Axion Dark Matter from Theory to Experiments

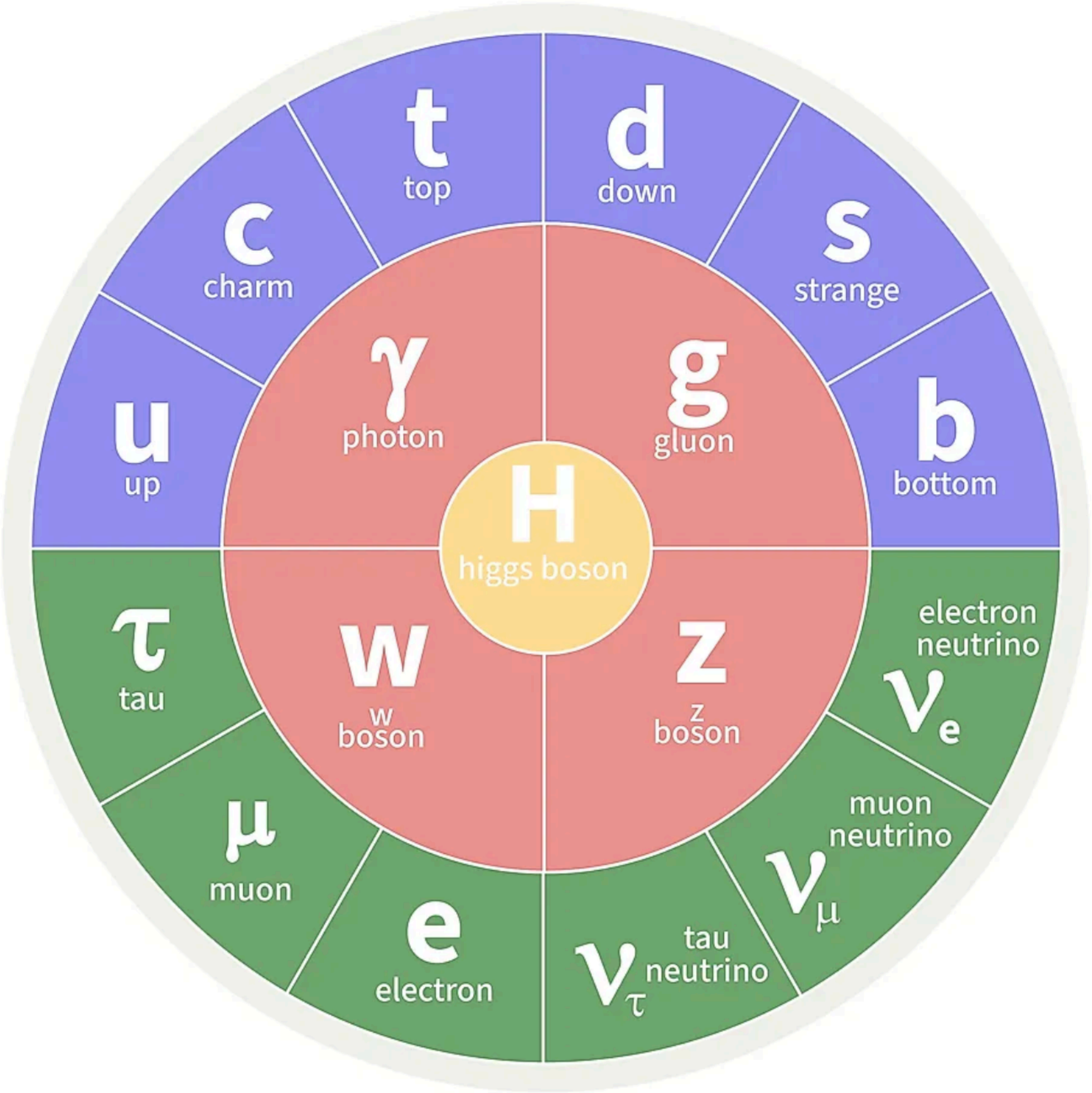
Peizhi Du

University of Science and Technology of China

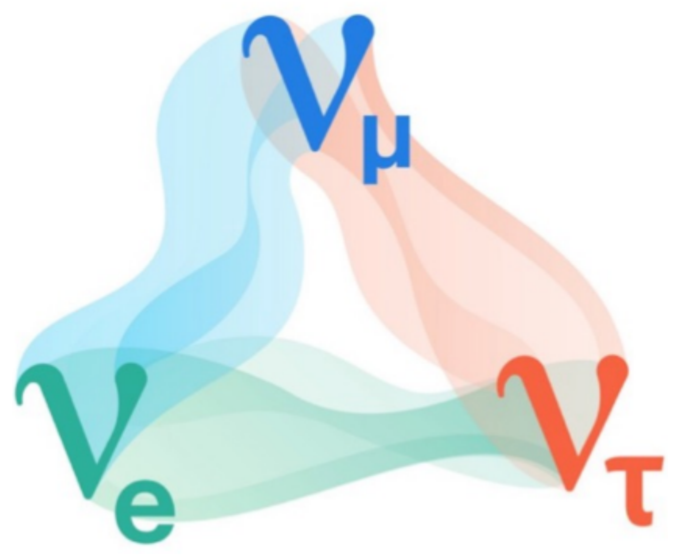
March 20, 2026

Physics Beyond the Standard Model

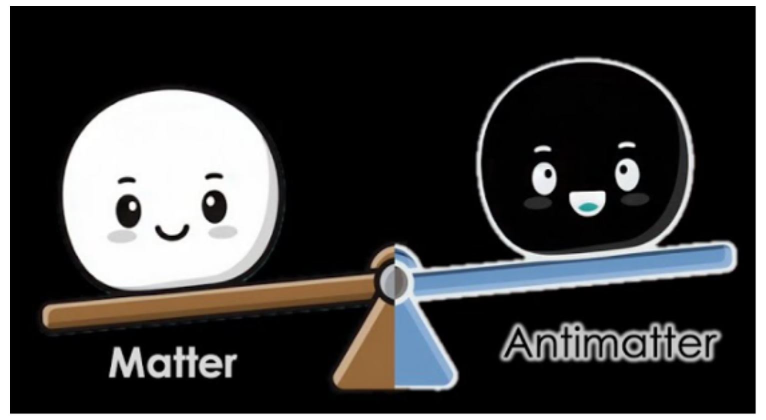
The Standard Model of particle physics



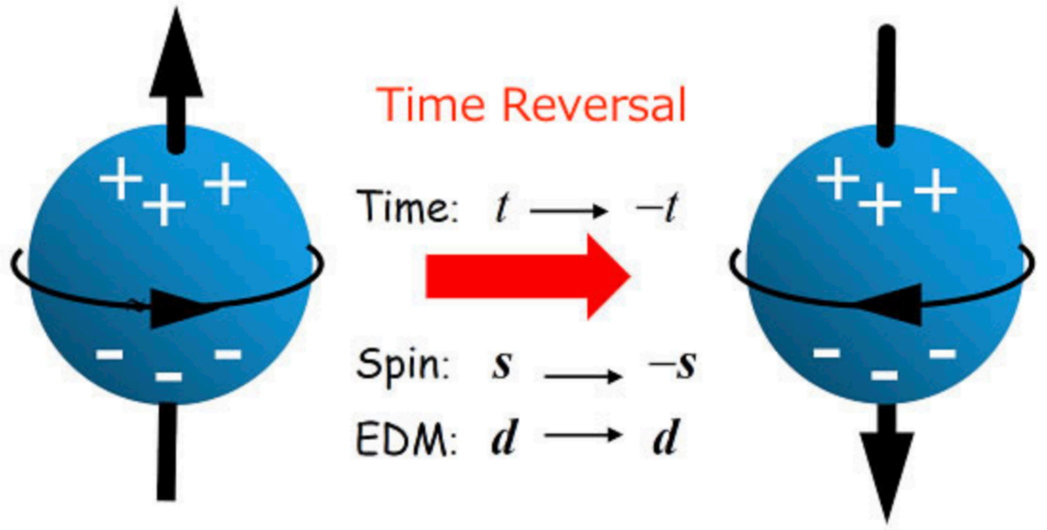
Problems/puzzels of the SM



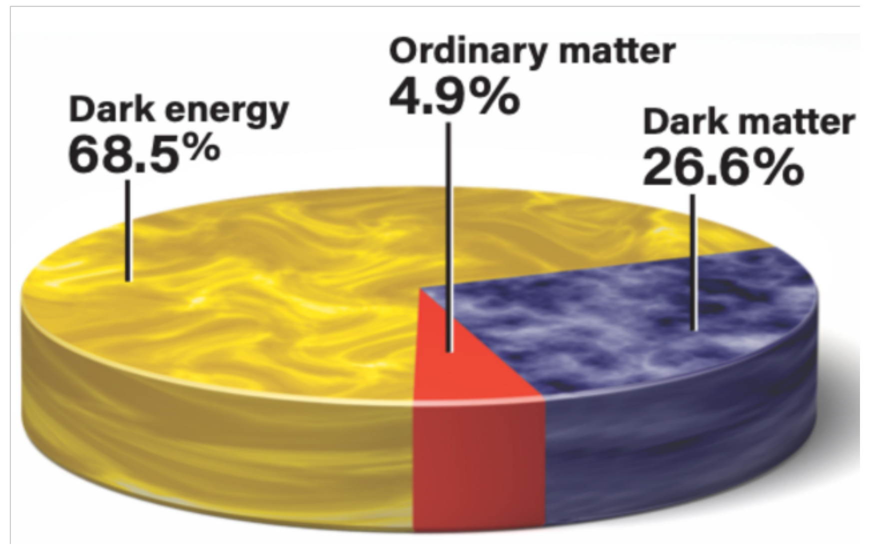
Origin of neutrino masses



Matter/antimatter asymmetry



Strong CP problem



Nature of dark matter/dark energy

Outline of the lecture

- Dark Matter

- The strong CP problem

  Classical picture and solutions

- QCD axions and axion-like particles

  Solution to the strong CP problem

  Why axions can be dark matter

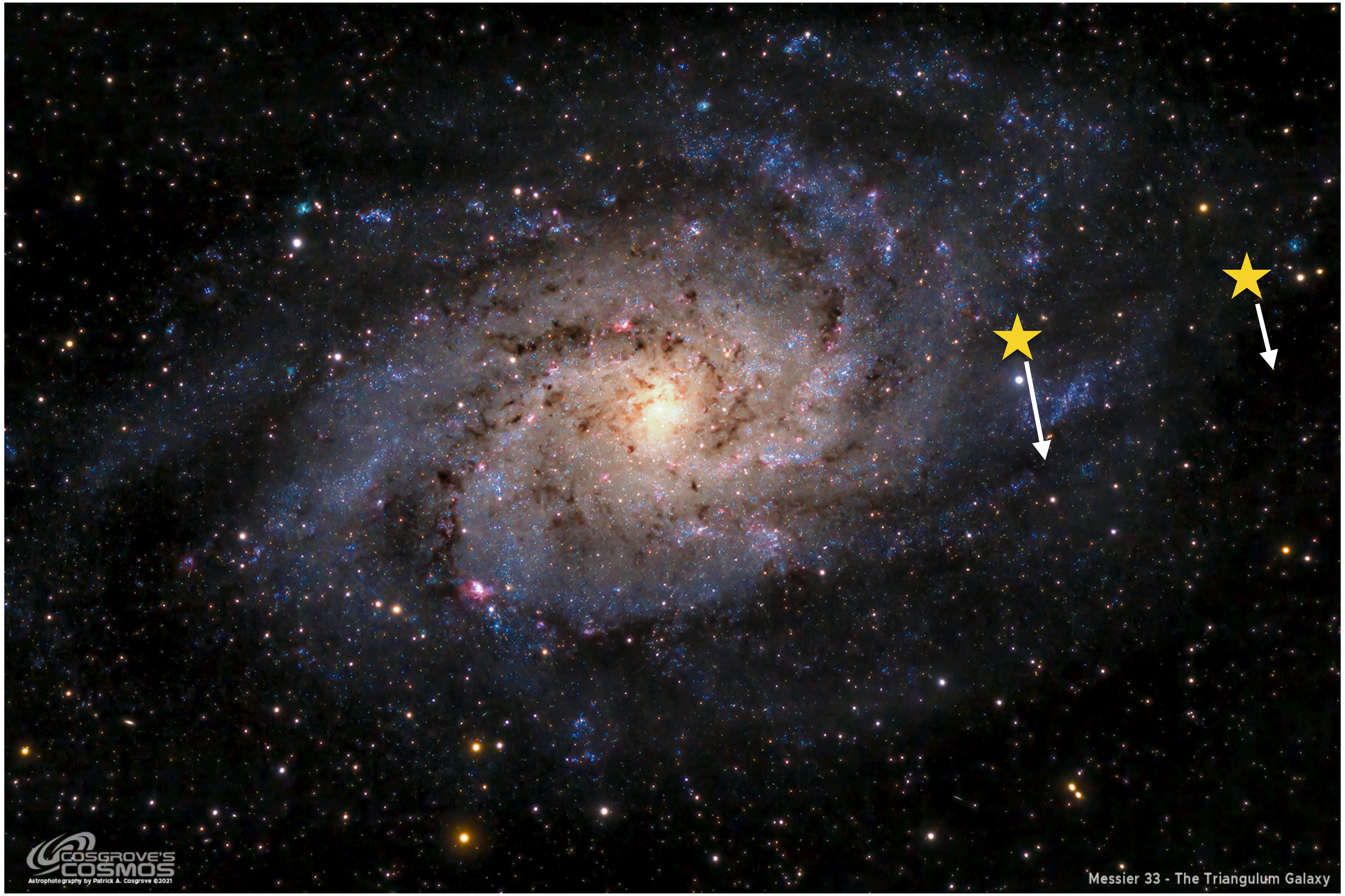
- Axion/ALP detection

  Axion DM: ADMX, ABRACADABRA, Spin sensors…

  Axion not as DM: LSW, stellar cooling, BH superradiance…

Evidence for Dark Matter

Stars velocity distribution in galaxies



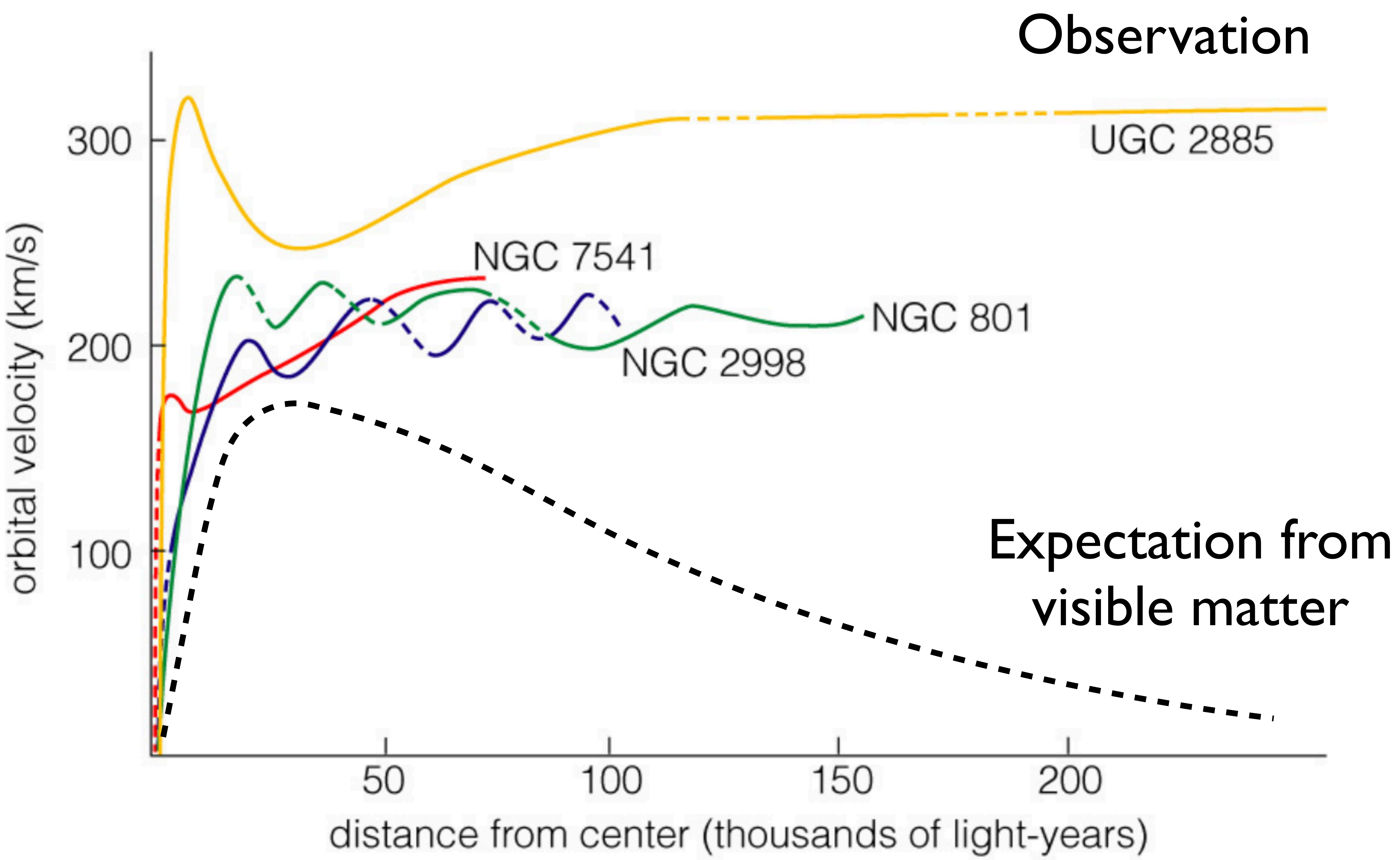
Expectation from Newton's gravity

$$v = \sqrt{\frac{GM}{r}}$$

Further stars move slower

Evidence for Dark Matter

Galaxy Rotation Curves

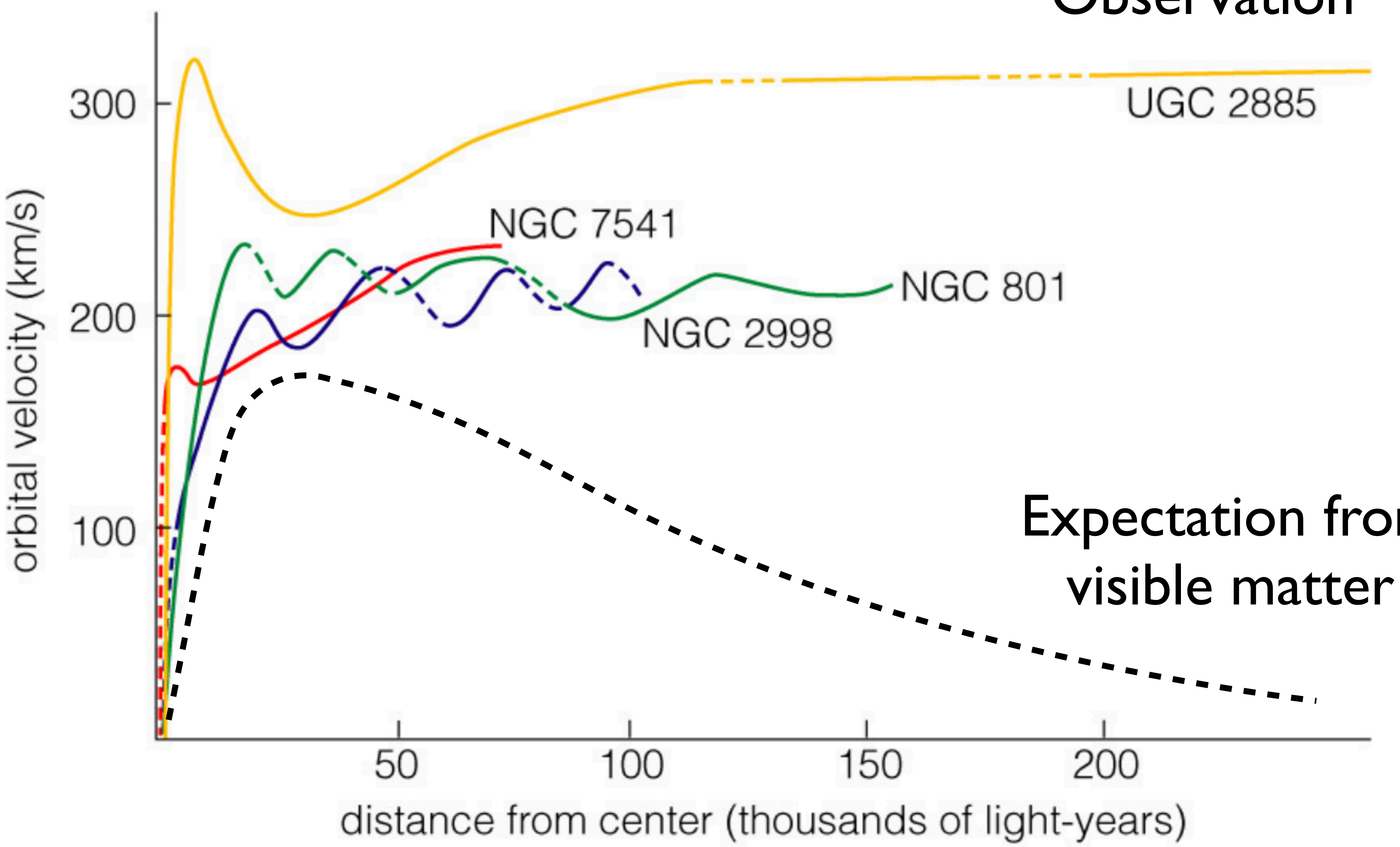


$$v = \sqrt{\frac{GM_{\text{vis}}}{r}}$$

Evidence for Dark Matter

Galaxy Rotation Curves

Observation



$$v = \sqrt{\frac{G(M_{\rm vis} + M_{\rm DM})}{r}}$$

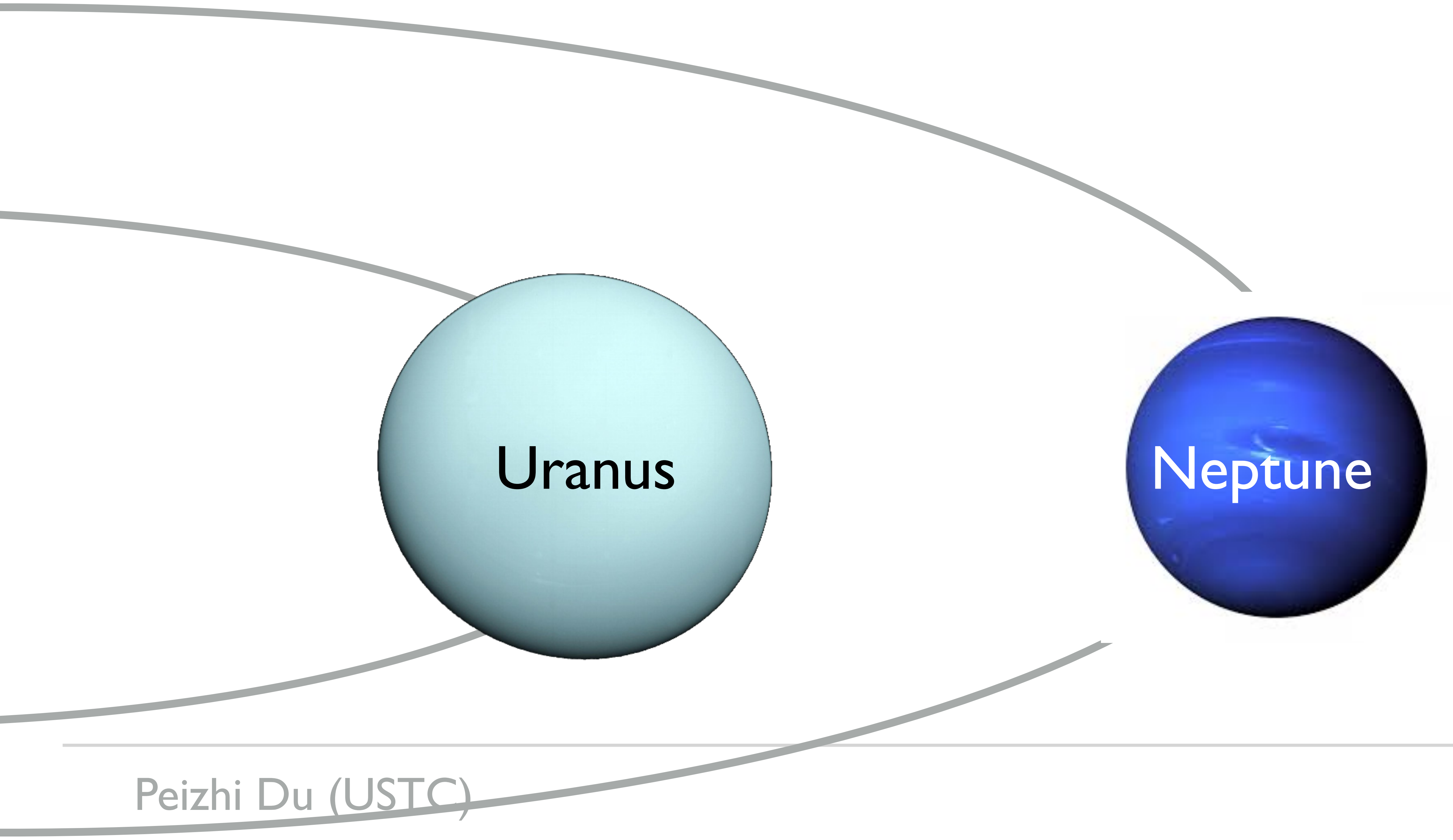
Expectation from visible matter

$$v = \sqrt{\frac{GM_{\rm vis}}{r}}$$

Prediction: the missing matter component is dark matter

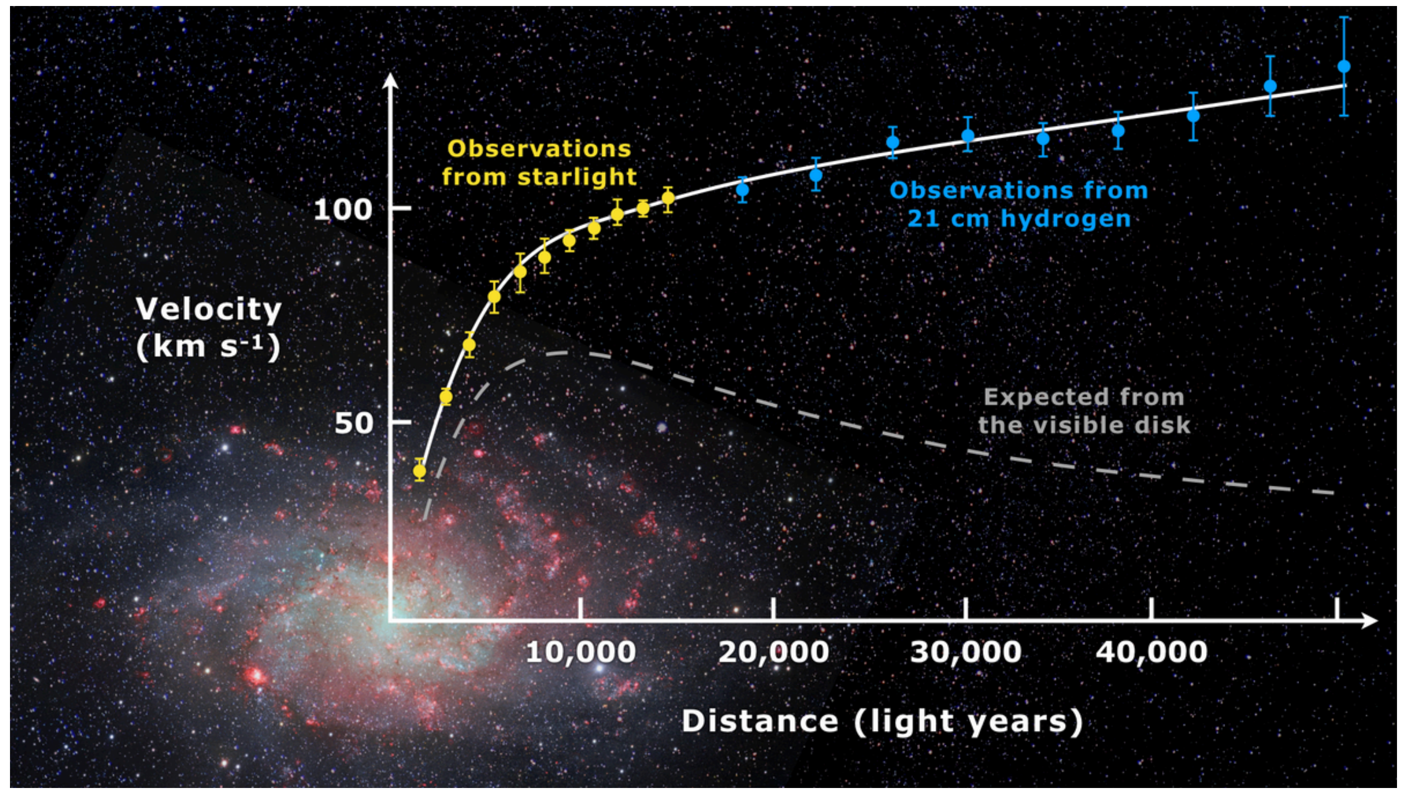
‘Dark Matter’ in the Solar System

Observation vs theory	Prediction	Discovery
Irregularities in Uranus orbits	unknown planet further than Uranus “dark planet”	Neptune
Irregularities in star motions	unknown matter component dark matter	?

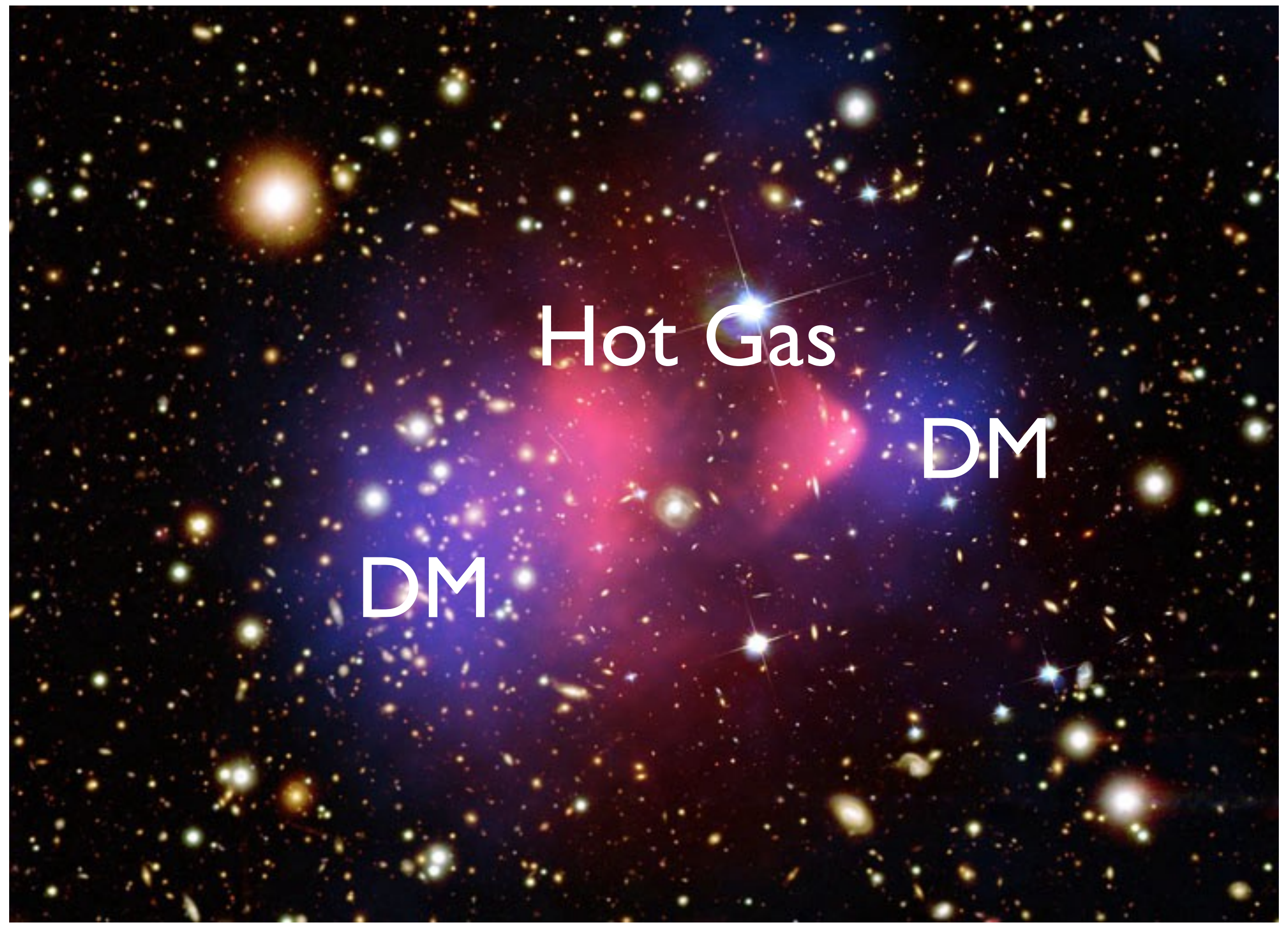


Dark Matter

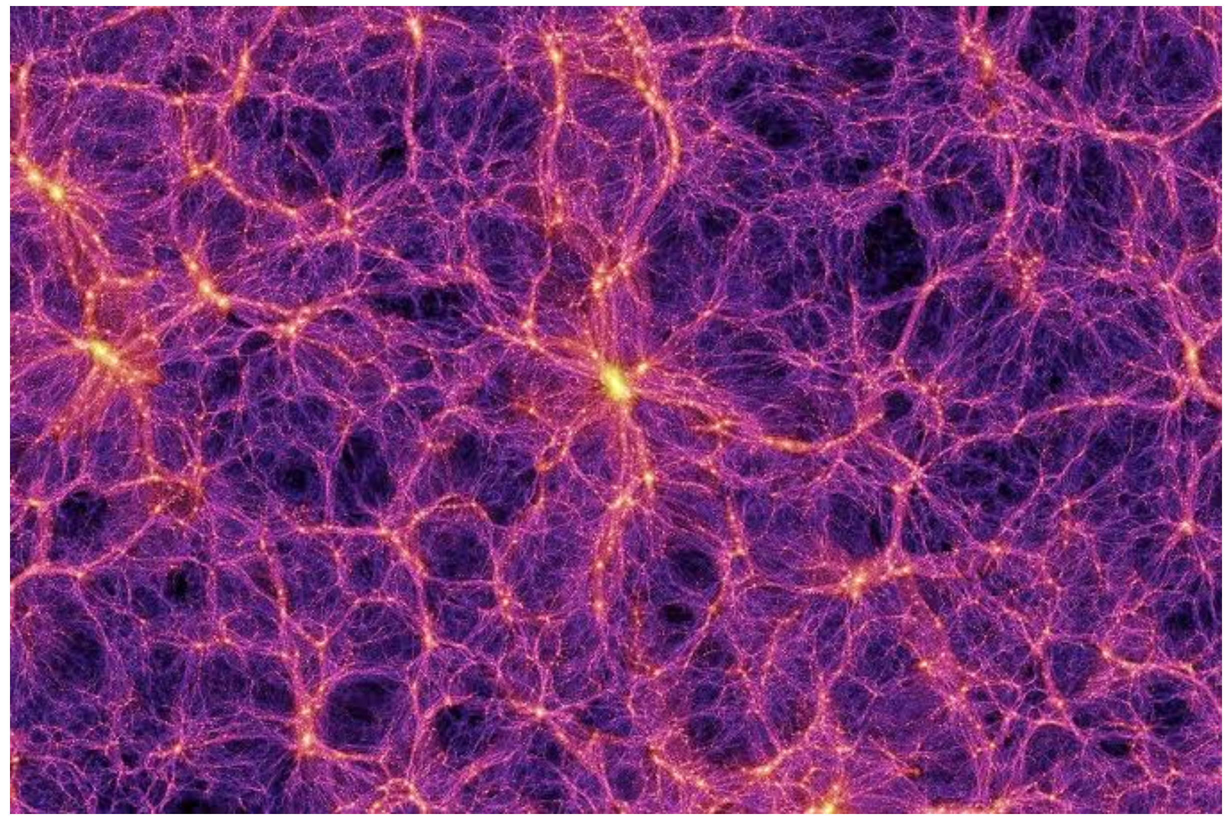
Numerous evidence for the existance of DM



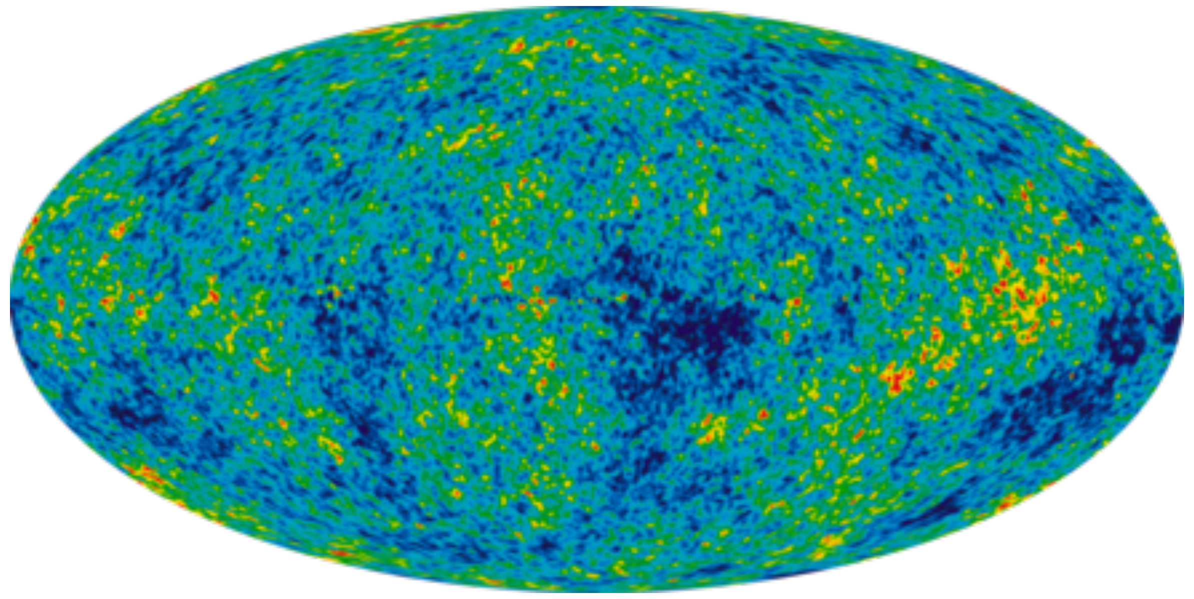
Galaxy (10^4-10^5 ly)



Galaxy Cluster (~10^6 ly)



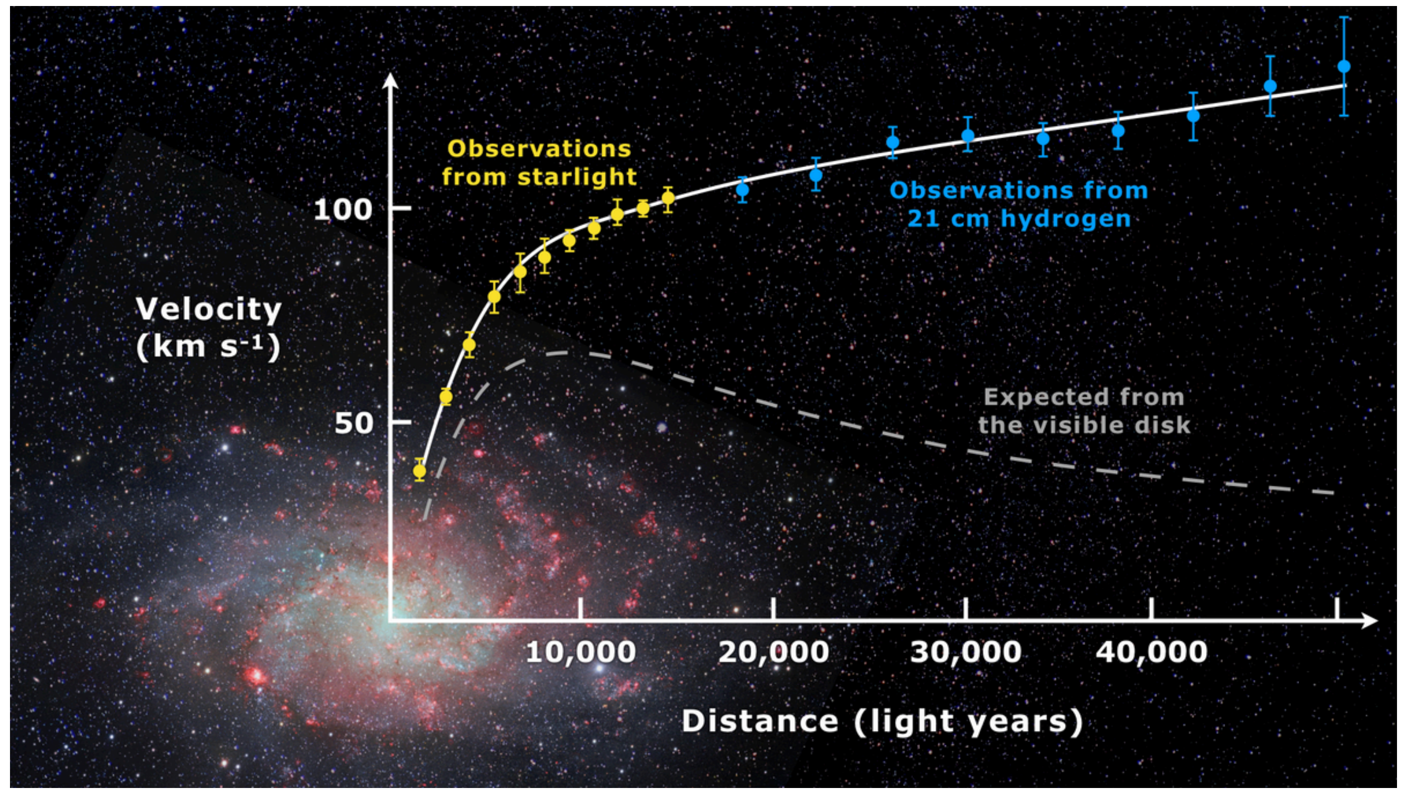
Large Scale Structure (~10^7 ly)



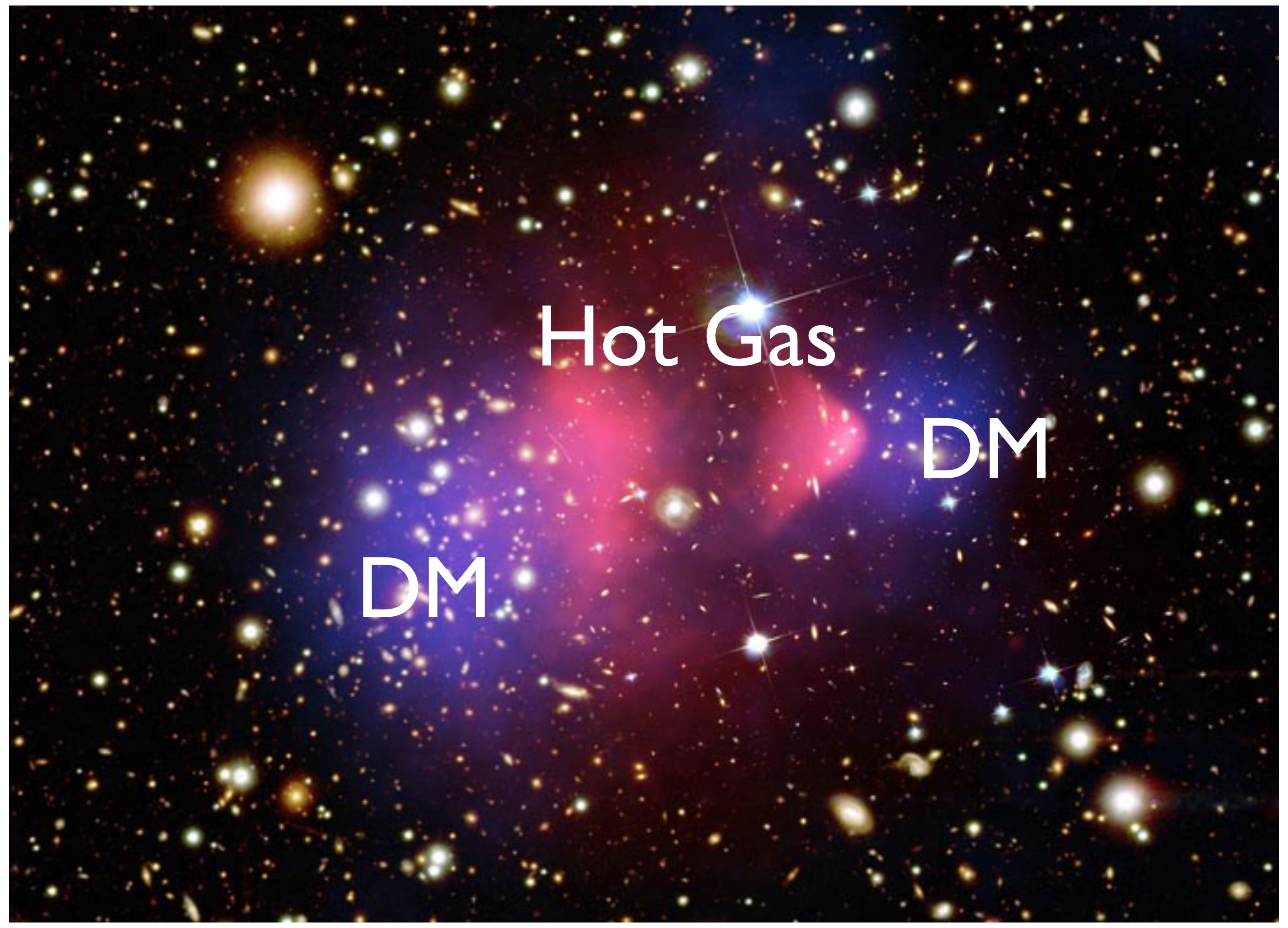
Cosmic Microwave Background (~10^{10} ly)

Dark Matter

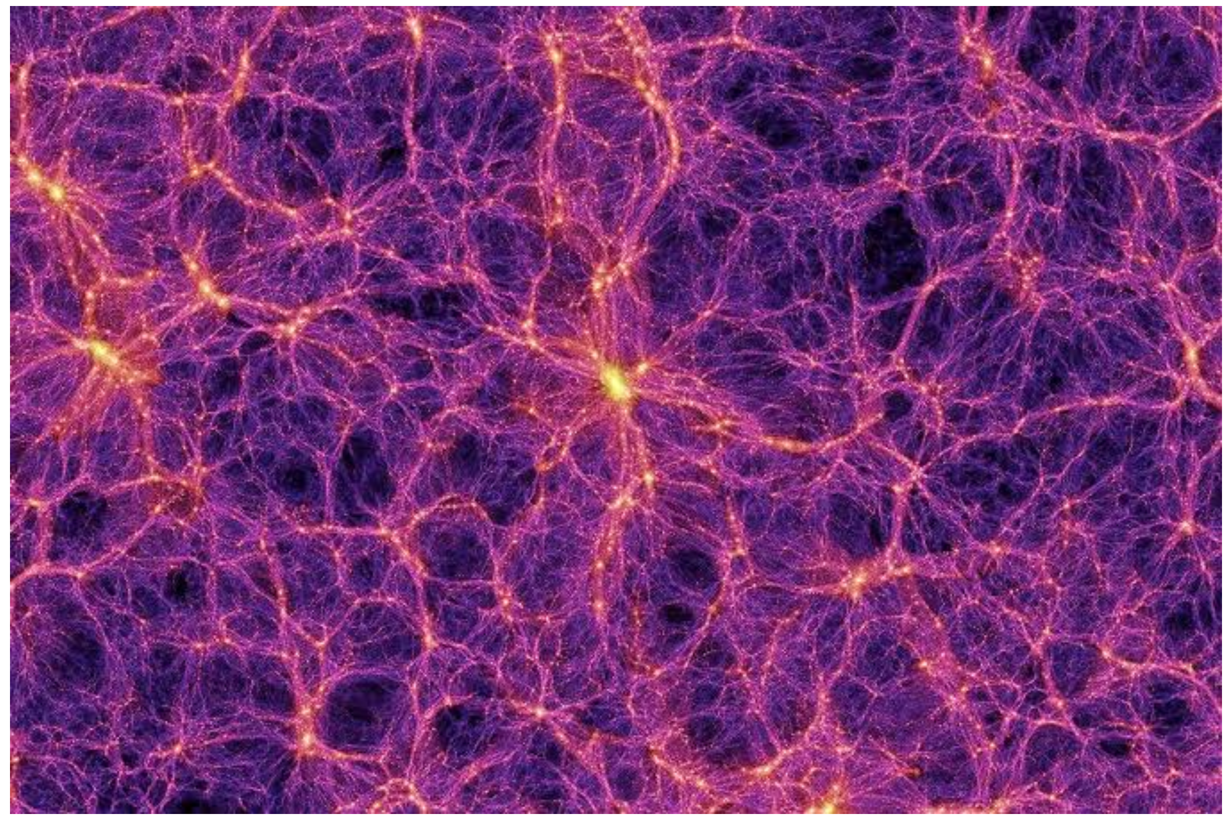
Numerous evidence for the existance of DM



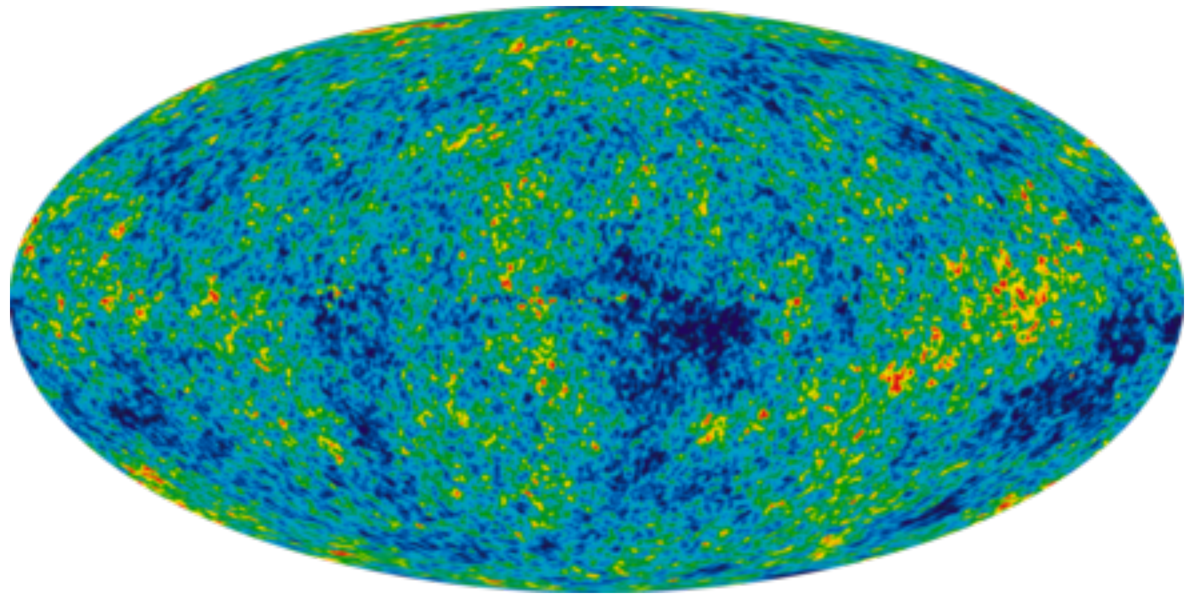
Galaxy (10^4-10^5 ly)



Galaxy Cluster (~10^6 ly)



Large Scale Structure (~10^7 ly)



Cosmic Microwave Background (~10^{10} ly)

What we know about DM

- Abundant: 85% of matter
- Massive
- Gravitational interactions
- Cold/Collisionless

What we don't know about DM

- Particle Nature
- Mass
- Interactions with visible matter?
- DM self-interactions?

…

What Could Dark Matter Be

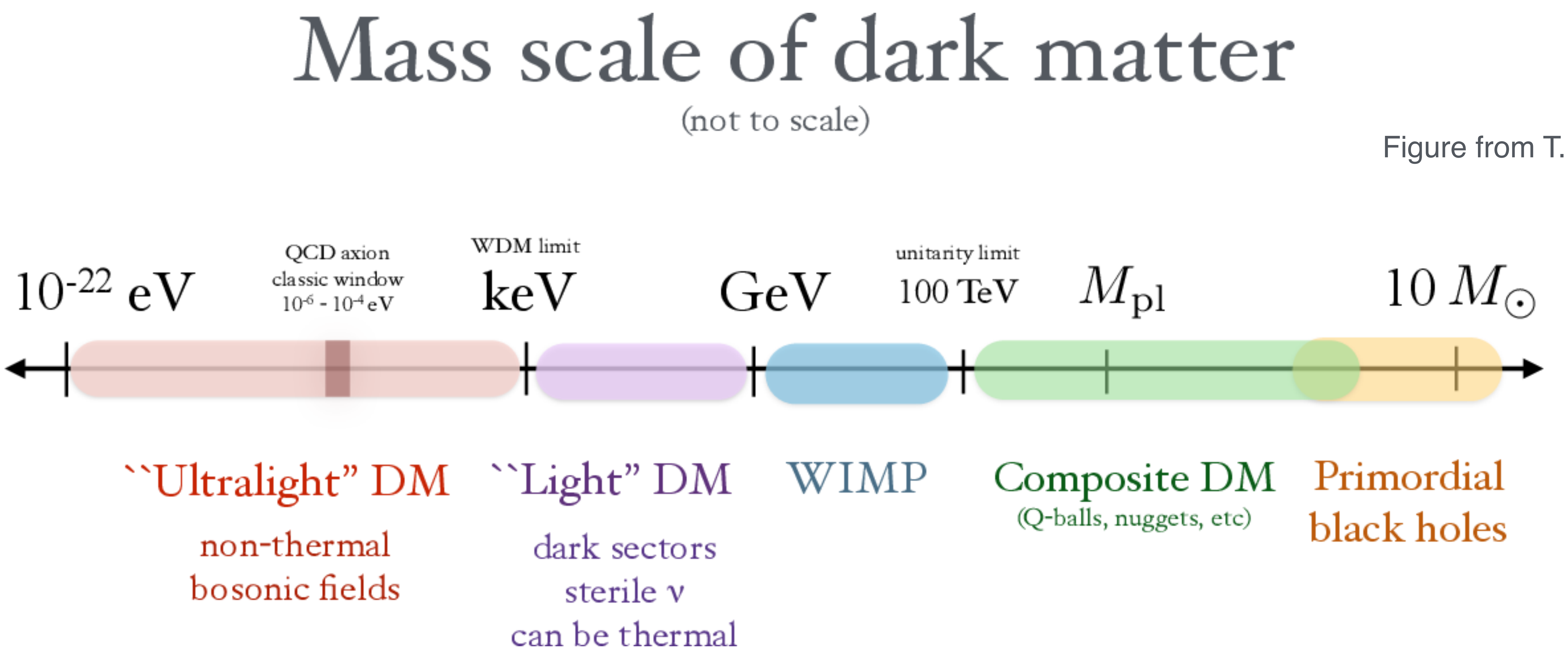
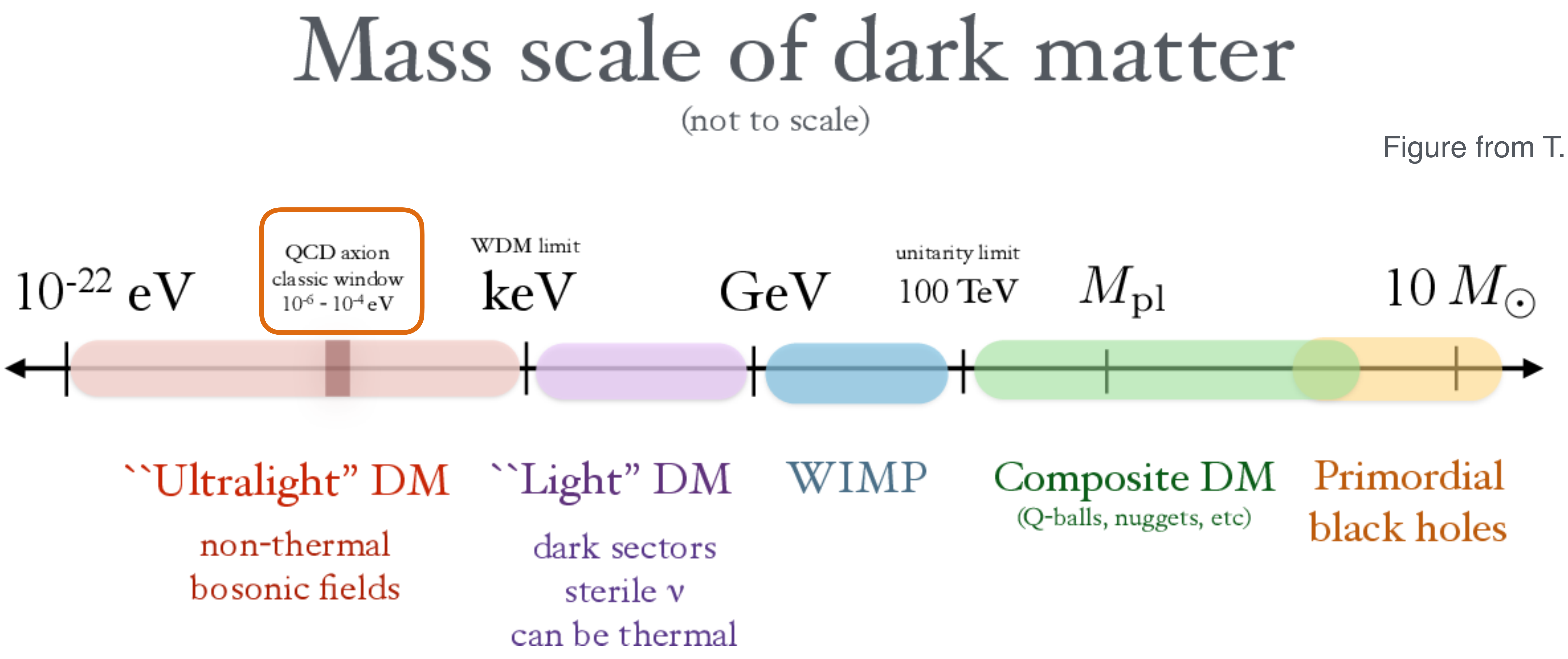


Figure from T. Lin (arXiv:1904.07915)

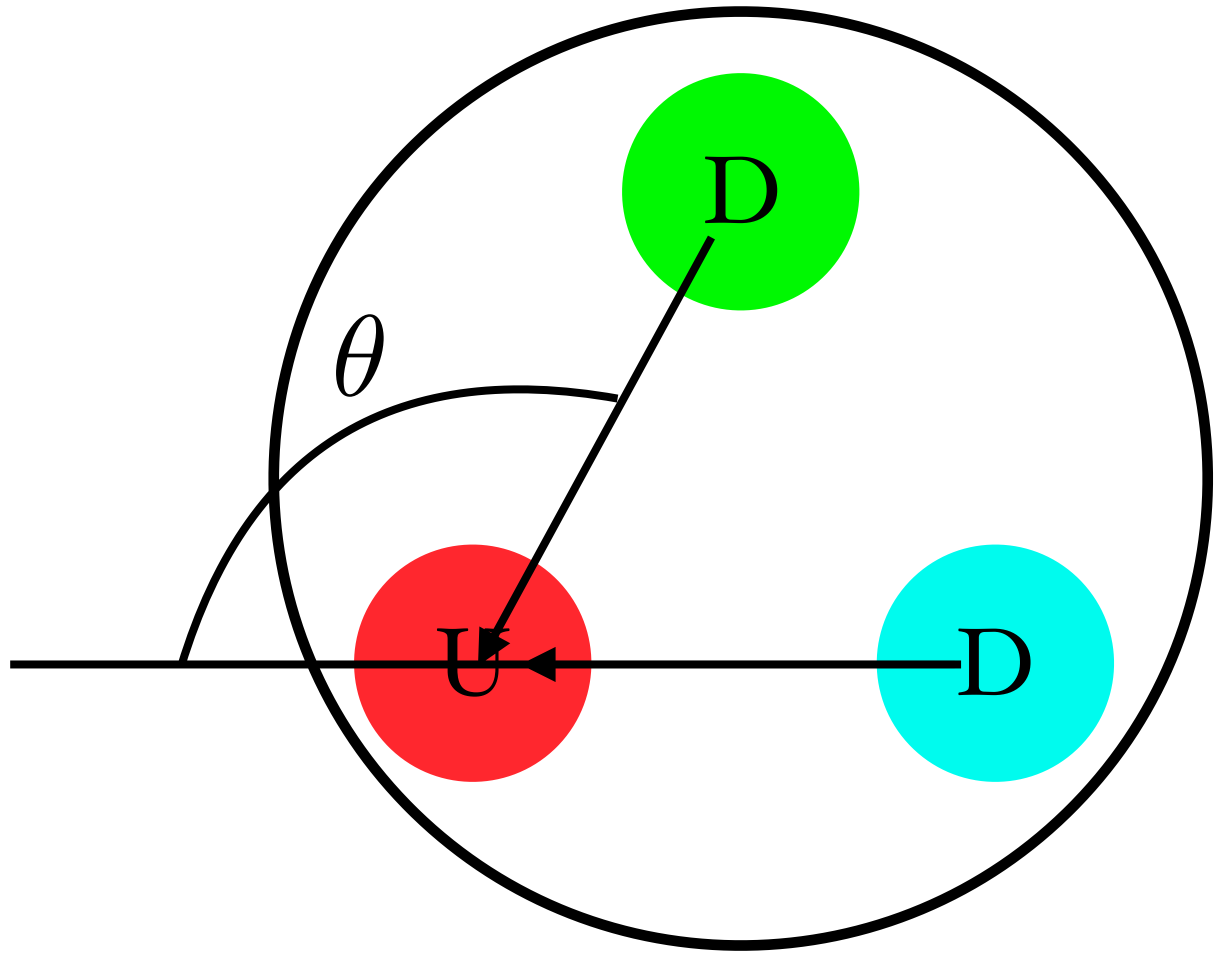
What Could Dark Matter Be

Figure from T. Lin (arXiv:1904.07915)



The Strong CP Problem

Neutron Electric Dipole Moment



Classical picture of a neutron

- Classical esitmation

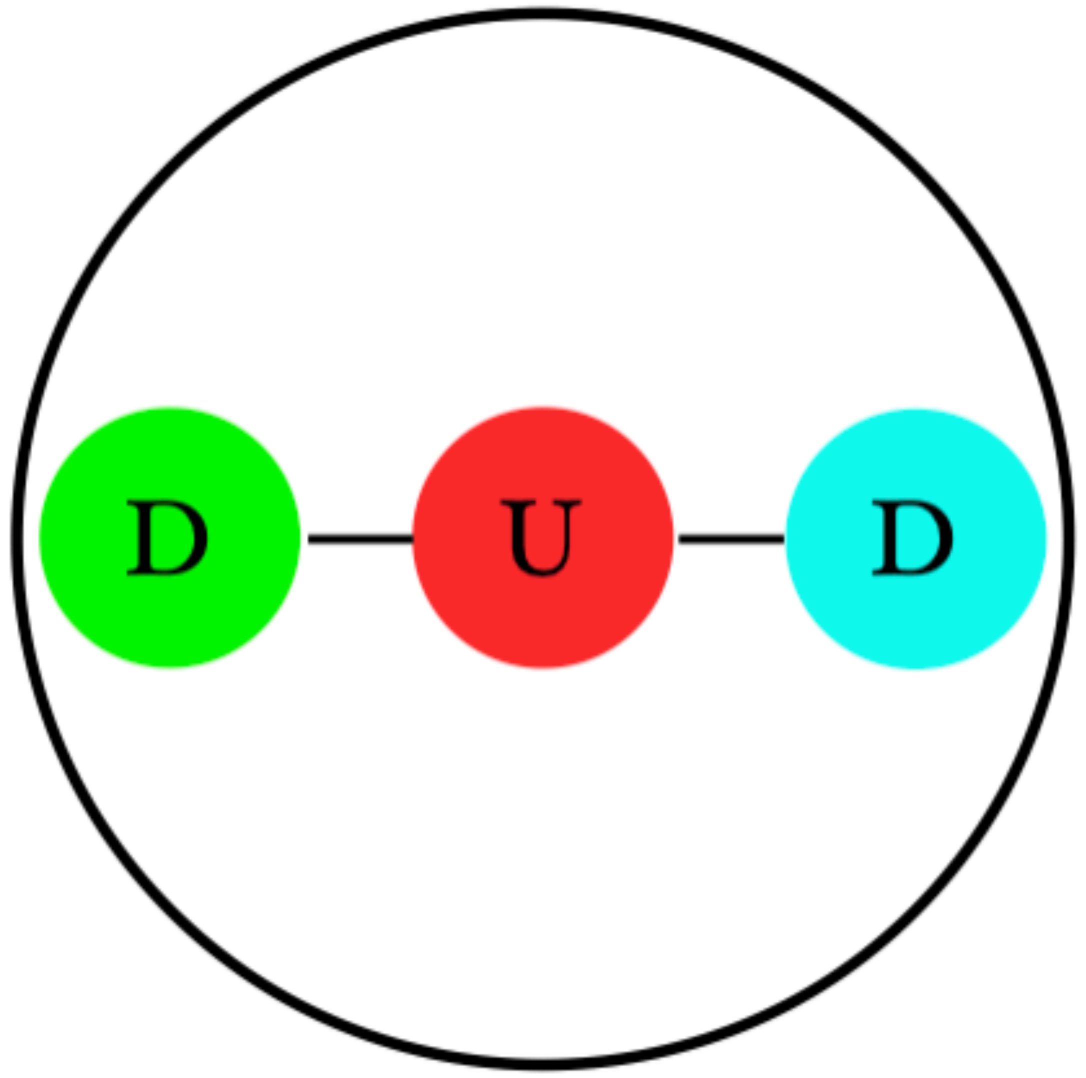
$$\vec{d}_n = \sum_i q_i \vec{r}_i$$

$$d_n \approx 10^{-13} \sqrt{1 - \cos\theta}\; e\,\mathrm{cm}$$

A. Hook's lecture note (arXiv:1812.02669)

The Strong CP Problem

Neutron Electric Dipole Moment



Classical picture of a neutron

- Classical esitmation

$$\vec{d}_n = \sum_i q_i \vec{r}_i$$

$$d_n \approx 10^{-13}\sqrt{1-\cos\theta}\; e\,\mathrm{cm}$$

- Experimental measurements:

$$|d_n| \leq 10^{-26}\, e\,\mathrm{cm}$$

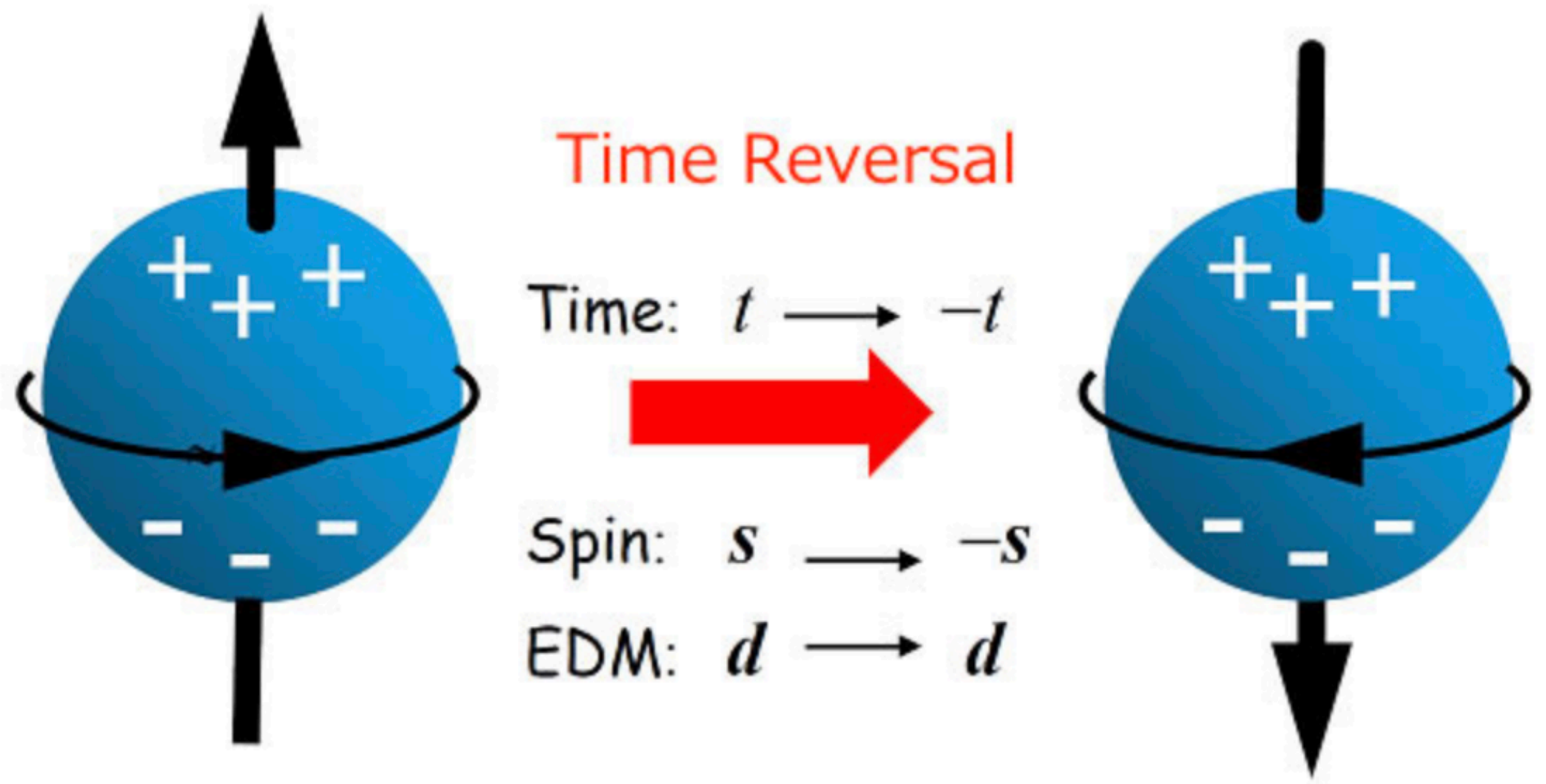
$$\theta \leq 10^{-13}$$

Why it is so small!

A. Hook's lecture note (arXiv:1812.02669)

The Strong CP Problem

CP properties of the EDM

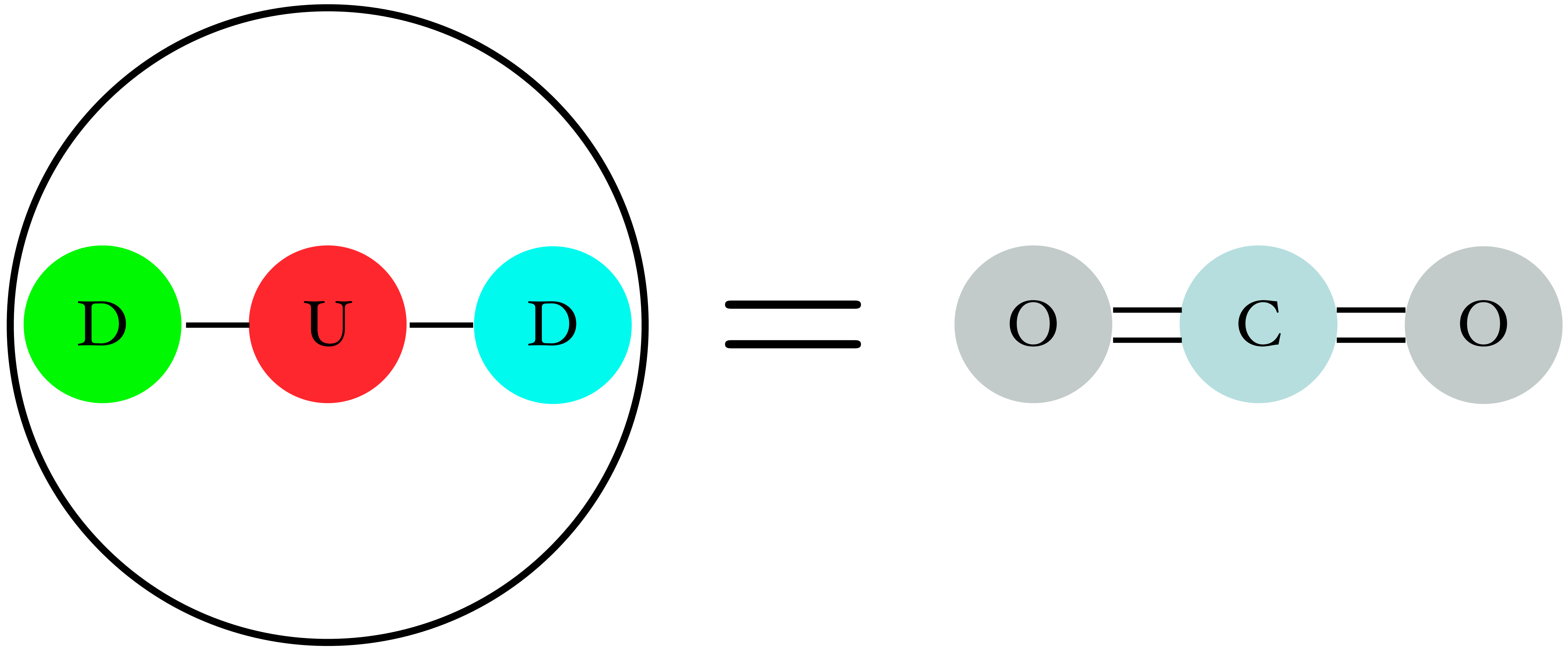


$\vec{d}_n \parallel \vec{s}$ $\vec{d}_n \parallel -\vec{s}$

Existance of EDM violates CP or T symmetry

- If CP or T is a fundamental symmetry of the theory, neutron EDM is force to be zero
- However, weak interactions violate CP maximally! CP is not a fundamental symmetry.
- Need a dynamical solution to the strong CP problem

The Classical Solution to the Strong CP Problem



- If the angle is dynamical, it will be relaxed to zero via Coulomb interactions.

QCD Axion Solution to the Strong CP Problem

- Strong CP problem in quantum field theory

$$\mathcal{L} \ni \frac{\theta}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} \quad \rightarrow \quad d_n \sim 10^{-16}\theta\, e\,\mathrm{cm}$$

- Introducing QCD axion field, making the theta parameter a dynamical field.

$$\mathcal{L} \ni \left(\theta + \frac{a}{f_a}\right) \frac{1}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \theta \to \theta + \frac{a}{f_a}$$

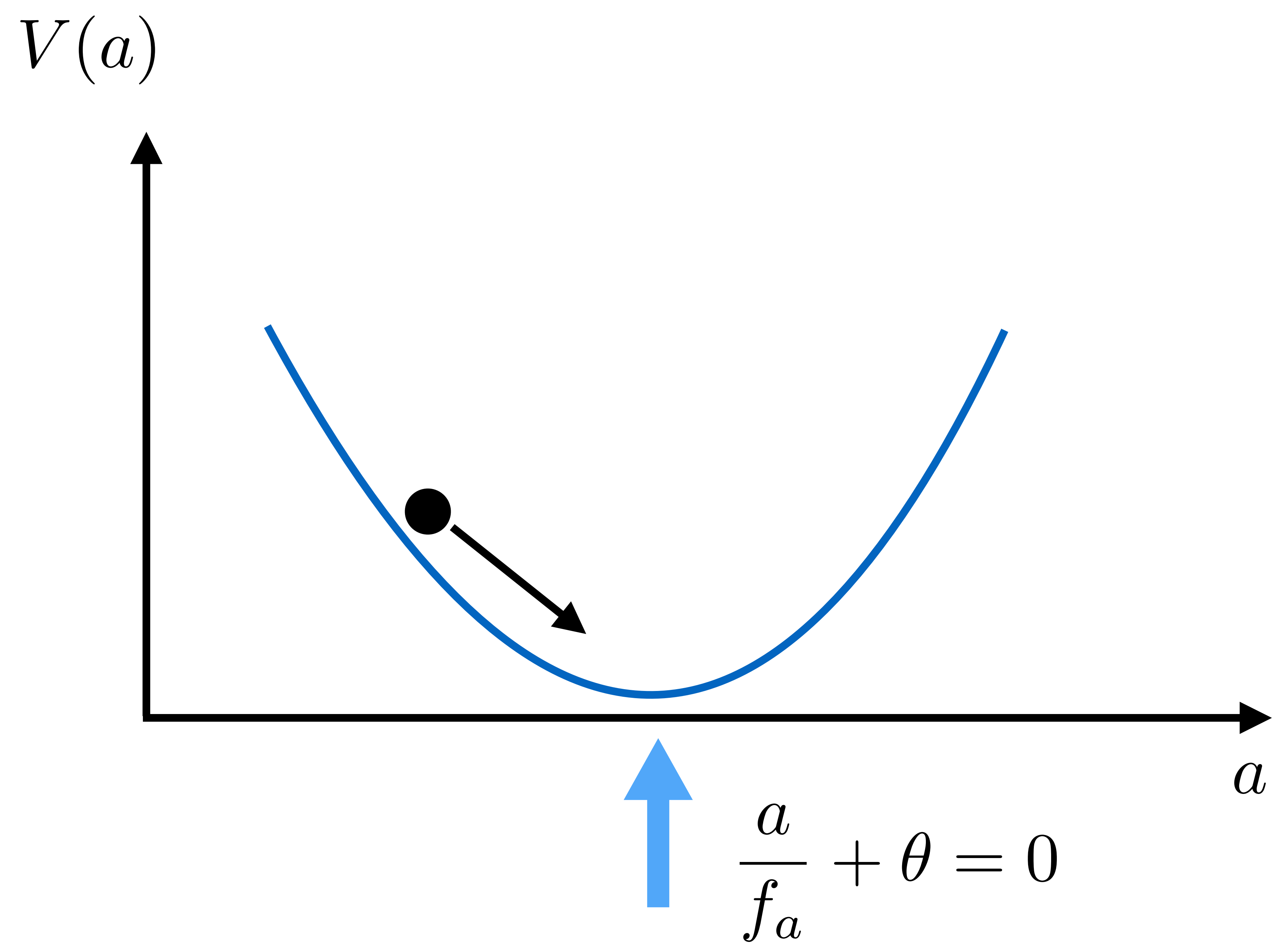
- Goldstone boson of PQ symmetry breaking, has shift symmetry perturbatively: $a \to a + c$

- The evolution of axion field dynamically set $\theta + \frac{a}{f_a}$ to be zero, thus solving the strong CP problem

Potential Energy of the QCD Axion

$$V(a) \sim m_u \Lambda_{\rm QCD}^3 \left[1 - \cos\left(\frac{a}{f_a} + \theta\right)\right]$$

from non-perturbative QCD instanton



Dynamical solution to the strong CP problem

- Axion mass

$$m_a^2 \sim m_u \Lambda_{\rm QCD}^3 / f_a^2$$

$$m_a \sim 10^{-6} {\rm eV} \left(\frac{10^{12} {\rm GeV}}{f_a}\right)$$

Experimental constraints force f_a to be high

QCD axions are generally light

QCD Axion vs Axion-like Particles

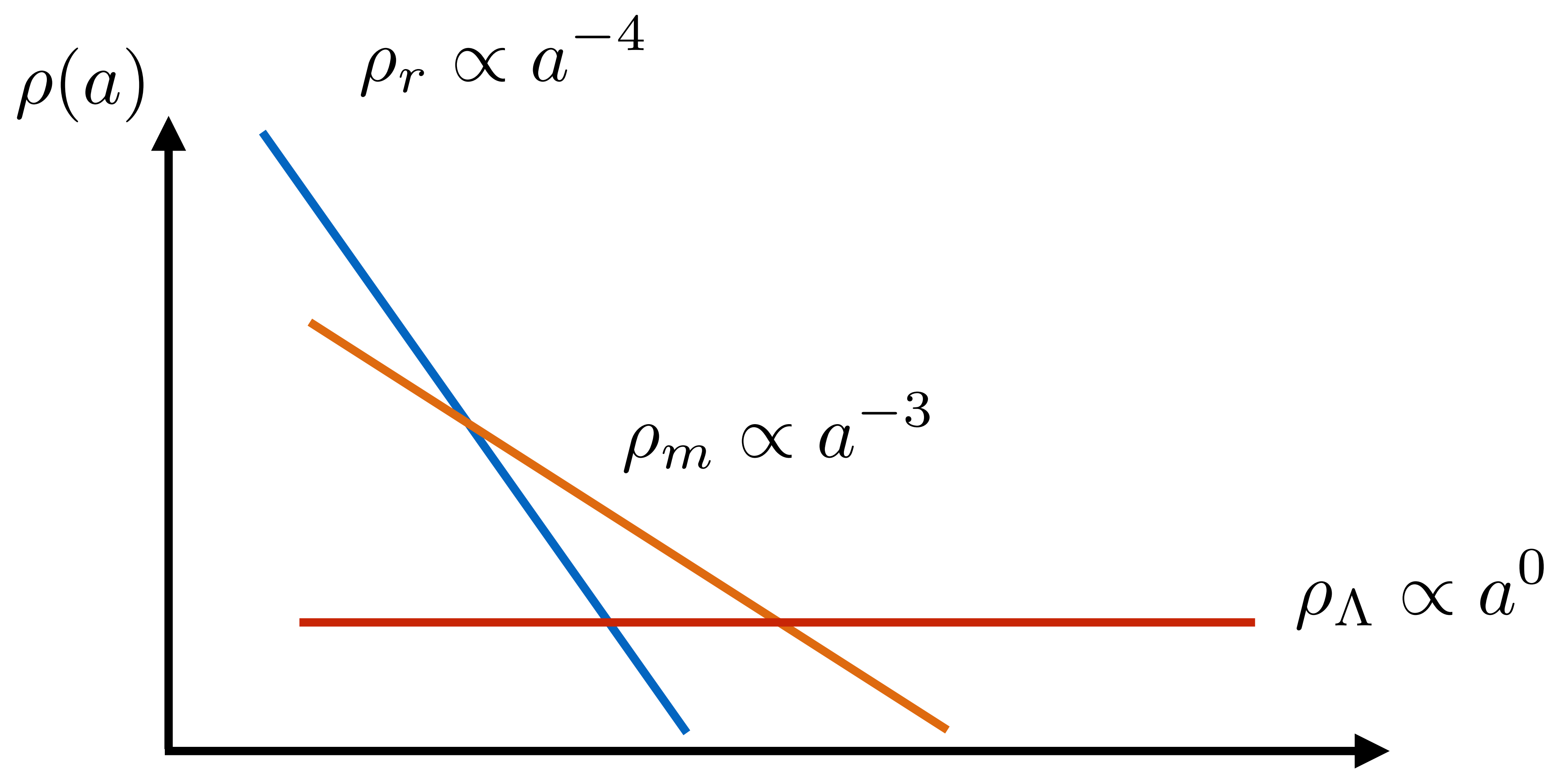
	QCD Axion	Axion-like particles (ALP)
Solve the strong CP problem?	Yes	No
Theoretical considerations	Minimal and predictive	Less predictive
Experimental considerations	Hard to probe	More interesting signals and search strategies

Why Can Axion/ALP be Dark Matter?

Basics of cosmology

$$ds^2 = dt^2 - a^2(t)\delta_{ij}dx^i dx^j$$ FRW metric

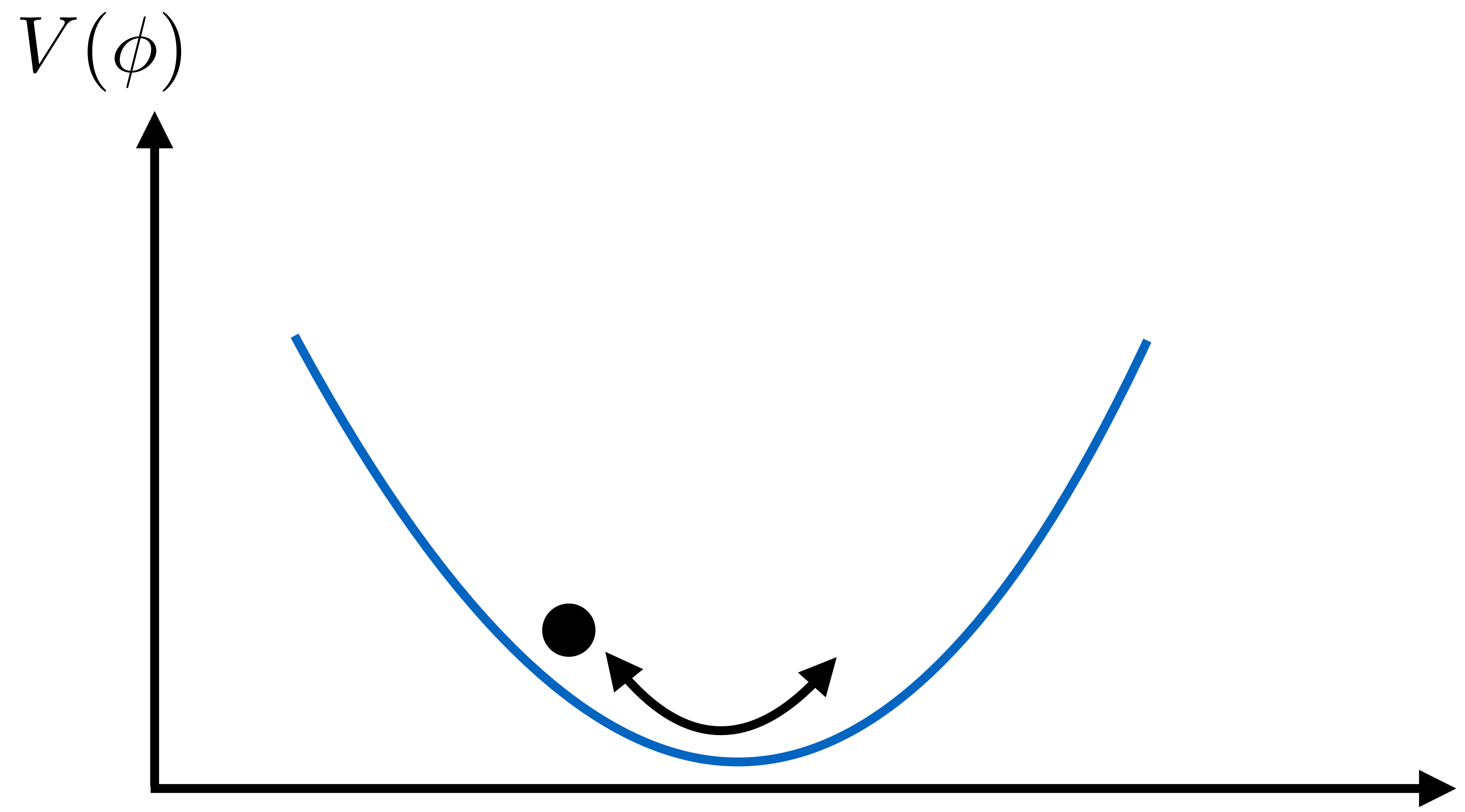
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$ Hubble parameter



ALP in cosmology

$$\ddot{\phi} + 3H\dot{\phi} + V(\phi)' = 0 \qquad V(\phi) = \frac{1}{2}m_\phi^2\phi^2$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m_\phi^2\phi^2$$



ALP (massive scalar field) behaves like dark matter in cosmology

Misalignment Mechanism

- ALP EoM

$$\ddot{\phi} + 3H\dot{\phi} + V(\phi)' = 0$$

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 \qquad H(a_{\rm osc}) = m_\phi/2$$

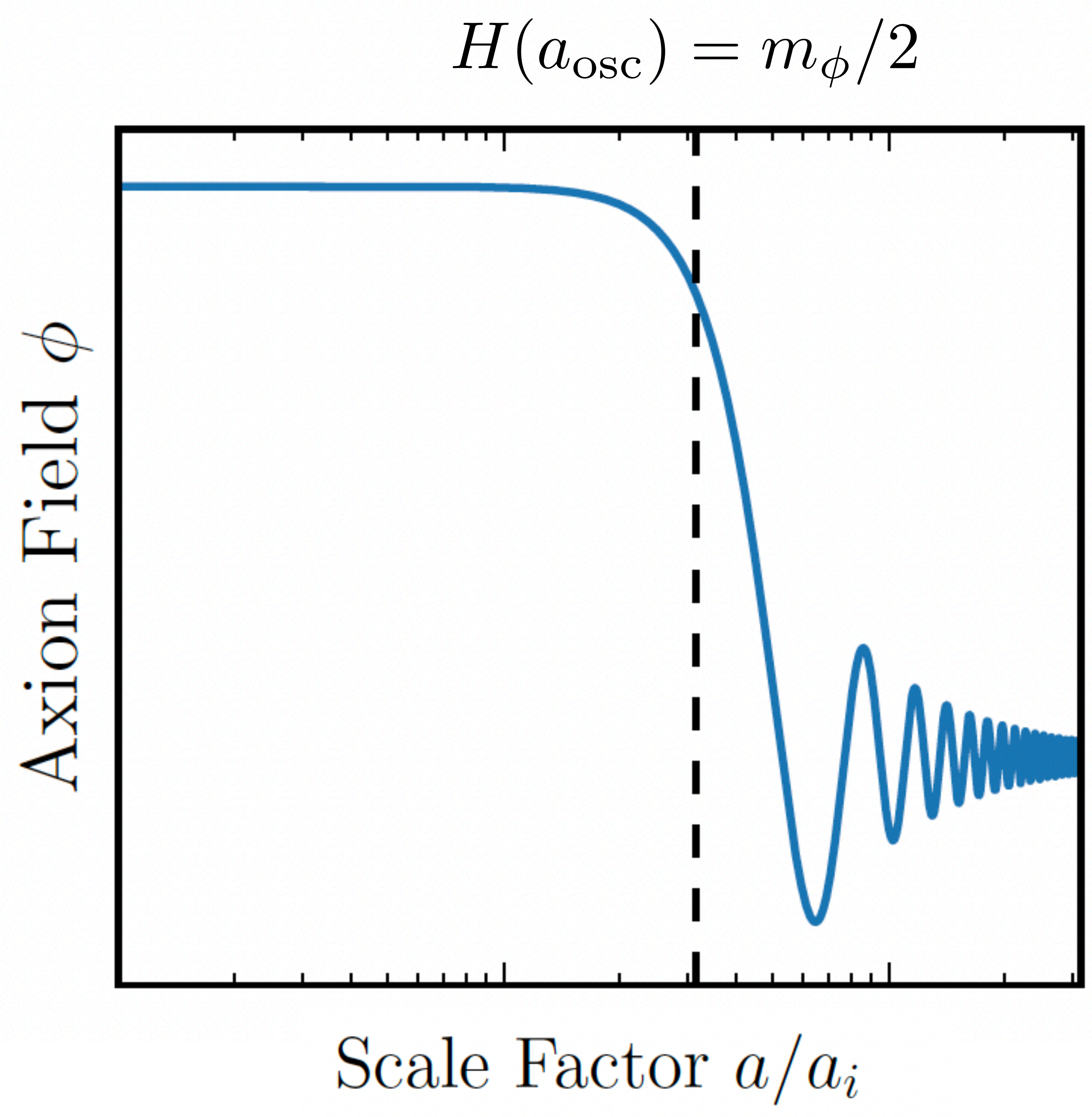
- ALP initial condition

$$\phi(a_i) = \theta_i f_a \quad , \quad \dot{\phi}(a_i) = 0$$

Misalignment angle

$$H \gg m_\phi \qquad \phi(a) \approx \theta_i f_a \qquad (a \ll a_{\rm osc})$$

$$H \ll m_\phi \qquad \phi(a) \sim \phi(a_{\rm osc})(a/a_{\rm osc})^{-3/2}\cos(m_\phi t) \qquad (a \gg a_{\rm osc})$$



- ALP energy density

$$\rho_\phi \sim m_\phi^2\phi_i^2(a/a_{\rm osc})^{-3} \sim \theta_i^2 m_\phi^2 f_a^2 (a/a_{\rm osc})^{-3}$$

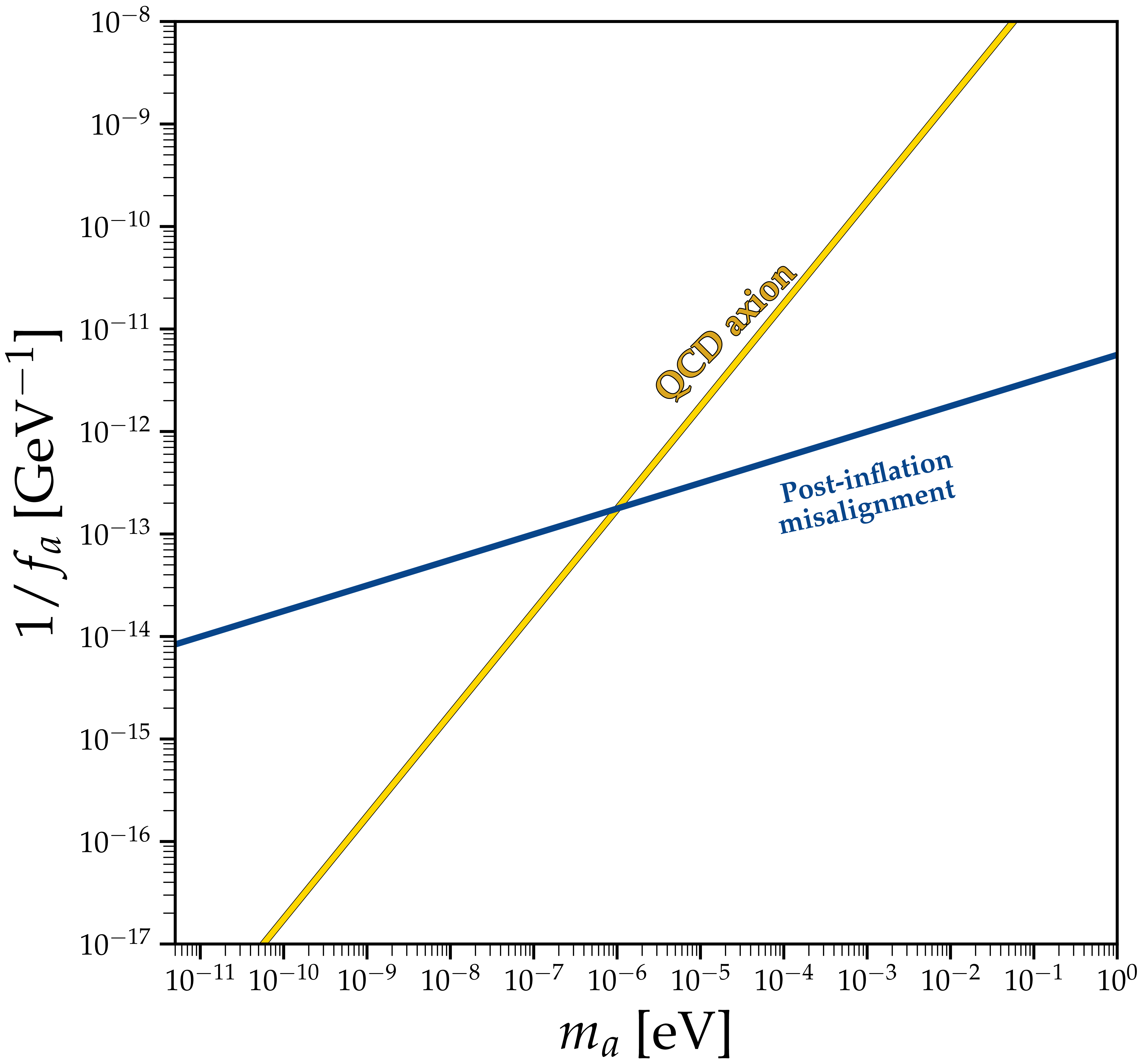
$$\Omega_a/\Omega_{\rm DM} \sim \theta_i^2 \left(\frac{f_a}{10^{14}{\rm GeV}}\right)^2 \left(\frac{m_\phi}{10^{-10}{\rm eV}}\right)^{1/2}$$

Misalignment Mechanism

$$\Omega_a/\Omega_{\rm DM} \sim \theta_i^2 \left(\frac{f_a}{10^{14}\mathrm{GeV}}\right)^2 \left(\frac{m_\phi}{10^{-10}\mathrm{eV}}\right)^{1/2}$$

Pre-inflation: θ_i^2 is a random number

Post-inflation: $\langle\theta_i^2\rangle \approx \pi^2/3$



Summary

- Dark Matter

- The strong CP problem

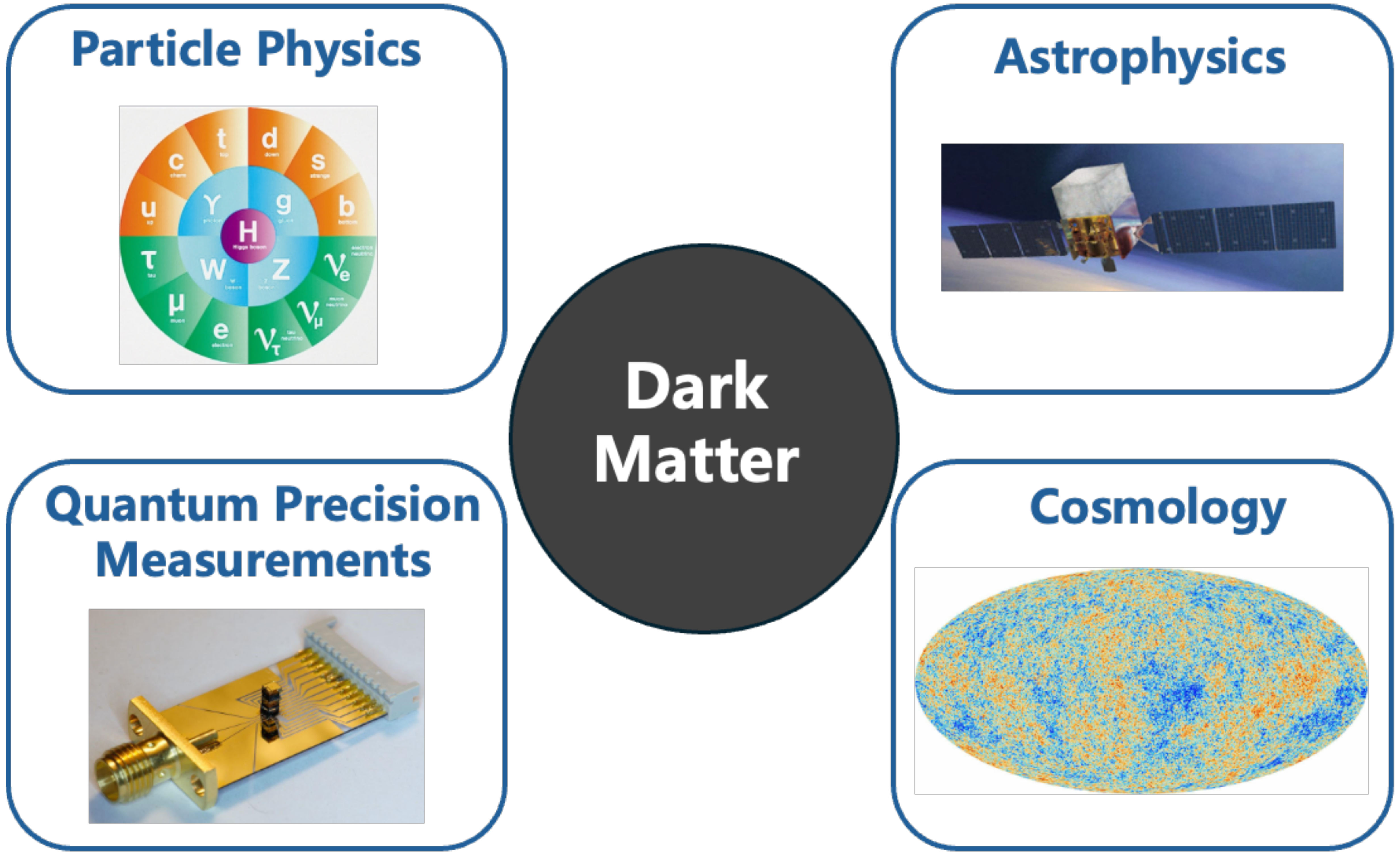
  Classical picture and solutions

- QCD axions and axion-like particles

  Solution to the strong CP problem

  Why axions can be dark matter: Misaligment mechanism

Detecting DM: frontier of multiple research fields



Challenges:

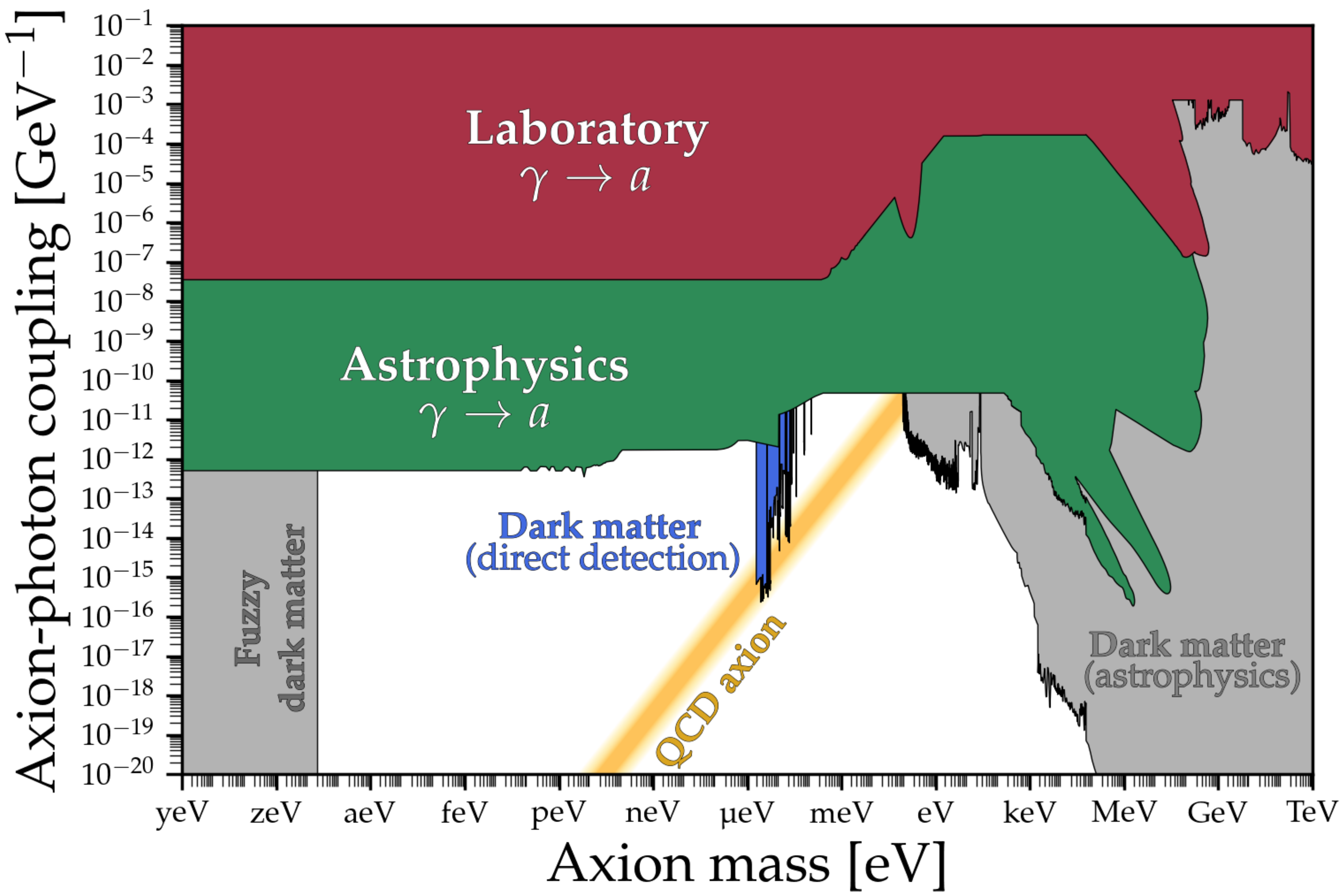
- Interactions too weak
- Signals are hard to detect
- Backgrounds are high

What we need:

High-precision low-threshold detectors
or unique observables with low backgrounds

How to look for Axion DM or ALP

$$\mathcal{L} = g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



General Features of Axion DM

- Behaves like a classical wave in stead of a particle

$$\lambda \sim (m_a v_a)^{-1} \qquad \gg \qquad d \sim (\rho_{\rm DM}/m_a)^{-1/3}$$

$$v_a = v_{\rm DM} \sim 10^{-3}$$

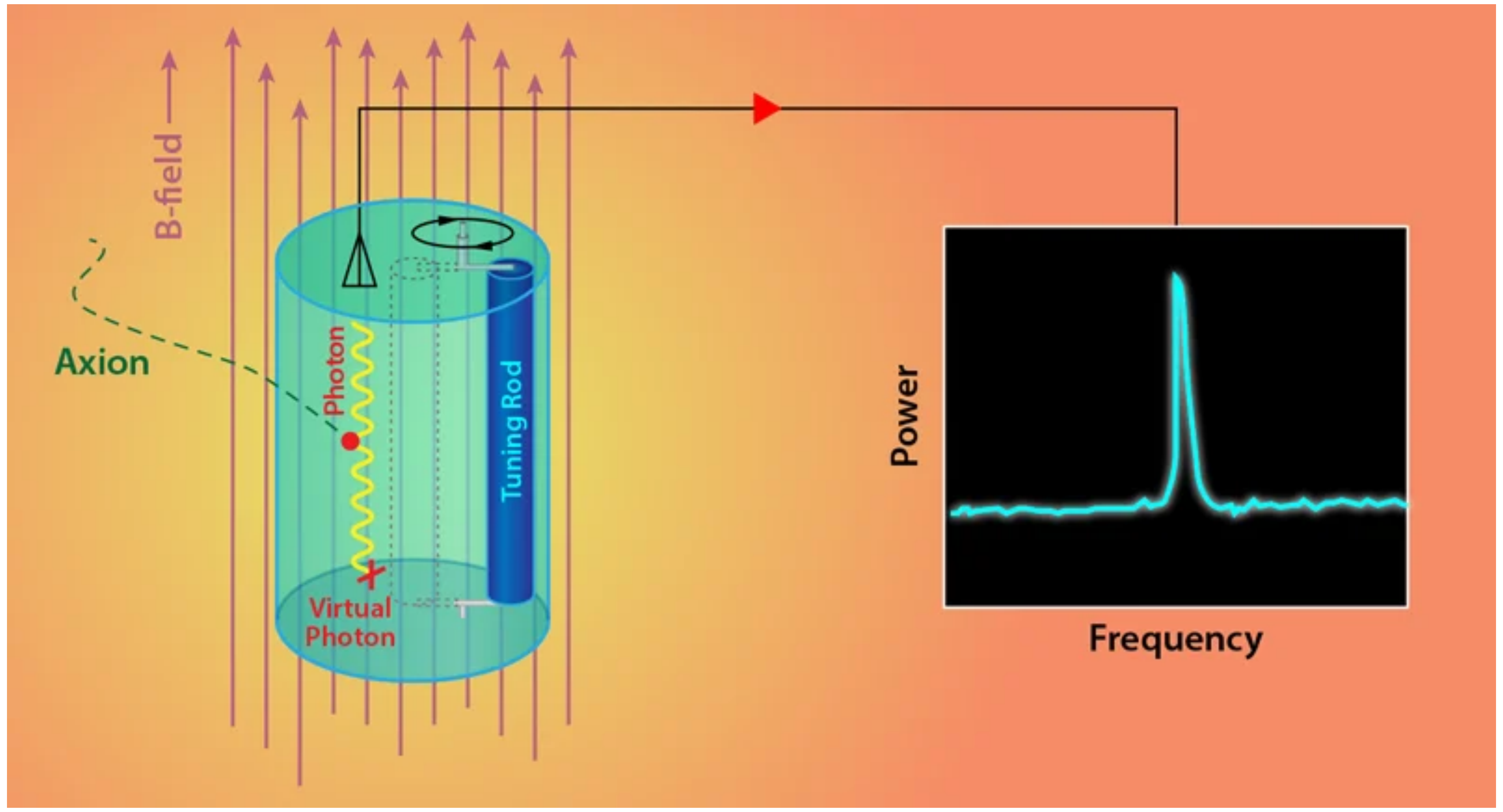
- Axion field: oscillating classical field with $\omega = m_a$, very small spatial gradiant

$$a \approx \frac{\sqrt{2\rho_{\rm DM}}}{m_a} \cos(m_a t - \mathbf{k}\cdot\mathbf{x}) \qquad \mathbf{k} = m_a \mathbf{v}_a$$

$$\rho_a \approx \frac{1}{2}\dot{a}^2 + \frac{1}{2} m_a^2 a^2 = \rho_{\rm DM}$$

Searches for Axions as DM

$$\mathcal{L}_{\rm int} = g_{a\gamma\gamma} a E \cdot B$$

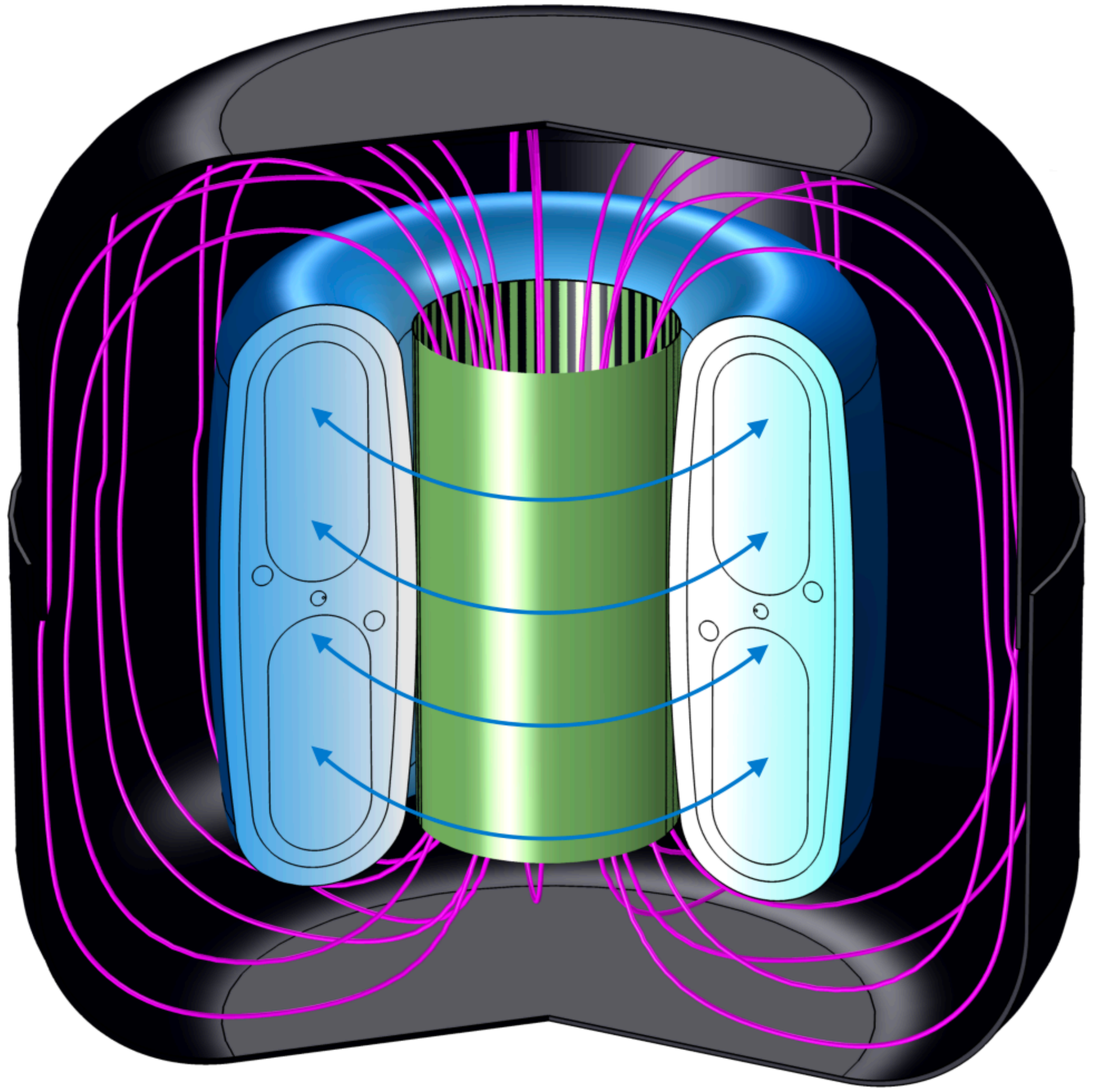


- With the background B field, axion field can convert to photons in the cavity
- If m_a matches the resonant frequency of the cavity, it triggers the resonant conversion

$$P_{a\to\gamma} \propto Q B_{\rm ext}^2 V g_{a\gamma\gamma}^2 \rho_{\rm DM}$$

Need a high Q cavity, strong B field, large volume

Searches for Axions as DM



$$\mathcal{L}_{\rm int} = g_{a\gamma\gamma} a E \cdot B$$

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J}_{\rm eff}$$

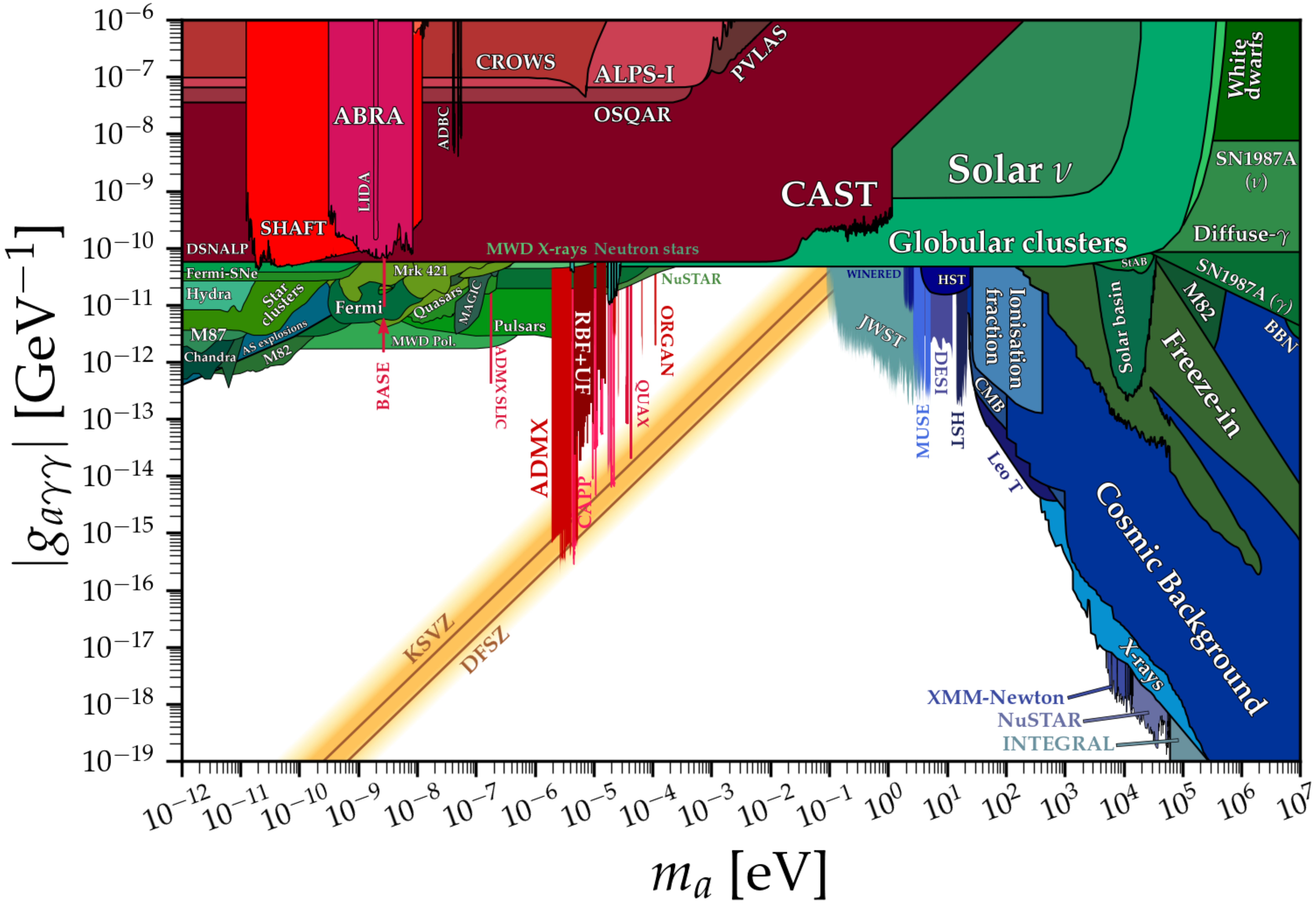
$$\mathbf{J}_{\rm eff} = g_{a\gamma\gamma} \partial_t a \mathbf{B}_0 = g_{a\gamma\gamma} \sqrt{2\rho_{\rm DM}}\, \mathbf{B}_0 \cos(m_a t)$$

- Axion induces a new effective current and generate B field where they usually can not exist

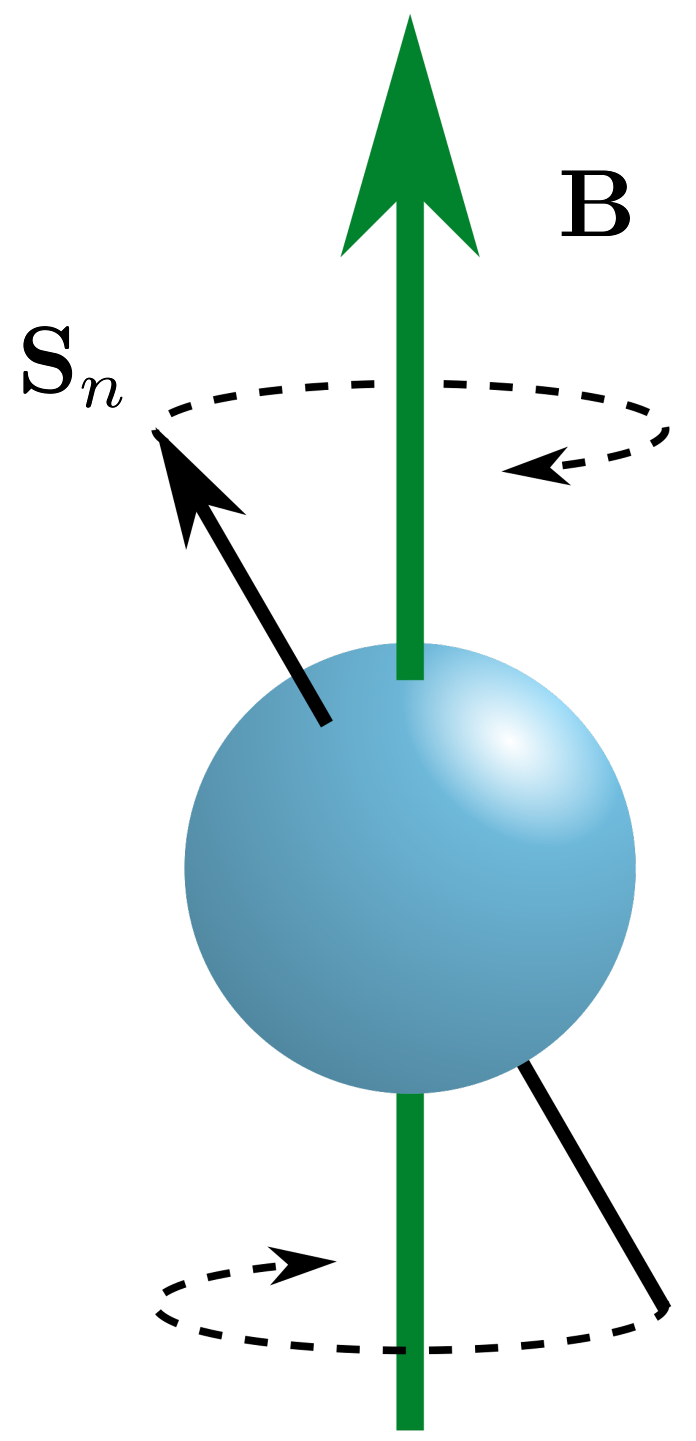
$$P_{\rm sig} \propto B_0^2 V^2 g_{a\gamma\gamma}^2 \rho_{\rm DM}$$

Axion Constraints

$$\mathcal{L} = g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Searches for Axions as DM



Larmor Precession

$$\tau = \gamma_N \mathbf{S}_n \times \mathbf{B}$$

Larmor Frequency

$$\omega = |\gamma_N B|$$

$$\mathcal{L}_{\text{int}} = g_{aNN}(\partial_\mu a)\,\bar{\psi}_n \gamma^\mu \psi_n$$
$$= g_{aNN} \nabla a \cdot \mathbf{S}_n$$

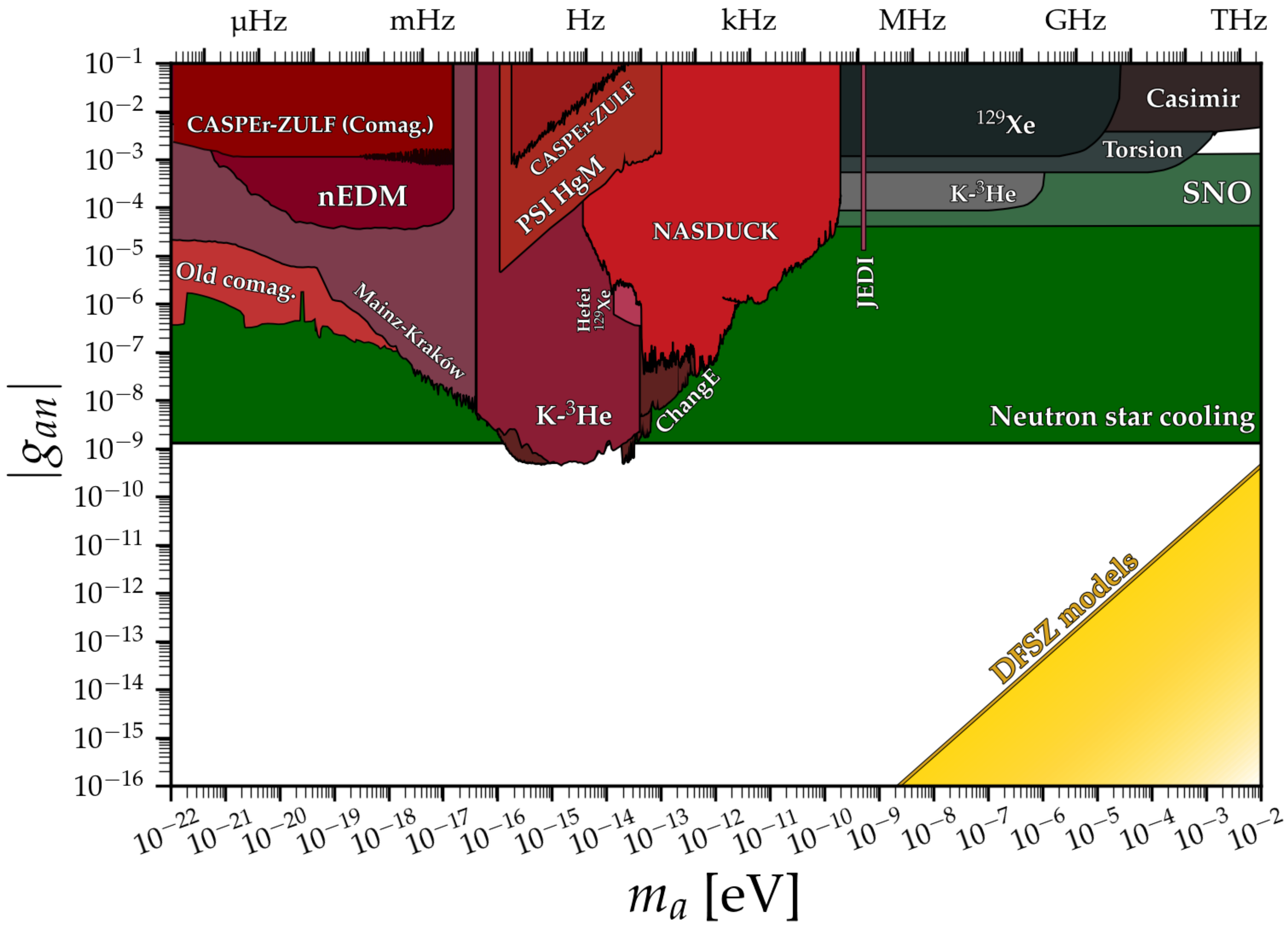
$$\mathbf{B}_{\text{eff}} = g_{aNN}\sqrt{2\rho_{\text{DM}}}\mathbf{v}_a \cdot \cos(m_a t)/\gamma_N$$

- Axion field induces an effective oscillating B field
- Quantum spin sensors can probe such small oscillating B field

Series searches done at USTC!

Axion Constraints

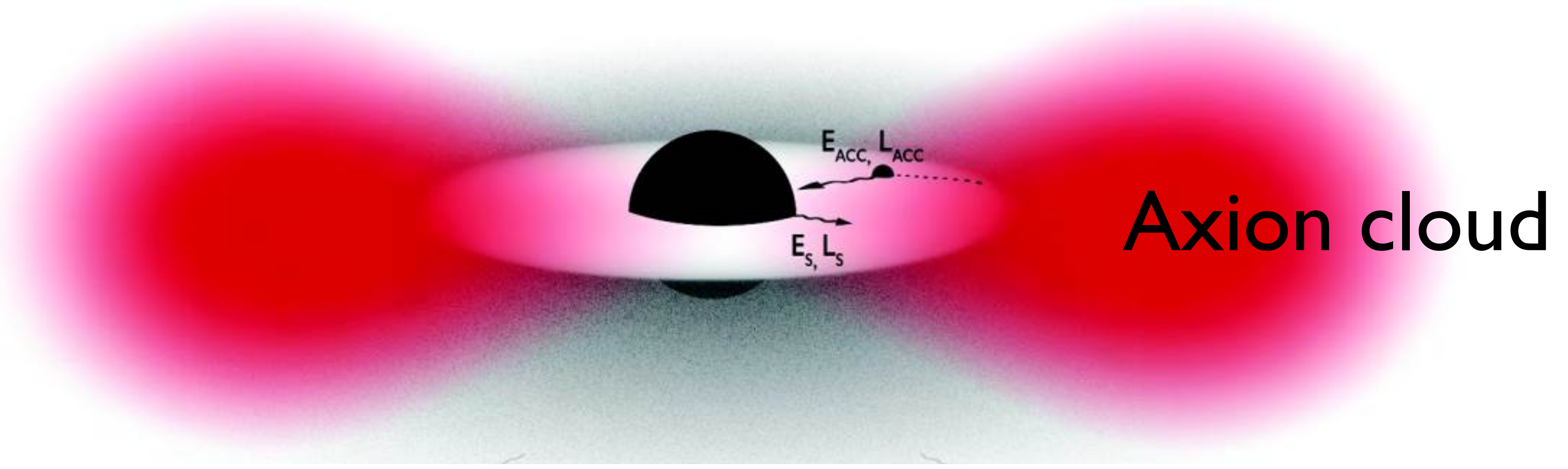
$$\mathcal{L}_{\text{int}} = g_{aNN}(\partial_\mu a)\,\bar{\psi}_n \gamma^\mu \psi_n$$



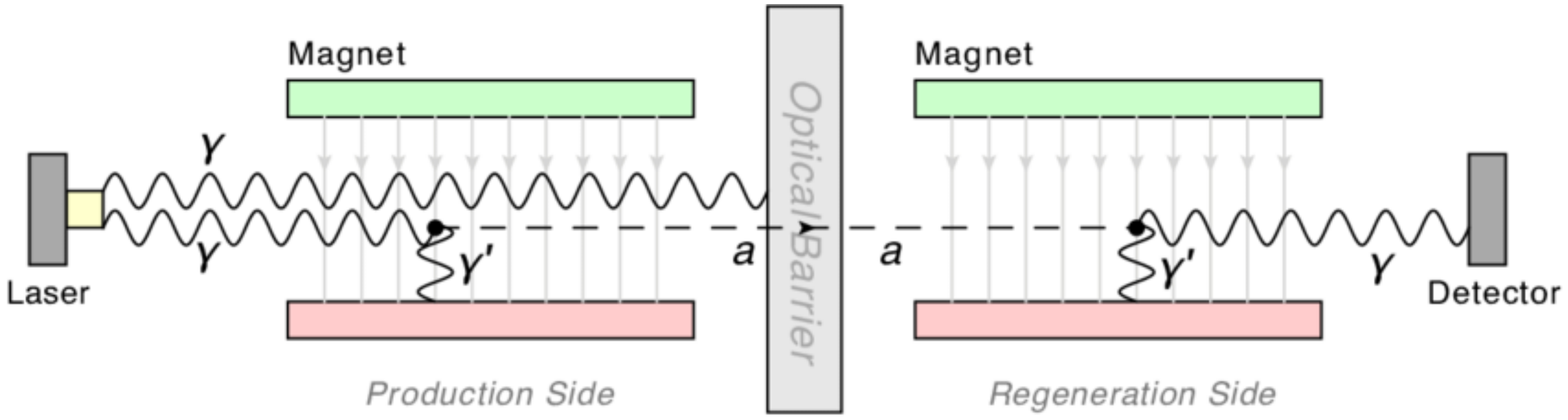
Searches for Axions Independent of DM

Stellar cooling

Supermassive BH



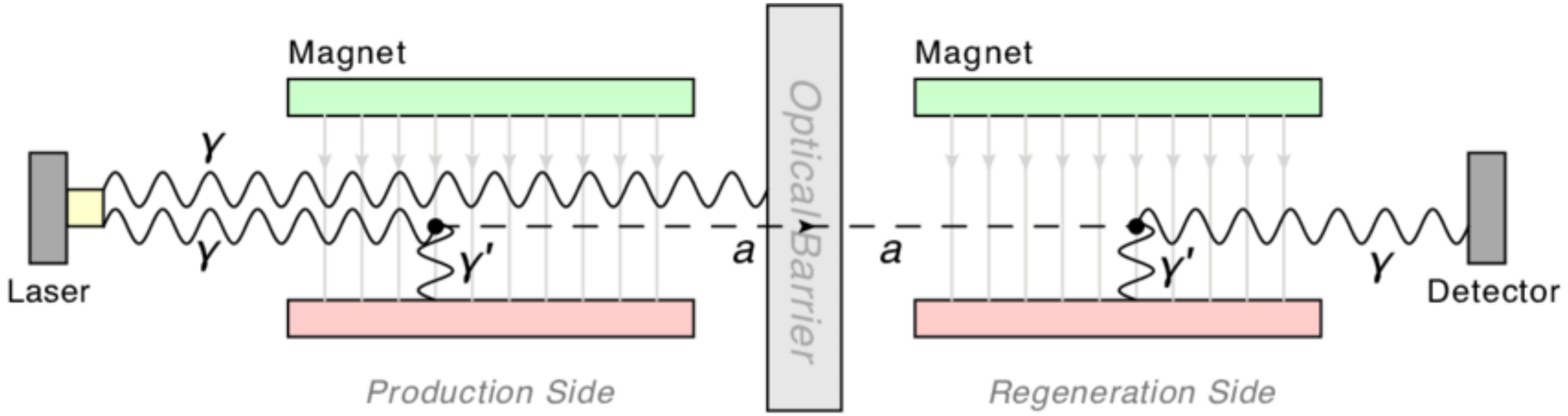
Blak hole superradiance



Light shining through wall

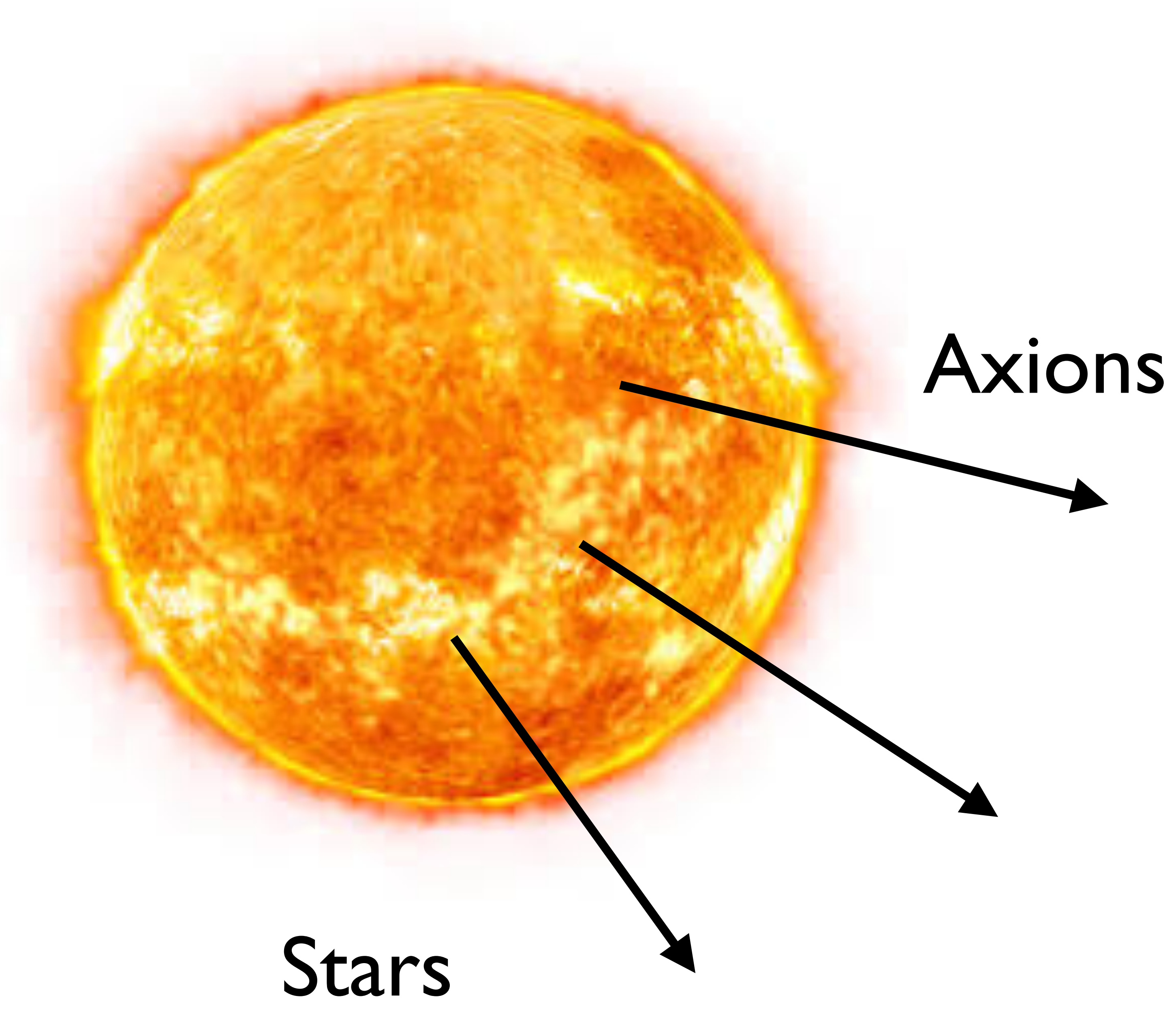
Light Shining Through Wall

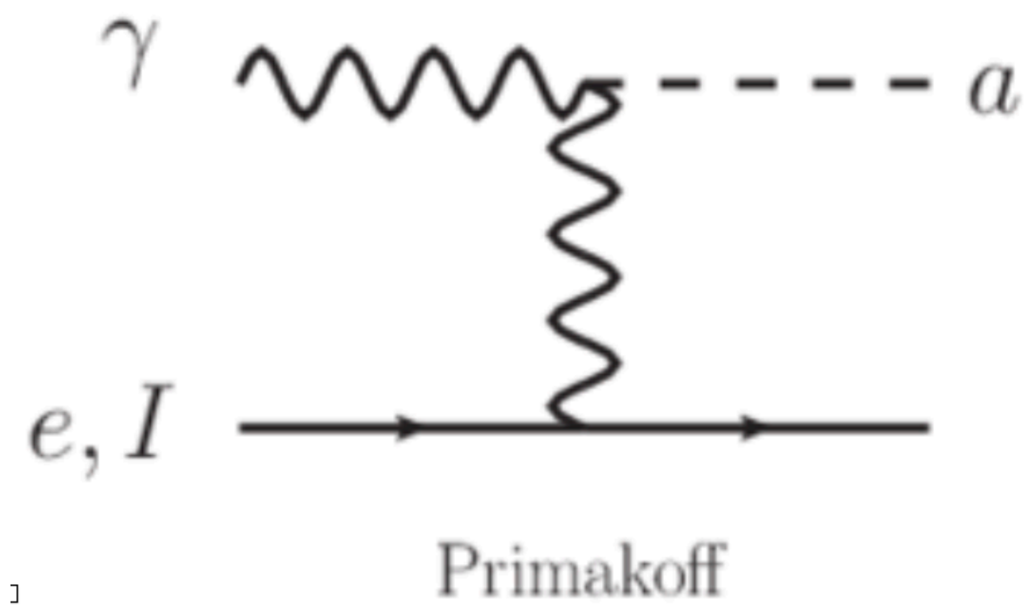
$$\mathcal{L}_{\rm int} = g_{a\gamma\gamma} a E \cdot B$$

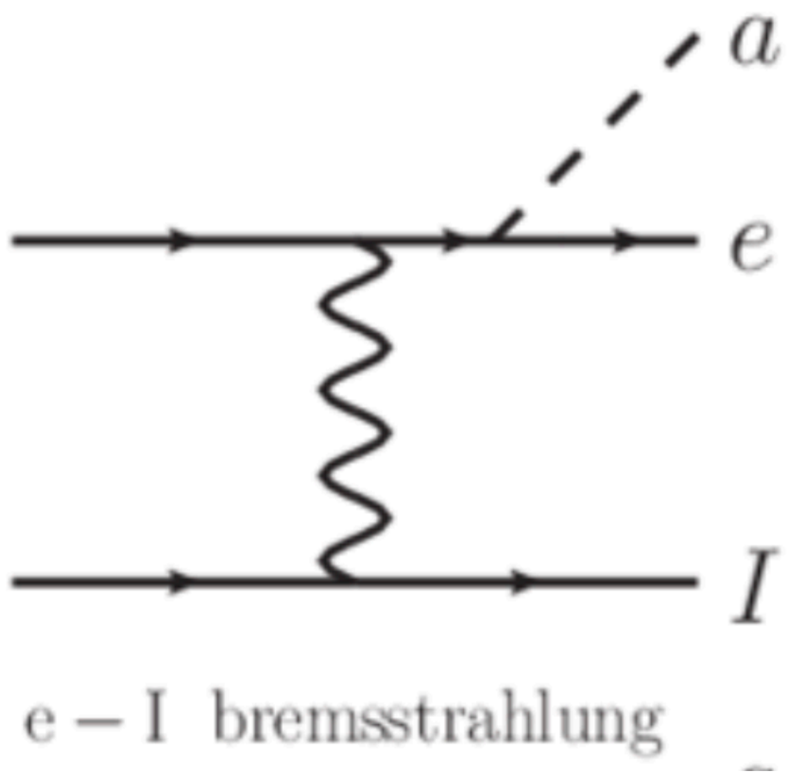


- Produce and detect axions in a lab, no need for it to be DM
- Low background ,but signal rate is suppressed by $g_{a\gamma\gamma}^4$

Stellar Cooling



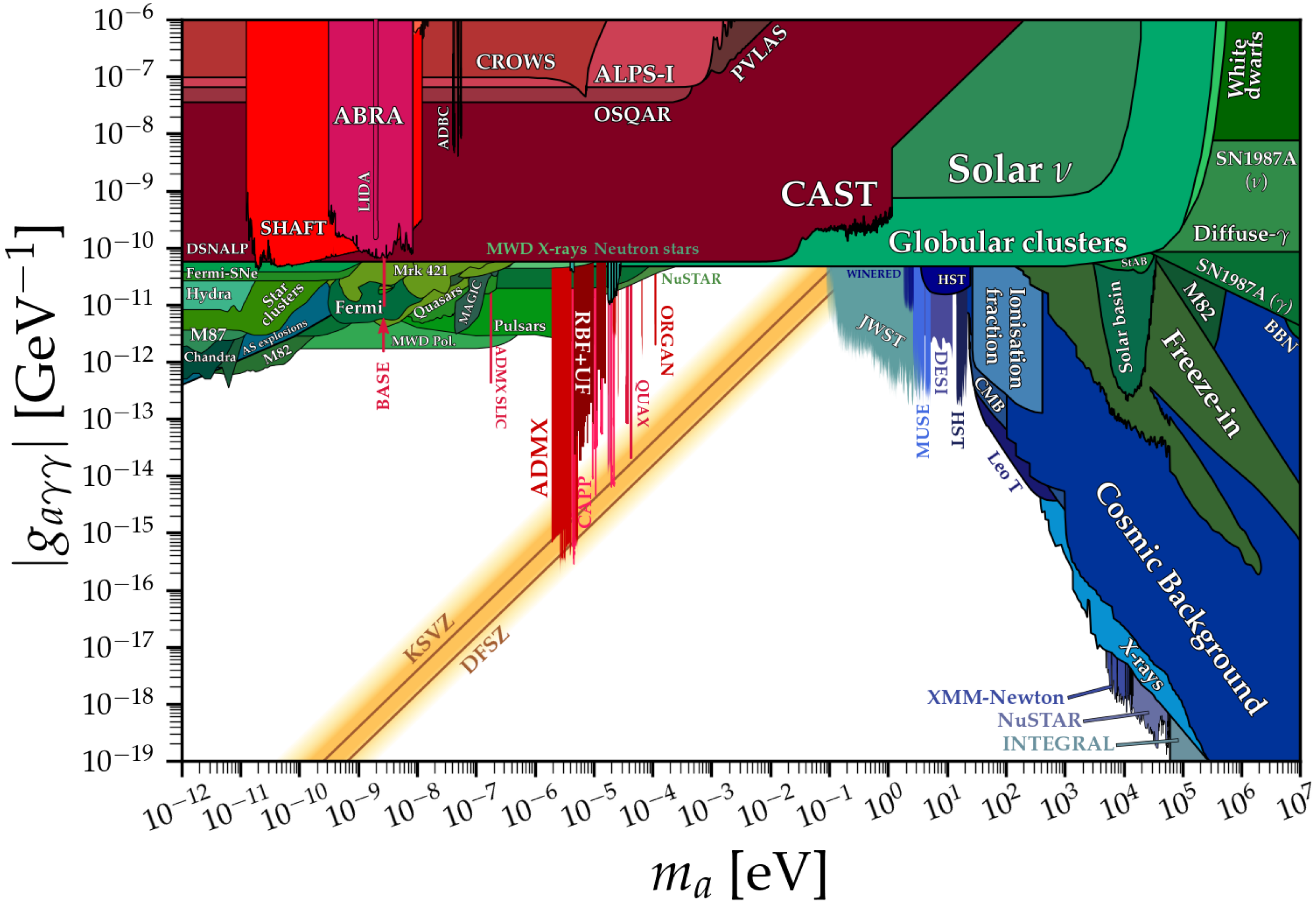




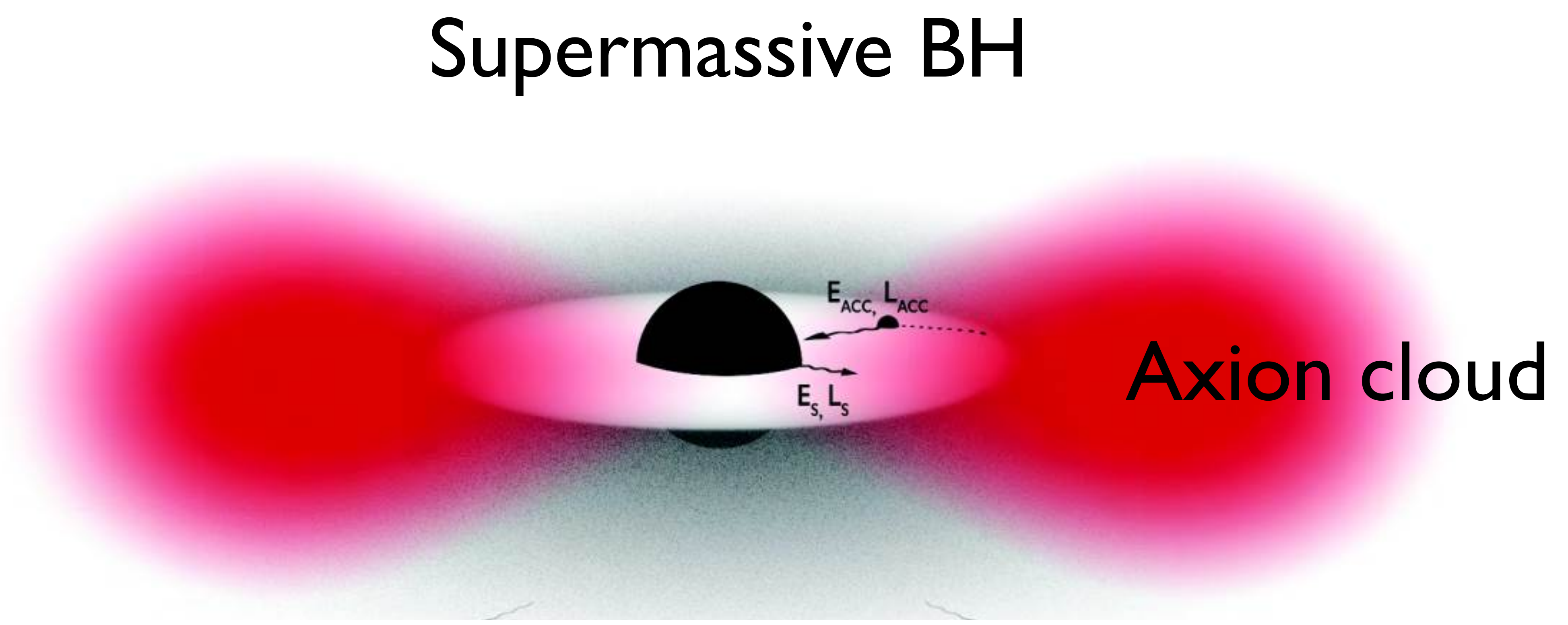
- Too much axion production leads to too fast stellar cooling
- We can also look for the axion flux form the sun on Earth: CAST experiment

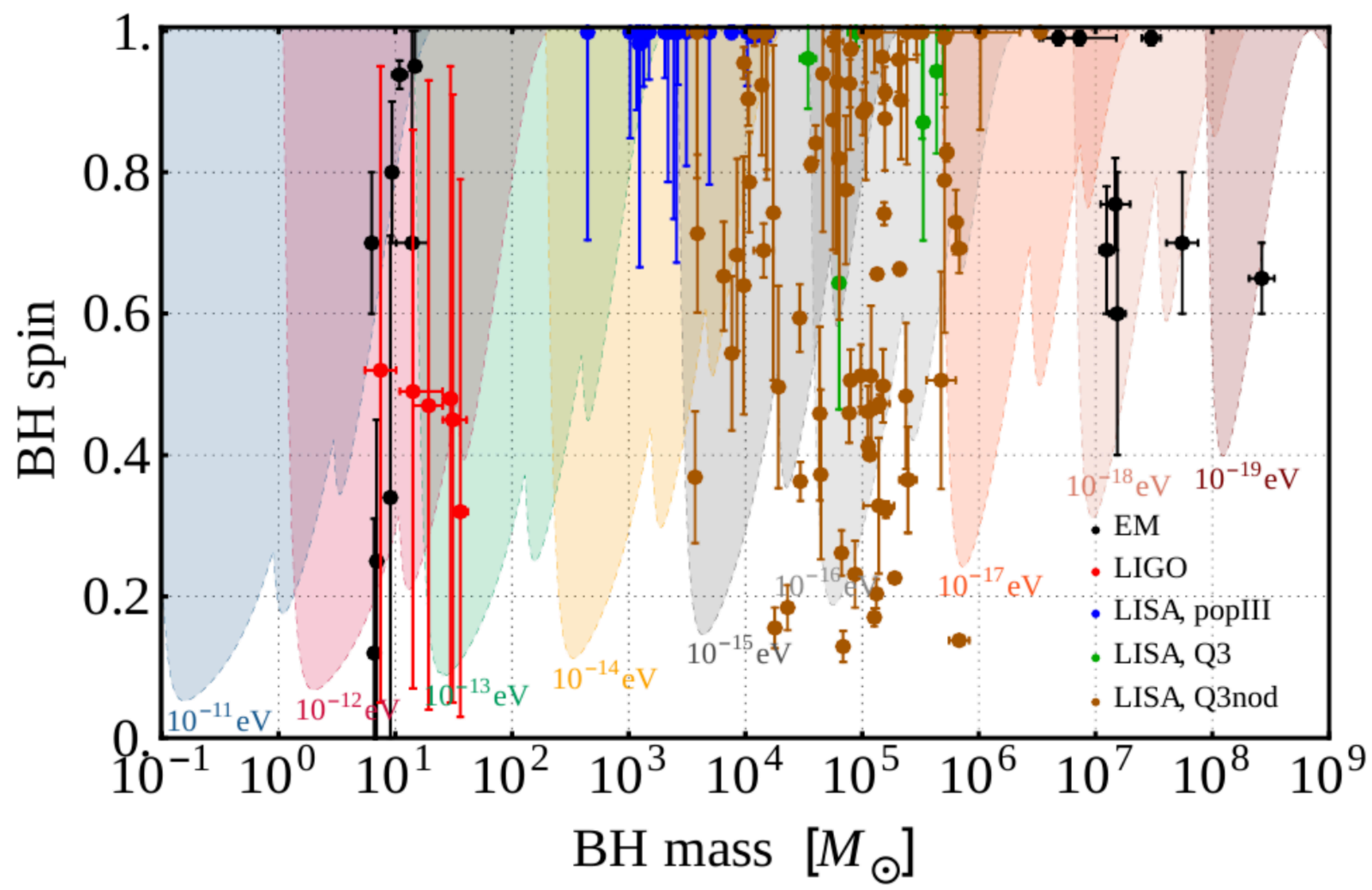
Axion Constraints

$$\mathcal{L} = g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



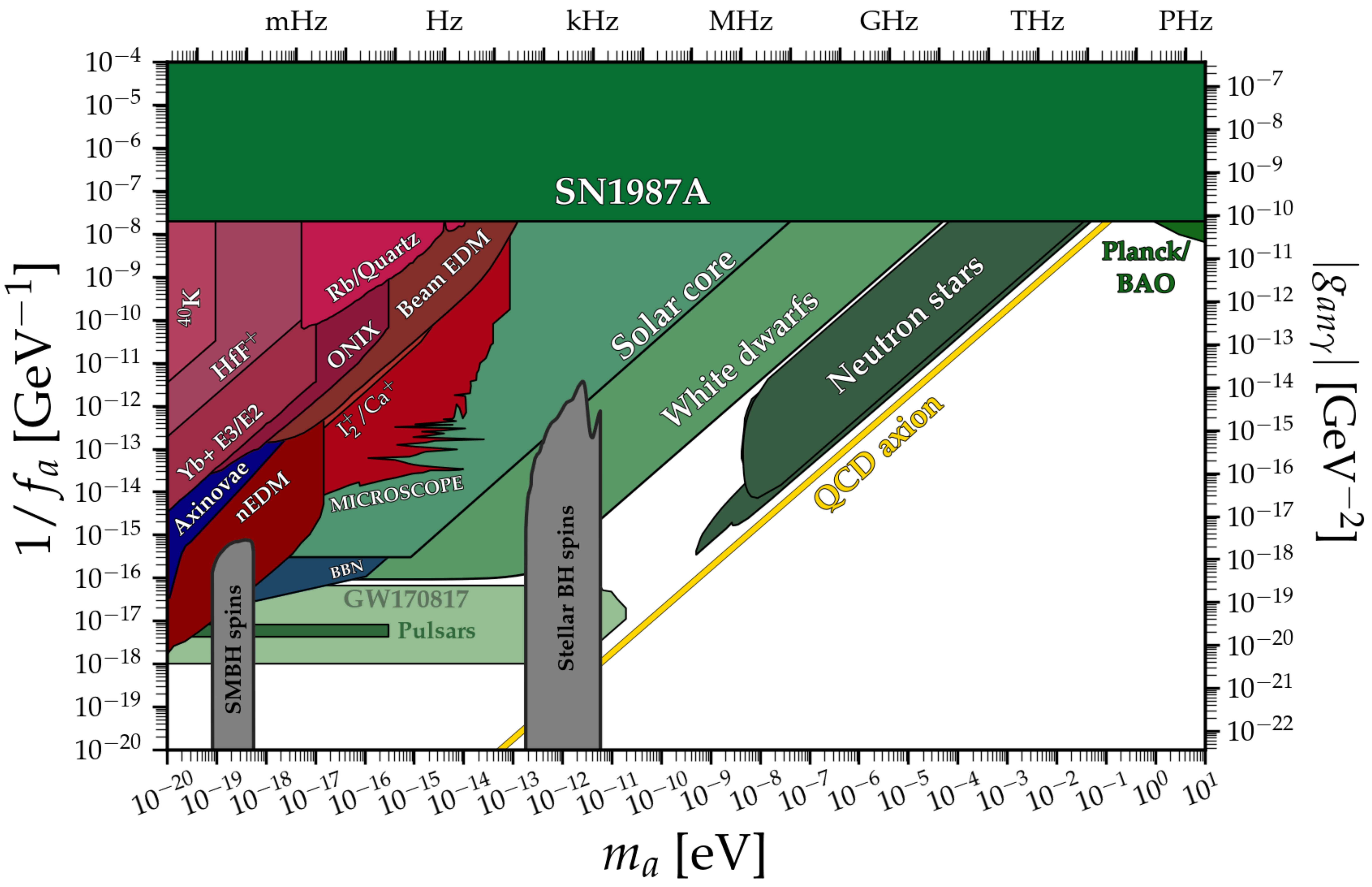
Black Hole Superradiance





- If ulta-light axion (massive scalar) exists, it can lead to superradiance of a certain mass BH, significantly reducing BH's angular momentum (spin).
- Independent of any couplings other than gravity!

Axion Constraints



Summary

- Dark Matter
- The strong CP problem

  Classical picture and solutions
- QCD axions and axion-like particles

  Solution to the strong CP problem

  Why axions can be dark matter: Misaligment mechanism
- Axion/ALP detection

  Axion DM: ADMX, ABRACADABRA, Spin sensors…

  Axion not as DM: LSW, stellar cooling, BH superradiance…

Galileo's observations of Neptune

Charles T. Kowal

Palomar Observatory, California Institute of Technology, Pasadena, California 91125

Stillman Drake

University of Toronto, Toronto, Ontario M5S 1A7, Canada

The planet Neptune was discovered in 1846. As its period of revolution is almost 165 years, Neptune has not yet completed one revolution since its discovery. Largely as a result of this, its orbit is not known with a precision comparable to that of the inner planets. A pre-discovery measurement of Neptune's position by Lalande in 1795 differs from the predicted position by 7 arc s. There is some debate about whether this discrepancy is real or an error of measurement[1]. Clearly, it would be worthwhile to find other pre-discovery observations of this planet. One possible way of finding such observations is to search for close approaches of Neptune to other objects which were frequently observed. Neptune was actually occulted by Jupiter in January 1613 and September 1702 (ref. 2). By 1702 the telescope was in widespread use, and examination of manuscripts of that period should reveal cases where Neptune was seen near Jupiter and mistaken for a star. The abundance of possible material, however, makes a search for such observations lengthy. We have found that Galileo observed the planet Neptune on 28 December 1612 and 28 January 1613. The latter observation may be of astrometric value, and differs by 1 arc min from the predicted position of Neptune. Galileo also detected the motion of Neptune.

Kowal, Drake, *Nature,* 1980

Galileo's observations of Neptune

Charles T. Kowal
Palomar Observatory, California Institute of Technology, Pasadena, California 91125

Stillman Drake
University of Toronto, Toronto, Ontario M5S 1A7, Canada

The planet Neptune was discovered in 1846. As its period of revolution is almost 165 years, Neptune has not yet completed one revolution since its discovery. Largely as a result of this, its orbit is not known with a precision comparable to that of the inner planets. A pre-discovery measurement of Neptune's position by Lalande in 1795 differs from the predicted position by 7 arc s. There is some debate about whether this discrepancy is real or an error of measurement[1]. Clearly, it would be worthwhile to find other pre-discovery observations of this planet. One possible way of finding such observations is to search for close approaches of Neptune to other objects which were frequently observed. Neptune was actually occulted by Jupiter in January 1613 and September 1702 (ref. 2). By 1702 the telescope was in widespread use, and examination of manuscripts of that period should reveal cases where Neptune was seen near Jupiter and mistaken for a star. The abundance of possible material, however, makes a search for such observations lengthy. We have found that Galileo observed the planet Neptune on 28 December 1612 and 28 January 1613. The latter observation may be of astrometric value, and differs by 1 arc min from the predicted position of Neptune. Galileo also detected the motion of Neptune.

Kowal, Drake, *Nature,* 1980

DM signals might already exist in current experimental data!

Thank you