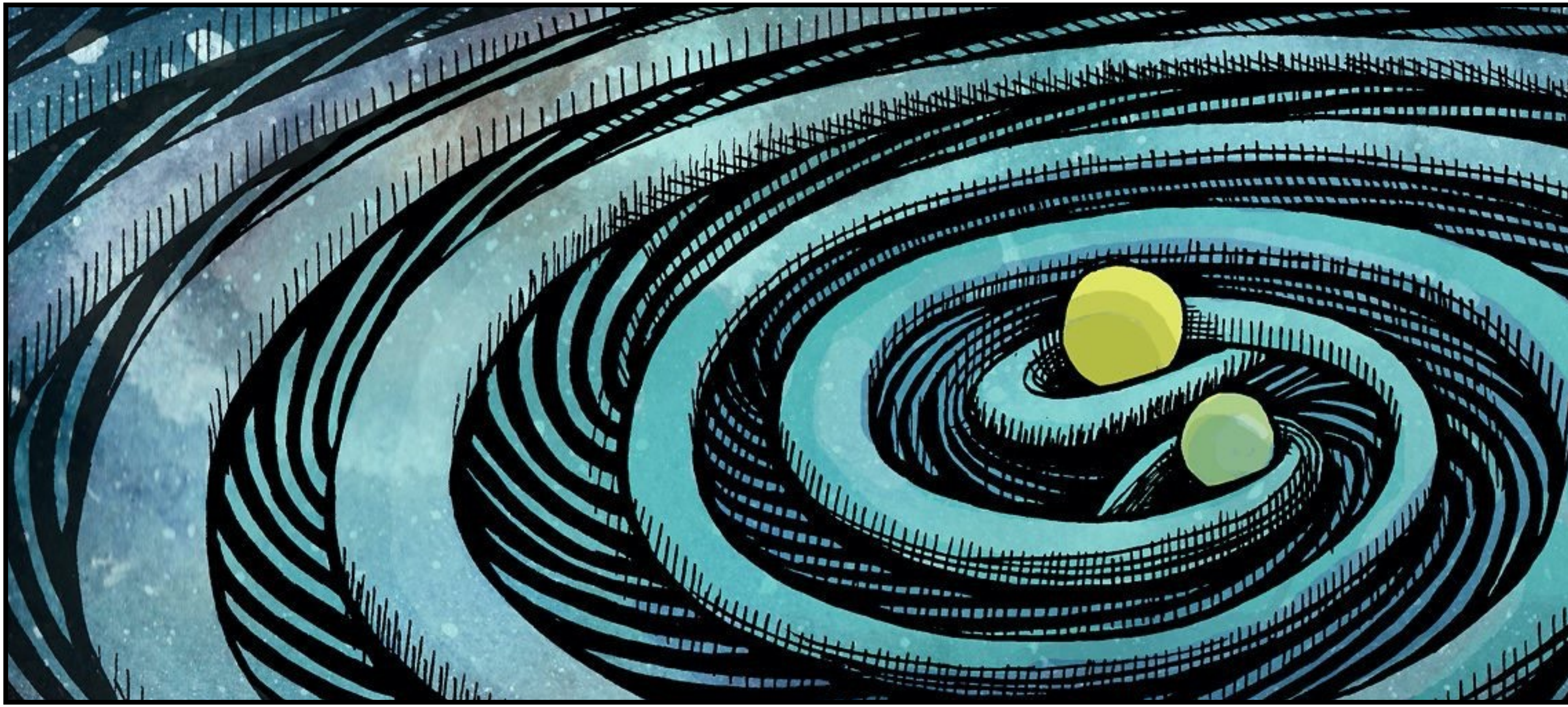
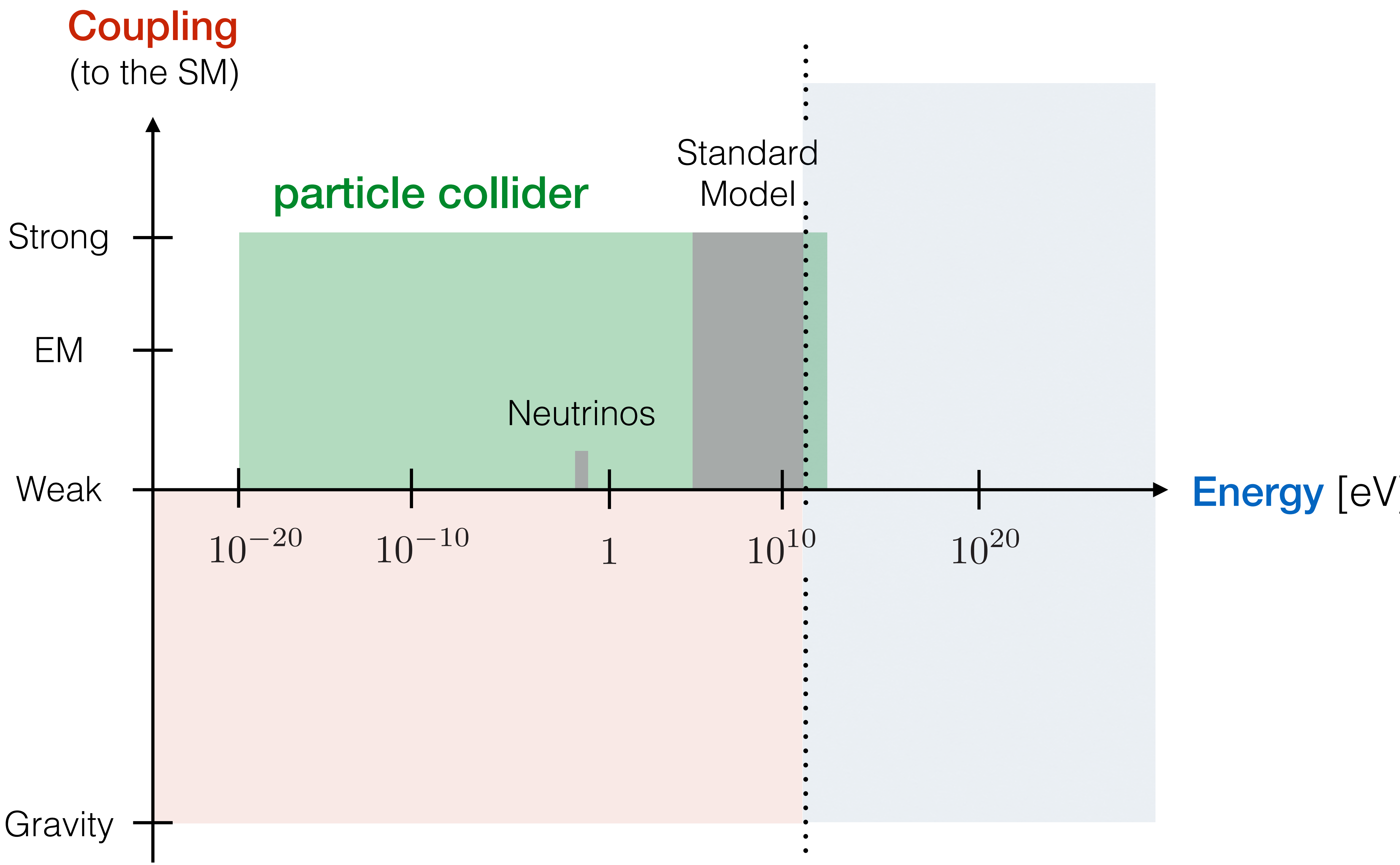


New Physics with Gravitational Waves

Daniel Baumann

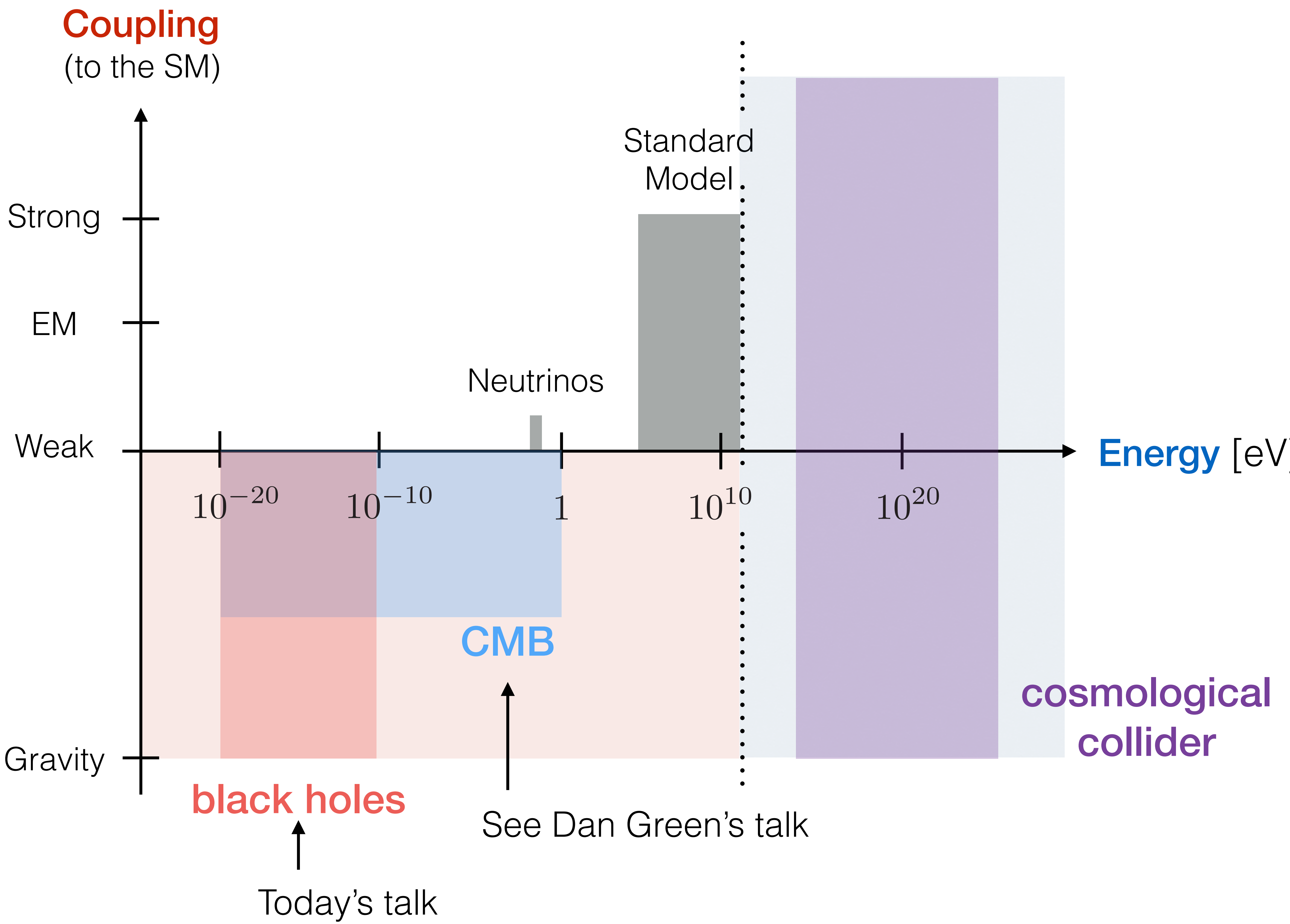
based on work with Horng Sheng Chia, Rafael Porto, John Stout, Lotte ter Haar, Giovanni Maria Tomaselli and Gianfranco Bertone

New physics may be hiding at **high energies** or **weak couplings**:

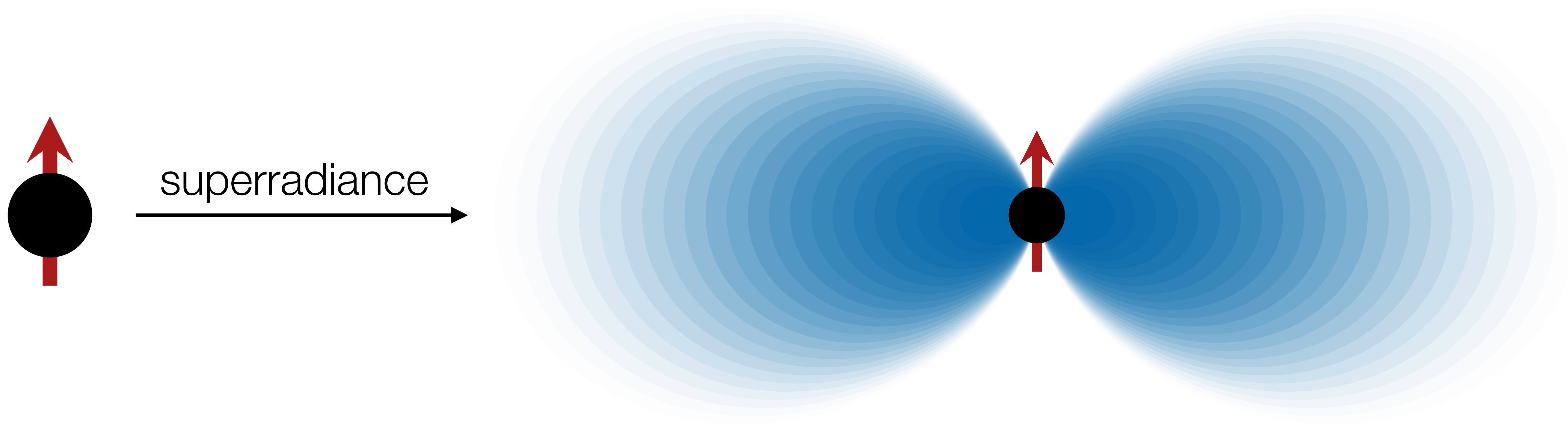


These regimes are inaccessible to traditional collider experiments.

Cosmology and **astrophysics** is sensitive to this type of new physics:



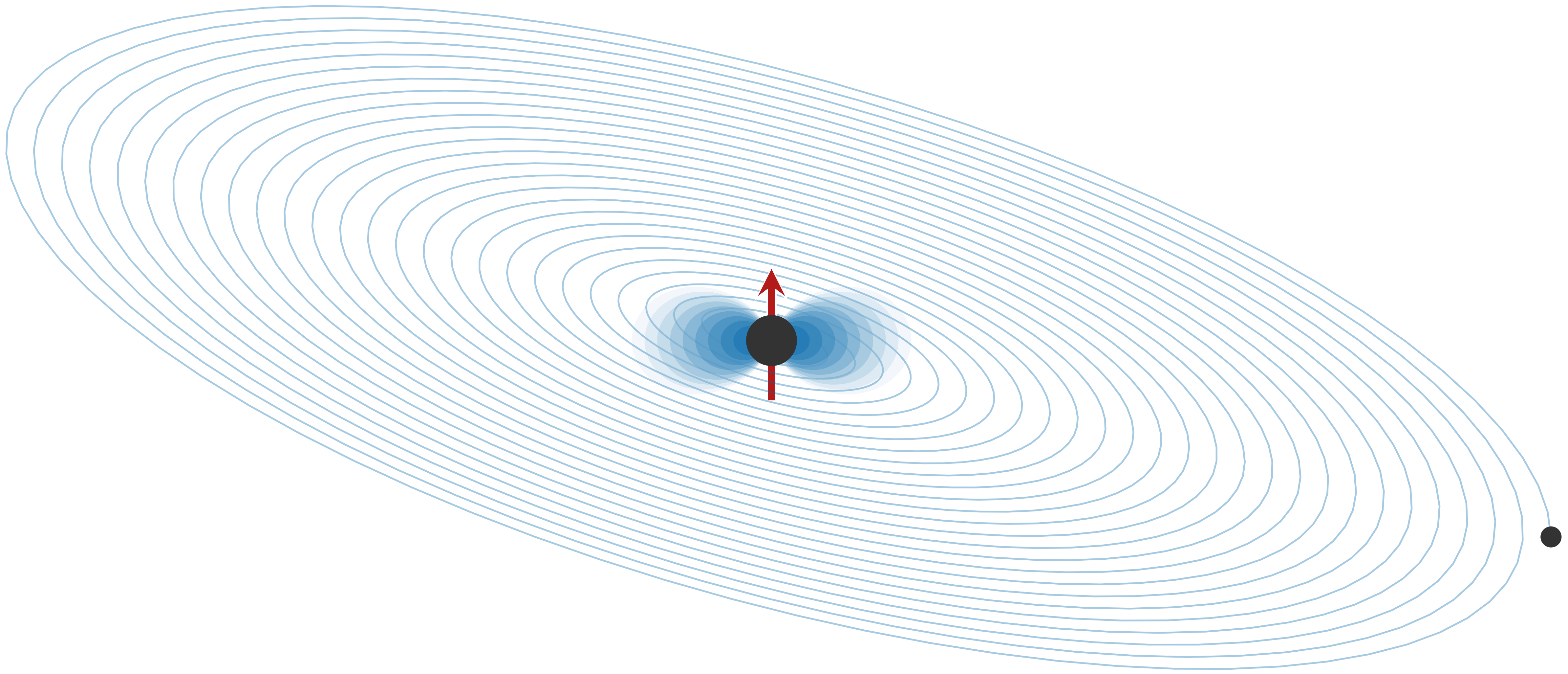
Ultralight bosons can form bound states around rotating black holes:



Zel'dovich '72
Starobinsky '73
Arvanitaki et al '09

This resembles the hydrogen atom and is therefore often called a **gravitational atom**.

DB, Chia, Porto, and Stout '20



A companion will perturb the **cloud** with a slowly increasing frequency.

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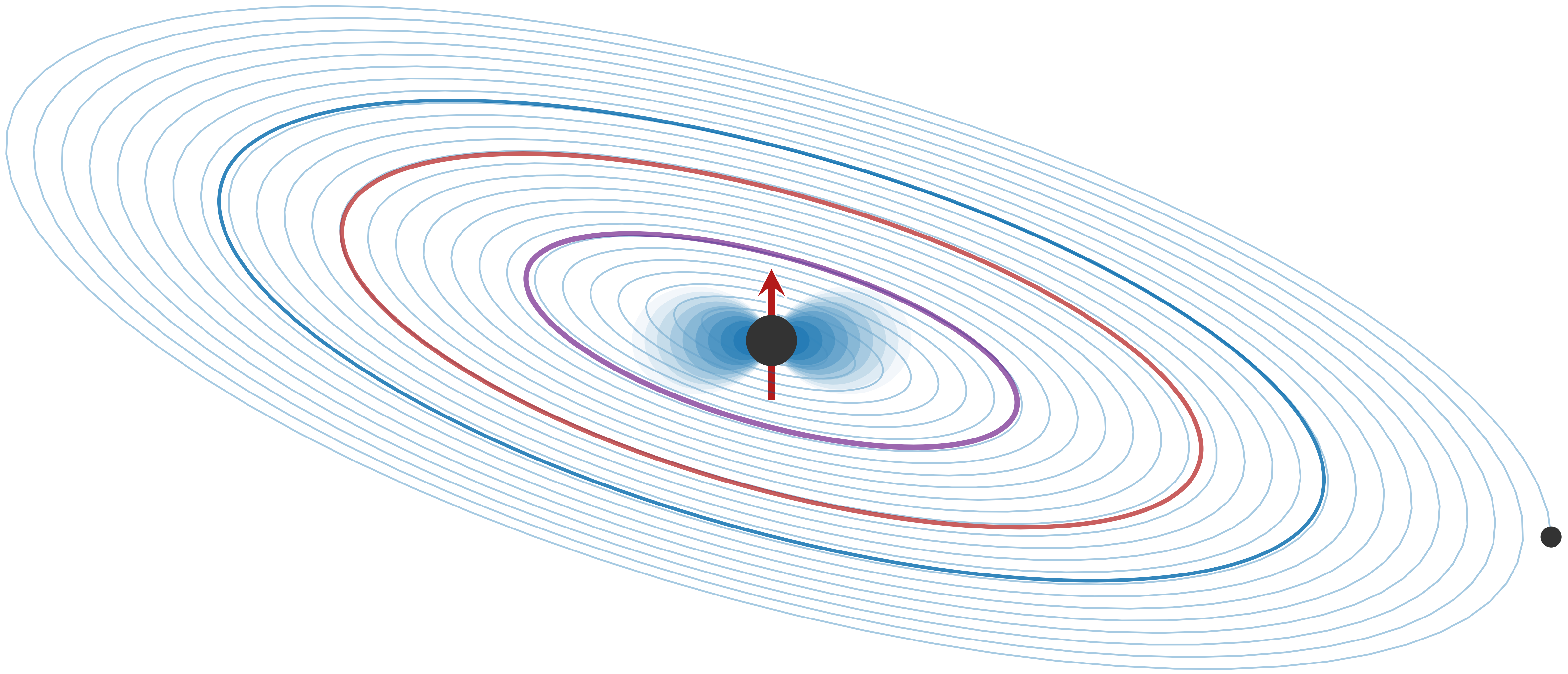
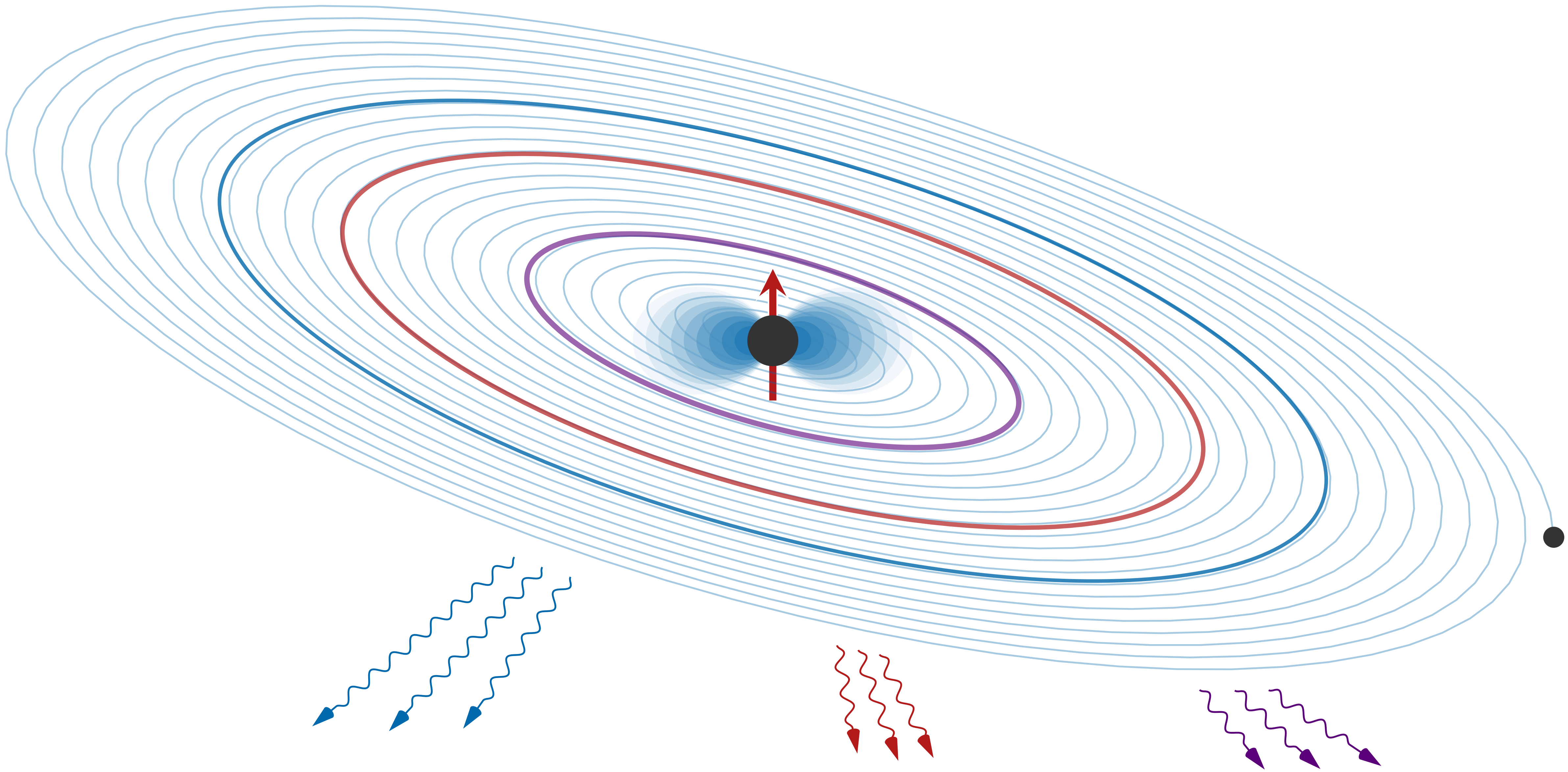


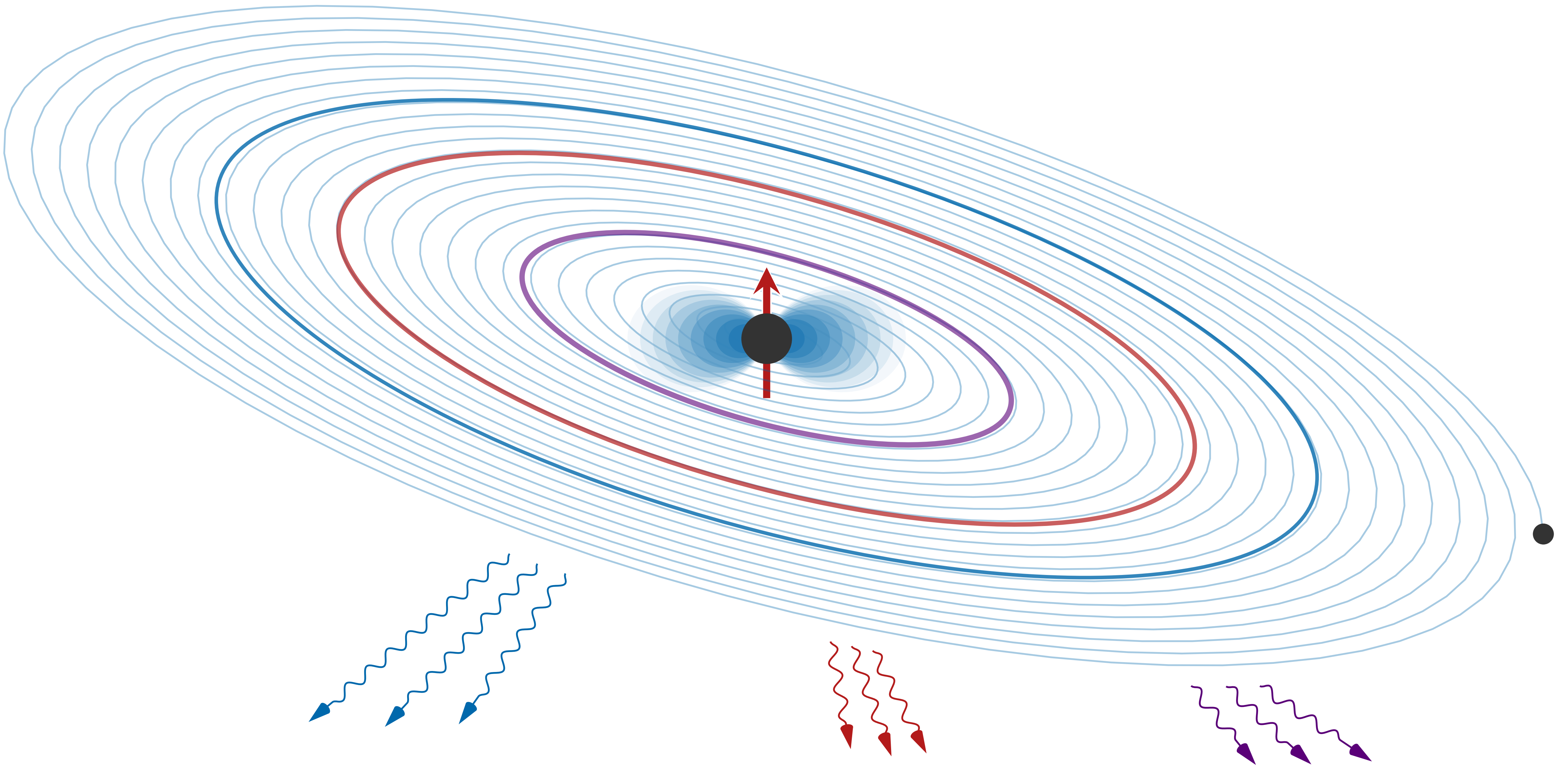
This interaction is enhanced at certain **resonance frequencies**.

DB, Chia, Porto, and Stout '20



The backreaction of the cloud's dynamics on the orbit leaves distinct imprints in the **gravitational waves** emitted by the binary.

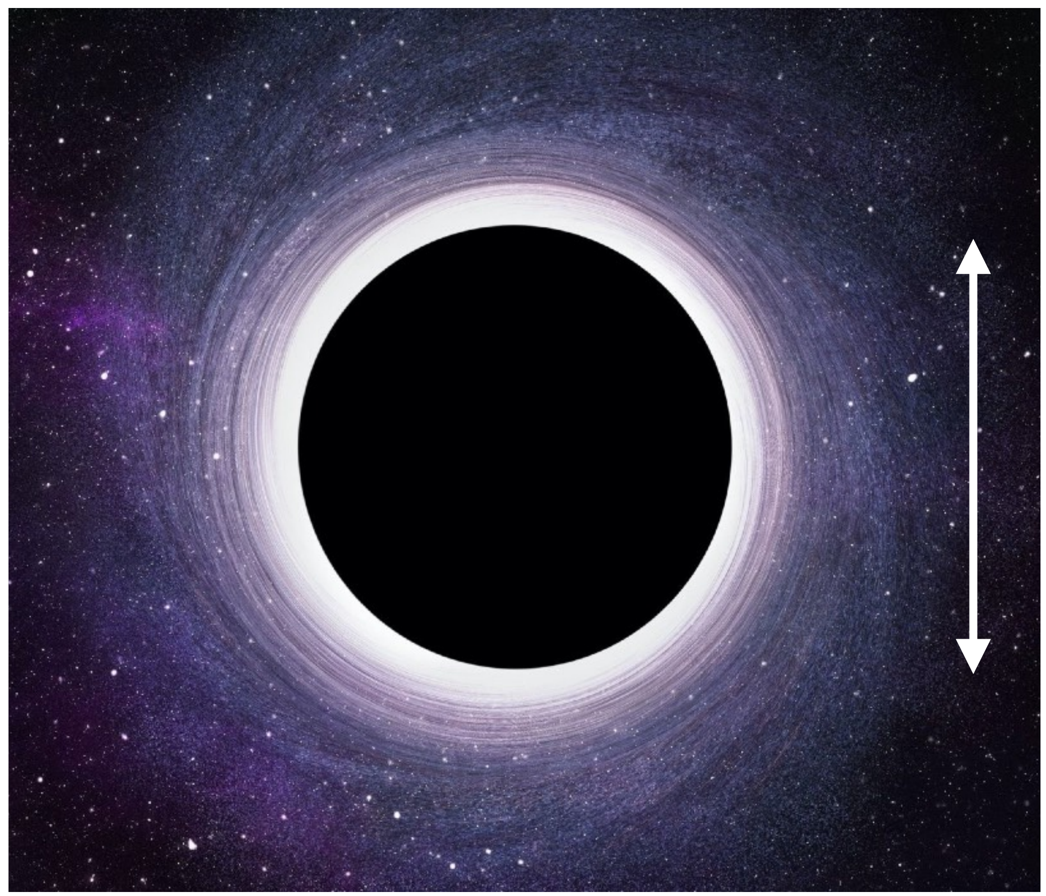
Outline



1) The Gravitational Atom
2) Evolution in Binaries
3) Gravitational Wave Signals

Superradiance

A light bosonic field experiences an instability if its Compton wavelength matches the size of the black hole:



$1\,\mathrm{km}$ – $10^{10}\,\mathrm{km}$

$10^{-10}\,\mathrm{eV}$ $10^{-20}\,\mathrm{eV}$

The physics is governed by the **gravitational fine structure constant**:

$$\alpha \equiv \frac{r_g}{\lambda_c} = 0.04 \left(\frac{M}{60 M_\odot}\right)\left(\frac{\mu}{10^{-13}\,\mathrm{eV}}\right)$$

Gravitational Atom

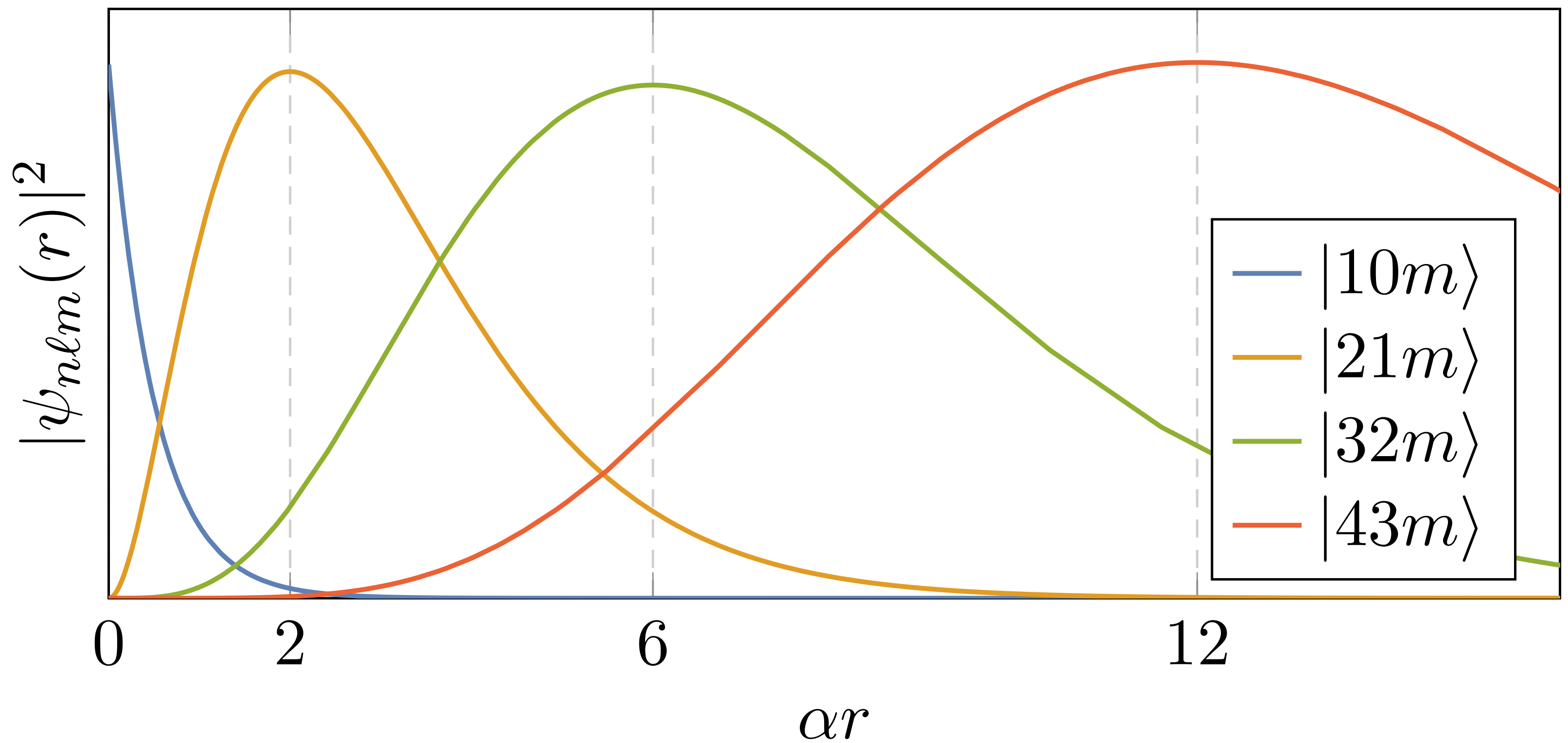
The structure of the cloud is determined by a **Schrödinger equation**:

$$i\frac{\mathrm{d}\psi}{\mathrm{d}t} = \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \Delta V\right)\psi \qquad \text{with} \qquad \Phi = \psi(t,\mathbf{x})\, e^{i\mu t}$$

Coulomb potential ($\frac{\alpha}{r}$)

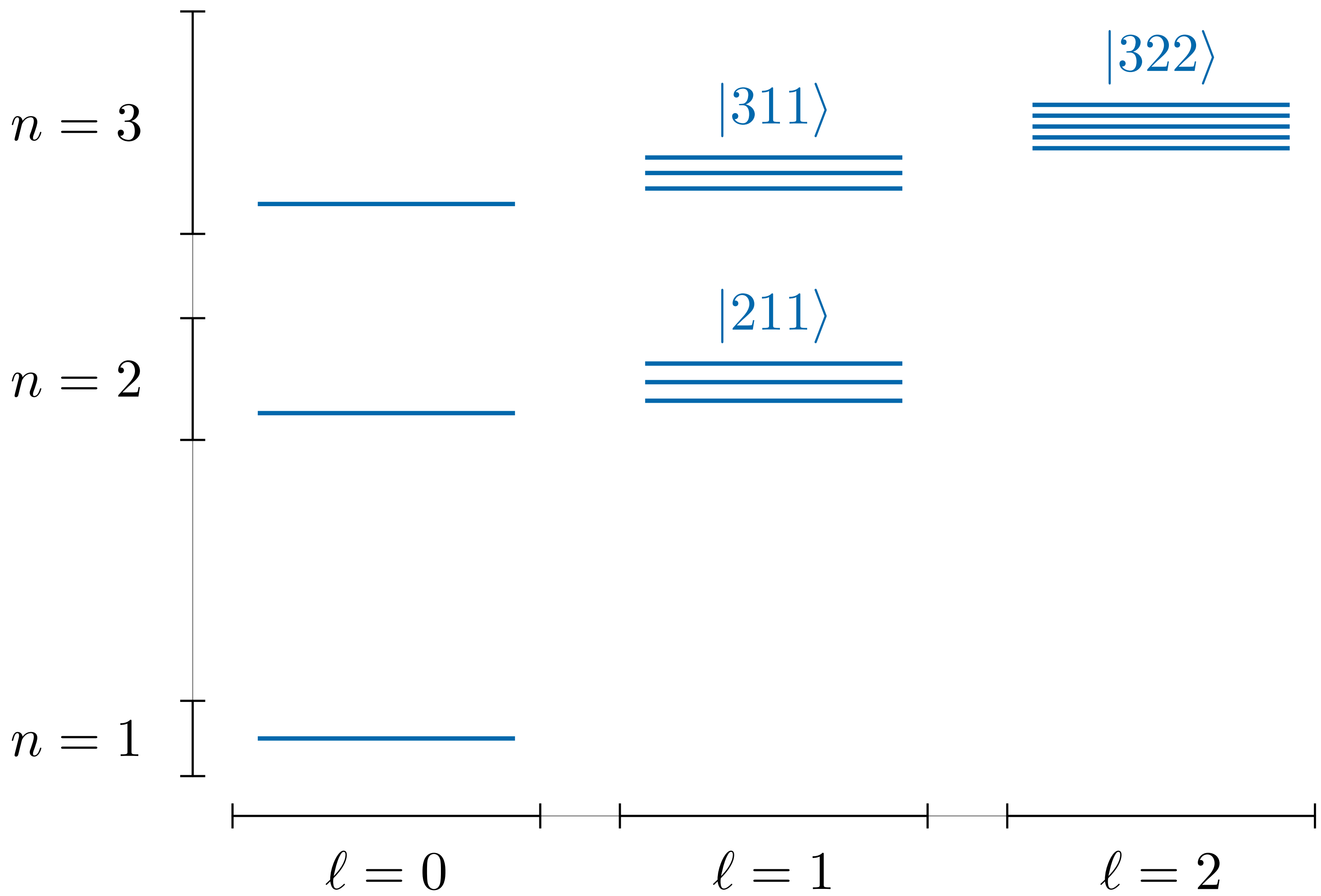
fine structure corrections (ΔV)

The energy eigenstates are the same as those of the **hydrogen atom**:



Scalar Spectrum

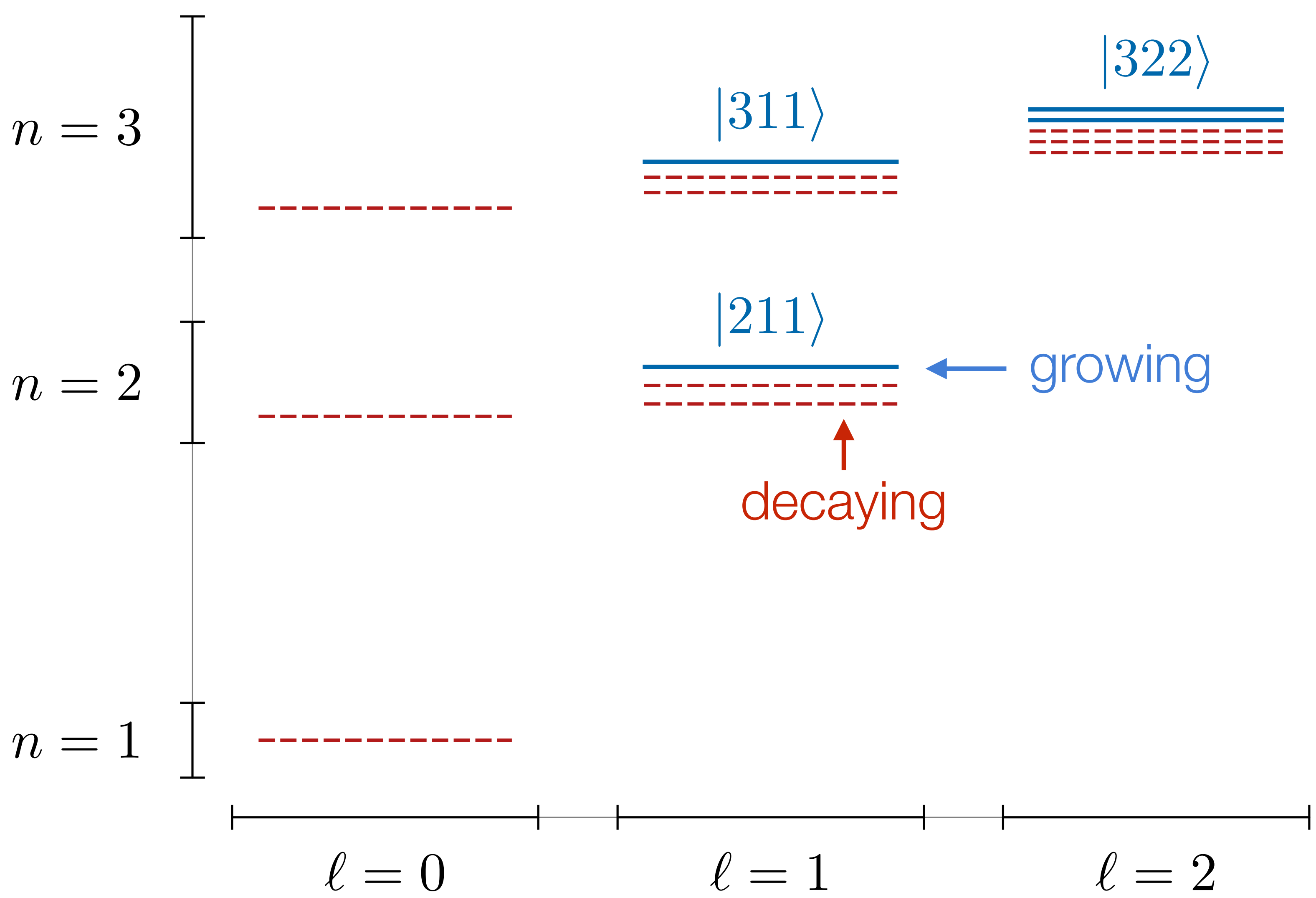
The spectrum of states is also hydrogenic:



$$E_{n\ell m} = \mu\left(1 - \frac{\alpha^2}{2n^2} + f_{n\ell}\alpha^4 + h_{n\ell m}\alpha^5 + \cdots\right)$$

Growing and Decaying Modes

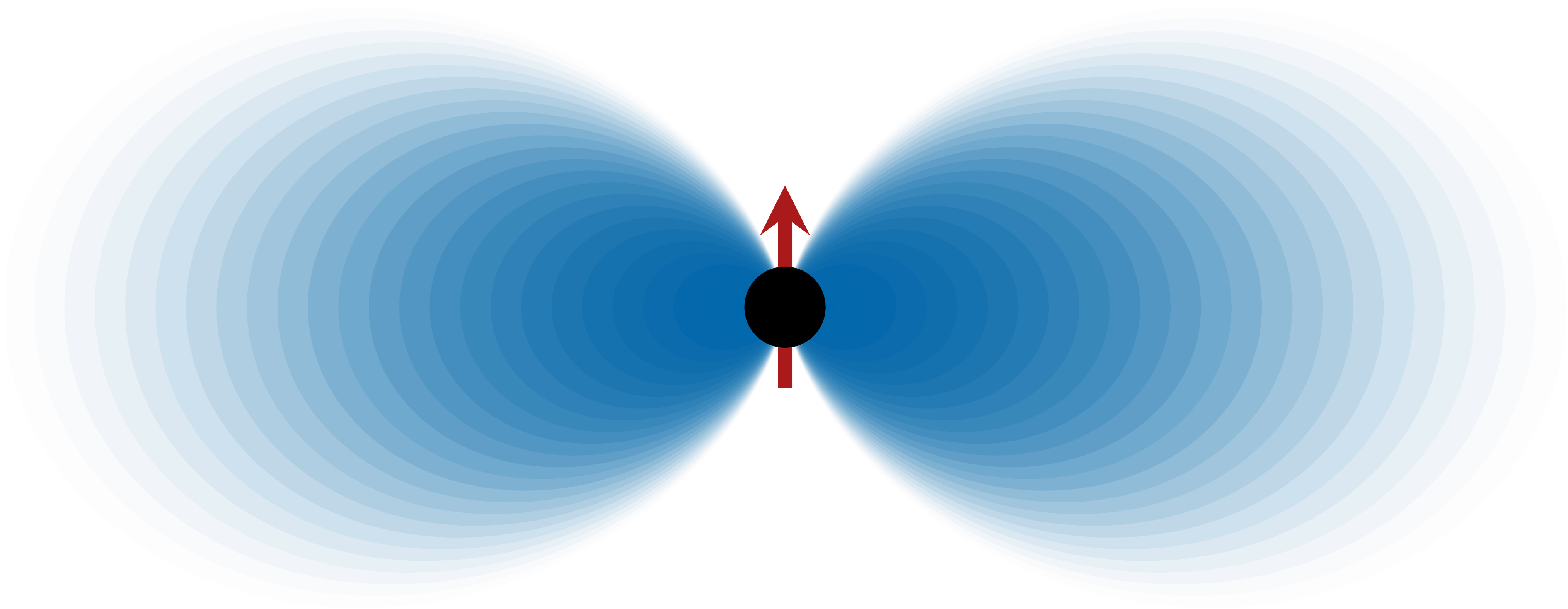
Unlike in the hydrogen atom, the states are only **quasi-stationary**:



$$\omega_{n\ell m} = E_{n\ell m} + i\Gamma_{n\ell m}$$

Initial State of the Cloud

The **fastest growing mode** looks like this

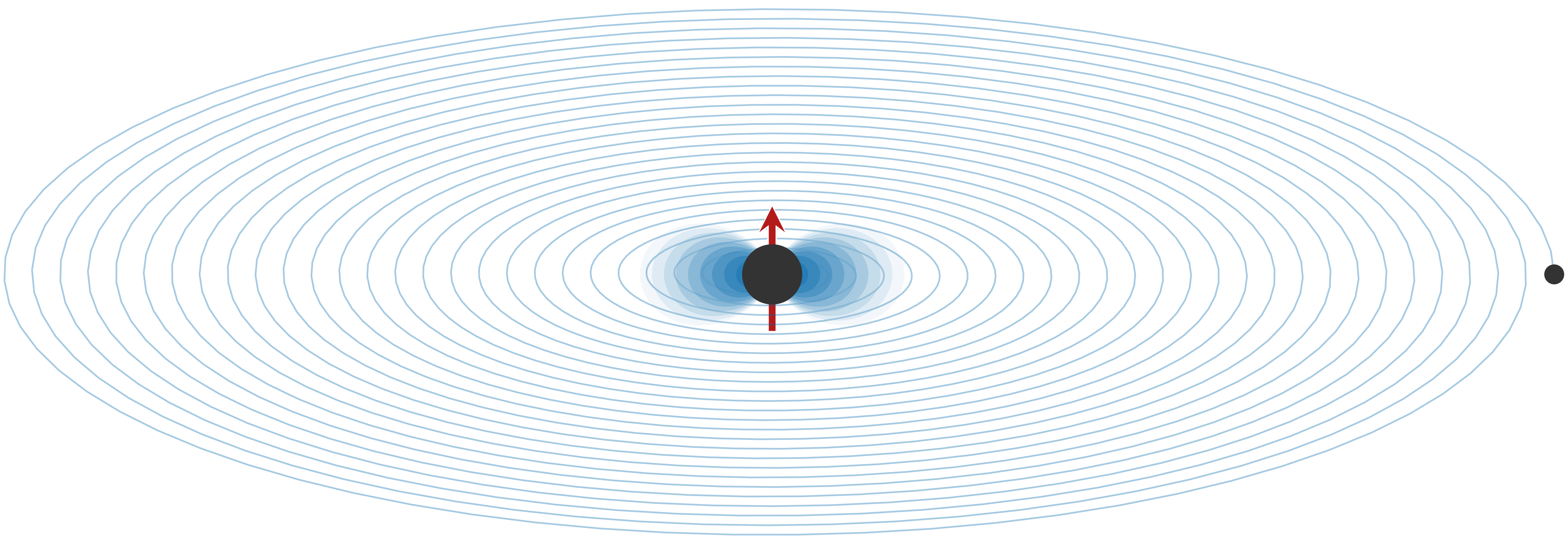


$$\Gamma_{211}^{-1} = 10^3 \,\mathrm{yrs} \left(\frac{M}{60 M_\odot}\right) \left(\frac{0.04}{\alpha}\right)^9$$

We take this as the **initial state of the cloud**.

Evolution in a Binary

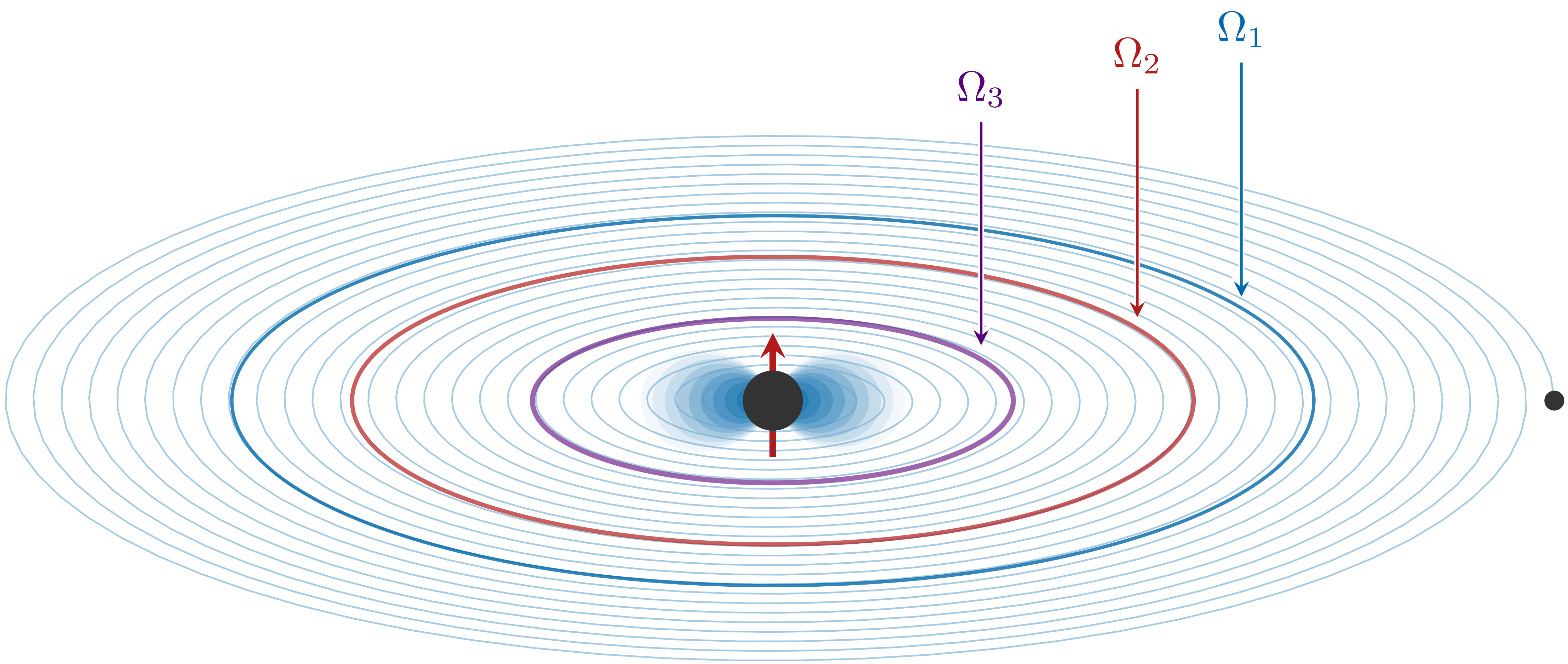
In a binary, the cloud gets **perturbed** at a slowly increasing frequency:



$$\langle n'\ell' m' | V_*(t) | n \ell m \rangle = \eta(t) \exp\left(-i \Delta m \int^t \mathrm{d}t' \, \Omega(t) \right)$$

Resonant Transitions

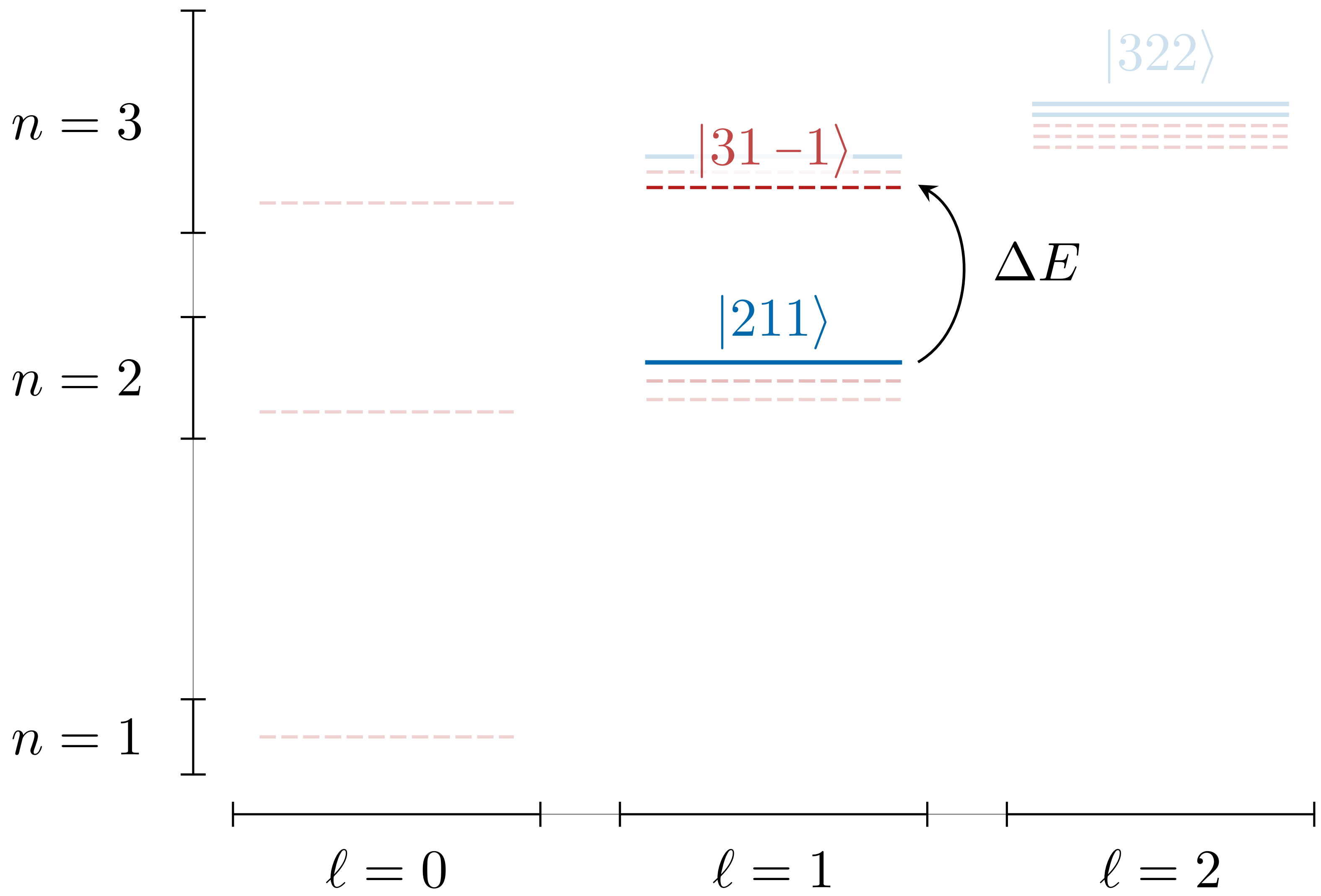
At specific frequencies, the perturbation is **resonantly enhanced**:



$$\Omega_i = \left|\frac{\Delta E_i}{\Delta m_i}\right| \sim 0.01\,\mathrm{Hz}\left(\frac{60 M_\odot}{M}\right)\left(\frac{\alpha}{0.04}\right)^3$$

Level Mixing

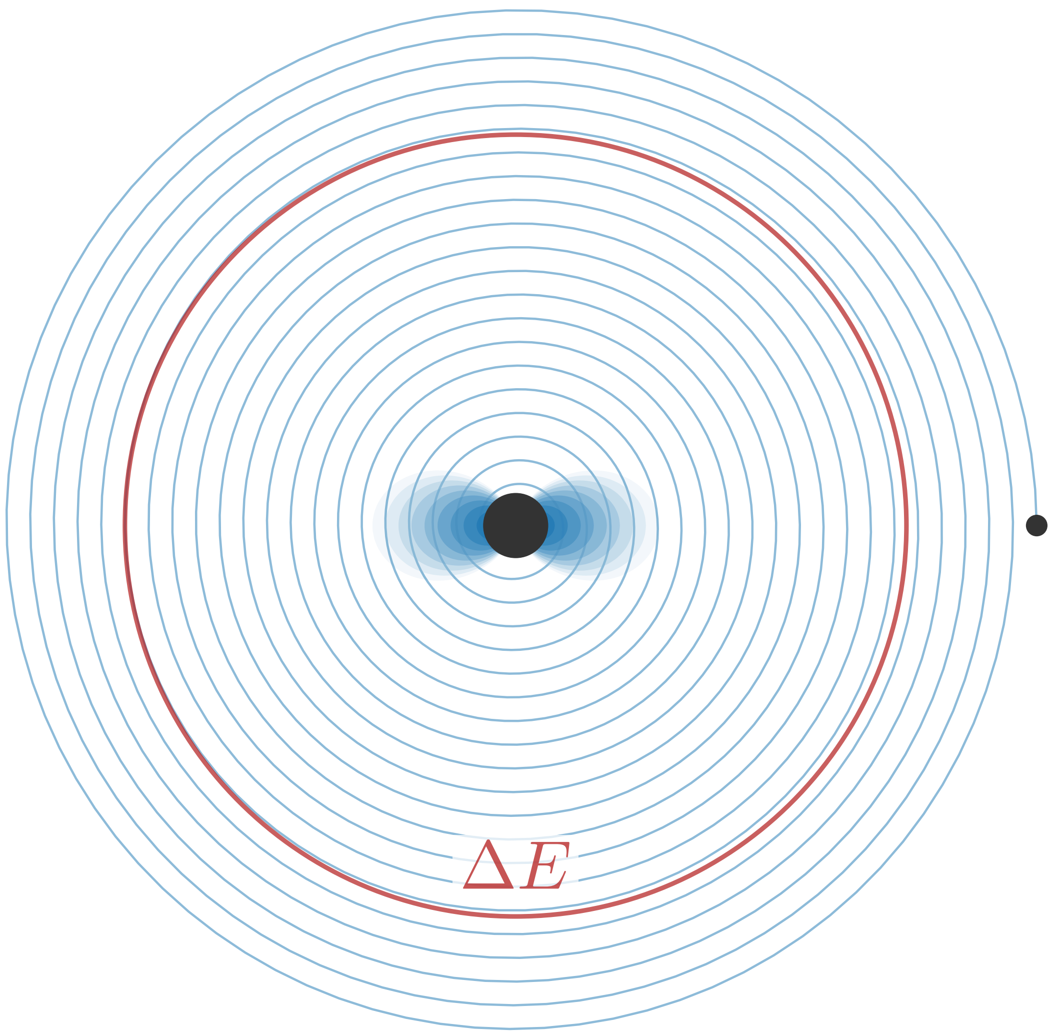
Only certain transitions are allowed by selection rules:



For the scalar atom, the level mixings typically involve only two states.

Two-State System

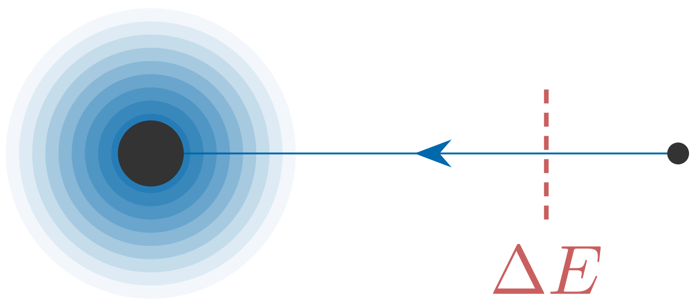
A simple two-state system is therefore a good model for the dynamics:



$$\mathcal{H} = \begin{pmatrix} -\Delta E/2 & \eta\, e^{i \int \mathrm{d}t'\, \Omega(t')} \\ \eta\, e^{-i \int \mathrm{d}t'\, \Omega(t')} & \Delta E/2 \end{pmatrix}$$

Two-State System

Rotating along with the companion, isolates the **slow** motion:

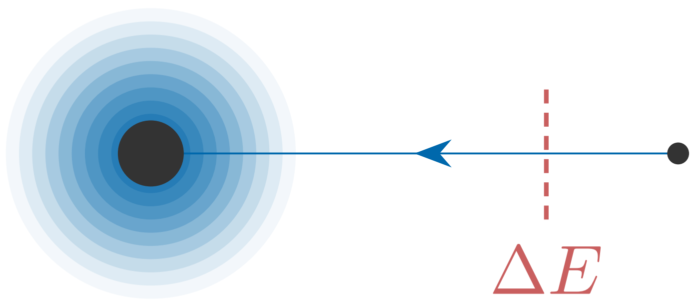


$$\mathcal{H}_{\mathrm{D}} = \begin{pmatrix} (\Omega(t) - \Delta E)/2 & \eta \\ \eta & (\Omega(t) - \Delta E)/2 \end{pmatrix}$$

Landau-Zener Transition

Near the resonance, we can write $\Omega(t) = \Omega_{\rm res} + \gamma\, t$

determines nature of transition

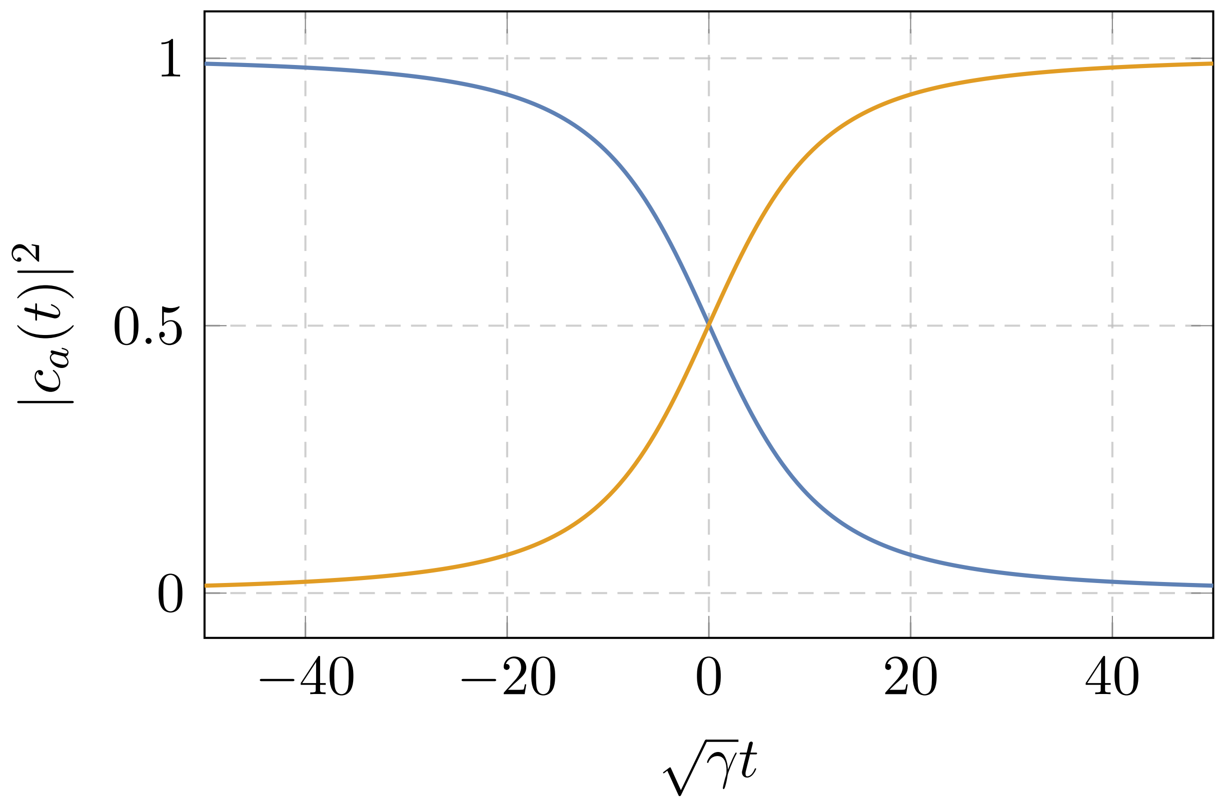


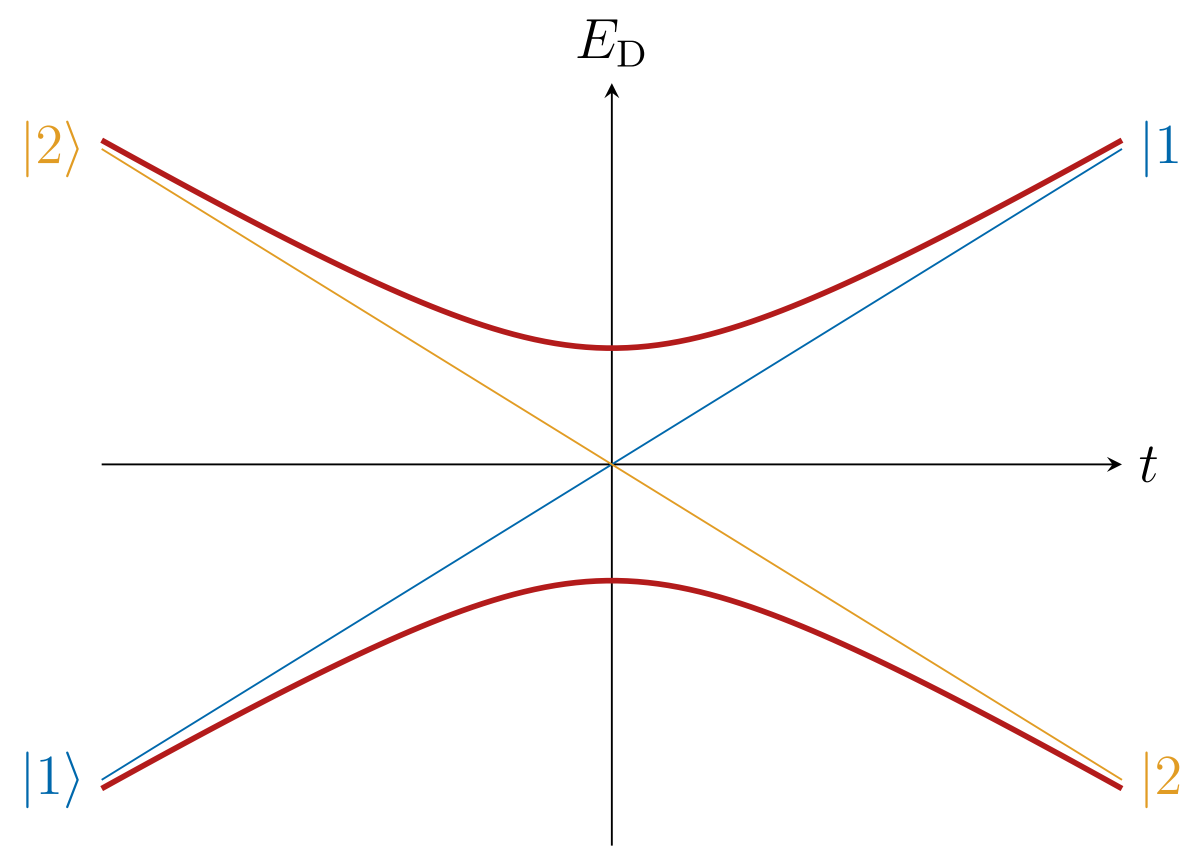
$$\mathcal{H}_{\rm D}(t) = \frac{\gamma t}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \eta \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Landau '32
Zener '32
DB, Chia, Porto, and Stout '20

Landau-Zener Transition

For **slow transitions**, the initial state gets fully converted:



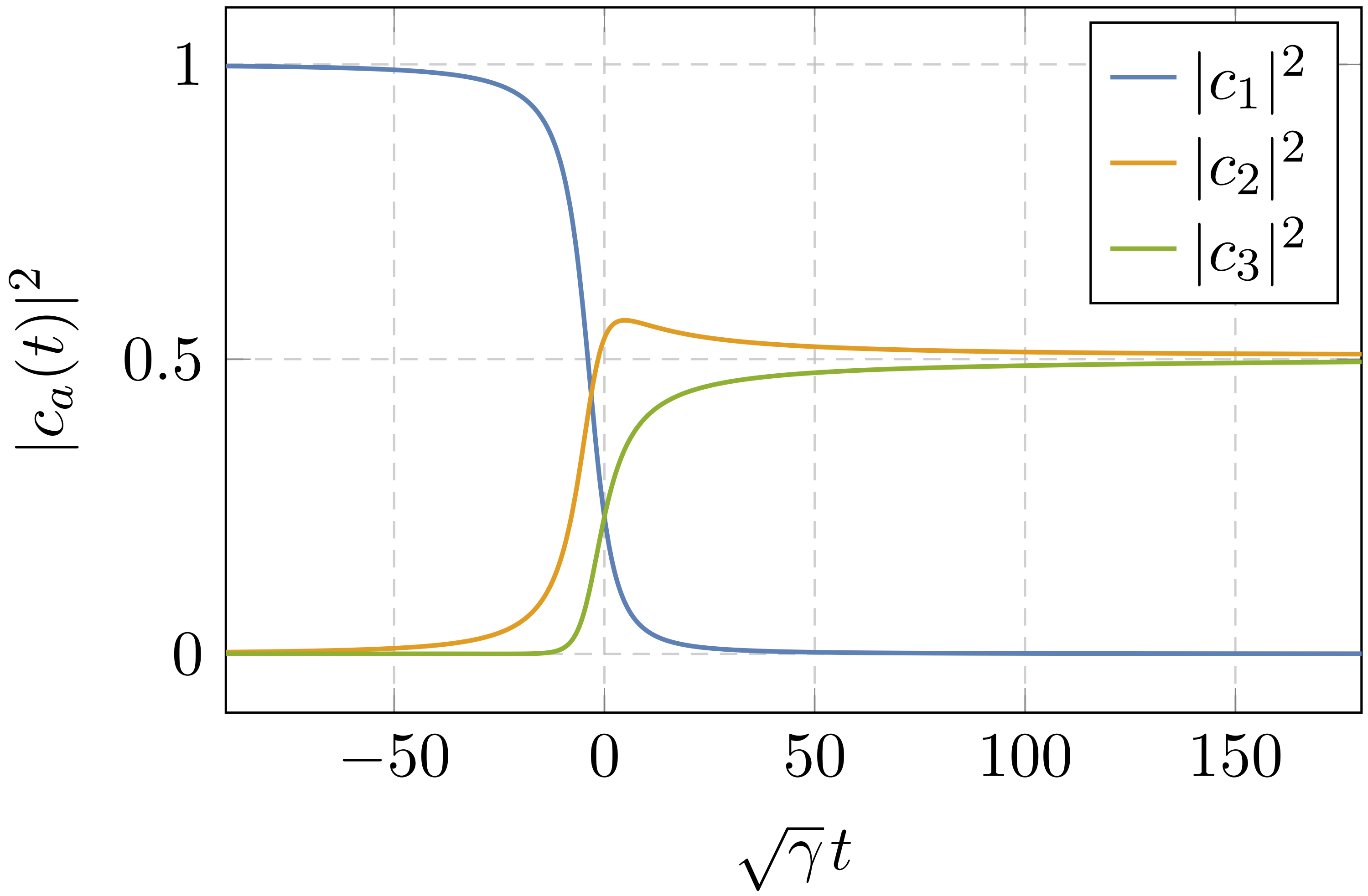


$$\mathcal{H}_D(t) = \frac{\gamma t}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \eta \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Landau ’32
Zener ‘32
DB, Chia, Porto, and Stout ’20

Multi-State Transitions

Clouds of **spinning particles** involve multi-state transitions:



- The final state is generically a **superposition of states**.
- There can be **neutrino-like oscillations** between the states.

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Backreaction on the Orbit

Conservation of angular momentum requires

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\mathbf{L} + \mathbf{S}_c\right) = \mathbf{T}_{\mathrm{GW}} \approx 0$$

orbit ($\mathbf{L}$) cloud ($\mathbf{S}_c$)

The dynamics of the cloud affects the orbital motion!

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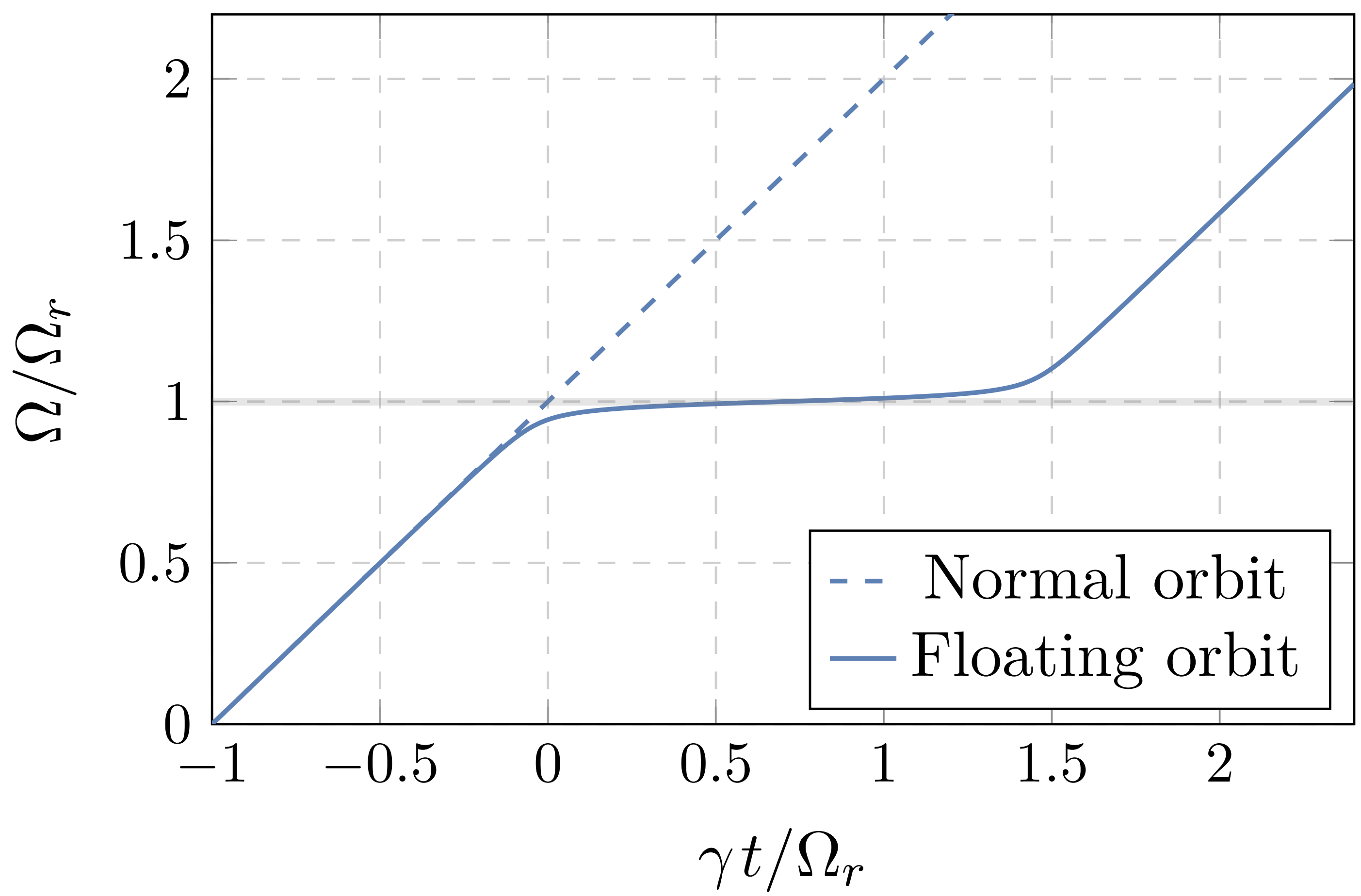
Floating Orbits

The binary **floats** when it absorbs angular momentum from the cloud:



The binary emits transient, nearly **monochromatic GWs**.

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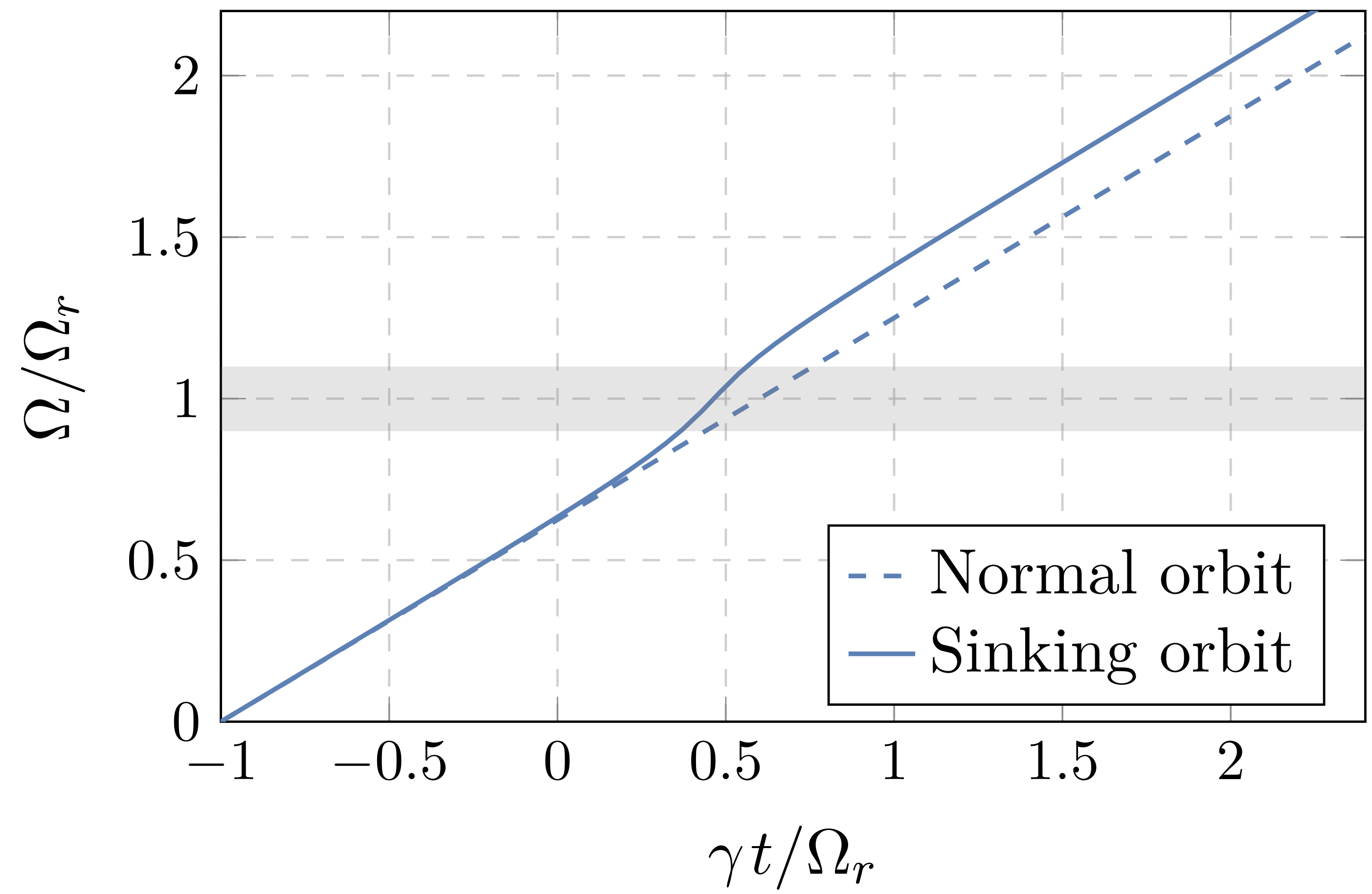
Sinking Orbits

The binary **sinks** when it releases angular momentum to the cloud:



This leads to a **dephasing** in the GW signal.

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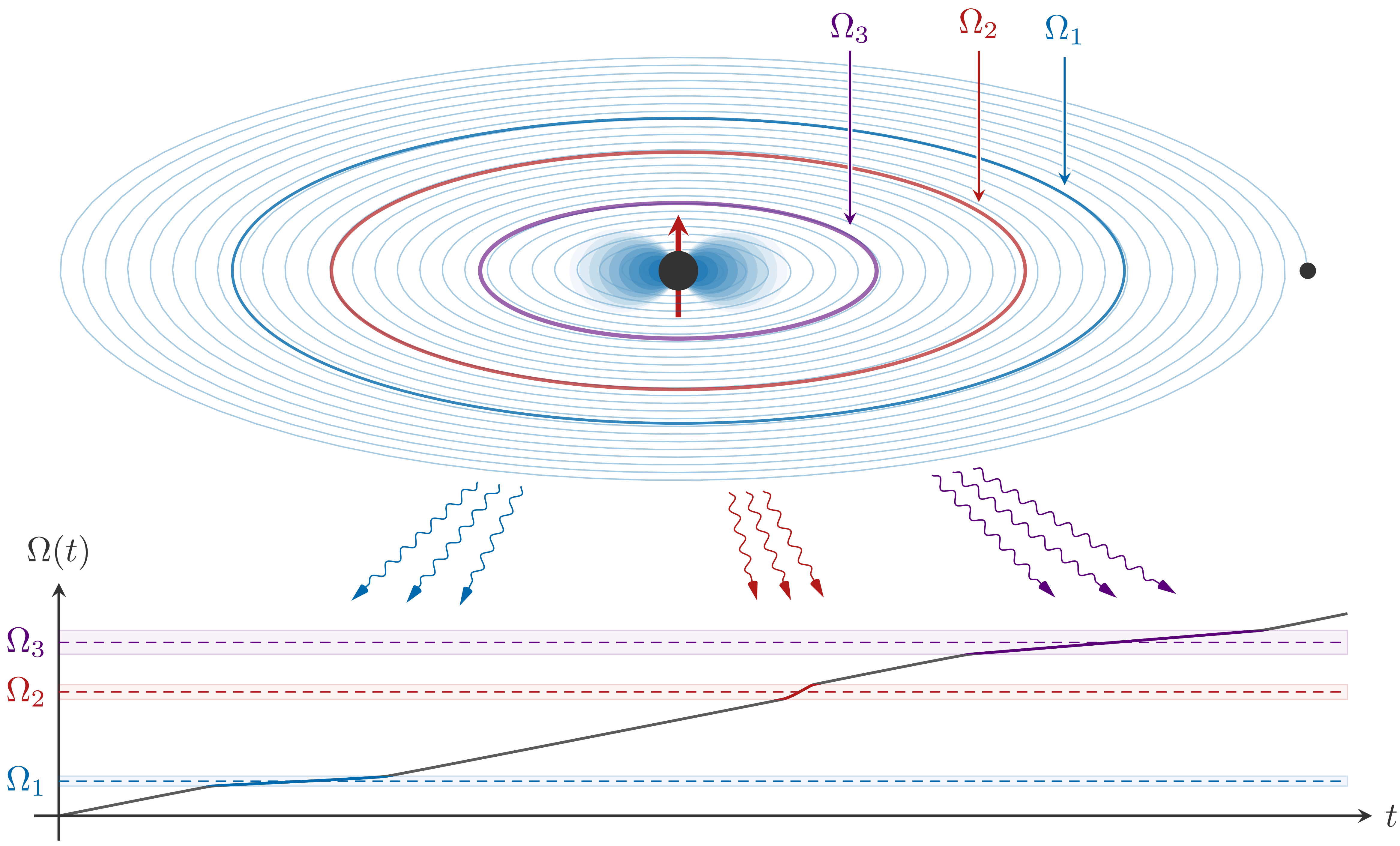
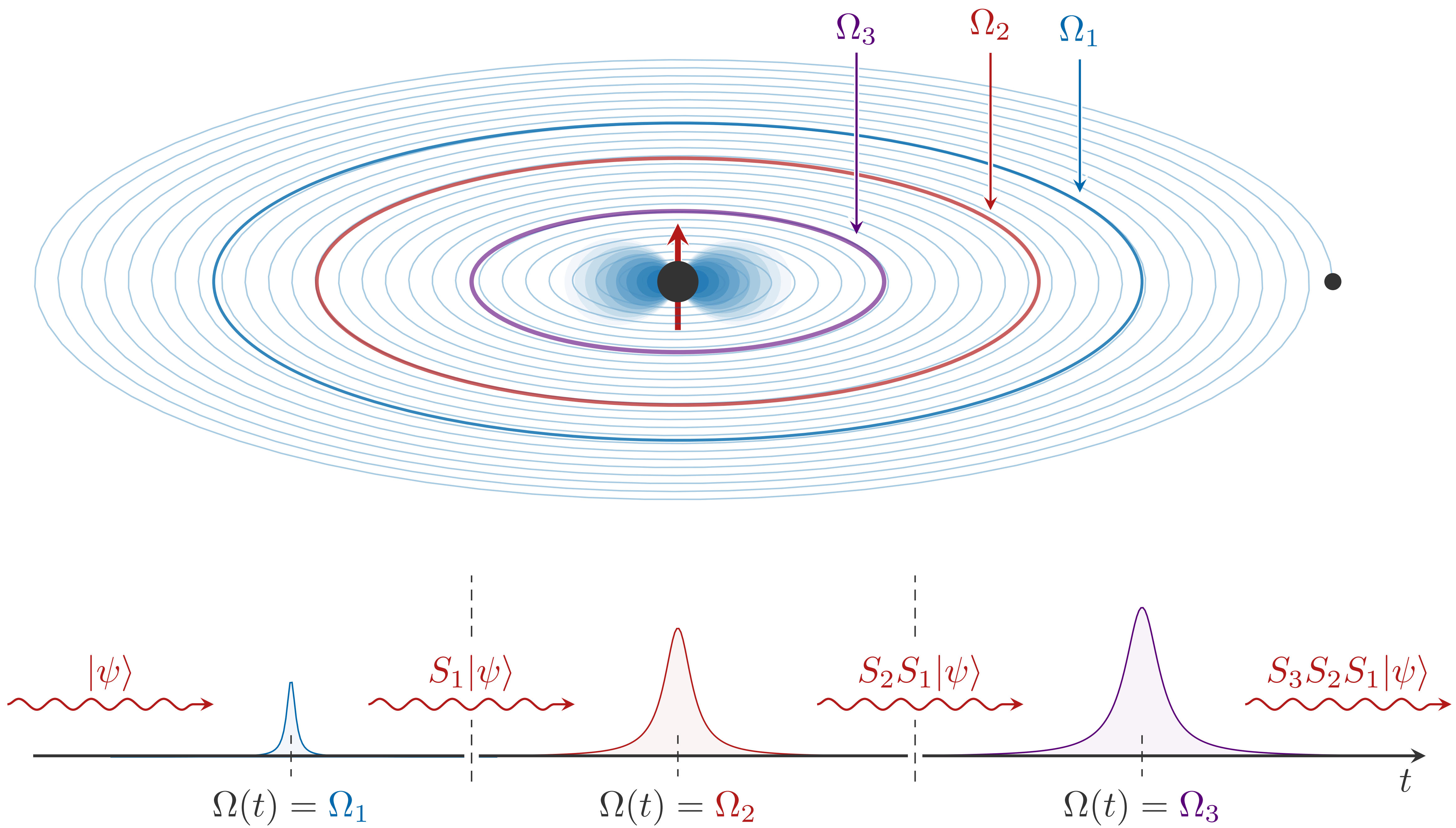
Multiple Transitions

The sequence of transitions is a **fingerprint** of the atomic spectra:



Multiple Transitions

The evolution can be described by a series of **scattering events**:



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Final State of the Cloud

The S-matrix formalism predicts the **final state** of the cloud:

$$|\,f\,\rangle = \prod_{n=1}^{N} S_n\,|\,i\,\rangle$$

The **shape** and **time dependence** of this state depends on the internal structure of the cloud:

$$Q_c(t) = \sum_a |c_a(t)|^2\, Q_{c,a} + \sum_{a\neq b} |c_a(t)c_b(t)|\, Q_{ab}\cos(\Delta E_{ab}\, t)$$

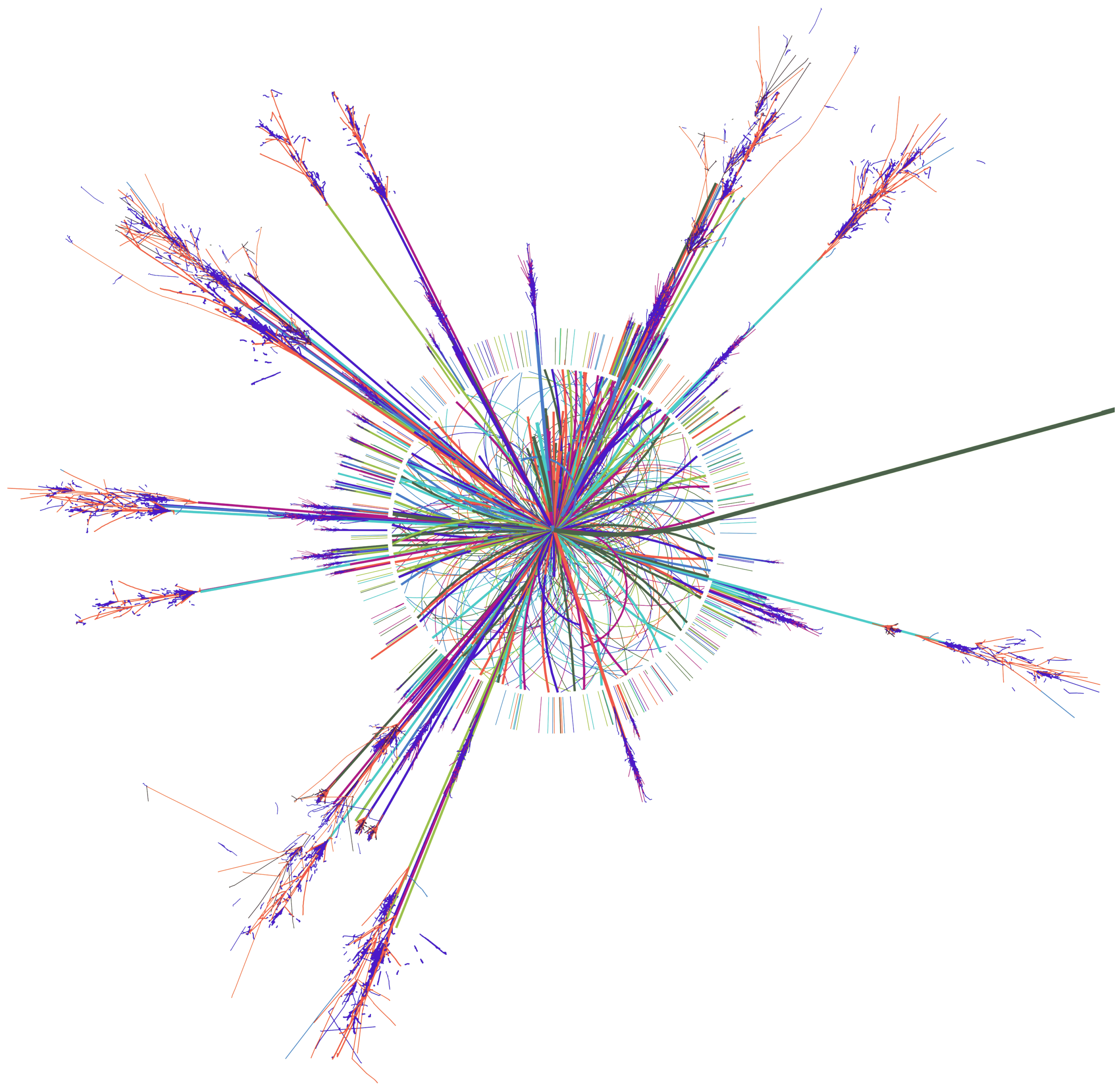
scalar cloud

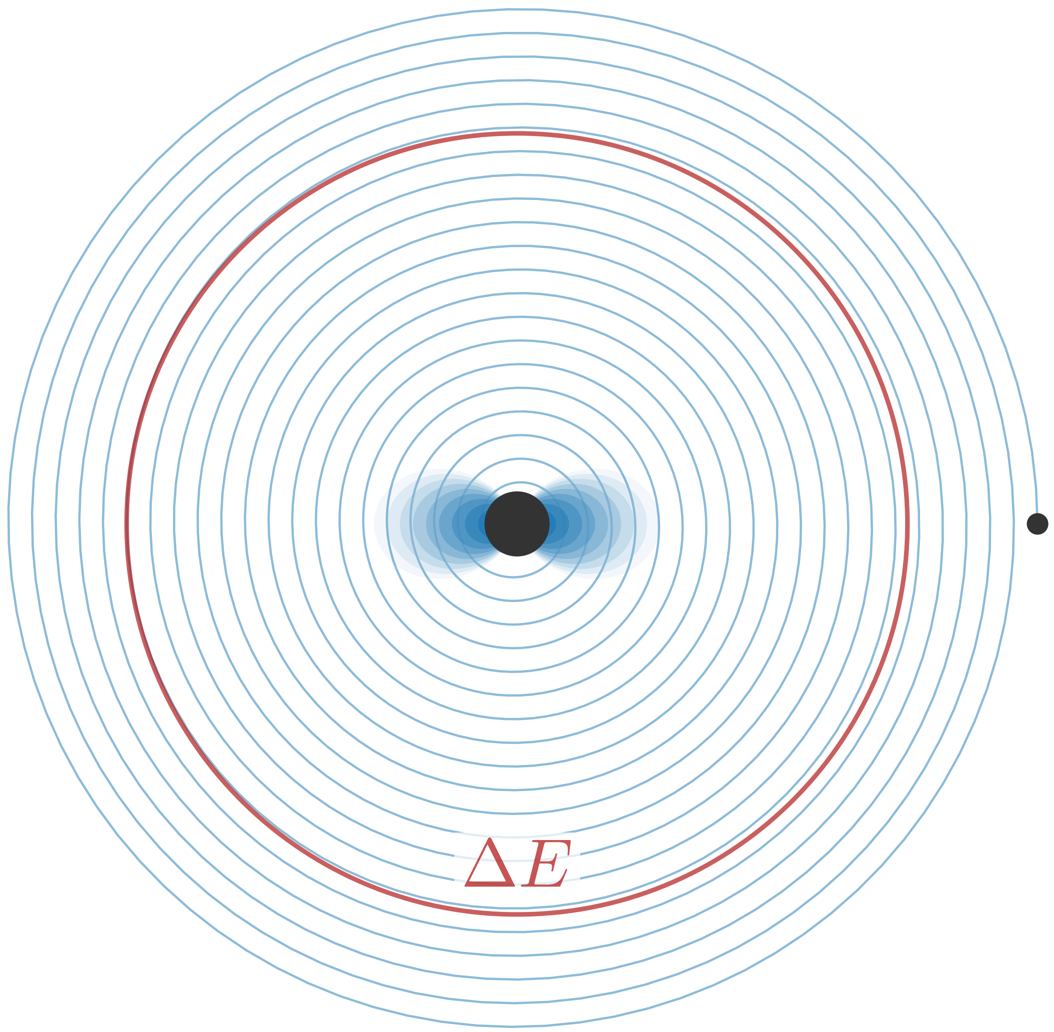
vector cloud

This affects the GW waveforms through **finite-size effects**.

Gravitational Collider Physics

As in ordinary particle colliders, the signals depend on the **mass** and **spin** of the particles:



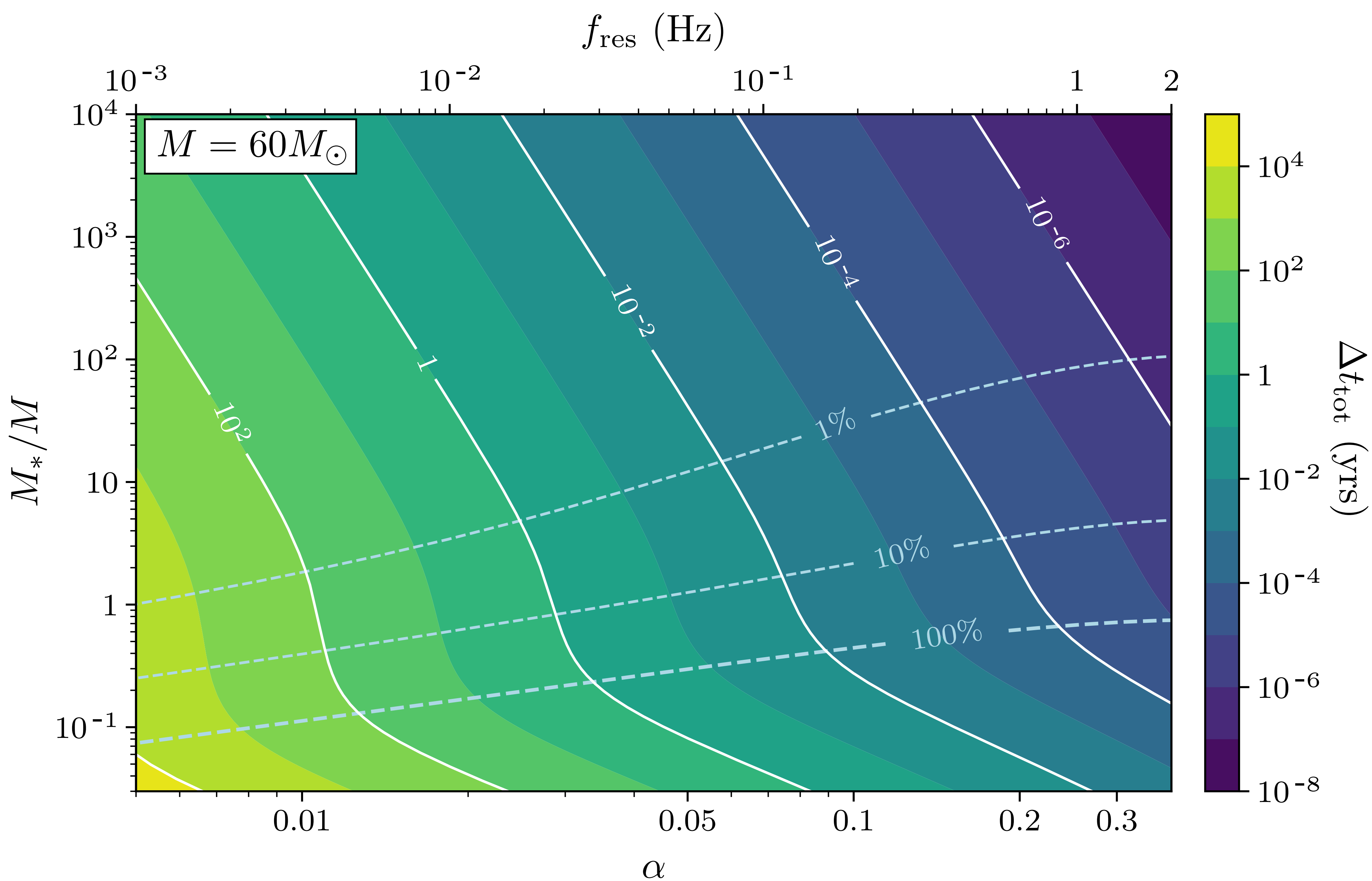


- **Mass**: Position of the resonance
- **Spin**: Angular dependence

- **Mass**: Position of the resonances
- **Spin**: Structure of the final state

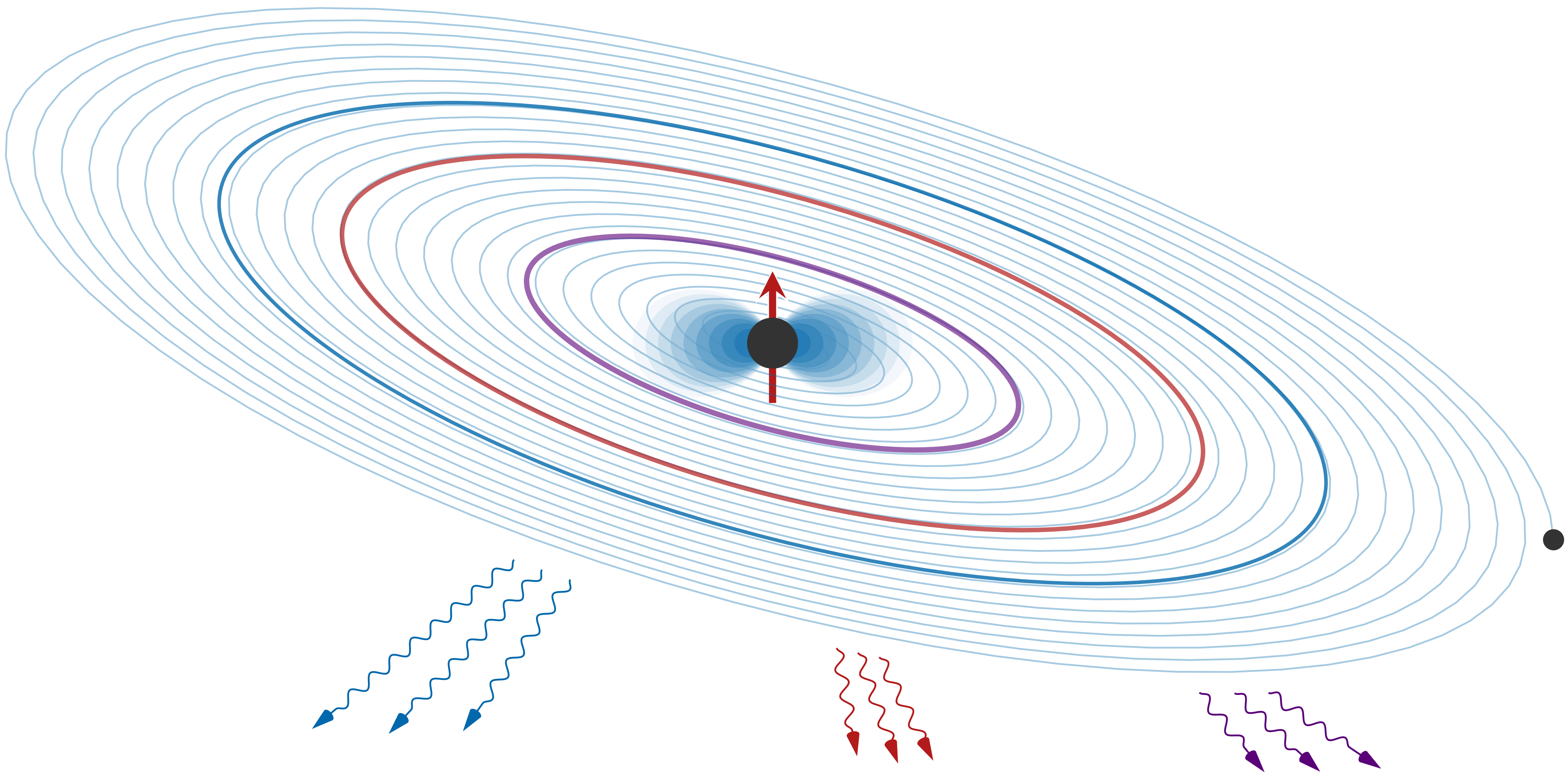
Gravitational Wave Signatures

- The resonances naturally occur in the **LISA** band:
- The **dephasing** of the signals can be significant:



Conclusions

- We studied the dynamics of boson clouds in black hole binaries.
- The backreaction on the orbit produces distinct GW signatures.



- Precise waveform modeling is needed to apply this to GW searches.


Thank you for your attention!