Search for Galactic hidden gas

The Optical Scintillation by Extraterrestrial Refractors Project
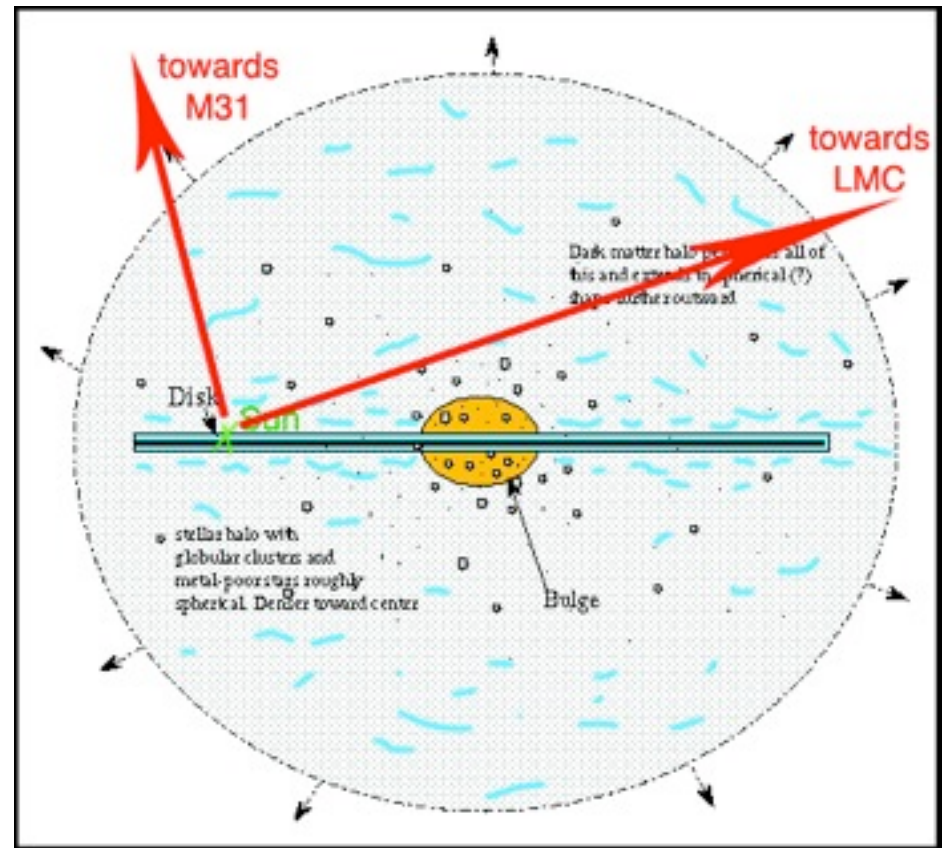
Marc MONIEZ, IN2P3, CNRS

Tucson 03/19/2010

OSER project: measure the last unknown contribution to the baryonic hidden matter: cold H_2 (+He)
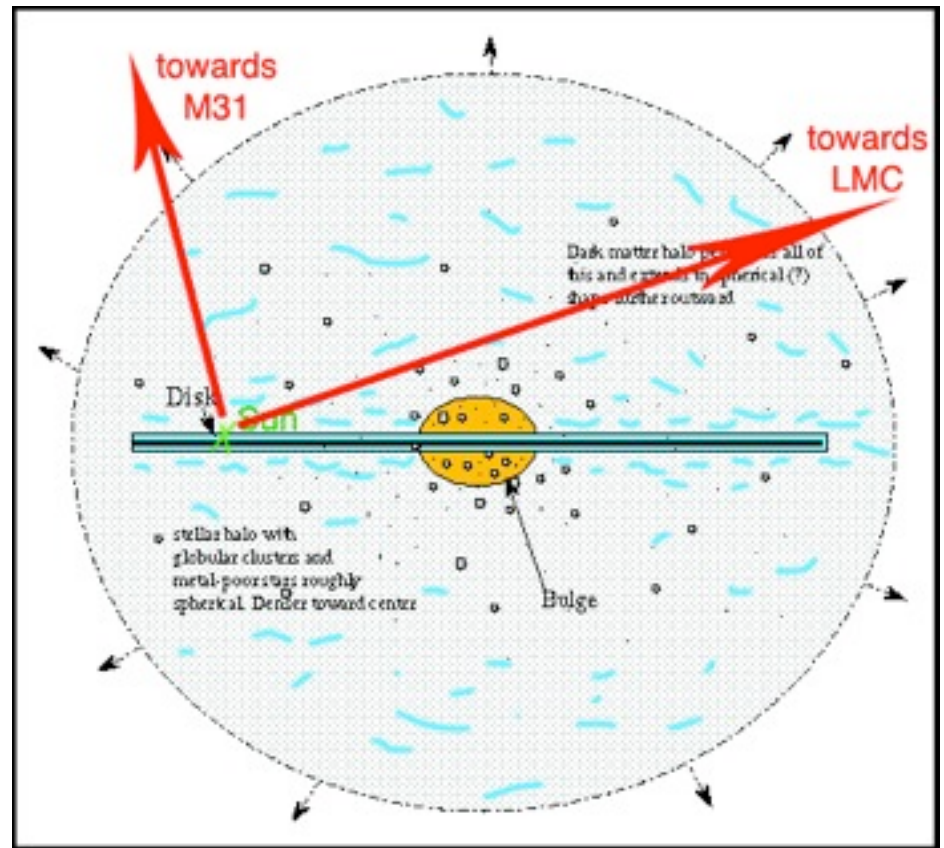
OSER project: measure the last unknown contribution to the baryonic hidden matter: cold H_2 (+He)

- Cold (**10K**) => no emission. Transparent medium.

OSER project: measure the last unknown contribution to the baryonic hidden matter: cold H_2 (+He)

- Cold (**10K**) => no emission. Transparent medium.
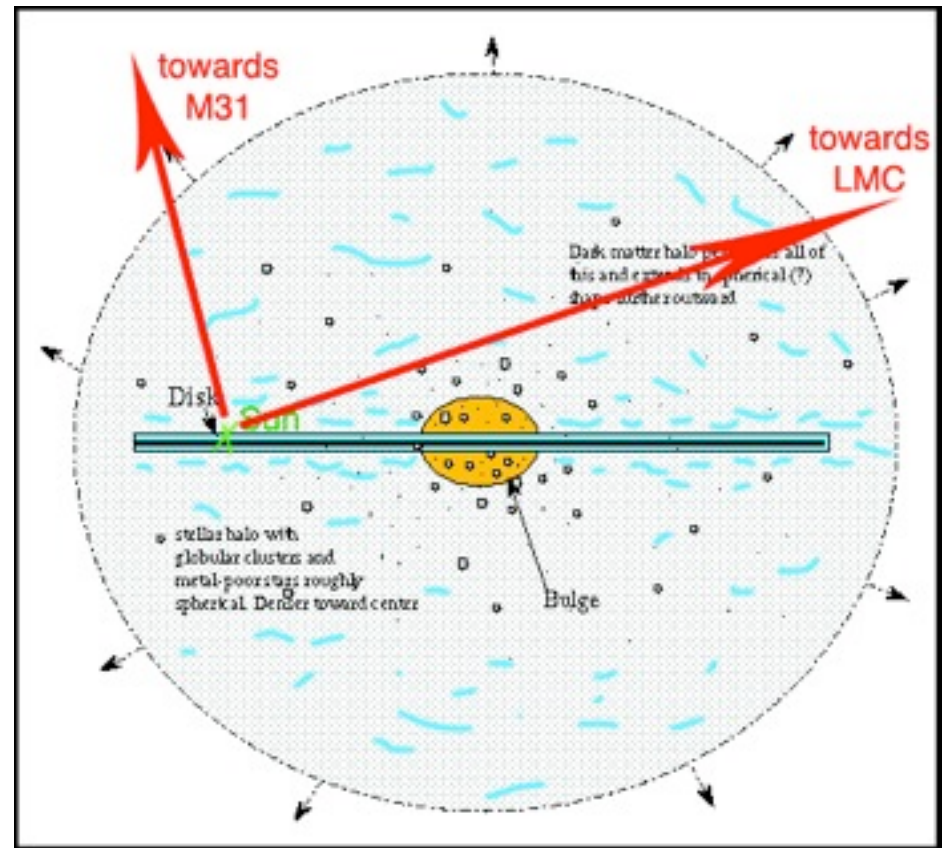- In the **thick disk** or/and in the **halo**

OSER project: measure the last unknown contribution to the baryonic hidden matter: cold H_2 (+He)

- Cold (**10K**) => no emission. Transparent medium.
- In the **thick disk** or/and in the **halo**
- Average column density toward LMC

OSER project: measure the last unknown contribution to the baryonic hidden matter: cold H_2 (+He)

- Cold (**10K**) => no emission. Transparent medium.

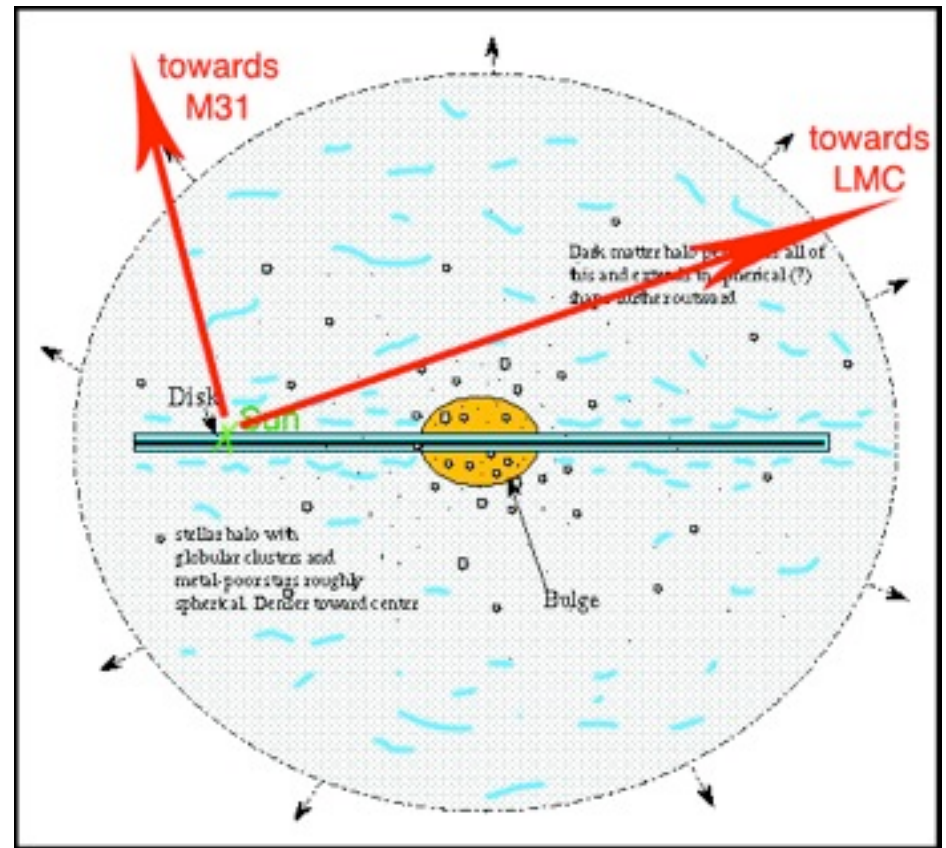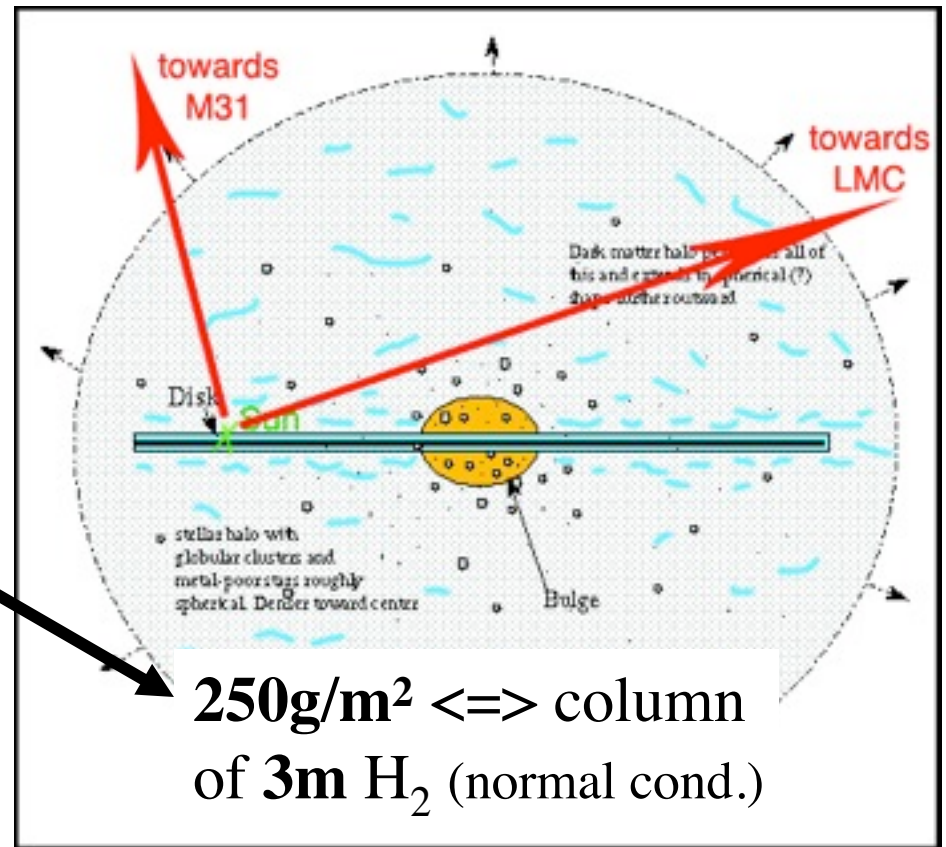- In the **thick disk** or/and in the **halo**

- Average column density toward LMC

250g/m² <=> column of **3m** H_2 (normal cond.)

OSER project: measure the last unknown contribution to the baryonic hidden matter: cold H_2 (+He)

- Cold (**10K**) => no emission. Transparent medium.
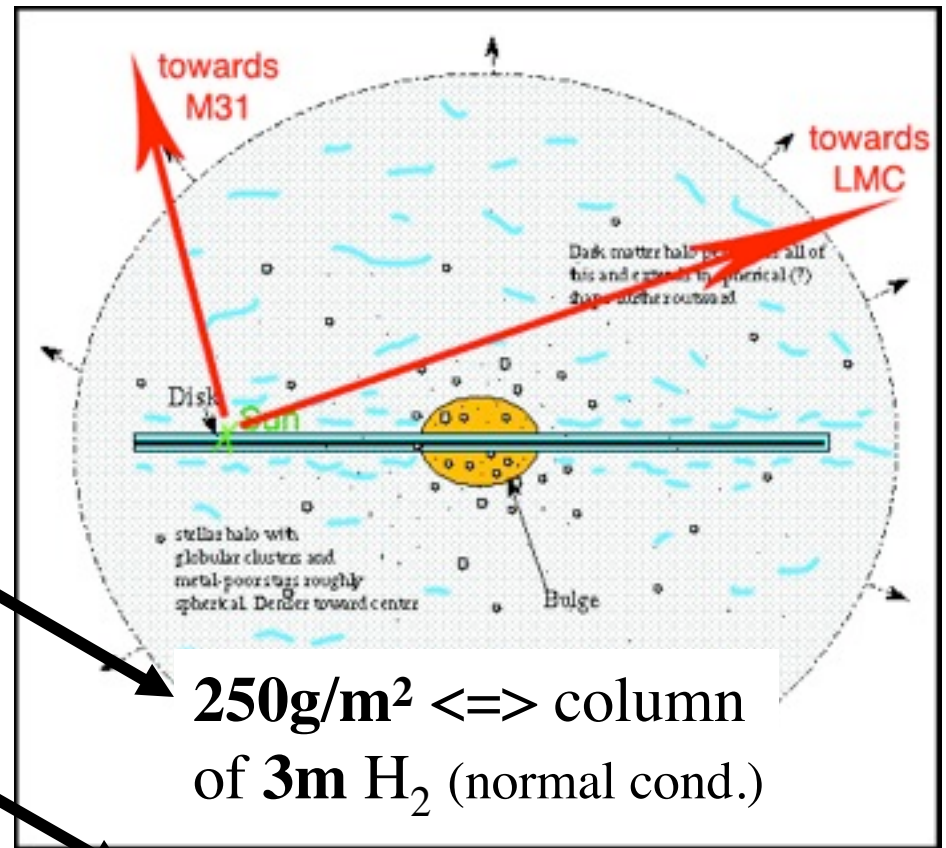- In the **thick disk** or/and in the **halo**
- Average column density toward LMC

  • *Fractal structure*: covers ~**1%** of the sky.
  Clumpuscules ~10 AU (Pfenniger & Combes 1994)

towards M31

towards LMC

Dark matter halo [...] all of this and extends in spherical (?) shape rather routinard

Disk

Sun

• stellar halo with globular clusters and metal-poor stars roughly spherical. Denser toward center

Bulge

250g/m² <=> column of **3m** H_2 (normal cond.)

~**300m** H_2 over 1% of the sky

# These clouds refract light

These clouds refract light

- Extra optical path due to H_2 medium
  $\Rightarrow$ Varies from **0** (99% sky) to **~80 000**λ (1%) @ λ=500nm

These clouds refract light

- Extra optical path due to H_2 medium

  $\Rightarrow$ Varies from **0** (99% sky) to **~80 000**λ (1%) @ λ=500nm

- If the medium has column density fluctuations (turbulences) **of order of a few 10^{-6}** then wavefront distorsions may be detectable
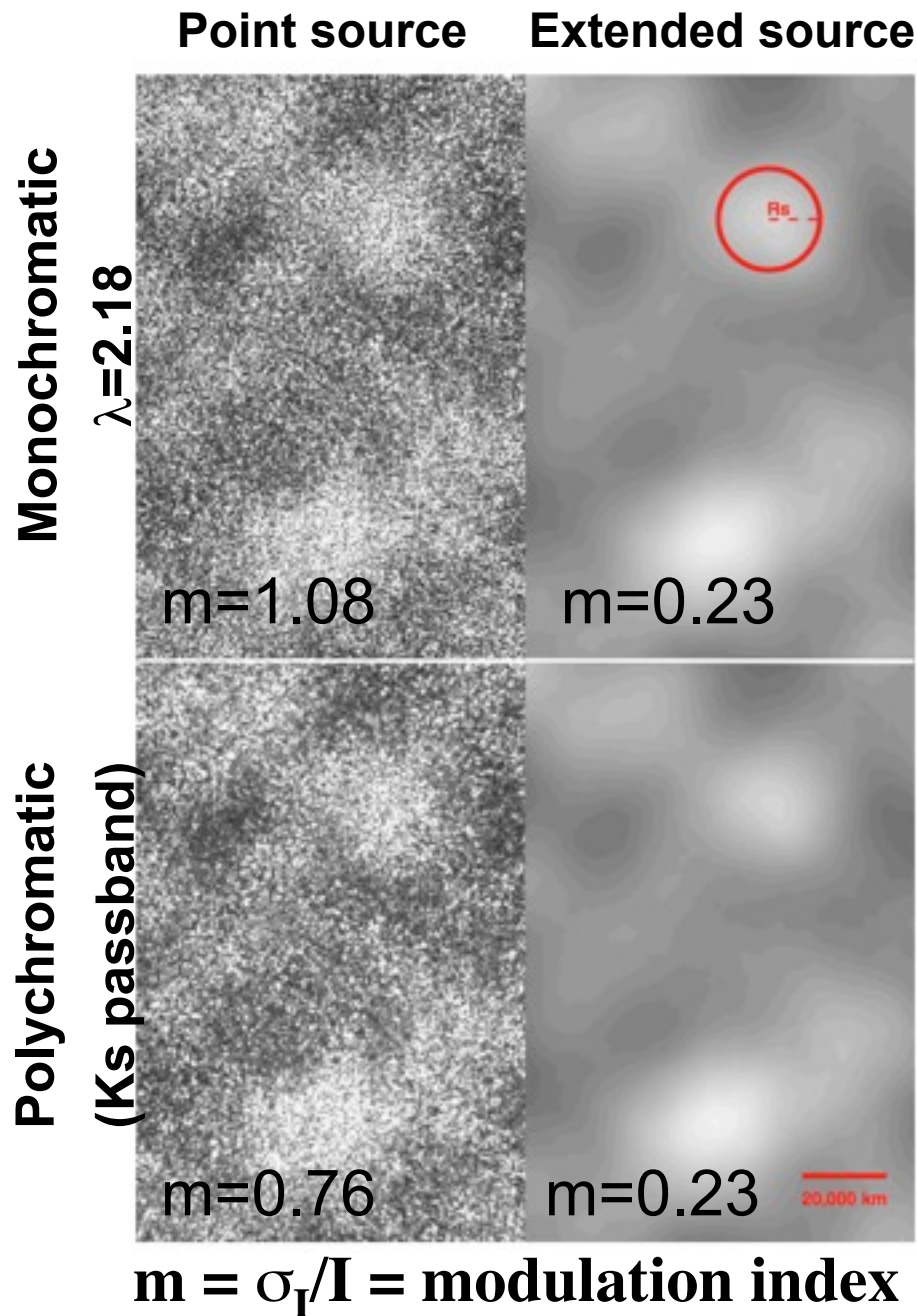
Scintillation through a diffusive screen

Propagation of distorted wave surface driven by:
Fresnel diffraction + « global » refraction
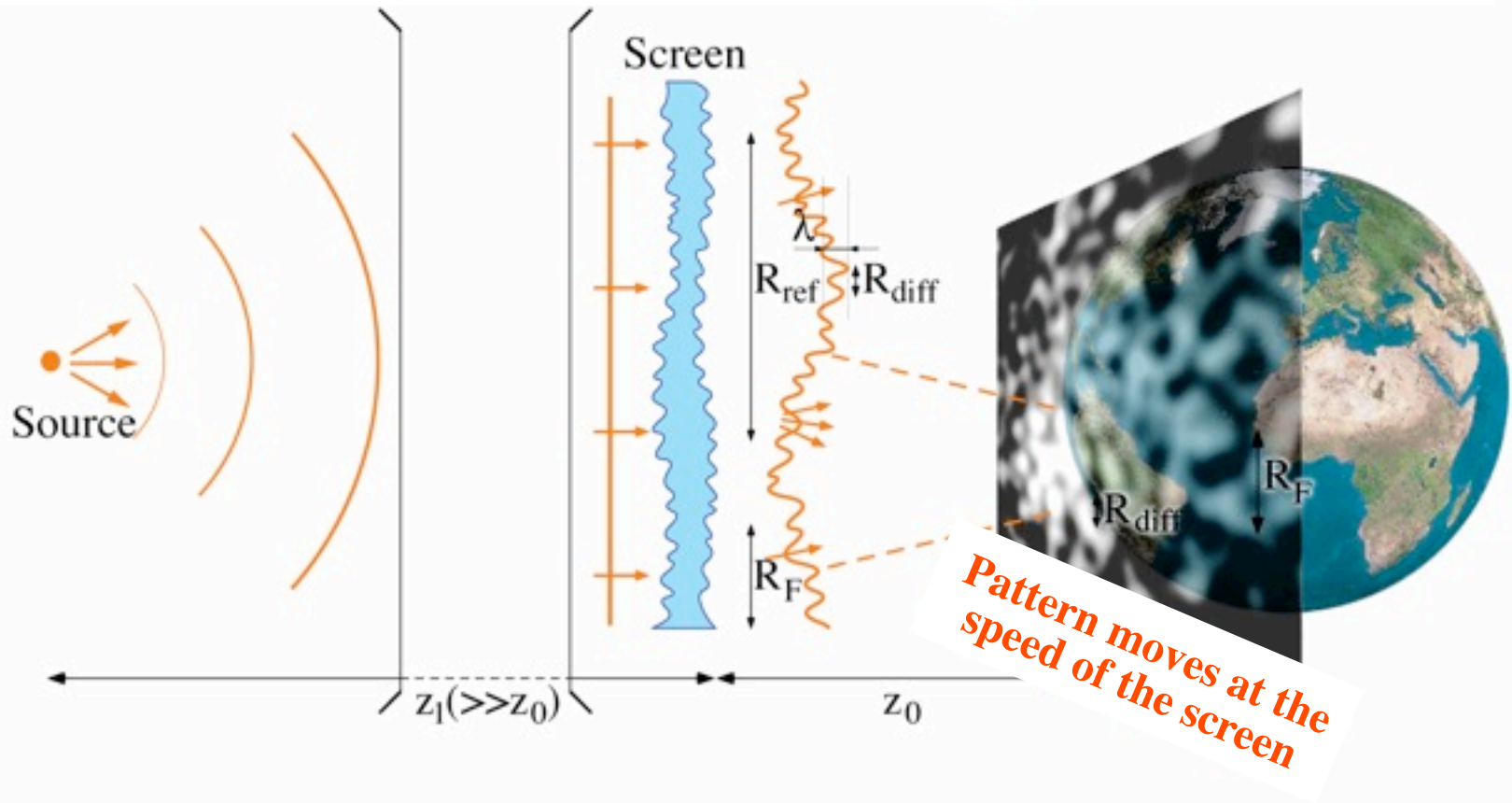
Point source   **Extended source**
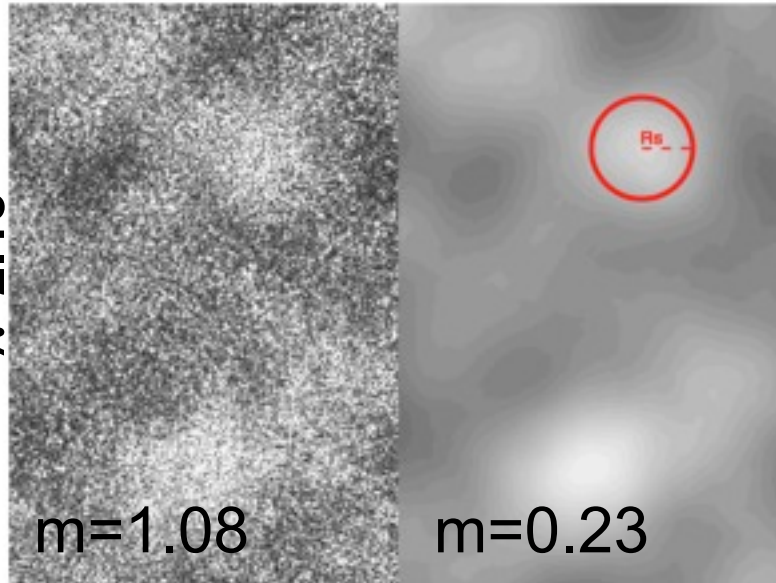
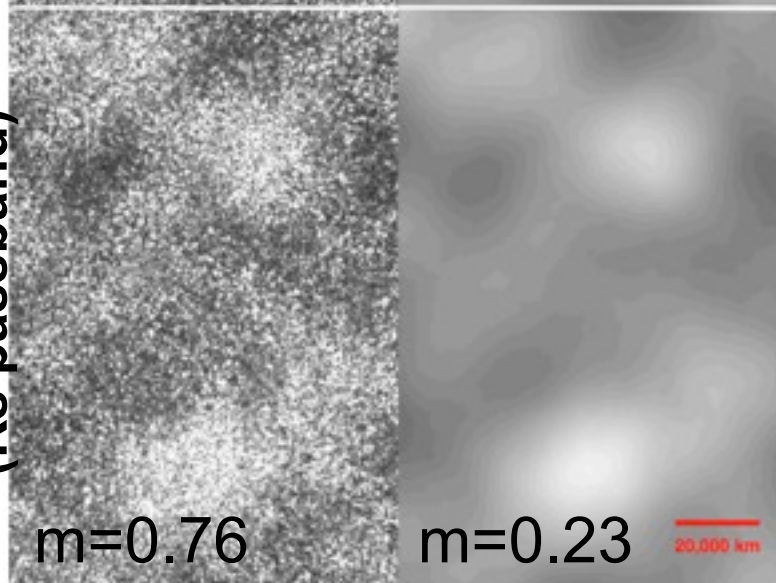Monochromatic λ=2.18

m=1.08   m=0.23

Polychromatic (Ks passband)

m=0.76   m=0.23

Simulation towards B68

$\mathbf{m = \sigma_I/I}$ = **modulation index**

Point source   **Extended source**

Monochromatic
$\lambda=2.18$

m=1.08   m=0.23

Polychromatic (Ks passband)

m=0.76   m=0.23

$\mathbf{m} = \sigma_I/I = \textbf{modulation index}$

Simulation towards B68

Illumination in **Ks** by a **K0V** star@8kpc (m_V=20.4) through a cloud@160pc
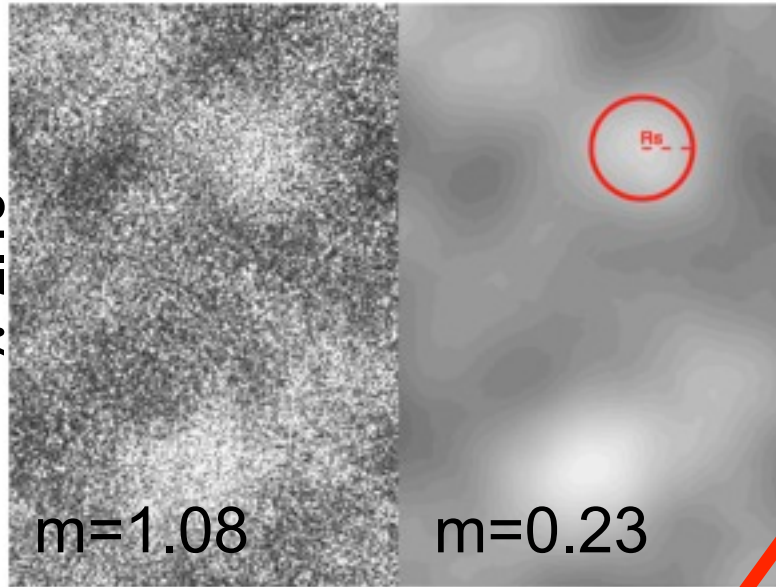
Simulation towards B68

Illumination in **Ks** by a **K0V** star@8kpc (m_V=20.4) through a cloud@160pc

Point source   **Extended source**

Monochromatic λ=2.18

m=1.08   m=0.23

Polychromatic (Ks passband)

m=0.76   m=0.23

m = σ_I/I = modulation index

Point source **Extended source**

Monochromatic $\lambda = 2.18$

m=1.08   m=0.23

Polychromatic (Ks passband)

m=0.76   m=0.23

20,000 km
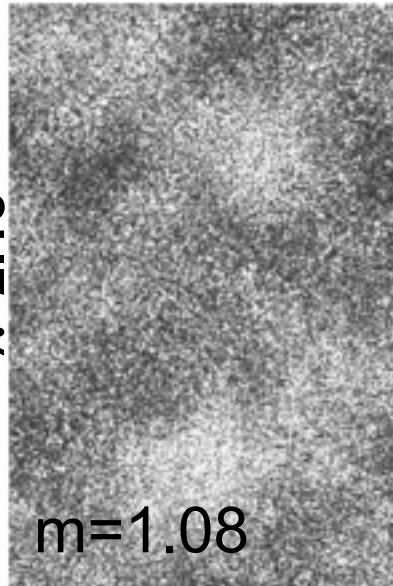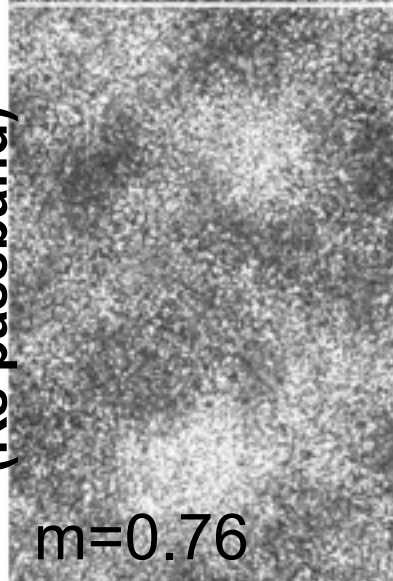
$\mathbf{m = \sigma_I/I = \text{modulation index}}$

Simulation towards B68

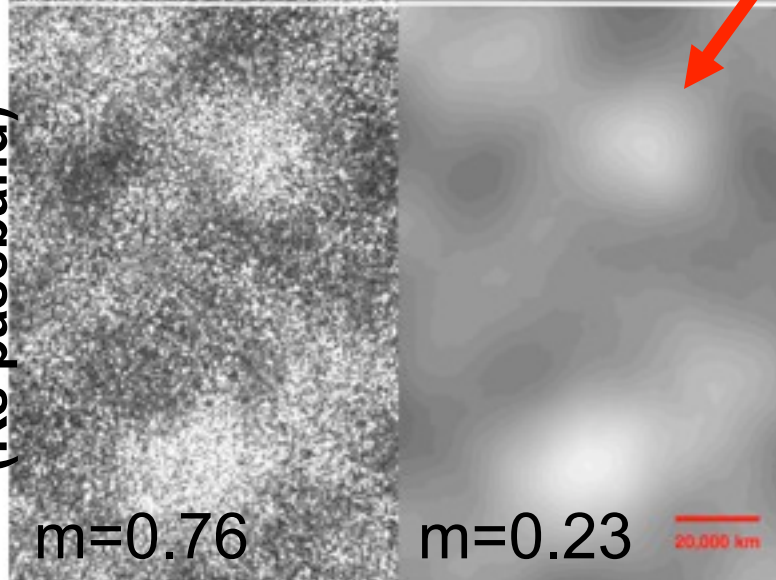Illumination in **Ks** by a **K0V** star@8kpc (m_V=20.4) through a cloud@160pc

Simulated light curve
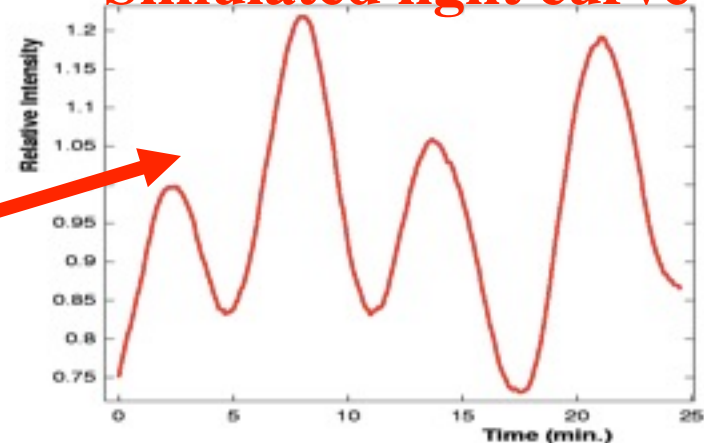
Distance scales

Distance scales

5 distance scales are found in the speckle pattern

Distance scales

5 distance scales are found in 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

Distance scales

5 distance scales are found in 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

- **Fresnel radius R_F**
  - scale of Fresnel diffraction $\sim 10^3$ km @$\lambda=1\mu$ for gas@1kpc

Distance scales

5 distance scales are found in the speckle pattern

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

- **Fresnel radius R_F**
  - scale of Fresnel diffraction $\sim 10^3$ km @$\lambda = 1\mu$ for gas@1kpc

- **Refraction radius R_{ref}**
  - diffractive spot of R_{diff} patches $\sim 2\pi R_F^2/R_{diff}$

Distance scales

5 distance scales are found in 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

- **Fresnel radius R_F**
  - scale of Fresnel diffraction $\sim 10^3$ km $@\lambda=1\mu$ for gas@1kpc

- **Refraction radius R_{ref}**
  - diffractive spot of R_{diff} patches $\sim 2\pi R_F^2/R_{diff}$

- **Larger scale structures** of the diffusive gaz can play a role if focusing/defocusing configurations happen

Distance scales

5 distance scales are found in 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

- **Fresnel radius R_F**
  - scale of Fresnel diffraction $\sim 10^3$ km $@\lambda=1\mu$ for gas@1kpc

- **Refraction radius R_{ref}**
  - diffractive spot of R_{diff} patches $\sim 2\pi R_F^2/R_{diff}$

- **Larger scale structures** of the diffusive gaz 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

Distance scales

5 distance scales are found in 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

- **Fresnel radius R_F**
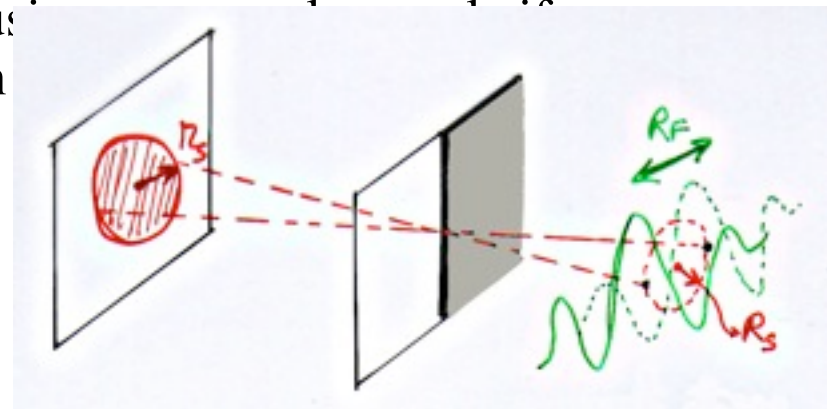   - scale of Fresnel diffraction $\sim 10^3$ km @$\lambda=1\mu$ for gas@1kpc

- **Refraction radius R_{ref}**
    - diffractive spot of R_{diff} patches $\sim 2\pi R_F^2/R_{diff}$

- **Larger scale structures** of the diffus... ...d...if focusing/defocusing configurations happen

- **Projected source size R_S**
speckle from a pointlike source is convoluted by the source projected profile

R_{diff} : Statistical characterization of a stochastic screen

Size of domain where
$\sigma(phase)$ **= 1 radian**

• i.e. (at λ = 500 nm)
$\sigma(column\ density\ nl)$
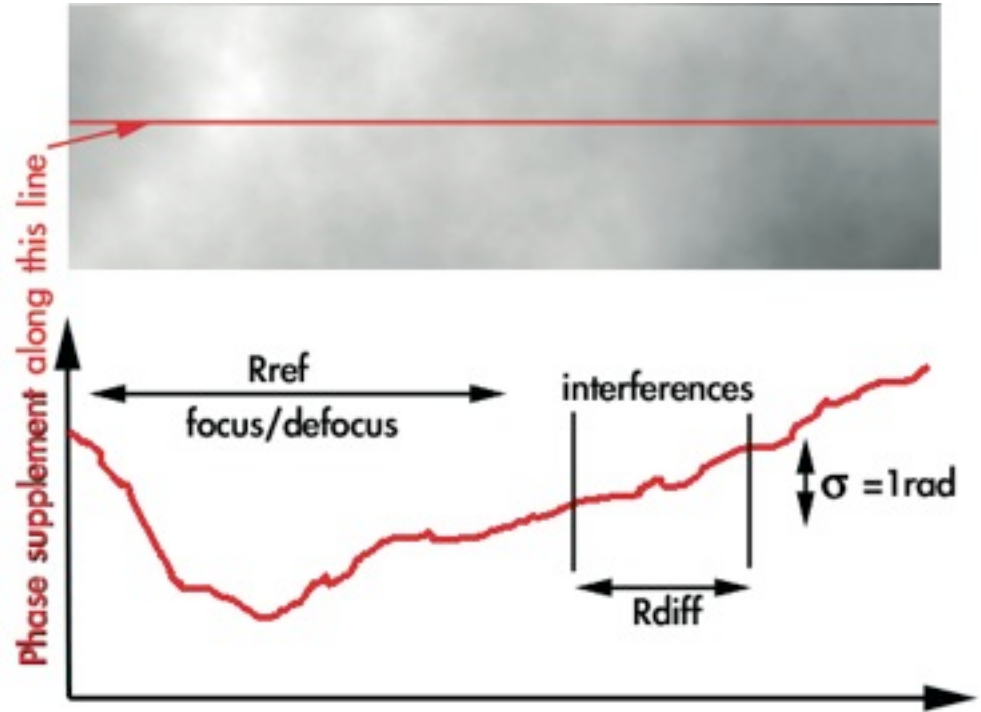 **= 1.8×10^{18}** molecules/cm^2

• This corresponds to

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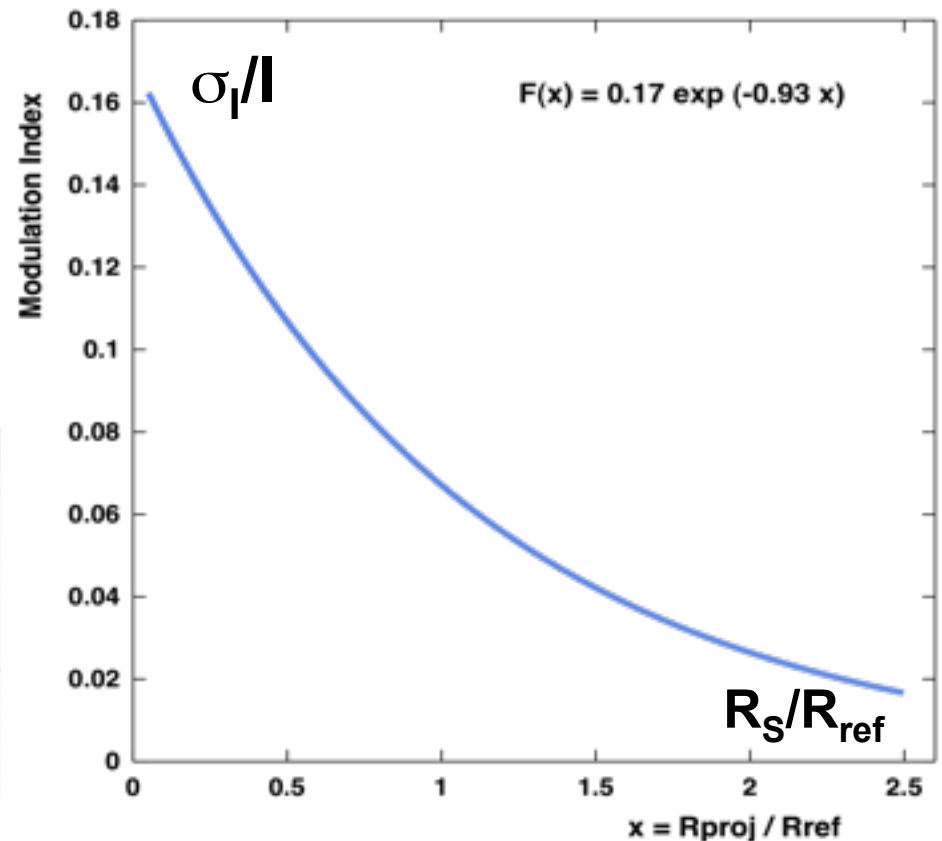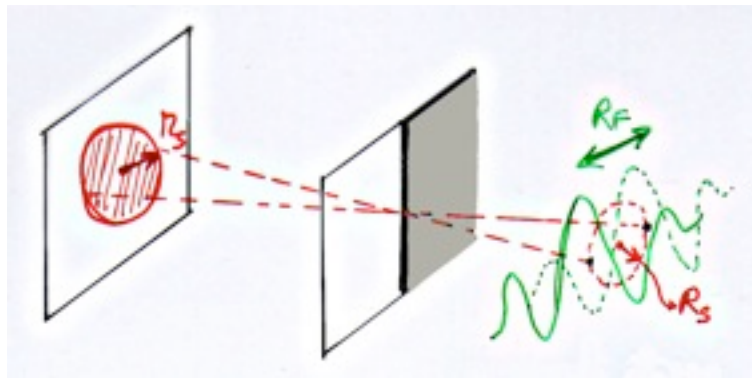- $\Delta nl/nl \sim 10^{-4}$
  for Bok globule (NTT search)

$$R_{diff} = 263\,km \times \left[\frac{\lambda}{1\mu m}\right]^{\frac{6}{5}} \left[\frac{L_z}{10\,A.U.}\right]^{-\frac{1}{5}} \left[\frac{\sigma_{3n}}{10^{15}}\right]^{-\frac{6}{5}}$$

Modulation index

Essentially depends on
R_S/R_{ref}
-> not on the details of
the power spectrum of
the fluctuations

σ_I/I

$F(x) = 0.17 \exp(-0.93 x)$

R_S/R_{ref}

$x = R_{proj} / R_{ref}$

$$\frac{R_S}{R_{ref}} = \frac{r_s R_{diff}}{\lambda z_1} \sim 2.25 \left[\frac{r_s}{R_\odot}\right]\left[\frac{R_{diff}}{1000\,km}\right]\left[\frac{\lambda}{1\mu m}\right]^{-1}\left[\frac{z_1}{10\,kpc}\right]^{-1}$$

z_1 is the cloud-source distance

Modulation index

Essentially depends on
R_S/R_{ref}
-> not on the details of
the power spectrum of
the fluctuations

σ_I/I

$F(x) = 0.17 \exp(-0.93\, x)$

Scintillation of
Sun@10kpc
through a cloud
with R_{diff}=1000km
at λ = 1 μm

R_S/R_{ref}

$x = Rproj / Rref$
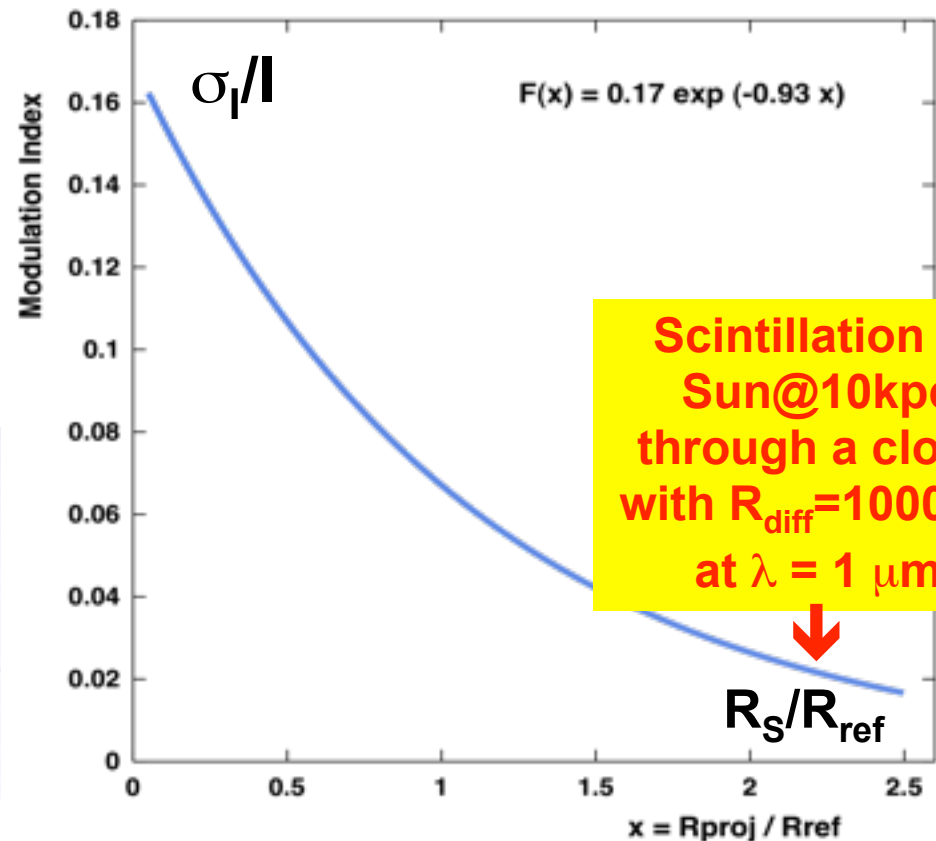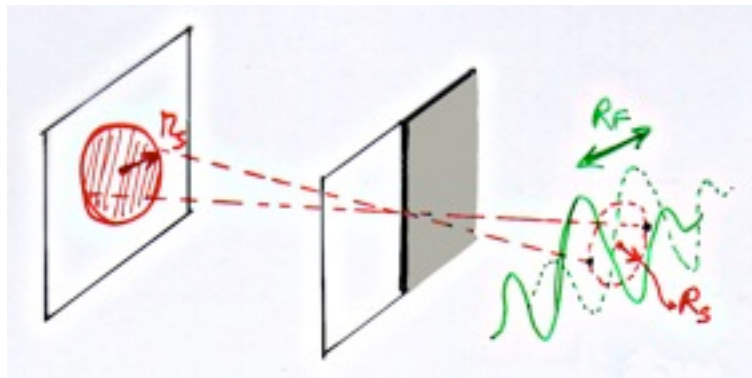
$$\frac{R_S}{R_{ref}} = \frac{r_s R_{diff}}{\lambda z_1} \sim 2.25 \left[\frac{r_s}{R_\odot}\right]\left[\frac{R_{diff}}{1000\,km}\right]\left[\frac{\lambda}{1\mu m}\right]^{-1}\left[\frac{z_1}{10\,kpc}\right]^{-1}$$

z_1 is the cloud-source distance

Time scale

If $R_{diff} < R_{ref}$, then R_{ref} is the largest scale and :

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

Where
z_0 is the distance to the cloud
V_T is the relative speed of the cloud w/r to the l.o.s.

Signature of scintillation

Signature of scintillation

- **Stochastic light-curve** (not random)

Signature of scintillation

- **Stochastic light-curve** (not random)
  - Autocorrelation (power spectrum)

Signature of scintillation

- **Stochastic light-curve** (not random)
  - Autocorrelation (power spectrum)
  - Characteristic times (10's minutes)

Signature of scintillation

- **Stochastic light-curve** (not random)
  - Autocorrelation (power spectrum)
  - Characteristic times (10's minutes)
  - Modulation index can be as high as 5%
    - decreases with star radius
    - depends on cloud structure

Signature of scintillation

- **Stochastic light-curve** (not random)
  - Autocorrelation (power spectrum)
  - Characteristic times (10's minutes)
  - Modulation index can be as high as 5%
    - decreases with star radius
    - depends on cloud structure
- **Signatures of a propagation effect**

Signature of scintillation

- **Stochastic light-curve** (not random)
  - Autocorrelation (power spectrum)
  - Characteristic times (10's minutes)
  - Modulation index can be as high as 5%
    - decreases with star radius
    - depends on cloud structure

- **Signatures of a propagation effect**
  - Chromaticity (optical wavelengths)
    - Long time-scale variations (10's min.) ~ achromatic
    - Short time-scale variations (~ min.) strongly change with λ

Signature of scintillation

- **Stochastic light-curve** (not random)
  - Autocorrelation (power spectrum)
  - Characteristic times (10's minutes)
  - Modulation index can be as high as 5%
    - decreases with star radius
    - depends on cloud structure
- **Signatures of a propagation effect**
  - Chromaticity (optical wavelengths)
    - Long time-scale variations (10's min.) ~ achromatic
    - Short time-scale variations (~ min.) strongly change with λ
  - Correlation between light-curves obtained with 2 telescopes decreases with their distance

Fore and back-grounds

Fore and back-grounds

- **Atmospheric turbulence**

  Prism effects, image dispersion, BUT Δ**I/I < 1%** at any time scale in a big telescope

  BECAUSE speckle with 3cm length scale is averaged in a >1m aperture

Fore and back-grounds

- ## Atmospheric turbulence

  Prism effects, image dispersion, BUT $\Delta I/I < 1\%$ at any time scale in a big telescope

  BECAUSE speckle with 3cm length scale is averaged in a >1m aperture

- ## High altitude cirruses

  Would induce easy-to-detect **collective** absorption on neighbour stars. Scintillation by a 10AU structure affect one only star.

Fore and back-grounds

- **Atmospheric turbulence**

  Prism effects, image dispersion, BUT Δ**I/I < 1%** at any time scale in a big telescope

  BECAUSE speckle with 3cm length scale is averaged in a >1m aperture

- **High altitude cirruses**

  Would induce easy-to-detect **collective** absorption on neighbour stars. Scintillation by a 10AU structure affect one only star.

- **Gas at ~10pc**

  Scintillation would also occur on the biggest stars

Fore and back-grounds

- **Atmospheric turbulence**

  Prism effects, image dispersion, BUT $\Delta I/I < 1\%$ at any time scale in a big telescope

  BECAUSE speckle with 3cm length scale is averaged in a >1m aperture

- **High altitude cirruses**

  Would induce easy-to-detect **collective** absorption on neighbour stars. Scintillation by a 10AU structure affect one only star.

- **Gas at ~10pc**

  Scintillation would also occur on the biggest stars

- **Intrinsic variability**

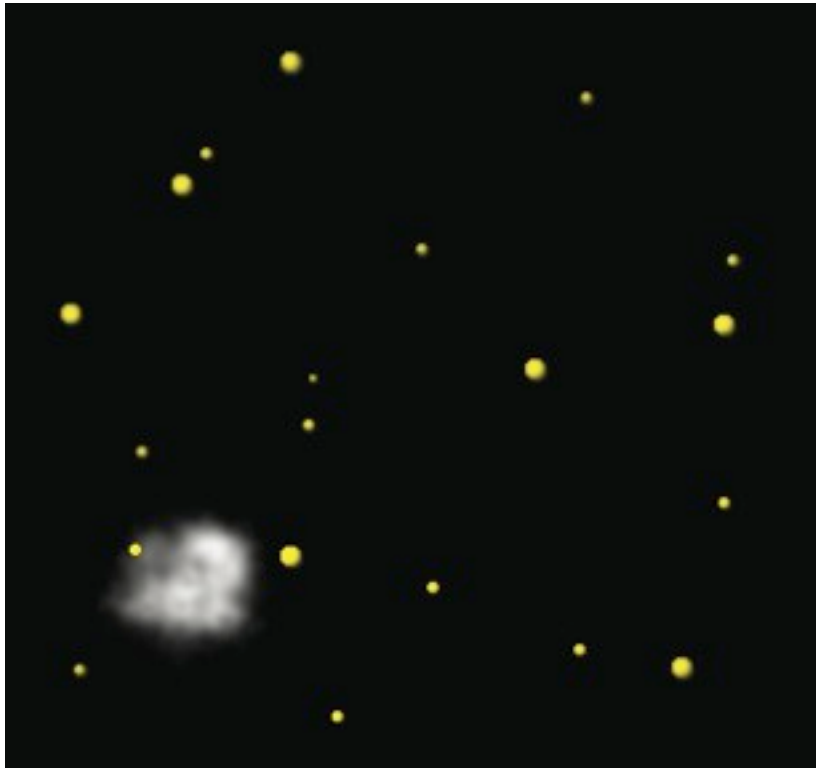 Rare at this time scale and only with special stars (UV Ceti, flaring Wolf-Rayet)

Optical depth due to halo gas towards LMC

Optical depth due to halo gas towards LMC

$$\tau_{\text{scintillation}} = 10^{-2} \times \alpha \times S$$

Optical depth due to halo gas towards LMC

$$\tau_{\text{scintillation}} = 10^{-2} \times \alpha \times S$$

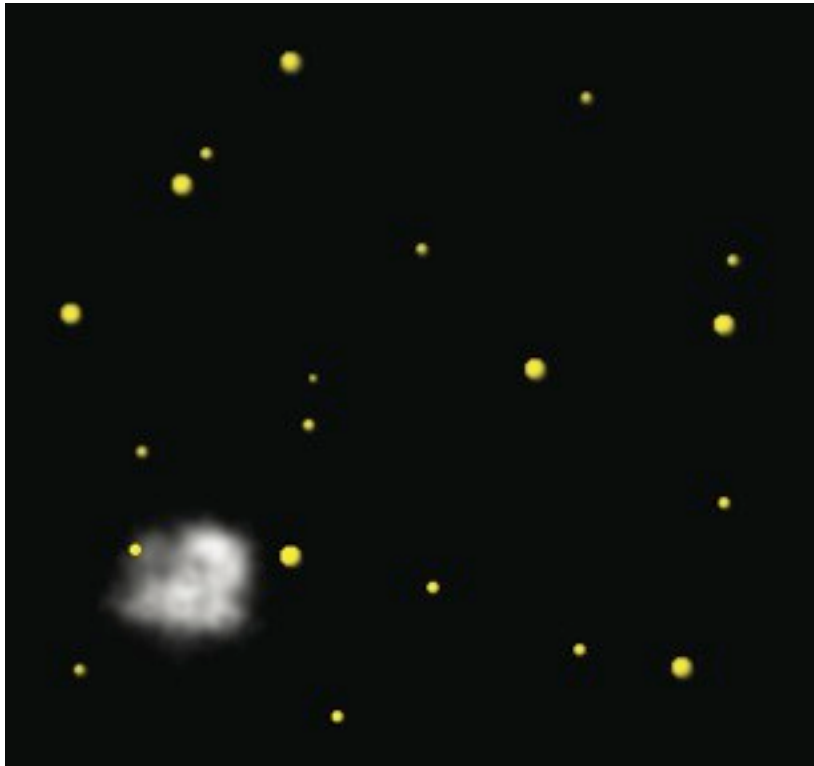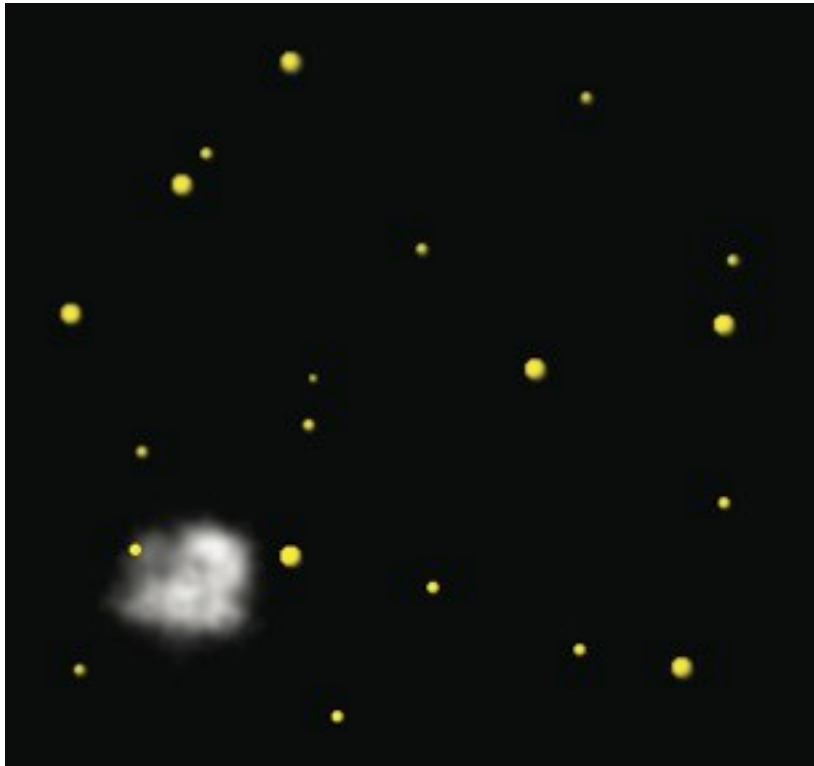# Optical depth due to halo gas towards LMC

$$\tau_{\text{scintillation}} = 10^{-2} \times \alpha \times S$$

Where

Optical depth due to halo gas towards LMC

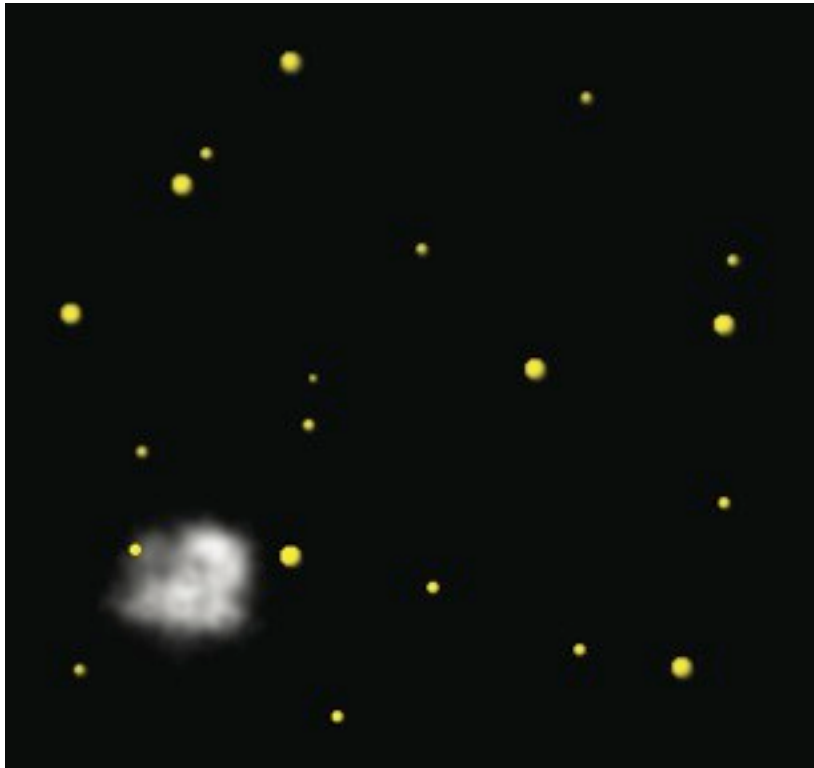$$\tau_{\text{scintillation}} = 10^{-2} \times \alpha \times S$$

Where

- 10^{-2} is the max. surface coverage of the fractal structures

Optical depth due to halo gas towards LMC

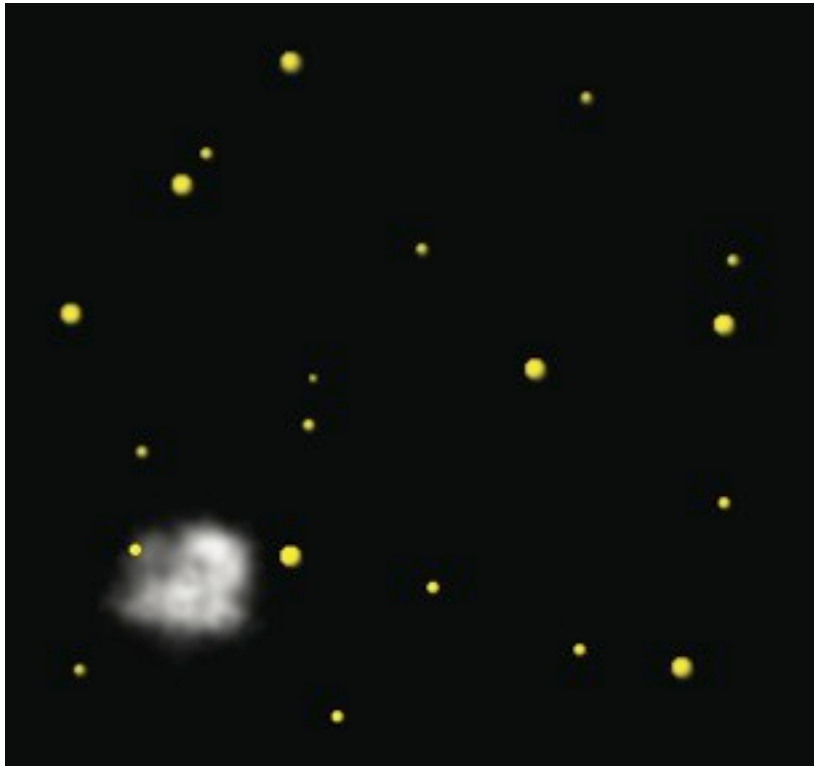$$\tau_{\text{scintillation}} = 10^{-2} \times \alpha \times S$$

Where

• 10^{-2} is the max. surface coverage of the fractal structures

• α is the fraction of halo into molecular gas

Optical depth due to halo gas towards LMC

$$\tau_{\text{scintillation}} = 10^{-2} \times \alpha \times S$$

Where

• 10^{-2} is the max. surface coverage of the fractal structures

• α is the fraction of halo into molecular gas

• S depends on the structuration… Unknown

Requirements for detection towards LMC

Requirements for detection towards LMC

- Assuming R_{diff} = 1000km (10 AU clumpuscules)

Requirements for detection towards LMC

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

Requirements for detection towards LMC

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

Requirements for detection 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~20.5**

Requirements for detection 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~20.5
  ✓ Characteristic time ~ 1 min.   =>   **few sec. exposures**

Requirements for detection towards LMC

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

    ✓ Smaller than **A5** type in LMC   =>   **M_V~20.5**

    ✓ Characteristic time ~ 1 min.   =>   **few sec. exposures**

    ✓ Photometric precision required   **~1%**

Requirements for detection 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~20.5**
  ✓ Characteristic time ~ 1 min.   =>   **few sec. exposures**
  ✓ Photometric precision required   **~1%**

Requirements for detection 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~20.5**
  ✓ Characteristic time ~ 1 min.   =>   **few sec. exposures**
  ✓ Photometric precision required   **~1%**

Requirements for detection towards LMC

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

  - ✓ Smaller than **A5** type in LMC   =>   **M_V~20.5**
  - ✓ Characteristic time ~ 1 min.   =>   **few sec. exposures**
  - ✓ Photometric precision required   **~1%**

  - ✓ Dead-time < few sec.   **=>**

Requirements for detection 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~20.5**

    ✓ Characteristic time ~ 1 min.   =>   **few sec. exposures**

    ✓ Photometric precision required   **~1%**

    ✓ Dead-time < few sec.   =>

    ✓ **B** and **R** partially correlated   =>

Requirements for detection 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 ~ 1 min.   =>   **few sec. exposures**

  ✓ Photometric precision required   **~1%**

  ✓ Dead-time < few sec.   =>

  ✓ **B** and **R** partially correlated   =>

  ✓ Optical depth probably small   =>

Requirements for detection 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 =>

✓ Characteristic time ~ 1 min. =>

✓ Photometric precision required

| M_V~20.5 |
| few sec. exposures |

~1%

✓ Dead-time < few sec. =>

✓ **B** and **R** partially correlated =>

✓ Optical depth probably small =>

Telescope > 2 meters
Fast readout Camera
2 cameras
Wide field

What will we learn from detection or non-detection?

What will we learn from detection or non-detection?

- Expect **1000x**α fluctuating light-curves (>5%) when monitoring **10^5** stars if column density fluctuations > 10^{-6} within 1000km

What will we learn from detection or non-detection?

- Expect **1000x**α fluctuating light-curves (>5%) when monitoring **10⁵** stars if column density fluctuations > 10^{-6} within 1000km

- **If detection**
  - Get details on the clumpuscule (structure, column density -> mass) through modelling (reverse problem)
  - Measure contribution to galactic hidden matter

What will we learn from detection or non-detection?

- Expect **1000x**α fluctuating light-curves (>5%) when monitoring **10^5** stars if column density fluctuations > 10^{-6} within 1000km

- **If detection**
  - Get details on the clumpuscule (structure, column density -> mass) through modelling (reverse problem)
  - Measure contribution to galactic hidden matter

- **If no detection**
  - Get max. contribution of clumpuscules as a function of their structuration parameter R_{diff} (fluctuations of column density)
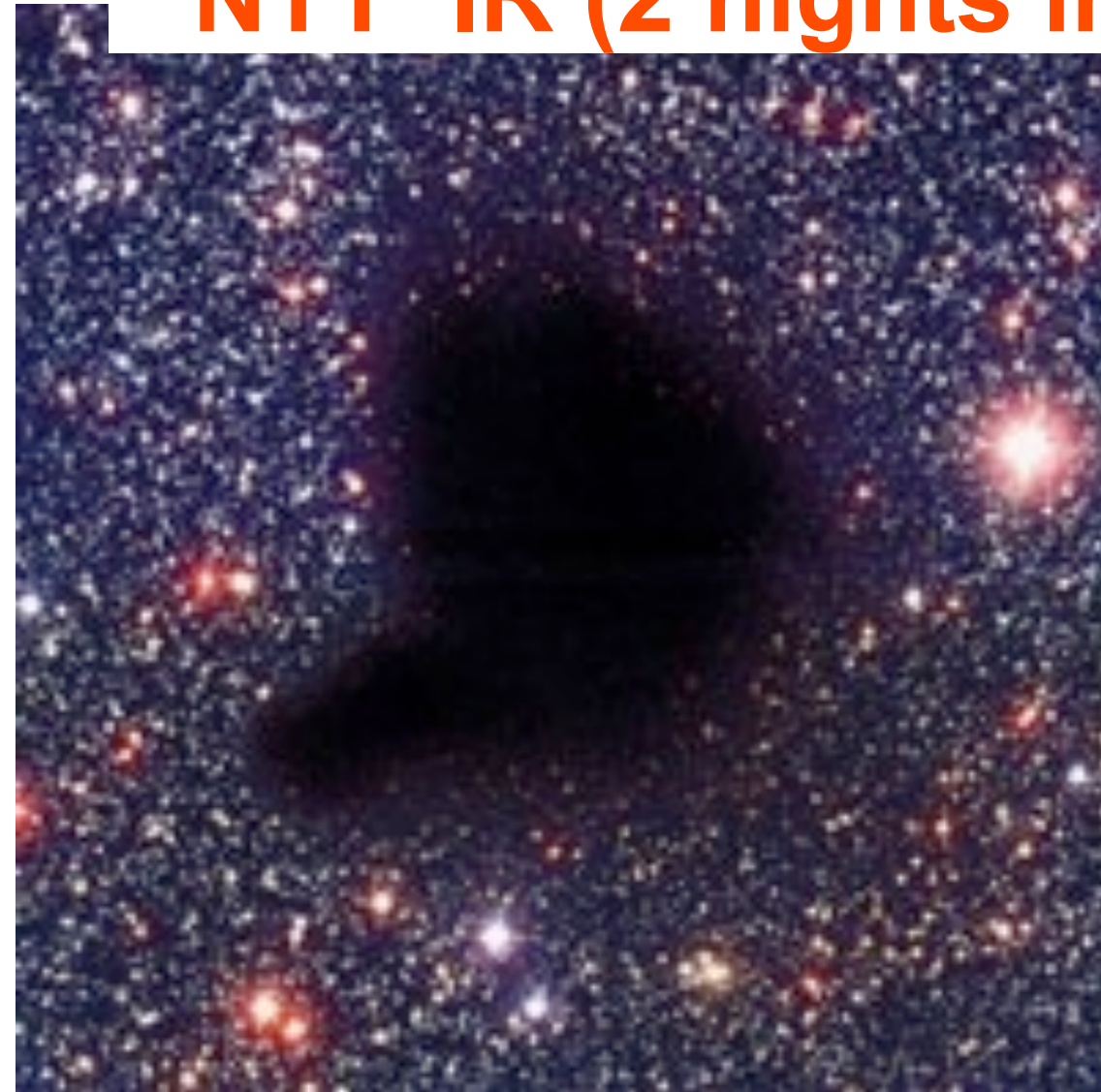
Test towards Bok globule B68 NTT IR (2 nights in june 2006)

Test towards Bok globule B68 NTT IR (2 nights in june 2006)
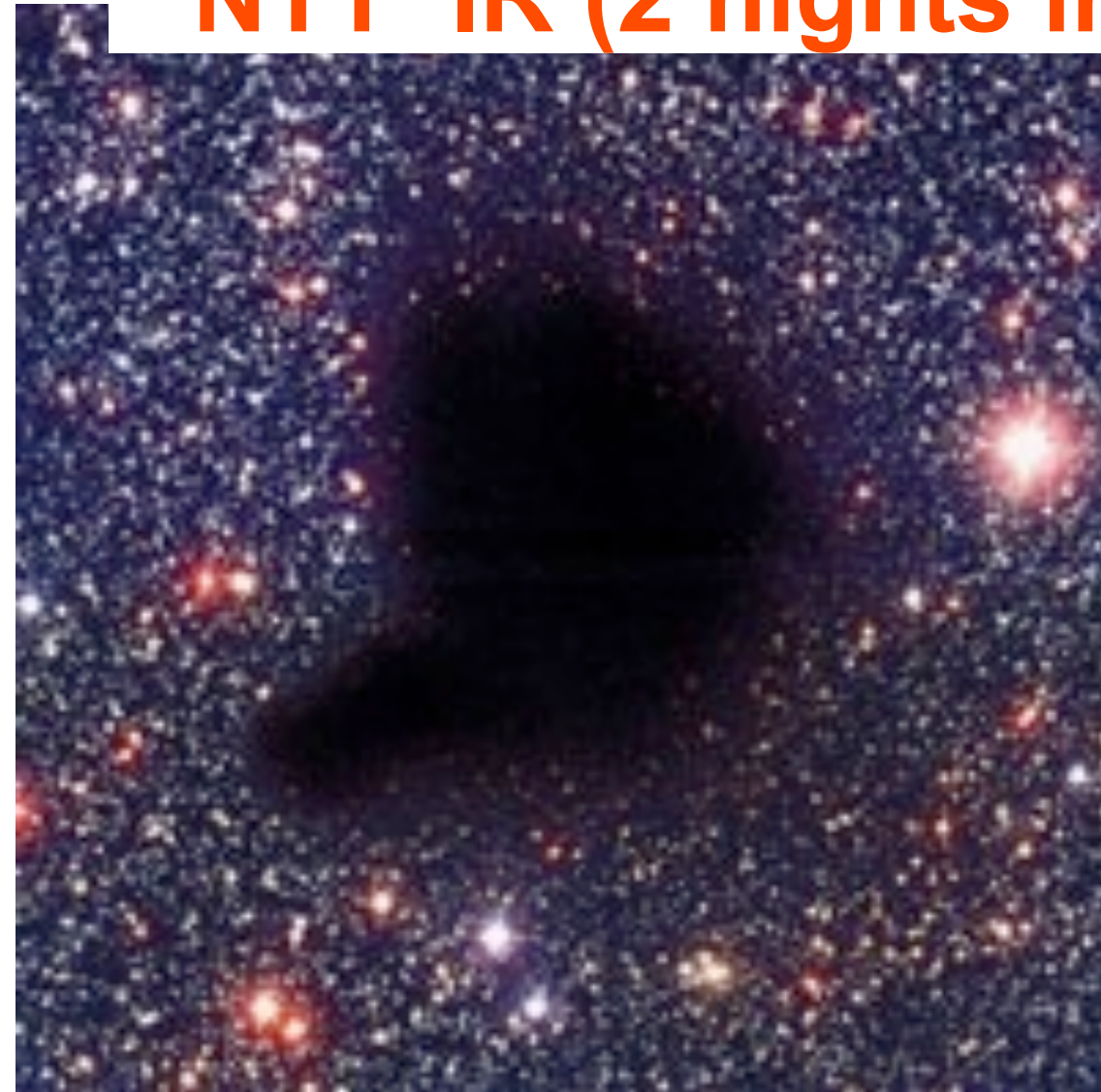

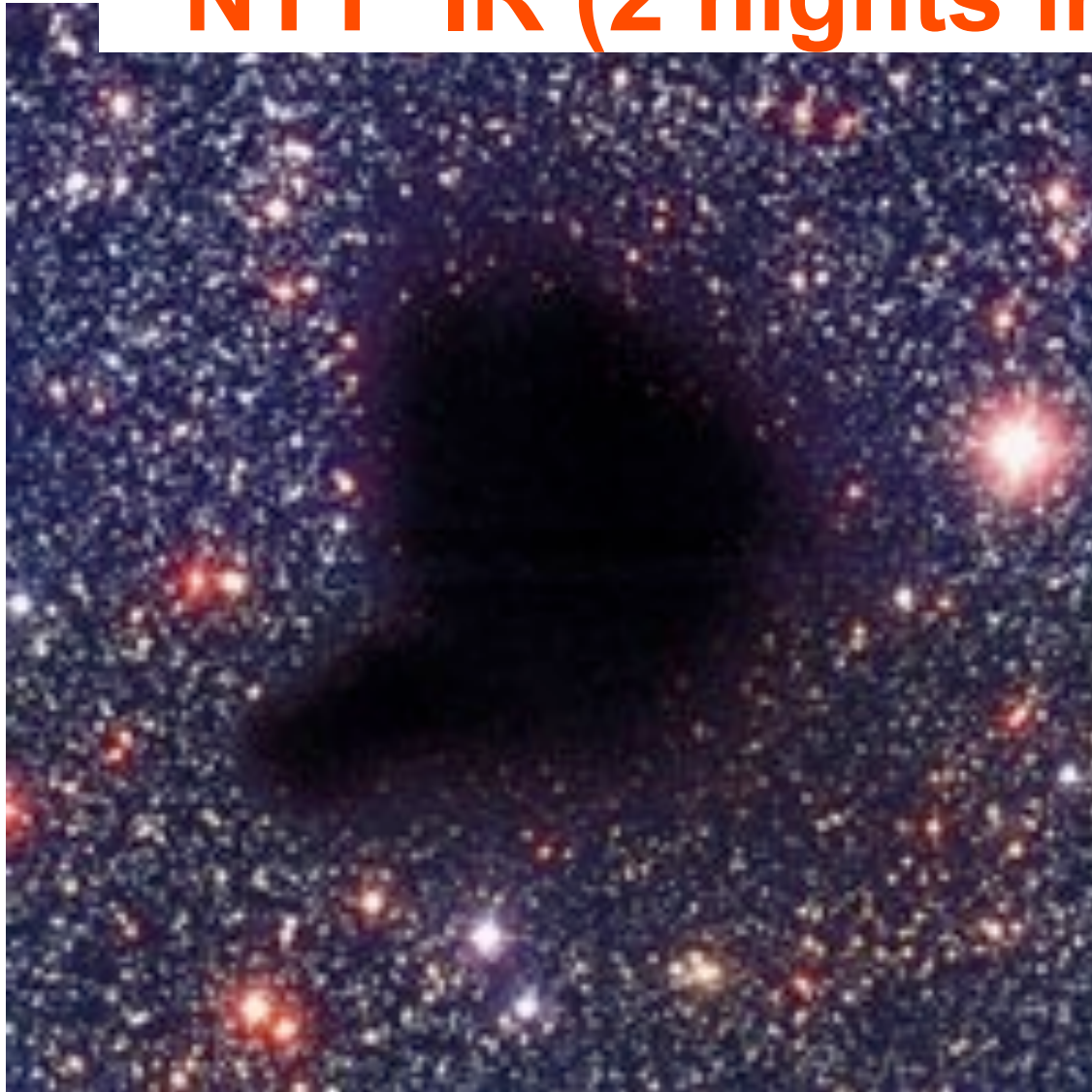- **9599 stars monitored**

Test towards Bok globule B68 NTT IR (2 nights in june 2006)

- 9599 stars monitored
- ~ 1000 exposures/night

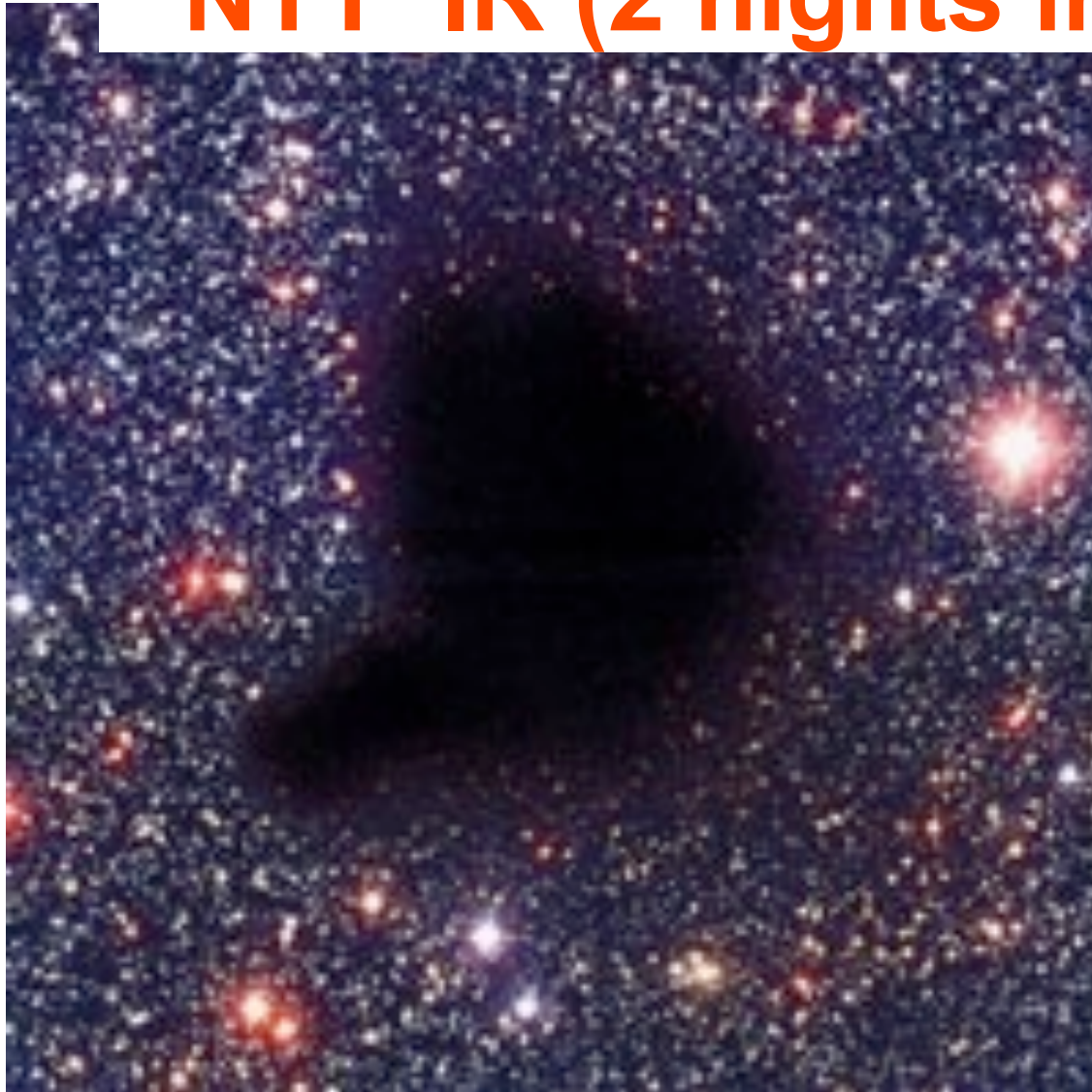# Test towards Bok globule B68 NTT IR (2 nights in june 2006)

- **9599 stars monitored**
- **~ 1000 exposures/night**
- **Search for ~10% variability on the 933 best measured stars**

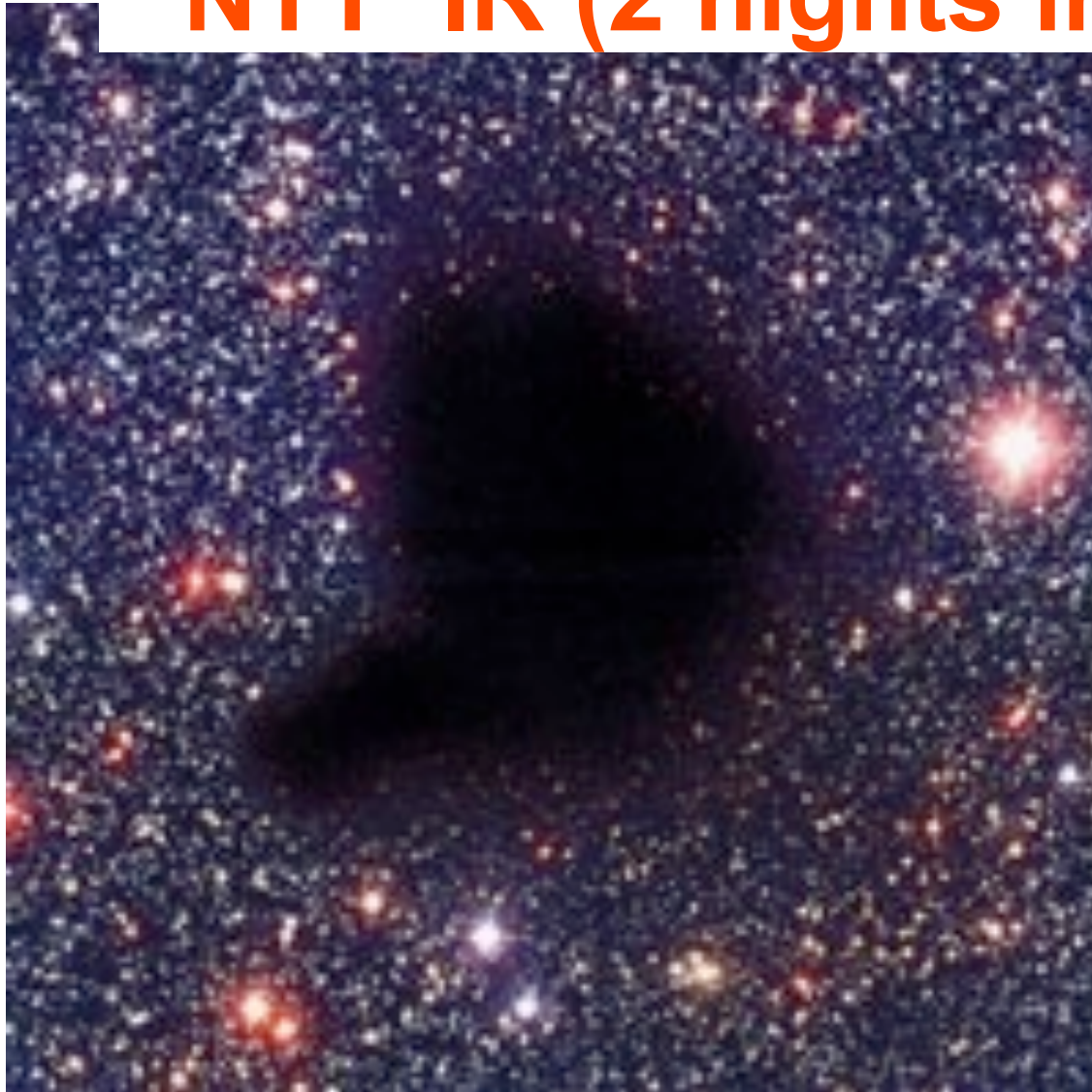# Test towards Bok globule B68 NTT IR (2 nights in june 2006)

- **9599 stars monitored**
- **~ 1000 exposures/night**
- **Search for ~10% variability on the 933 best measured stars**
- **Signal if $\Delta(nl)/(nl) \sim 10^{-4}$ per ~1000 km (nl = column density)**
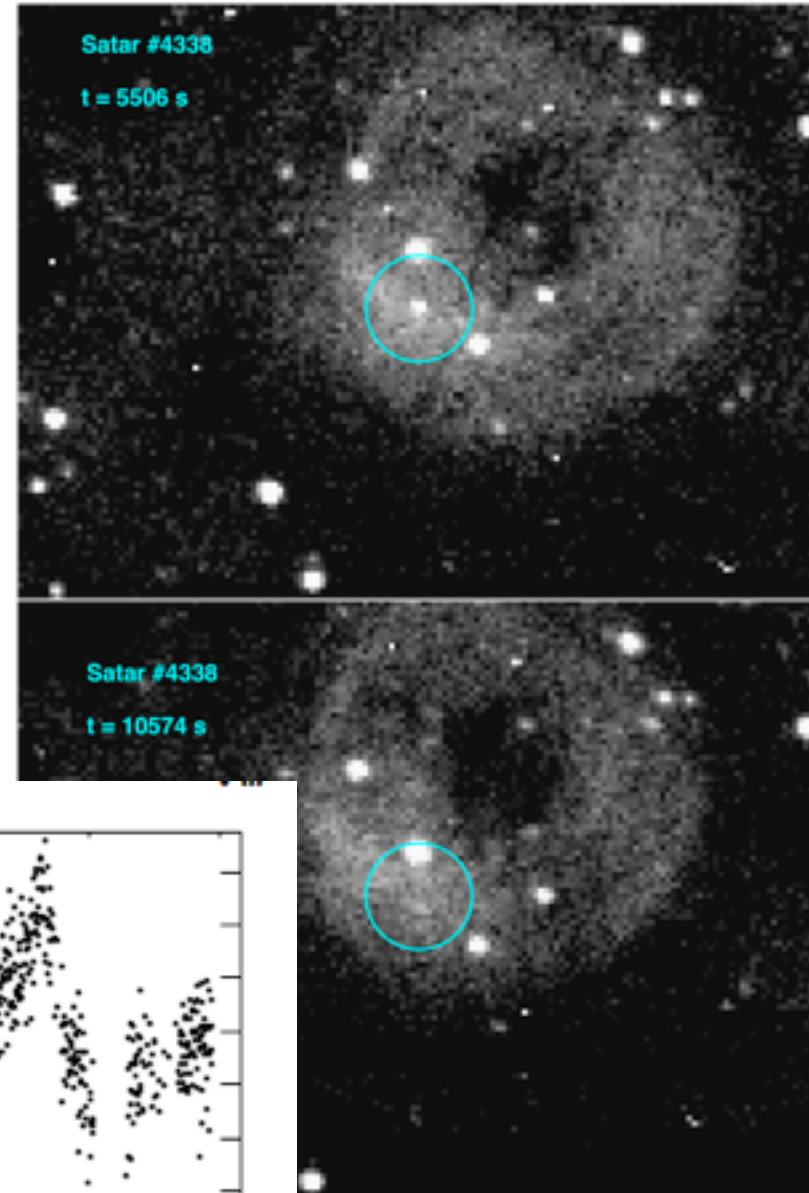
Test towards Bok globule B68 NTT IR (2 nights in june 2006)

- **9599 stars monitored**
- **~ 1000 exposures/night**
- **Search for ~10% variability on the 933 best measured stars**
- **Signal if $\Delta(nl)/(nl) \sim 10^{-4}$ per ~1000 km (nl = column density)**
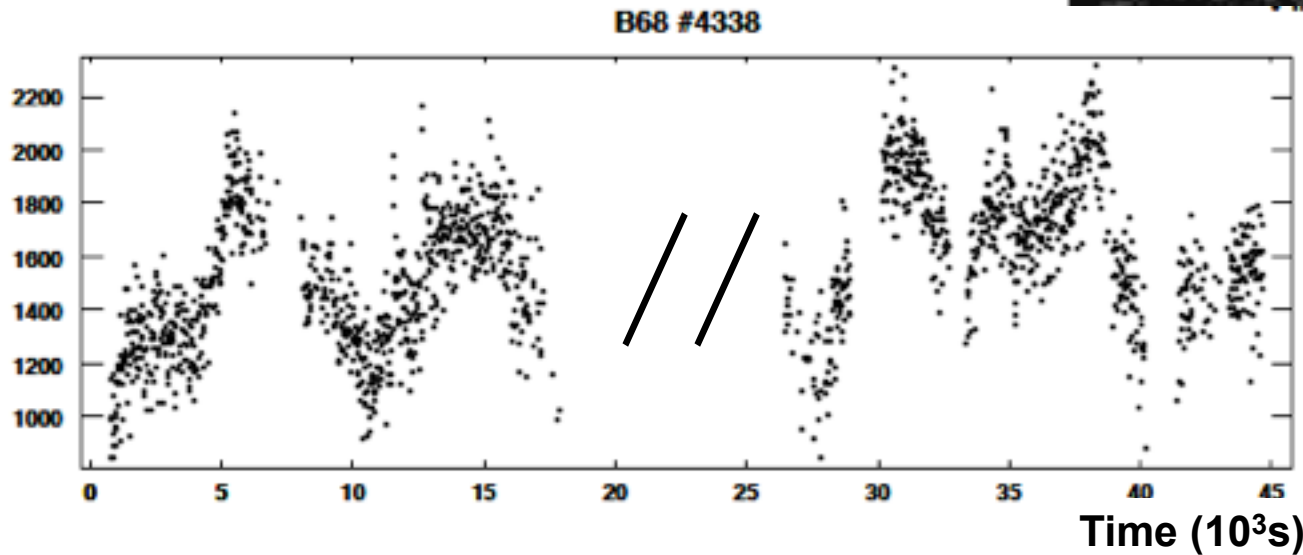- **Mainly test for back-ground and feasibility**

Test towards Bok globule B68
NTT IR (2 nights)

one fluctuating star?
(other than known artifacts)

Conclusion: optical interstellar scintillation with LSST

Conclusion: optical interstellar scintillation with LSST

- **LSST has the capacity for this search**
  - Large enough (diameter and field)
  - **Fast readout** (2s) -> allows fast sampling

Conclusion: optical interstellar scintillation with LSST

- **LSST has the capacity for this search**
  - Large enough (diameter and field)
  - **Fast readout** (2s) -> allows fast sampling
- **But current sampling strategy does not fit**
  - Need few hours series of short exposures
  - But no need for regular long time sampling (contrary to microlensing or SN searches)

Conclusion: optical interstellar scintillation with LSST

- **LSST has the capacity for this search**
  - Large enough (diameter and field)
  - **Fast readout** (2s) -> allows fast sampling
- **But current sampling strategy does not fit**
  - Need few hours series of short exposures
  - But no need for regular long time sampling (contrary to microlensing or SN searches)
- **Complementary synchronized observations for**
  - test of chromaticity
  - decorrelation with distant simultaneous observations

complements

For the future…

For the future…

A network of distant telescopes

For the future…

A network of distant telescopes

- Would allow to decorrelate scintillation from interstellar clouds and atmospheric effects

For the 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)

Expected difficulties, cures

Expected difficulties, cures

- **Blending** (crowded field)=> differential photometry

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)

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…)