Axions: Past, Present and Future

ICTP Summer School, 2015

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Axions

Axions and axion-like-particles are the goldstone bosons of symmetries broken at some high scale f_a

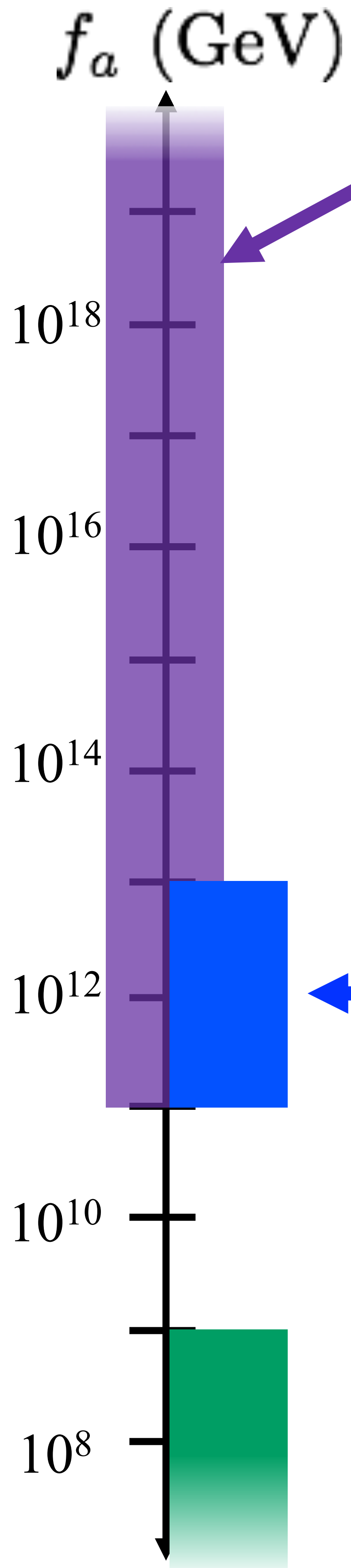
The QCD axion (***a***) was introduced to solve the strong CP problem. This problem arises because instanton effects in QCD give rise to large CP violating effects. The axion dynamically solves this problem since it acquires a potential from these instantons which is minimized at a point where CP is restored.

Goldstone bosons that acquire a mass through a different source are called axion like particles ($\boldsymbol{\phi}$)

As goldstone bosons, these particles are light. By detecting them, we get a peek into ultra-high energy physics without having to build ultra-high energy colliders

Can easily be dark matter

The Bottomline



QCD Axion dark matter

Large parameter space still unconstrained

For large f_a, need to beat small coupling

ADMX,
ADMX-HF

How do we find these?

axion emission affects SN1987A, White Dwarfs, other astrophysical objects
collider & laser experiments, ALPS, CAST

Experiments

New Ideas

Produce and detect

Super-radiance in astrophysical systems

Axion dark matter

NMR style searches for oscillating moments (CASPEr)

Super-radiance in Extremal Astrophysical Systems

Overview

Super-radiance can be extremely efficient in certain extremal rotating astrophysical systems, if there are light massive bosons (e.g. axions) that are coupled to the star.

Observations of such rotating objects constrain such particles.

Statistically significant gaps in rotation rates may imply existence of such particles.

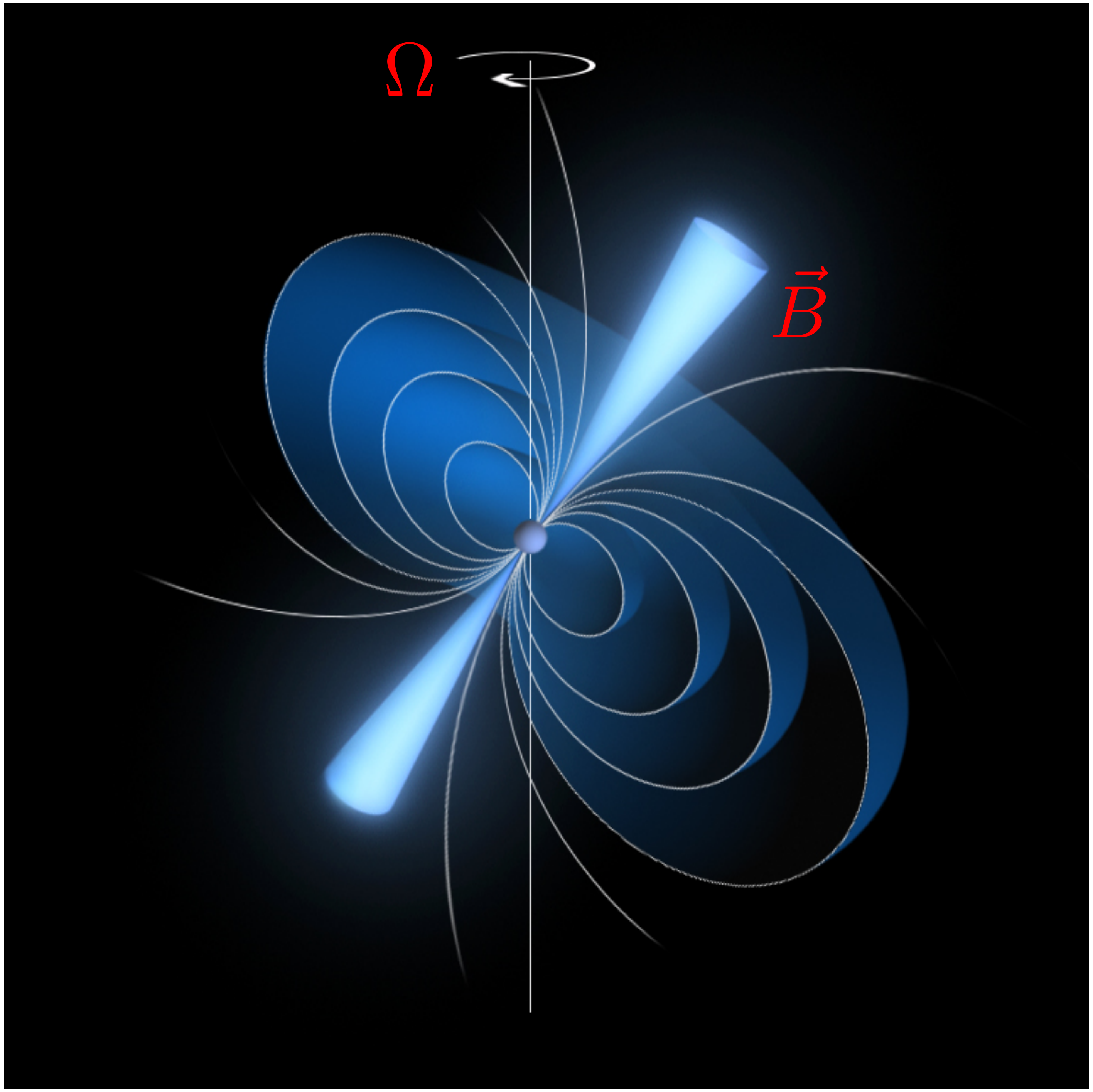
Previous work limited to black-holes.

A. Arvanitaki et.al. (2009)

General instability, could also use milli-second pulsars.

SR (in progress)

Radiation from Rotating Objects



Magnetic field not aligned with rotation.

Time varying magnetic dipole.

Dipole radiation at frequency Ω

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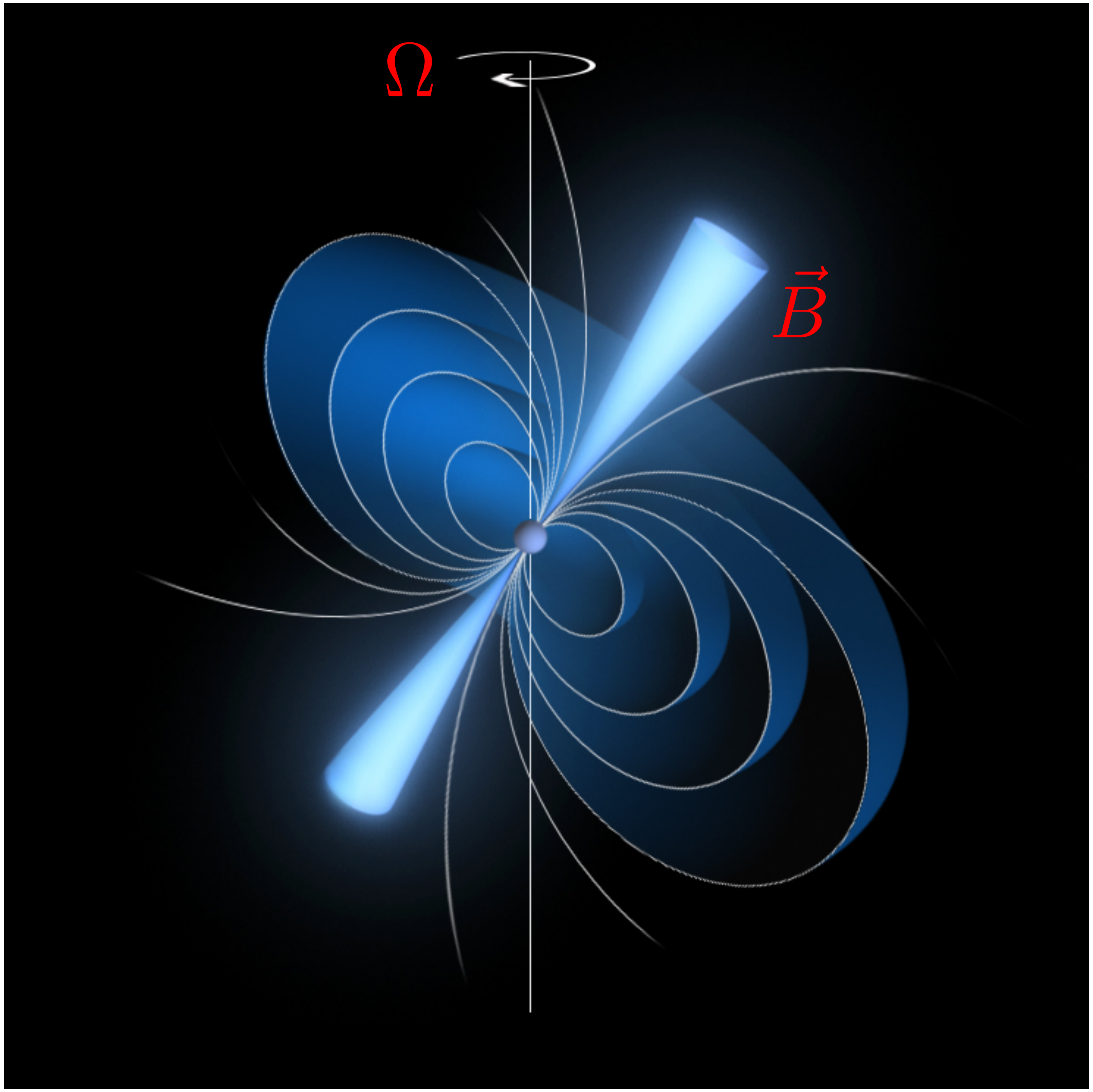

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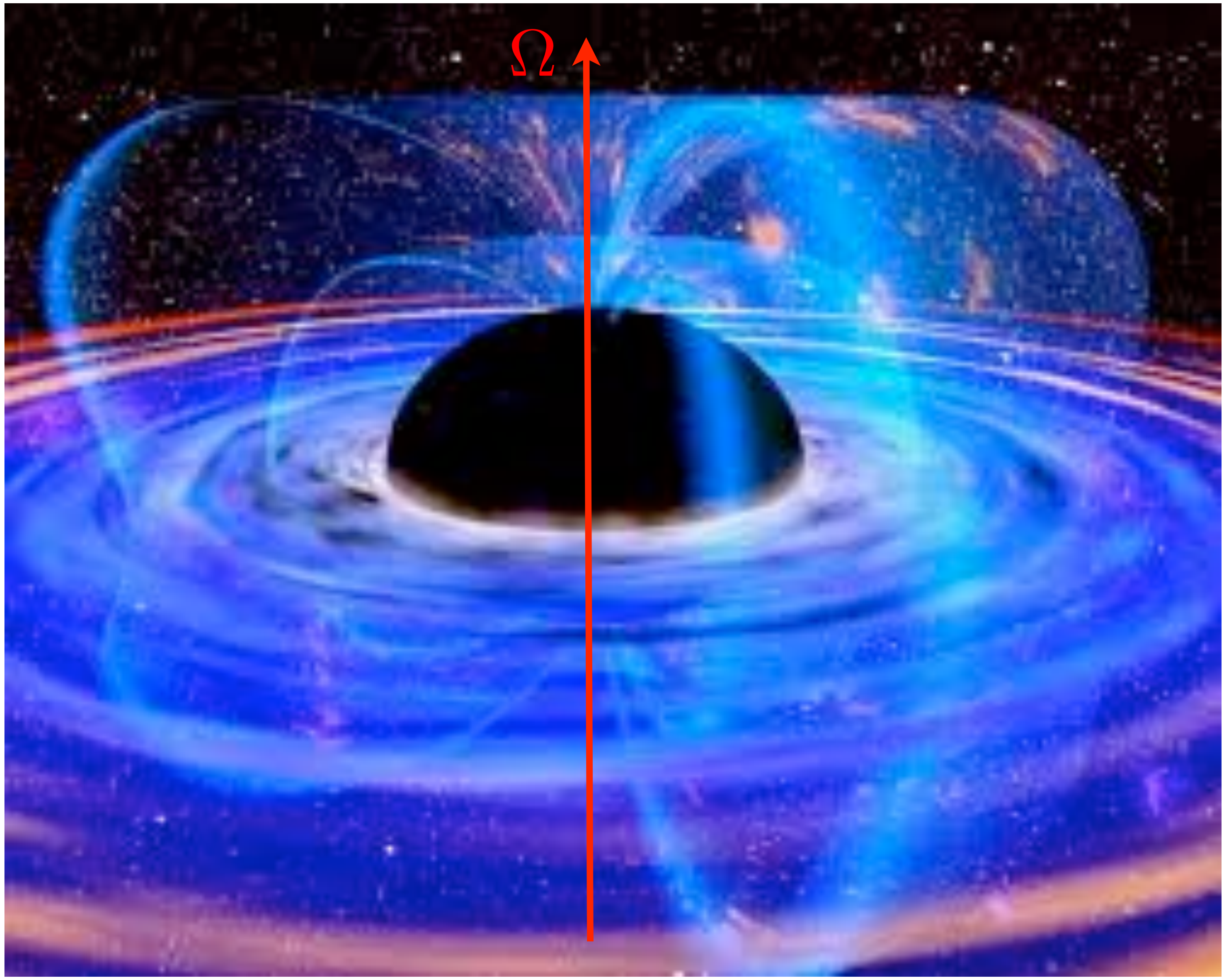
What if the magnetic field is aligned with the rotational axis?

Axisymmetric Rotating Objects



Radiated photon must carry angular momentum.

Cannot couple to rigid axisymmetric star.

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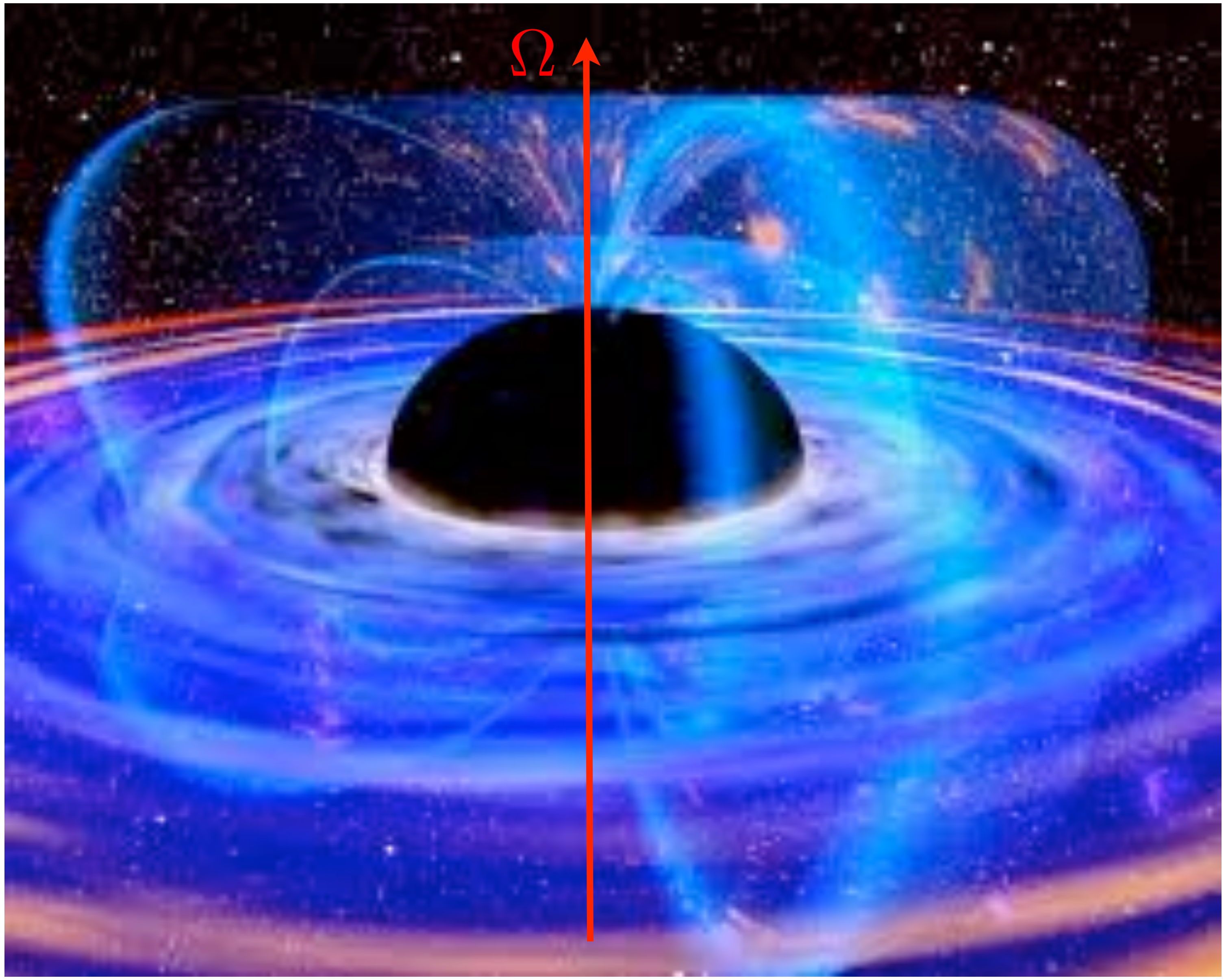

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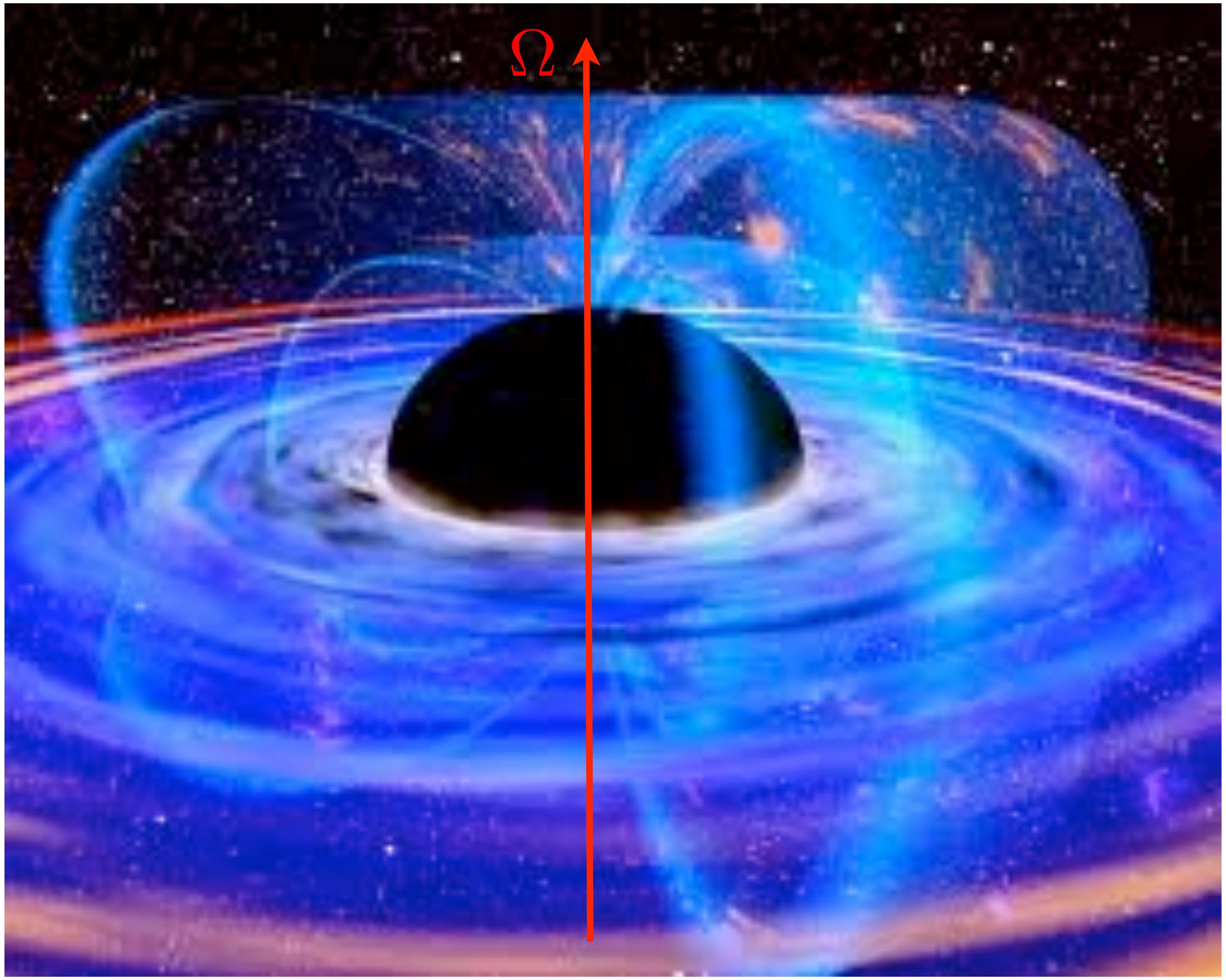

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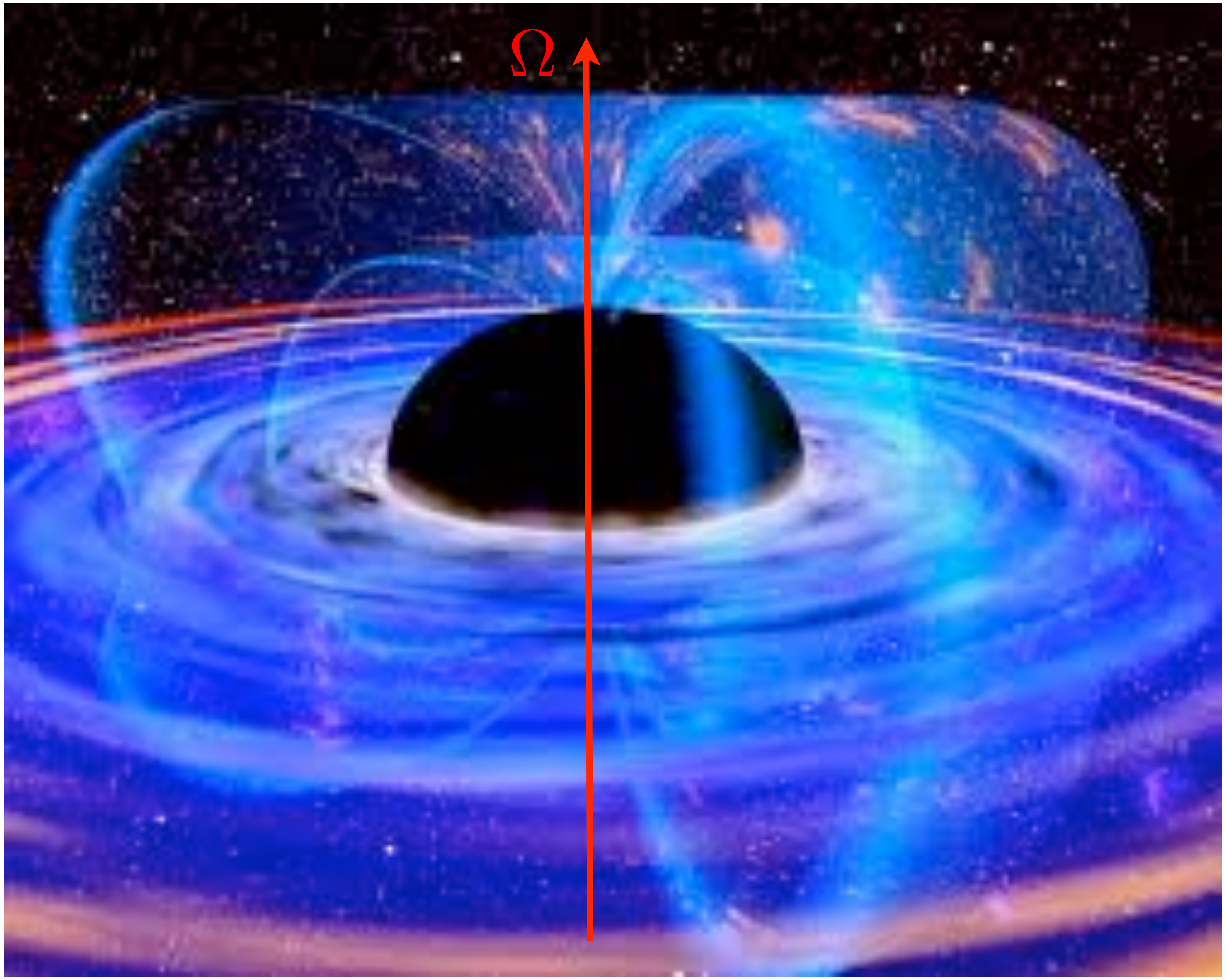

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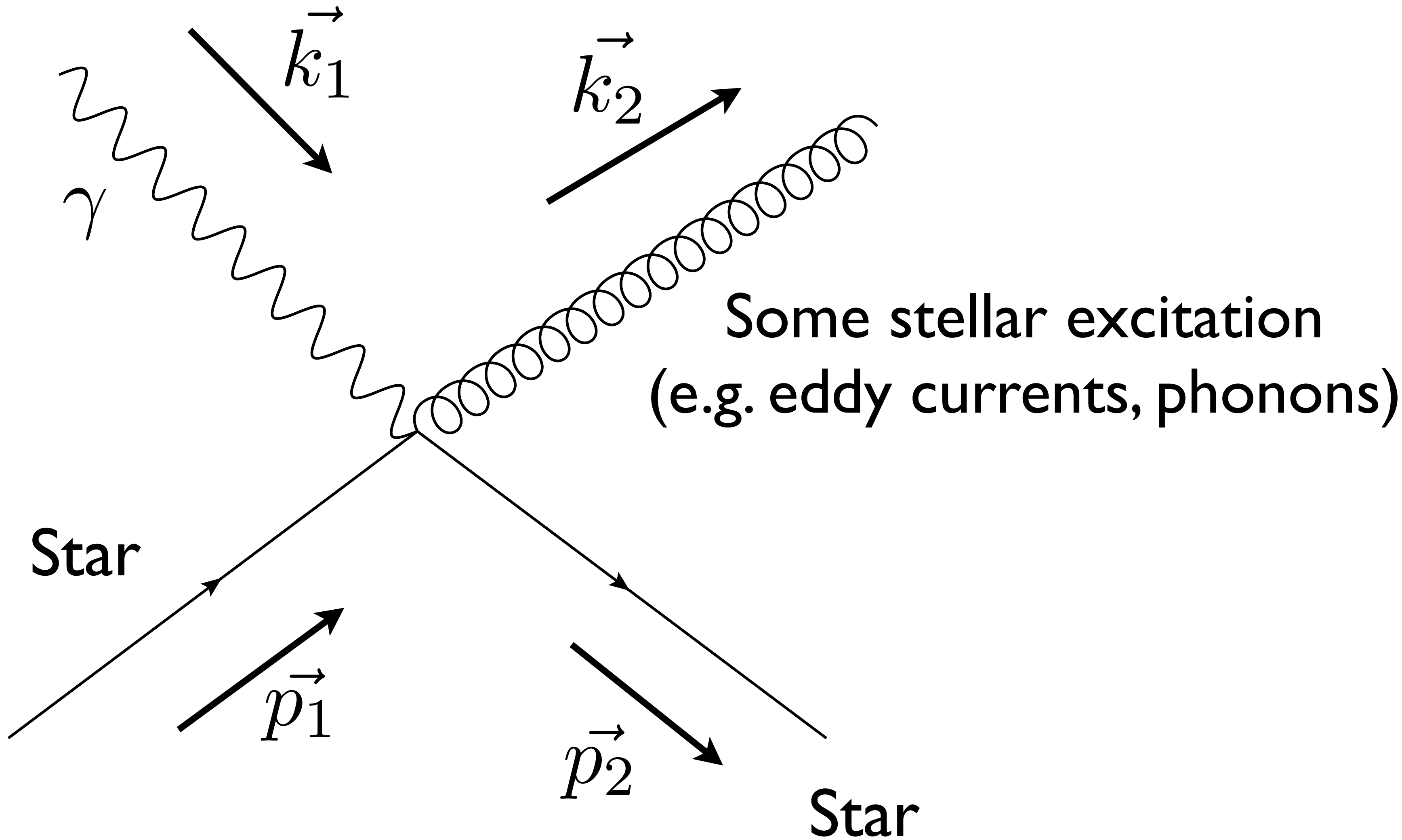
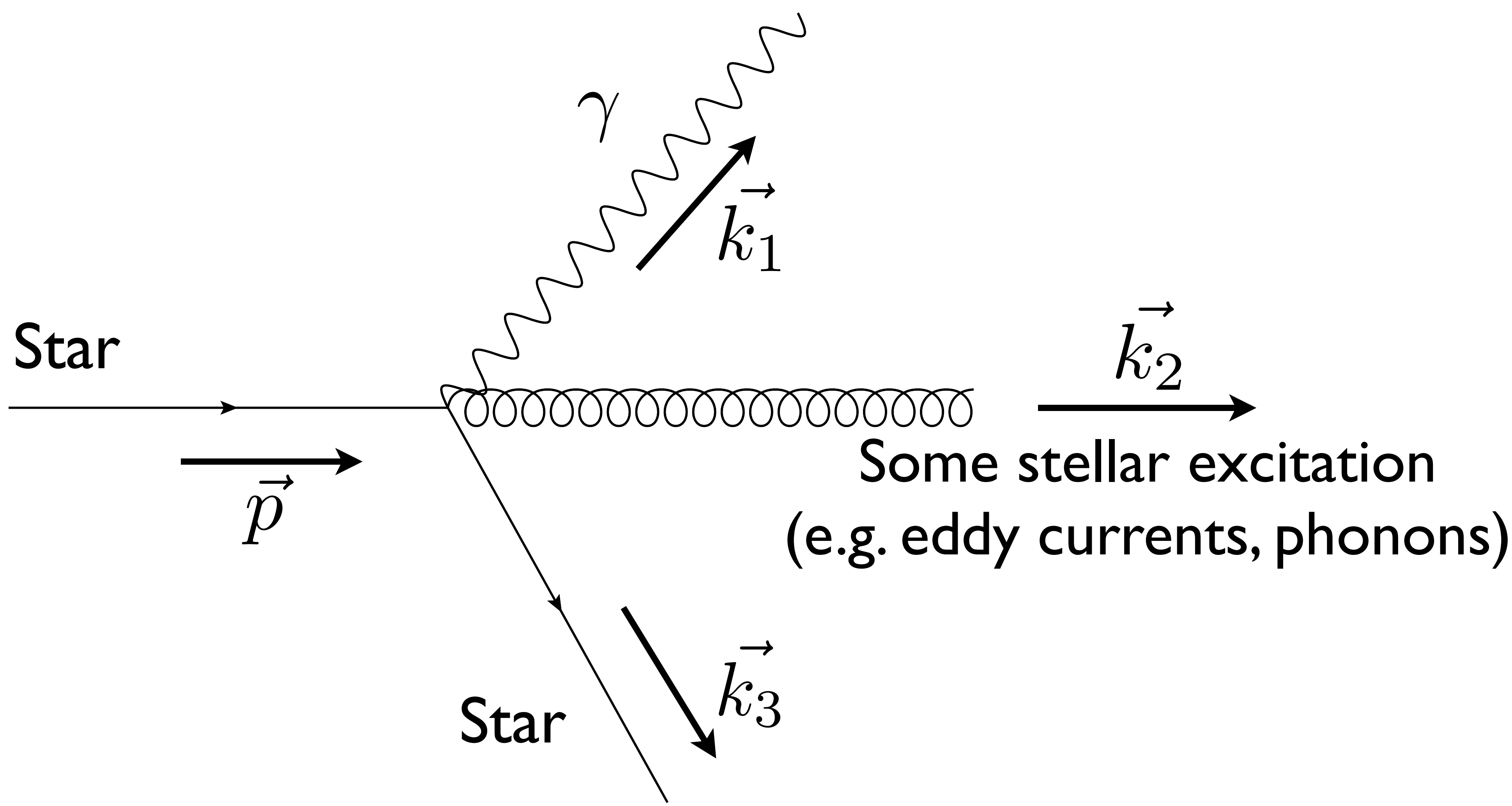
At some level, there must be radiation!

Absorption



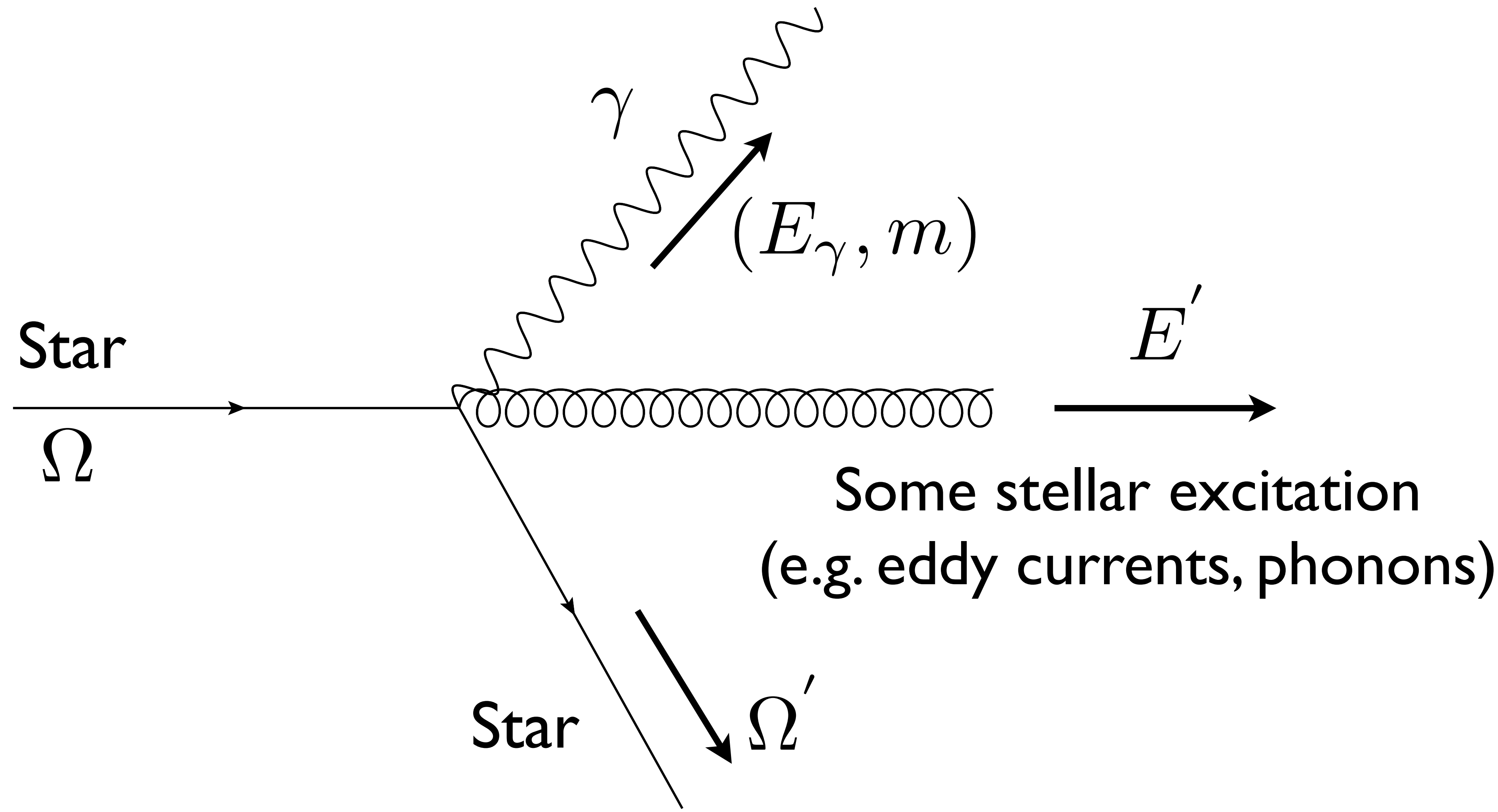
Angular momentum of the photon couples to moments of the stellar excitation.

Super-radiance
(Inverse Absorption)



Non-zero Matrix element from Absorption.
Will happen if kinematically allowed.

Super-radiance: The Kinematics



Solve for E'

$$E^{'} \approx m\Omega - E_\gamma > 0$$

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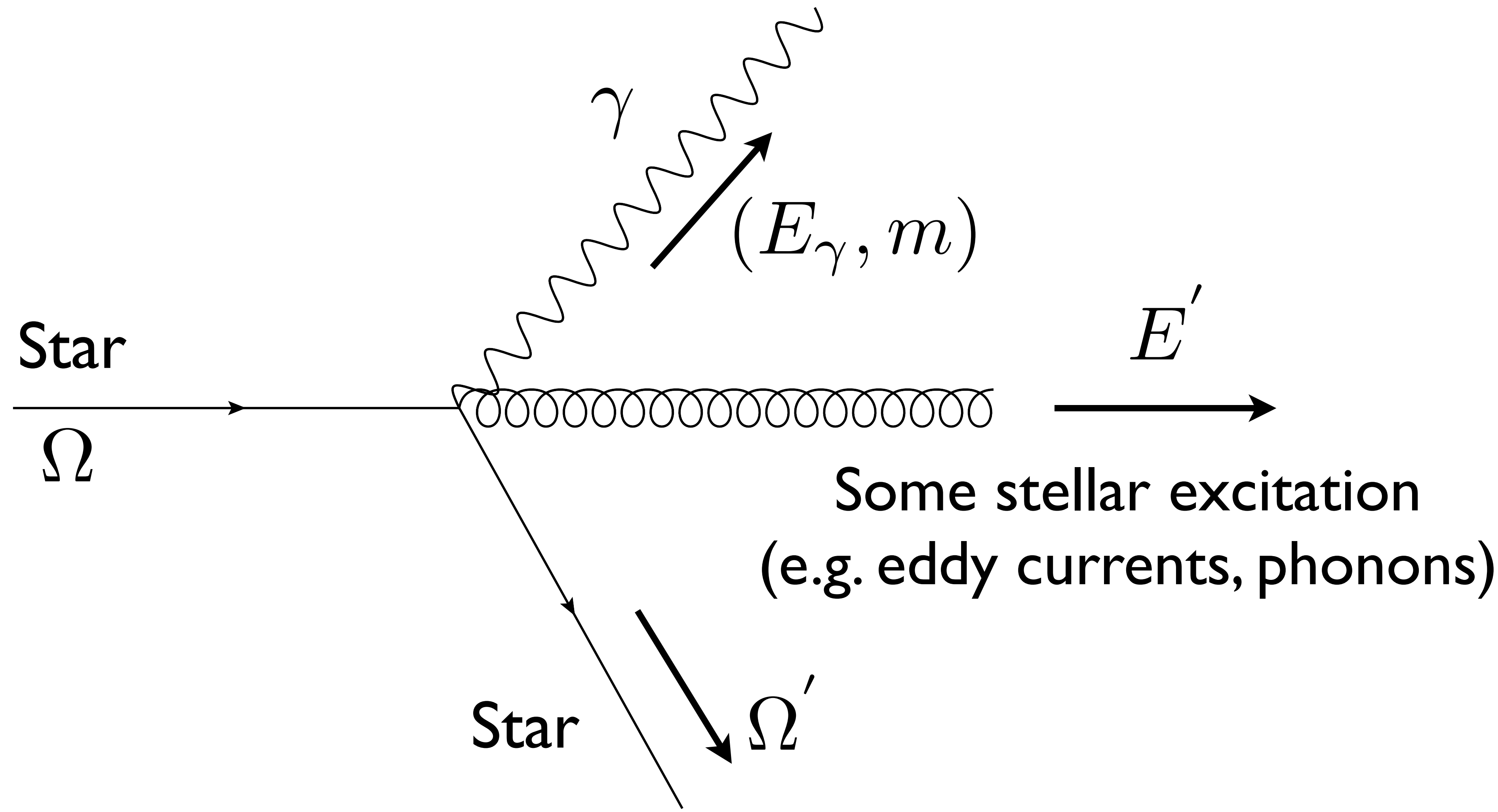

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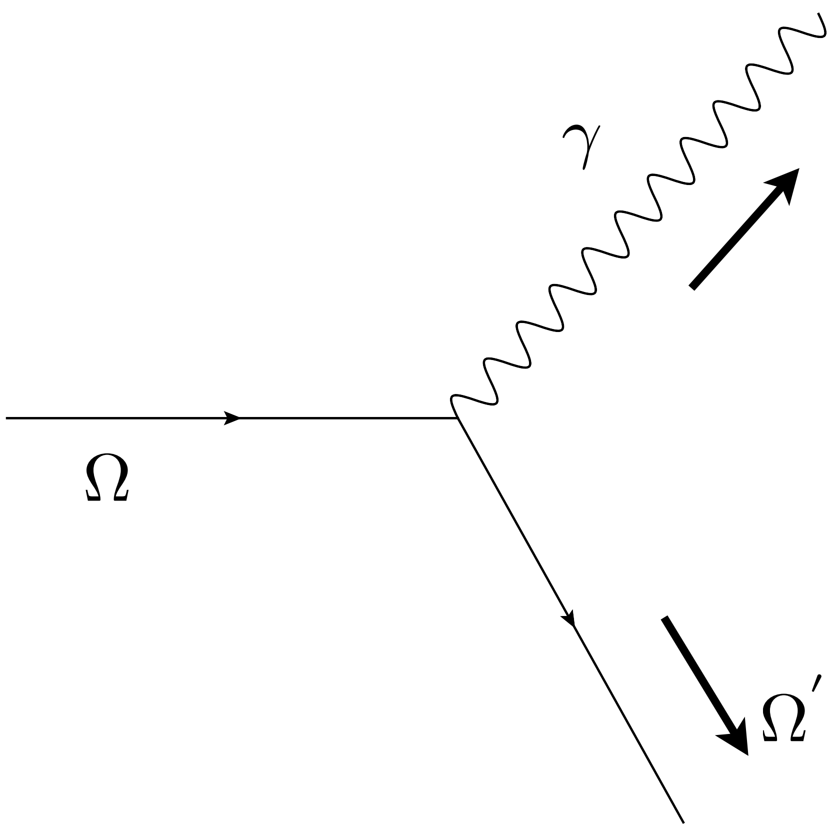
Photons of arbitrarily high energy can be emitted provided the angular momentum is also high.

High angular momentum => mode localized far from star => suppressed coupling.

Comparison

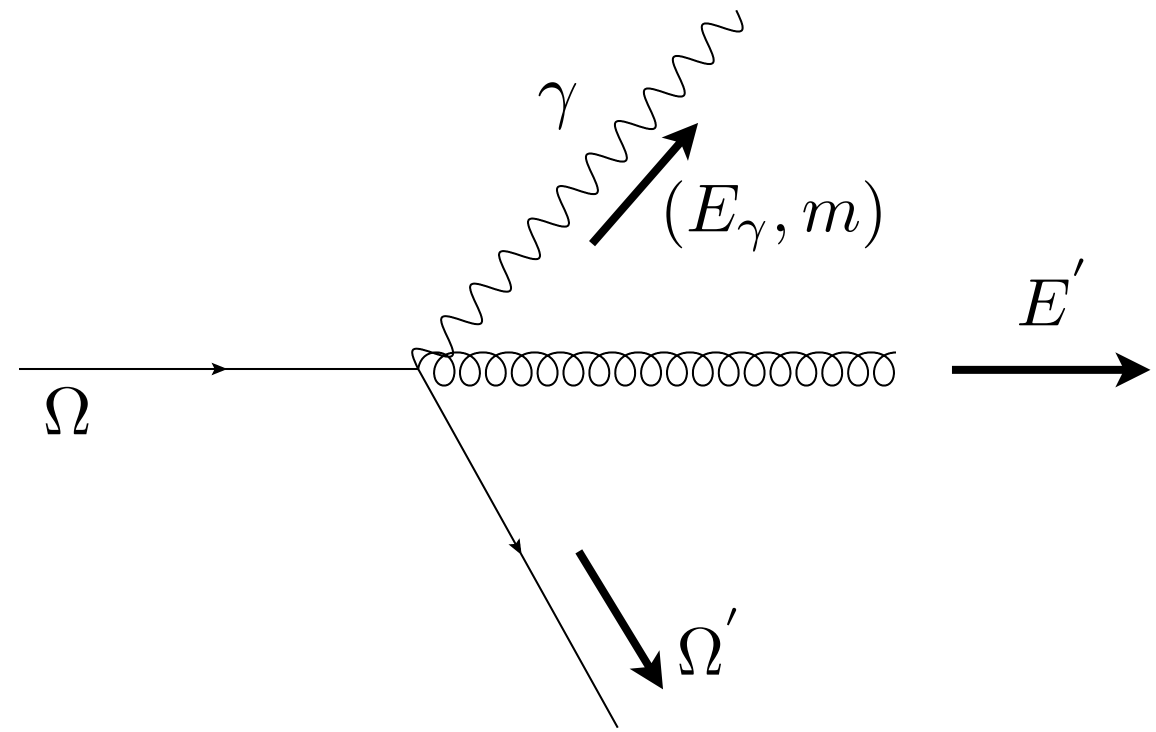
Multipole Radiation



Non axi-symmetric systems.

Radiation at multiples of Ω

Super-radiance



Instability of any absorptive, rotating system.

Continuum emission.

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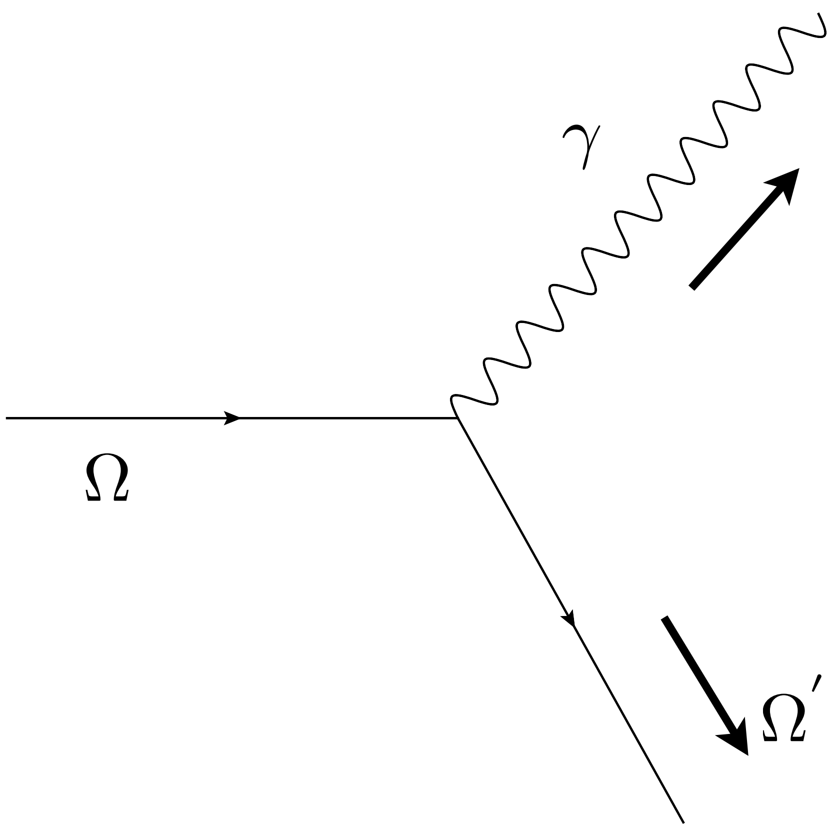

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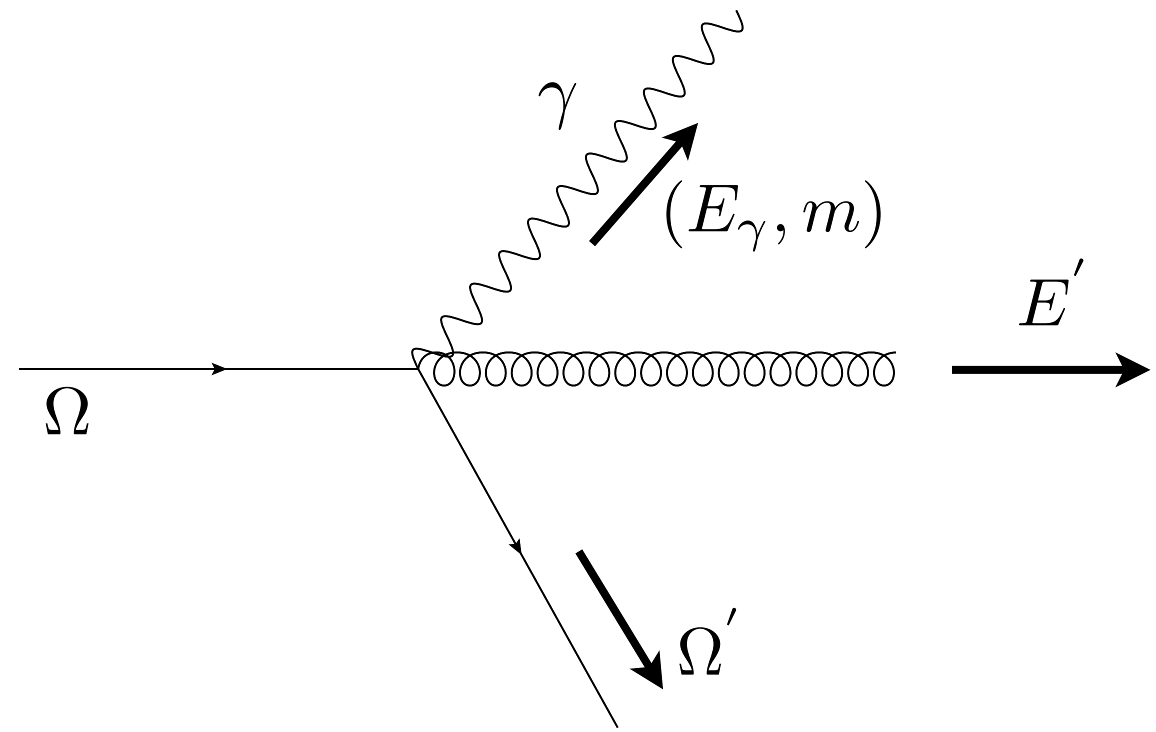

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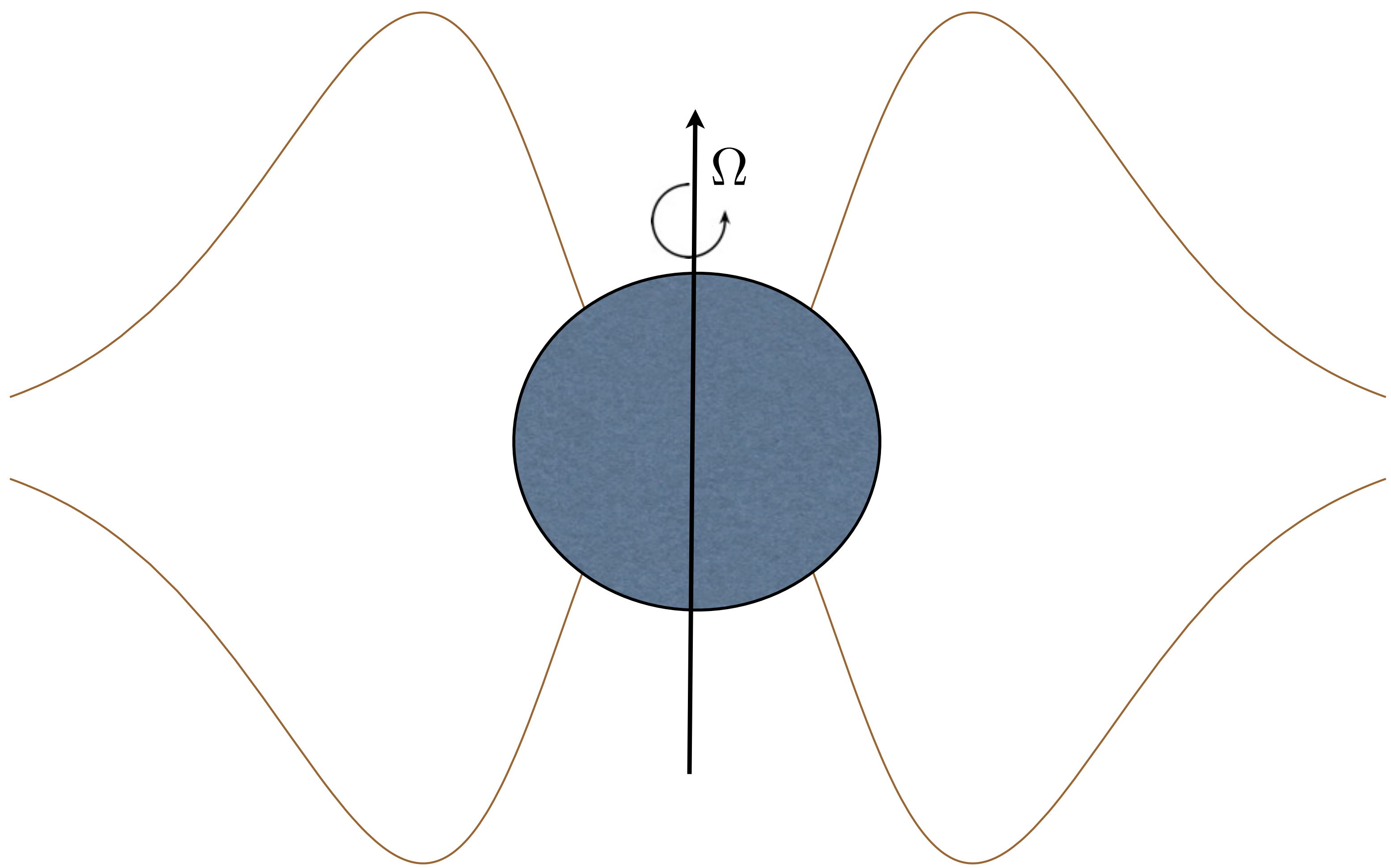
Continuum emission.

Absorption => Super-radiance usually sub-dominant to multipole radiation.

Massive Particles and Massive Stars



Particle of mass μ, star of mass M.

Gravitationally bound states at $r_b \sim \dfrac{1}{GM\mu^2}$

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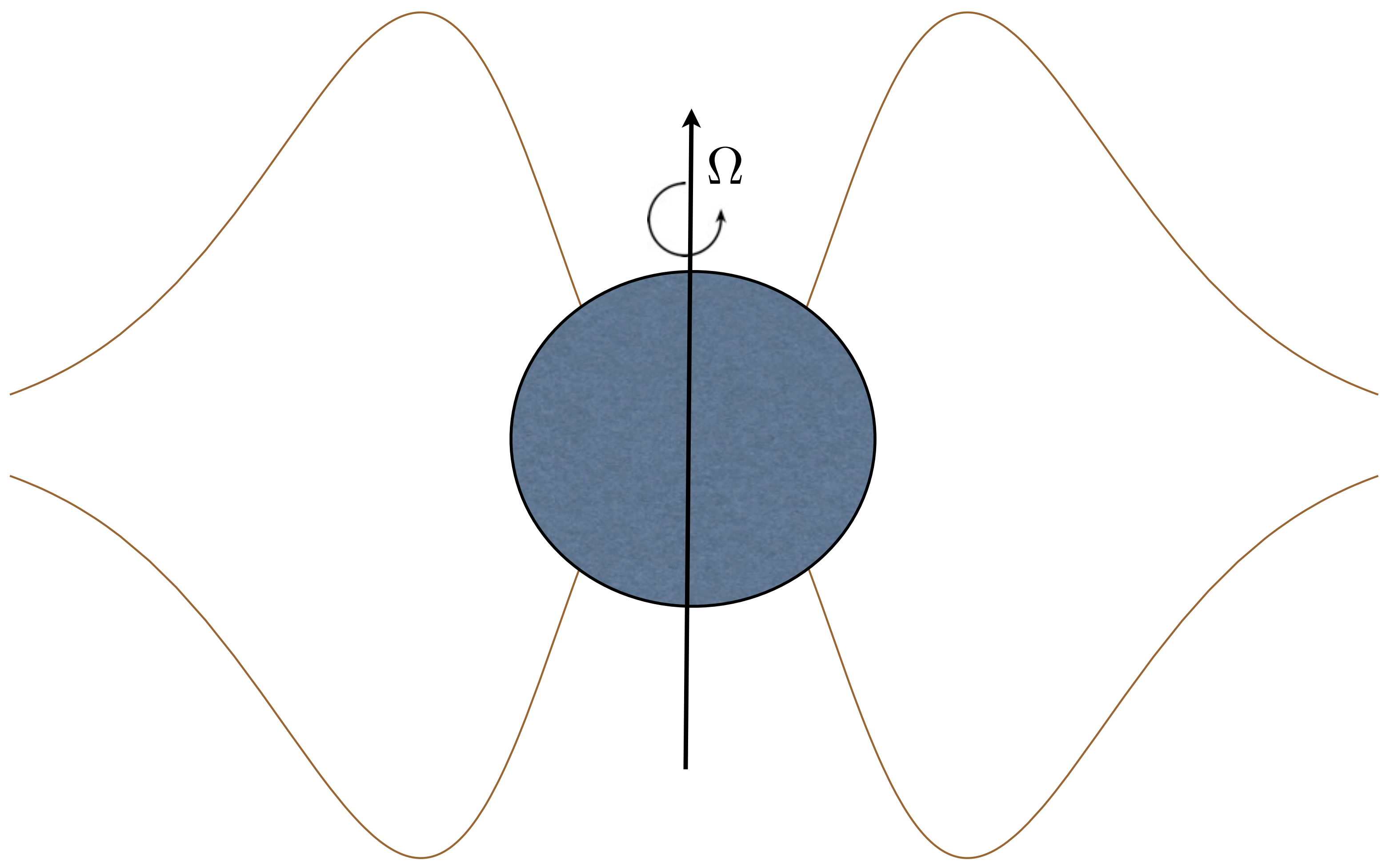

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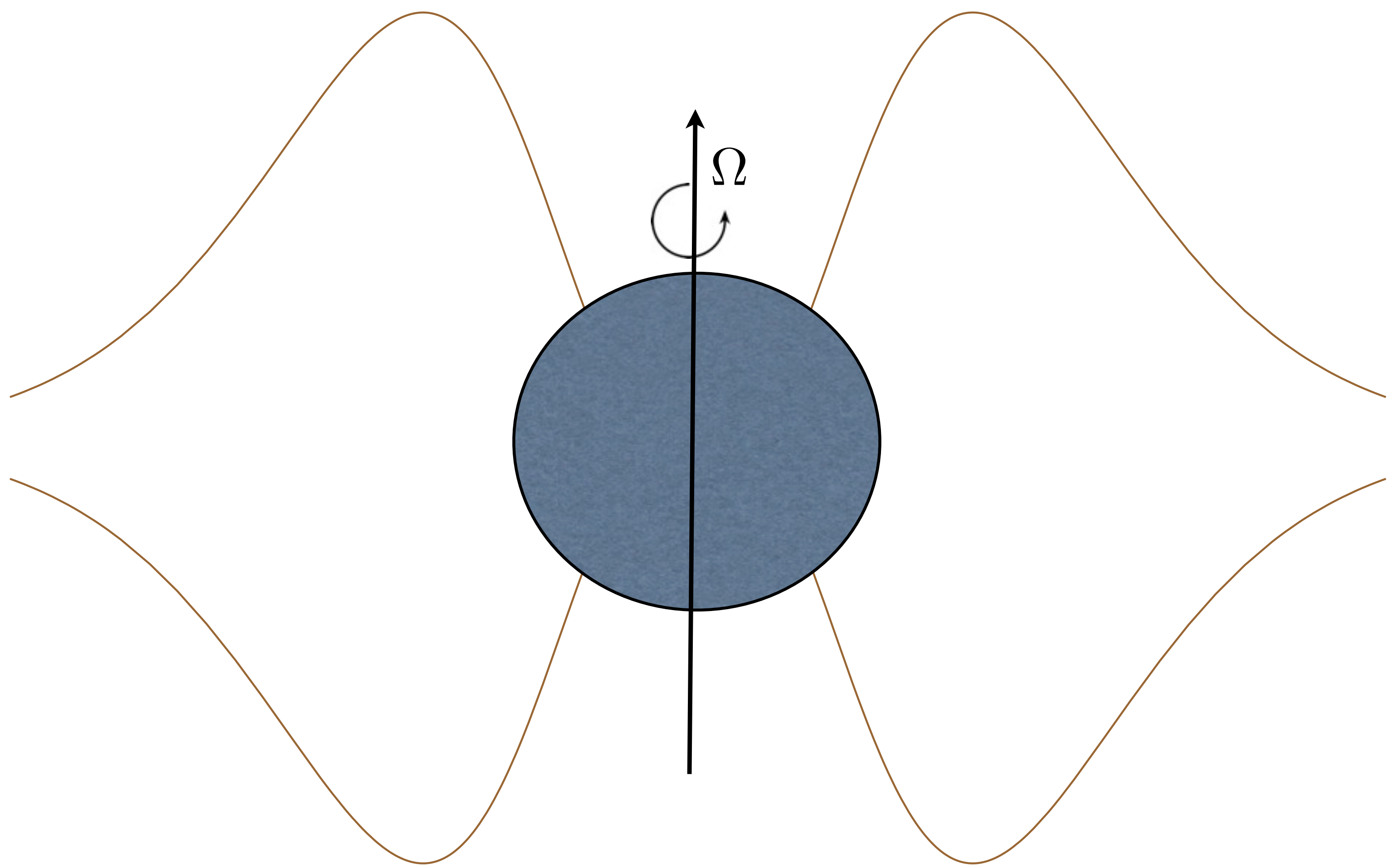

$$\text{Gravitationally bound states at } r_b \sim \frac{1}{GM\mu^2}$$

Bose enhancement => exponential amplification!

Could be efficient if there were new light particles coupled strongly enough to stellar medium.

Use observations of rotating black holes/pulsars to constrain and perhaps discover such particles.

Absorption in a Medium

Particle Ψ, mass μ, interacting with a medium moving at v^α.

$$\Box\Psi + \mu^2\Psi + Cv^\alpha\nabla_\alpha\Psi + V_{eff}(\Psi) = 0$$

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$$\Downarrow$$

$$\Psi(t) \propto \mathrm{Exp}\left(-\frac{Ct}{2}\right)$$

For positive C, mode is damped (absorbed).
C is the absorption coefficient.

Rotating Medium

Particle Ψ, mass μ, medium rotates at Ω

$$\Box\Psi + \mu^2\Psi + Cv^\alpha\nabla_\alpha\Psi + V_{eff}(\Psi) = 0$$

Spherical co-ordinates aligned with rotation axis.

$$v^\alpha = (1, 0, 0, \Omega r \sin\theta)$$

(Zeldovich)

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$$\Downarrow$$

For large m, $(\mu - m\Omega) < 0$.

(Zeldovich)

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Same kinematic condition.

For large m, $(\mu - m\Omega) < 0$.

Absorption becomes emission. (Zeldovich)

Region of Growth

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Absorption occurs only inside the star (radius R)

↓

Rate depends upon overlap of mode with the stellar medium.

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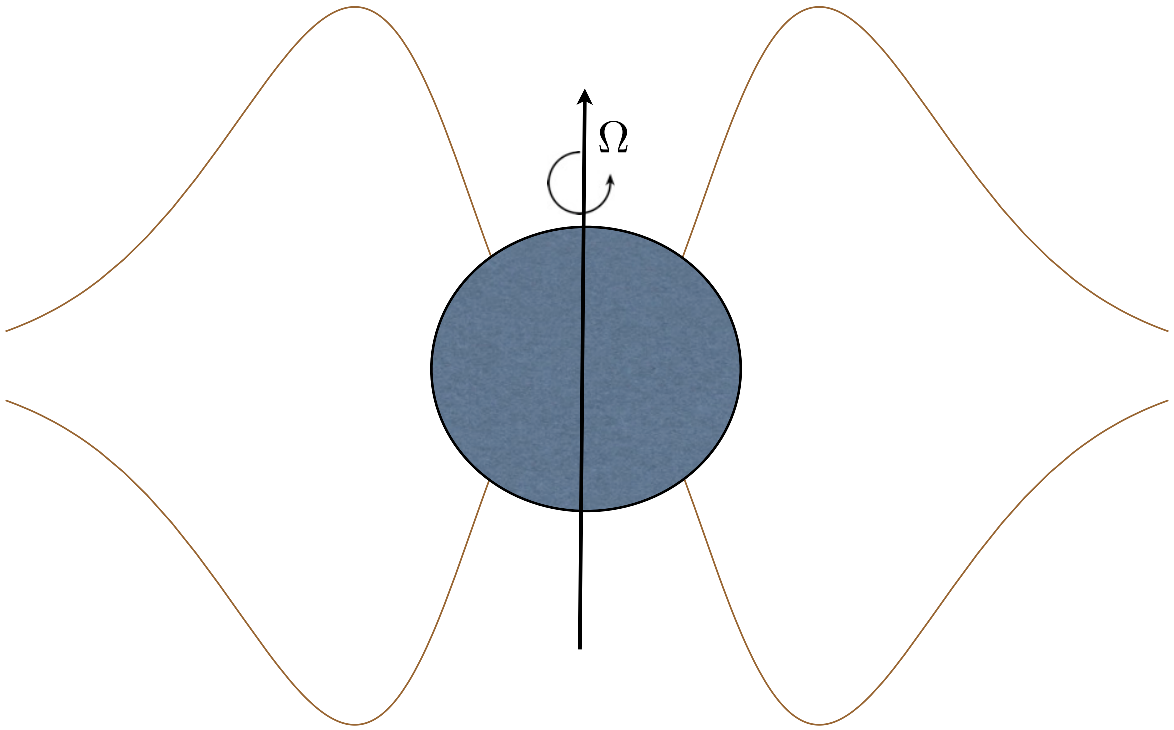
Rate depends upon overlap of mode with the stellar medium.

Proportional to the probability of finding particle in the star.

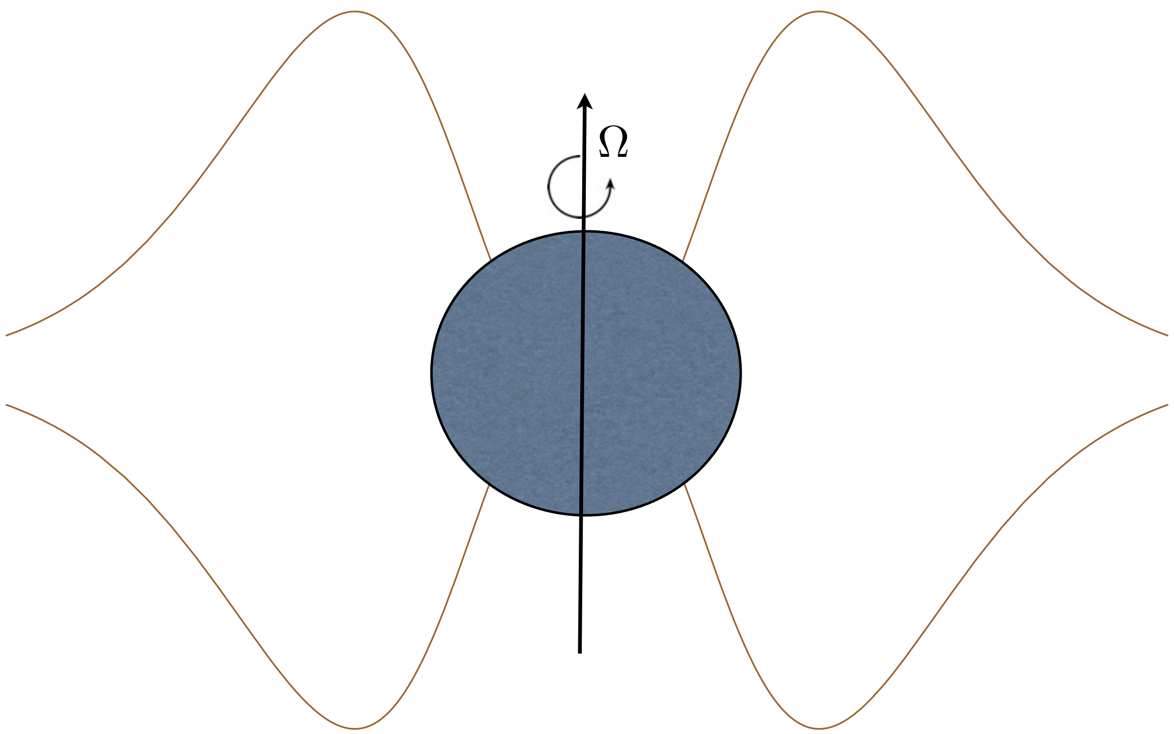
Region of Growth



Hydrogenic ψ_{nlm} with Bohr radius $r_b \sim \frac{1}{GM\mu^2}$

$$\psi_{nlm} \sim \left(\frac{r}{r_b}\right)^l \sim r^l \left(GM\mu^2\right)^l$$

Region of Growth



$$\psi_{nlm} \sim \left(\frac{r}{r_b}\right)^l \sim r^l \left(GM\mu^2\right)^l$$

$$\Gamma_{nlm} \propto \left(\frac{r}{r_b}\right)^{2l+3} \propto \left(GM\mu^2 R\right)^{2l+3}$$

Efficient Super-radiance

$$\Gamma_{nlm} \propto \left(\frac{r}{r_b}\right)^{2l+3} \propto \left(GM\mu^2 R\right)^{2l+3}$$

For super-radiance, $\mu - m\Omega < 0$, with $l \geq |m|$

Very low mass, lowest angular momentum mode is super-radiant.

Large Bohr-radius.

High mass, only large angular momentum modes are super-radiant.

Large Bohr-radius.

Most efficient $\mu \sim \Omega$

Extremal Objects

$$\Gamma_{nlm} \propto \left(\frac{r}{r_b}\right)^{2l+3} \propto \left(GM\mu^2 R\right)^{2l+3}$$

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Largest M, R consistent with Ω.

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Relativity $\Omega R \lessapprox 1$

Given μ, need extremal object at μ.

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Extremal Kerr Black-holes, Millisecond Pulsars.

(fastest pulsars at 642 Hz, 714 Hz)

Superradiance

Extremal Black Holes

Absorption by gravity

Spin measurement is an evolving field, subject to astrophysical modeling

Systematic: Unknown close orbiting companions

One clean measurement in one clean system is good

Millisecond Pulsars

Absorption through non-gravitational interactions

Spin and orbital issues well measured

Known clean systems

Good for particles that couple to number density (dark photons)

For axions, bounds depend on internal magnetic fields

Axion Dark Matter

Cosmic Axion Spin Precession Experiment
(CASPEr)

D. Budker et.al, 2013

P.W. Graham, SR (2010,2013)

Axion Dark Matter

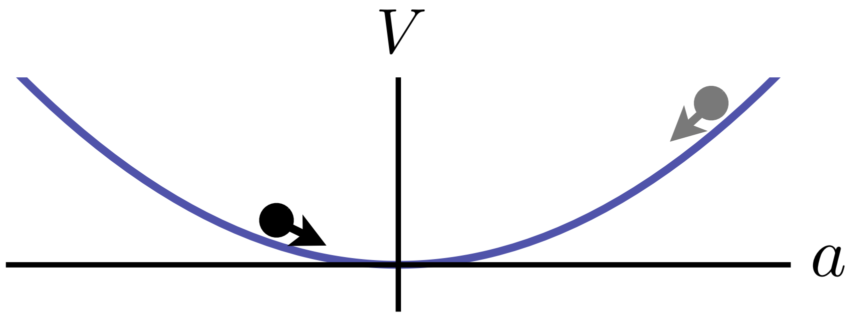
Photons

$$\vec{E} = E_0 \cos\left(\omega t - \omega x\right)$$

Detect Photon by measuring time varying field

Dark Bosons

Early Universe: Misalignment Mechanism

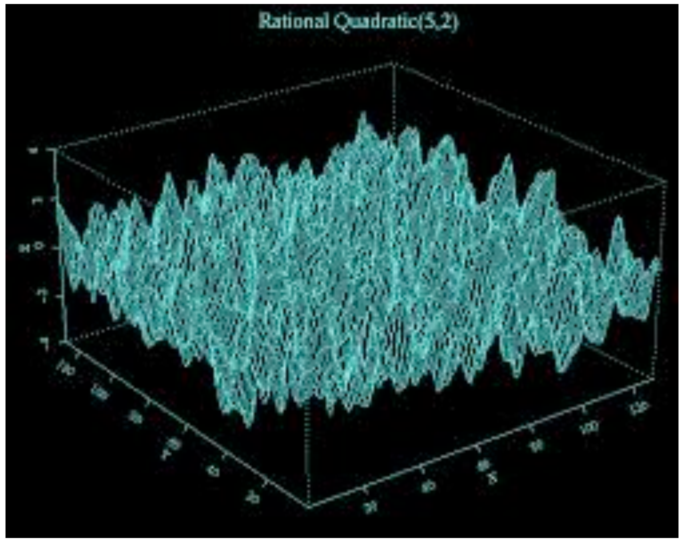


$$a(t) \sim a_0 \cos\left(m_a t\right)$$

Spatially uniform, oscillating field

$$m_a^2 a_0^2 \sim \rho_{DM}$$

Today: Random Field



Correlation length $\sim 1/(m_a\ v)$

Coherence Time $\sim 1/(m_a\ v^2)$ $\sim 1\ \mathrm{s}\ (\mathrm{MHz}/m_a)$

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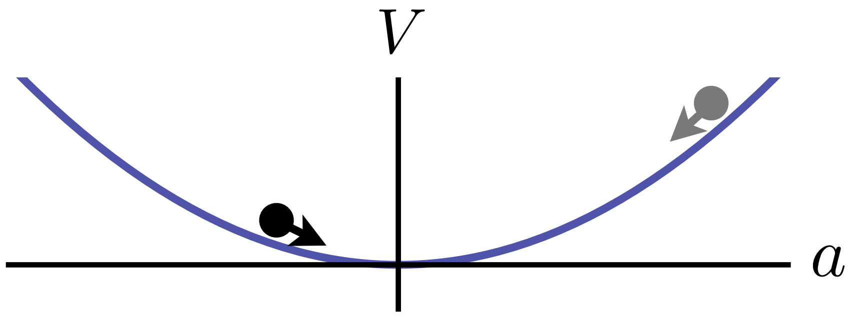

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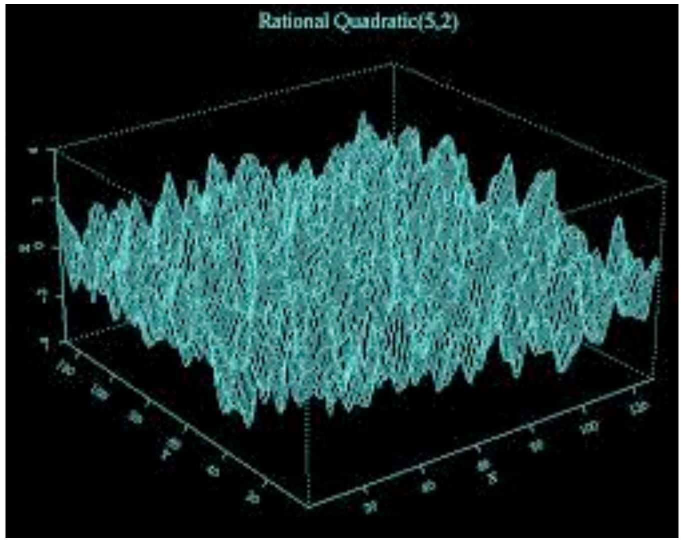


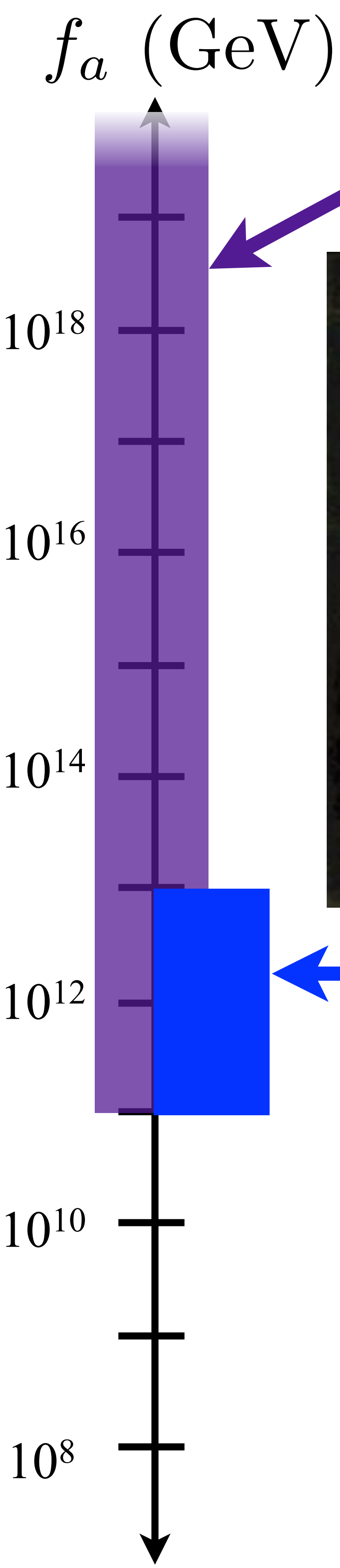
Correlation length
~ $1/(m_a v)$

Coherence Time
~ $1/(m_a v^2)$
~ 1 s (MHz/m_a)

Detect effects of oscillating dark matter field

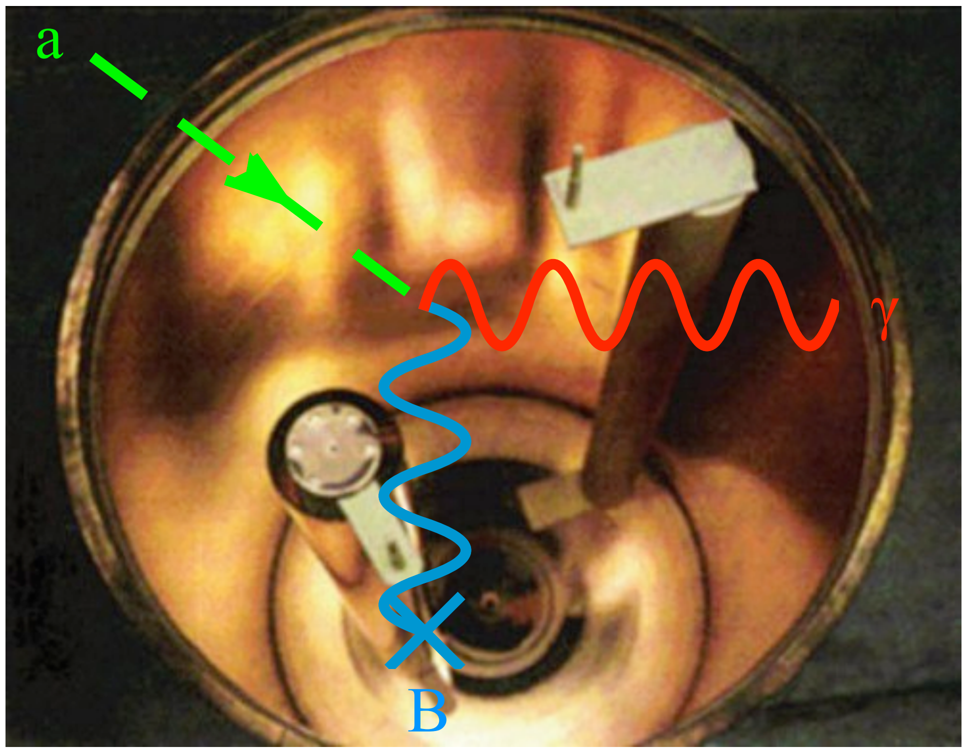
Resonance possible. Q ~ 10^6 (set by v ~ 10^{-3})

Beyond Axion-Electrodynamics



Axion dark matter

in most models: $\mathcal{L} \supset \frac{a}{f_a} F\widetilde{F} = \frac{a}{f_a} \vec{E} \cdot \vec{B}$



axion-photon conversion suppressed $\propto \frac{1}{f_a^2}$

size of cavity increases with f_a

signal $\propto \frac{1}{f_a^3}$

microwave cavity (ADMX)

Physical effects always suppressed by powers of the axion's compton wavelength

Signal suppressed by size of experiment/axion wavelength

Other ways to search for light (high f_a) axions?

Axions

Global symmetry broken at high scale f_a

Light Goldstone boson

Gauge Fields

$$\frac{a}{f_a} F \wedge F, \quad \frac{a}{f_a} G \wedge G$$

Fermions

$$\frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma_5 \psi$$

Current Searches

QCD axion (CASPEr)

Axion-like Particles (CASPEr)

A Different Operator For Axion Detection

So how can we detect high f_a axions?

Strong CP problem: $\mathcal{L} \supset \theta \, G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16} \, \theta \, e \, \mathrm{cm}$

the axion: $\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16} \, \frac{a}{f_a} \, e \, \mathrm{cm}$

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$a(t) \sim a_0 \cos(m_a t)$ with $m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz}\left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$

axion dark matter $\rho_{\mathrm{DM}} \sim m_a^2 a^2 \sim (200\mathrm{MeV})^4 \left(\frac{a}{f_a}\right)^2 \sim 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}$

so today: $\left(\frac{a}{f_a}\right) \sim 3 \times 10^{-19}$ independent of f_a

axion gives all nucleons an oscillating EDM (kHz-GHz) independent of f_a,
a non-derivative operator

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So how can we detect high f_a axions?

Axion interacts with fermions: $\mathcal{L} \supset \frac{\partial_\mu \phi}{f_\phi} \bar{\psi}\gamma^\mu \gamma_5 \psi$

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$$m_\phi \phi_0 \sim \sqrt{\rho_{DM}} \sim 10^{-5} \text{ T}$$

A Different Operator For Axion Detection

So how can we detect high f_a axions?

Axion interacts with fermions: $\mathcal{L} \supset \frac{\partial_\mu \phi}{f_\phi} \bar{\psi} \gamma^\mu \gamma_5 \psi$

Non-relativistic Nucleon Hamiltonian: $H_N \supset \frac{\nabla \phi . \vec{S}}{f_\phi}$

Axion dark matter $\implies \phi\left(t, \vec{x}\right) = \phi_0 \cos\left(m_\phi t + m_\phi \vec{v}.\vec{x}\right)$

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Taking f_Φ ~ 10^9 GeV, this looks like a ~ fT a/c magnetic field

CASPEr: Axion Effects on Spin

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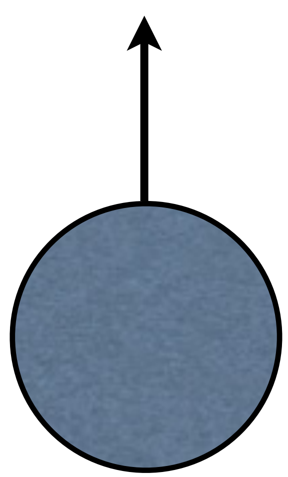
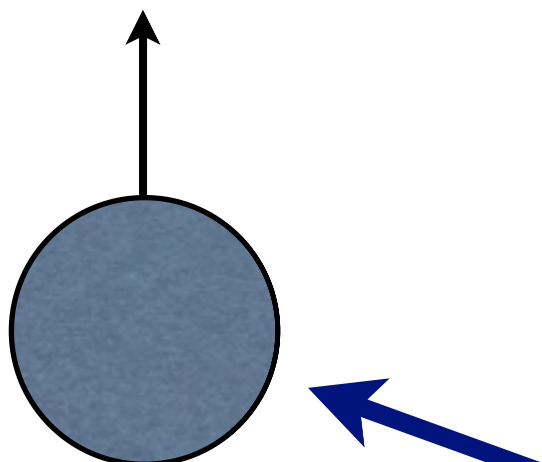
General Axions



CASPEr: Axion Effects on Spin

General Axions

Neutron in Axion Wind



$\left(\frac{\partial_\mu a}{f_a} \bar{N} \gamma^\mu \gamma_5 N\right)$

$\vec{v}$

$$H_N \supset \frac{a}{f_a} \vec{v_a} . \vec{S}_N$$

Spin rotates about dark matter velocity

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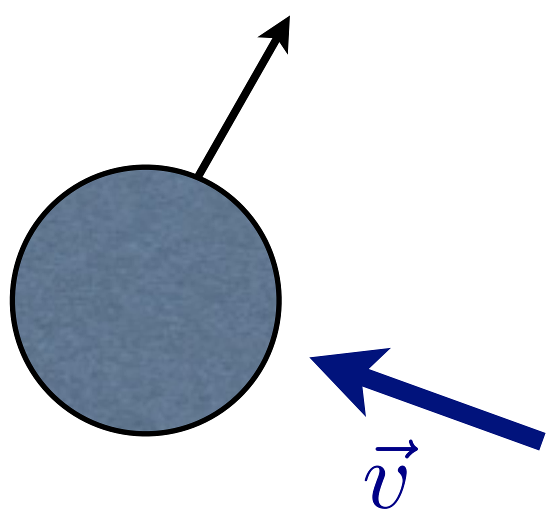

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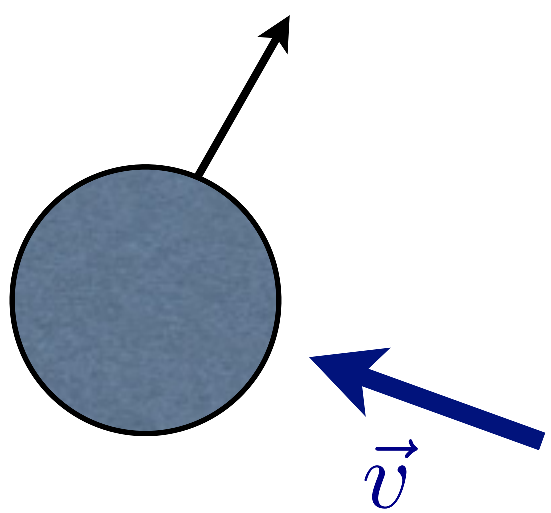

$$H_N \supset \frac{a}{f_a}\vec{v_a}.\vec{S}_N$$

Spin rotates about
dark matter velocity

Effective time varying
magnetic field

$$B_{eff} \lessapprox 10^{-16}\ \cos\left(m_a t\right)\ \mathrm{T}$$

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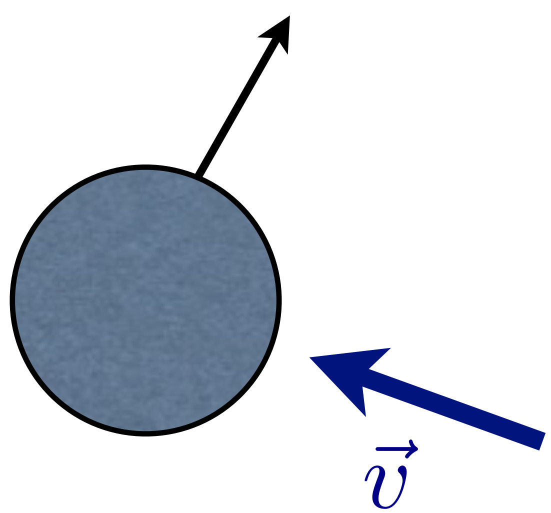

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Other light dark matter (e.g. dark photons) also induce similar spin precession

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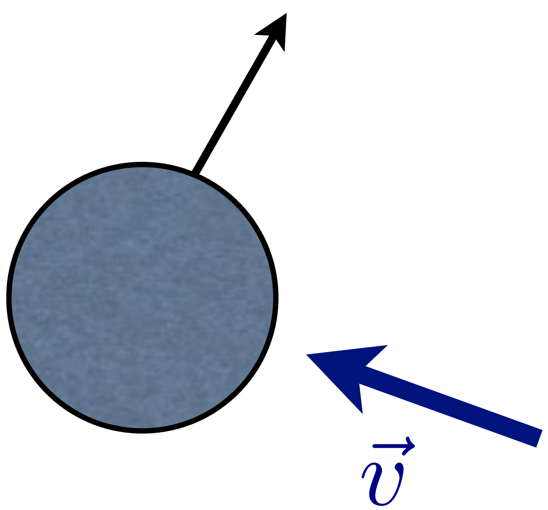

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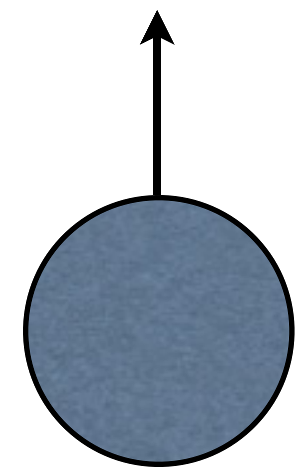
QCD Axion

Neutron



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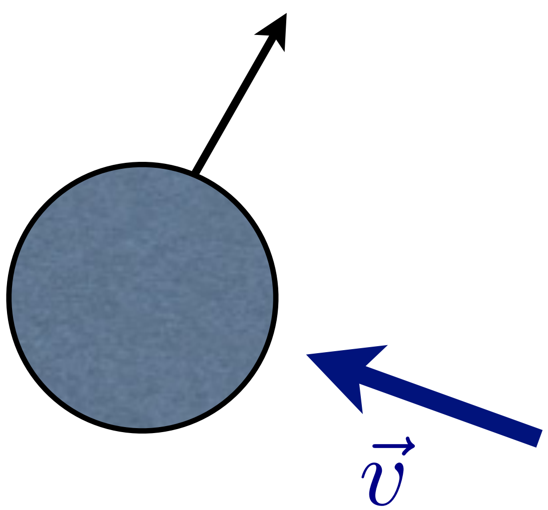

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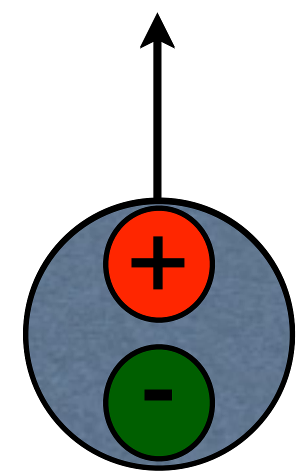
QCD Axion

Neutron in
QCD Axion Dark Matter



$$\left(\frac{a}{f_a}G\tilde{G}\right)$$

QCD axion induces electric dipole moment
for neutron and proton

Dipole moment
along nuclear spin

Oscillating dipole: $d \sim 3\times10^{-34}\ \cos\left(m_a t\right)\ e\,\mathrm{cm}$

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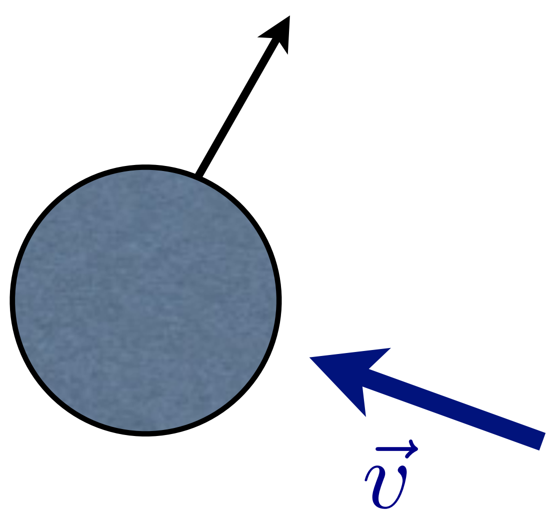

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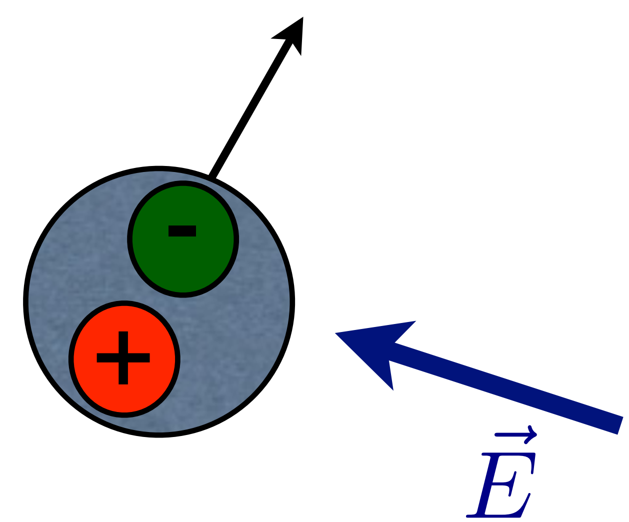
QCD Axion

Neutron in QCD Axion Dark Matter



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Apply electric field, spin rotates

CASPEr: Axion Effects on Spin

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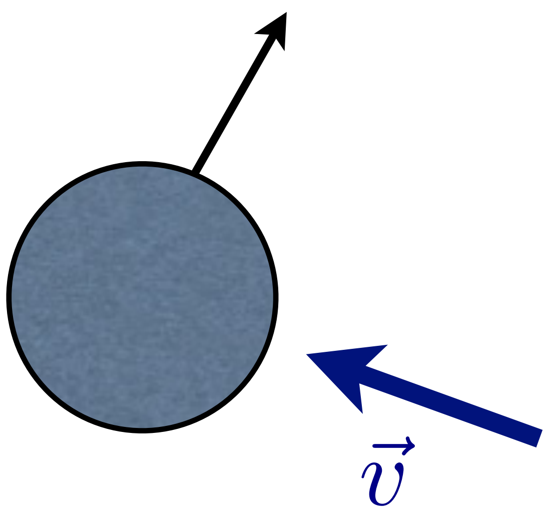

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Spin rotates about
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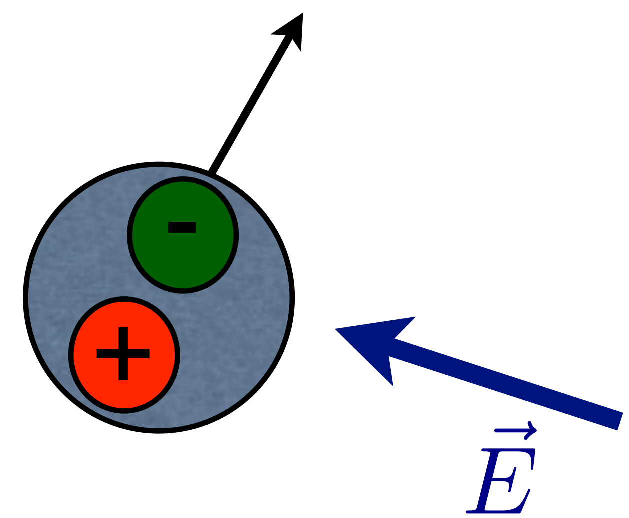
QCD Axion

Neutron in QCD Axion Dark Matter



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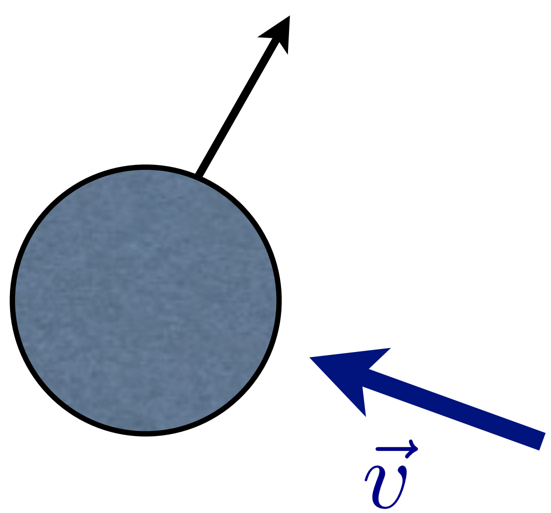

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Other light dark matter (e.g. dark photons) also
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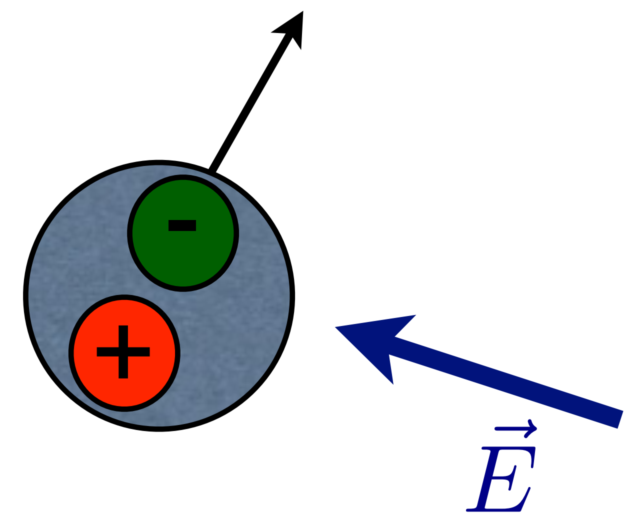
Measure Spin Rotation, detect Axion

QCD Axion

Neutron in QCD Axion Dark Matter



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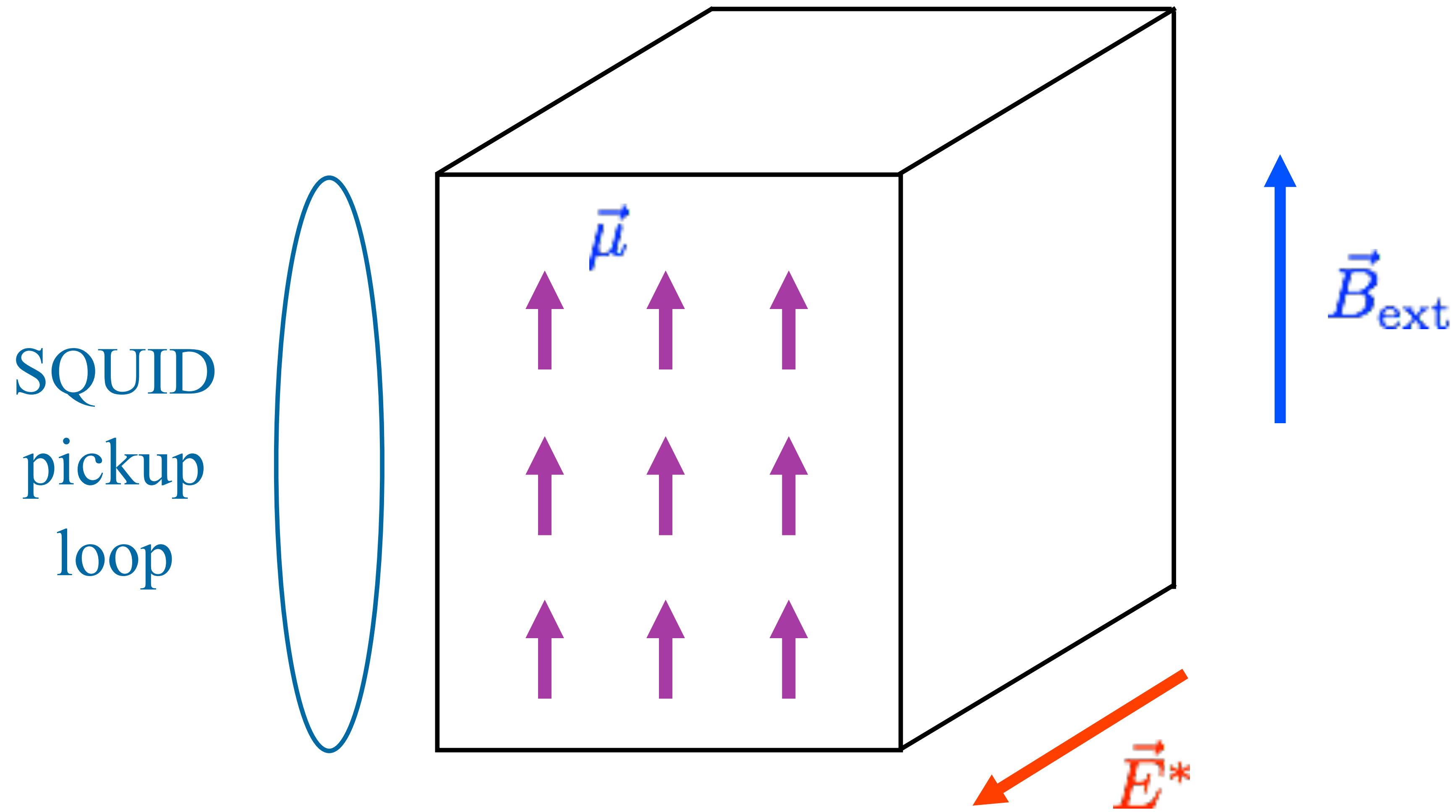
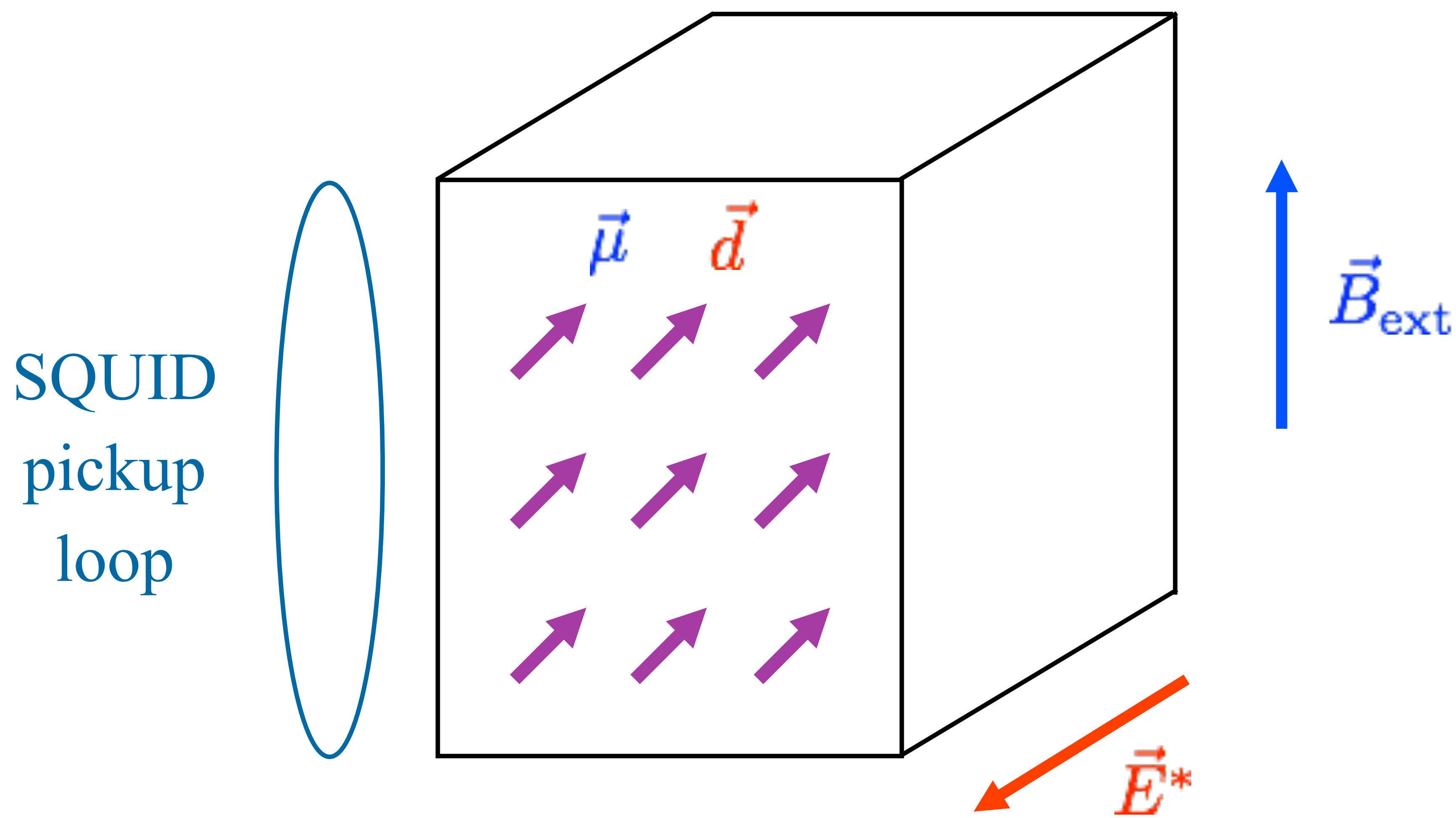
NMR Technique



high nuclear spin orientation achieved in several systems, persists for T_1 ~ hours

NMR Technique



high nuclear spin orientation achieved in several systems, persists for $T_1 \sim$ hours

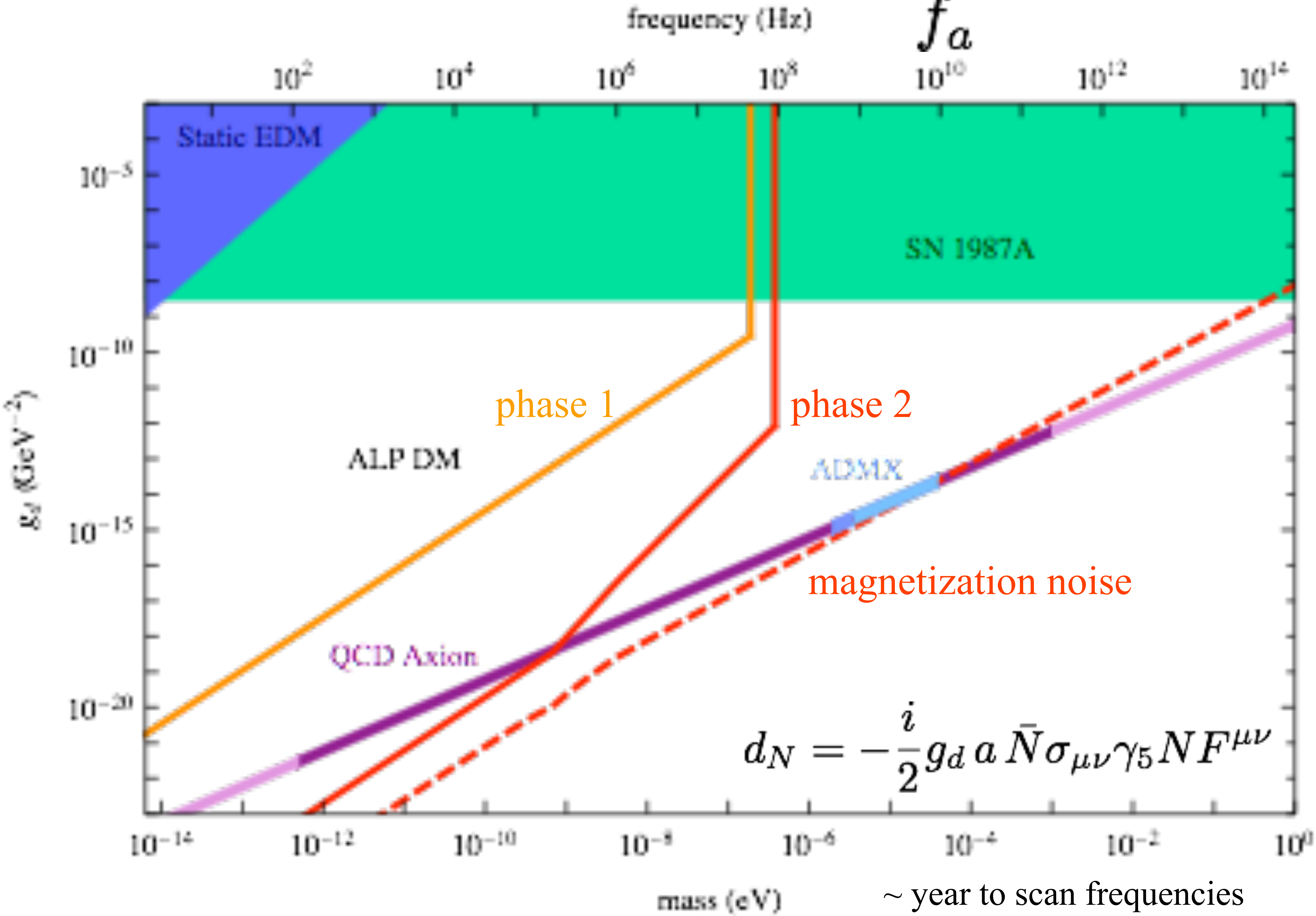
applied E field causes precession of nucleus

SQUID measures resulting transverse magnetization

Larmor frequency = axion mass $\Longrightarrow$ resonant enhancement

resonance ➜ scan over axion masses by changing B_{ext}

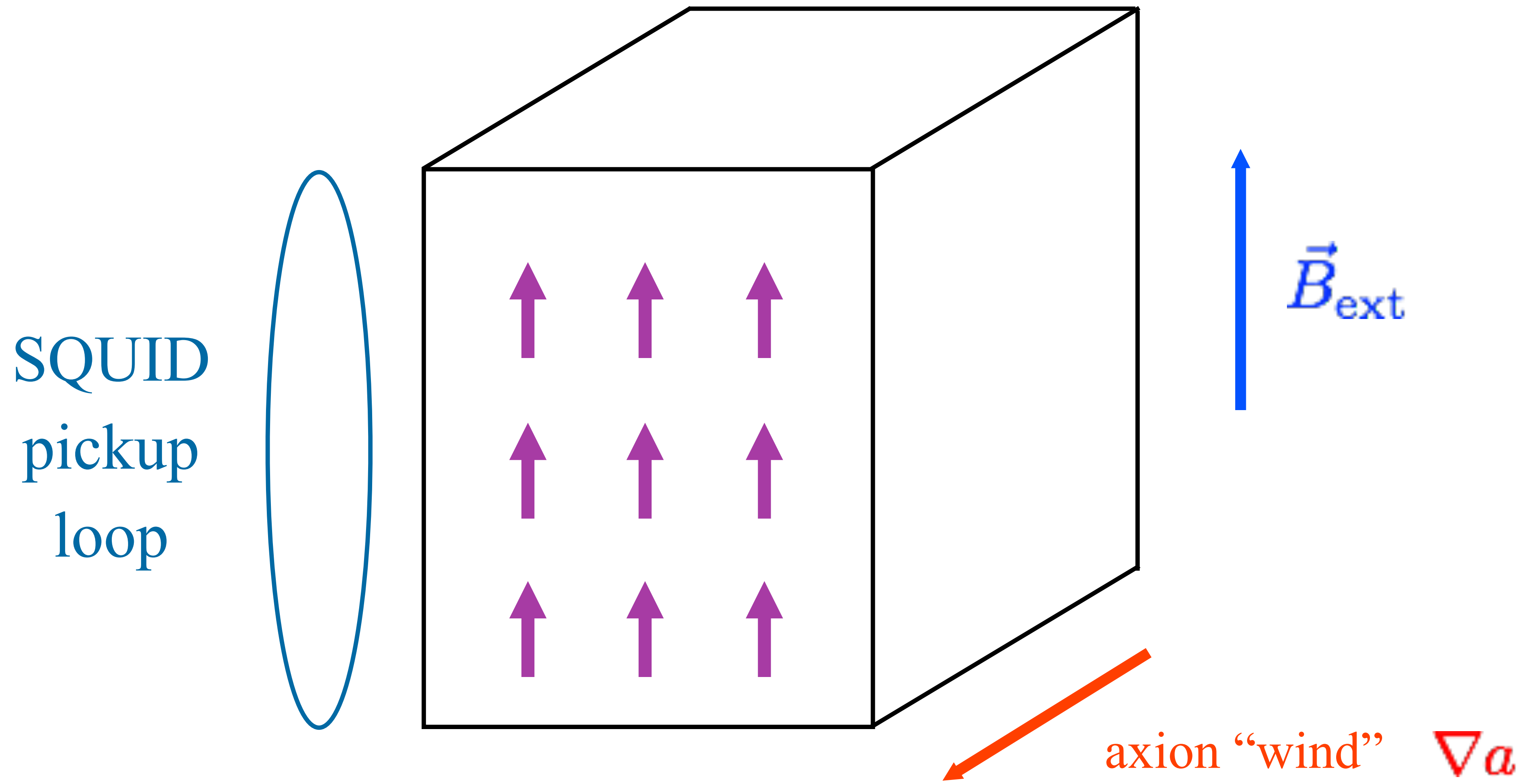
Axion Limits on $\frac{a}{f_a} G\widetilde{G}$



~ year to scan frequencies

Verify signal with spatial coherence of axion field

Axion Wind



use nuclear spins coupled to axion DM

$$g_{\rm aNN}\,(\partial_\mu a)\,\bar{N}\gamma^\mu\gamma_5 N \implies H_N \supset g_{\rm aNN}\vec{\nabla}a.\vec{S}_N$$

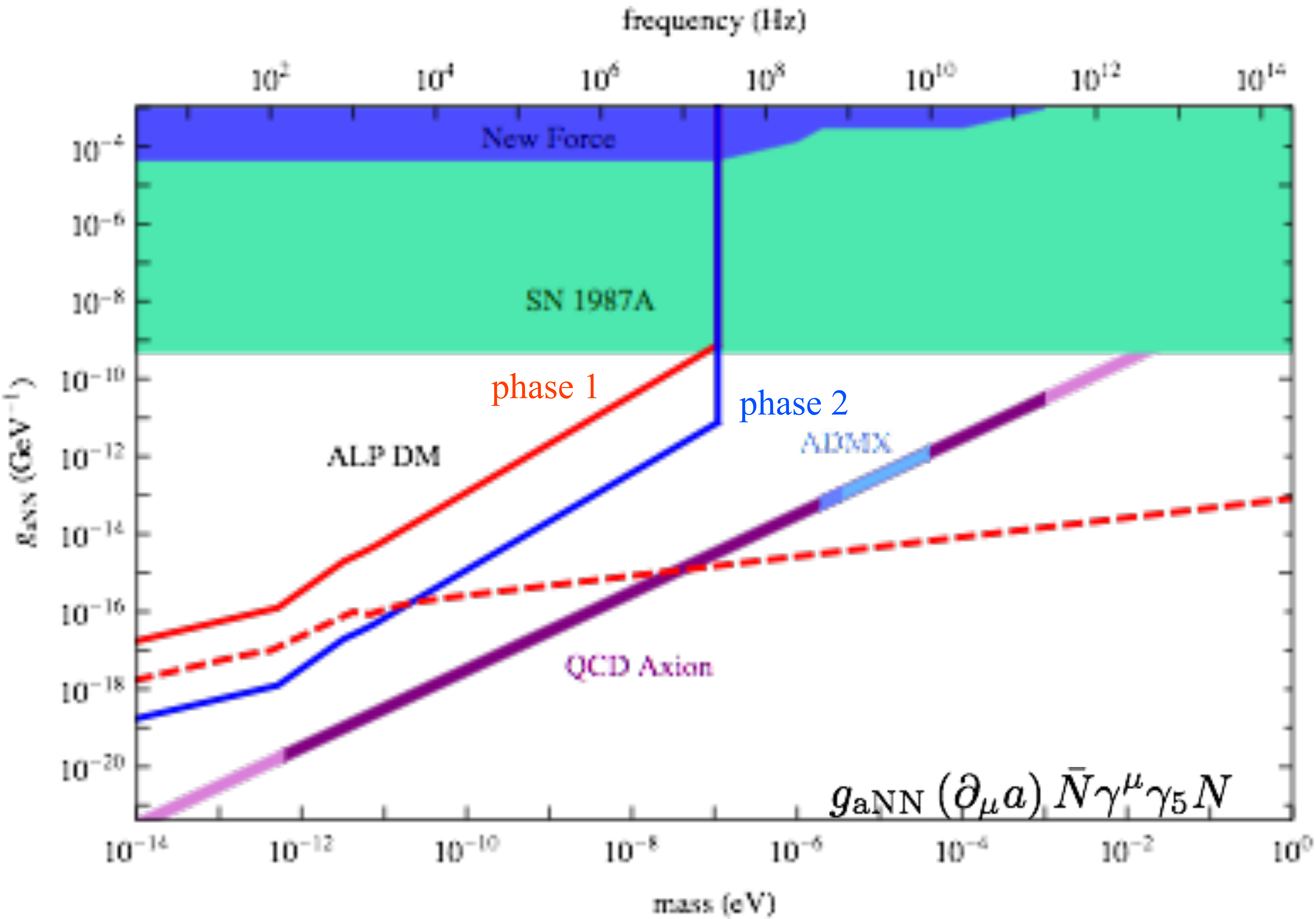
effects suppressed by v ~ 10^{-3}

Similar to EDM experiment but no Schiff suppression, no E-field (polar crystal)

makes a directional detector for axions (and gives annual modulation)

also works for any other spin-coupled DM (e.g. dark photon)

Limits on Axion-Nucleon Coupling



~ year to scan one decade of frequency

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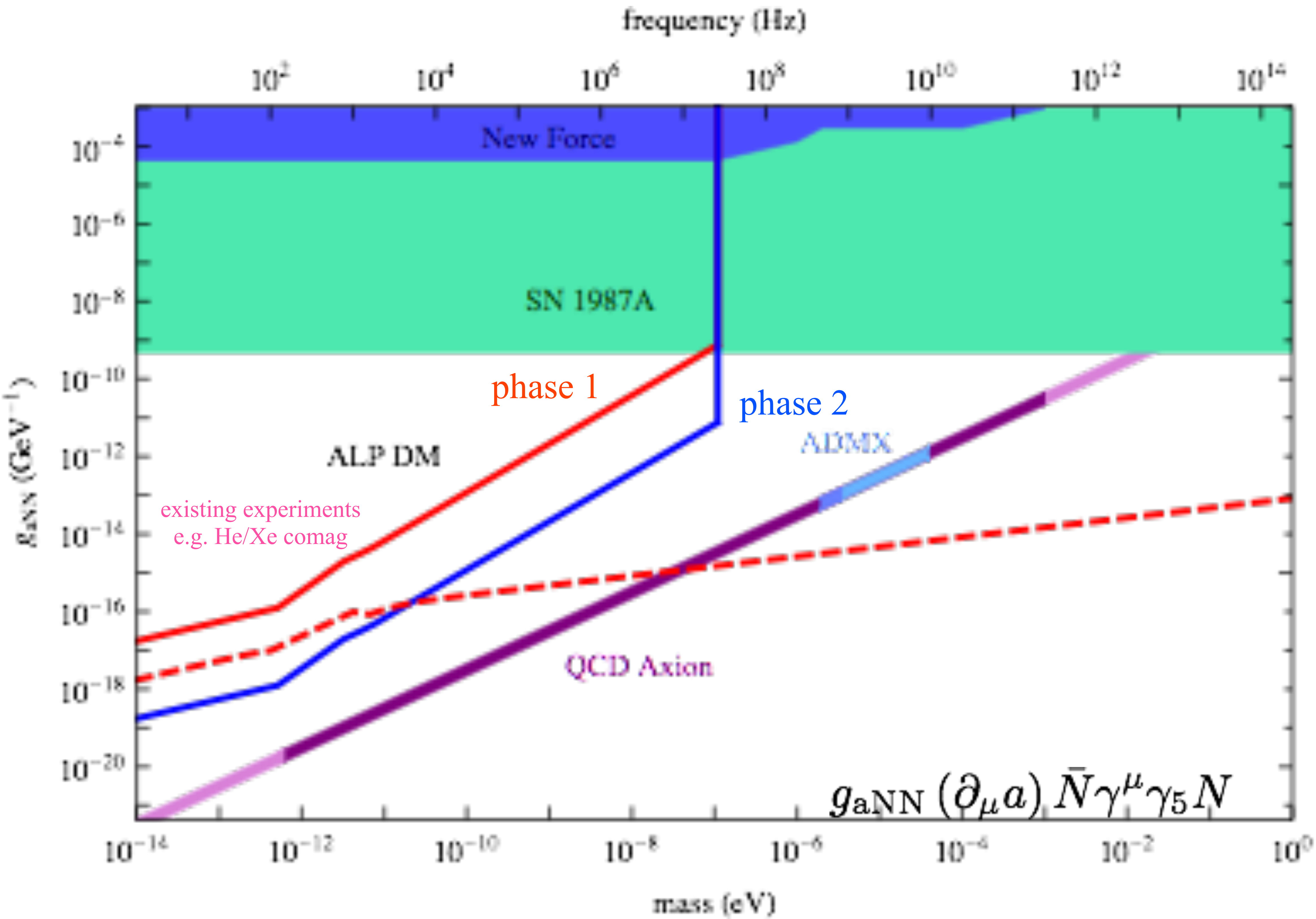

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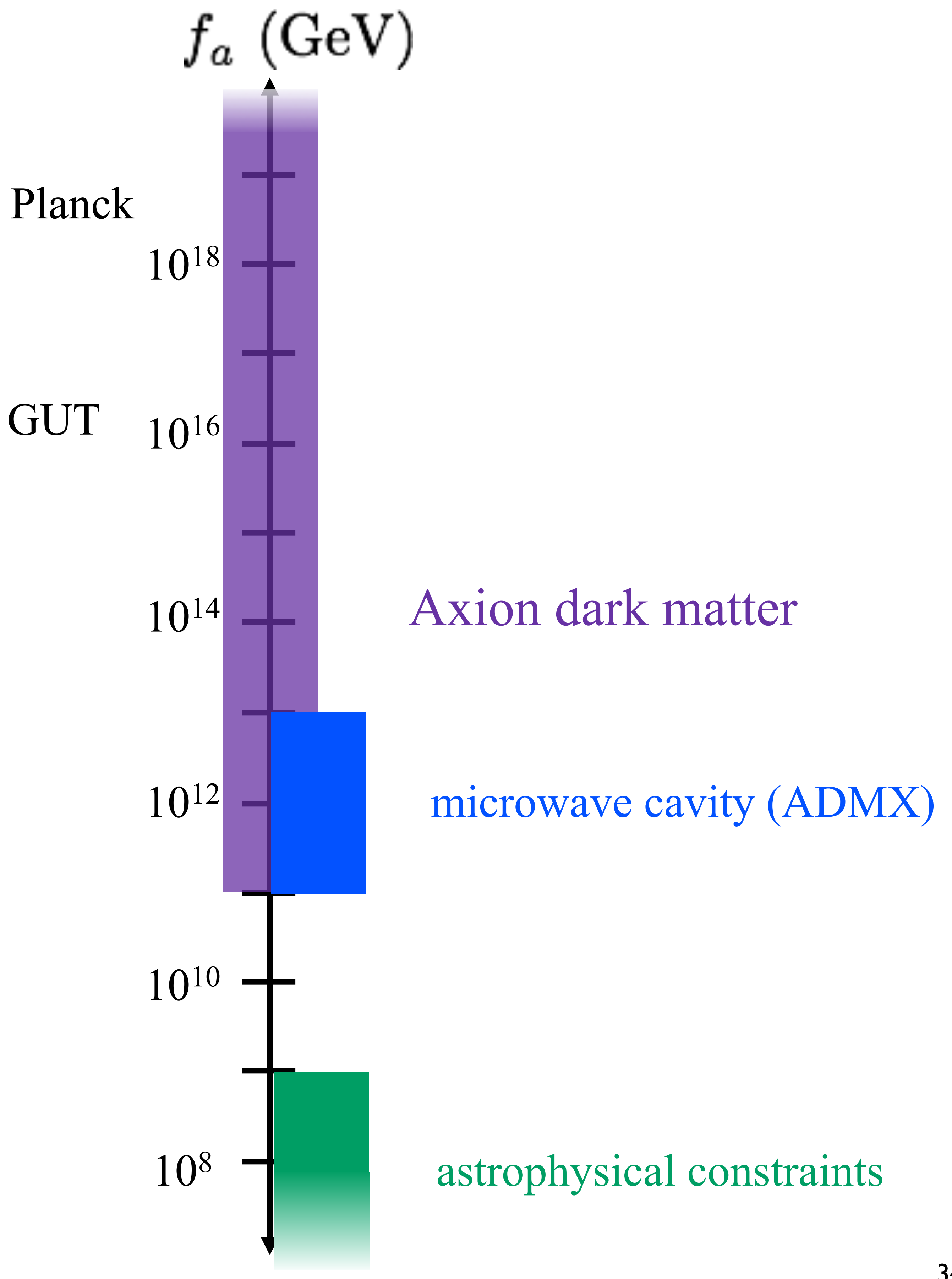
CASPEr Discovery Potential



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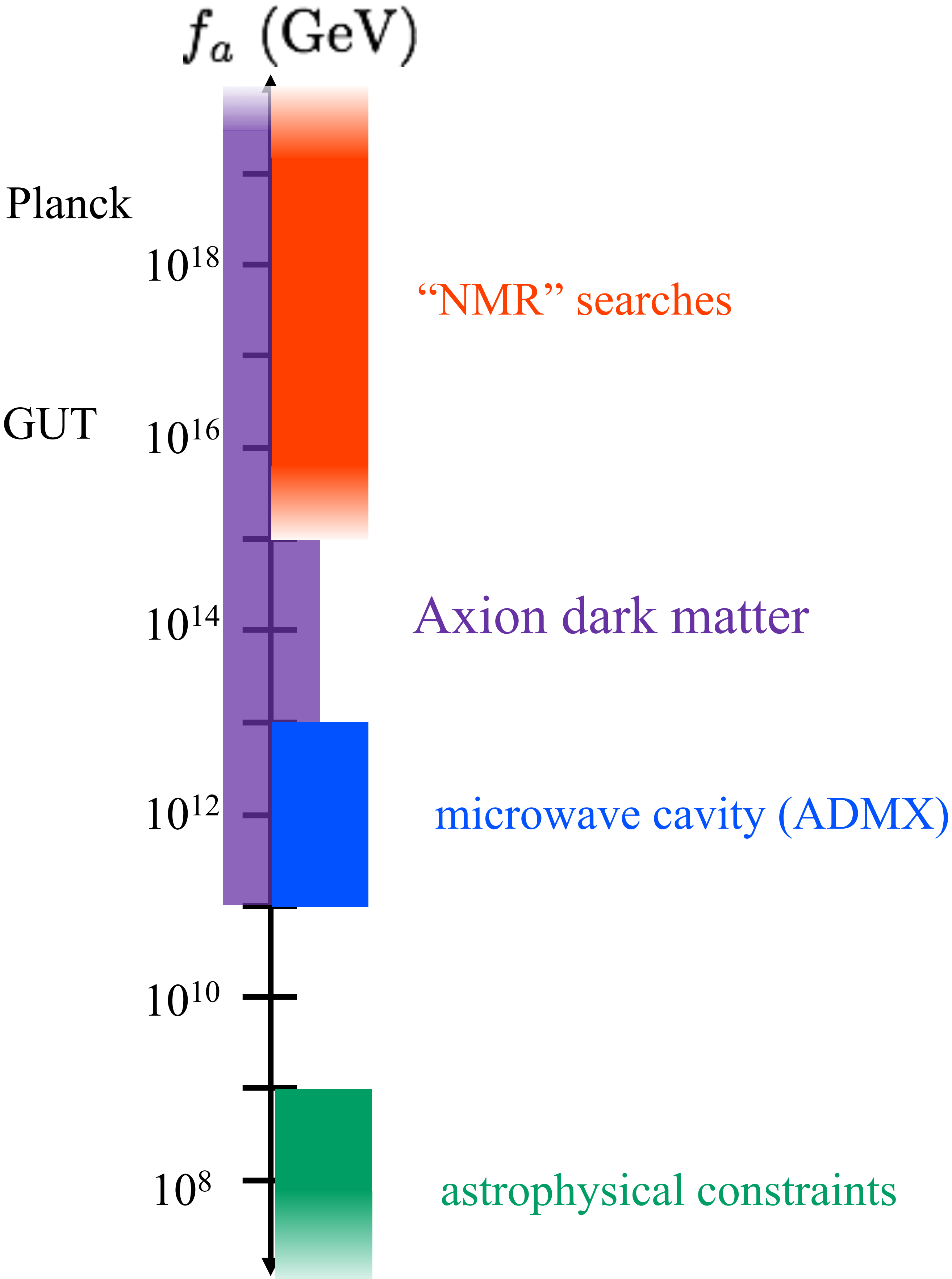
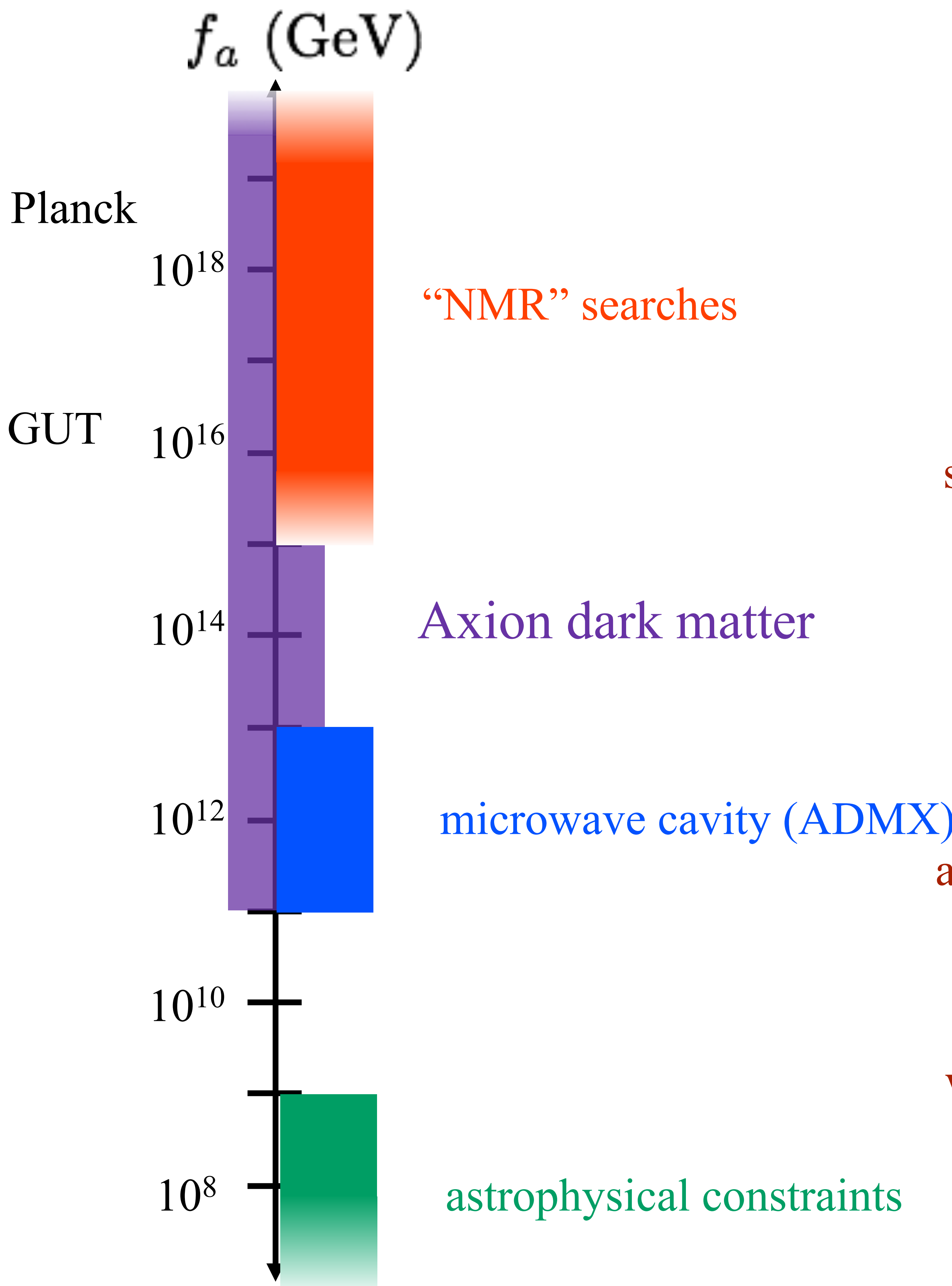


laboratory experiment

significant reach in kHz - 10 MHz
frequencies ➞ high f_a

CASPEr Discovery Potential



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frequencies ➞ high f_a

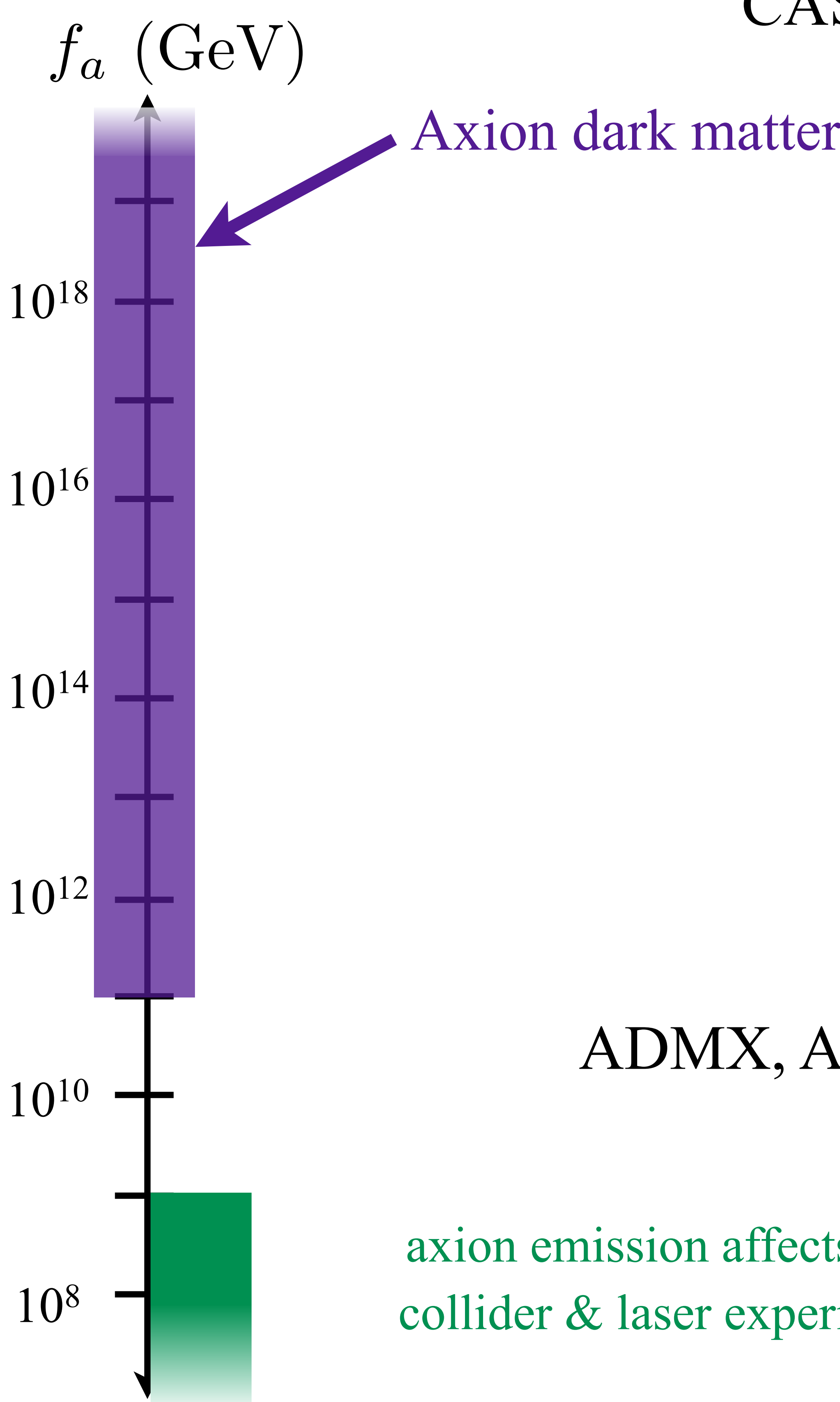
technological challenges,
similar to early stages of WIMP detection, axions deserve similar effort

technology broadly useful for community.

axion dark matter is very well-motivated, no other way to search for light axions (high f_a)

would be both the discovery of dark matter and a glimpse into physics at very high energies

Summary



CASPEr, Superradiance,...

Future

Plenty of new developments (theory and experiment)!

ADMX, ADMX-HF, Spin-Spin Forces, ALPS,...

axion emission affects SN1987A, White Dwarfs, other astrophysical objects
collider & laser experiments, ALPS, CAST