Constraining Ultralight Scalars with Neutron Star Superradiance

Paul Riggins
UC Berkeley

Planck 2018

In collaboration with
David E. Kaplan (Johns Hopkins University)
Surjeet Rajendran (UC Berkeley)

Our Story

Rotational Superradiance has been well studied in Black Holes,

[e.g., Brito, et al., 2015]

and

applied to constrain new ultralight particles,

[e.g., Arvanitaki, et al., 2009, 2015]

Our Story

Rotational Superradiance has been well studied in Black Holes,

[e.g., Brito, et al., 2015]

and

applied to constrain new ultralight particles,

[e.g., Arvanitaki, et al., 2009, 2015]

BUT

these constraints are highly sensitive to the (difficult-to-measure) BH rotation rate

and

superradiance can occur in any rotating system with dissipation

[Zel'dovich, 1971]

Our Story

Rotational Superradiance has been well studied in Black Holes,

[e.g., Brito, et al., 2015]

and

applied to constrain new ultralight particles,

[e.g., Arvanitaki, et al., 2009, 2015]

BUT

these constraints are highly sensitive to the (difficult-to-measure) BH rotation rate

and

superradiance can occur in any rotating system with dissipation

[Zel'dovich, 1971]

SO

we consider superradiance in millisecond pulsars

to constrain ultralight scalars with Yukawa couplings to neutrons

Our Story

1 Rotational Superradiance has been well studied in Black Holes,

[e.g., Brito, et al., 2015]

and

applied to constrain new ultralight particles,

2 [e.g., Arvanitaki, et al., 2009, 2015]

BUT

these constraints are highly sensitive to the 3
(difficult-to-measure) BH rotation rate

and

superradiance can occur in any rotating system with dissipation

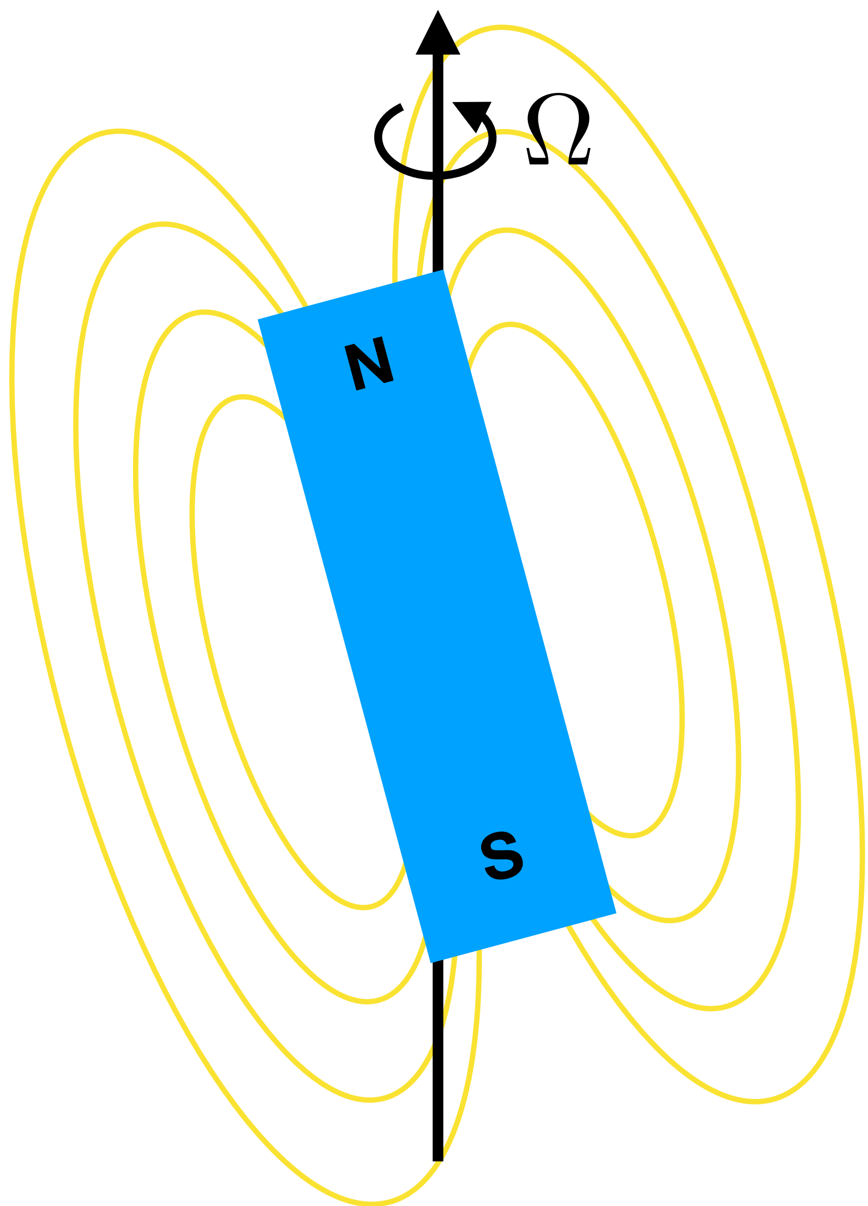
[Zel'dovich, 1971]

SO

we consider 4 superradiance in millisecond pulsars

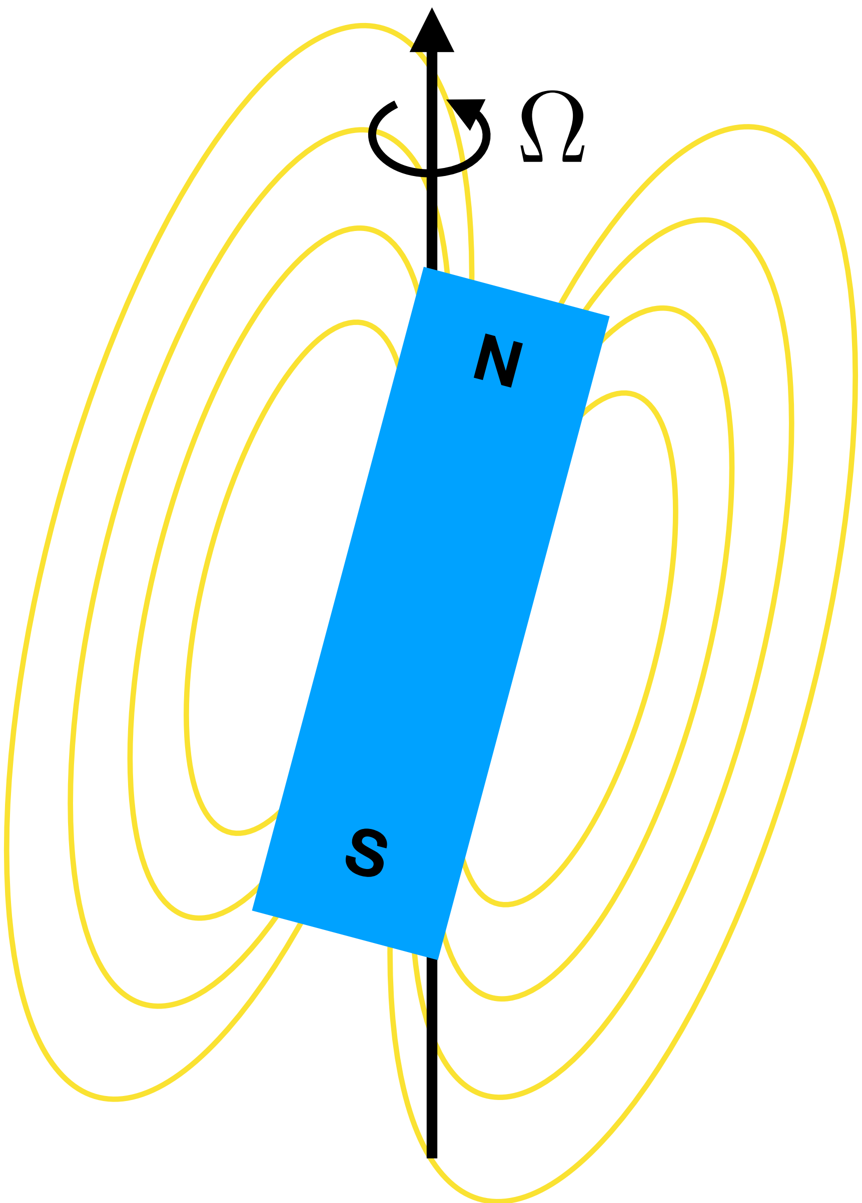
5 to constrain ultralight scalars with Yukawa couplings to neutrons

Radiation from rotating objects



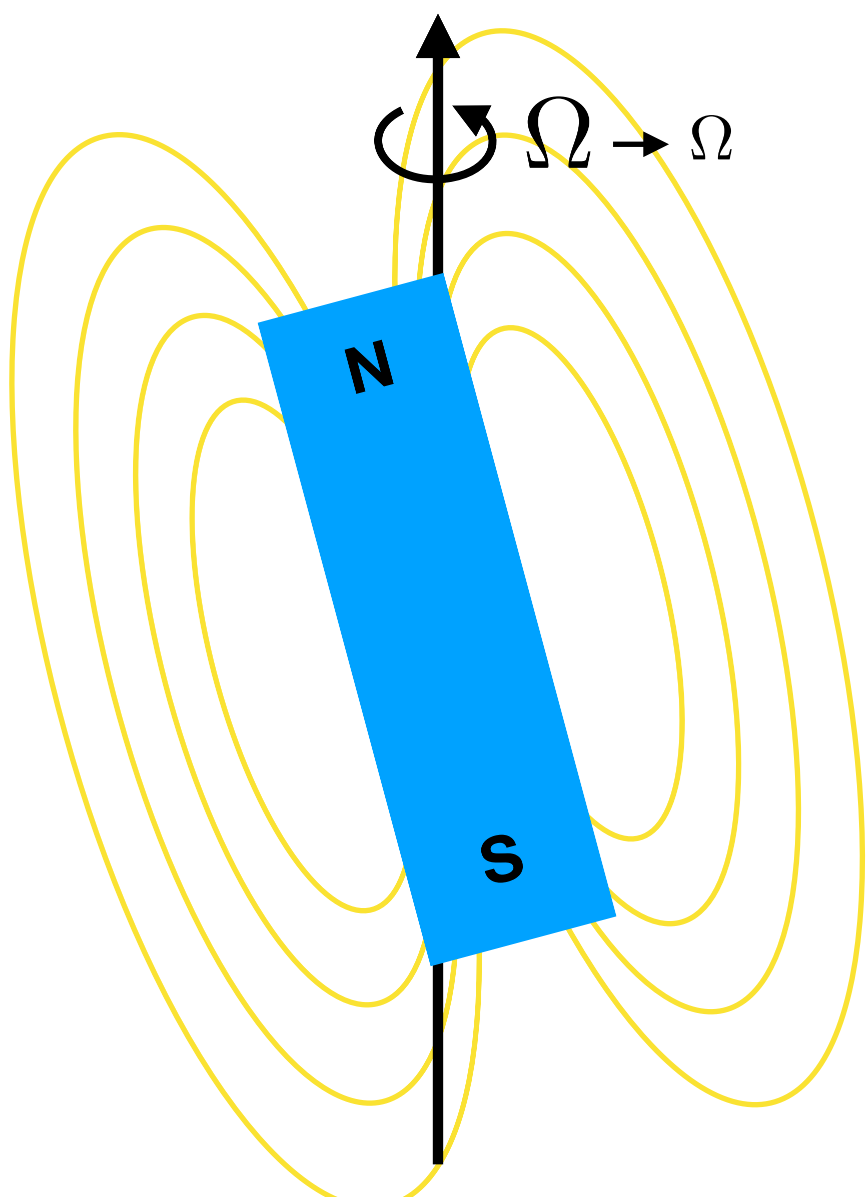
Non-axisymmetric objects can radiate by multipole radiation.

Radiation from rotating objects



Non-axisymmetric objects can radiate by multipole radiation.

Radiation from rotating objects

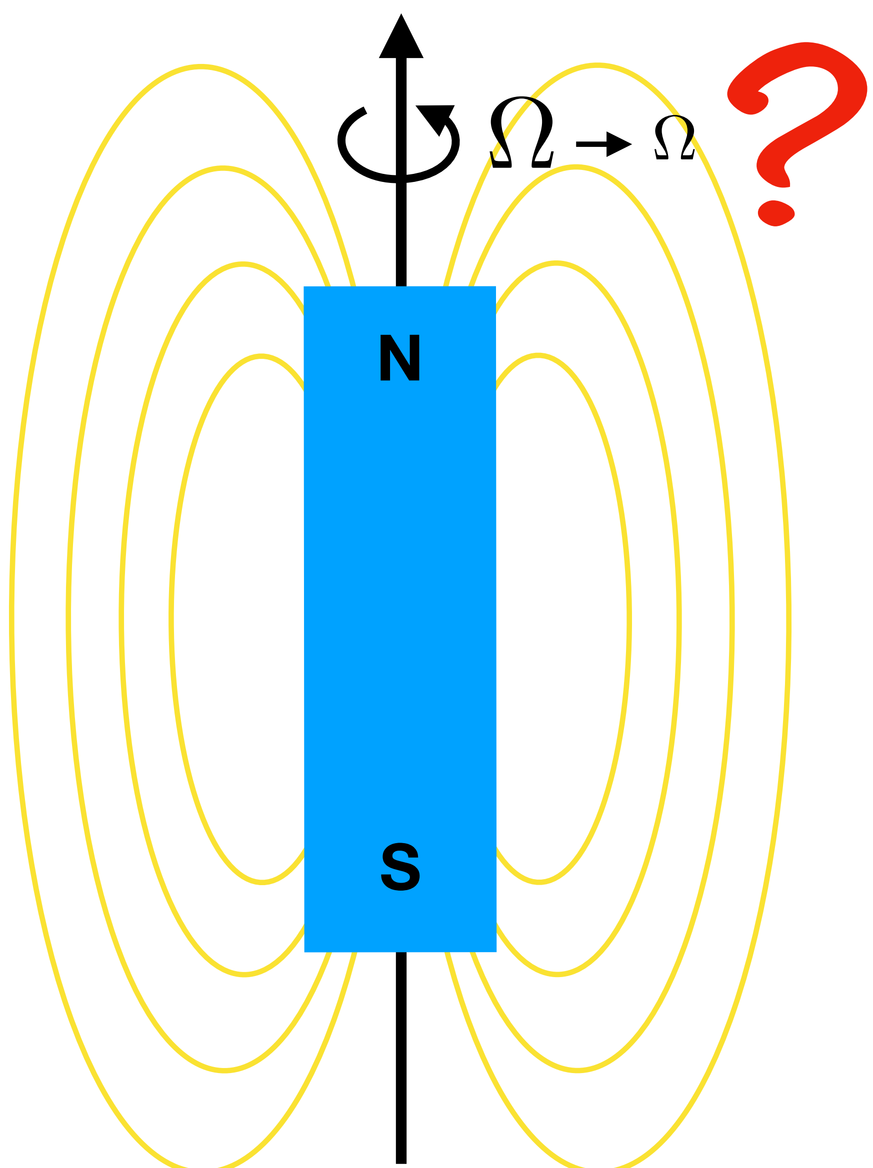


Non-axisymmetric objects can radiate by multipole radiation.

phase space ✓

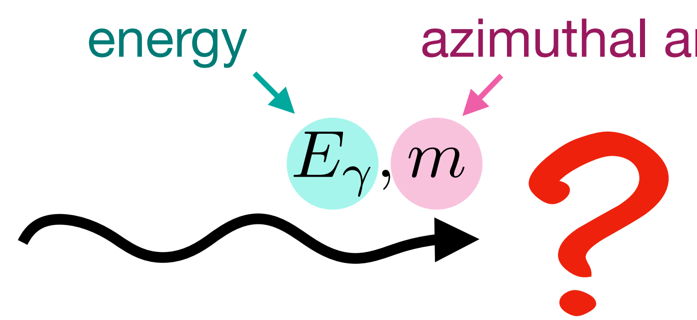
coupling ✓

Radiation from rotating objects



Non-axisymmetric objects can radiate by multipole radiation.

What if the object is axisymmetric?

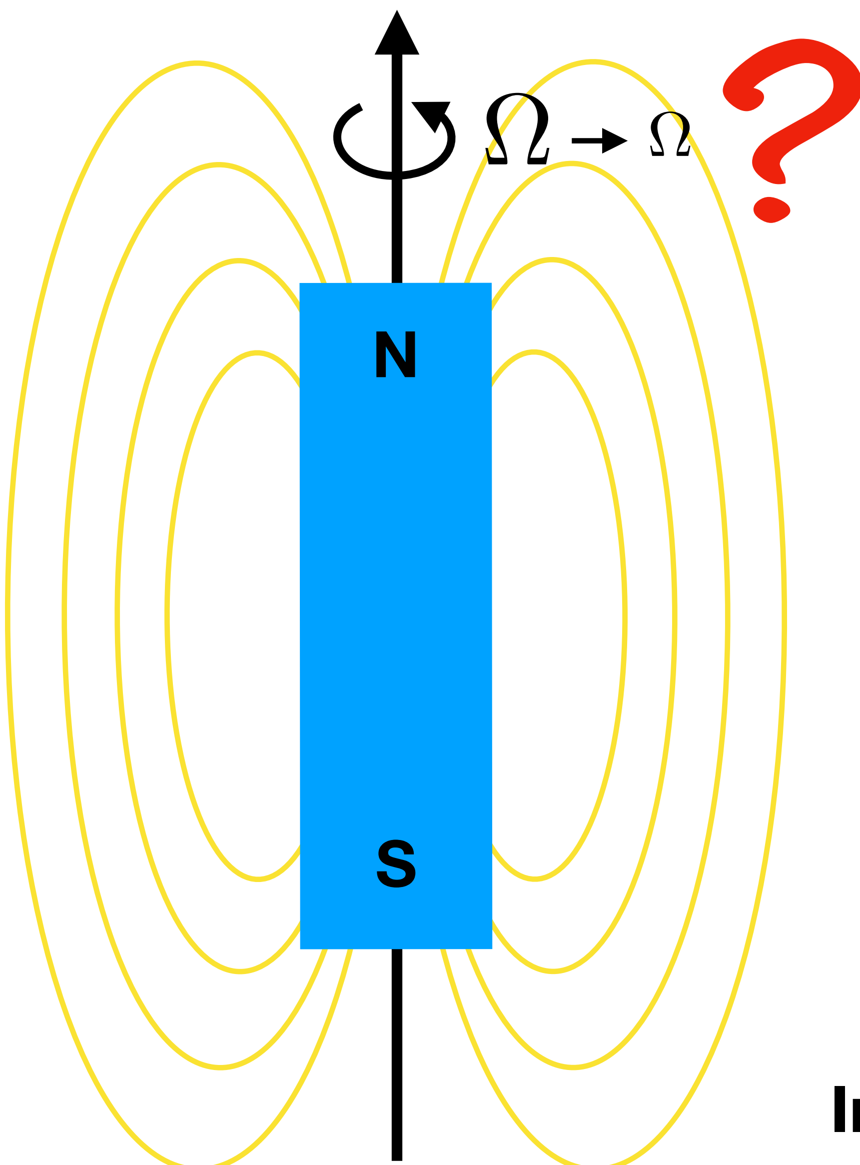


phase space ✓

coupling ✗

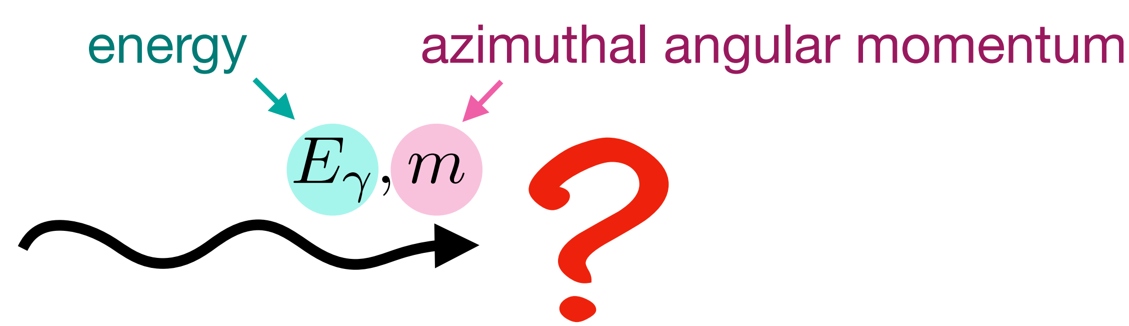
1

Radiation from rotating objects



Non-axisymmetric objects can radiate by multipole radiation.

What if the object is axisymmetric?



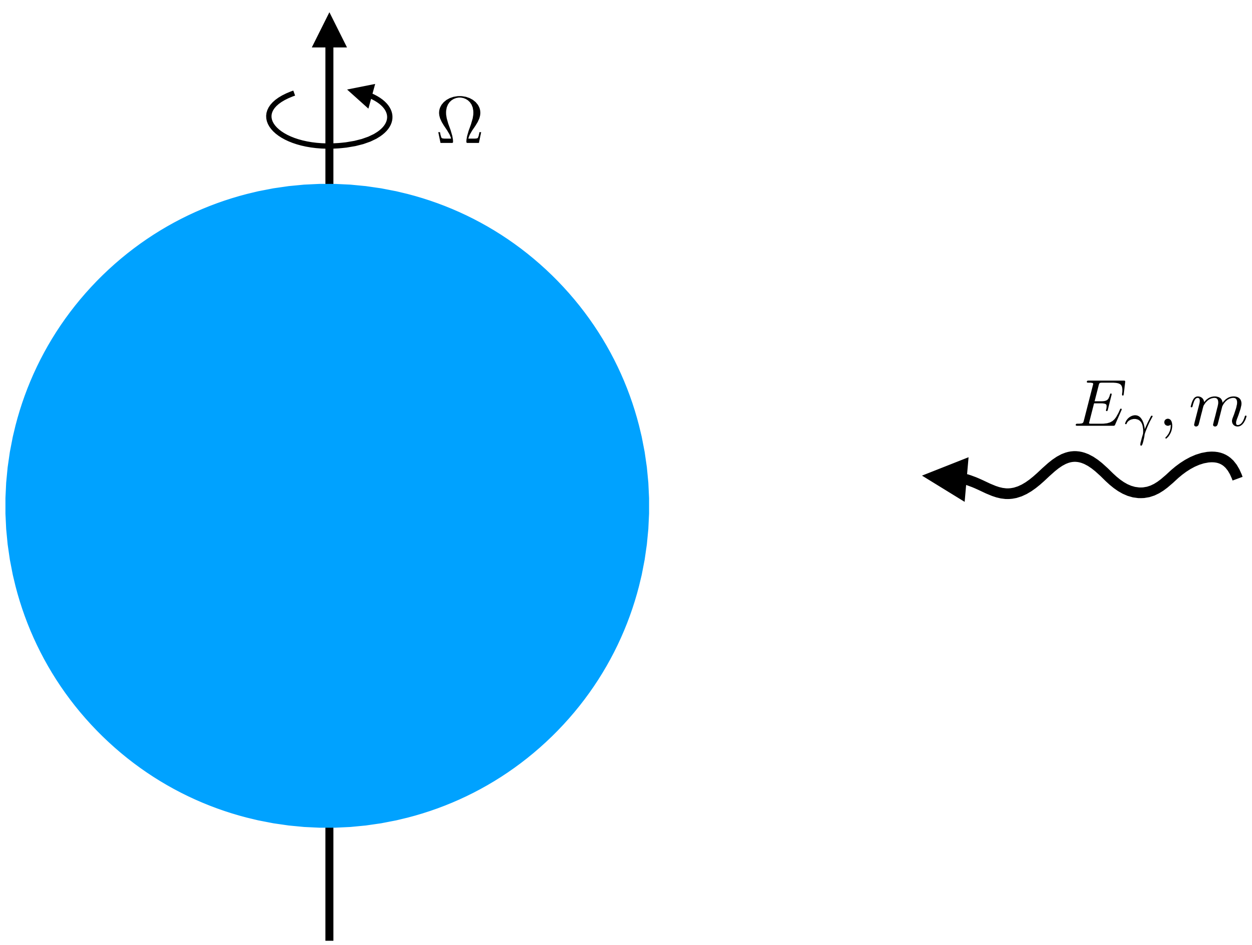
phase space ✓

coupling ✗

Internal degrees of freedom (e.g., phonons) can break axisymmetry and provide coupling

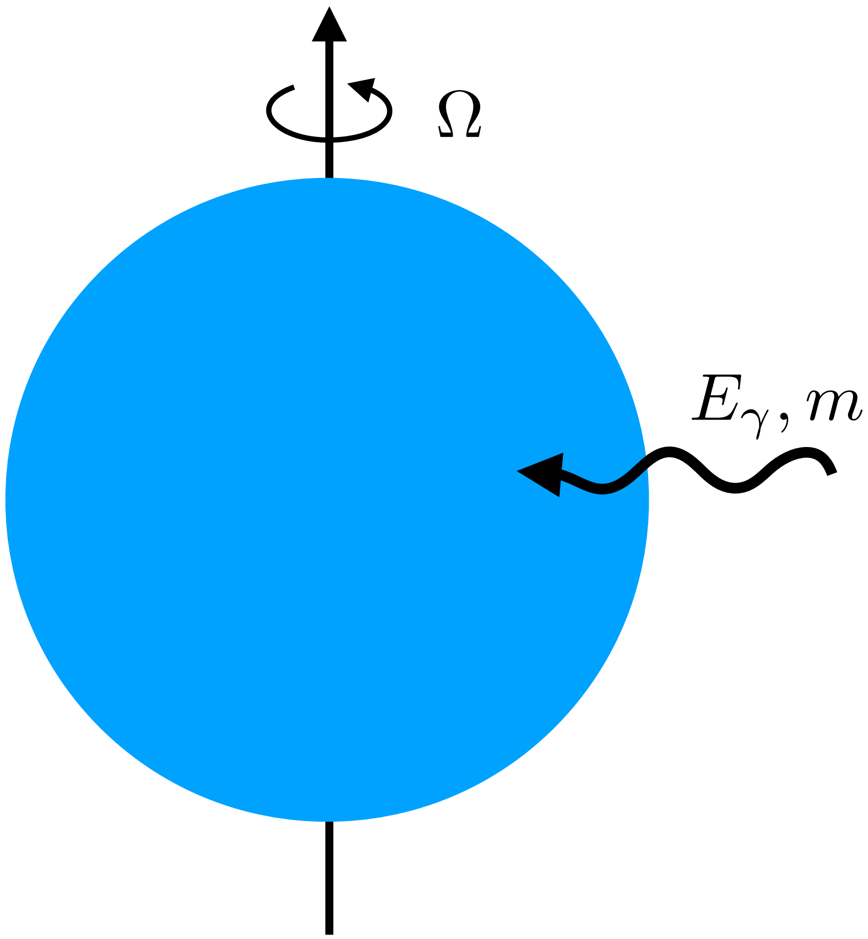
Rotational Superradiance

Example: photons can excite oscillations in a star



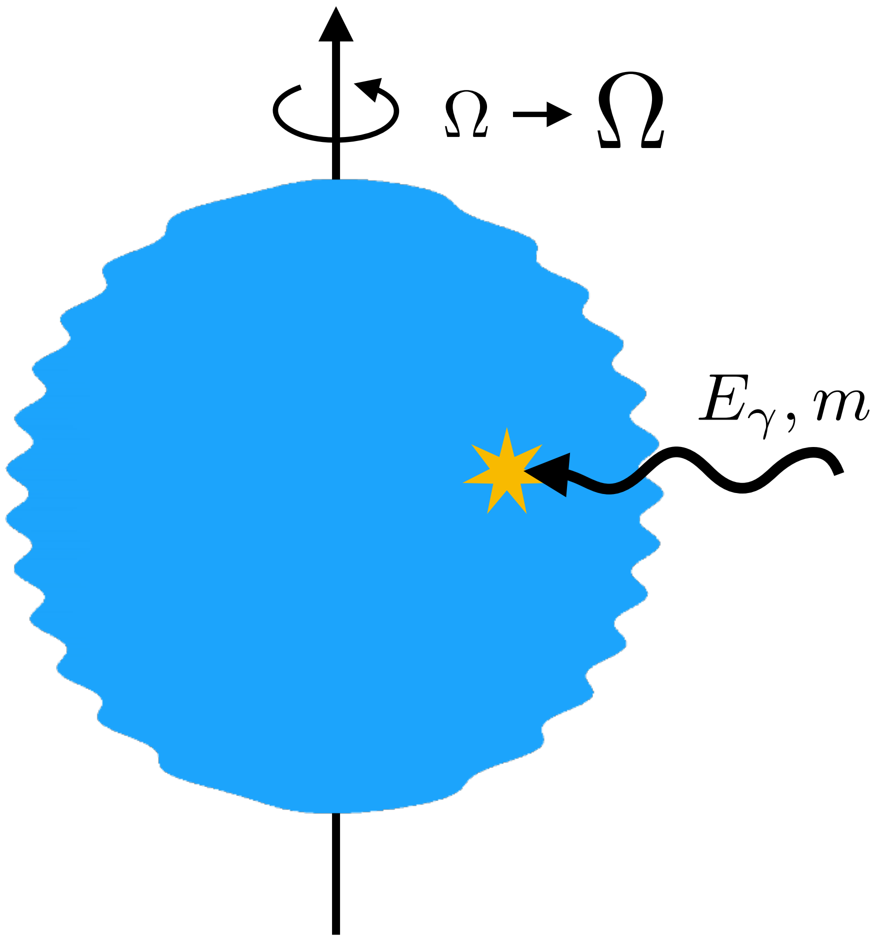
Rotational Superradiance

Example: photons can excite oscillations in a star



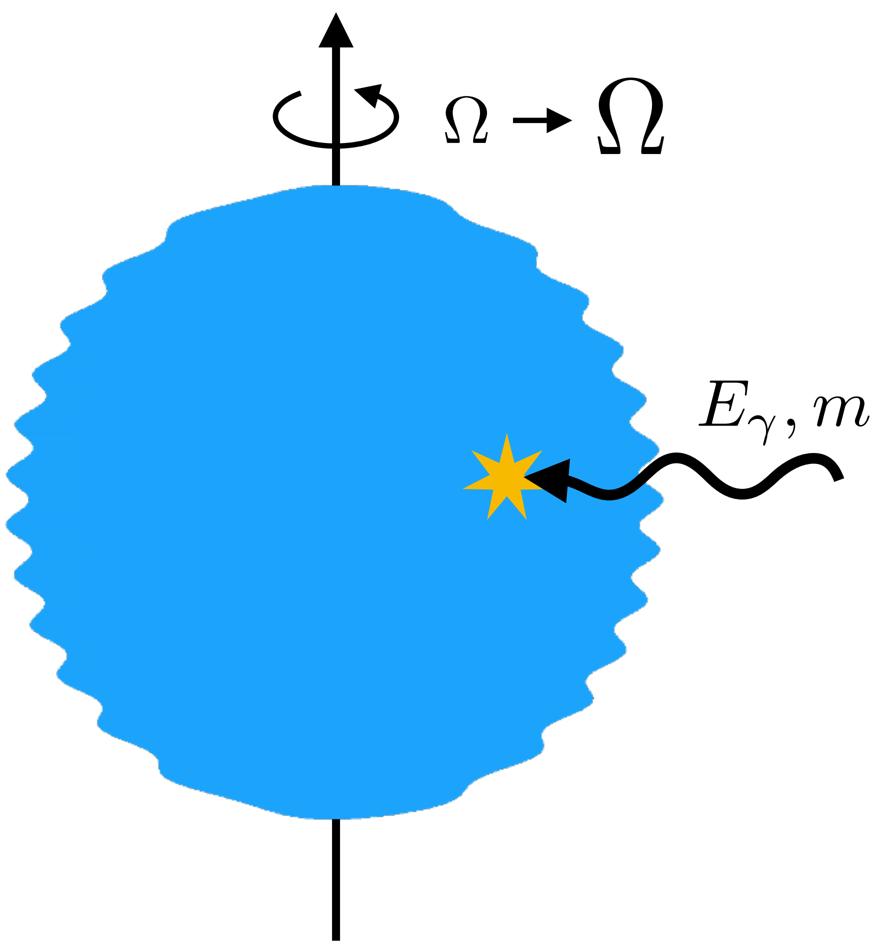
Rotational Superradiance

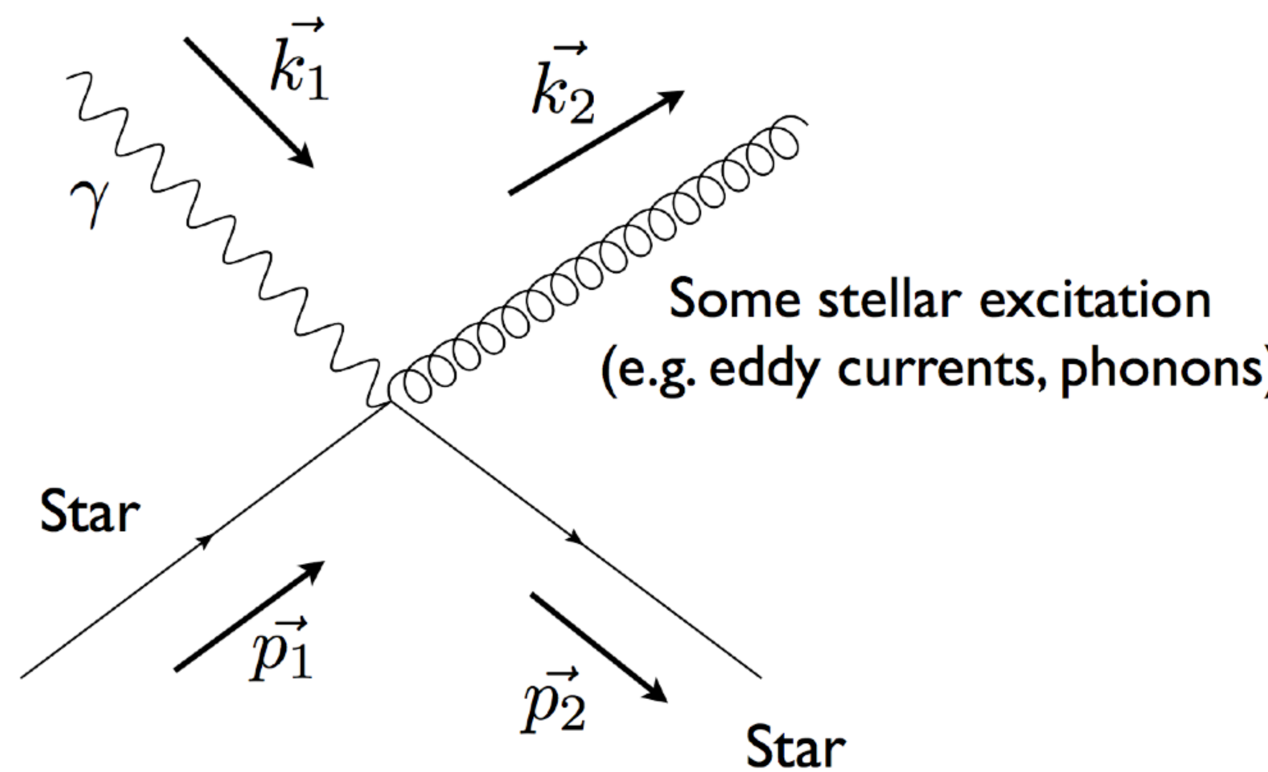
Example: photons can excite oscillations in a star



Rotational Superradiance

Example: photons can excite oscillations in a star

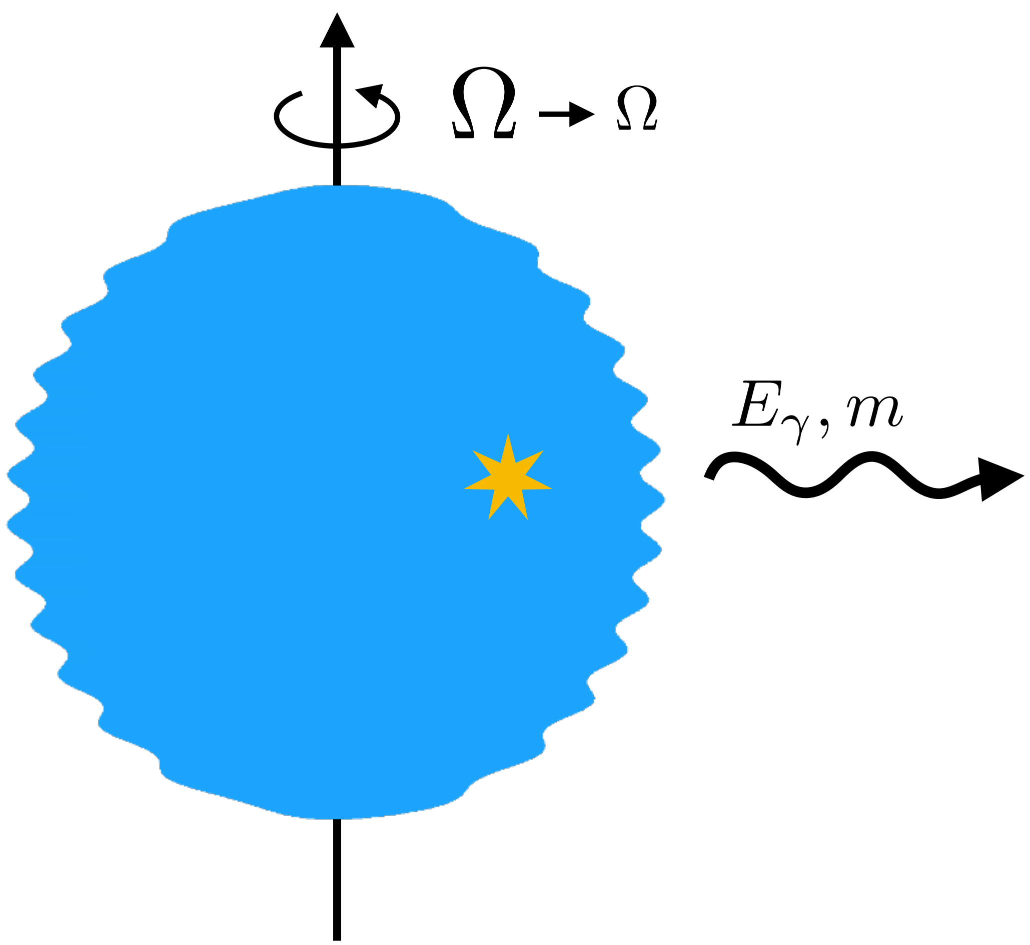


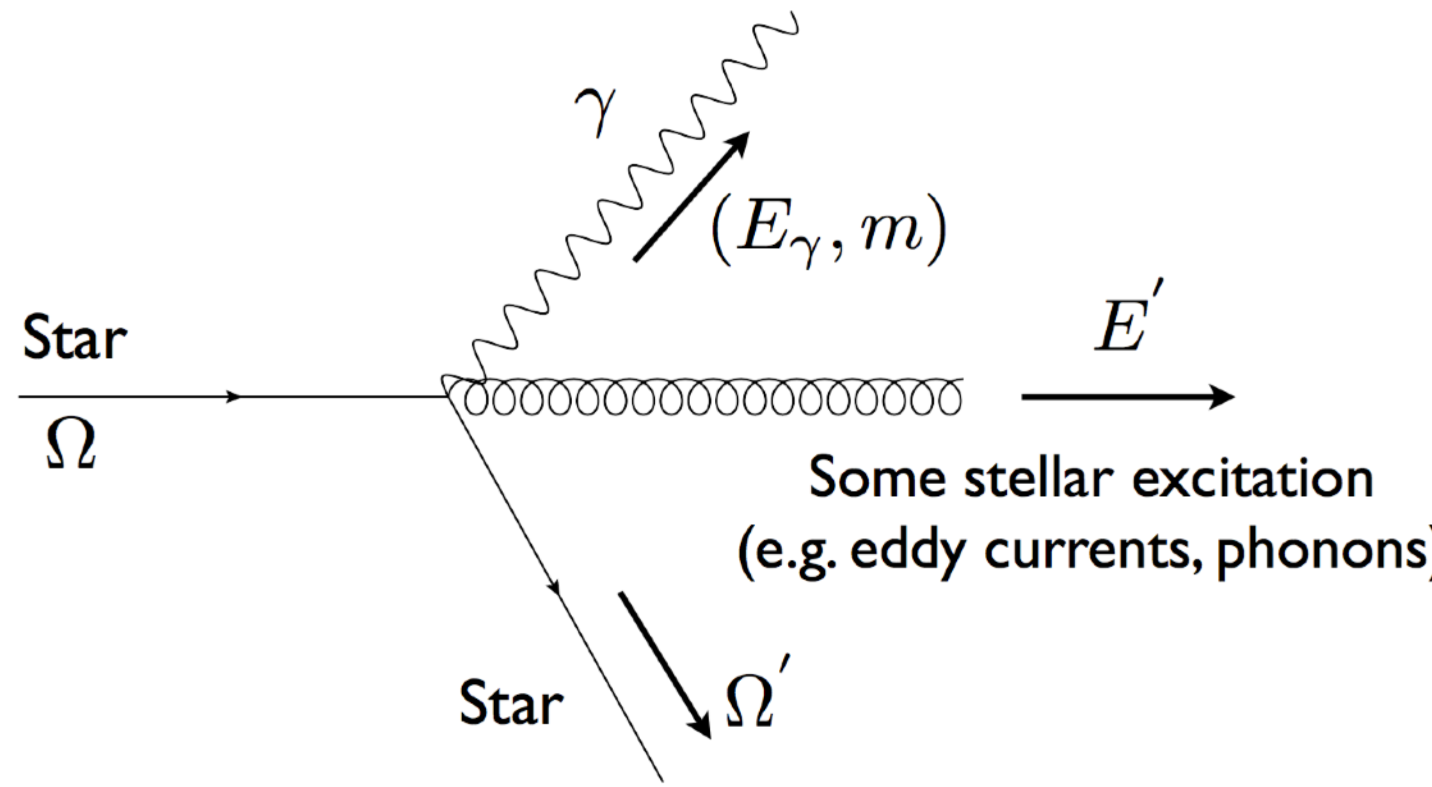


The absorption process demonstrates: this matrix element exists.

Rotational Superradiance

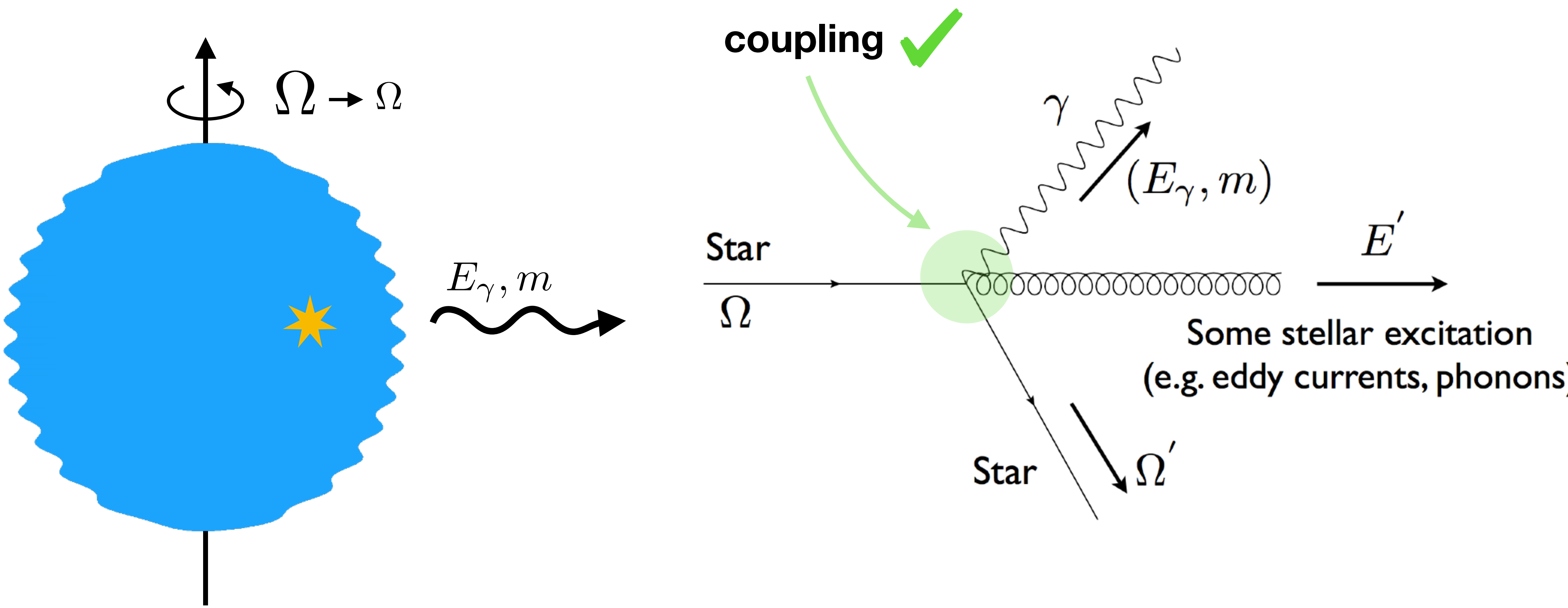
Example: photons can excite oscillations in a star





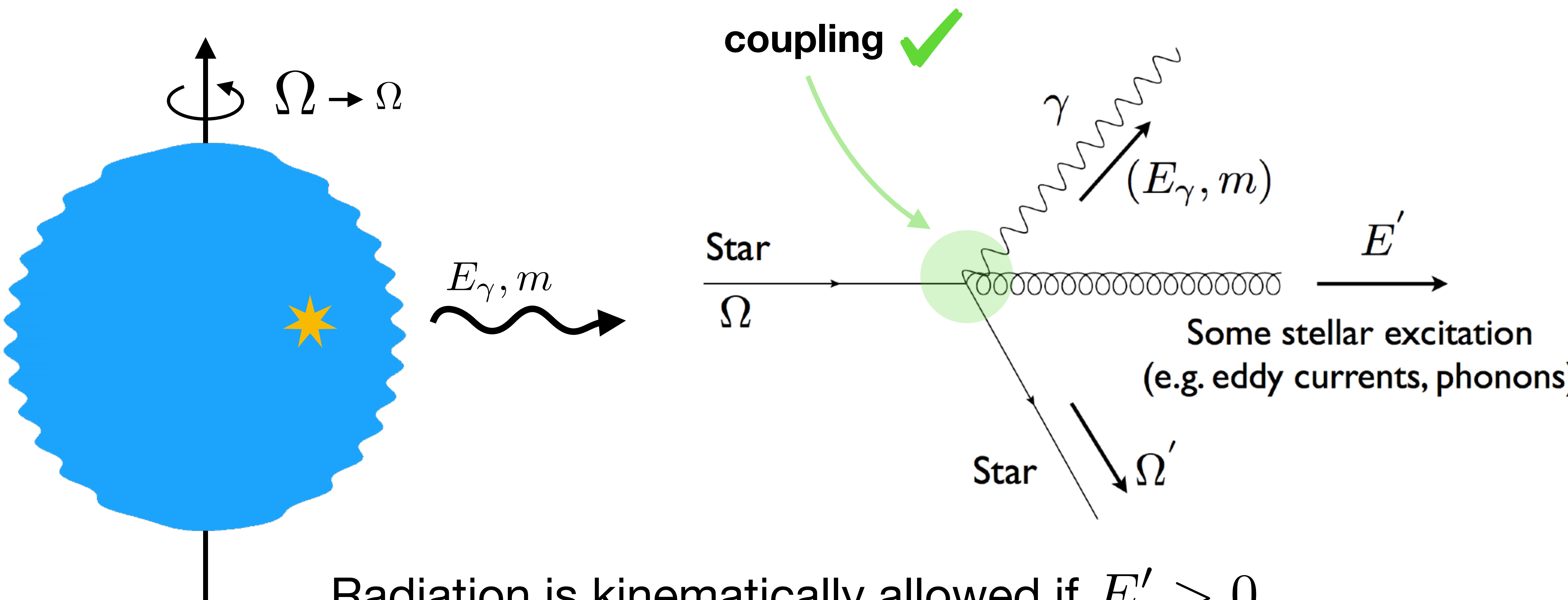
Rotational Superradiance

Example: photons can excite oscillations in a star



Rotational Superradiance

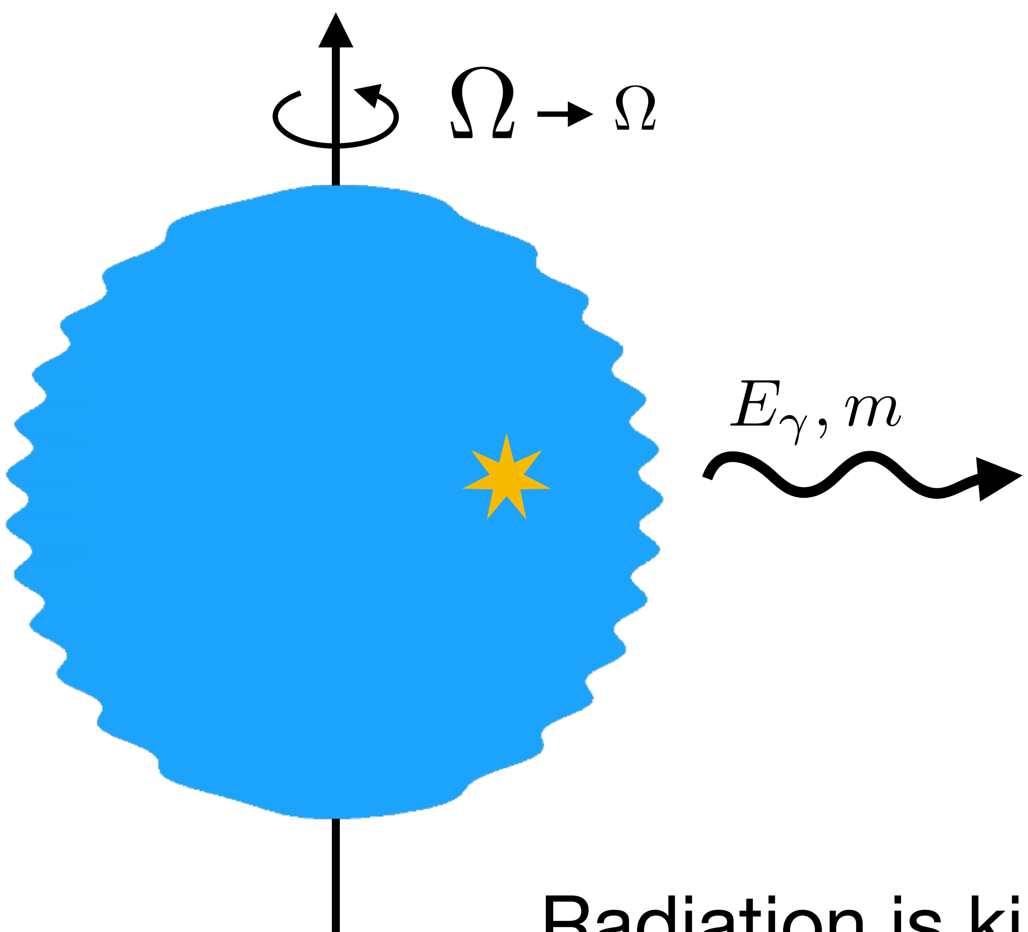
Example: photons can excite oscillations in a star

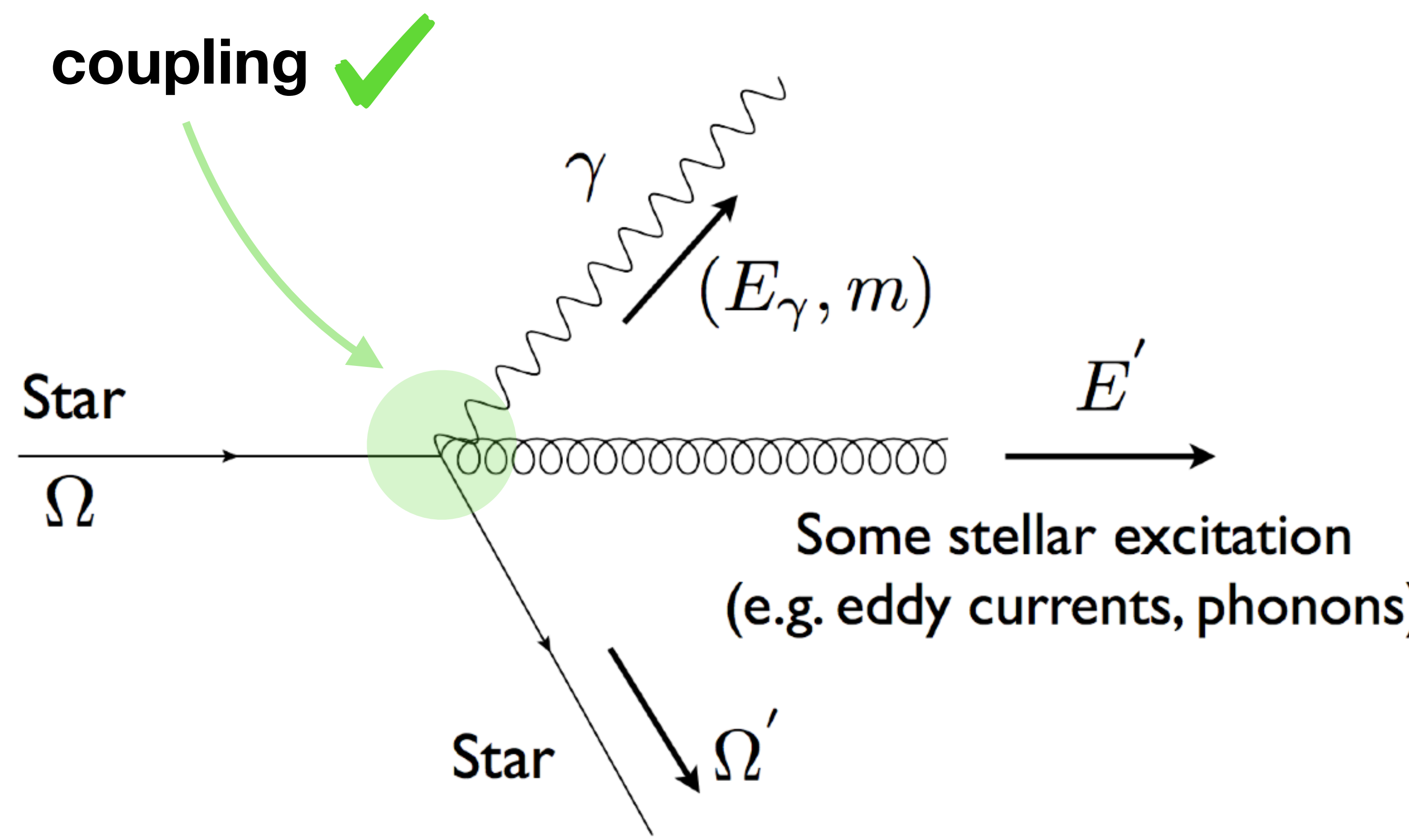


Radiation is kinematically allowed if $E' > 0$

Rotational Superradiance

Example: photons can excite oscillations in a star





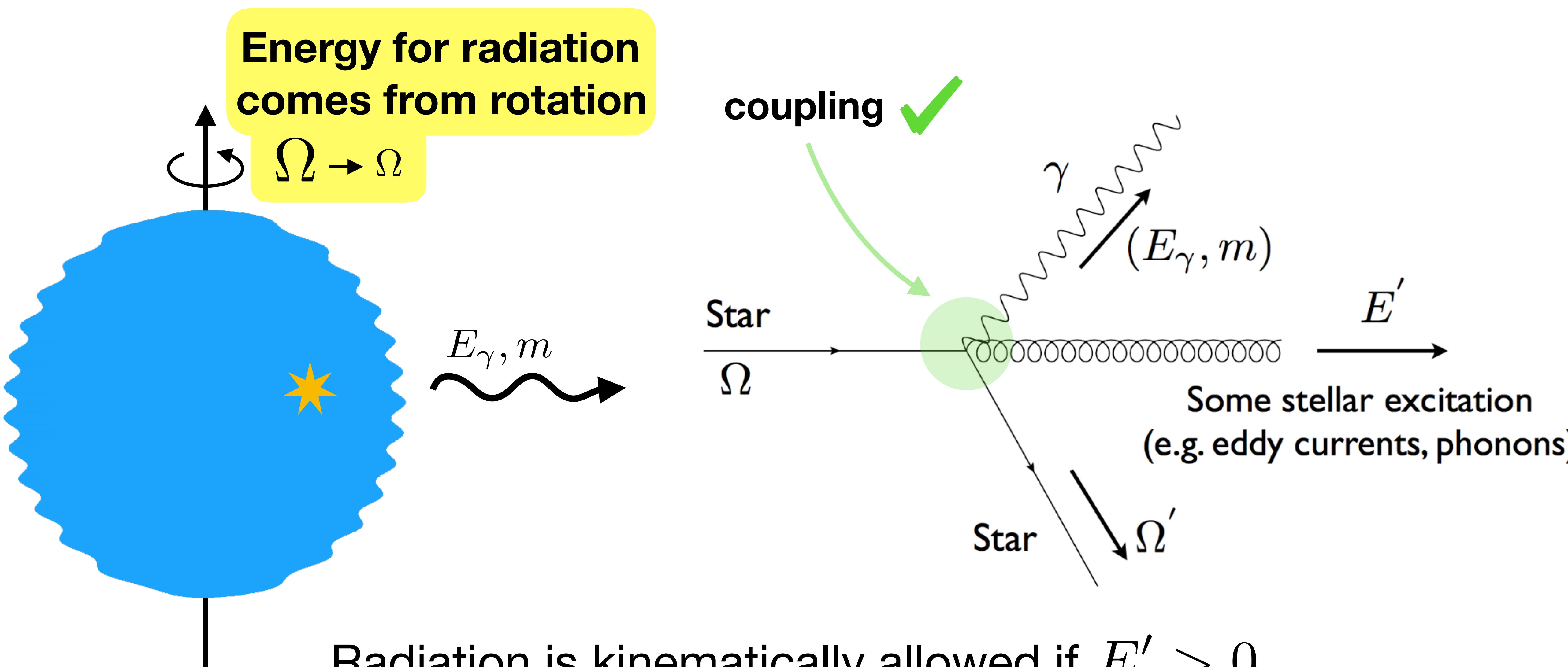
Radiation is kinematically allowed if $E' > 0$

conserve energy & angular momentum

$$\Rightarrow \quad E' = m\Omega - E_\gamma > 0$$

phase space

Rotational Superradiance

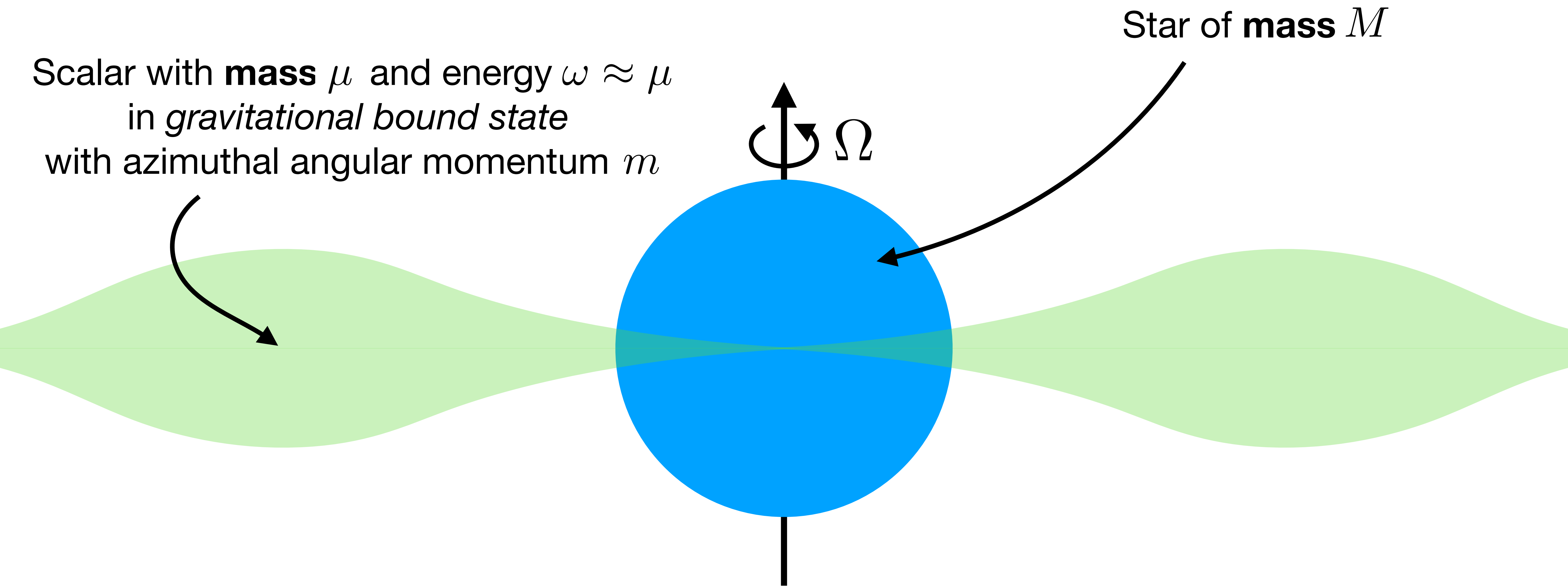


Radiation is kinematically allowed if $E' > 0$

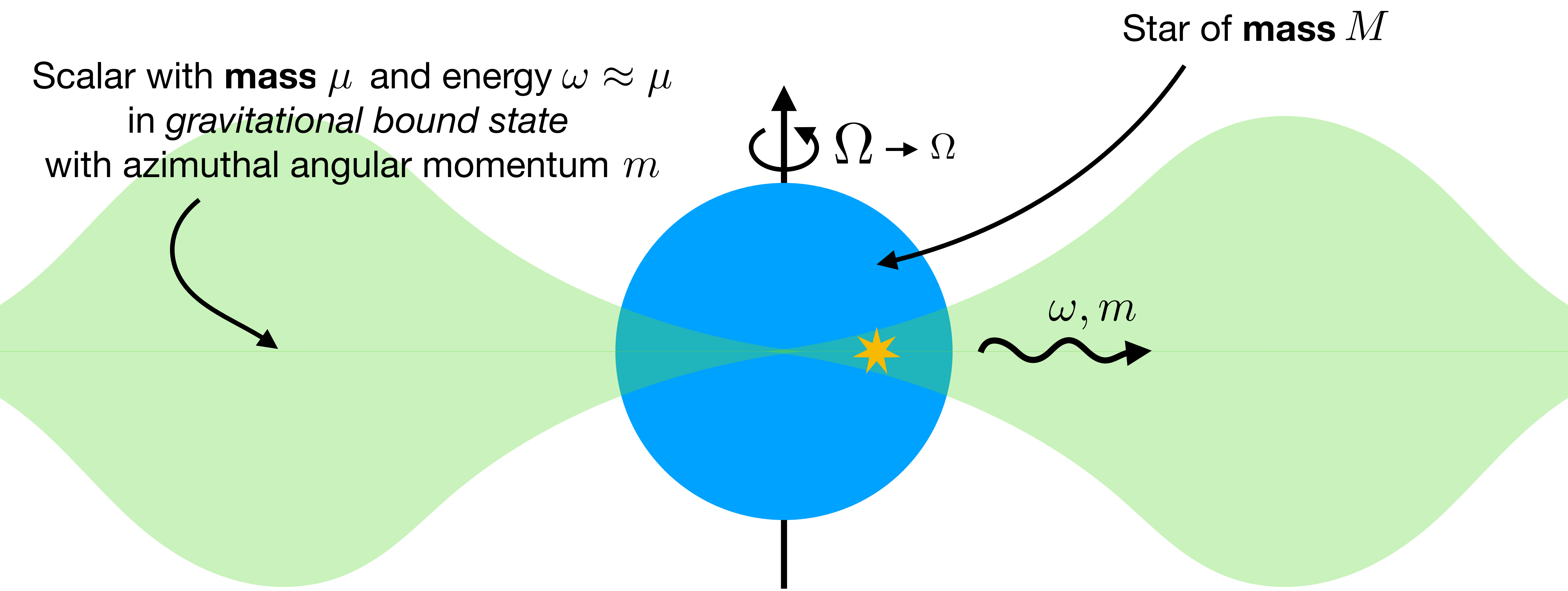
conserve energy & angular momentum $\Rightarrow$ $E' = m\Omega - E_\gamma > 0$ ← **phase space** ✓

"Superradiance condition"

Placing Bounds with Superradiance



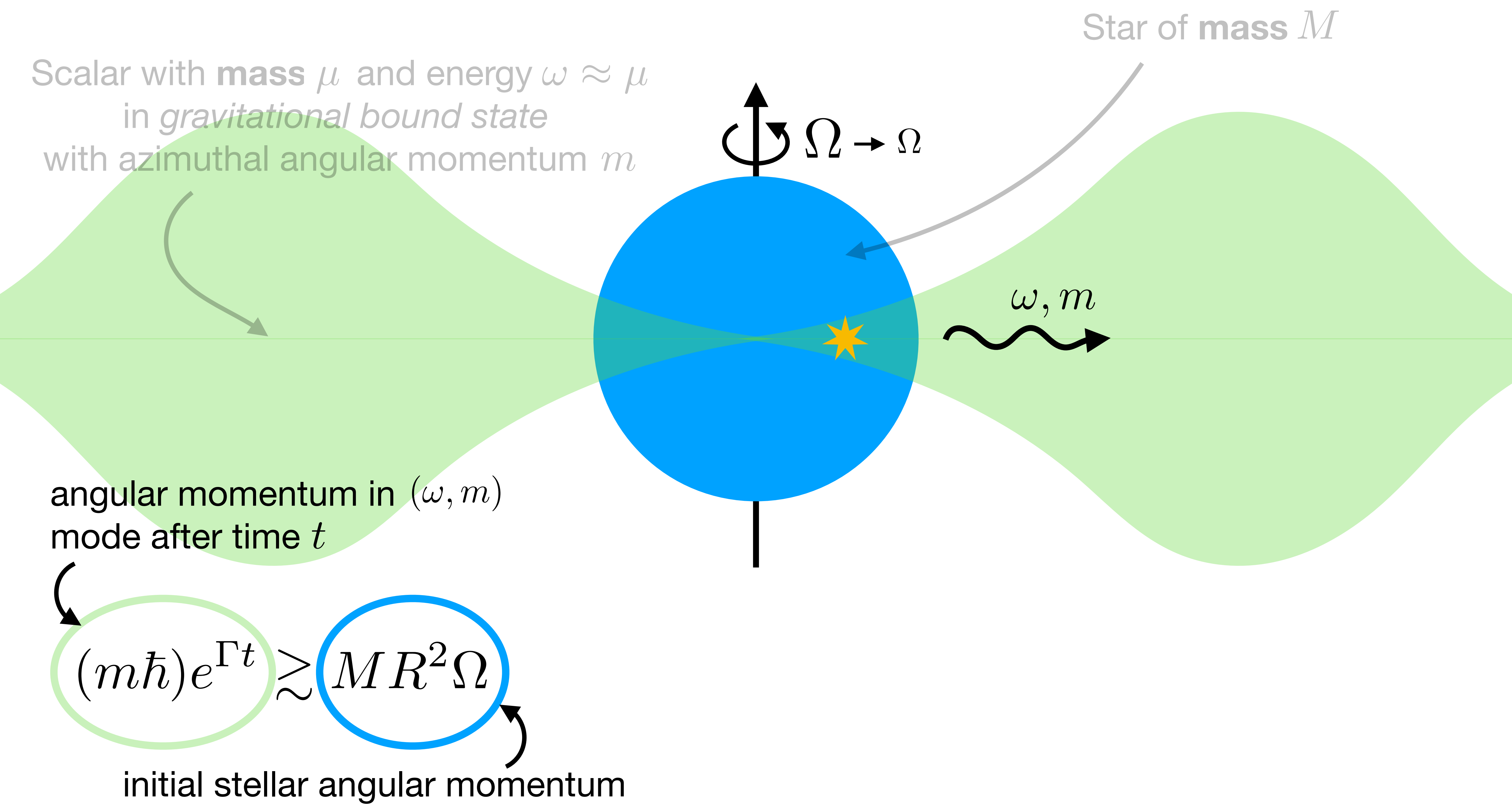
Placing Bounds with Superradiance



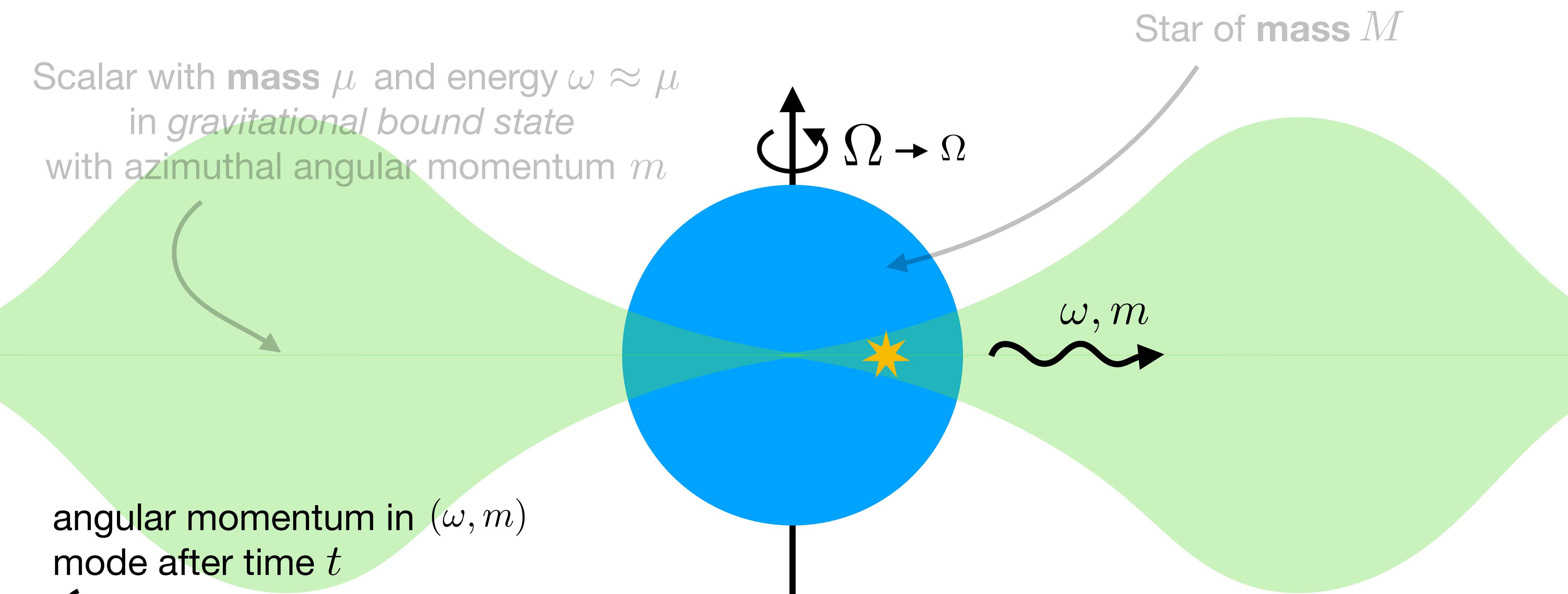
$(m\Omega - \omega > 0)$

Bound state → exponential growth

Placing Bounds with Superradiance



Placing Bounds with Superradiance



angular momentum in (ω, m) mode after time t

$$(m\hbar)e^{\Gamma t} \gtrsim MR^2\Omega \quad \Rightarrow \quad \Gamma \gtrsim \frac{1}{t_\odot} \log \frac{MR^2\Omega}{m\hbar} \quad \Rightarrow \quad \text{ruled out}$$

initial stellar angular momentum

superradiance rate for (ω, m) mode

Superradiance Rate

Scalar Ψ with mass μ, interacting with medium moving at v^α

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

[Zel'dovich, 1971]

Superradiance Rate

Scalar Ψ with mass μ, interacting with medium moving at v^α

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

[Zel'dovich, 1971]

Superradiance Rate

Scalar Ψ with mass μ, interacting with medium moving at v^α

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

[Zel'dovich, 1971]

$\Psi \propto e^{\Gamma t/2}$

medium rotating at Ω

Superradiance Rate: $$\Gamma = \frac{(m\Omega - \omega)}{\omega} C$$

Related to medium-at-rest absorption rate

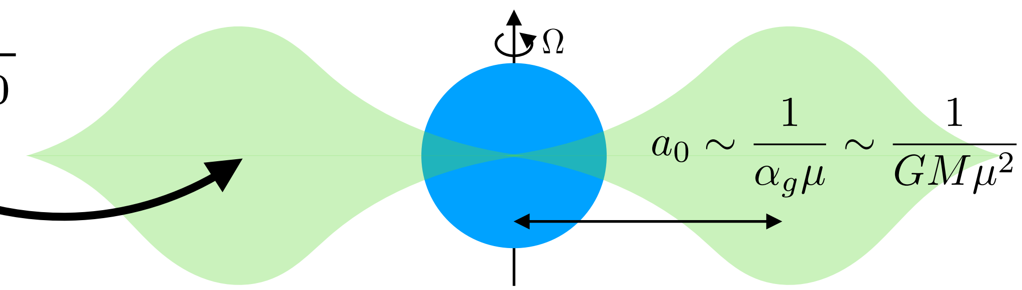
Absorption is only nonzero in the medium.

Superradiance rate depends on ***overlap*** of scalar with medium.

SR rate is sensitive to Ω

"hydrogenic" scalar wavefunction:

$$\psi_{nlm} \sim \frac{r^l}{a_0^{3/2+l}} e^{-\frac{r}{n a_0}}$$

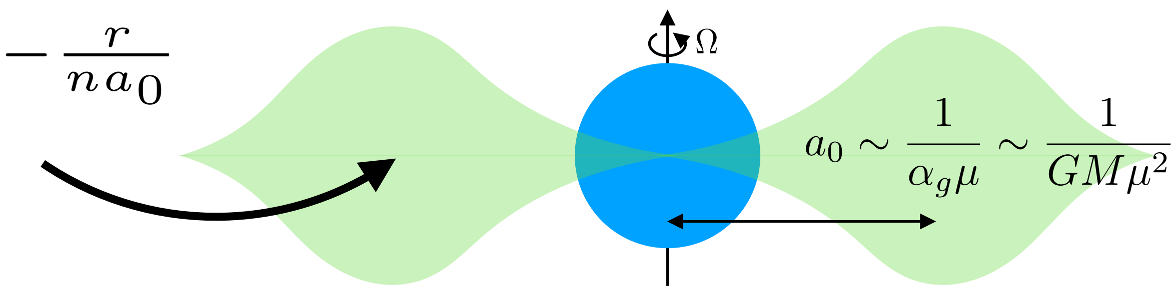


Superradiance rate depends on overlap:

$$\Gamma \propto \int_{\mathrm{star}} d^3r |\psi_{nlm}|^2 \sim \left(\frac{R}{a_0}\right)^{2l+3}$$

SR rate is sensitive to Ω

"hydrogenic" scalar wavefunction: $\psi_{nlm} \sim \frac{r^l}{a_0^{3/2+l}} e^{-\frac{r}{n a_0}}$



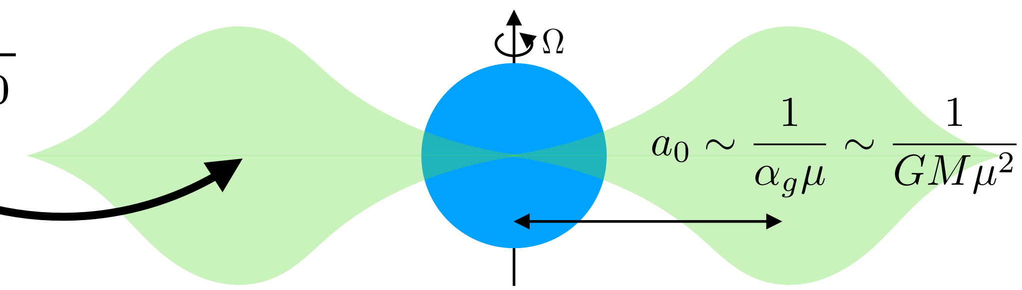
Superradiance rate depends on overlap:

$$\Gamma \propto \int_{\rm star} d^3r |\psi_{nlm}|^2 \sim \left(\frac{R}{a_0}\right)^{2l+3}$$

Superradiance condition: $m\Omega - \mu > 0 \quad (|m| \leq l)$

SR rate is sensitive to Ω

"hydrogenic" scalar wavefunction: $$\psi_{nlm} \sim \frac{r^l}{a_0^{3/2+l}} e^{-\frac{r}{n a_0}}$$



Superradiance rate depends on overlap:

$$\Gamma \propto \int_{\rm star} d^3r |\psi_{nlm}|^2 \sim \left(\frac{R}{a_0}\right)^{2l+3}$$

Superradiance condition: $m\Omega - \mu > 0 \quad (|m| \leq l)$

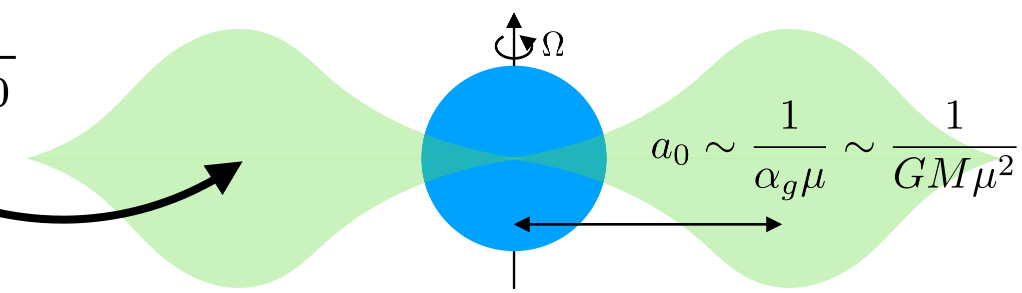
$$\mu \lesssim \Omega$$

Gravitational coupling is weak

large Bohr radius, small overlap

SR rate is sensitive to Ω

"hydrogenic" scalar wavefunction: $\psi_{nlm} \sim \frac{r^l}{a_0^{3/2+l}} e^{-\frac{r}{n a_0}}$



Superradiance rate depends on overlap:

$$\Gamma \propto \int_{\text{star}} d^3 r |\psi_{nlm}|^2 \sim \left(\frac{R}{a_0}\right)^{2l+3}$$

Superradiance condition: $m\Omega - \mu > 0 \quad (|m| \leq l)$

$\mu \lesssim \Omega$

Gravitational coupling is weak

large Bohr radius, small overlap

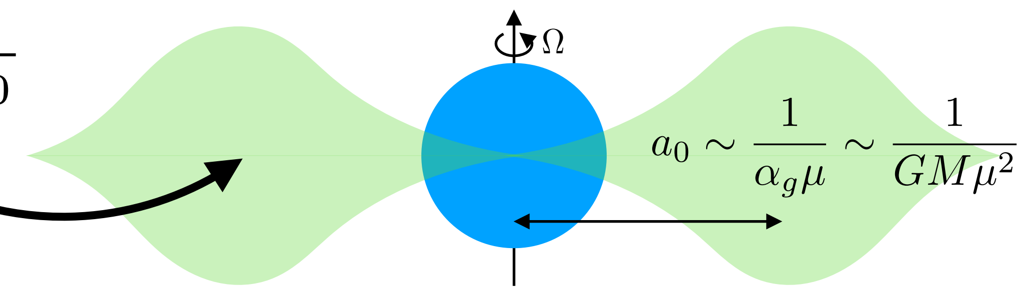
$\mu \gtrsim \Omega$

SR requires large m, hence large l

large Bohr radius, small overlap

SR rate is sensitive to Ω

"hydrogenic" scalar wavefunction: $\psi_{nlm} \sim \frac{r^l}{a_0^{3/2+l}} e^{-\frac{r}{n a_0}}$



Superradiance rate depends on overlap:

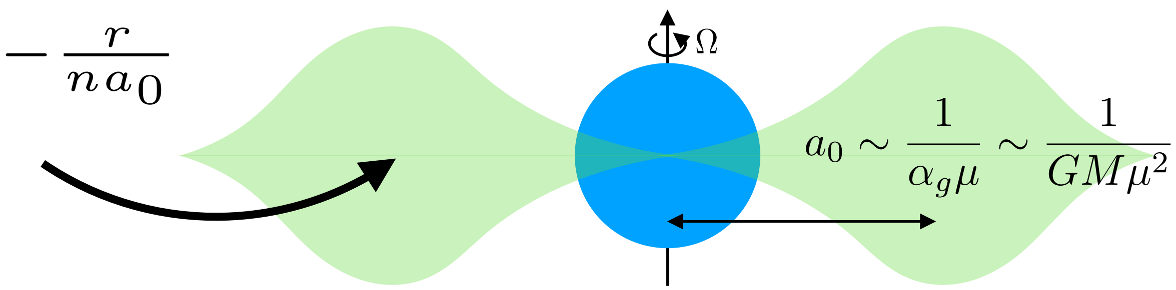
$$\Gamma \propto \int_{\text{star}} d^3 r |\psi_{nlm}|^2 \sim \left(\frac{R}{a_0}\right)^{2l+3}$$

Superradiance condition: $m\Omega - \mu > 0 \quad (|m| \leq l)$

$\mu \lesssim \Omega$	$\mu \sim \Omega$	$\mu \gtrsim \Omega$
Gravitational coupling is weak **large Bohr radius, small overlap**	Strongest superradiance	SR requires large m, hence large l **large Bohr radius, small overlap**

SR rate is sensitive to Ω

"hydrogenic" scalar wavefunction: $\psi_{nlm} \sim \dfrac{r^l}{a_0^{3/2+l}} e^{-\frac{r}{n a_0}}$



Superradiance rate depends on overlap:

$$\Gamma \propto \int_{\text{star}} d^3 r |\psi_{nlm}|^2 \sim \left(\frac{R}{a_0}\right)^{2l+3} \propto \mu^{4l+6} \sim \Omega^{4l+6}$$

Superradiance condition: $m\Omega - \mu > 0 \quad (|m| \leq l)$

$\mu \lesssim \Omega$	$\mu \sim \Omega$	$\mu \gtrsim \Omega$
Gravitational coupling is weak **large Bohr radius, small overlap**	Strongest superradiance	SR requires large m, hence large l **large Bohr radius, small overlap**

$\Rightarrow$ bounds are a strong function of Ω.

Superradiance in Pulsars

How do scalars couple to the star?

Any scalar or
(CP-violating) psuedoscalar

$$\epsilon \Psi \bar{n} n$$

QCD Axion:

$$\epsilon \sim \theta_{\mathrm{eff}} \frac{m_n}{f_a} \sim \frac{\mathrm{GeV}}{f_a}$$

Superradiance in Pulsars

How do scalars couple to the star?

Any scalar or (CP-violating) psuedoscalar →

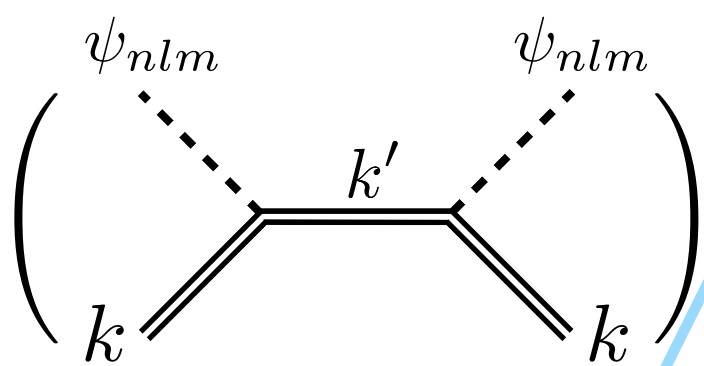
$$\epsilon \Psi \bar{n} n$$

QCD Axion:

$$\epsilon \sim \theta_{\text{eff}} \frac{m_n}{f_a} \sim \frac{\text{GeV}}{f_a}$$

Scalars can be absorbed by exciting phonons.

$$C_{nlm} = \text{Im} \left(\vphantom{\sum} \right.$$



$$= \text{Im} \left(\sum_{k'} \langle k, \psi_{nlm} | H_{\text{int}} | k' \rangle \frac{1}{E - E_{k'} + i\Gamma_{k'}} \langle k' | H_{\text{int}} | k, \psi_{nlm} \rangle \right)$$

Intermediate state can decay by gravitational wave emission

Superradiance in Pulsars

Absorption rate:

$$C_{nlm} \sim \epsilon^2 \left(\frac{\sqrt{T/\omega_{l'm'}}}{\sqrt{2 m_n \omega_{l'm'}}} \right)^2 \left| \int_S d^3\mathbf{r}\, n(\mathbf{r}) \frac{\nabla \psi_{nlm}}{\sqrt{2\mu}} \cdot \mathbf{y}_{l'm'}(\mathbf{r}) \right|^2 \left(\frac{\Gamma_{l'm'}}{(\mu - \omega_{l'm'})^2} \right)$$

phonon decay rate (grav. radiation)

enhanced by thermal phonon amplitude

enhanced by neutron number density

phonon wavefunction

Superradiance in Pulsars

Absorption rate:

$$C_{nlm} \sim \epsilon^2 \left(\frac{\sqrt{T/\omega_{l'm'}}}{\sqrt{2m_n\omega_{l'm'}}} \right)^2 \left| \int_S d^3\mathbf{r}\, n(\mathbf{r}) \frac{\nabla\psi_{nlm}}{\sqrt{2\mu}} \cdot \mathbf{y}_{l'm'}(\mathbf{r}) \right|^2 \left(\frac{\Gamma_{l'm'}}{(\mu - \omega_{l'm'})^2} \right)$$

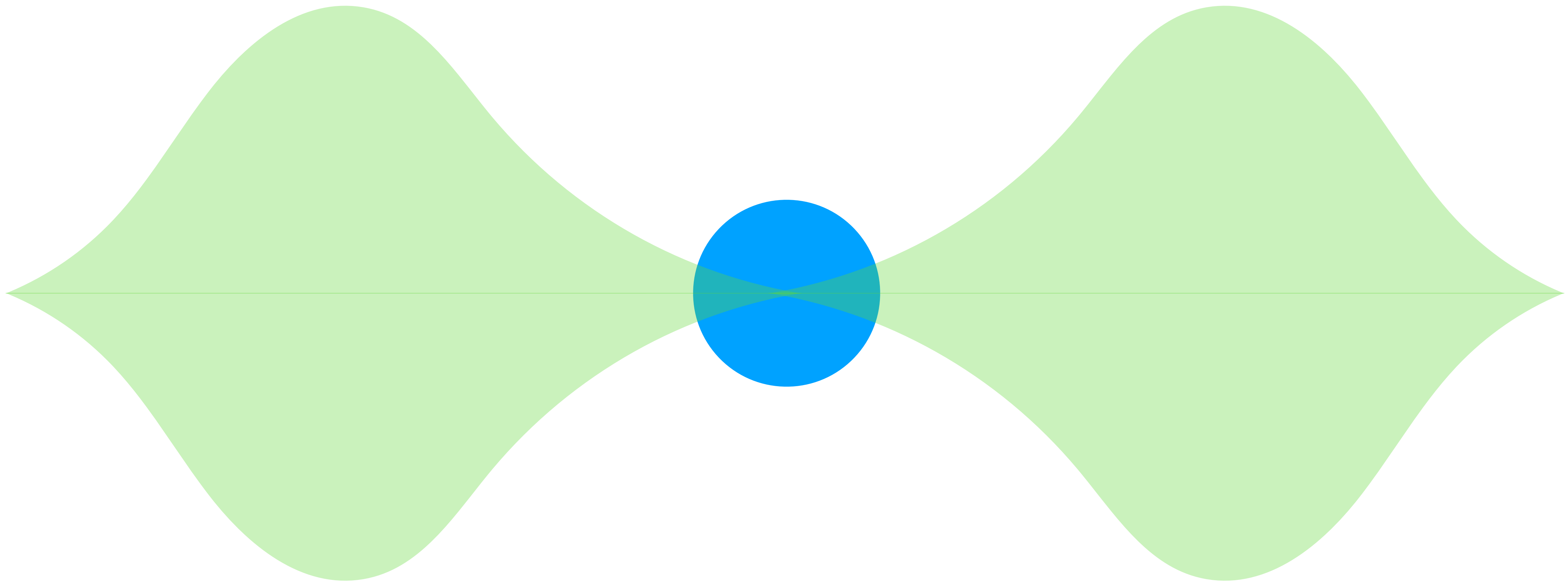
- $\sqrt{T/\omega_{l'm'}} / \sqrt{2m_n\omega_{l'm'}}$: enhanced by thermal phonon amplitude
- $n(\mathbf{r})$: enhanced by neutron number density
- $\mathbf{y}_{l'm'}(\mathbf{r})$: phonon wavefunction
- $\Gamma_{l'm'}$: phonon decay rate (grav. radiation)

Superradiance Rate:

$$\Gamma_{nlm} \approx \frac{(m\Omega - \mu)}{\mu} C_{nlm}$$

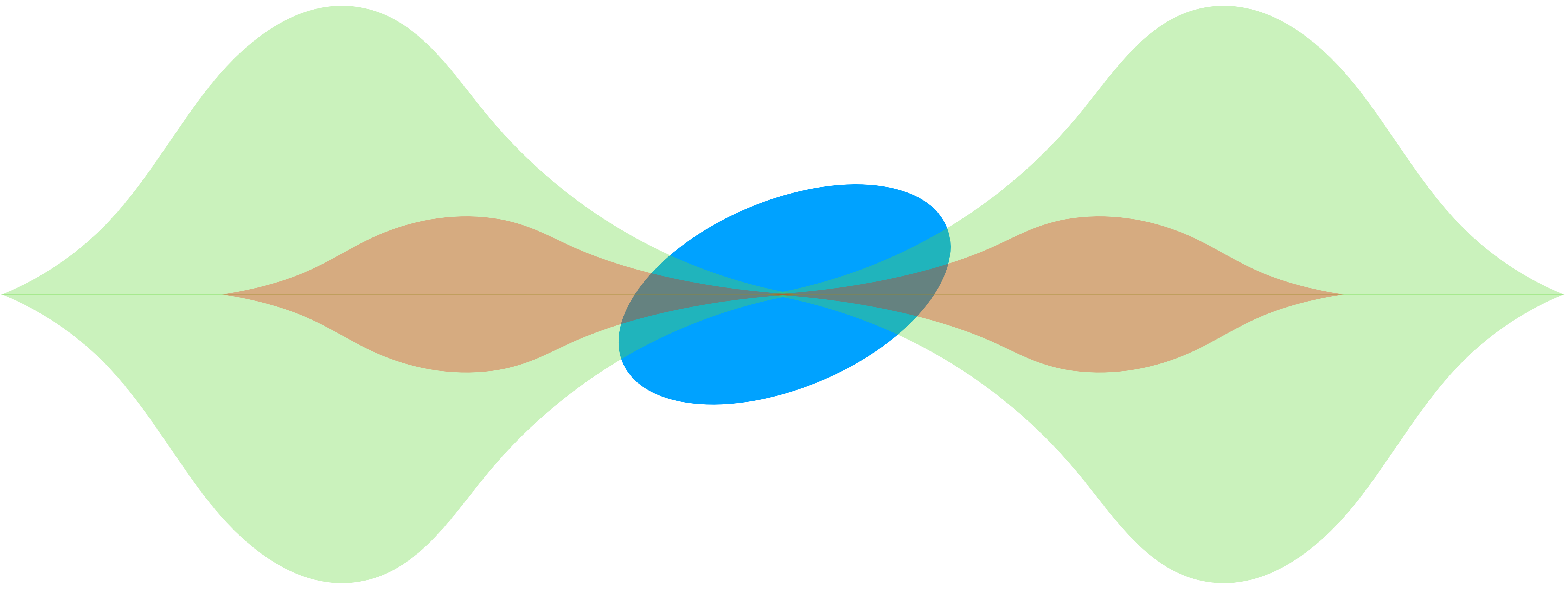
Mixing:
Superradiance Shutdown

- Only modes with $m > \omega/\Omega$ are superradiant
- ***Azimuthal* asymmetries** in the system can cause mixing with *non-superradiant* modes, with $m' < \omega/\Omega$.



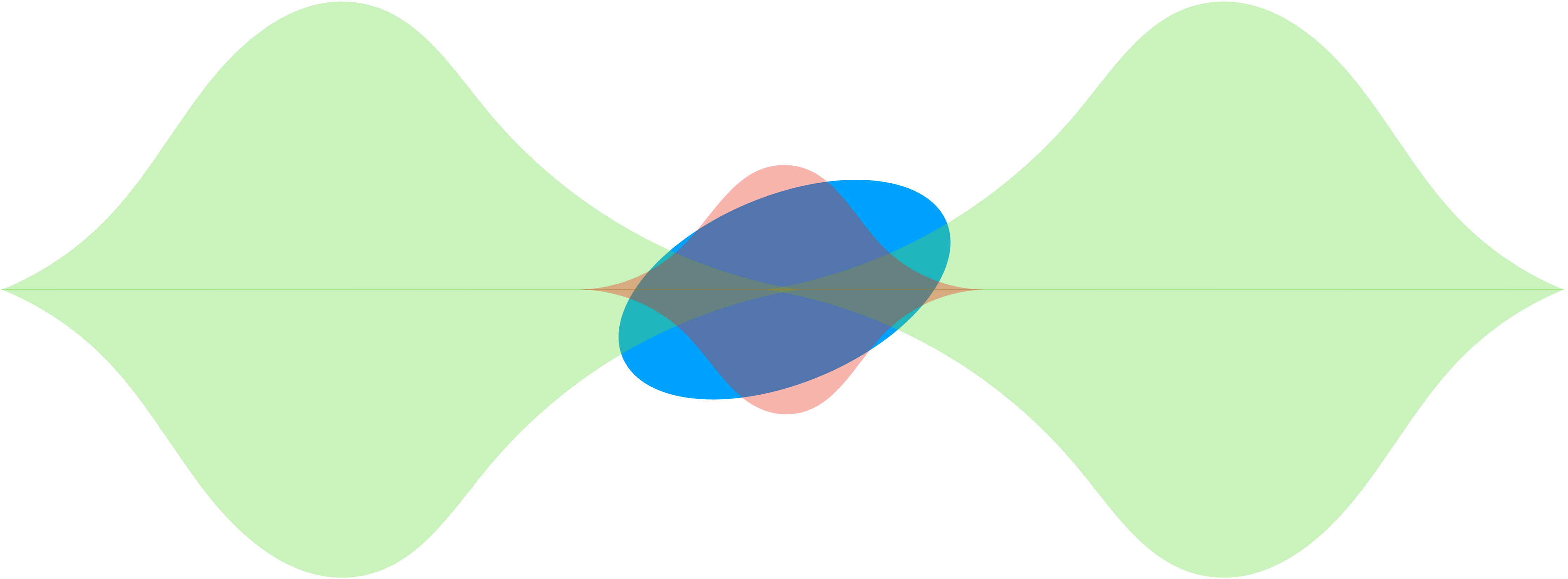
Mixing:
Superradiance Shutdown

- Only modes with $m > \omega/\Omega$ are superradiant
- ***Azimuthal* asymmetries** in the system can cause mixing with *non-superradiant* modes, with $m' < \omega/\Omega$.



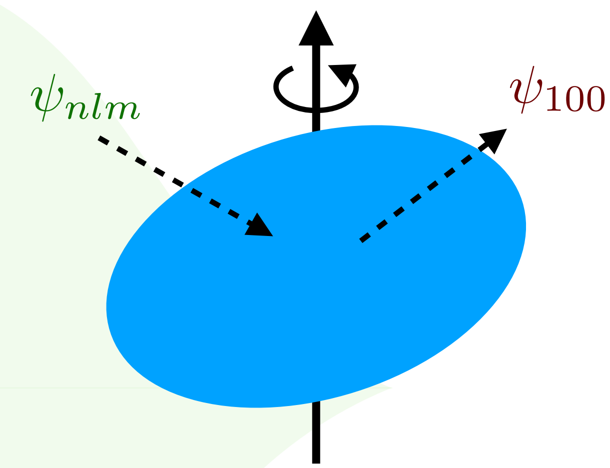
Mixing:
Superradiance Shutdown

- Only modes with $m > \omega/\Omega$ are superradiant
- ***Azimuthal* asymmetries** in the system can cause mixing with *non-superradiant* modes, with $m' < \omega/\Omega$.



Mixing:
Superradiance Shutdown

- Only modes with $m > \omega/\Omega$ are superradiant
- ***Azimuthal* asymmetries** in the system can cause mixing with *non-superradiant* modes, with $m' < \omega/\Omega$.
- Most dangerous asymmetries:
  - Centrifugal bulge + Free precession wobble
    - *Elastic scattering off neutrons (Yukawa interaction)*

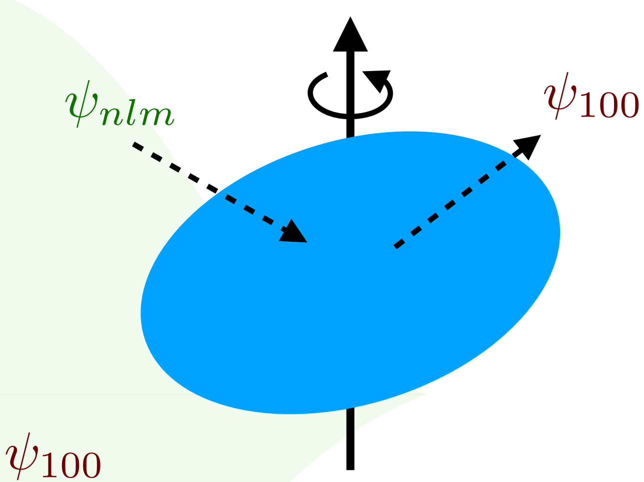


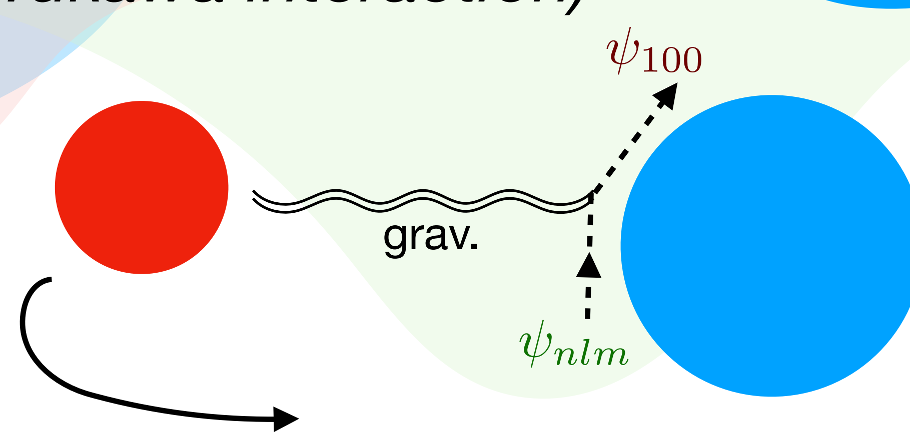
Mixing:
Superradiance Shutdown

- Only modes with $m > \omega/\Omega$ are superradiant

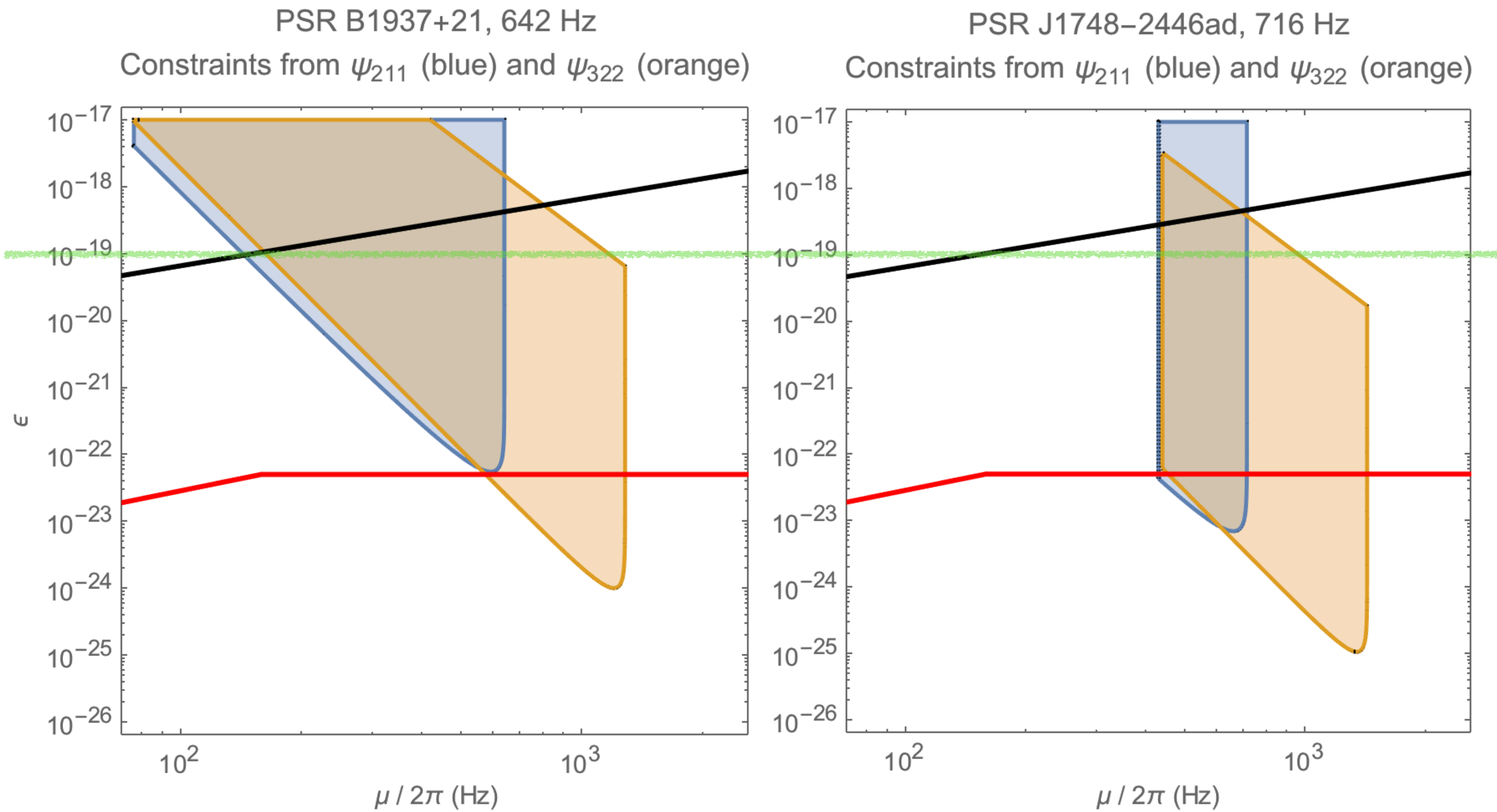
- ***Azimuthal* asymmetries** in the system can cause mixing with *non-superradiant* modes, with $m' < \omega/\Omega$.

- Most dangerous asymmetries:
    - Centrifugal bulge + Free precession wobble
        - *Elastic scattering off neutrons (Yukawa interaction)*
    - Tidal forces from companion
        - *Gravitational perturbation*





Constraints



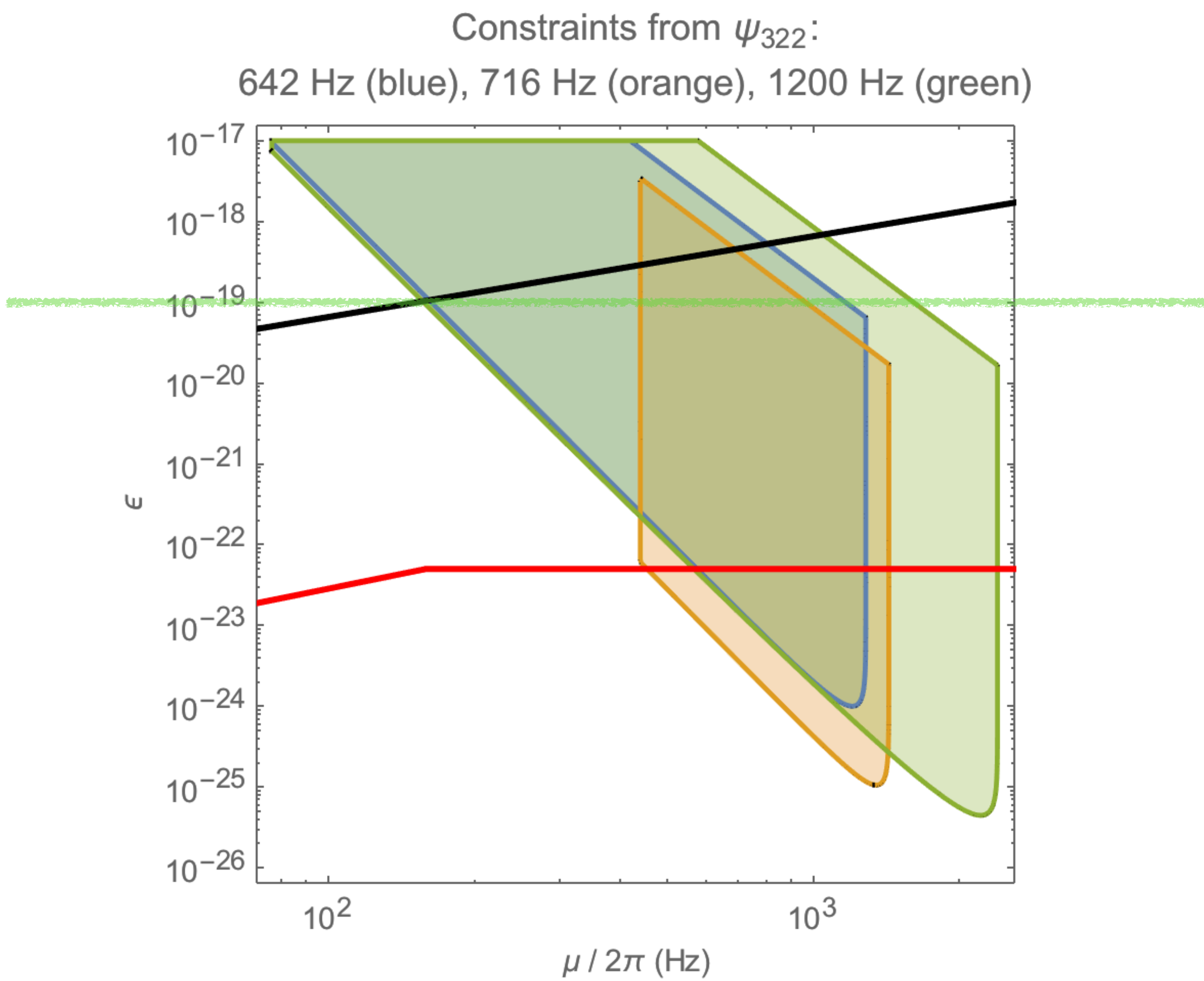
QCD axion: $\epsilon \sim \theta_{\rm eff} \frac{m_n}{f_a} \sim \frac{\rm GeV}{f_a}$

$\mu \sim \Lambda_{\rm QCD}^2 / f_a$

Torsion balance constraints

$\epsilon^2 \sim G m_n^2$

Constraints



QCD axion: $\epsilon \sim \theta_{\rm eff} \dfrac{m_n}{f_a} \sim \dfrac{\rm GeV}{f_a}$

$\mu \sim \Lambda_{\rm QCD}^2 / f_a$

Torsion balance constraints

$\epsilon^2 \sim G m_n^2$

Conclusions

- Bounds from superradiance are a strong function of the rotation rate
- Superradiance can be efficient in millisecond pulsars
- Depending on the pulsar equation of state, Planck-scale QCD axions can be probed and excluded
- Other interactions could produce similar effects, constraining other particles