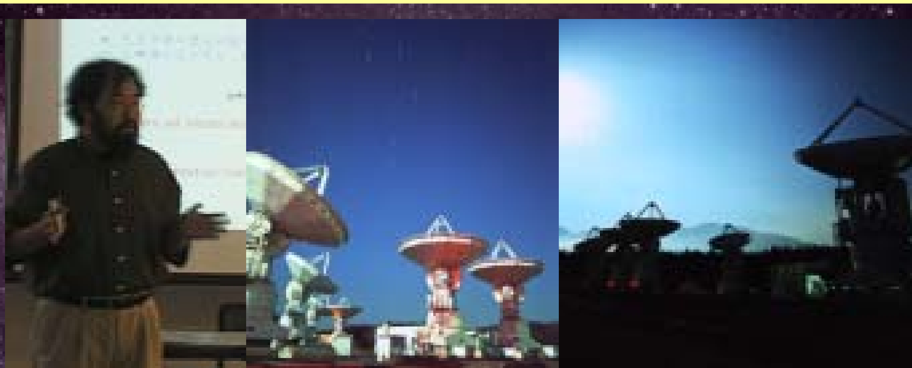
VERA WORKSHOP 2003.10.14-15 @NAOJ, Mitaka

ASTROMETRIC STUDY



Astrometric Microlensing and Macrolensin

OF GALACTIC CENTER

Kouji Ohnishi

ohnishi@ge.nagano-nct.ac.jp

Nagano National College of Technology, Japan

Mizuhiko Hosokawa

Communications Research Laboratory, Japan

Toshio Fukushima

National Astronomical Observatory Japan

toward the Galactic Center

BY VERA

Abstract

Astrometric observation of 10 micro arcsecond accuracy will be possible by using VERA .

1. We estimated the optical depth and the event rate of the positional fluctuation of the extragalactic radio sources near Sgr A* due to the astrometric microlensing by disk stars and bulge stars are estimated and found that such position wander degrades the measurement of trigonometric parallax of Sgr A* significantly.

2.The collective gravitational deflection by the bulge, that is called MACRO-Lens, are observable magnitude. This effect reaches 0.6 micro-arcsecond/yr and it has a secular component. The measurement of these effects will provide us valuable information on the density and mass function of the Galactic Center.

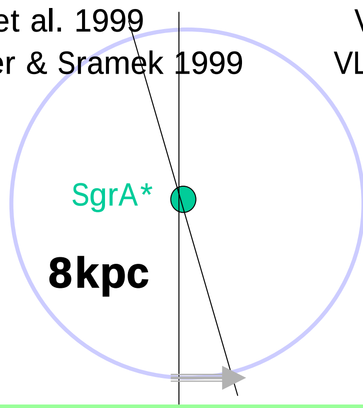
Background Photo by Kouji Ohnishi@ Mt. John University Observatory, NZ

1. Introduction

1-1 Detection of Galactic Rotation of Solar System

phase-referenced to QSOs J1748-291 J1745-283

- Reid et al. 1999 VLBA 43GHz,2yr
- Backer & Sramek 1999 VLA 4.9GHz, 17yr



VLBI observation of SgrA* =>6mas/y

1. Introduction

1-2 Gravitational Lens effect to the G.C.

Micro Lens effect

of reference QSOs
by the star near the line of sight to G.C

Individual Star

Astrometric Microlensing

(Hosokawa,et al 2002)

Macro Lens effect

of reference QSOs
by galactic potential
near the line of sight to G.C

Group of Stars

(1) SgrA* (Massive BH)
(2) Core
(3) Bulge

Macro Lens

(Ohnishi, et al. 2003)

1. Introduction

1-3 Apparent Motion

SgrA*	QSOs
Section 1: Secular, 6 mas/yr, Galactic Rotation	Section5: Secular, 0.6 μas/yr, Macro Lens
Section 3: Periodic, 250 μas/yr, Annual Parallax	Random (several years), 10 μas/yr, Microlensing

2. Astrometric Microlensing

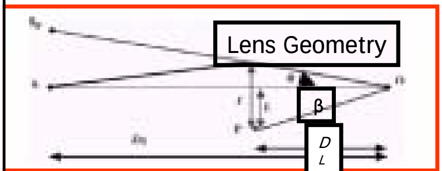
2-1 Review of Astrometric Microlensing

- **Gravitational Lens**

Gravitational lensing is one of the most promising tools for studying invisible lenses like MACHO and low-mass star in tl Galaxy.

- **Astrometric Microlensing**

The positional shift of the image centroid due to stars and MACHO are observable by means of high-precision interferometric astrometry at the level of a few micro arc second.



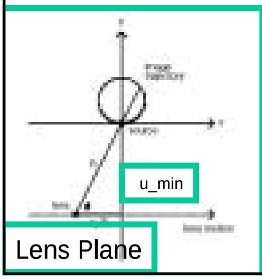
Impact parameter in the unit of Einstein ring angle:

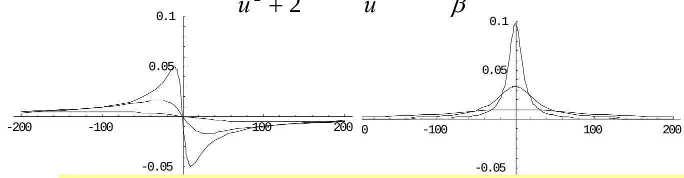
$$u = \frac{\beta}{\theta_E} \quad ; \theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_S - D_L}{D_S D_L}}$$

β ; angle between lens and source

Deflection angle in the unit of Einstein ring angle:

$$\theta = \frac{u}{u^2+2}\theta_E \approx \frac{1}{u}\theta_E = \frac{\theta_E{}^2}{\beta}$$

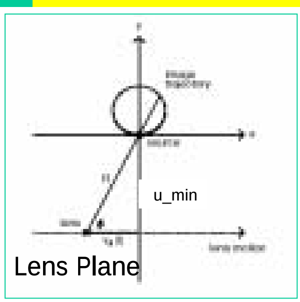




The shift of image along the direction of motion(left) and perpendicular motion(Right)
Each panel shows the case of u_min=10,30,100 in the unit of Einstein angle

2. Astrometric Microlensing

2-2 Optical Depth and Event Rate



Deflection angle: $\theta = \frac{\theta_E{}^2}{\beta}$

Detection limiting accuracy: $\theta_{\min}$

$$\theta_{\min} \equiv \frac{\theta_E{}^2}{\beta_{\max}}$$

The radius of detectable region : $u_A R_E$

$$u_A \equiv \frac{\beta_{\max}}{\theta_E} = \frac{\theta_E}{\theta_{\min}}$$

Optical Depth

$$\tau_A = \int dm \int_0^{D_S} dD_d \pi (u_A R_E)^2 (\frac{\rho}{m}) = \frac{16\pi G^2}{c^4}\frac{D_S \overline{m}}{\theta_{\min}{}^2}\rho_0 \overline{\tau_A}$$

here $\rho = \rho_0 \overline{\rho}(x)$ and

$$\overline{\tau_A} \equiv \int_0^1 dx \overline{\rho}(x)(1-x)^2$$ If $\rho_0=1$; then $\overline{\tau_A} = \frac{1}{3}$

Event Rate

$$\Gamma_A = \frac{8G}{c^2}\left(\frac{\overline{V}}{\theta_{\min}}\right) D_s \rho_0 \overline{\Gamma_A}$$

here $$\overline{\Gamma_A} \equiv \int_0^1 dx \overline{\rho}(x)(1-x)$$

If $\rho_0=1$; then $\overline{\Gamma_A} = \frac{1}{2}$

2. Astrometric Microlensing

2-3 Scaling Law

Image shift and motion

$$\theta = \frac{\theta_E}{u} \Leftarrow (u >> 1)$$

$$\frac{d\theta}{dt} = -\frac{1}{u^2}\left(\frac{du}{dt}\right)\theta_E \Leftarrow\Leftarrow \frac{du}{dt} = \frac{\mu}{\theta_E}$$

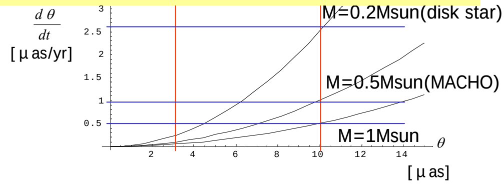
$$= -\left(\frac{\mu}{\theta_E{}^2}\right)\theta$$

Relation between θ measured in μas and $\frac{d\theta}{dt}$ in μas /yr

$$\frac{d\theta}{dt} = -0.01\theta^2\left(\frac{m}{0.5m_{sun}}\right)^{-1}\left(\frac{<V>}{180km/s}\right)$$

$$<t_e> = 100\theta^{-1}\left(\frac{m}{0.5m_{sun}}\right)\left(\frac{<V>}{180km/s}\right)^{-1} year$$

Relation between Image shift and its motion



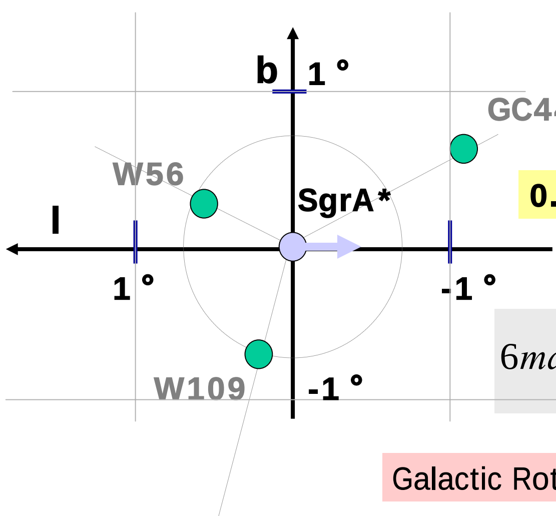
	10 μas	3 μas
M=0.2Msun	2.5 μas/yr	0.25 μas/yr
M=0.5Msun	1 μas/yr	0.1 μas/yr
M=1.0Msun	0.5 μas/yr	0.05 μas/yr

Scaling law on the Optical depth and Event Rate

$$\tau_A(k\theta) = \frac{\tau_A(\theta)}{k^2}; \Gamma_A(k\theta) = \frac{\Gamma_A(\theta)}{k}$$

3. Astrometric Microlensing and Parallax

3-1 Motion of SgrA* Referred to QSOs



0.7° =100pc

$$6mas/yr = \frac{220km/s}{8kpc}$$

Galactic Rotation

3. Astrometric Microlensing and Parallax

3-2 Optical depth and Event rate

The optical depth and the event rate of the positional fluctuation of the extragalactic radio sources near Sgr A* are estimated.

$$\tau(\theta) = 9.8 \times 10^{-3} \left(\frac{M}{0.2\ M_\odot}\right)\left(\frac{\sigma}{10^3\ M_\odot\ \mathrm{pc}^{-2}}\right) \times \left(\frac{\theta}{10\ \mu\mathrm{as}}\right)^{-2}, \quad (6)$$

$$\Gamma(\theta) = 8.1 \times 10^{-4} \left(\frac{\sigma}{10^3\ M_\odot\ \mathrm{pc}^{-2}}\right)\left(\frac{\theta}{10\ \mu\mathrm{as}}\right)^{-1} \times \left(\frac{v}{100\ \mathrm{km\ s}^{-1}}\right)\ [\mathrm{yr}^{-1}]. \quad (7)$$

$$\langle t_c \rangle = 12.1 \left(\frac{M}{0.2\ M_\odot}\right)\left(\frac{\theta}{10\ \mu\mathrm{as}}\right)^{-1}\left(\frac{v}{100\ \mathrm{km\ s}^{-1}}\right)^{-1}\ [\mathrm{yr}]. \quad (9)$$

Four-Component Model

$$\rho_{\rm core}(r) = \rho_c/[1 + 3(r/r_c)^2], \quad (10)$$

$$\rho_{\rm bulge}(r) = \rho_b K_0(r/r_b), \quad (11)$$

$$\rho_{\rm disk}(r) = \rho_d \exp(-r/r_d), \quad (12)$$

3. Astrometric Microlensing and Parallax

3-3 Trigonometric Parallax of Sgr A*

TABLE 1

CHARACTERISTICS OF GRAVITATIONAL DEFLECTION

From 2002ApJ...580L..43

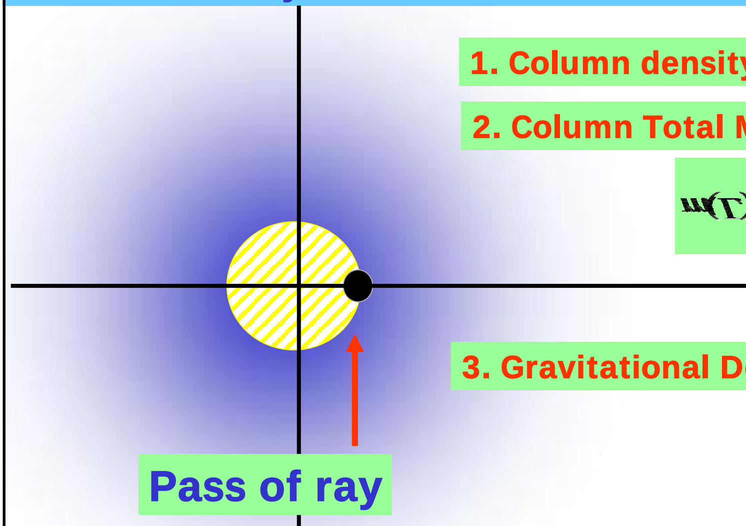
Item	σ ($\times 10^3\ M_\odot\ \mathrm{pc}^{-2}$)	$\bar{v}$ (km s^{-1})	τ ($\times 10^{-2}$)	Γ ($\times 10^{-2}$ yr^{-1})	$\langle t_c \rangle$ (yr)
Disk (far)	6.4	440	6.5	2.3	3.2
Bulge	6.4	220	6.5	1.2	5.6
Core	6.0	220	6.1	1.1	5.7
Disk (near)	5.8	30	5.9	0.14	42
Total	24.6	...	25	4.7	5.5

NOTE.—The values in this table are estimated in the case $M = 0.2\ M_\odot$ and $\theta = 10\ \mu$as. For other cases, τ, Γ, and $\langle t_c \rangle$ are easily obtained from this table and the relations $\tau \propto M\sigma\theta^{-2}$, $\Gamma \propto \sigma v\theta^{-1}$, and $\langle t_c \rangle \propto Mv^{-1}\theta^{-1}$.

There is a considerable probability that the gravitational deflection due to the stars in the Galaxy causes the positional error of the order of 10 micro-arcsecond in the measurement of the trigonometric parallax of Sgr A*.
When we observe the position of Sgr A* and nearby extragalactic sources in order to measure the trigonometric parallax of Sgr A*, we must observe their positions for several years and examine whether or not there is a gravitationally induced positional shift.
If a discrepancy is found in the measurements conducted in 2 consecutive yr, one should first doubt the possibility of the gravitational deflection by the stars in the Galaxy.
A few years of observation will be required to separate the effect of the gravitational deflection from the other effects with the accuracy of 25 as.
Aiming for an accuracy of 10 micro-arcsecond , about 10 yr of observation is needed.

4. Astrometric Macro-lens

4-1 Gravitational Deflection by Axis Symmetric Mass Distribution



1. Column density $\sum(L)$

2. Column Total Mass within *L*

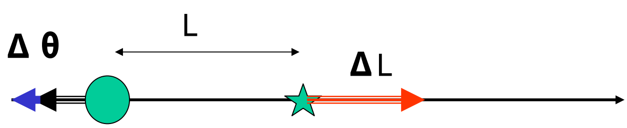
$$m(L)=\int_0^L 2\pi l\Sigma(l)dl$$

3. Gravitational Deflection

$$\theta = \frac{m}{L}$$

4. Astrometric Macro-lens

4-2 Gravitational Deflection



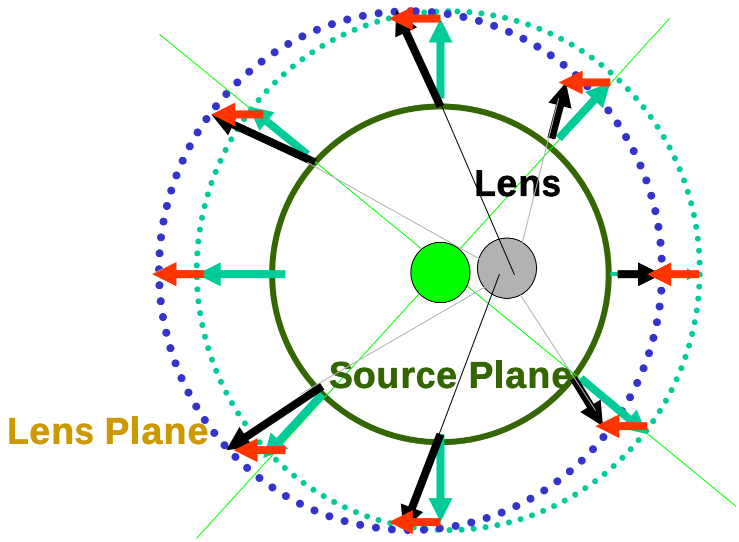
$$\Delta\theta(L)=\left(\frac{m(L)}{L^2}-2\pi\Sigma(L)\right)\Delta L$$

If **Σ =** Constant

$$\Delta\theta(L)=-\pi\Sigma_0\Delta L$$

4. Astrometric Macro-lens

4-3 Illustration of Shift by Bulge Motion



5. Astrometric Macro-lens in our Galaxy

5-1 Adopted Galactic Model

Alexander & Sternberg (1999)

Core + Bulge + Disk

Characteristic Length Scale

Core	Bulge	disk
0.38pc	667pc	3kpc

$$\rho_{core}(r) = \frac{\rho_o}{1+3(r/r_c)^2}$$

$$\rho_o = 4\times10^6 M_{SUM}\, pc^{-3}, r_c = 0.38pc$$

[illegible]

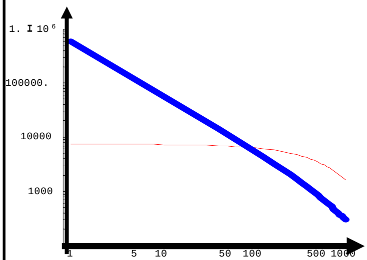
$$r_b = 3000\,pc$$

Disk contribution is negligible

5. Astrometric Macro-lens in our Galaxy

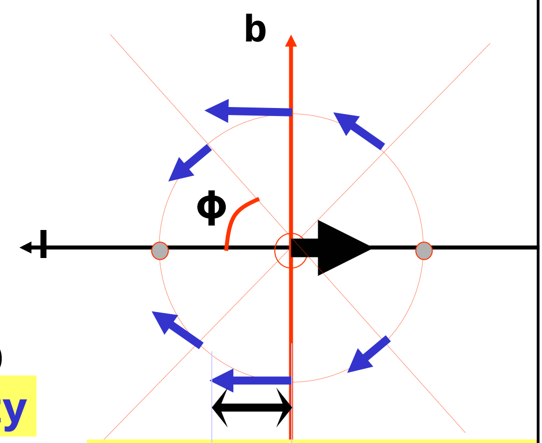
5-2 Effect of Core Motion

Log **Σ** Msun/pc^2



Log (Impact parameter [pc])

Core column density



~4 μ as / 10yr @100pc

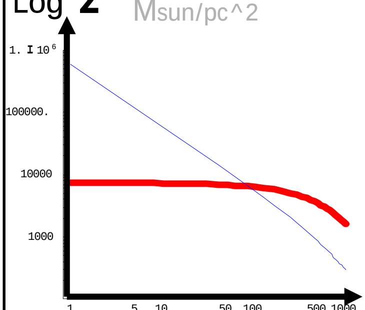
$$\overline{\mu_l} = \mu_c(1-\cos 2\phi)$$
$$\overline{\mu_b} = \mu_c(-\sin 2\phi)$$

$$\mu_c = 2\mu as/10yr\left(\frac{L}{100pc}\right)\left(\frac{\rho_c}{4\times10^6 M_{sun}/pc^3}\right)\left(\frac{a}{0.38pc}\right)^2\left(\frac{V}{220km/s}\right)$$

5. Astrometric Macro-lens in our Galaxy

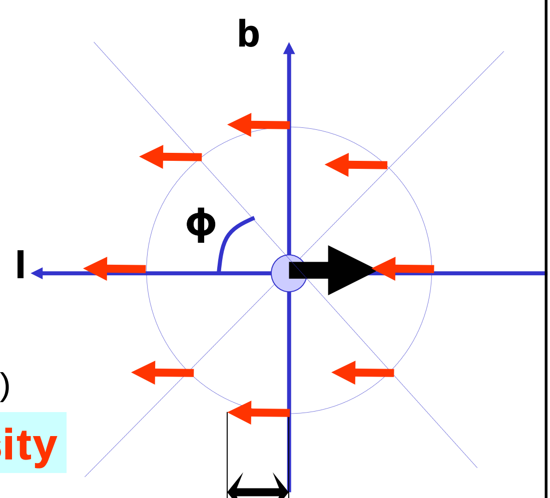
5-3 Effect of Bulge Motion

Log **Σ** Msun/pc^2



Log (Impact parameter [pc])

Bulge column density



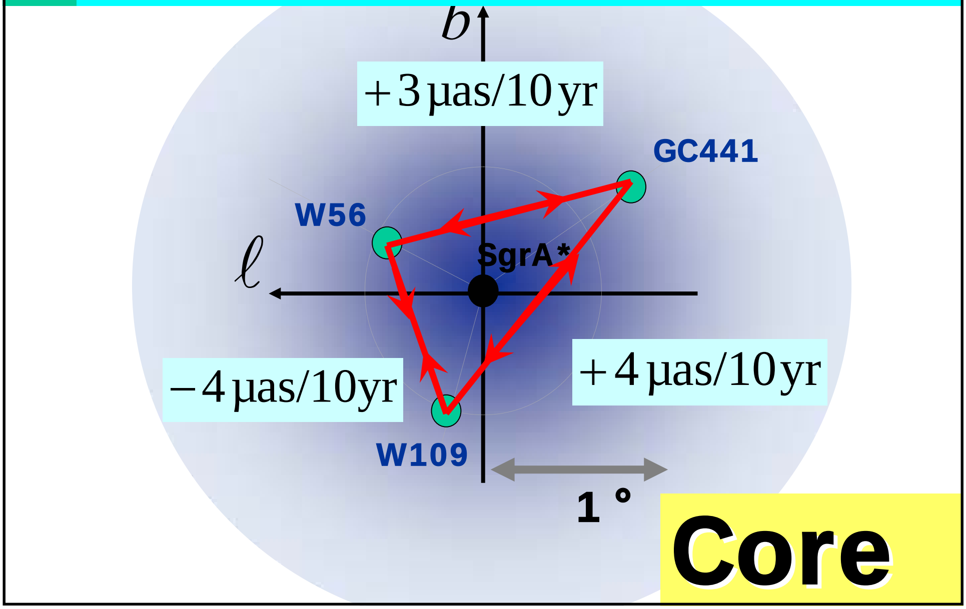
$$\overline{\mu_l} = \mu_B$$
$$\overline{\mu_b} = 0$$

$$\mu_B = 2\mu as/10\,yr\left(\frac{\Sigma(100\,pc)}{6\times10^6 M_{sun}/pc^2}\right)$$

~2 μ as / 10yr

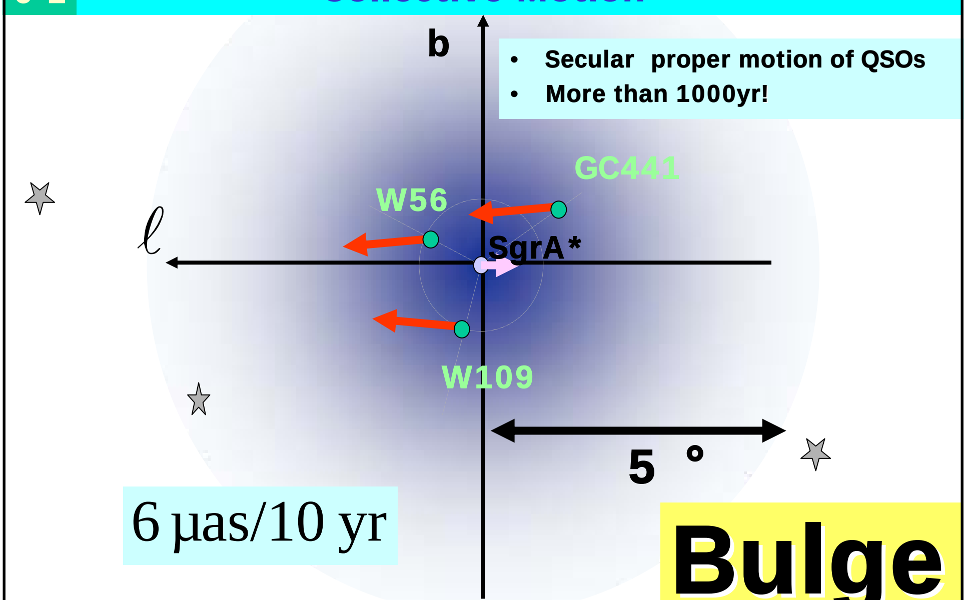
6. Conclusion

6-1 Internal Motion



6. Conclusion

6-2 Collective Motion



6. Conclusion

6-3 Summary of MACRO Lens

Macro lens effect of Galaxy is important

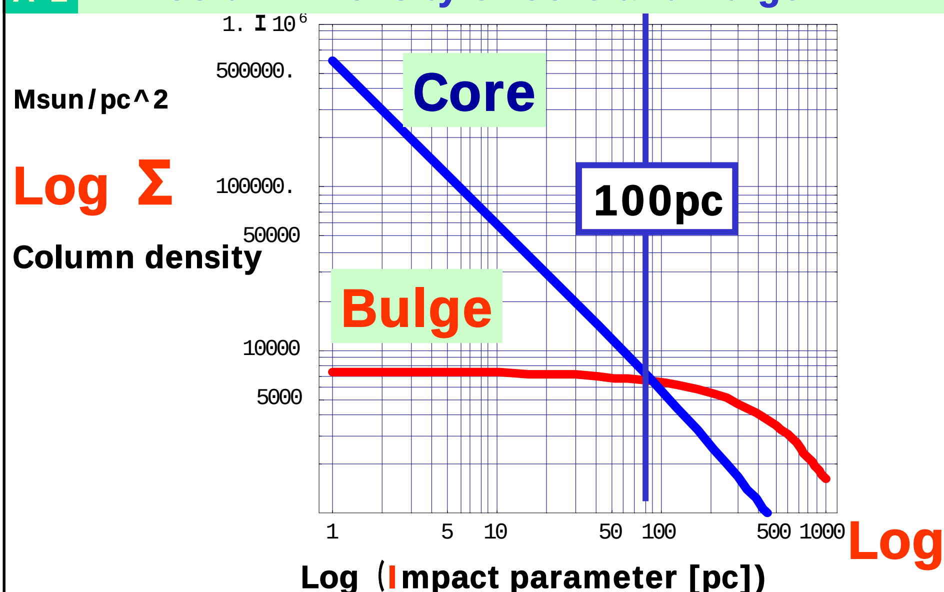
Apparent Motion of QSOs	
Internal	Collective
Core	Core + Bulge
4μas/10yr	6μas/10yr

The collective gravitational deflection by the bulge, that is called **MACRO-Lens**, are observable magnitude. This effect reaches 0.6 micro-arcsecond/yr and it has a secular component.

The measurement of these effects will provide us valuable information on the visible and dark matter density and mass function of the Galactic Center.

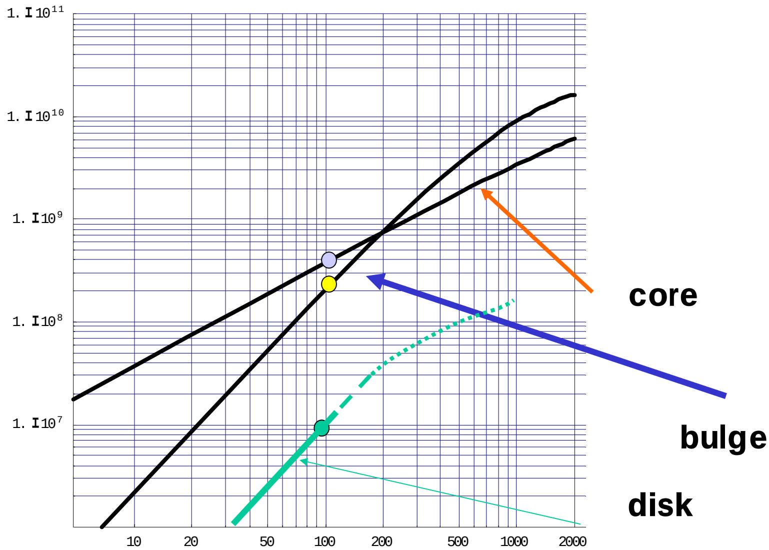
A. Astrometric Macro-lens in our Galaxy

A-1 Column Density of Core and Bulge



A. Astrometric Macro-lens in our Galaxy

A-2 Total Mass inside the Impact Parameter



A. Astrometric Macro-lens in our Galaxy

A-3 Total Mass inside the Impact Parameter

- **0.6 μ as/year** @ 100pc (0.7 °)

  nearly 0 @1000pc.

To make a **QSO Grid**

Need **10-20 year**

to detect

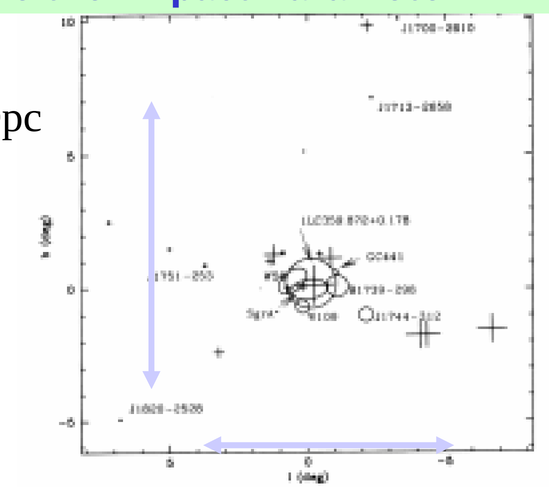


FIG. 3.—Scattered sources in the Galactic center. The size of the ellipse or crosshair indicates the size of the scattered image at 1.6 GHz with a scaling factor of 3" arcsec^{-1}. The program sources are shown with their elliptical structure. Crosshairs indicate OH 1612 MHz masers from van Langevelde et al. (1992). Labeled extragalactic sources are from references in the text.