# GRAVITATIONAL MICROLENSING

## *New synergy between ground-based observations, space observations and theory*

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*Structure evolution and cosmology*

**Santiago de Chile, October 2002**

CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

Observatoire
Midi-Pyrénées

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**I.** A quick summary of basic concepts in microlensing

**II.** Galactic structure : halo & bar properties

**III.** Nature of lenses : problems

**IV.** Gravitational imaging of stars : unveiling photospheres

**V.** Prospects

# GRAVITATIONAL MICROLENSING : THE CONCEPT

# Simple test cases with a Schwarzschild lens

- Simulated event with impact parameter 0.20
- Simulated event with impact parameter 0.05
- Event at 0 impact parameter (the Chwolson/Link/Einstein ring)

# BASIC CONCEPTS IN MICROLENSING

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Magnification of a point source by a Schwarzschild lens

$$A_p(t) = (y^2 + 2)/y\sqrt{y^2 + 4}$$

$$y = \sqrt{{\alpha_p}^2 + (t - t_o)^2/{t_E}^2}$$

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$\alpha_p = \theta_p/\theta_E$ minimum impact parameter (at $t = t_o$)

$t_E = D_{OL} \times \theta_E/v_\perp$ time scale

$\theta_E = \sqrt{(4GM_L/c^2)\cdot(D_{LS}/D_{OL}D_{OS})}$ Angular Einstein radius

## Expected ML event properties :

1 – symmetric in $t$
2 – achromatic
3 – unique
4 – $\forall$ position $\in$ HRD
5 – uniform distribution of $\alpha_p$
6 – $\tau$ uncorrelated to $A_p(t_o)$

## Expected number of events : optical depth

$$\overline{\tau} = \int_o^{D_{OS}} d\ell \; \pi \; \theta_E(\ell)^2 \; \ell^2 \; \frac{\rho(\ell)}{M_L}$$

*i.* does not depend on $M_L$, just on the spatial density along l.o.s.
*ii.* number of events : $N_{events} \; = \; \left(\frac{T}{t_E}\right) \epsilon(t_E) \, \tau \, N_*$

## Is it a new type of variable star ?

ML characteristic features :

1 $\tau$ of days/months
2 non periodic
3 amplitude of some 0.1 $10^{\pm 1}$ mag
4 achromatic
5 symmetric

| variability type | violates criteria # |
|---|---|
| pulsating stars | 2 4 5 |
| binaries | 2 |
| flares | 1 4 5 |
| spots | 2 4 |
| outbursts | 3 4 5 |
| envelope ejections | 4? 5 |

# Microlensing surveys : a quick summary

| Program | | $N_* / 10^6$ | $\Delta t$ | events |
|---|---|---|---|---|
| EROS1 (LMC) | Schmidt | 2 | 11 months | 2 |
| | CCD | 0.02 | 11 months | 0 |
| EROS2 | LMC | 25.5 | 3 years | 5 |
| | SMC | 5.3 | 3 years | 1 |
| | arms | 9.1 | 3 years | 7 |
| MACHO | LMC | 11.9 | 5.7 years | 13–17 |
| | SMC | 8.2 | 4 years | 2 |
| | Bulge | 17 | 3 years | 99 |
| OGLE II | Bulge | 20.5 | 3 years | 314 |
| DUO (plates) | Bulge | 12 | 6 months | 12 |
| POINT-AGAPE | M31 | pixel lensing | 3 seasons | 3+139 ? |
| MEGA+VATT | M31 | pixel lensing | 5 seasons | 6 ? |

# Partial list of results on $\overline{\tau}$

Observations towards the Large Magellanic Cloud :

$\overline{\tau}_{\rm LMC} \sim (1.2^{+0.4}_{-0.3}) \times 10^{-7}$ ($\pm 25\%$ syst) MACHO 13-17 events

More than expected from known stellar populations
but about 20% of a full halo..

Observations towards the Galactic Bulge :

$\overline{\tau}_{\rm bulge} \sim (3.3 \pm 1.2) \times 10^{-6}$ OGLE 9 events
$\overline{\tau}_{\rm bulge} \sim (3.23 \pm 0.5 \times 10^{-6}$ MACHO 99 events

a factor 3 larger than expected from a spherical bulge

# WHAT ARE THE LENSES ?

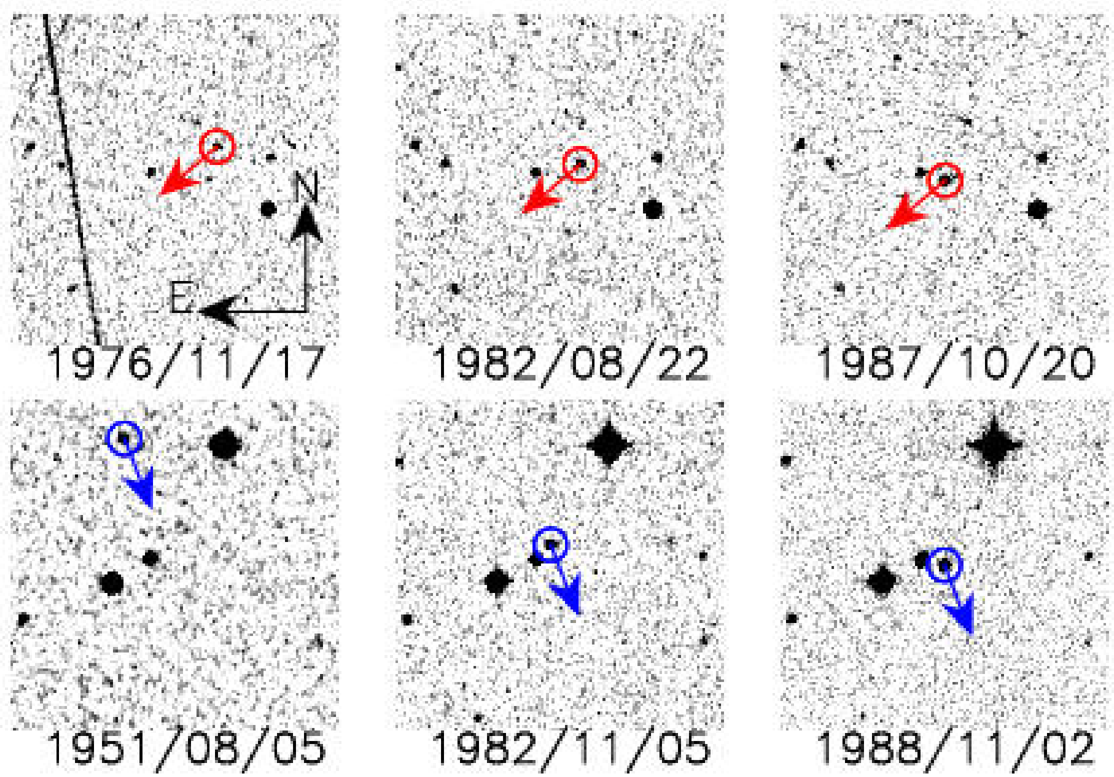
Inferred typical mass of 0.2 $M_\odot$(but large dispersion: 0.01 to 0.9 $M_\odot$)

M dwarfs Far too few, even in thick disc

Black holes Unless top heavy IMF, not enough of them

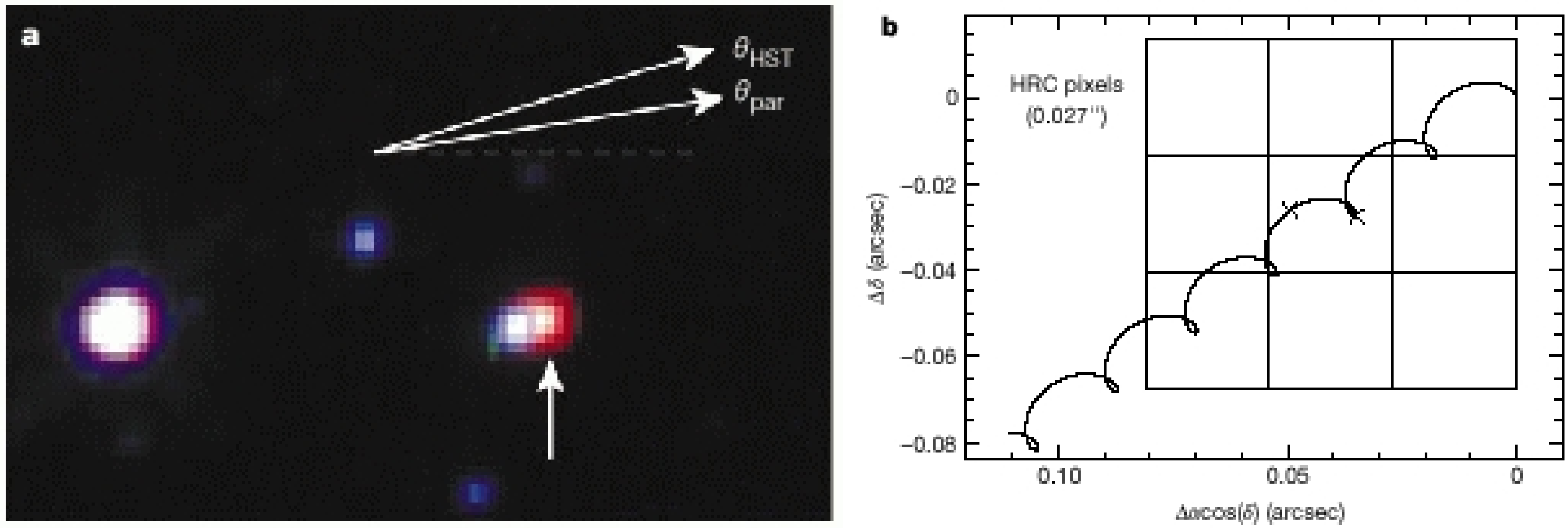
White dwarfs But galaxies would be too bright at high $z$

# Yet evidence for a white dwarf population in the halo ?



Ibata et al. (2000), Méndez & Minniti (2001)

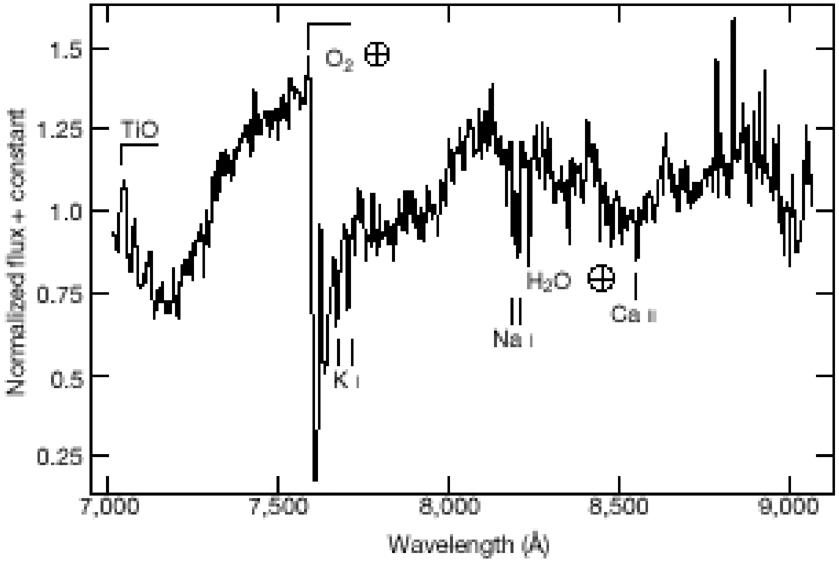
# TOWARDS DIRECT DETECTIONS



combining HST (imaging) + VLT (spectra)

# FORS2 spectra at VLT

- CaII blend of LMC star (F type) plus lens
- Presence of KI, NaI but absence of TiO (7100Å), VO $\Longrightarrow$ M4-5 V



Alcock et al. (2001) Nature **414**, 617

# GRAVITATIONAL IMAGING OF STARS

Compare the stellar angular radius to the Einstein radius :

$$\theta_* = 0.0465 \left(\frac{R_*}{10R_\odot}\right)\left(\frac{D_{OS}}{\mathrm{kpc}}\right)^{-1} \text{milliarcsec}$$

$$\theta_E = 0.902 \left(\frac{M_L}{0.1M_\odot}\right)^{1/2}\left(\frac{D_{OS}}{\mathrm{kpc}}\right)^{-1/2}\cdot\left(\frac{D_{LS}}{D_{OS}}\right)^{1/2}\left(1-\frac{D_{LS}}{D_{OS}}\right)^{-1/2} \text{m.a.s}$$

- **Expected number of transit events :** $\mathcal{F} = \langle\theta_*\rangle \times \langle\frac{1}{\theta_E}\rangle$

When $D_{LS} \ll D_{OS}$ the sources are not point-like, and some subtle effects may appear

## ❍ Magnification of extended sources

$$A_{ext}(\theta) = \int_{\underline{\Omega}} d\varpi\ B(\varpi)\ A_p(\theta)\ \ /\ \ \int_{\underline{\Omega}} d\varpi\ B(\varpi)$$

$\alpha_* = \theta_*/\theta_E$
$\gamma = \theta/\theta_*$
$x = r/R_* = \theta_r/\theta_*$

$$A_{ext}(\gamma) = \left[\int_o^{2\pi} d\phi \int_o^1 dx \cdot x \cdot B(x) \cdot A_p(p\alpha_*)\right] \left[2\pi \int_o^1 dx \cdot x \cdot B(x)\right]^{-1}$$

with $p^2 = \gamma^2 + x^2 + 2 \cdot \gamma \cdot x \cos\phi$

① **Uniform brightness profile** If $B(x) =$ constant, then for $\gamma = 0$ :

$$A_u^{\max} = \left(1 + 4/\alpha_*^2\right)^{1/2}$$

② **Point source limit** $\gamma \gg 1 \Longrightarrow p^2 \approx \gamma^2 \Longrightarrow$

$$A_p(\gamma) = (y^2 + 2)/y(y^2 + 4)^{1/2}$$

with $\gamma\alpha_* = \theta/\theta_E = y$

③ **Actual stars : limb darkening profiles**

$\Longrightarrow$ chromatic effects due to differential amplification across the disc

# SPECTROSCOPIC EFFECT

- Milne–Eddington approximation (Chandrasekhar, 1947) :

$$\rho = \sigma / [\sigma + \kappa_c]$$

$$\beta_\lambda = \kappa_\lambda \phi_\lambda / [\sigma + \kappa_c]$$

$$\wp = [1 - \rho + \epsilon \beta_\lambda] / [1 + \beta_\lambda]$$

If $B_c = a + b\tau$ and $B_\lambda = a + p_\lambda \tau_\lambda$ and $\wp, \epsilon$ and $\rho$ are constants, then :

$$I_\lambda^o(\mu) = (a + p_\lambda \mu) + \frac{(p_\lambda - \sqrt{3}a)(1 - \wp)}{\sqrt{3}(1 + \sqrt{\wp})(1 + \sqrt{3\wp}\mu)} \quad \text{and} \quad I_c^o(\mu) = a + b\mu$$

## Two extreme cases :

❍ Resonance line : $\epsilon = 1$ and $\wp = 1$

$$r_\lambda = \frac{I^o_\lambda(\mu)}{I^o_c(\mu)} = \frac{1 + (b/a)(\mu/[1+\beta])}{1 + (b/a)\mu}$$

when $\mu \longrightarrow 0$, then $r_\lambda \longrightarrow 0$ and the line vanishes at the limb...

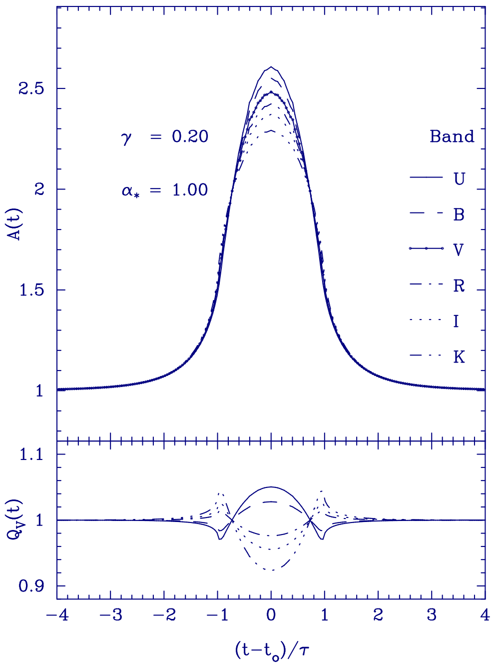
❍ Strong scattering line : $\epsilon = 0$ and $\beta_\lambda \longrightarrow \infty$ then $\wp \longrightarrow 0$

thus $\forall\mu \quad : \quad I^o_\lambda(\mu) \longrightarrow 0$ and the centre of the line remains dark at all positions across the stellar disc

# CHROMATIC EFFECTS IN MICROLENSING EVENTS

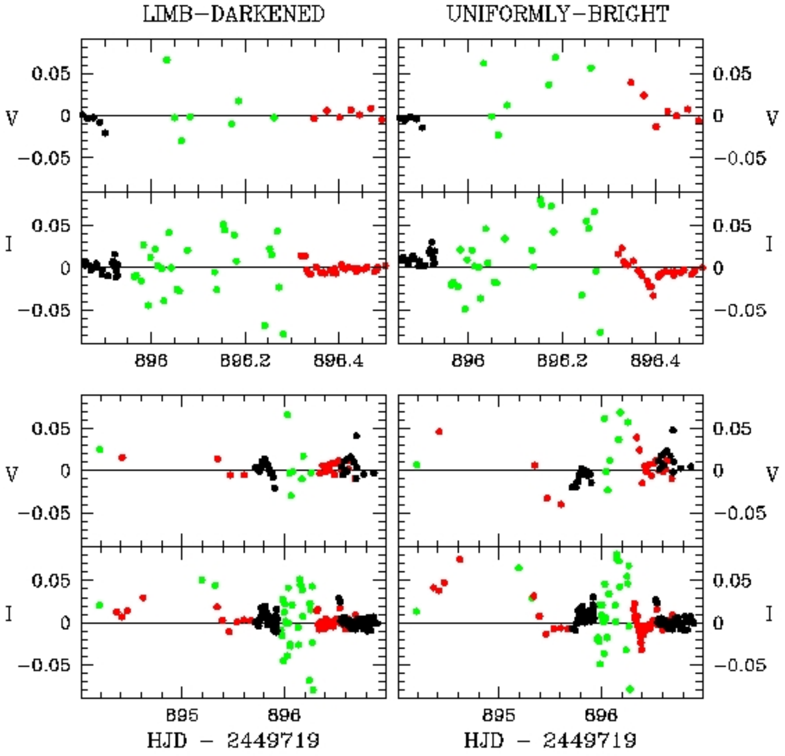
## Predictions

Valls-Gabaud (1994)



## Observations

Albrow et al. (2001a)



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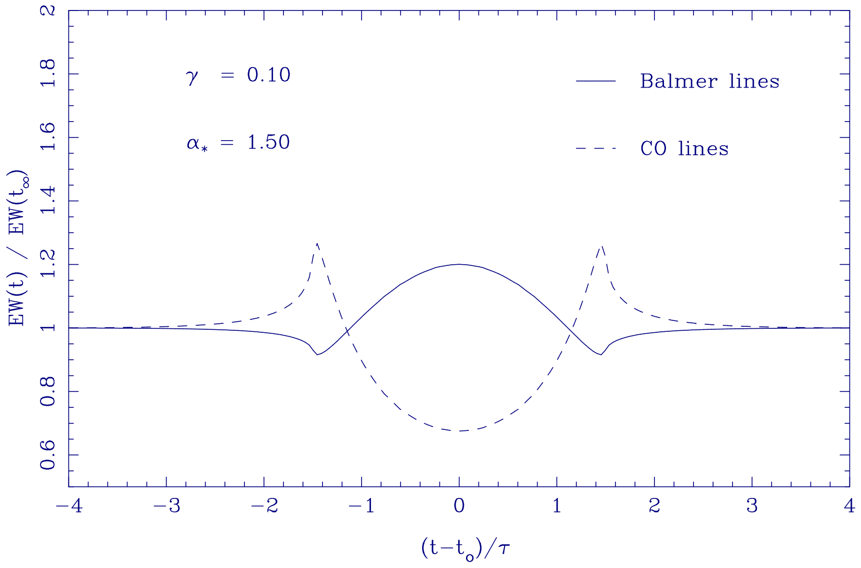

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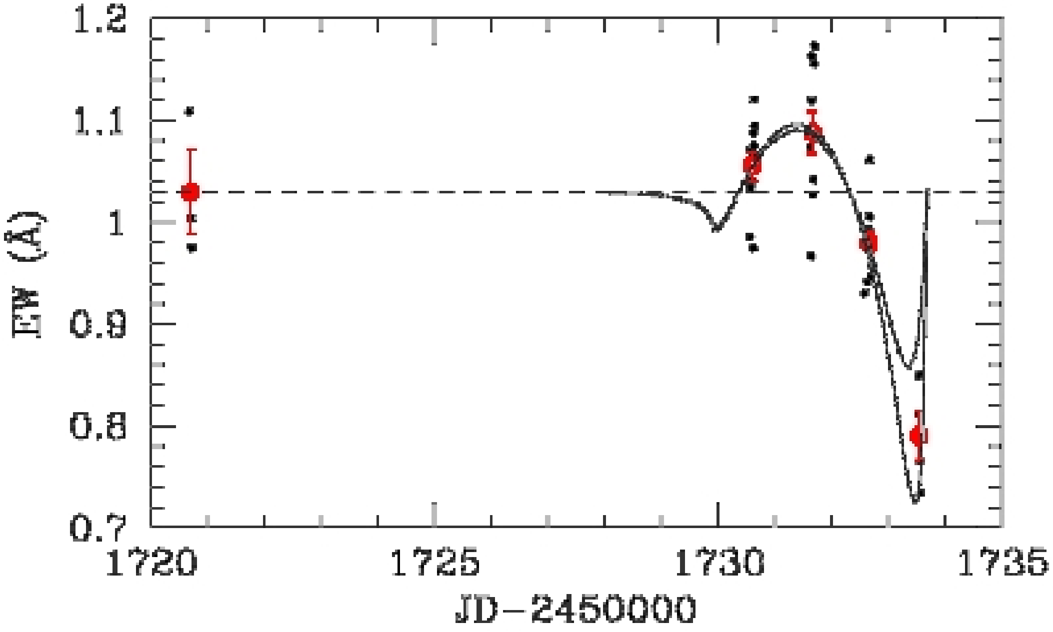

# M31 as a unique microlensing target

Basic idea (Crotts 1992, Baillon et al. 1993)

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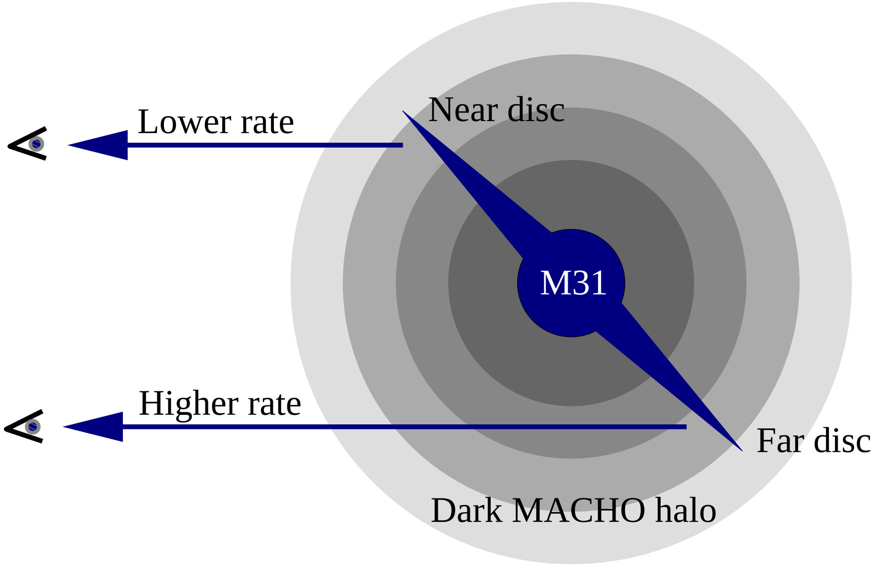
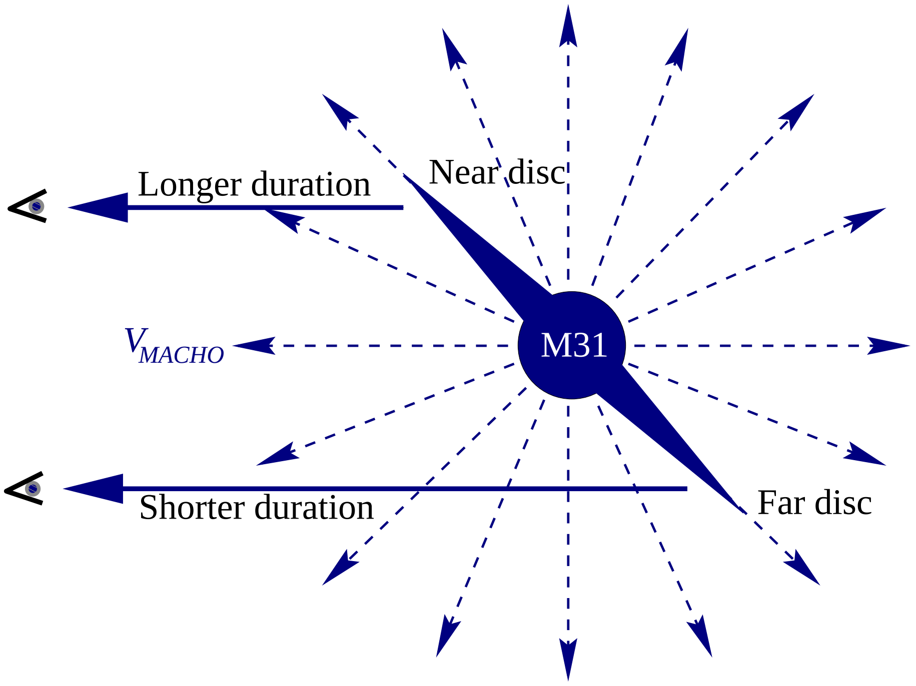
**2.** Additional line of sight through the Galactic halo :
$\Longrightarrow$ disentangle self-lensing interpretations for LMC/SMC

**3.** External viewpoint :
$\Longrightarrow$ mapping the MACHO spatial distribution across M31

**4.** Inclination ($i = 77^o$) $\Longrightarrow$ gradient in ML rate

$\Longrightarrow$ unique spatial asymmetry (if roundish halo)





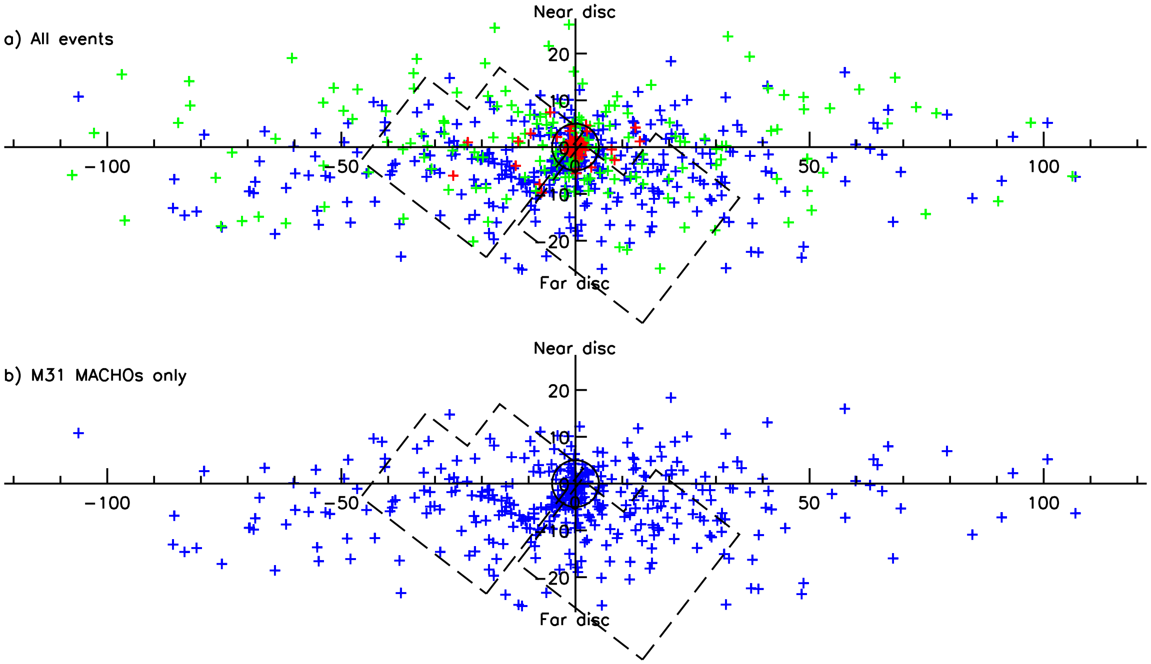
**5.** Constraints on velocity distribution function of MACHOS :

$\Longrightarrow$ near/far timescale asymmetry if strong radial anisotropy

# MACHOS IN M31 BY PIXEL LENSING : THE *POINT-AGAPE* SURVEY

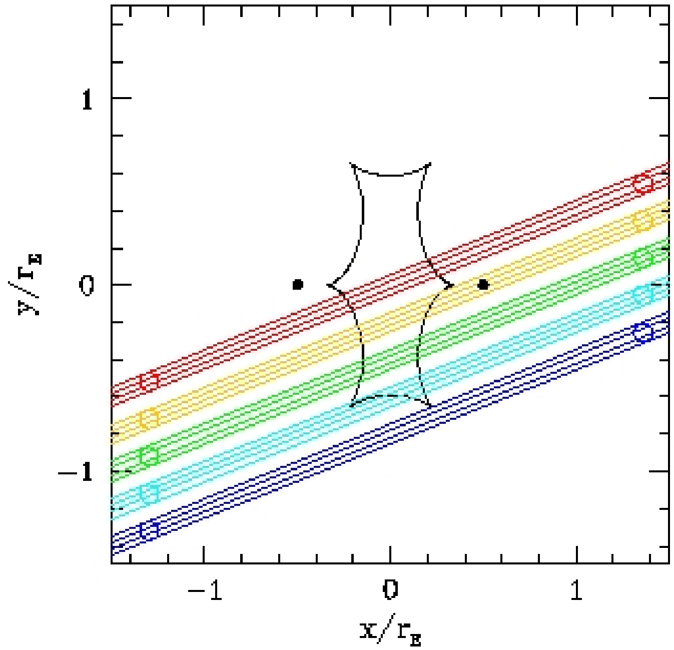
WFC at INT : large field, same instrument (same systematics), 3 seasons

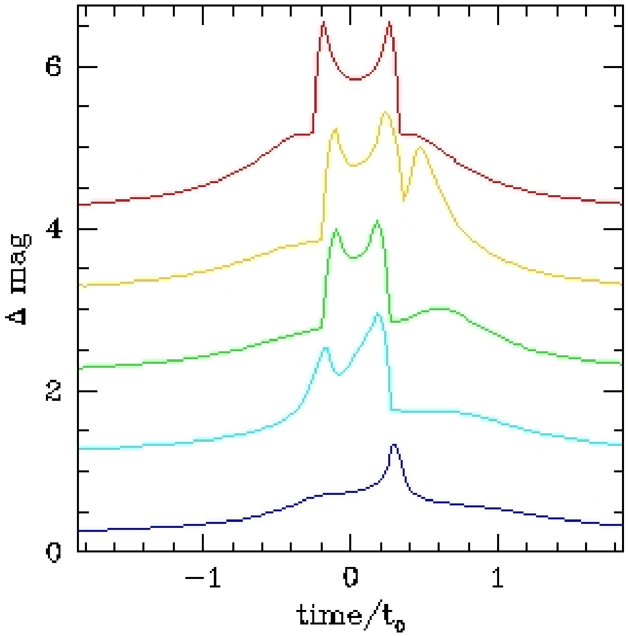
Expected events : Monte Carlo simulations, Kerins et al. (2001) MNRAS **323** 13



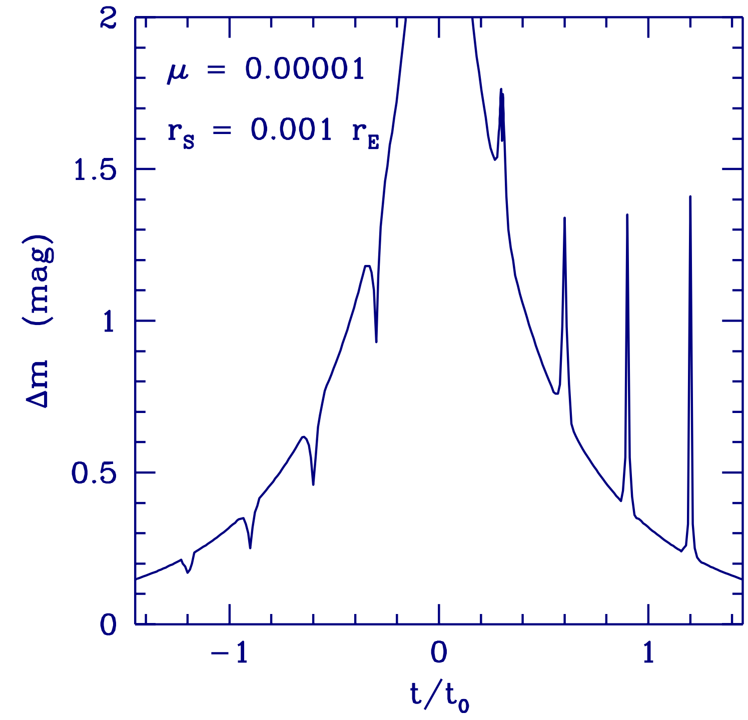
# FROM SIMPLE TO WORSE, YET INTERESTING

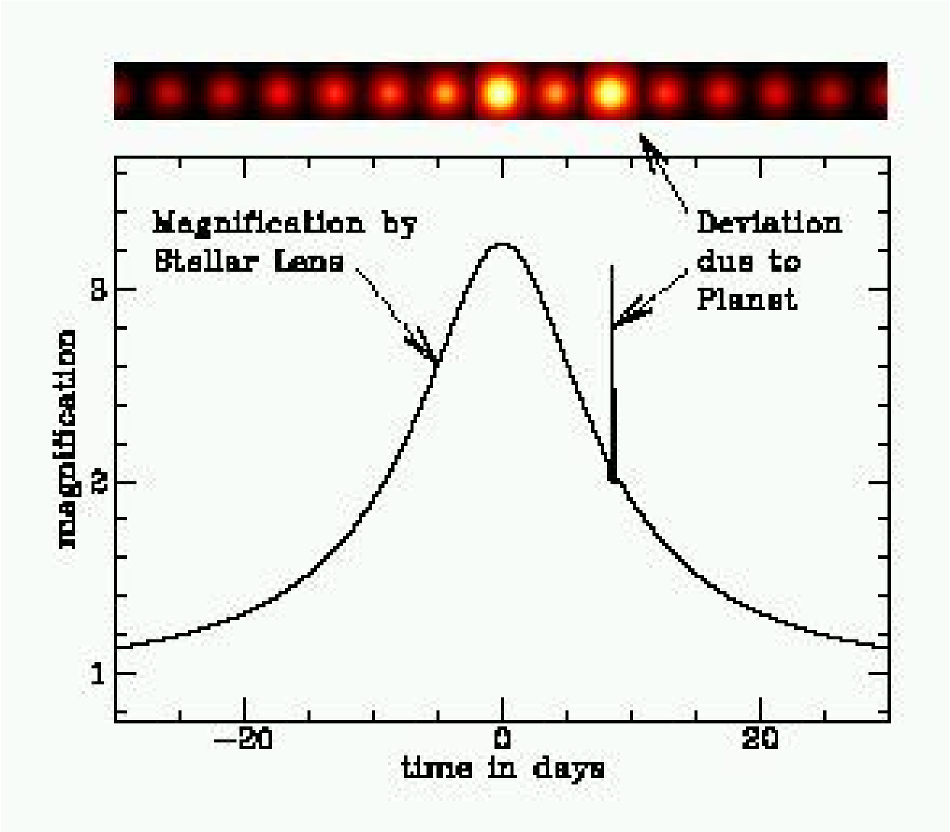
The zoo of binary lenses



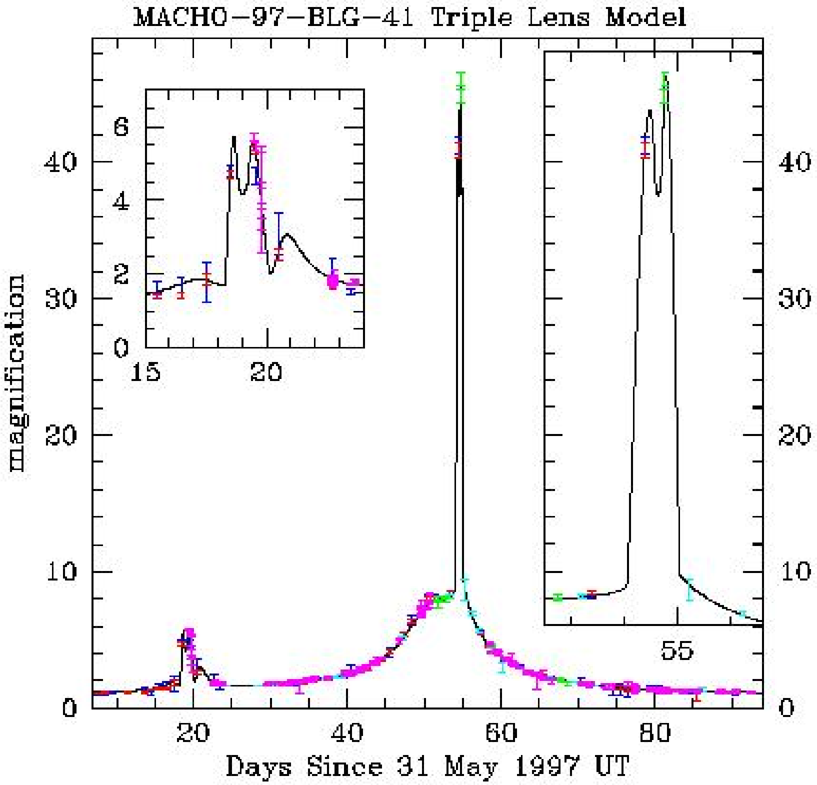


Binary events lift partially the degeneracy between mass and distance

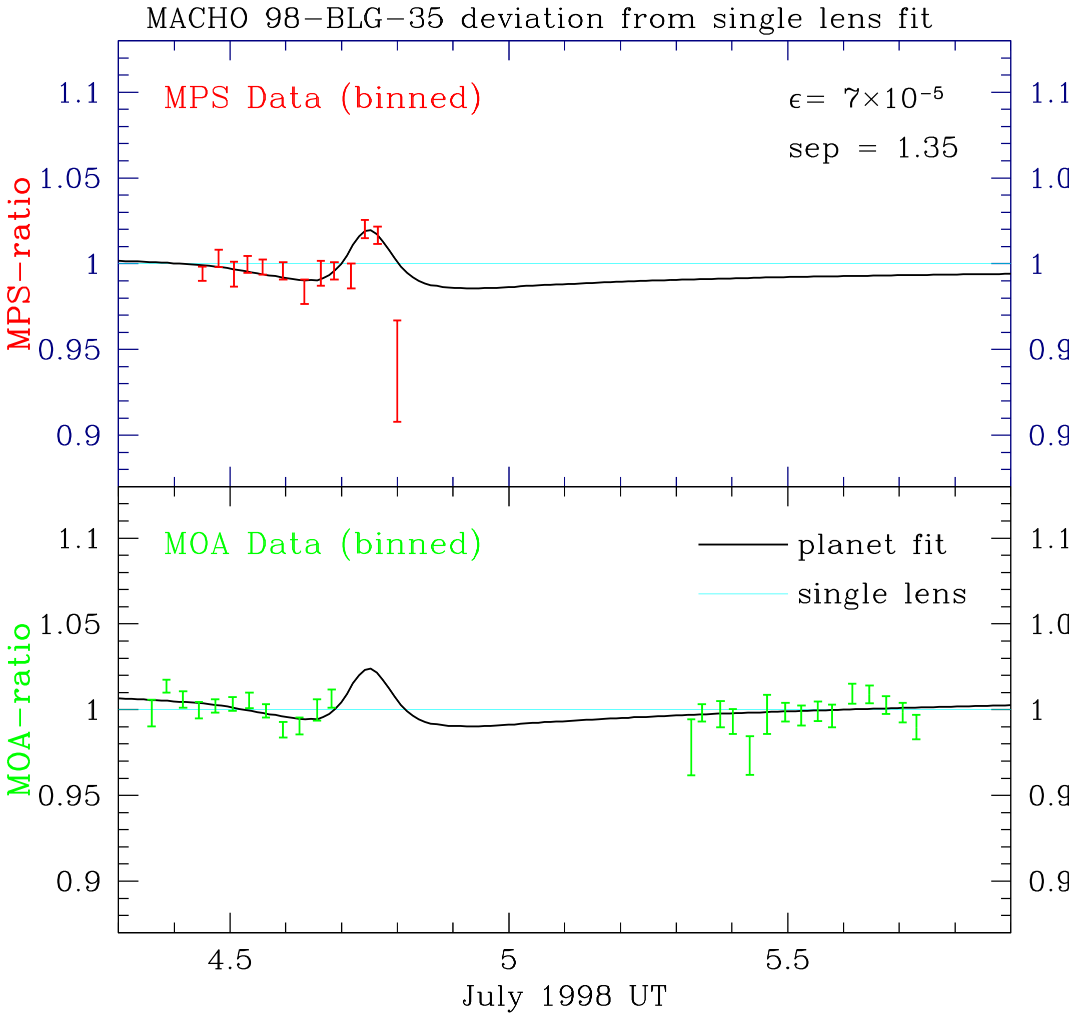

μ = 0.00001
r_S = 0.001 r_E
Δm (mag)
t/t_0
0
0.5
1
1.5
2
−1
0
1


Magnification by Stellar Lens
Deviation due to Planet
magnification
time in days
1
2
3
−20
0
20

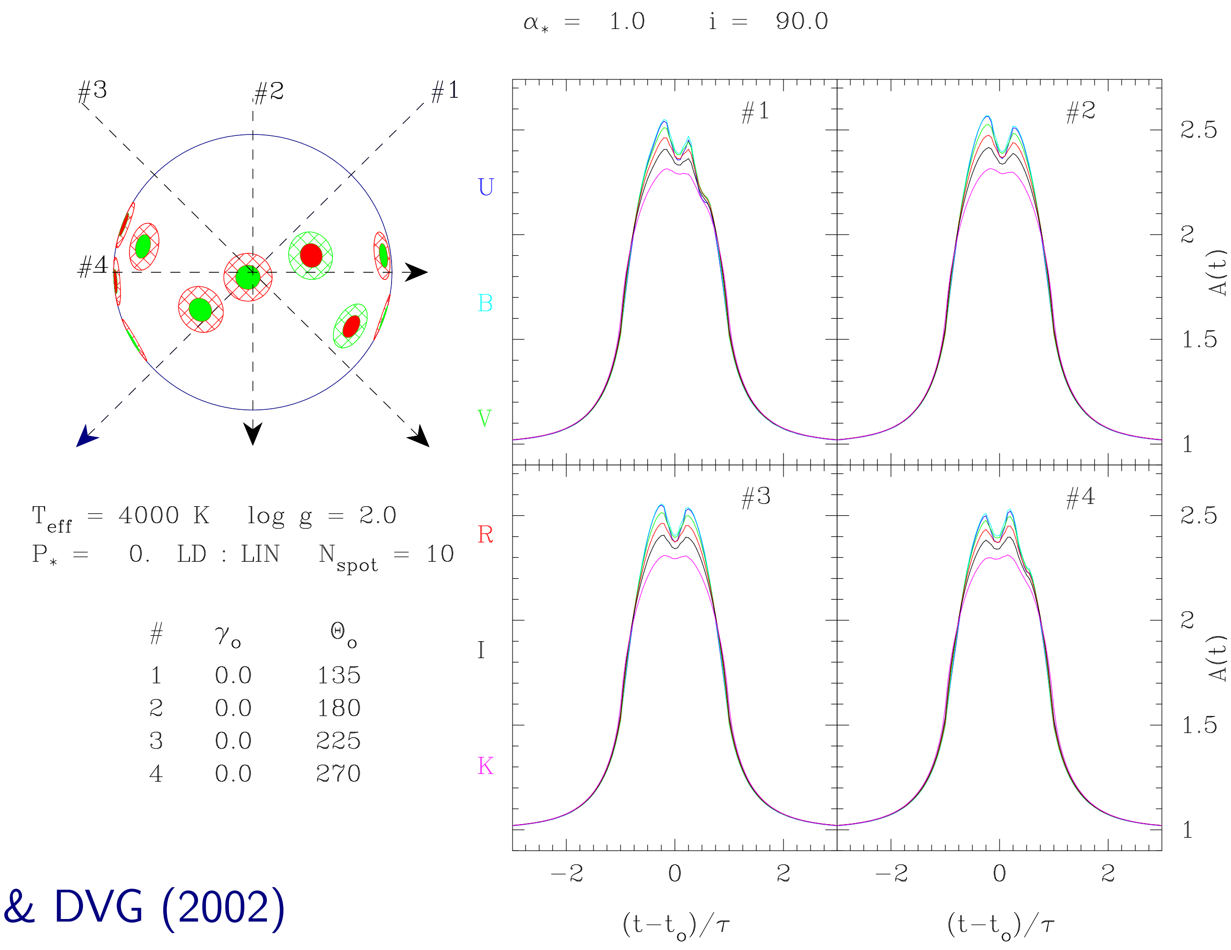
# A possible 3.5 $M_J$ planet at 7 AU in a binary system



Bennett et al. (1999) Nature **402** 57


MACHO 98−BLG−35 deviation from single lens fit
MPS Data (binned)
$\epsilon = 7\times10^{-5}$
sep = 1.35
MPS−ratio
1.1
1.05
1
0.95
0.9
MOA Data (binned)
planet fit
single lens
MOA−ratio
1.1
1.05
1
0.95
0.9
4.5
5
5.5
July 1998 UT

# CONTAMINATION BY STELLAR SPOTS ??



Bryce, Hendry & DVG (2002)

# SUMMARY

## Results

0. Unambiguous detection of ML events within the Local Group

1. MACHOs may account for about 20% of the mass of the halo

2. The Galactic bulge is barred

3. First imaging of stellar photospheres

# Prospects

0. Upgraded ML setups (SUPERMACHO) /
   / dedicated telescopes (OGLE-III)

1. Increase LMC statistics to get proper constraints on $f_{halo}$ and $m_L$ : microlensing optical depth $\tau$ maps and mass function of lenses

2. Nature of lenses? Very long timescale events?

3. Control experiments :
   M31 (AGAPE) : essential to understand nature of DM haloes
   GAIA : ML vs dynamical estimates of DM

## Implications

Nature of the lenses : compact baryonic dark matter
*vs* diffuse lukewarm baryons in clusters ?

Finite size effects : gravitational imaging : stellar atmospheres

Massive databases of stellar variability : stellar structure and evolution

Distant (?) future : dedicated telescope in orbit : no degeneracy

*No light, but rather darkness revealed*

Milton