b06

Weak lensing effect on cosmic birefringence and its tomographic analysis

RESearch Center for Early Universe,
The University of Tokyo, J.Yokoyama lab. M2

Fumihiro Naokawa

T. Namikawa (IPMU), E. Komatsu (Max Planck Institute for Astrophysics)
K. Kamada (the University of Tokyo)

Cosmic Birefringence (宇宙複屈折)

photon

axion

- A new signal from CMB Minami & Komatsu (2020)
  - ► Violating Parity Symmetry : beyond Standard Model ?
  - ► Origin : Axion ? 

    Carroll et al. (1990), Harari & Sikivie (1992), Carroll (1998)
- Next generation CMB experiments → It requires precise theoretical predictions

Cosmic Birefringence (宇宙複屈折)

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  - Origin：Axion ? 

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Weak Gravitational Lensing (重力レンズ)

- Crucial factor for precise CMB observations
- Especially important for ground-based observation →
  - ex) Simons Observatory (under development)

(As for C_l^{EE} in high l)

measurement error < Shift by Lensing ~ more than 10 %

CLASS Lesgourgues (2011)

(public code for CMB)

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$C_l^{\Theta\Theta}$ $C_l^{\Theta E}$ C_l^{EE} C_l^{BB}

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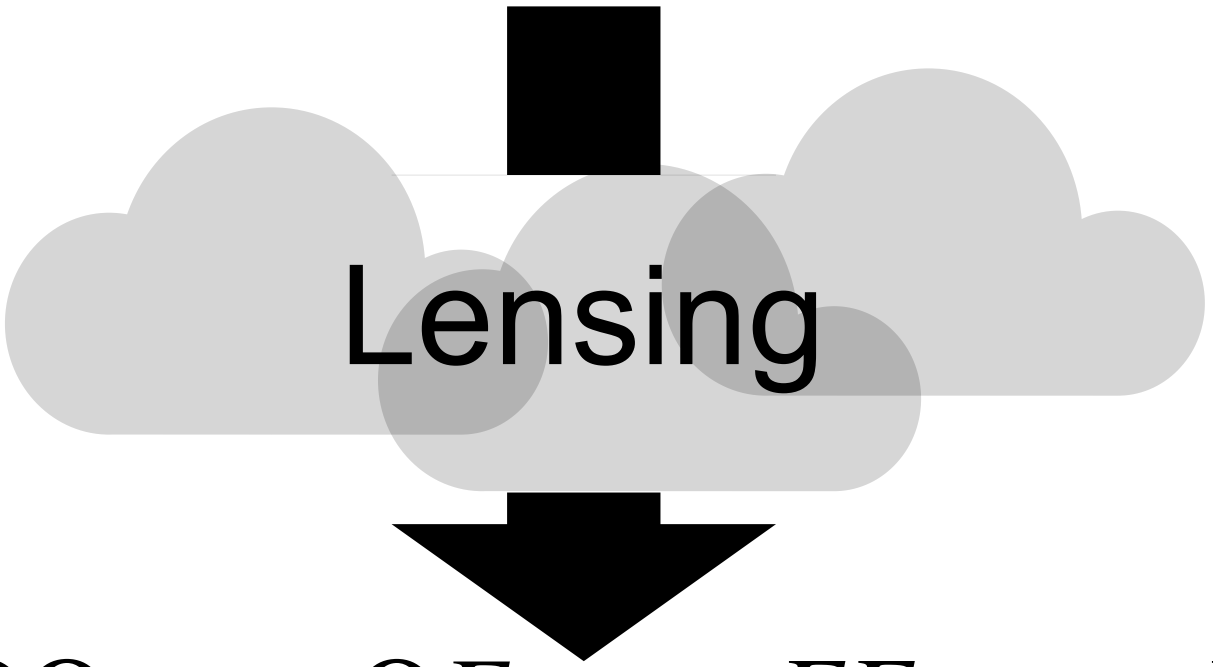

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Lensing

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modify

CLASS + 

Axion

(including cosmic birefringence)

Nakatsuka et al. (2022)

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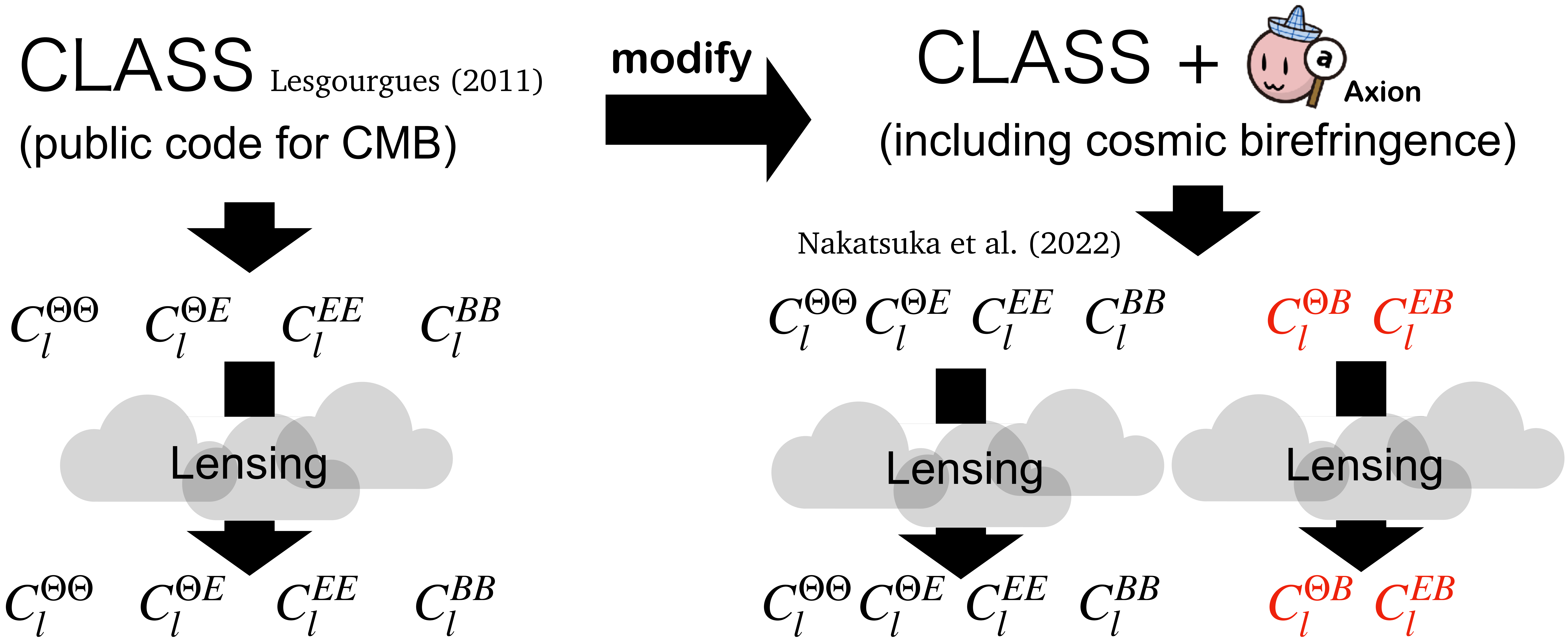
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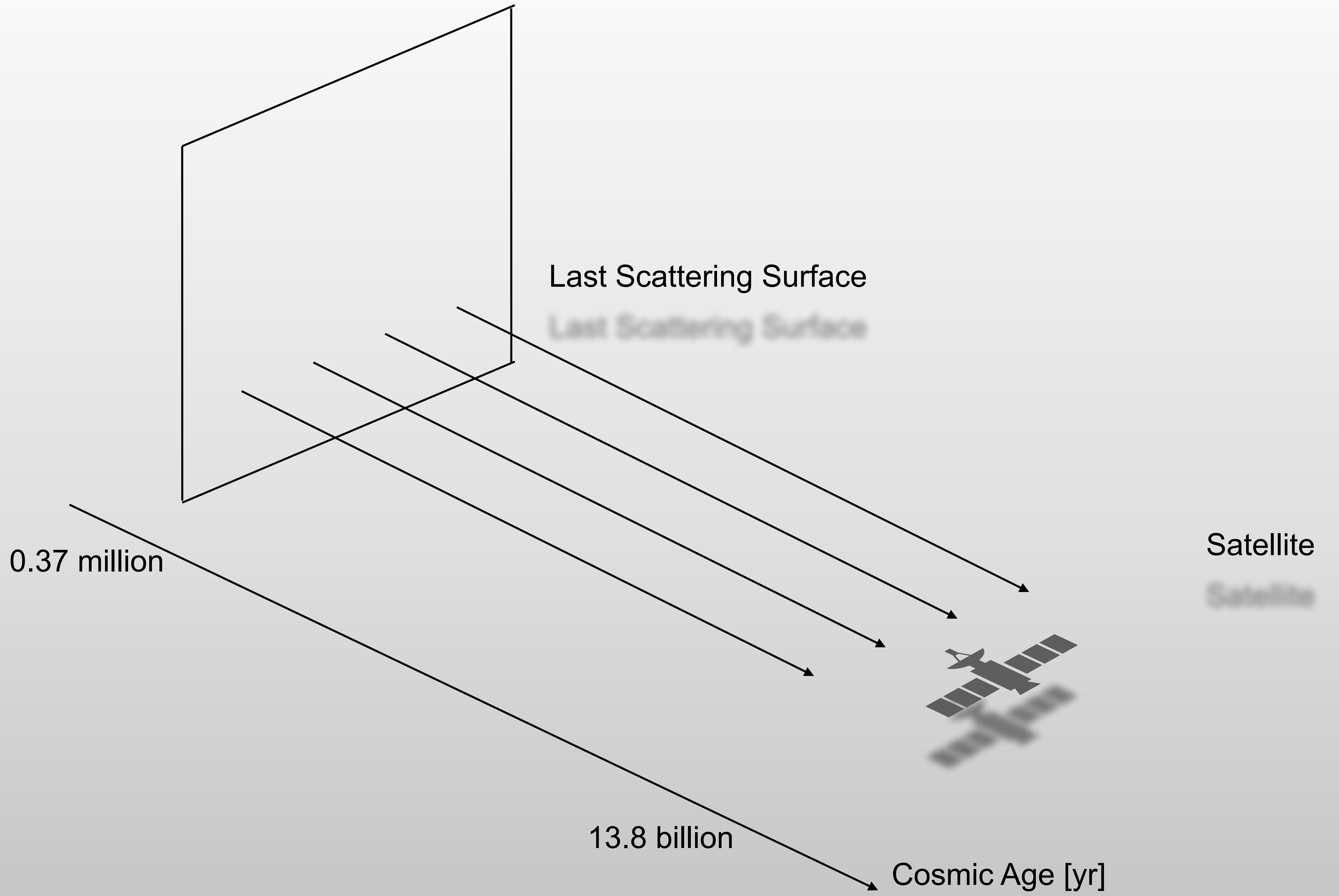
This work

Weak gravitational lensing : lensing effect on CMB



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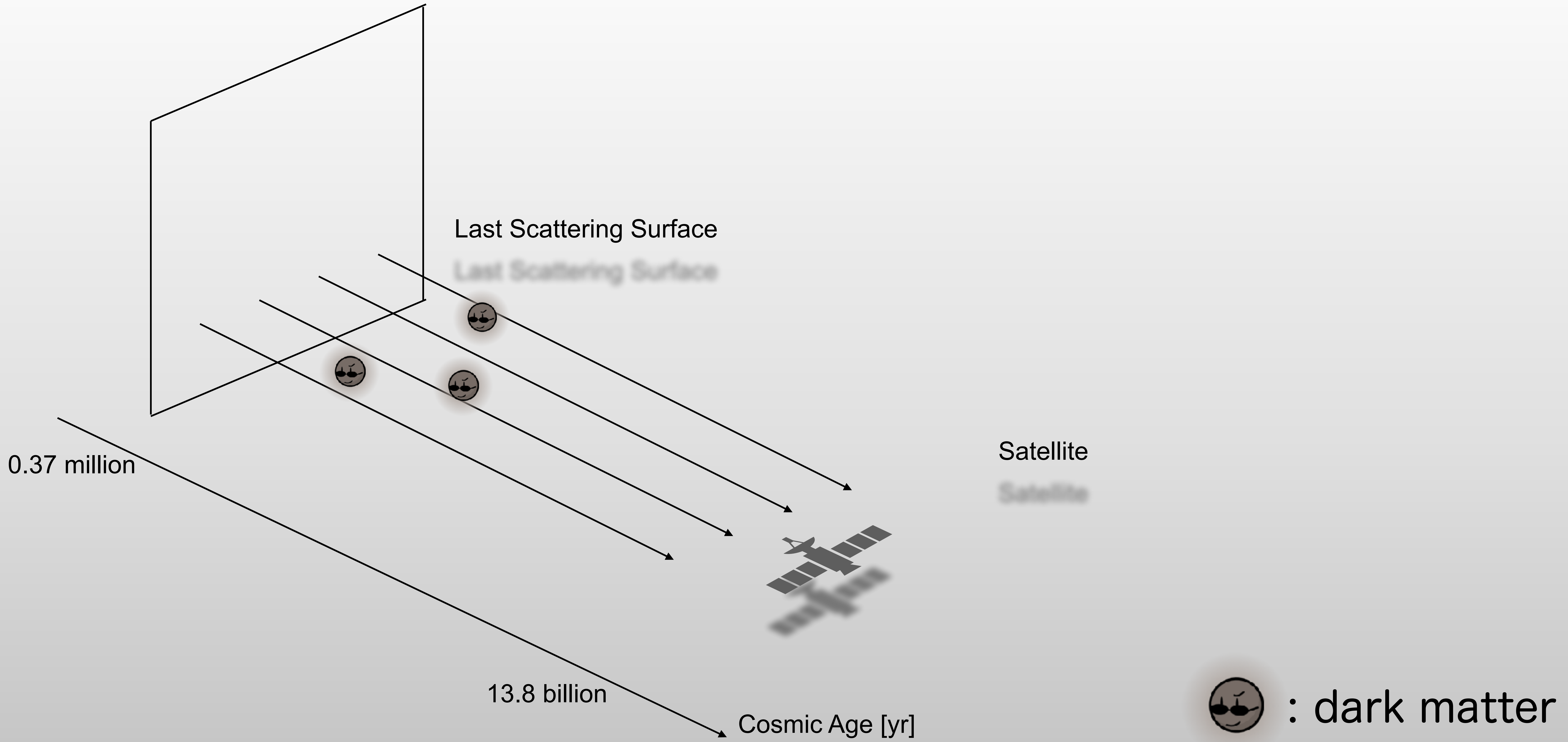

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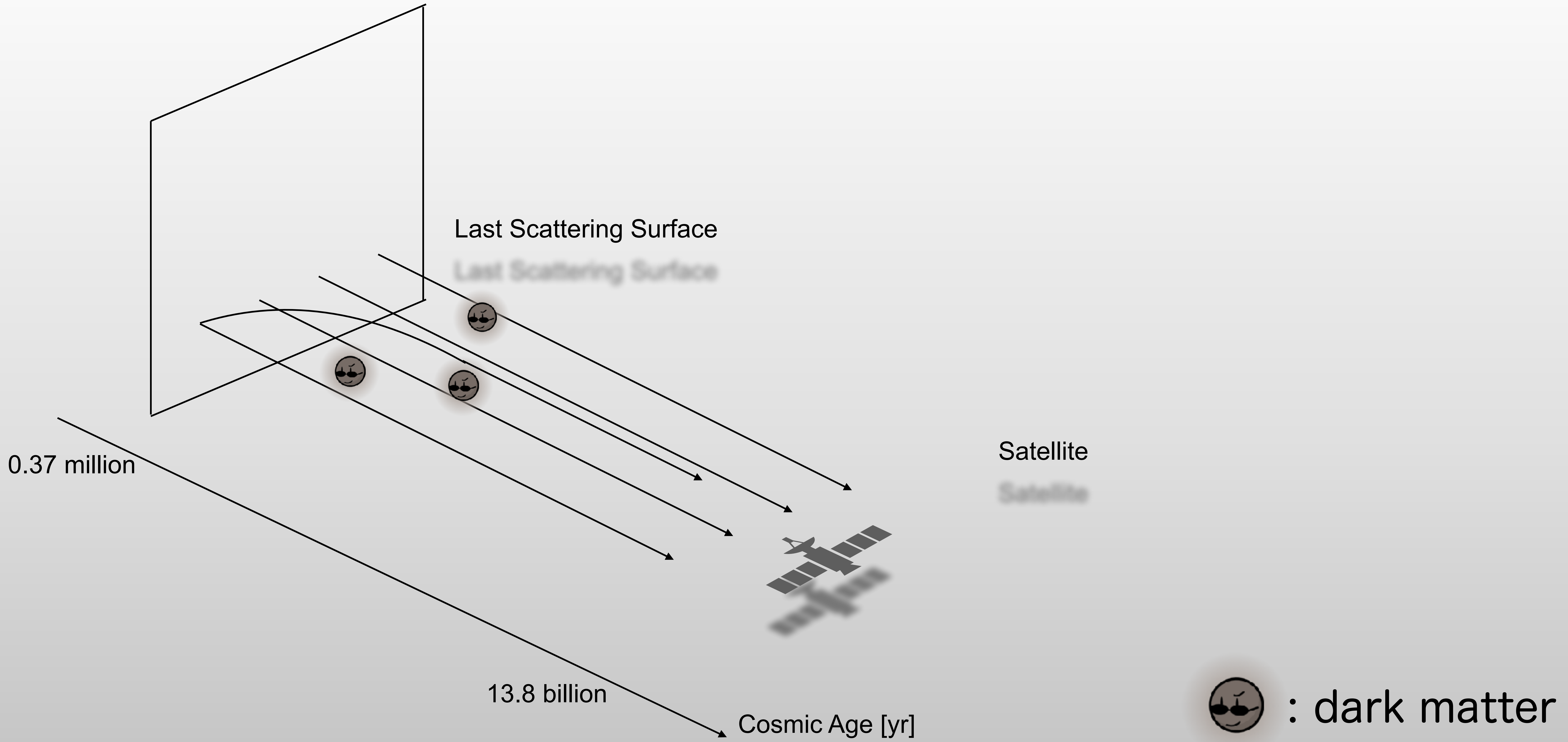

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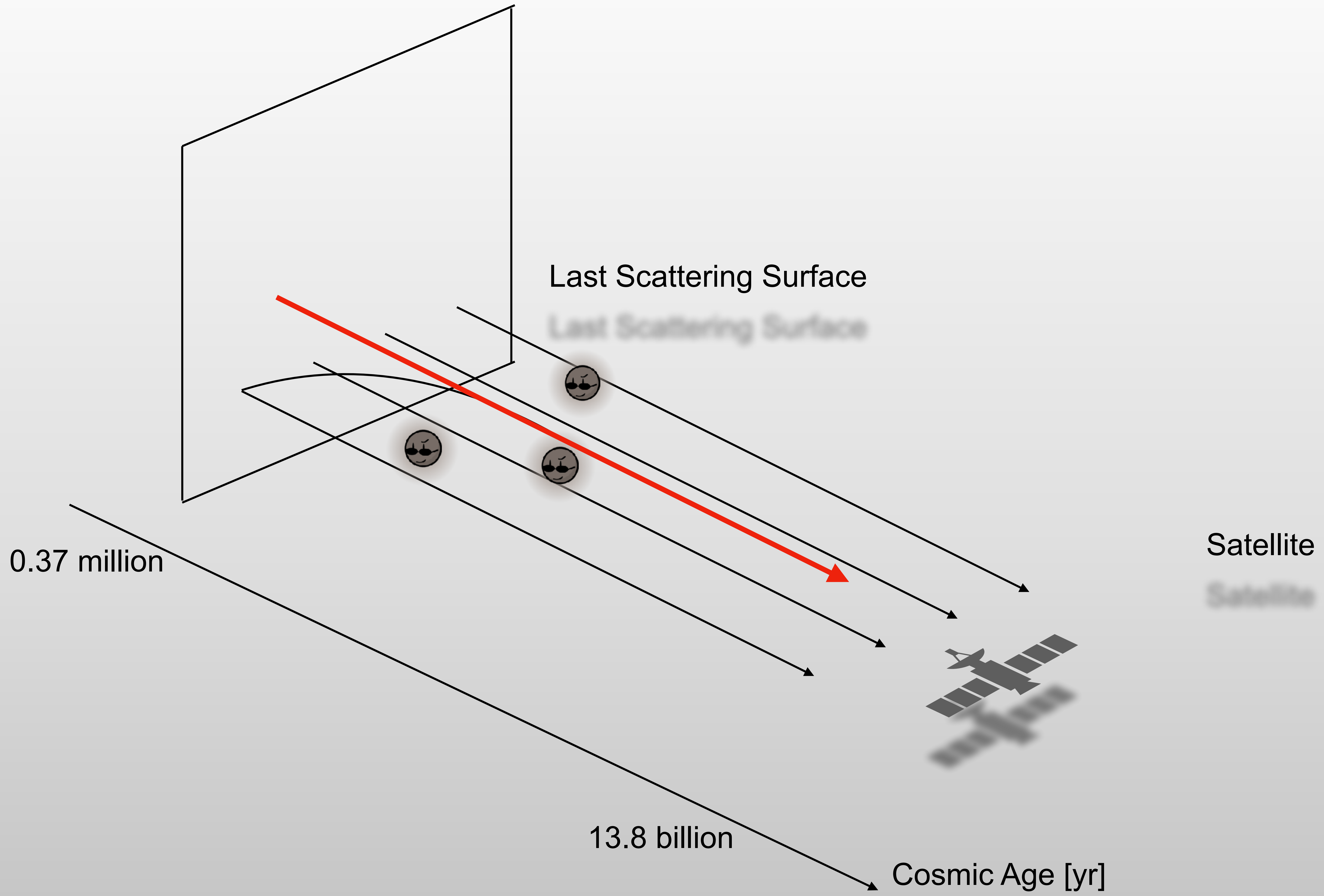

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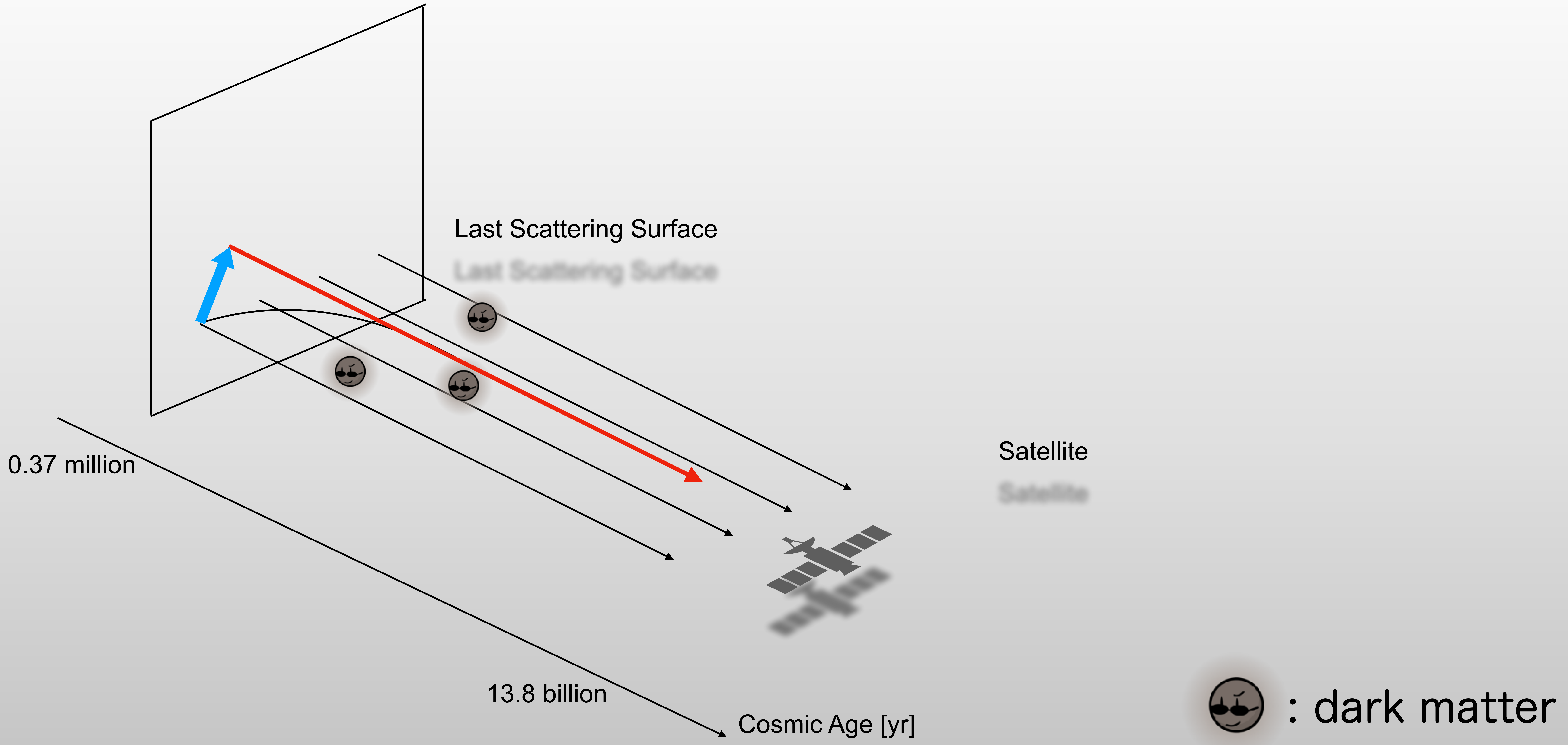

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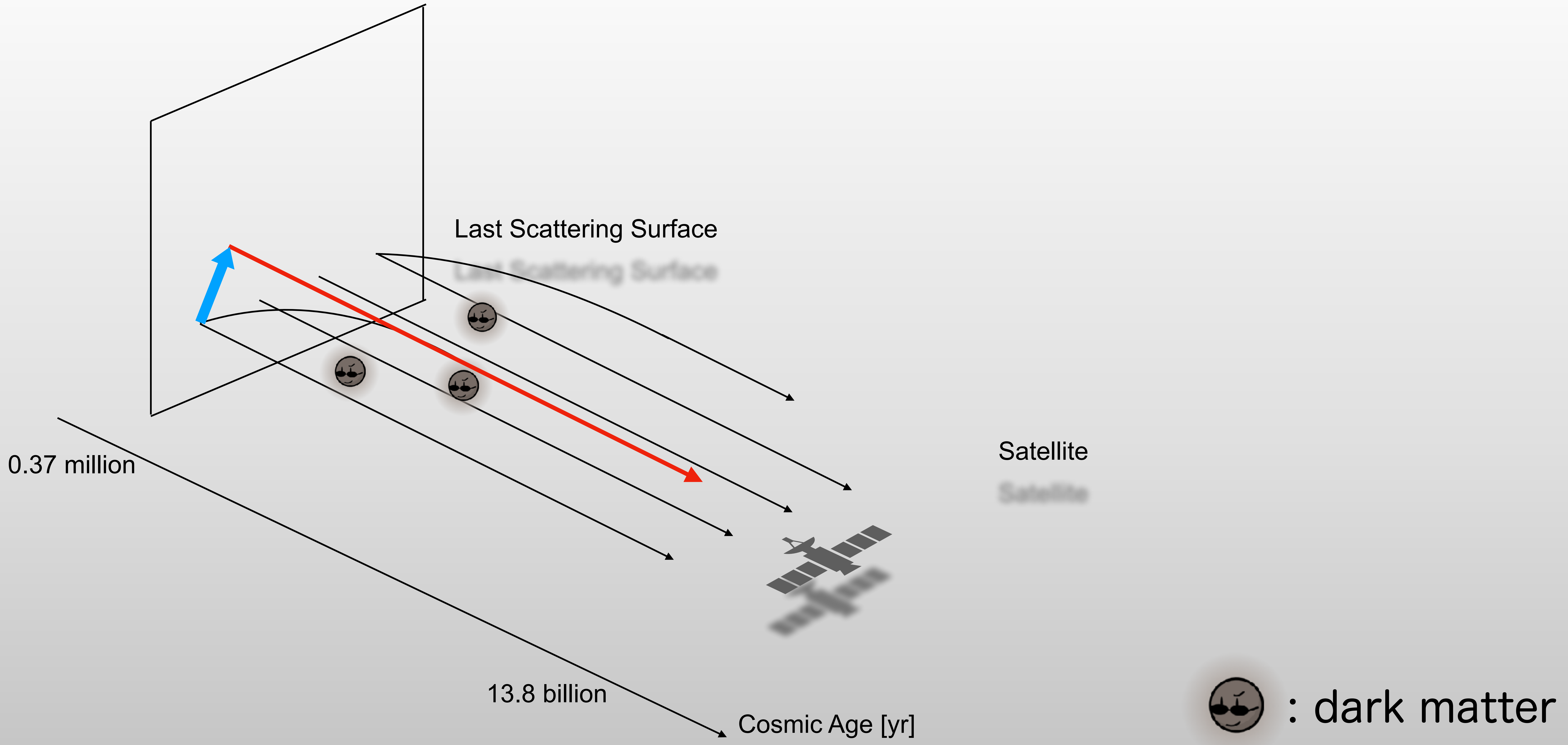

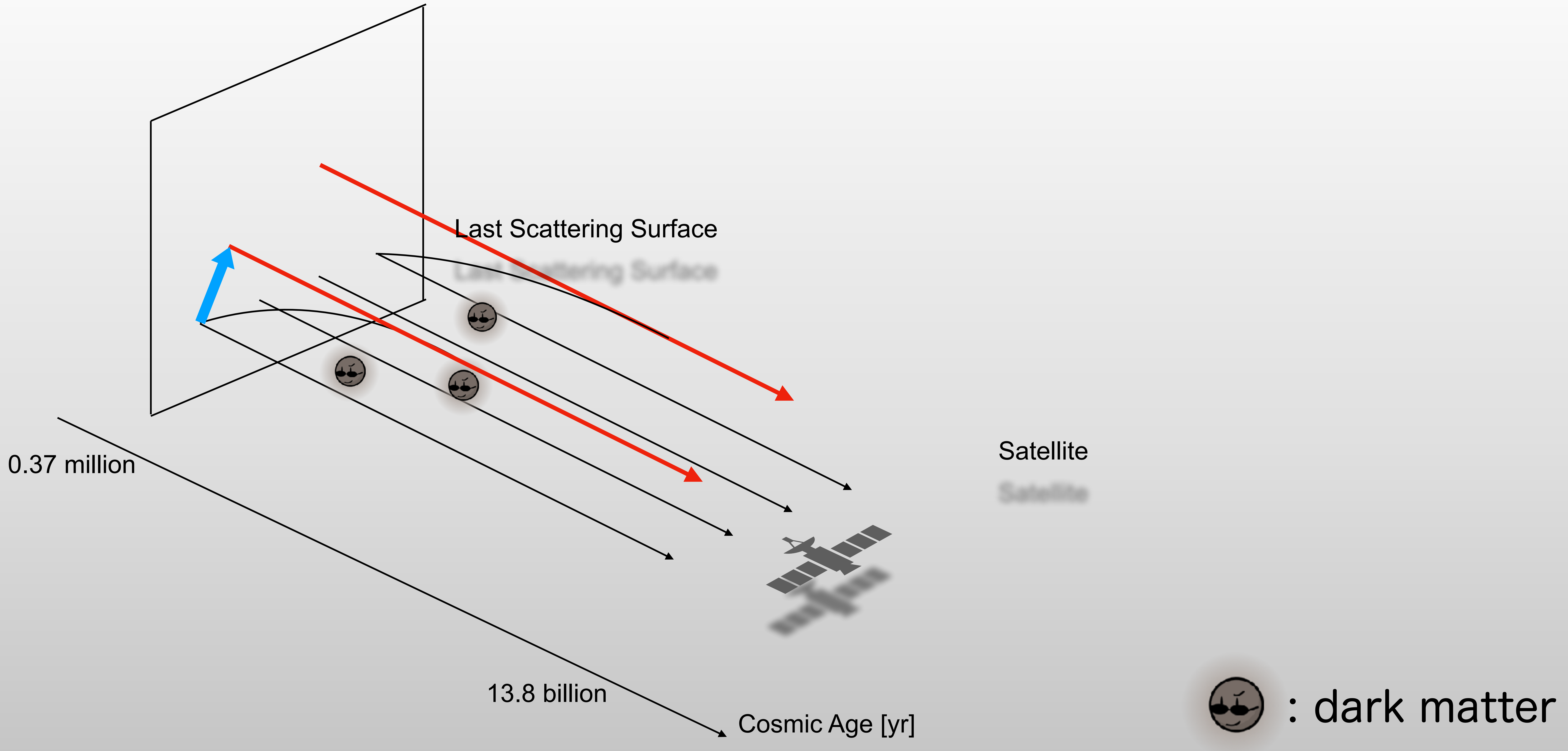
Last Scattering Surface
0.37 million
Satellite
13.8 billion
Cosmic Age [yr]
: dark matter

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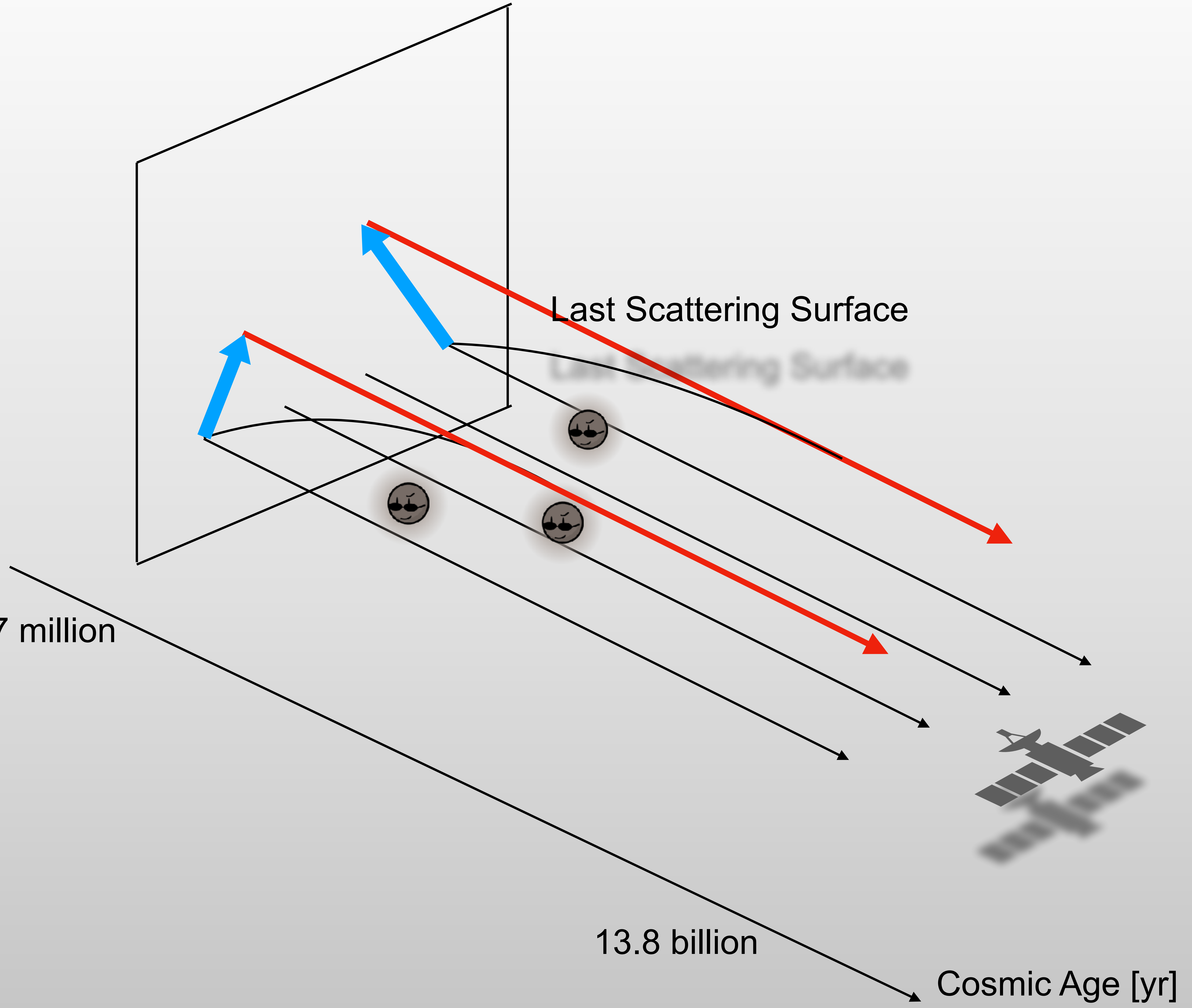

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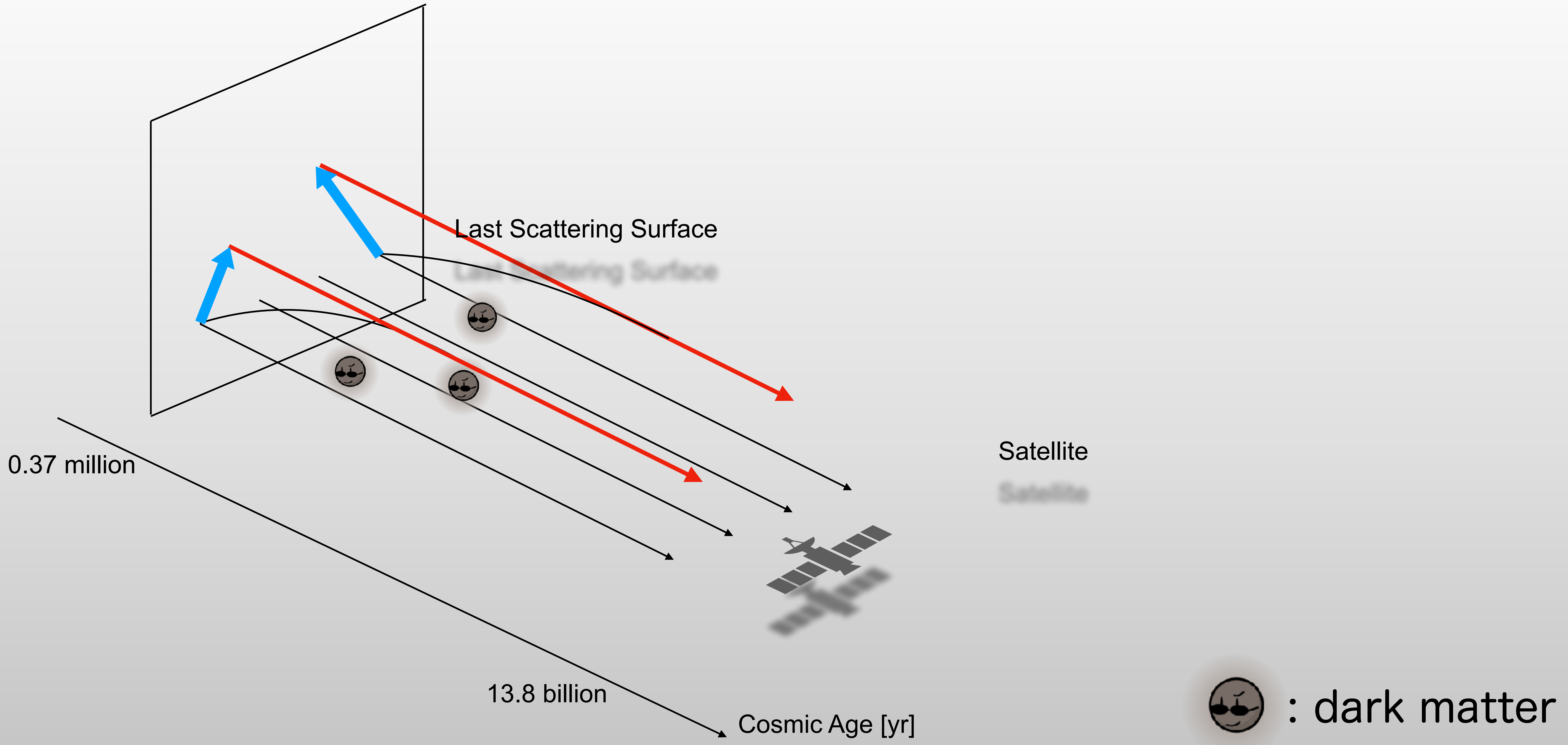
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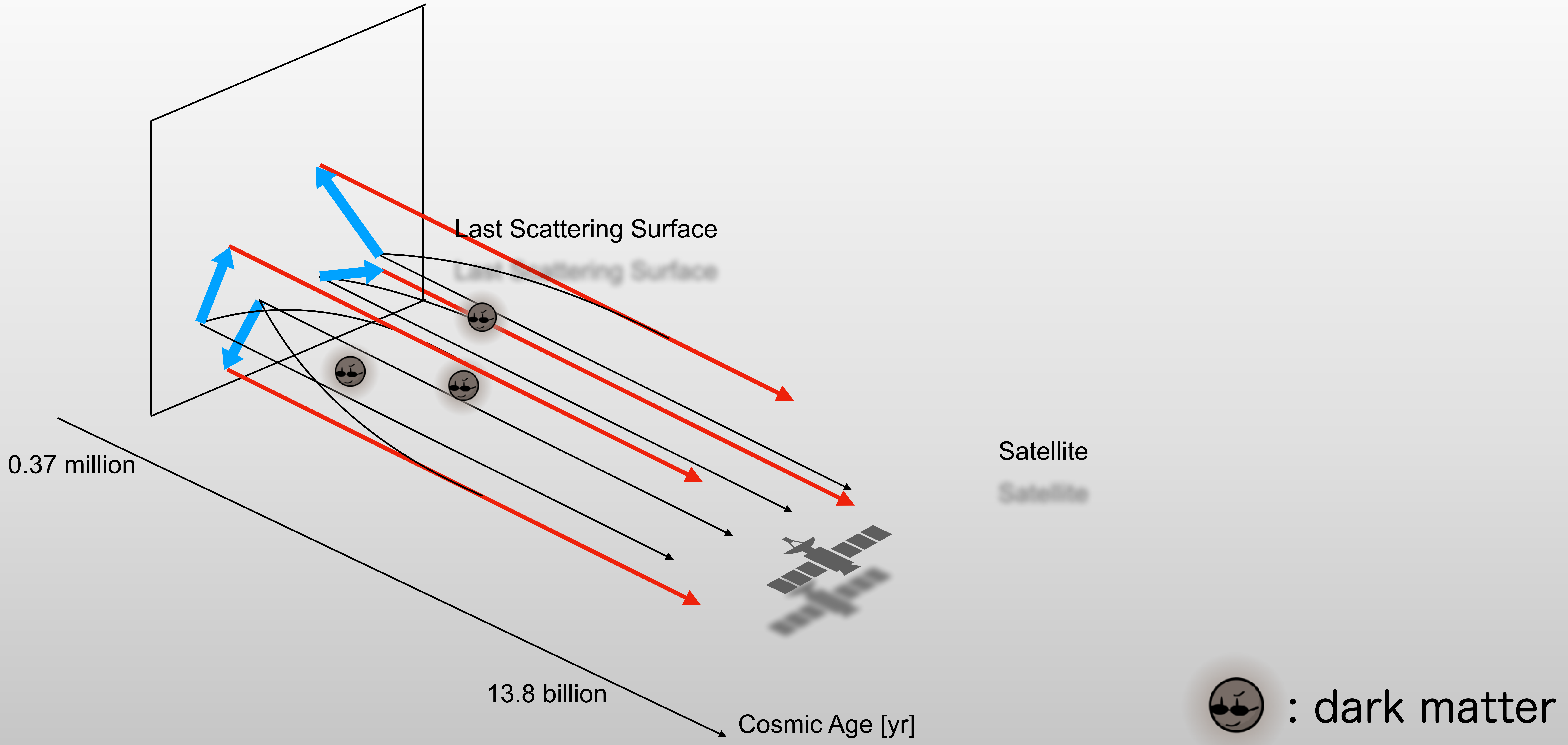
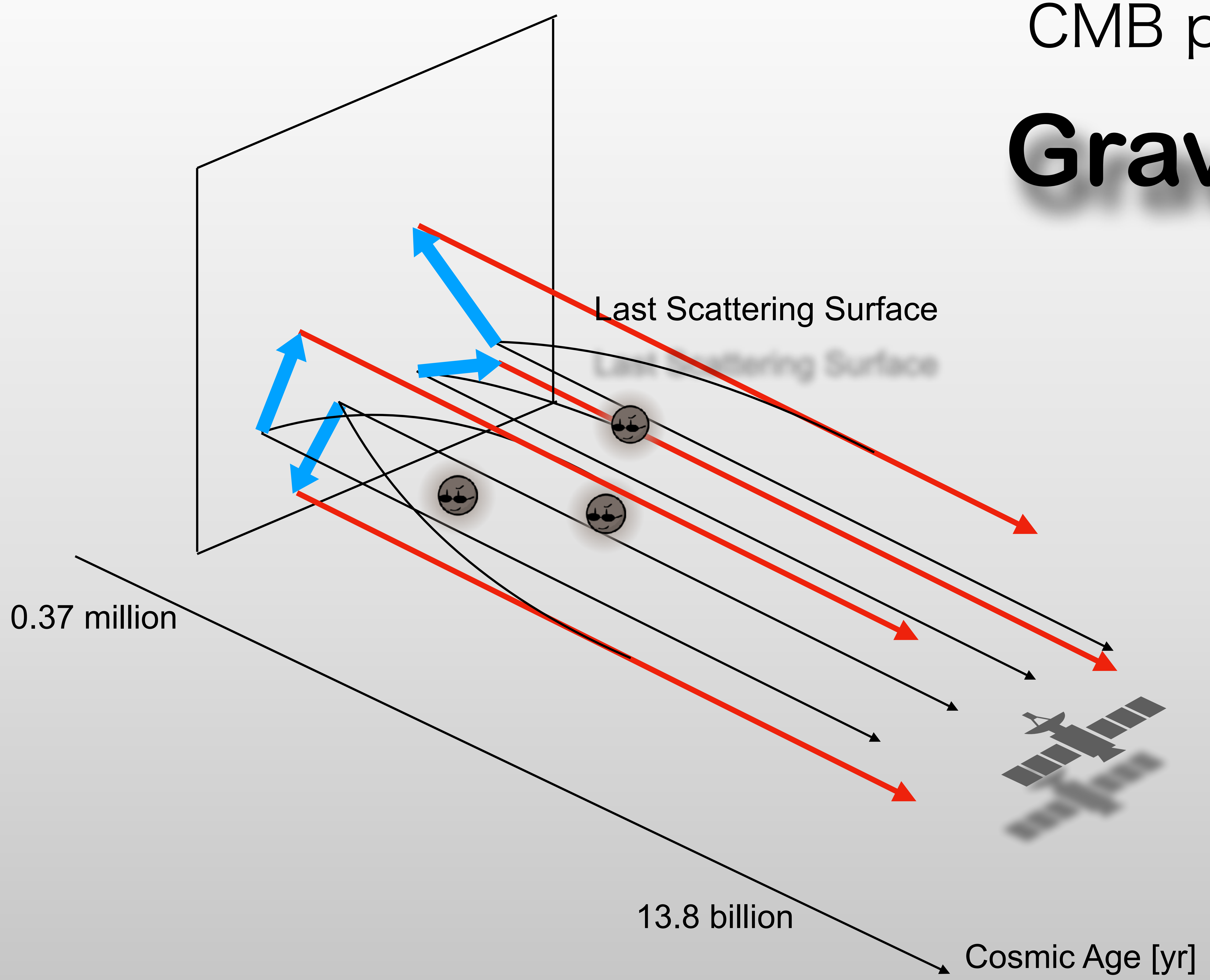


CMB photons are deflected

Gravitational Lensing

Lewis & Challinor(2006)



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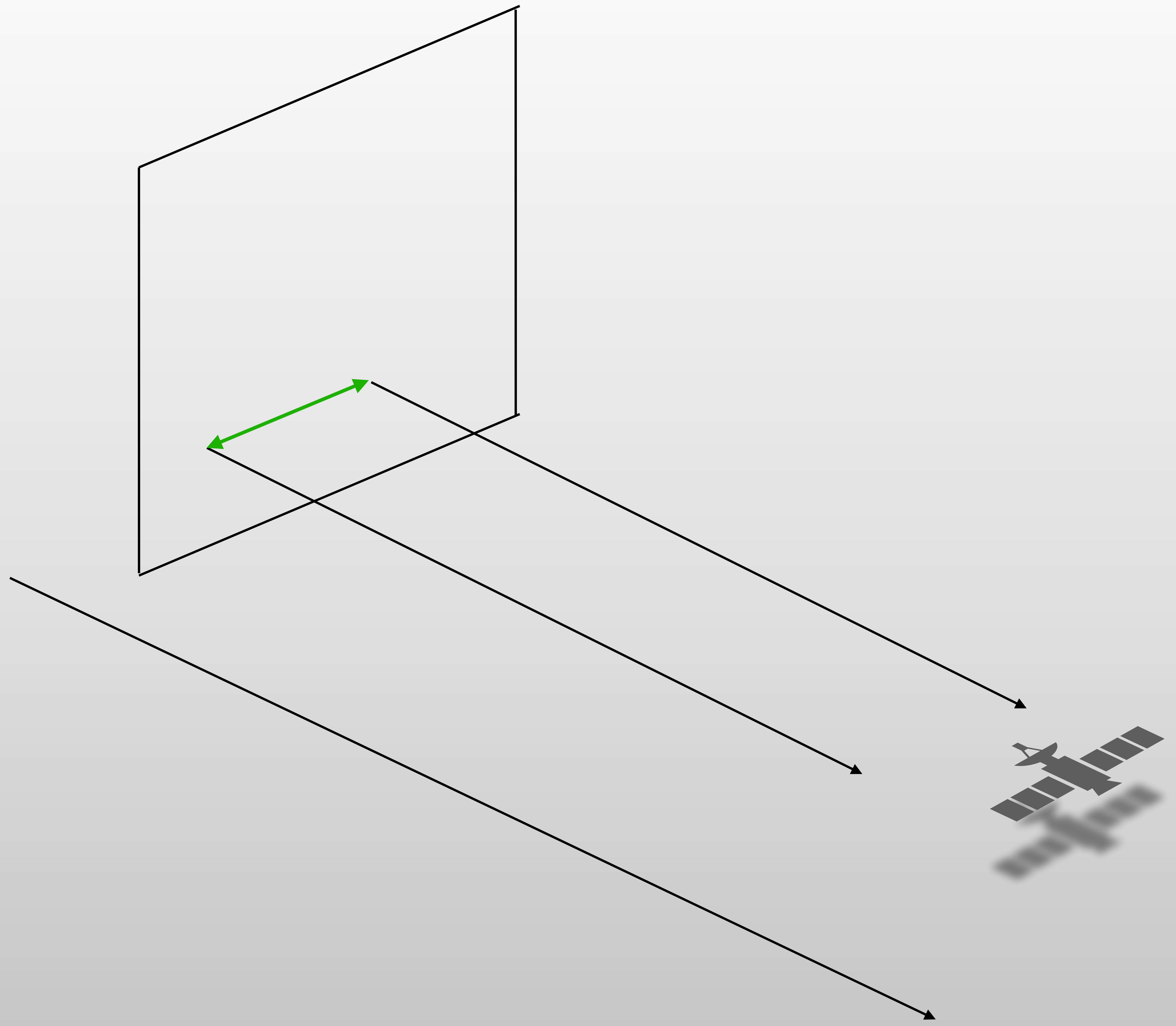

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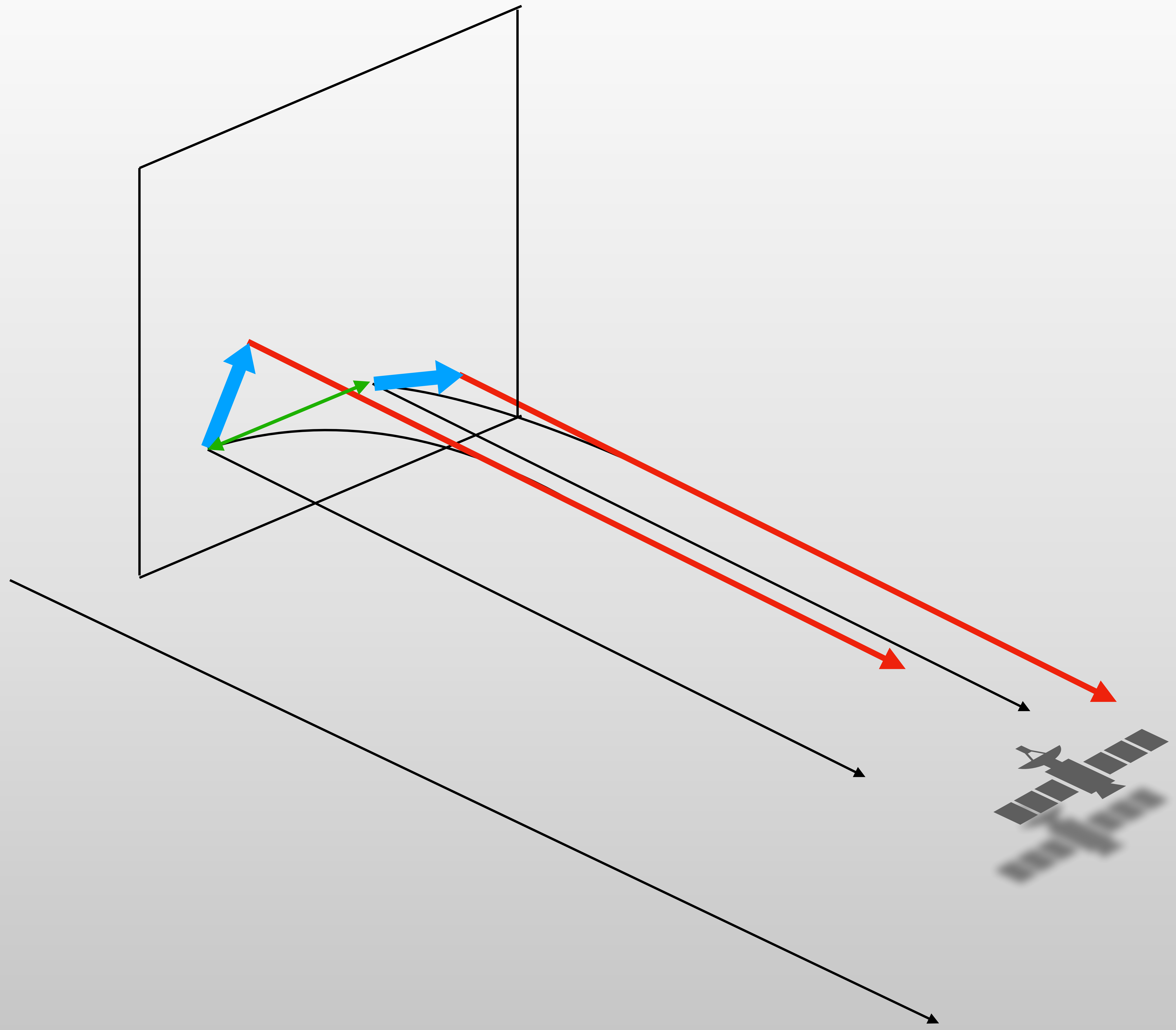

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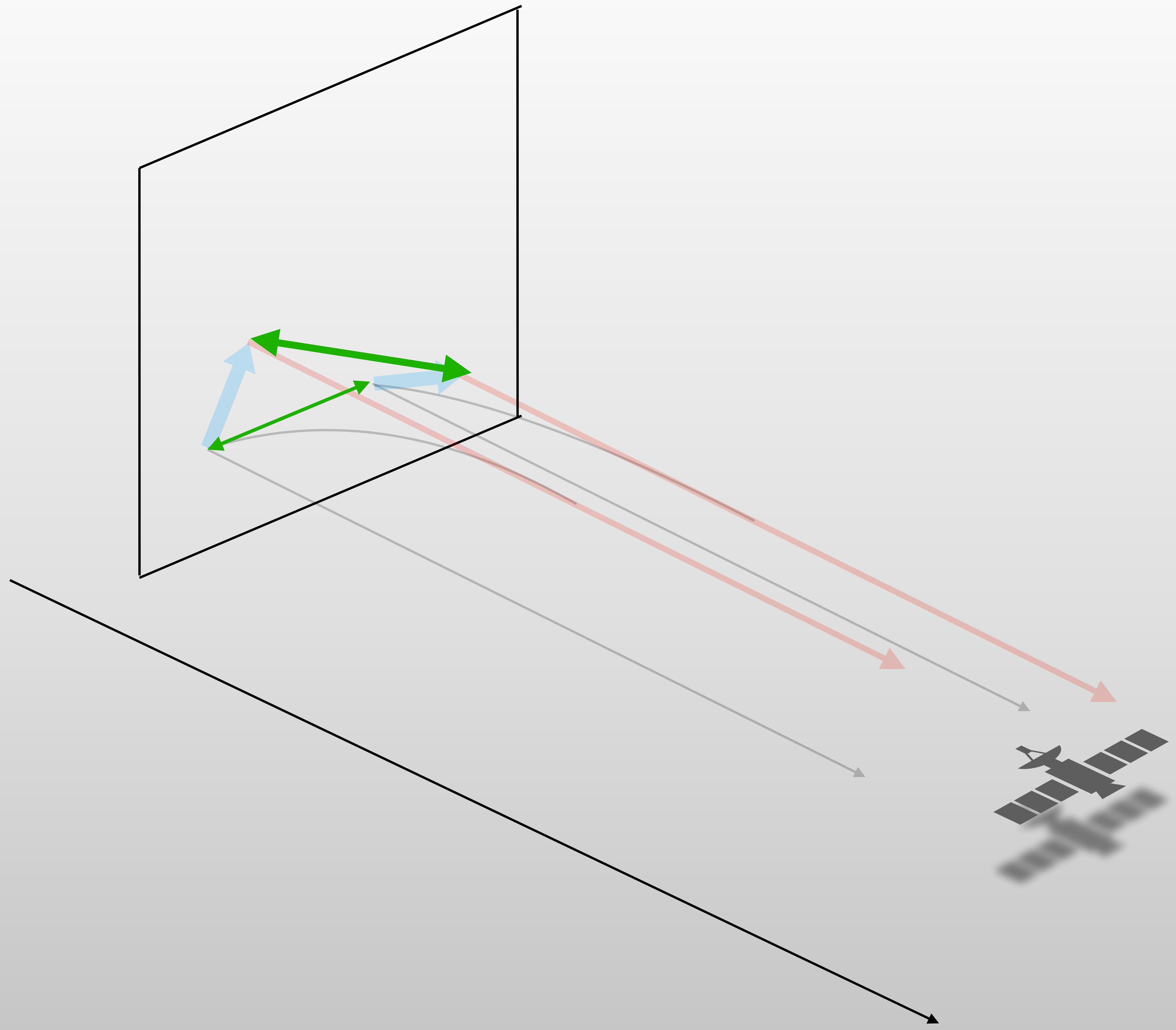

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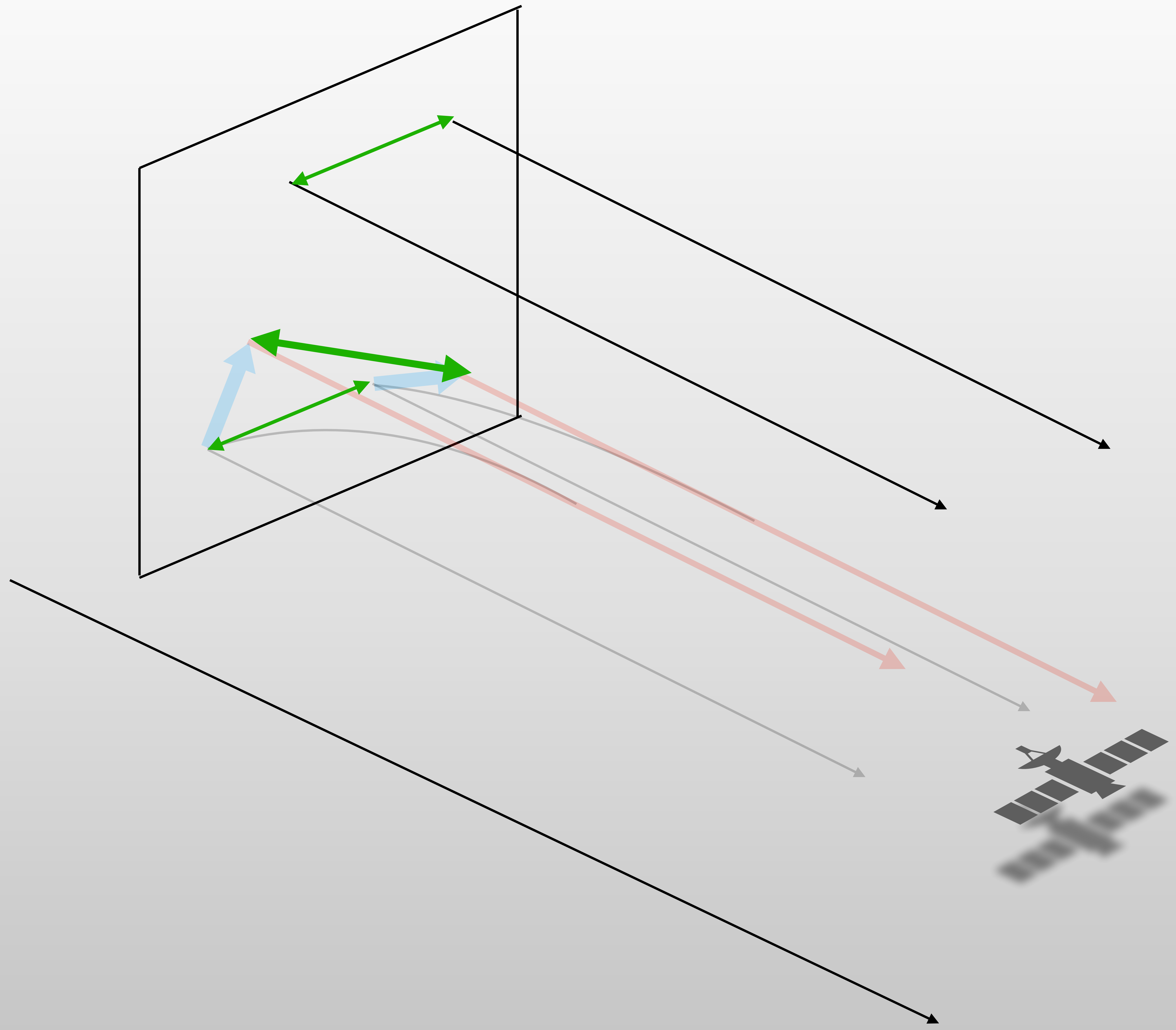

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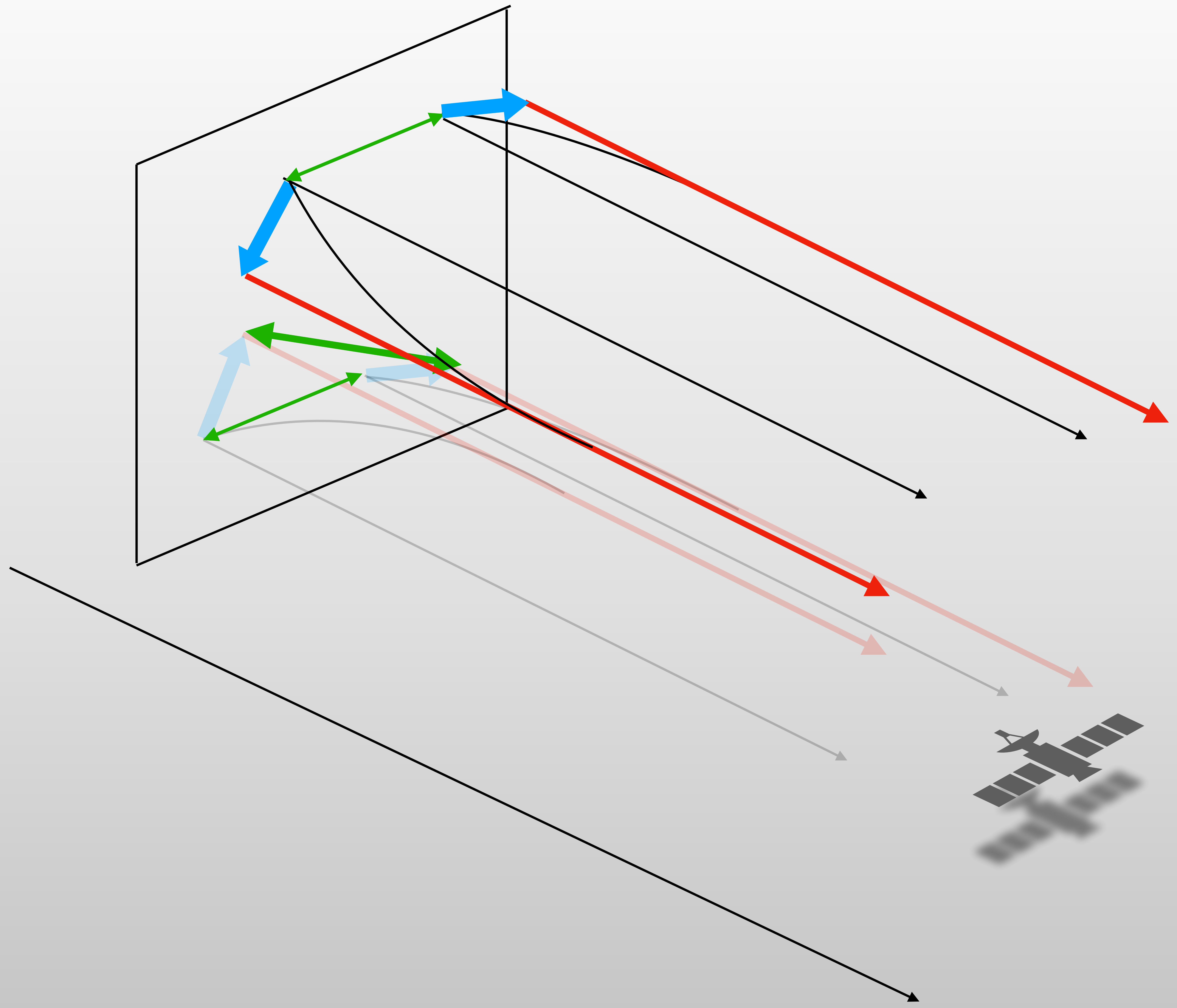

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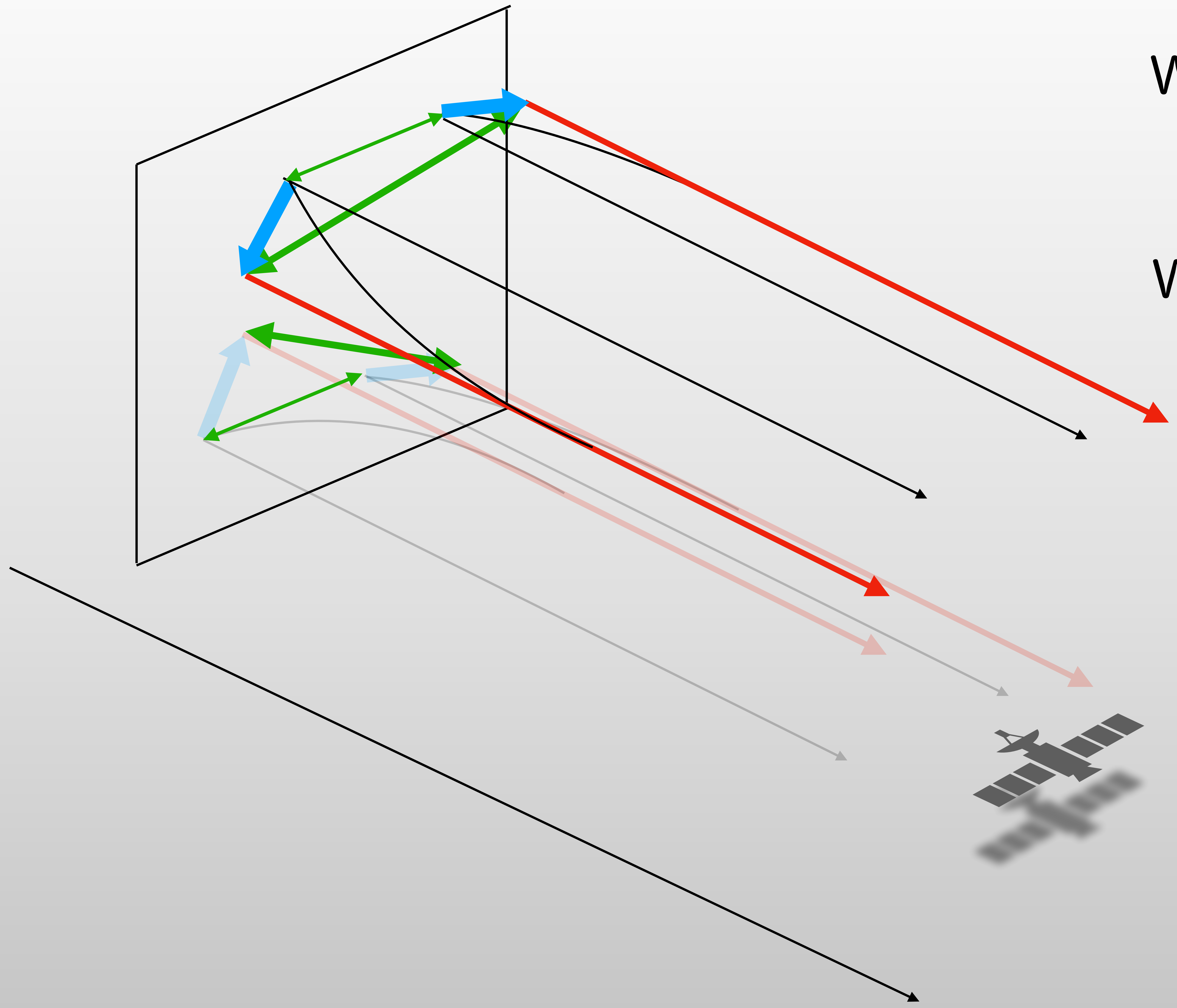

We want to correlate

distorted by gravitational lensing

We have to correlate

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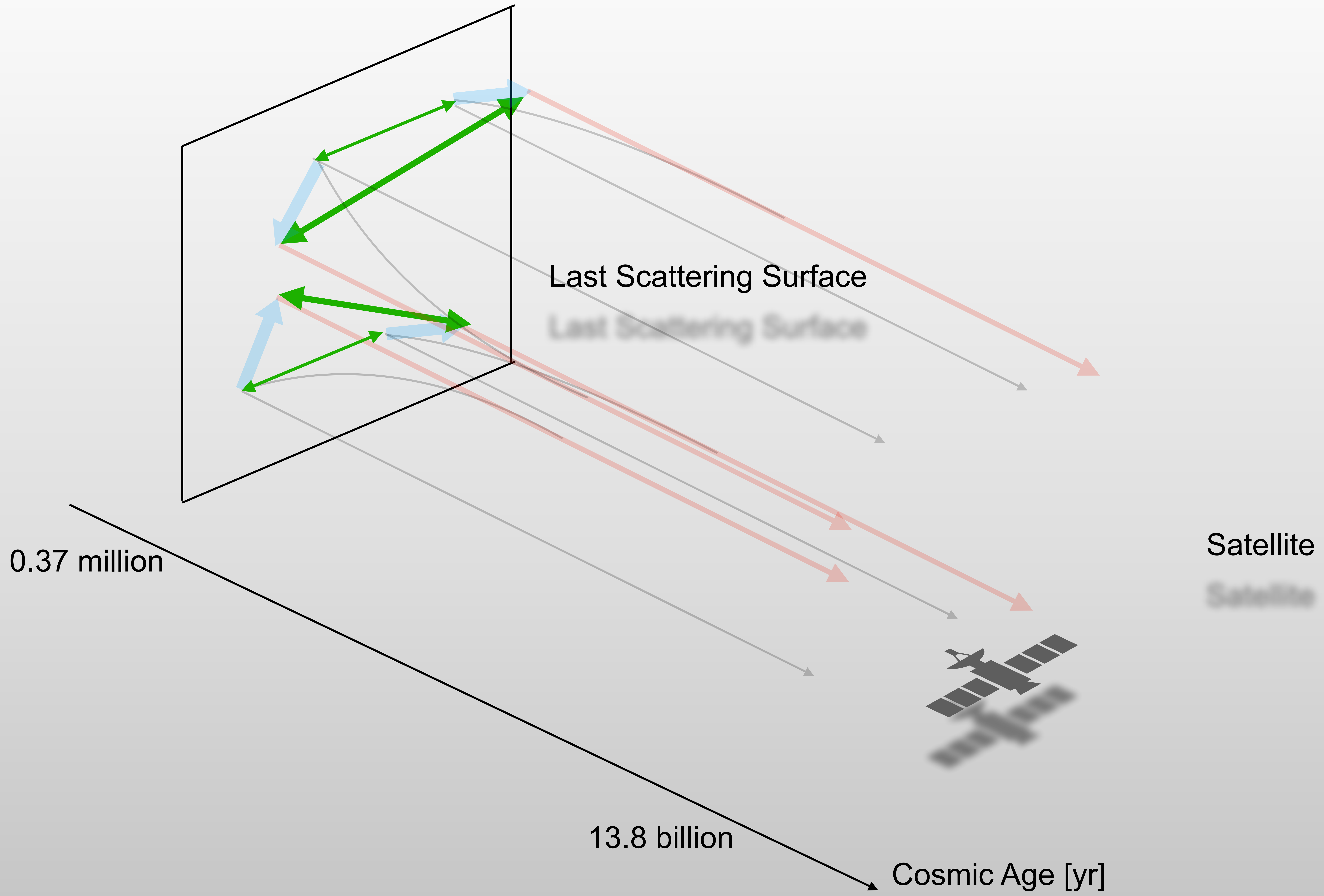

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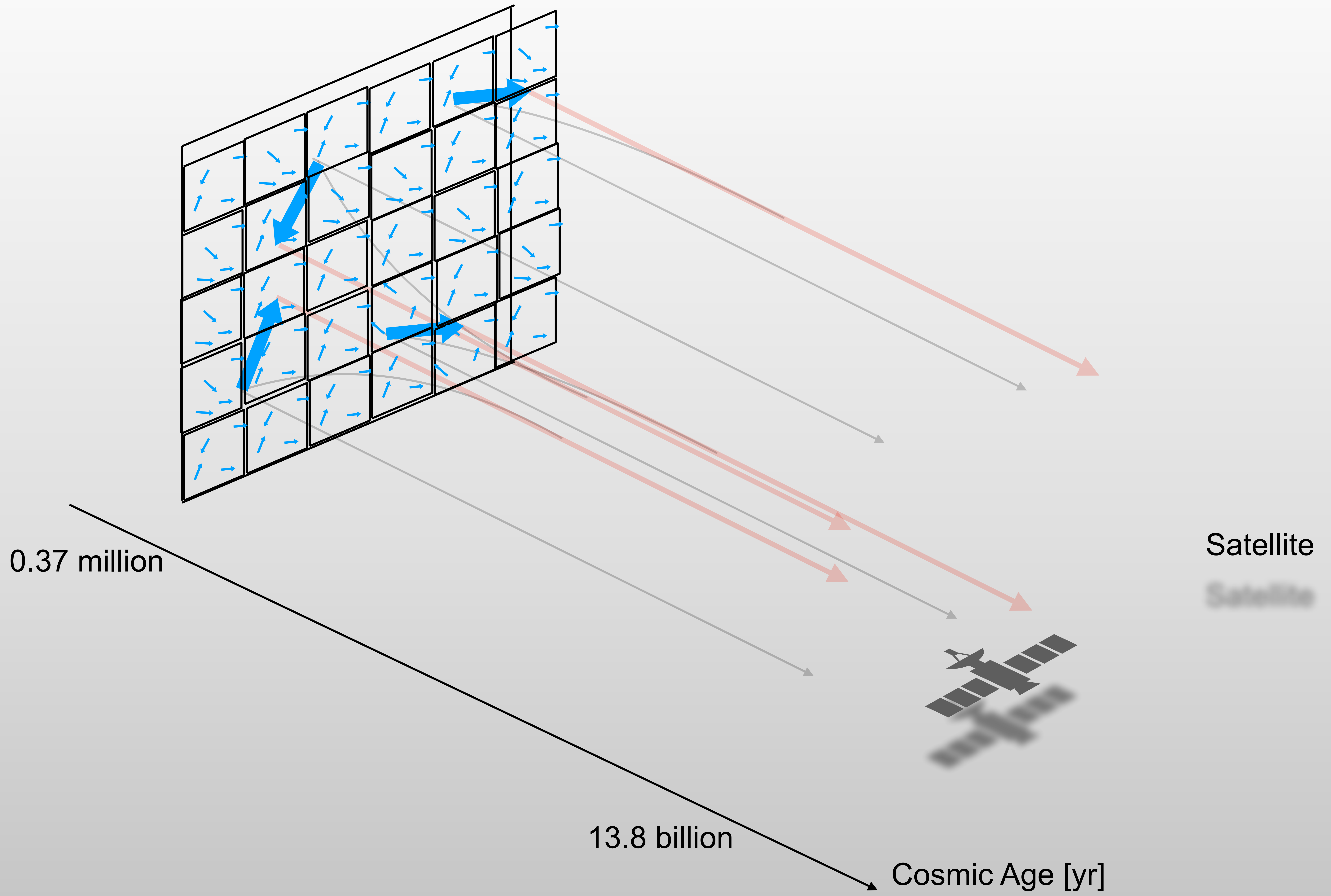

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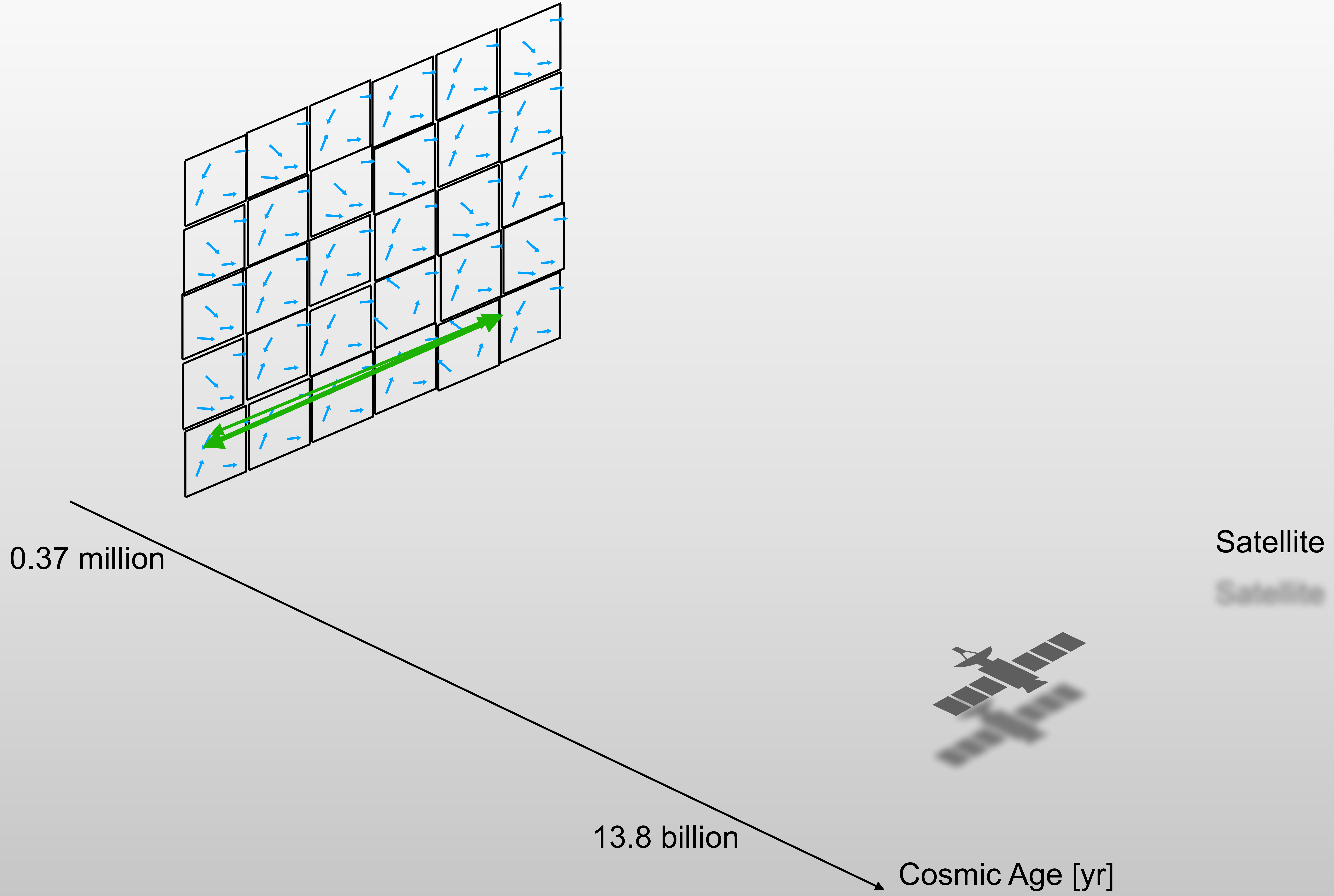

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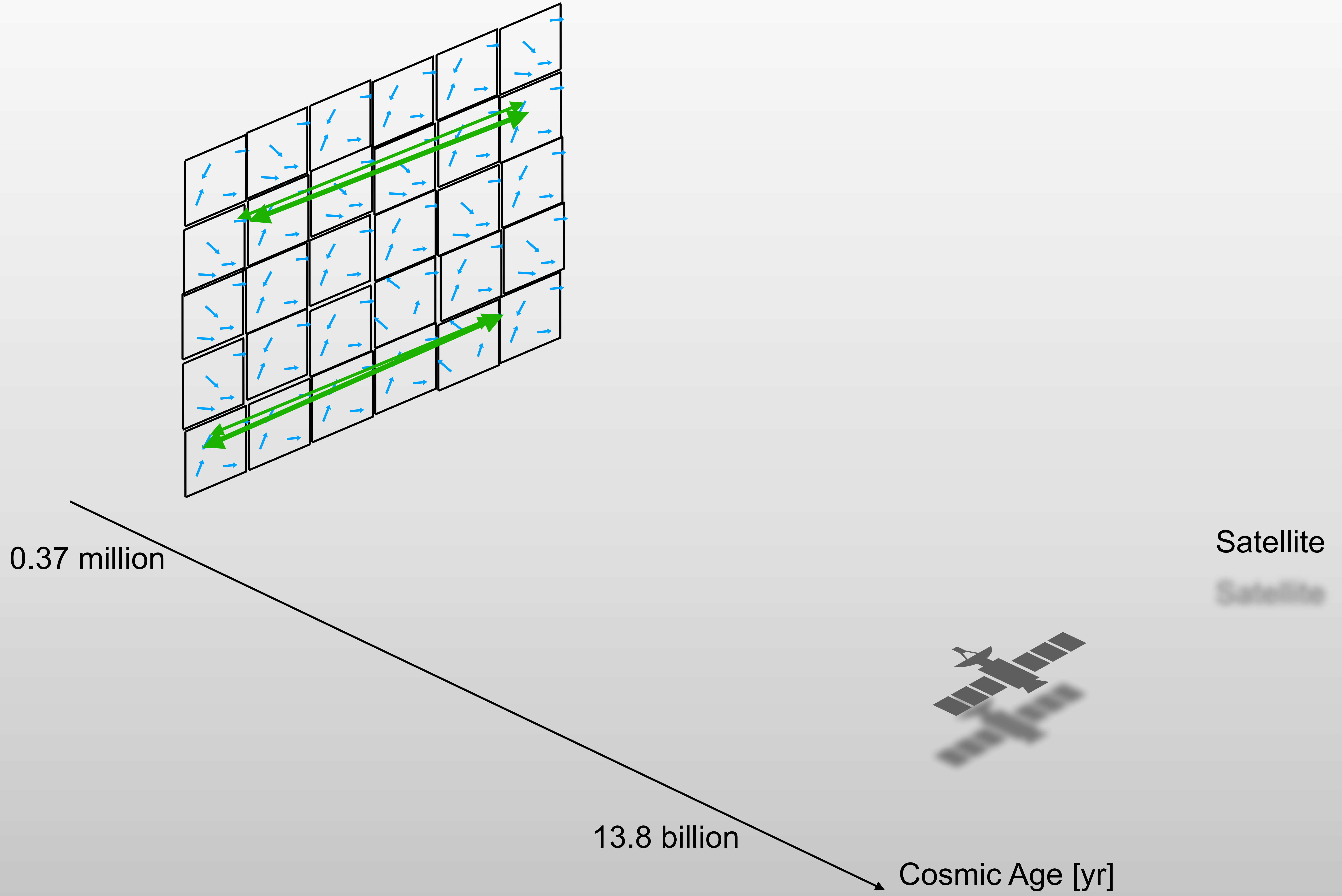
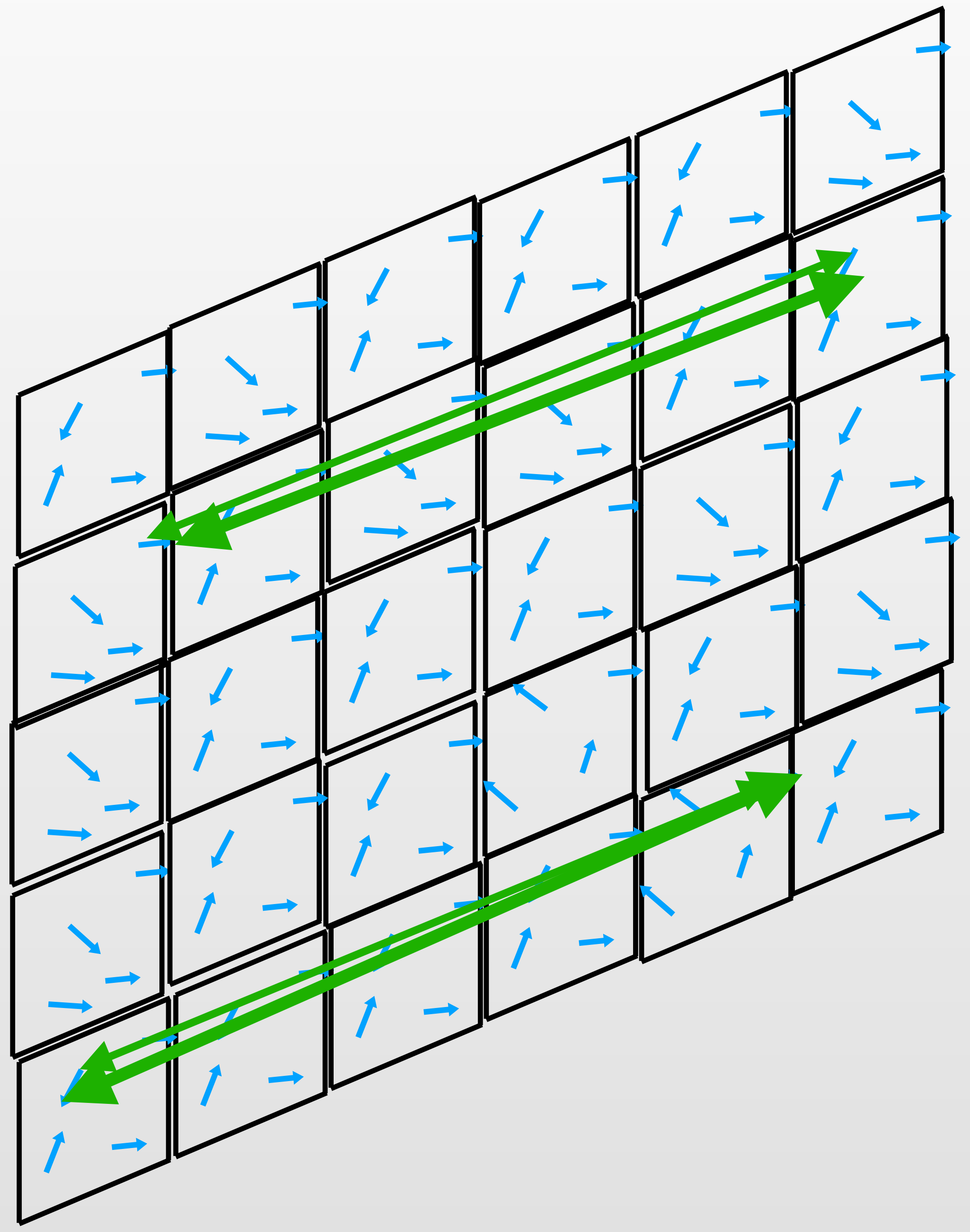
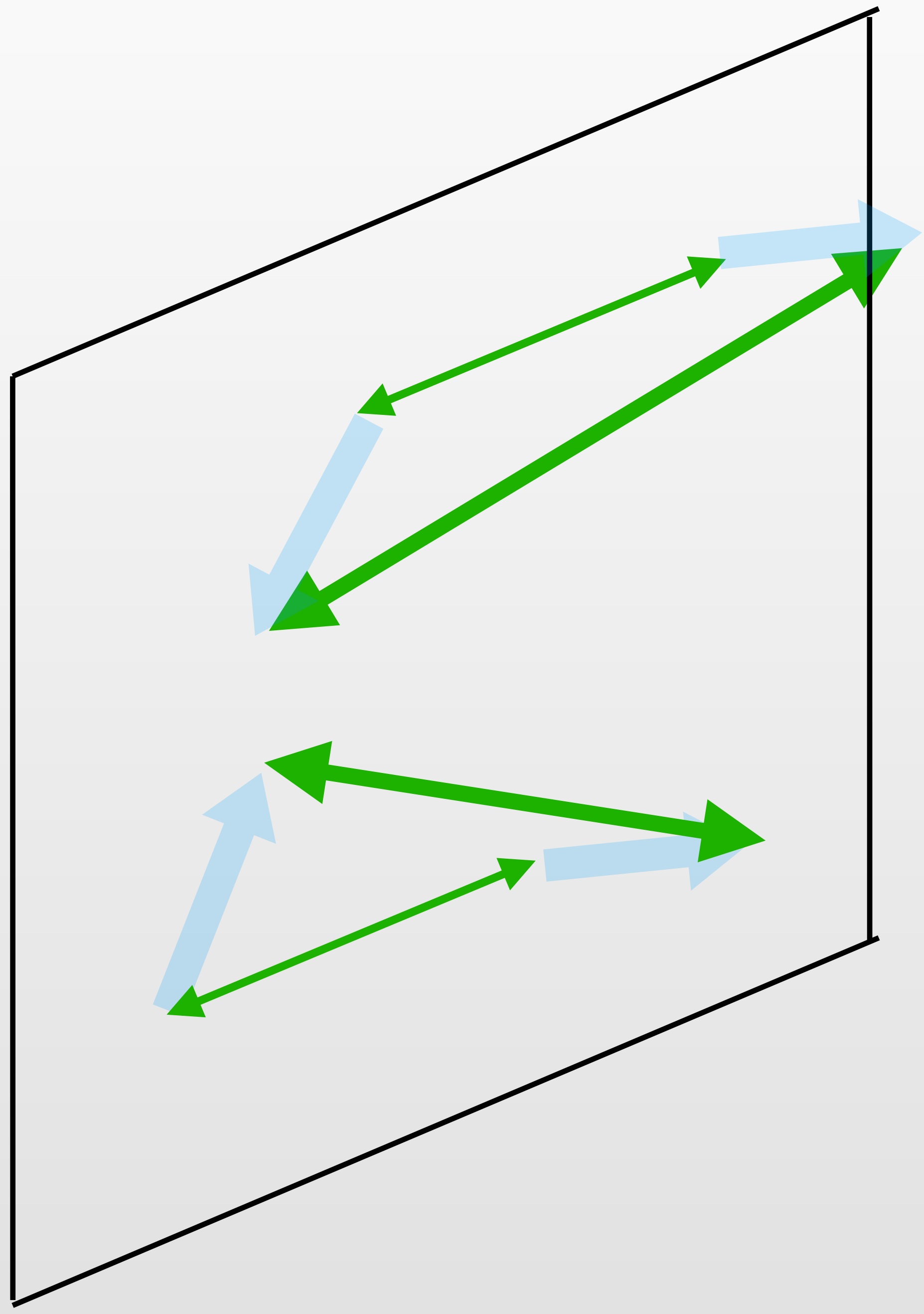






large scale

lensing effect is small

small scale

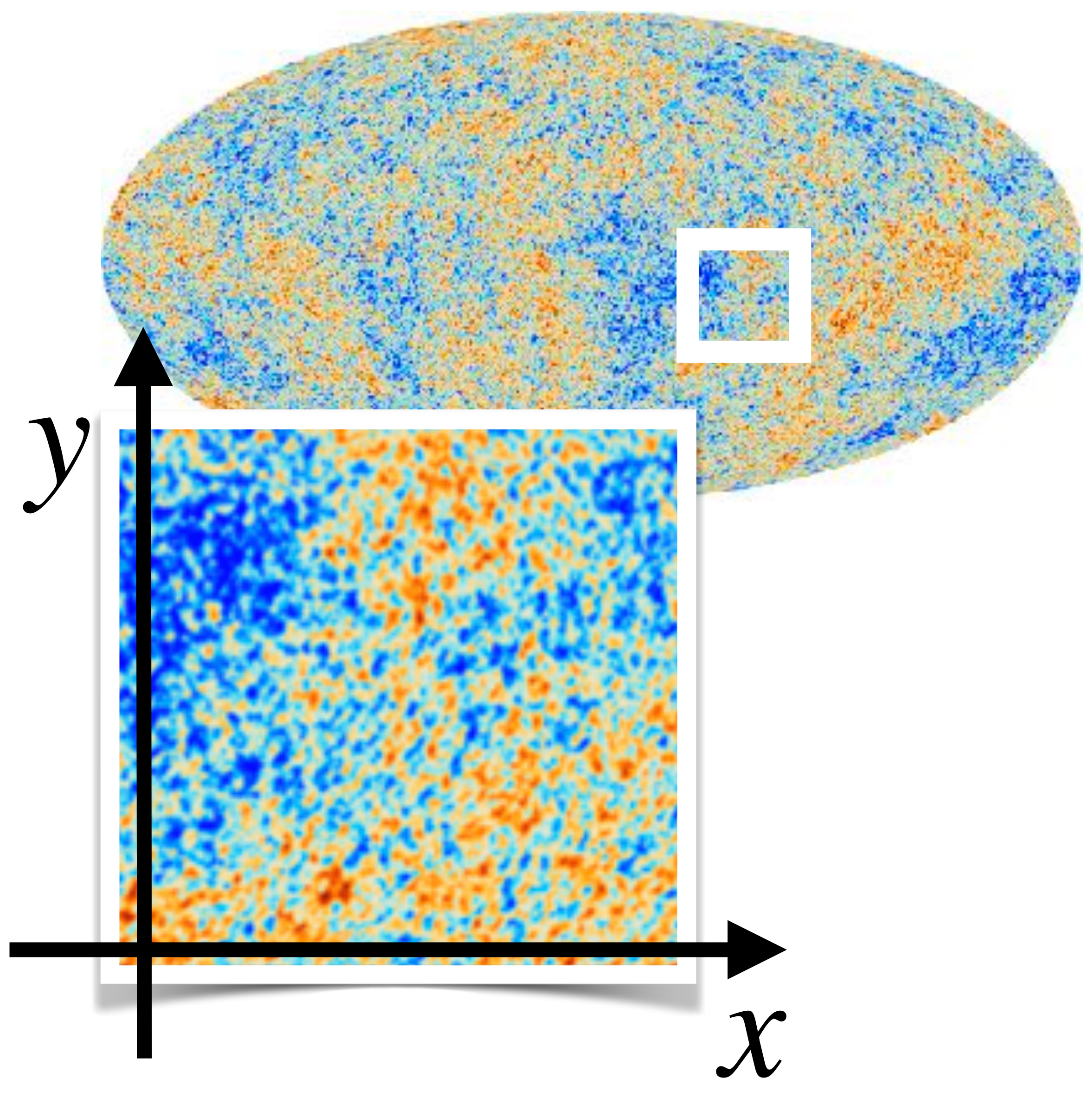
lensing effect is large

How to do lensing correction ?

How to do lensing correction ?

Temperature fluctuation

$$\Theta(x, y) \left(= \frac{\delta T}{T}(x, y) \right)$$



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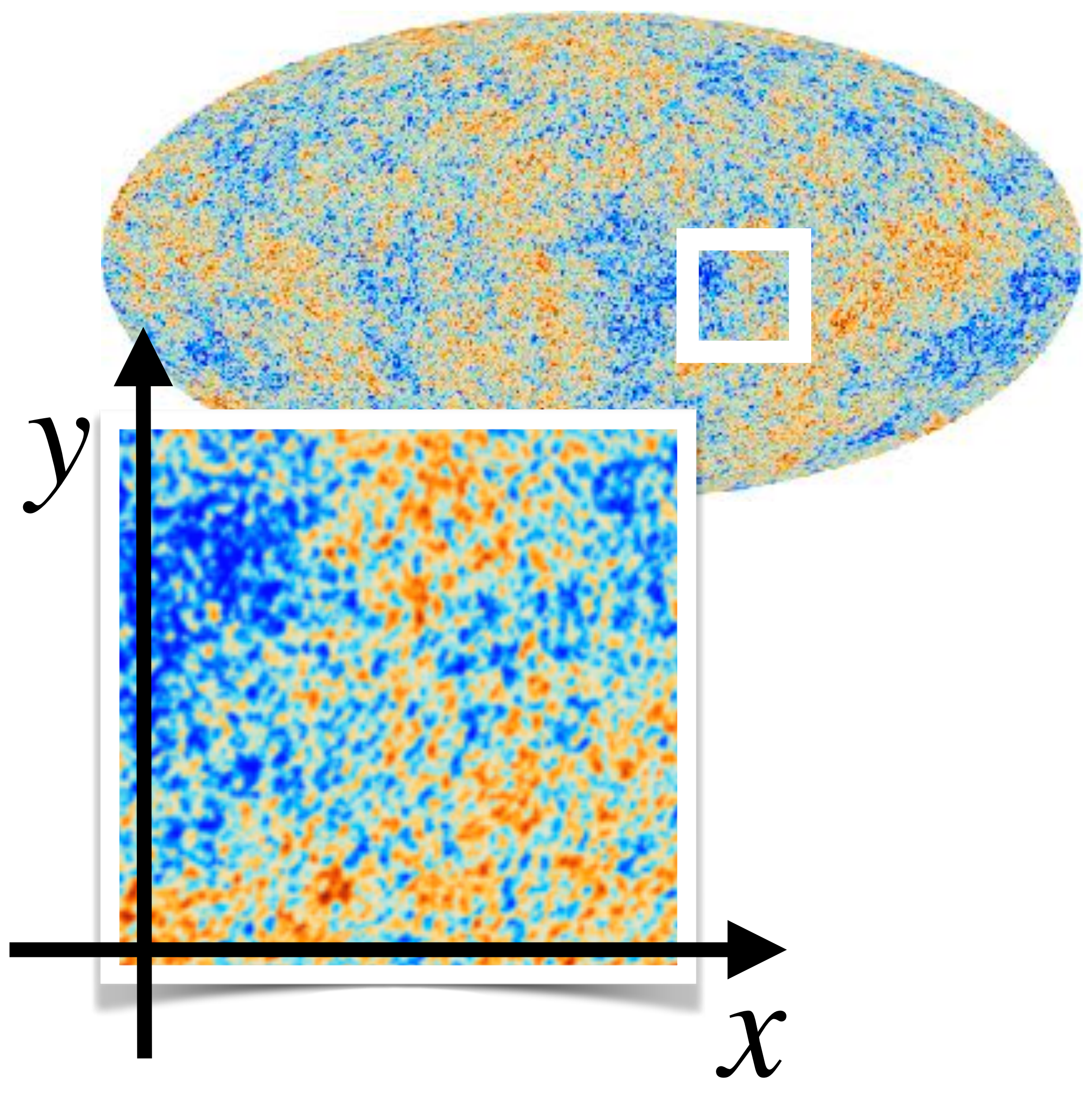

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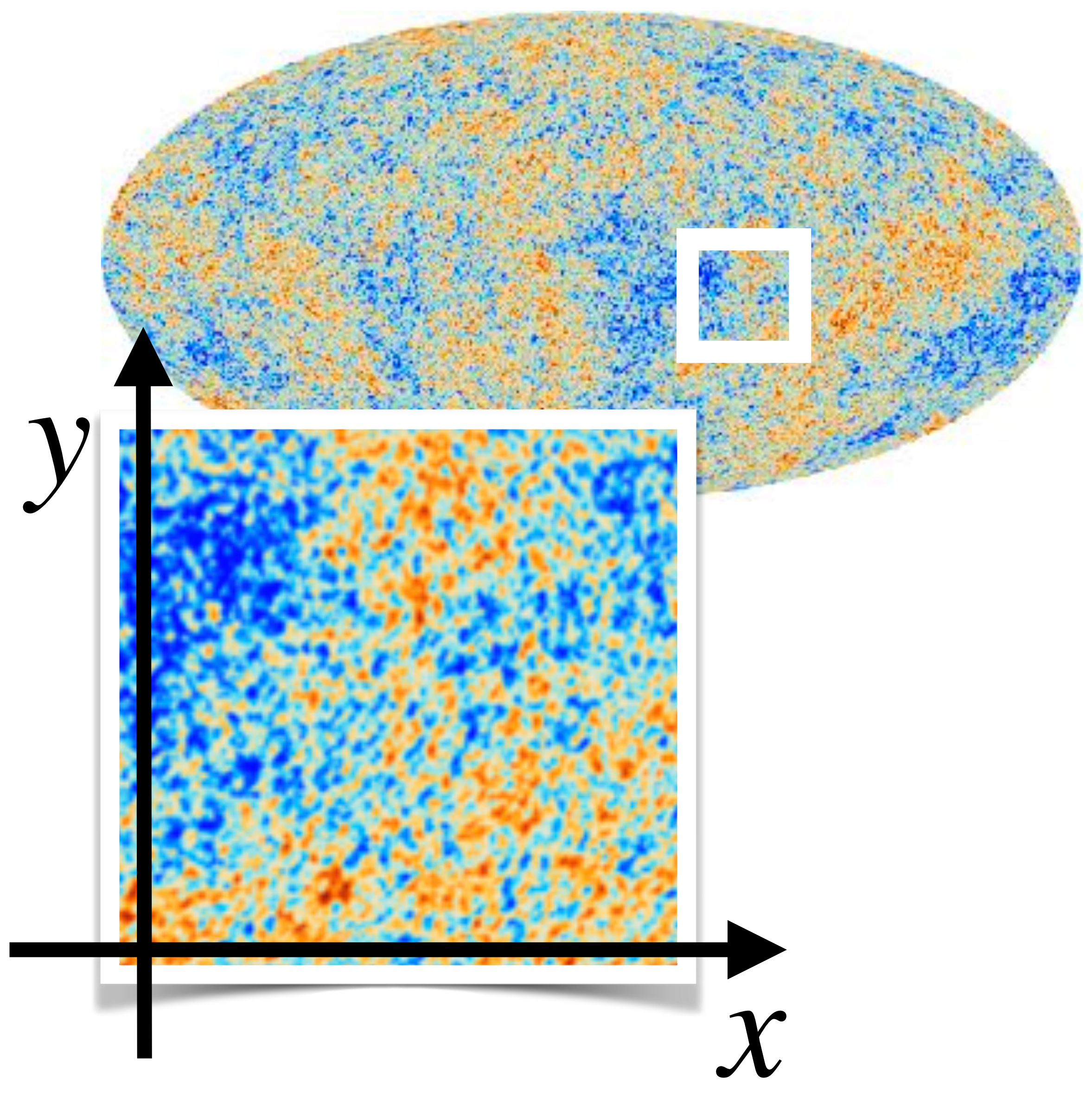

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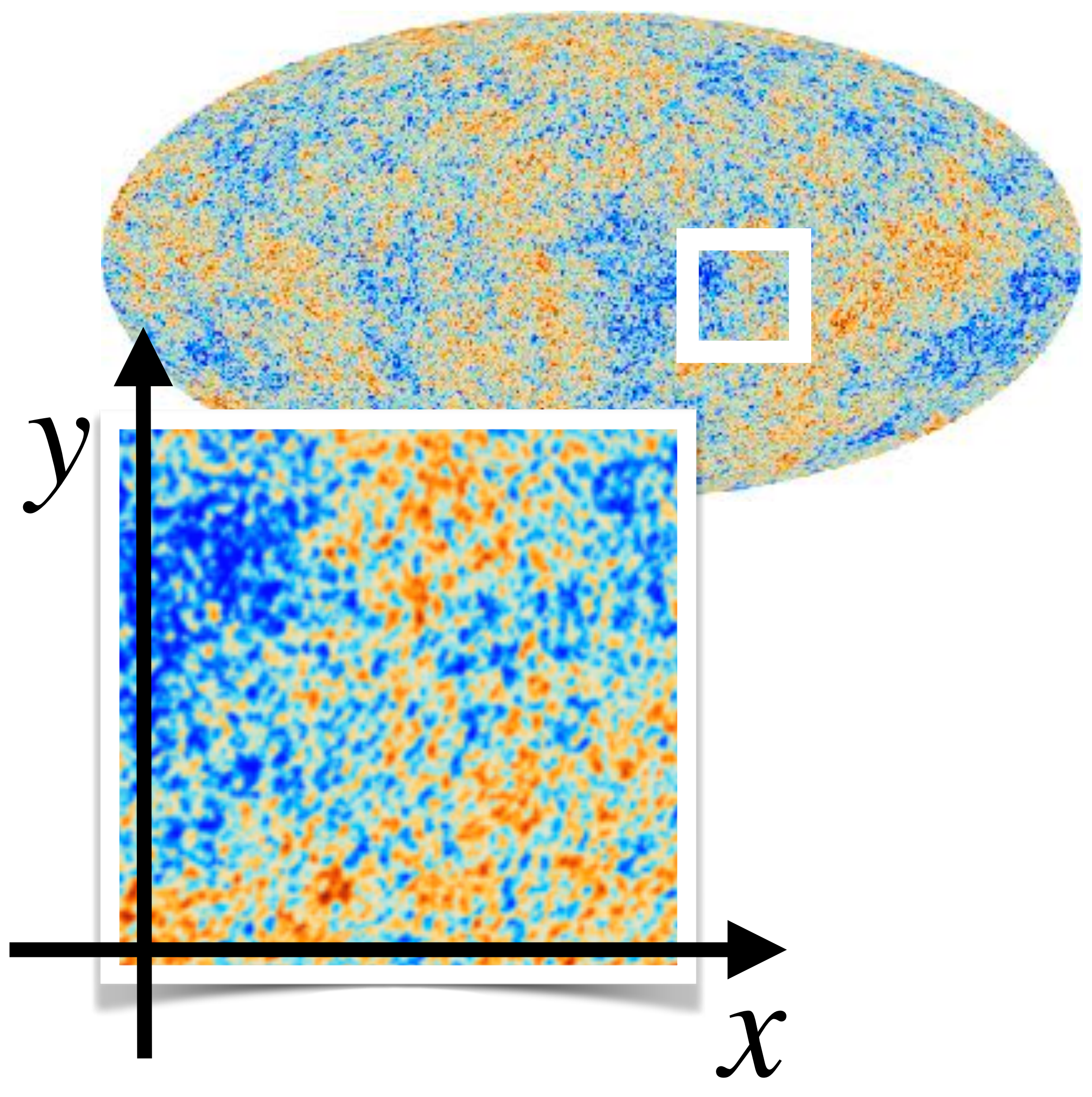

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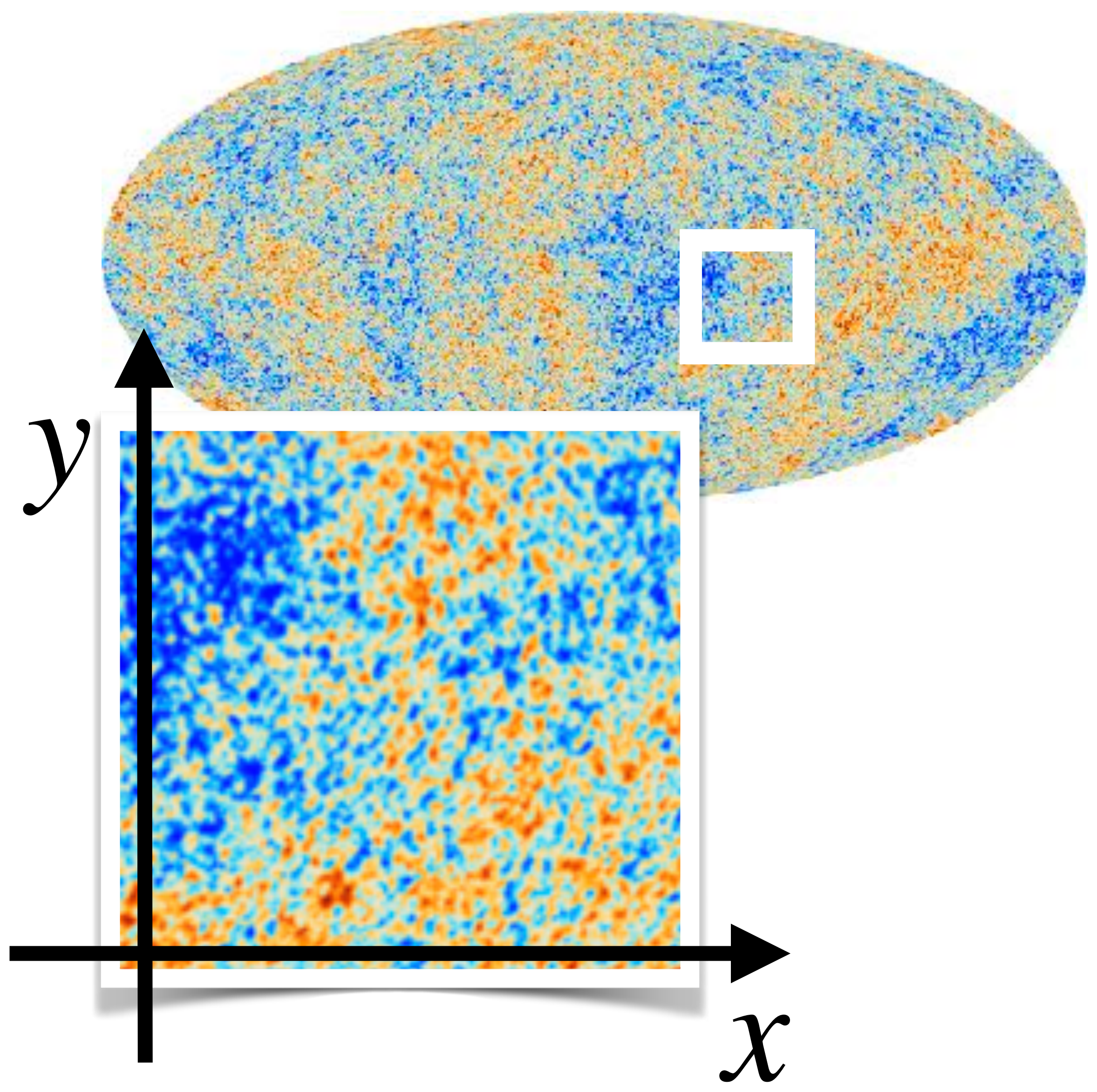
Fourier →

Power spectrum

$$C_l^{\Theta\Theta} = \int d^2\beta\ \xi(\beta)\exp\left(i\mathbf{l}\cdot\beta\right)$$



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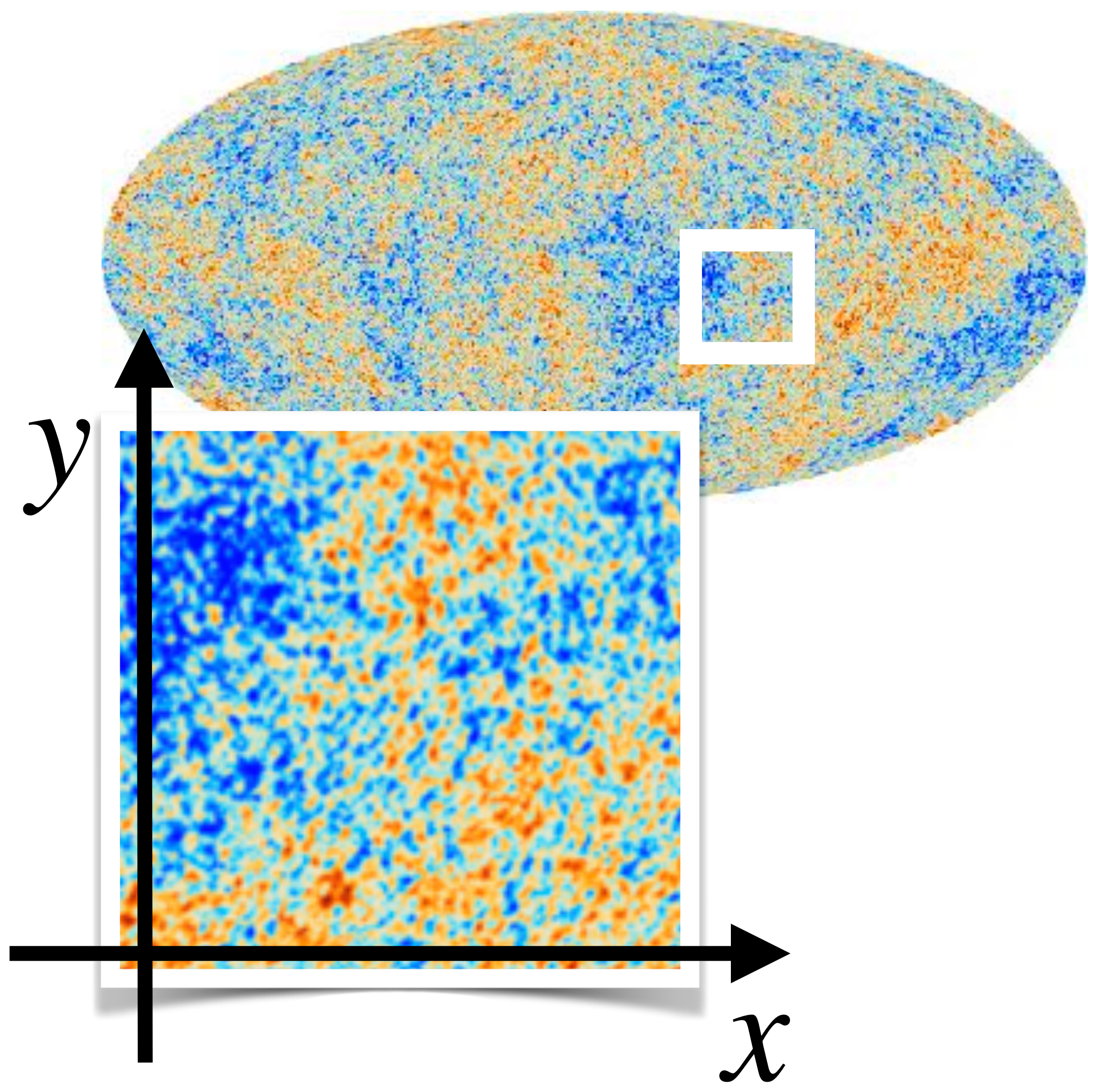
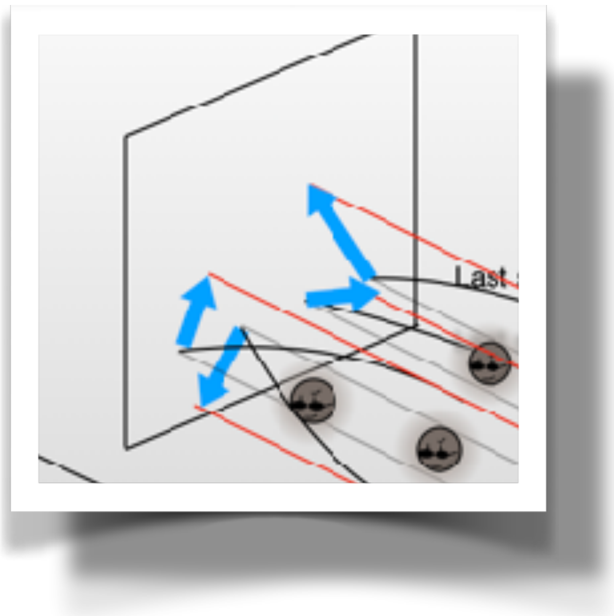


Lensing distortion



$$\tilde{\mathrm{x}} = (\tilde{x}, \tilde{y})$$
$$= (x, y) + ↗$$
$$= \mathbf{x} + \mathbf{d}$$

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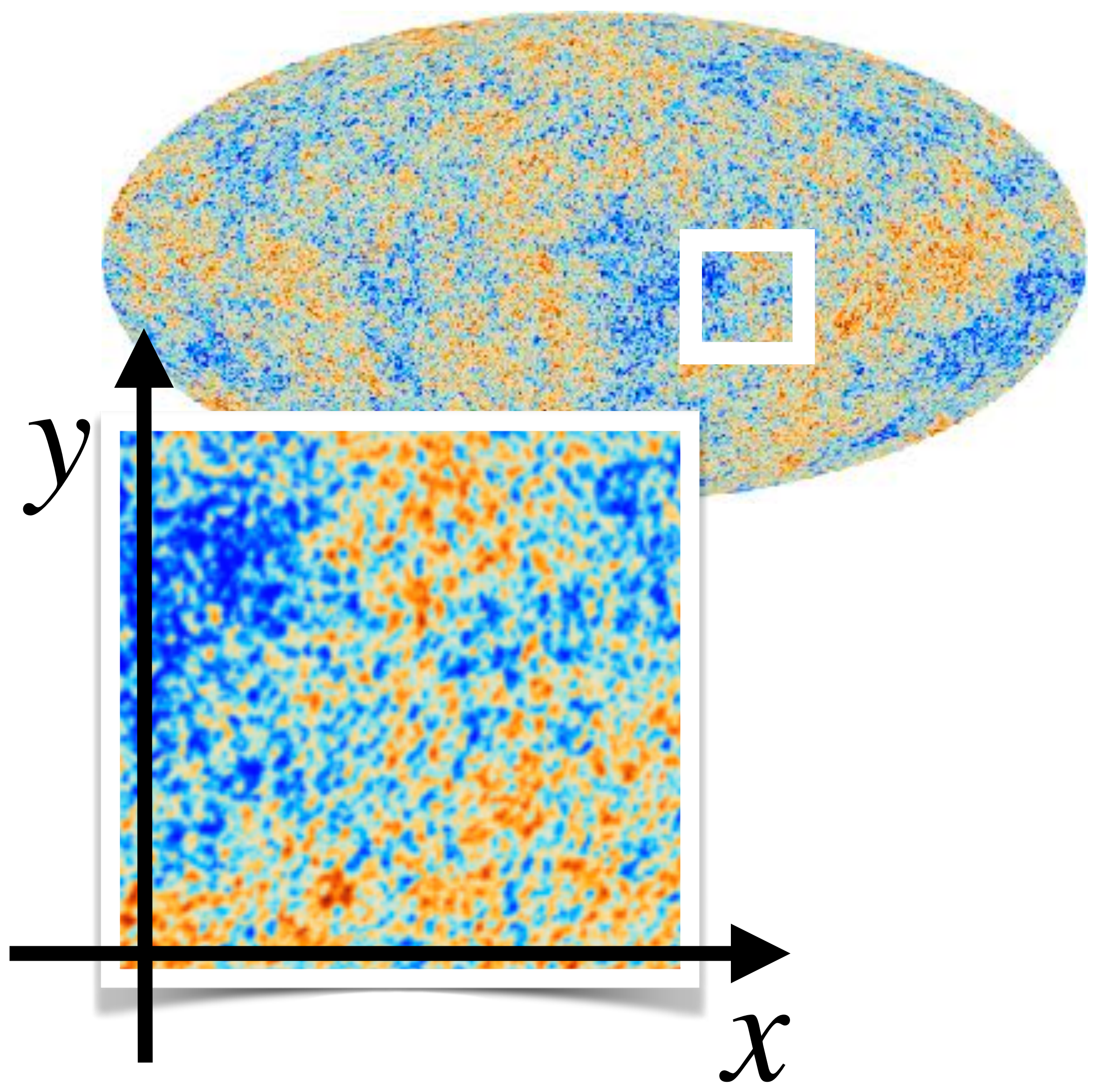

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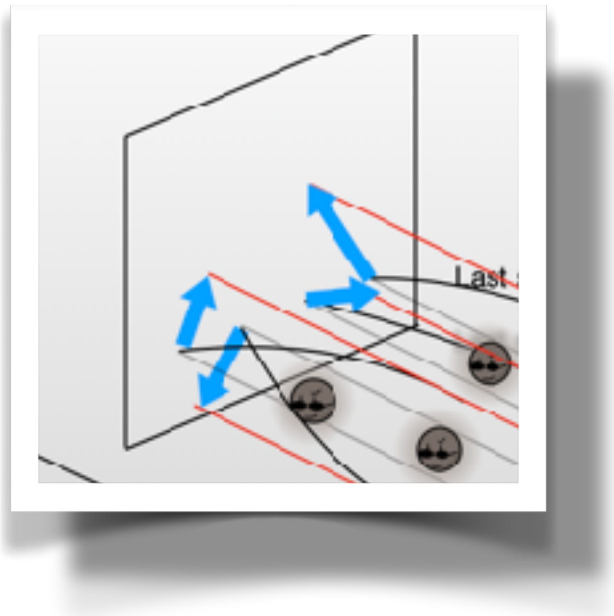

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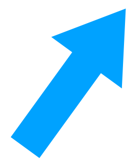
$$= (x,y) \ +$$ 
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Auto correlation

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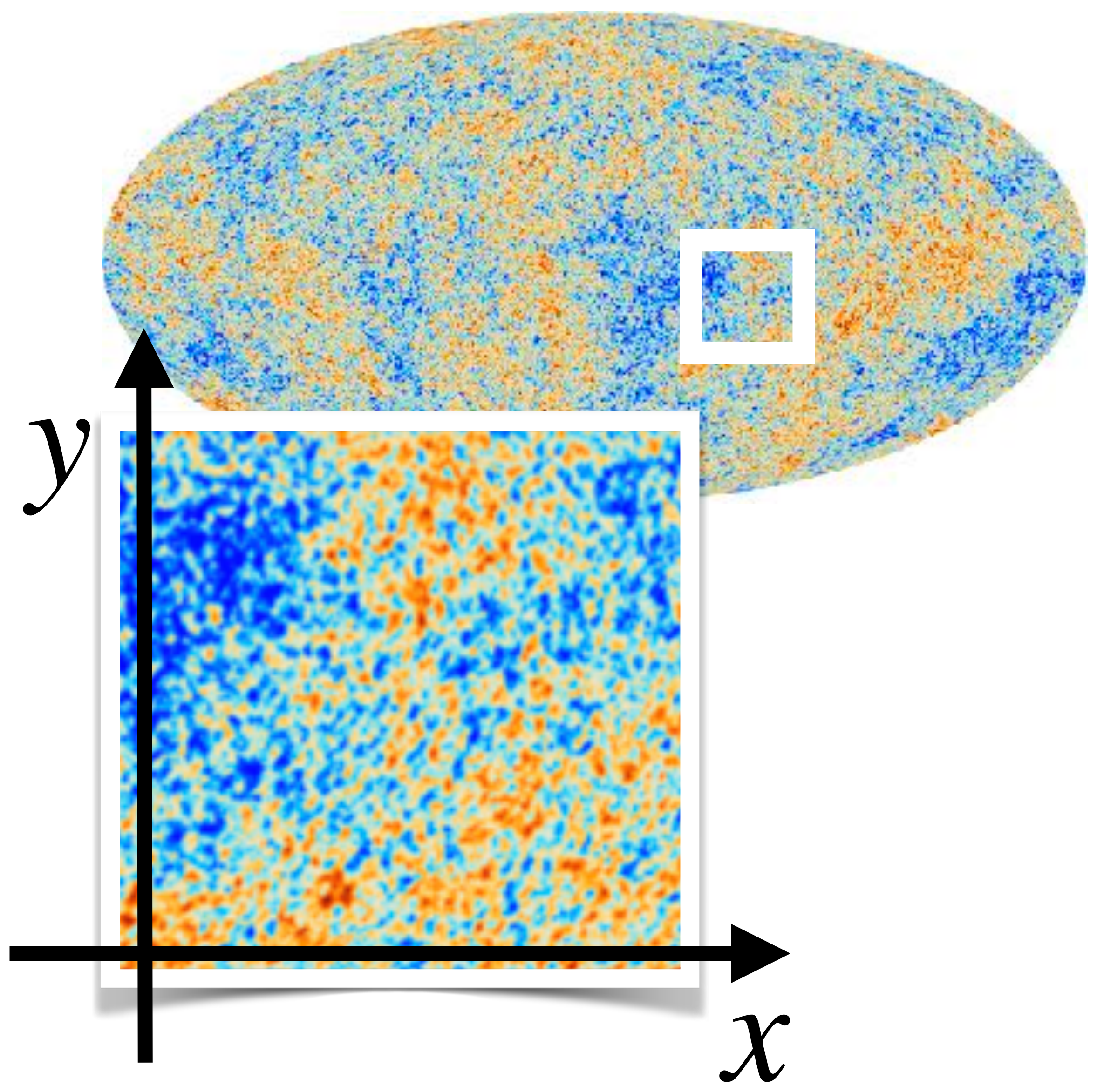

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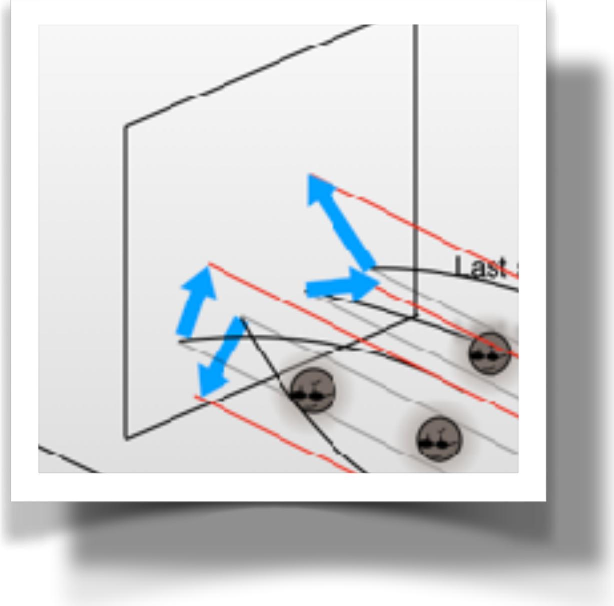

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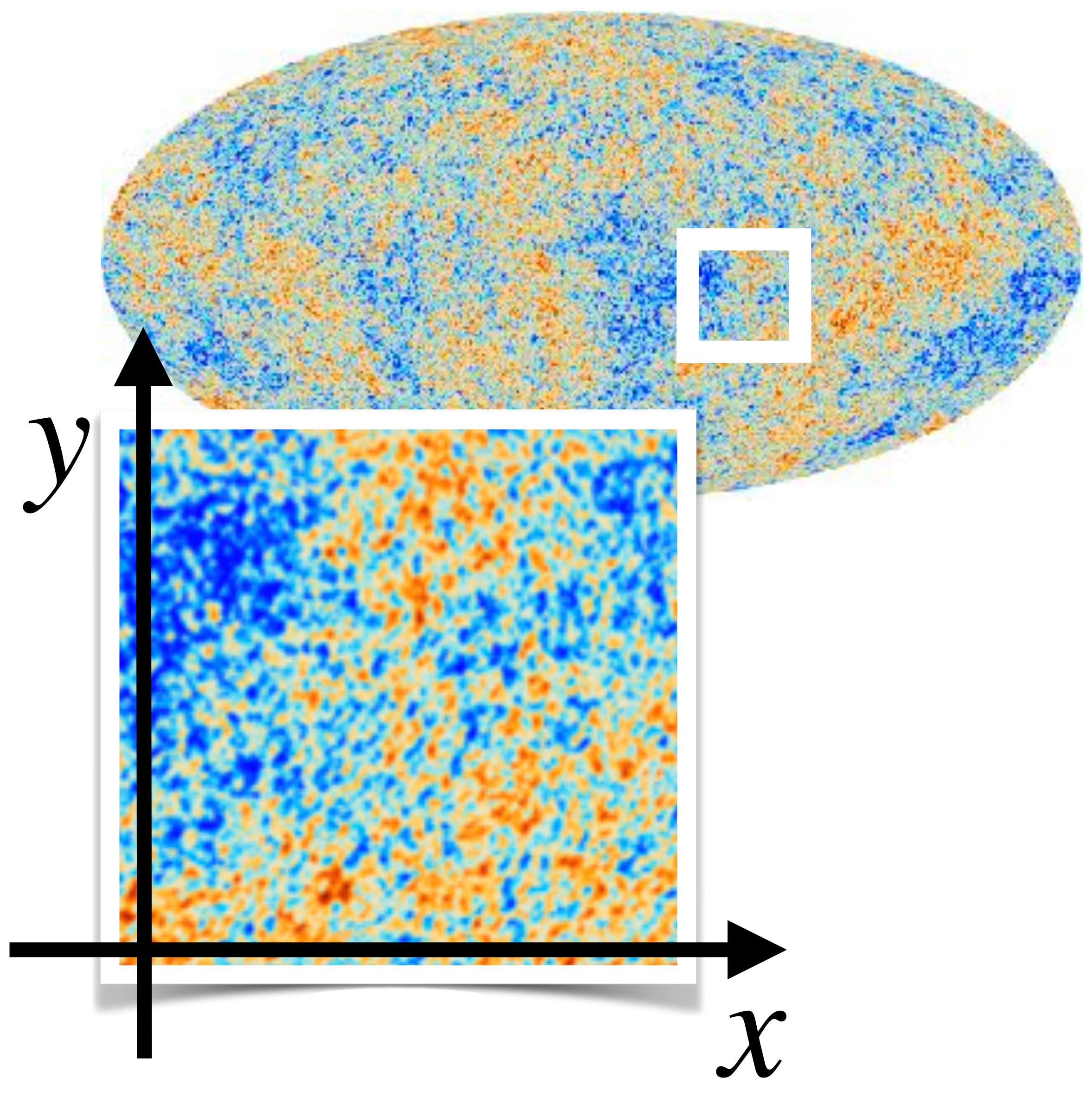

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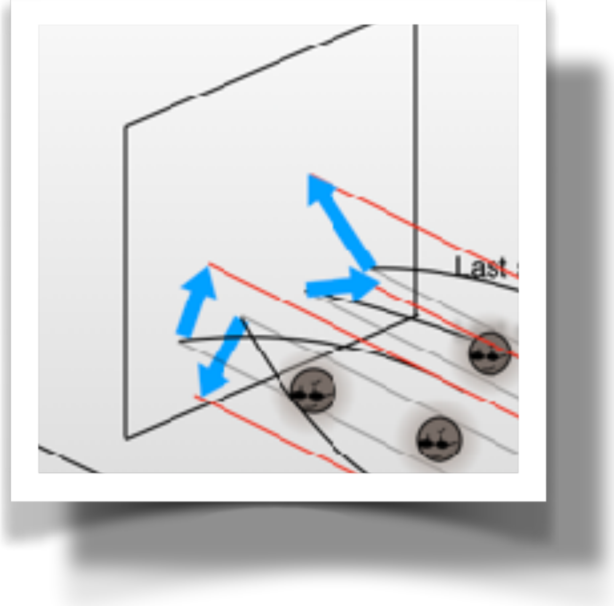

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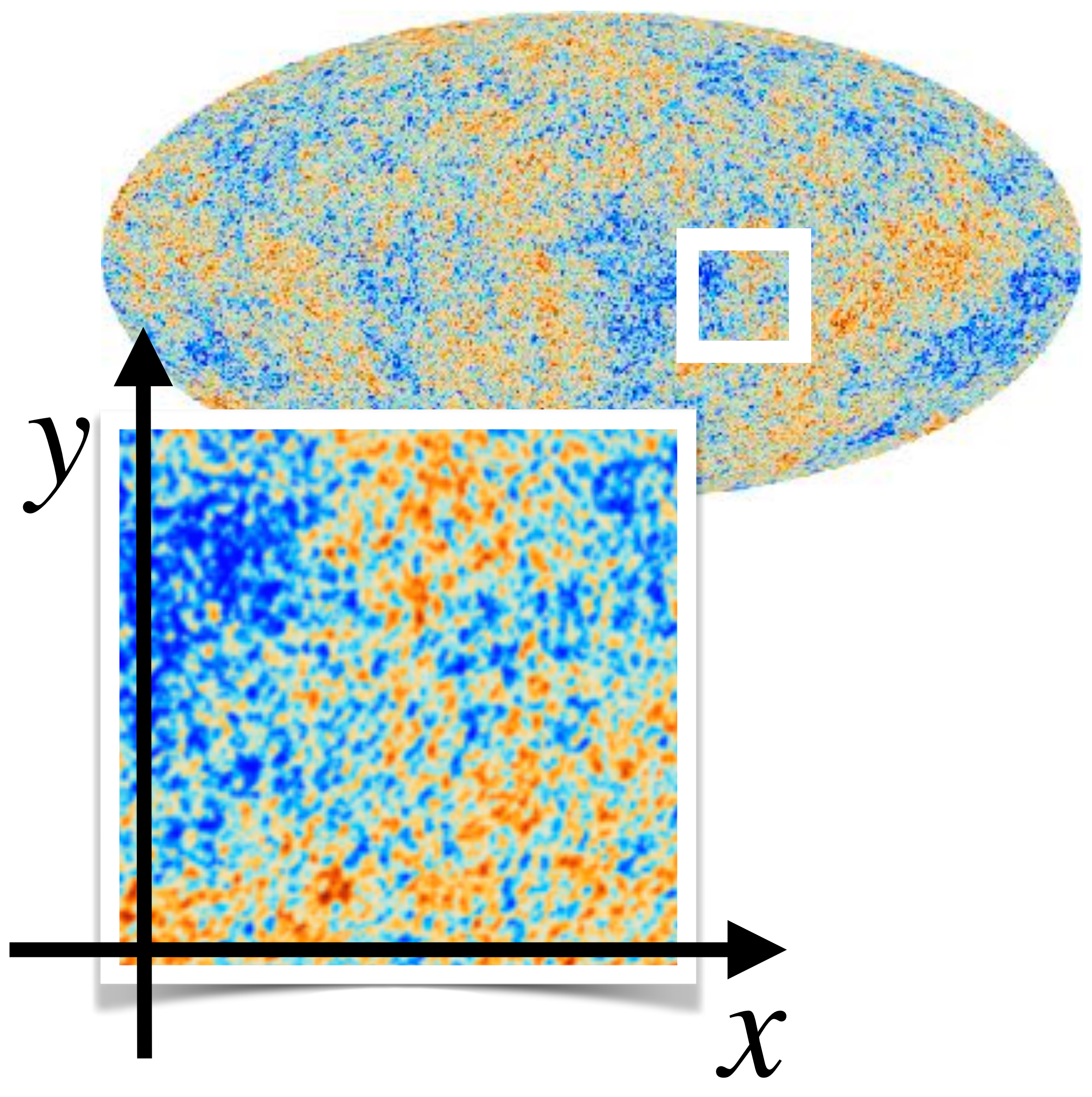

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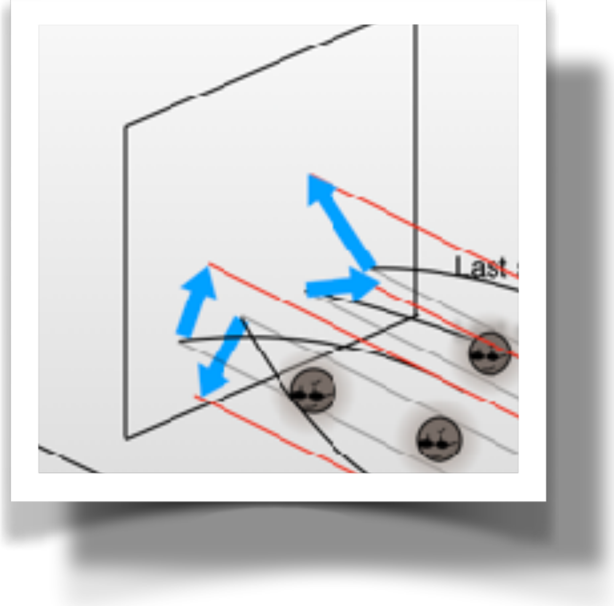

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Fourier

Lensed Power spectrum

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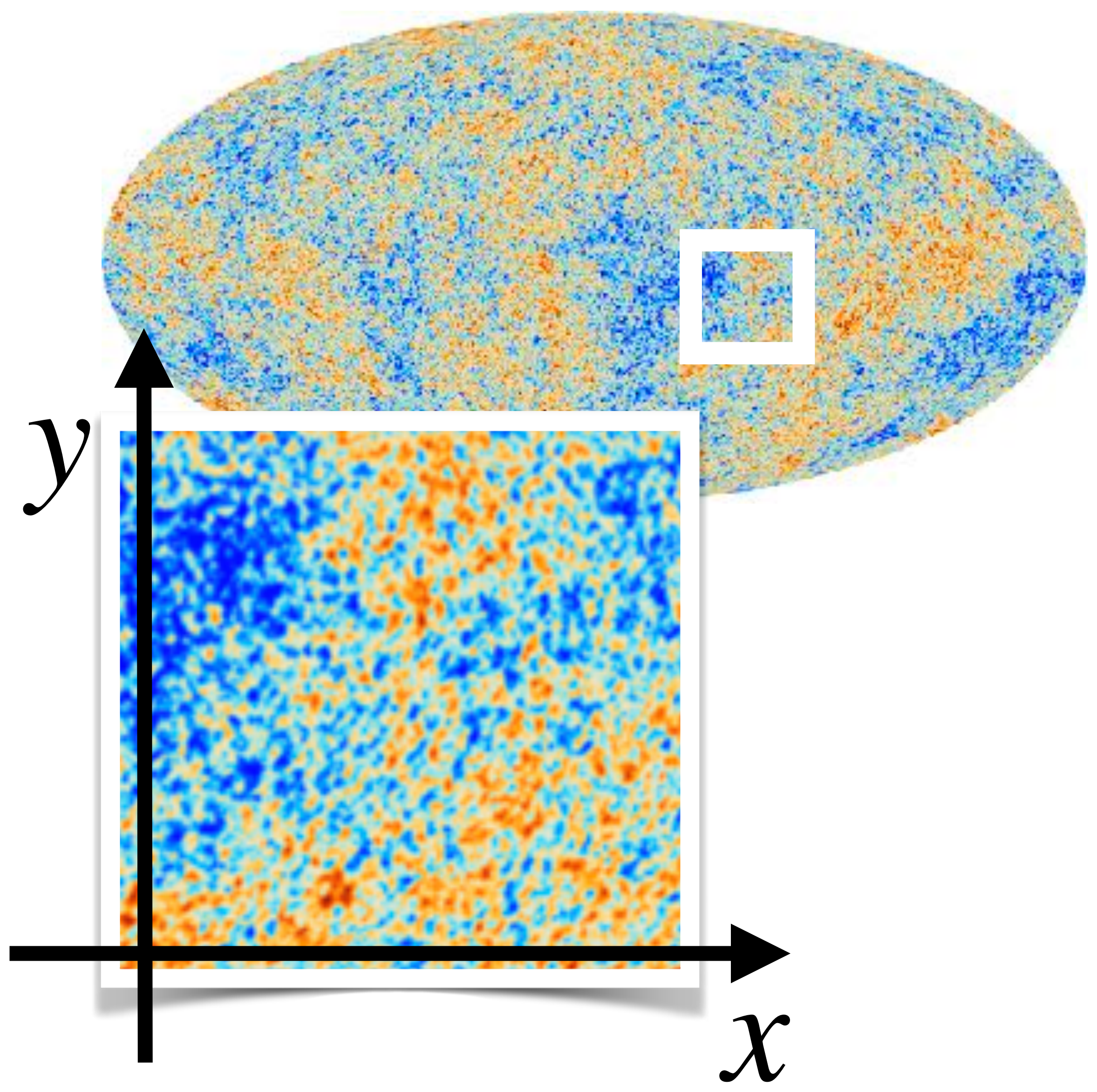

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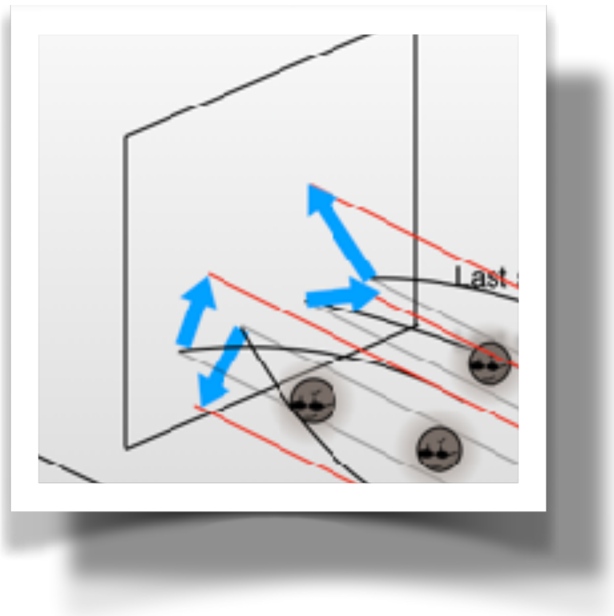

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$$\tilde{C}_l^{\Theta\Theta} \simeq \int d^2\beta \; \tilde{\xi}(\beta) \exp\left(i\mathbf{l} \cdot \beta\right)$$

$$\simeq \frac{1}{\sqrt{2}} \int_0^\infty \frac{dl'}{\sqrt{2\pi\epsilon l'}} \sqrt{l'} C_{l'}^{\Theta\Theta} \exp\left[-\frac{(l - l')^2}{2(\epsilon l')^2} \right]$$

ϵ is a constant << 1

Weak gravitational lensing : lensing correction of TB & EB

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$$C_l^{EE},\quad C_l^{BB},\quad C_l^{EB},\quad C_l^{\Theta E},\quad C_l^{\Theta B}$$

Weak gravitational lensing : lensing correction of TB & EB

$$\tilde{C}_l^{EE}, \quad \tilde{C}_l^{BB}, \quad \tilde{C}_l^{EB}, \quad \tilde{C}_l^{\Theta E}, \quad \tilde{C}_l^{\Theta B} \quad \longleftarrow \quad C_l^{EE}, \quad C_l^{BB}, \quad C_l^{EB}, \quad C_l^{\Theta E}, \quad C_l^{\Theta B}$$

$$\tilde{C}_l^{EE}, \quad \tilde{C}_l^{BB}, \quad \tilde{C}_l^{EB}, \quad \tilde{C}_l^{\Theta E}, \quad \tilde{C}_l^{\Theta B} \longleftarrow C_l^{EE}, \quad C_l^{BB}, \quad C_l^{EB}, \quad C_l^{\Theta E}, \quad C_l^{\Theta B}$$

$$\tilde{C}_l^{EE} + \tilde{C}_l^{BB} = 2\pi \int_{-1}^{1} d(\cos\beta) \int \frac{l'dl'}{2\pi} \left(C_{l'}^{EE} + C_{l'}^{BB}\right) A_+$$

$$\tilde{C}_l^{EE} - \tilde{C}_l^{BB} + i\tilde{C}_l^{\Theta B} = 2\pi \int_{-1}^{1} d(\cos\beta) \int \frac{l'dl'}{2\pi} \left(C_{l'}^{EE} - C_{l'}^{BB} + iC_{l'}^{\Theta B}\right) A_-$$

$$\tilde{C}_l^{\Theta E} + i\tilde{C}_l^{\Theta B} = -2\pi \int_{-1}^{1} d(\cos\beta) \int \frac{l'dl'}{2\pi} \left(C_{l'}^{\Theta E} + iC_{l'}^{\Theta B}\right) A_X$$

$A_+, \quad A_-, \quad A_X$: lensing factor

$\tilde{C}_l^{EE},\ \tilde{C}_l^{BB},\ \tilde{C}_l^{EB},\ \tilde{C}_l^{\Theta E},\ \tilde{C}_l^{\Theta B}$ ← $C_l^{EE},\ C_l^{BB},\ C_l^{EB},\ C_l^{\Theta E},\ C_l^{\Theta B}$

$$\underbrace{\tilde{C}_l^{EE} + \tilde{C}_l^{BB}}_{\text{lensed}} = 2\pi \int_{-1}^{1} d(\cos\beta) \int \frac{l'dl'}{2\pi} \underbrace{(C_{l'}^{EE} + C_{l'}^{BB})}_{\text{unlensed}} A_+$$

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$A_+,\ A_-,\ A_X$: lensing factor

$\tilde{C}_l^{EE}, \quad \tilde{C}_l^{BB}, \quad \tilde{C}_l^{EB}, \quad \tilde{C}_l^{\Theta E}, \quad \tilde{C}_l^{\Theta B} \quad \longleftarrow \quad C_l^{EE}, \quad C_l^{BB}, \quad C_l^{EB}, \quad C_l^{\Theta E}, \quad C_l^{\Theta B}$

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$A_+, \quad A_-, \quad A_X$: lensing factor

$$\tilde{C}_l^{EE},\quad \tilde{C}_l^{BB},\quad \tilde{C}_l^{EB},\quad \tilde{C}_l^{\Theta E},\quad \tilde{C}_l^{\Theta B} \longleftarrow C_l^{EE},\quad C_l^{BB},\quad C_l^{EB},\quad C_l^{\Theta E},\quad C_l^{\Theta B}$$

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$A_+,\ A_-,\ A_X$: lensing factor

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lensed — unlensed

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lensed — unlensed

Parity even

$C_l^{EE}, \quad C_l^{BB}, \quad C_l^{\Theta E}$

→ real part

Parity odd

$C_l^{EB}, \quad C_l^{\Theta B}$

→ imaginary part

$A_+, \quad A_-, \quad A_X$: lensing factor

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$\tilde{C}_l^{EE}, \tilde{C}_l^{BB}, \tilde{C}_l^{EB}, \tilde{C}_l^{\Theta E}, \tilde{C}_l^{\Theta B}$ ← $C_l^{EE}, C_l^{BB}, C_l^{EB}, C_l^{\Theta E}, C_l^{\Theta B}$

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$$\underbrace{\tilde{C}_l^{\Theta E}}_{\text{lensed}} = -2\pi \int_{-1}^{1} d(\cos\beta) \int \frac{l'dl'}{2\pi} \underbrace{(C_{l'}^{\Theta E})}_{\text{unlensed}} A_X$$

$$\tilde{C}_l^{EB} = 2\pi \int_{-1}^{1} d(\cos\beta) \int \frac{l'dl'}{2\pi} C_{l'}^{EB} A_-$$

$$\tilde{C}_l^{\Theta B} = 2\pi \int_{-1}^{1} d(\cos\beta) \int \frac{l'dl'}{2\pi} C_{l'}^{\Theta B} A_X$$

Parity even

$C_l^{EE}, \ C_l^{BB}, \ C_l^{\Theta E}$

→ real part

Parity odd

$C_l^{EB}, \ C_l^{\Theta B}$

→ imaginary part

$A_+, \ A_-, \ A_X$: lensing factor

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$\tilde{C}_l^{EE}, \tilde{C}_l^{BB}, \tilde{C}_l^{EB}, \tilde{C}_l^{\Theta E}, \tilde{C}_l^{\Theta B} \longleftarrow C_l^{EE}, C_l^{BB}, C_l^{EB}, C_l^{\Theta E}, C_l^{\Theta B}$

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$$\underbrace{\tilde{C}_l^{EB}}_{\text{lensed}} = 2\pi \int_{-1}^{1} d(\cos\beta) \int \frac{l'dl'}{2\pi} \underbrace{C_{l'}^{EB}}_{\text{unlensed}} A_-$$

$$\underbrace{\tilde{C}_l^{\Theta B}}_{\text{lensed}} = 2\pi \int_{-1}^{1} d(\cos\beta) \int \frac{l'dl'}{2\pi} \underbrace{C_{l'}^{\Theta B}}_{\text{unlensed}} A_X$$

Parity even

$C_l^{EE}, C_l^{BB}, C_l^{\Theta E}$

→ real part

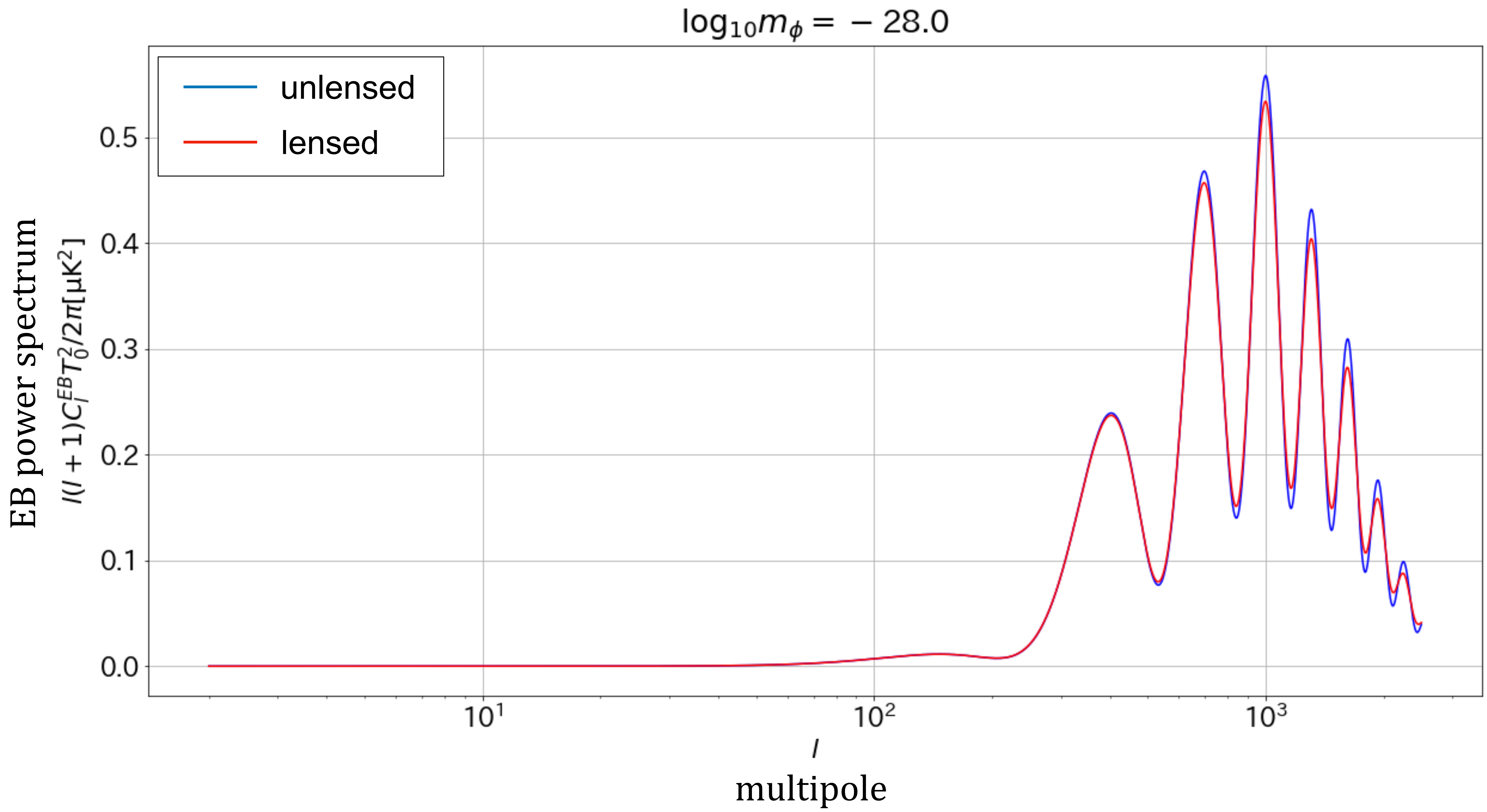
Parity odd

$C_l^{EB}, C_l^{\Theta B}$

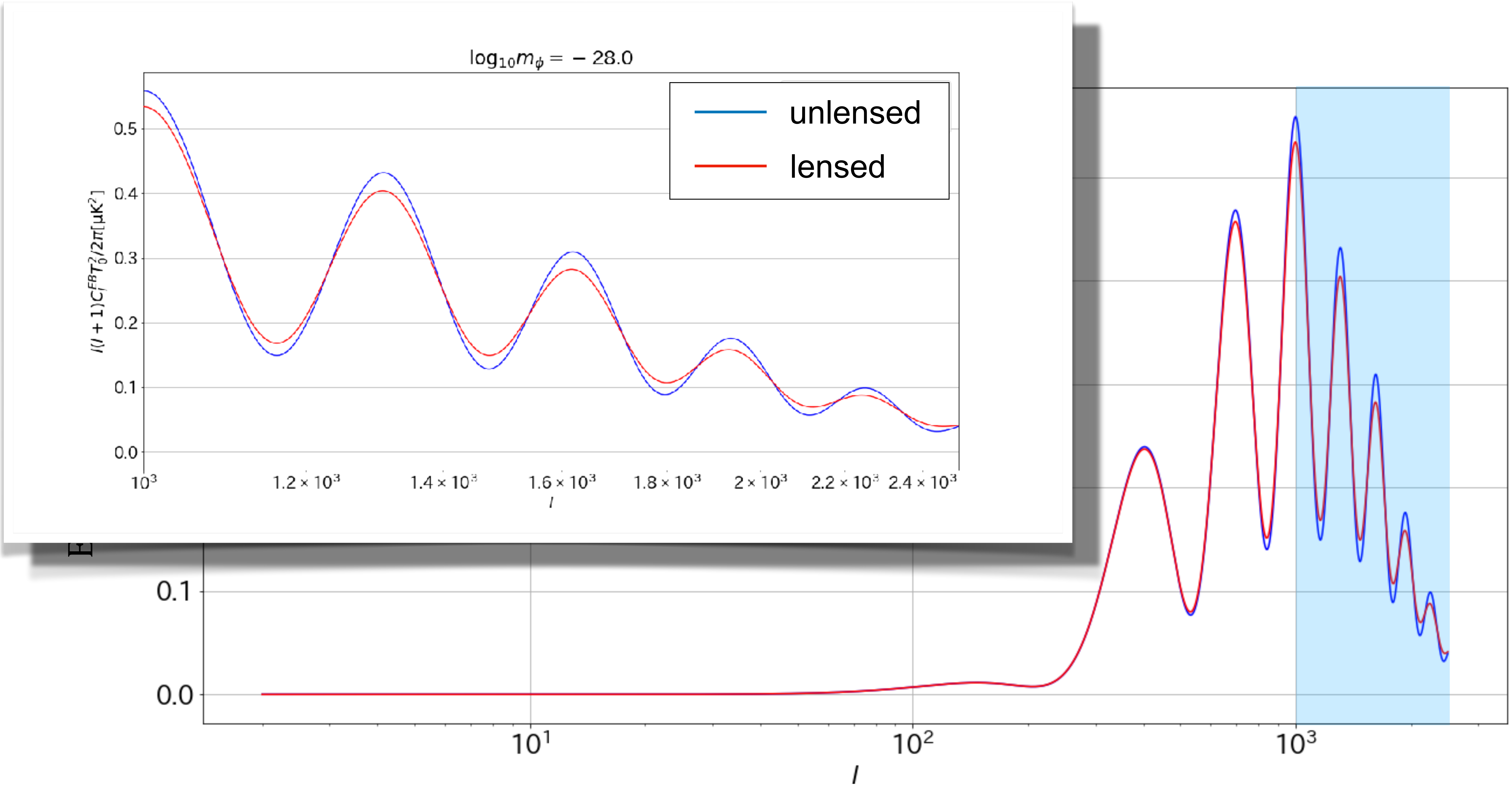
→ imaginary part

A_+, A_-, A_X : lensing factor

Results of this work : lensed EB power spectrum

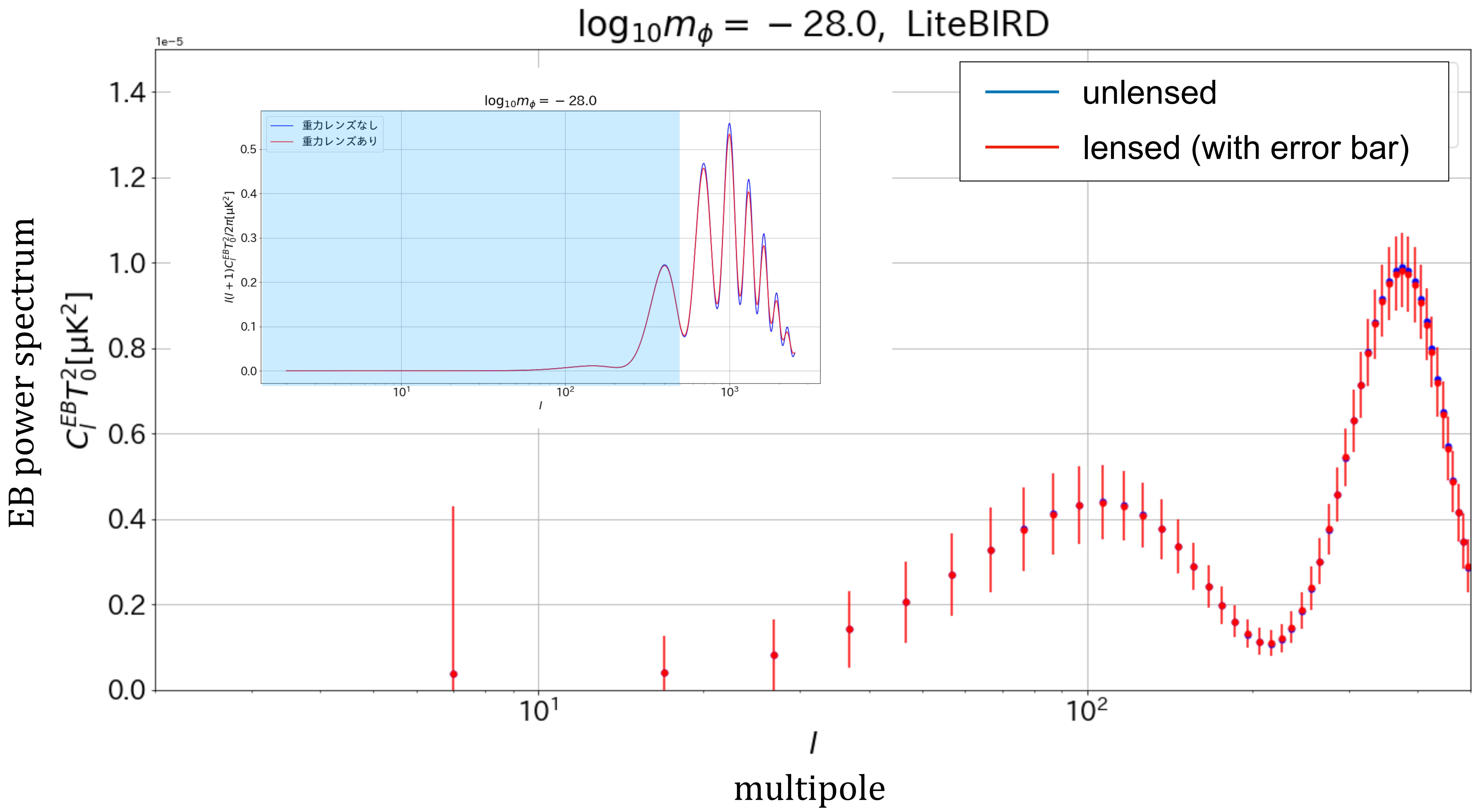


Results of this work : lensed EB power spectrum

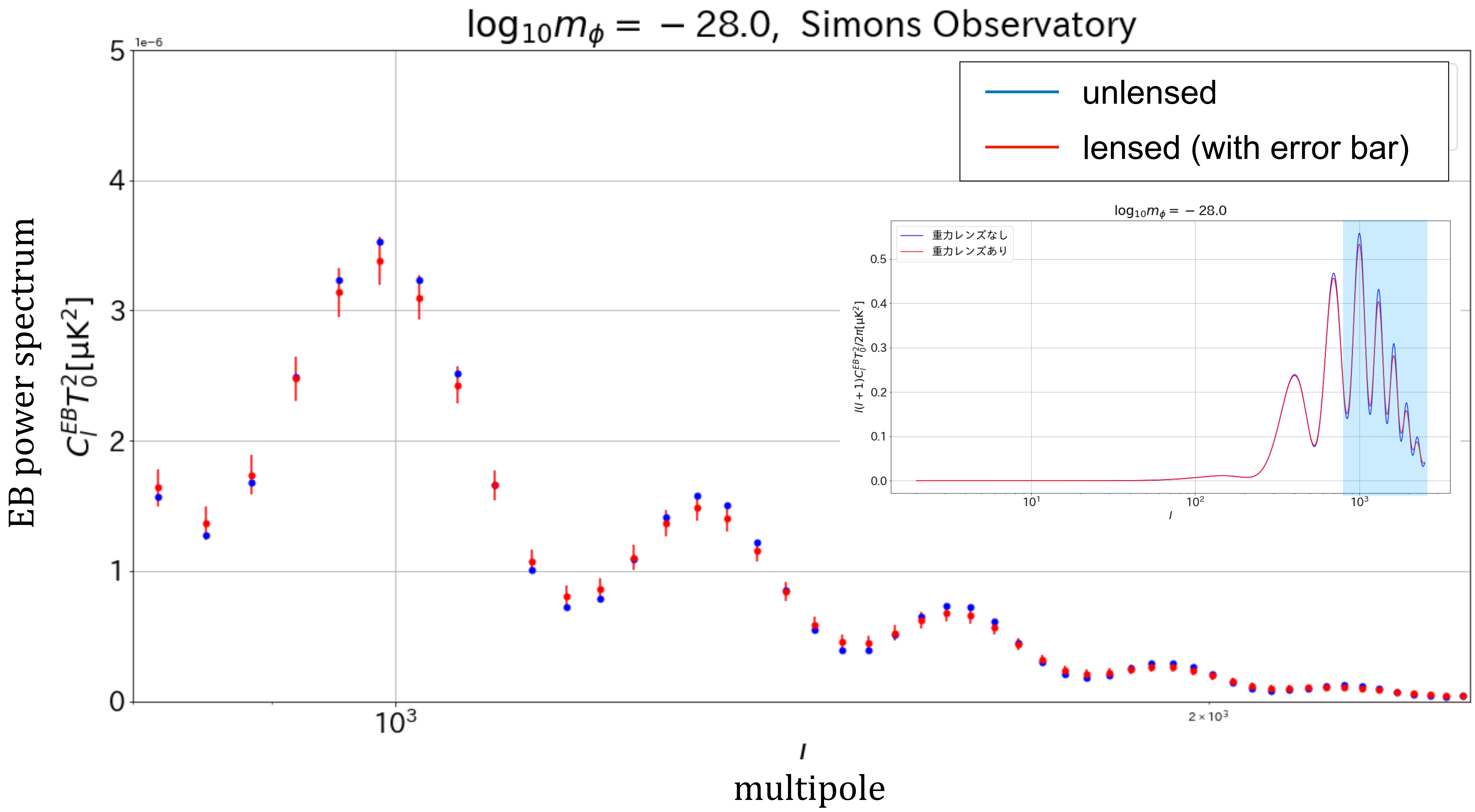


multipole

Results of this work : detectability



Results of this work : detectability



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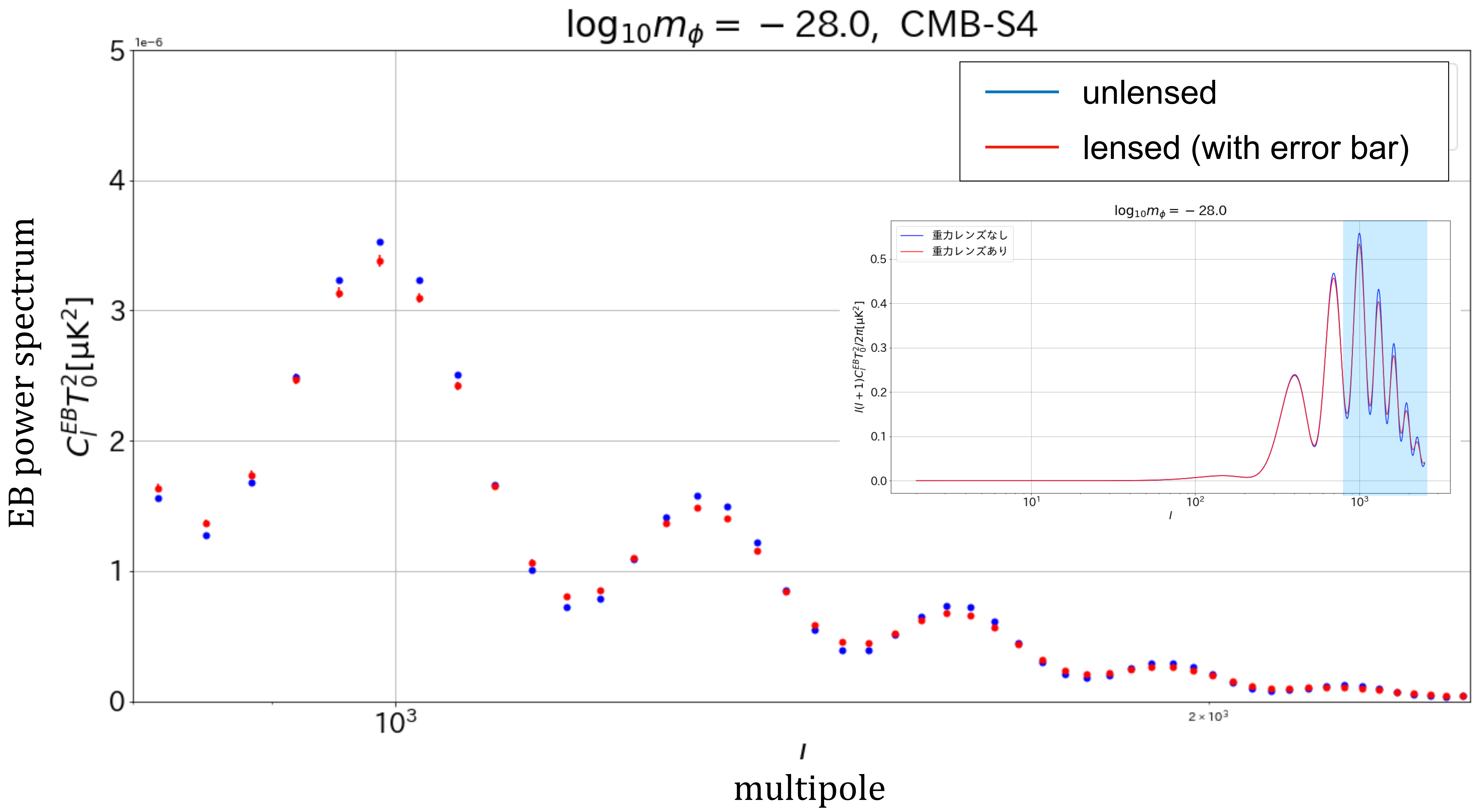
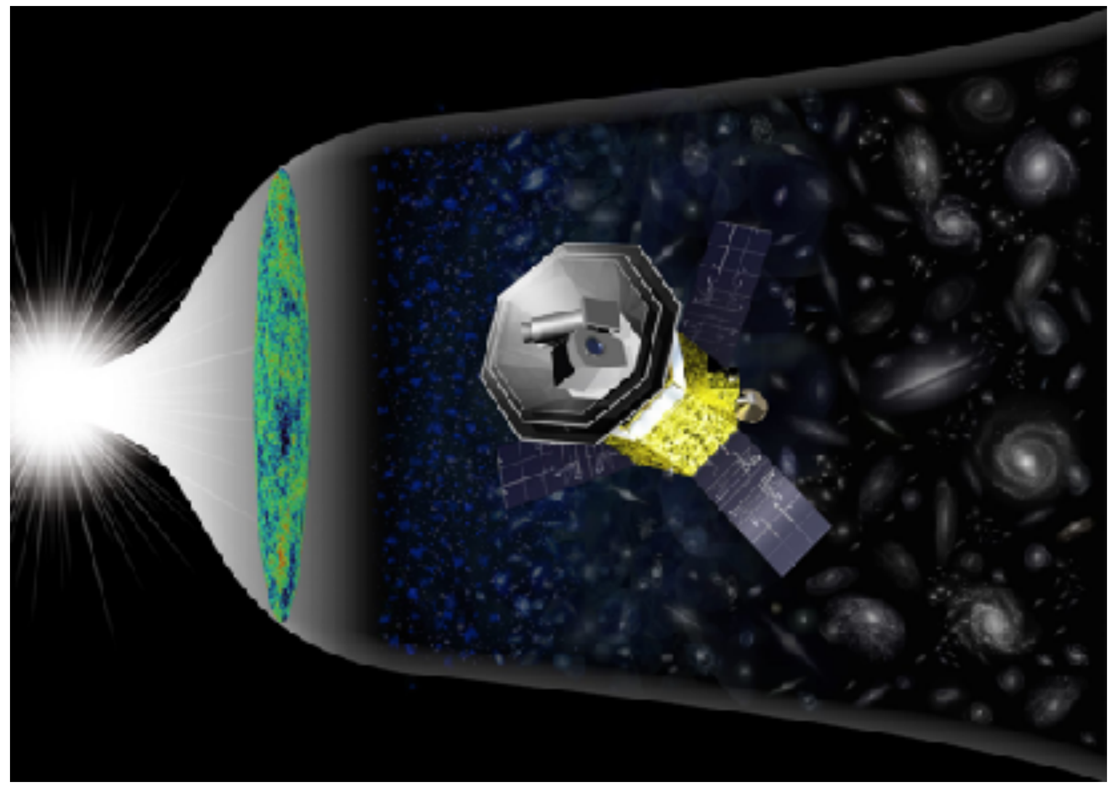


We conducted a forecast of parameters search of ALPs by Cosmic Birefringence to estimate lensing effect on it.

Mock observational C_l^{EB} with lensing

C_l^{EB} without lensing

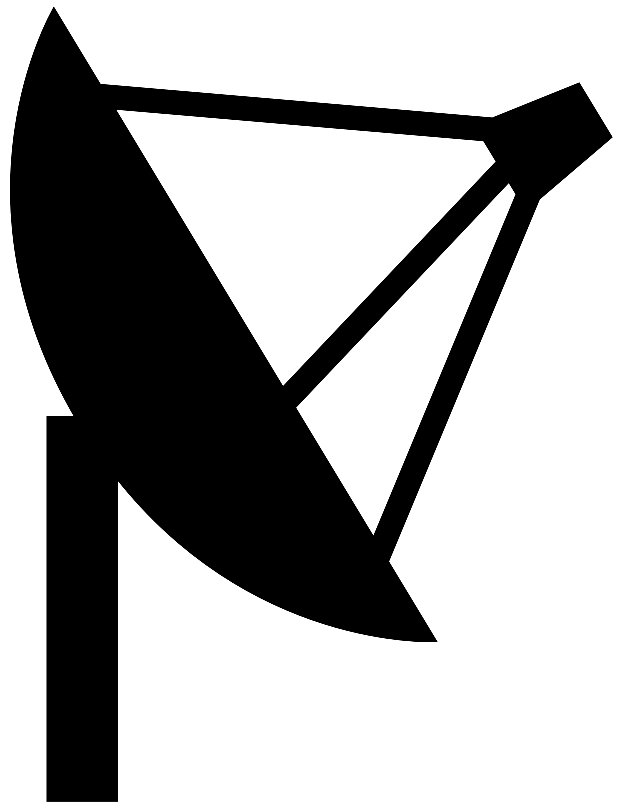
LiteBIRD

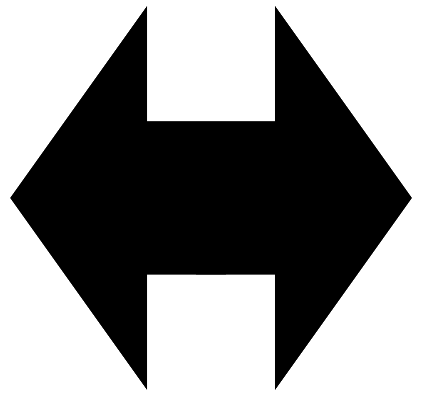


Credit：ISAS/JAXA

Simons Observatory

CMB-S4





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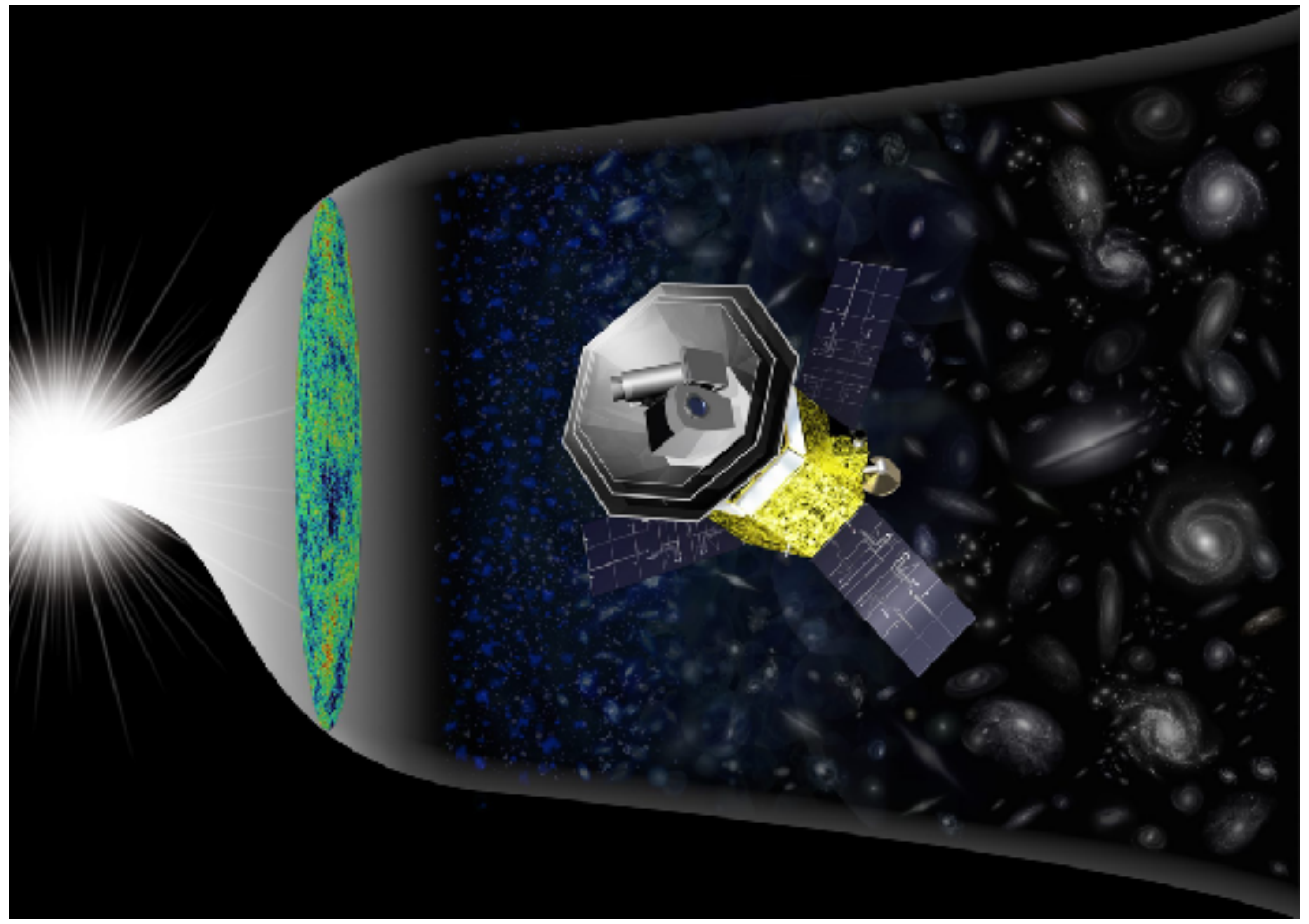
fiducial

$$\left(m_\phi, \frac{1}{2} g \phi_{\rm ini}\right) = (10^{-28}\ {\rm eV},\ 0.78)$$

2σ contour

1σ contour



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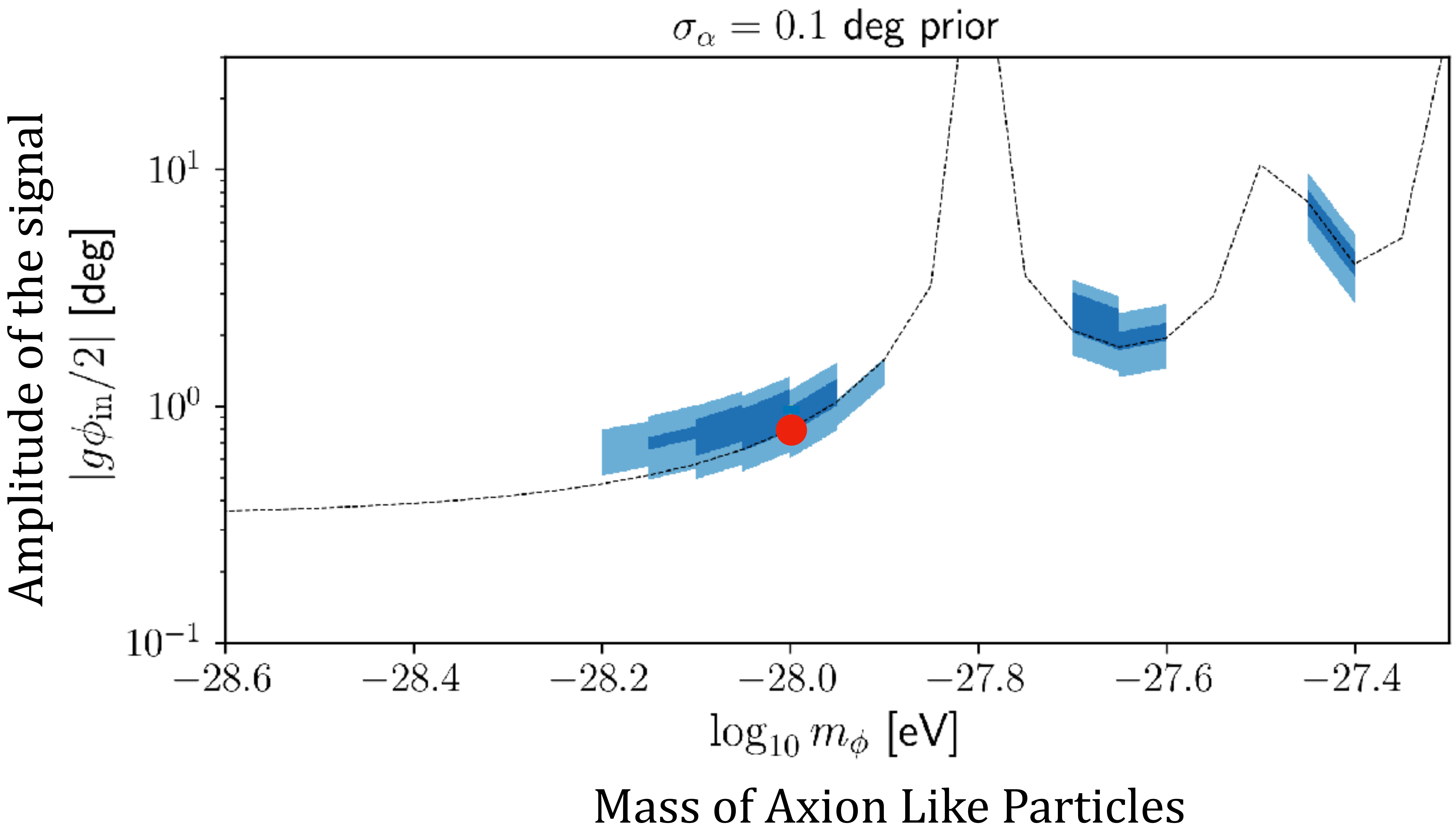

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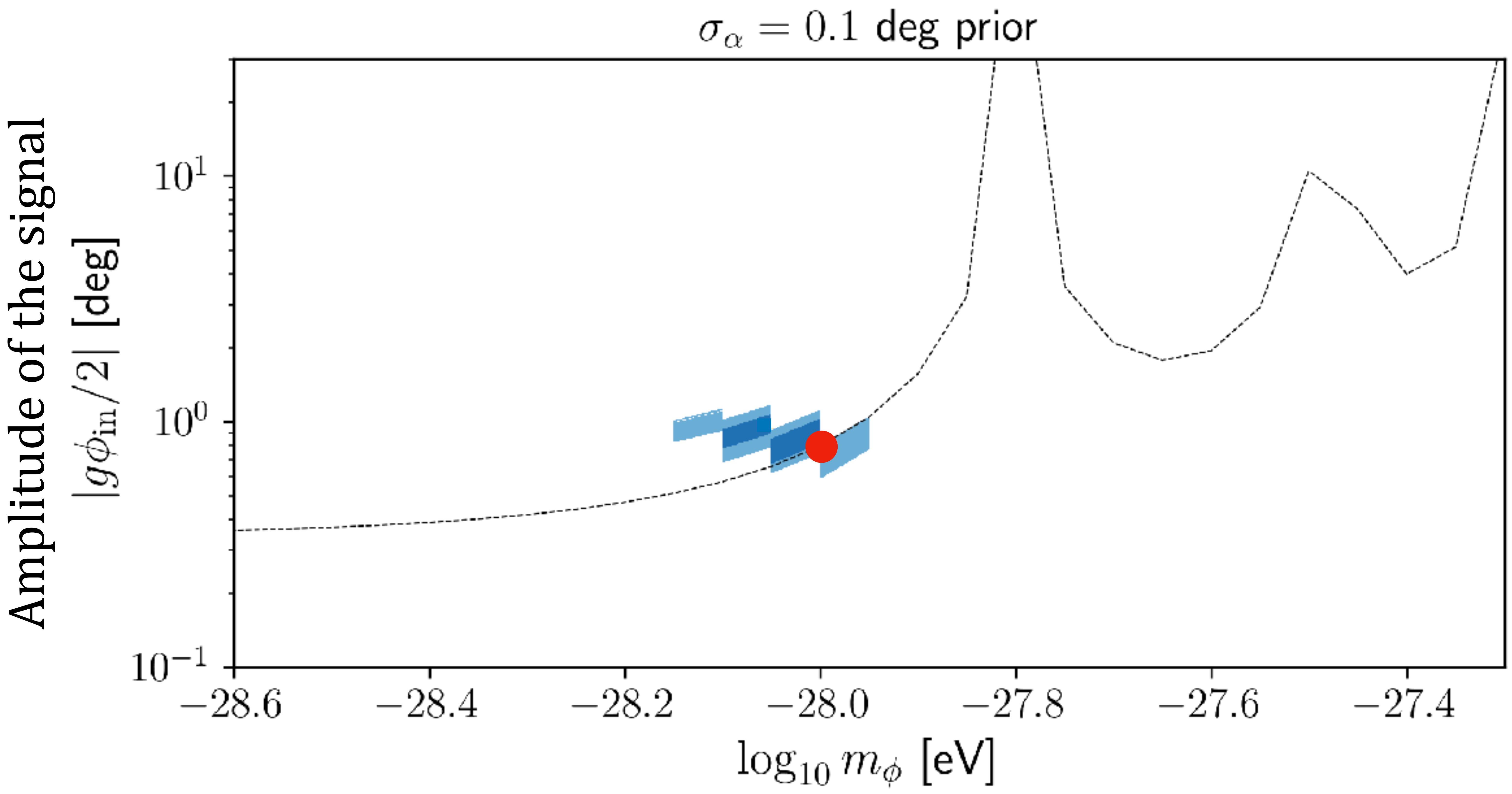

Mass of Axion Like Particles

fiducial

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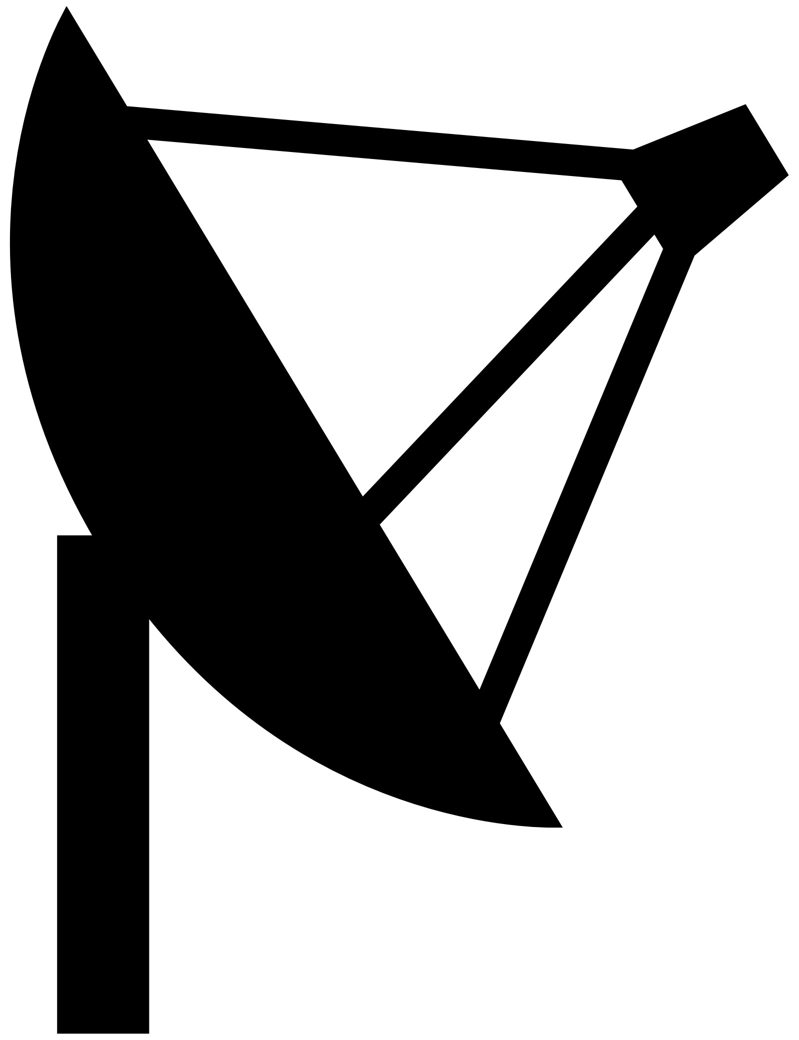
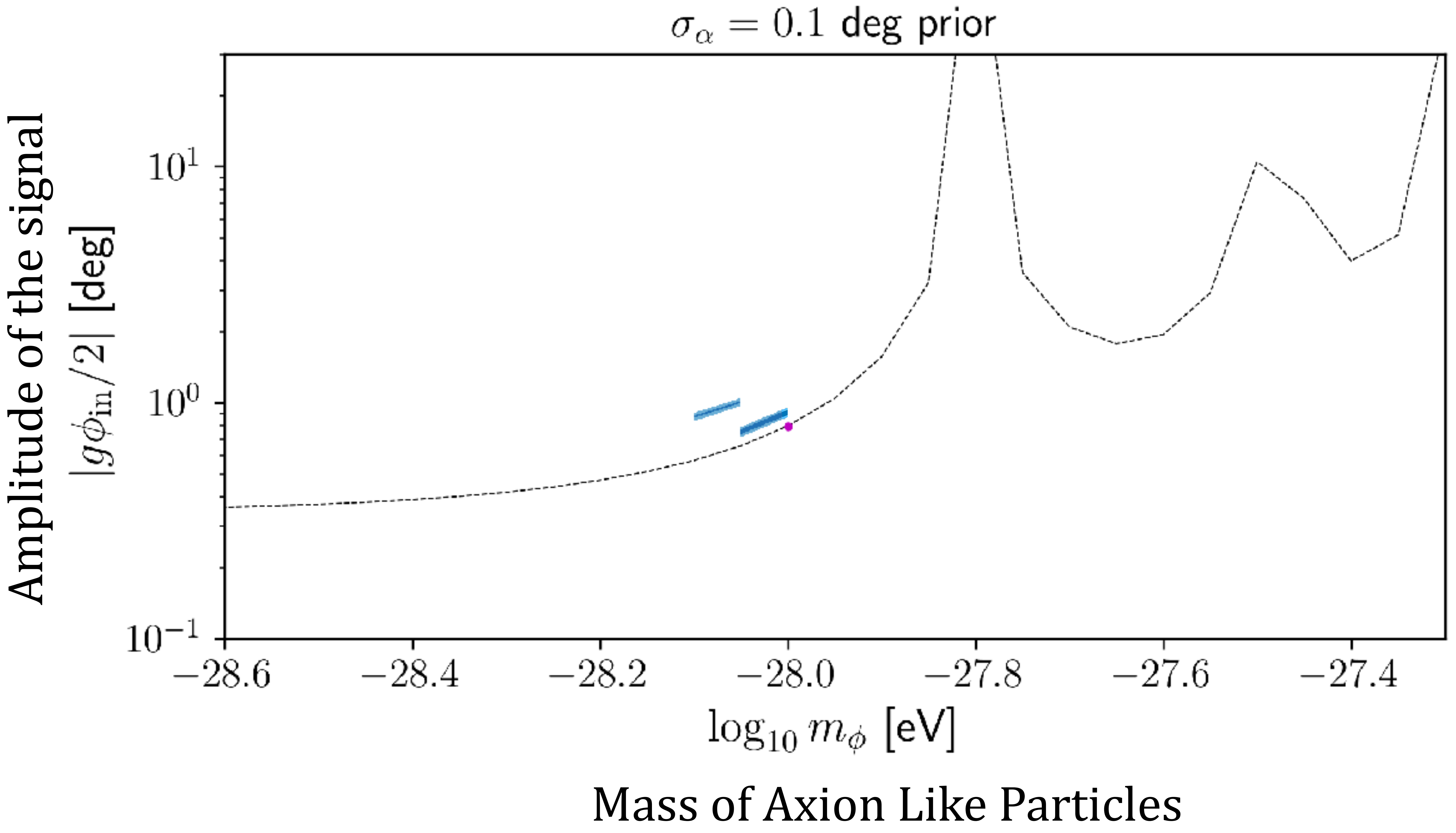
2σ contour

1σ contour



CMB - S4



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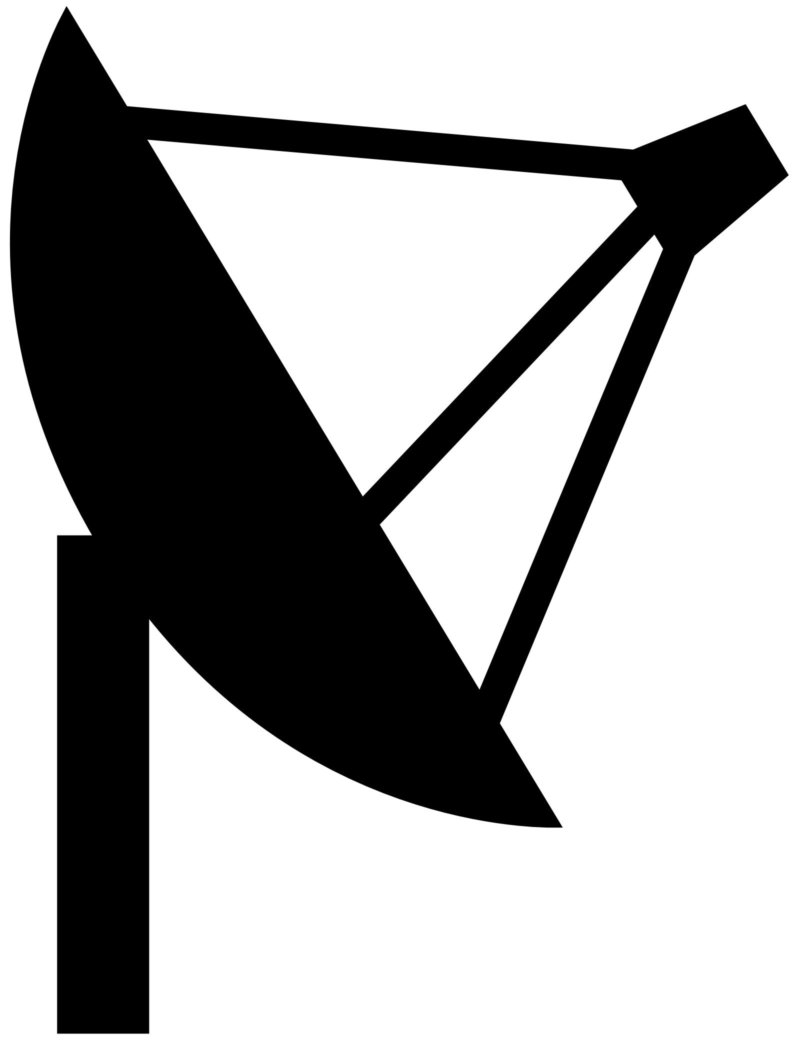
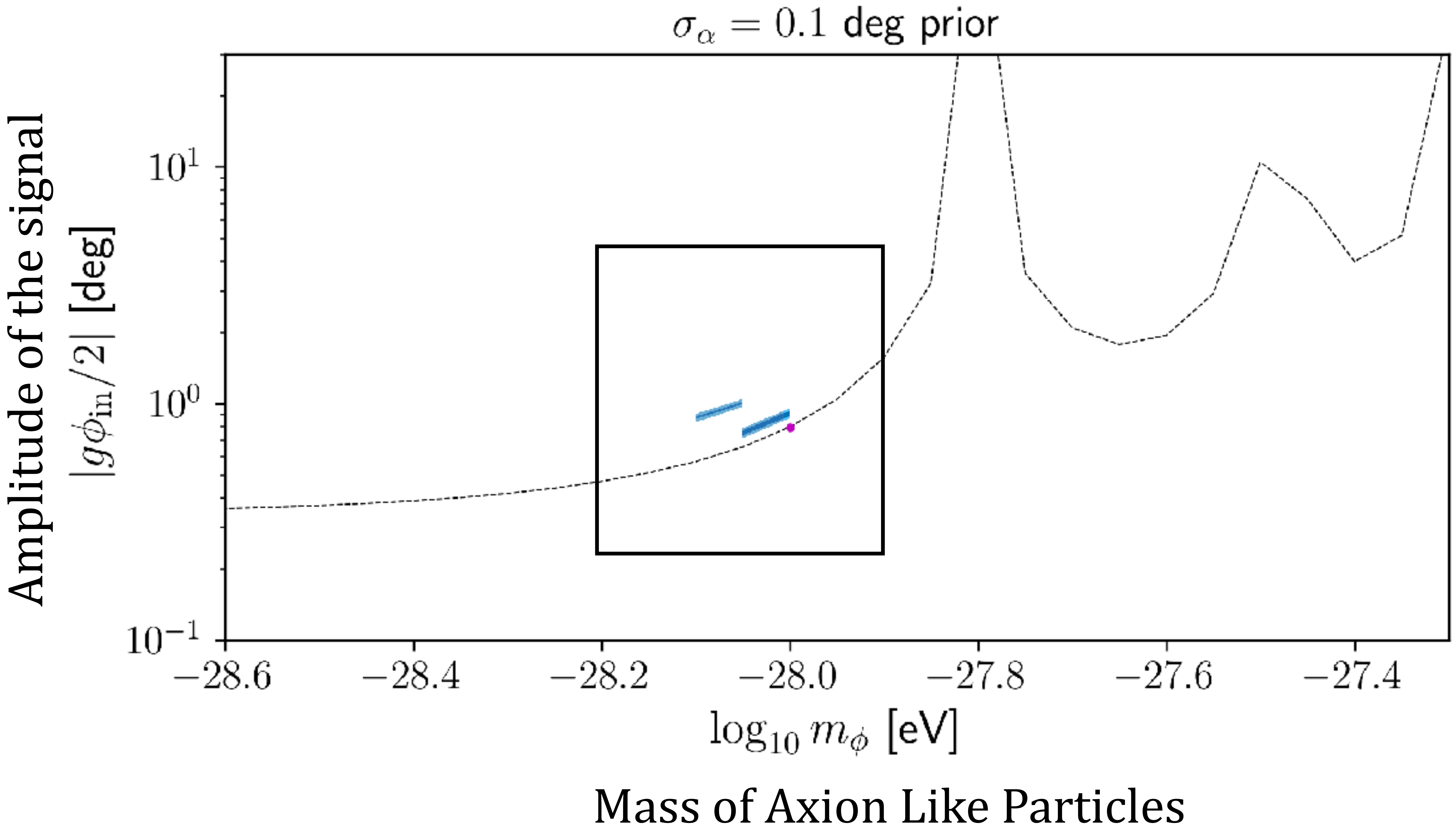


CMB - S4



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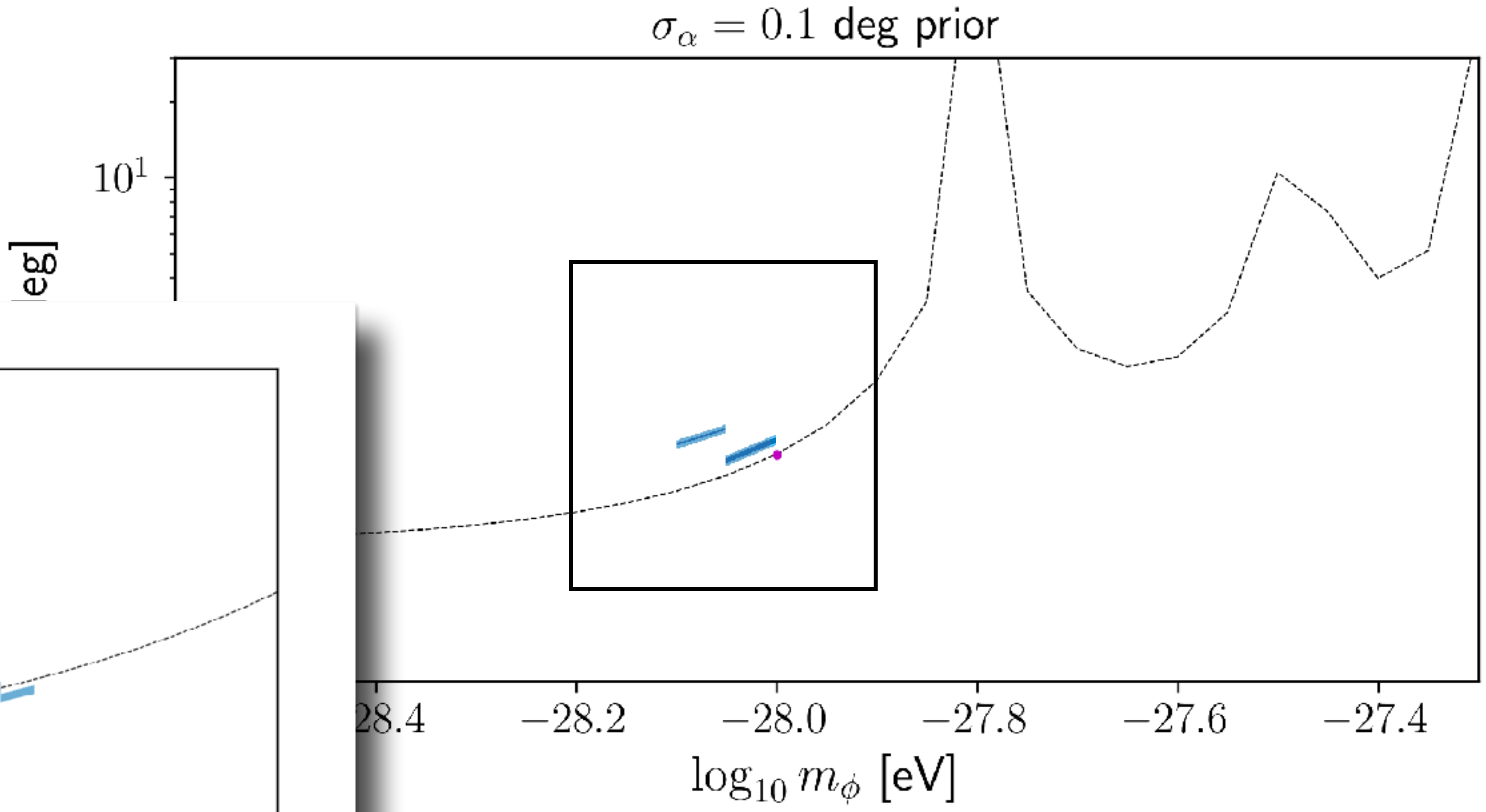

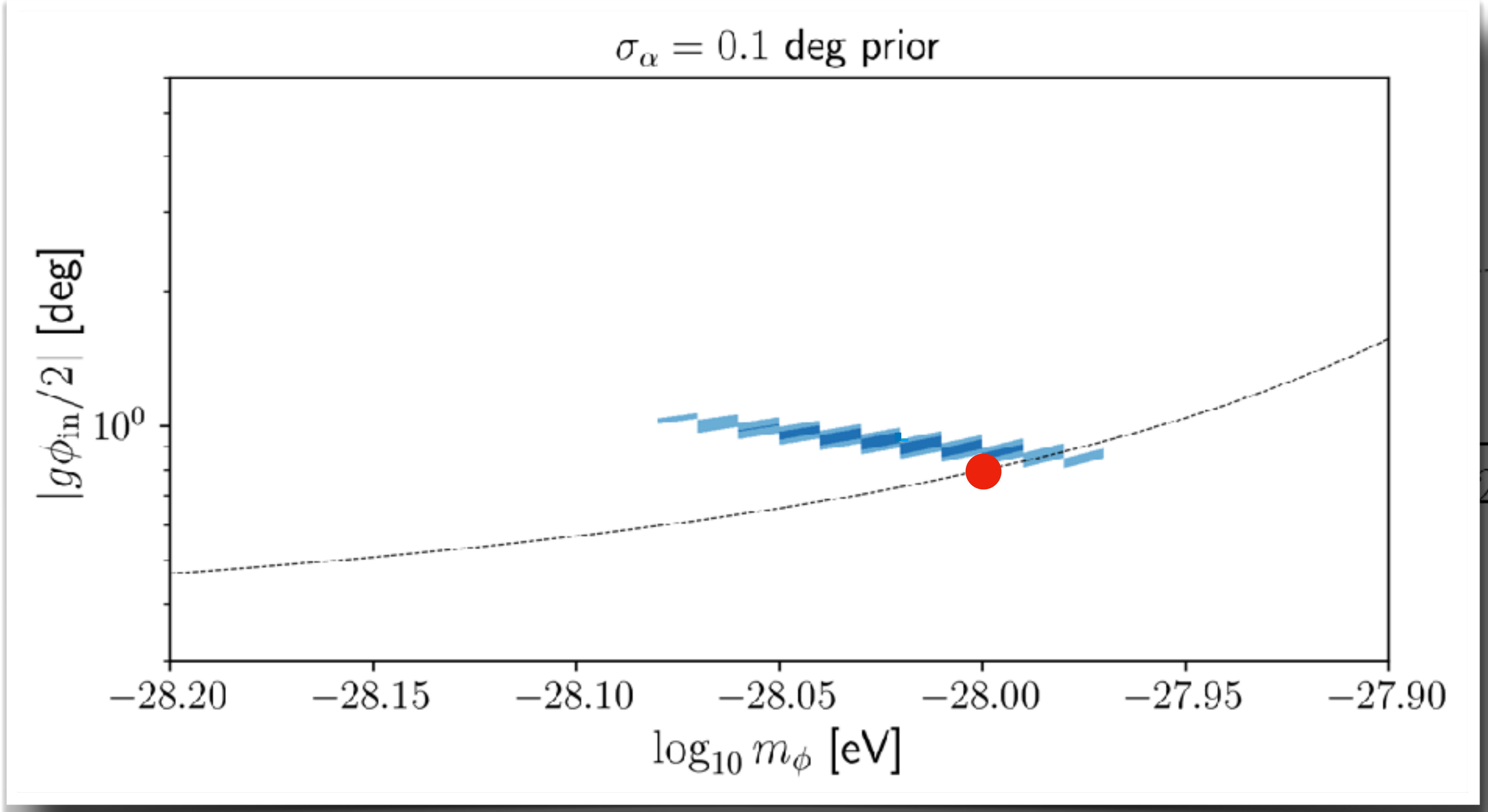

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Motivation

- We need to improve the **precision of theoretical prediction** of Cosmic Birefringence.
- **Gravitational lensing** correction should be crucial.

Method

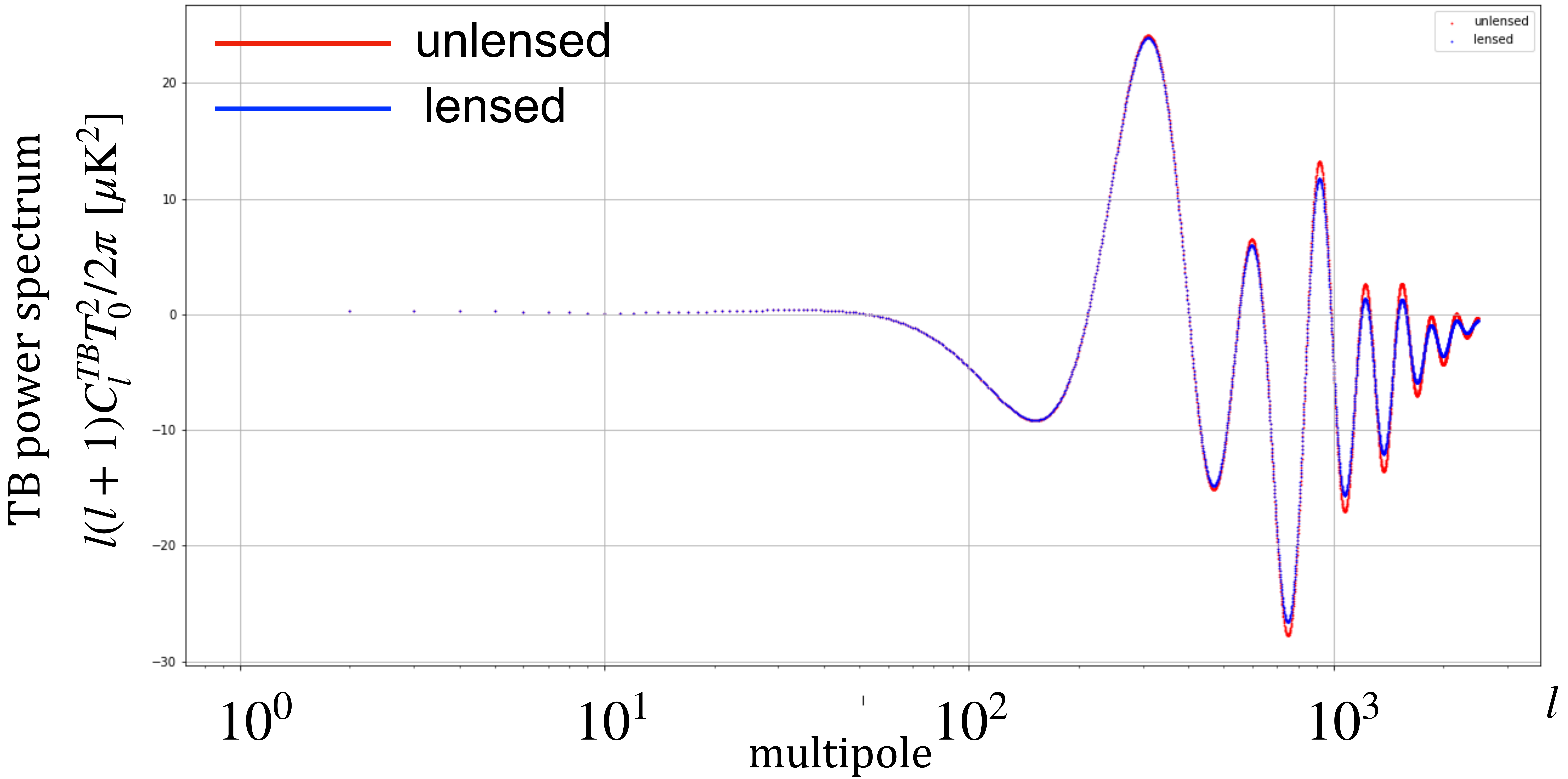
- We have developed lensing correction tool for EB & TB

Results

- Lensing effect on EB is **detectable** in the future ground-based observations.
- Estimated parameters of ALPs by Cosmic Birefringence can be **biased without lensing correction**.

Backup

Results of this work : lensed TB power spectrum



解析的な計算式：漸近的な振る舞い

例：温度ゆらぎ・Eモードパワースペクトル

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$$\tilde{C}_l^{\Theta E} = 2\pi \int_{-1}^{1} d(\cos\beta) \int \frac{l' dl'}{2\pi} C_{l'}^{\Theta E} \exp\left[-\frac{l^2}{2}\sigma_0^2(\beta)\right] J_2(l'\beta) J_2(l\beta)$$

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レンジング後

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レンジング後　　レンジング前

$\beta \ll 1$ として、$d(\cos\beta) = -\sin\beta d\beta \simeq -\beta d\beta$

$\sigma_0^2(\beta) \simeq \epsilon\beta$, $\epsilon \simeq 0.7$

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ベッセル関数の積分公式

修正ベッセル関数の漸近表現

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ベッセル関数の積分公式

修正ベッセル関数の漸近表現

↓

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ベッセル関数の積分公式

修正ベッセル関数の漸近表現

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レンジング後　　レンジング前

例：温度ゆらぎ・Eモードパワースペクトル

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レンジング後　　レンジング前

ガウシアン

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$l' = l$ が中心

l が大きい → 分散が大きい

l が小さい → 分散が小さい

による畳み込み積分

解析的な計算式：漸近的な振る舞い

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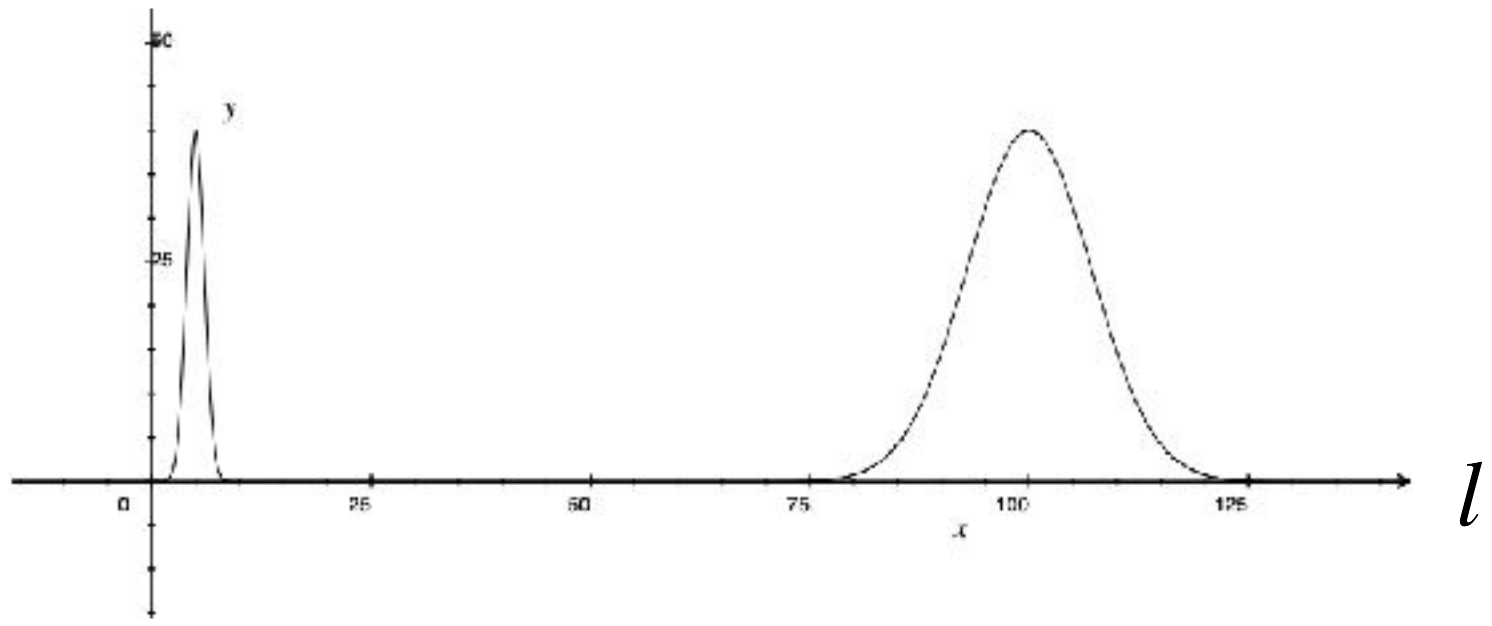

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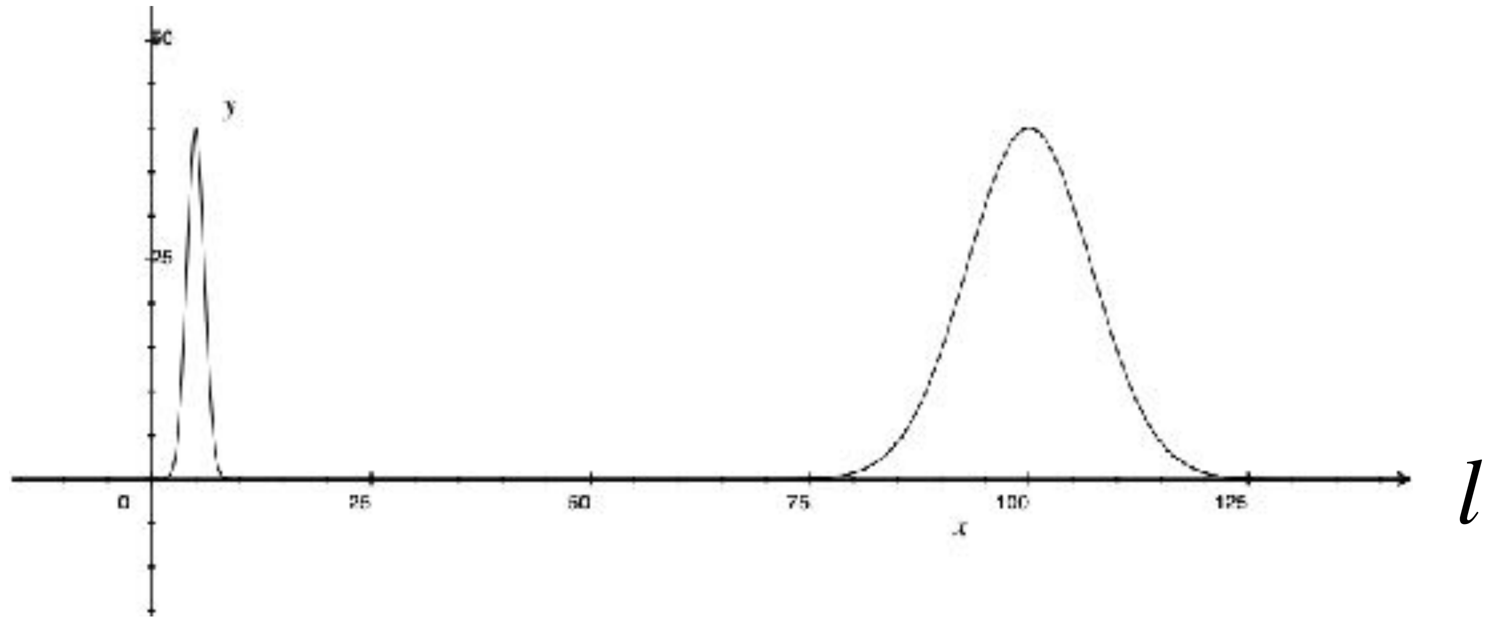

大きな l でパワースペクトルが

なまされるような効果