Constraint on Warm dark matter with Lensing power spectrum

Speaker

Takumi Shinohara (Saga Univ.)

Collaborators

K. Inoue (Kinki Univ.), T. Suyama (Tokyo Tech), T. Takahashi (Saga Univ.)

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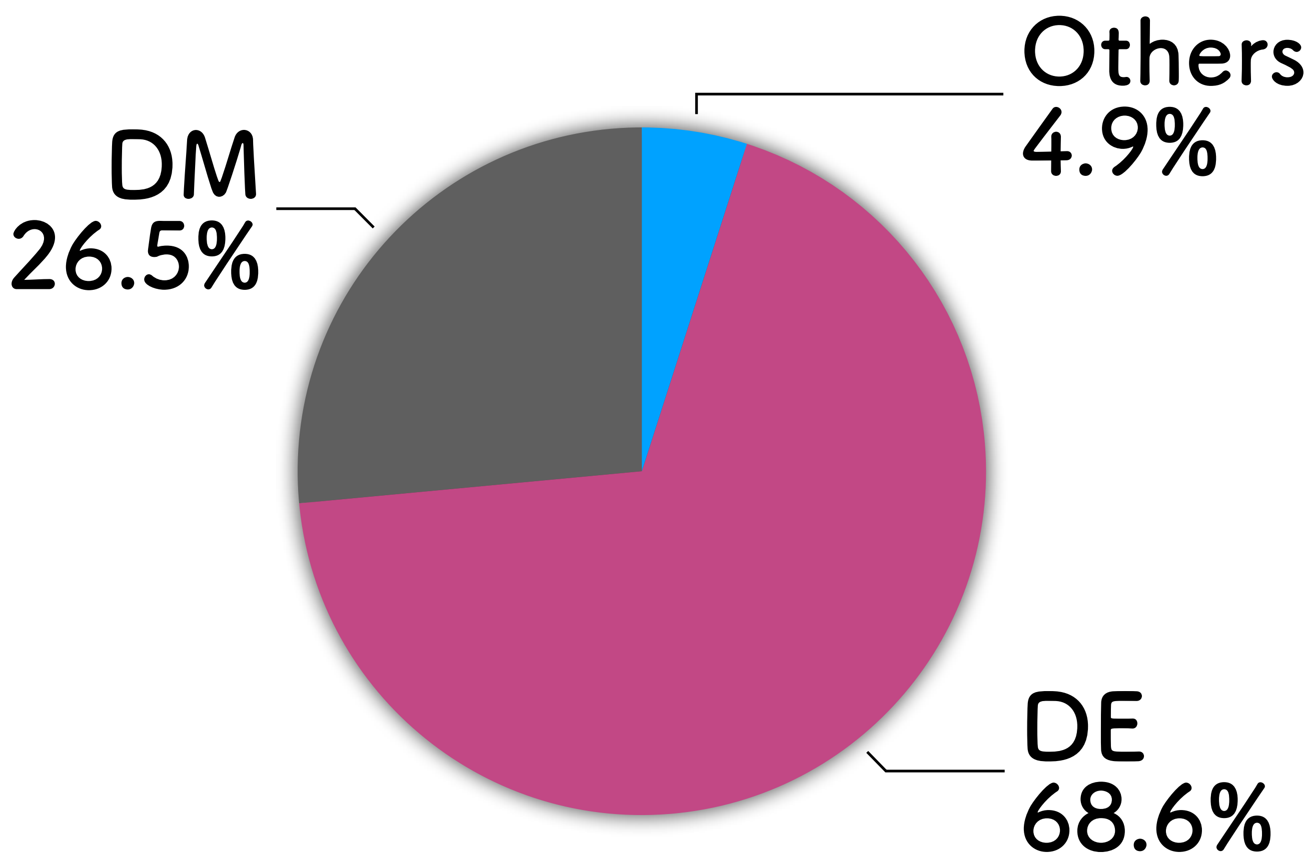
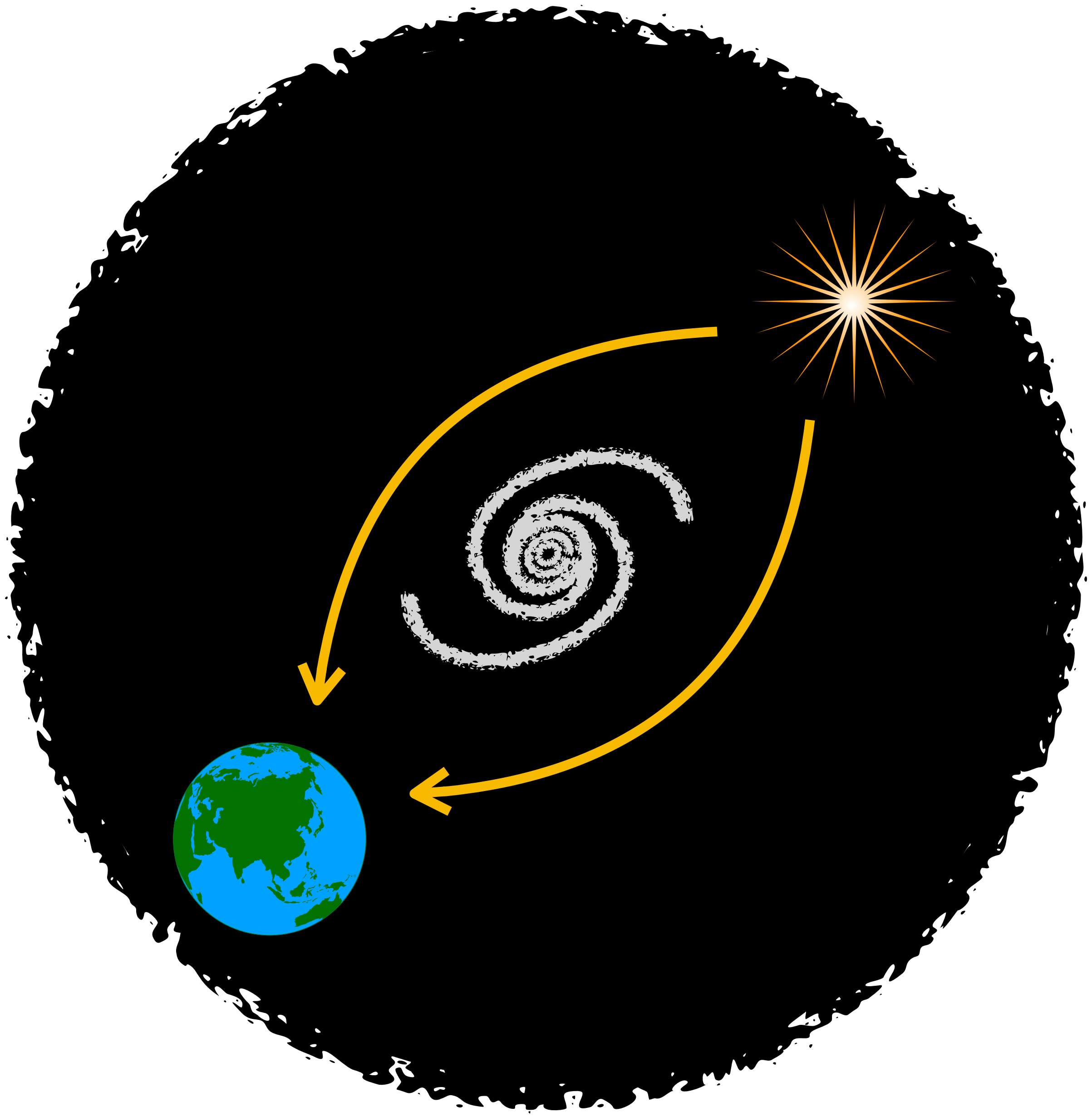
Abstract

Observation of **"fluctuation of image shift by strong lensing"** can constrain on a nature of **warm dark matter**!



Planck collab. (2018)

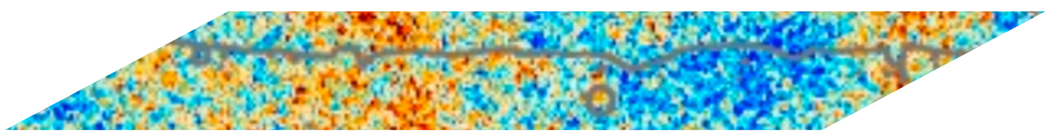


Basis

(galaxy , cluster of galaxies,,,)

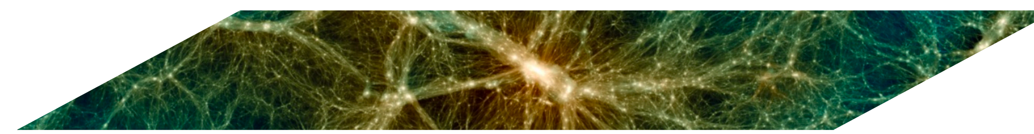
Density fluctuation of matter

Structures of the Universe



Planck collab. (2018)

Gravity

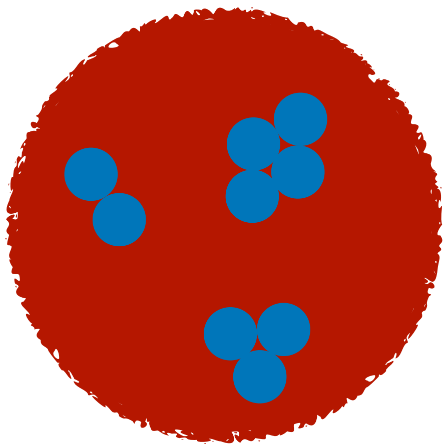


Ishiyama et al. (2021)

The density fluctuation is the seed of cosmic structures!

Motivation

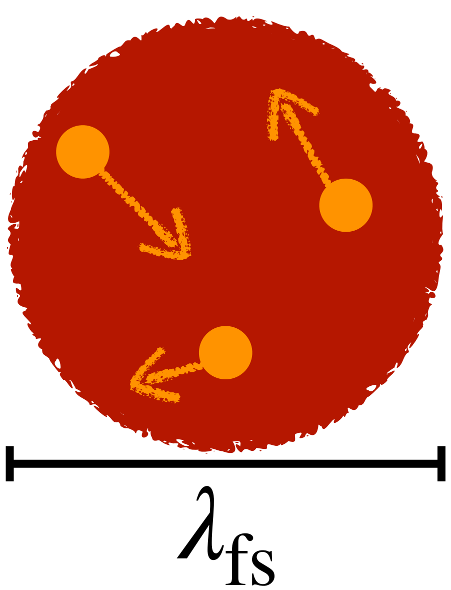
- Cold Dark Matter (=CDM) …… Successful in large scale ($\gtrsim 1\,\mathrm{Mpc}$)



⇨ Discrepancy with observations of small scale structures

- Missing-satellite problem
- Too-big-to-fail problem
- Core-cusp problem

- **Warm Dark Matter (=WDM)** …… Density fluctuations are smoothed due to large speed **(Free-streaming)**



$$\lambda_{\rm fs} = 0.114\ \mathrm{Mpc} \left(\frac{1\ \mathrm{keV}}{m_{\rm WDM}}\right) \left(\frac{10.75}{g_*(T_D)}\right)^{1/3} \left[2 + \log\left(\frac{t_{\rm eq}}{t_{\rm NR}}\right)\right]$$

→ **Structure formation on small scale is suppressed**

WDM can be constrained from various observations on small scales

WDM models

1. pure WDM

⇨ WDM mass: $m_{\rm WDM}$ **Constrained!**

2. CDM + WDM (mixed dark matter: MDM)

☆ Prohibited $m_{\rm WDM}$ in the pure WDM may be allowed again.

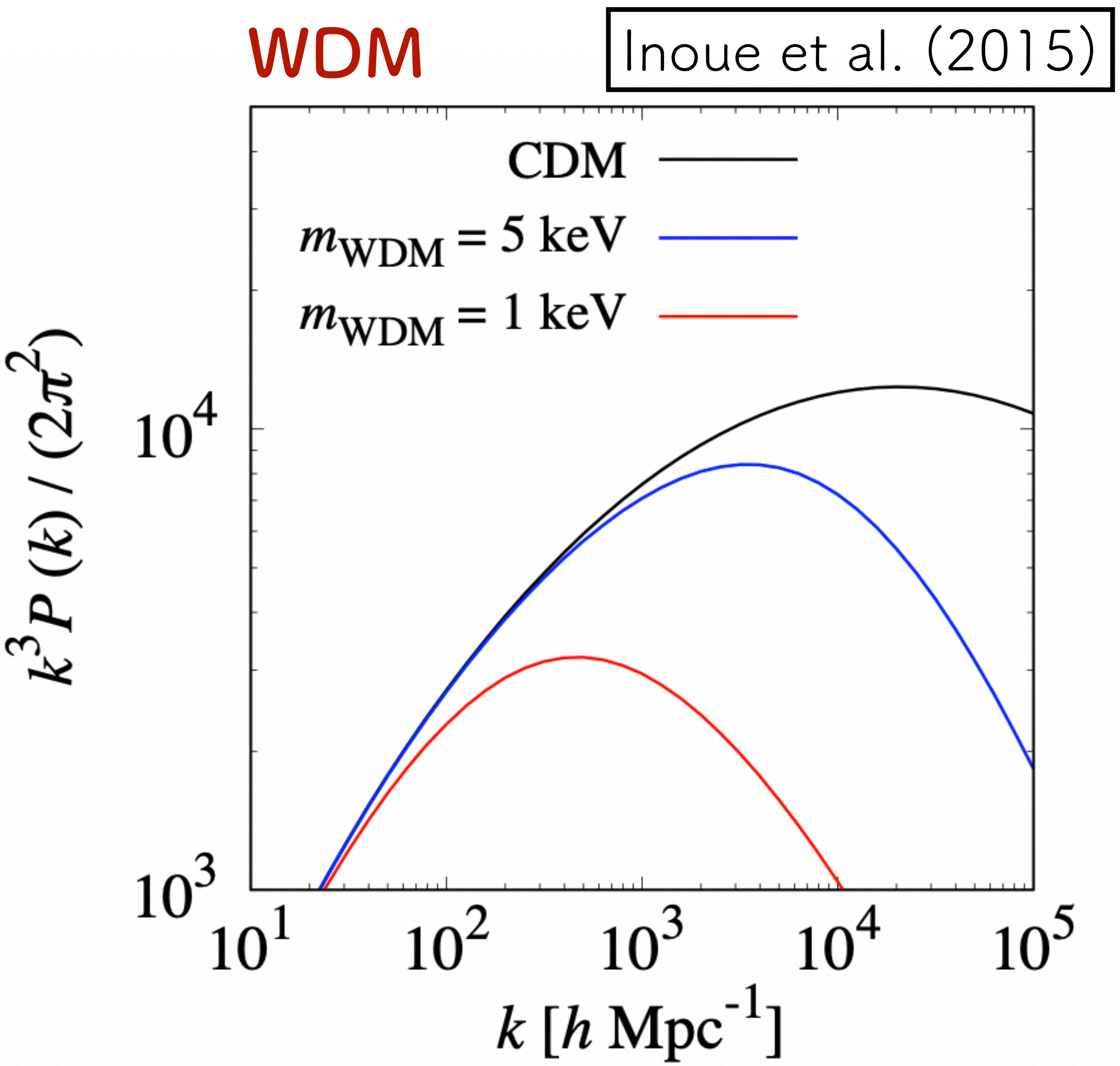
☆ Feasible in *particle physics* (e.g., Harada and Kamada (2016) $\cdots$).

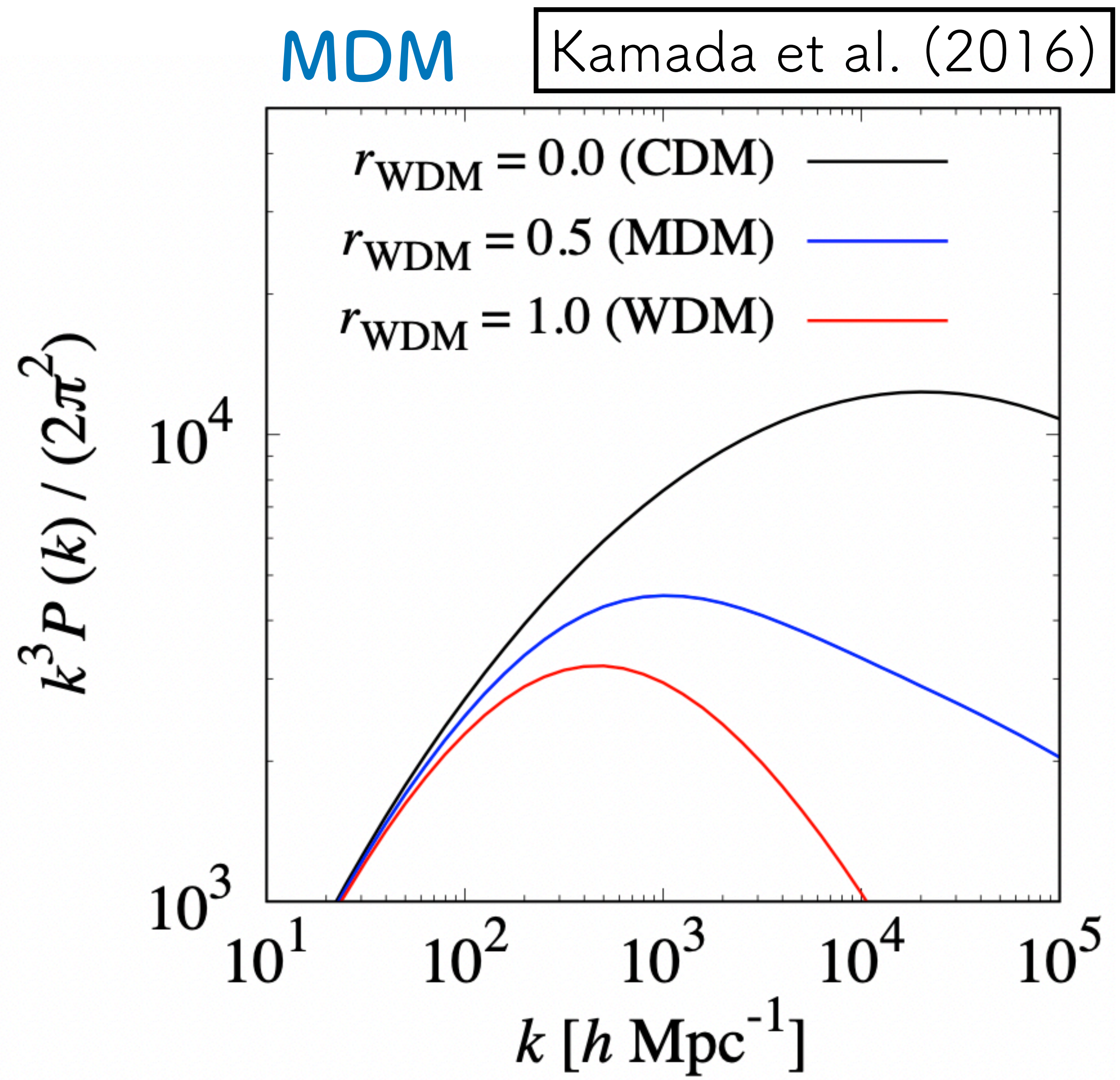
⇨ WDM fraction: $r_{\rm WDM} \equiv \dfrac{\Omega_{\rm WDM}}{\Omega_{\rm CDM} + \Omega_{\rm WDM}}$

Constrained!

Non-linear matter power spectra

(Used fitting formula)



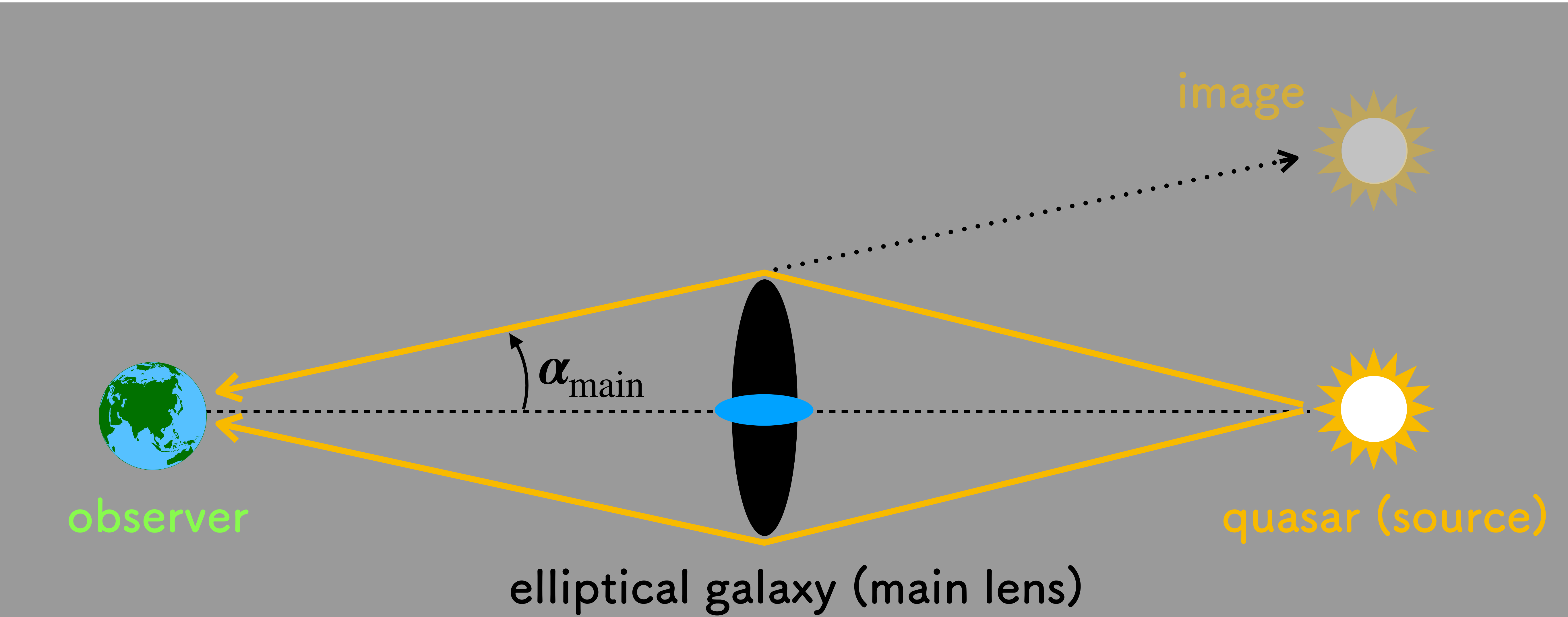


The lighter DM,
the lower the amplitude

Suppression: MDM < WDM

Strong lensing

- Observation



Strong lensing

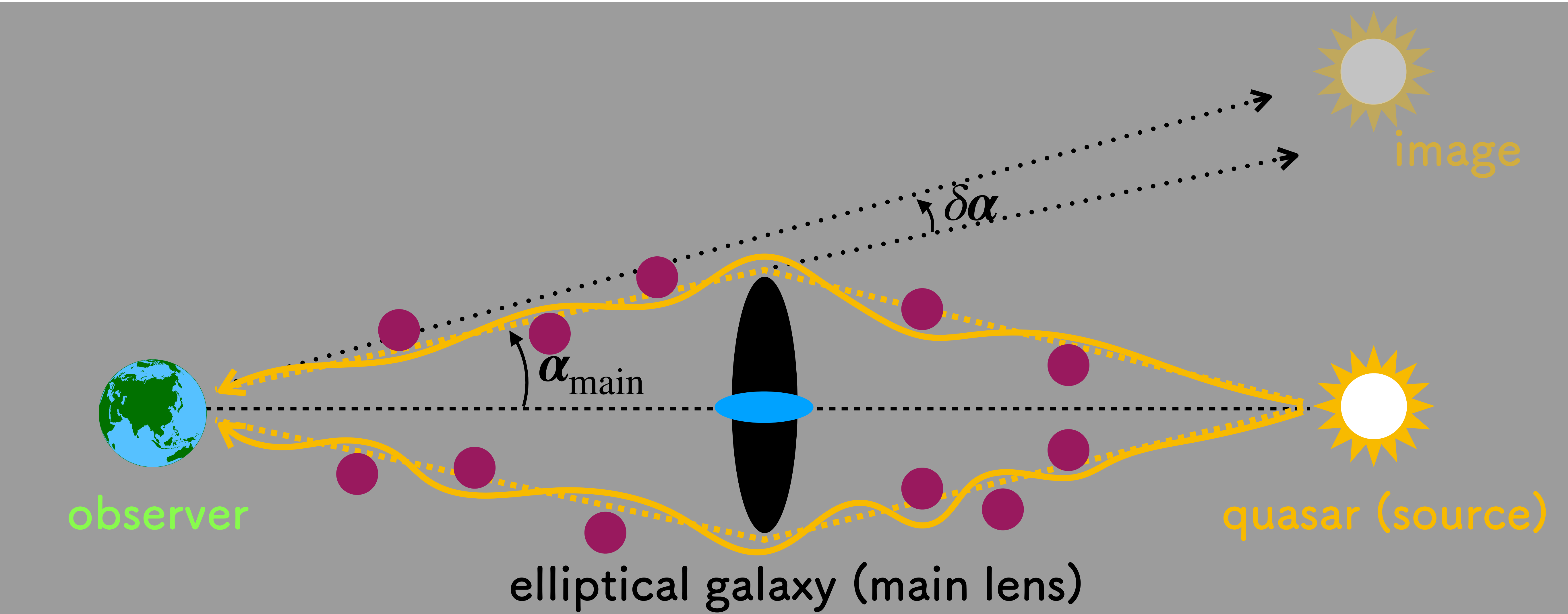
- **Observation**

Inoue et al. (2021)

Observation of quadruple image quasar by ALMA (radio telescope)
(MG J0414+0534)

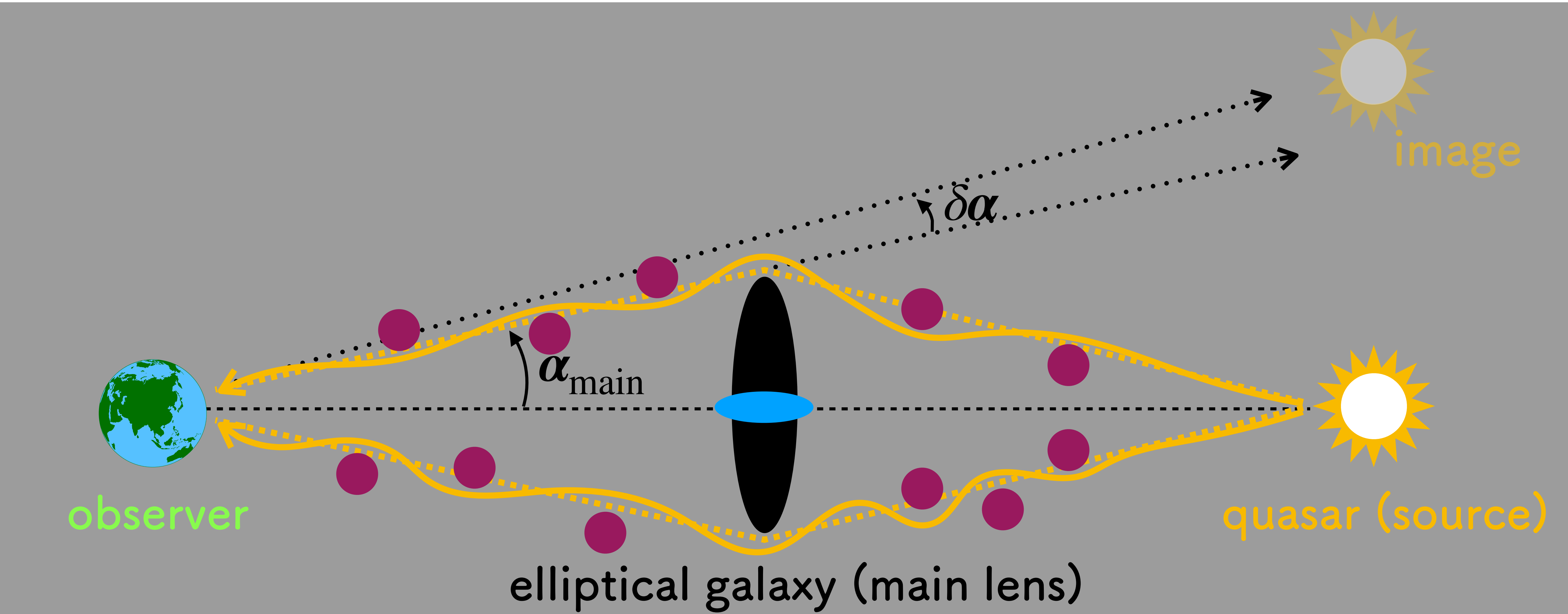
→ **First measurement of power spectrum of astrometric shift perturbation**

Δ_α $\delta\alpha$



Basic idea

- If DM is much lighter WDM,,,

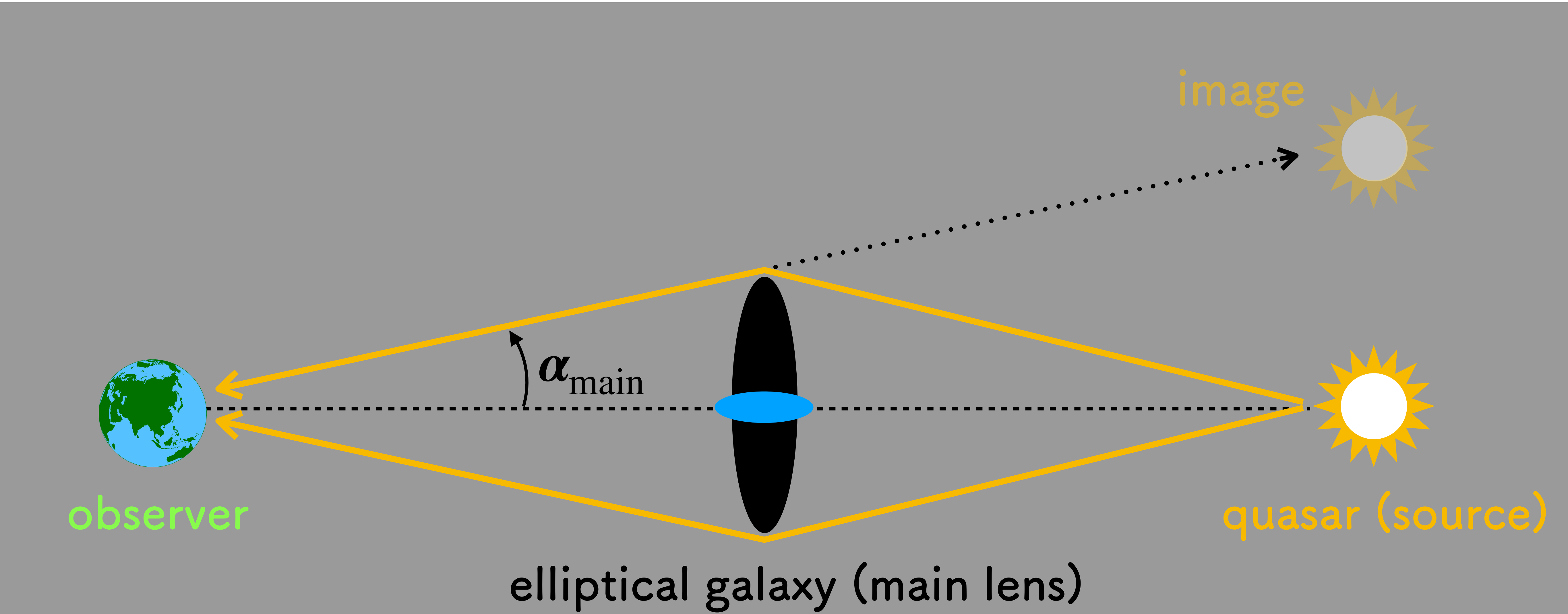


Basic idea

- If DM is much lighter WDM,,,

  → Structures would not exist!

  → Shift fluctuation $\delta\alpha$ would disappear!!



Basic idea

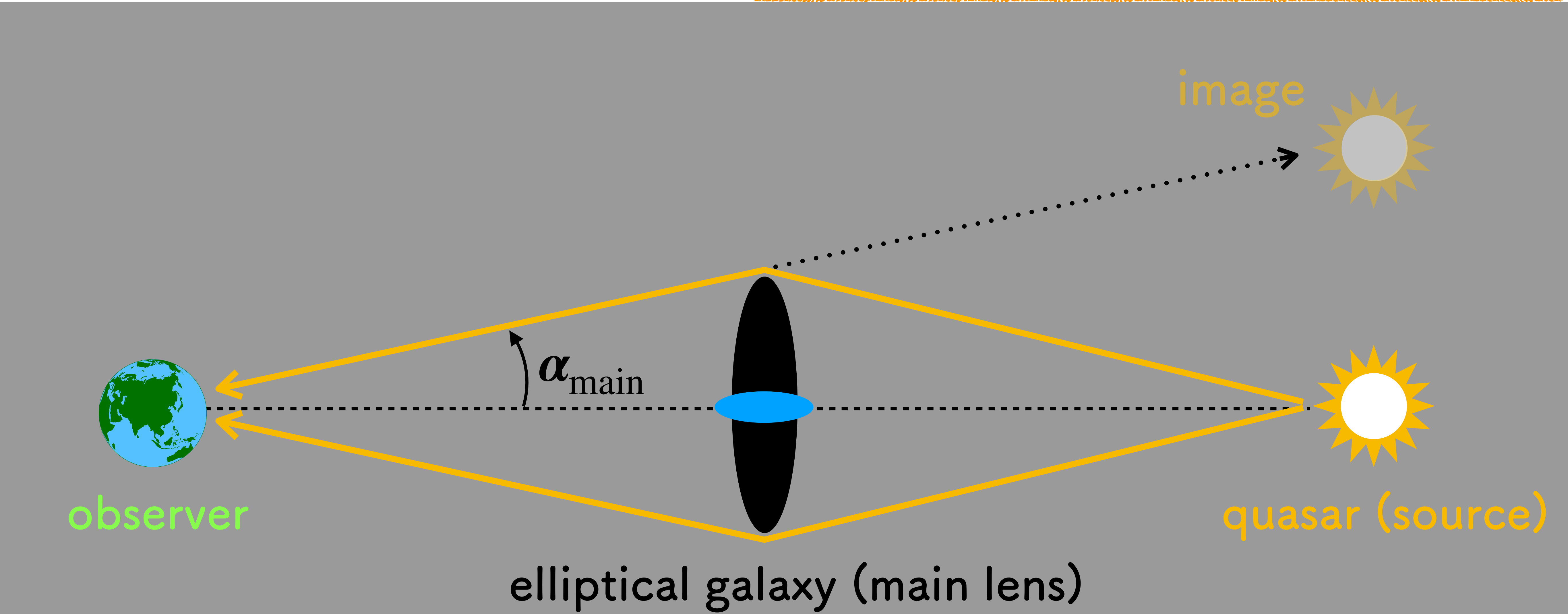
- If DM is much lighter WDM,,,

  → Structures would not exist!

  → Shift fluctuation $\delta\alpha$ would disappear!!

  ⇨ Inconsistent with the observation!!!

How heavy must DM be at least?



Lensing power spectrum

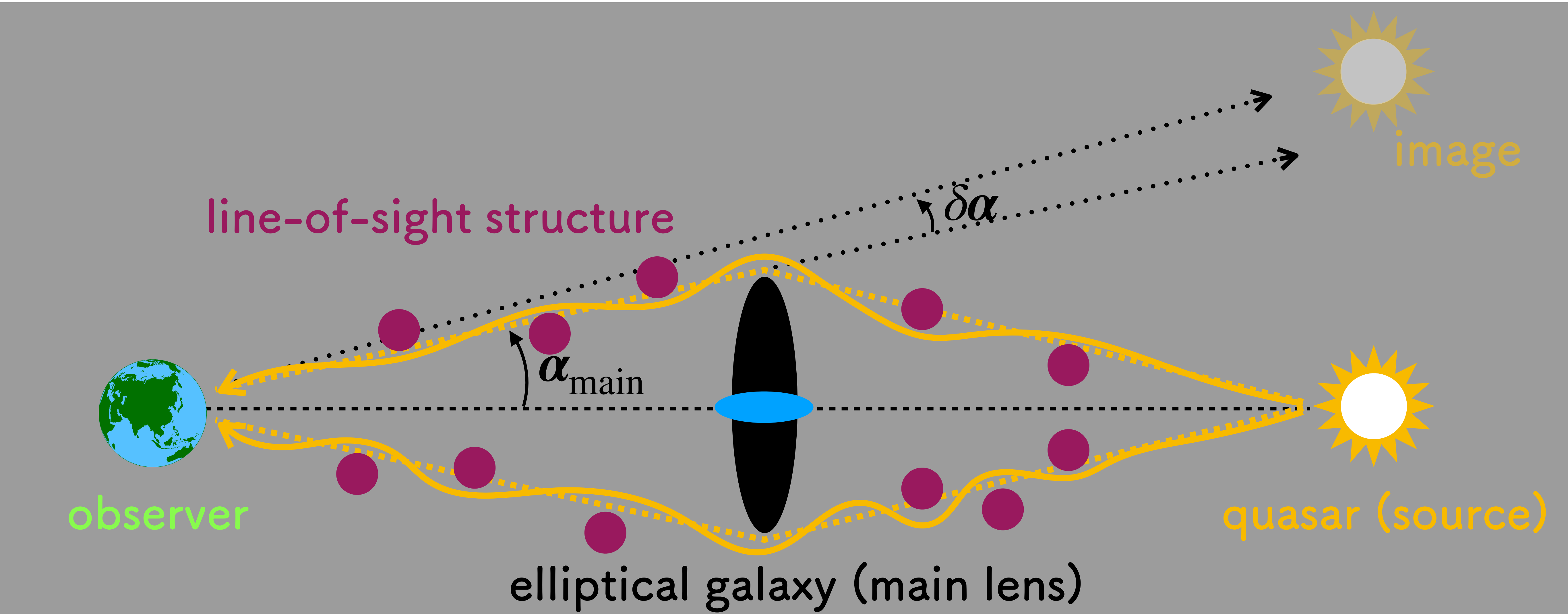
- Decomposition of lensing contributions

$$\boldsymbol{\alpha} = \boldsymbol{\alpha}_{\rm main} + \boxed{\delta\boldsymbol{\alpha}}$$

Contributions except for main lens

$$\rightarrow \quad \delta\boldsymbol{\alpha} \approx \delta\boldsymbol{\alpha}_{\rm subhalo} + \boxed{\delta\boldsymbol{\alpha}_{\rm LOS}}$$

Dominant! Inoue (2016)



Lensing power spectrum

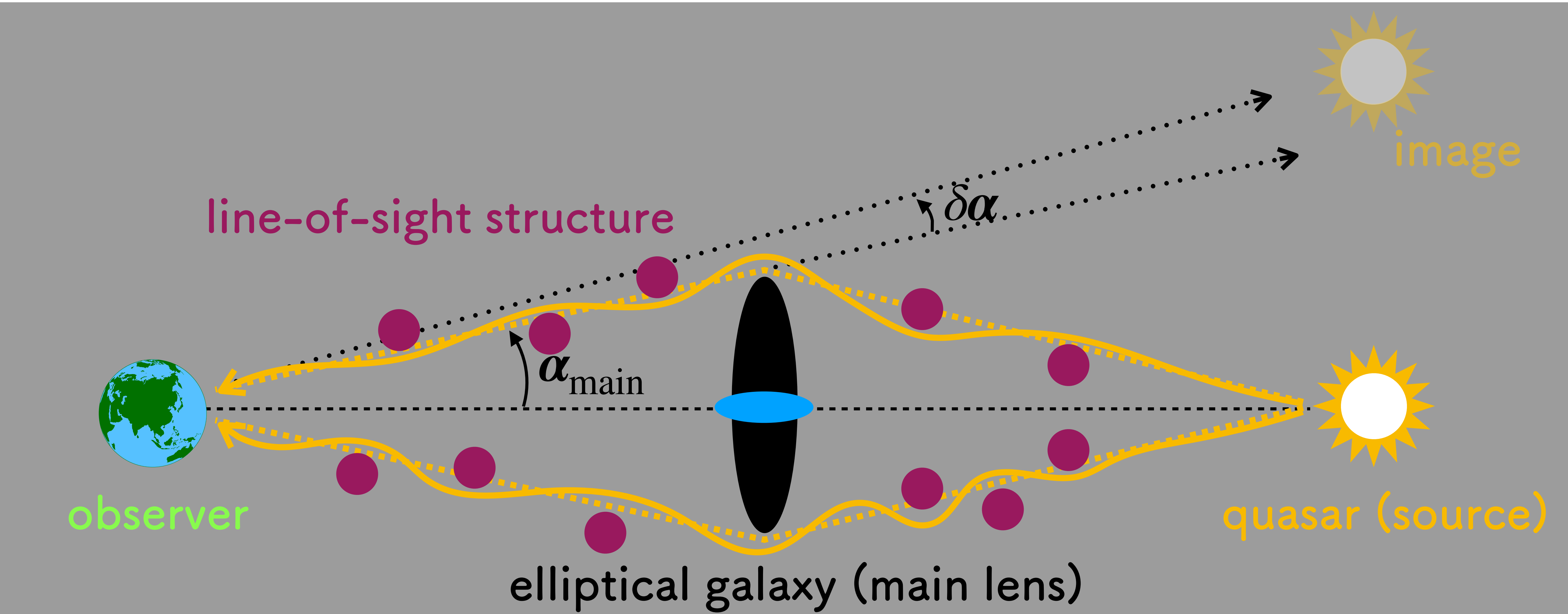
- Power spectrum of astrometric shift perturbation

(Angular wave number: $l = 180k/\pi$)

$m_{\rm WDM}\,,\, r_{\rm WDM}$

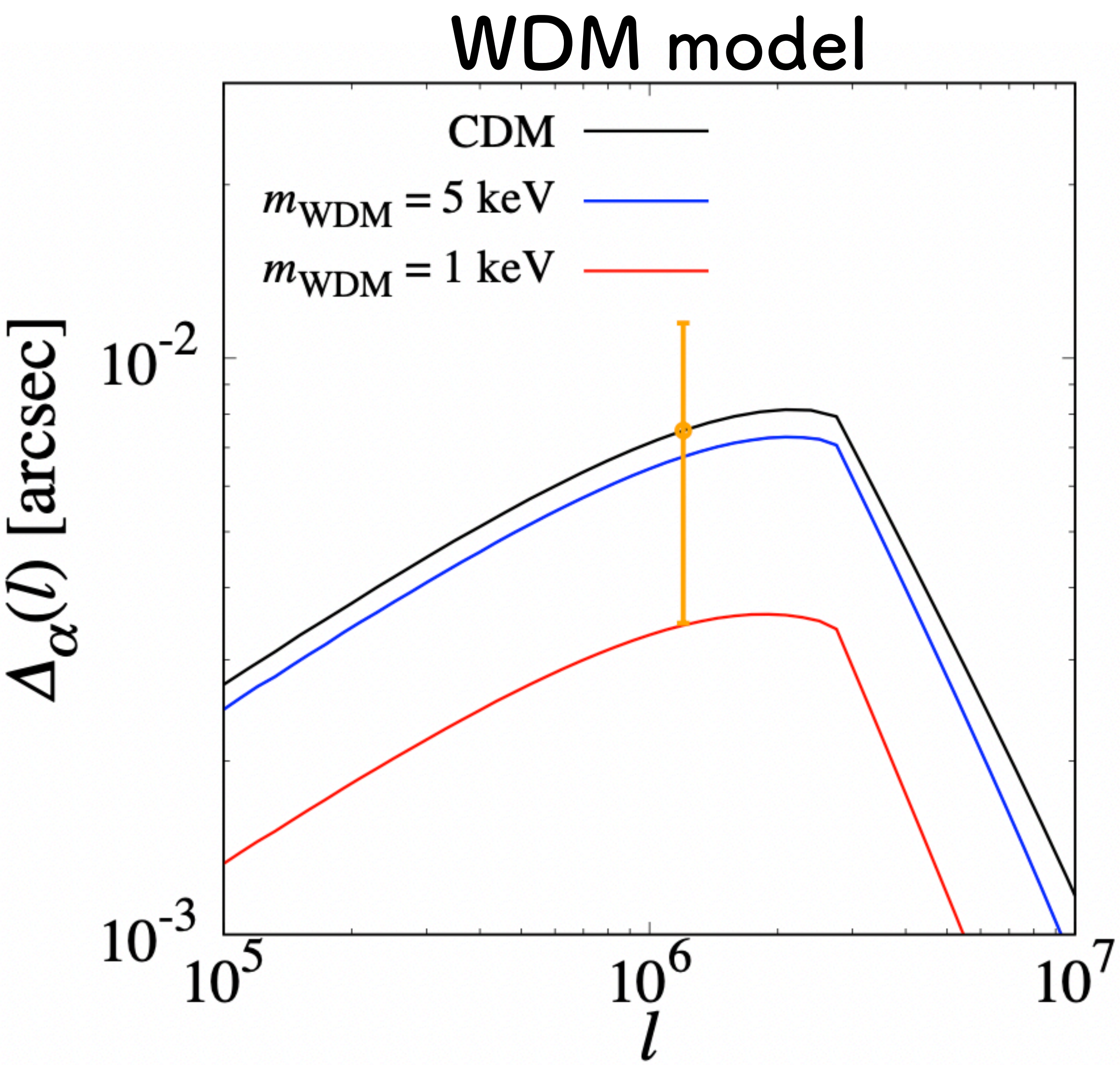
$$P_\alpha(l) = \begin{cases} \dfrac{4}{l^2}\displaystyle\int_0^{r_S} dr \left(\dfrac{Q(r)}{g(r)}\right)^2 P\left(\dfrac{l}{g(r)};r\right) & (k_{\rm min} \le l/g(r) \le k_{\rm max}) \\ 0 & ({\rm otherwise})\,, \end{cases}$$

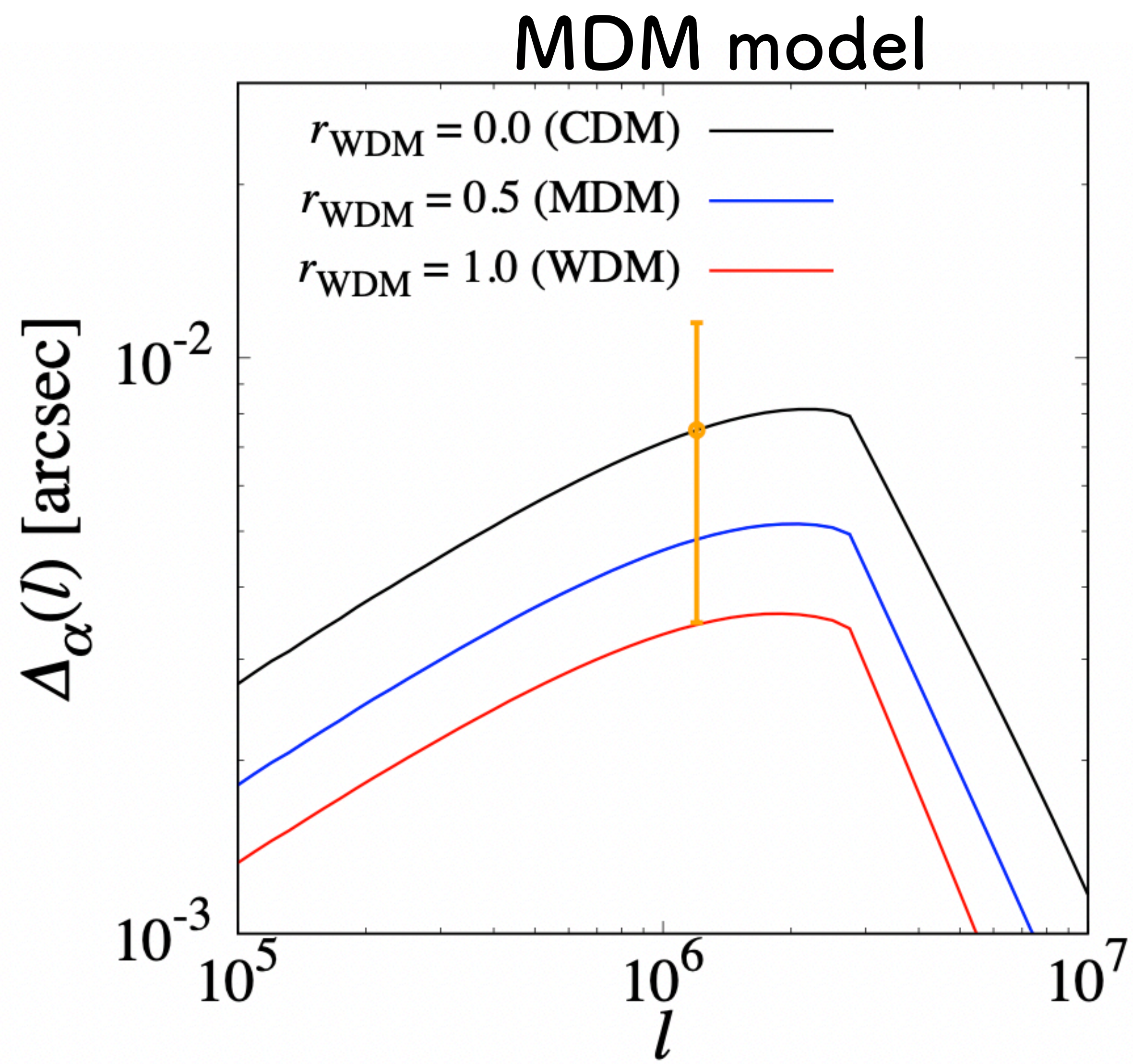
Select LOS



Lensing power spectrum

$$\Delta_\alpha(l) \equiv \sqrt{2\pi l^2 P_\alpha(l)}$$





Inoue et al. (2021)

How to constrain

[Theory]

$$\Delta_\alpha(l) \equiv \sqrt{2\pi l^2 P_\alpha(l)}$$

[Observation] $(l_* = 1.2 \times 10^6)$ Inoue et al. (2021)

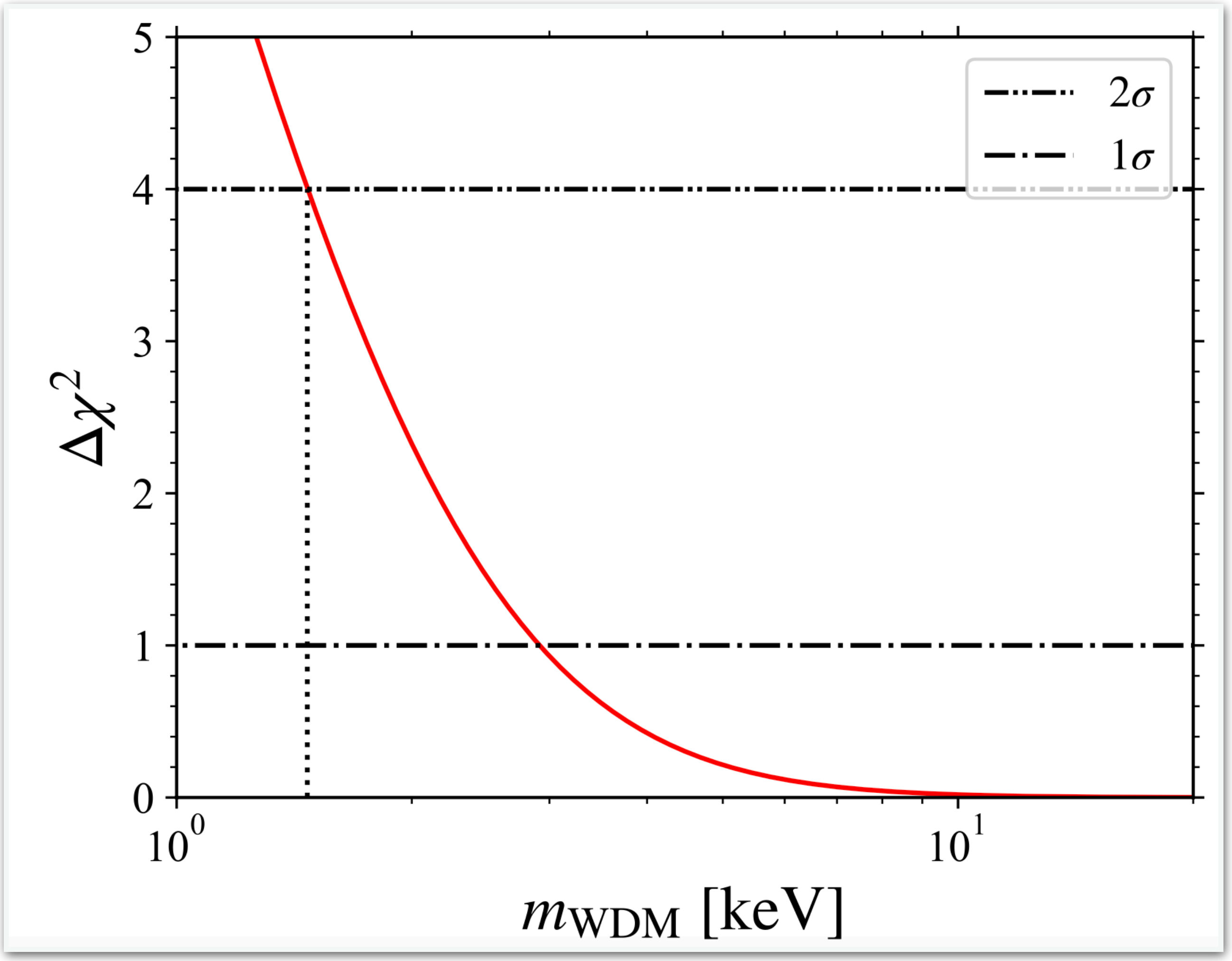
observable	mean	1σ error	cosmic variance
$\Delta_\alpha^{\rm obs} \pm \sigma_\alpha \pm \sigma_{\alpha,\rm cv}$ [arcsec]	0.00749	± 0.00059	± 0.00142

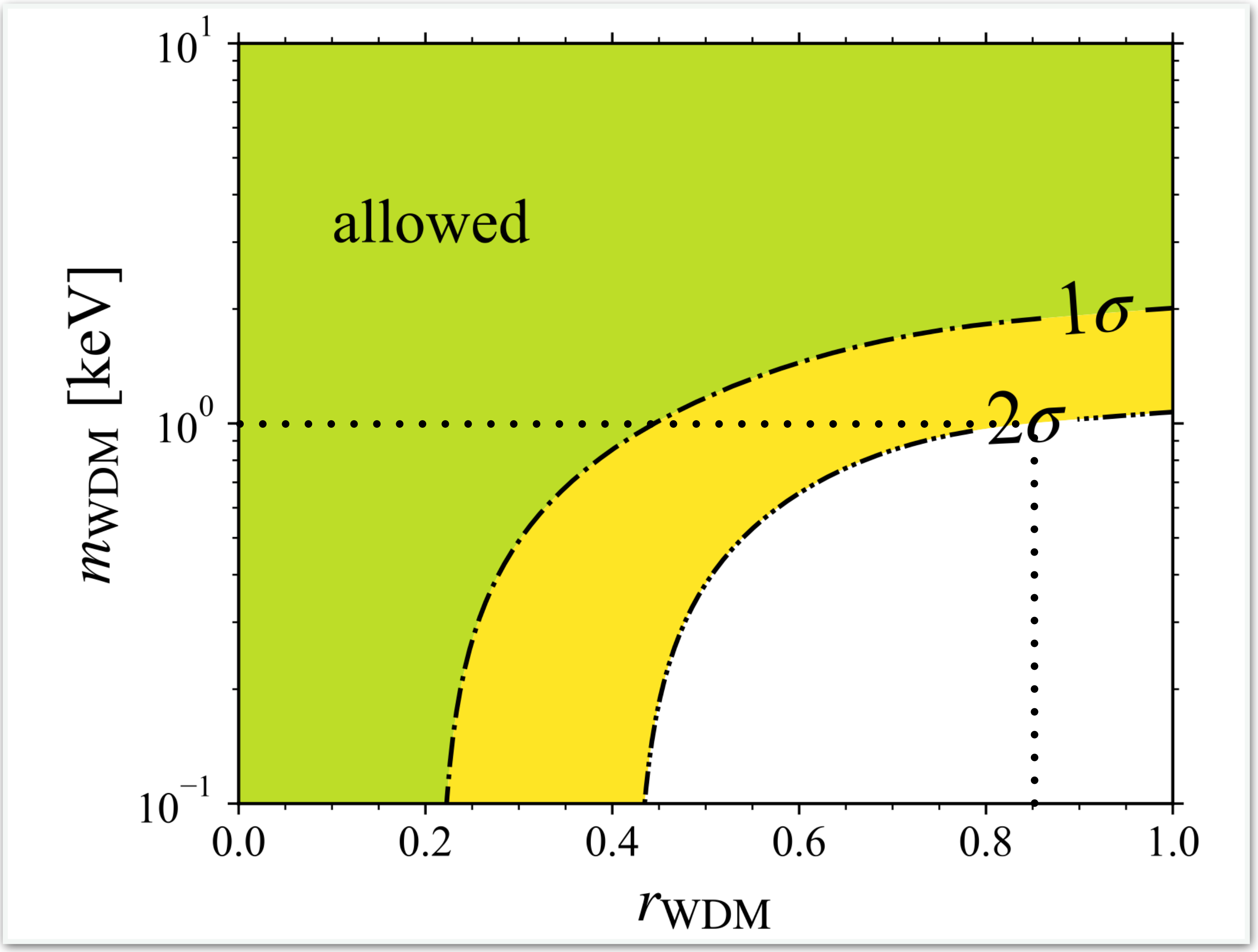
$$\chi^2(m_{\rm WDM}) \text{ or } \chi^2(m_{\rm WDM}, r_{\rm WDM}) = \frac{\left(\Delta_\alpha - \Delta_\alpha^{\rm obs}\right)^2\Big|_{l=l_*}}{\sigma_\alpha^2 + \sigma_{\alpha,\rm cv}^2}$$

WDM mass $m_{\rm WDM}$ and fraction $r_{\rm WDM}$ are constrained!

Results

- $\Delta\chi^2 \equiv \chi^2 - \chi^2_{\rm min}$





(Constraint at 95% C.L.)

$$m_{\rm WDM} \geq 1.5\,{\rm keV}$$

$$\begin{cases} r_{\rm WDM} \leq 0.43 \;\; ({\rm for} \;\; m_{\rm WDM} = 0.1\,{\rm keV}) \\ r_{\rm WDM} \leq 0.85 \;\; ({\rm for} \;\; m_{\rm WDM} = 1\,{\rm keV}) \end{cases}$$

Results

- Recent results of constraint on $m_{\rm WDM}$ (95 % C . L.)

☆ Lyman- α forest: $m_{\rm WDM} > 5.3\,{\rm keV}$ — Irˇsiˇc et al. (2020)

☆ Strong lensing: $m_{\rm WDM} > 5.58\,{\rm keV}$ — Hsueh et al. (2020)

$m_{\rm WDM} > 5.2\,{\rm keV}$ — Gilman et al. (2020)

☆ Satellite Gs in MW G: $m_{\rm WDM} > 3.99\,{\rm keV}$ — Newton et al. (2021)

$m_{\rm WDM} > 4.4\,{\rm keV}$ — Dekker et al. (2021)

☆ Strong lensing + Lyman- α + Satellite Gs in MW G:

$m_{\rm WDM} > 6.048\,{\rm keV}$ — Enzi et al. (2021)

☆ Strong lensing + Satellite Gs in MW G:

$m_{\rm WDM} > 9.7\,{\rm keV}$ — Nadler et al. (2021)

Our result: $m_{\rm WDM} \geq 1.5\,{\rm keV}$

Results

- Recent results of constraint on $r_{\rm WDM}$ (95 % C . L.)

☆ Strong lensing:

$$r_{\rm WDM} < 0.47 \quad \text{for} \quad 0.1\,{\rm keV}$$

Kamada et al. (2016)

☆ Planck + BOSS DR11 + BAO:

$$r_{\rm WDM} < 0.29 \quad \text{for} \quad 1-10\,{\rm keV}$$

Diamanti et al. (2017)

Our results: $r_{\rm WDM} \leq 0.43 \quad (\text{for} \;\; m_{\rm WDM} = 0.1\,{\rm keV})$

$r_{\rm WDM} \leq 0.85 \quad (\text{for} \;\; m_{\rm WDM} = 1\,{\rm keV})$

Results

- Future observations (ALMA, JWST, ngVLA)

⇨ More data (number ≡ N_L) → Uncertainty of measurement is relaxed ($\sigma \propto 1/\sqrt{N_L}$)

$m_{\rm WDM}$

N_L	$r_{\rm WDM} = 1$ (pure WDM)	$r_{\rm WDM} = 0.5$ (mixed)	$r_{\rm WDM} = 0.1$ (mixed)
30	> 5.21 keV	> 3.46 keV	> 0.85 keV
300	> 10.08 keV	> 6.85 keV	> 2.12 keV
1000	> 13.84 keV	> 9.45 keV	> 3.05 keV

$r_{\rm WDM}$

N_L	$m_{\rm WDM} = 1$ keV	$m_{\rm WDM} = 2$ keV	$m_{\rm WDM} = 5$ keV
30	< 0.118	< 0.256	< 0.905
300	< 0.038	< 0.092	< 0.323
1000	< 0.022	< 0.056	< 0.202

⇨ More stringent constraints may be imposed in future

Summary

- We show the method to constrain WDM with the new observable.

  = fluctuation of "shift of the image position due to strong lensing"

- We constrain on the **mass and fraction of WDM based on the latest observation.**

  (One system)

$$\begin{cases} \text{WDM:} \quad m_{\rm WDM} \geq 1.5\,\text{keV}, \\ \text{MDM:} \quad r_{\rm WDM} \leq 0.43 \quad \text{for} \quad m_{\rm WDM} = 0.1\,\text{keV} \end{cases} \qquad (95\,\%\ \text{C.L.})$$

- More stringent constraints may be imposed from **future observations**.

Backup

※Small-scale problems

☆ **missing-satellite** Moore et al. (1999)

⇨ Discrepancy regarding the number of satellite galaxies: **(simulation) > (observation)**

※Currently, many satellite galaxies have found. It expects to find more ones.

☆ **too-big-to-fail** Boylan-Kolchin et al. (2011)

⇨ Discrepancy regarding the density of subhalo

Simulation: "There are subhalos dense enough for star formation to occur."

Observation: "There are no such halos anywhere."

☆ **core-cusp** e.g., Moor (1994)

⇨ Discrepancy regarding the density profile of halo

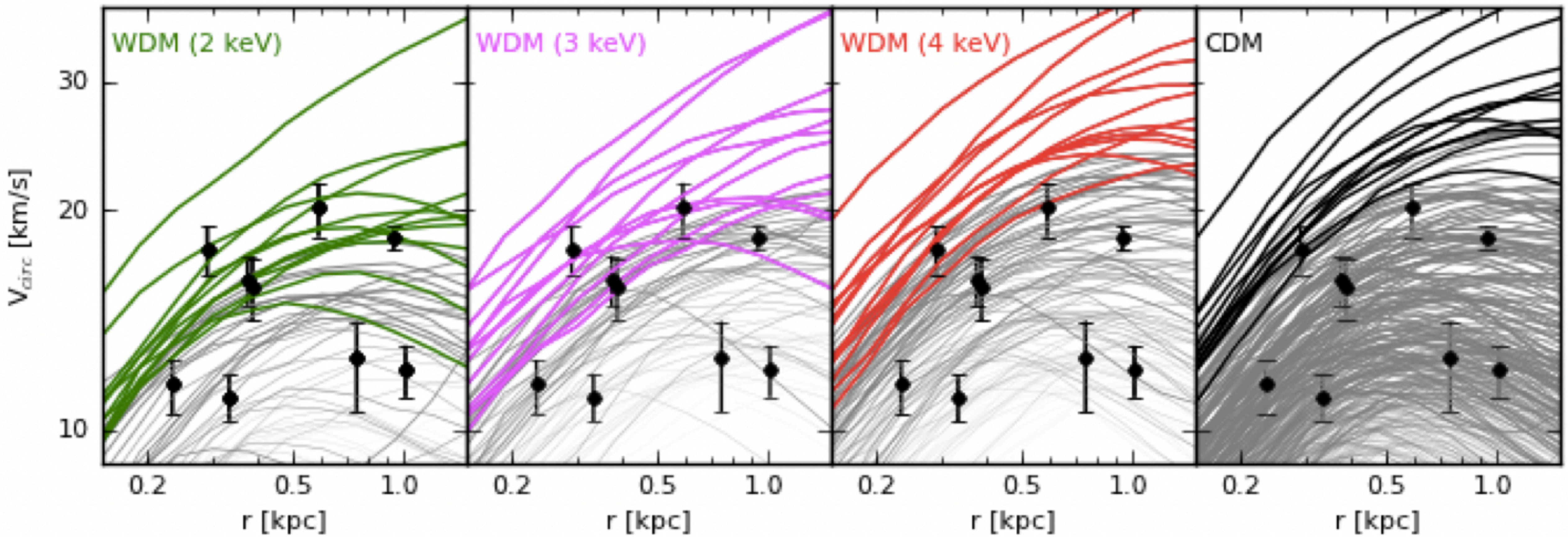
Simulation: **cusp**

Observation: **core**

※MDM

・Rotation curves of twelve satellite galaxies

A. Schneider et al. (2014)



⇨ It requires $m_{\rm WDM} \lesssim 3\,{\rm keV}$

↔ $m_{\rm WDM} > 3.3\,{\rm keV}$ from Lyman-α forest

CDM＋WDM model may allow $m_{\rm WDM} \leq 3.3\,{\rm keV}$

※Astrometric shift perturbation

- **convergence** ······ Indirectly observed.
  Modeling of shear perturbation is needed.

- **astrometric shift** ······ Directly observed.
  Less uncertainty!

※Two-point correlation function

$$\xi_\alpha(\theta) \equiv \langle \delta\alpha(\mathbf{0})\, \delta\alpha(\boldsymbol{\theta}) \rangle$$
$$= 4 \int_0^{r_S} dr \left(\frac{Q(r)}{g(r)} \right)^2 \int_0^\infty \frac{dk}{2\pi k}\, W_k(k; k_{\min}, k_{\max})\, P(k; r)\, J_0\big(k g(r)\, \theta\big)$$

$$Q(r) = \frac{3 H_0^2 \Omega_{m,0}}{2c^2}\, \frac{r(r - r_S)}{r_S}\, \big[1 + z(r)\big]$$

Light pass curved by main lens: $$g(r) = \begin{cases} r & (r < r_L) \\ \dfrac{r_L(r_S - r)}{r_S - r_L} & (r \geq r_L) \end{cases}$$

Window function
selecting LOS contributions: $$W_k(k; k_{\min}, k_{\max}) = \begin{cases} 1 & (k_{\min} \leq k \leq k_{\max}) \\ 0 & (\text{otherwise})\,. \end{cases}$$

※Scale of LOS contributions

$k_{\rm min}$ ⋯⋯ Result of CDM simulation consists with the observational result. Inoue et al. (2021)

⇨ Fixed so that the theoretical result for CDM is equal to median of the observational one.

$k_{\rm max}$ ⋯⋯ Determined so that it does not includes contributions of subhalos.