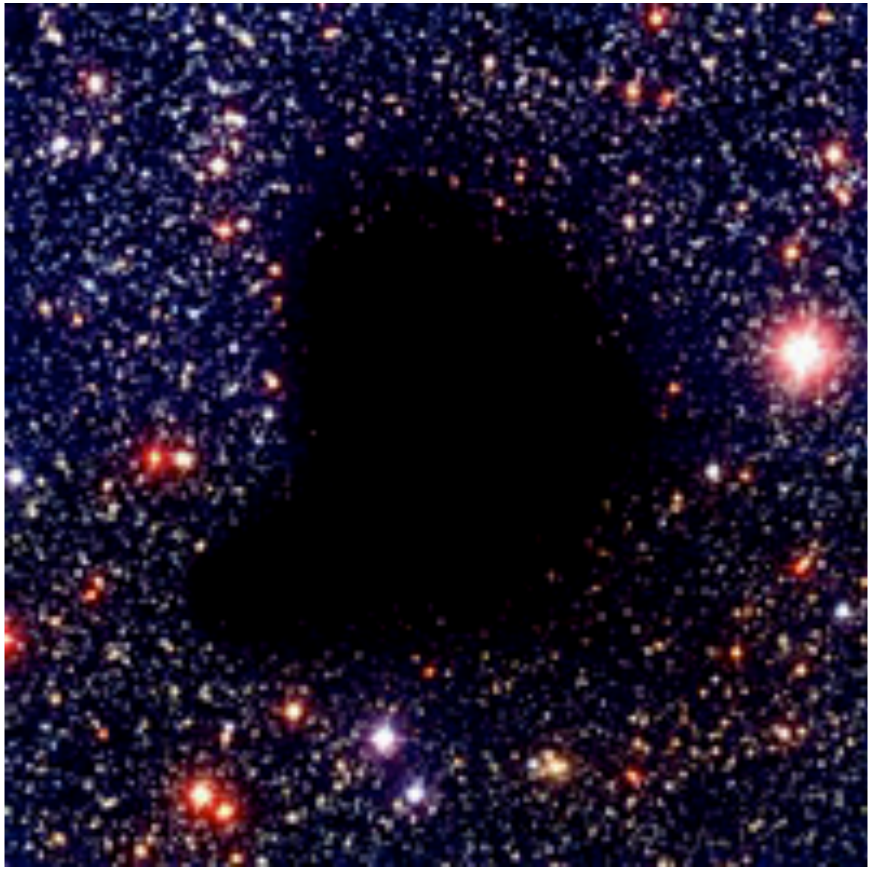


- **ESO-NTT telescope**
  - *3.6m*
  - *2 nights*
- **Infrared**
  - *to see stars through gas*
  - *allows short exposures with small dead-time*
- **Search for fluctating stars**
  - *other than known artifacts*

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

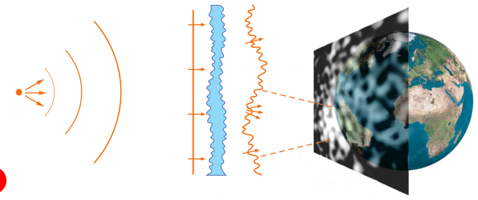


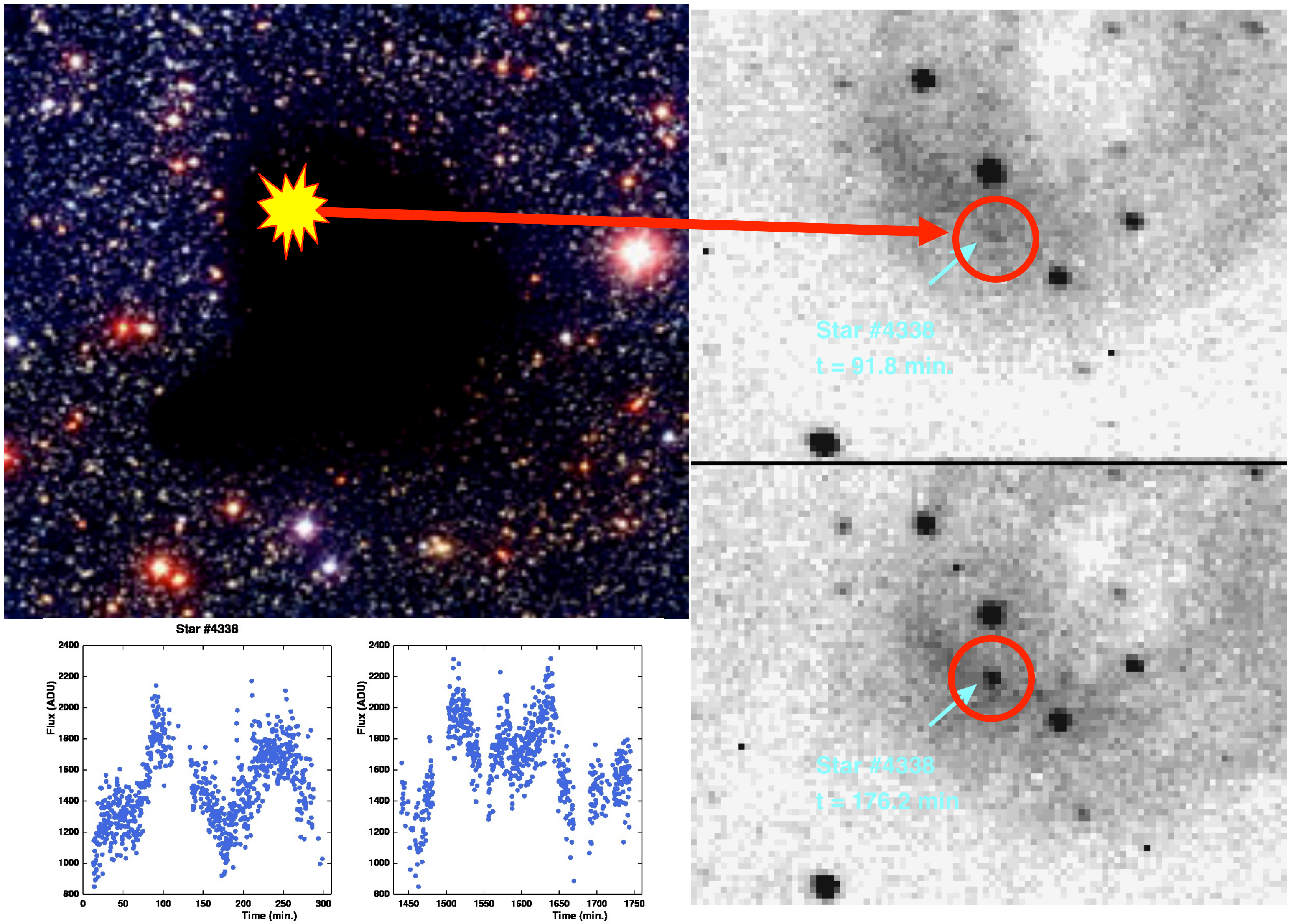
Mainly a test for background estimates and feasibility



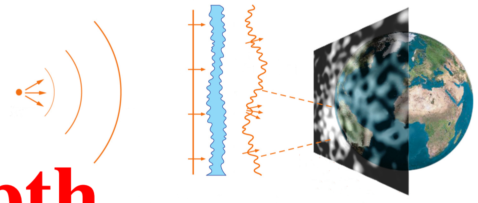
- **B68 (& cb131, Circinus nebula)**
  - **dust + existing gas at $z_0 \sim 80$ pc**
  - Column density $Nl \sim 2.6 \times 10^{22} cm^{-2}$
  - Signal if $\Delta N_l / N_l \sim 10^{-4}$ per 1000 km
  - **1114 stars monitored at $z_1 \sim 7$ kpc**
  - **50% are behind the nebula, 50% make a control sample**
  - **2000 exposures of 10s in 2 nights**
- **SMC**
  - **blind search for invisible bas**
  - **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?





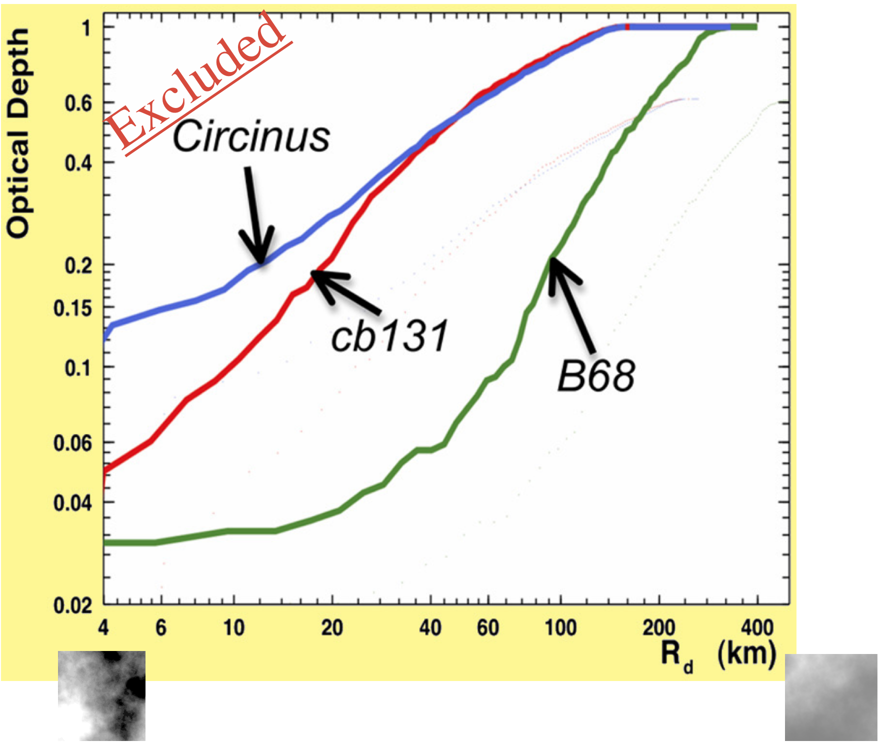
Results from faisibility studies: upper limits on scintillation optical depth



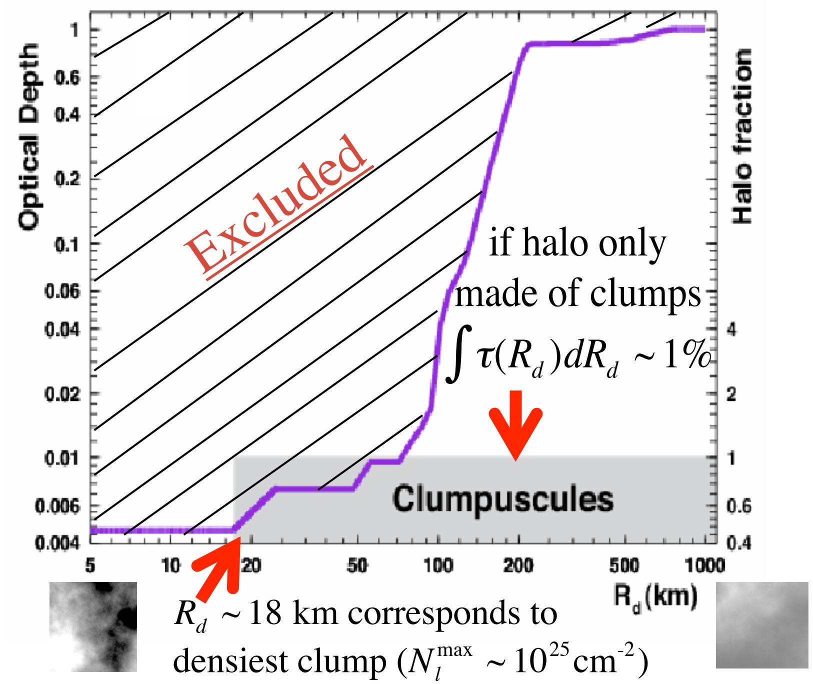
First fundamental result : **no overwhelming background**

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

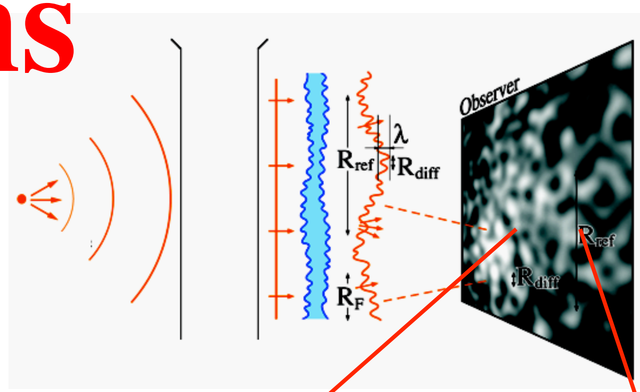
stars behind visible gas (B68 and other nebulae)



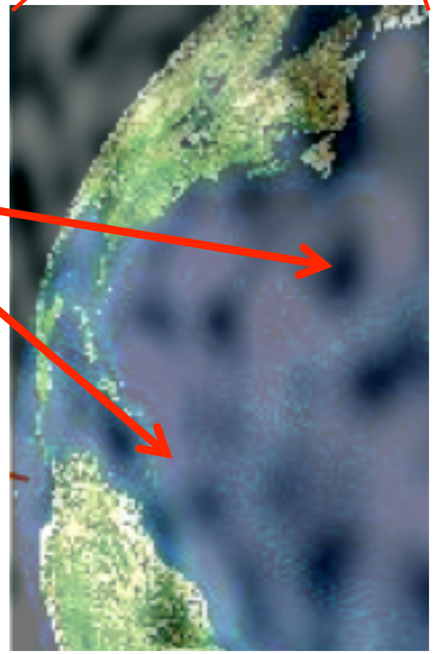
stars behind invisible gas (SMC)



short term plans

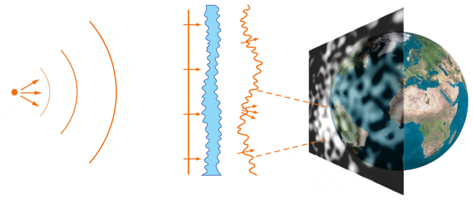


synchronized observations
through > **4m** class telescopes
to probe the strongest signature
-> ***fluctuations are not correlated at large distance***



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

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)**

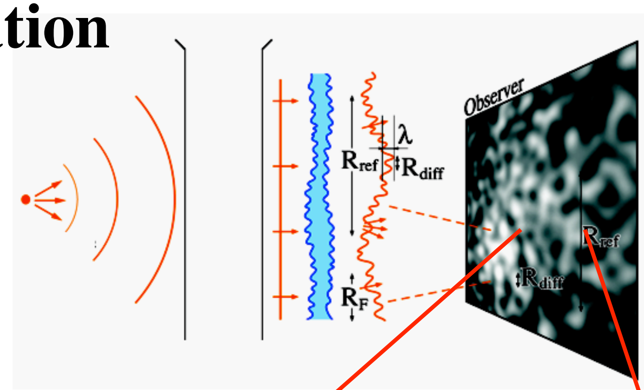
For the long term future…

A network of distant telescopes

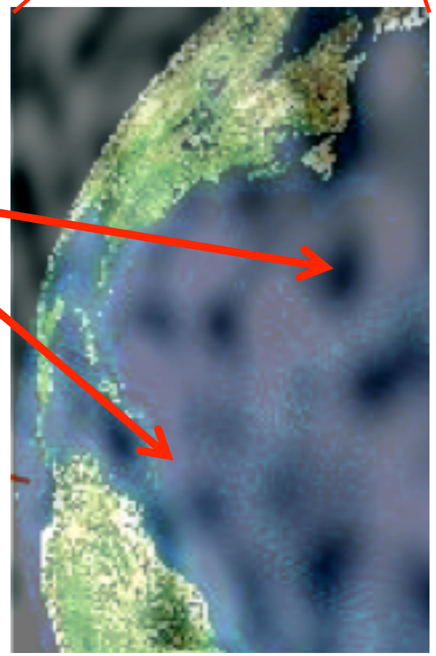
- Would allow to decorrelate scintillation from interstellar clouds and atmospheric effects
- Snapshot of interferometric pattern + follow-up
  - ✓ Simultaneous R_{diff} and V_T measurements
  - ✓ => positions and dynamics of the clouds
  - ✓ Plus structuration of the clouds (inverse problem)

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)

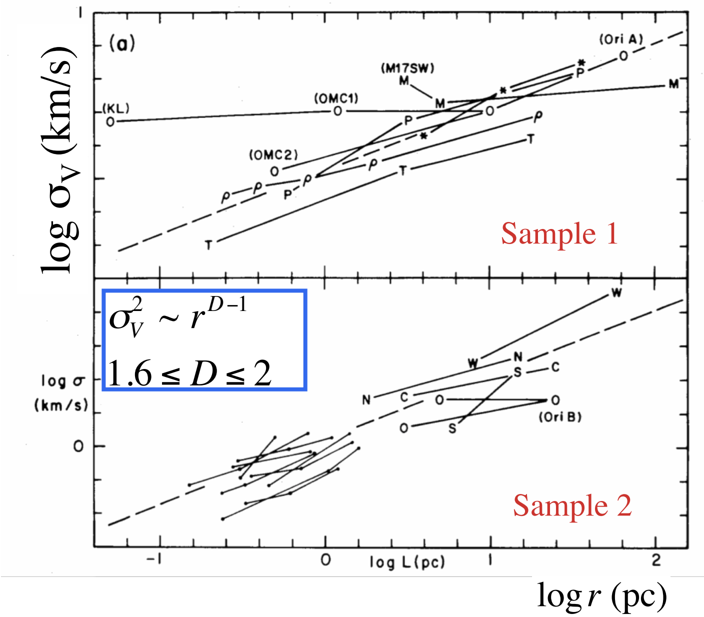
complements

Transparent molecular clouds

ISM turbulence and fractal dimension

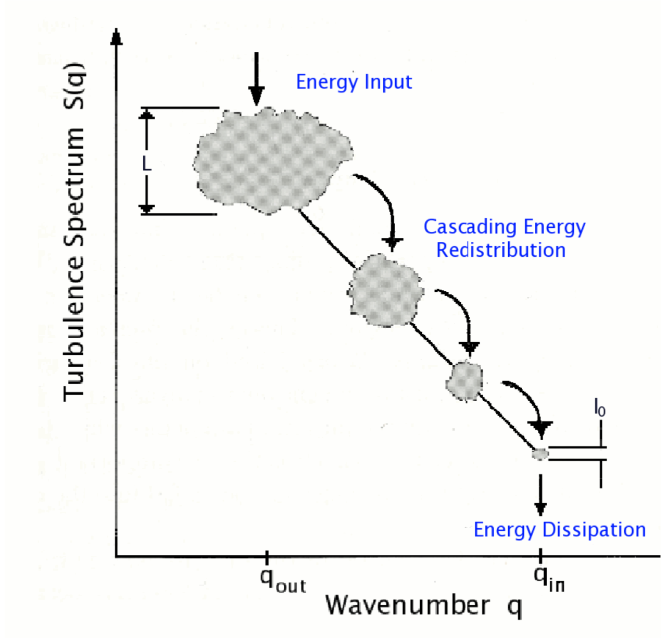
Large cloud is gravitationally unstable,
it fragments into smaller sub-clouds and
produce a self-similar hierarchy structure.

Velocity dispersion σ_ς ϖσ. region size r
in composite clouds from Milky Way
(Larson 1981)



Clouds are bound (virialized systems):

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



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 :

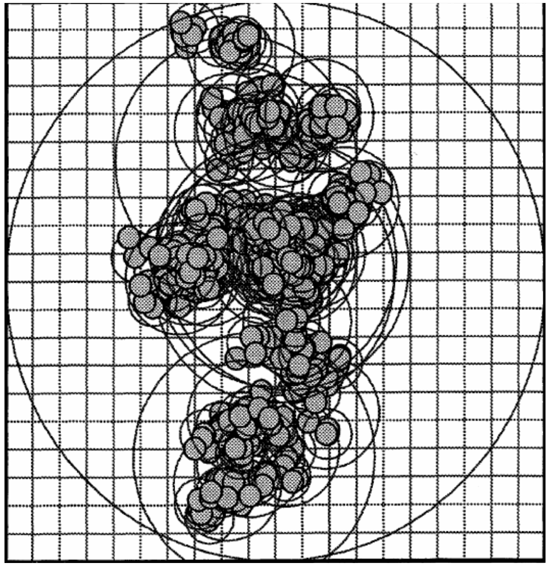
Mass $\sim 0.8 - 2.3 \times 10^{-3}\ M_{sun}$

Size $\sim 23 - 73$ A.U.

Density $\sim 0.6 - 6 \times 10^{9}\ H_2\ cm^{-3}$

Column density $\sim 0.8 - 2.7 \times 10^{24}\ H_2\ cm^{-2}$

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