Title: Search for hidden turbulent gas through interstellar scintillation

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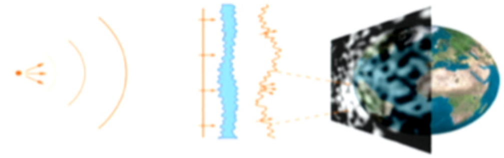
URL: http://pirsa.org/14120008

Abstract: <p>We propose a new way to search for (hidden) cool molecular hydrogen H2 in the Galaxy through diffractive and refractive effects: Stars twinkle because their light crosses the atmosphere. The same phenomenon is expected on a longer time scale when the light of a remote star crosses an interstellar turbulent molecular cloud, but it has never been observed at optical wavelengths. Our simulations and test observations show that in favorable cases, the light of a background star can be subject to stochastic fluctuations on the order of a few percent at a characteristic time scale of a few minutes.</p>

<p>We searched for scintillation caused by molecular gas within visible dark nebulae as well as by hypothetical halo clumpuscules of cool molecular hydrogen (H2-He) with the ESO-NTT telescope. Within a few thousands of densely sampled light-curves, we found one candidate that shows variabilities compatible with a strong scintillation effect through a turbulent structure of the B68 nebula. Furthermore, since no candidate has been found toward the SMC, we were also able to establish upper limits on the contribution of gas clumpuscules to the Galactic halo mass.</p>

<p>I will discuss the perspectives of synchronized observations with two large distant telescopes, to observe the time decorrelation between the light curves, an undisputable signature of the scintillation process. I will then show that a few nights of observation using the so-called Â« movie-mode Â» of LSST should allow one to significantly constrain the last unknown baryonic contribution to the Galactic mass.</p>



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

π , 9 december 2014

Not an easy seminar…

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- **Hidden matter problematics** are known by cosmologists and particle physicists

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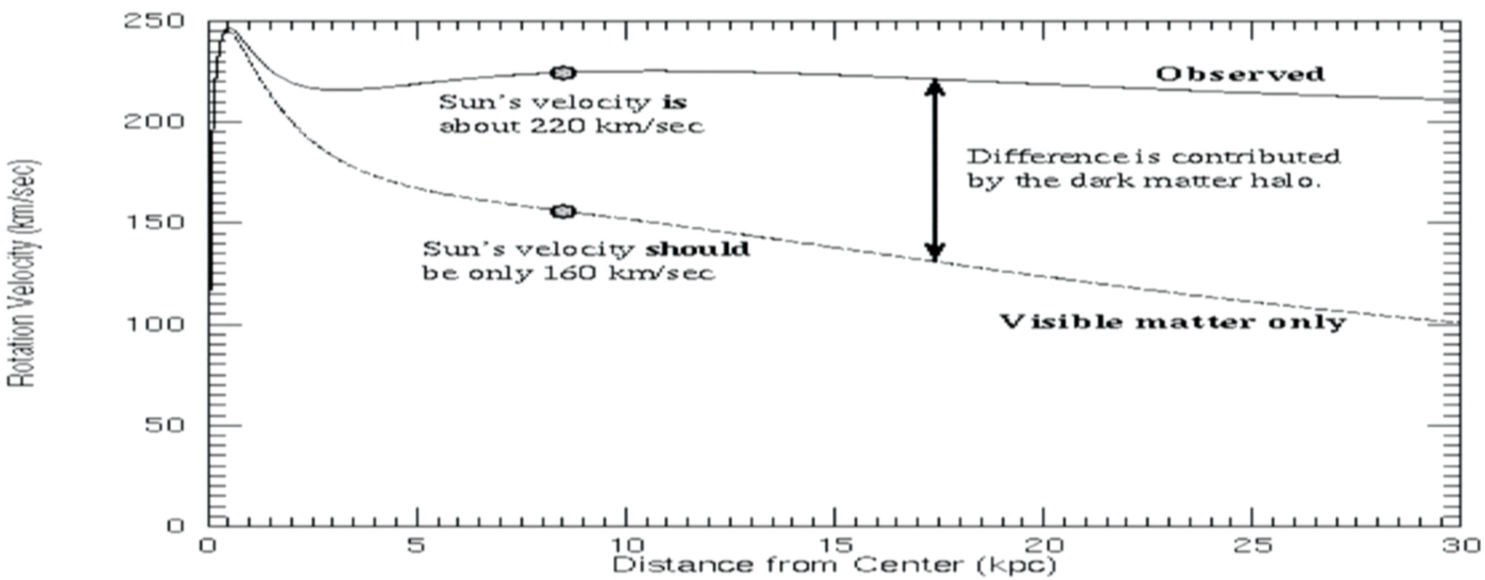
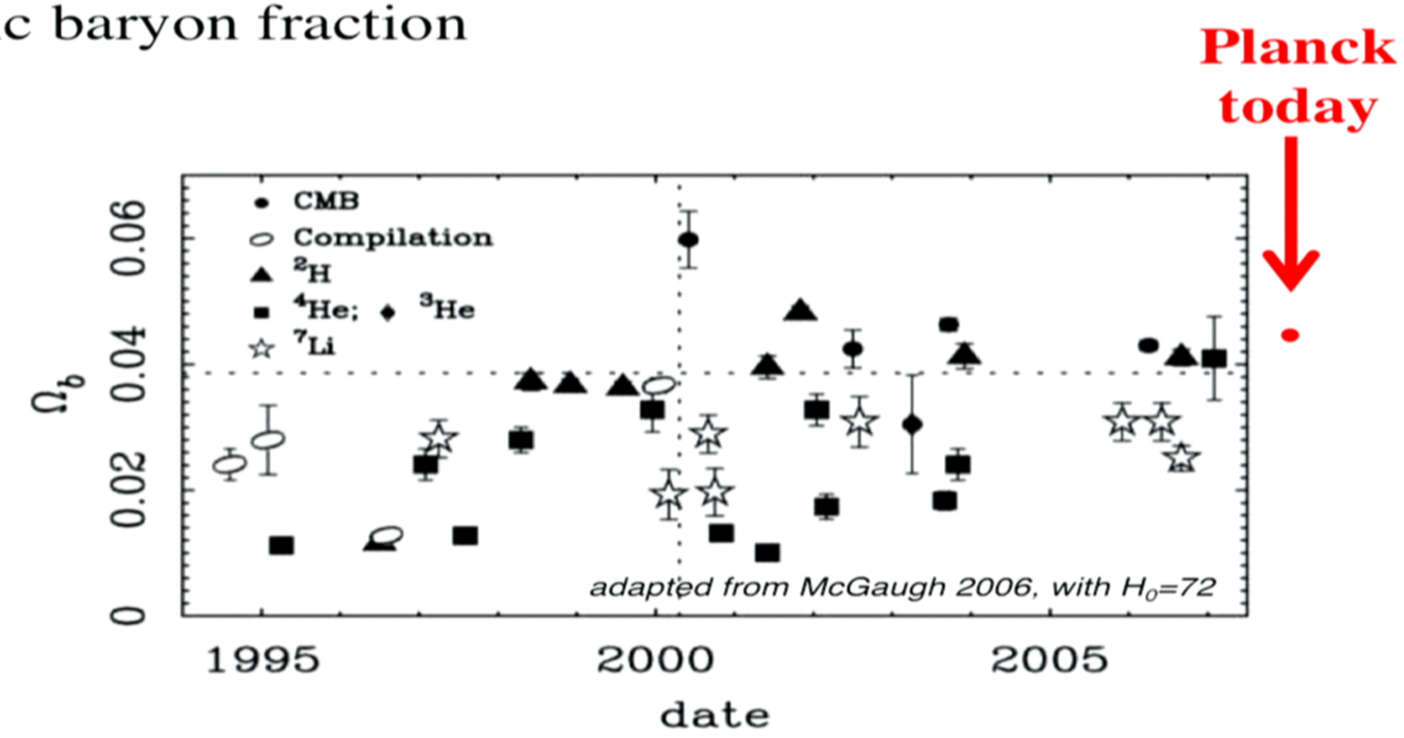
The Milky Way rotation curve
An evidence for hidden matter



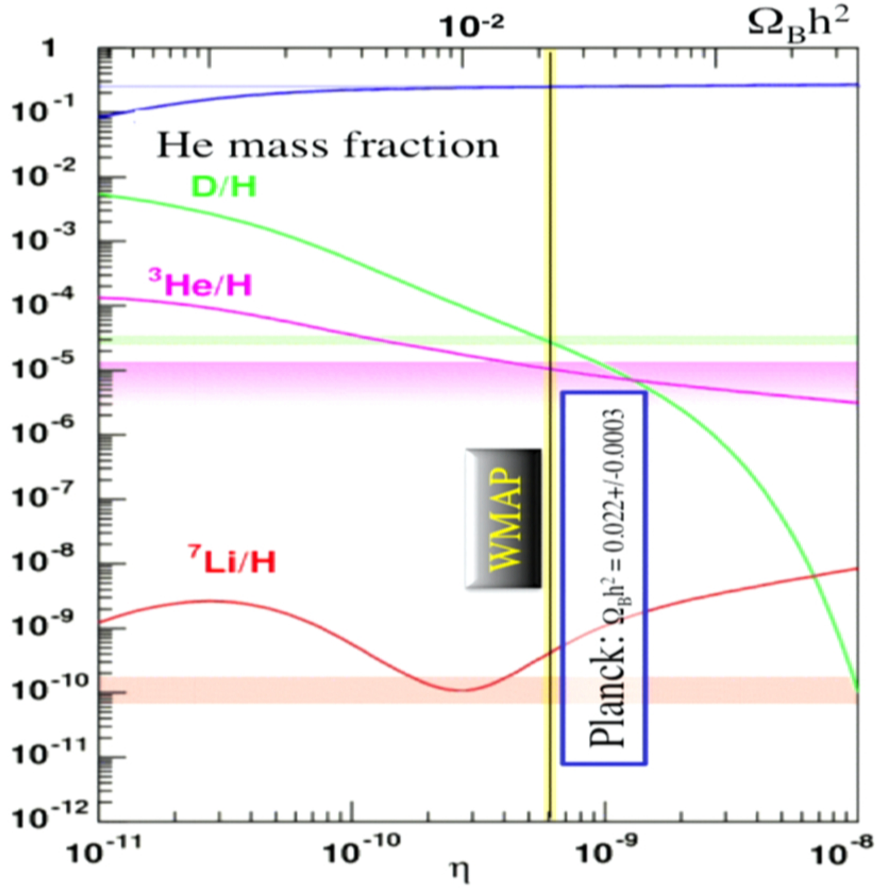
The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two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

A brief history of the baryons…

- Before the first CMB measurements (~ 2000), BBN favoured low values of the cosmic baryon fraction



Todays' cosmic abondance of Baryons



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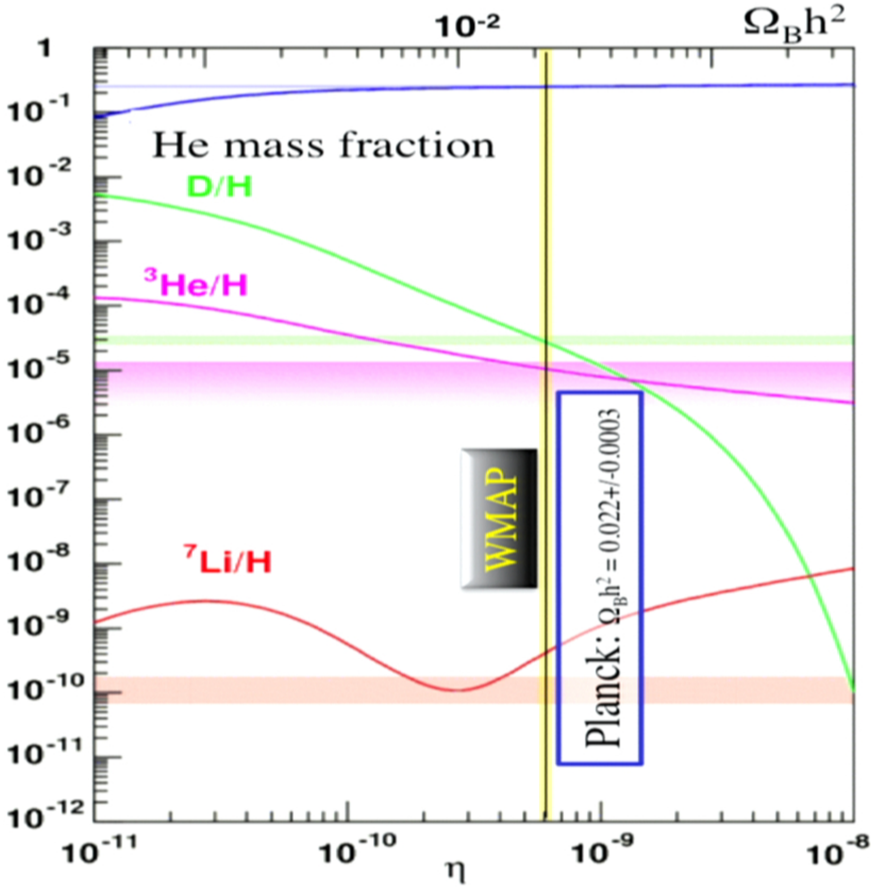

- Primordial nucleo-synthesis => $\mathbf{\Omega_b = 0.04}$
- Planck results: $\Omega_b h^2 = 0.0224$ => $\mathbf{\Omega_b = 0.048}$

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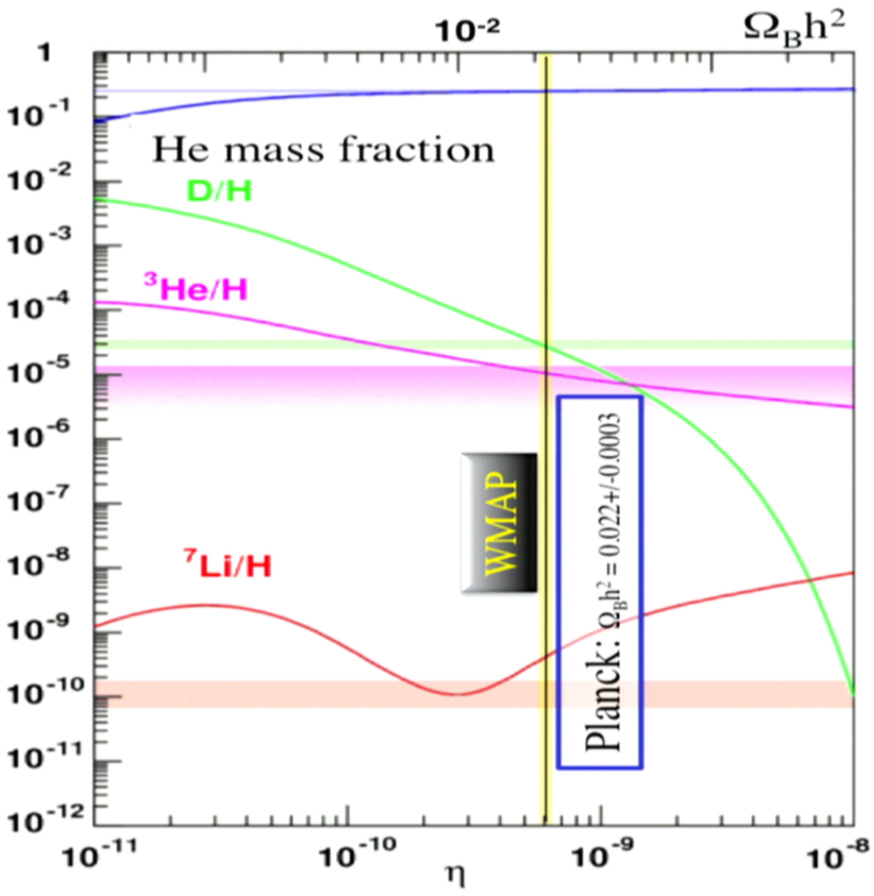

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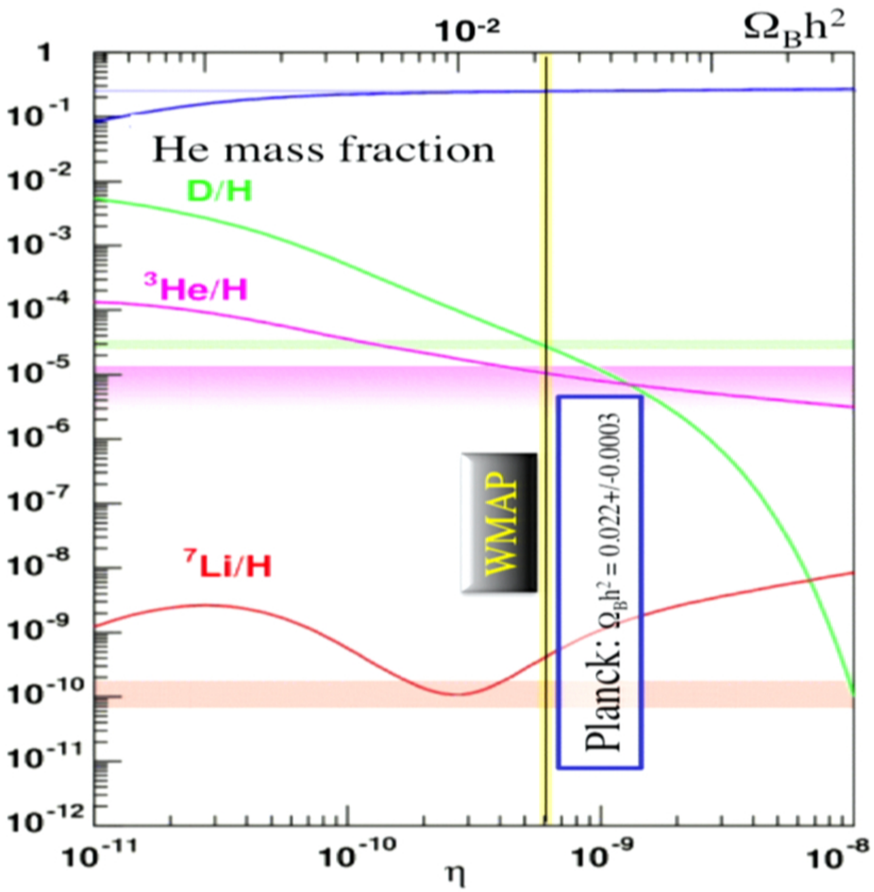

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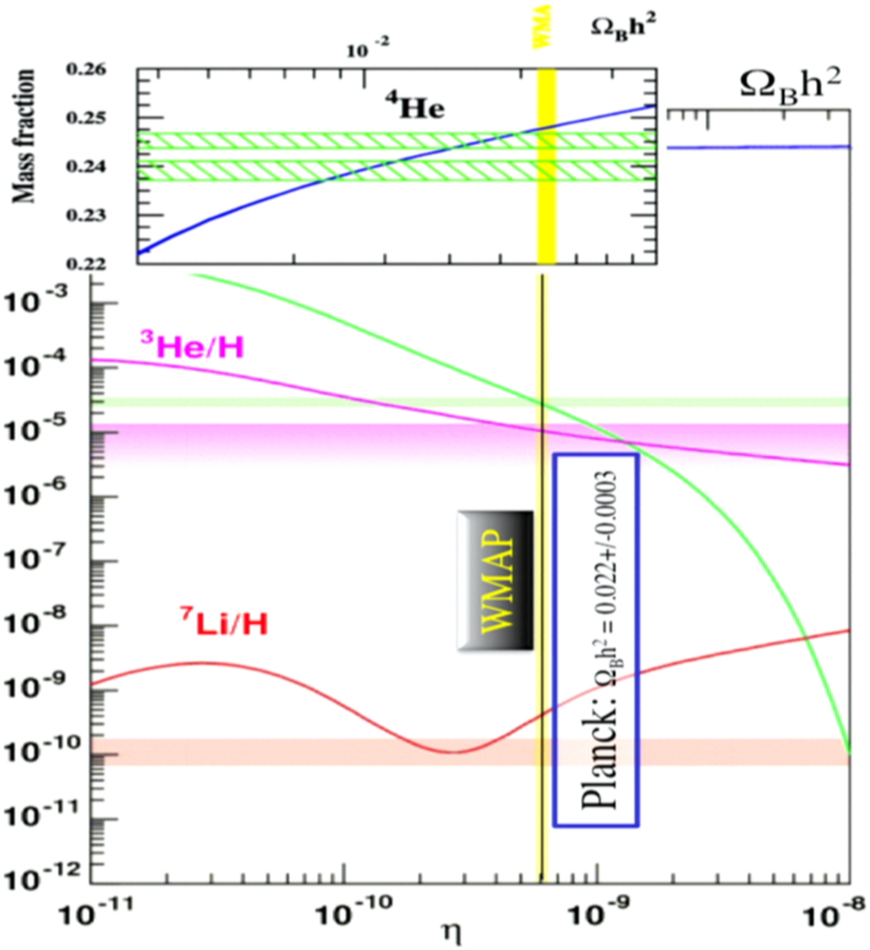

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Cluster baryonic pie

(Ettori et al. 2009)

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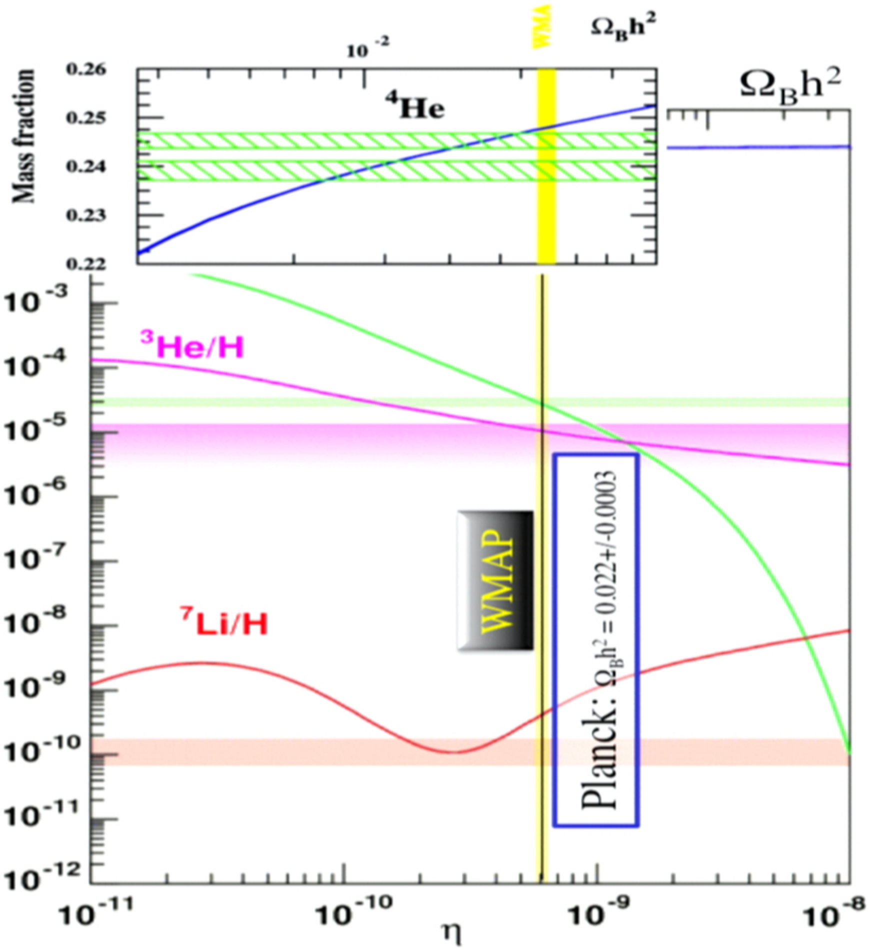

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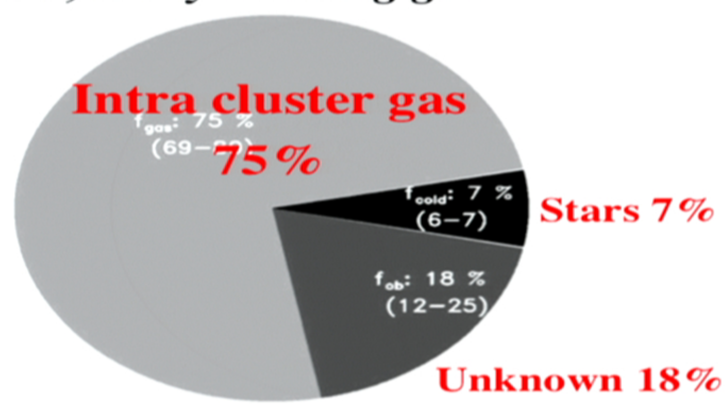
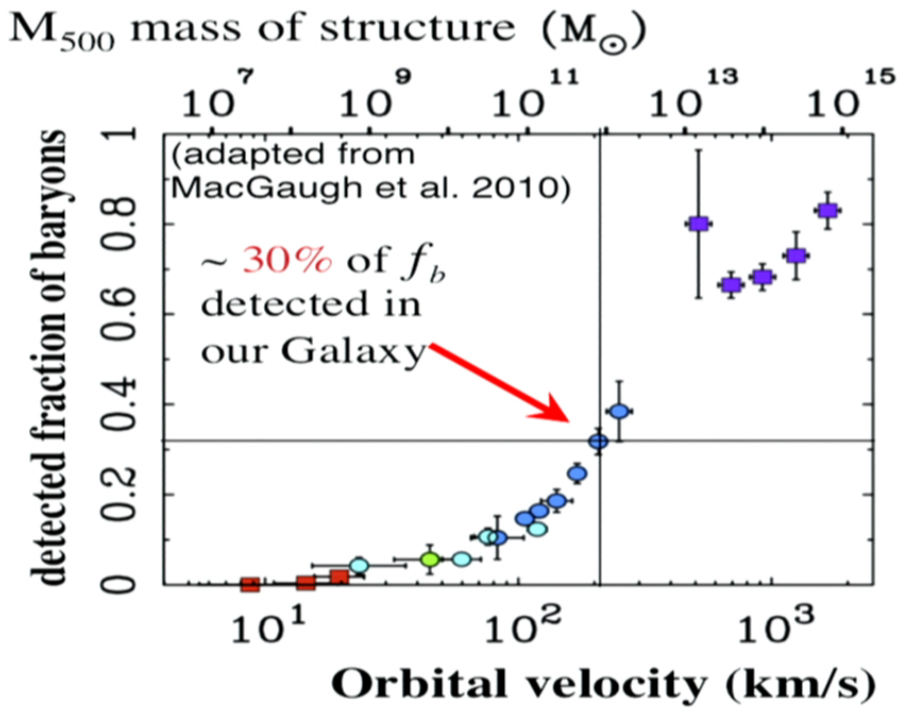


More unknown baryons at smaller scales?

Cosmic Baryonic Fraction: $f_b = \frac{M_b}{M_b + M_{CDM}} \approx 0.17$



Situation of the Milky-Way

- **Visible mass** is 6.1+/- 0.5 x10^{10} M_{sol} (5 stars, 1 gas)
- **Dynamical mass** from 50 (until LMC) to 200 (until Leo I) x10^{10} M_{sol}

-> Visible mass fraction < 10%

-> We see (probably much) less than half of the expected baryons

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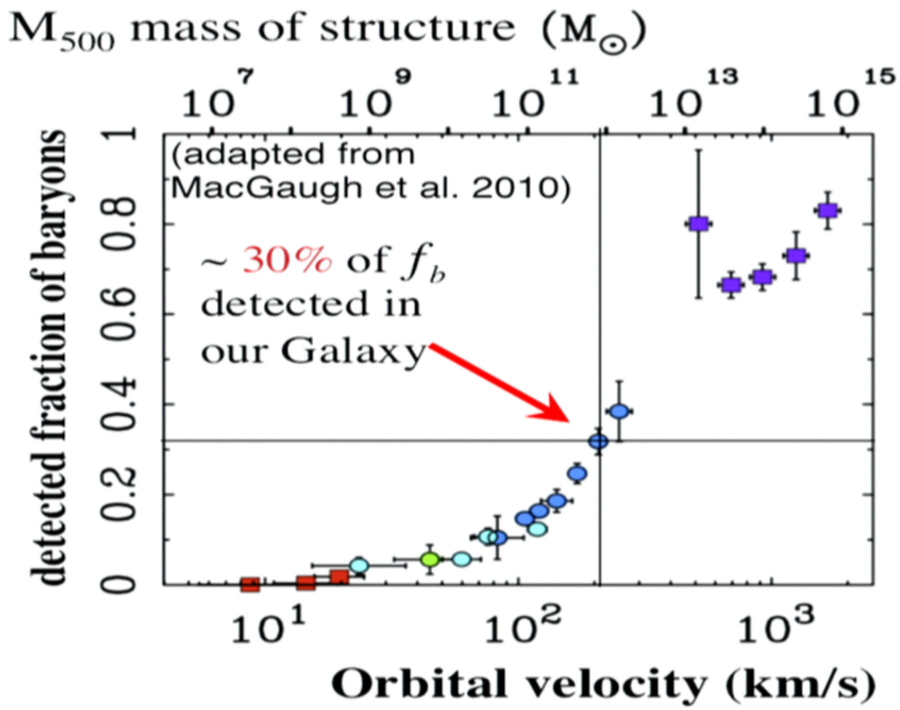

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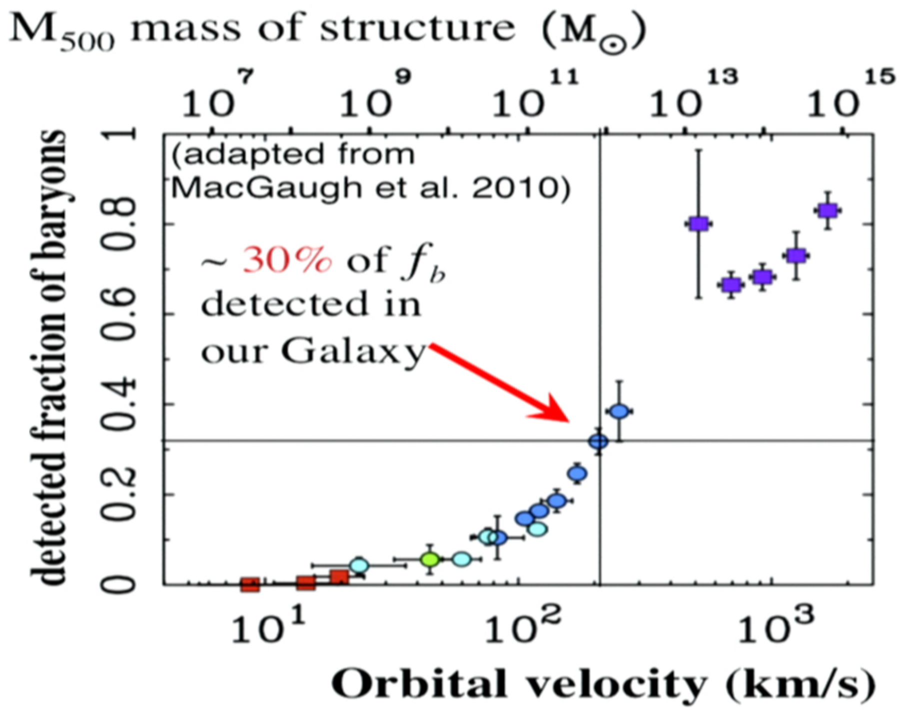

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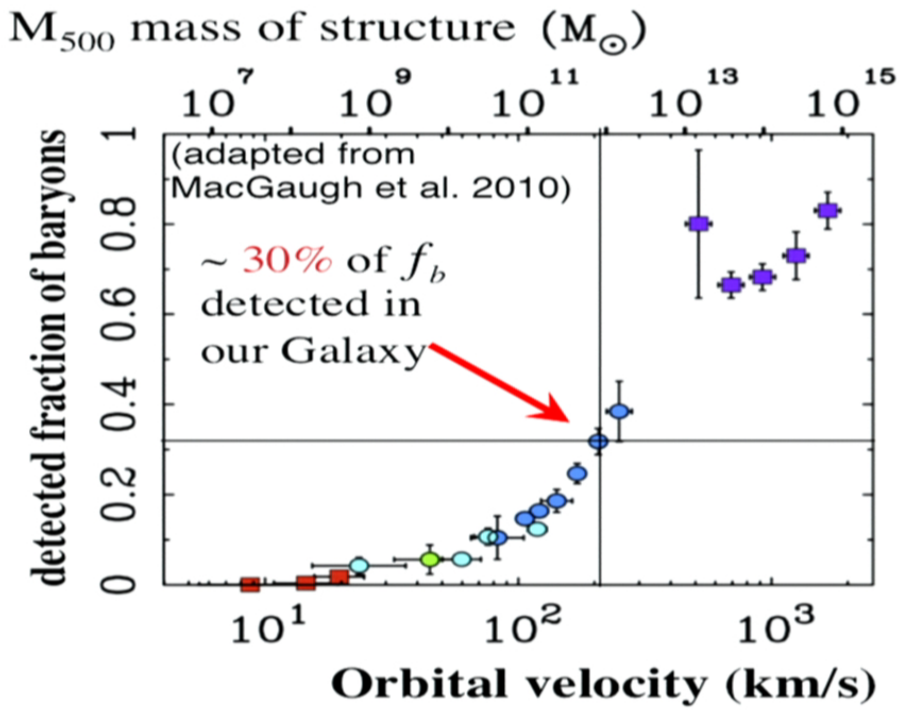

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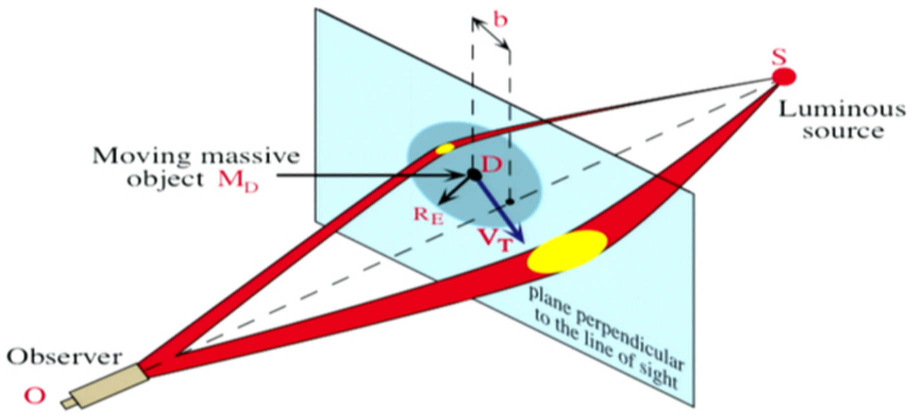
2 options

- baryon/DM ratio varies with the scale
  -> find segregation mechanism
- Baryons are undetectable in smaller structures
  -> find these structures

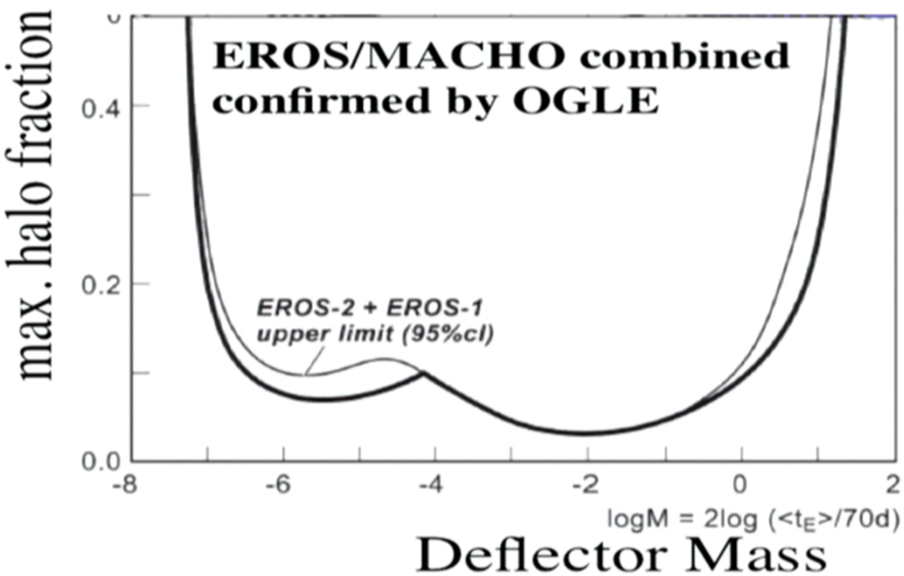
Very unsatisfactory isn't it?

Where are these baryons?

- Not in MACHOs => microlensing results



GRAVITATIONAL MICROLENSING EFFECT



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- **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).

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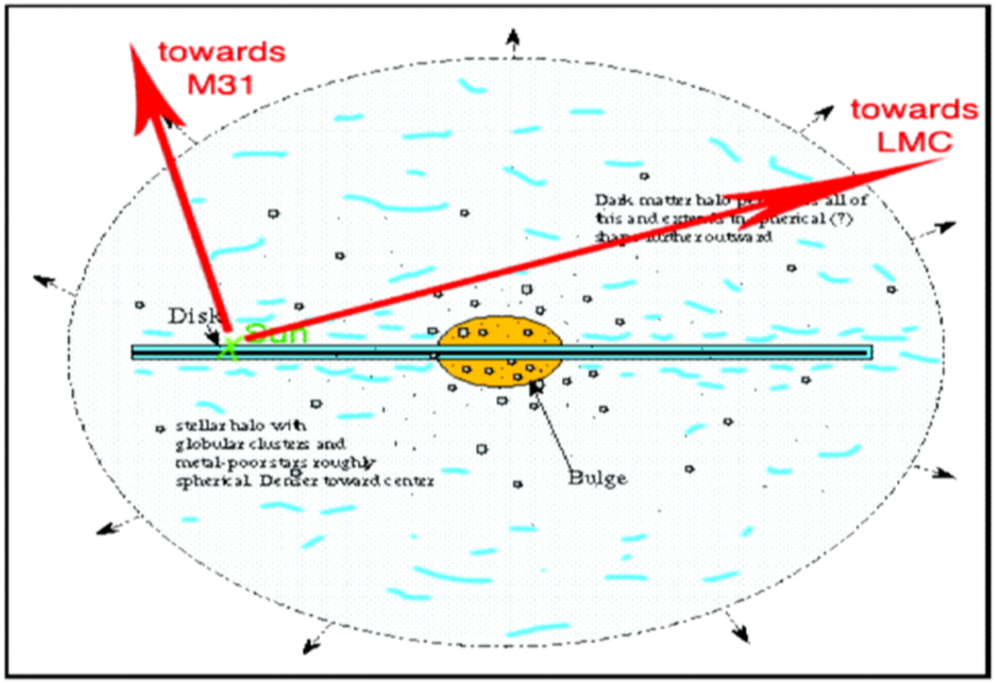
No resonant process

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

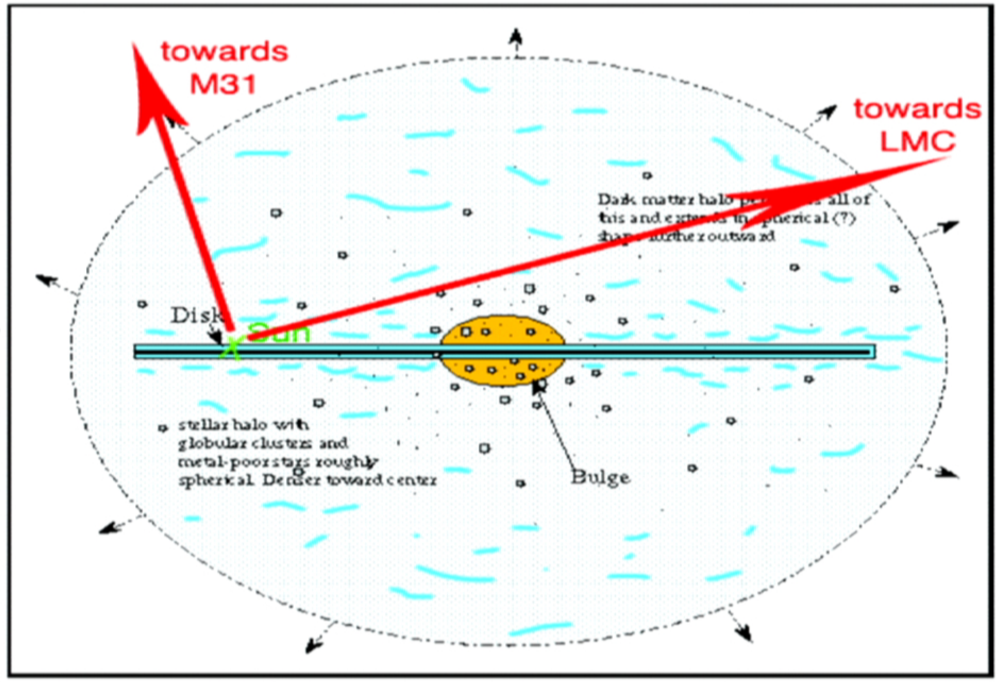
Orders of magnitude

- 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

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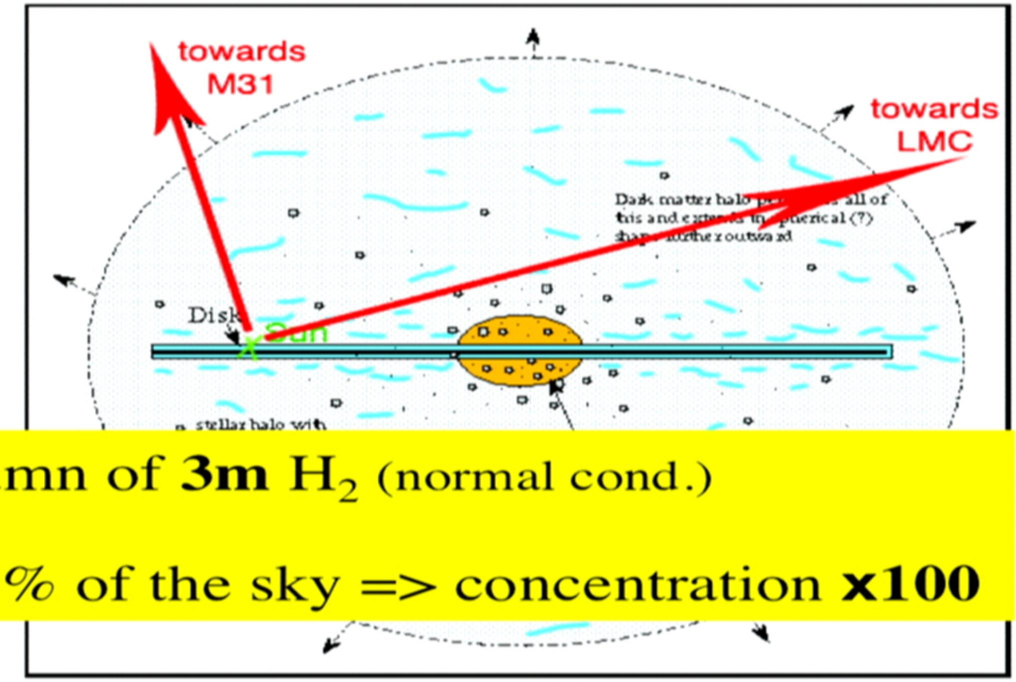
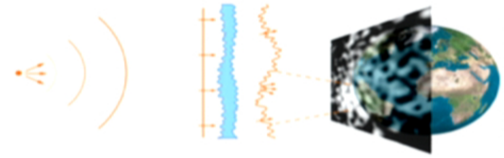
- **Average** column-density toward LMC



- **$250 g/m^2$** <=> column of **3m** H_2 (normal cond.)
- These clouds fill 1% of the sky => concentration **x100**



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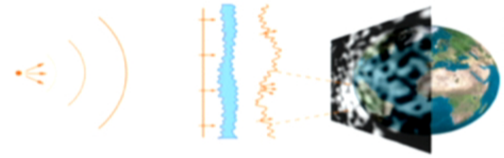
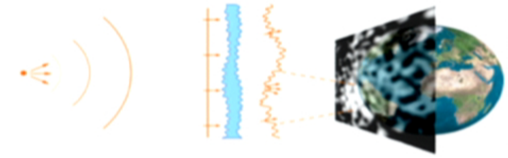


These clumpuscules refract light

- 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} ($<1/\lambda^3$)



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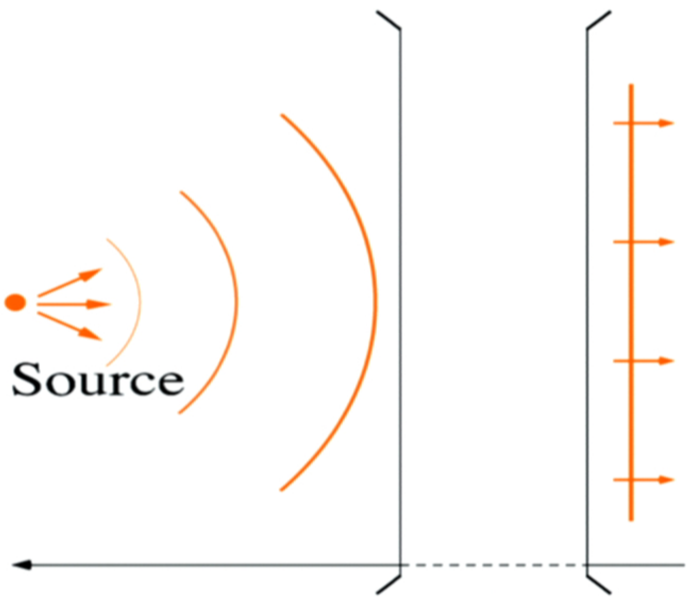
- Supplement of phase ϕ when crossing H_2 medium
  $\Rightarrow$ typically **80,000 x2π** (for 1% of the sky) @ λ=500nm
  $\Rightarrow$ Column density fluctuations (turbulences) in the medium **as small as 10^{-6}** are sufficient to produce detectable wavefront distorsions

Scintillation through a strongly diffusive screen



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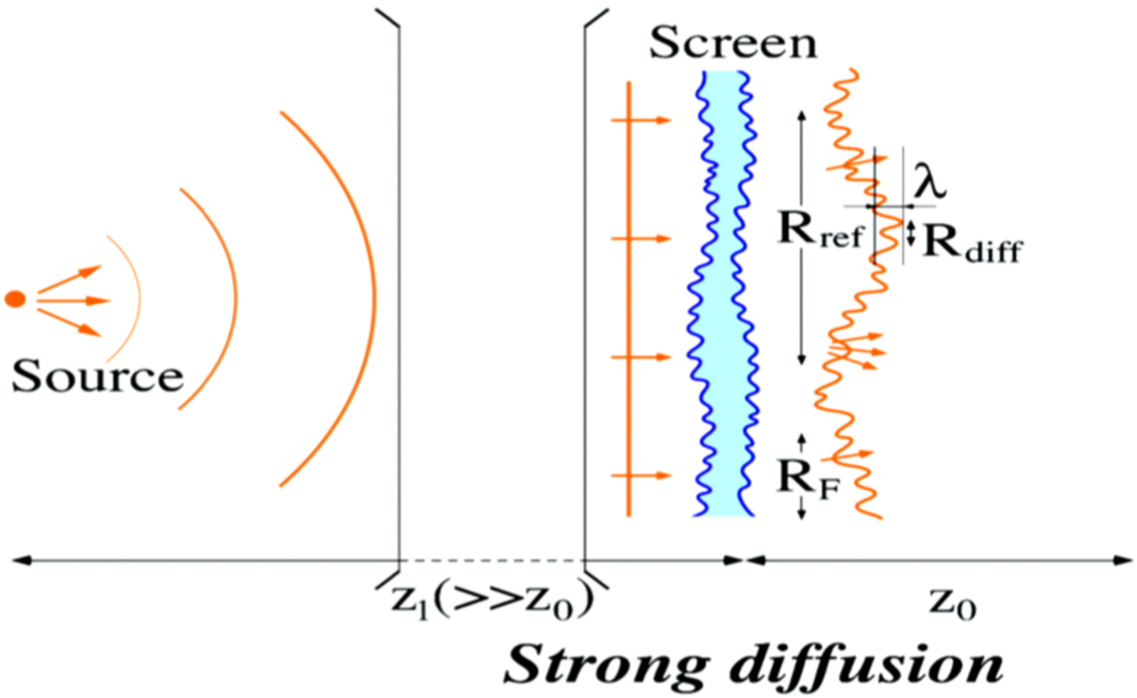

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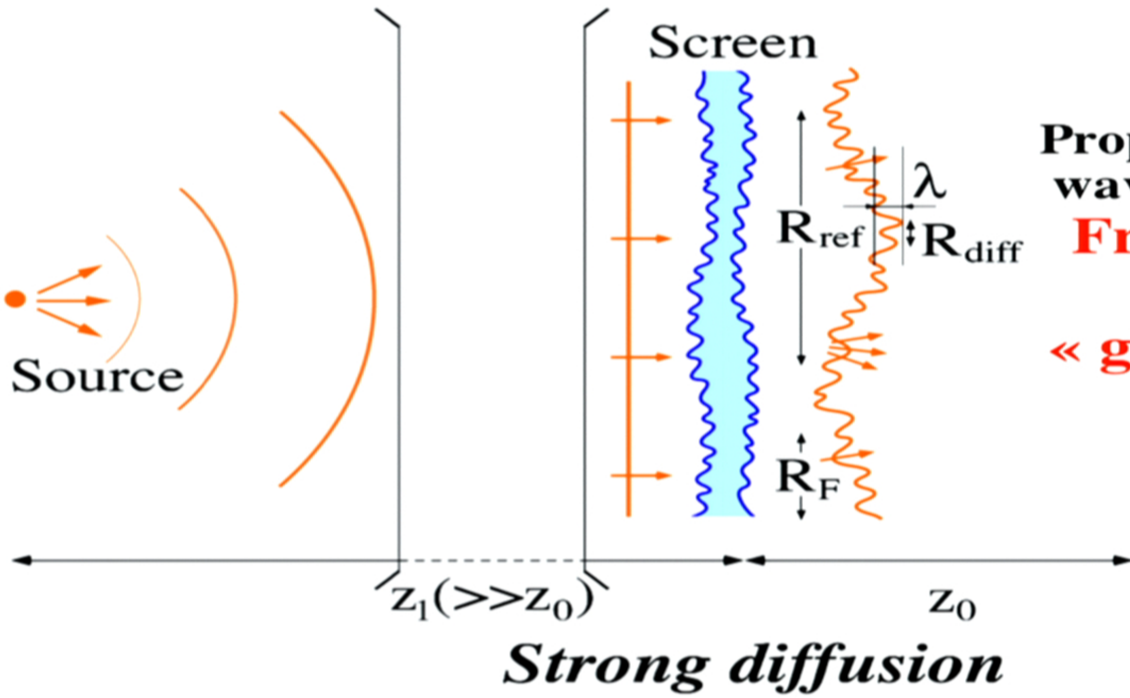
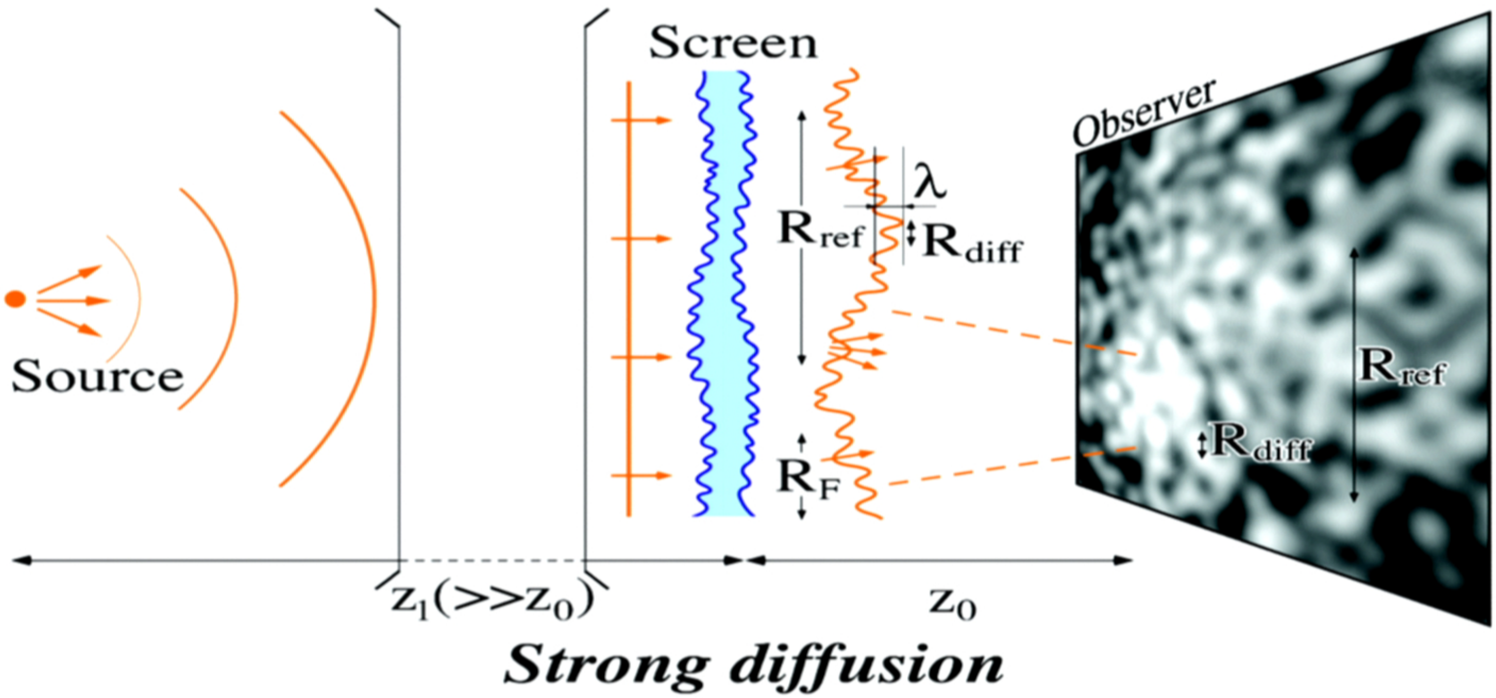


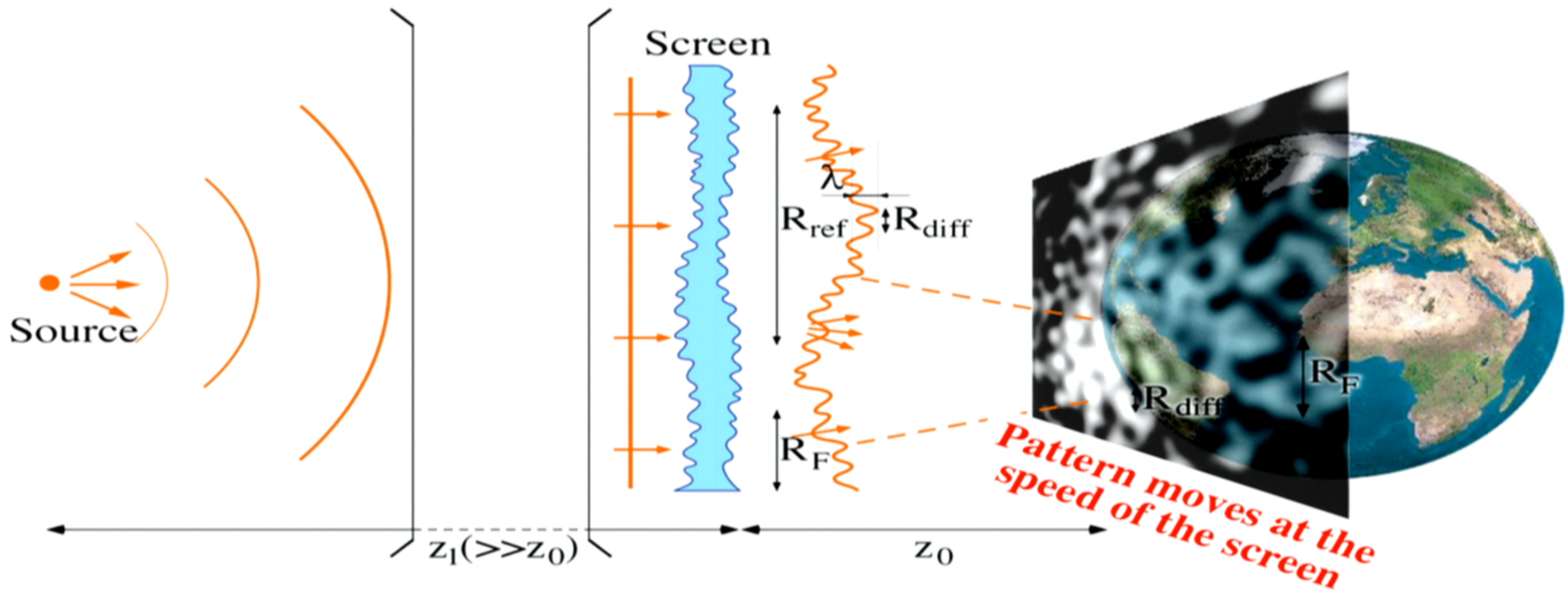
Propagation of distorted wave surface driven by:
Fresnel diffraction
+
« global » refraction

Scintillation through a strongly diffusive screen

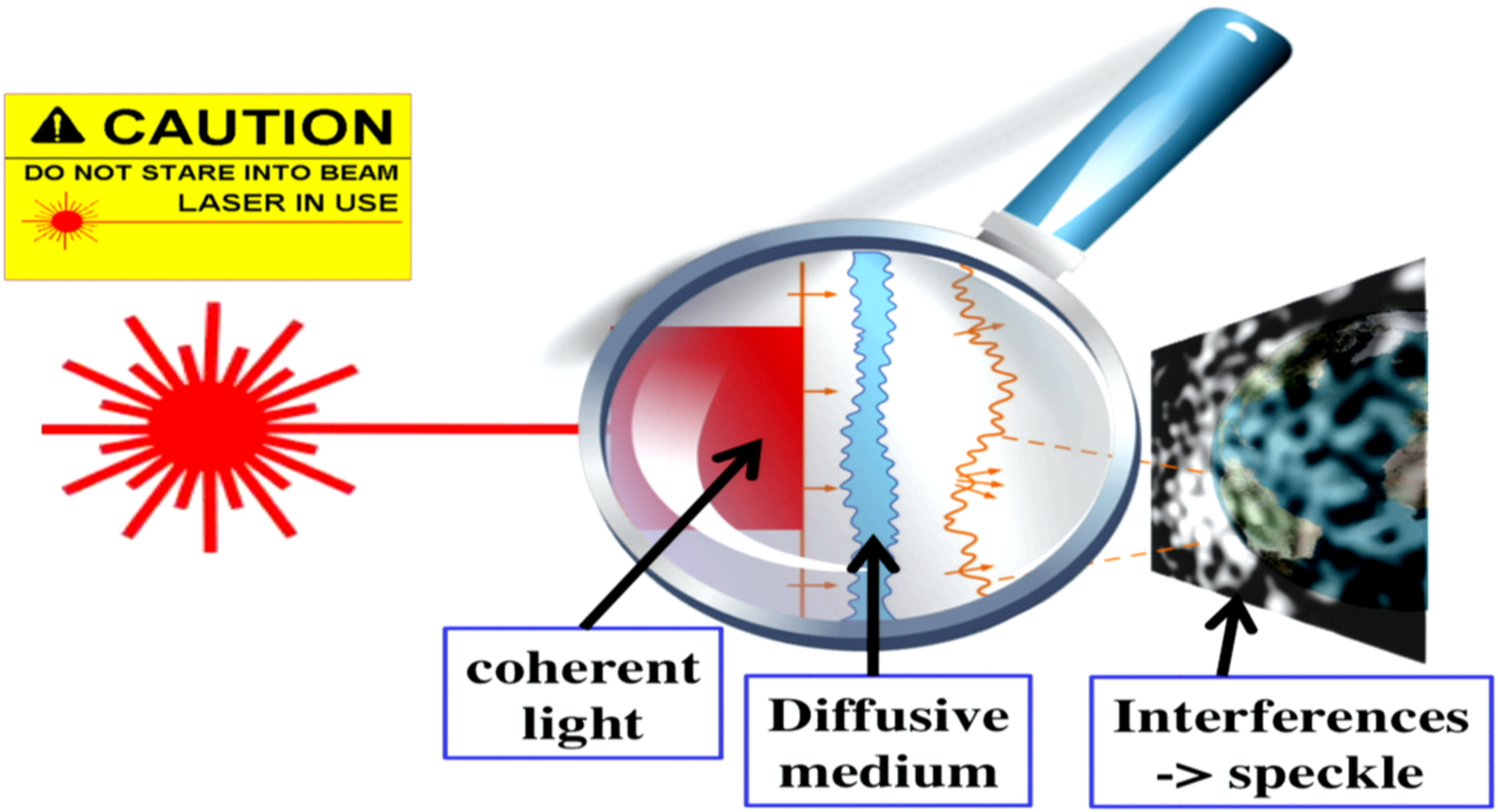


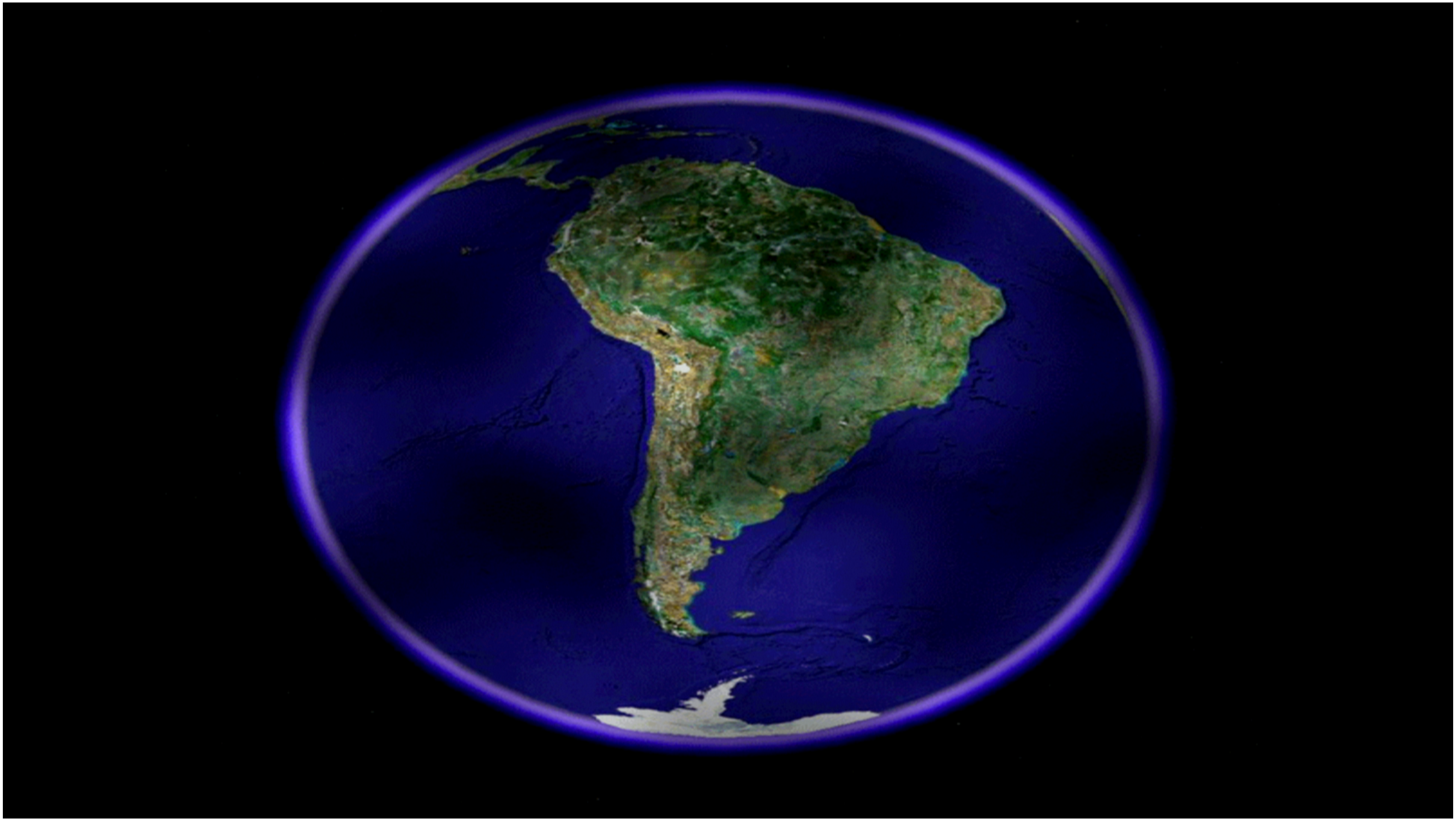
Scintillation through a diffusive screen

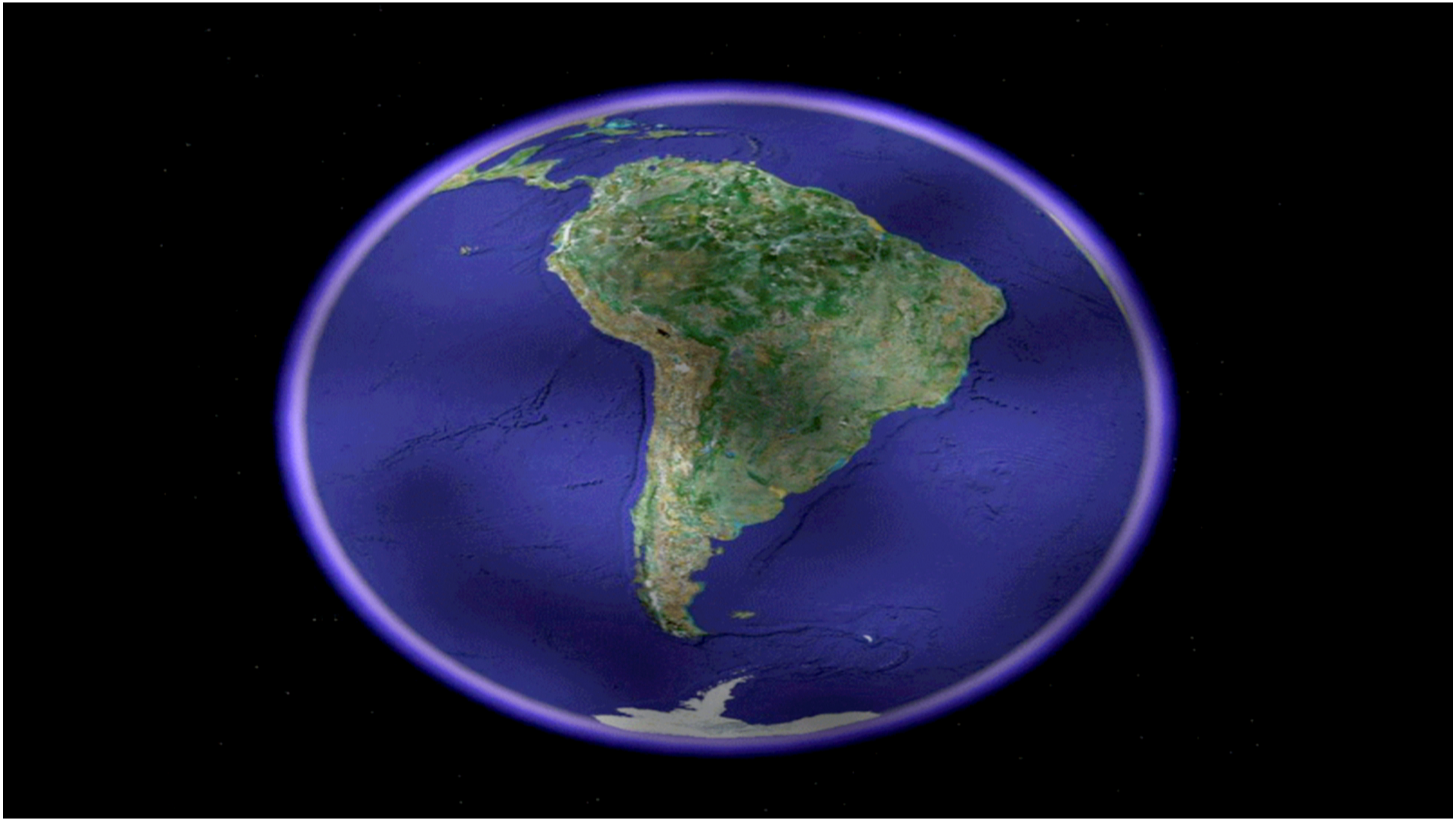
After refraction, propagation of distorted wave surface is driven by Fresnel diffraction that produces speckle



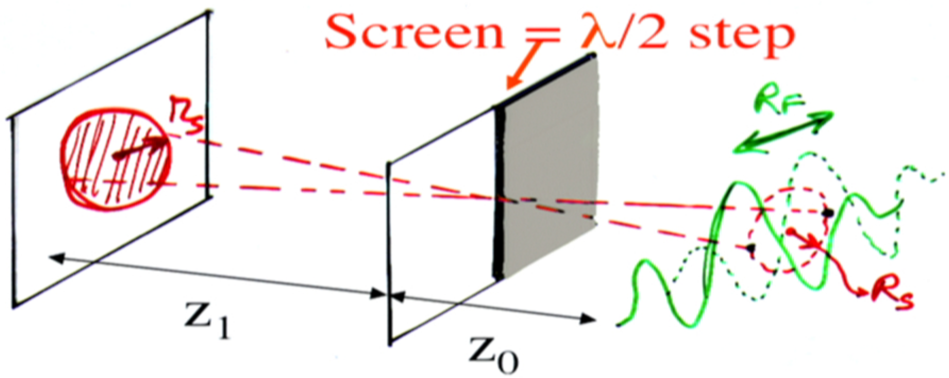
Demonstrator







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



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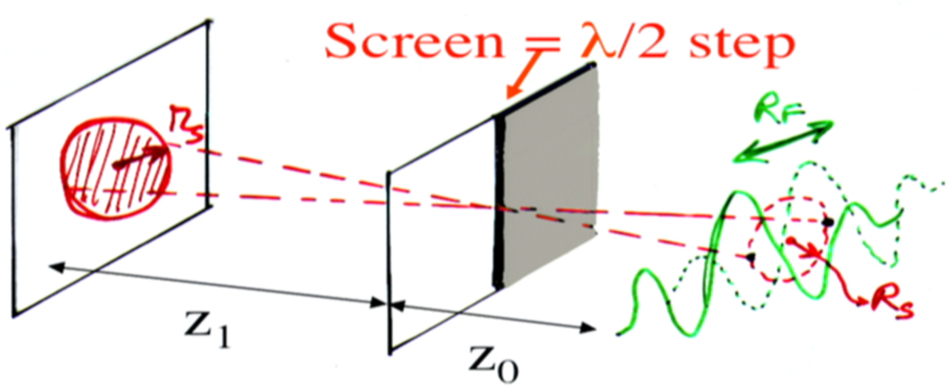

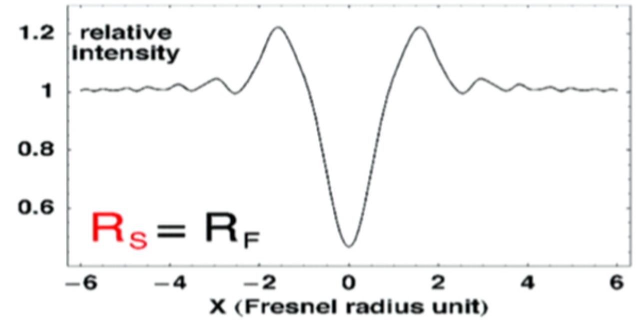

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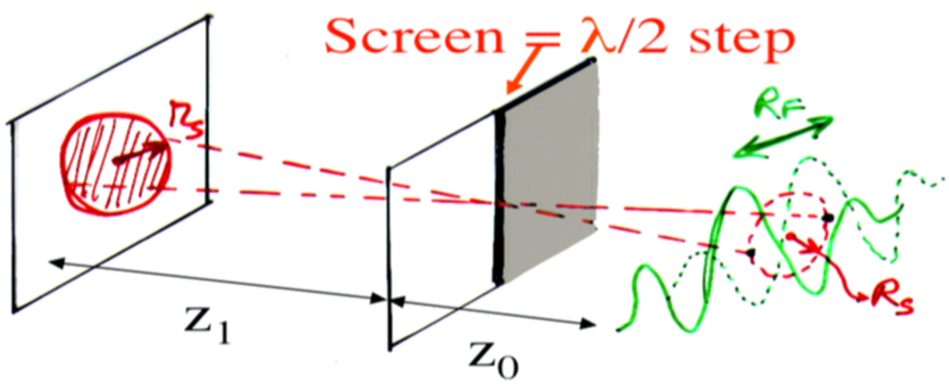

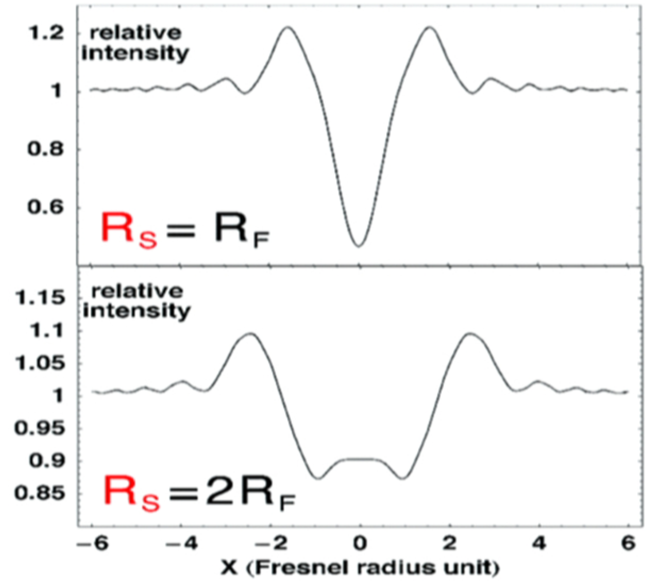

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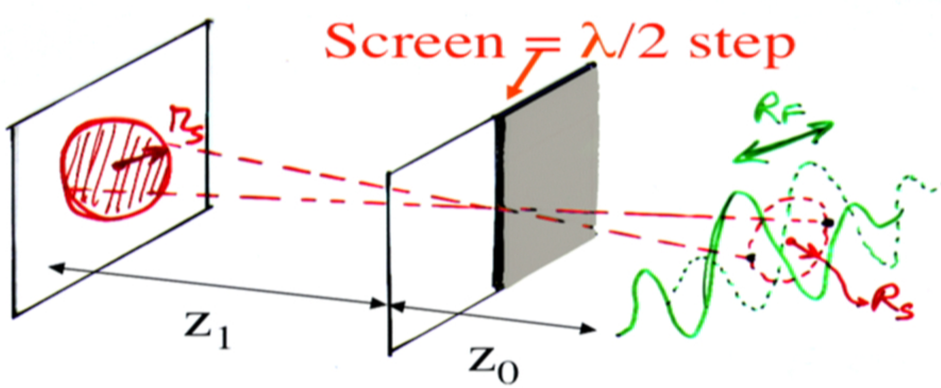
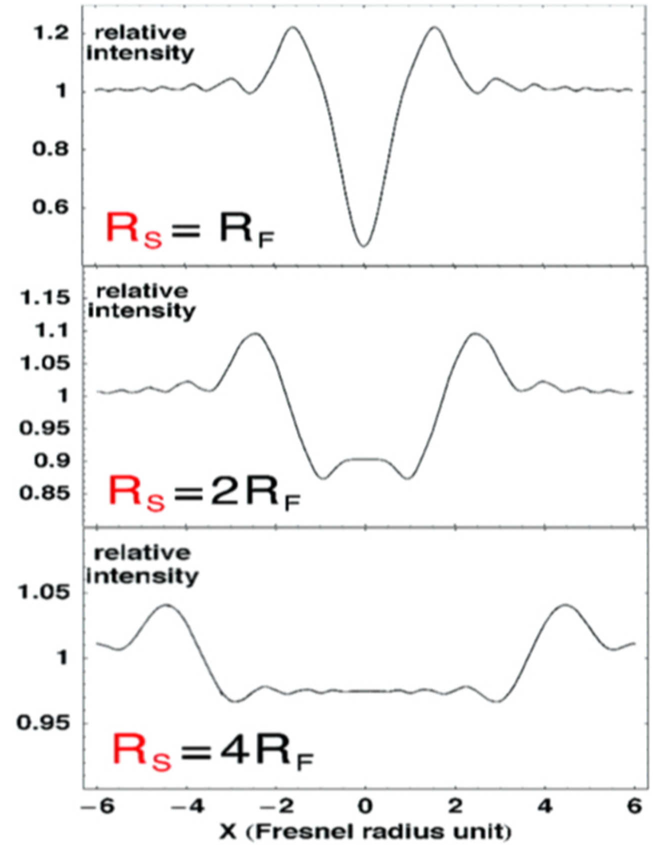
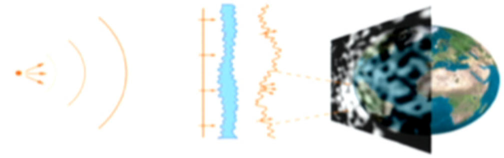
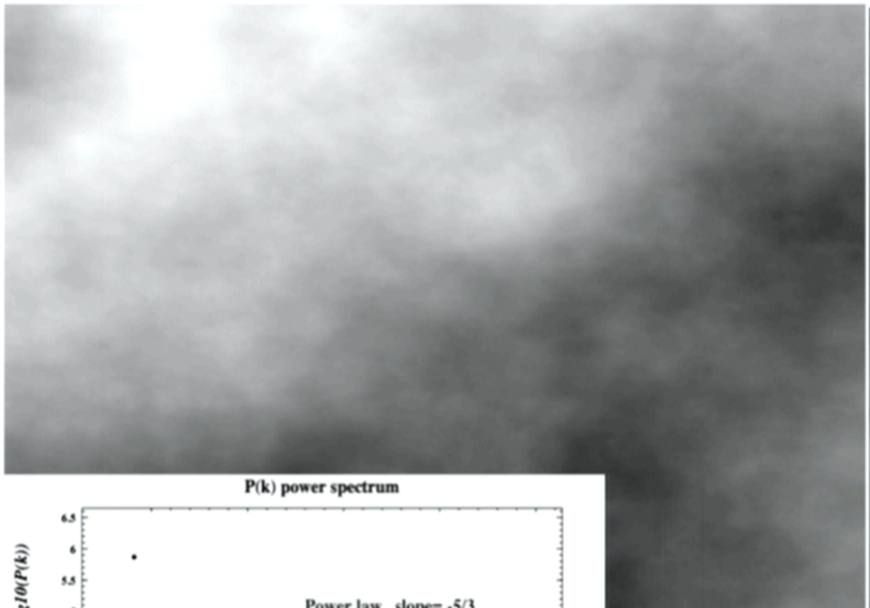


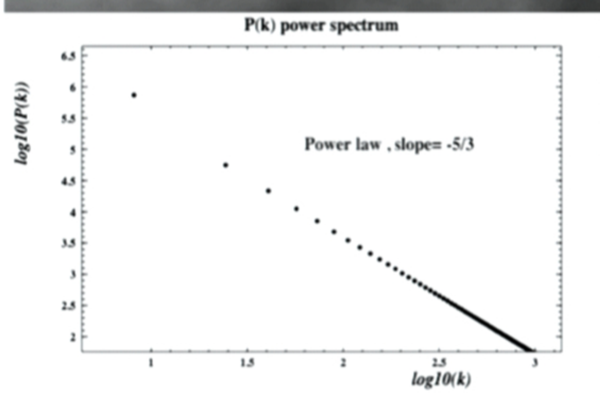


- Depression width ~ R_S
  => Info on source size
- Contrast ~ R_F / R_S
- Also depends on **Δλ** (time coherence), but not critically: $\Delta\lambda/\lambda<0.1 \Rightarrow \Delta R_F/R_F<0.05$



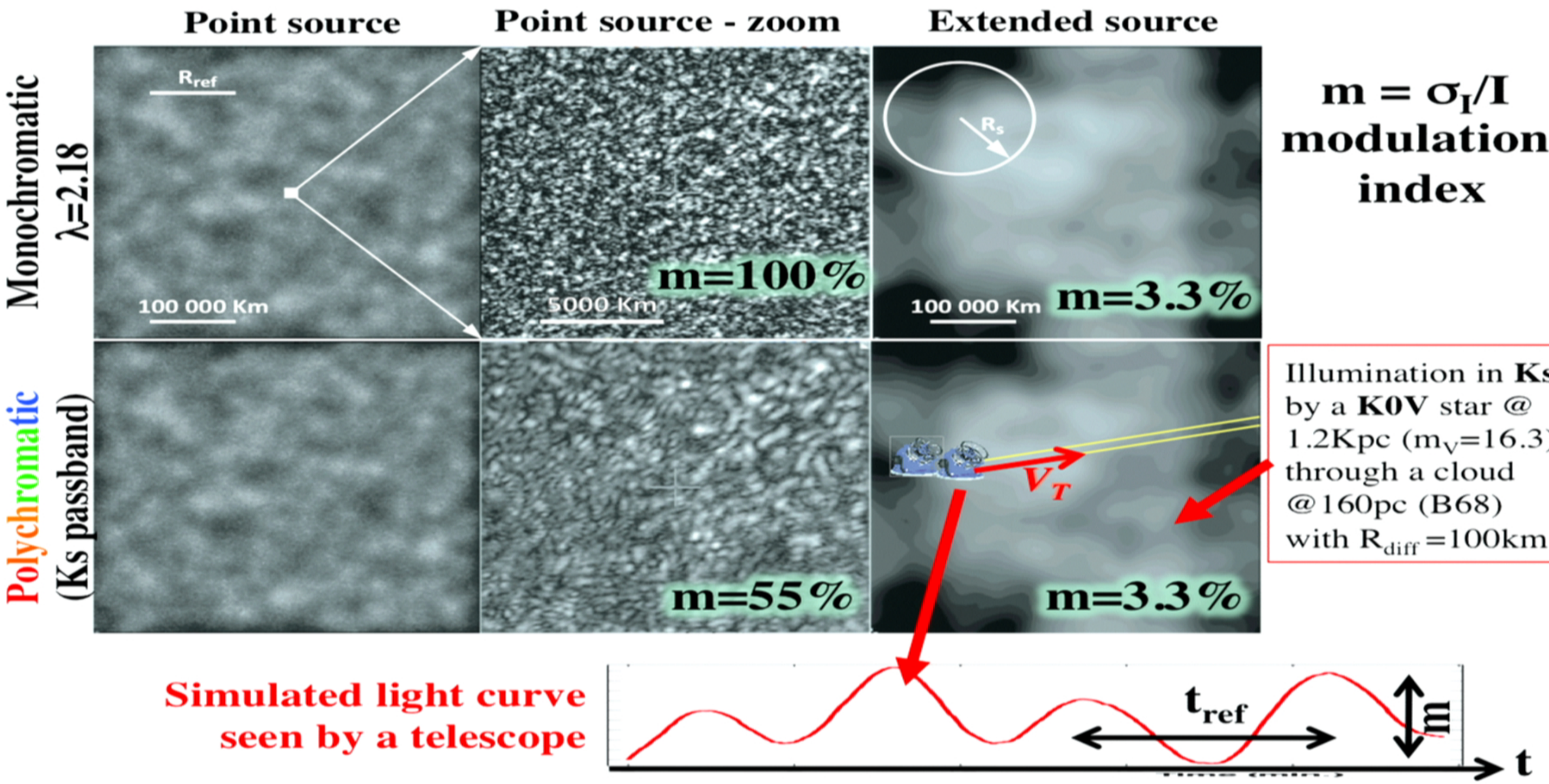
Simulation: Fractal phase screen



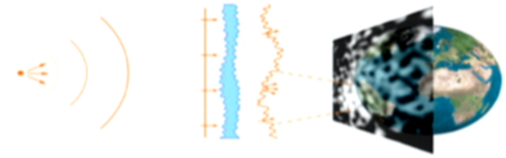


- Kolmogorov turbulence -> realistic
- Other power laws have been studied

Speckle image after crossing screen (simulation)



Distance scales



4 distance scales characterize the speckle pattern

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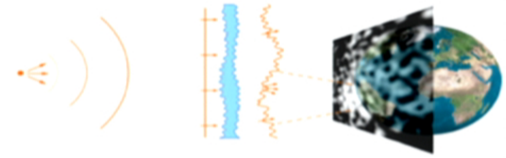


4 distance scales characterize the speckle pattern

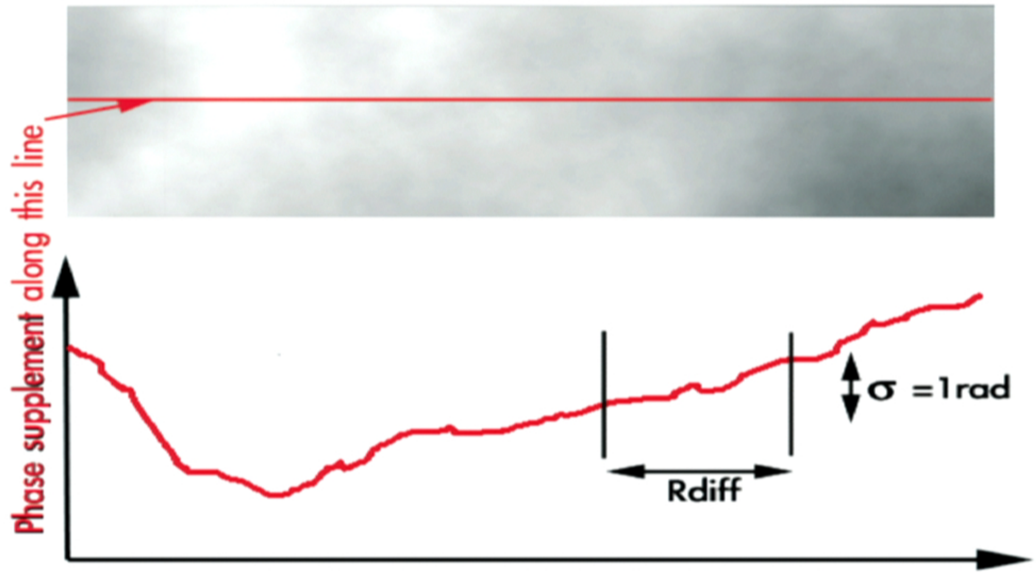
- **Diffusion radius R_{diff}**
  - **separation such that:** $\sigma[\phi(\mathbf{r}+\mathbf{R}_{diff})-\phi(\mathbf{r})] = 1$ radian
  - Characterizes the turbulence

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

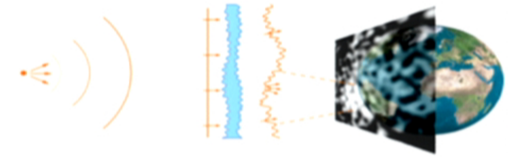


- This corresponds to
- $\Delta N_l / N_l \sim 10^{-6}$ for disk/halo clumpuscule
- $\Delta N_l / N_l \sim 10^{-4}$ for Bok globule (NTT search)

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

L_z : Cloud size L_{out} : Turbulence outer scale

Distance scales



4 distance scales characterize the speckle pattern

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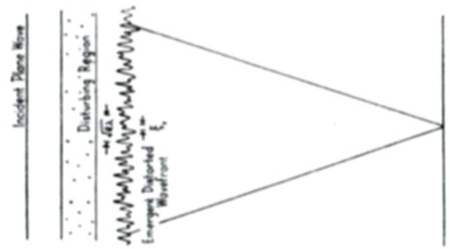

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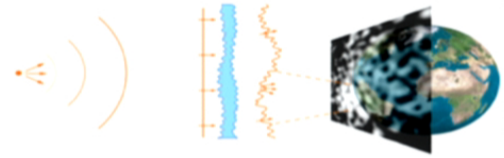

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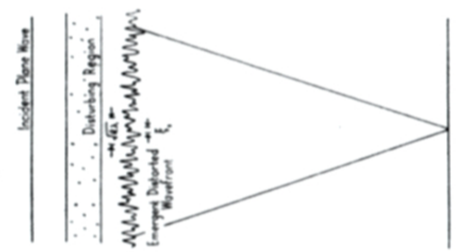

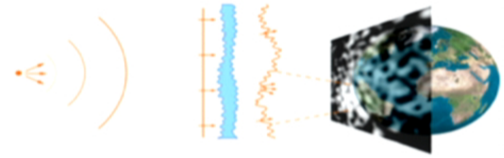

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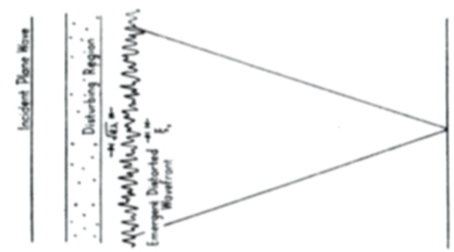

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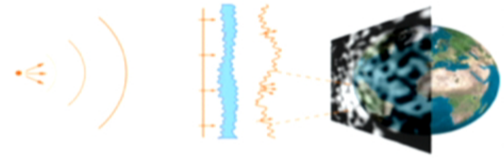

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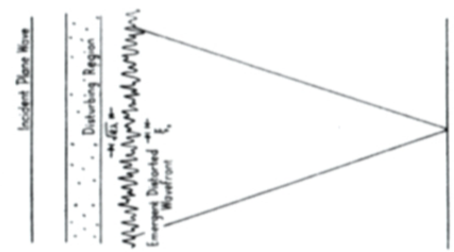

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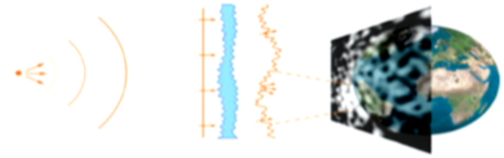

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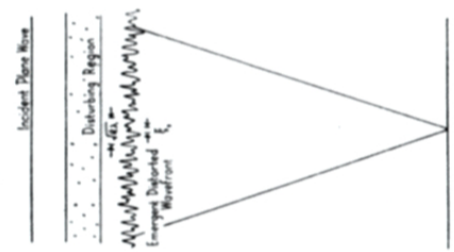

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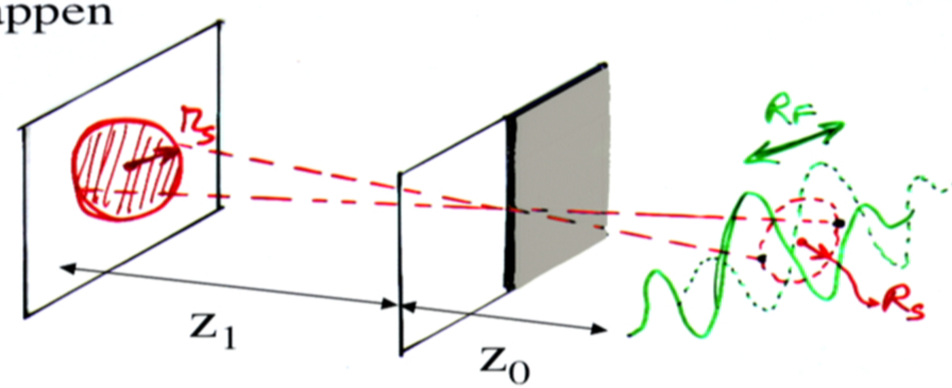
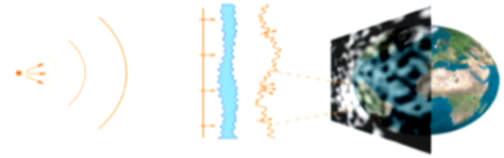


Time scale (observable)



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

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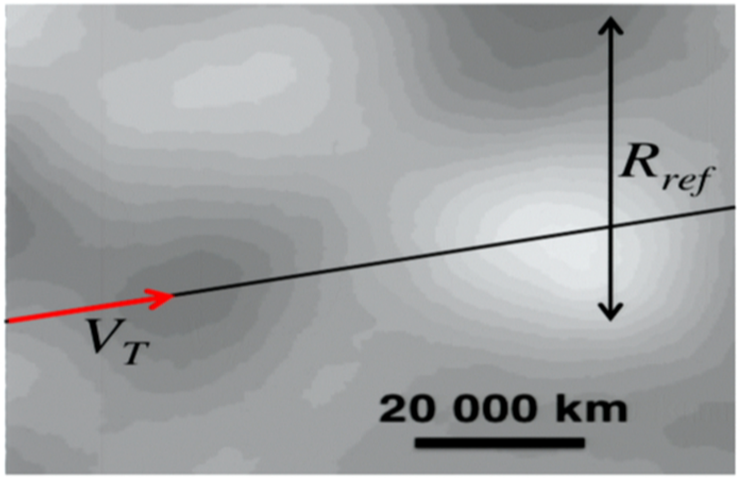

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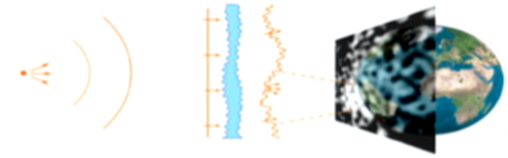

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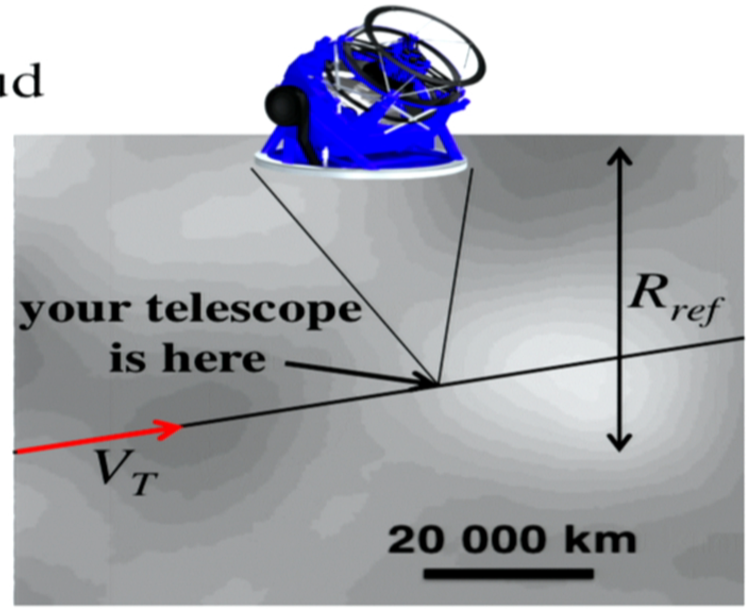

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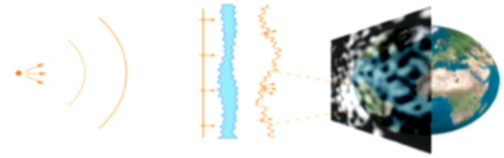

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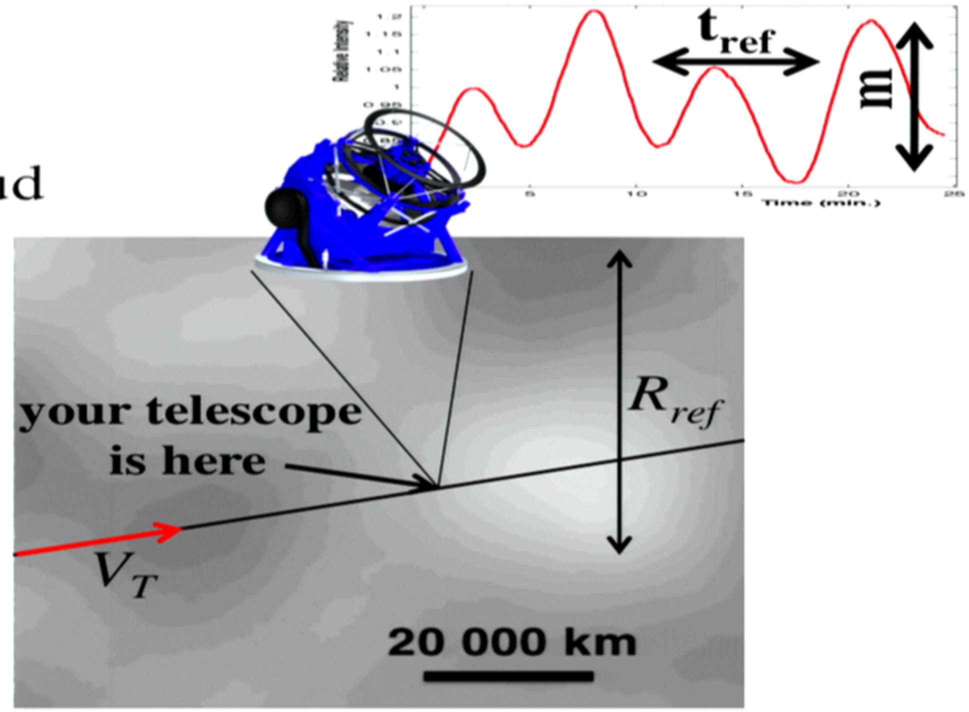
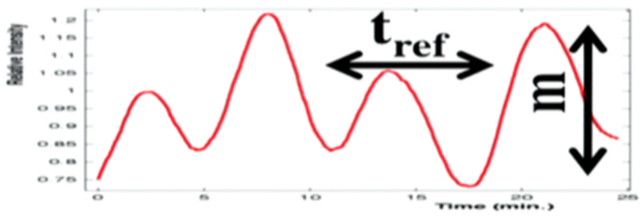


Modulation Index
(observable)



Essentially depends on $\mathbf{R_S}$ and $\mathbf{R_{ref}}$
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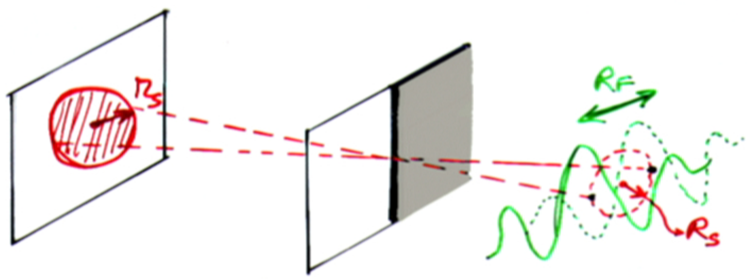

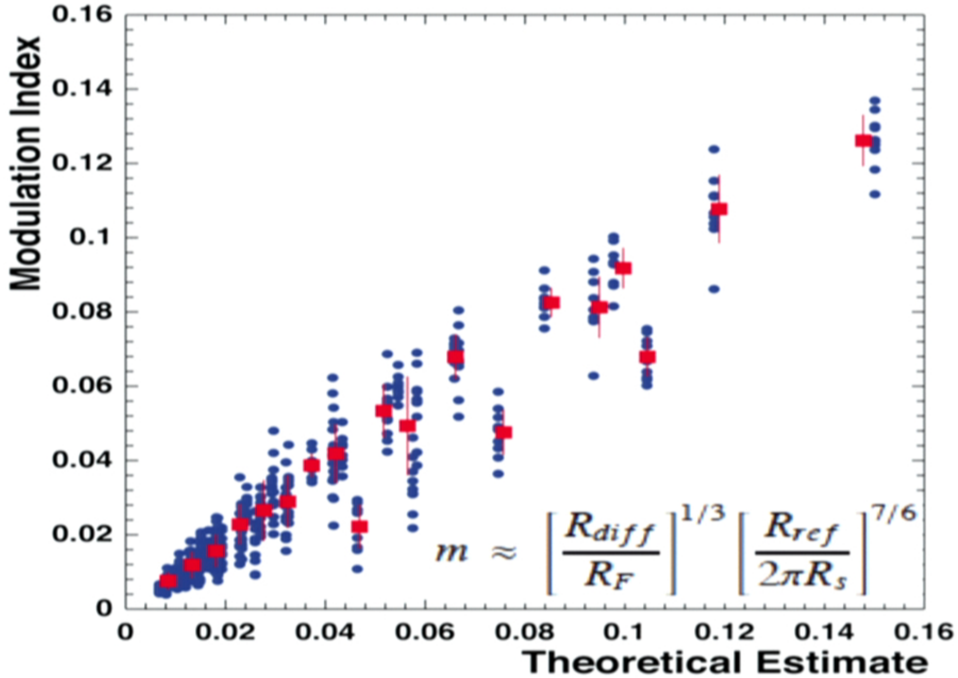

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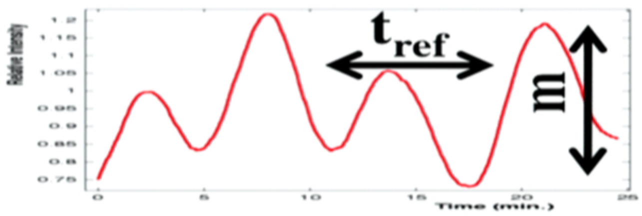

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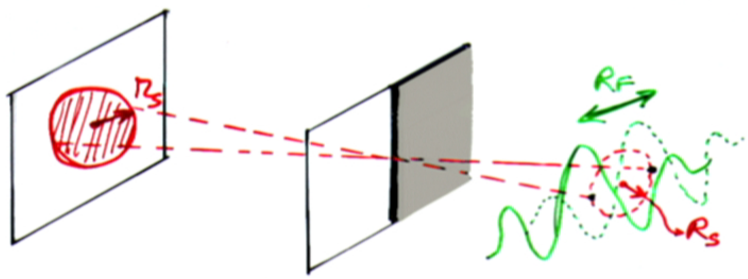
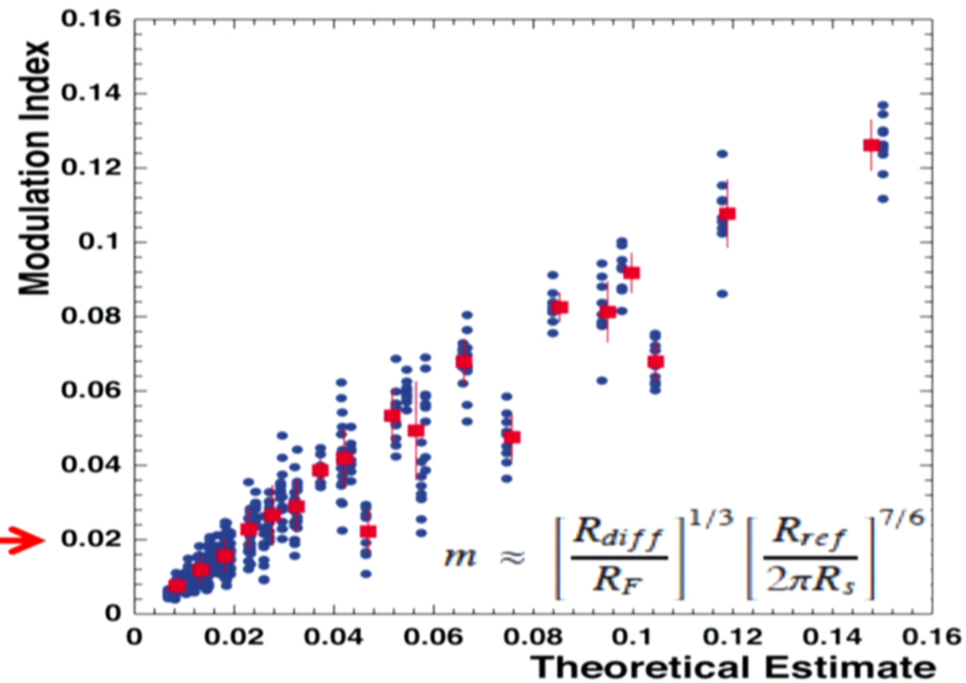


Scintillation@λ = 1 μm of Sun@10kpc (V~20) through a cloud@160pc with R_{diff}=1000km



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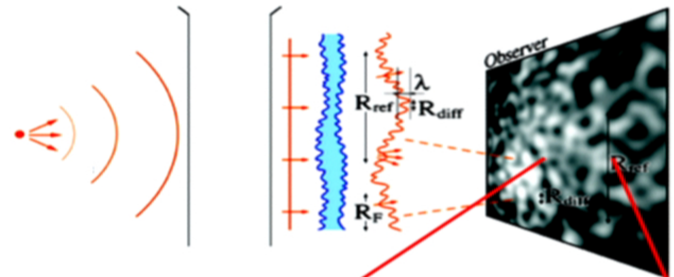
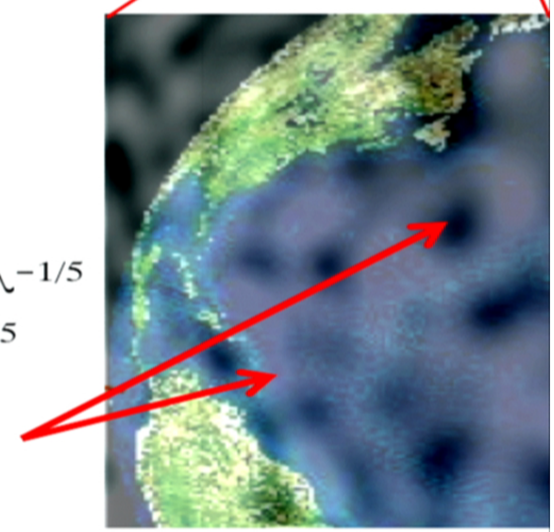
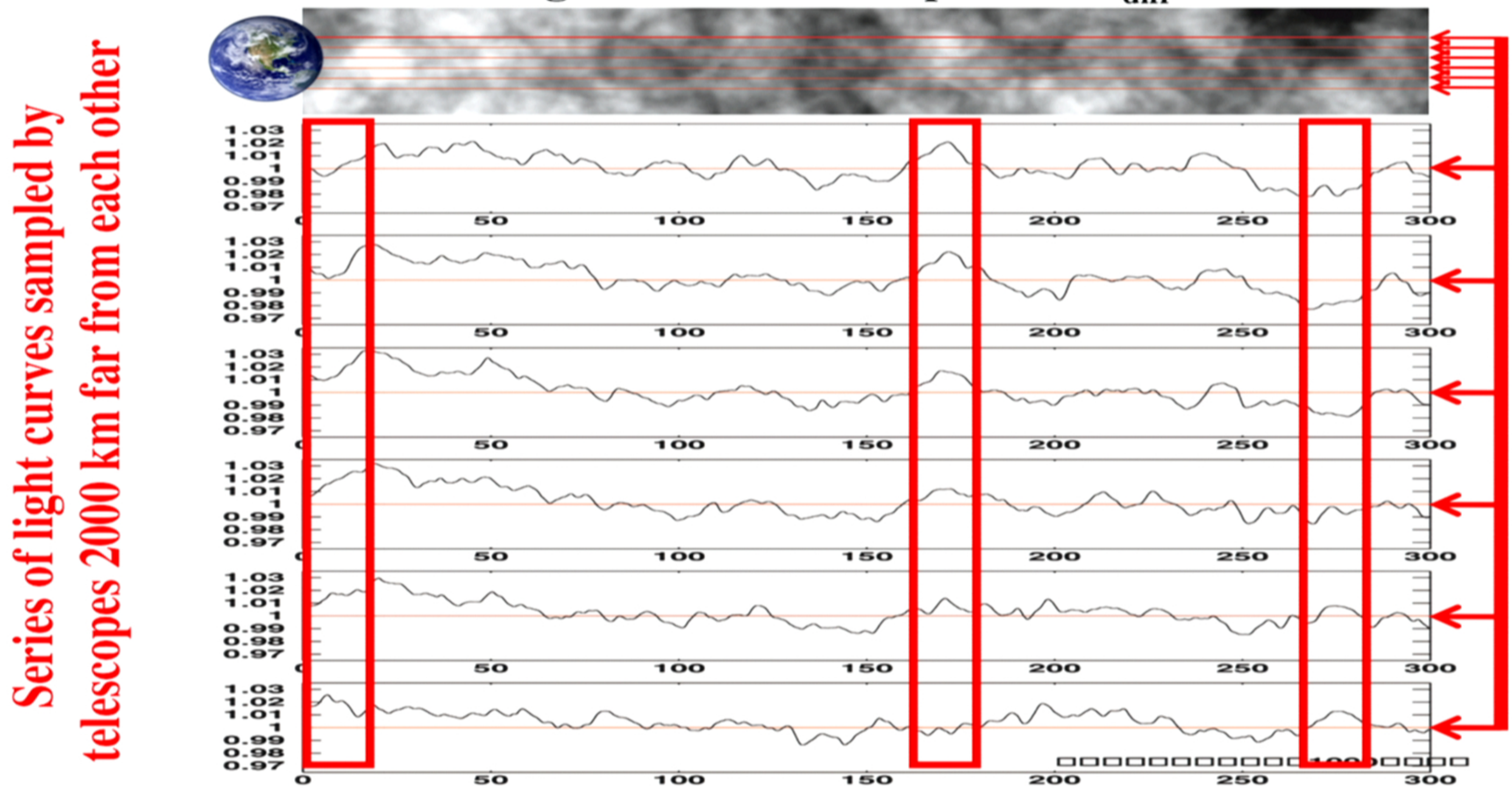


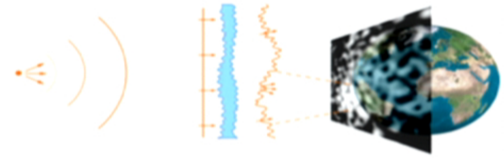


Illumination from a $0.5xR_{sun}$ star@1Kpc

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



Fore and backgrounds



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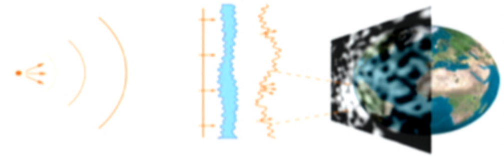
- **High altitude cirruses**
  - Would induce easy-to-detect **collective** effects on neighbour stars, whereas scintillation by a 10AU object affects only one star.



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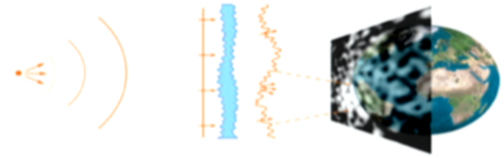

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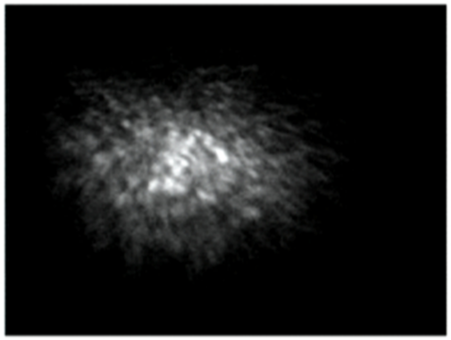
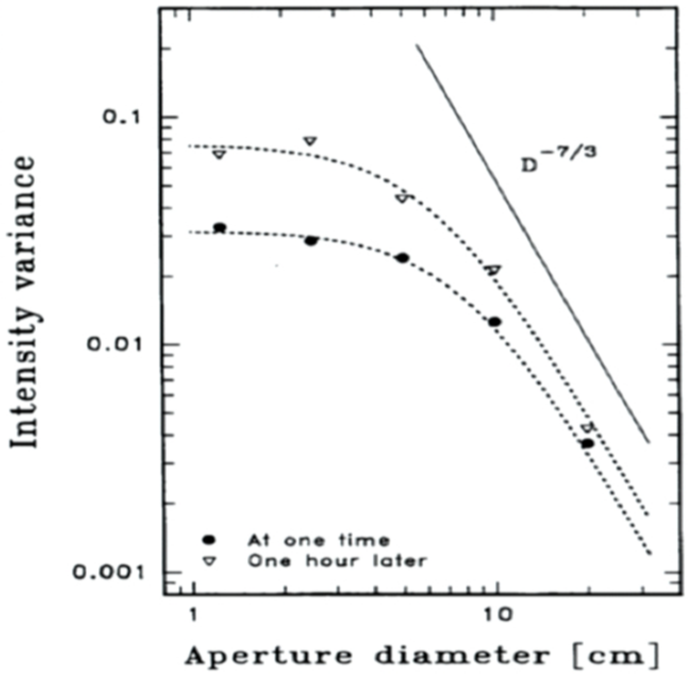
- **Intrinsic variability**
  - •Rare at this time scale and only with special stars (UV Ceti, flaring Wolf-Rayet)

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 »

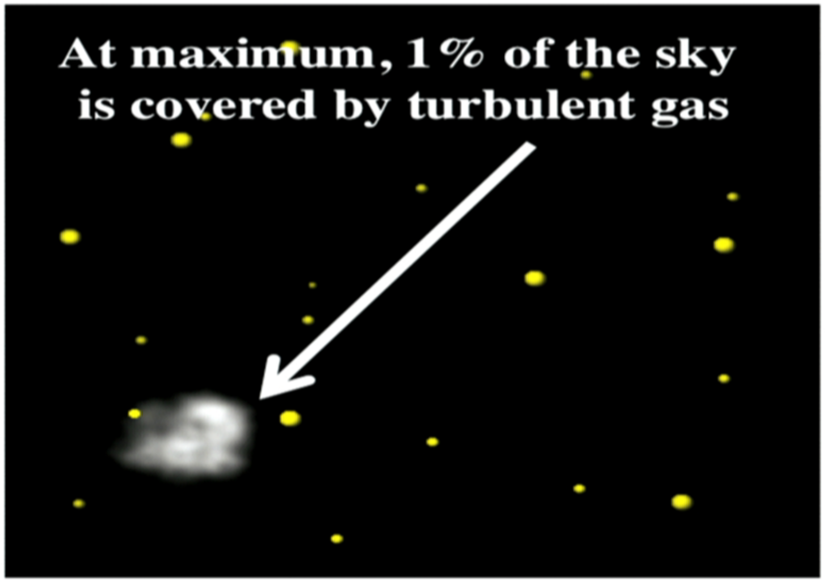




Aperture dependence of the intensity variance (2 series of measurements)

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 $m > m_{threshold}$

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- **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 $r_s < r_{A5}$ ($10^5/deg^2$)

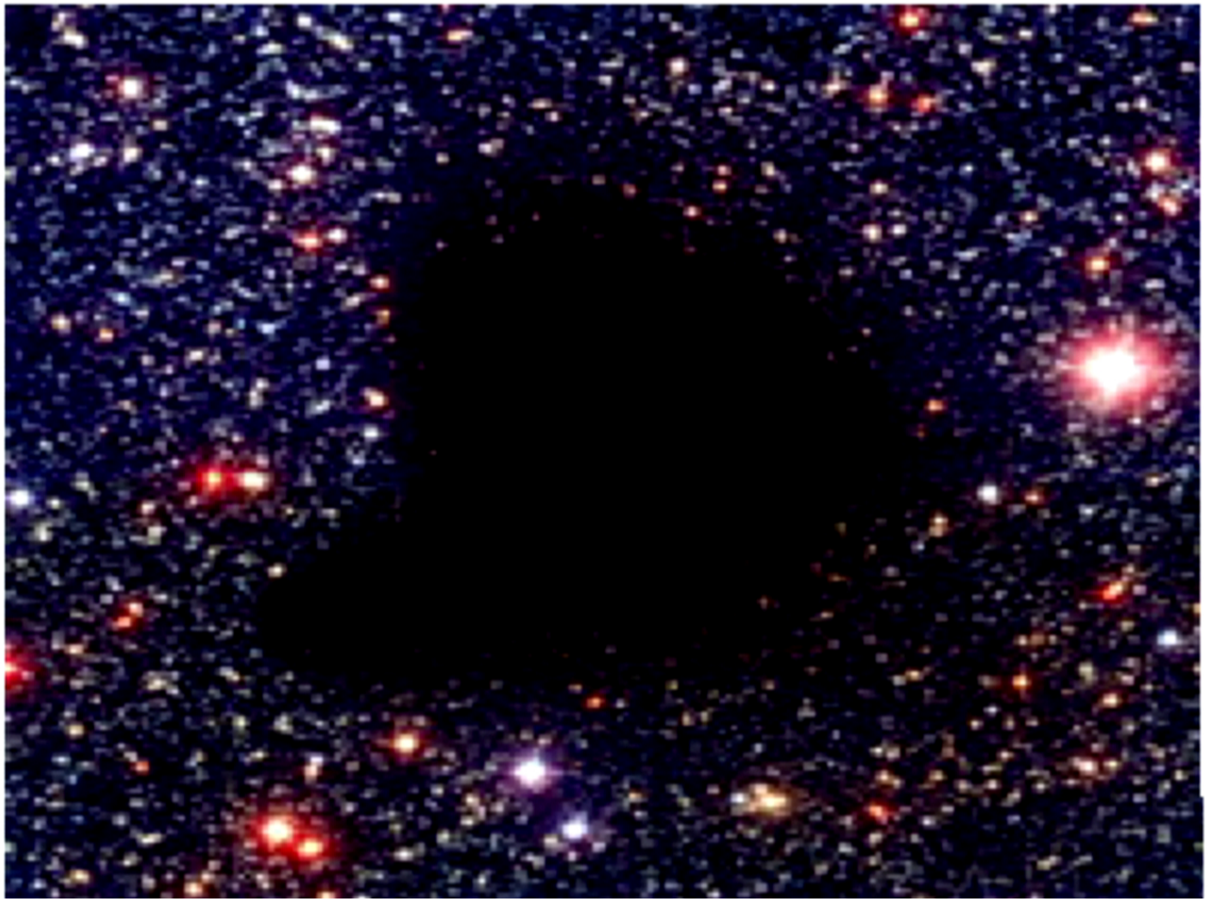
✓ Smaller than **A5** type in LMC =>
✓ Characteristic time ~ few min. =>
✓ Photometric precision required

$M_V \sim 20.5$
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*
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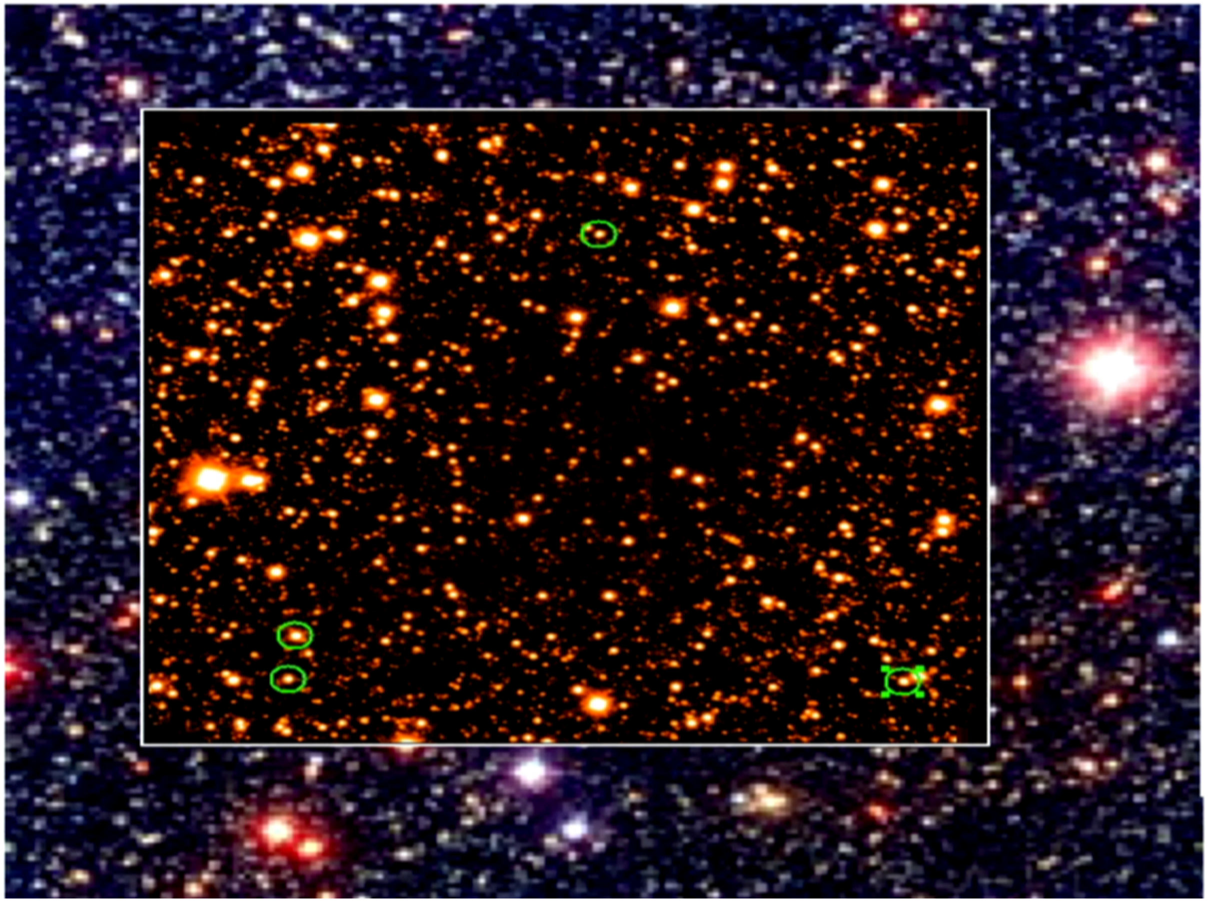

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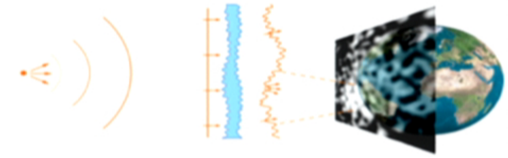
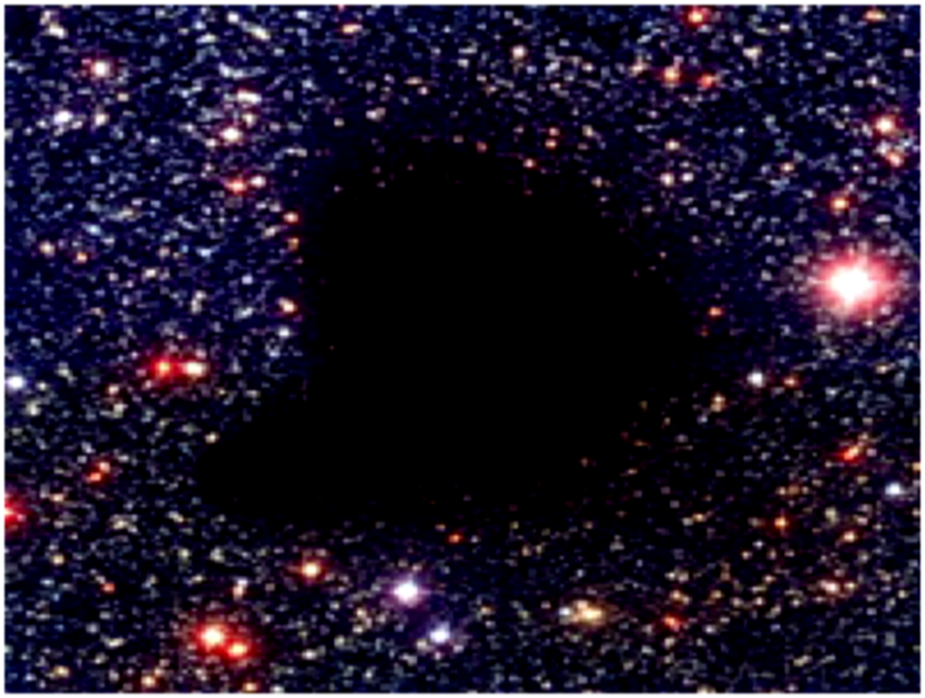


Mainly a test for background estimates and feasibility



- **B68 (& cb131, Circinus nebula)**
  - **dust + existing gas at $z_0 \sim 160\ pc$**
  - Column density $\boldsymbol{Nl} \sim 2.6 \times 10^{22} cm^{-2}$
  - 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**
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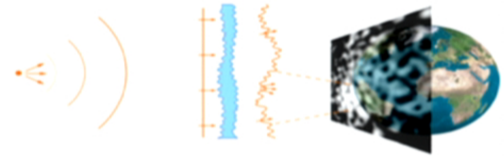

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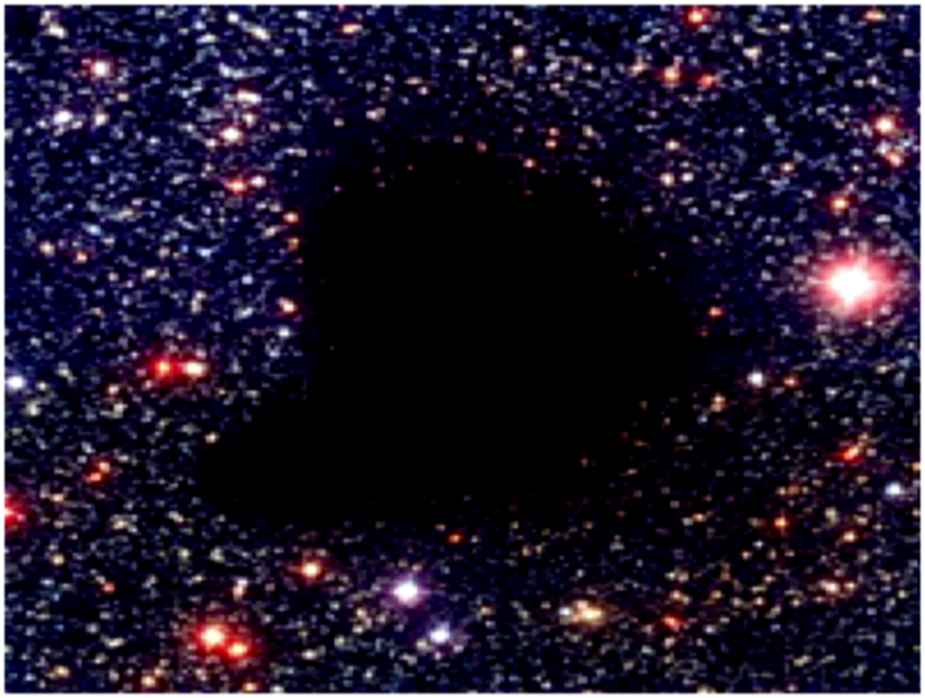

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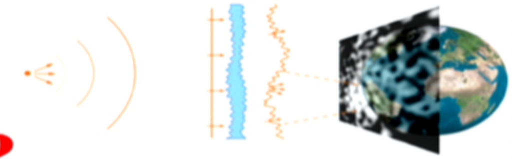
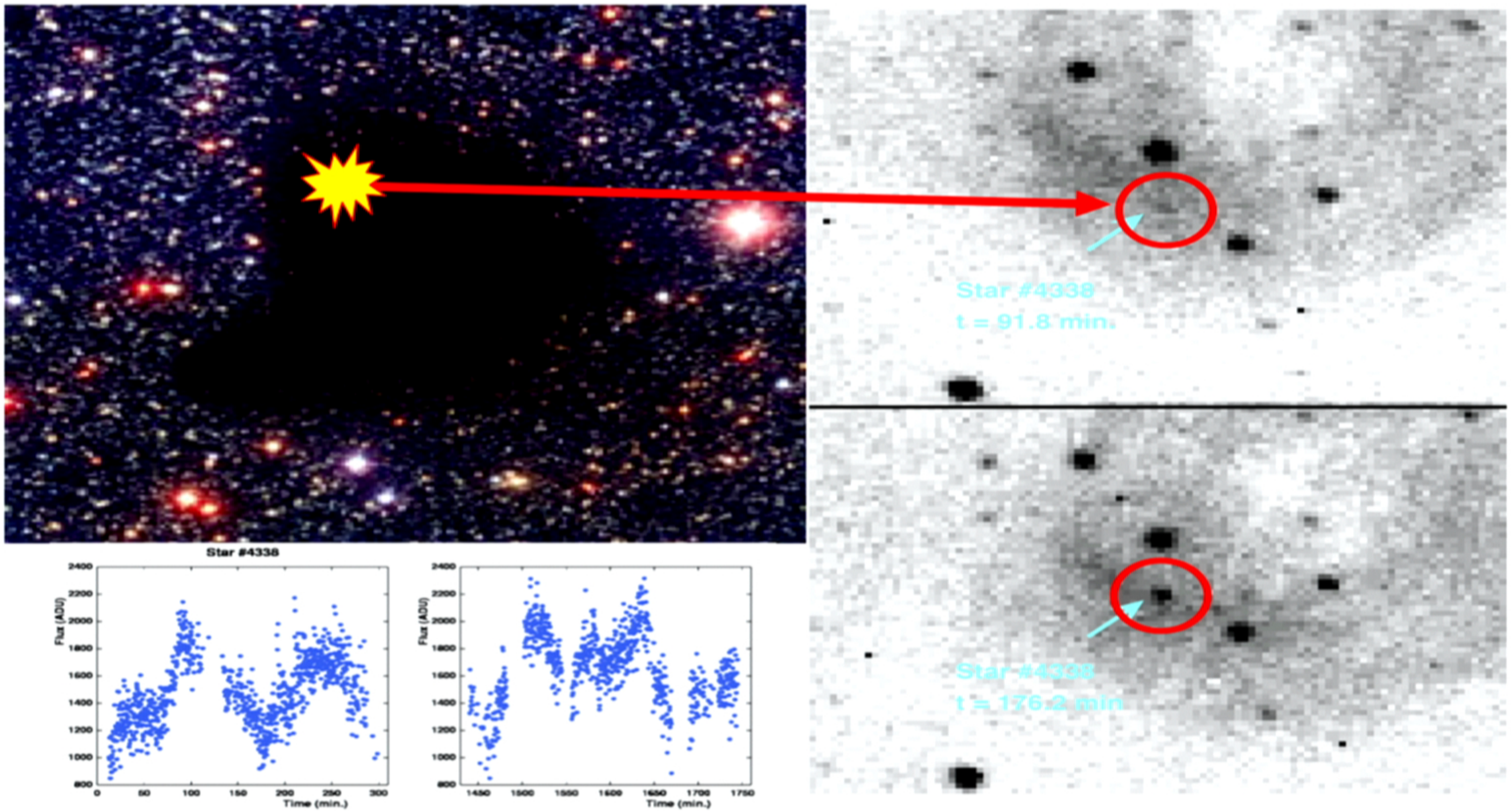
- **SMC**
  - **blind search for invisible gas**
  - **980 stars monitored at $z_1 \sim 64\ kpc$**
  - **1000 exposures of 10s in 2 nights**
- **Search for few % variability**

Results toward B68:
A star scintillating through visible gas?





Results from faisibility studies:
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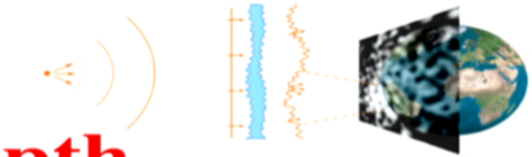

First fundamental result : **no overwhelming unexpected background**

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

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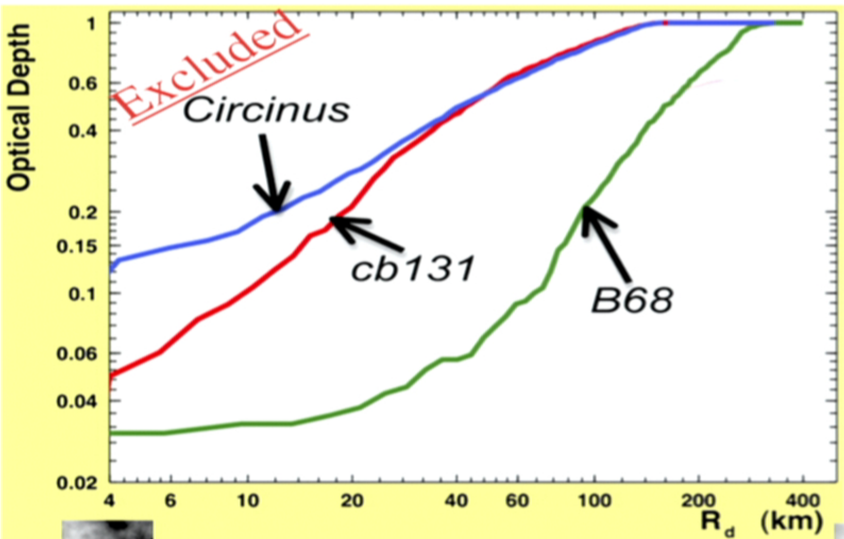
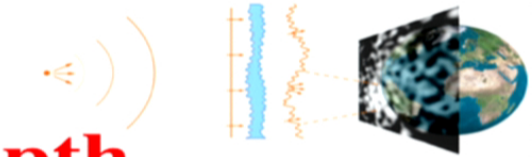
stars behind visible gas (B68 and other nebulae)



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**

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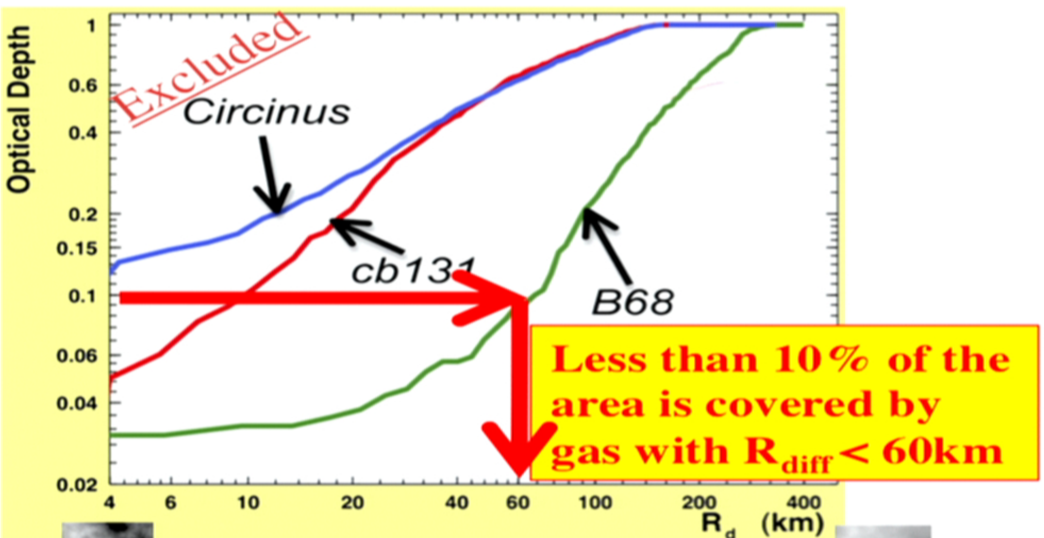

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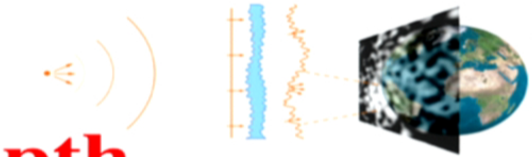

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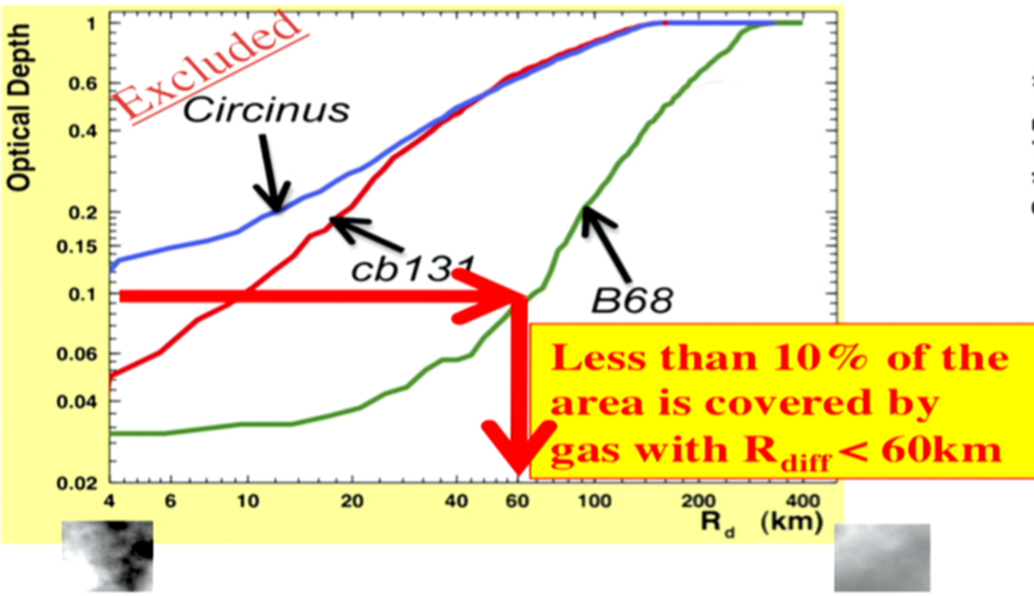
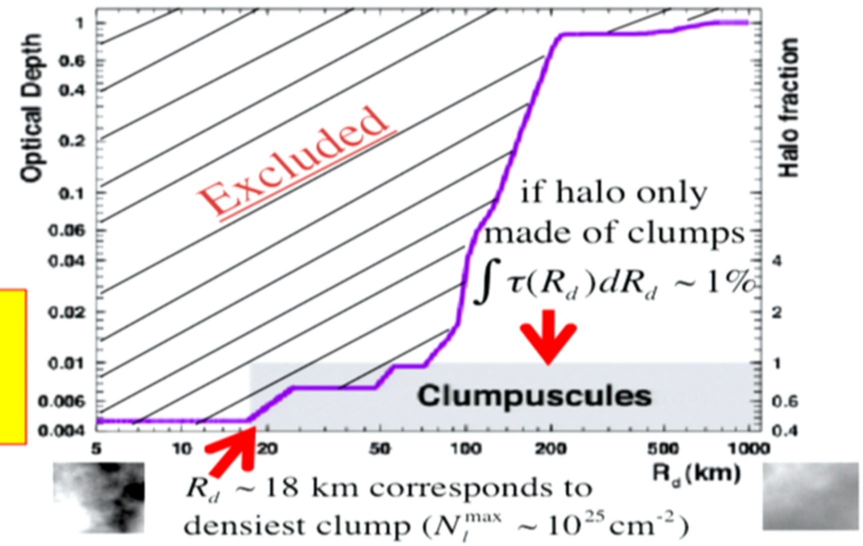
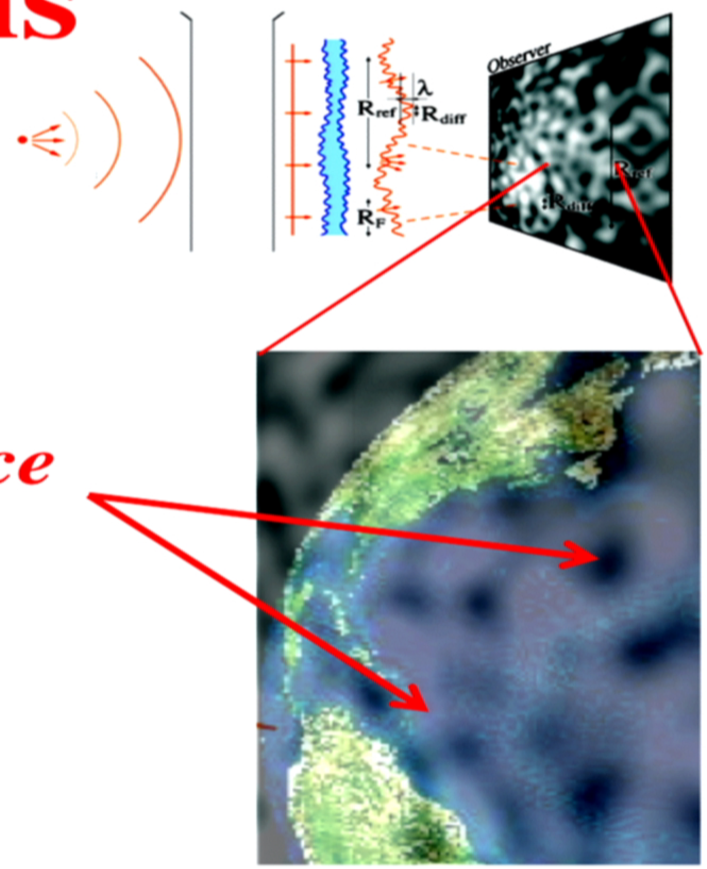


blind search with stars behind invisible gas (SMC)



short term plans

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

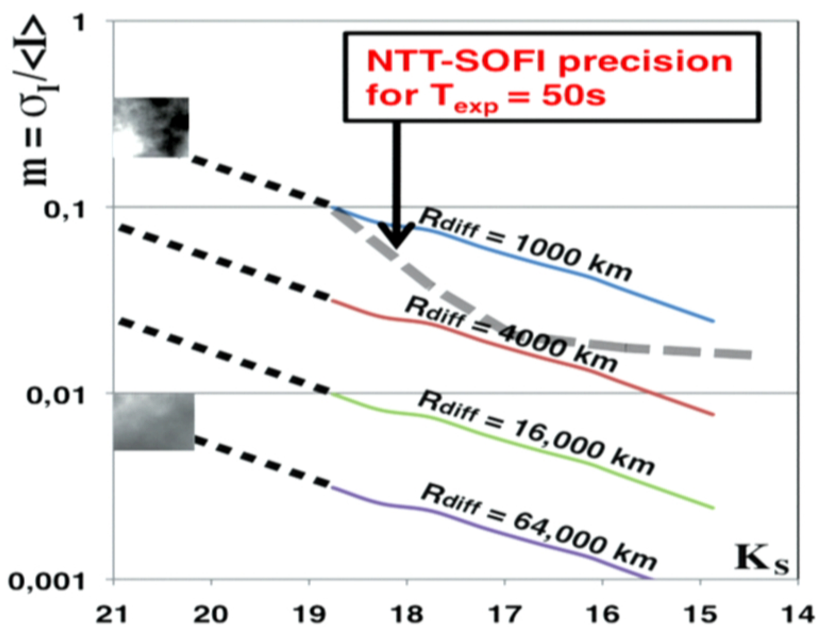


- Obtain synchronous observations from 2 **very** distant telescopes
-> **GEMINI** telescopes?
- And/or « standard » telescope observations with complementary observations on candidates

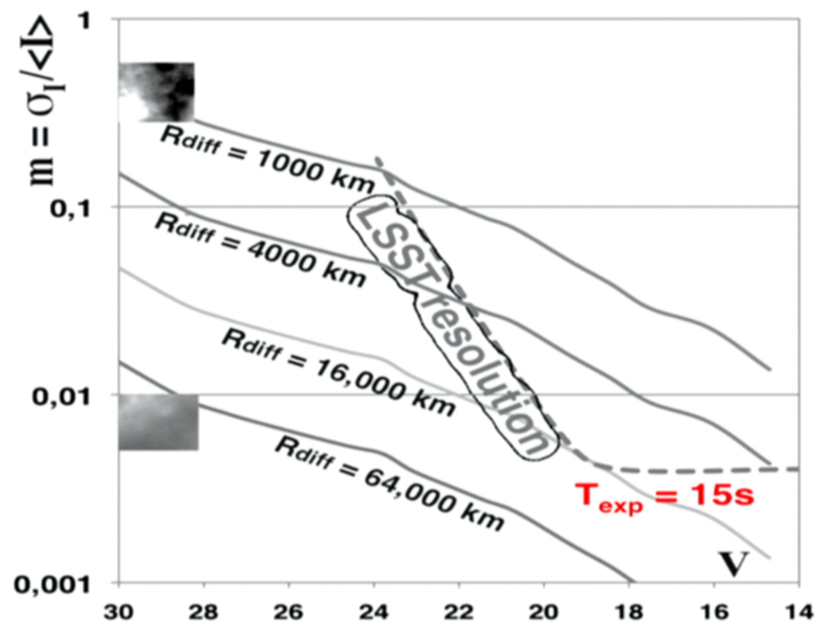
Scintillation with LSST (15s exp.) or your telescope

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**



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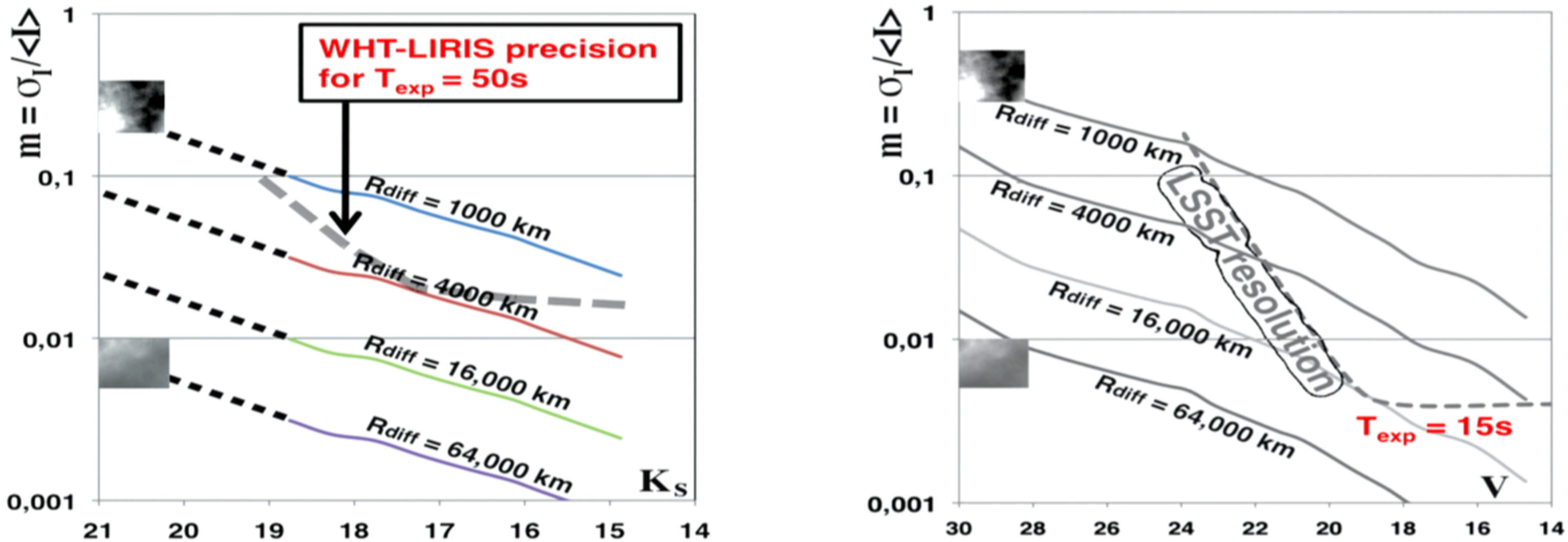

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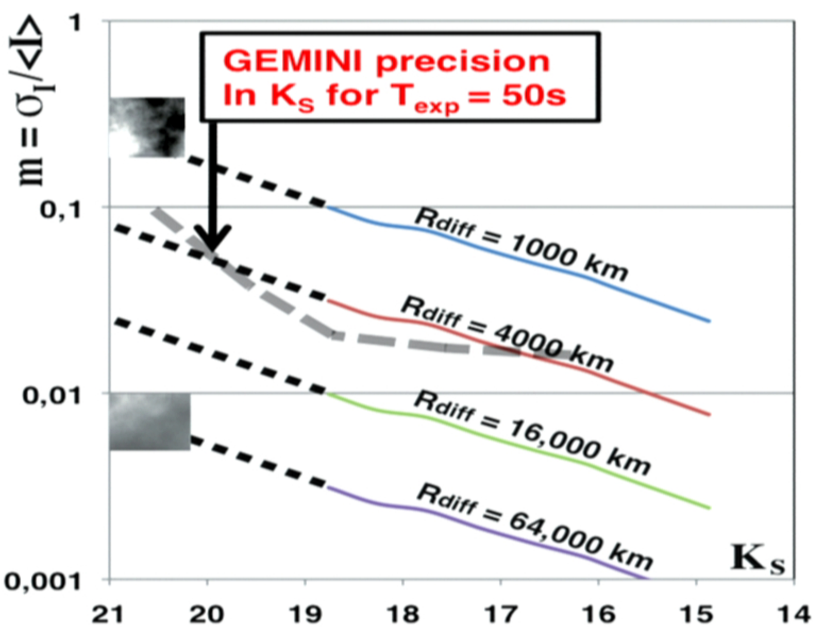

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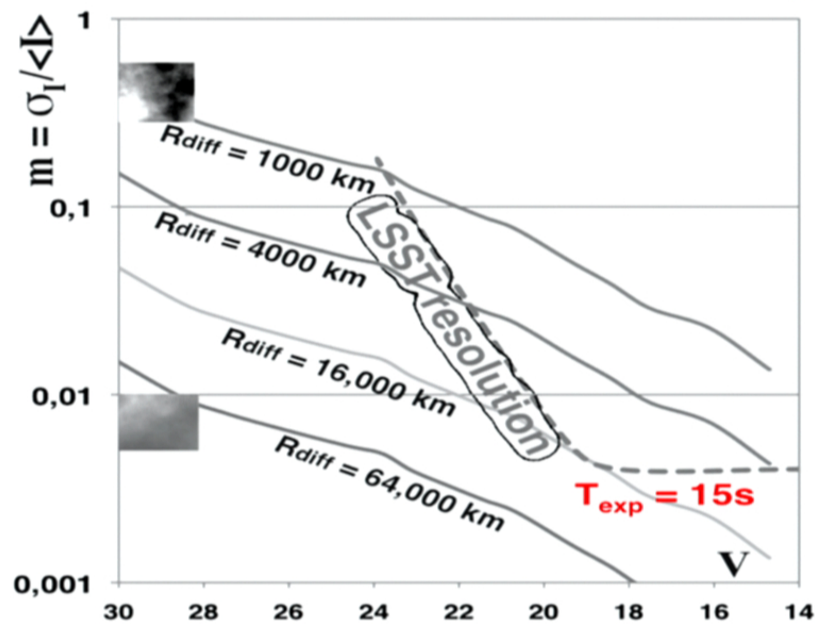
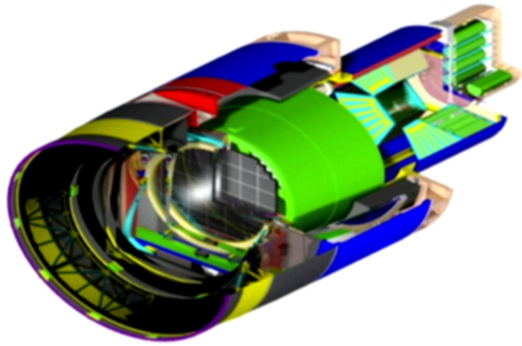


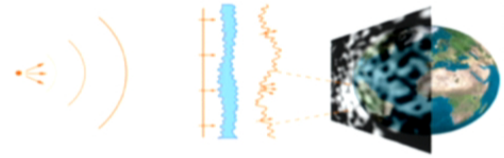
LSST : Large Synoptic Survey Telescope

- 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…



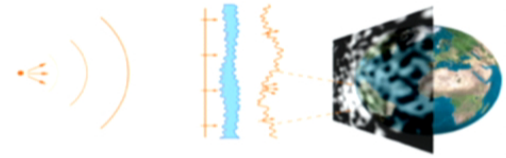
http://www.lsst.org/

Scintillation with LSST



Need for long series (hours)
of short exposures (15s)

Scintillation with LSST



Need for long series (hours)

of short exposures (15s)

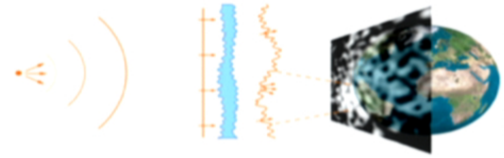
from the same wide field

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?

Scintillation with LSST



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>> 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

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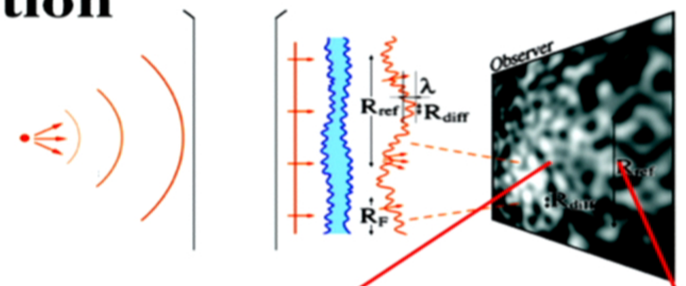
A network of distant telescopes

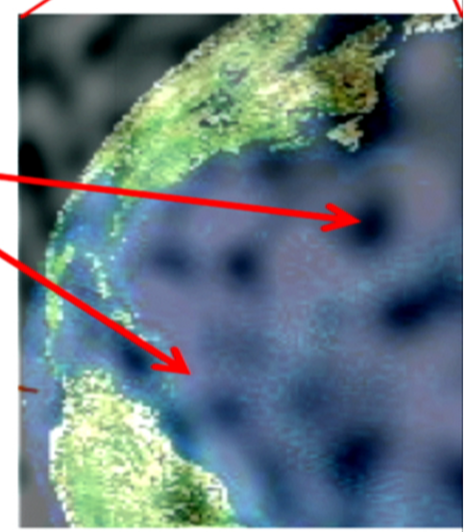
- Would allow to distinguish scintillation from intrinsic variabilities

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)