# PIKIMO Spring 2024

# Detecting Axion Dark Matter with Black Hole Polarimetry

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with

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2311.02149

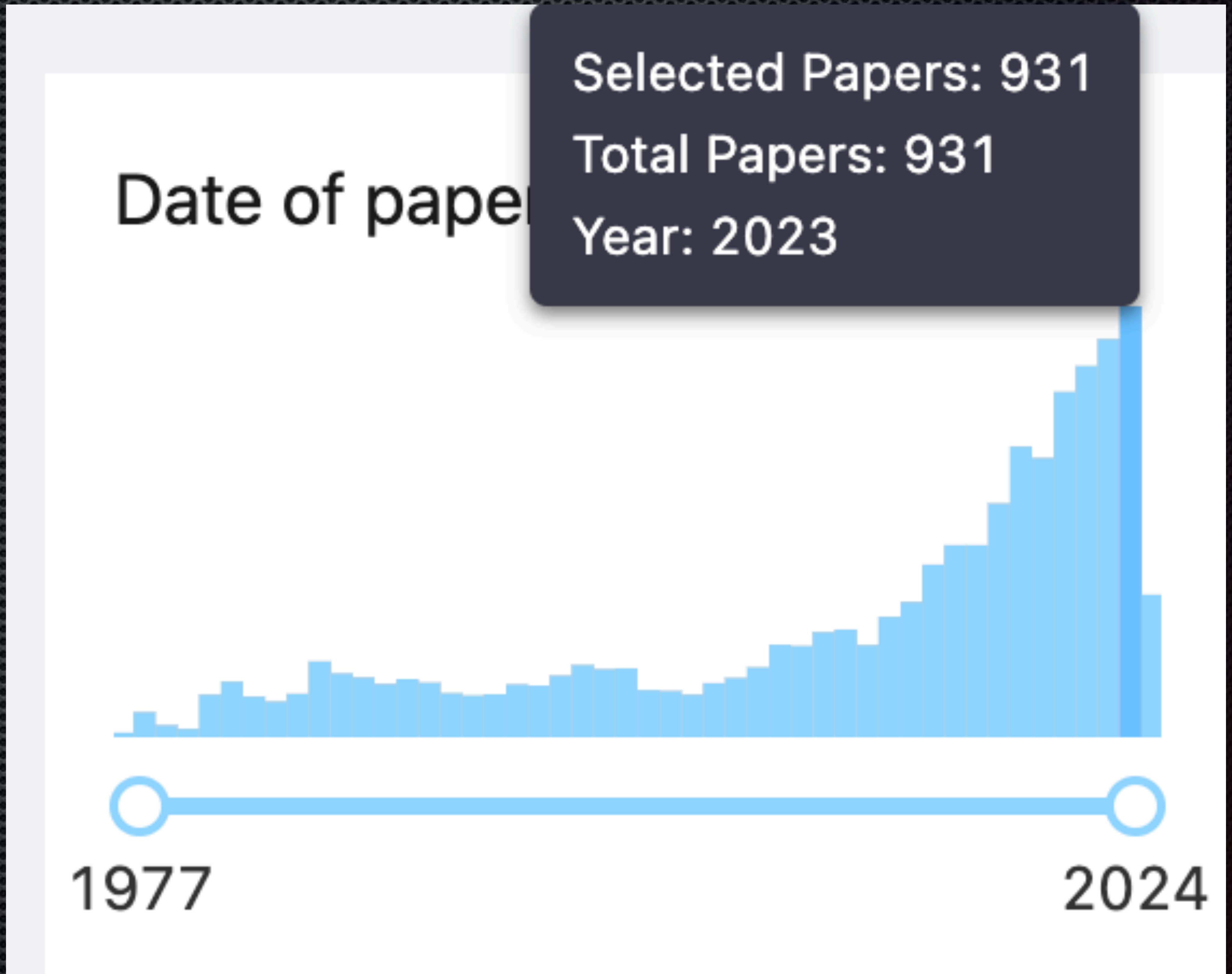
# Why Axion

Strong CP Problem

Dark Matter Candidate

Misalignment Mechanism

Rich phenomena



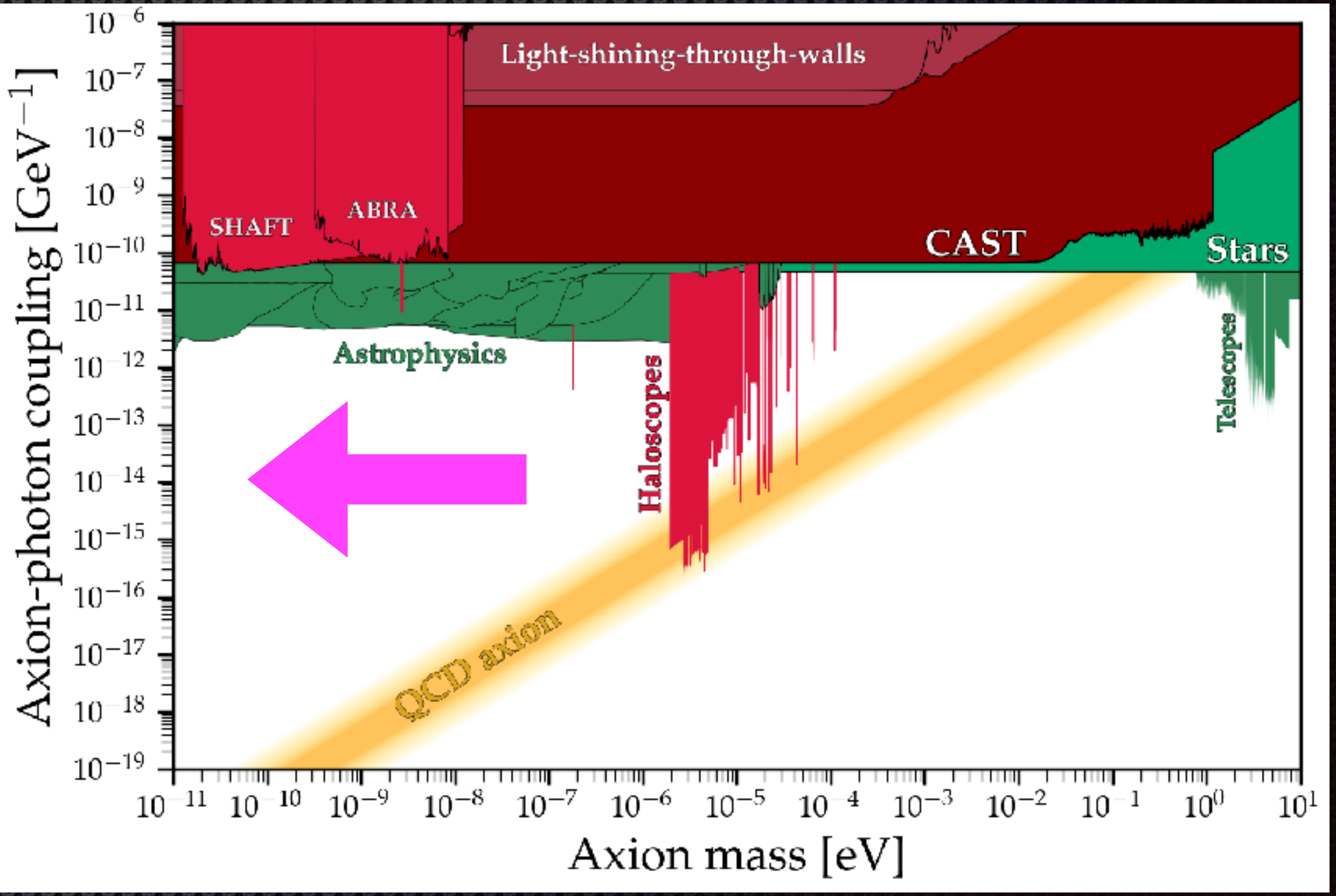
# Current Status: Axion-Photon

$$\mathscr{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F \widetilde{F}$$

Ultralight axion : $m_a \ll 10^{-10} eV$

1. Solar Telescope: CAST

2. Spectral Distortion of X-ray source



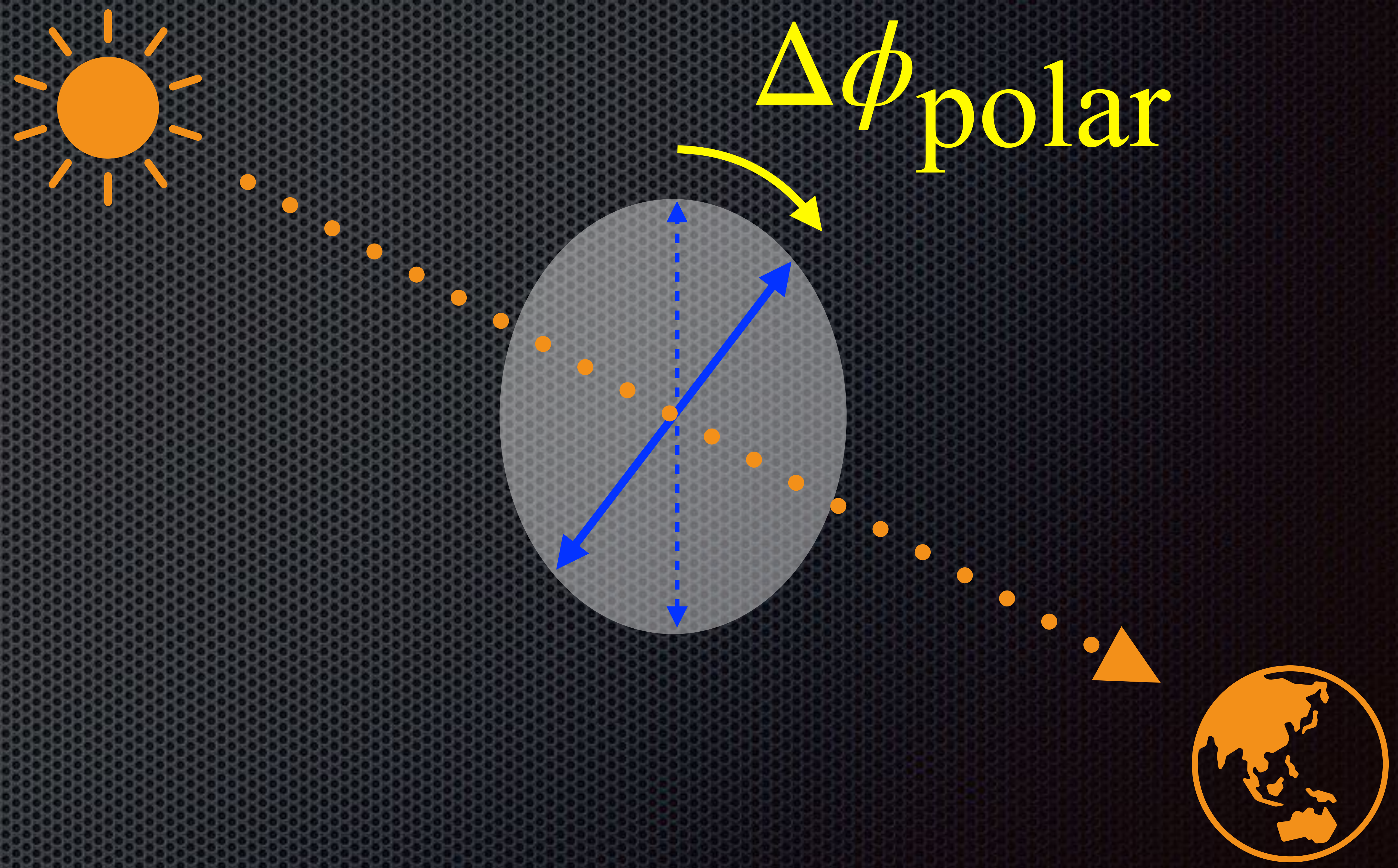

AxionLimits, Ciaran O'Hare

# Axion Dark Matter Detection

## Axion-Photon Interaction

$$\mathscr{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F \widetilde{F}$$

$$\Delta\phi_{\rm polar} = \frac{g_{a\gamma\gamma}}{2}\left(a_{\rm earth} - a_{\rm source}\right)$$

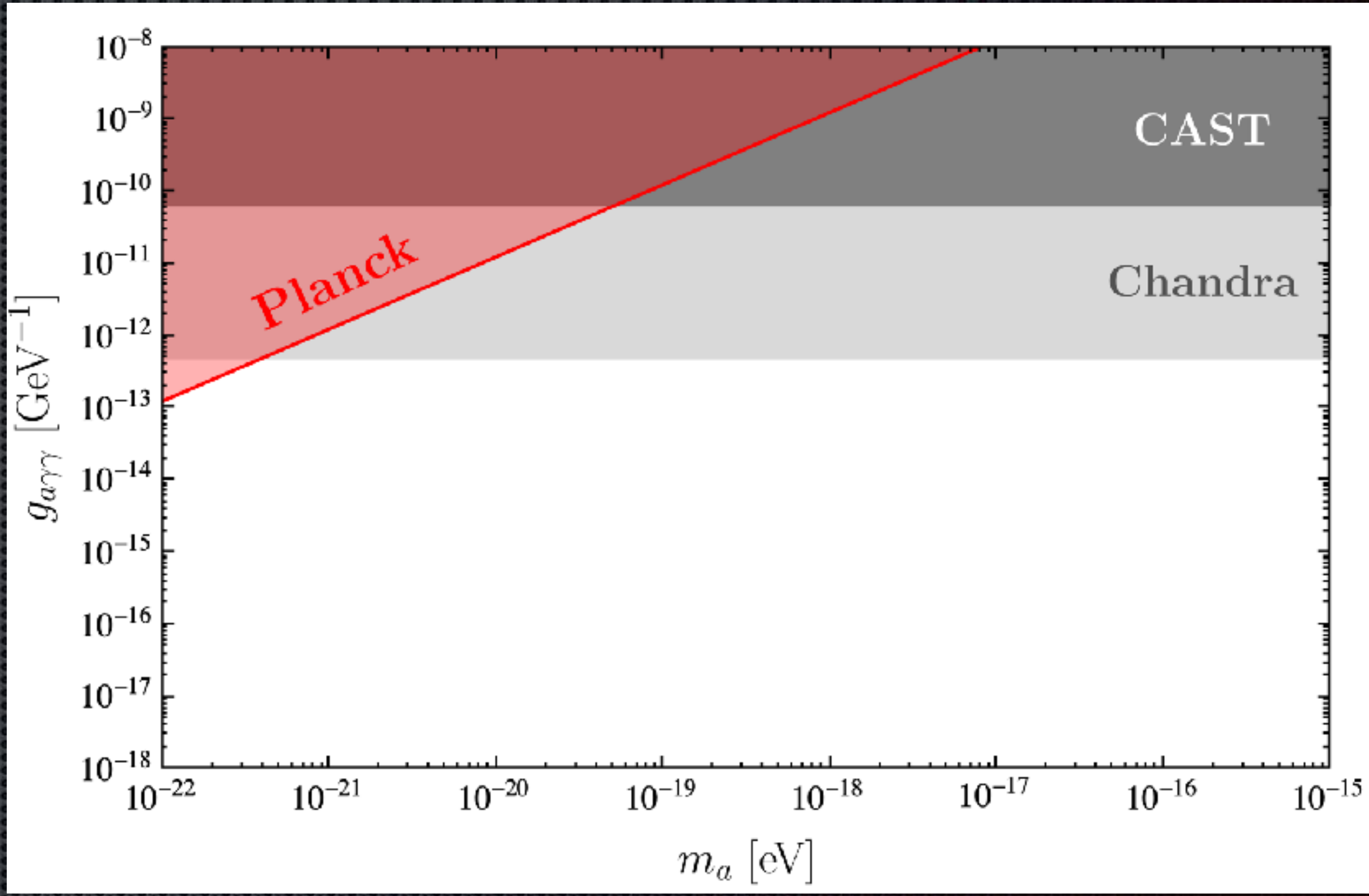


# Detecting Axion Dark Matter: CMB Polarization

$$\rho_a|_{\text{CMB}} \sim \rho_a|_{\text{Today}}(1+z_{\text{CMB}})^3$$
$$\sim 10^3\ \text{GeV/cm}^3$$

$$a|_{\text{CMB}} \sim \frac{\sqrt{2\rho_a|_{\text{CMB}}}}{m_a} \sim 10^8\ \text{GeV}\left(\frac{10^{-18}\text{eV}}{m_a}\right)$$

$$g_{a\gamma\gamma} \sim \cdot\ 10^{-9}\ \text{GeV}^{-1}\left(\frac{\text{Washout}}{10^2}\right)\left(\frac{\Delta\phi_{\text{CMB}}}{0.1^\circ}\right)\left(\frac{m_a}{10^{-18}\text{eV}}\right)$$




Fedderke, Graham, Rajendran, 2019

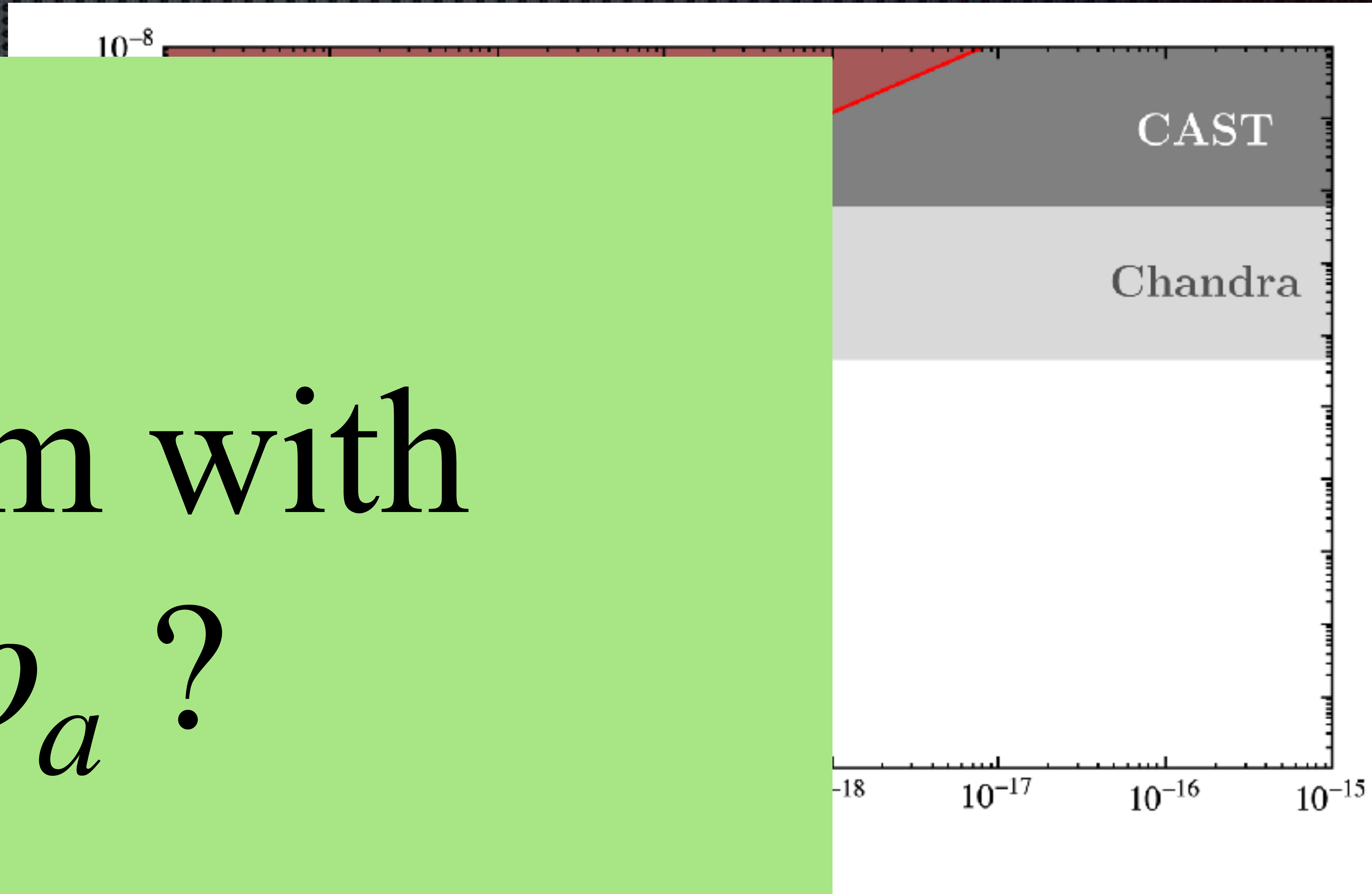
# Detecting Axion Dark Matter: CMB Polarization

$\rho_a|_{\mathrm{CMB}} \sim$

$\sim$

$a|_{\mathrm{CMB}} \sim \frac{\sqrt{2\rho_a}}{m}$

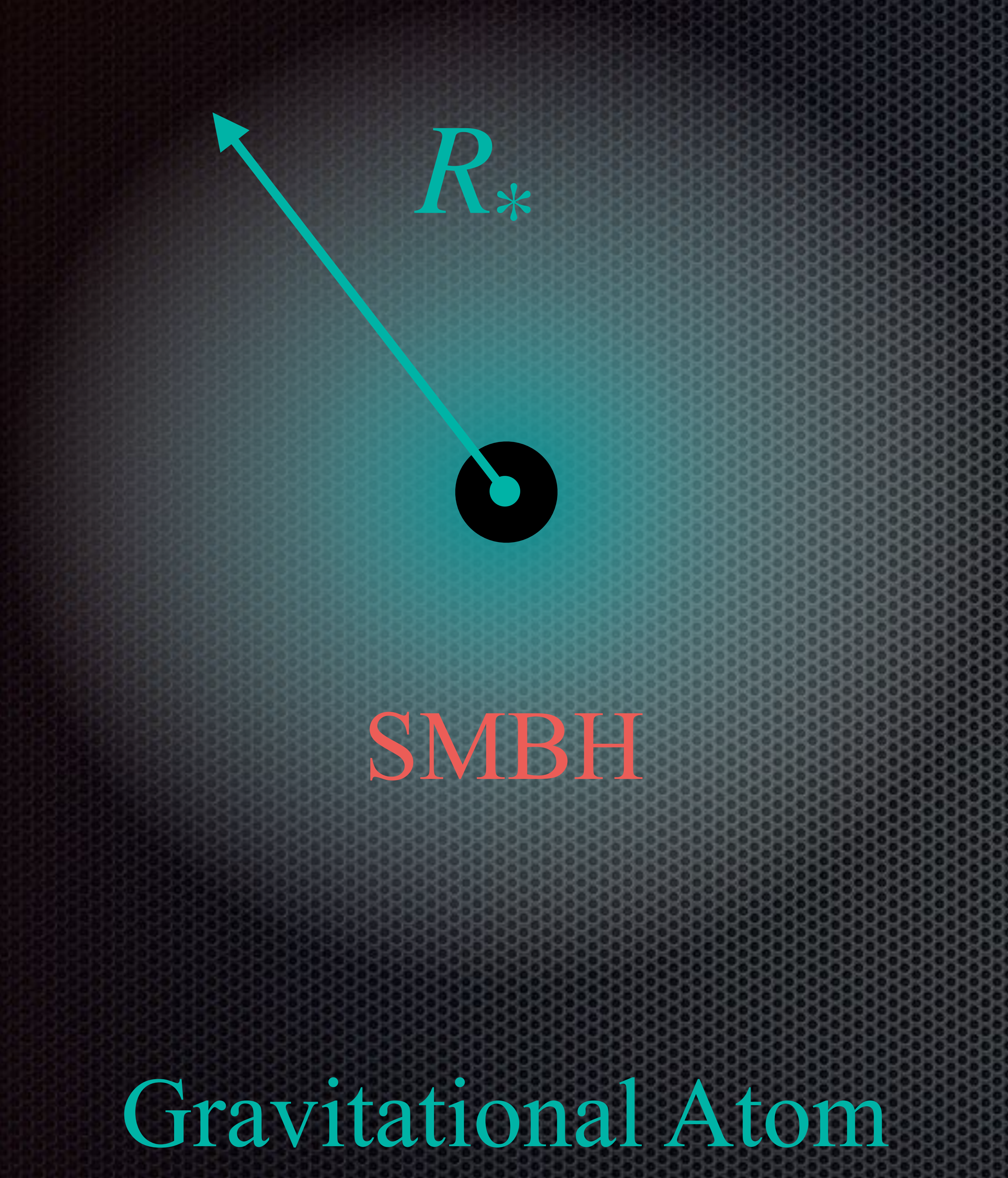
$g_{a\gamma\gamma} \sim \cdot 10^{-9}\,\mathrm{GeV}^{-}$




jendran, 2019

Any system with larger $\rho_a$?

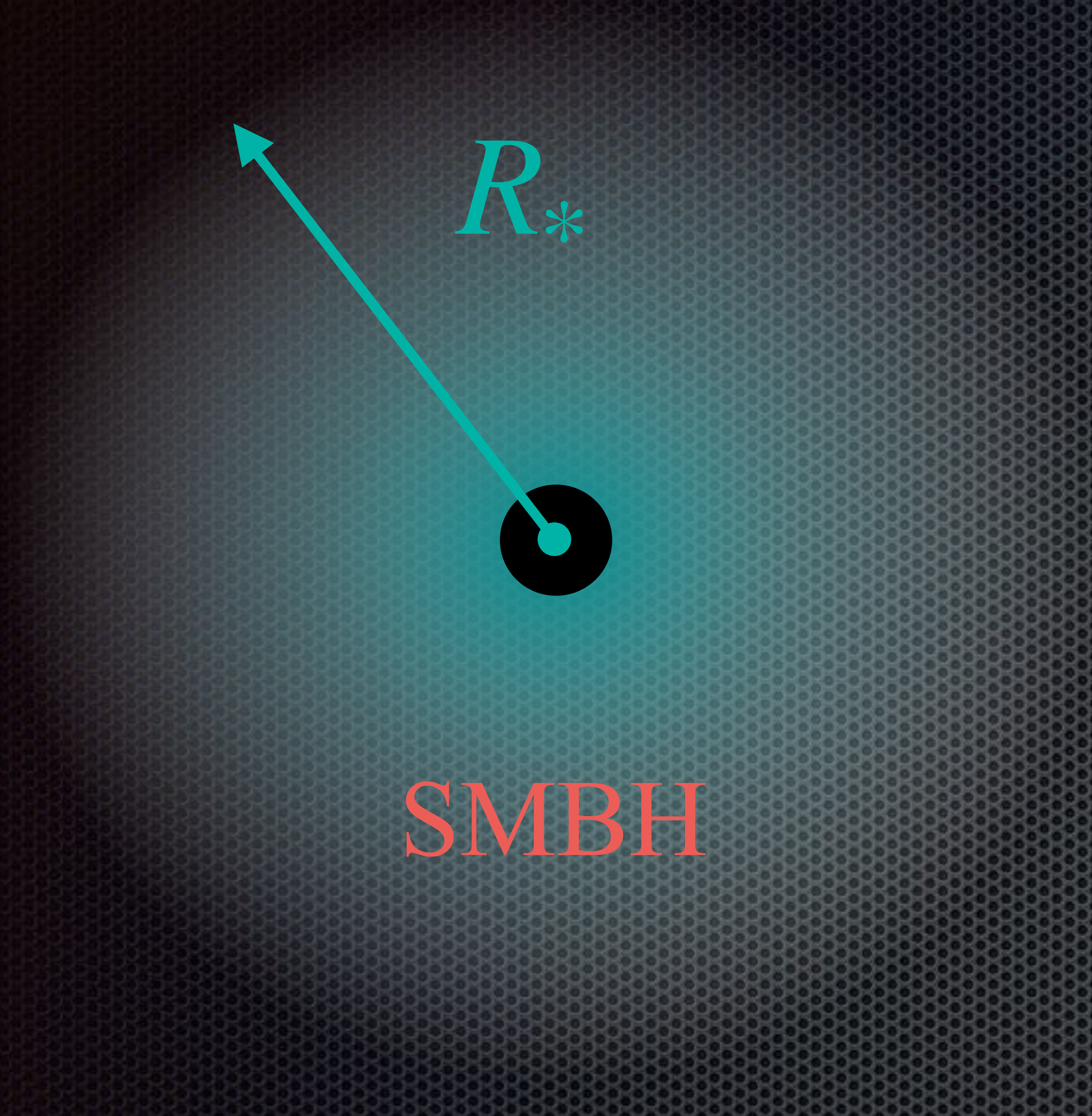
# Supermassive Black Hole




Axion Field $a(\mathbf{r},t) = f_a\, \Theta(\mathbf{r})\, \cos(\omega_a t)$

Schrodinger Equation $\left(-\frac{1}{2m_a}\nabla^2 - \frac{GM_{BH}m_a}{r}\right)\Theta = \frac{\omega_a^2 - m_a^2}{2m_a}\Theta$

# Supermassive Black Hole




Gravitational Atom

Axion Field $\quad a(\mathbf{r}, t) = f_a\, \Theta(\mathbf{r}) \cos(\omega_a t)$

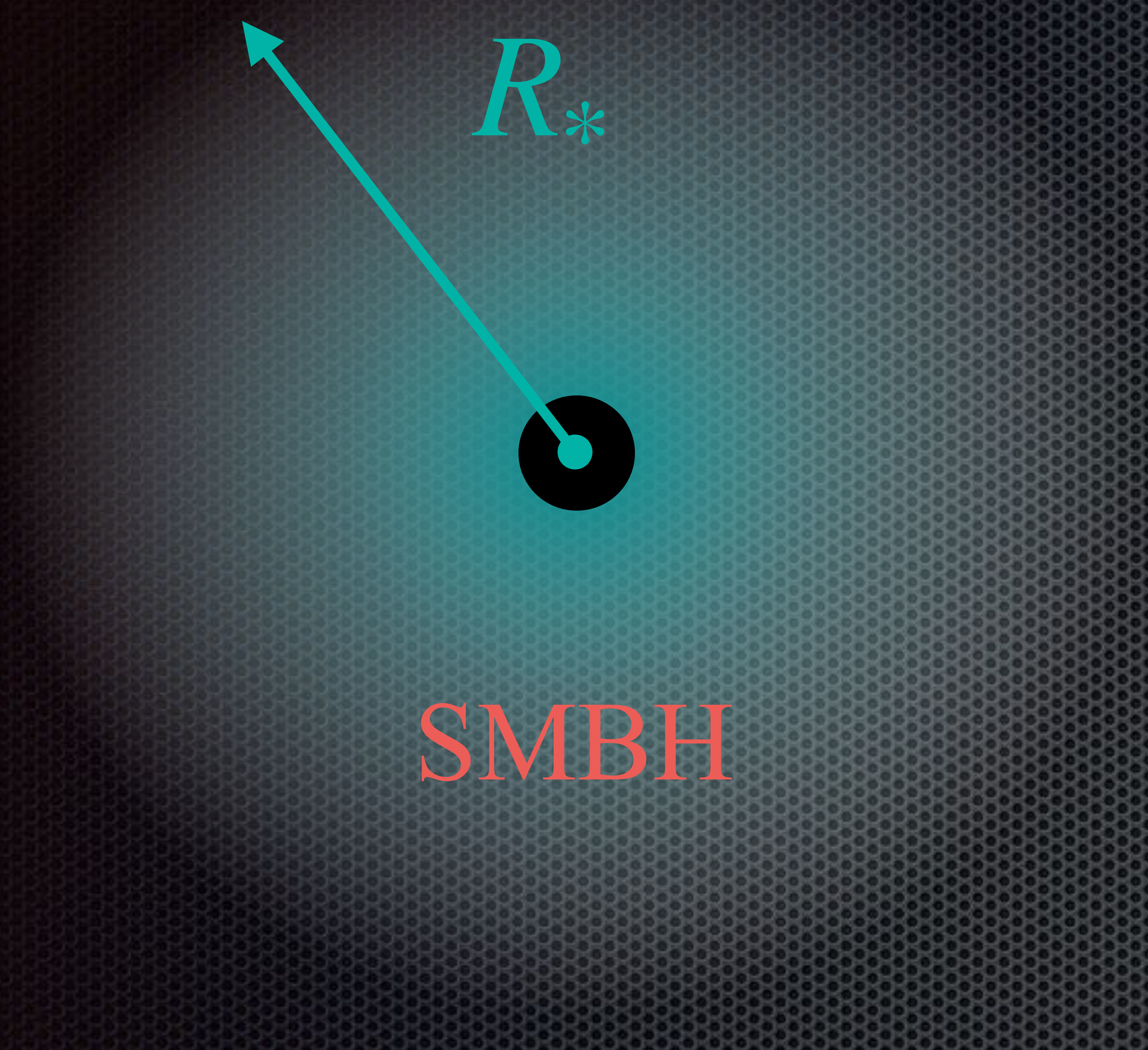
Schrodinger Equation $\quad \left(-\frac{1}{2m_a}\nabla^2 - \frac{GM_{BH}m_a}{r}\right)\Theta = \frac{\omega_a^2 - m_a^2}{2m_a}\Theta$

**Ground State:** $l = 0$ **!**

Spatial Configuration $\quad \Theta \propto e^{-r/R_*} \qquad R_* \sim \frac{1}{GM_{BH}m_a^2}$

Oscillation Frequency $\quad \omega_a = m_a\sqrt{1 - (GM_{BH}m_a)^2}$

# Supermassive Black Hole

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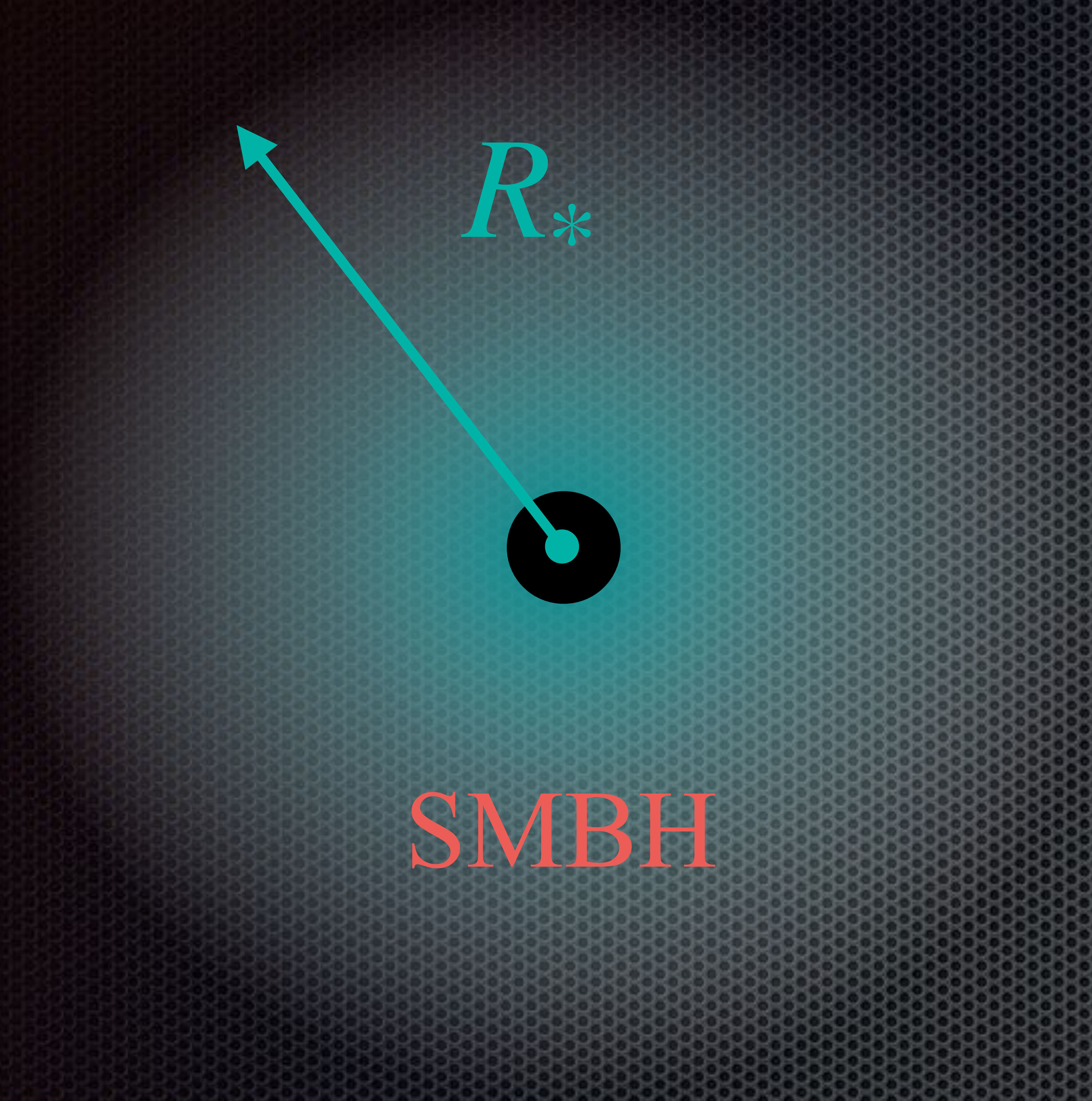
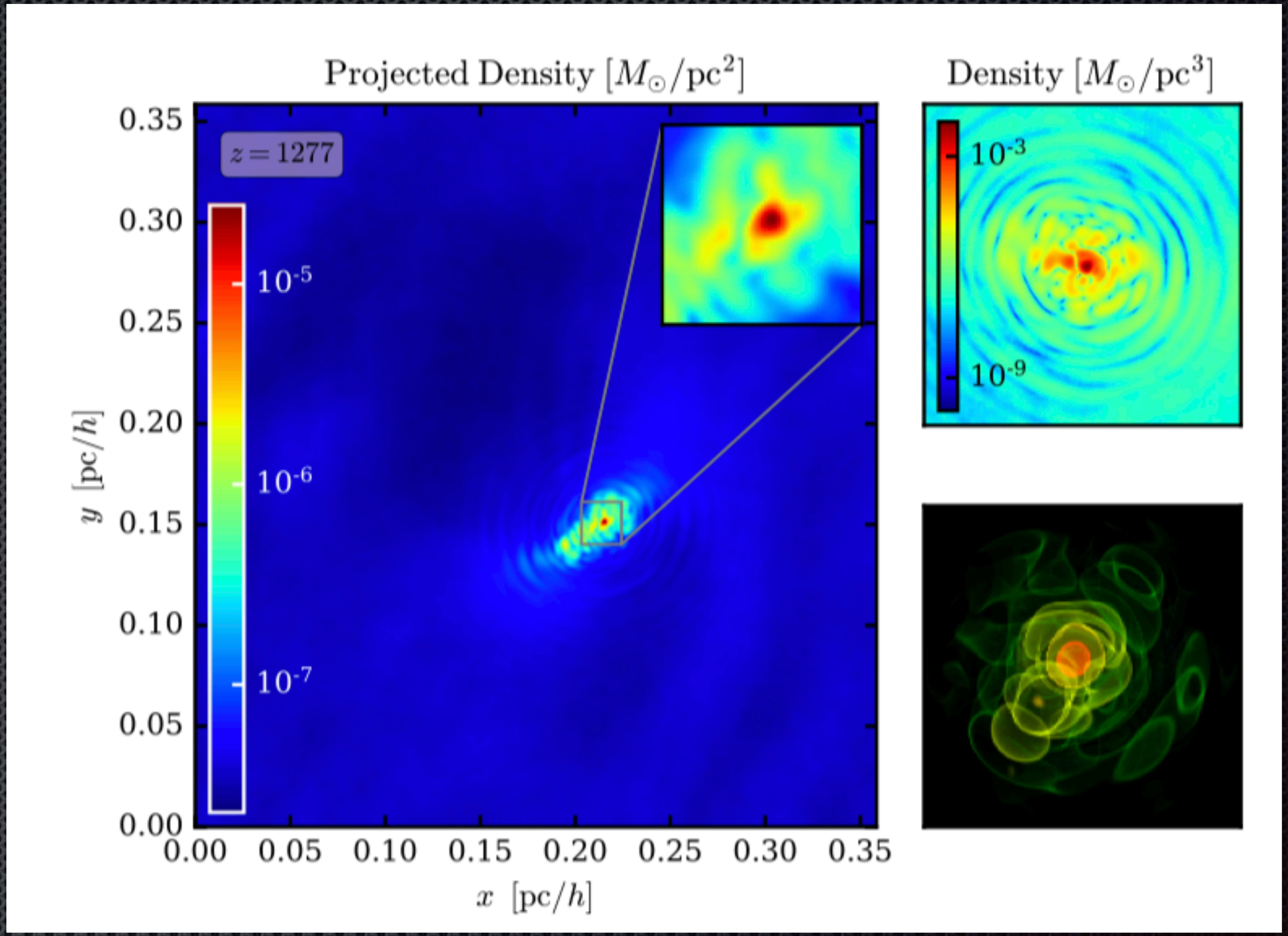
Oscillation Frequency $\omega_a = m_a\sqrt{1 - (GM_{BH}m_a)^2}$

Cutoff at $m_a \sim 1/GM_{BH}$,
gravitational atom absorbed by BH

# Supermassive Black Hole

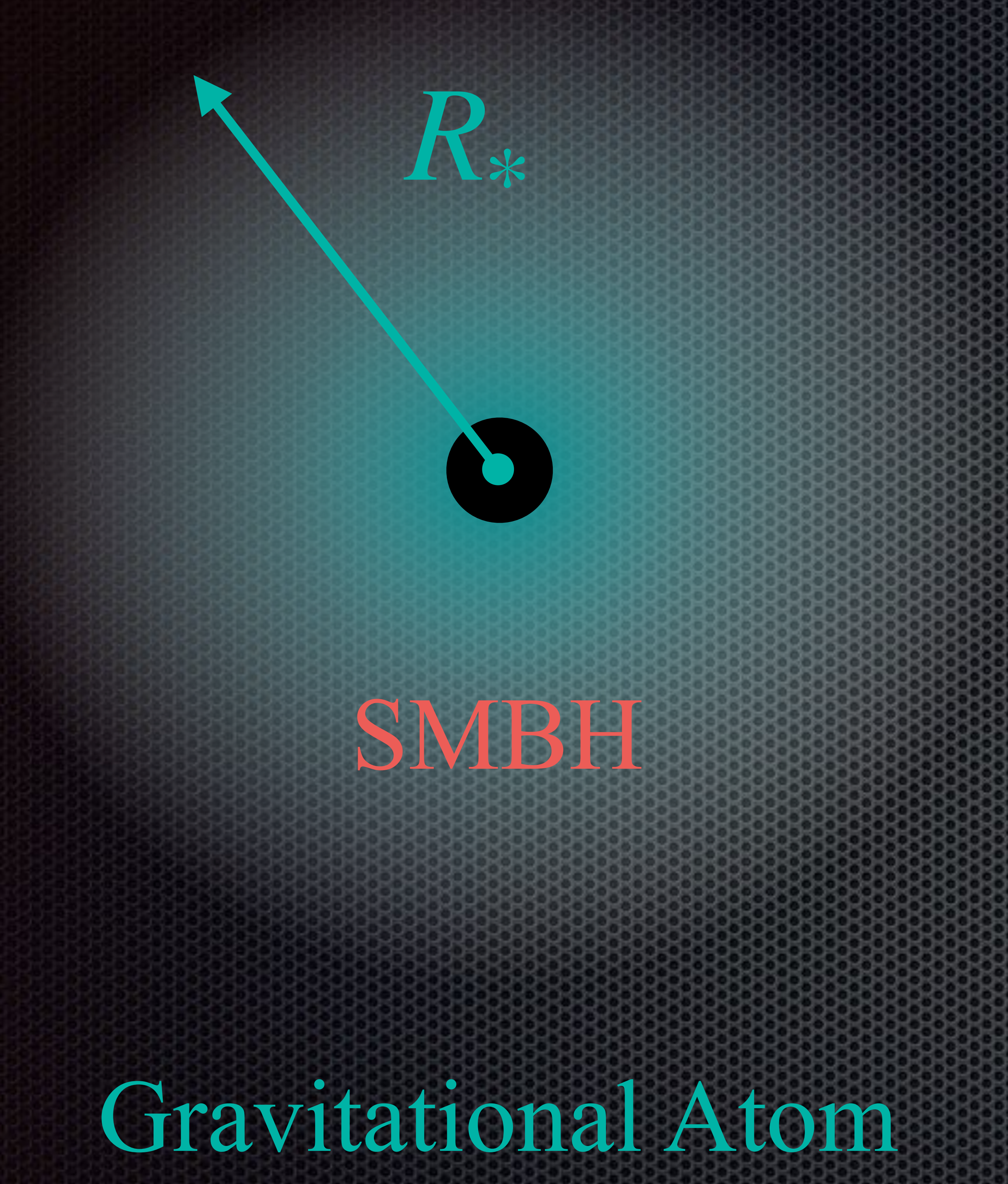



Gravitational Atom




Eggemeier, Niemeyer, 2019

# Supermassive Black Hole

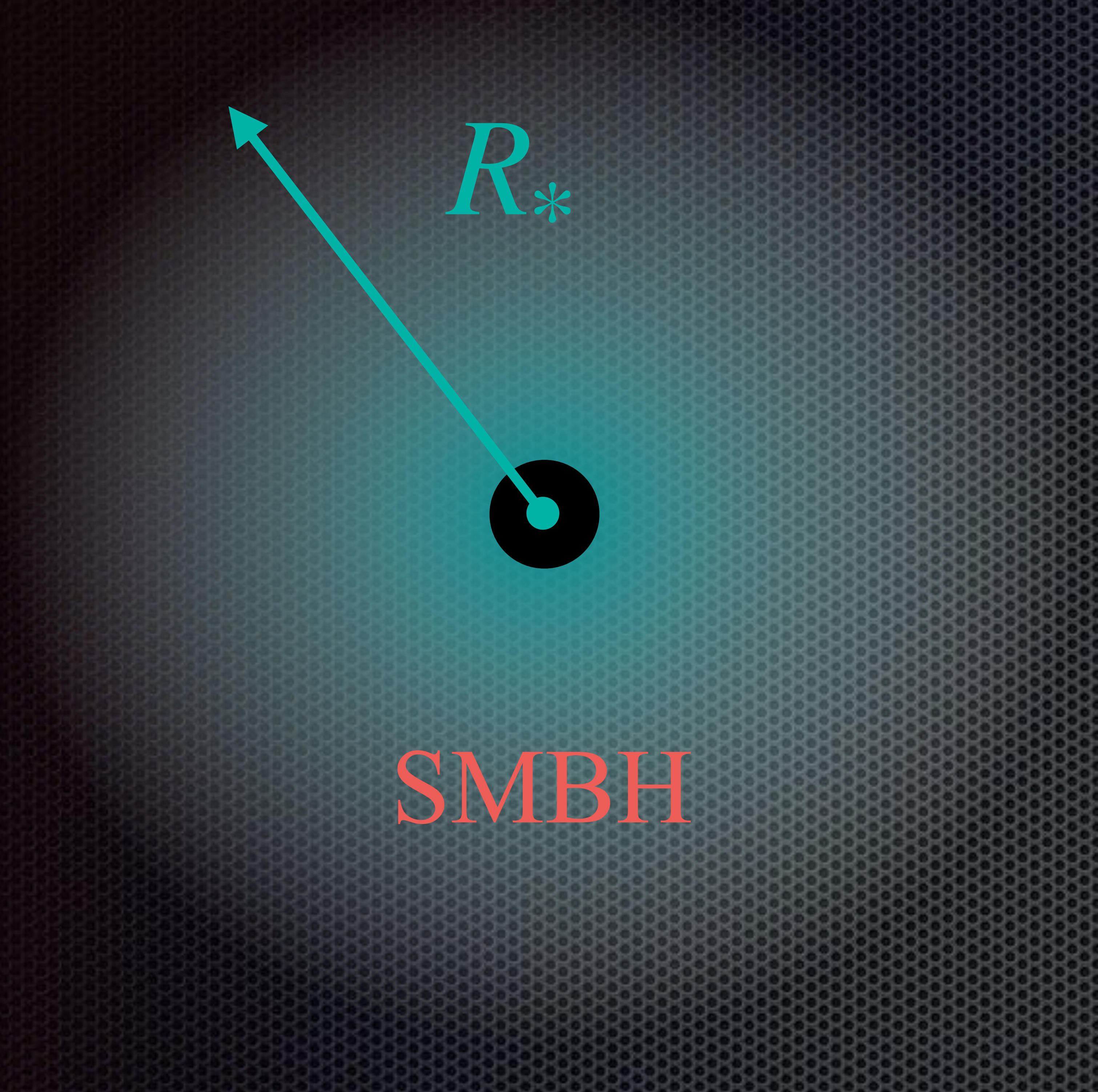



$$\frac{dM_*}{dt} = \frac{\overline{M}_*^2}{\tau_{grav}} \frac{1}{M_*} - M_* \Gamma_{decay}$$

$$\overline{M}_* \sim \rho_a^{1/6} G^{-1/2} m_a^{-1} M_{\text{halo}}^{1/3} \qquad \tau_{grav} \sim \frac{m_a^3 v_a^6}{G^2 \rho_a^2}$$

$$\Gamma_{decay} \sim m_a \left( G M_{BH} m_a \right)^{5+4l}$$

# Supermassive Black Hole




Gravitational Atom

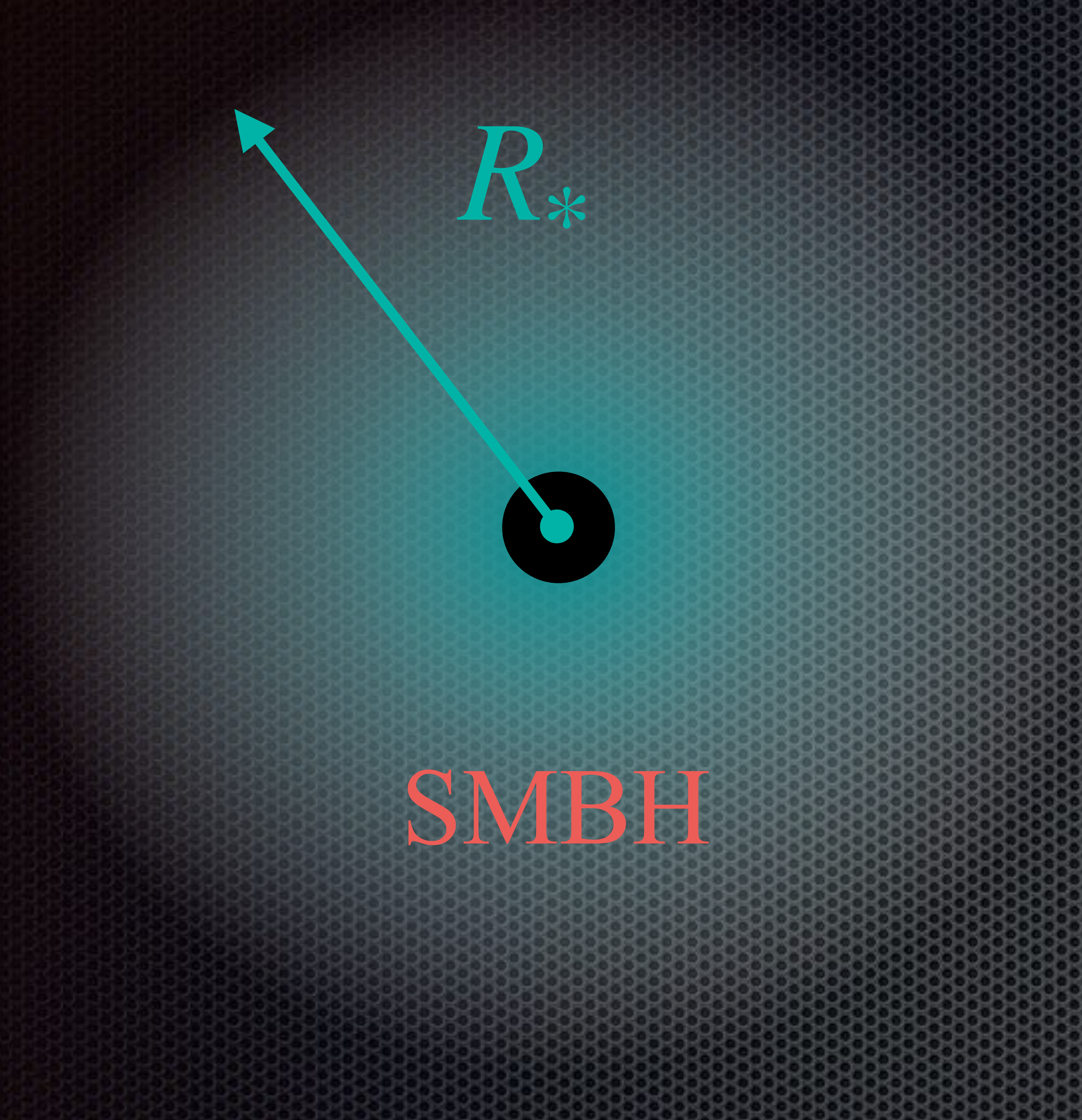
**Sgr A***

$$R_* \sim 10^{-4}\textbf{pc}\left(\frac{10^{-18}\textbf{eV}}{m_a}\right)^2$$

$$\rho_* \sim \frac{M_*}{R_*^3} \sim 10^{11}\,\textbf{GeV/cm}^3\left(\frac{m_a}{10^{-18}\textbf{eV}}\right)^{1/2}$$

$$\gg \rho_a|_{\mathrm{CMB}}$$

# Supermassive Black Hole




Gravitational Atom

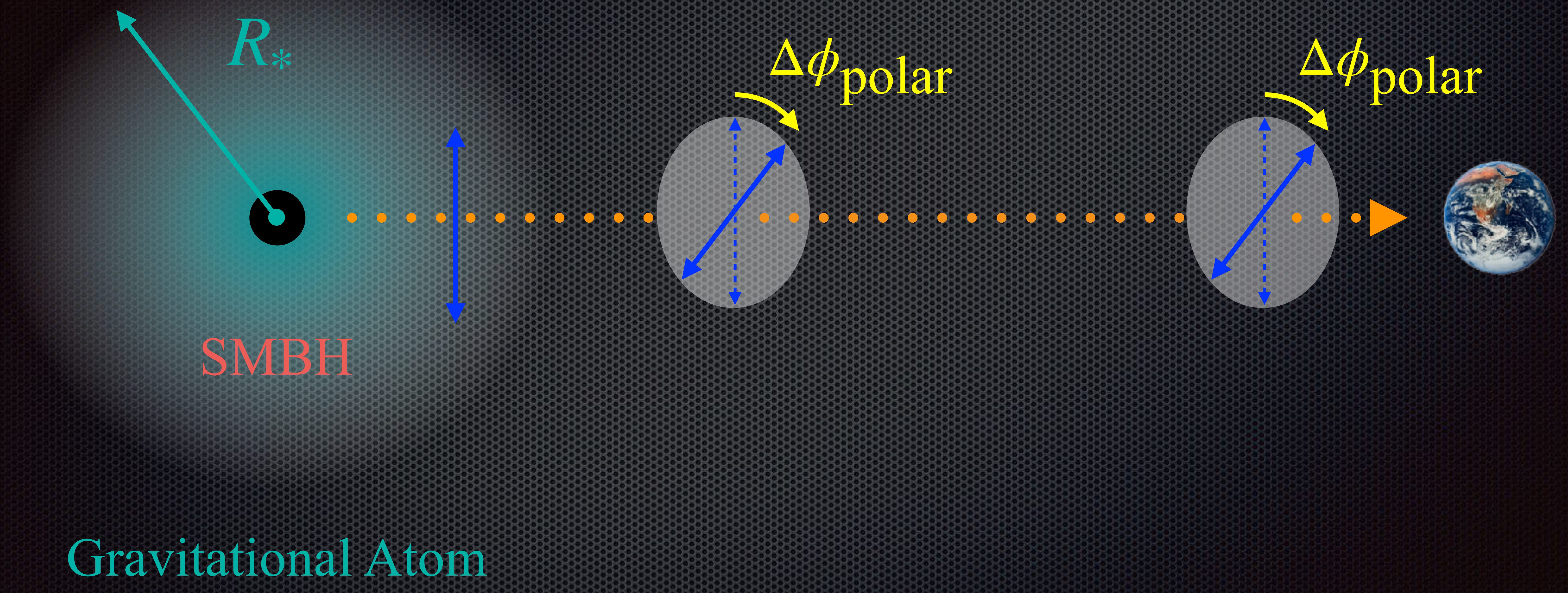
M87*

$$R_* \sim 10^{-3}\,\textbf{pc}\left(\frac{10^{-20}\,\textbf{eV}}{m_a}\right)^2$$

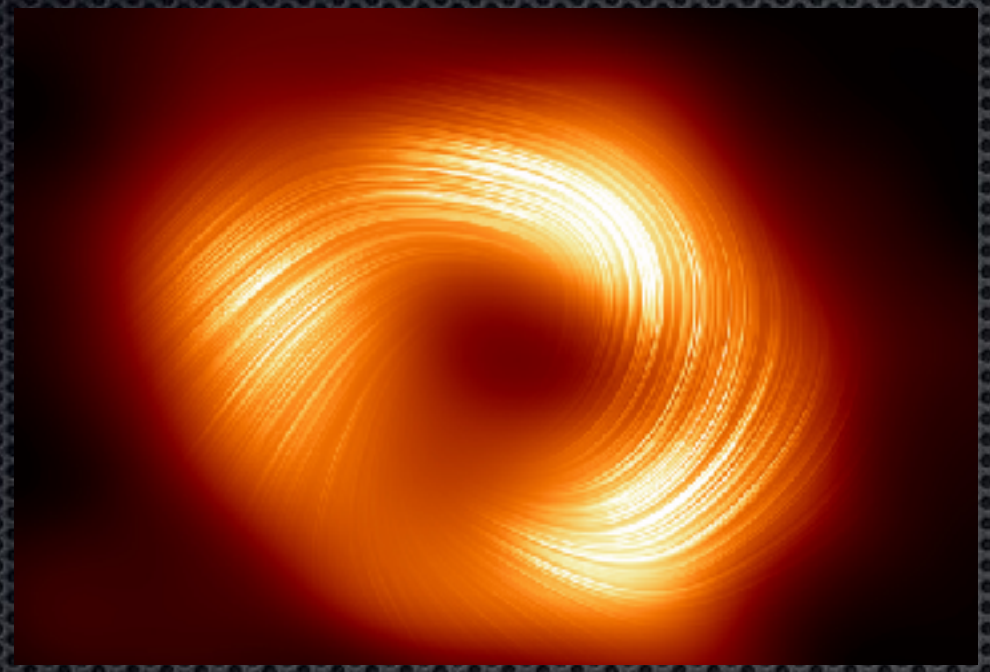
$$\rho_* \sim \frac{M_*}{R_*^3} \sim 10^8\,\textbf{GeV/cm}^3\left(\frac{m_a}{10^{-20}\,\textbf{eV}}\right)^{1/2}$$

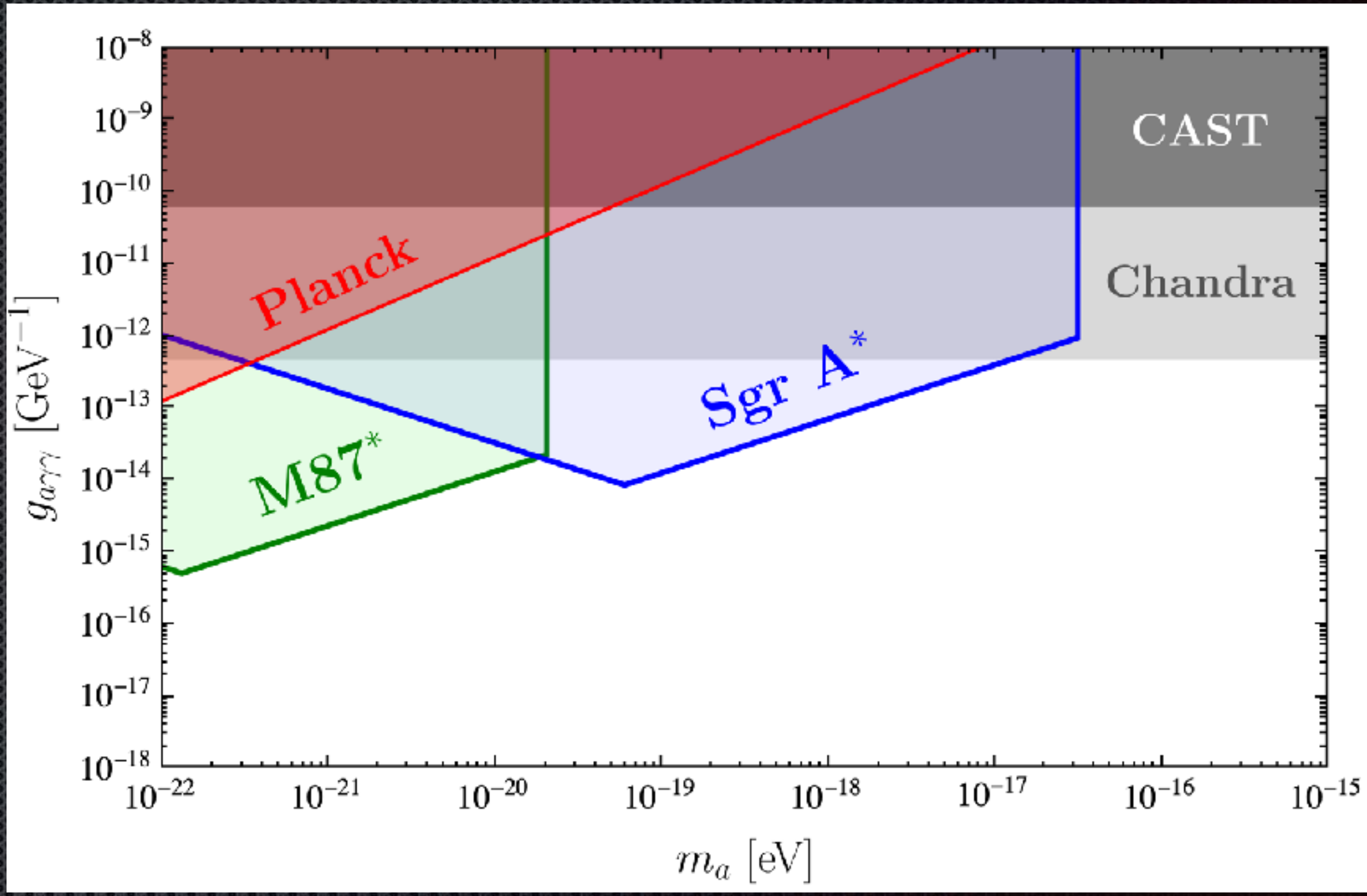
$$\gg \rho_a|_{\mathrm{CMB}}$$

# Supermassive Black Hole



# Sensitivity of EHT






M87*    SgrA*

$\Delta\phi_{polar} \sim 3^\circ$

**X. Gan**, L-T. Wang, H. Xiao, 2023

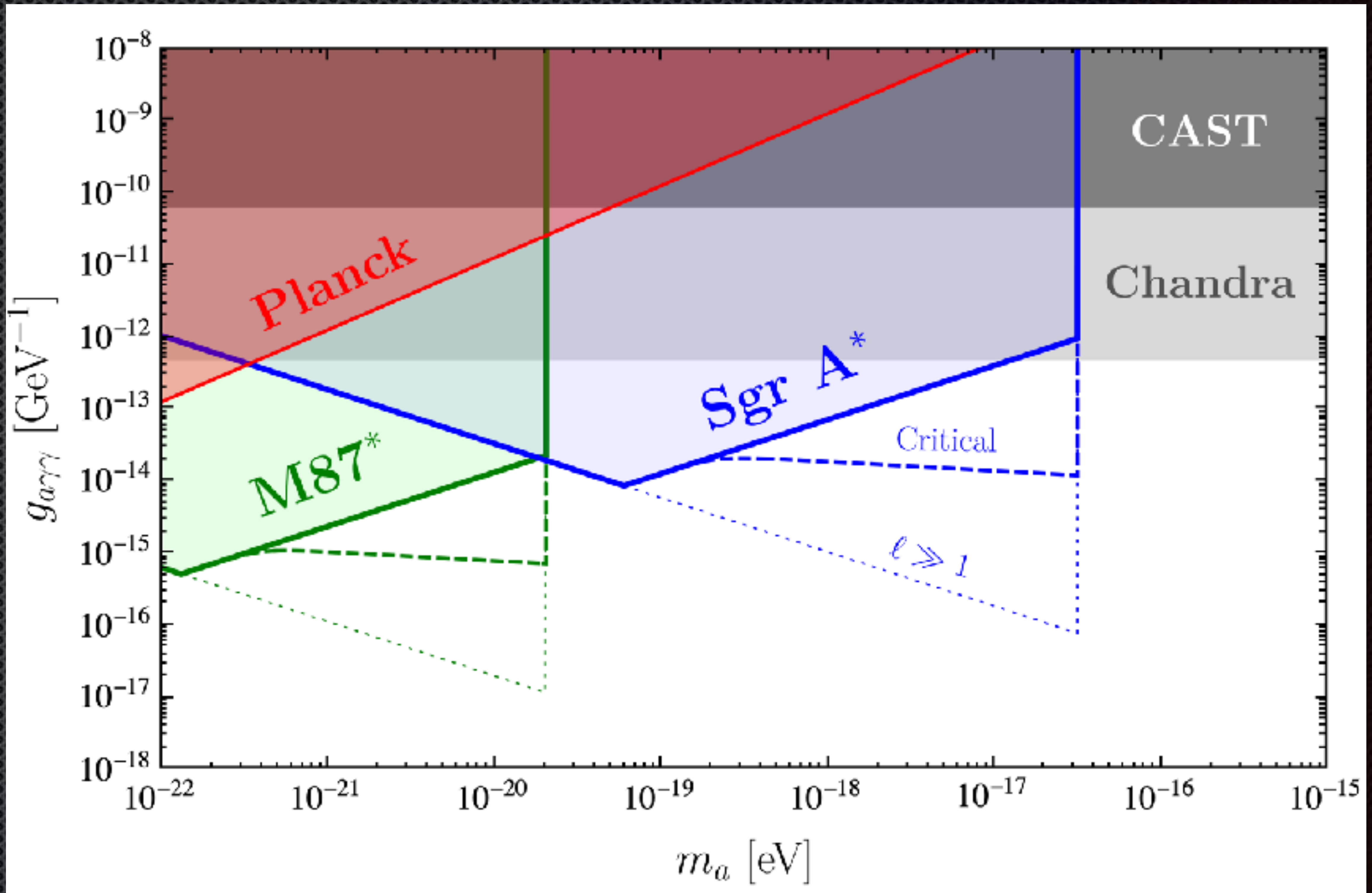
# Enhancement of Signals

Large self-interaction

$M(t_H) = M_*^{crit}$

Excited States $l \gg 1$

$\Gamma_{decay} \sim m_a \left(GM_{BH} m_a\right)^{5+4l}$




**X. Gan**, L-T. Wang, H. Xiao, 2023

# Enhancement of Signals

Large self-interaction

$M(t_H) = M_*^{crit}$

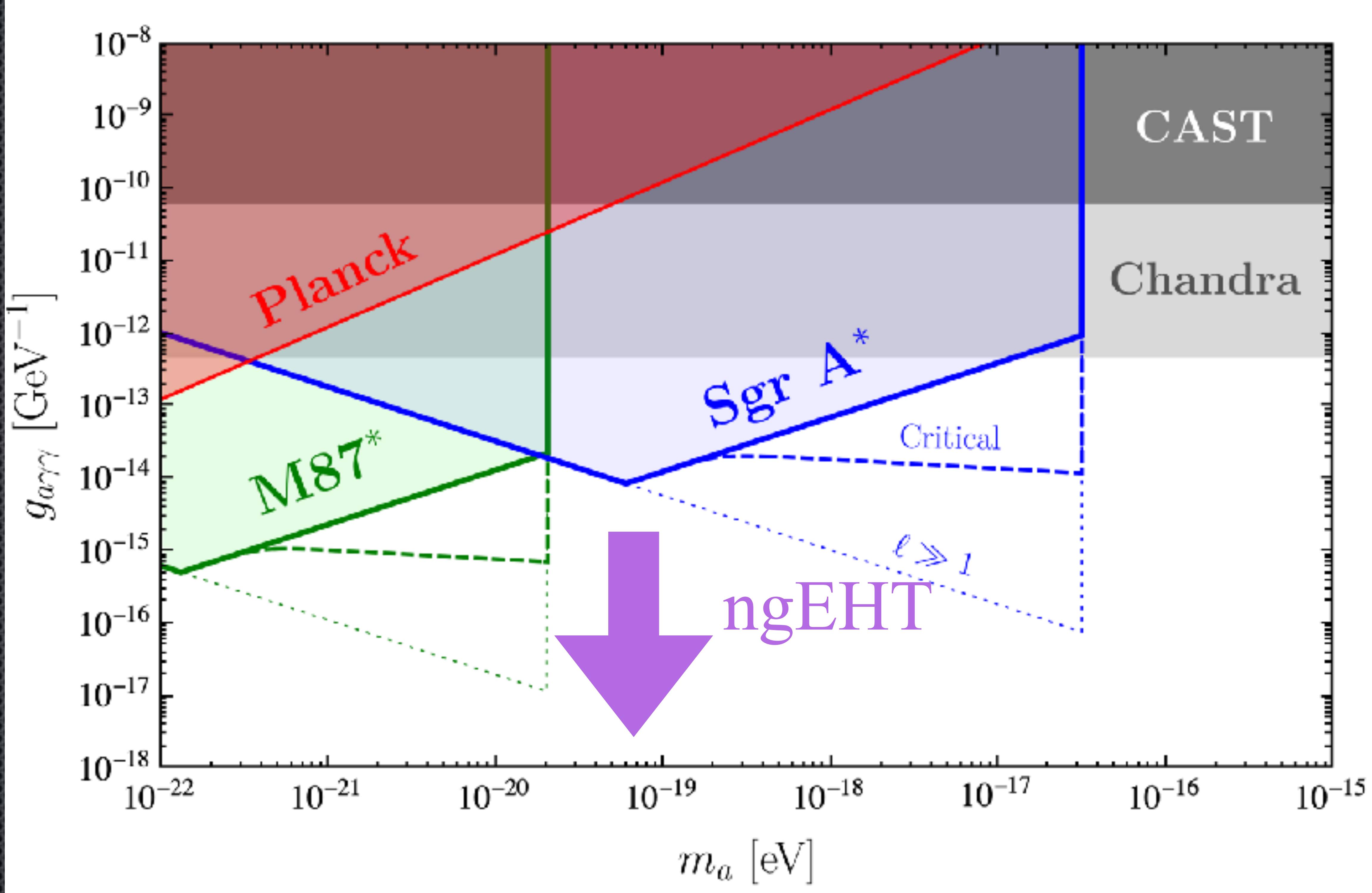
Excited States $l \gg 1$

$\Gamma_{decay} \sim m_a \left(GM_{BH}m_a\right)^{5+4l}$

Better Polarimetry

EHT $\Delta\phi_{polar} \sim 3^\circ$

ngEHT $\Delta\phi_{polar} \sim 0.01^\circ$




**X. Gan**, L-T. Wang, H. Xiao, 2023

# Summary

(1) Axion is a solution to the strong CP problem and a good dark matter candidate with a simple production mechanism and rich phenomena.

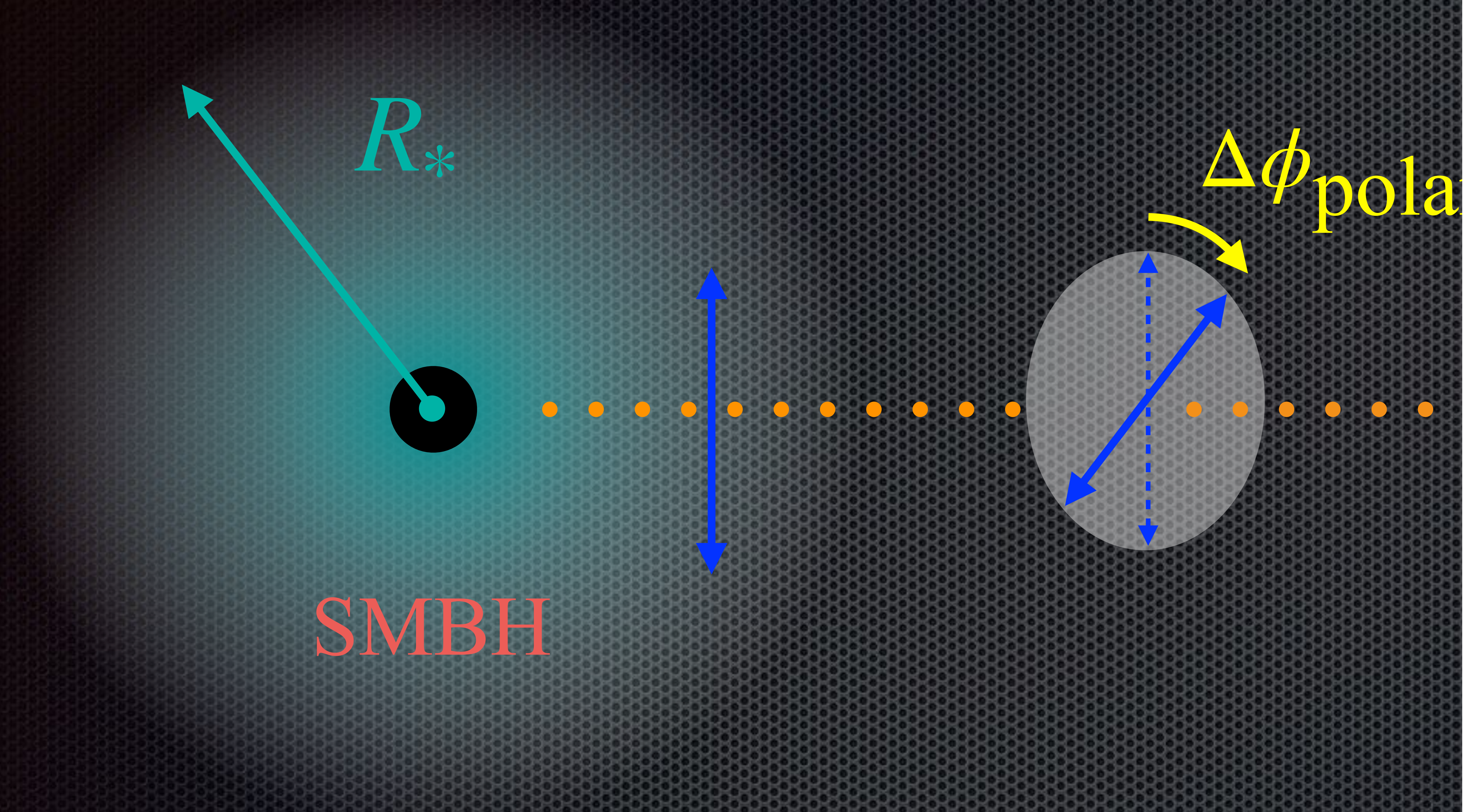
(2) The current strongest constraints on axion in the ultralight region are from solar telescope and astrophysical observation.

(3) CMB Polarization can be used to detect axion dark matter with axion-photon interaction, because it has enhanced density (10^3 GeV/cm^3) compared to the dark matter local density (1GeV/cm^3)

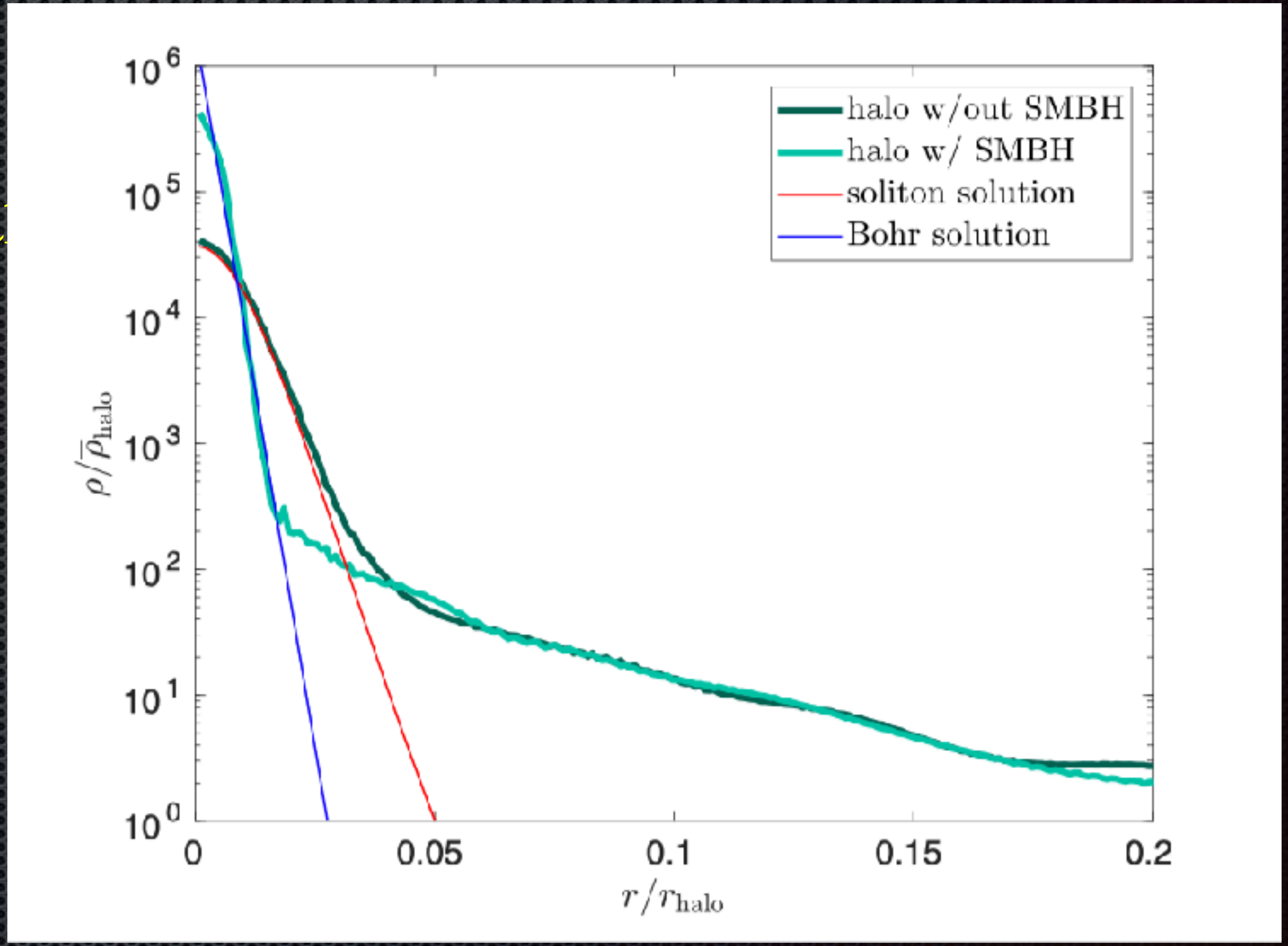
(4) Black Hole Polarimetry is better for observing ultralight axion DM, because it has much enhanced axion energy density caused by the axion star accretion.

(5) The polarization rotation signals can be enhanced by the large self-interaction, the excited states with l>>1, and the next generation EHT.

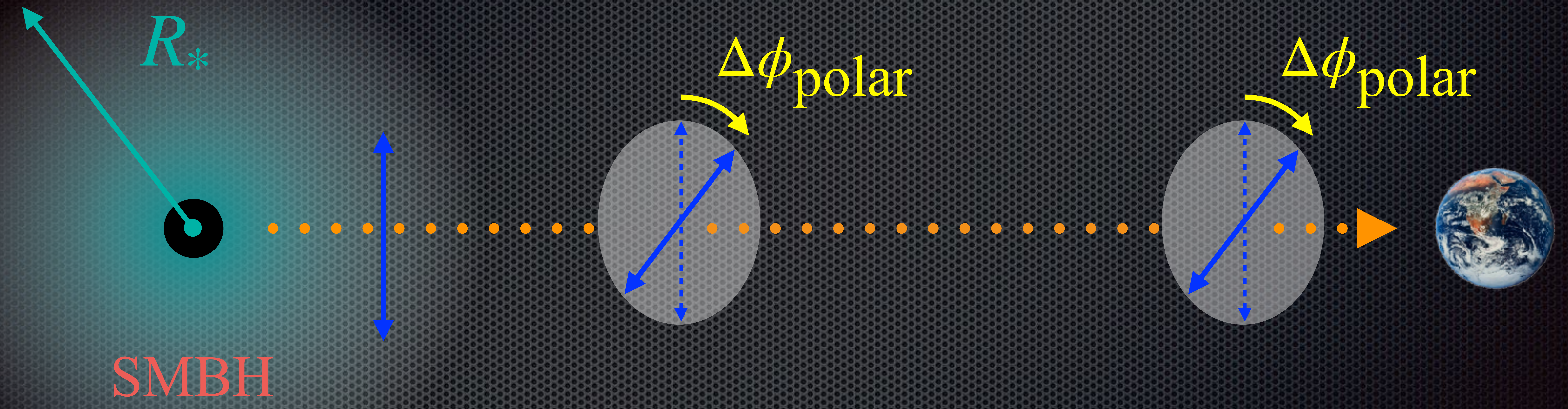
# Appendix




Gravitational Atom




Davies, Mocz, 2020




Gravitational Atom

$$\Delta\phi_{polar} = g_{a\gamma\gamma}\sqrt{2\rho_*}/m_a$$

$$= g_{a\gamma\gamma}\left(G^3 M_{BH}^3 m_a^4 M_*\right)^{1/2}$$

# Axion Dark Matter Detection

$$\mathscr{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F \widetilde{F}$$

$$\omega_{\pm} = k \pm \frac{1}{2} g_{a\gamma\gamma} \frac{da}{dt}$$

$$\Delta\phi_{\text{polar}} = \int \frac{\omega_+ - \omega_-}{2} dt = \frac{g_{a\gamma\gamma}}{2} \left(a_{\text{earth}} - a_{\text{sourth}}\right)$$