Black Hole Superradiance of Self-Interacting Scalar Fields

based on arXiv: 2011.11646

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Ultra-Light Bosons and Black Holes

This work

- **Rotating black holes** can source "clouds" of ultra-light **bosons** through **superradiance** independently of cosmological abundance
- **Weakly interacting** scalars **spin down BHs** and **source GWs**

- **More strongly interacting** scalars source **scalar waves**

Outline

1. Review of black hole of superradiance

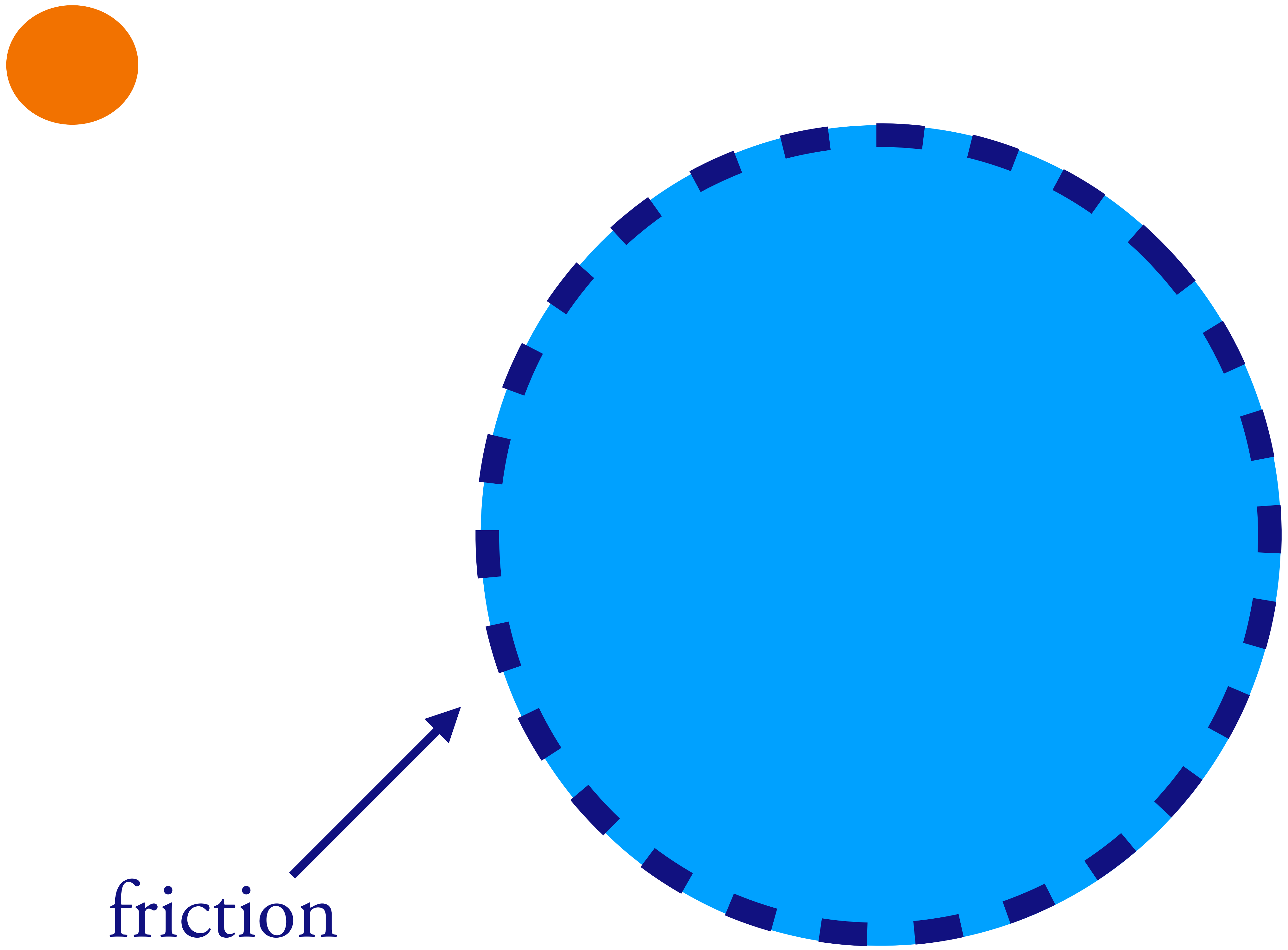
2. Self-interactions in the SR cloud

3. (New) Signatures at large self-interactions

Review of Black Hole Superradiance

Superradiance

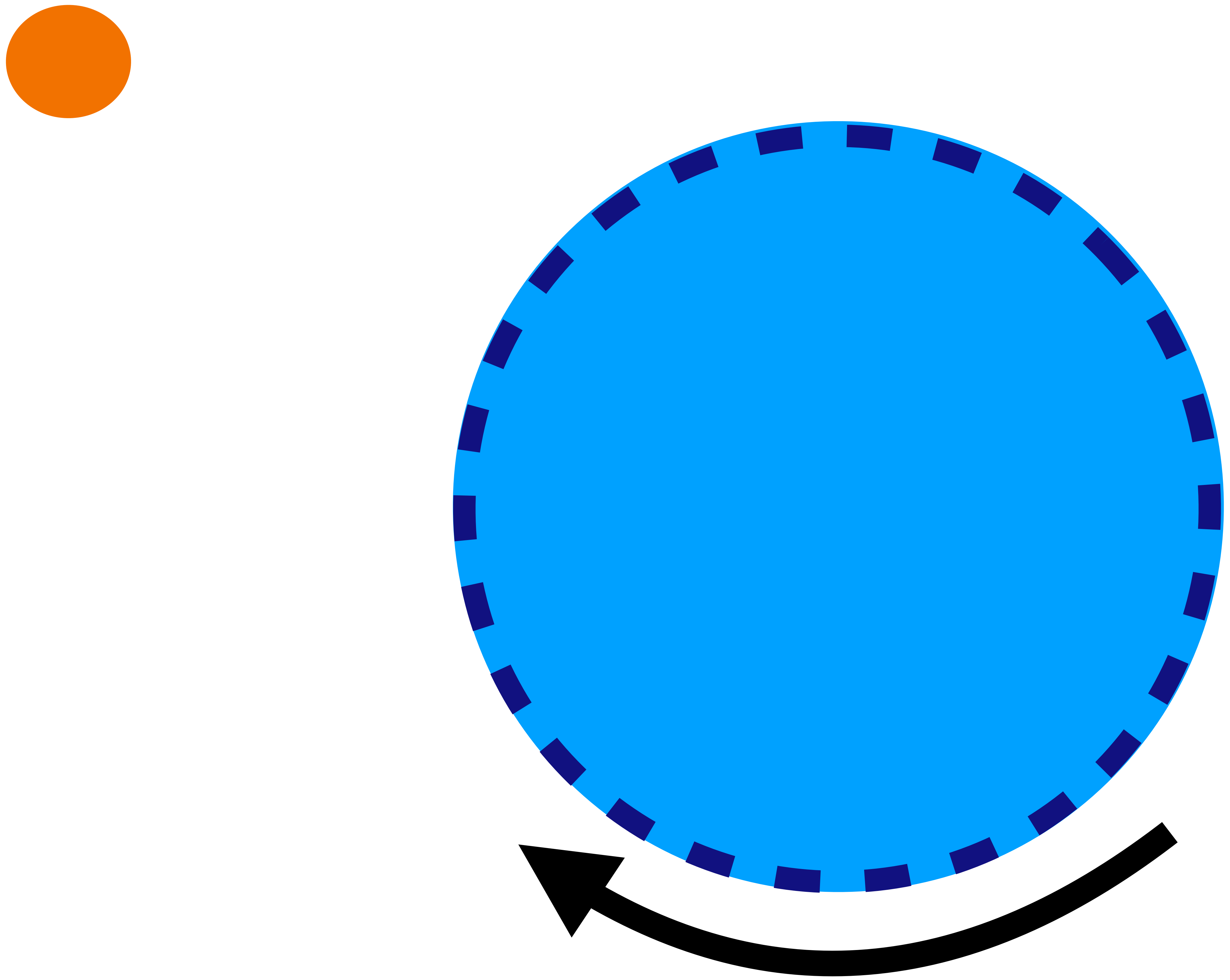
- Object scattering off a stationary cylinder will **lose energy** and **angular momentum** if there is friction (**dissipation**)



Superradiance

- Objects scattering off a rotating cylinder will **extract energy** and **angular momentum if a kinematic condition is satisfied:**

$$\Omega_{\rm c} > v_\varphi$$

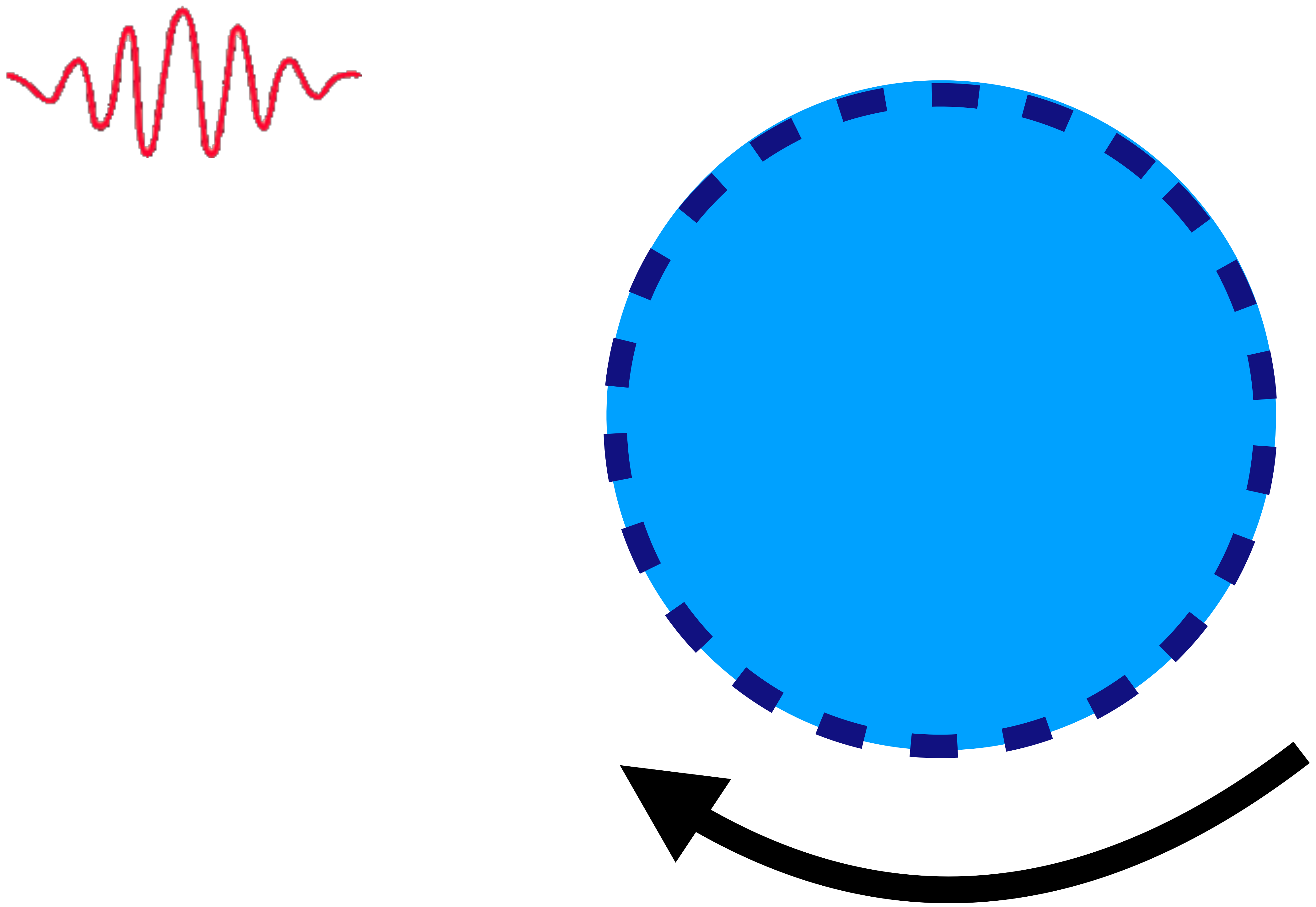


- **Dissipation** now leads to **enhancement!**

Wave Superradiance

- A wave incident on rotating dissipative surface (∂_t or absorbing B.C.) will **grow in amplitude** by **extracting energy and angular momentum** if kinematic condition satisfied

$$\Omega_c > \omega/m$$



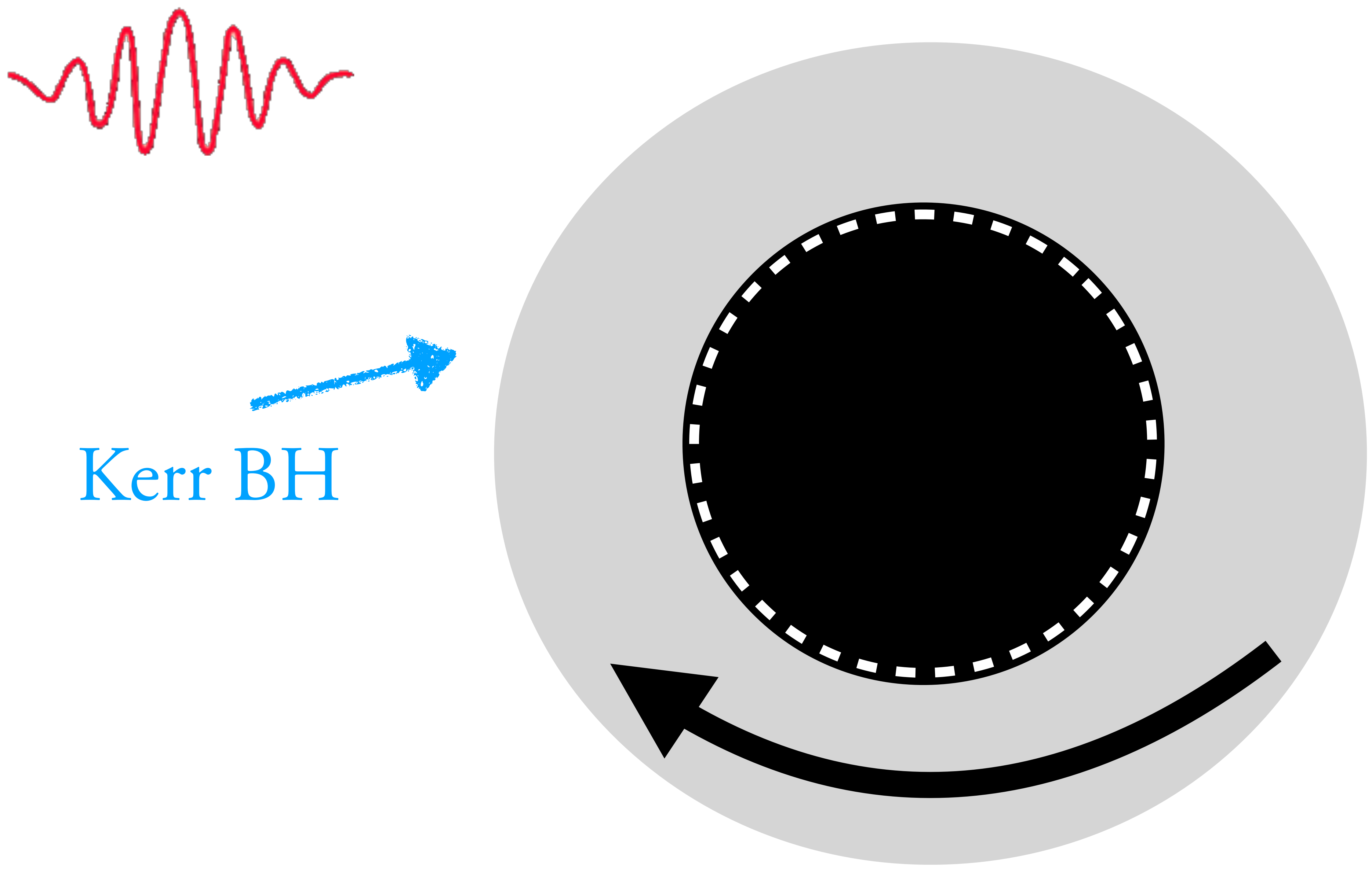
- Growth in amplitude = more quanta

- Growth proportional to probability of **absorption** when object at rest

Zel'dovich '71, Zel'dovich '72

BH Superradiance

- Nature provides us with **rapidly rotating absorbers: rotating BHs!**



$$\boxed{\Omega_{\rm BH} > \omega/m}$$

- Growth in amplitude = more quanta

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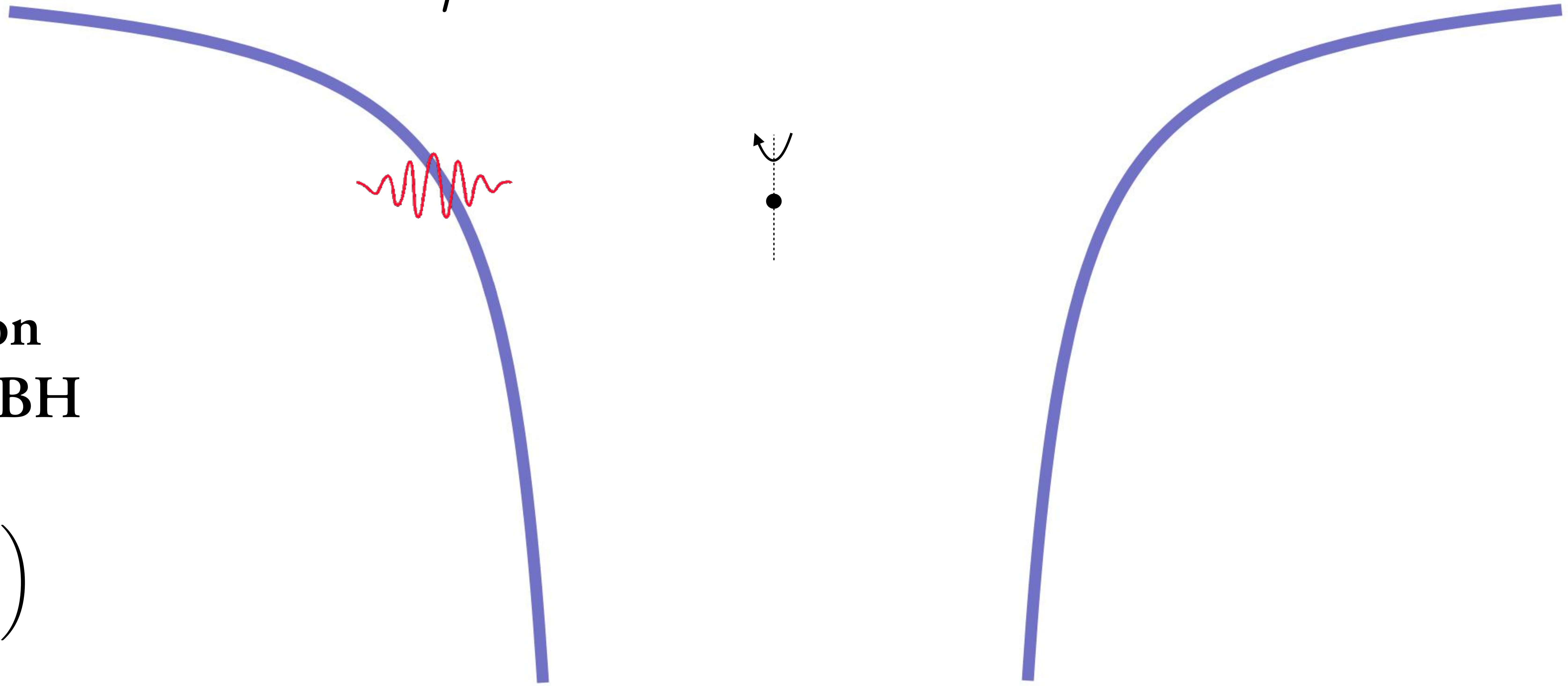
Zel'dovich '71, Zel'dovich '72, Starobinski '73

BH Superradiance of Massive Scalars

- Newtonian potential confines motion in **massive bound states** around the BH

$$V(r) = -\frac{G_{\rm N} M_{\rm BH} \mu}{r}$$

- **Repeated amplification** makes state **unstable** to growth



- Growth largest when **Compton wavelength** is **comparable** to **BH radius**

$$r_g \sim \lambda_C \sim 3 \text{ km} \left(\frac{7 \times 10^{-11} \text{ eV}}{\mu} \right)$$

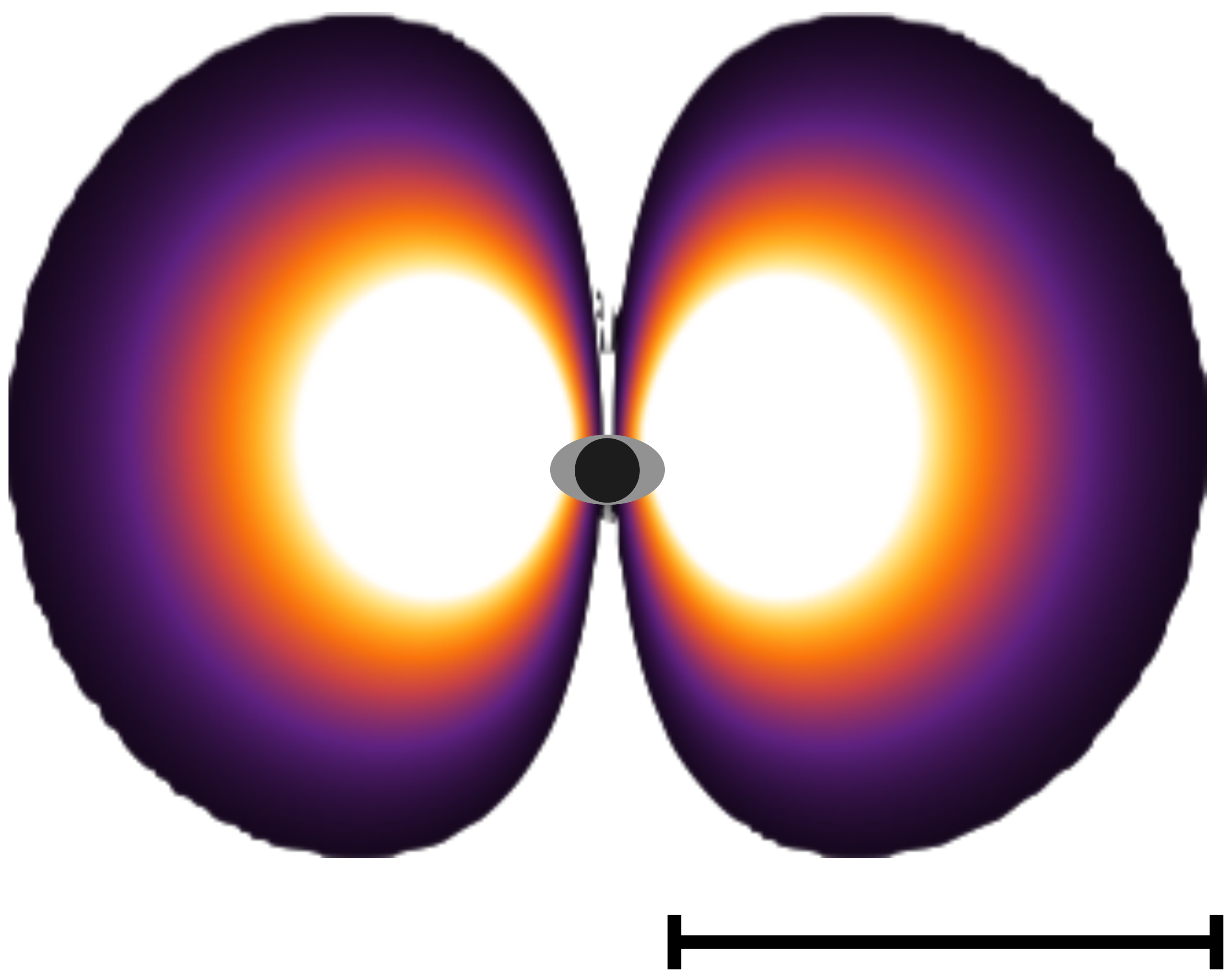
Press & Teukolsky '72, Zouros & Eardley '79, Damour et al. '76, Detweiler '80, Gaina et al. '78
Arvanitaki et al. '09, Arvanitaki et al. '10

Gravitational Atom Spectroscopy

- **Massive bound states** approximately **hydrogenic**

$$V(r) = -\frac{G_{\rm N} M_{\rm BH}\mu}{r} = -\frac{\alpha}{r}$$

$n = 2 \quad \ell = 1 \quad m = 1$



$r_c \simeq \frac{n^2}{\alpha^2} r_g$

- "Fine-structure constant"

$$\alpha \equiv G_{\rm N} M_{\rm BH}\mu = r_g \mu = 0.1 \left(\frac{M_{\rm BH}}{10 M_\odot}\right)\left(\frac{\mu}{10^{-12}\ {\rm eV}}\right)$$

"ultra-light"

For astrophysical BHs: $10^{-2} \lesssim \alpha \lesssim 0.5$

- Quasi-normal mode frequencies

$$E \simeq \mu\left(1 - \frac{\alpha^2}{2n^2}\right) + i\Gamma^{\rm SR}_{n\ell m} + \ldots$$

1-particle energy

rest mass

binding

SR rates
Detweiler '80

Fine + hyper-fine corrections
Baumann et al. '18, '19

- Occupation number

$$N_c \simeq \Delta J_{\rm BH} \simeq G_{\rm N} M_{\rm BH}^2 \simeq 10^{76} (M/M_\odot)^2$$

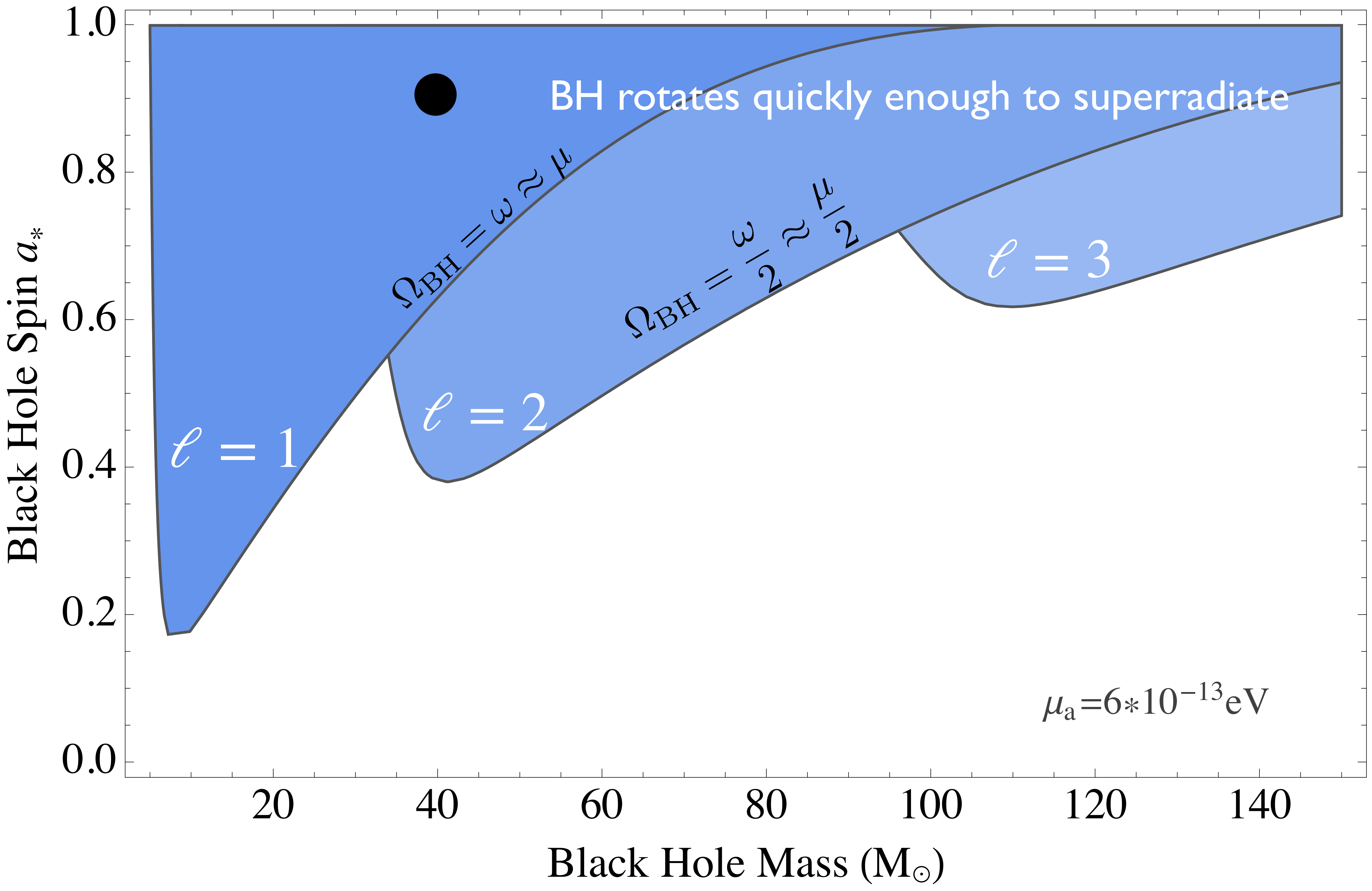
Cloud grows from zero-point fluctuations (like laser, "spontaneous emission"→"stimulated emission")

Cloud Growth and BH Spin Down

- If new light scalar exist, **fast spinning BHs** will **spin down** as energy and angular momentum is **converted to scalar cloud**

$$\dot{N}_{n\ell m} = \Gamma^{\rm SR}_{n\ell m} N_{n\ell m} + \ldots$$

$$\dot{J}_{\rm BH} = -m\Gamma^{\rm SR}_{n\ell m} N_{n\ell m}$$



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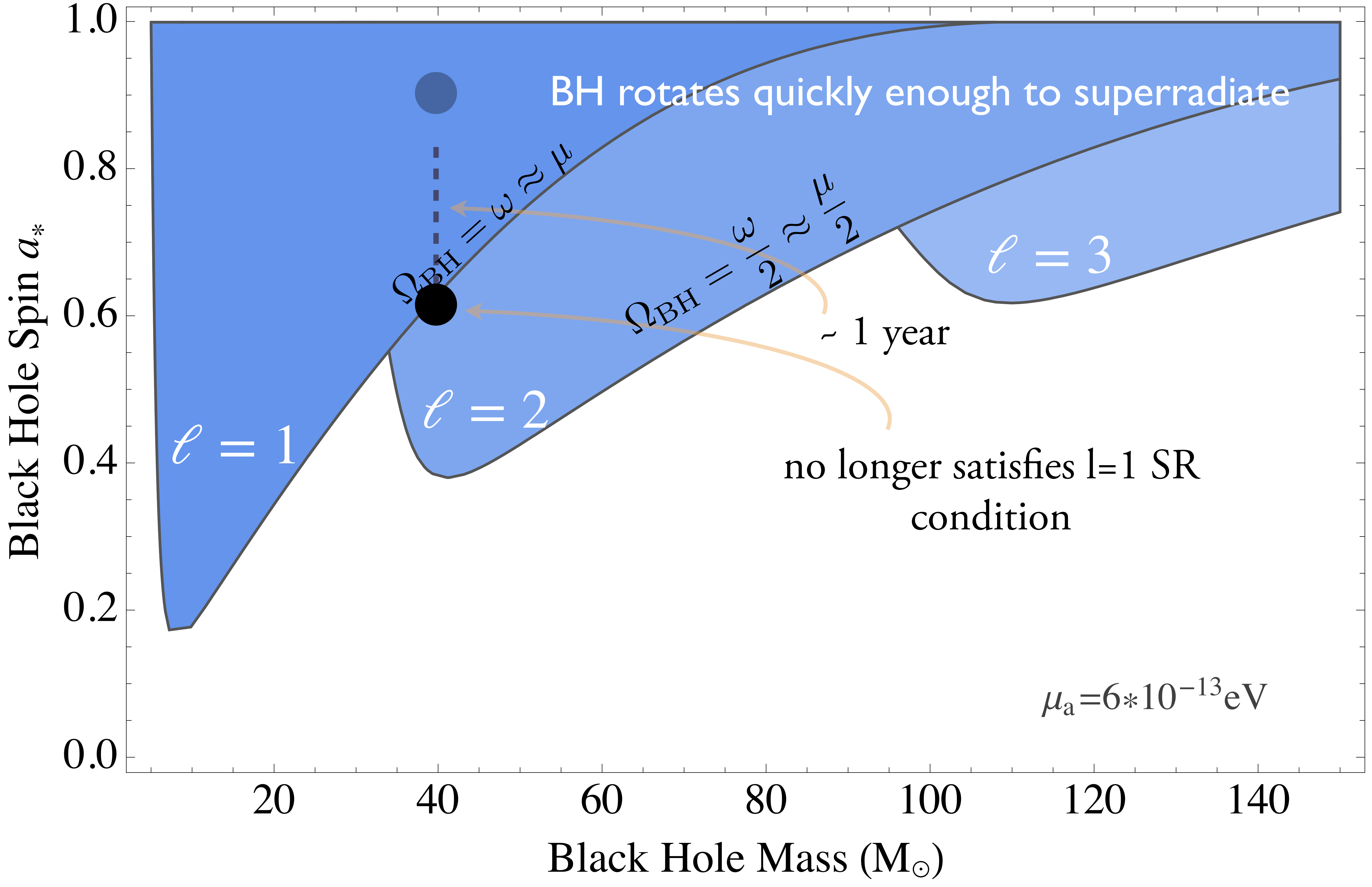

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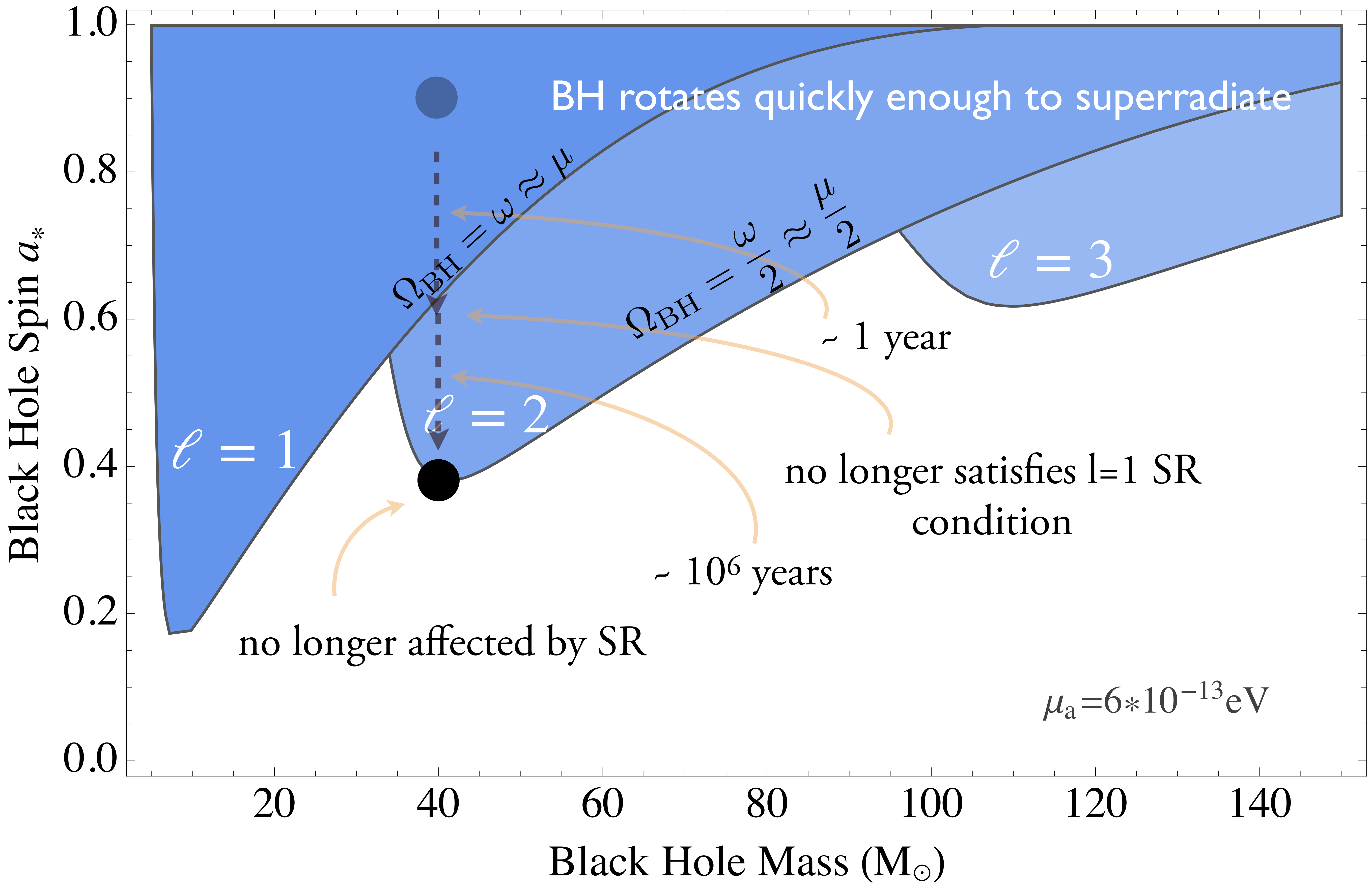


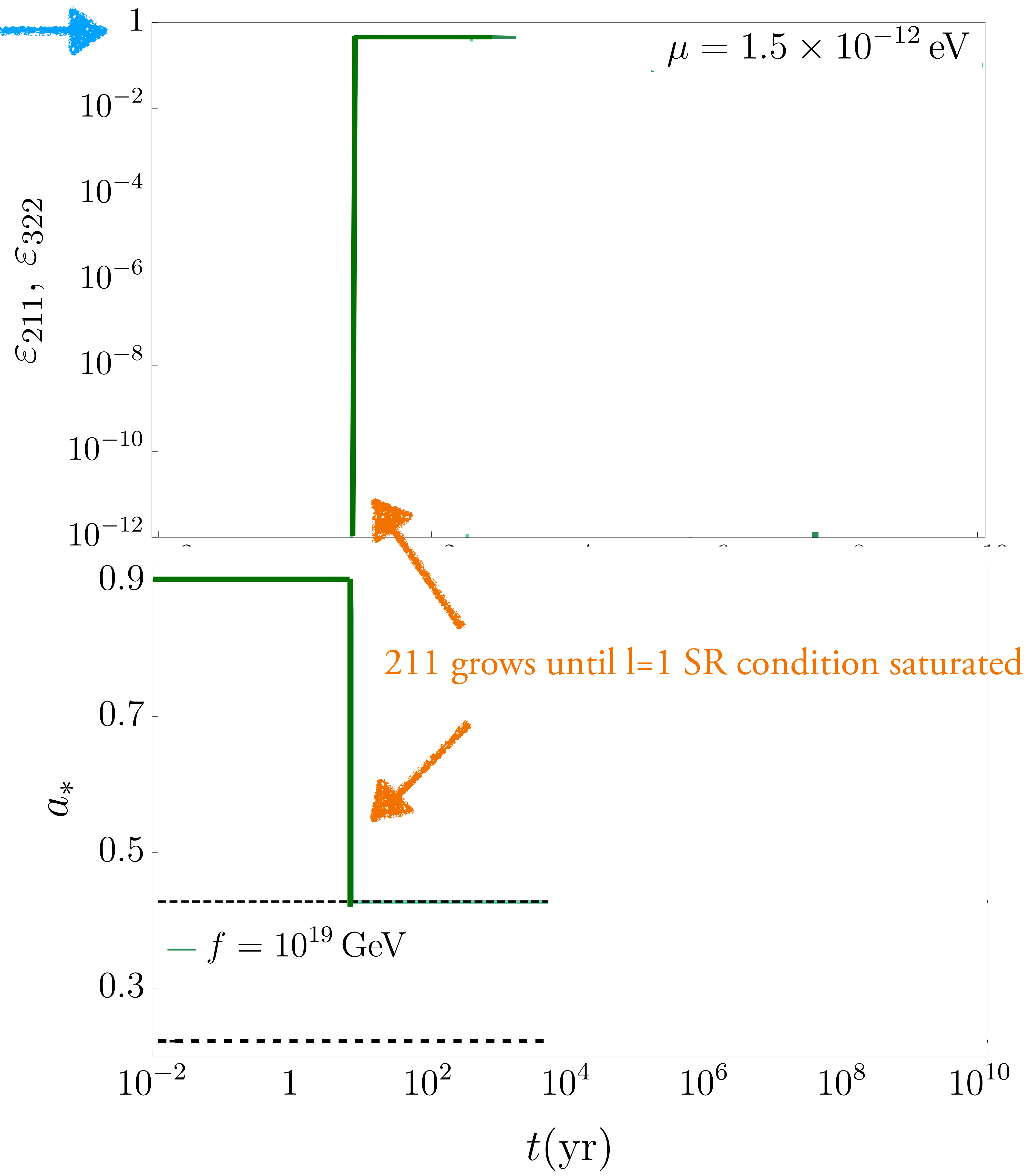
Cloud Growth and BH Spin Down

"full" cloud →

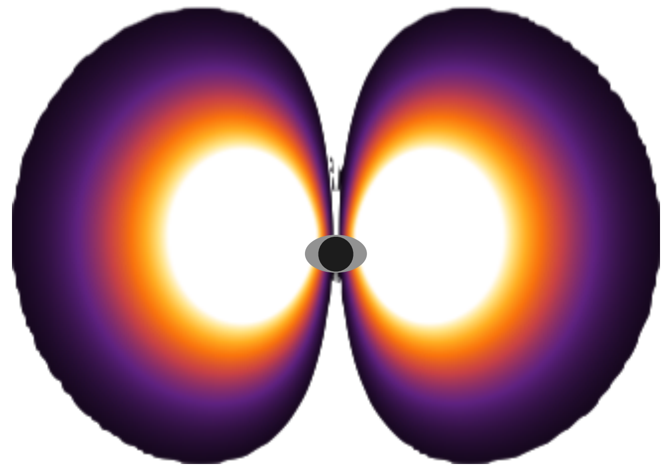
$$\varepsilon_{n\ell m} = \frac{N_{n\ell m}}{G_N M_{BH}^2}$$

$$\Gamma^{SR}_{211} \gg \Gamma^{SR}_{322} \gg \ldots$$

$$a_* = \frac{J_{BH}}{G_N M_{BH}^2}$$



$M_{BH} = 10 M_\odot$



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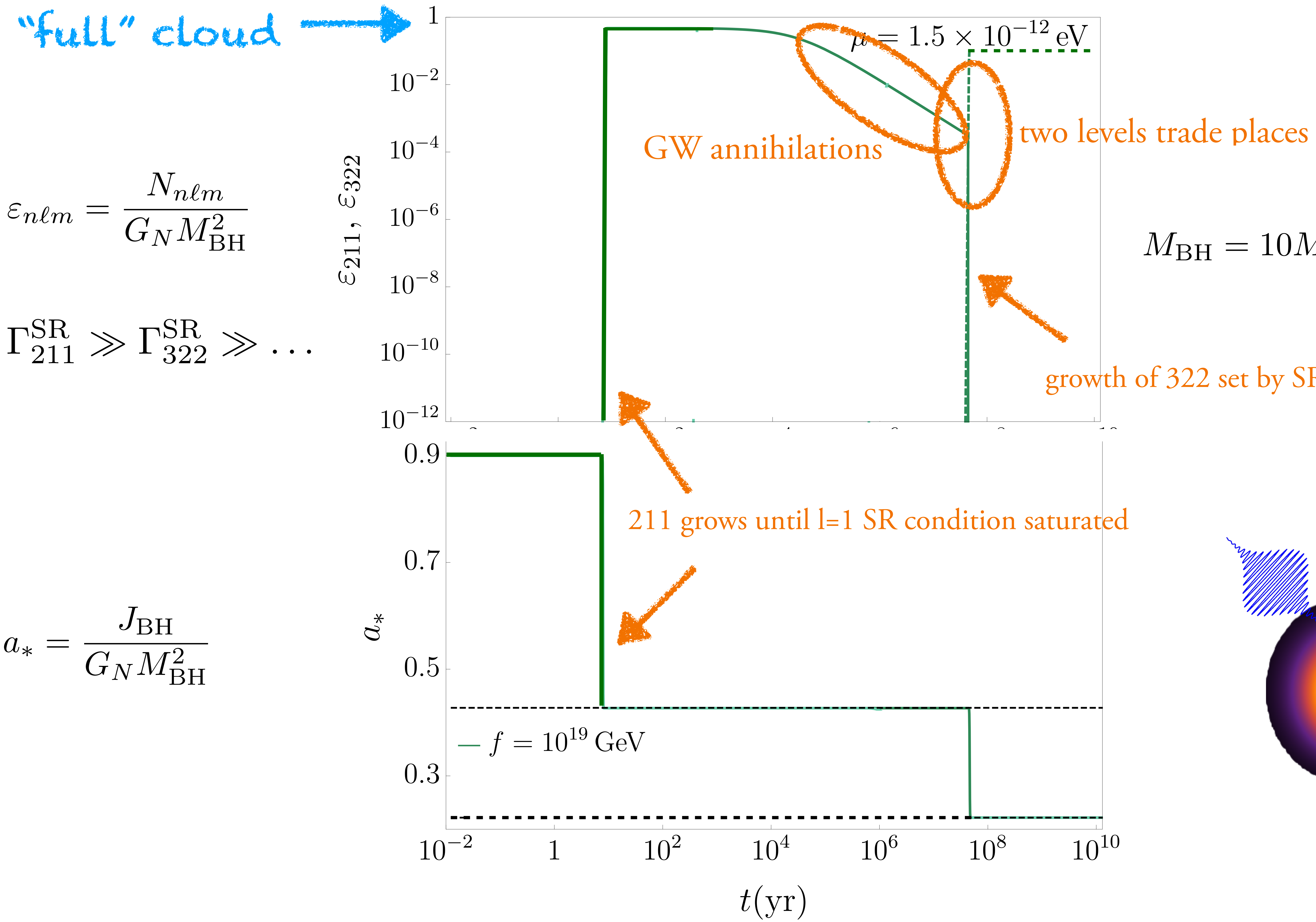

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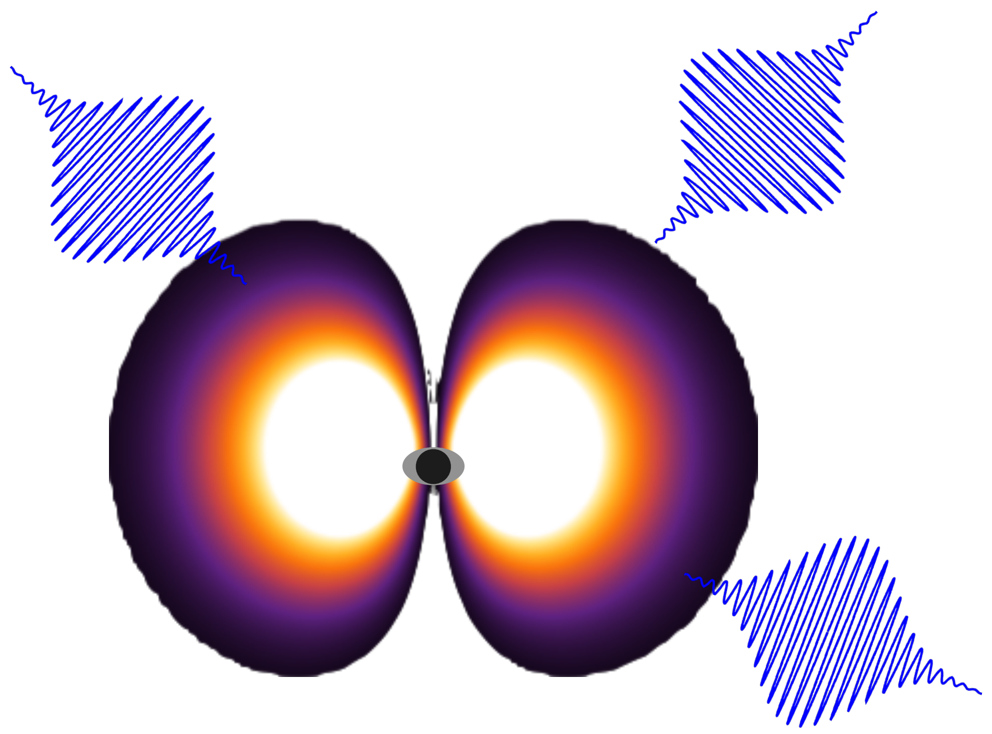
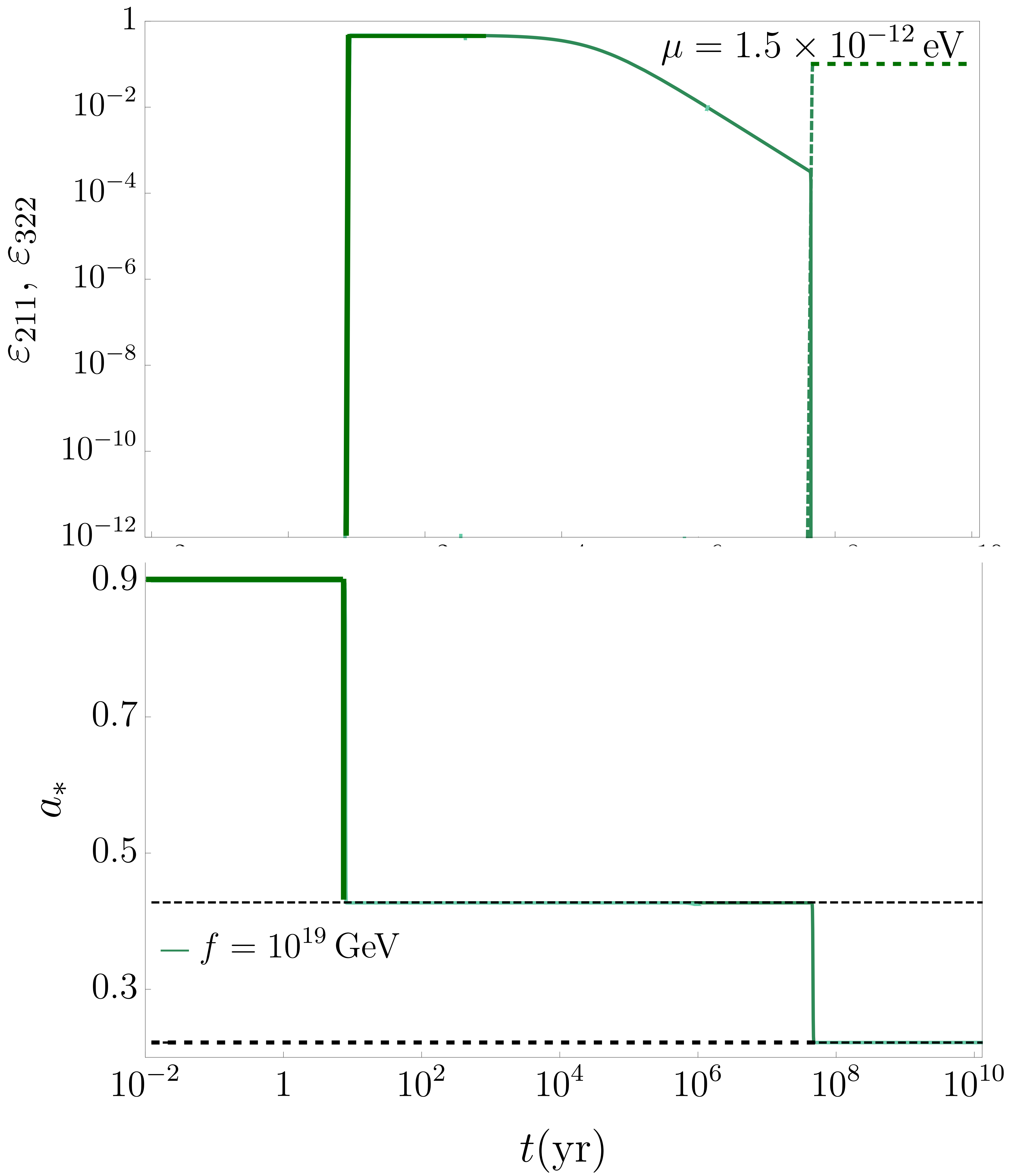


“Purely” Gravitational SR

- Cycles of growth via SR and depletion via annihilations to GWs

- Only 1 level at the time builds significant occupation



Self-Interactions in the SR Cloud

Self-Interacting Scalars

Well motivated scalar extensions to the Standard Model are expected to have quartic self-interactions.

$$\mathcal{L} \supset \frac{\lambda}{4!}\phi^4$$

Self-Interacting Scalars

- E.g. QCD axion solution to strong CP problem $V(\phi) \approx m_\pi^2 f_\pi^2 \left[1 - \cos\left(\phi/2f_a\right)\right]$

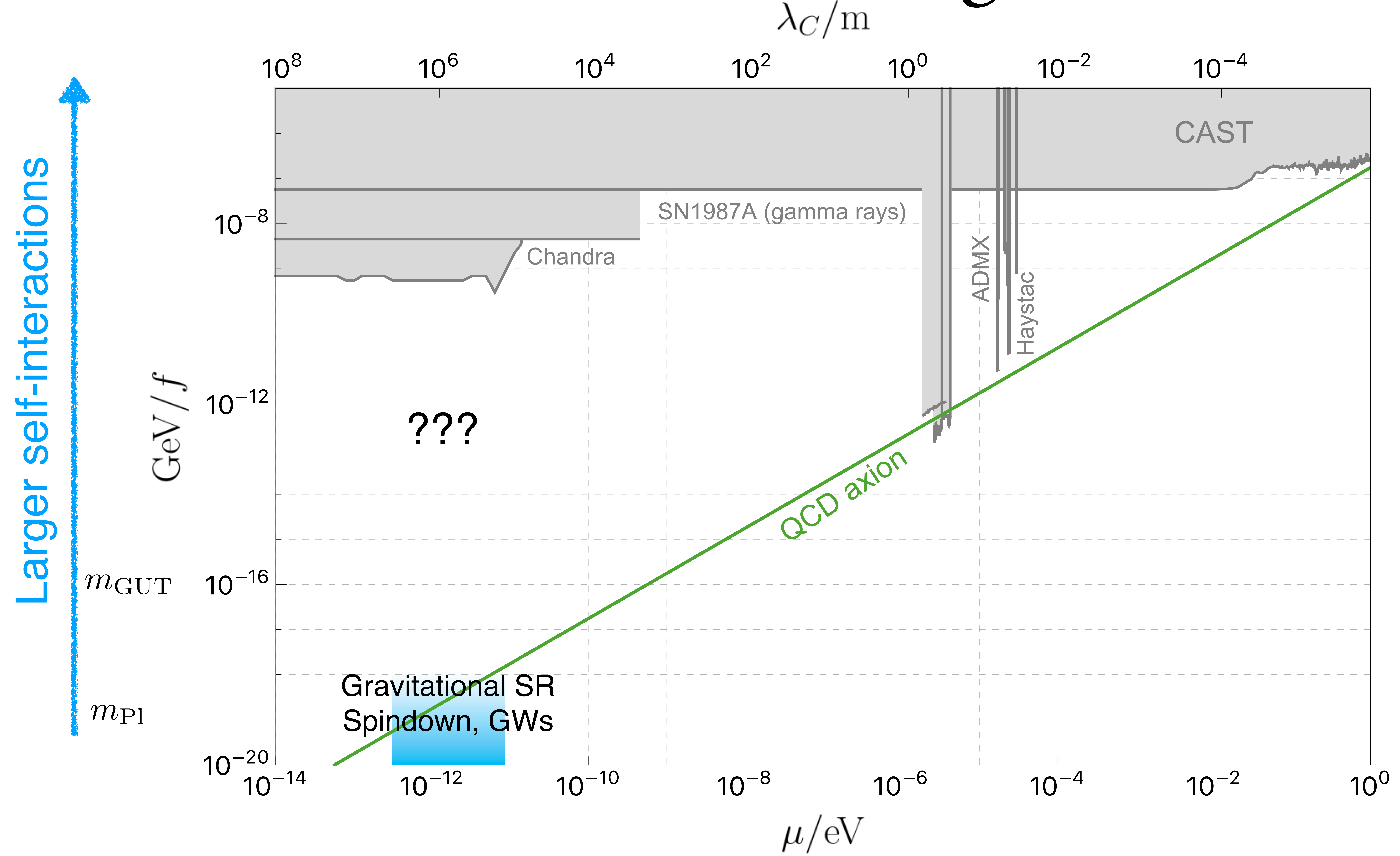
mass: $\mu \simeq 6 \times 10^{-12}\ \text{eV} \left(\frac{10^{18}\ \text{GeV}}{f_a}\right)$ self-coupling: $\lambda \simeq 0.3\mu^2/f_a^2 \simeq 10^{-80} \left(\frac{\mu}{10^{-12}\ \text{eV}}\right)^4$

- "Axion-like particles": Arise naturally as KK modes from compactification of in string theory (axiverse)

Green et al. '88, Svreck & Witten '06, Arvanitaki et al. '10, Dine '16, Halverson et al. '17, Bachlechner et al '19

$$\lambda = \frac{\mu^2}{f^2} \sim \frac{\mu^2}{f_a^2} \simeq 10^{-74} \left(\frac{\mu}{10^{-12}\ \text{eV}}\right)^2 \left(\frac{10^{16}\ \text{GeV}}{f}\right)^2$$

Self-Interacting Scalars



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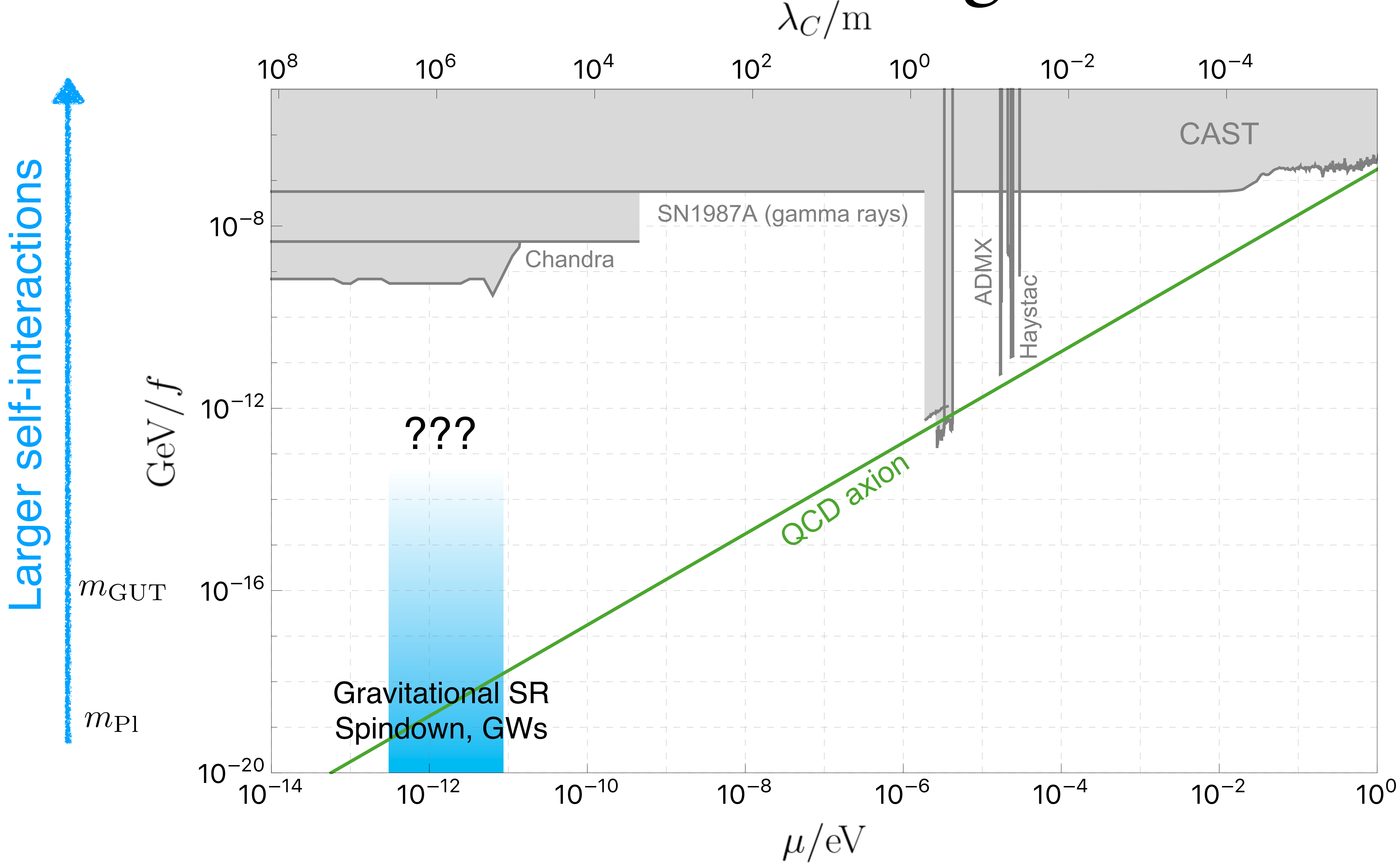

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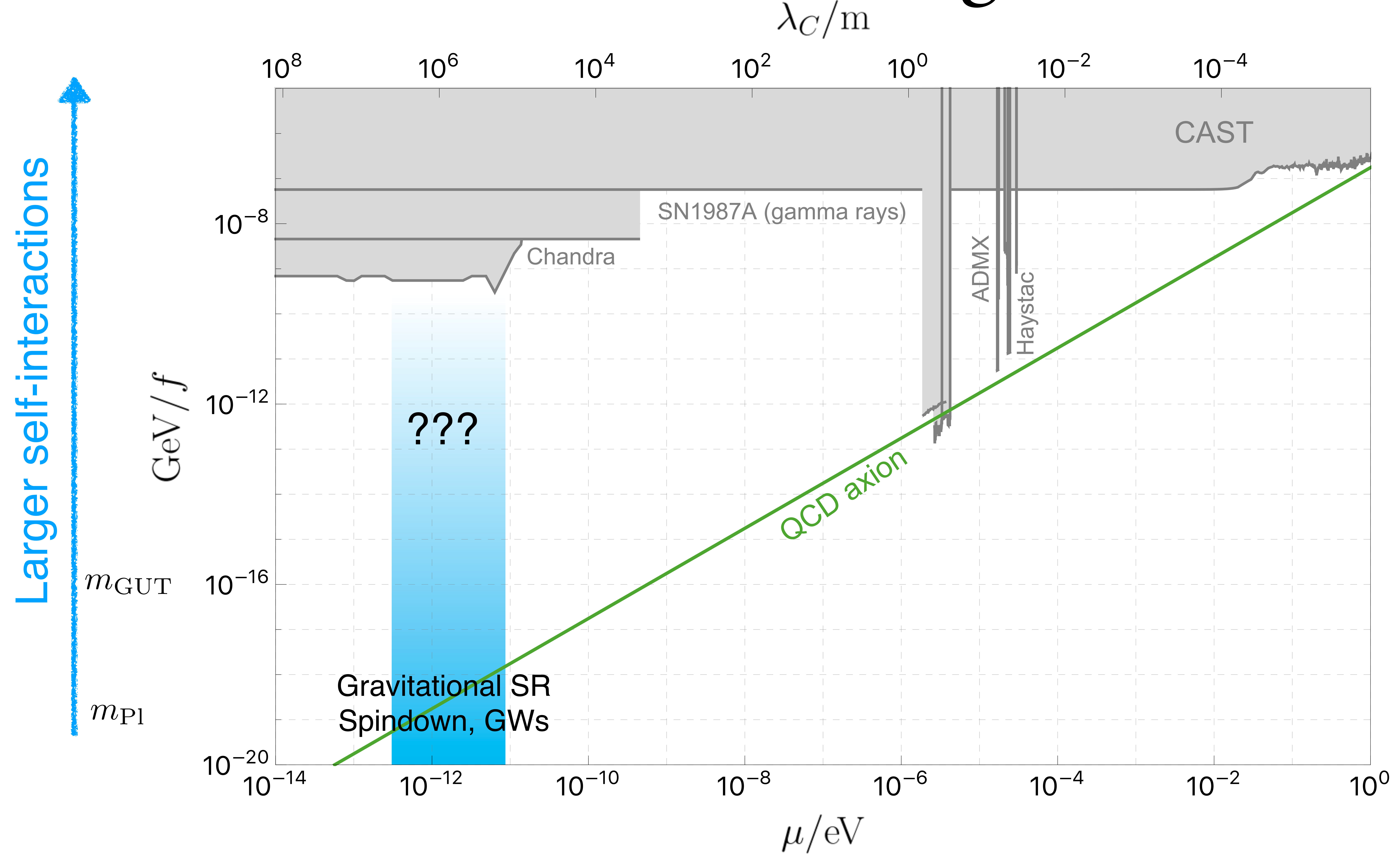
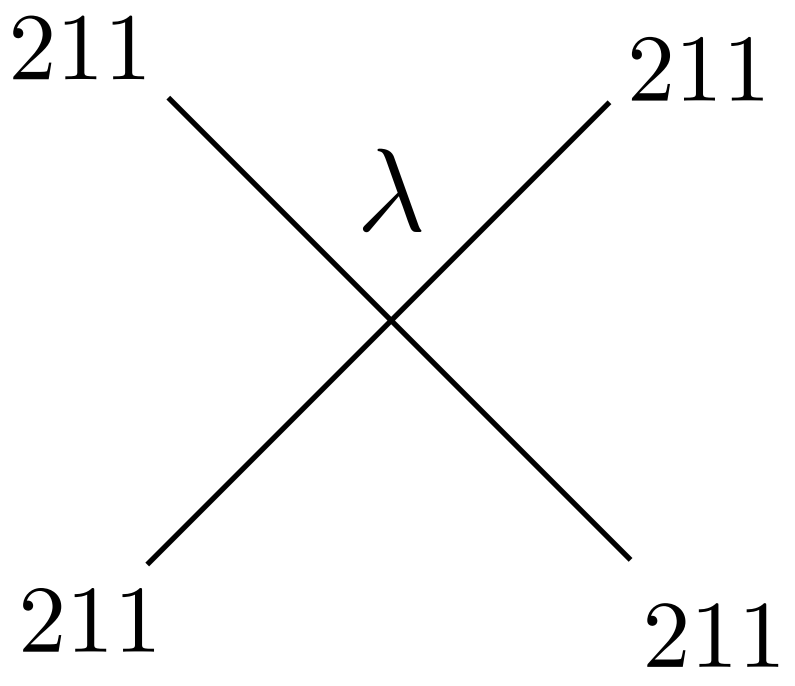
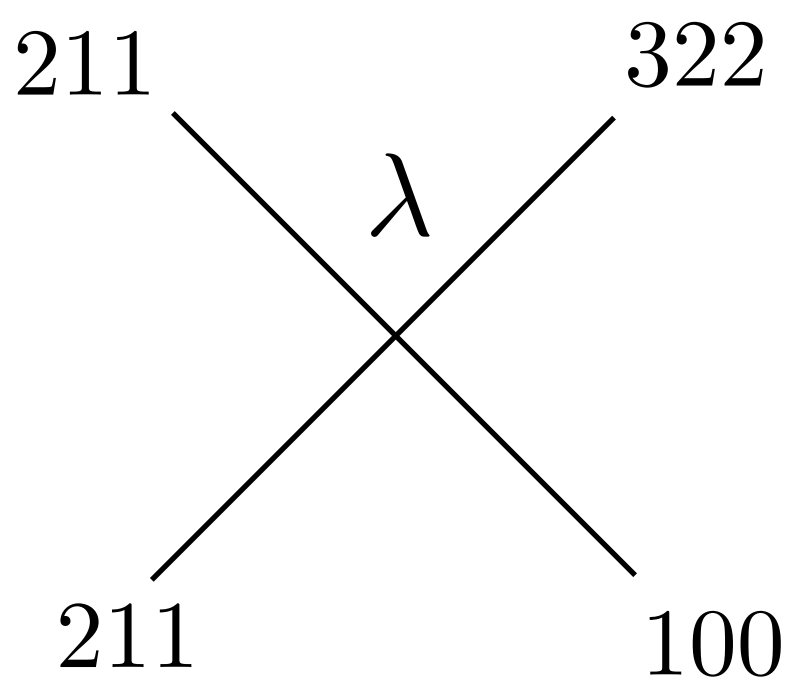


Self-Interacting SR Cloud

Self-energy corrections

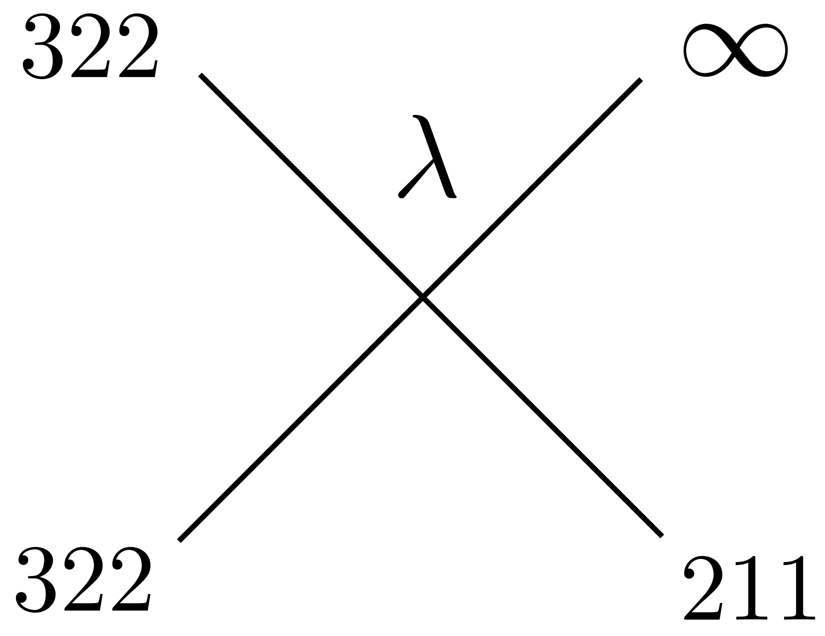


Bound states interactions



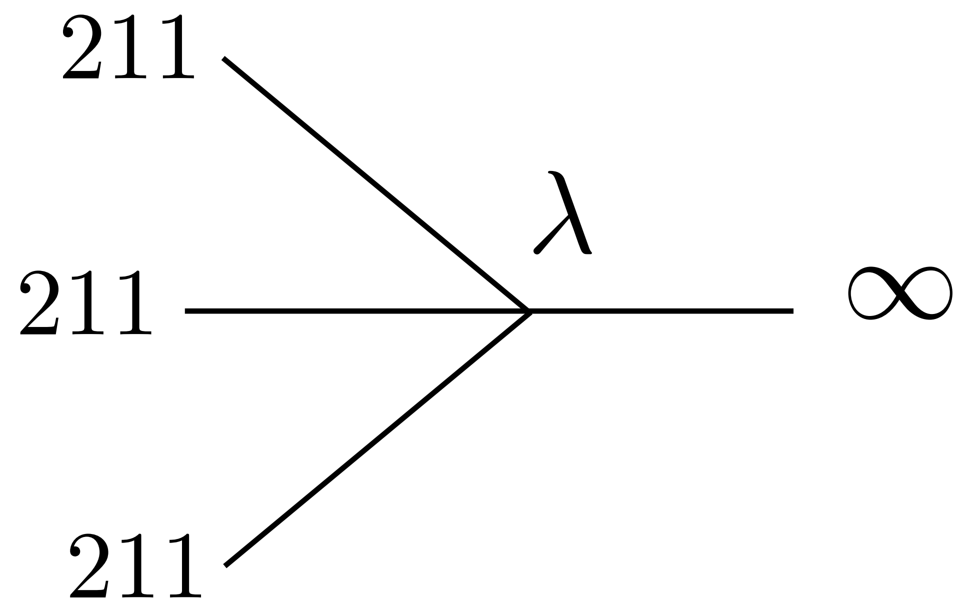
Bound-continuum interactions

Non-relativistic emissions



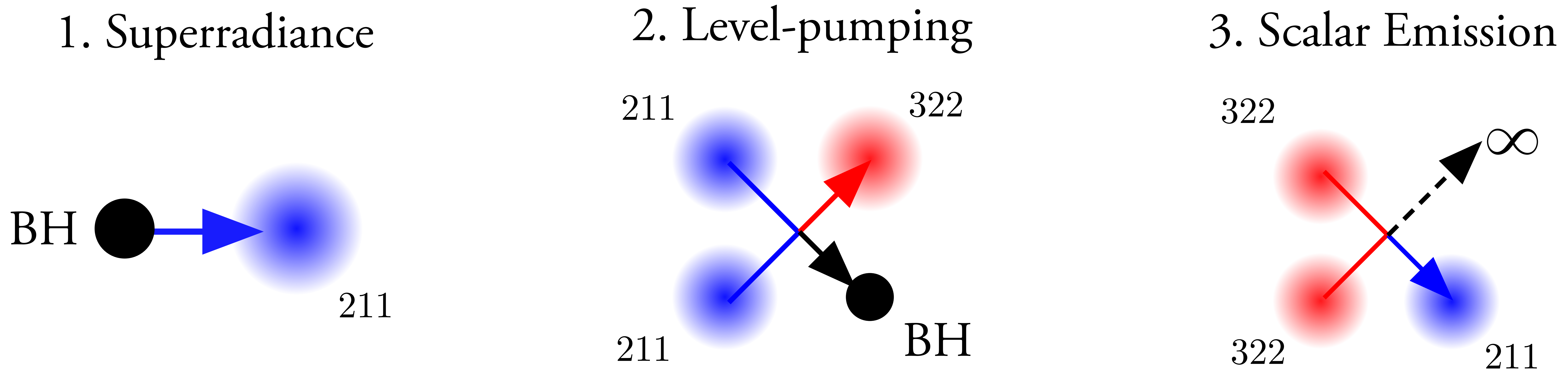
Relativistic emissions

(suppressed in α^{large} b/c cloud is non-rel.)



At what value of $\lambda = \mu^2/f^2$ do self-interactions become important? What are the new effects?

Two-level system

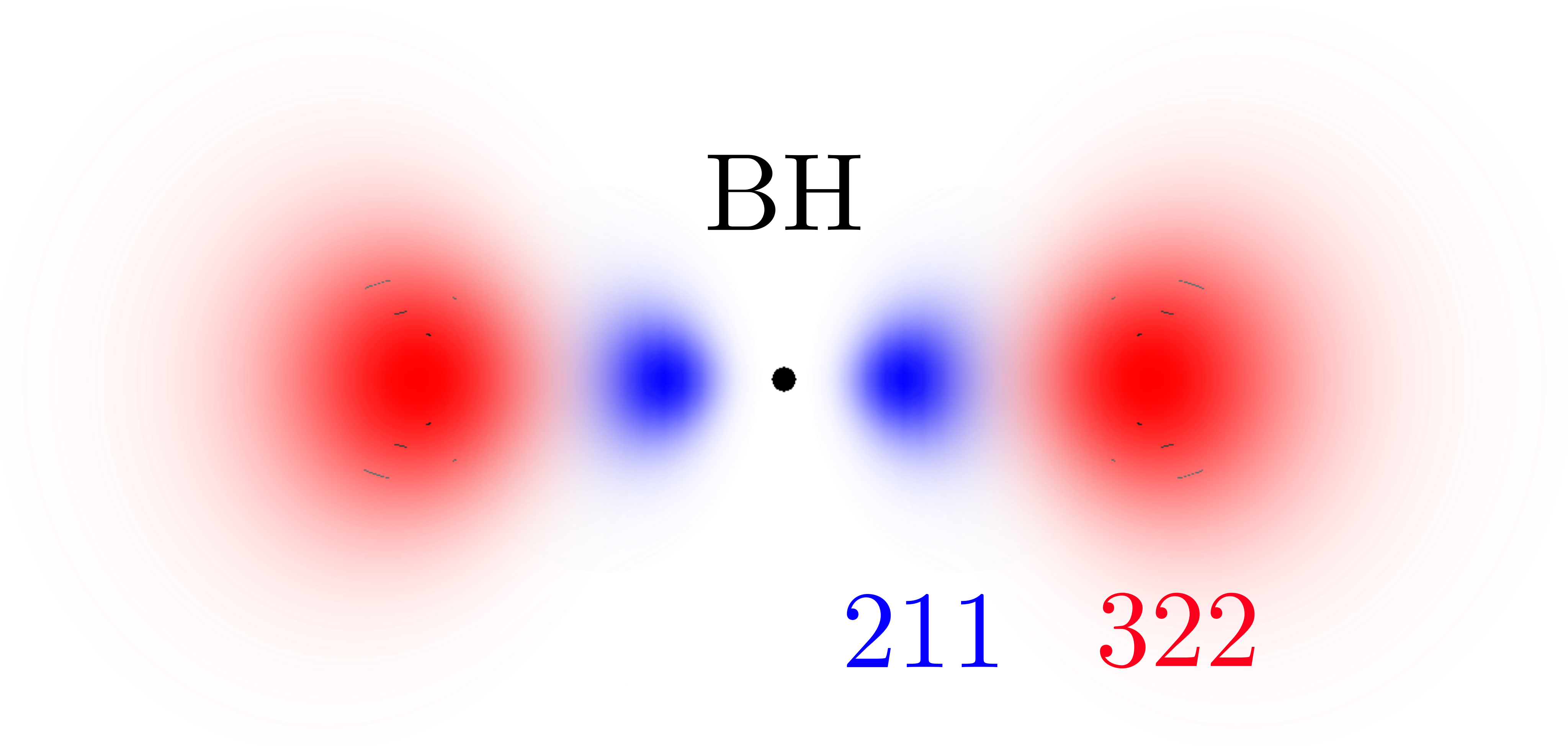


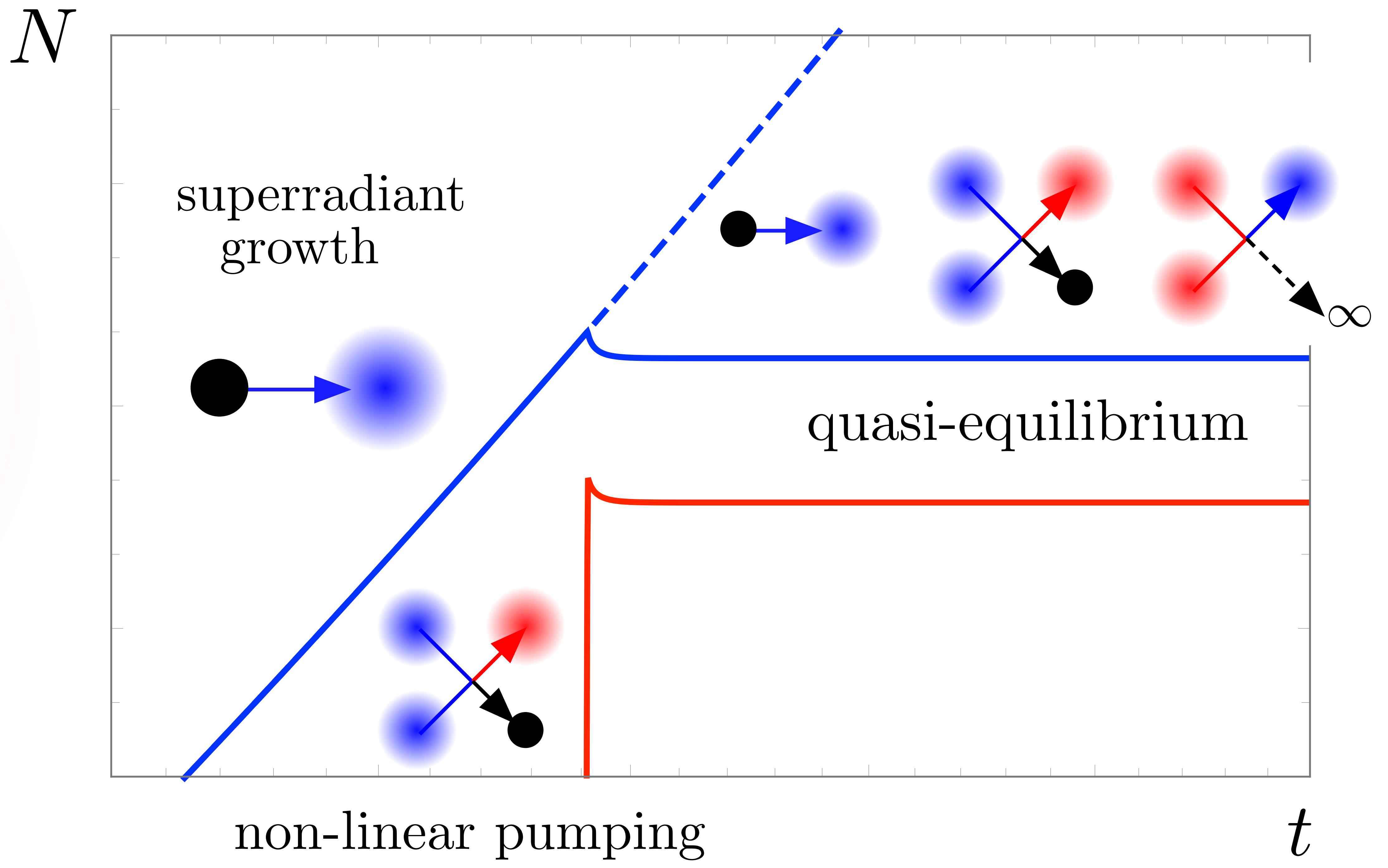
1. BH populates cloud through SR (211 = most SR level)
2. Second level gets populated though self-interactions
3. Non-relativistic scalar waves carry energy and angular momentum to infinity

Gruzinov '16

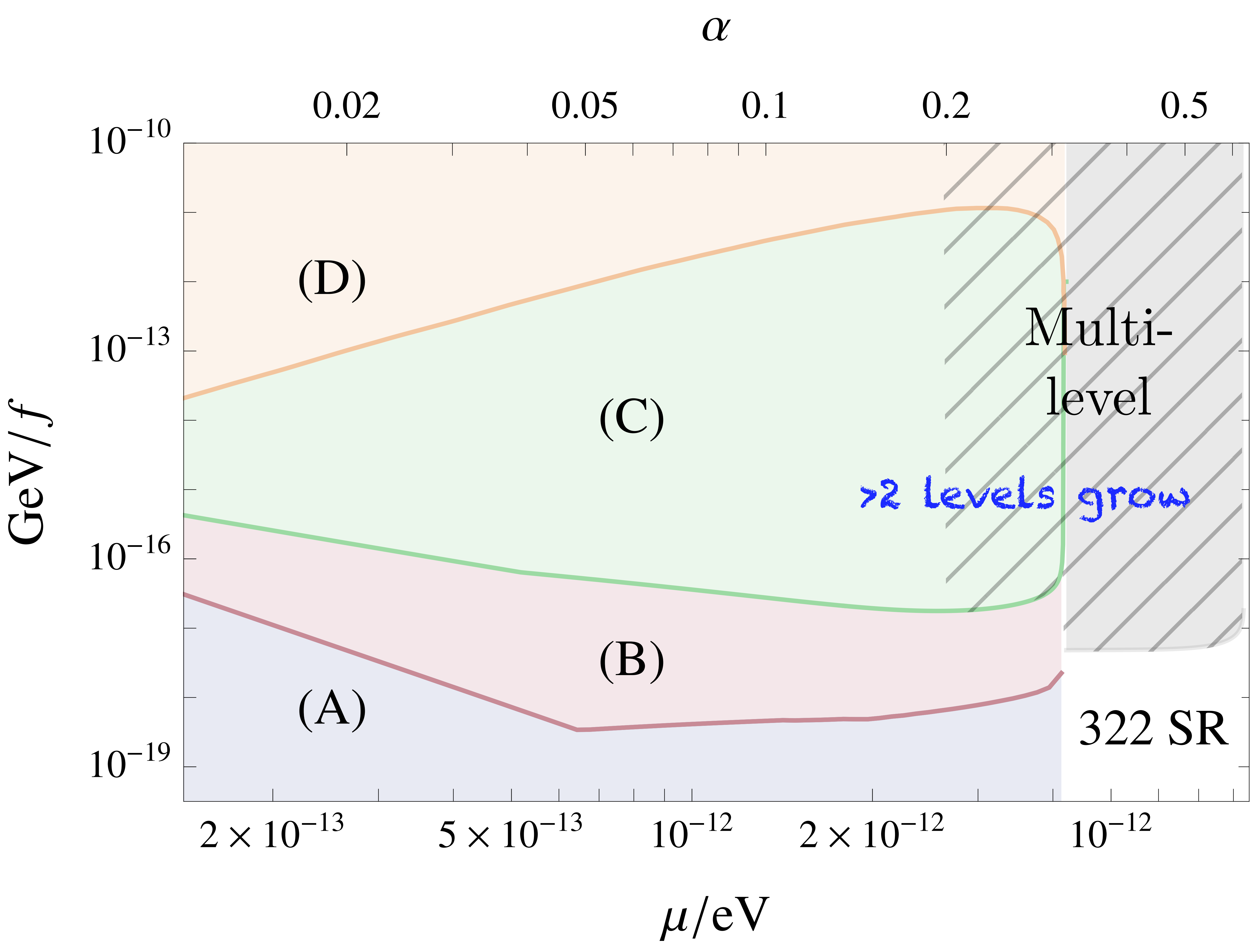
Two-level Quasi-Equilibrium

- A quasi-equilibrium between the two levels is possible
- Cloud stops growing. Momentum circulated from BH to infinity via cloud





Regimes of self-interactions



$M = 10 M_\odot$ $\quad a_*(t_0) = 0.9$ $\quad T = 10^{10}$ yr

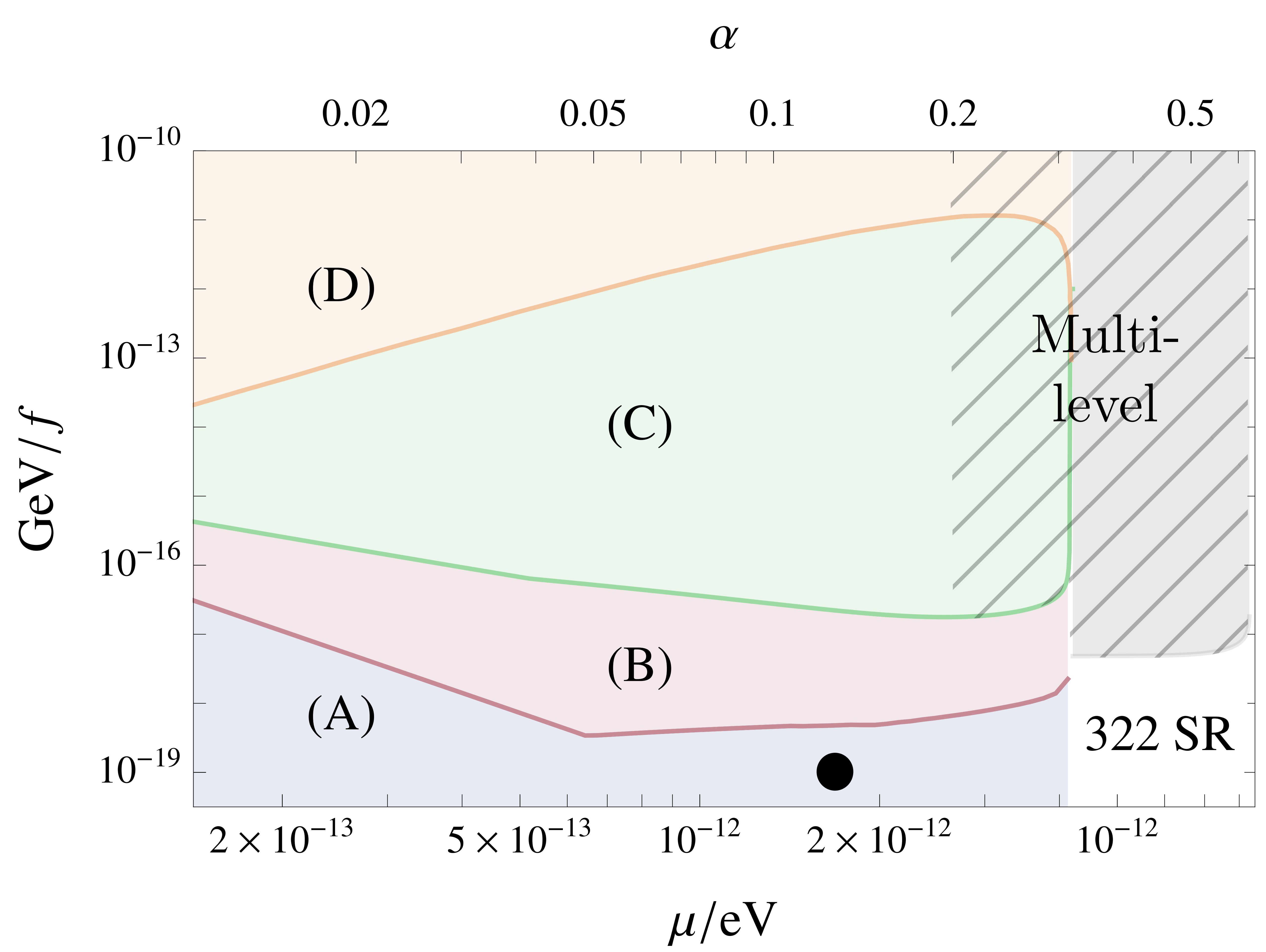
(A) "Gravitational SR". Spindown, GW annihilations.

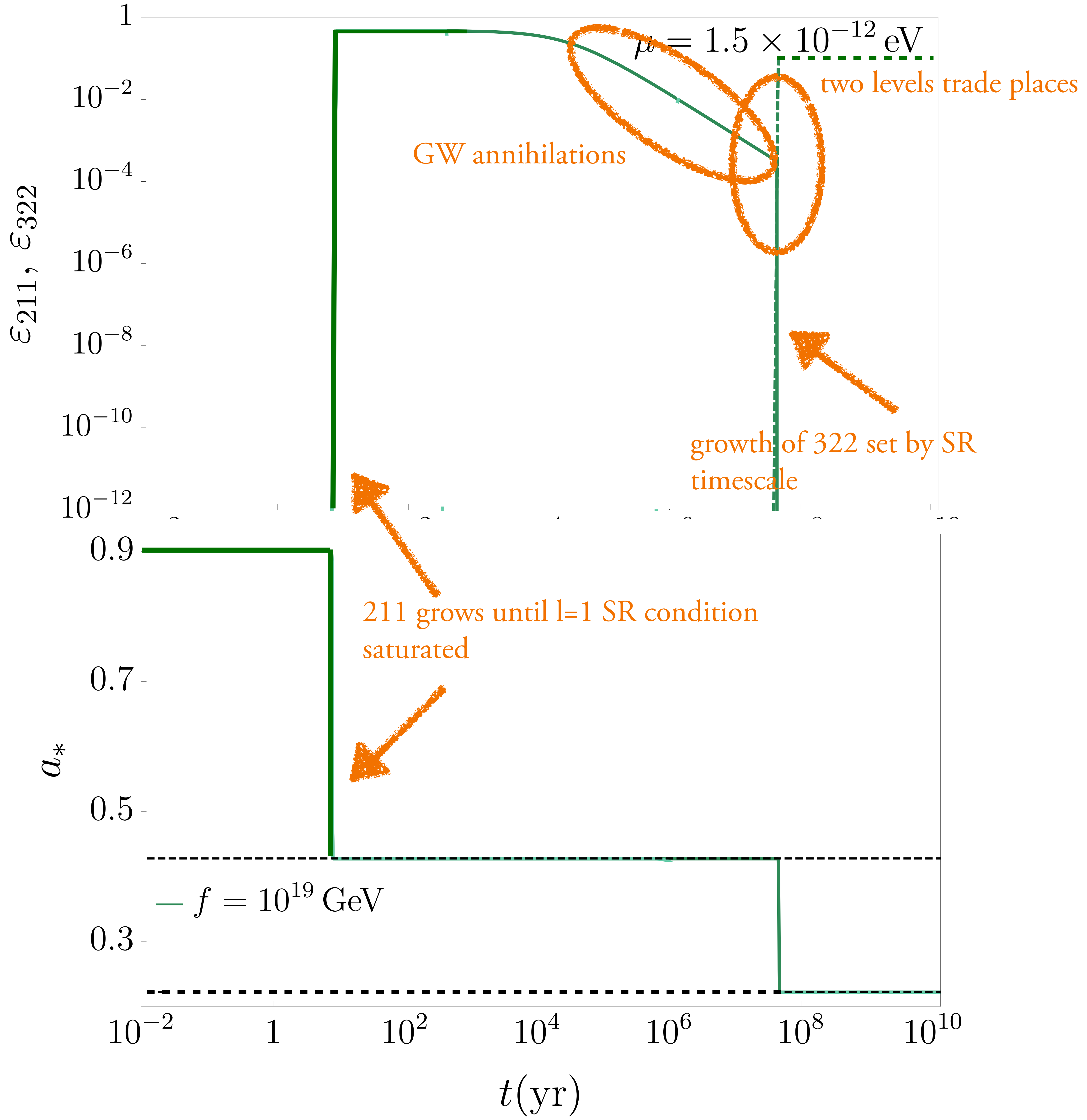
(B) "Moderate self-interactions". Early 322 growth. Spindown, GW annihilations.

(C) "Large self-interactions". Simultaneous growth. Spindown. Scalar waves.

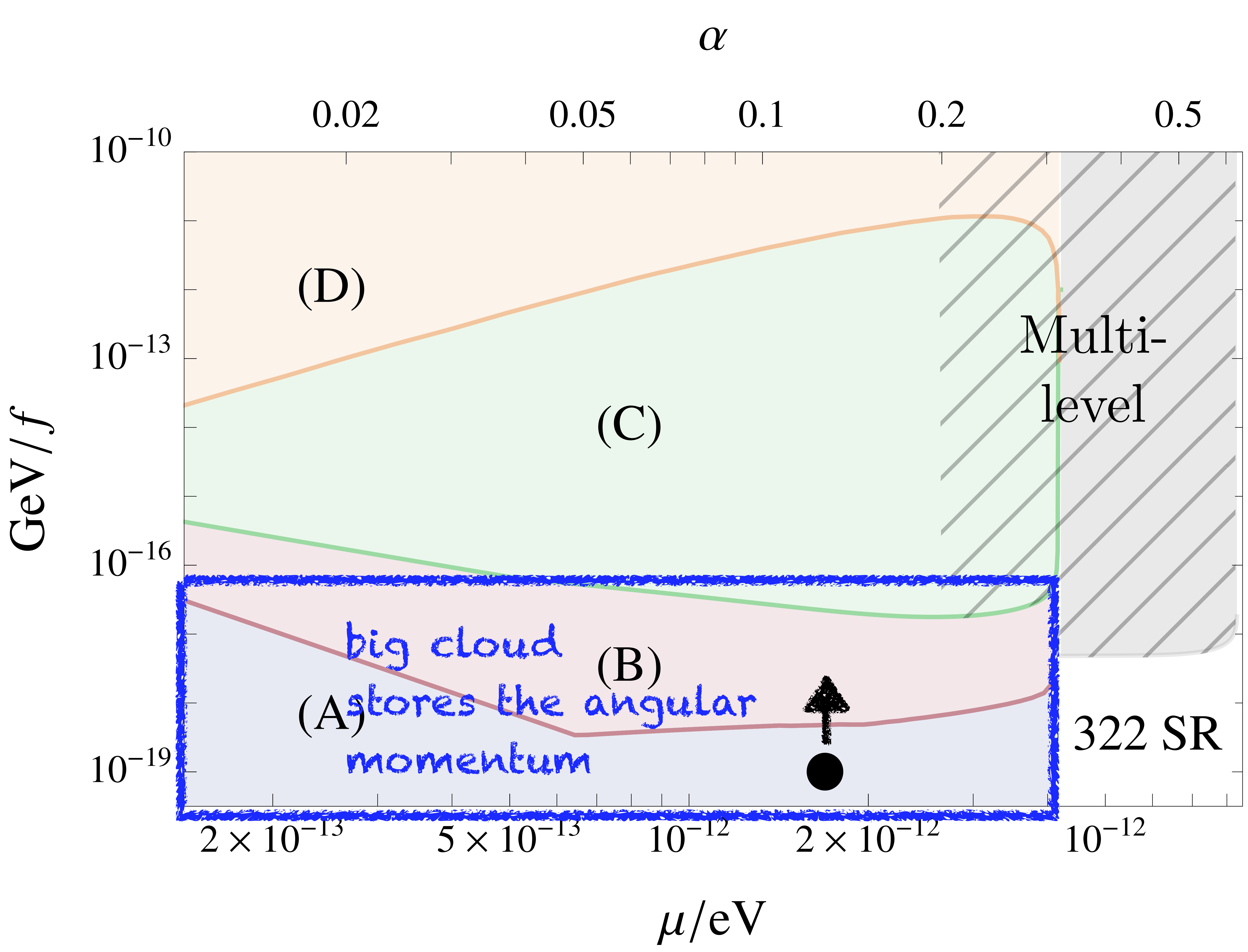
(D) "Very large self-interactions". Simultaneous growth. No spindown. Scalar waves.

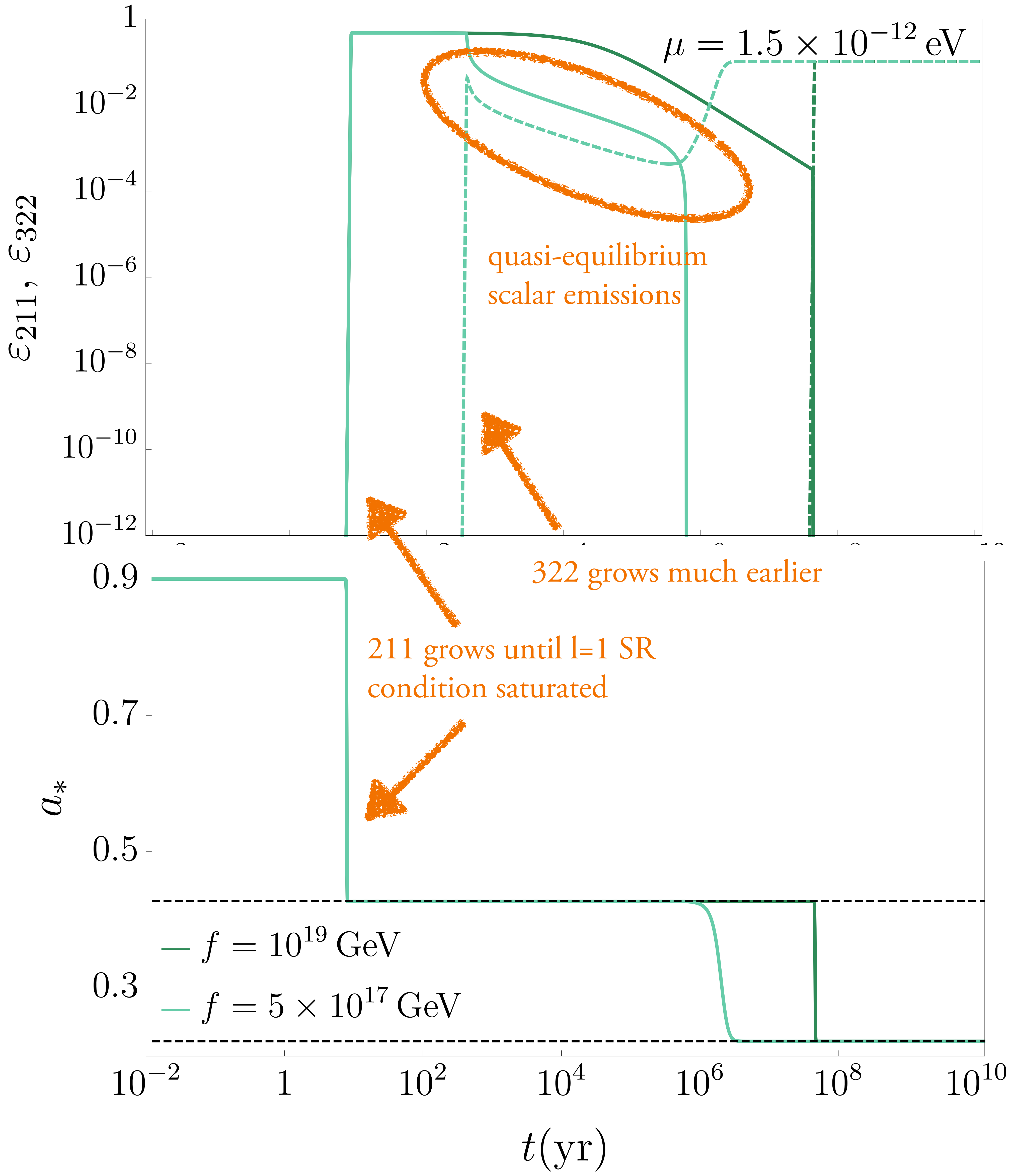
Small Interactions: Gravitational SR



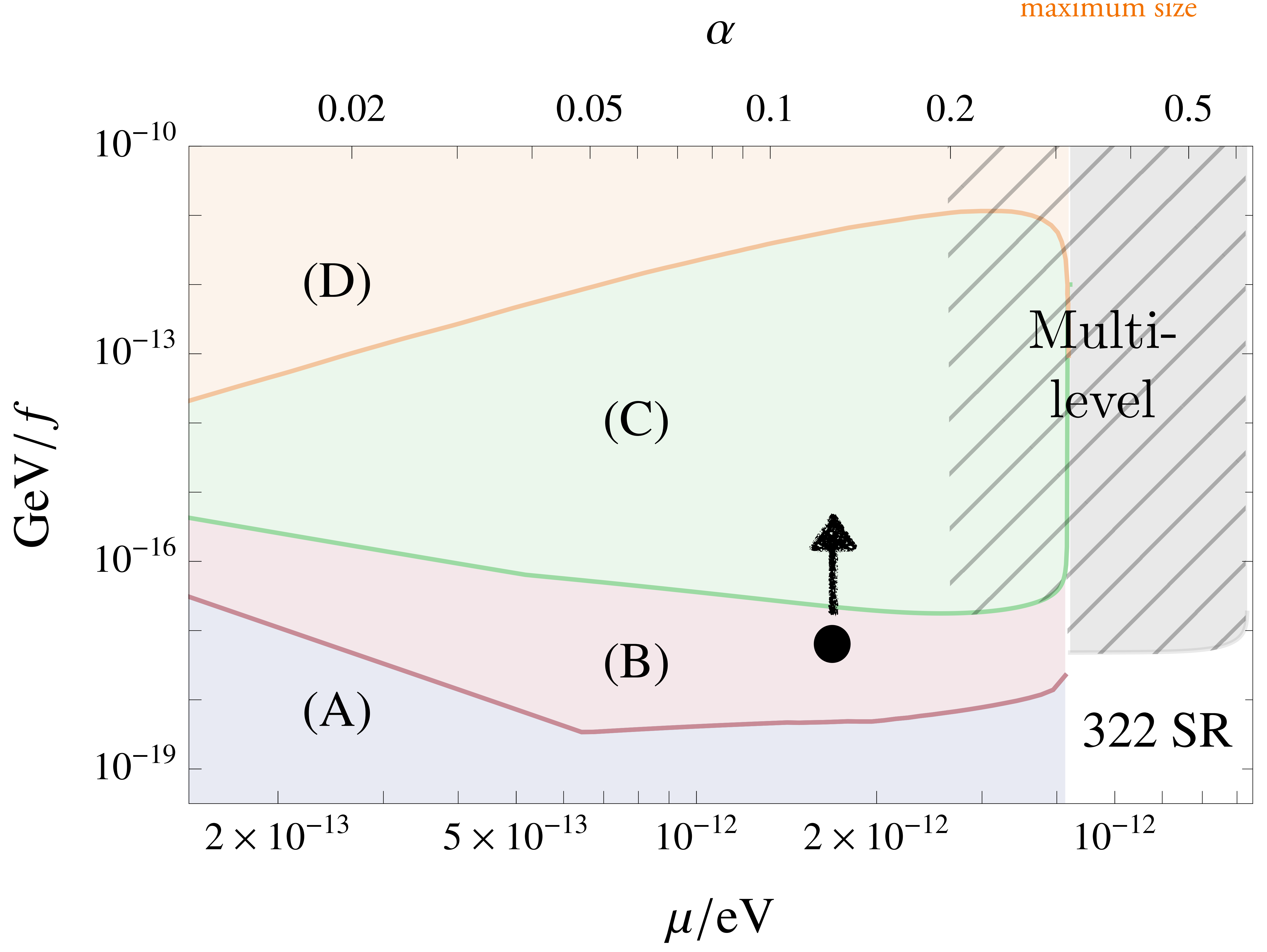


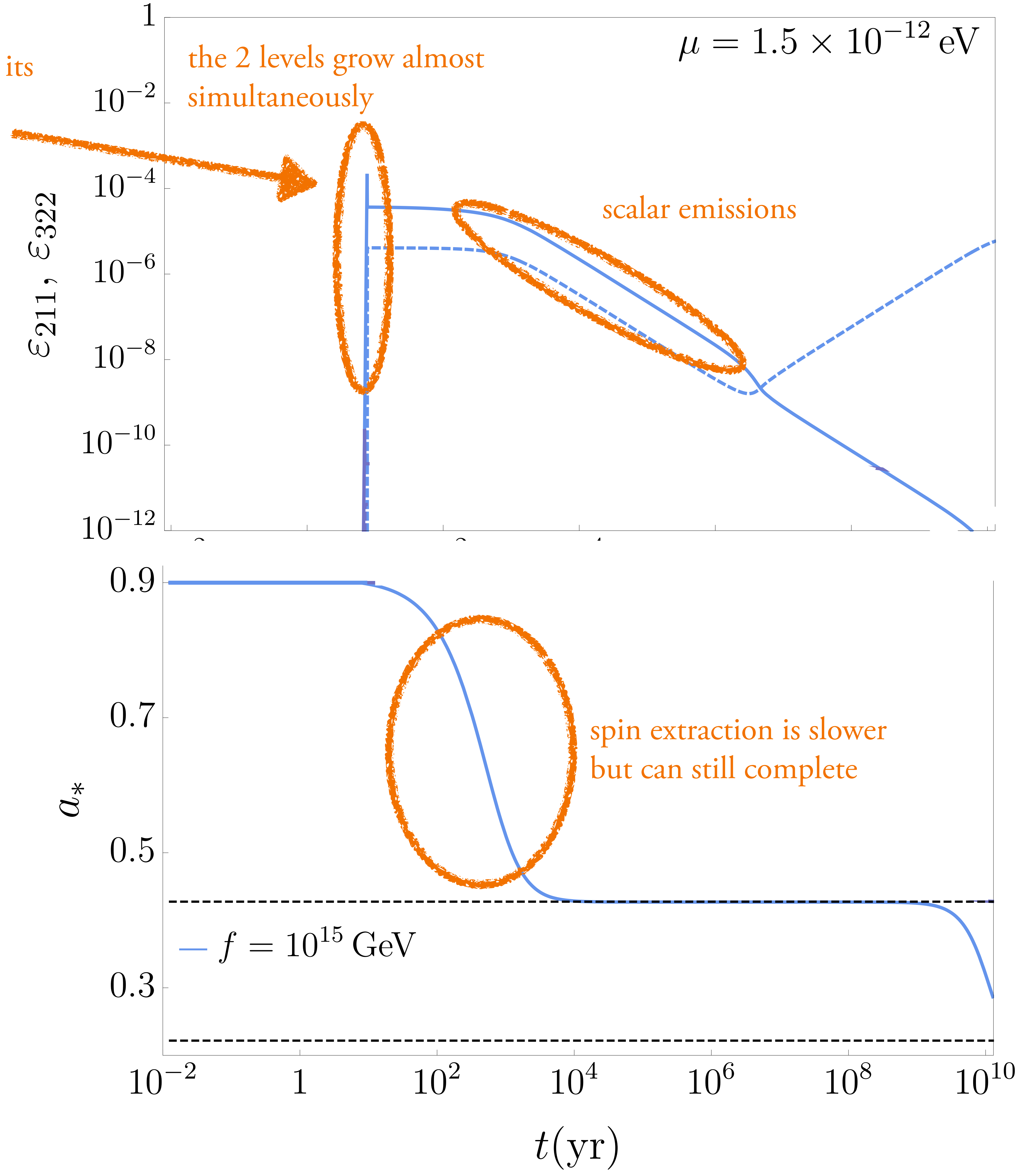
Moderate Interactions: Late Equilibrium



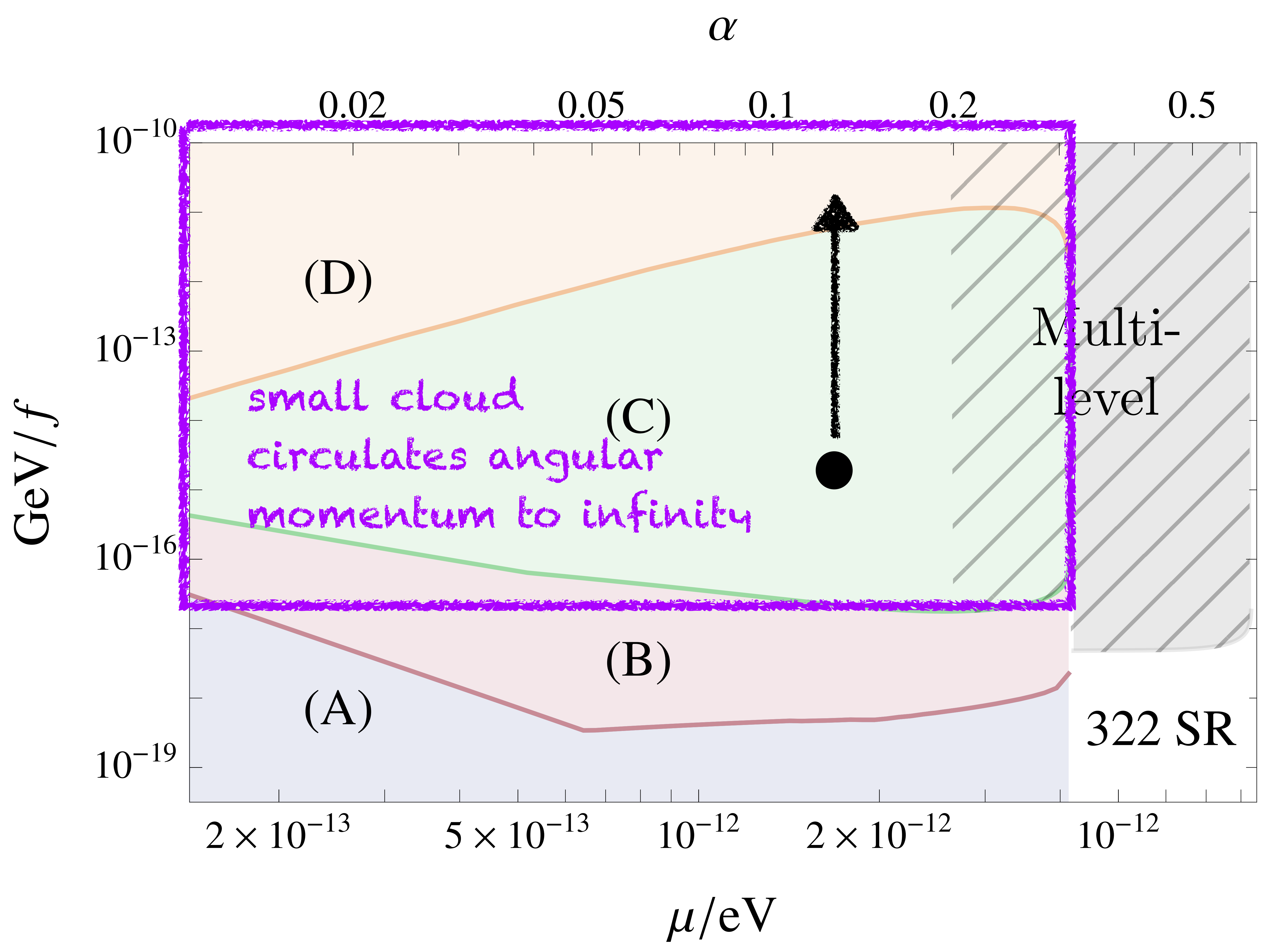


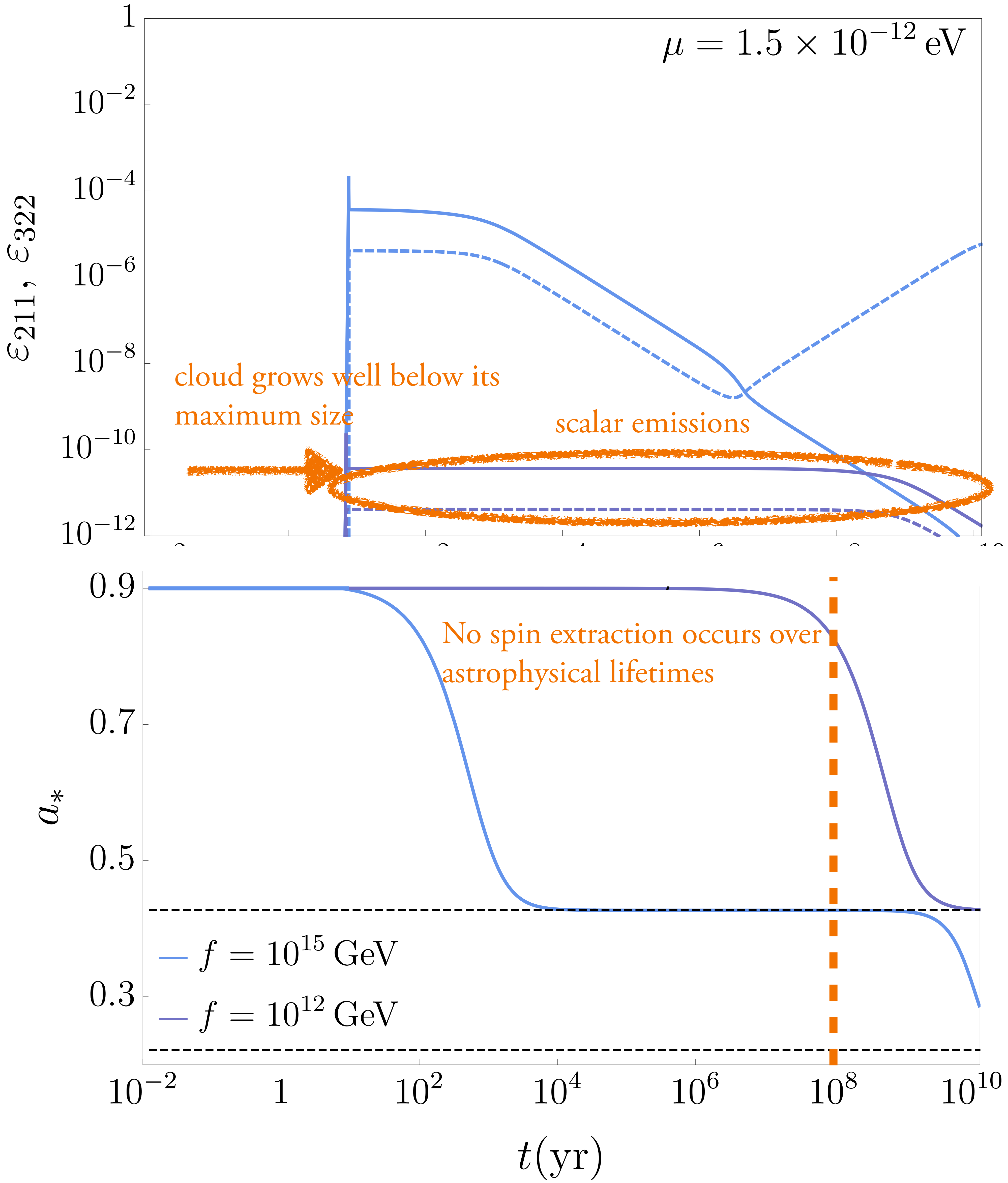
Large Interactions: Early Equilibrium





(Very) Large Interactions: No Spindown





Collapse From Attractive SI (Bosenova)

- Recall: For "gravitational SR", number of particles in the cloud is

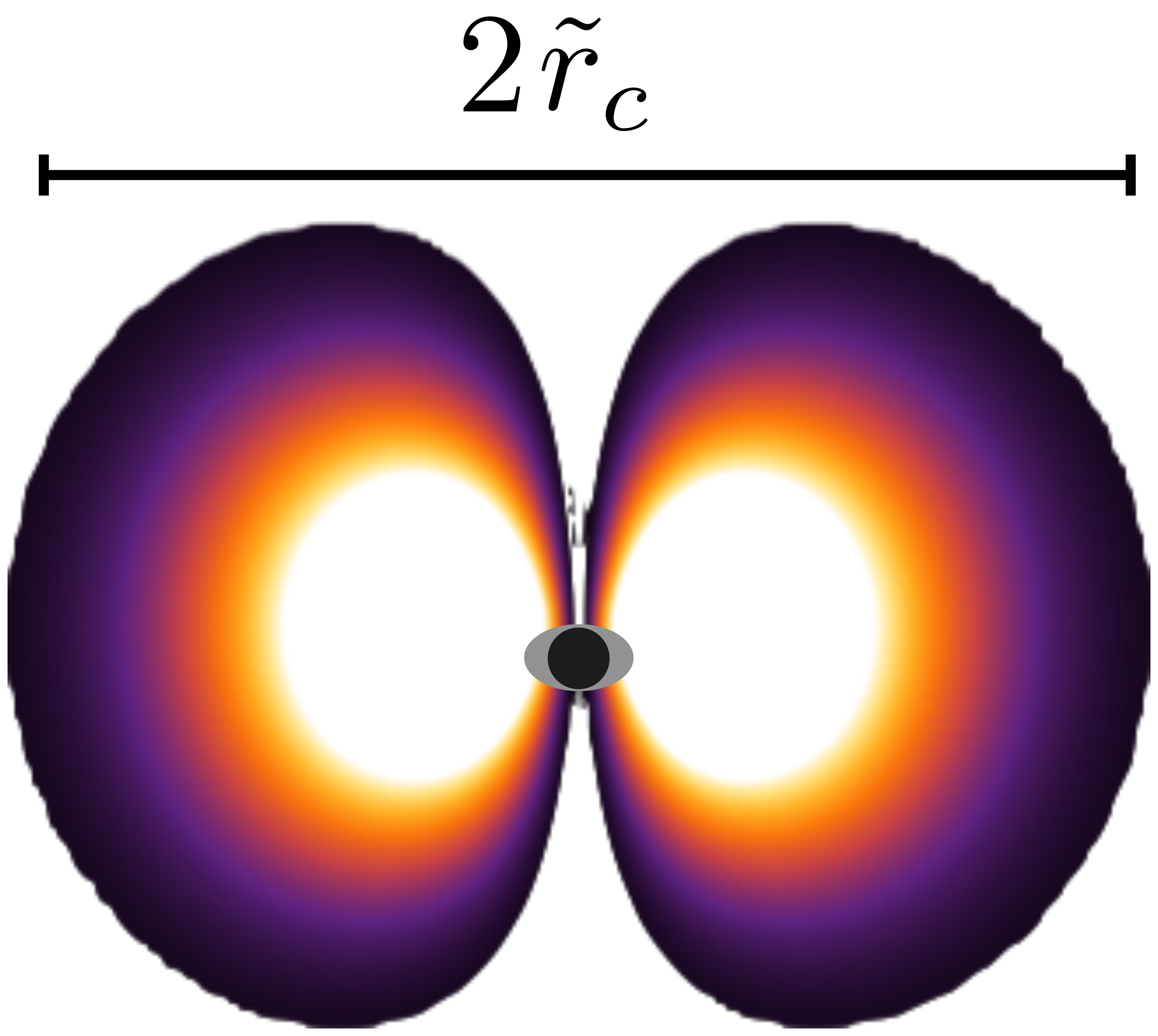
$$N_c \simeq G_N M_{\rm BH}^2$$

entirely determined by BH mass

- Use variational method to estimate **critical occupation number** and compare to what is expected from 2-level evolution from zero-point fluctuations

$$V(\tilde{r}_c) \simeq N_c \frac{\ell(\ell+1)+1}{2\mu \tilde{r}_c^2} - N_c \frac{\alpha}{\tilde{r}_c} - \frac{N_c^2}{f^2 \tilde{r}_c^3}$$

modified Bohr radius



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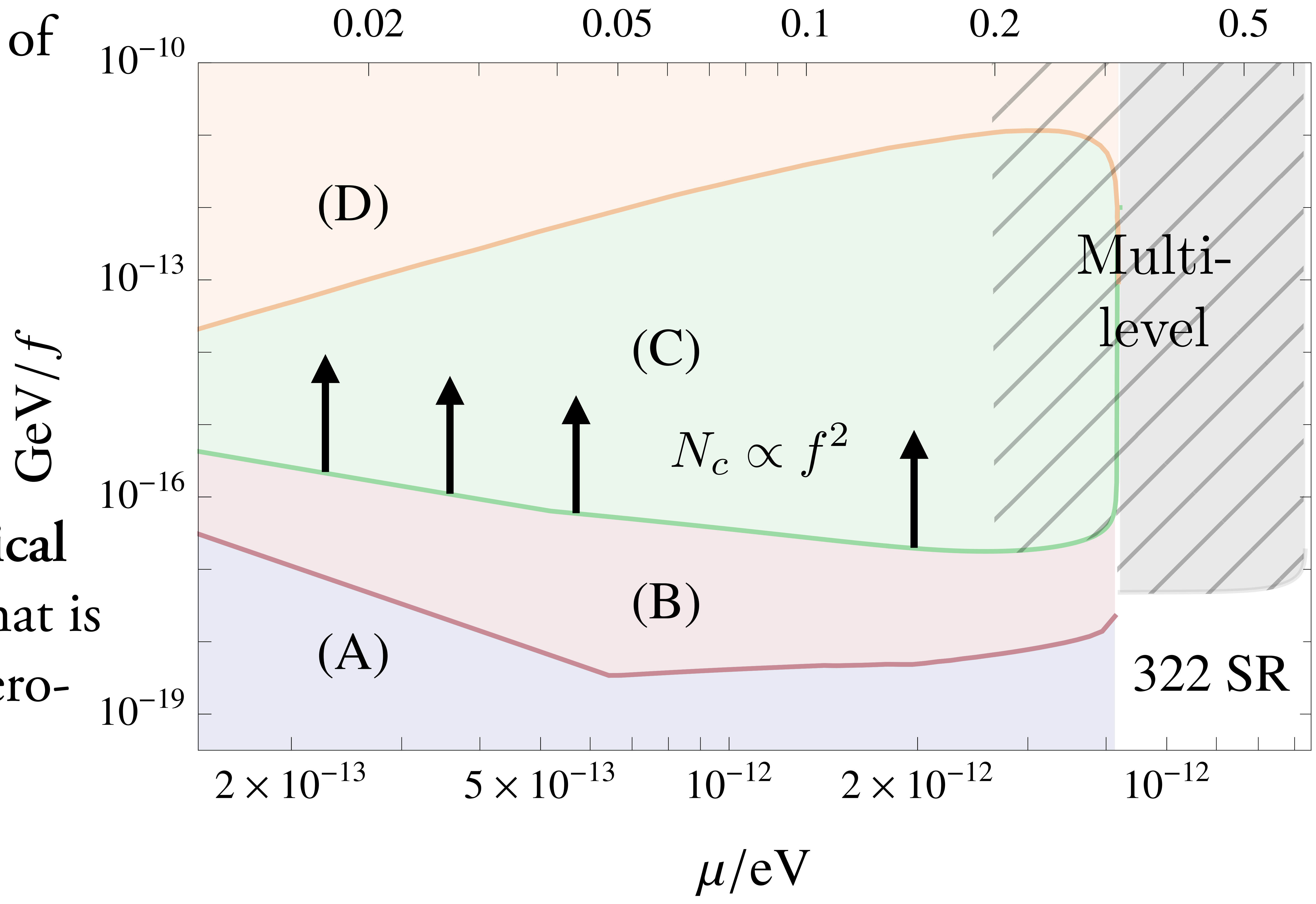

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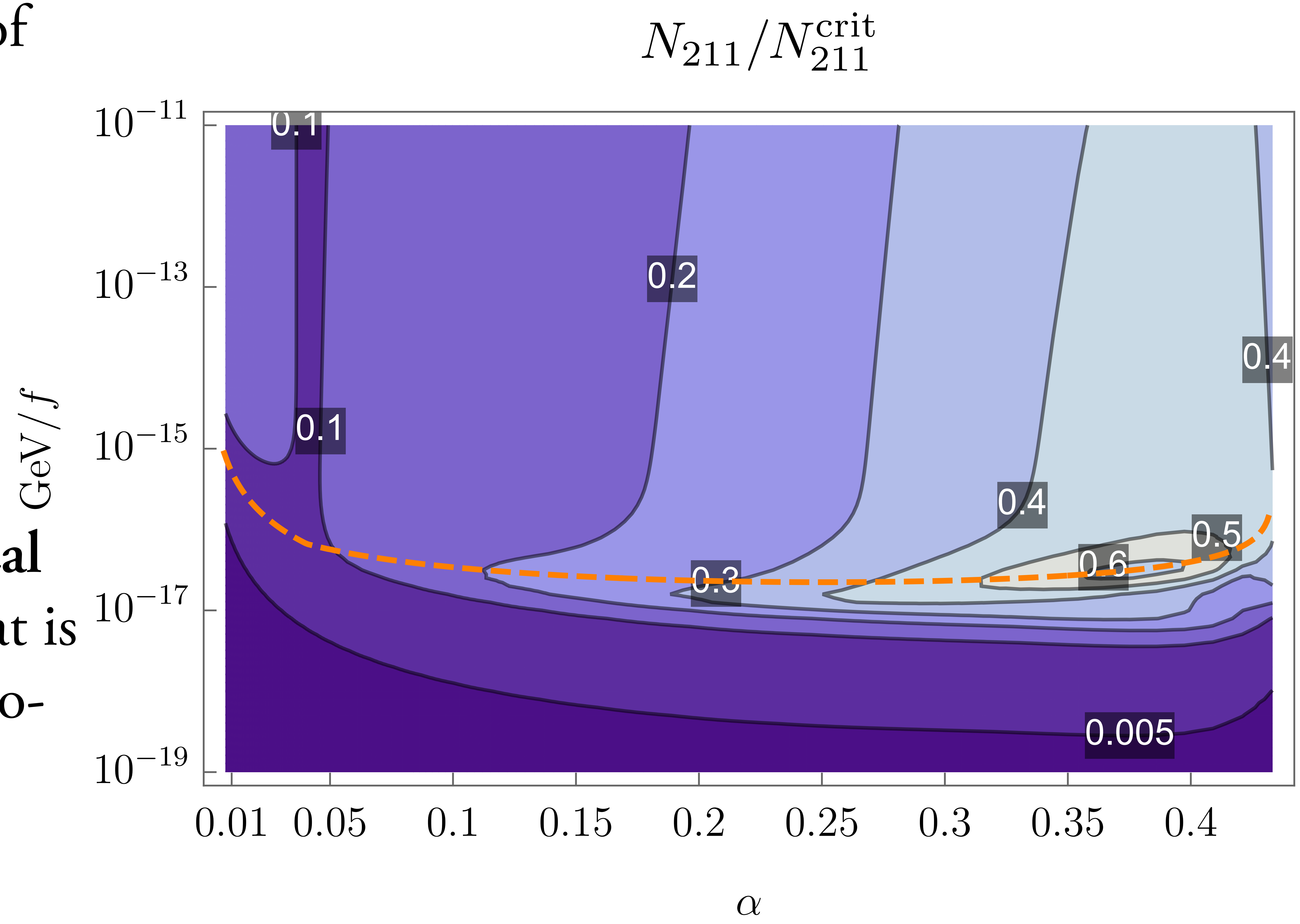

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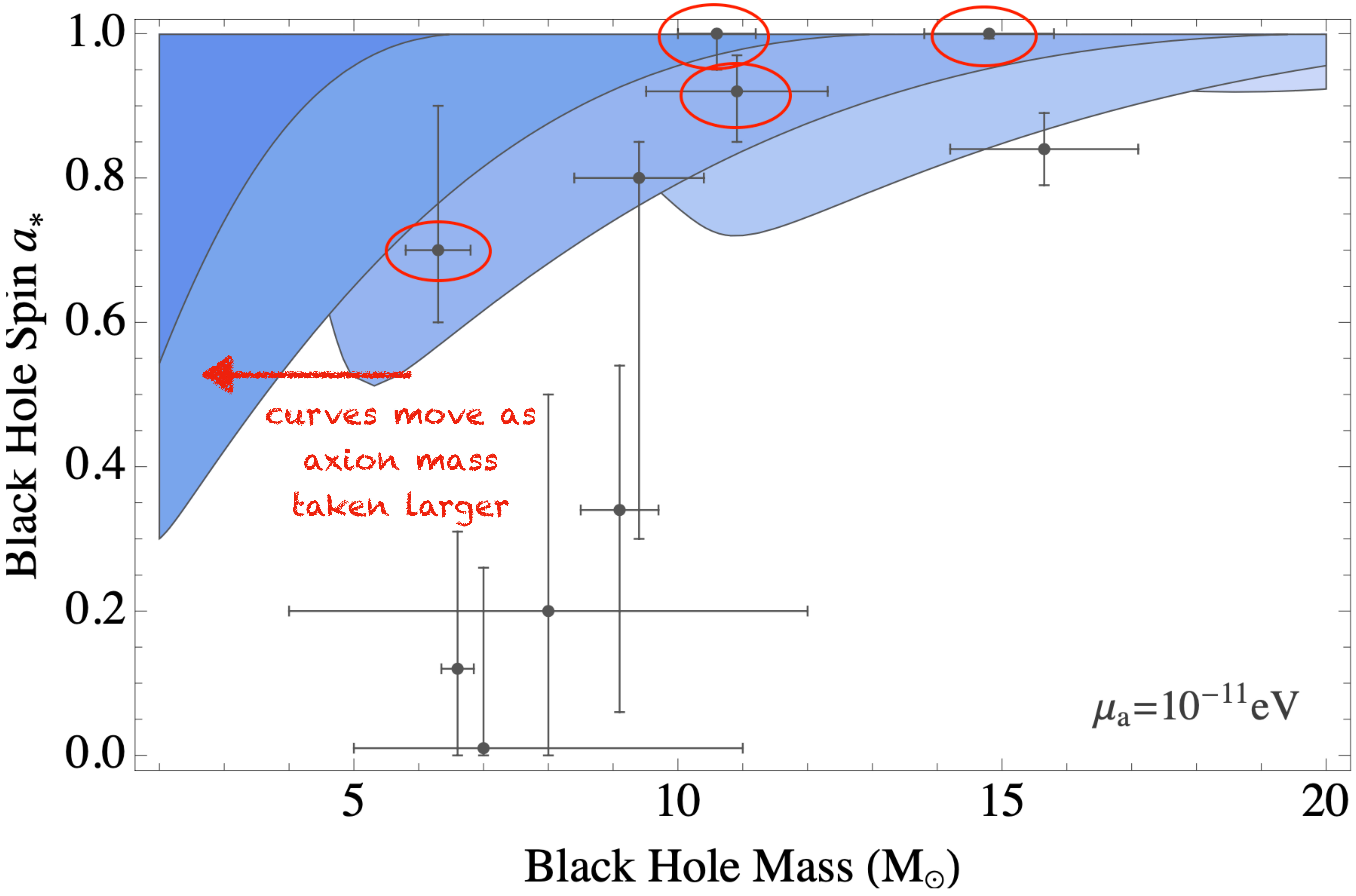
Signatures at large self-interactions

Bounds From Spindown

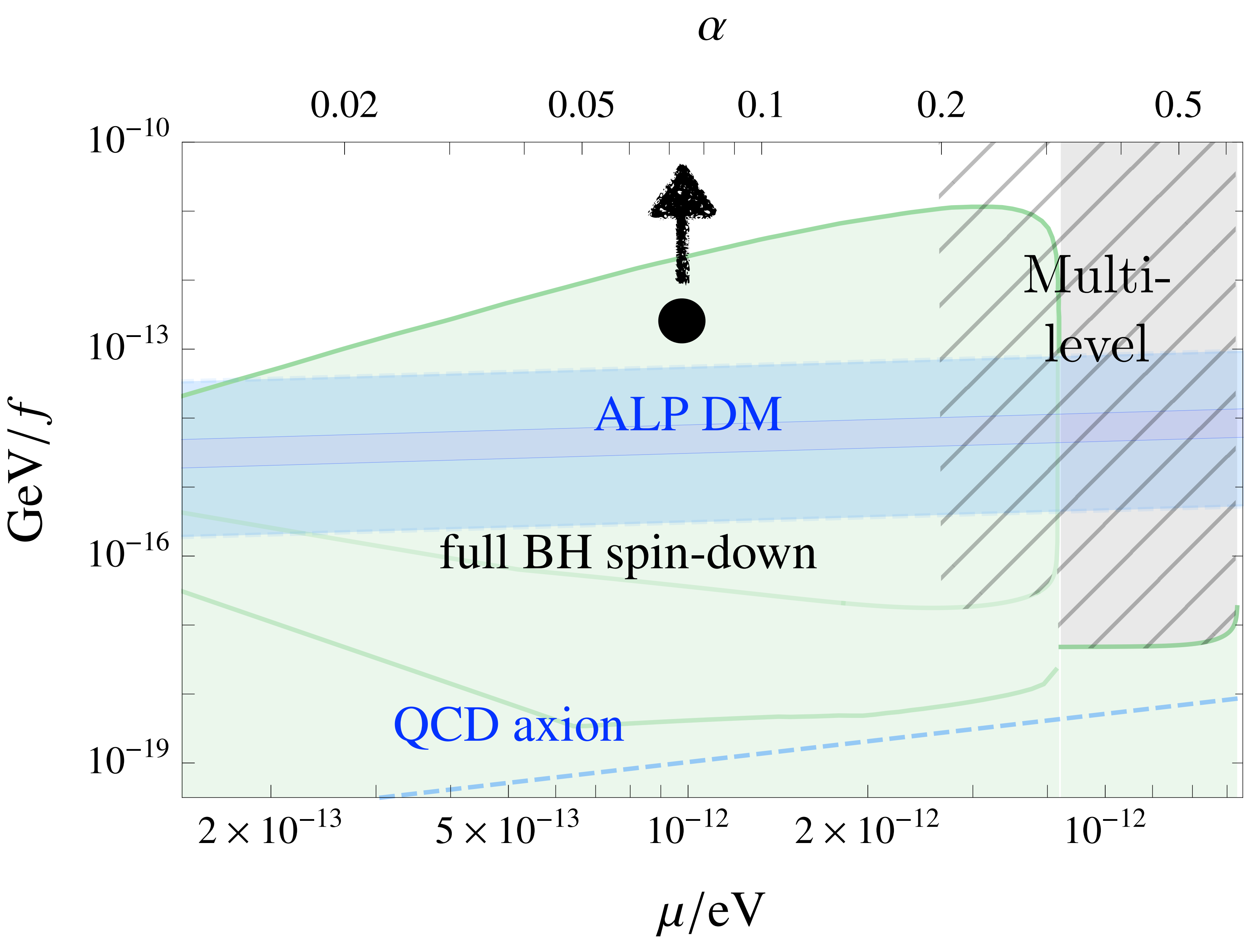
- Fast spinning BHs can be used to place bounds on parameter space of light scalars



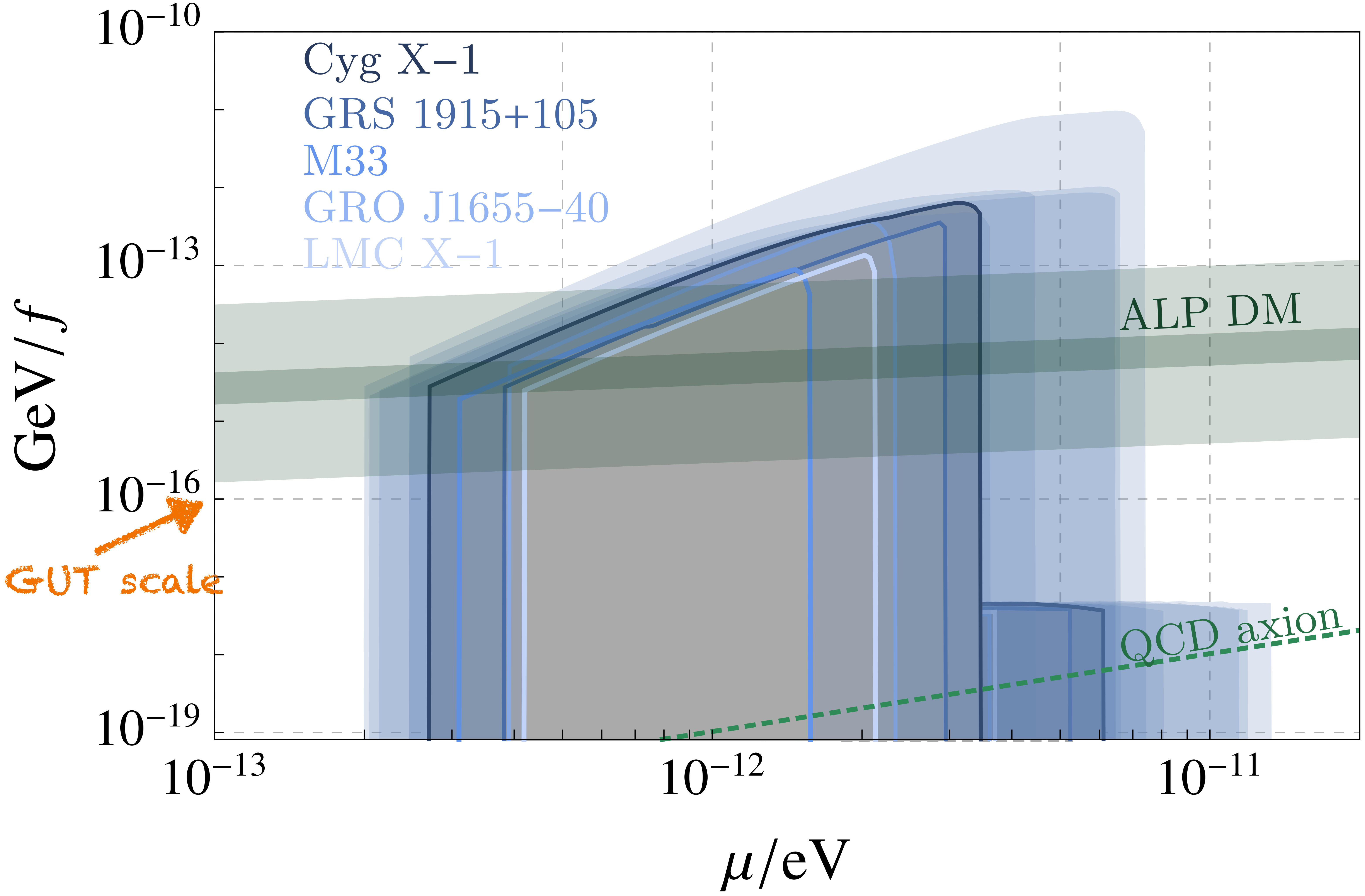
Arvanitaki et al. '15

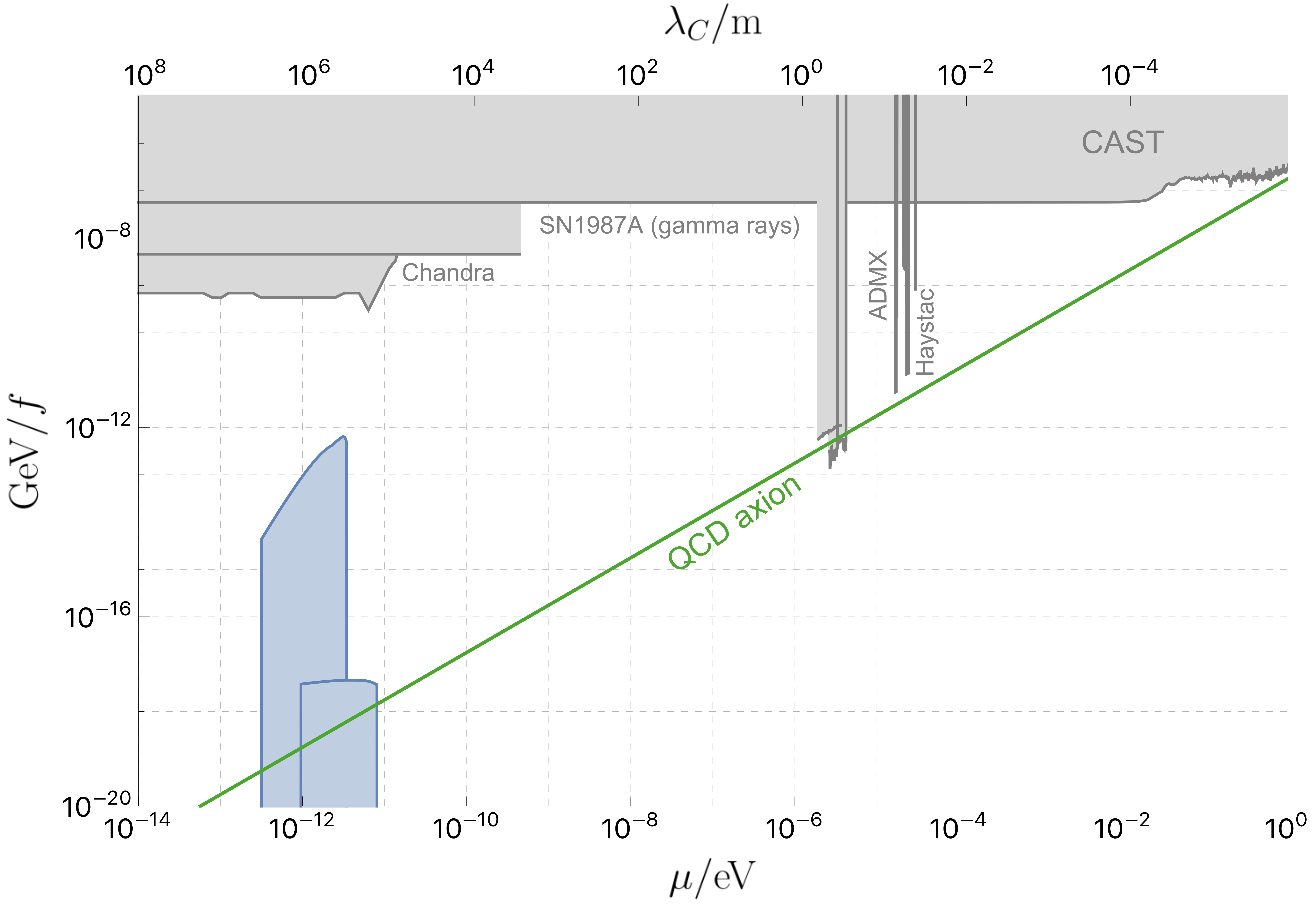
Bounds From Spindown

- Because **large self-interactions prevent spindown**, bounds are **relaxed** at large couplings



Updated bounds on axion masses
from measurements of astrophysical BHs with high spins



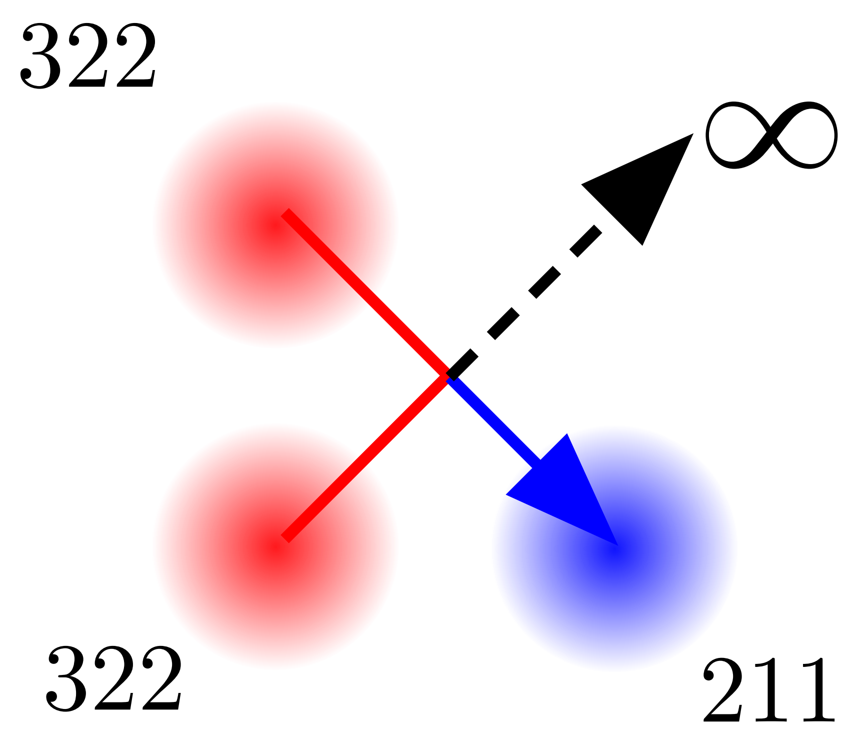


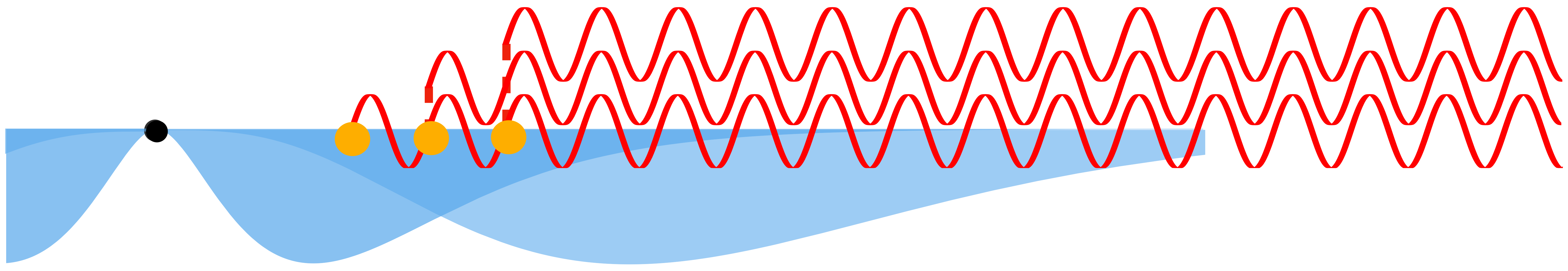
λ_C/m
10^8
10^6
10^4
10^2
10^0
10^−2
10^−4
CAST
SN1987A (gamma rays)
Chandra
ADMX
Haystac
QCD axion
GeV / f
10^−8
10^−12
10^−16
10^−20
10^−14
10^−12
10^−10
10^−8
10^−6
10^−4
10^−2
10^0
μ/eV

Axion Waves: Coherent

- For large self-interactions, detecting **coherent, monochromatic axion waves** becomes possible

- Unlike most astrophysical signals



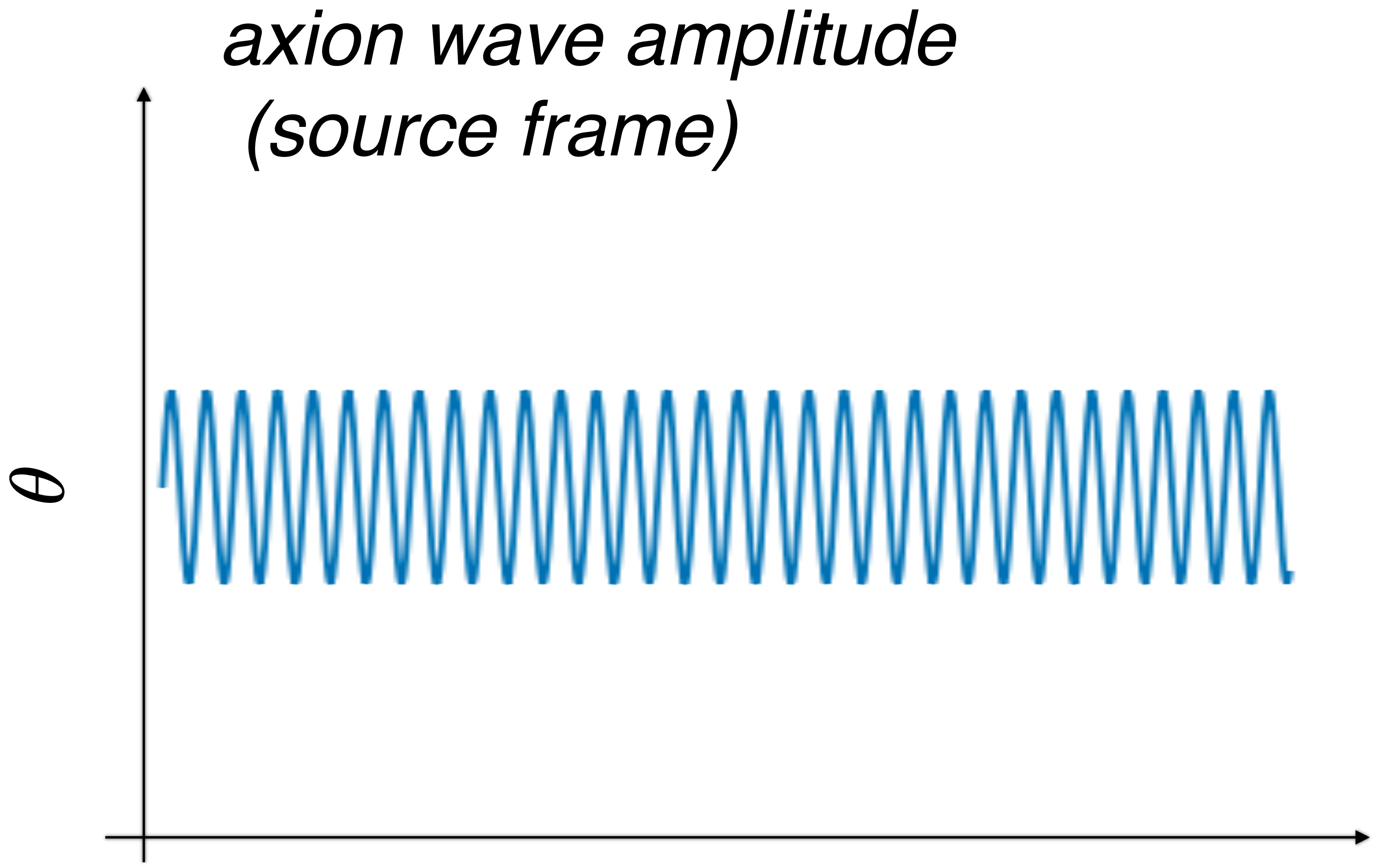


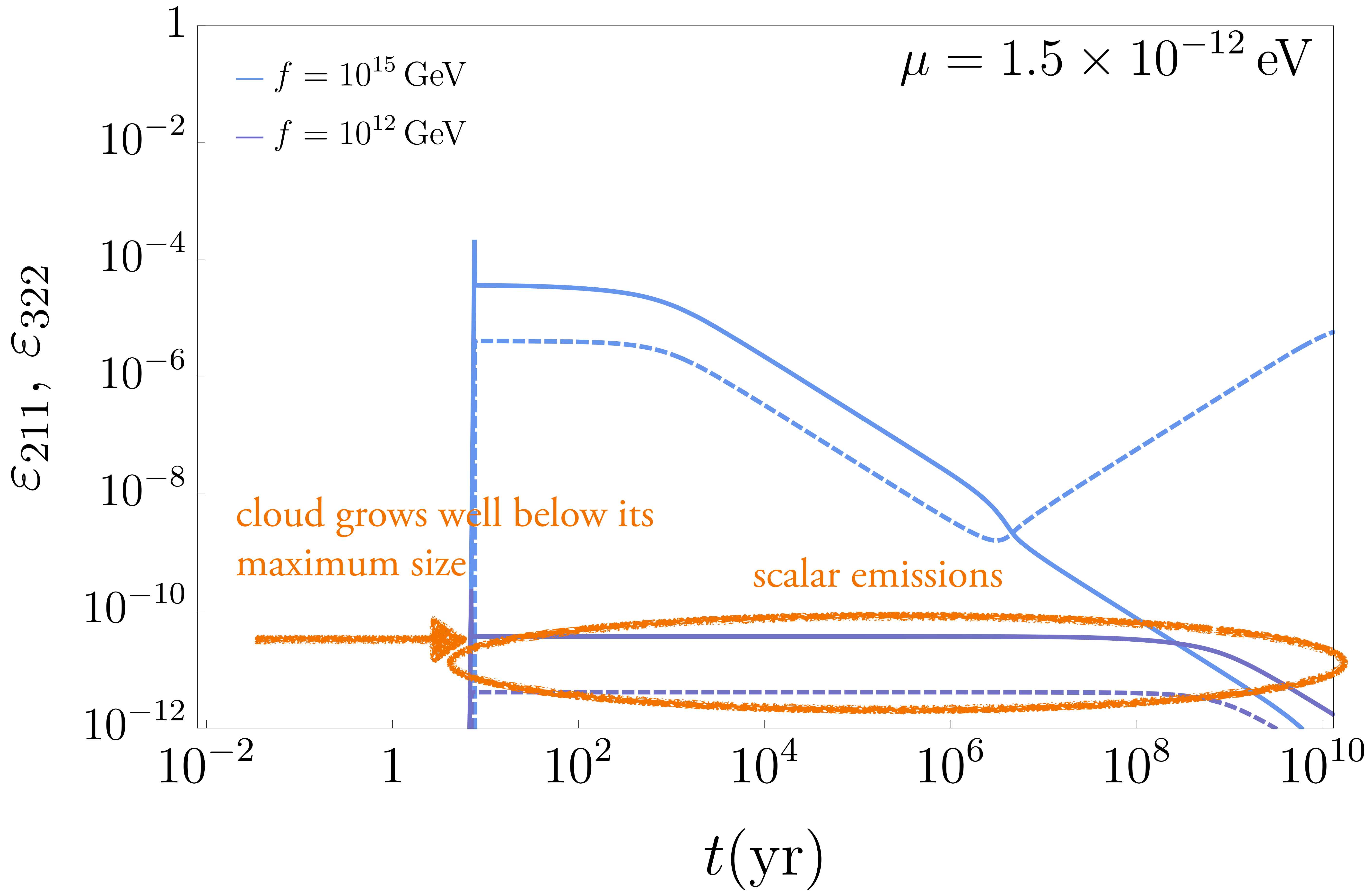
Fixed phase relation between radiation and its source.
Entire cloud is coherent emitter, like laser.

Axion Waves: Long-lasting

- Benefit from very long signal times: **thousands to billions of years**

- Longer than age of the Universe for $f \lesssim 10^{12}$ GeV





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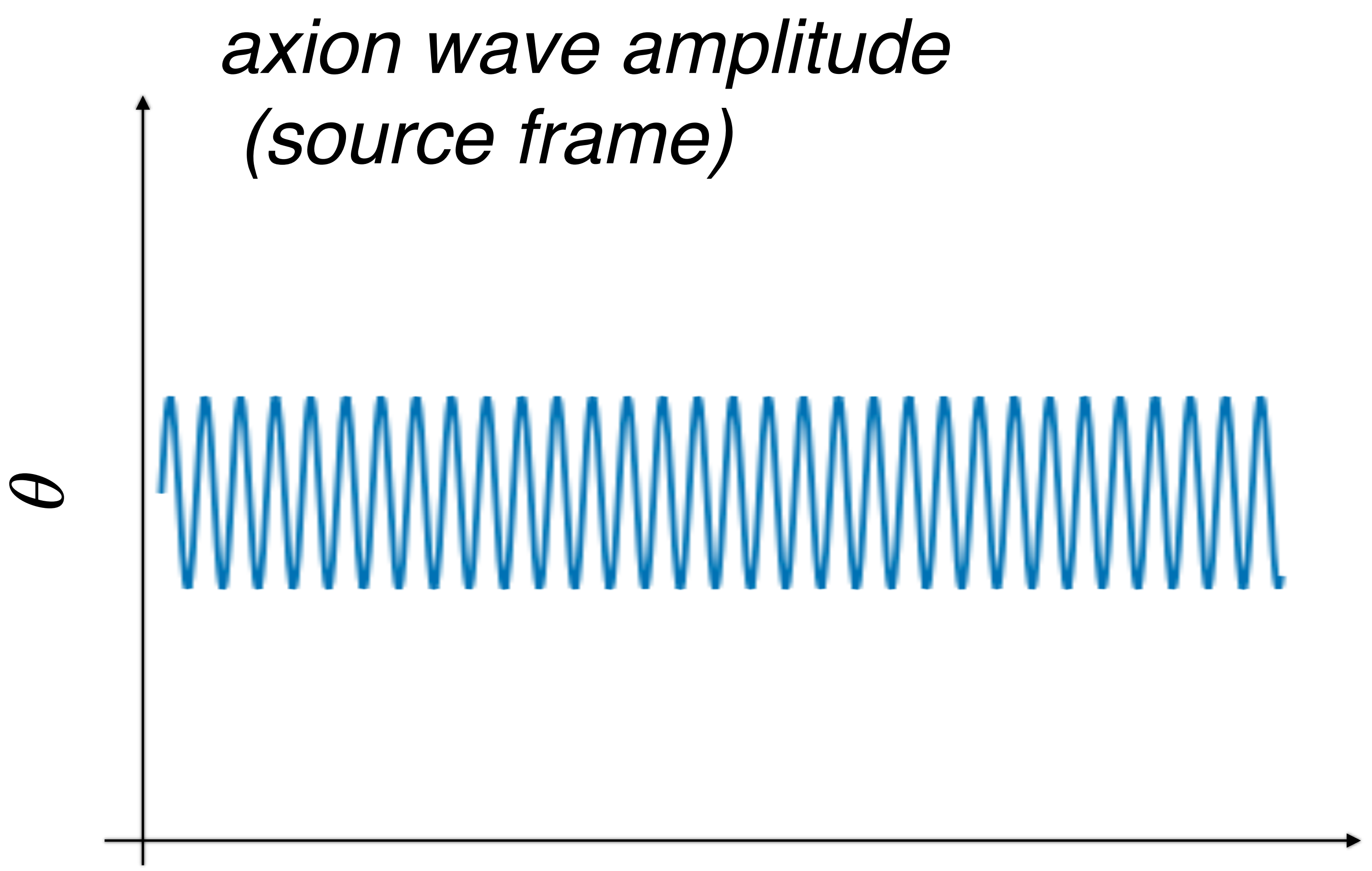
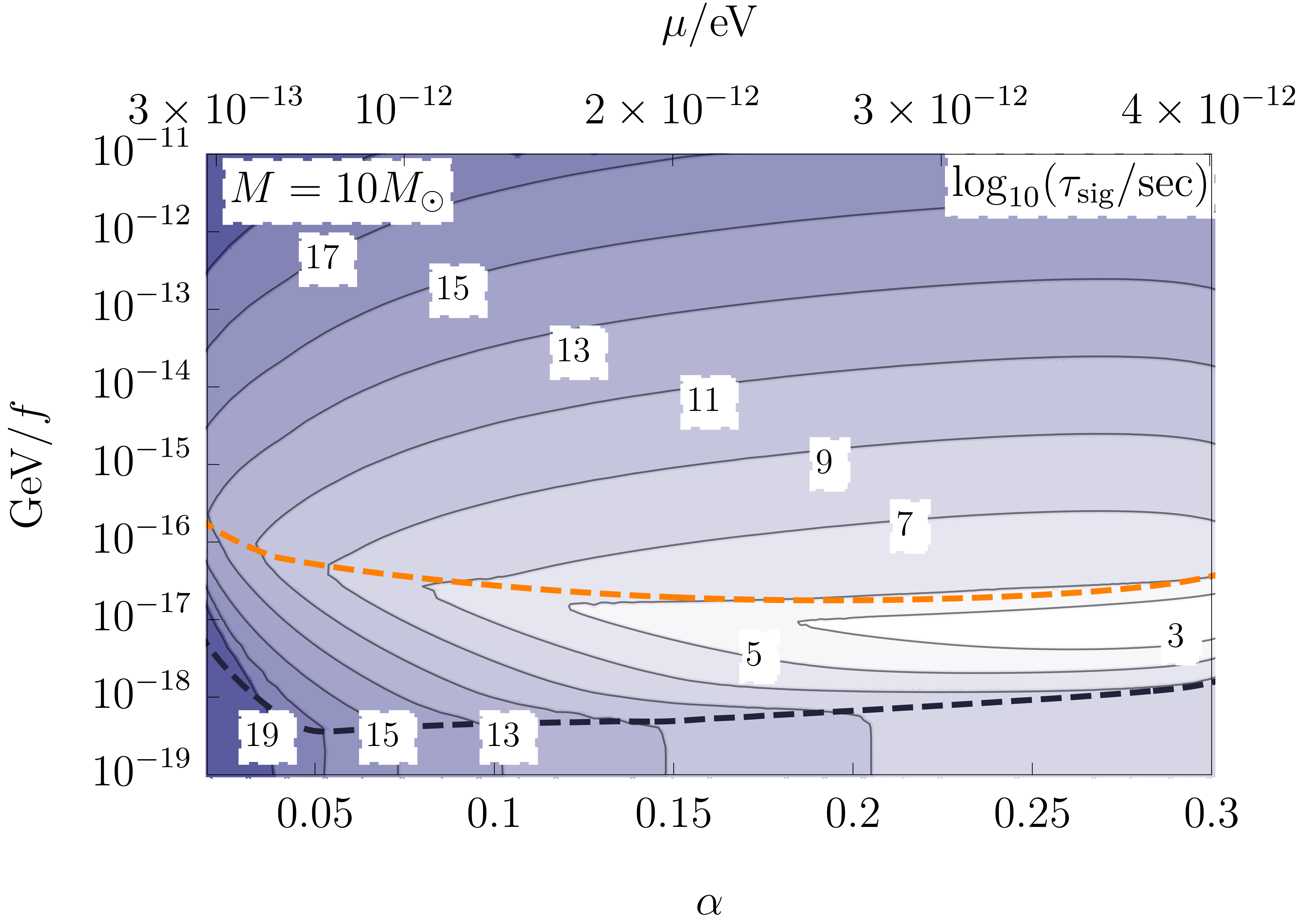




Unsuppressed Signal

same scaling as
cloud size

- Generate local axion energy density

$$\rho_{\phi,\ \mathrm{Earth}} \simeq 10^{-6}\ \mathrm{GeV/cm^3} \left(\frac{\alpha}{0.1}\right)^6 \left(\frac{10\ \mathrm{kpc}}{r}\right)^2 \left(\frac{f}{10^{16}\ \mathrm{GeV}}\right)^2$$

- SM interactions are sensitive to

$$\theta \simeq \frac{\sqrt{\rho_\phi}}{f} \simeq 10^{-19} \left(\frac{10^{-12}\ \mathrm{eV}}{\mu}\right) \left(\frac{\alpha}{0.1}\right)^3 \left(\frac{10\ \mathrm{kpc}}{r}\right)$$

$$\propto f^0$$

Signal does not decouple even as the cloud gets smaller!

Direct detection

- Proposed DM detectors use axion "wind" coupling to Standard Model spins

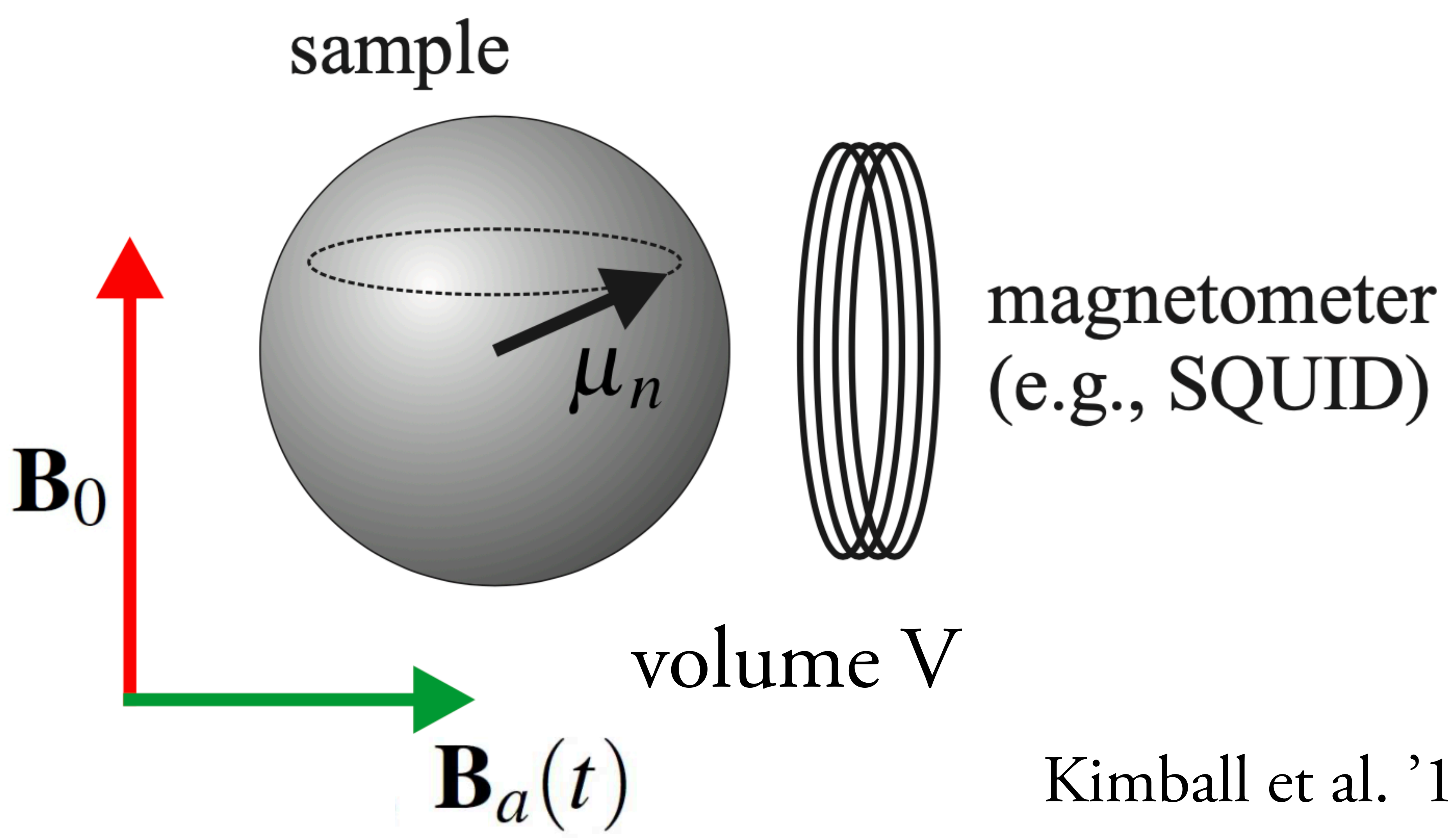
$$H_{\rm wind} = g_N \vec{\sigma} \cdot \vec{\nabla}\phi \equiv \vec{B}_a \cdot \vec{\mu}_n$$

where $g_N \simeq C_N/f.$

- Axion creates an effective oscillatory "magnetic" field

$$\vec{B}_a \propto C_N \times (\mu \vec{v}) \times \theta_0 \cos\left[\mathrm{kHz}\left(\frac{\mu}{10^{-12}\ \mathrm{eV}}\right) t\right]$$

- Look for oscillating "magnetic" field by looking for precession of polarized nuclear spins (e.g. CASPER)



Kimball et al. '17

- For non-rel. radiation from the cloud

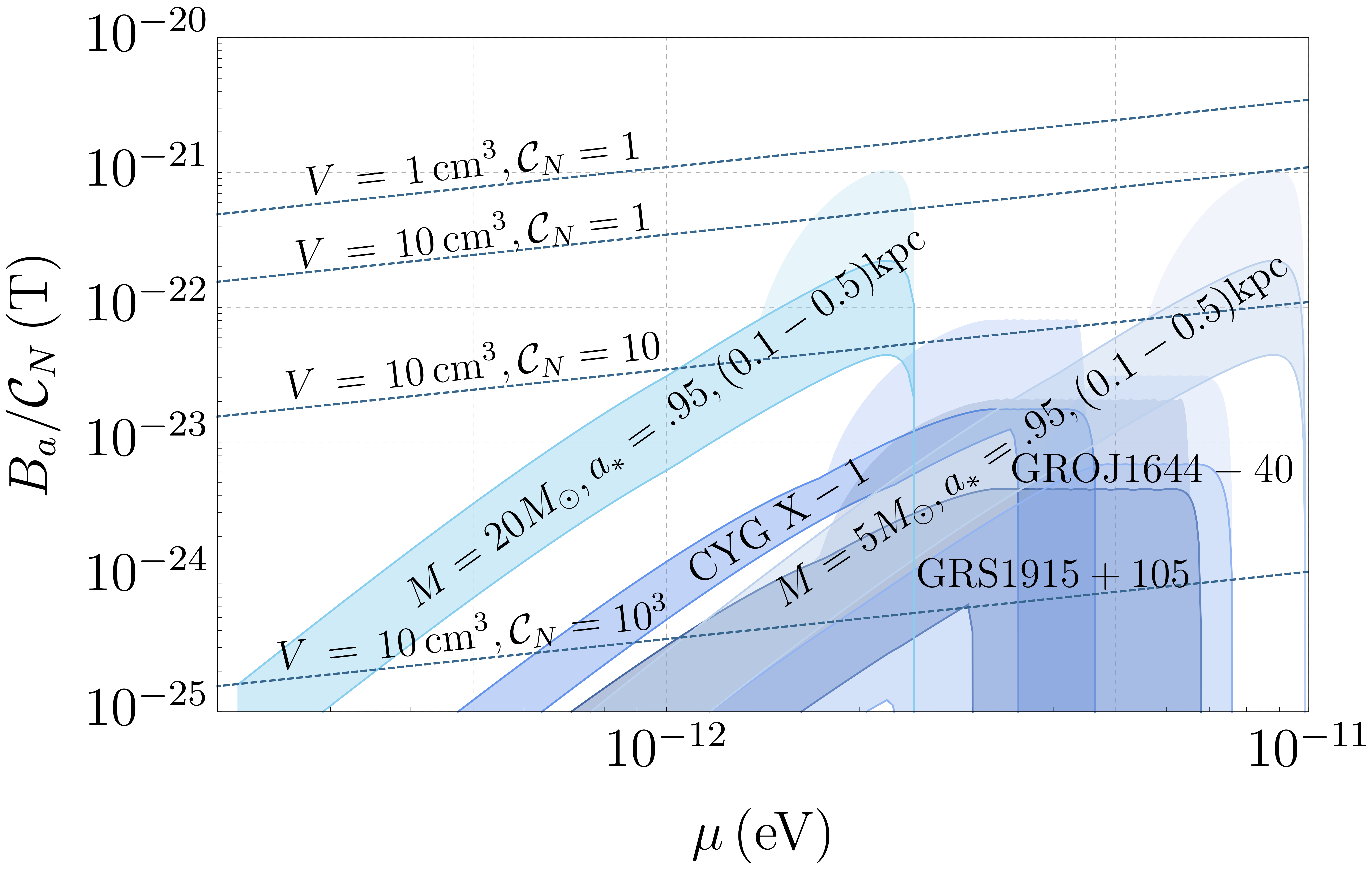
$\vec{v} \simeq \alpha/6$ (non-relativistic, **but faster** than DM)

Direct detection

- Look for signal that is nearly constant in time

- Signal independent of interaction strength

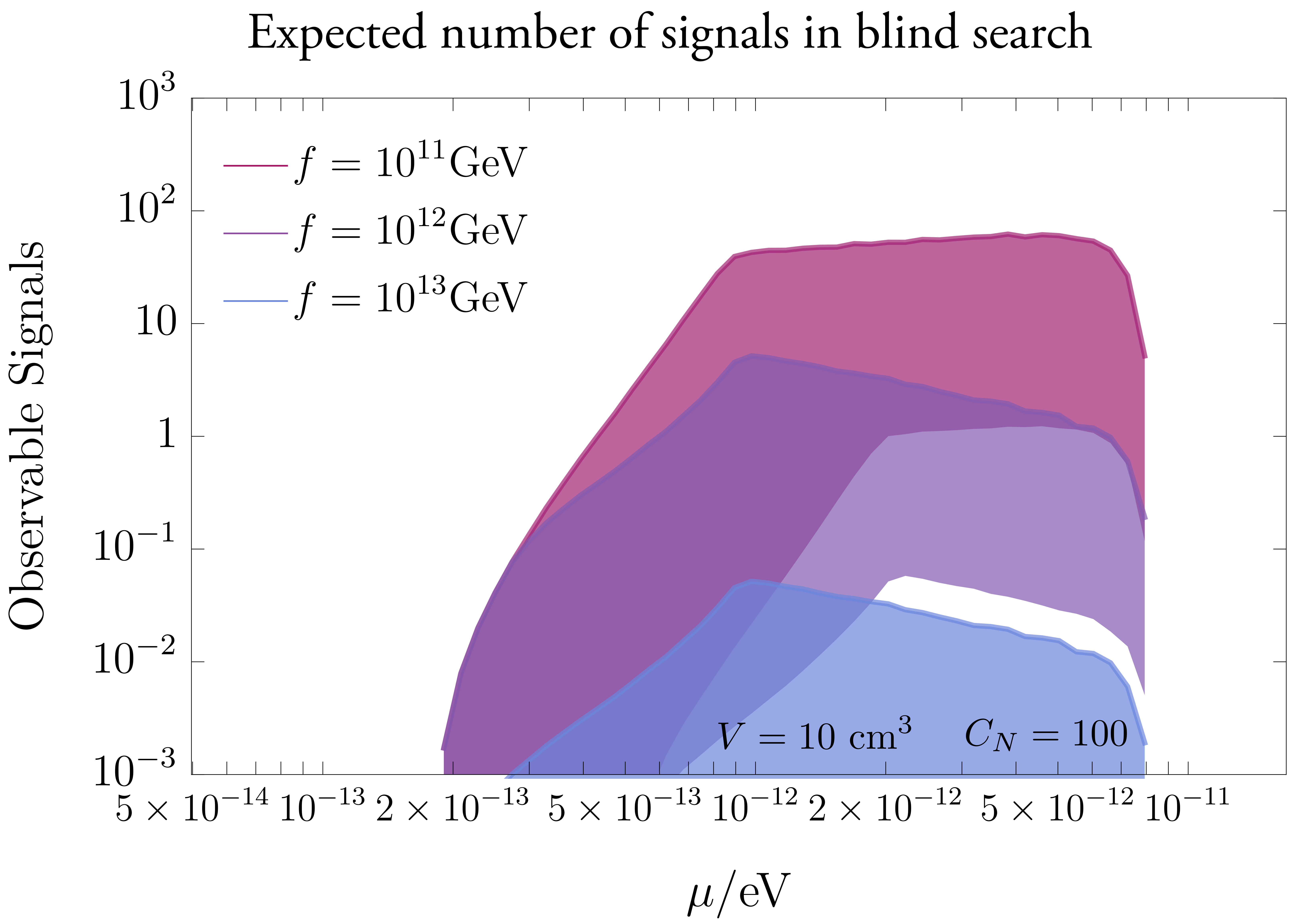
Detectability prospects for nearby BHs



Direct detection

- Look for signal that is nearly constant in time

- **Number** of expected signals in blind search grows for smaller f because signal duration is longer

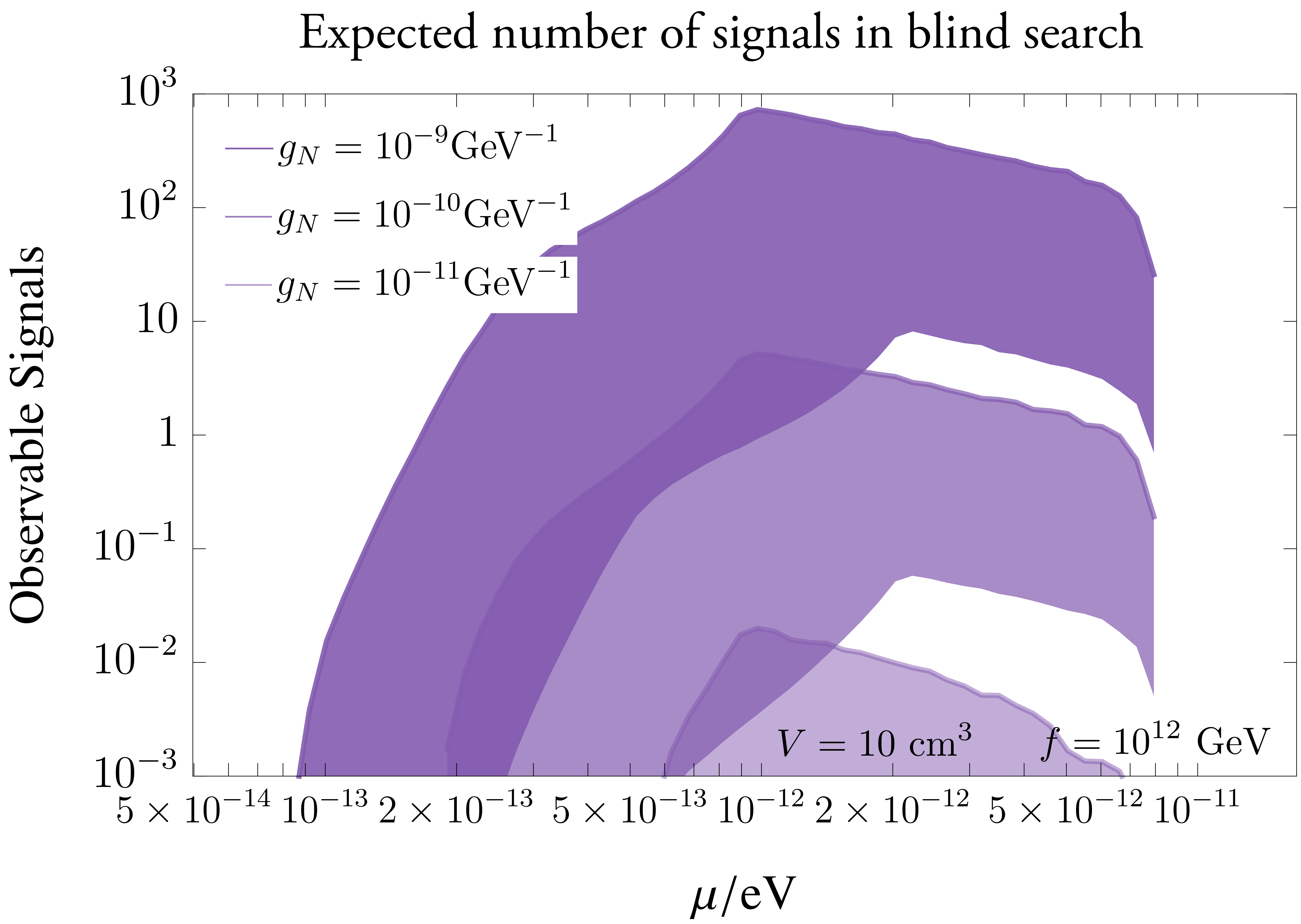


Direct detection

- SN1987A constrains

  $g_N \lesssim 10^{-9}\ \text{GeV}^{-1}$

- Blind searches could yield large number of signals for a lot of open parameter space



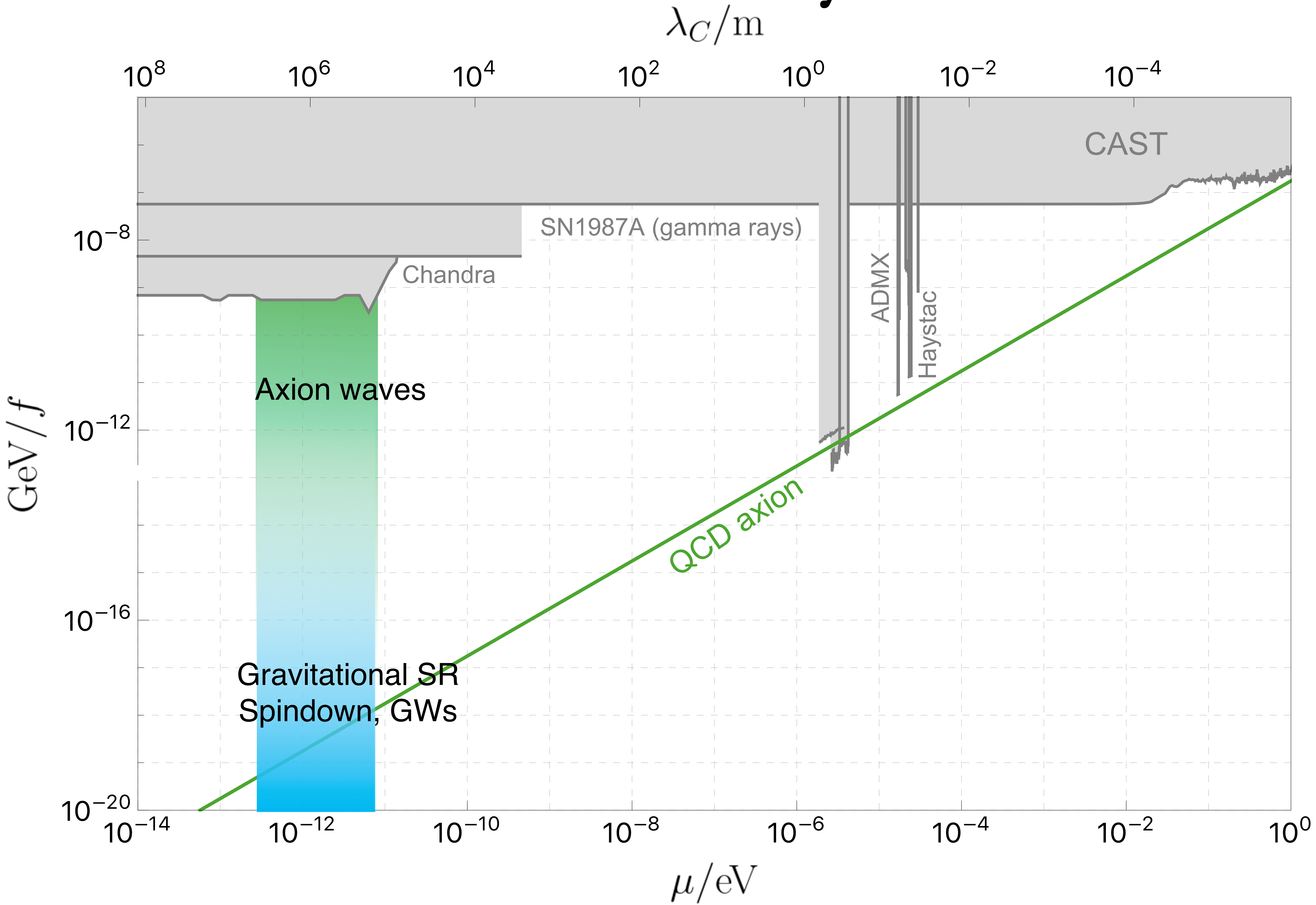
Summary

- Self-interactions lead **simultaneous occupation of two or more levels in a quasi-equilibrium configuration in the SR cloud**

- "B**osenova**" phenomenon **likely does not occur**

- Large self-interactions **suppress** BH spindown and GWs but **introduces axion waves**

Summary



λ_C/m
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
CAST
SN1987A (gamma rays)
Chandra
ADMX
Haystac
Axion waves
QCD axion
Gravitational SR
Spindown, GWs
GeV/f
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
μ/eV

Backup slides

Superradiance rates

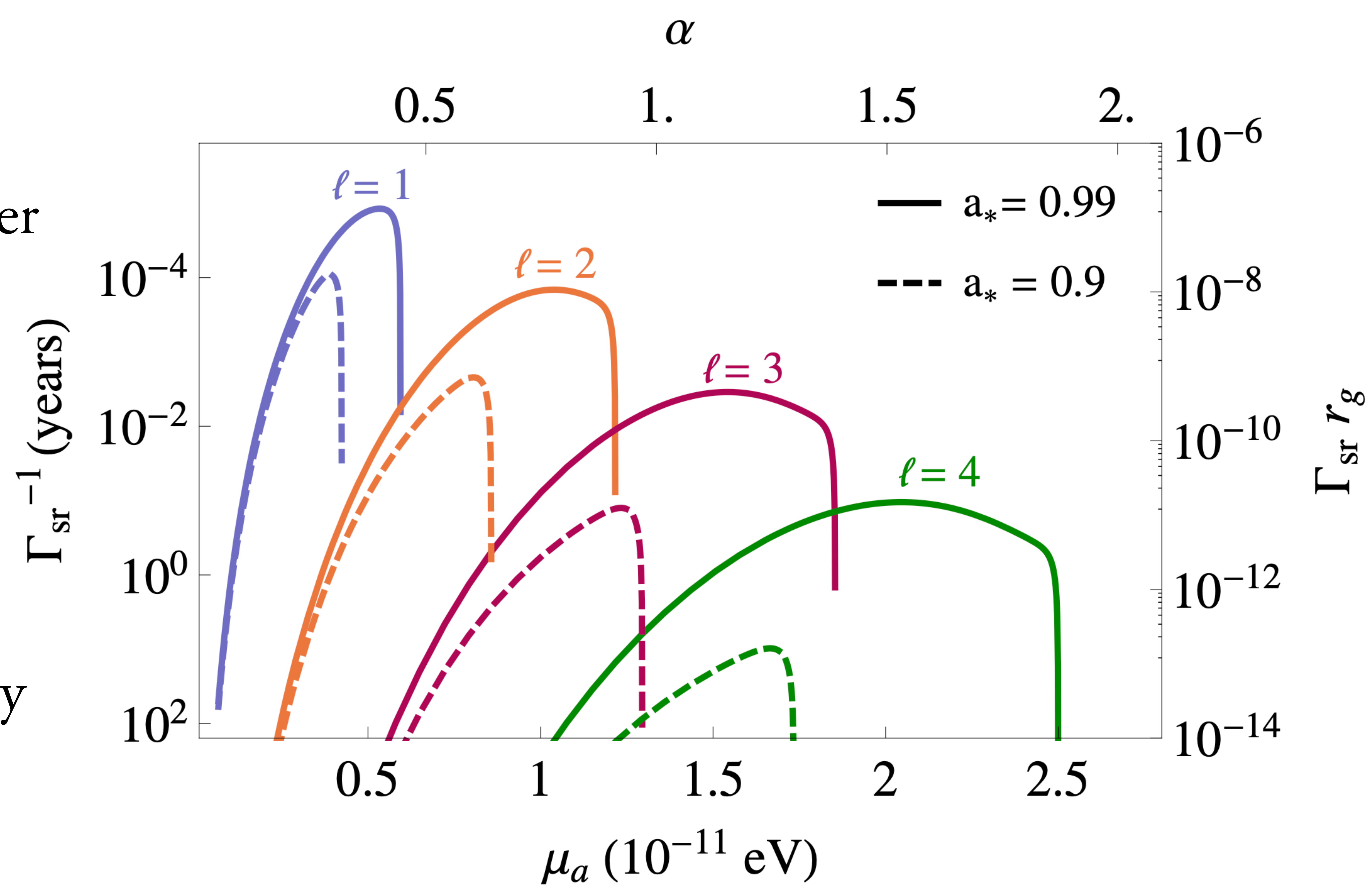
- Larger ℓ can satisfy SR condition for larger μ
- Larger ℓ are exponentially suppressed because of kinetic barrier
- Larger n are suppressed because smaller density near horizon

SR condition

$$\Gamma^{SR}_{n\ell m} \sim n(r_g) r_g^2 \left(\frac{m\Omega_{BH}}{\mu} - 1 \right)$$

$$\sim \frac{\alpha^{5+4\ell}(m\Omega_{BH} - \mu)}{n^3}$$

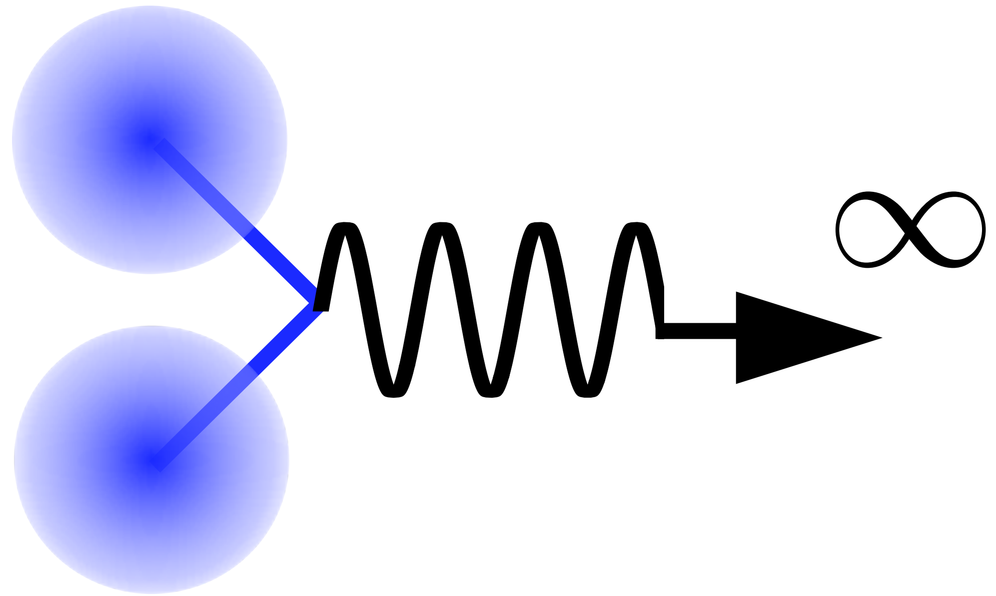
- Individual event rates small; boosted by **large occupation numbers**
- Exponential growth for ~ **200 e-folds**



Arvanitaki et al. 2015

GWs Emissions

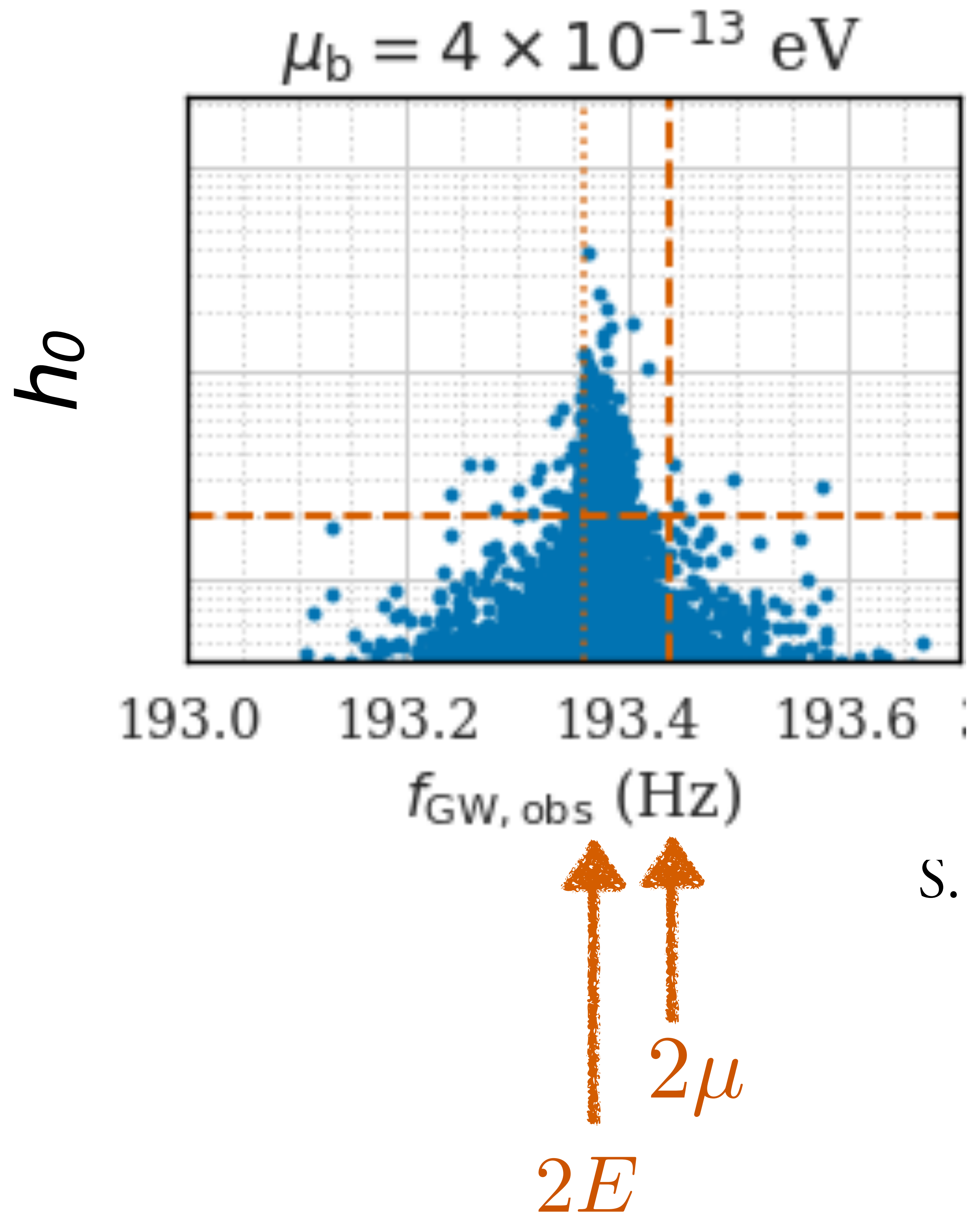
- Coherent, monochromatic gravitational waves from annihilations in the cloud



- Visible at Advanced LIGO with continuous wave search strategy (similar to isolated neutron stars)

- Can expect 1000+ events from BHs in the MW

Strain distribution from BHs in the MW



S. Zhu et al. '20

Self-Interacting Scalars

- Scalar field ϕ with small mass μ

- Axion-Like particles: Pseudo Nambu-Goldstone boson associated with spontaneous breaking of some continuous shift symmetry at some high scale f_a.

- Non-perturbative effects generate potential $V(\phi) = \mu^2 f_a^2 g(\phi/f_a)$, with $\mu \ll f_a$

$$V(\phi) = g^{(0)} + \frac{g^{(2)}}{2!}\mu^2\phi^2 + \underbrace{\boxed{\frac{g^{(4)}}{4!}\frac{\mu^2}{f_a^2}\phi^4}}_{\frac{\lambda}{4!}\phi^4} + \dots$$

Previous Estimates of SI

- People predicted explosive "**bosenova**" collapse, when **attractive self-energy** becomes comparable to **gravitational binding energy**

$$\int n(\vec{r})\frac{\alpha}{r}d^3\vec{r} \sim \int \frac{n(\vec{r})^2}{8f^2}d^3\vec{r}$$

$$N_c \gtrsim 16\pi\alpha^{-1}f^2/\mu^2$$

- For fixed $N_c \sim G_{\rm N}M_{\rm BH}^2$, one can always pick f small enough that collapse occurs.

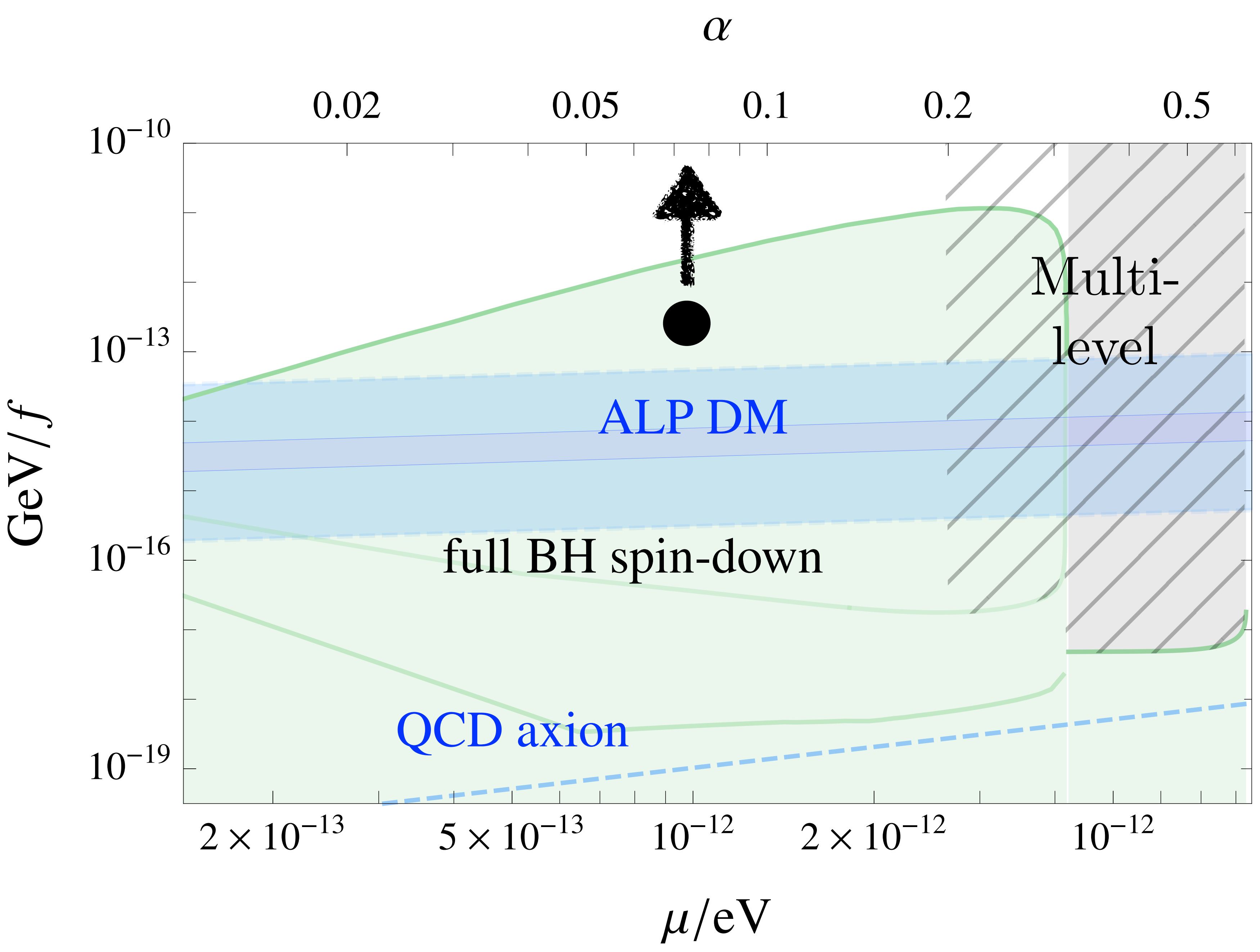
If self-interactions are large, can the cloud ever get that large in the first place?

Largely, no.

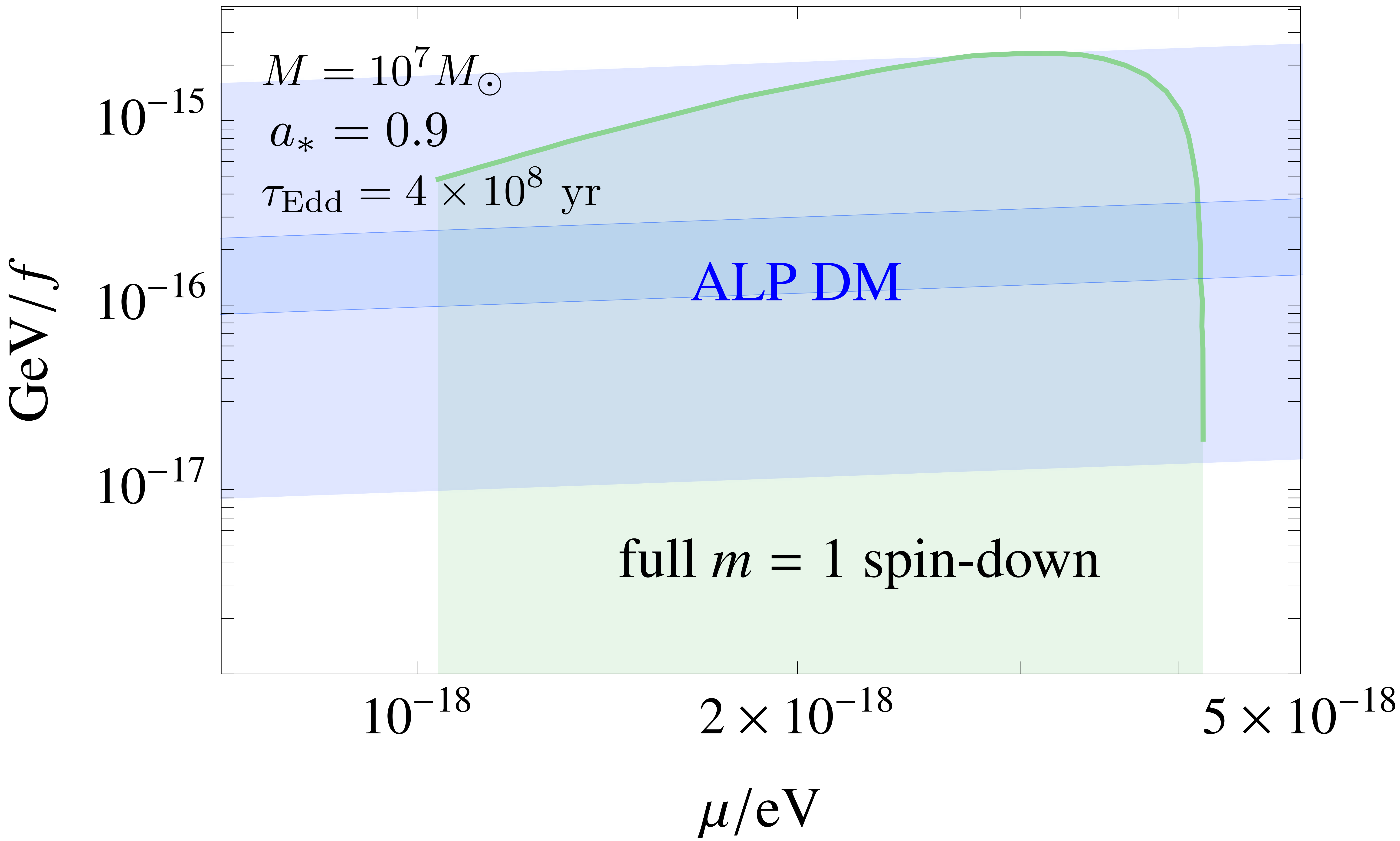
Arvanitaki & Dubovsky '11

Spin Bounds

- Because **large self-interactions prevent spindown**, spin bounds are **relaxed** at large couplings



Example of updated bounds from a SMBH

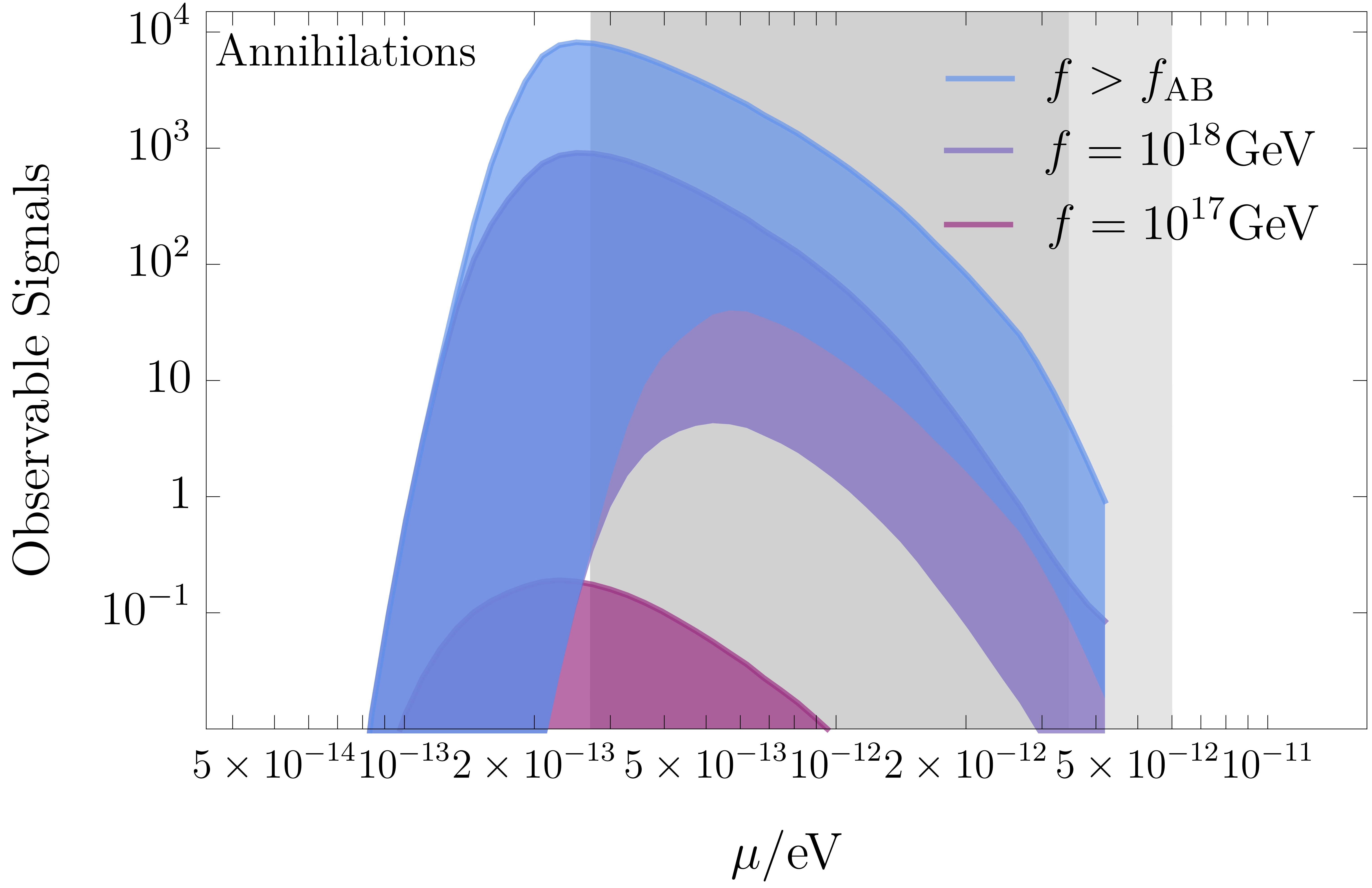


GW Emissions

- GW annihilations rapidly **suppressed by smallness** of the cloud

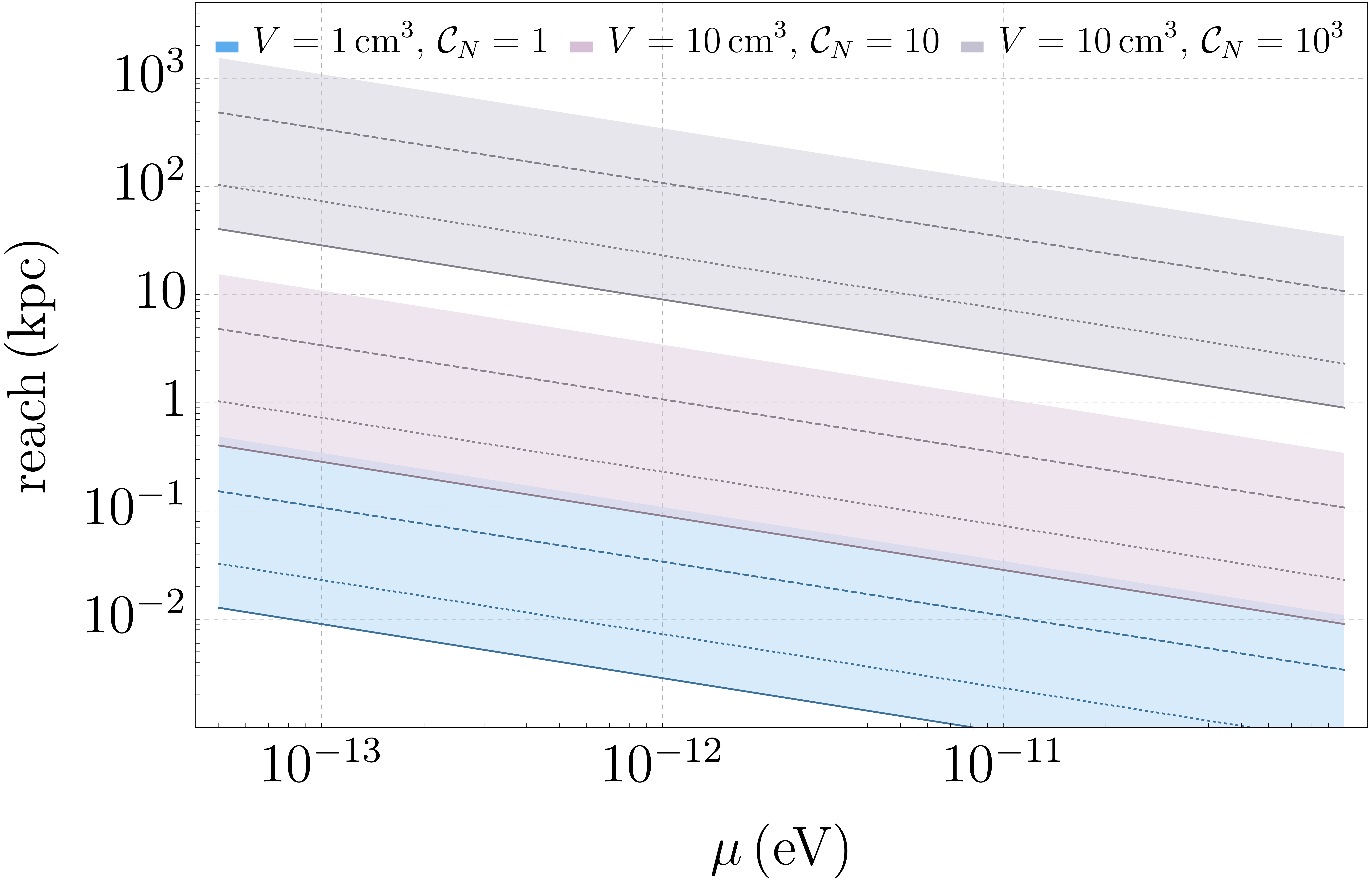
- GW transitions enhanced compared to no SI, but too low frequencies for current detectors

Expected number of signals in blind search

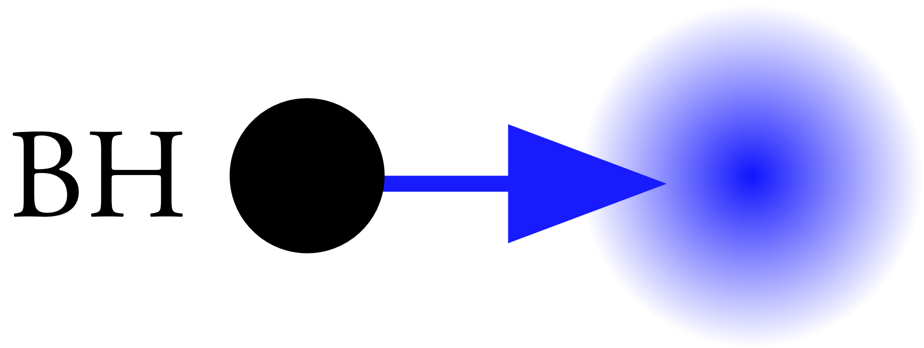


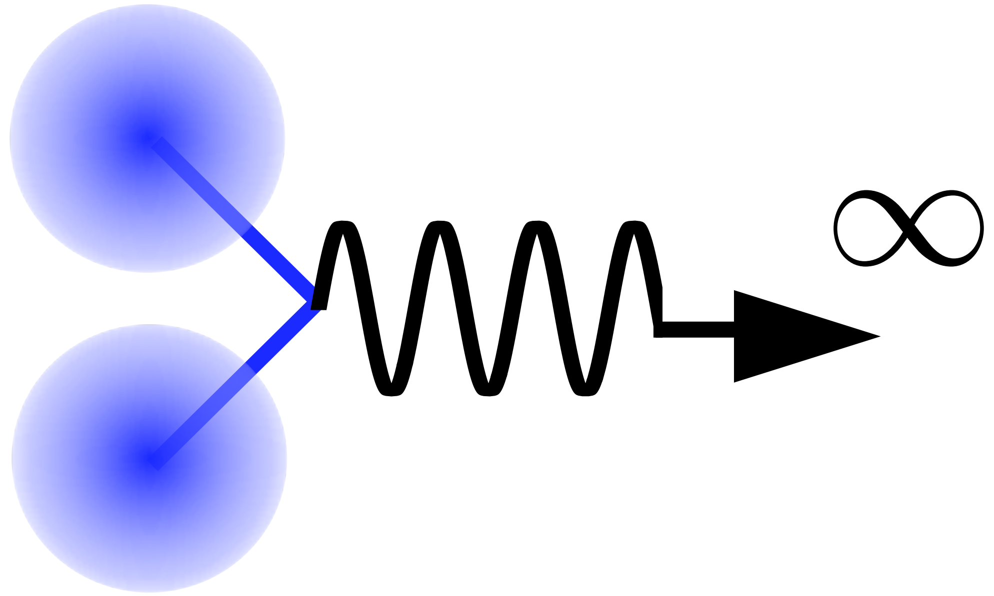
Direct detection

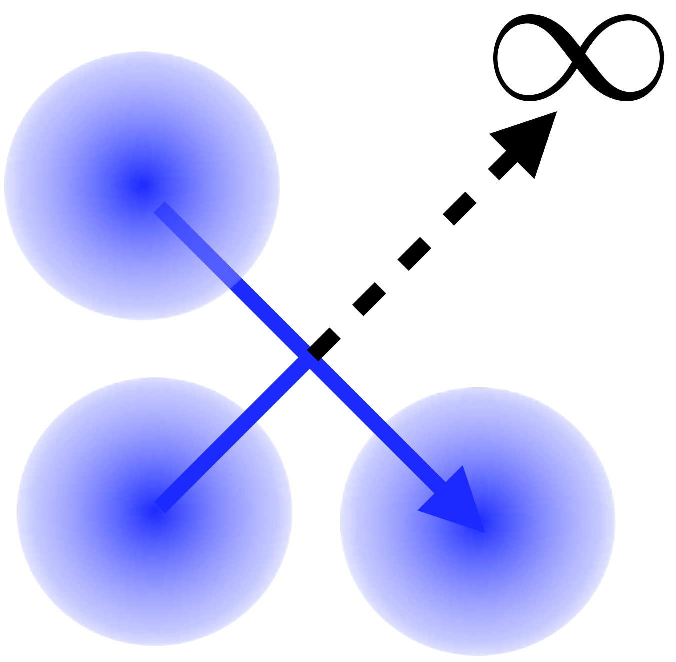
Reach (SNR = 1) for different for difference volume samples and coupling strengths



Self-Interactions and Other Processes







$\sim \mu N$

$\sim \mu \frac{\mu^2}{M_{\text{Pl}}^2} N^2$

$\sim \mu \frac{\mu^4}{f^4} N^3$

Bosenova

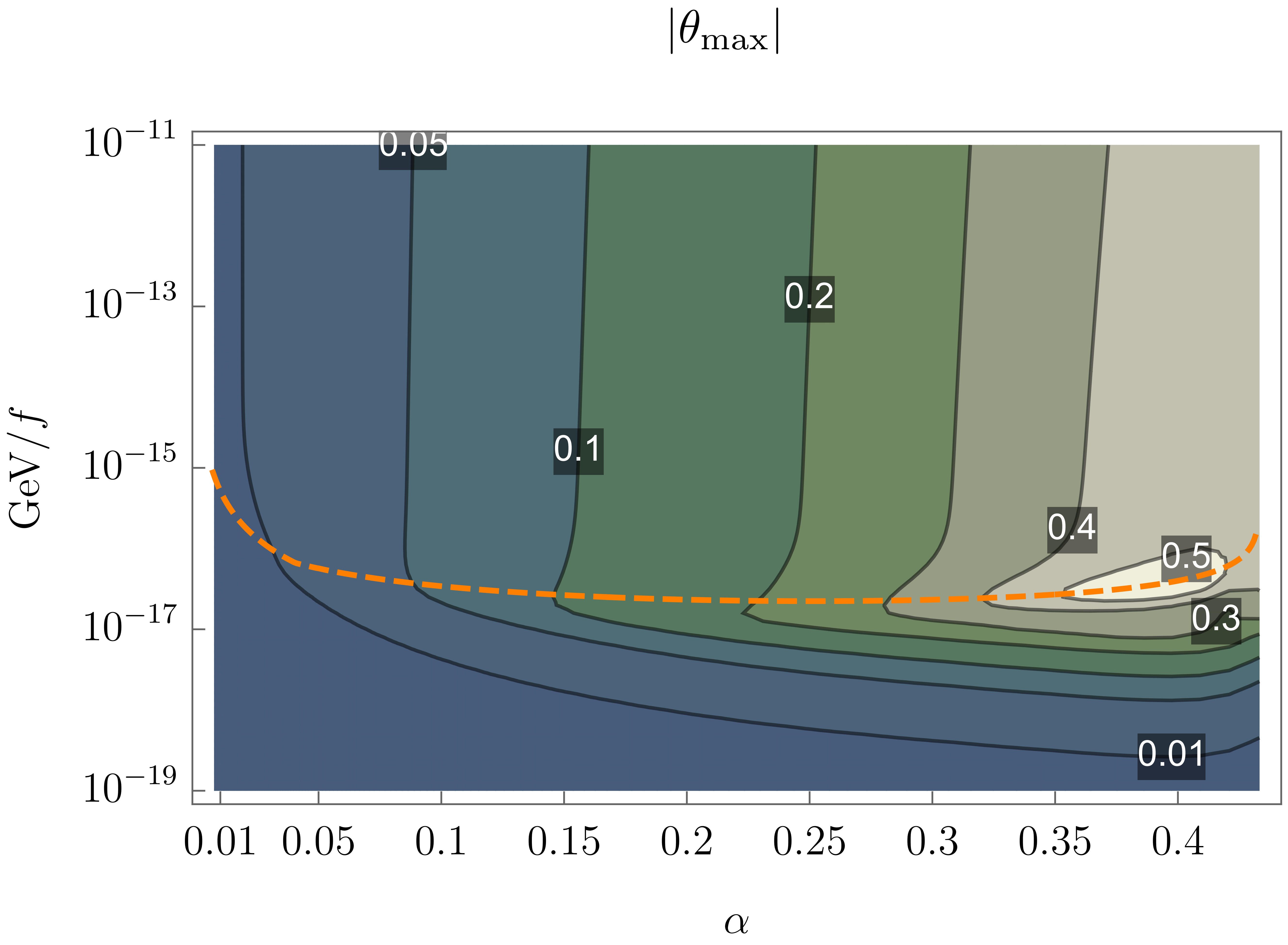
- Some numerical simulations have observed collapse (Kodama et al. '12, Kodama et al. '15)

- Assumed large initial conditions for $\theta = \phi/f \sim \sqrt{N_c}/f$

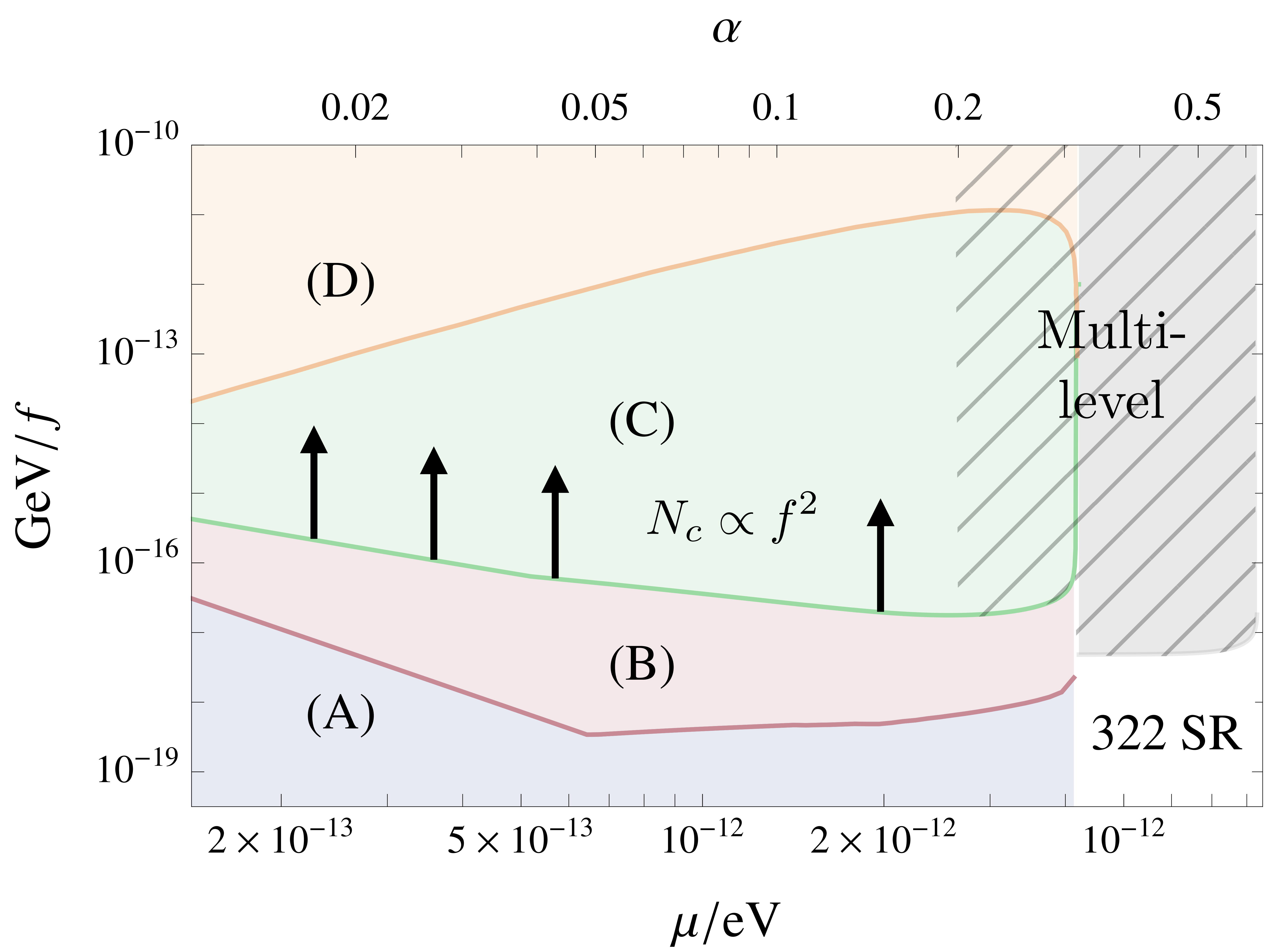
- For $a_\star = 0.99$ and $\alpha = 0.3$, observed collapse for $|\theta(t_0)| = 0.45$ and no collapse for

- Our variational method predicts

$$|\theta^{\rm crit}_{\rm max}| \simeq 0.42 \left(\frac{\alpha}{0.3}\right)$$



Bosenova



- With large self-interactions

$$N_c \propto f^2$$

- At small enough f, N_c **decreases** as f decreases further

$$N_c \gtrsim \alpha^{-1} f^2/\mu^2$$

both sides scale as f^2 !