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Gravitational Microlensing and Dark Matter

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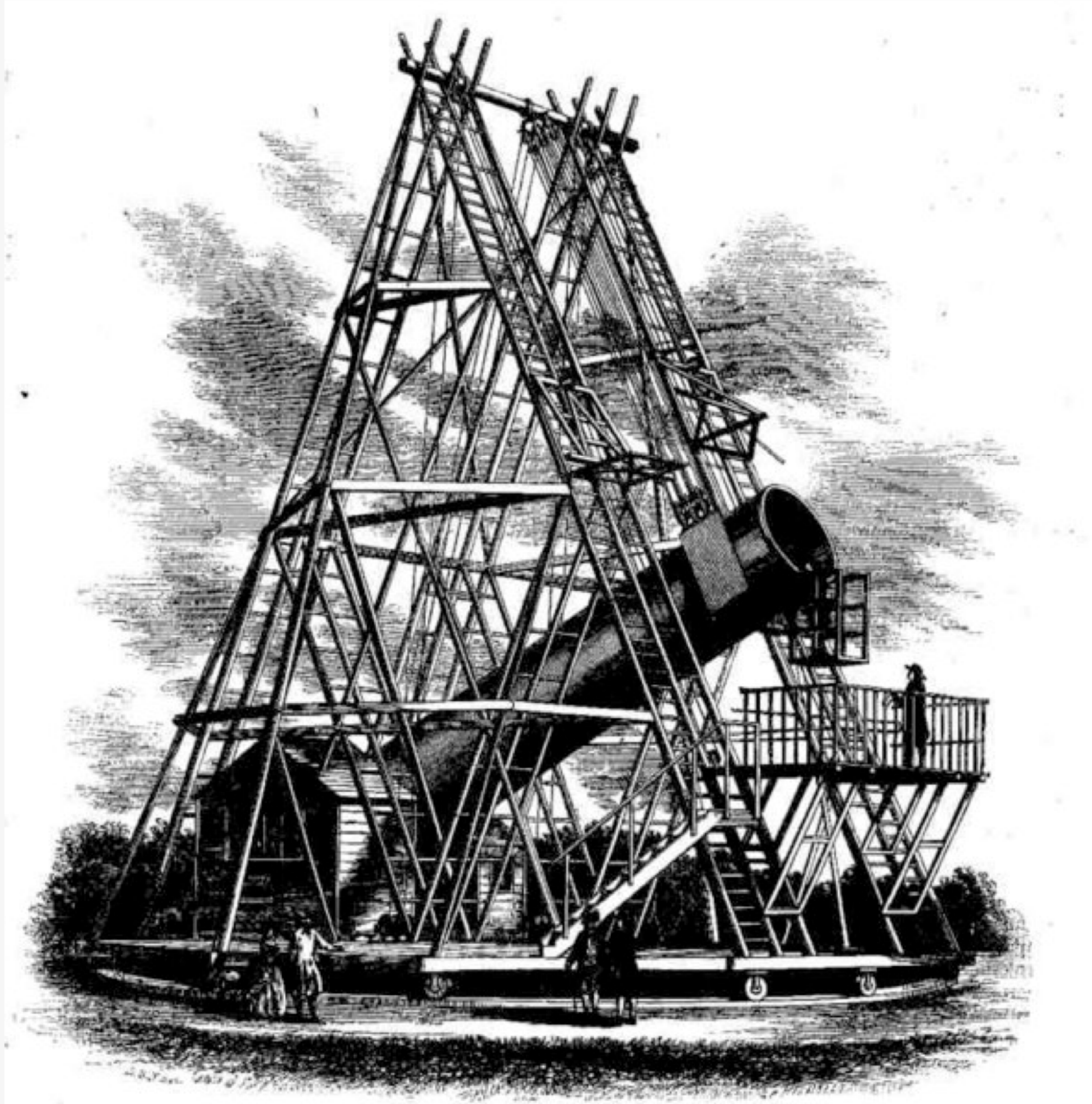
Distribution of matter in the Milky Way

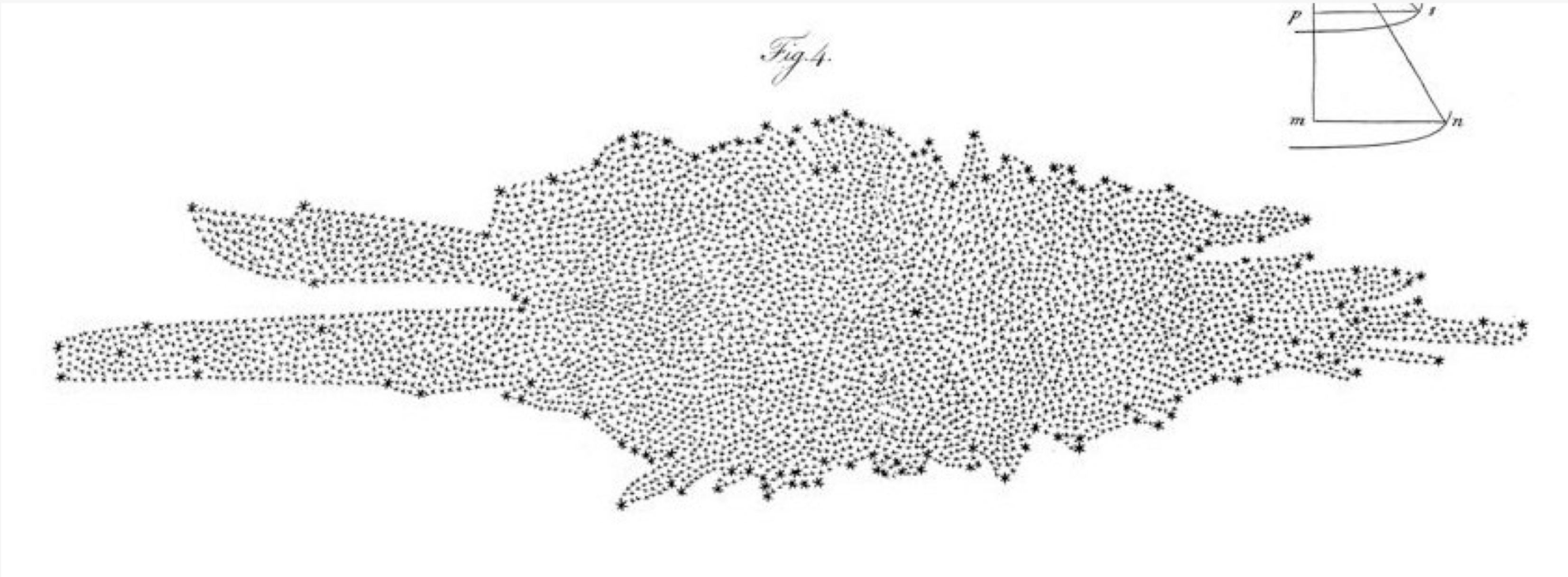


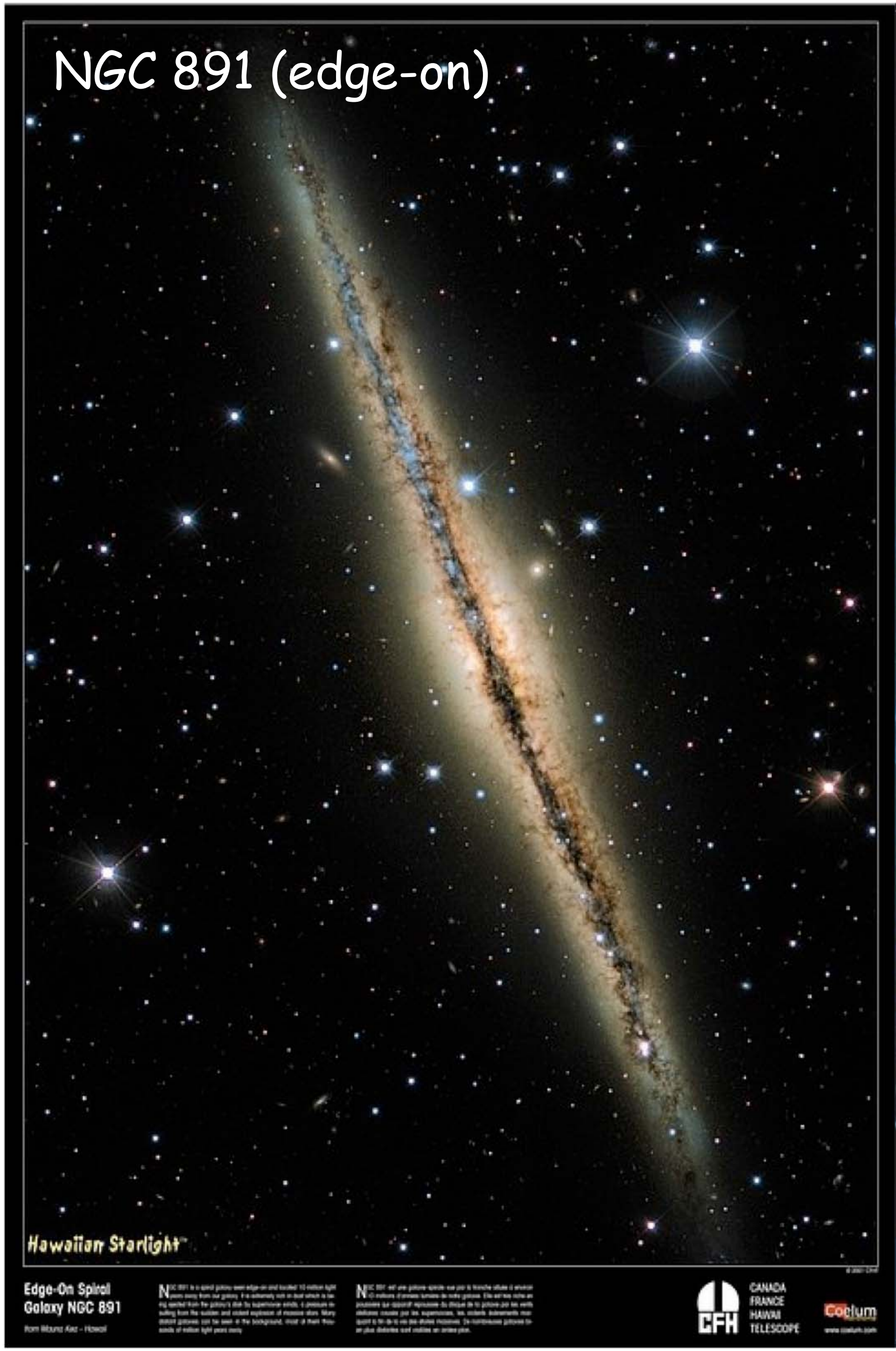
Herschel's 1.25m telescope

- **Galileo** (17th) discovers that the Milky Way is composed of stars
- **Herschel** (18th) obtains the first star counts of the Milky Way
- **Lord Rosse** (19th) observes the first external galaxies

Distribution of matter in the Milky Way

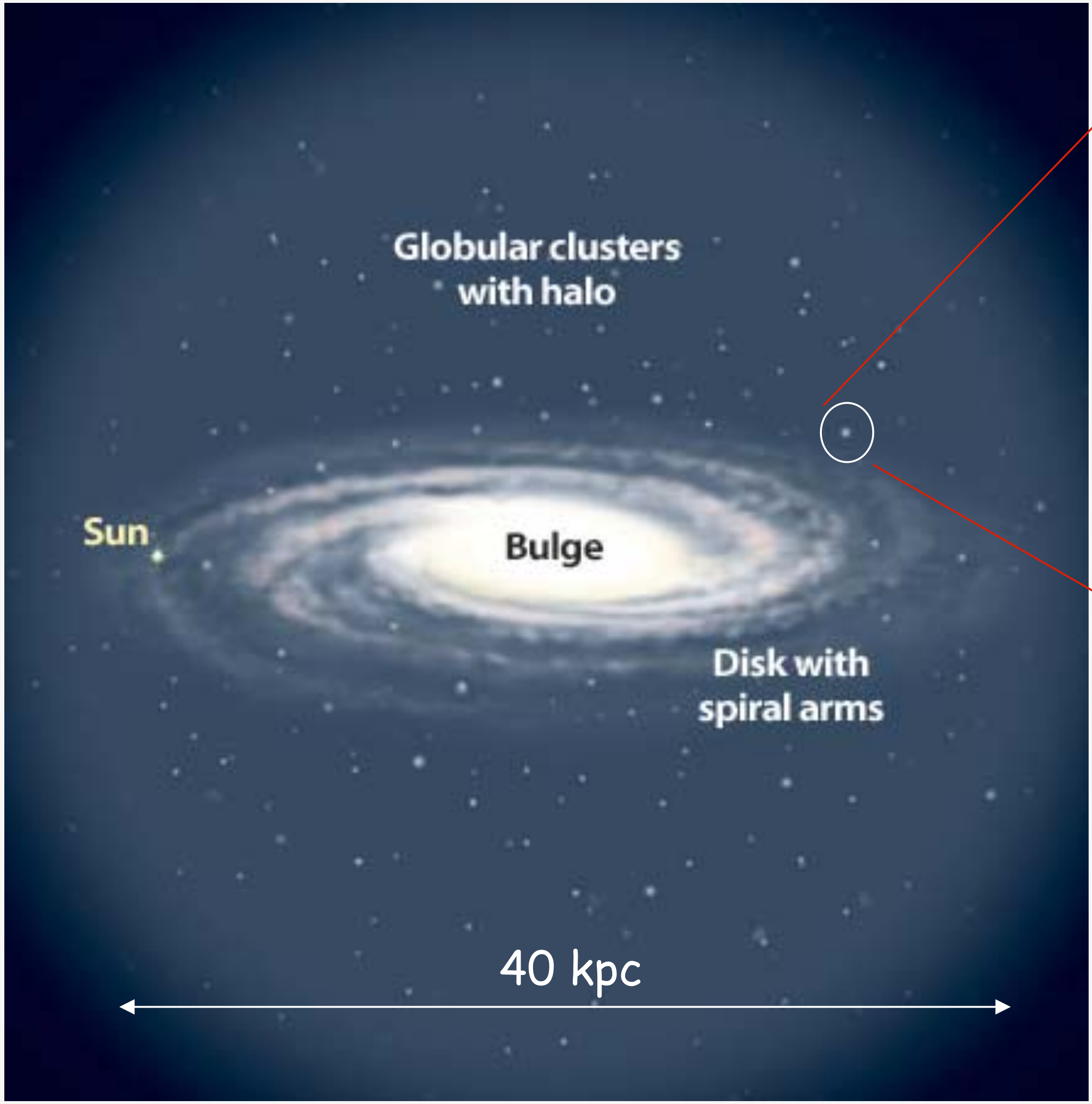
Tentative map of the Milky Way by **Herschel** (18th century) using star counts towards different directions on plane of the sky

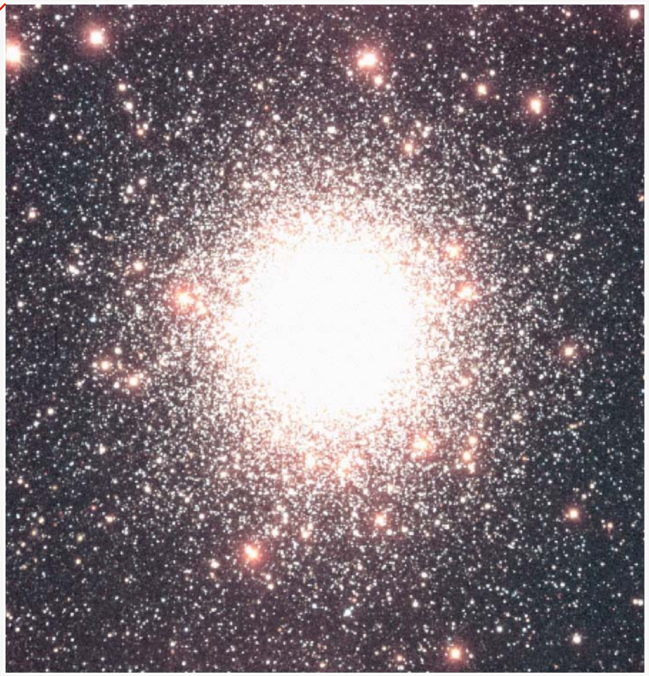



NGC 891 (edge-on)
Hawaiian Starlight
Edge-On Spiral Galaxy NGC 891
CANADA FRANCE HAWAII TELESCOPE
CFH
Coelum


NGC 1232 (face-on)
The Magnificent Spiral Galaxy NGC 1232 (VLT/FORS)
ESO. Astronomy made in Europe

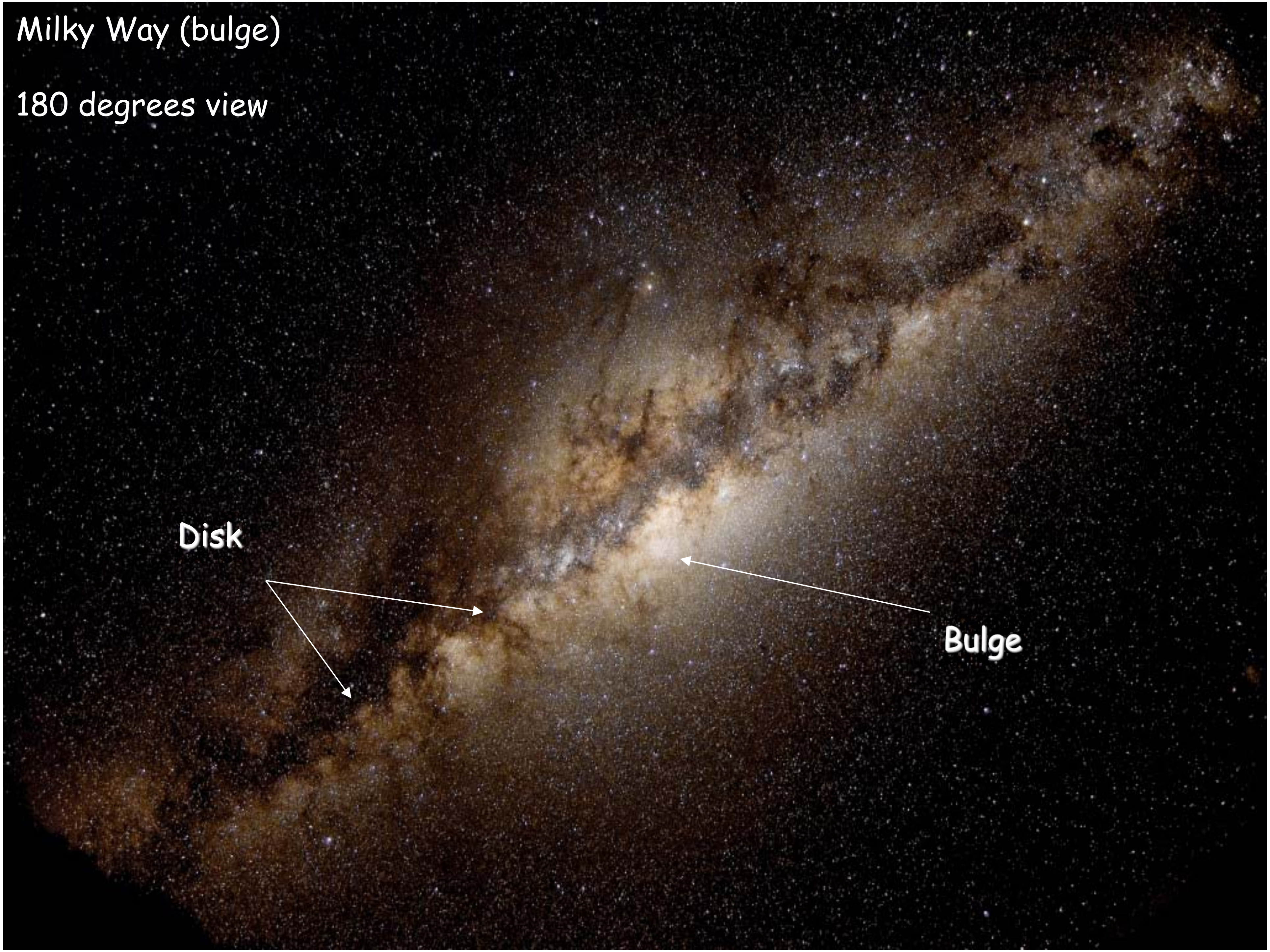
La Voie Lactée





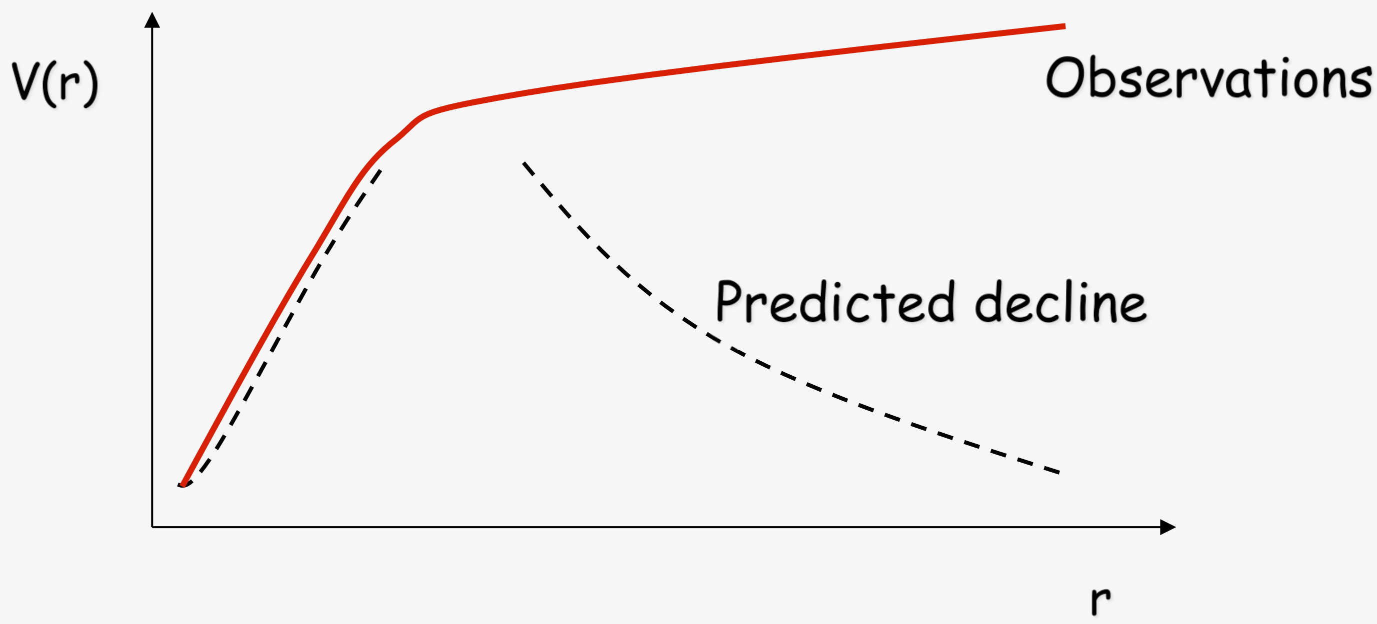
- Disk: young stars, dust, gas, dark matter
- Bulge: old stars + central black hole
- Halo: 200 globular cluster and **dark matter**

- A few satellite galaxies


Milky Way (bulge)
180 degrees view
Disk
Bulge

Flat rotation curves of spiral galaxies

- Close to the bulge (< 5 kpc) : $V_{rot}(r) \alpha r$
- External parts (> 10 kpc) : $V_{rot}(r) \alpha r^{-1/2}$



Mass is missing in the outter parts of the spiral galaxies

Candidates for the missing matter

1. Massive elementary particles

Neutralinos
Higgs particle
WIMPS
Axions

2. « Astrophysical » dark matter

Sub-stellar mass black holes
White dwarfs
Brown dwarfs
Planets

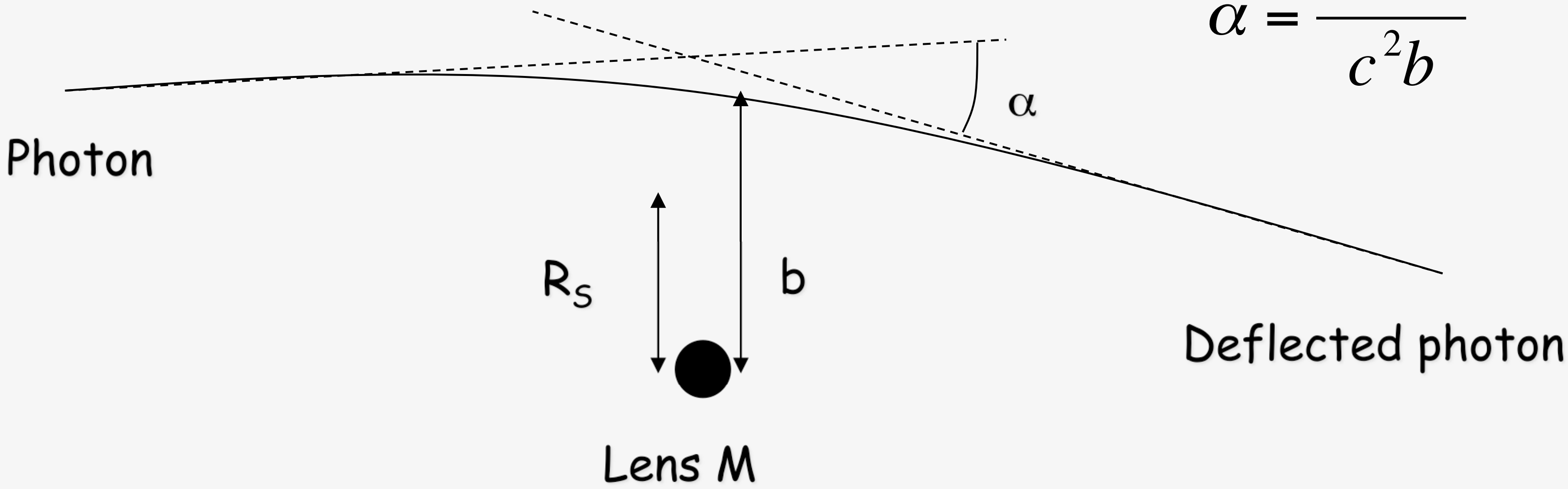
Gravitational lensing

Curved geodesics due to the gravitational field of a compact object

$\longrightarrow$ photons are defleted by mass

Deflection angle independent of photon's energy

$$\alpha = \frac{4GM}{c^2 b}$$



Gravitational lensing

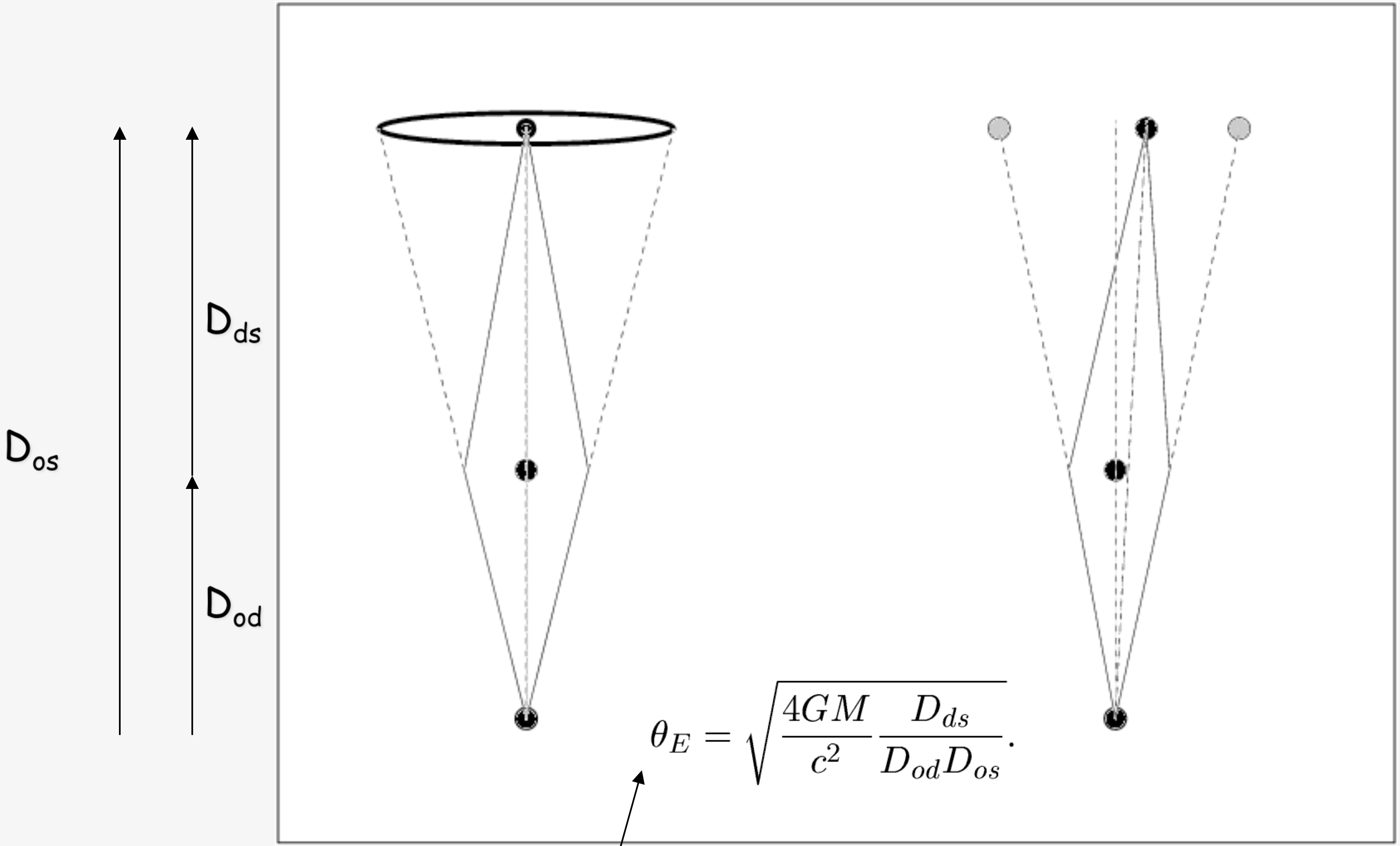
Effet on the « lensed objects »:

- distorsion
- surface brightness is conserved
- apparent light magnification
- formation of multiple images
- centroïd change

Achromatic effect

Three main regimes: Strong
Weak
Micro

Multiple images and Einstein rings

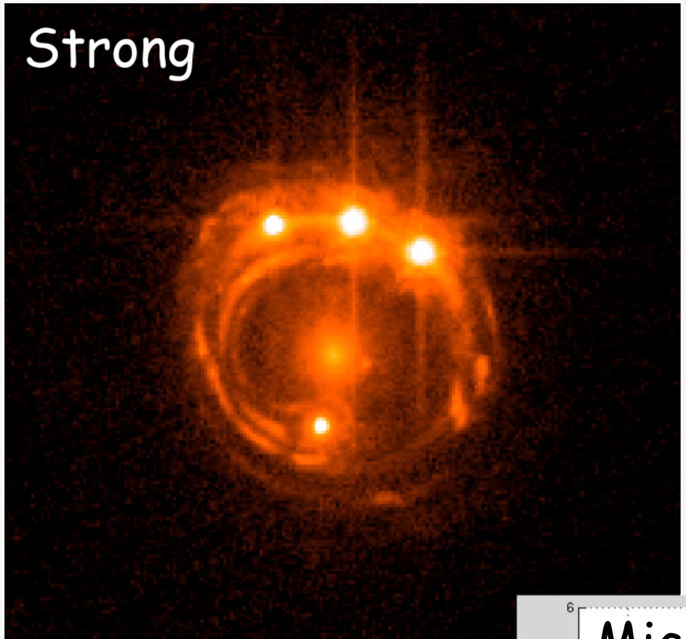


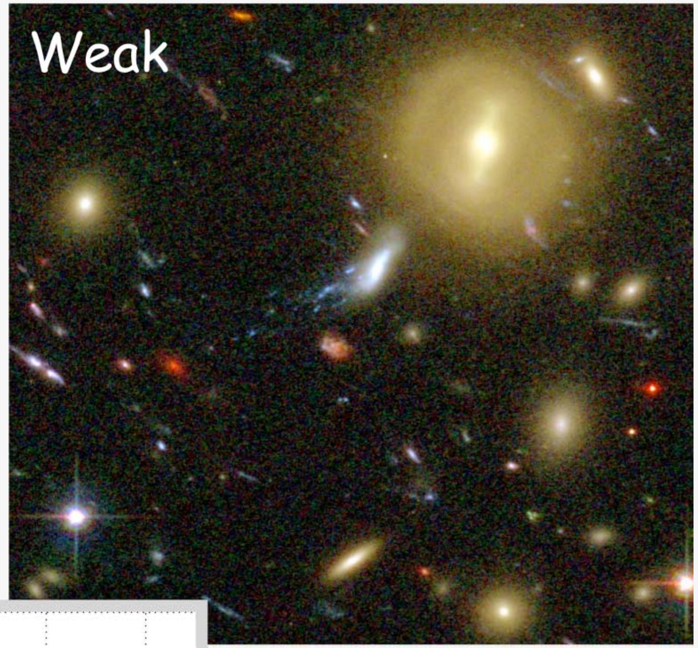
$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{ds}}{D_{od}D_{os}}}.$$

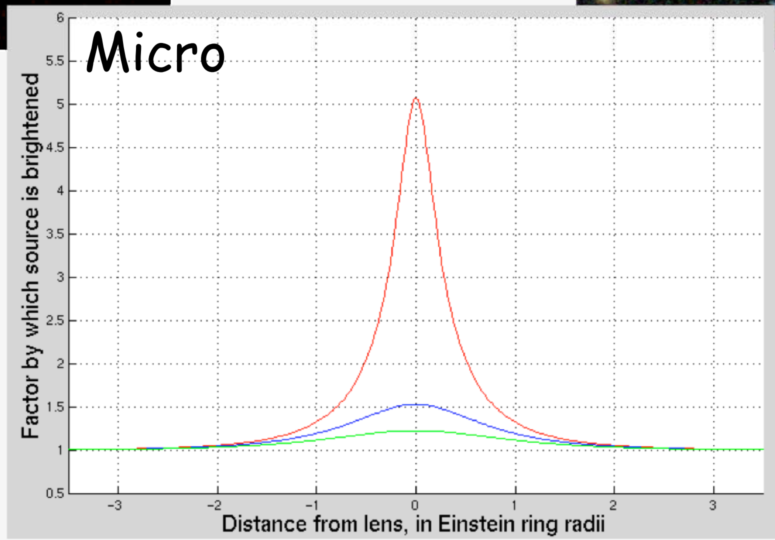
Einstein radius (dimensionless)

Effect of a Jupiter-mass black hole

Examples of gravitational lensing







Gravitational microlensing

- Simple idea: look for star-star lensing (Paczynski, 1986)

- Deflection angles are too small to see a strong lensing effect 10^{-3} arcsec

- Probability of alignment is negligible: 10^{-6} (microlensing « optical depth »)

- Time-scales of microlensing « events » in the range 1 day to 1 year

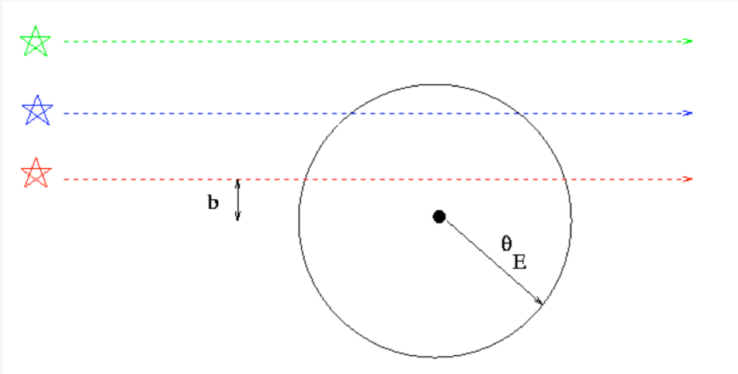
-> need to follow millions of stars for a long time with good sampling

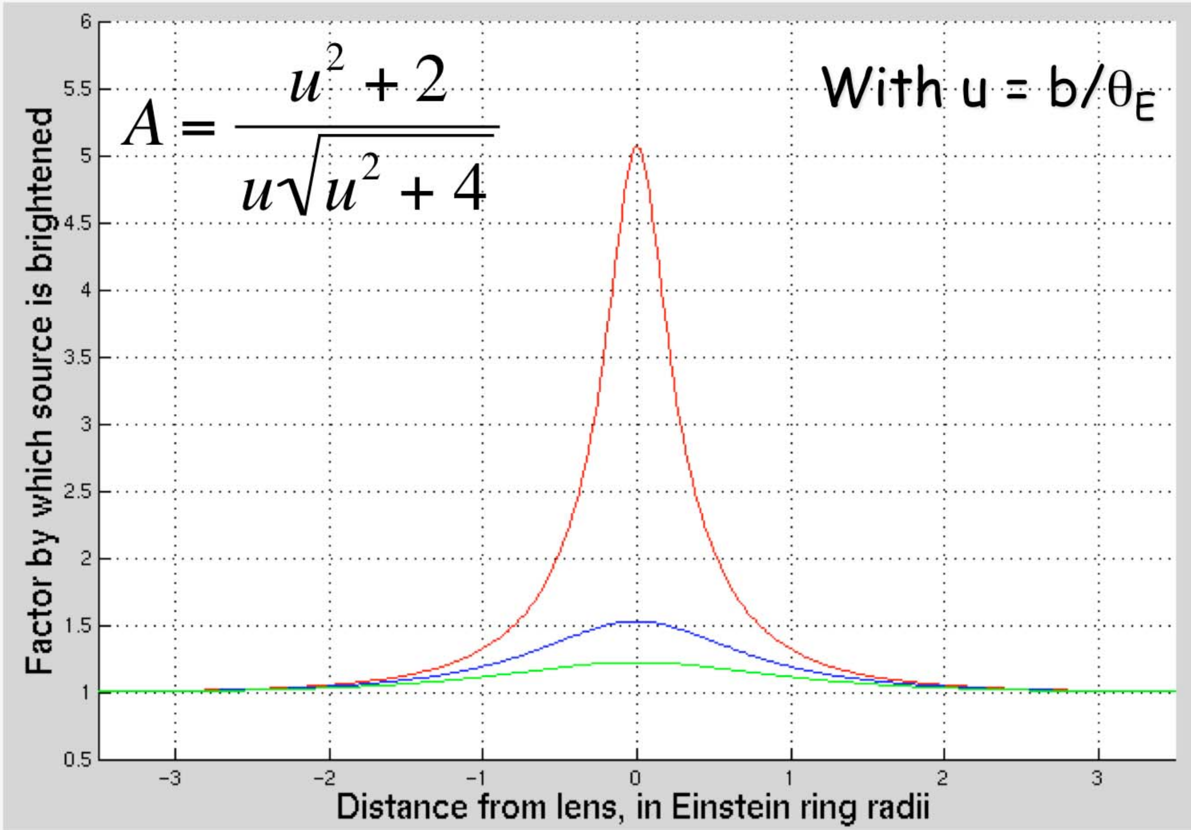
- Experiment is possible thanks to :

    1. Large format CCDs
    2. Improved computers and photometry algorithms
    3. Dedicated telescopes

-> microlensing surveys are probably the first « experiment » in astrophysics

Gravitational microlensing





Gravitational microlensing

Main surveys

1. **MACHO** : Massive Compact Halo Objects
   in the direction of the LMC

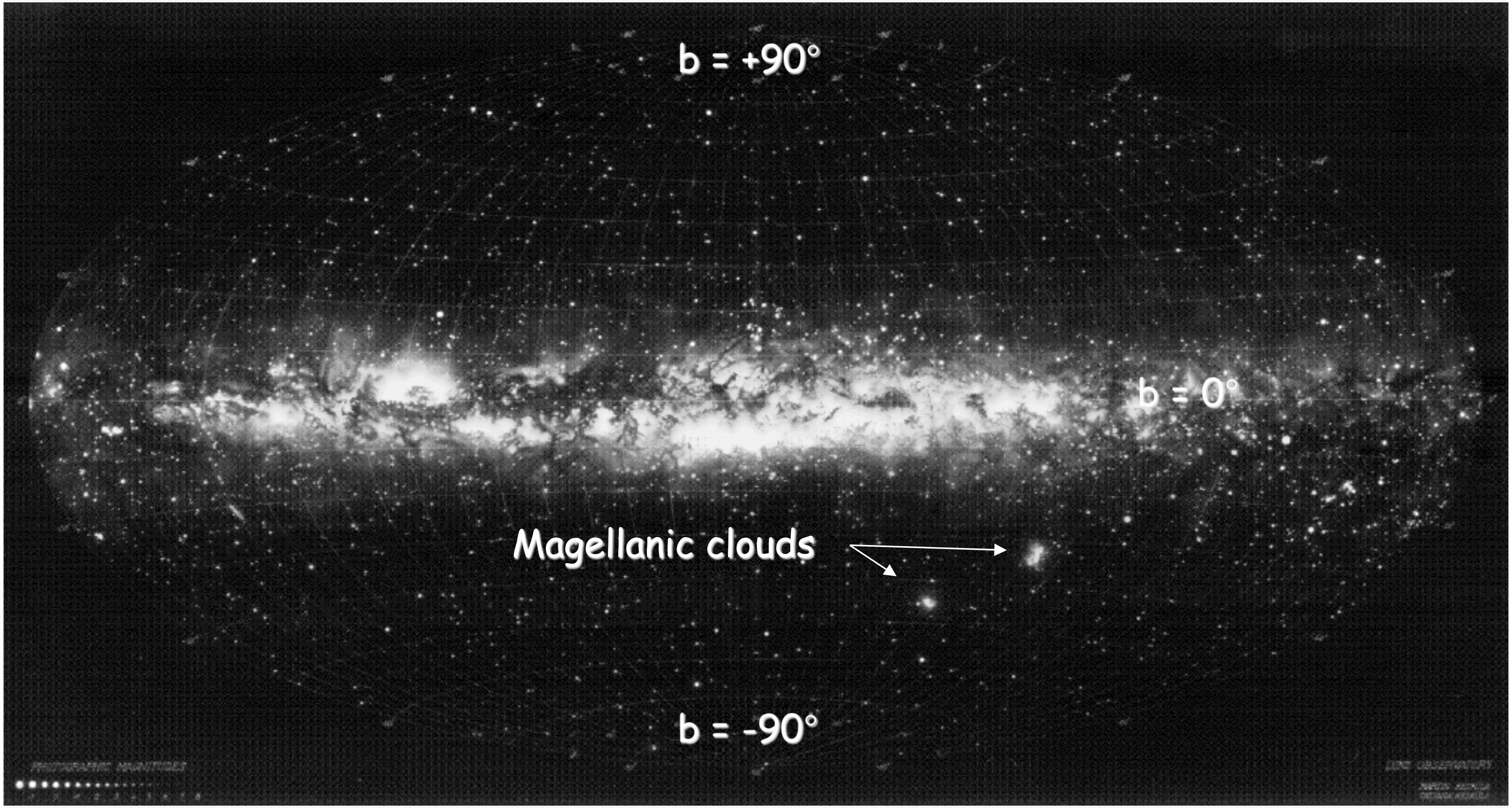
2. **EROS** : Expérience pour la Recherche d'Objets Sombres
   LMC and SMC

3. **OGLE** : Optical Gravitational Lensing Experiment
   in the Galactic Bulge (originally cross check of MACHO)

4. **MOA** : Microlensing Observations in Astrophysics

5. **Pixel lensing** experiments in the Andromeda galaxy

Target fields of the main microlensing surveys



Results

1. About 20 confirmed events in the direction of the LMC and SMC
2. $>$ 4000 events in the Galactic Bulge : larger than expected
3. Duration of events: 30 to 239 days (MACHO)
4. **MACHO**: Only 20% of the dark matter in the Milky Way's halo is made of objects with masses in the range $0.15 < M < 0.9$ solar masses
5. **EROS**: less than 25% of the mass of the halo is in the form of objects with masses in the range $10^{-7} < M < 1$ solar mass
6. Lack of long duration events rules out black holes with $0.3 < M < 30$ solar masses

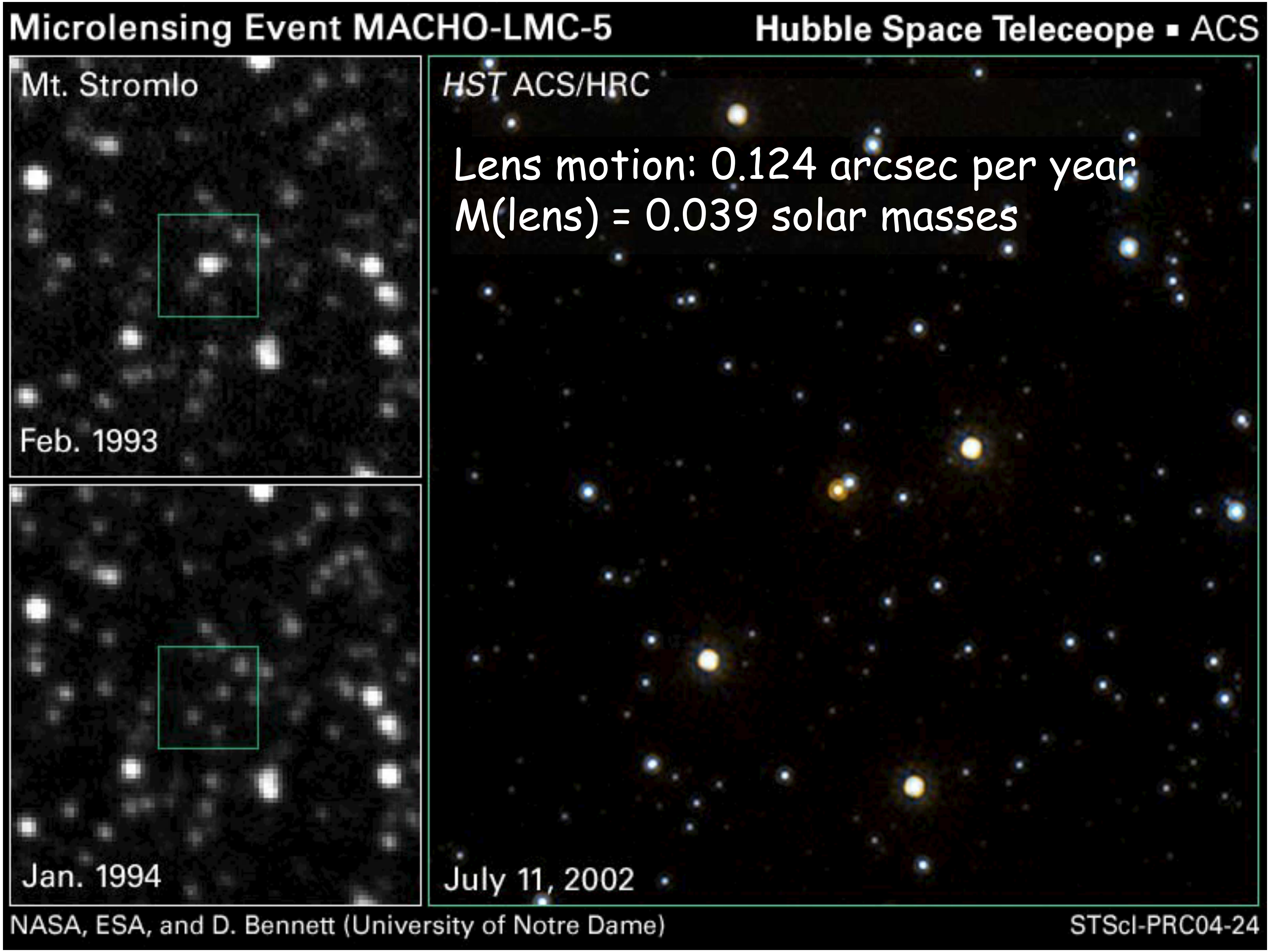
Caveats

The transverse velocity of the lens and its mass are degenerate

We need to know the distance the lens to get its mass !

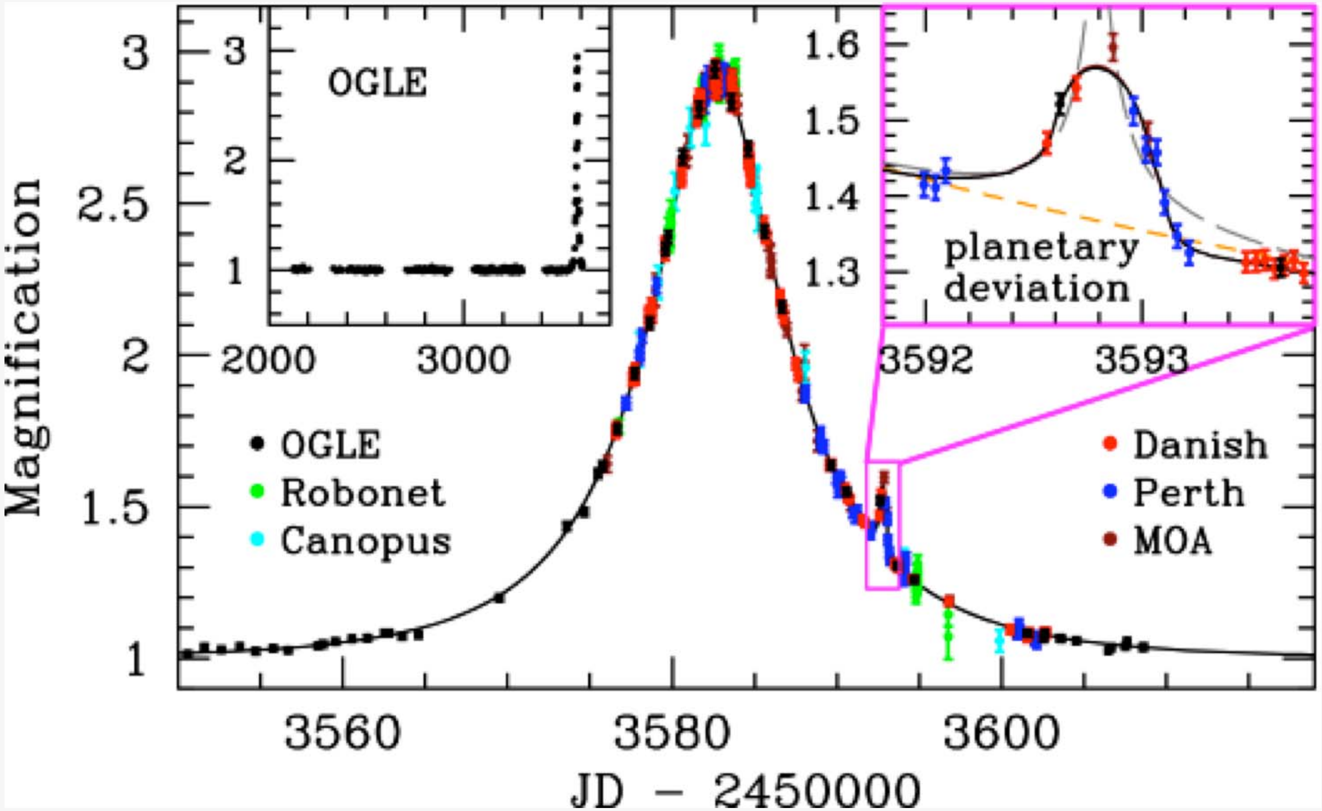
This can be done :

- by measuring parallaxes (satellite GAIA)
- by measuring transverse velocities


Microlensing Event MACHO-LMC-5
Hubble Space Teleceope ▪ ACS
Mt. Stromlo
Feb. 1993
Jan. 1994
HST ACS/HRC
Lens motion: 0.124 arcsec per year
M(lens) = 0.039 solar masses
July 11, 2002
NASA, ESA, and D. Bennett (University of Notre Dame)
STScI-PRC04-24

Byproduncts: small mass planets

One gets planets (associated with the lensing star) for free !
(Beaulieu et al. 2006, Nature 439, 437-440)

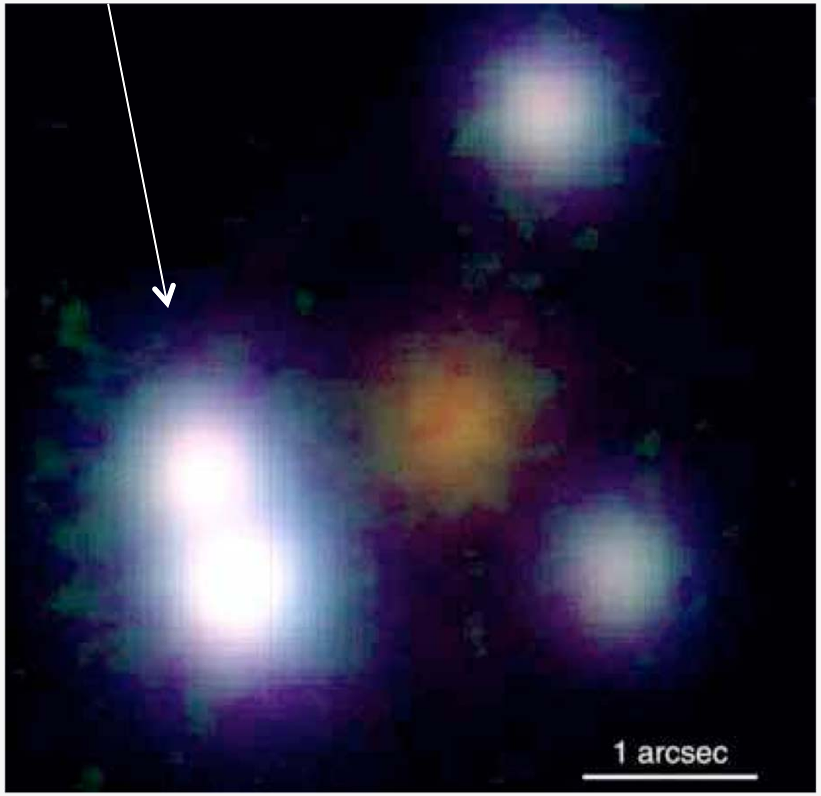


Date (Julian days)

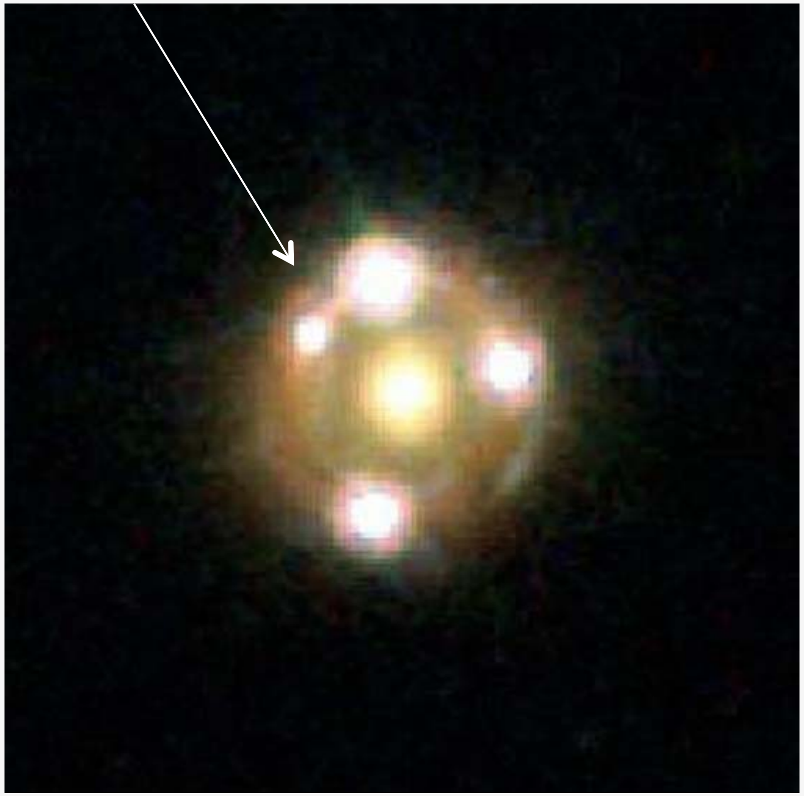
Compact vs. smooth dark matter

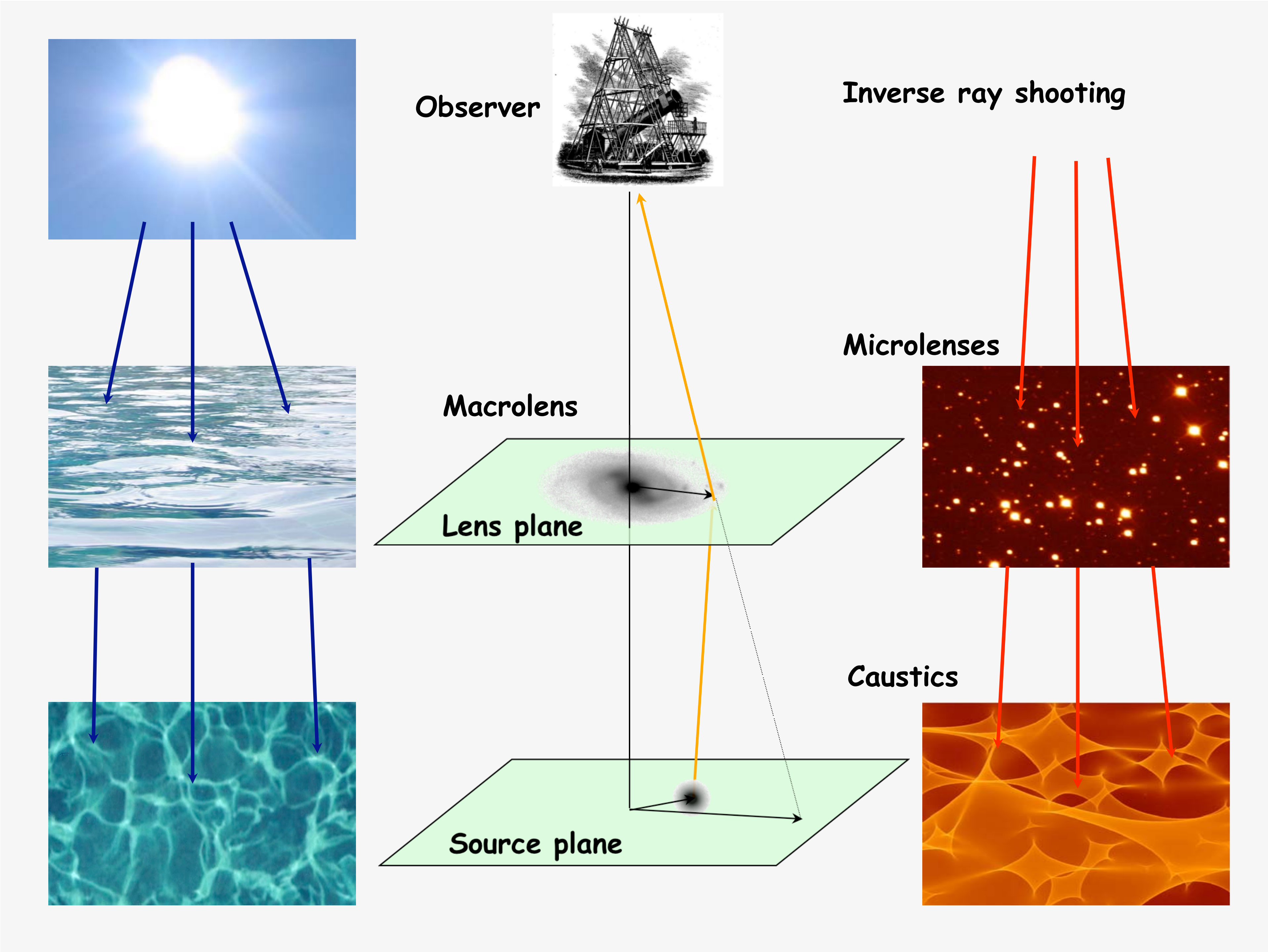
Flux anomalies in strong lensed quasars

PG1115+080
normal flux ratio



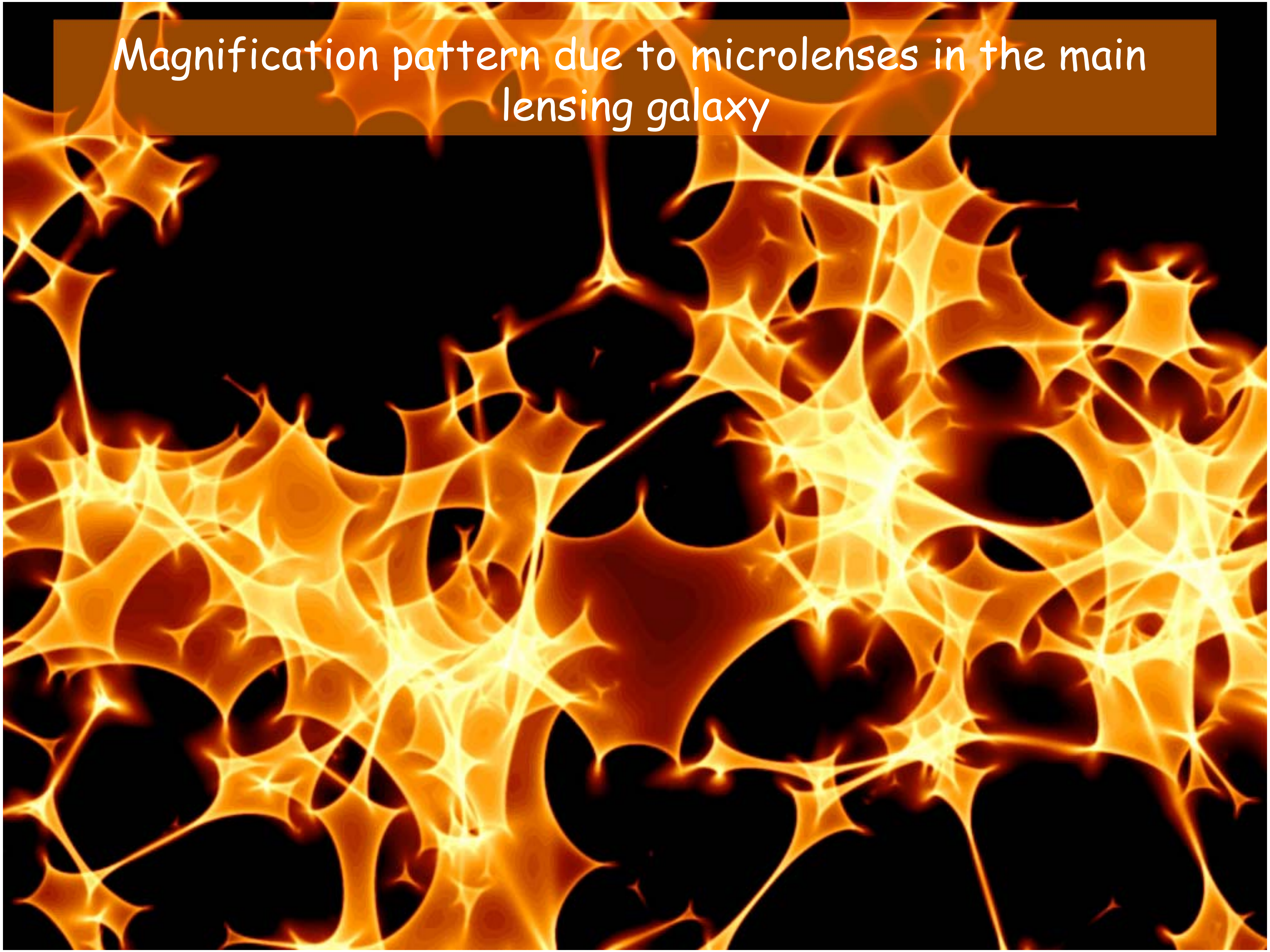
SDSS 0924+0219
anomalous flux ratio





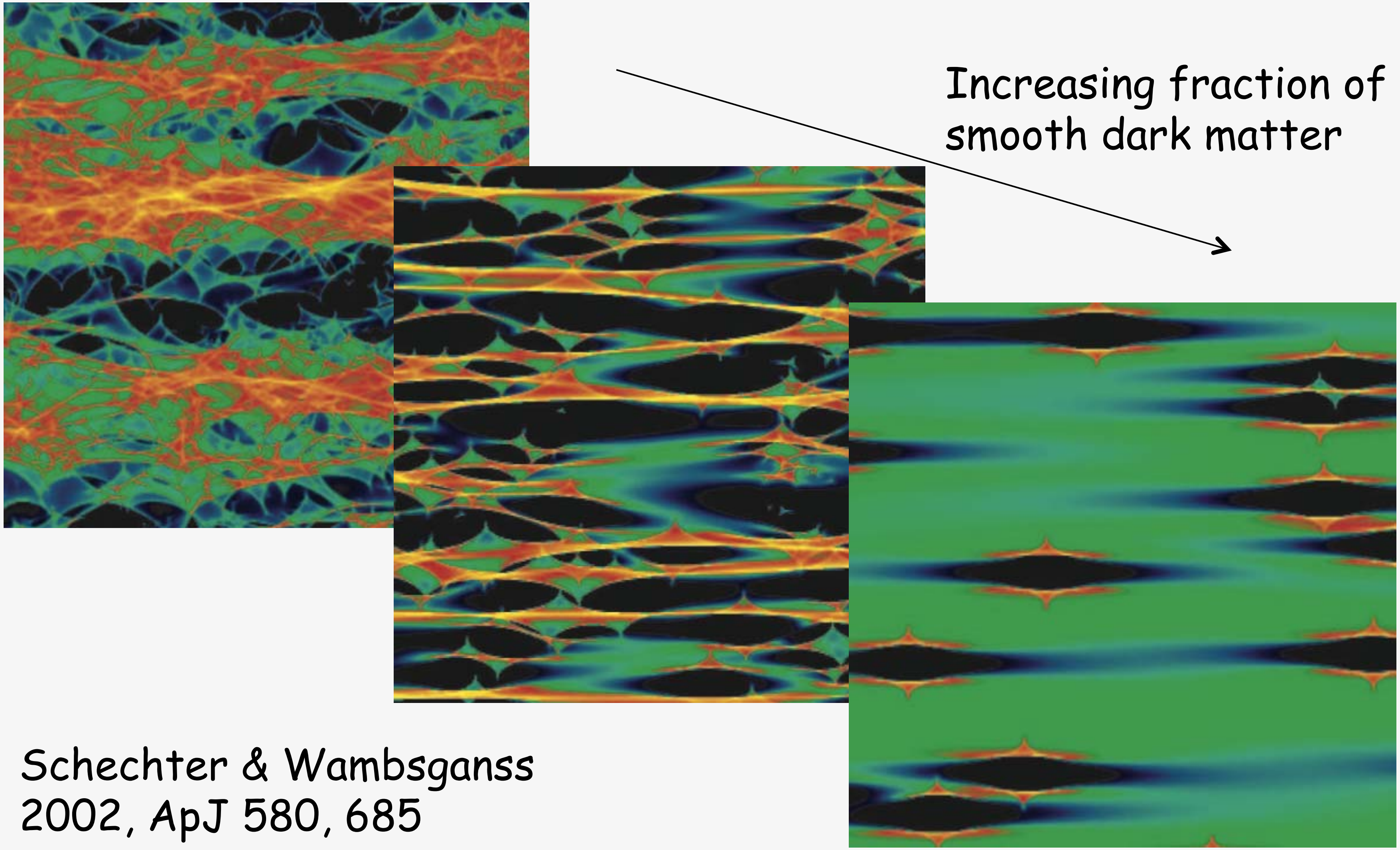
Observer
Inverse ray shooting
Microlenses
Macrolens
Lens plane
Caustics
Source plane

Magnification pattern due to microlenses in the main lensing galaxy



Compact vs. smooth dark matter

Flux anomalies in strong lensed quasars



Schechter & Wambsganss
2002, ApJ 580, 685


« Bullet cluster » : evidence for collisionless dark matter
Clowe et al. 2006, ApJ 648, L109

Summary

- Dark matter under form of compact objects is not sufficient to explain all the mass in the Galaxy halo
- At most 25% of the dark matter ingalactic halos is in low mass stars
- Microlensing is efficient to detect compact masses (OGLE)
- A combination of strong and microlensing indicate that most of the dark matter is « smooth »
- The « bullet cluster » may be an evidence for diffuse collisionless dark matter
- Lensing in general is a great tool to map dark matter
- EUCLID (ESA) / JDEM (NASA) are furture space-based experiments to use strong, weak and micro lensing to study dark matter and dark energy.