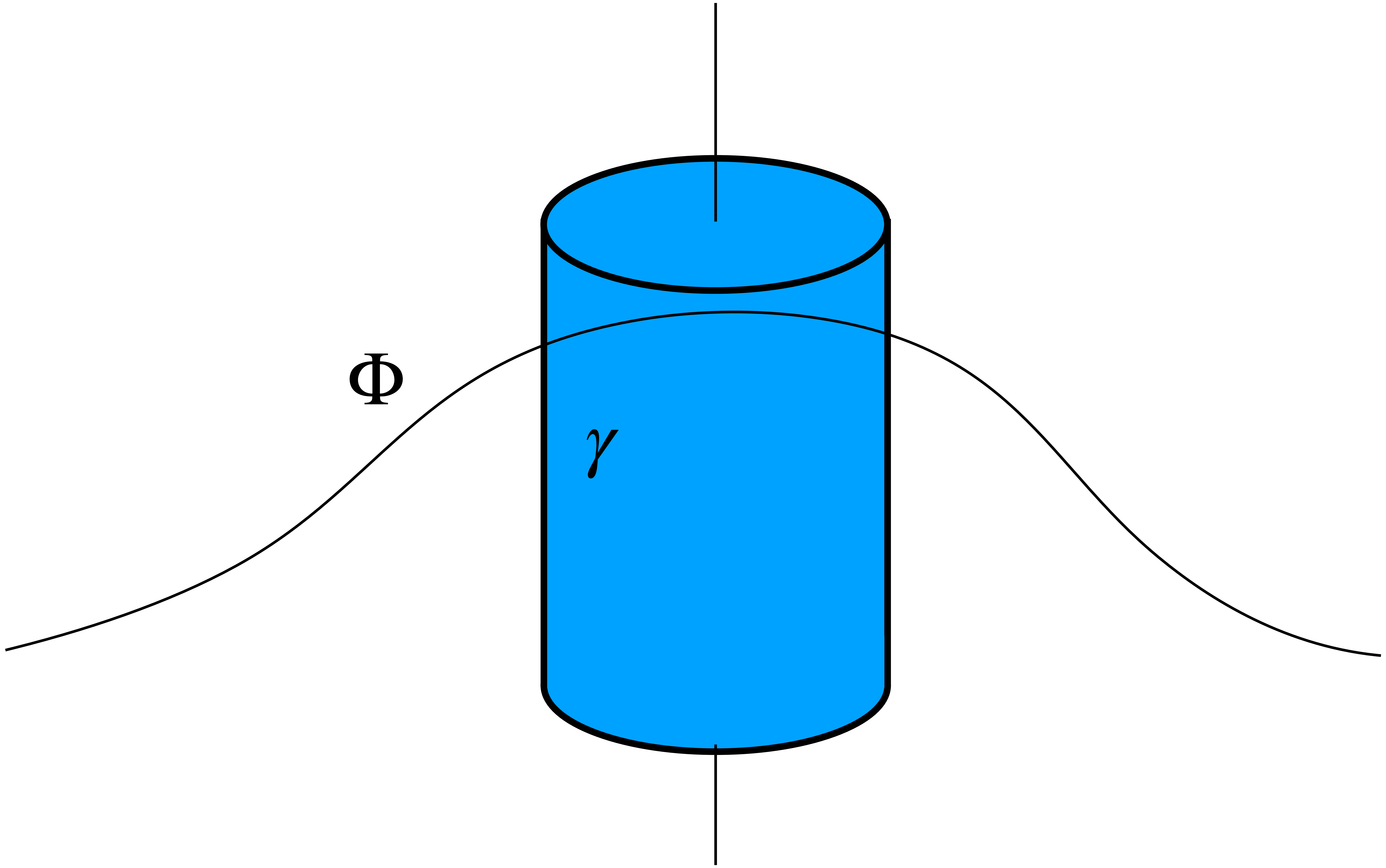
Axion Superradiance in Neutron Stars and Stellar Medium Effect

Hyeonseok Seong (HKUST)

in collaboration with
Zhaoyu Bai, Vitor Cardoso, Yifan Chen,
Yuyan Li, and Jamie I. McDonald

Rotational Superradiance

Zel’dovich (1971)



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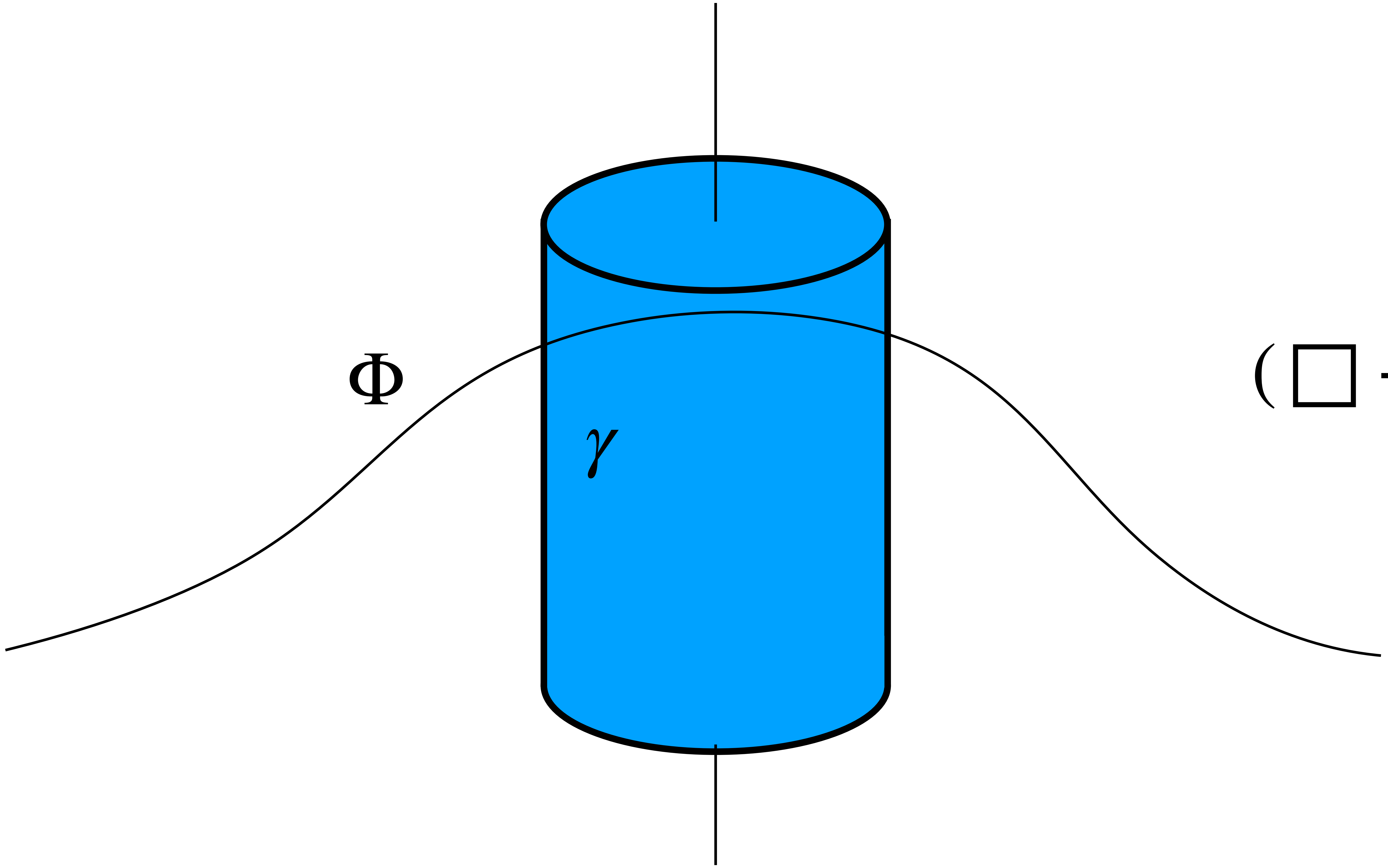

$$(\Box - \mu^2)\,\Phi + \gamma \frac{\partial \Phi}{\partial t_{\text{co-rot}}} = 0$$

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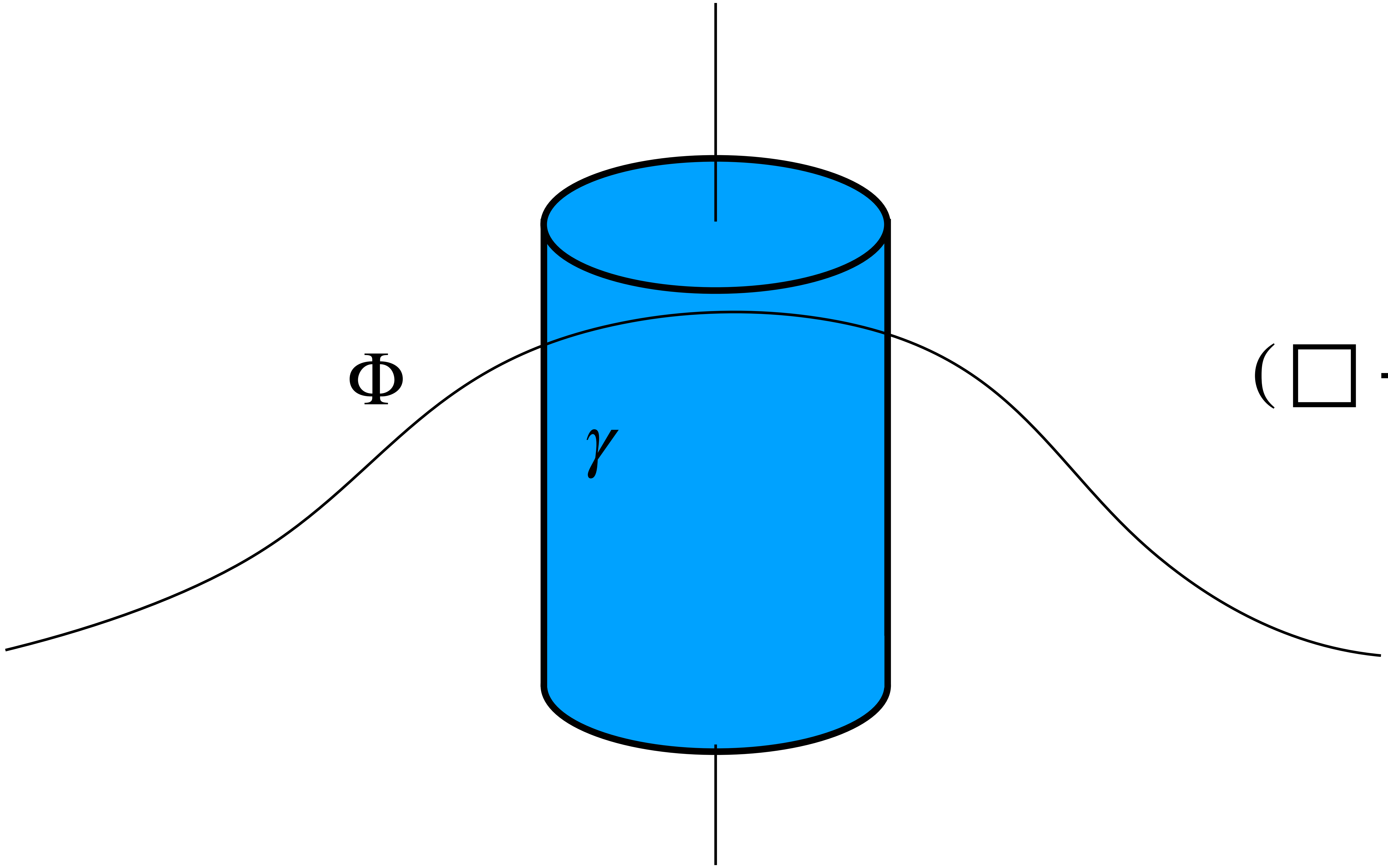

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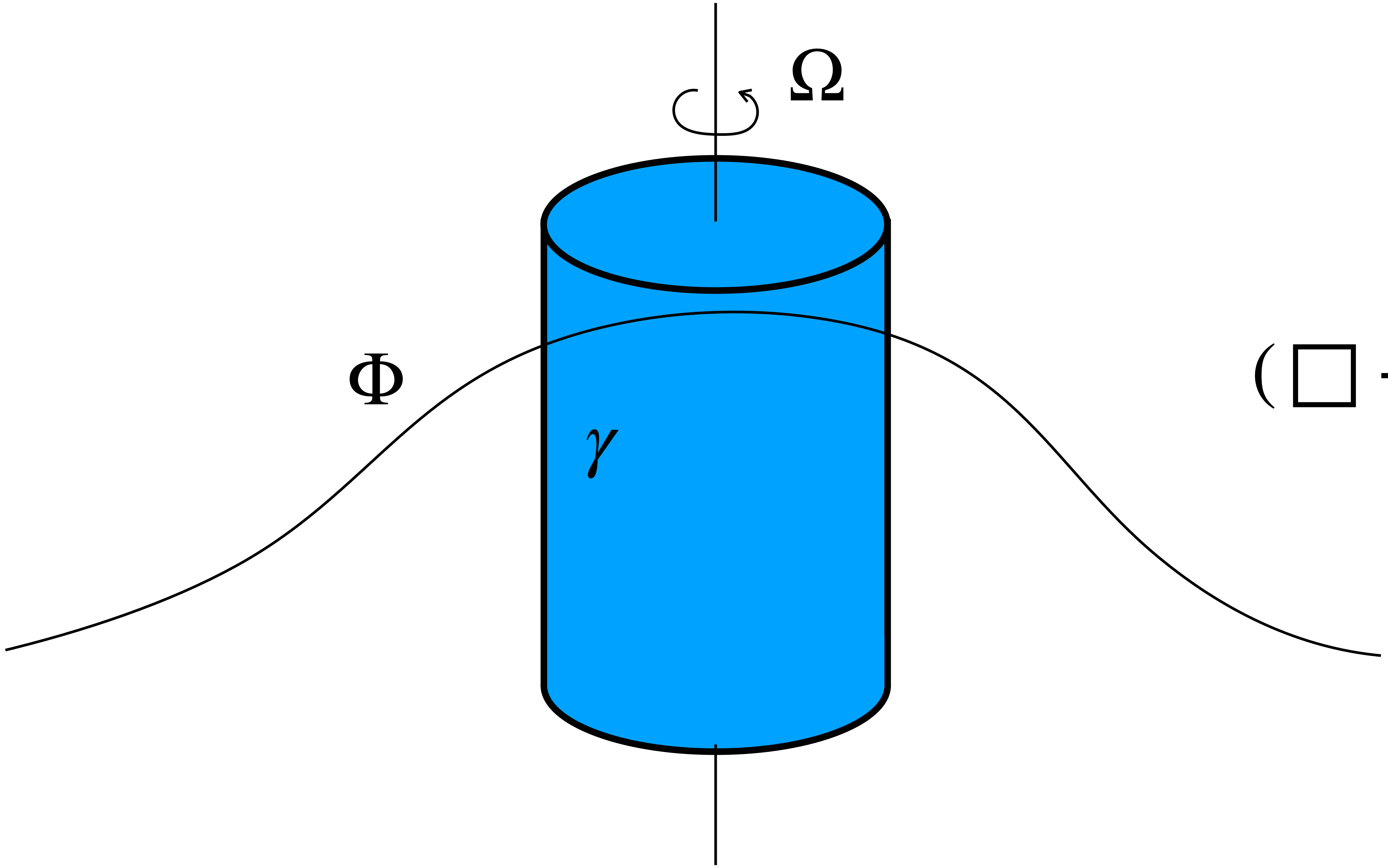

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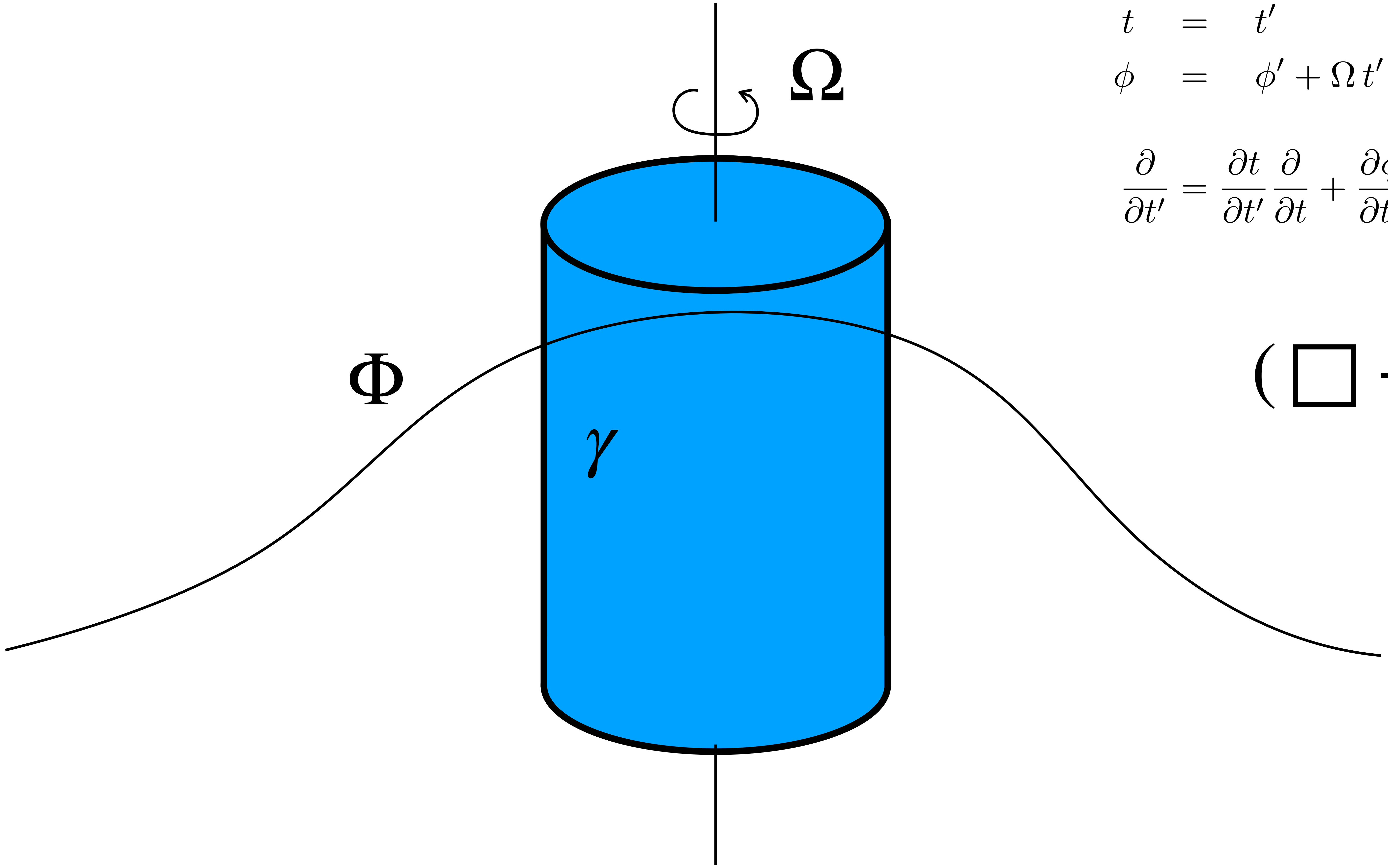

lab		co-rotating
t	$=$	t'
ϕ	$=$	$\phi' + \Omega\, t'$

$$\frac{\partial}{\partial t'} = \frac{\partial t}{\partial t'}\frac{\partial}{\partial t} + \frac{\partial \phi}{\partial t'}\frac{\partial}{\partial \phi} = \frac{\partial}{\partial t} + \Omega \frac{\partial}{\partial \phi}$$

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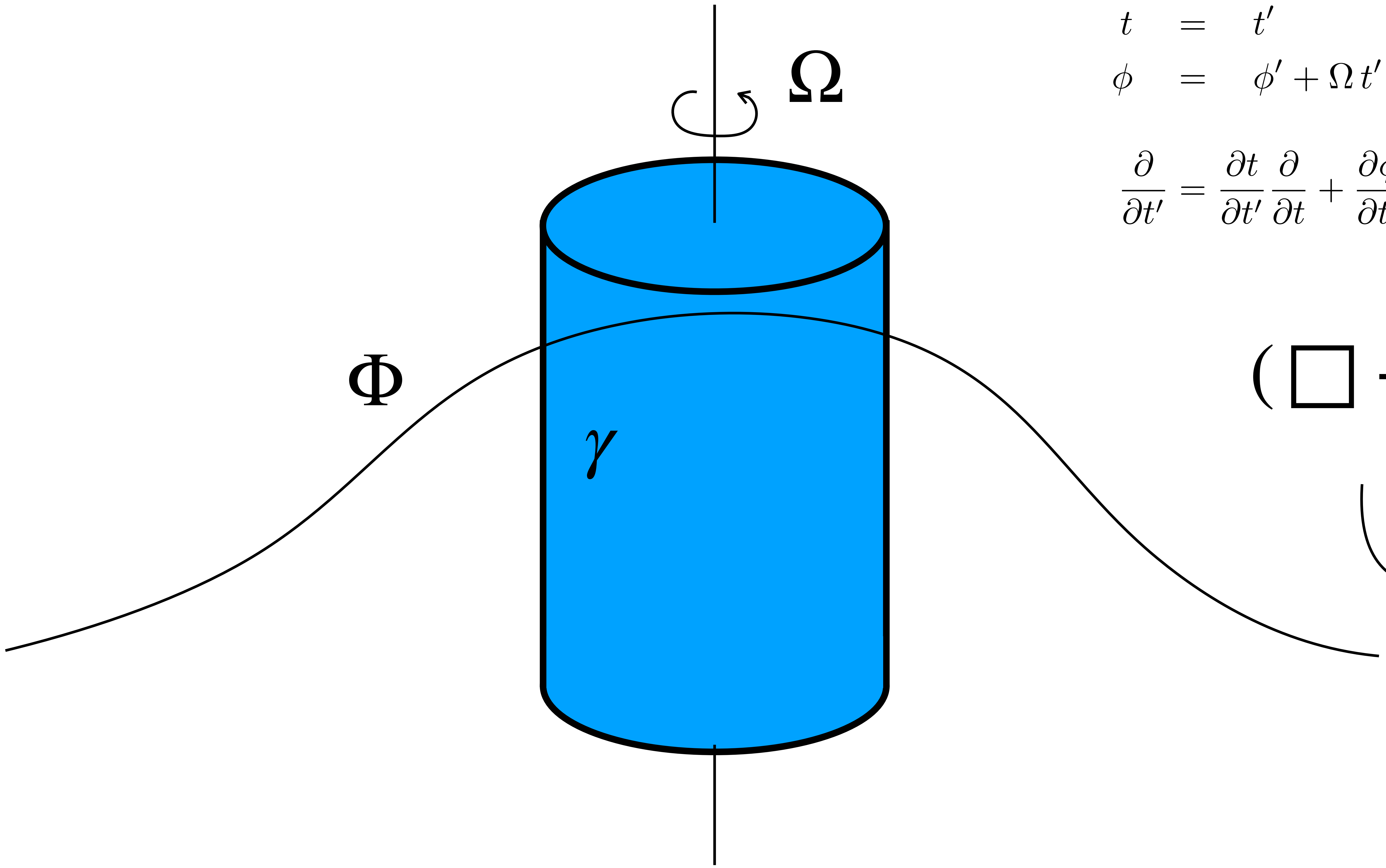

$$\begin{array}{ccl} \text{lab} & & \text{co-rotating} \\ t & = & t' \\ \phi & = & \phi' + \Omega\, t' \end{array}$$

$$\frac{\partial}{\partial t'} = \frac{\partial t}{\partial t'}\frac{\partial}{\partial t} + \frac{\partial \phi}{\partial t'}\frac{\partial}{\partial \phi} = \frac{\partial}{\partial t} + \Omega\frac{\partial}{\partial \phi}$$

$$(\Box - \mu^2)\,\Phi + \gamma\frac{\partial \Phi}{\partial t_{\text{co-rot}}} = 0$$

$$\Phi \propto e^{-i(\omega t - m\phi)} = e^{-i(\omega t' - m(\phi' + \Omega t'))}$$

Rotational Superradiance

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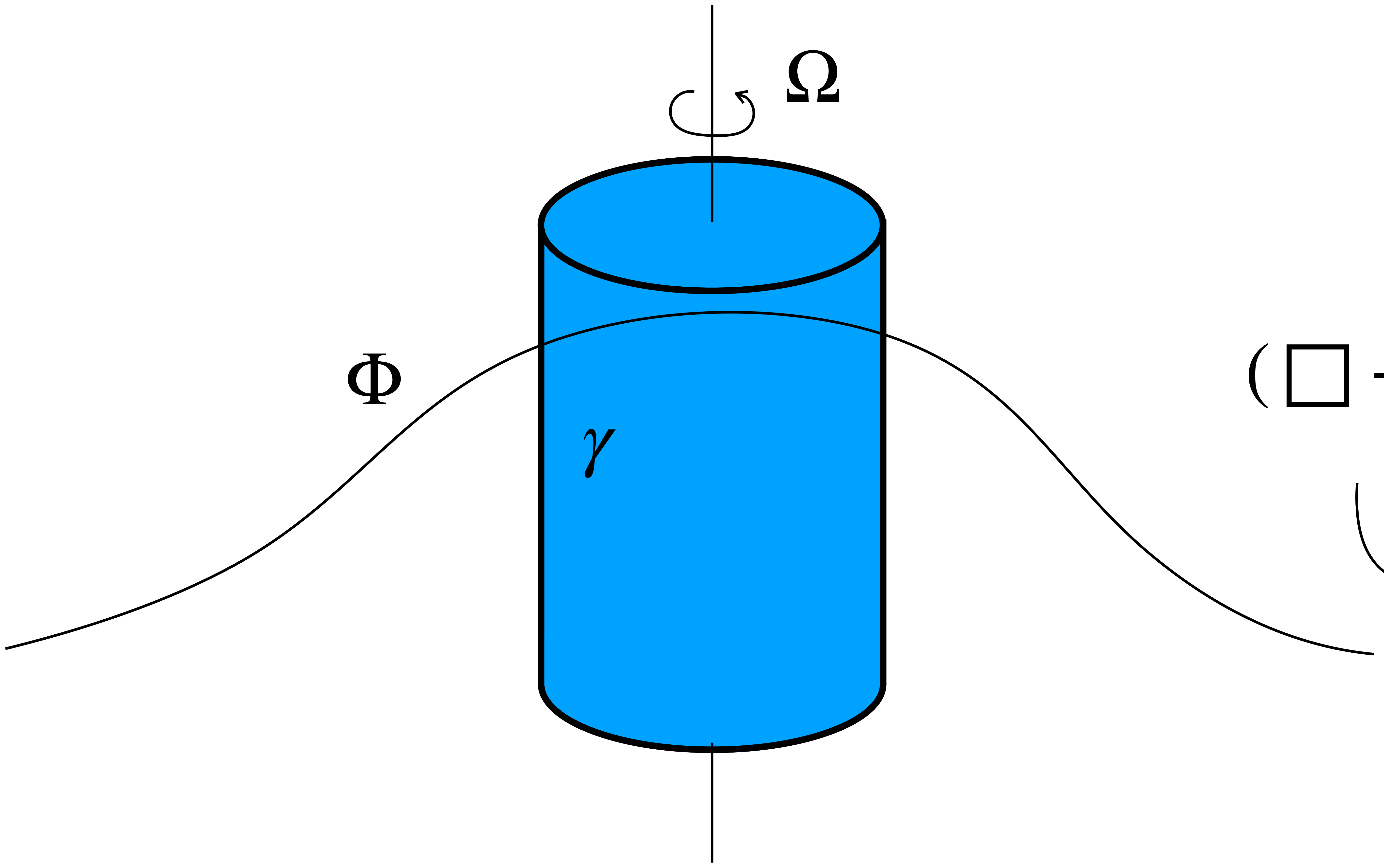

$$\omega \to \omega - m\Omega$$

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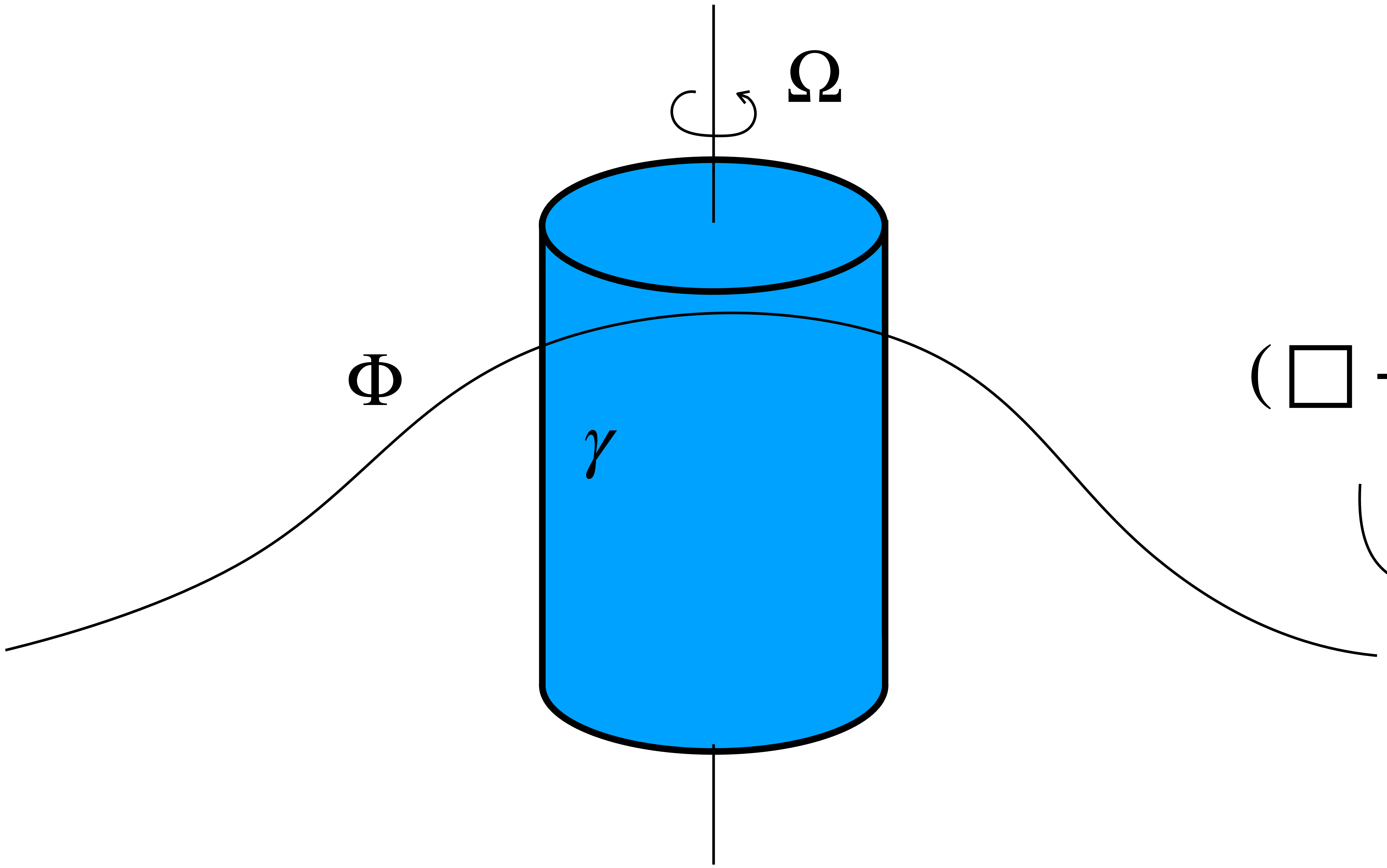

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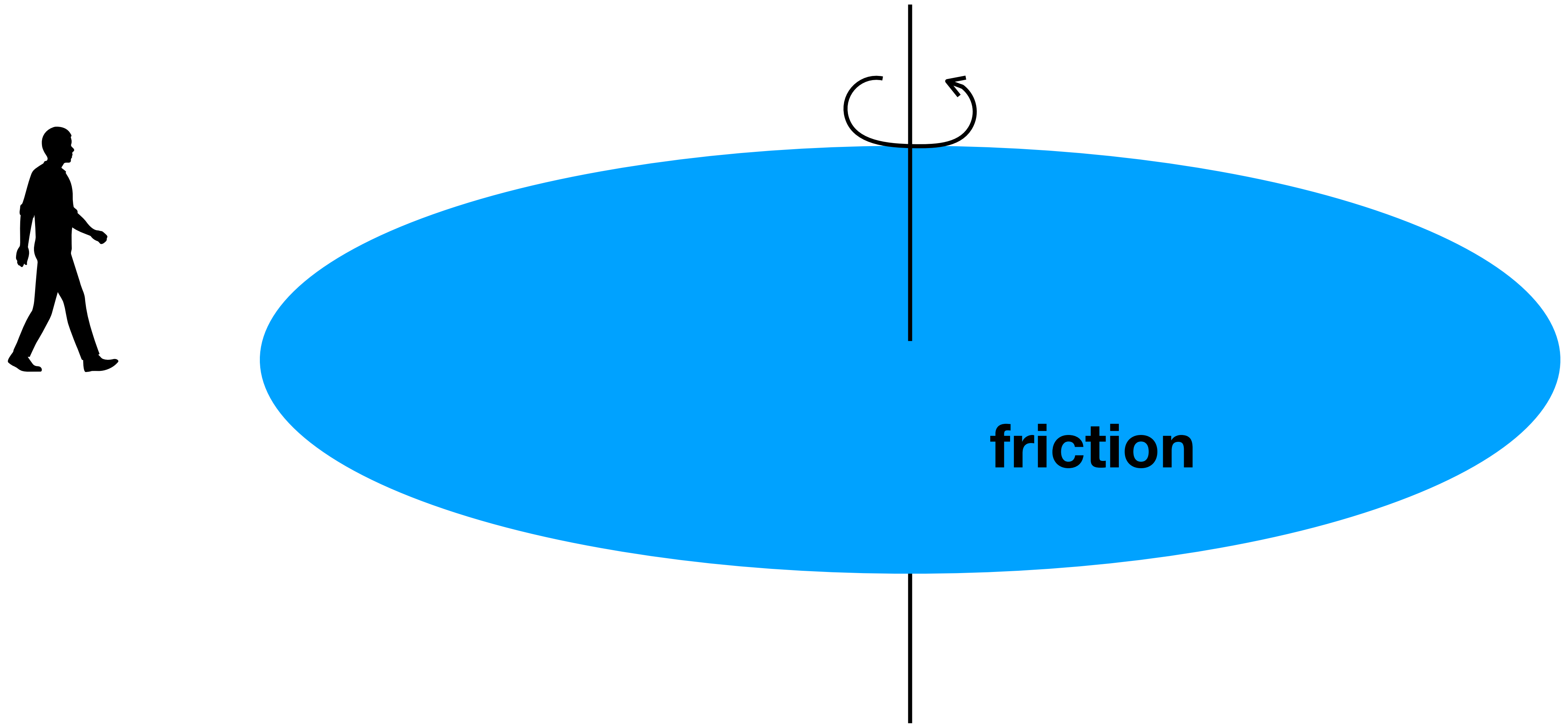
$m\Omega > \omega > 0$ (**sign flips**)

Rotational Superradiance



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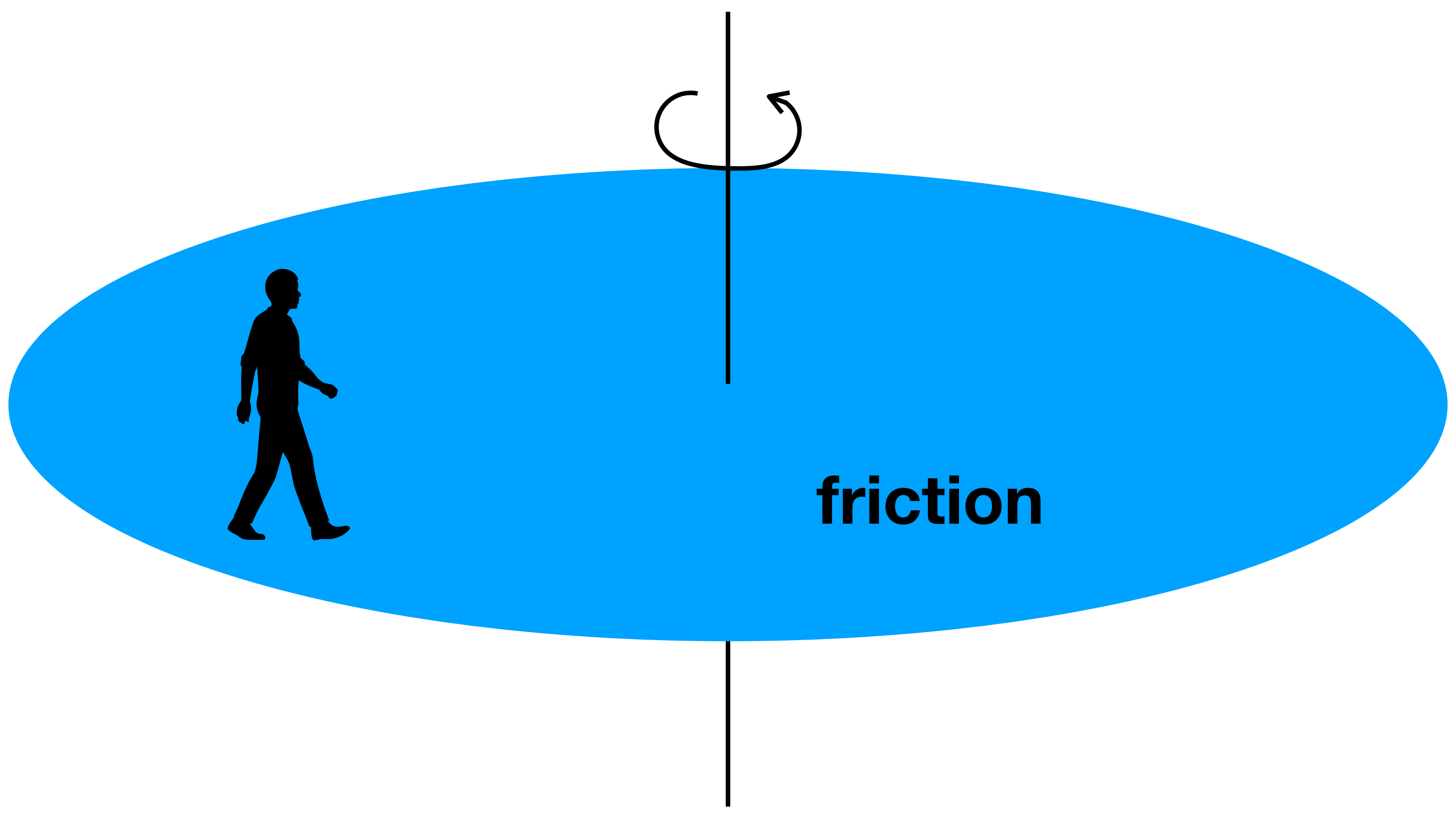

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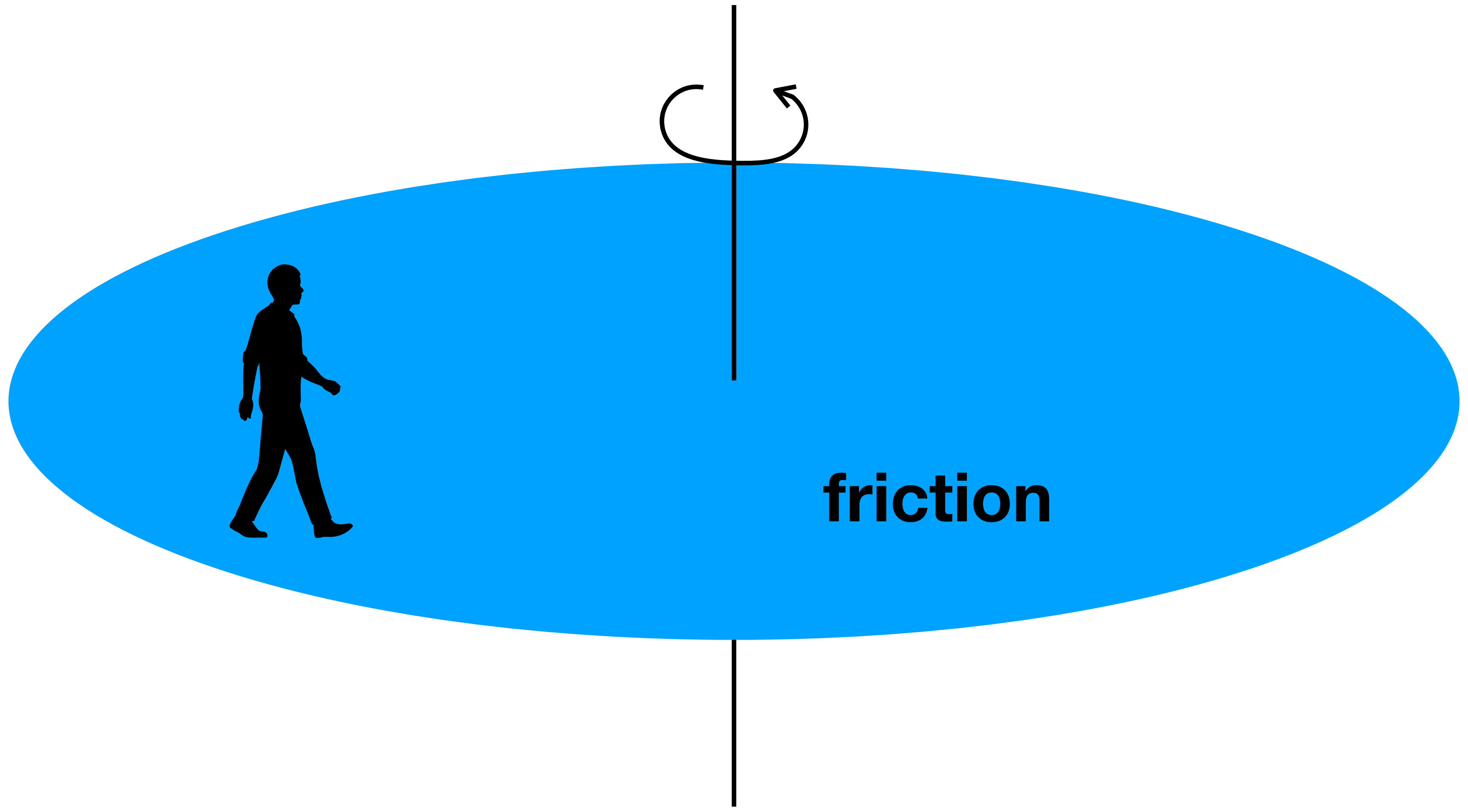
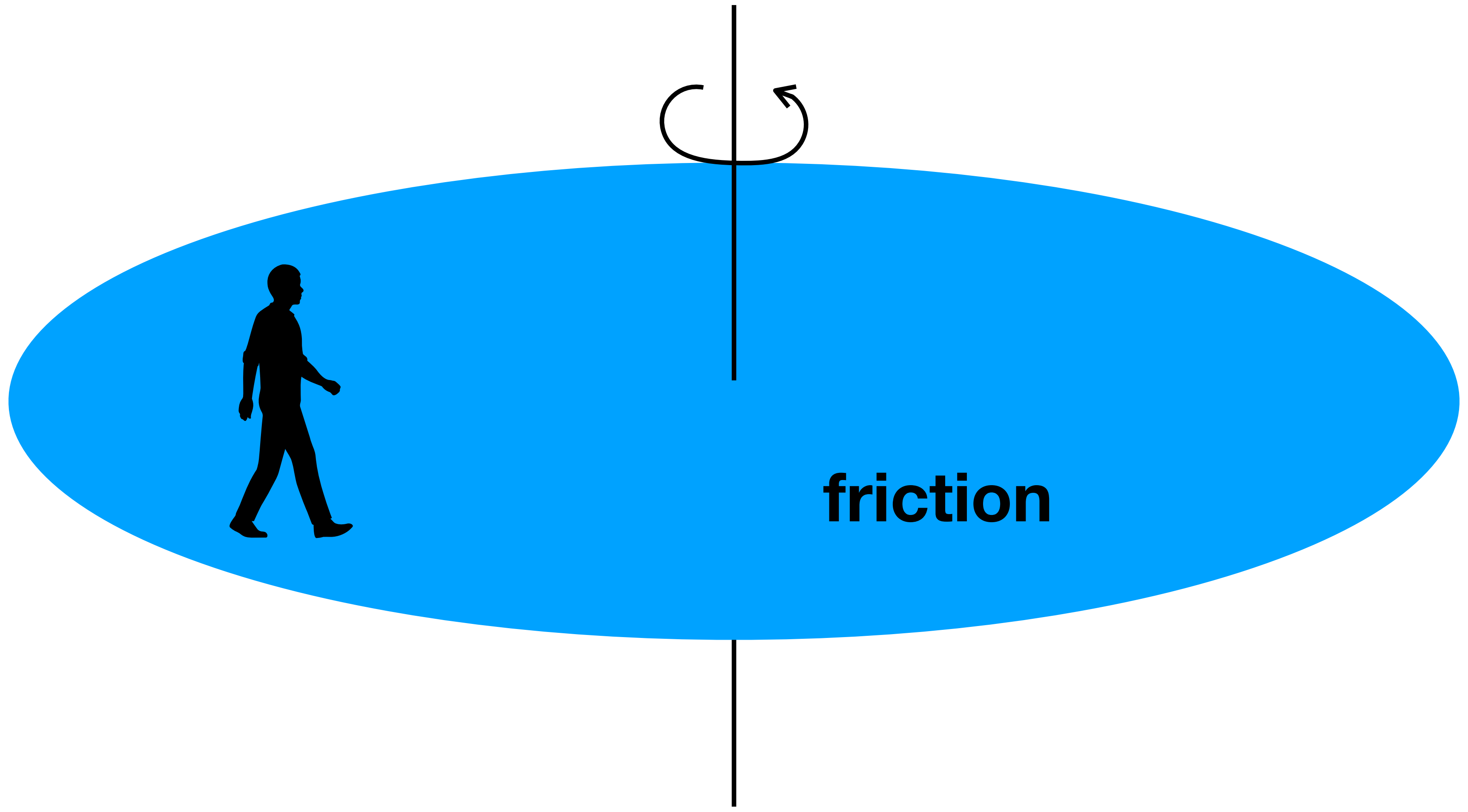


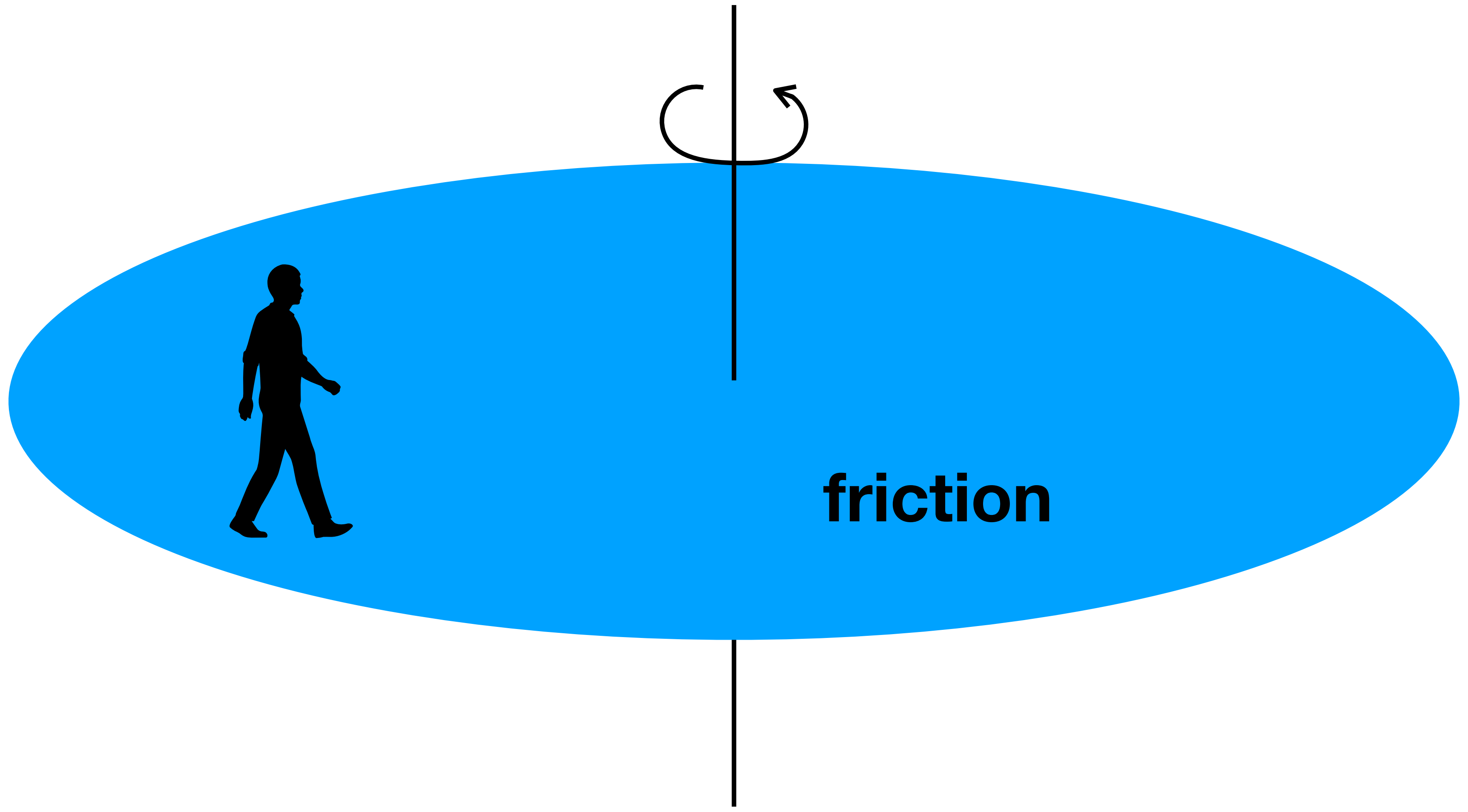
$$R\,\Omega > v_{\mathrm{obj}}$$

Rotational Superradiance



$$\Omega > v_{\mathrm{obj}}/R$$

Rotational Superradiance



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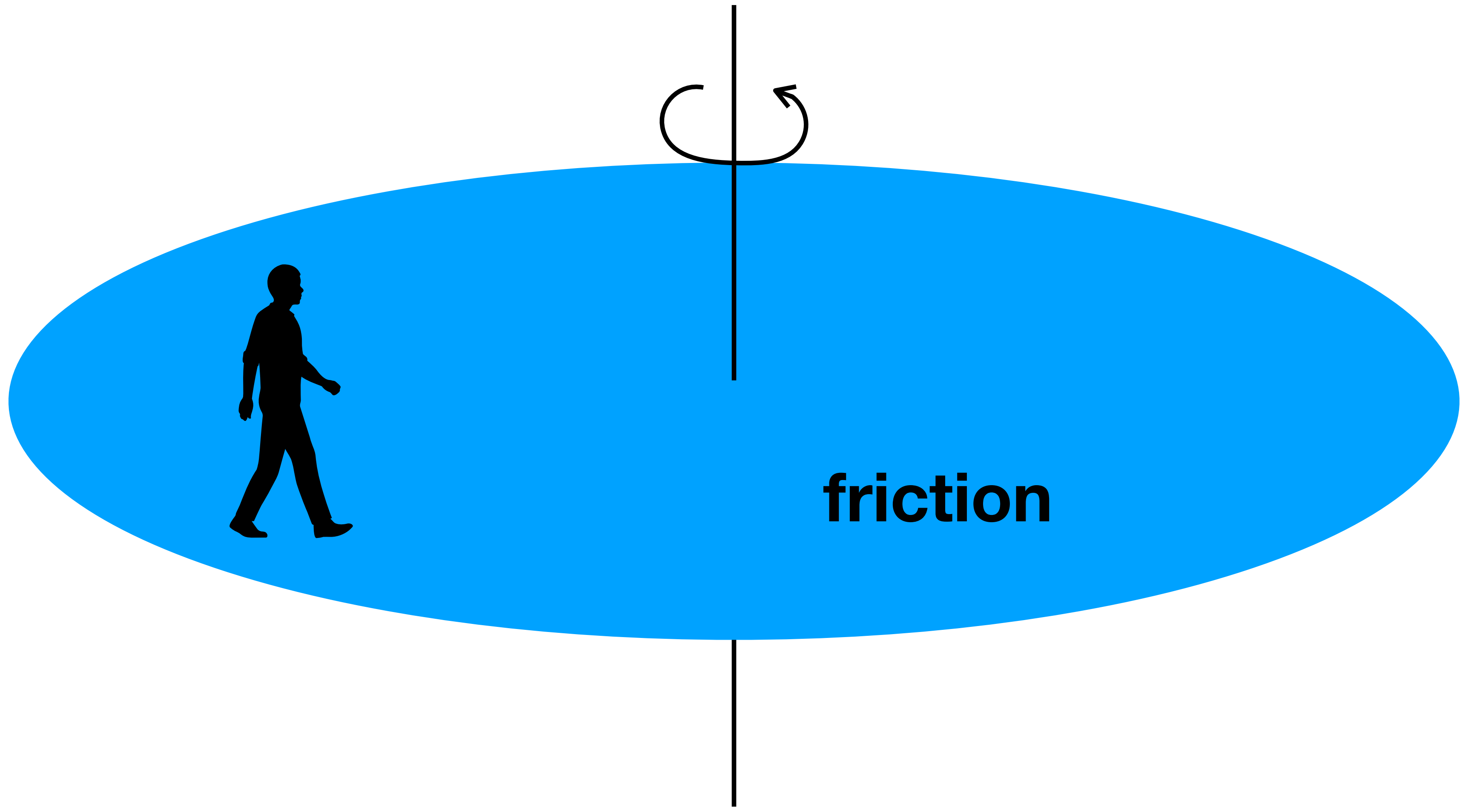

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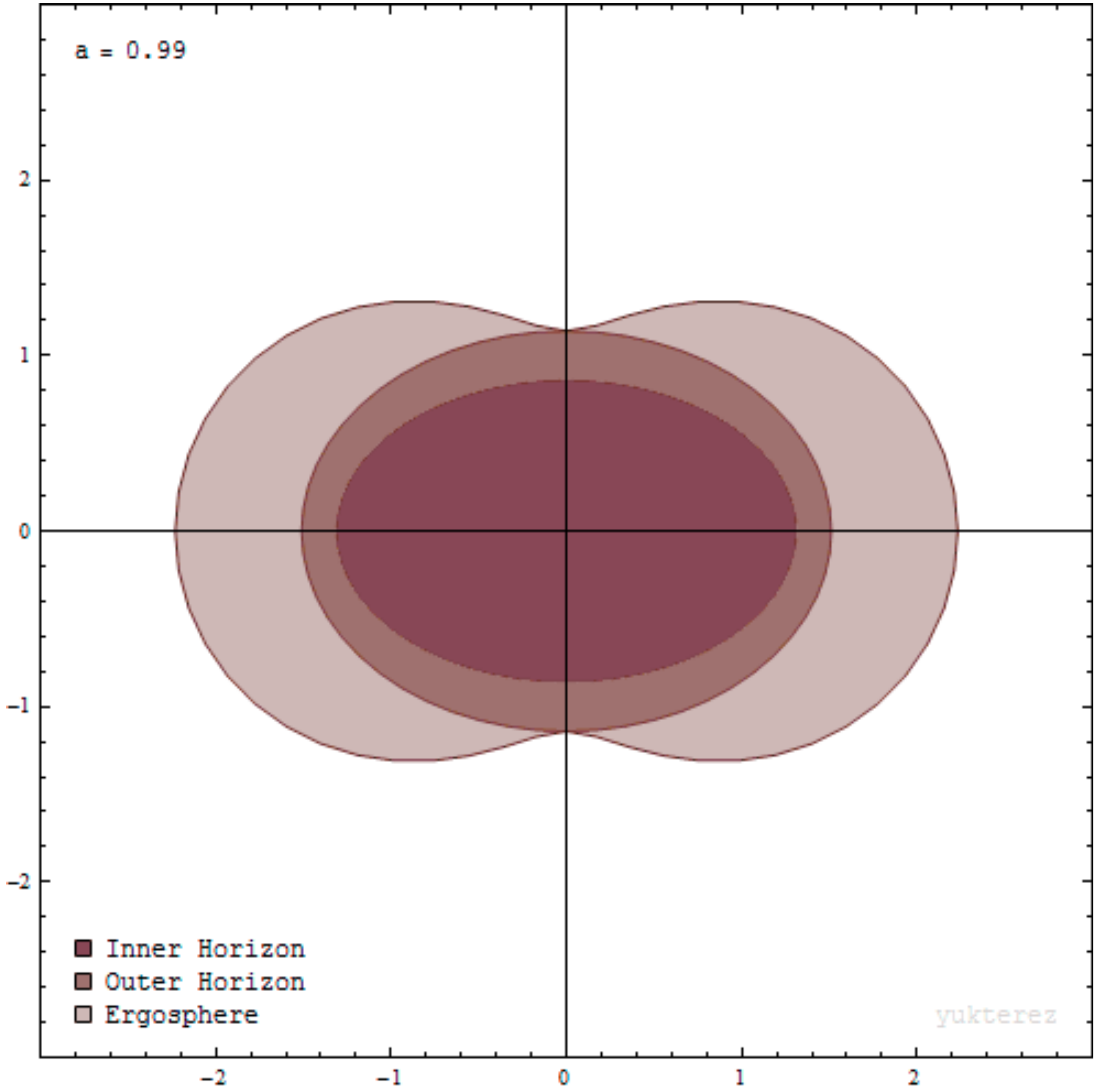
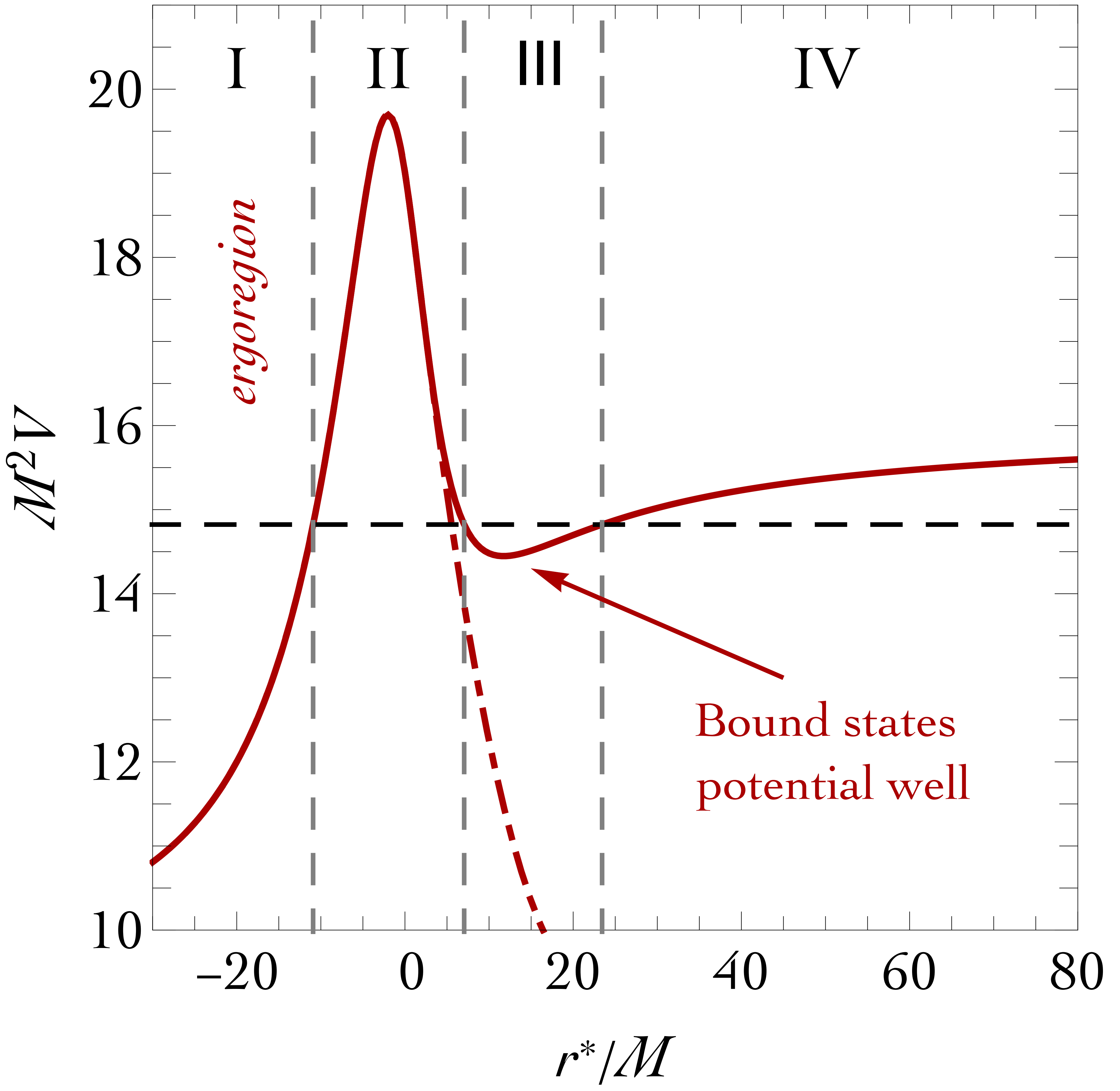
Black hole superradiance



[Wiki]

Black hole superradiance



Plascencia and Urbano, [1711.08298]

Press and Teukolsky, `72

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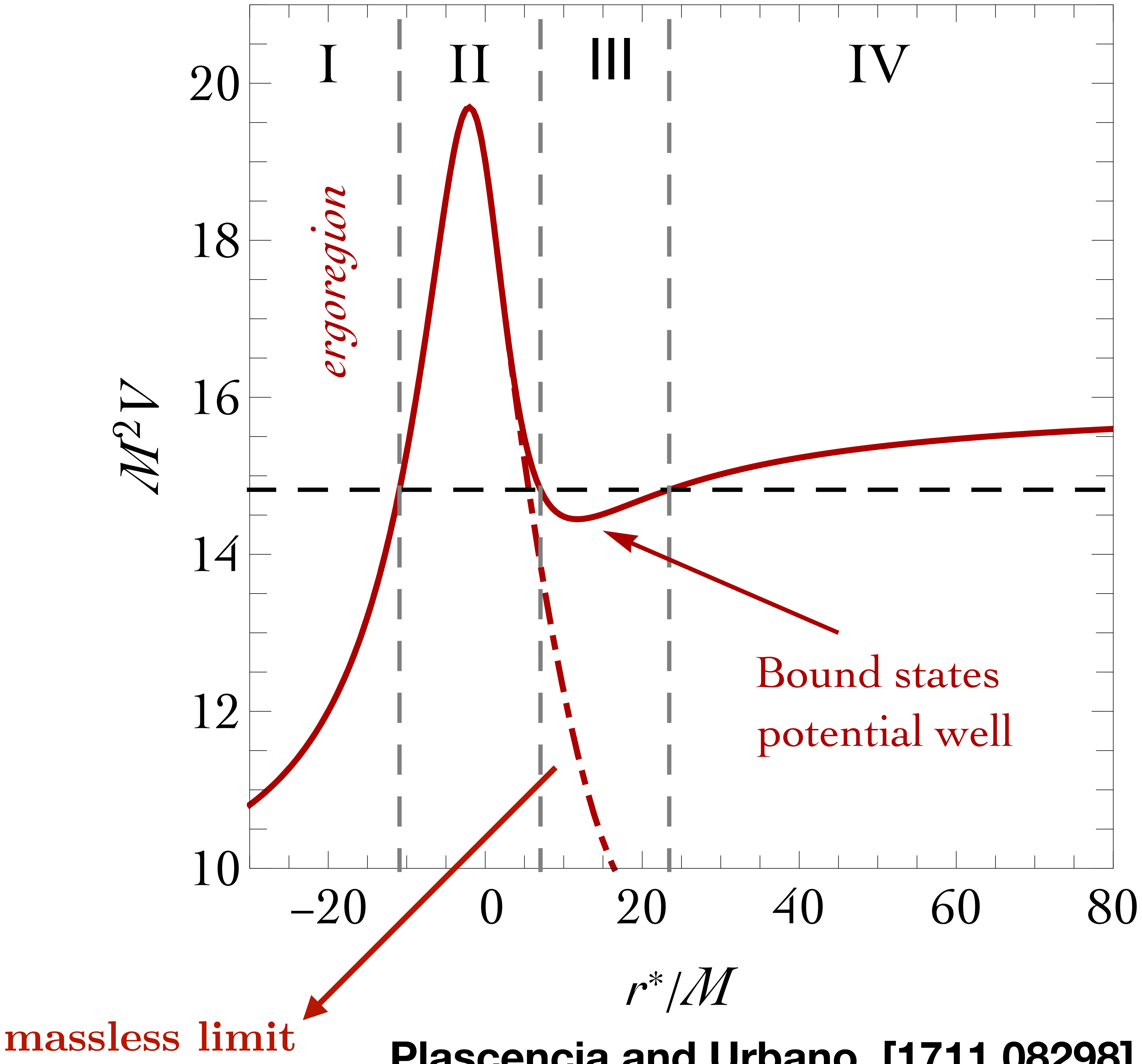

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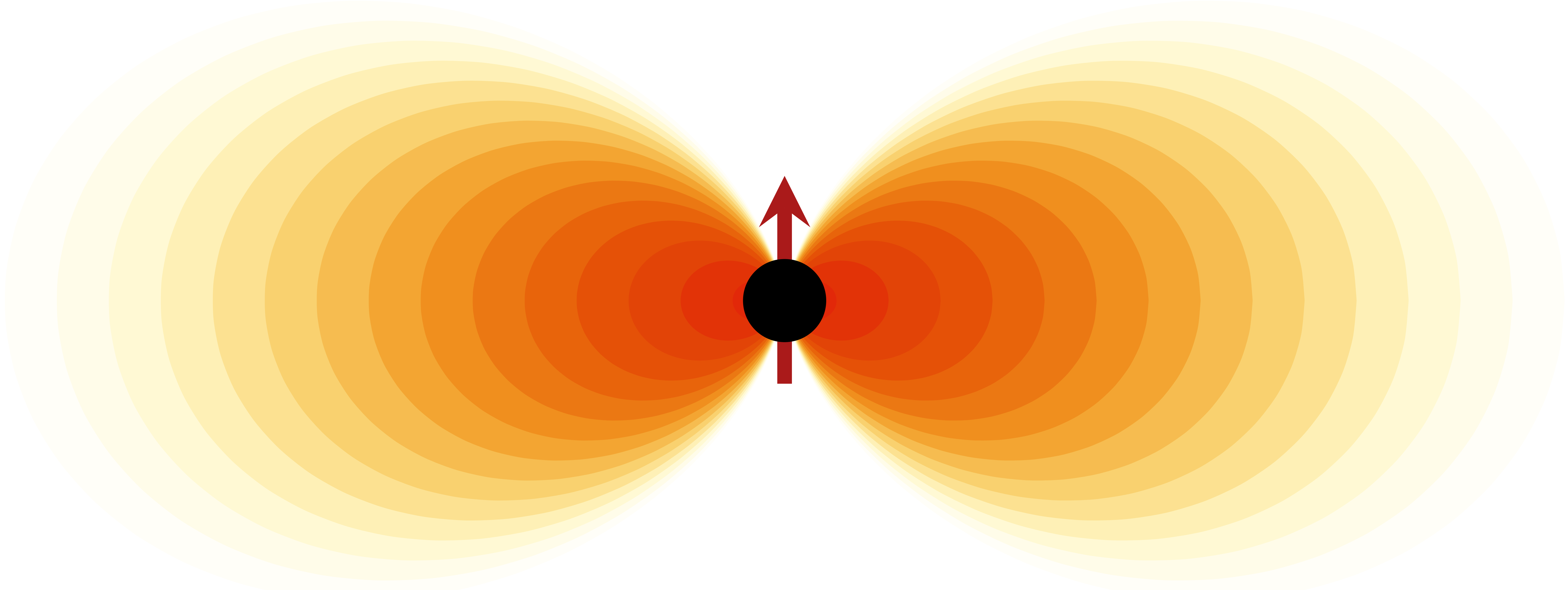
Gravitational atom

$$(\Box - \mu^2)\,\Phi = 0$$



Baumann et al., [1908.10370]

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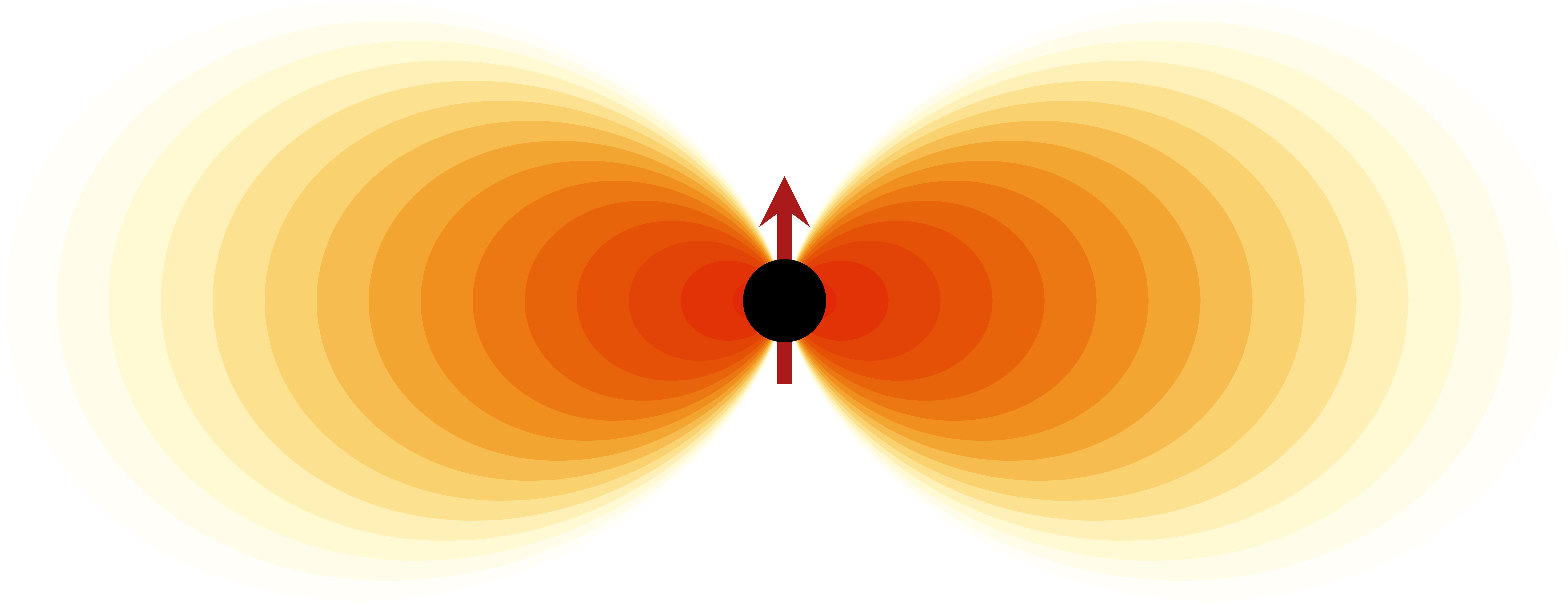

$\alpha \equiv GM\mu \ll 1$ **(non-rel limit)**

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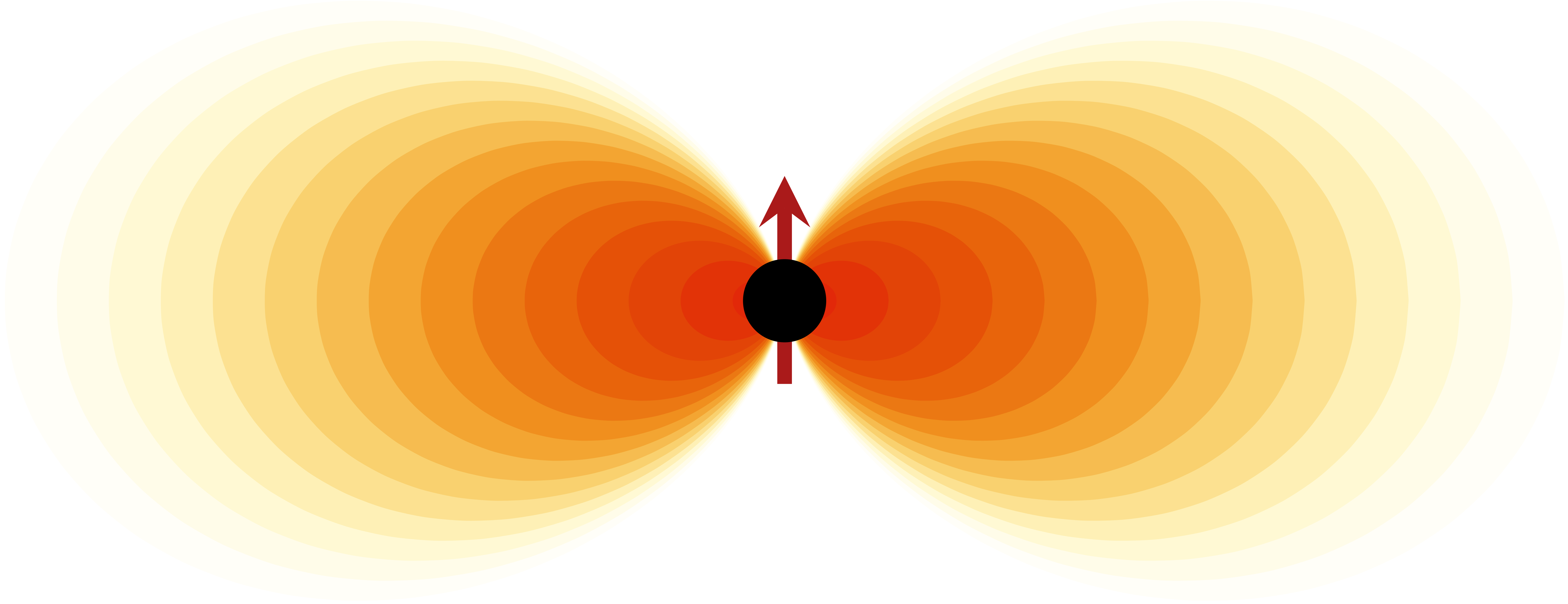

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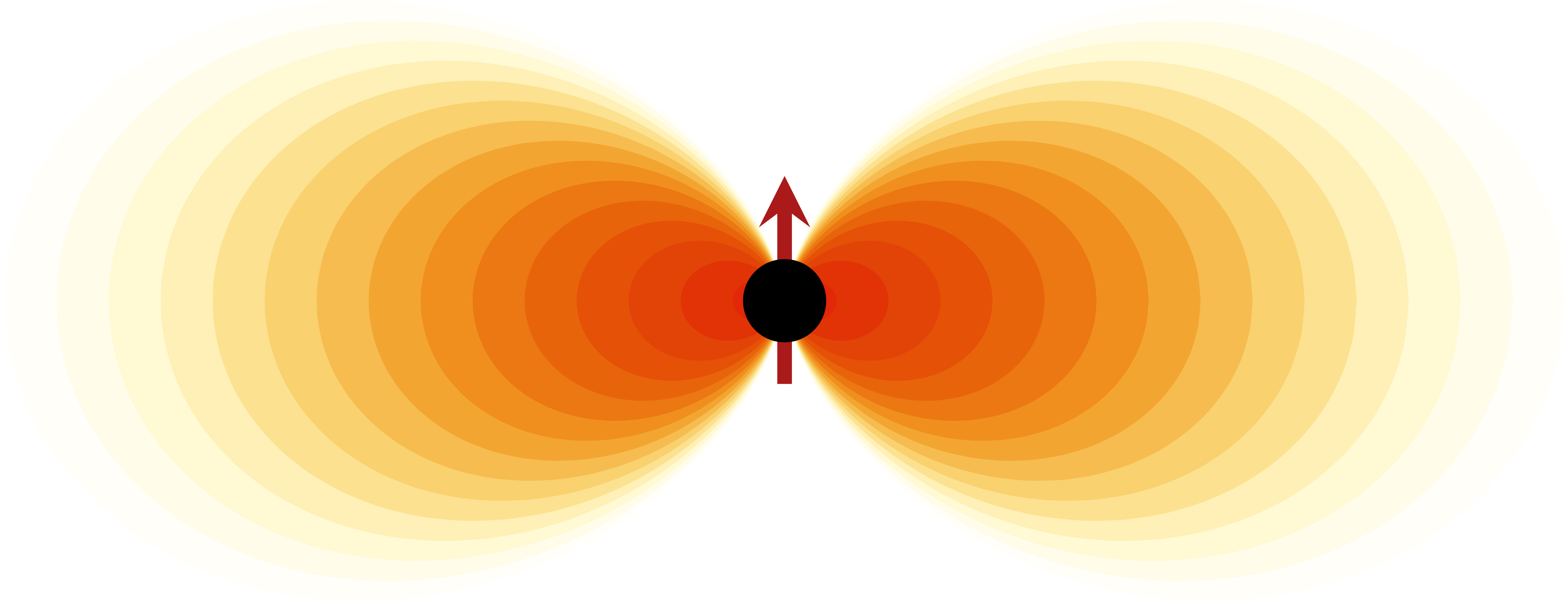

$$\alpha \equiv GM\mu \ll 1$$ **(non-rel limit)**

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$$r \gg GM$$

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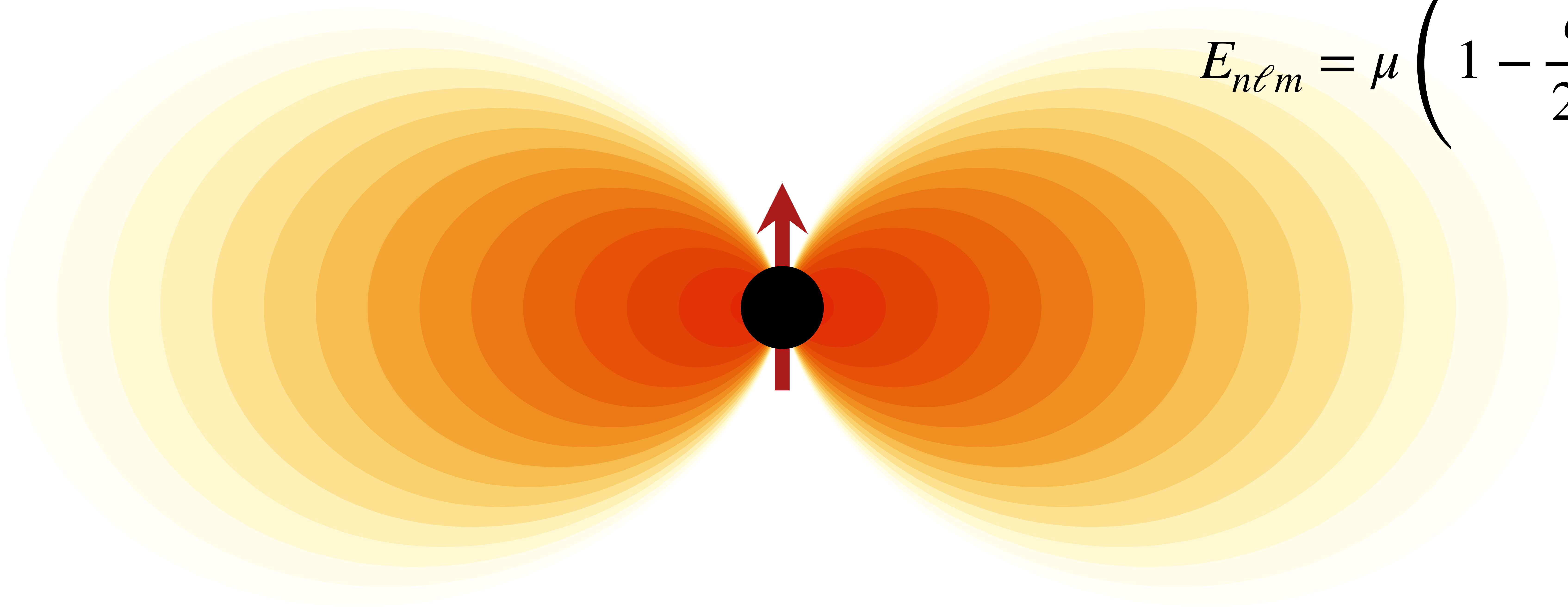
Gravitational atom

$$E_{n\ell m} = \mu\left(1 - \frac{\alpha^2}{2n^2} - \mathcal{O}(\alpha^4)\right)$$



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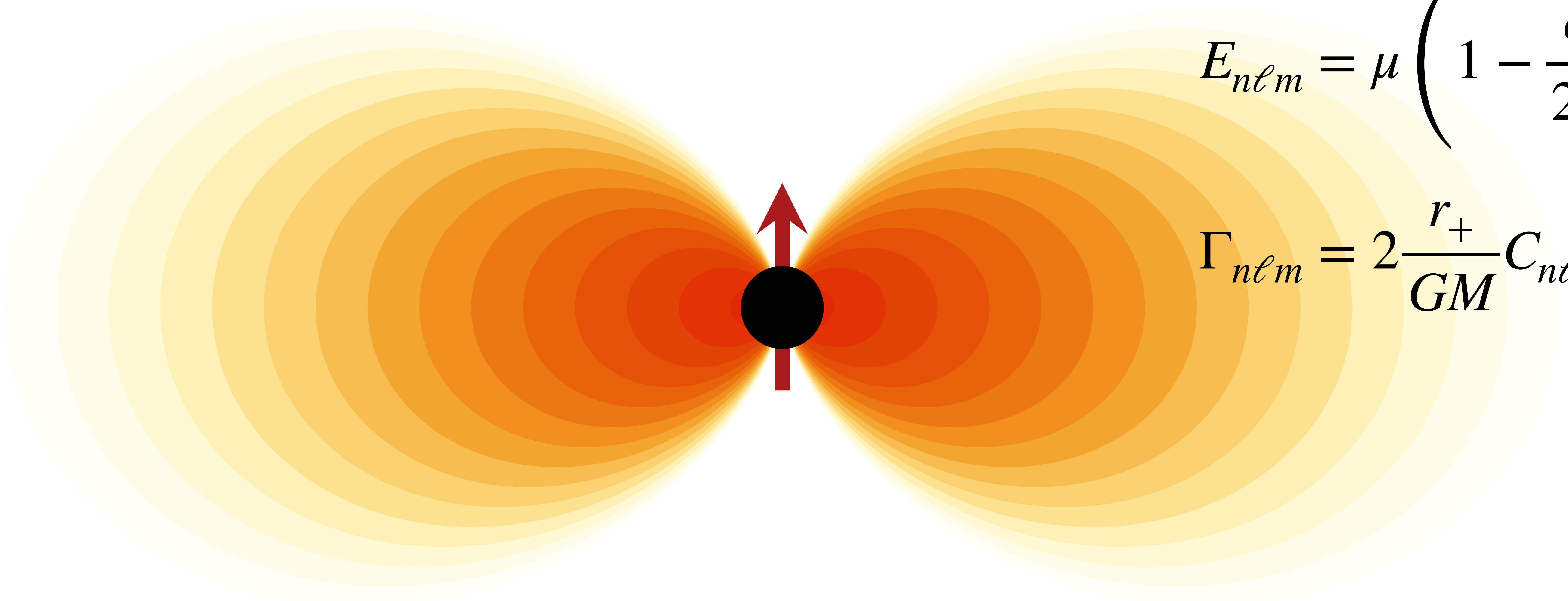


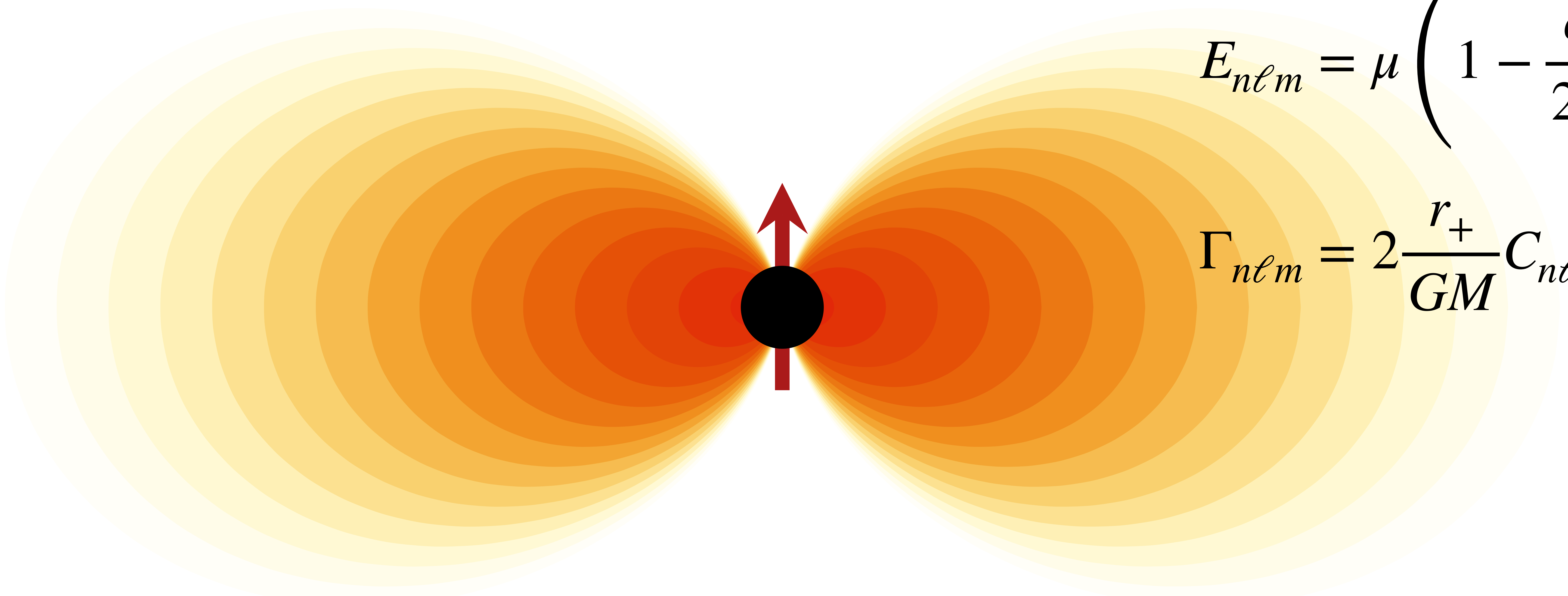
$$E_{n\ell m} = \mu\left(1 - \frac{\alpha^2}{2n^2} - \mathcal{O}(\alpha^4)\right)$$

$$\Gamma_{n\ell m} = 2\frac{r_+}{GM}C_{n\ell}g_{\ell m}(\tilde{a}, \alpha, E_{n\ell m})\,(m\Omega_H - E_{n\ell m})\,\alpha^{4\ell+5}$$

$$\Omega_H = \frac{\tilde{a}}{2r_+}$$

Baumann et al., [1908.10370]

Gravitational atom



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Phenomenology

List of Questions

- What are the observables?

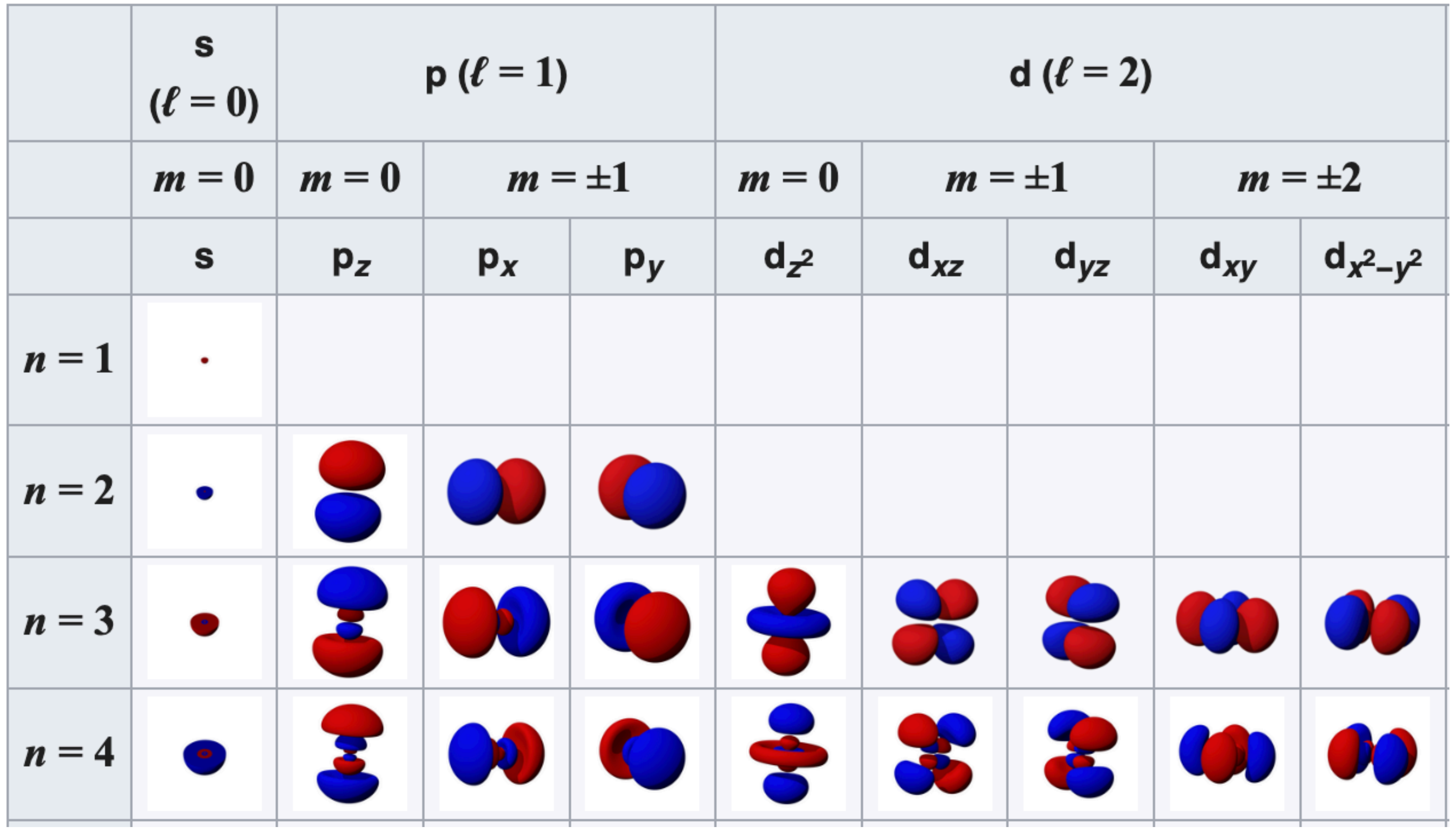
  $\Rightarrow$ BH spin-mass distribution, GWs from clouds

- Similarities to atomic physics?

  $\Rightarrow$ (hyper-)fine structures, transitions

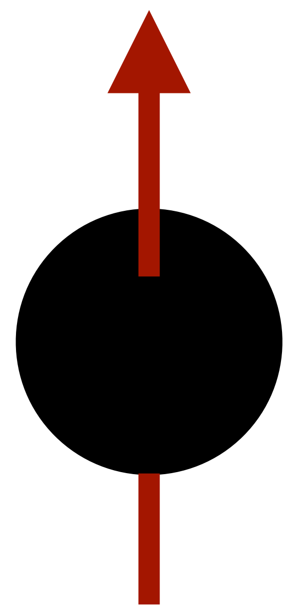
- Relevant BSM particles?

  $\Rightarrow$ Axion-like particles, dark photons



[Wiki]

Phenomenology



S. R. Dolan, [0705.2880]

A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, [0905.4720]

A. Arvanitaki and S. Dubovsky, [1004.3558]

M. J. Stott and D. J. E. Marsh, [1805.02016]

D. Baumann, H. S. Chia, J. Stout and L. ter Haar, [1908.10370]

M. Baryakhtar, M. Galanis, R. Lasenby, and O. Simon, [2011.11646]

Y. Chen, X. Xue, R. Brito, V. Cardoso, [2211.03794]

T. F.M. Spieksma, E. Cannizzaro, T. Ikeda, V. Cardoso, Y. Chen, [2306.16447]

S. J. Witte, A. Mummery, [2412.03655]

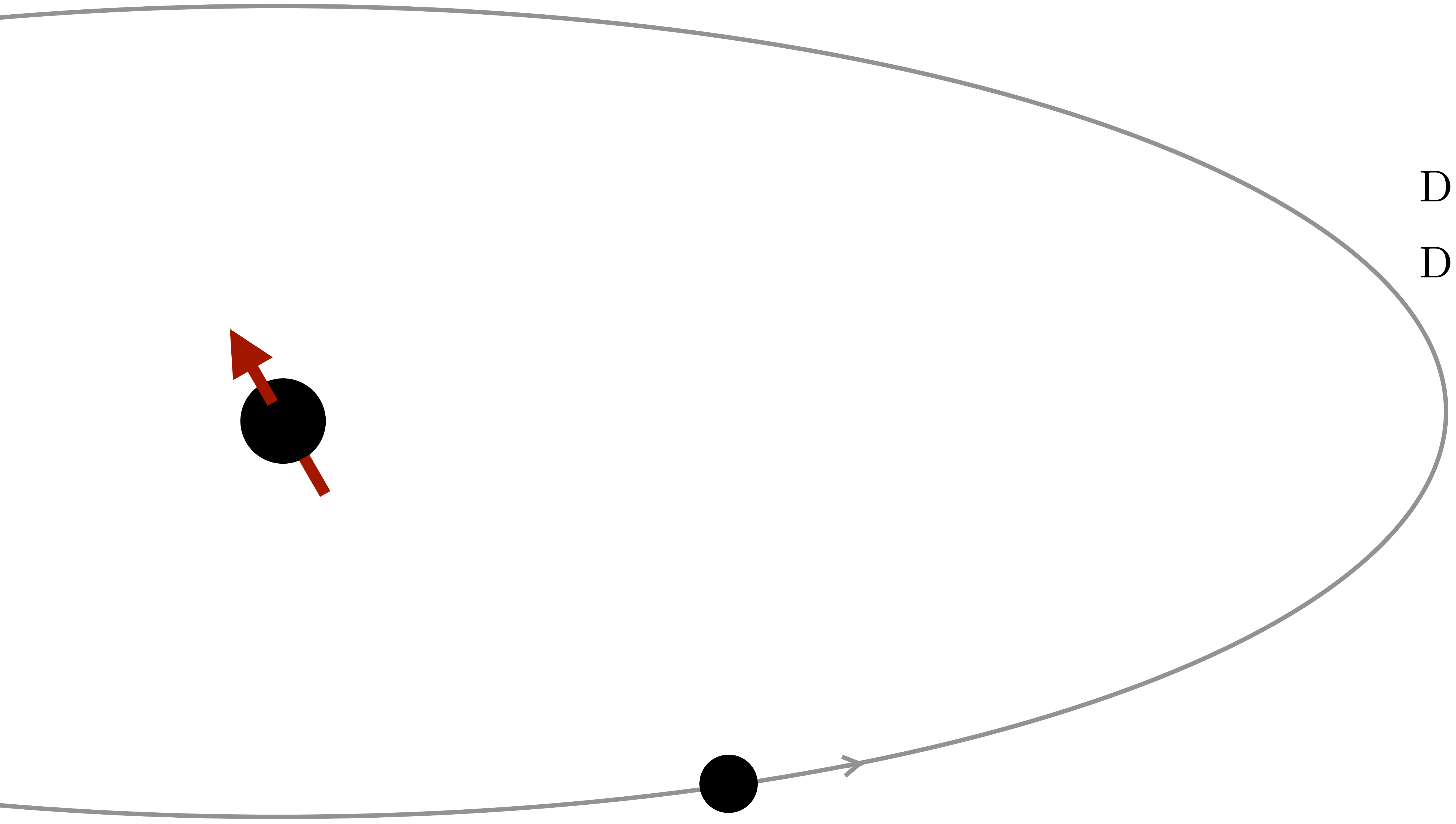
A. Caputo, G. Franciolini, S. J. Witte, [2507.21788]

L. Fu, H. Omiya, T. Tanaka, X. Tong, Y. Wang, and H.-Y. Zhu, [2512.06790]

...

Review paper: R. Brito, V. Cardoso, P. Pani, [1501.06570]

Phenomenology



D. Baumann, H. S. Chia, and R. A. Porto, [1804.03208]

D. Baumann, H. S. Chia, R. A. Porto, and J. Stout, [1912.04932]

D. Baumann, G. Bertone, J. Stout, and G. M. Tomaselli, [2112.14777]

D. Baumann, G. Bertone, J. Stout, and G. M. Tomaselli, [2206.01212]

G. M. Tomaselli, T. F.M. Spieksma, and G. Bertone, [2305.15460]

K. Fan, X. Tong, Y. Wang, H.-Y. Zhu, [2311.17013]

M. Bošković, M. Koschnitzke, and R. A. Porto, [2403.02415]

G. M. Tomaselli, T. F.M. Spieksma, and G. Bertone, [2403.03147]

G. M. Tomaselli, T. F.M. Spieksma, and G. Bertone, [2407.12908]

H. Kim, A. Lenoci, [2508.08367]

...

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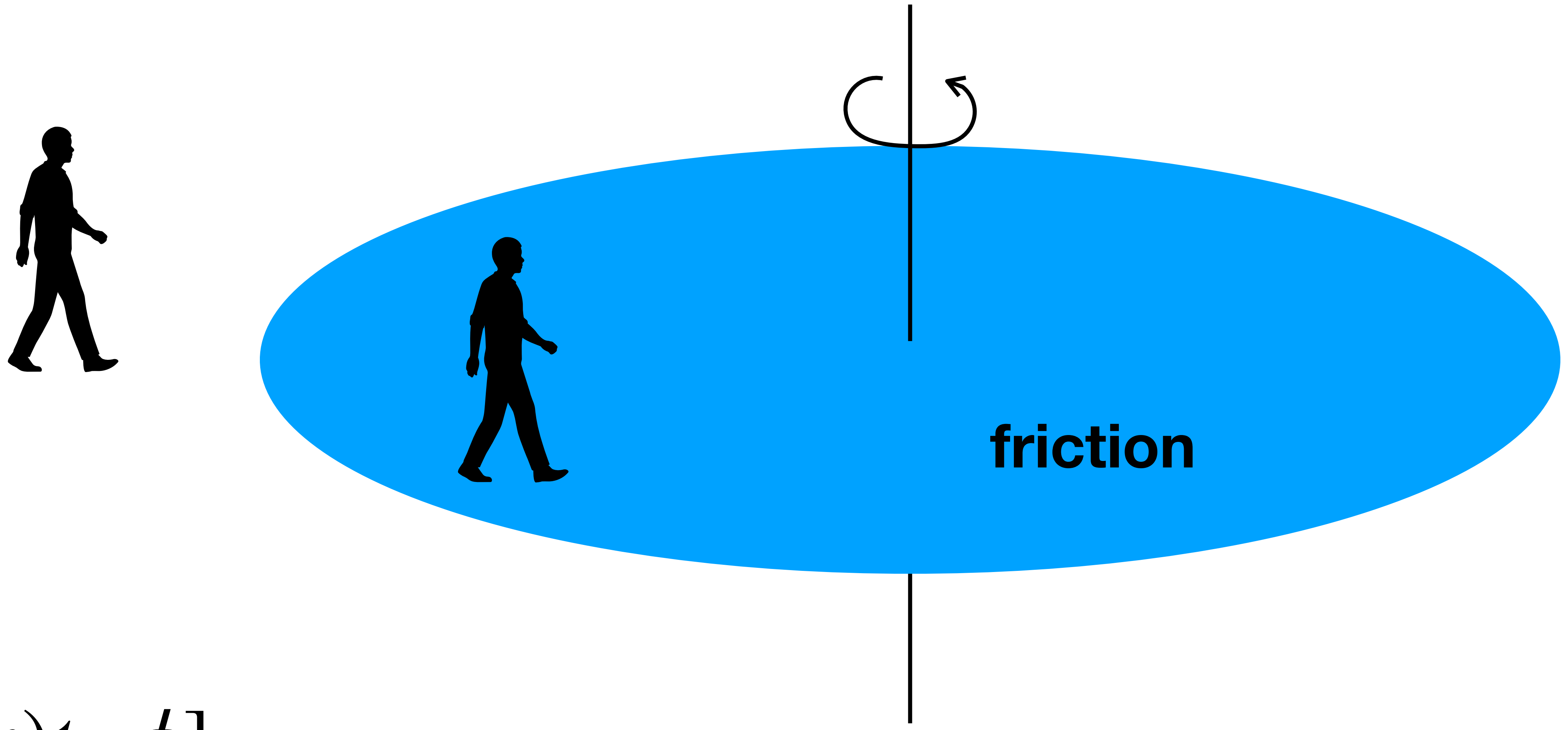

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$$\Omega > \omega/m$$

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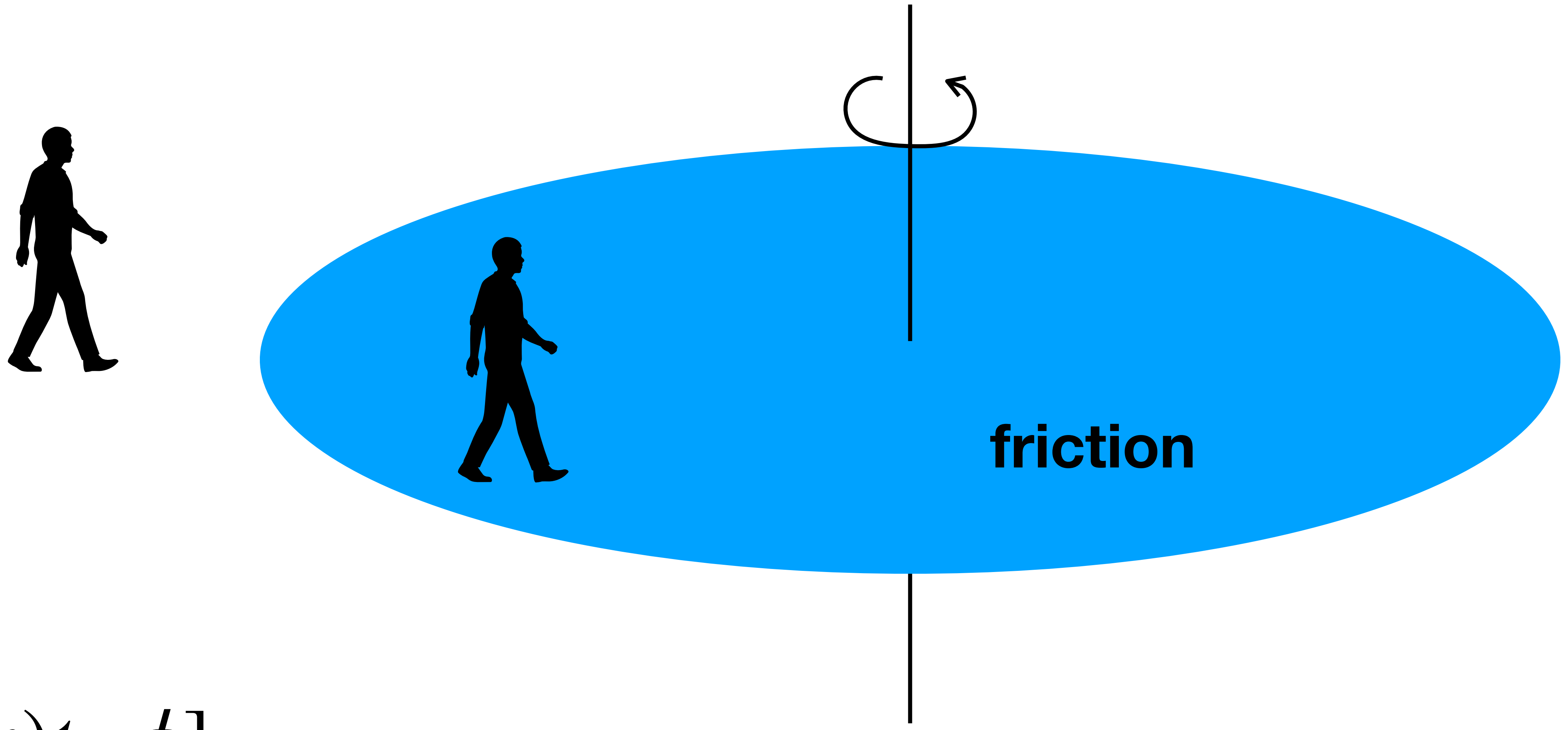

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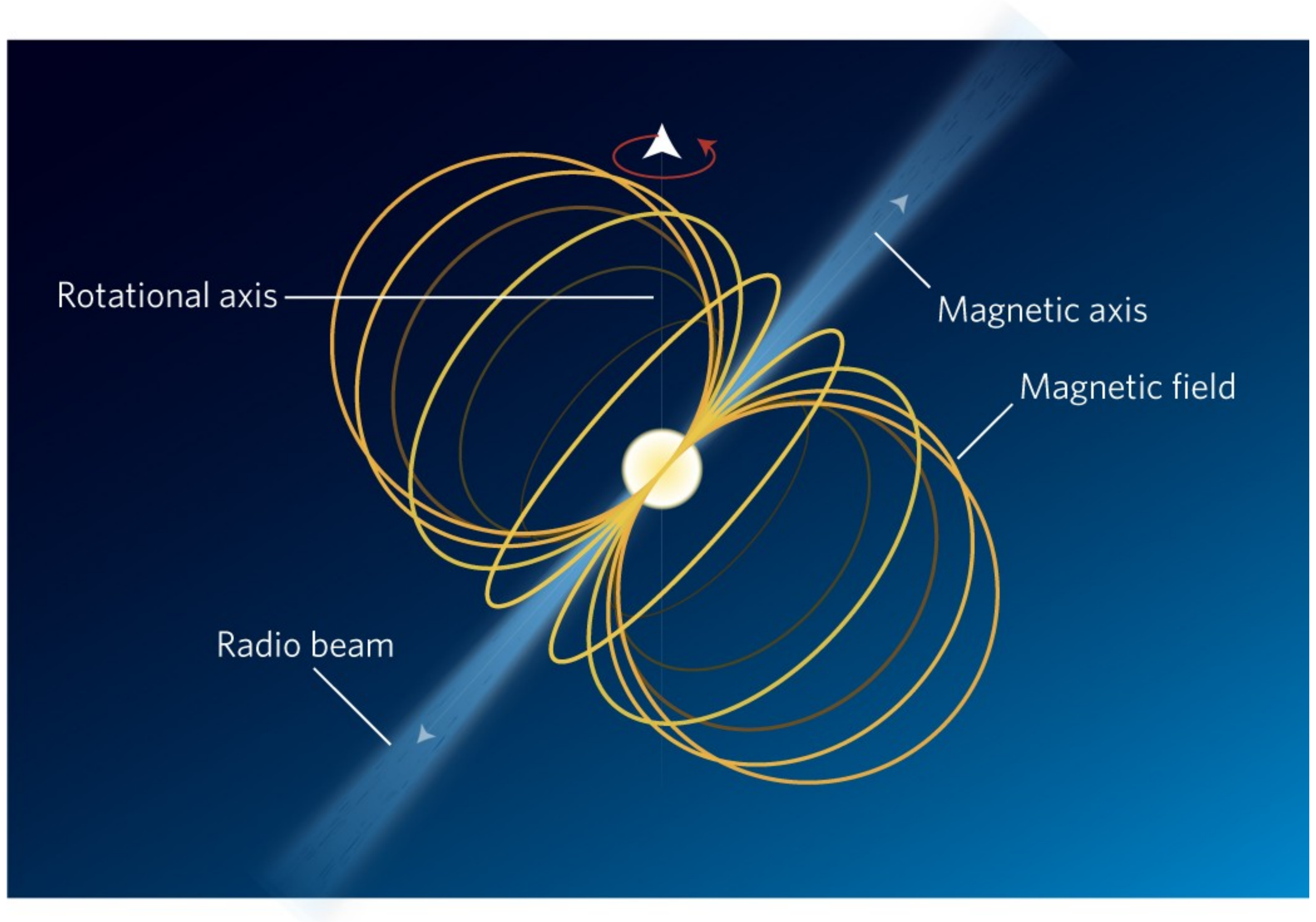
Benchmark stellar-mass BH

Mass	$\mathcal{O}(10)\, M_\odot$
Radius	$\mathcal{O}(10)\,\mathrm{km}$
$\Omega/(2\pi)$	$\mathcal{O}(\mathrm{kHz})$

Neutron star superradiance



Jocelyn Bell Burnell, [Nature Astronomy (2017)]

Review: F. Chadha-Day, [2601.05055]

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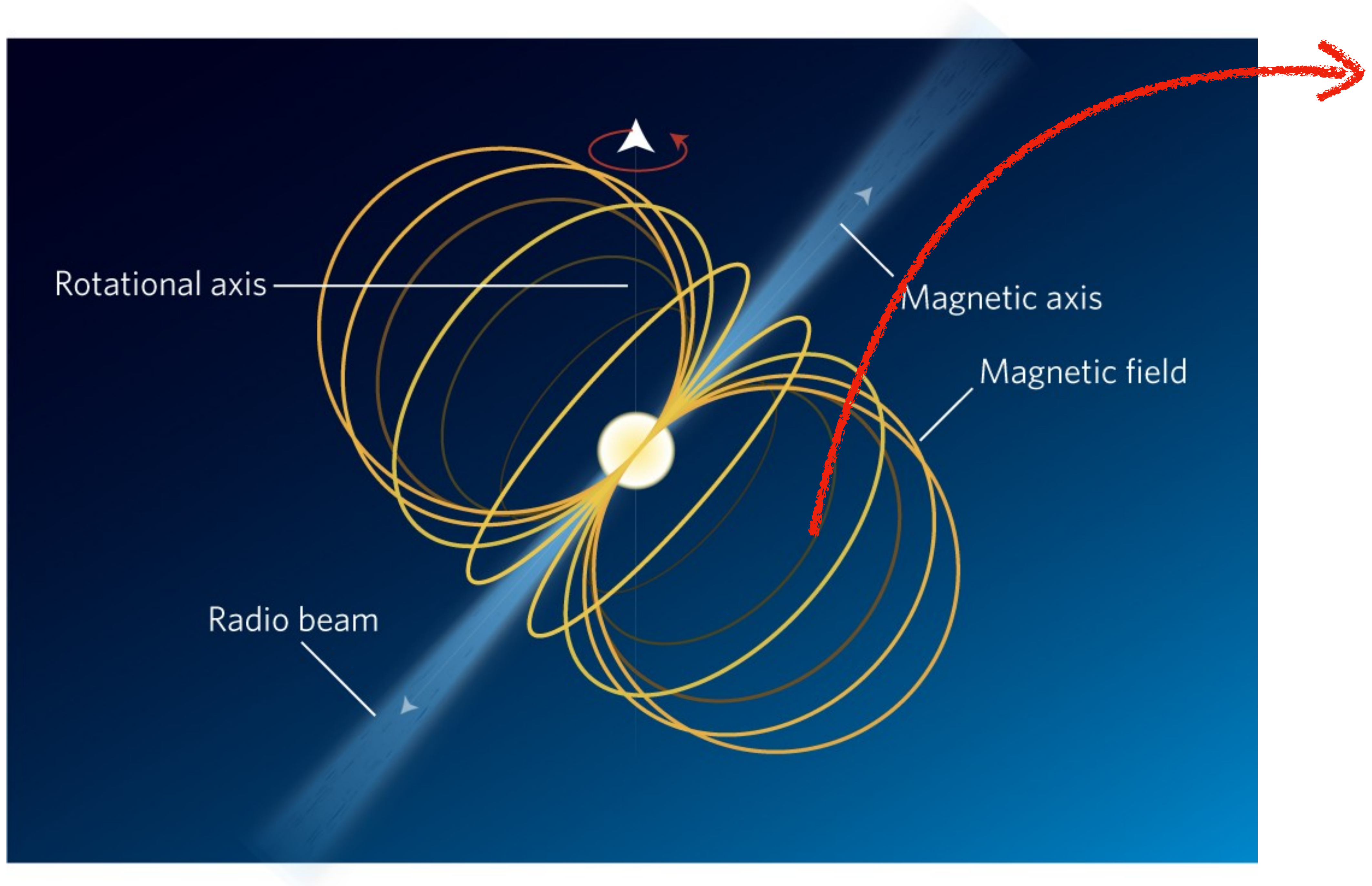

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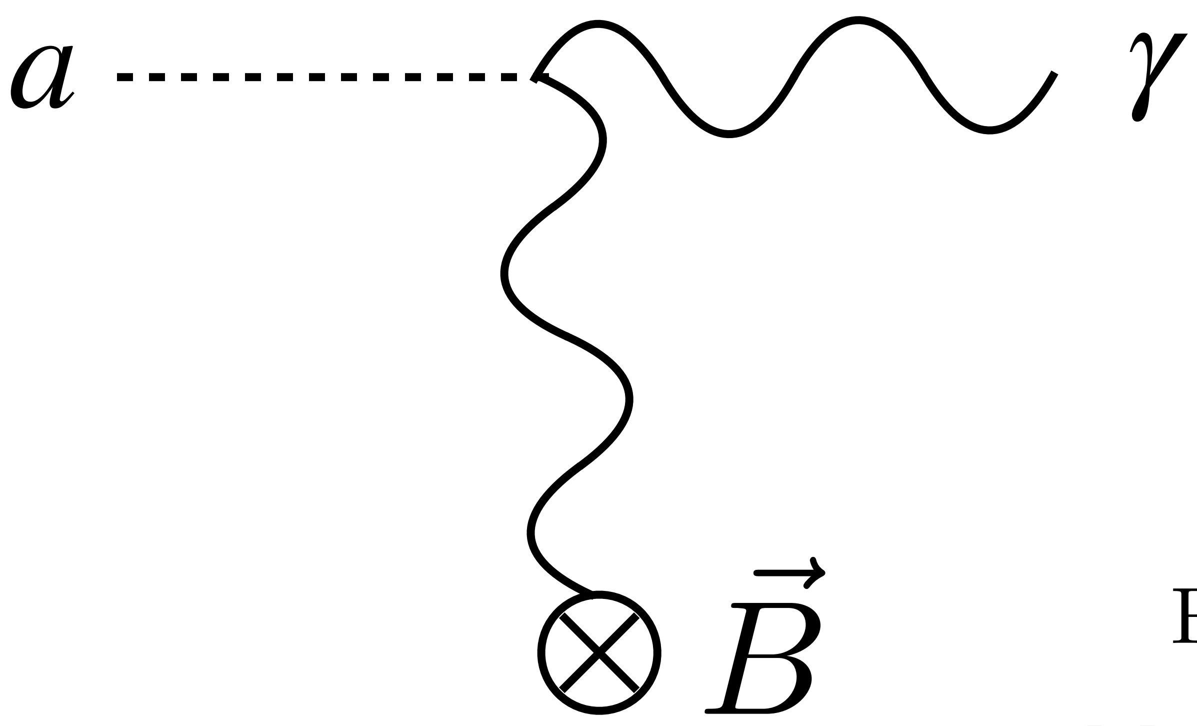

F. V. Day and J. I. McDonald, [1904.08341]

T. F.M. Spieksma, and E. Cannizzaro, [2503.19978]

T. Sirkiä, M. Heikinheimo, and K. Tuominen, [2504.04209]

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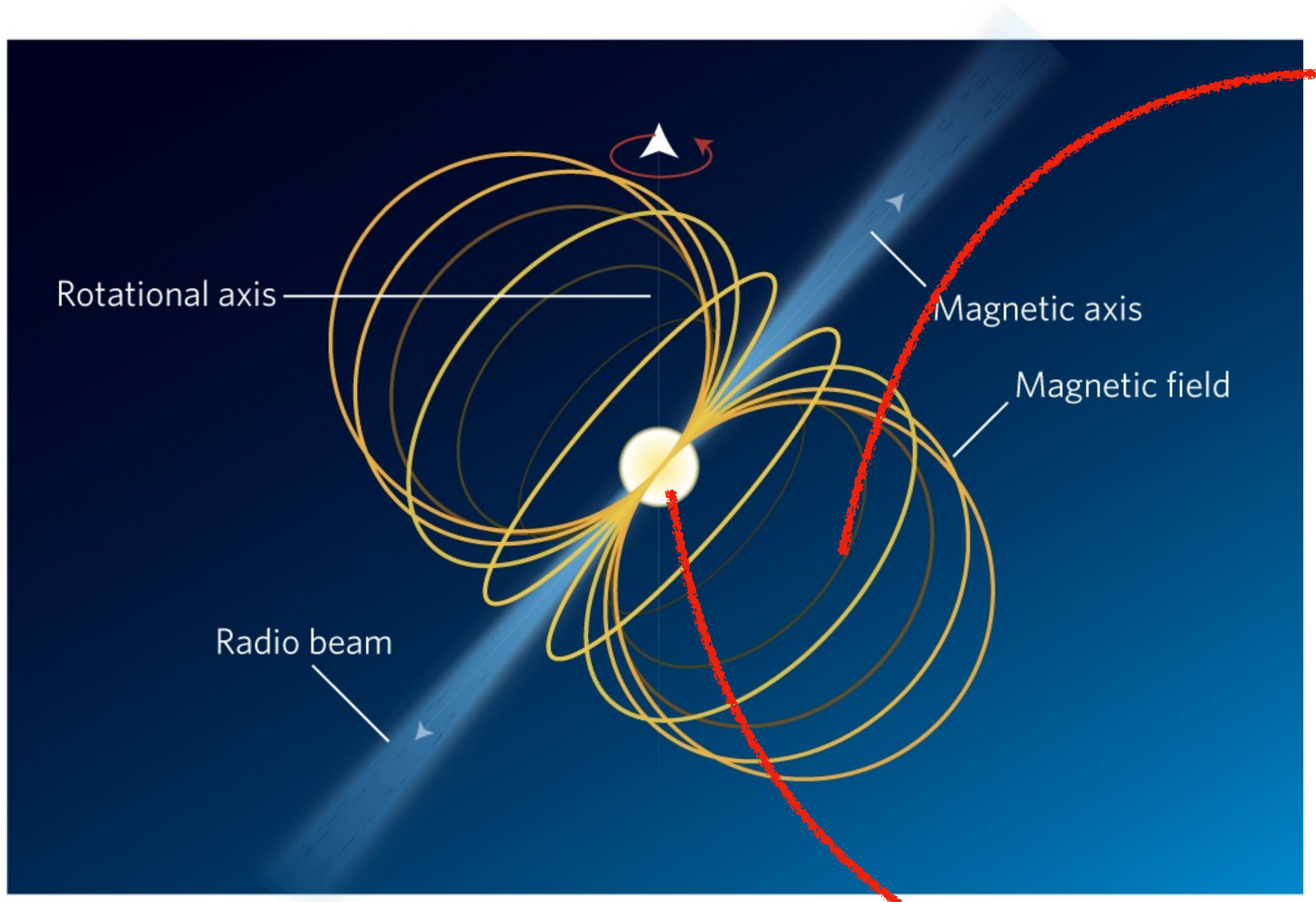

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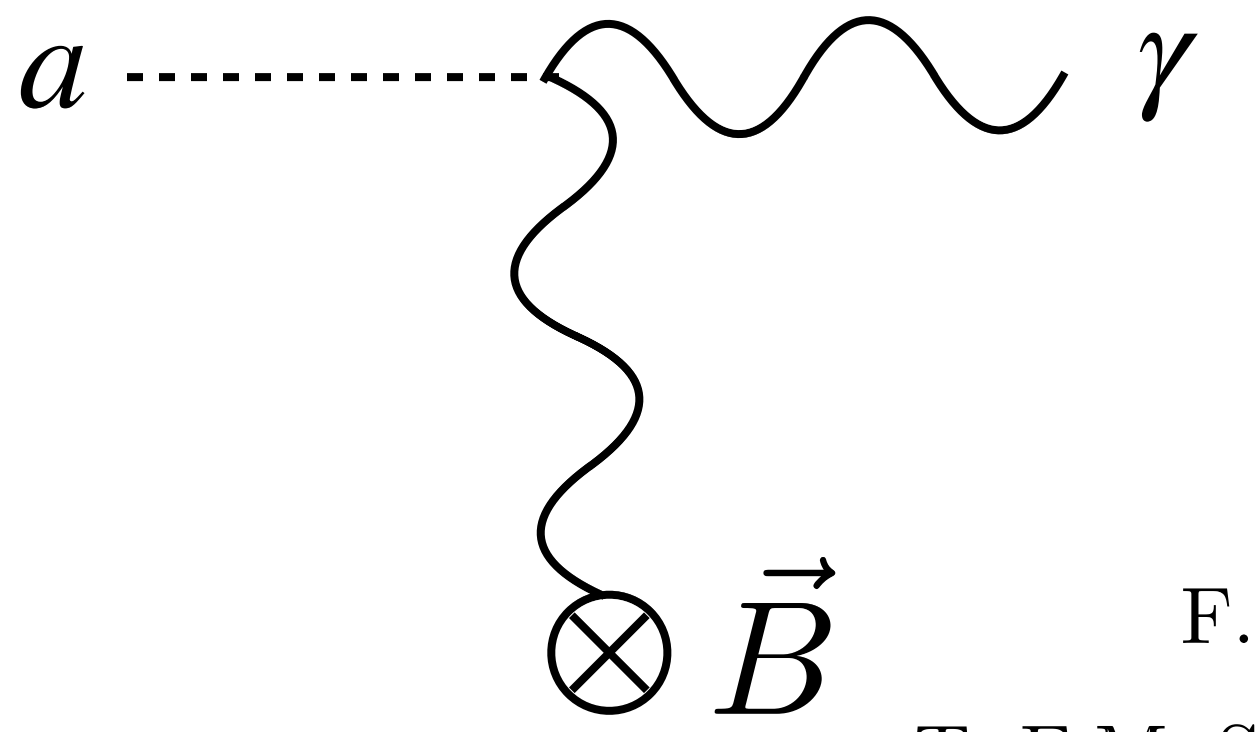

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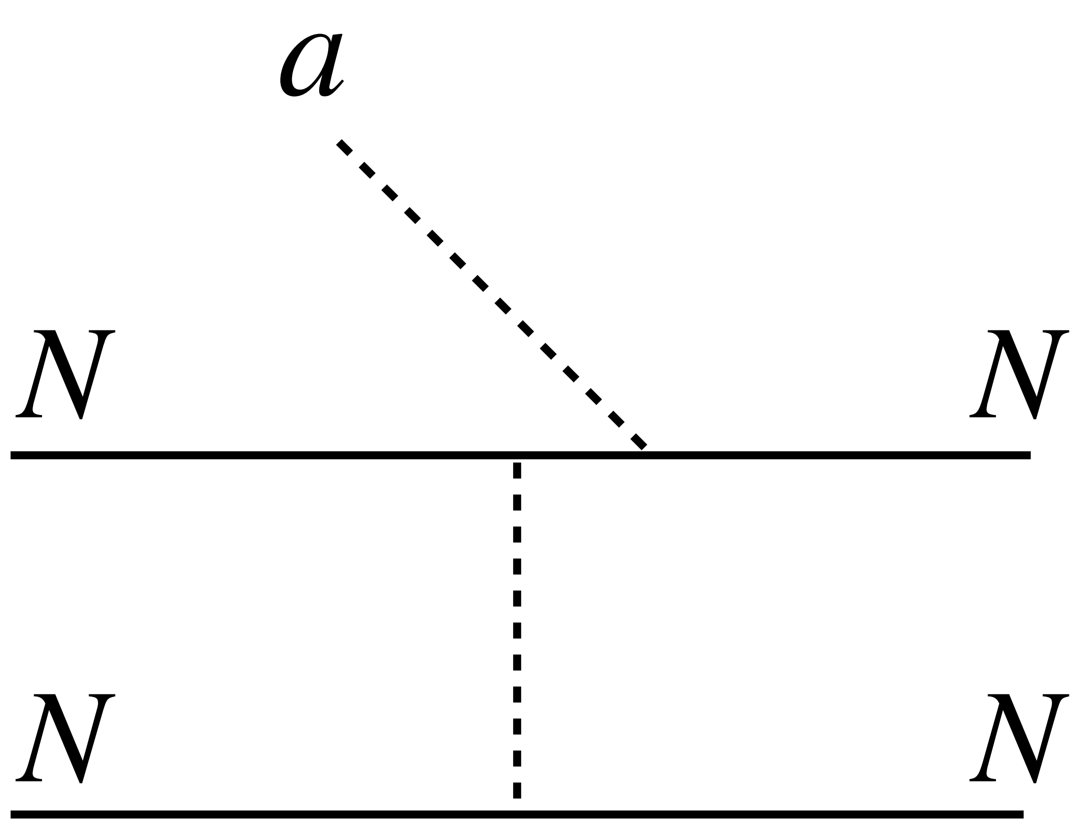

F. Chadha-Day, B. Garbrecht, and J. McDonald, [2207.07662]

Z. Bai, V. Cardoso, Y. Chen, Y. Li, J. I. McDonald, and HS, [2512.13816]

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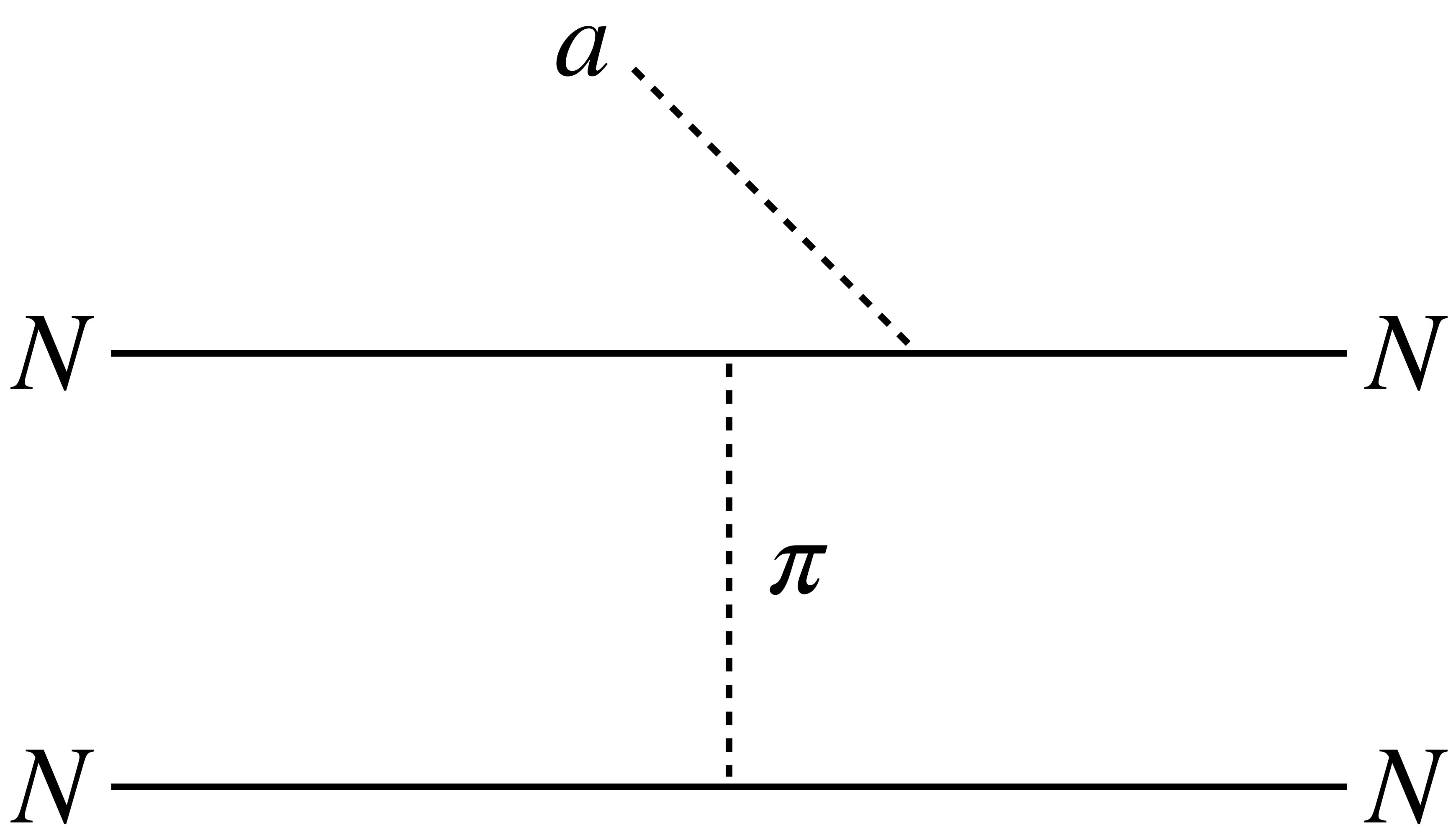
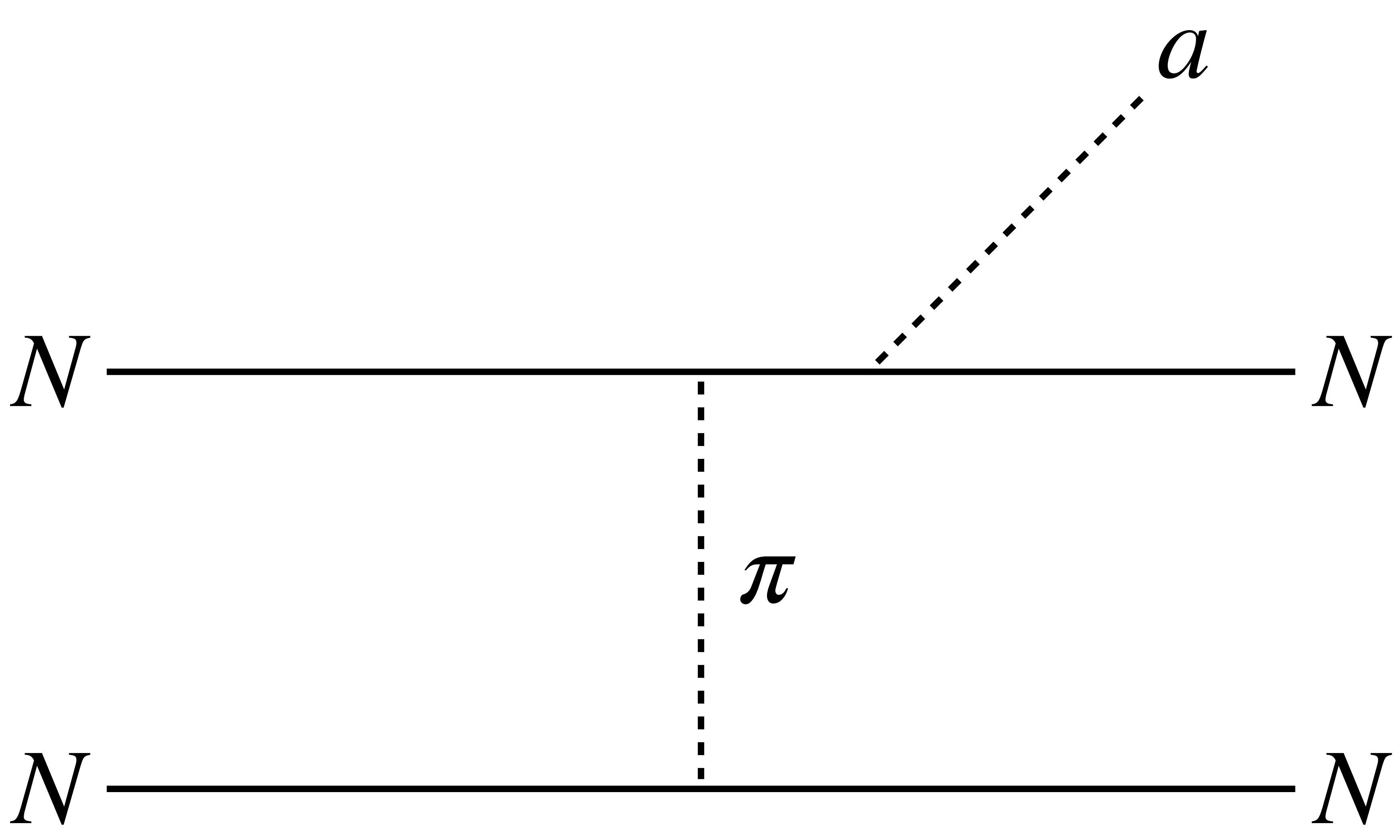
Microphysical processes



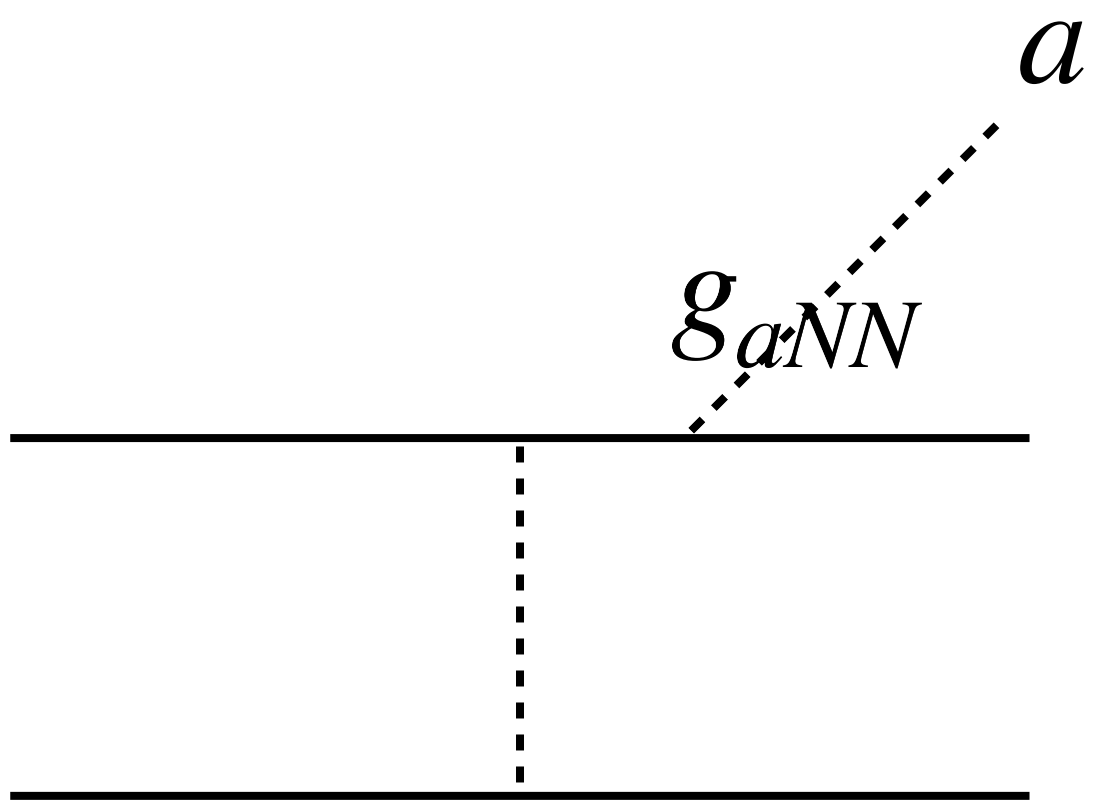
Stellar superradiance

Microphysical processes

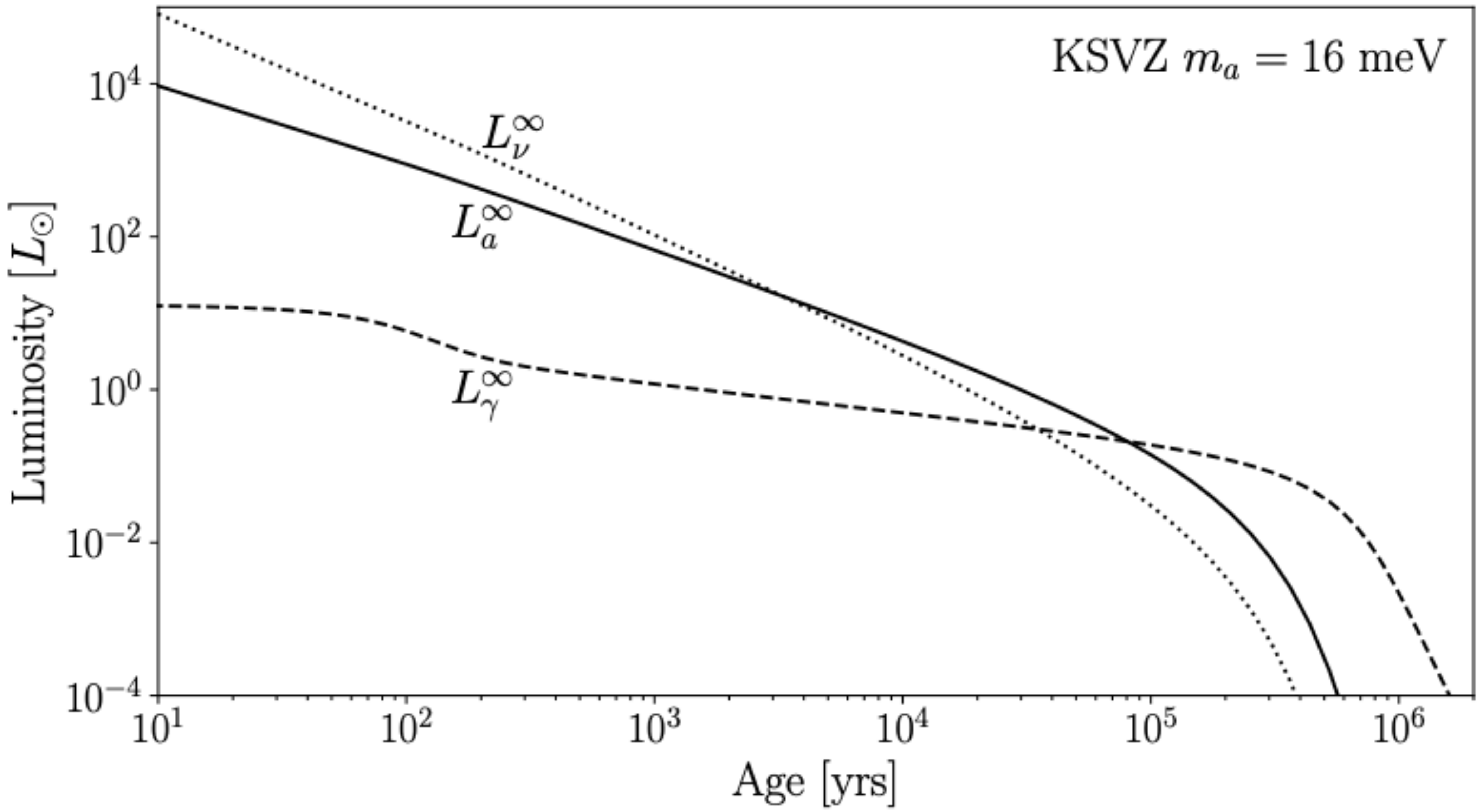


Stellar cooling

Neutron star cooling



M. Buschmann, C. Dessert, J. W. Foster, A. J. Long, and B. R. Safdi, [2111.09892]



Review: A. Caputo and G. Raffelt, [2401.13728]

N. Iwamoto, PRL (1984)

R. P. Brinkmann and M. S. Turner, PRD (1988)

N. Iwamoto, PRD (2001)

S. Stoica, B. Pastrav, J. E. Horvath and M. Allen, [0906.3134]

L. B. Leinson, [1405.6873]

J. H. Chang, R. Essig, S. D. McDermott, [1803.00993]

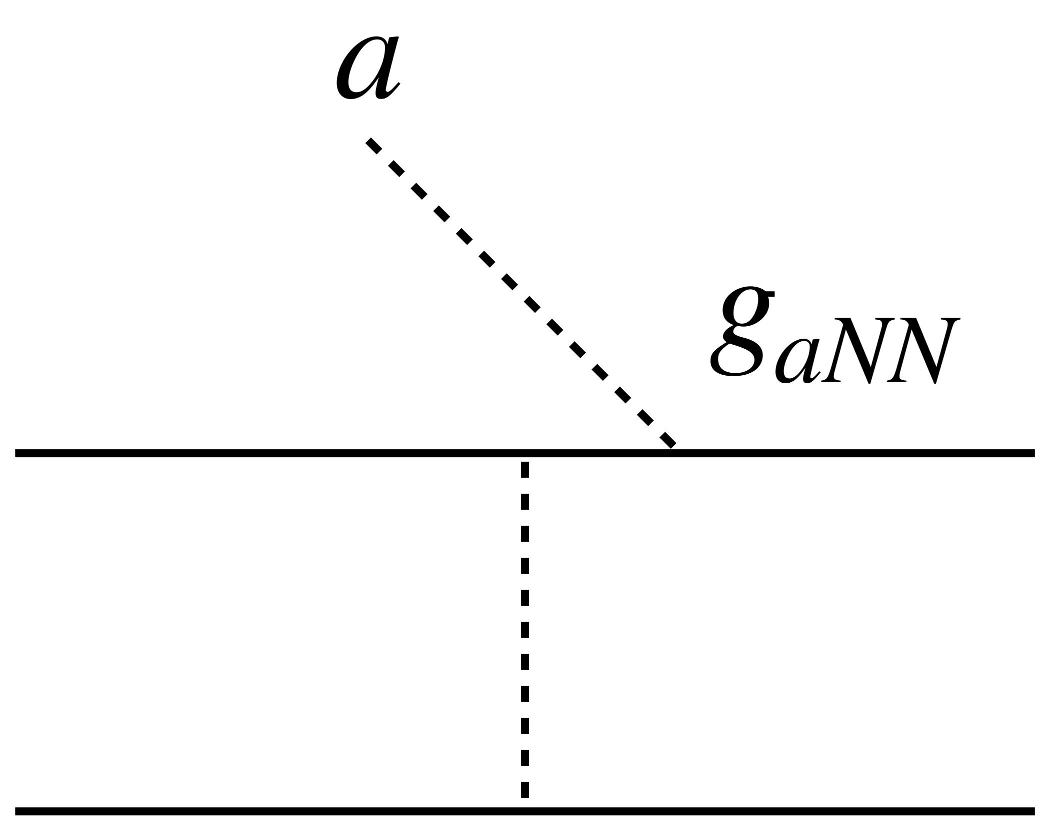
K. Hamaguchi, N. Nagata, K. Yanagi and J. Zheng, [1806.07151]

P. Carenza, T. Fischer, M. Giannotti, G. Guo, G. Martínez-Pinedo and A. Mirizzi, [1906.11844]

D. K. Hong, C. S. Shin and S. Yun, [2012.05427]

K. Hamaguchi, N. Nagata and J. Zheng, [2502.18931]

Neutron star superradiance



Pulsar	$\Omega_S/(2\pi)$[Hz]	τ_{spindown}[yr]	$M_S[M_\odot]$	R_S[km]
P1 [94]	716	$> 2.5 \times 10^7$	1.4	12
P2 [91–93, 95]	707	4.7×10^9	2.4	14
P3 [96, 97]	641	2.8×10^8	1.4	12
P4 [98, 99]	541	3.1×10^9	1.4	12
P5 [90, 100]	380	5.5×10^{10}	1.4	12

F. Chadha-Day, B. Garbrecht, and J. McDonald, [2207.07662]

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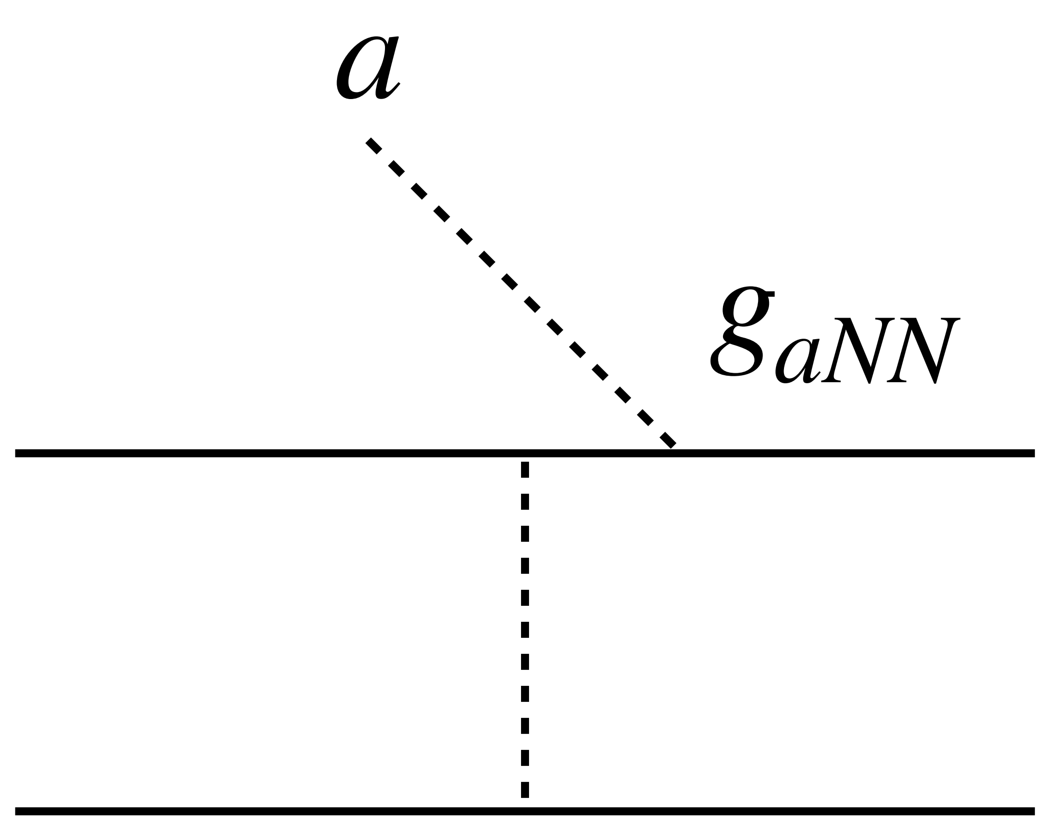
Neutron star superradiance



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$$\Gamma_{\text{SR}} \quad \text{vs.} \quad \tau^{-1}_{\text{spin down}} = \frac{2\dot{\Omega}_S}{\Omega_S}$$

F. Chadha-Day, B. Garbrecht, and J. McDonald, [2207.07662]

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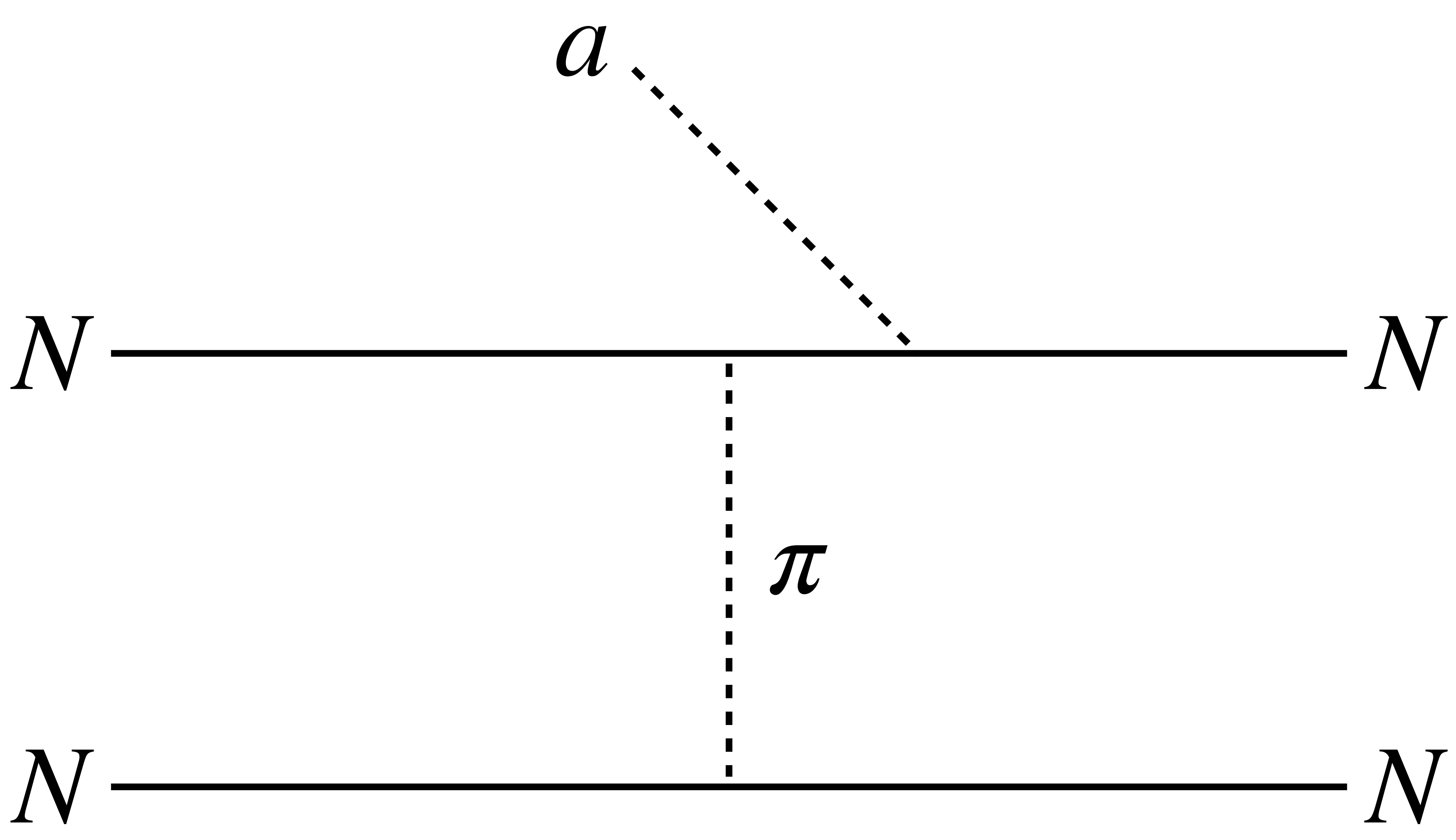
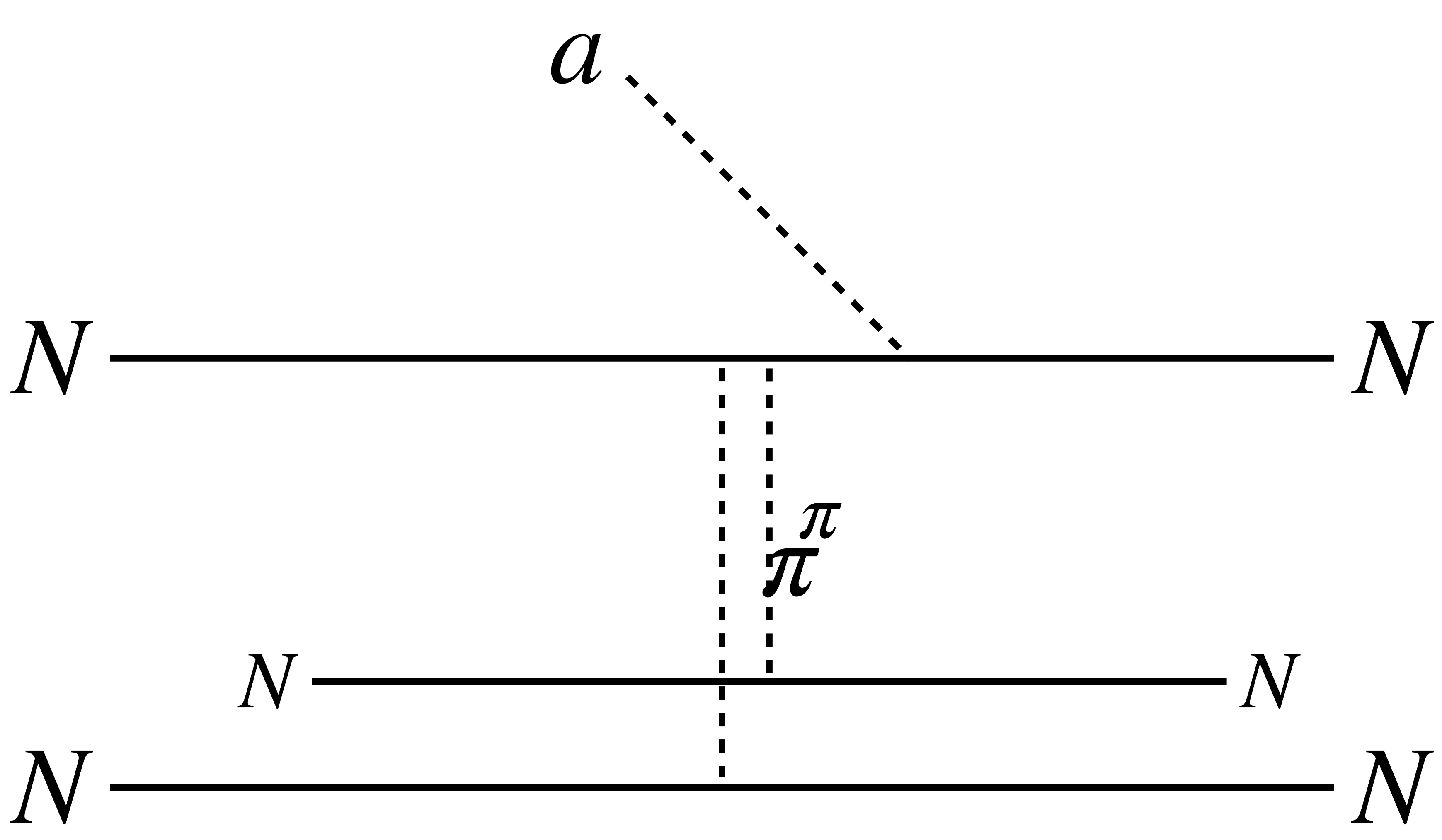
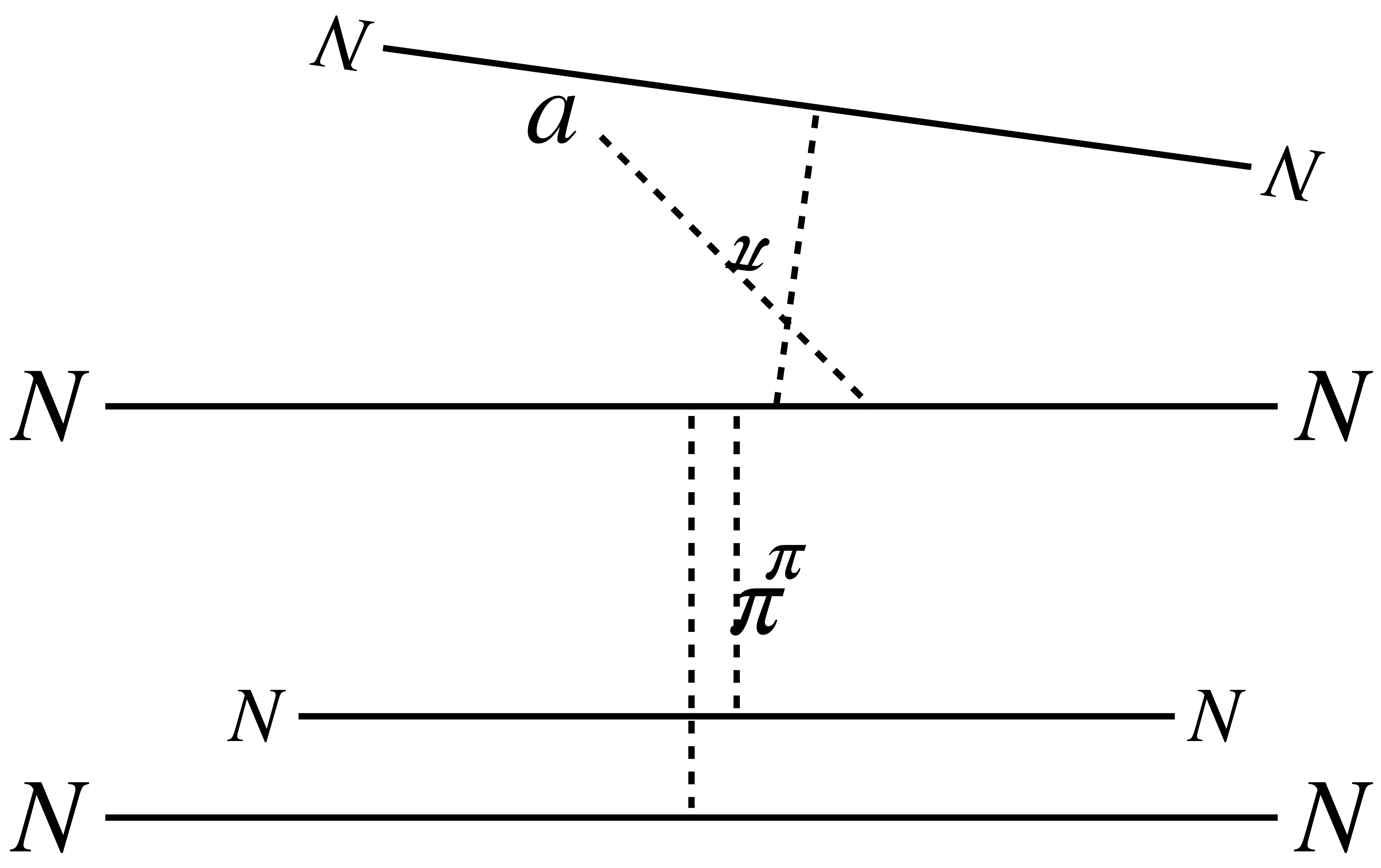


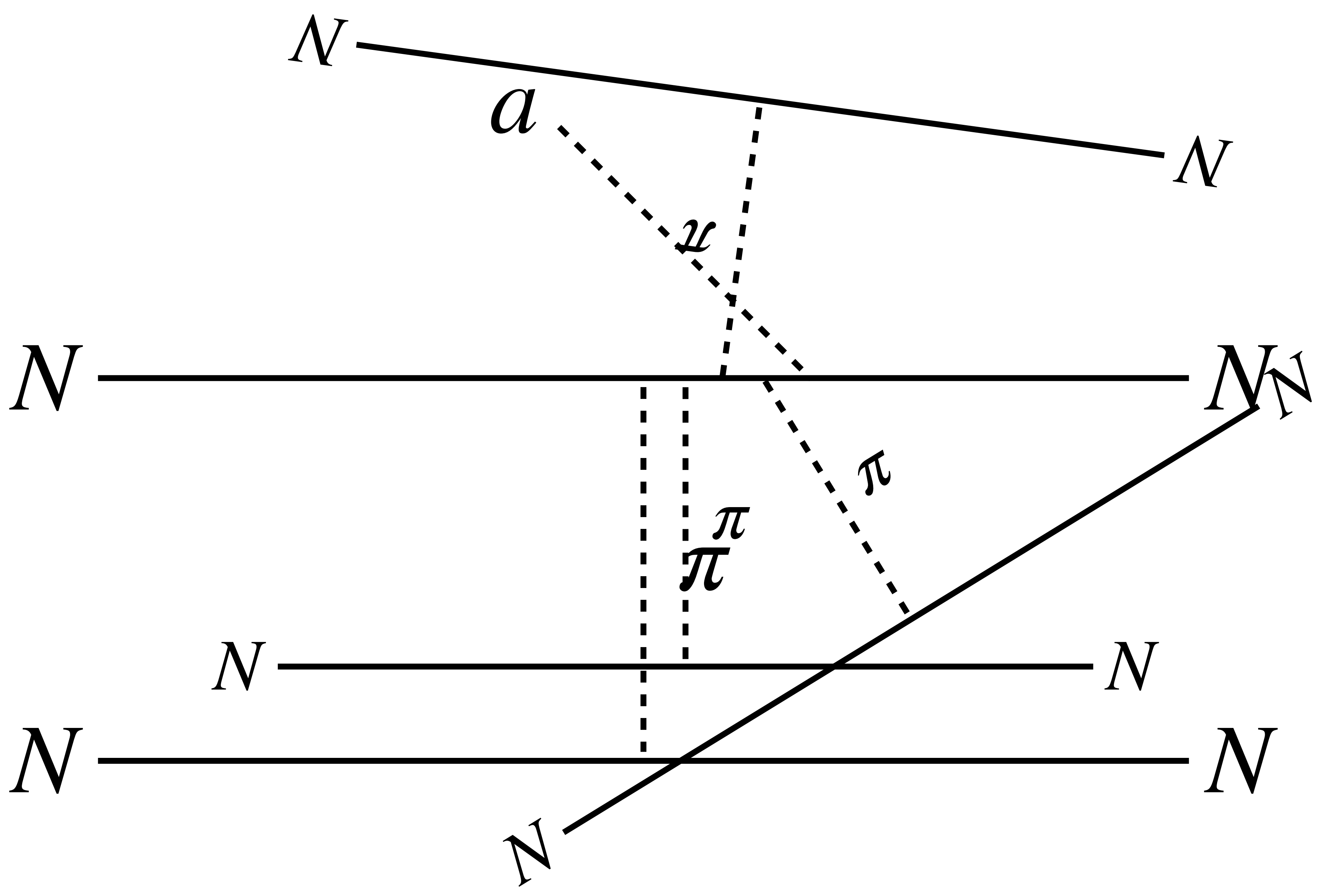
Microphysical processes



Microphysical processes



Microphysical processes

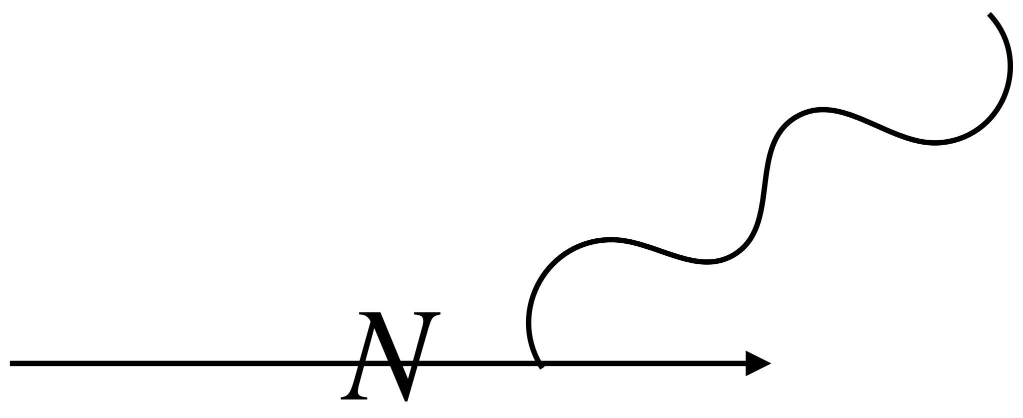


Landau-Pomeranchuk-Migdal effect

L. Landau and I. Pomeranchuk (1953)

A. B. Migdal (1956)

high-energy e

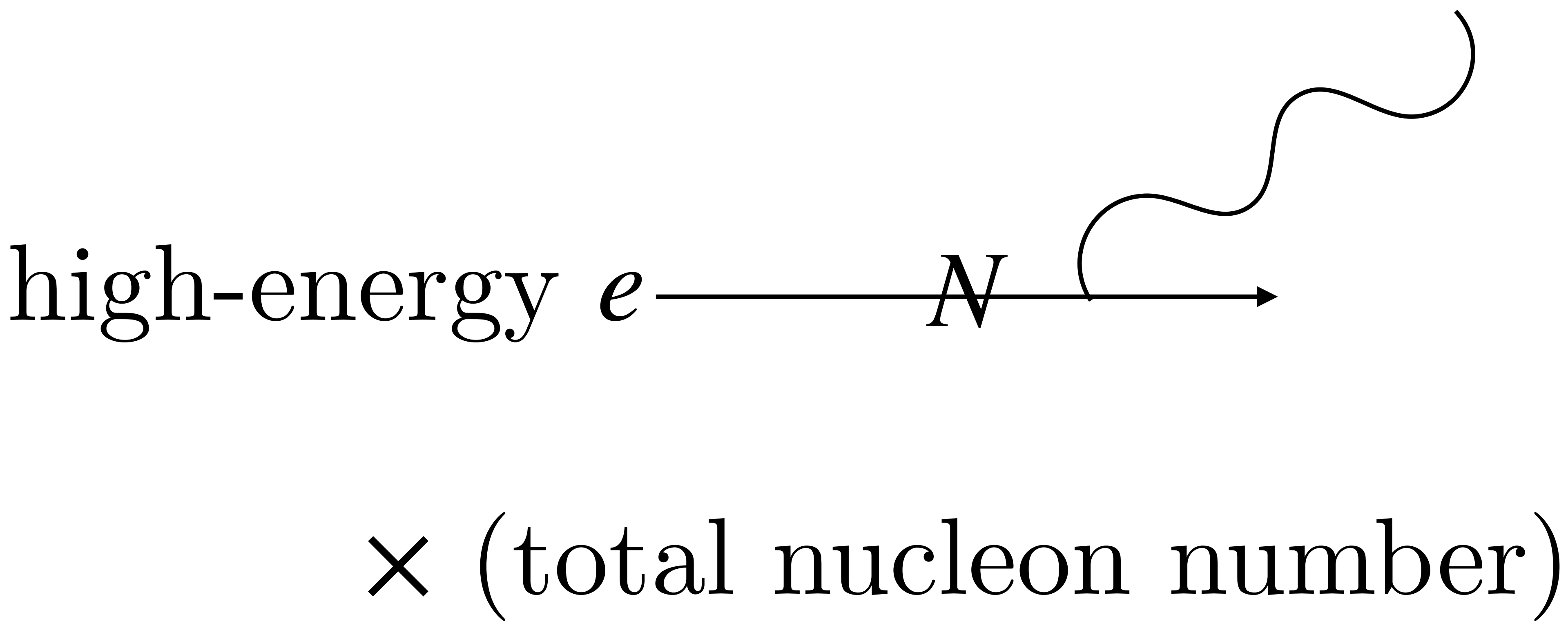


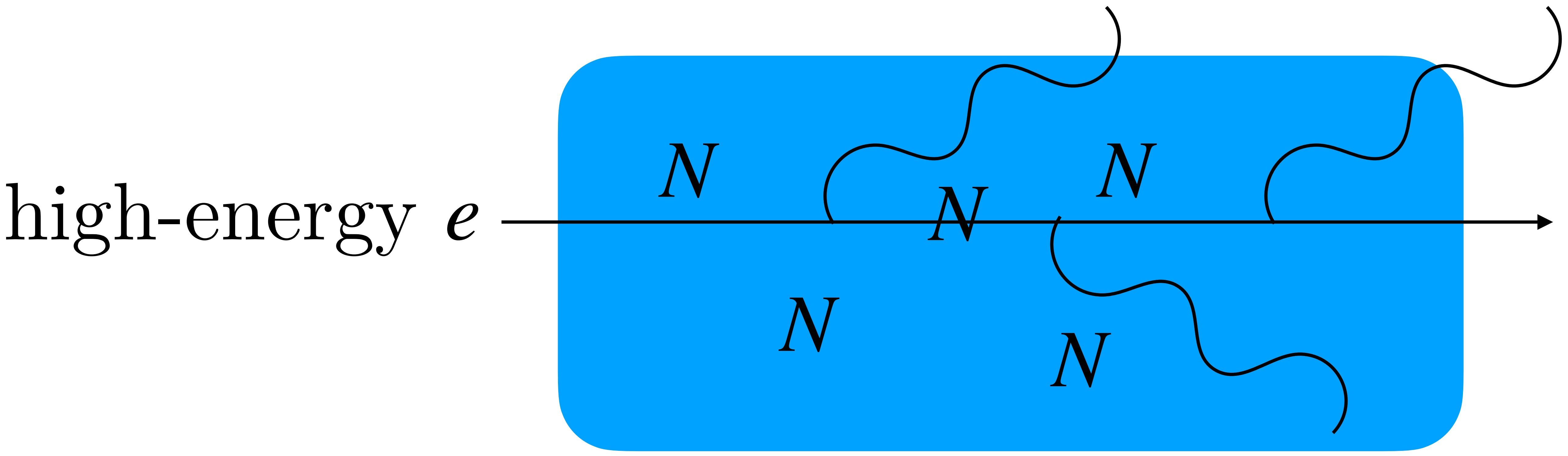
$\times$ (total nucleon number)

Landau-Pomeranchuk-Migdal effect

L. Landau and I. Pomeranchuk (1953)

A. B. Migdal (1956)

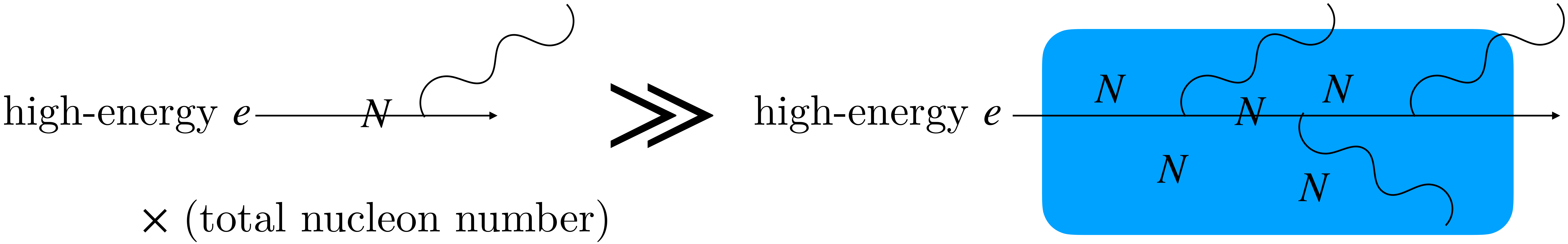




Landau-Pomeranchuk-Migdal effect

L. Landau and I. Pomeranchuk (1953)

A. B. Migdal (1956)



Landau-Pomeranchuk-Migdal effect

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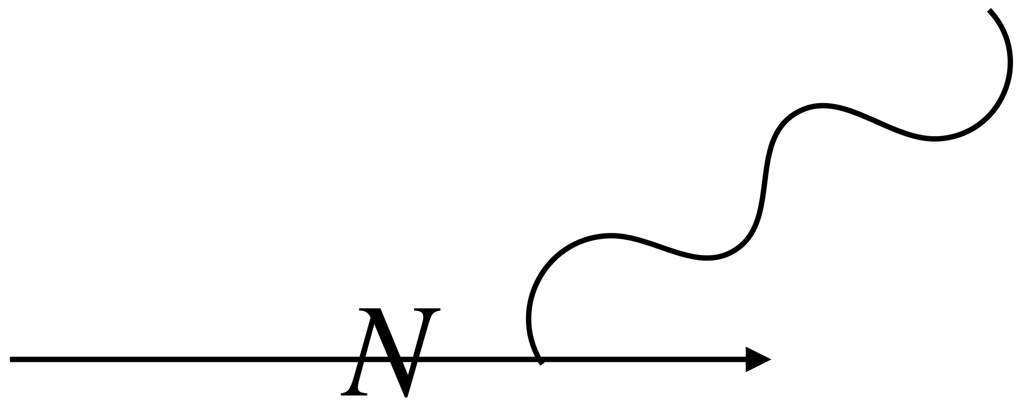
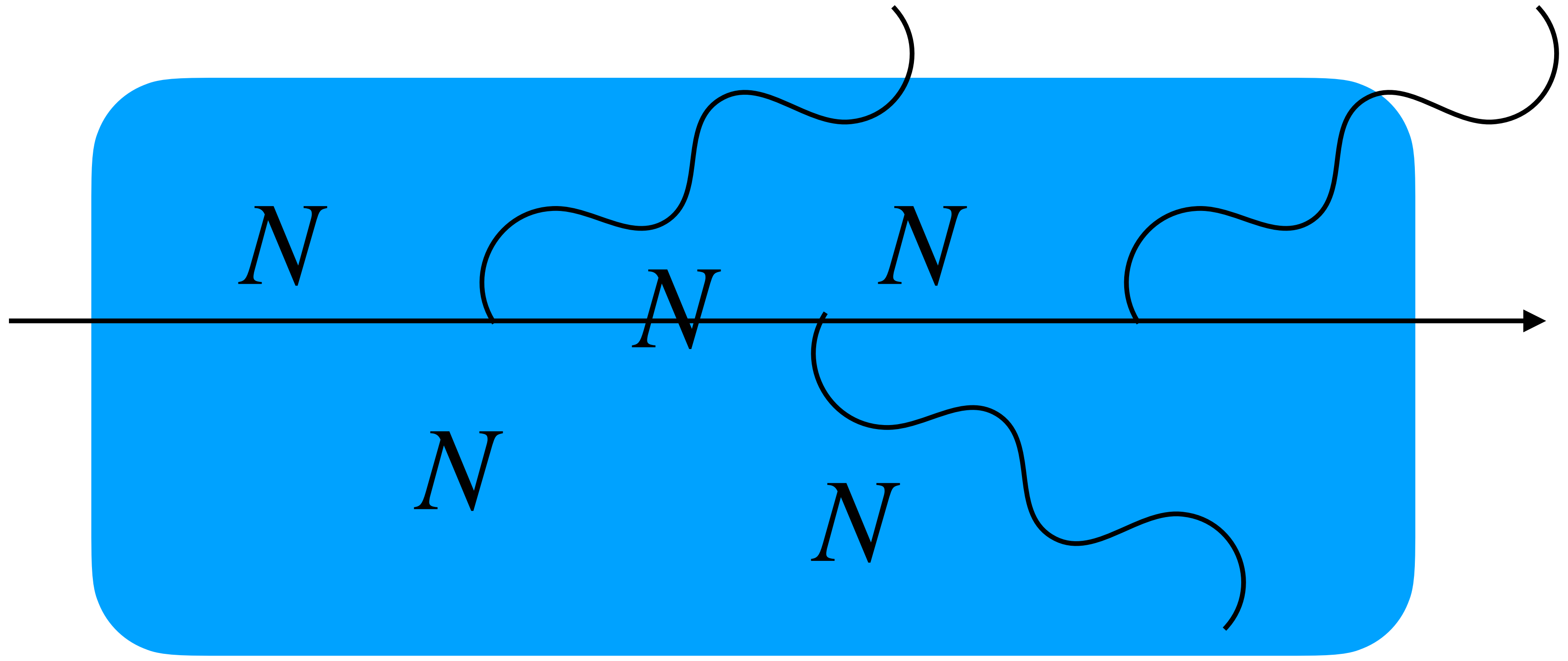
high-energy e 

$\gg$

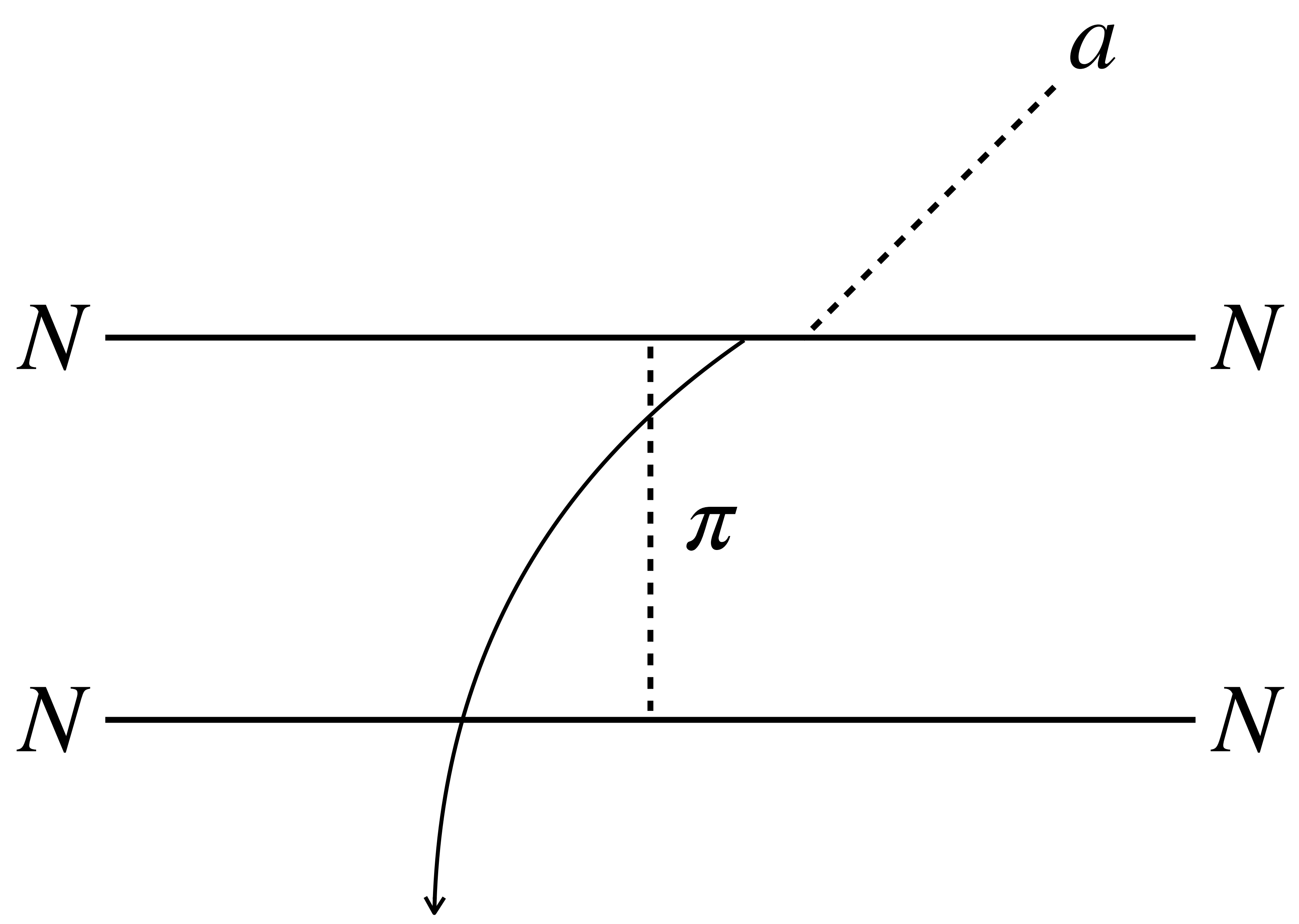
high-energy e 

$\times$ (total nucleon number)

$$t_{\mathrm{emission}} \sim \frac{\lambda}{1 - v_e/c} \sim \frac{E_e^2}{m_e^2 \omega}$$

Landau-Pomeranchuk-Migdal effect

G. Raffelt and D. Seckel (1991)



$$\frac{1}{p^2 - m_N^2} \to \frac{1}{p^2 - m_N^2 + i m_N \Gamma_{\rm coll}}$$

Landau-Pomeranchuk-Migdal effect

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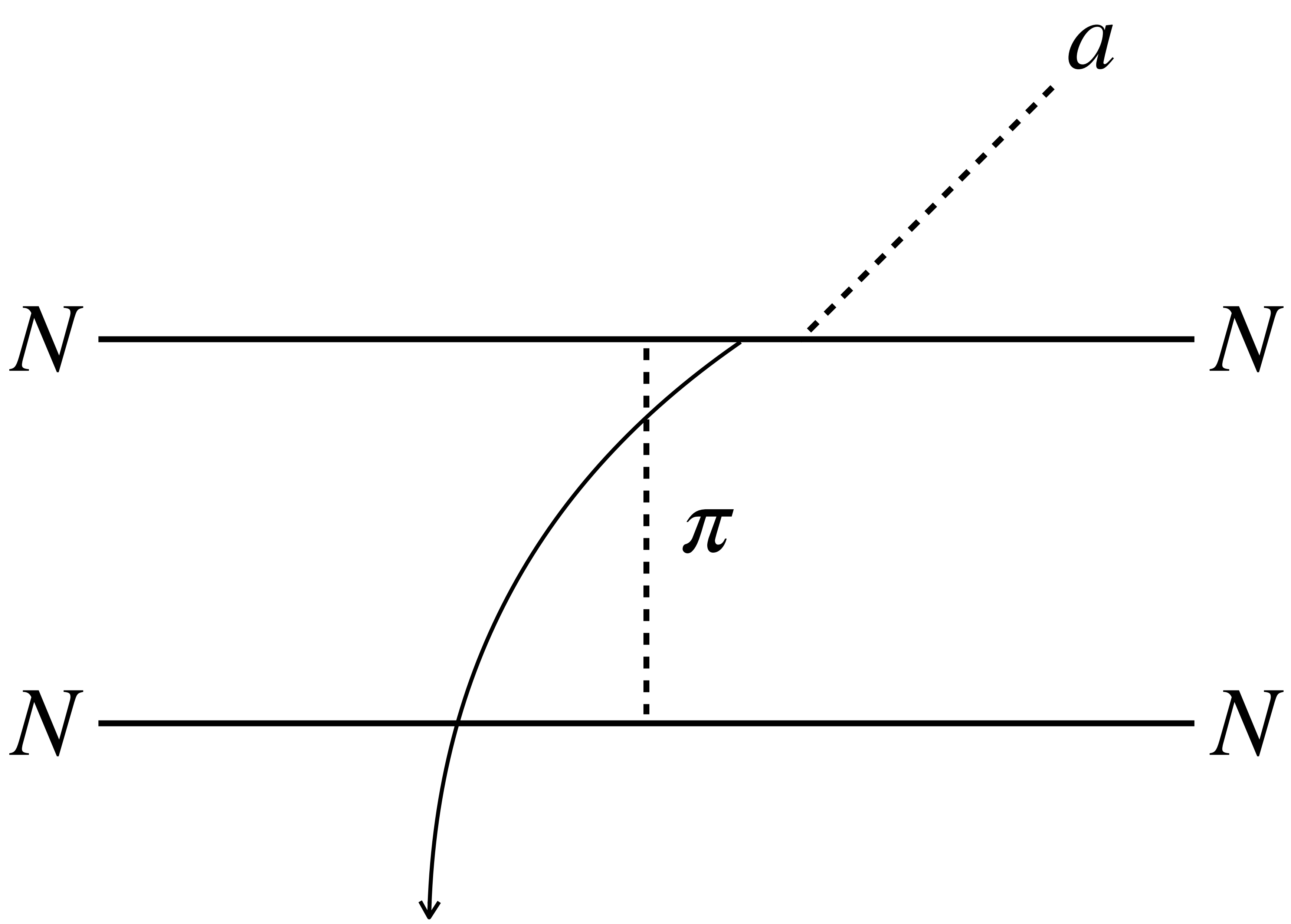

$$\frac{1}{p^2 - m_N^2} \to \frac{1}{p^2 - m_N^2 + im_N\Gamma_{\text{coll}}} = \frac{1}{E^2 - \mathbf{p}^2 - m_N^2 + im_N\Gamma_{\text{coll}}} = \frac{1}{(E + E_{\text{on-shell}})(E - E_{\text{on-shell}}) + im_N\Gamma_{\text{coll}}}$$

Landau-Pomeranchuk-Migdal effect

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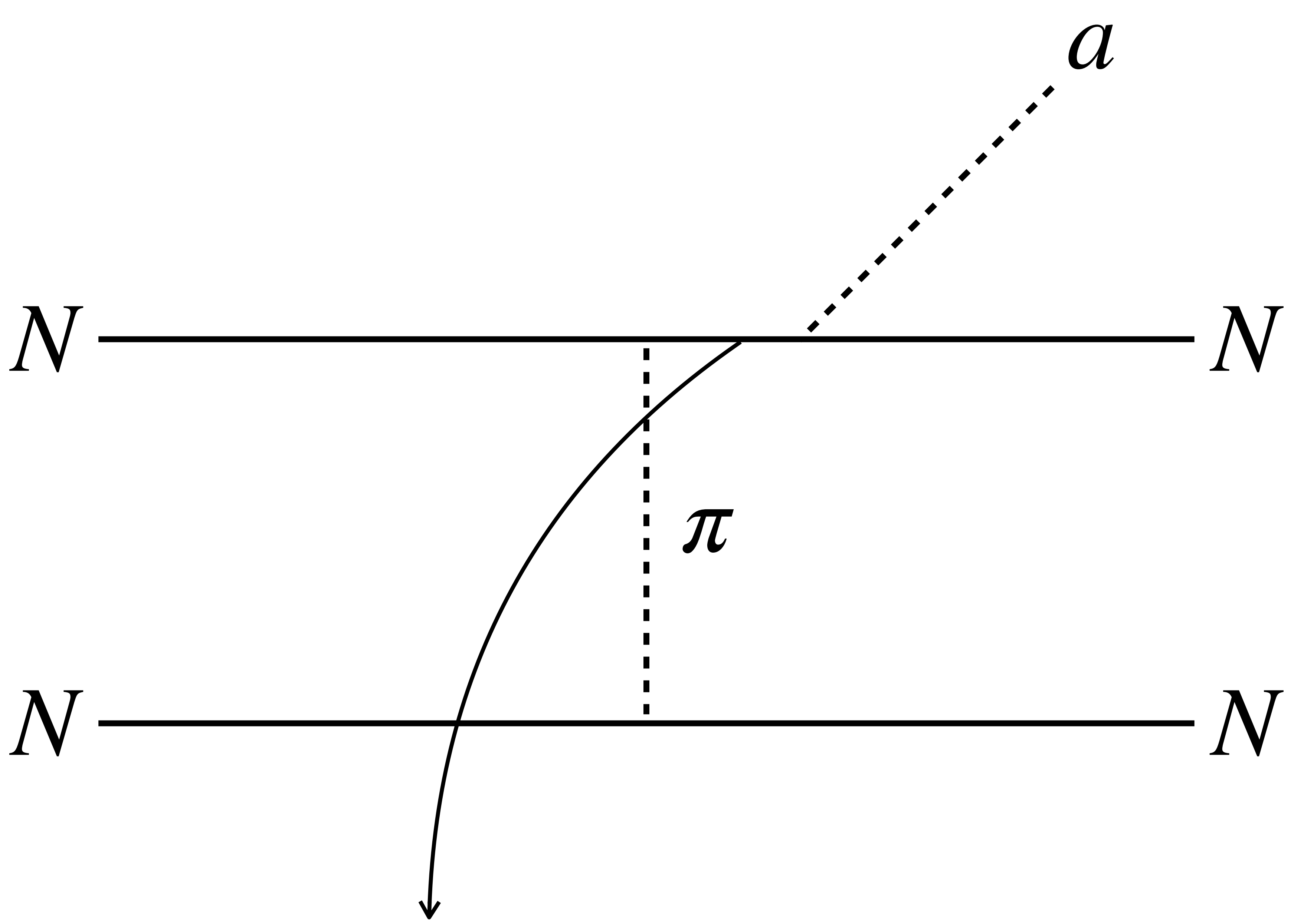

$$\frac{1}{p^2 - m_N^2} \to \frac{1}{p^2 - m_N^2 + i m_N \Gamma_{\rm coll}} = \frac{1}{E^2 - \mathbf{p}^2 - m_N^2 + i m_N \Gamma_{\rm coll}} = \frac{1}{(E + E_{\rm on-shell})(E - E_{\rm on-shell}) + i m_N \Gamma_{\rm coll}} \simeq \frac{1}{2 m_N \omega + i m_N \Gamma_{\rm coll}}$$

Landau-Pomeranchuk-Migdal effect

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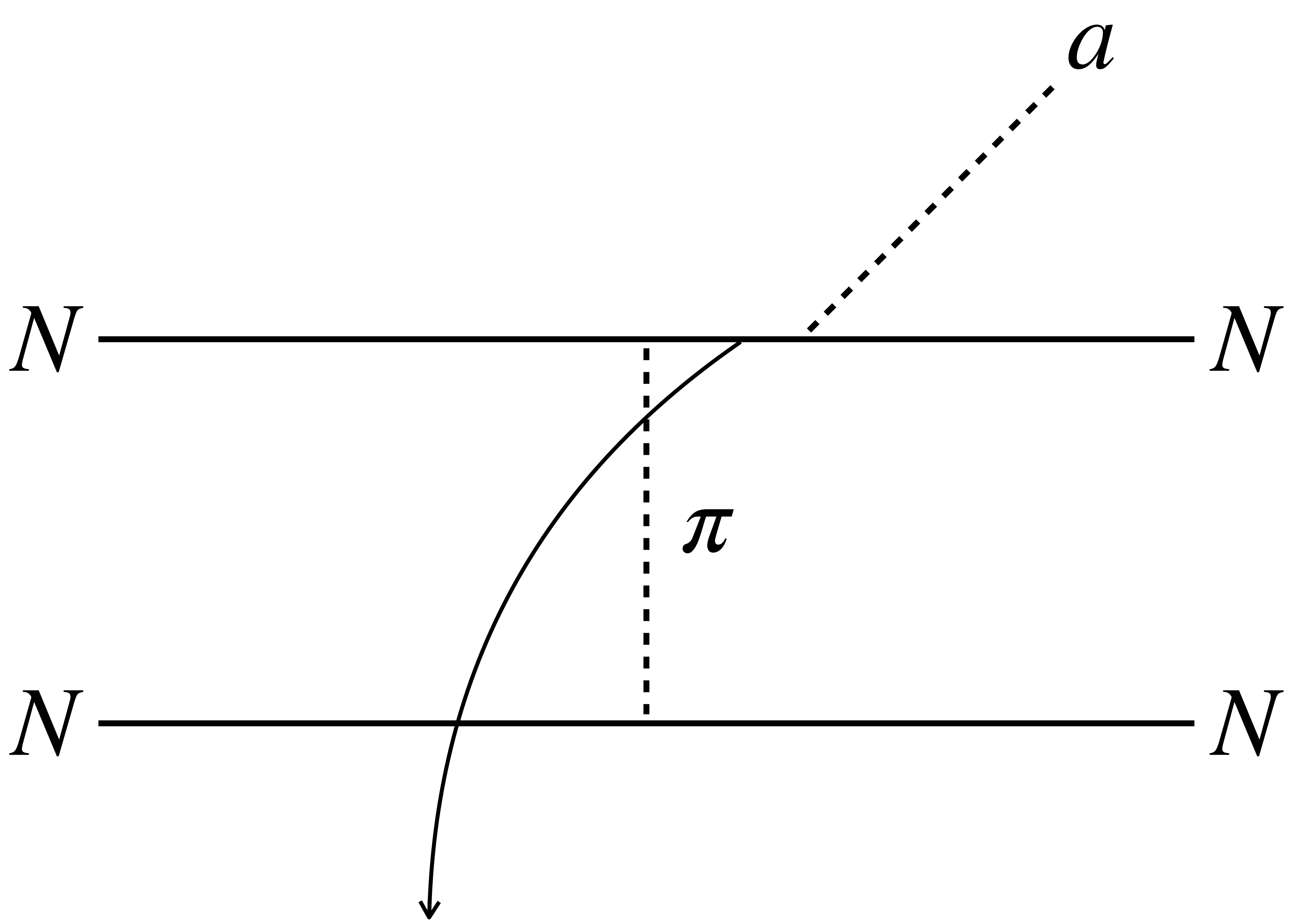

$$\frac{1}{p^2 - m_N^2} \to \frac{1}{p^2 - m_N^2 + i m_N \Gamma_{\rm coll}} = \frac{1}{E^2 - \mathbf{p}^2 - m_N^2 + i m_N \Gamma_{\rm coll}} = \frac{1}{(E + E_{\rm on-shell})(E - E_{\rm on-shell}) + i m_N \Gamma_{\rm coll}} \simeq \frac{1}{2 m_N \omega + i m_N \Gamma_{\rm coll}}$$

$$\Longrightarrow \frac{1}{\omega^2} \to \frac{1}{\omega^2 + \Gamma_{\rm coll}^2/4}$$

Collision rate calculation

G. Raffelt, [Stars as Laboratories]
P. S. Shternin and D. G. Yakovlev, [0808.2018]
P. S. Shternin, M. Baldo and P. Haensel, [1311.4278]
P. Shternin and M. Baldo, [2004.14909]

$$\Gamma_{\rm coll} \simeq \langle n\sigma v \rangle$$

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$$\Gamma_{\rm coll} \simeq \langle n\sigma v\rangle$$

Degenerate matter

$$\Gamma_{\rm coll} = 4\pi\,\alpha_\pi^2\frac{T^3}{p_F^2} \simeq \mathcal{O}(10\,\mathrm{meV})\left(\frac{T}{10^8\,\mathrm{K}}\right)^3\left(\frac{300\,\mathrm{MeV}}{p_F}\right)^2$$

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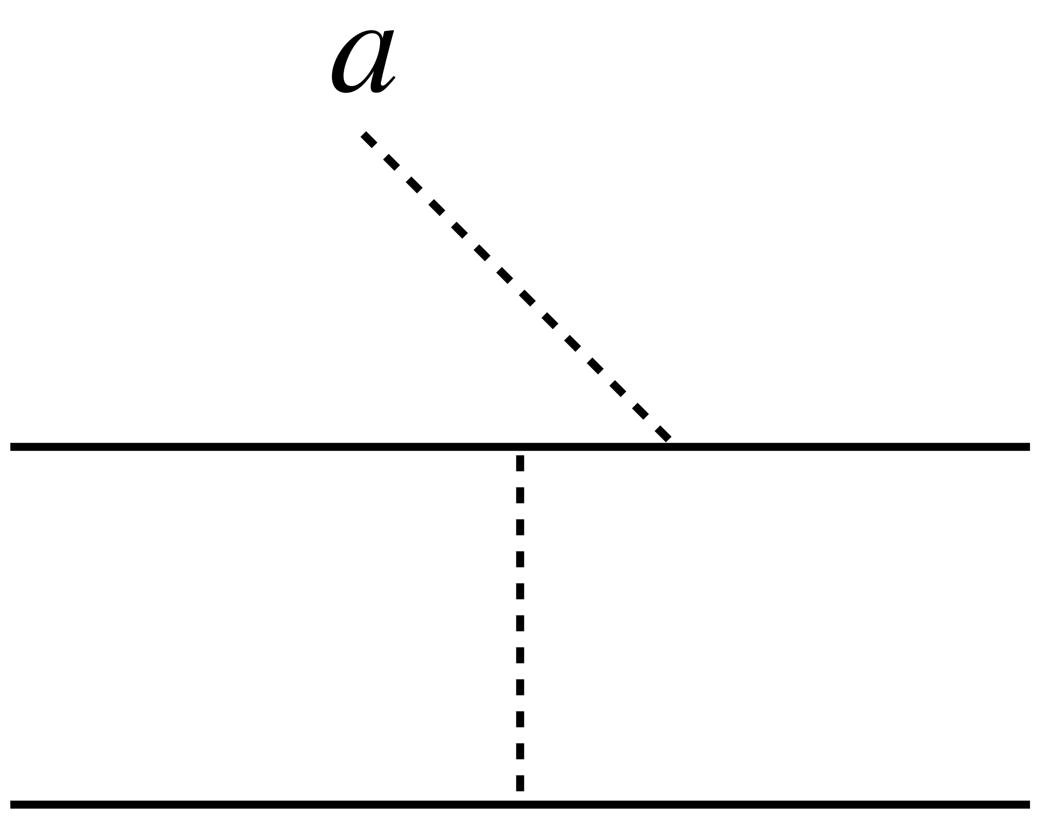
Fermi-liquid theory

$$\Gamma_{\rm coll}^{\rm Fermi-Liq} = \frac{1}{5}\frac{n_n p_F^2}{m_n}\frac{1}{\eta_n} \simeq \mathcal{O}({\rm eV})\left(\frac{10^{18}\,{\rm g\,cm^{-1}\,s^{-1}}}{\eta_n}\right)\left(\frac{n}{n_0}\right)\left(\frac{p_F}{300\,{\rm MeV}}\right)^2$$

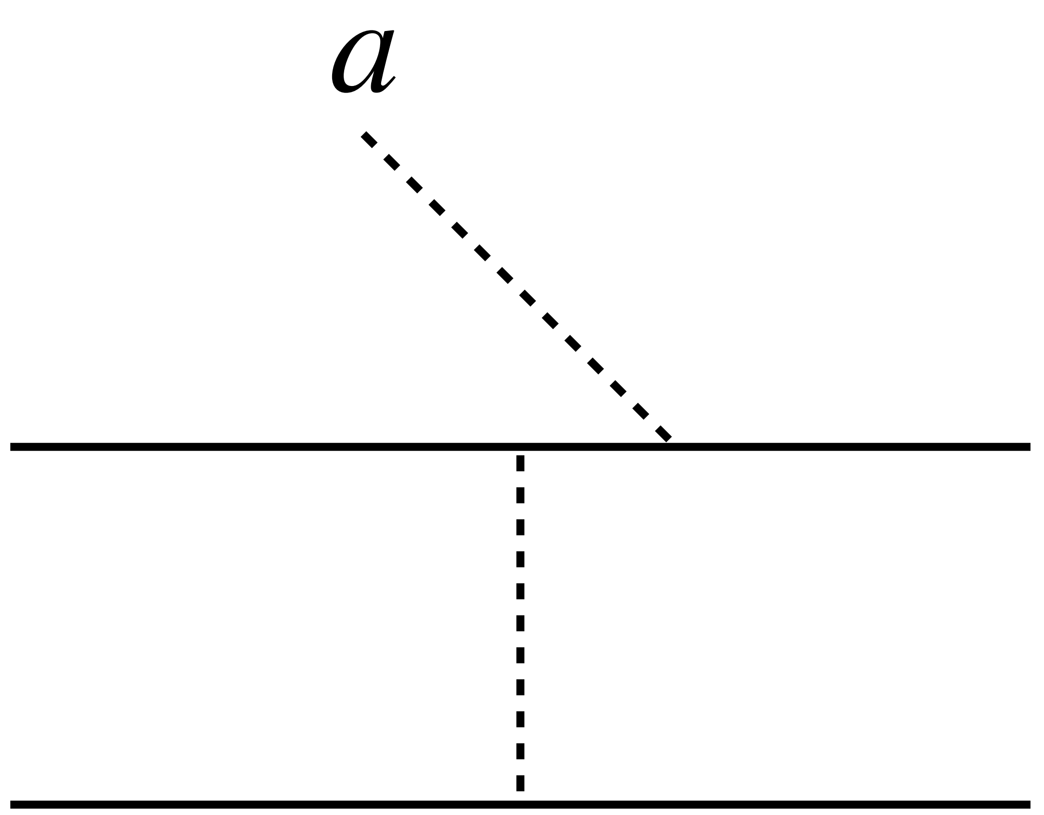
η_n : **shear viscosity of neutrons**

Medium effect



Z. Bai, V. Cardoso, Y. Chen, Y. Li, J. I. McDonald, and HS, [2512.13816]

Medium effect



$\omega_a \sim \mathcal{O}(R_{NS}^{-1})$

Z. Bai, V. Cardoso, Y. Chen, Y. Li, J. I. McDonald, and HS, [2512.13816]

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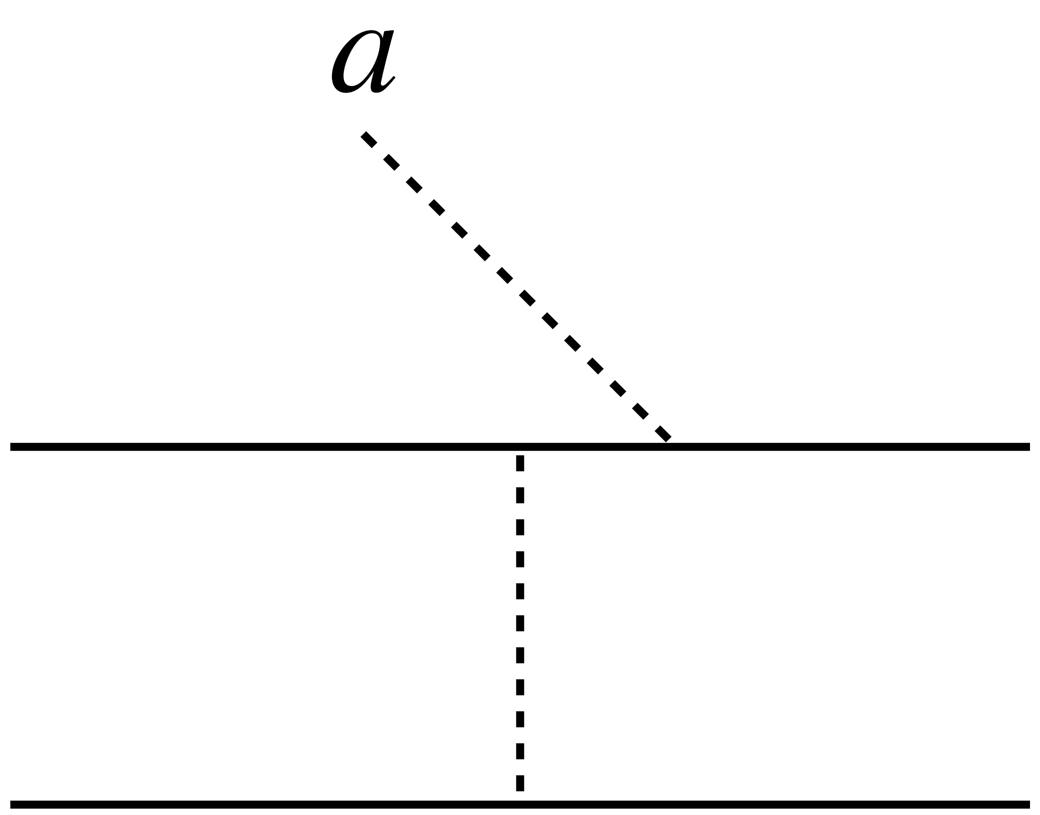

$$\omega_a \sim \mathcal{O}(R_{NS}^{-1})$$

$$\sim \mathcal{O}(10^{-11})\,\mathrm{eV}$$

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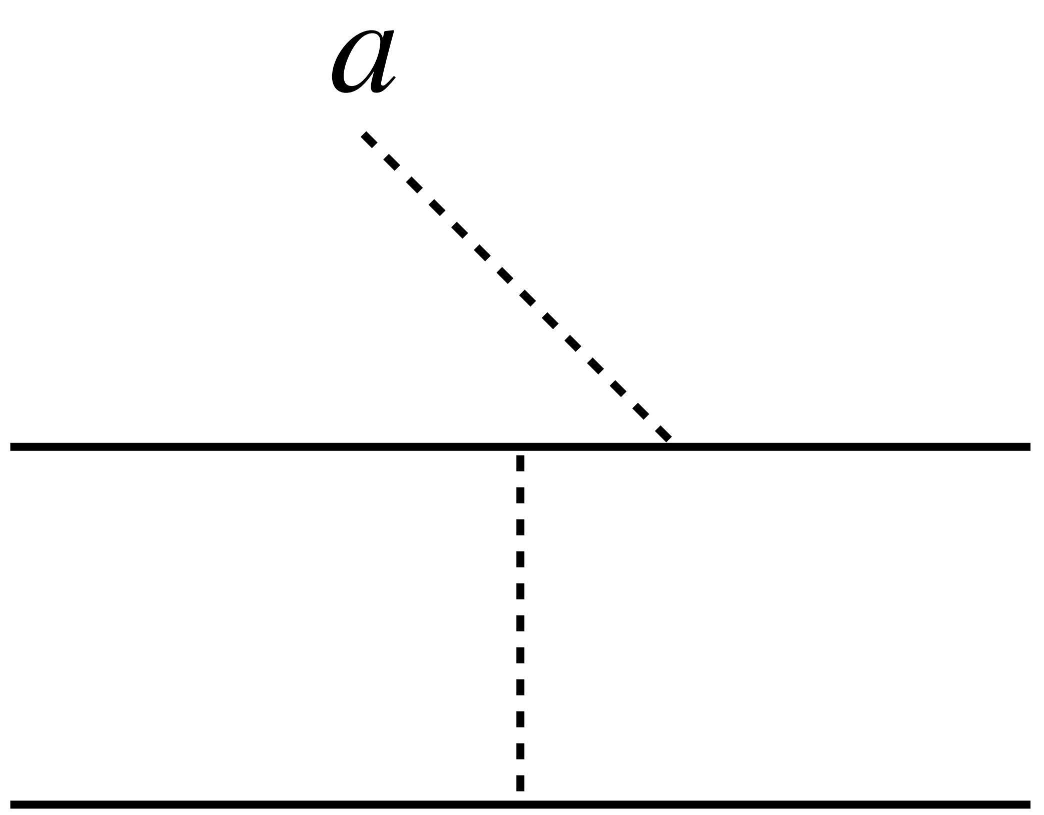

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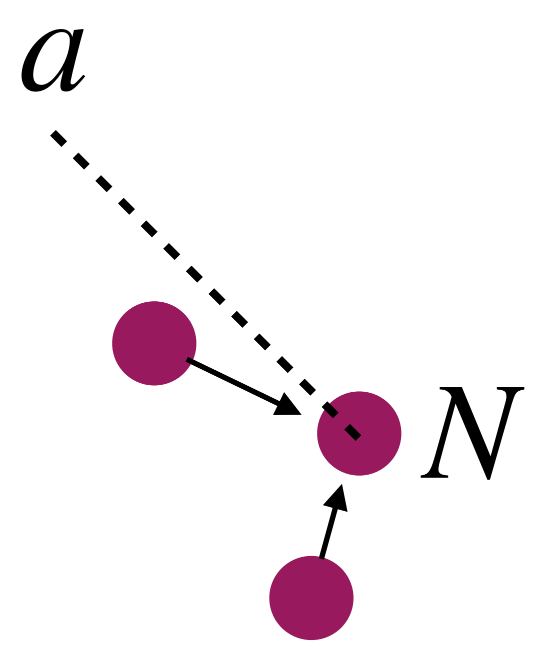

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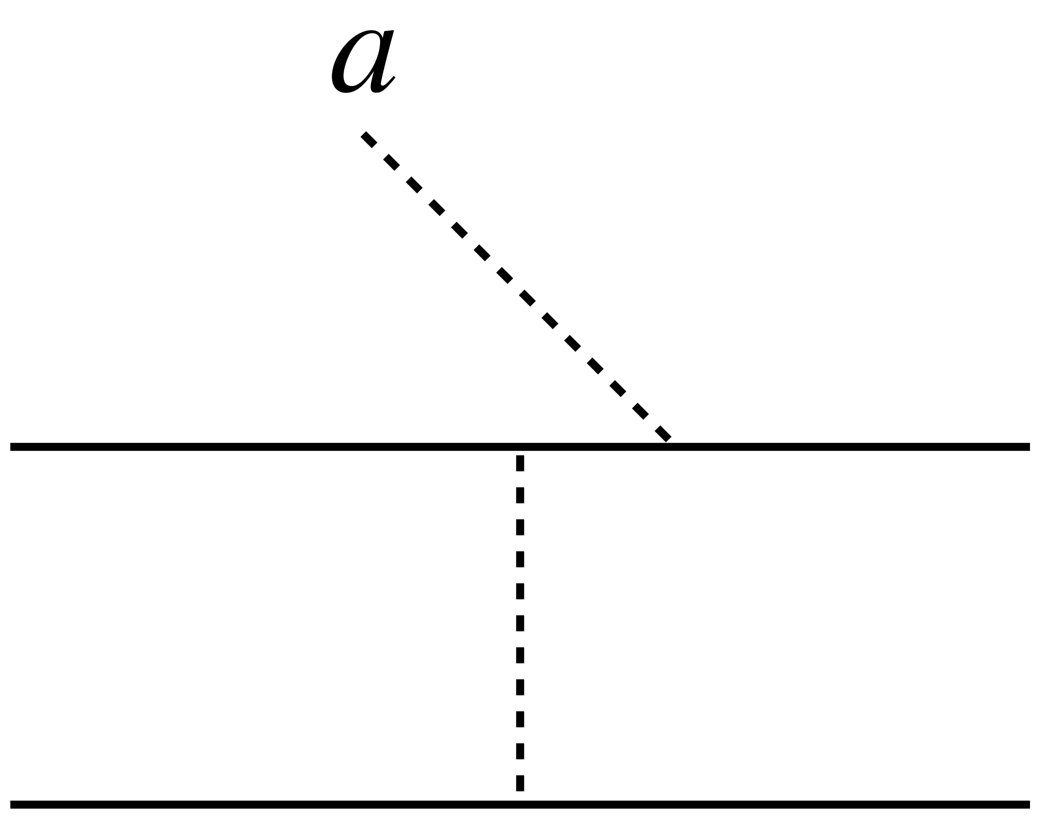

$$\omega_a \sim \mathcal{O}(R_{NS}^{-1})$$

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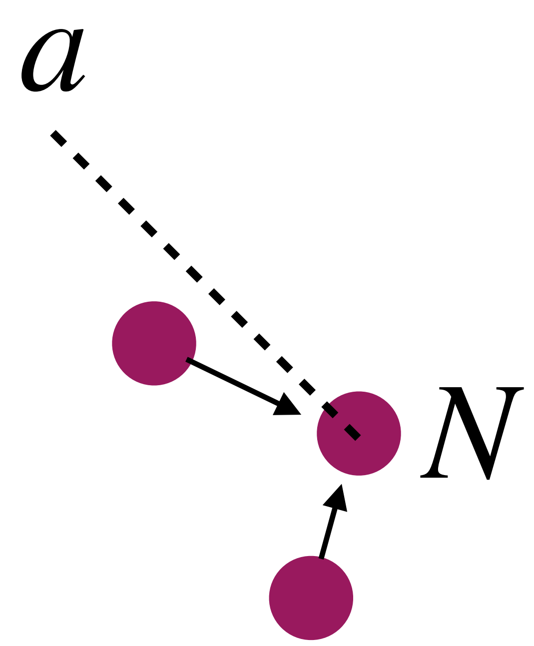

$$\Gamma_{\mathrm{coll}} \sim \mathcal{O}(1)\,\mathrm{eV}$$

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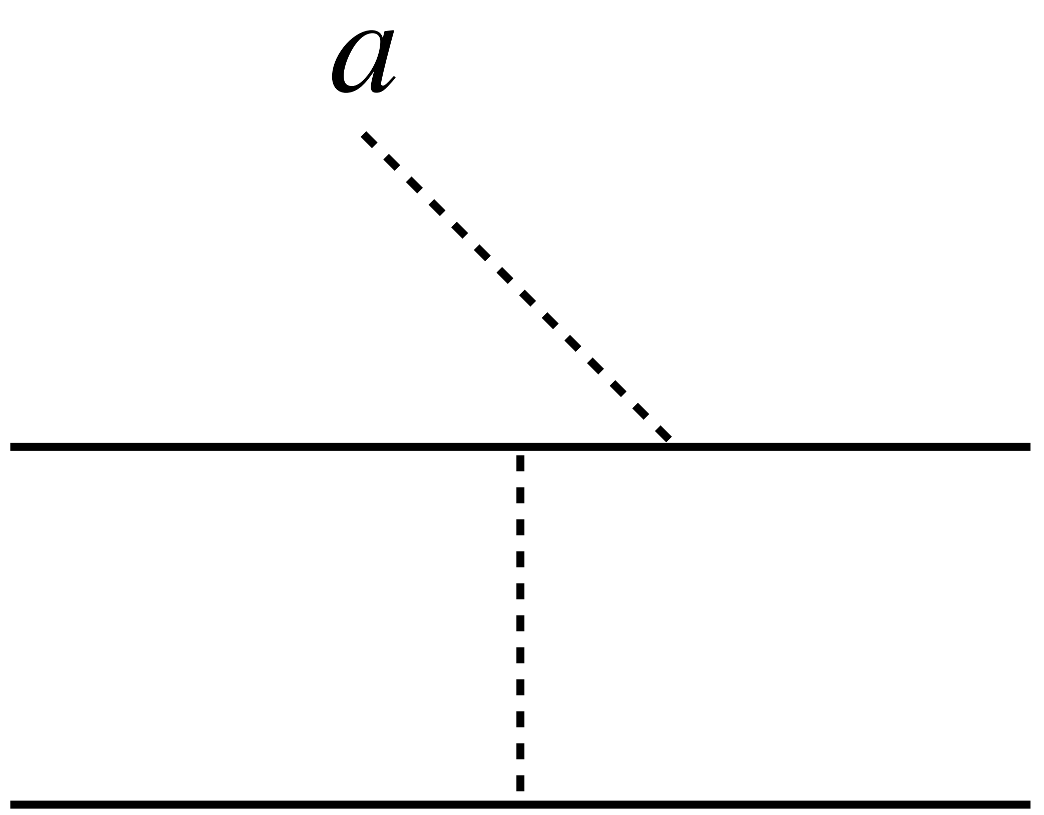
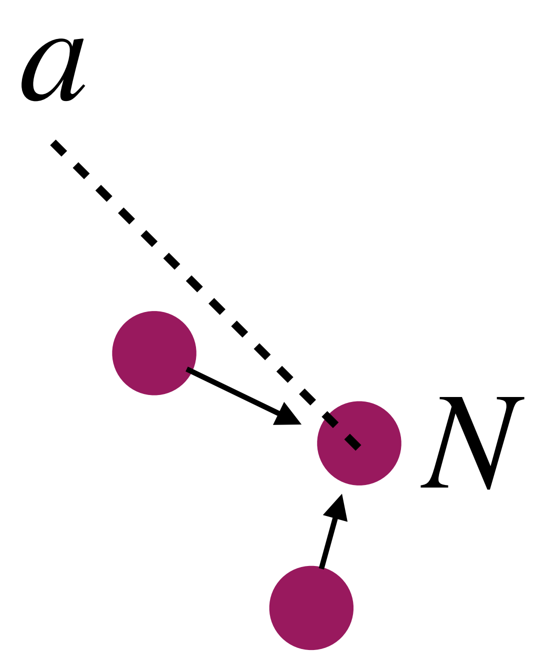
Medium effect



$$\omega_a \sim \mathcal{O}(R_{NS}^{-1})$$

$$\sim \mathcal{O}(10^{-11})\,\mathrm{eV}$$

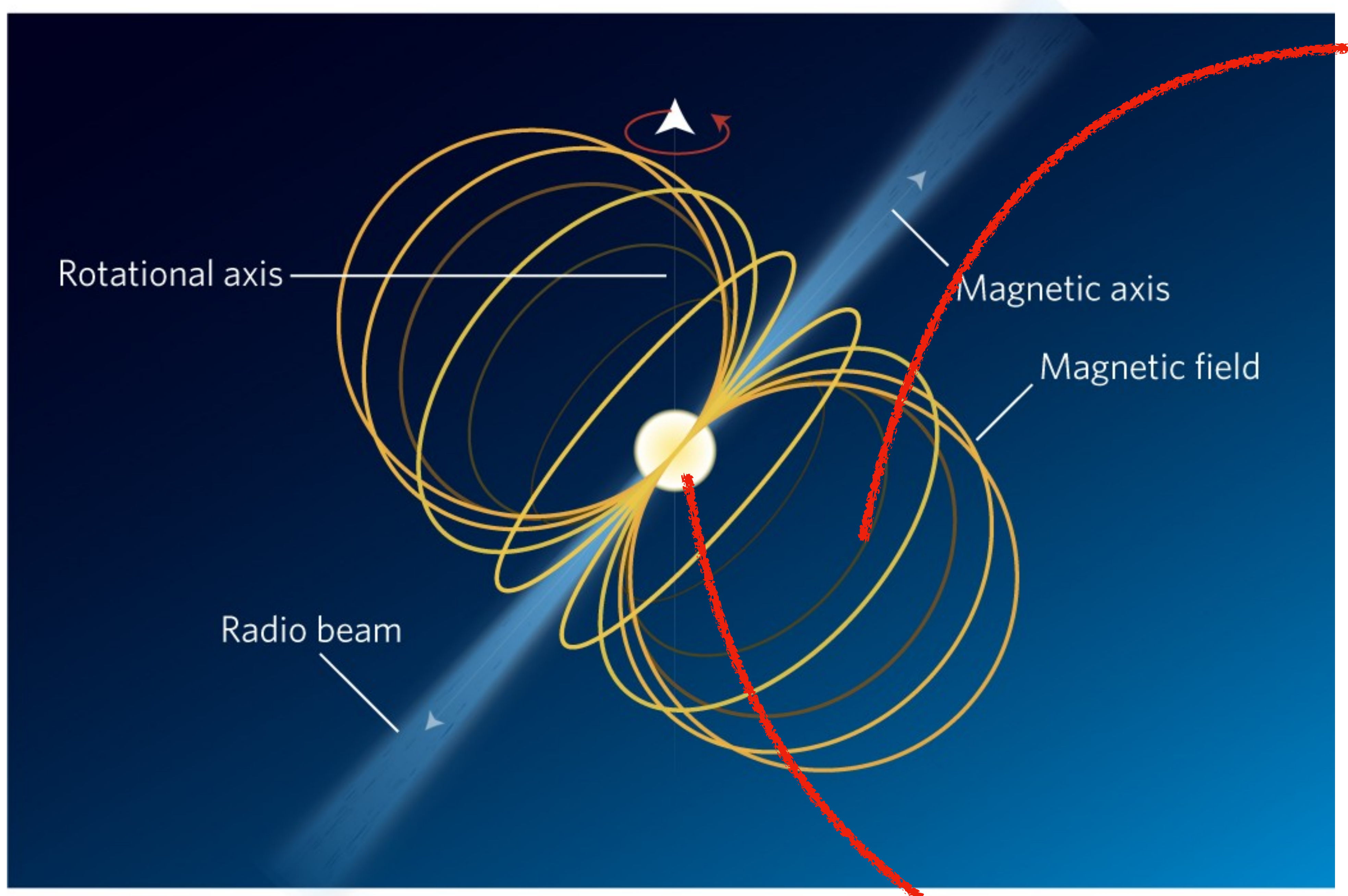


$$\Gamma_{\mathrm{coll}} \sim \mathcal{O}(1)\,\mathrm{eV}$$

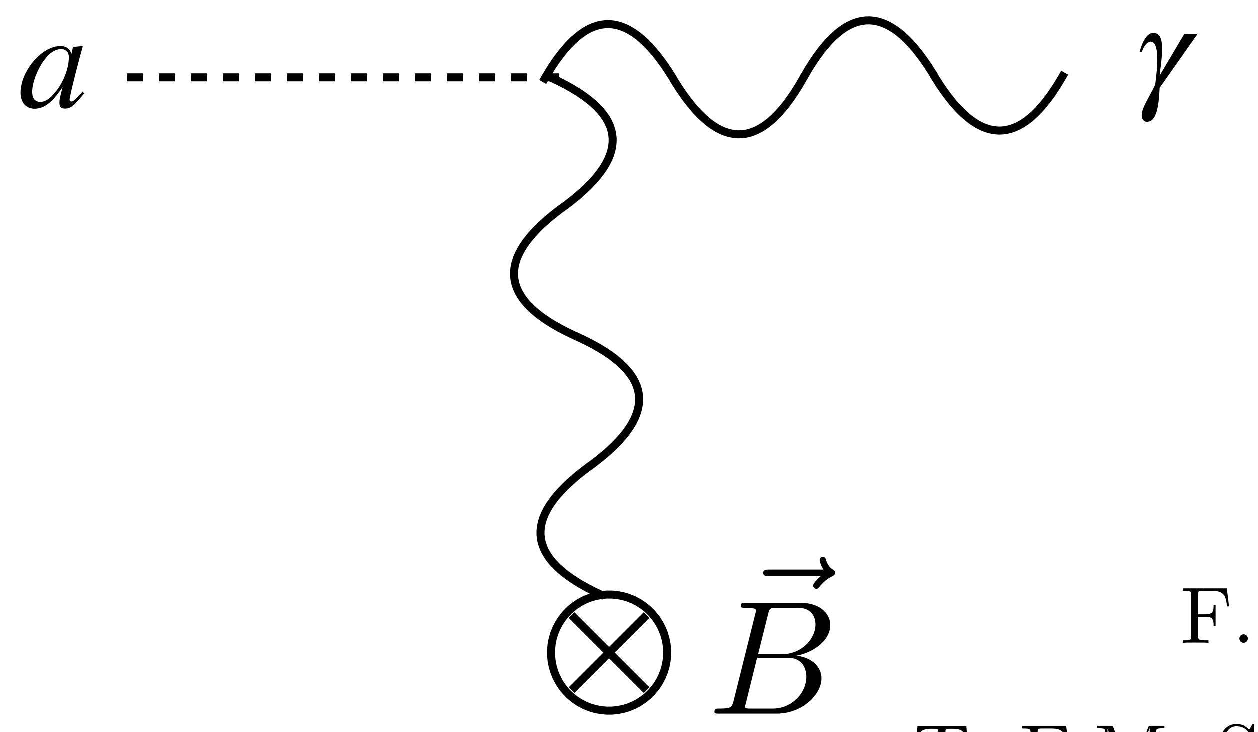
$$\Gamma_{\mathrm{SR}} \propto \frac{\omega_a^2}{\Gamma_{\mathrm{col}}^2} \sim 10^{-22}$$

Z. Bai, V. Cardoso, Y. Chen, Y. Li, J. I. McDonald, and HS, [2512.13816]

Summary: NS Superradiance and Medium Effect



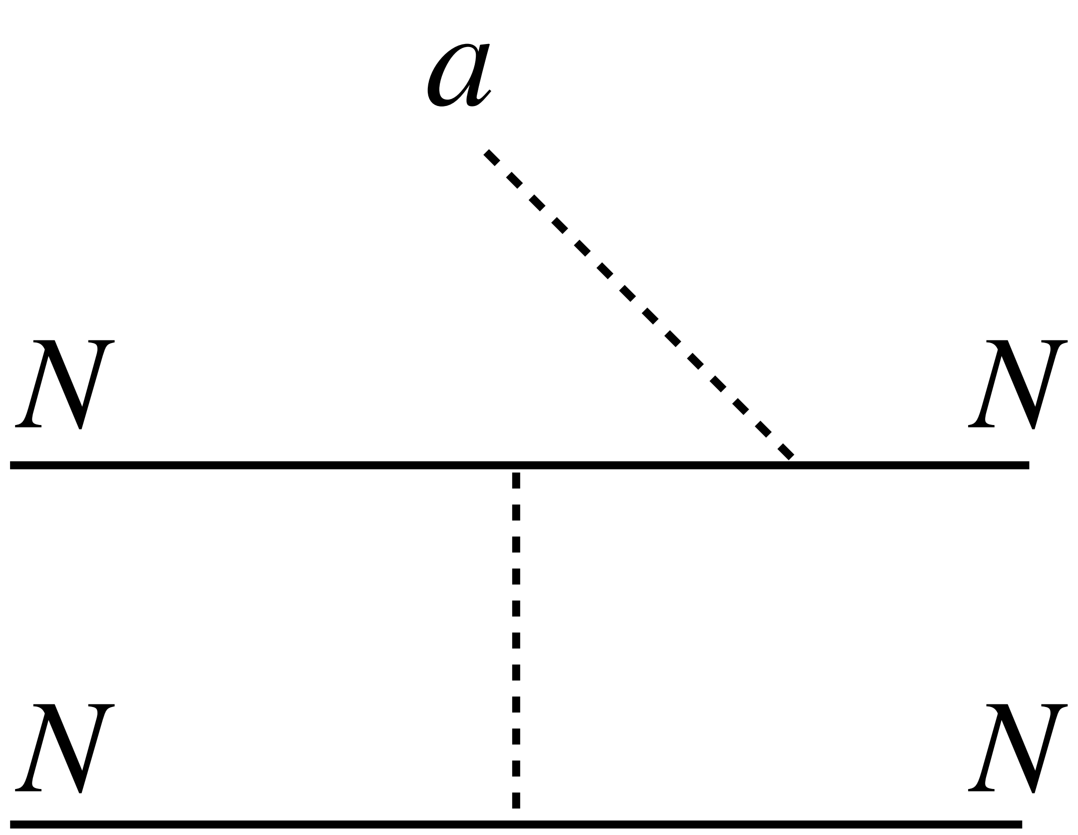
Jocelyn Bell Burnell, [Nature Astronomy (2017)]



F. V. Day and J. I. McDonald, [1904.08341]

T. F.M. Spieksma, and E. Cannizzaro, [2503.19978]

T. Sirkiä, M. Heikinheimo, and K. Tuominen, [2504.04209]



F. Chadha-Day, B. Garbrecht, and J. McDonald, [2207.07662]

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Review: F. Chadha-Day, [2601.05055]

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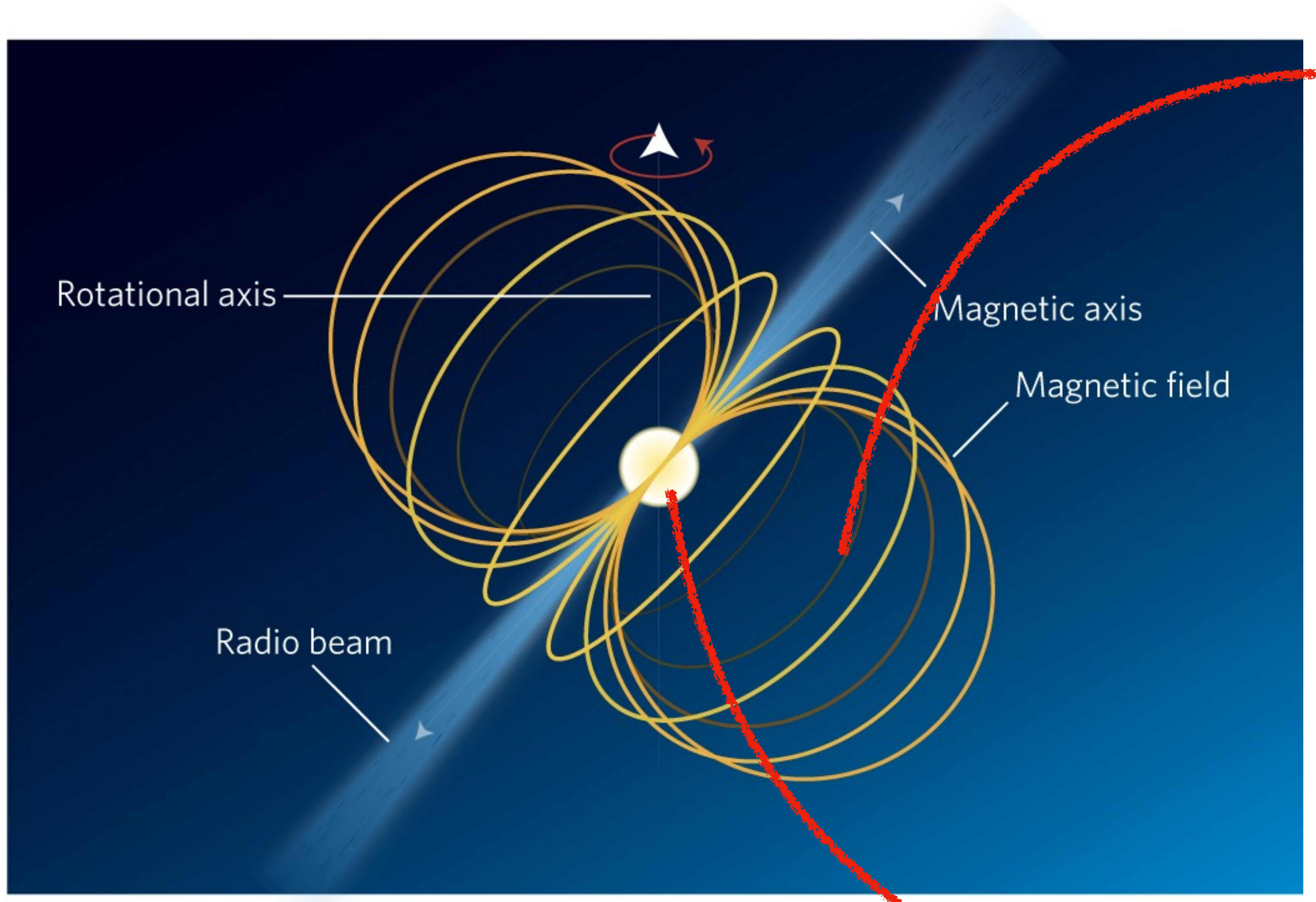

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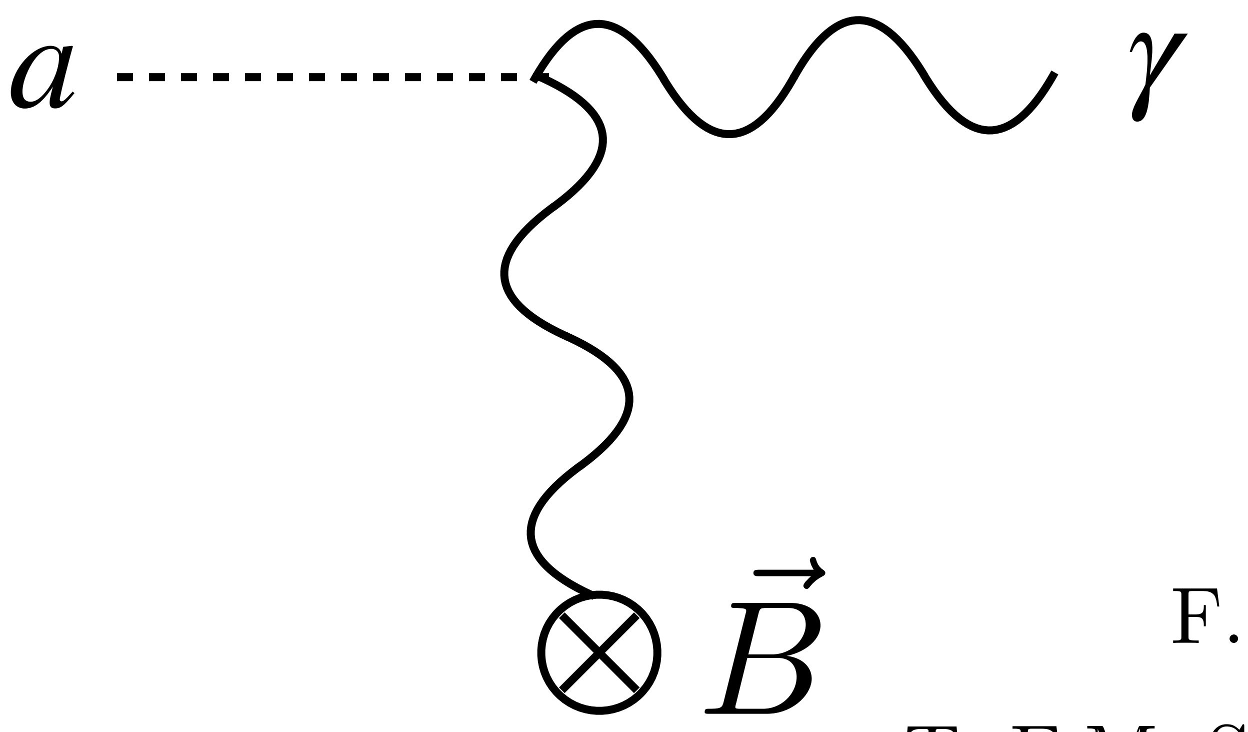

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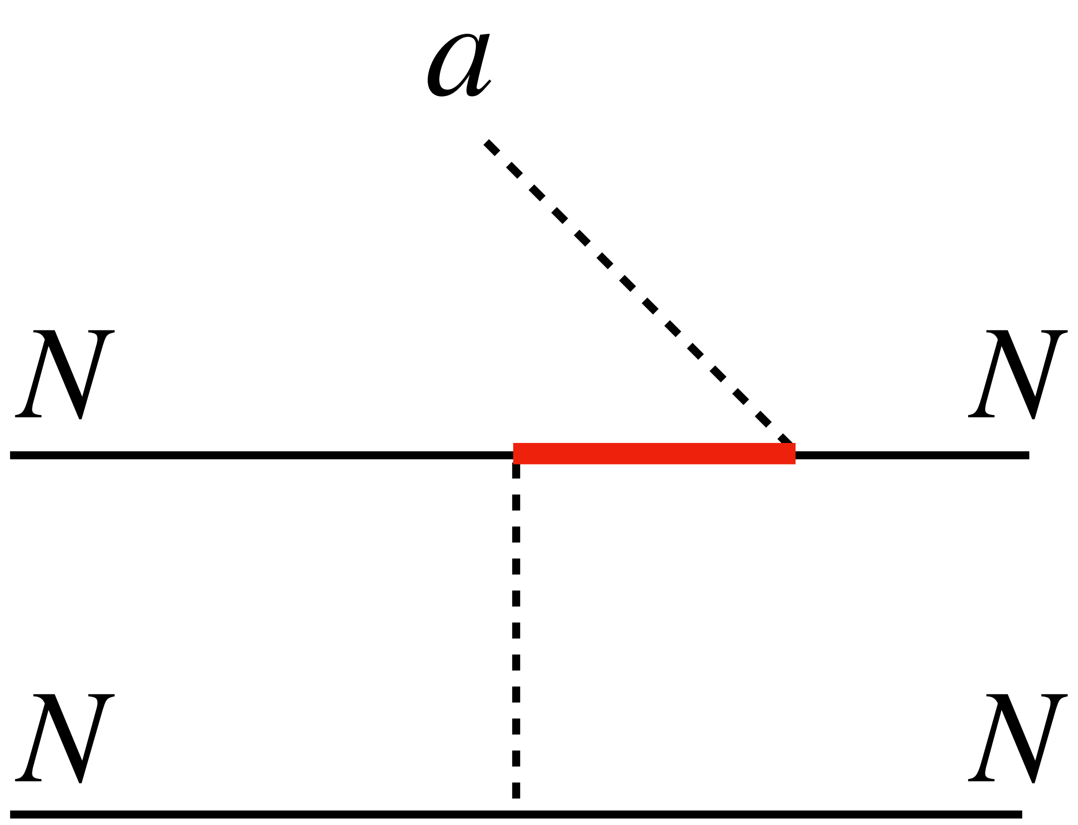

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