Exploring fundamental physics with gravitational waves

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PART I: Motivations

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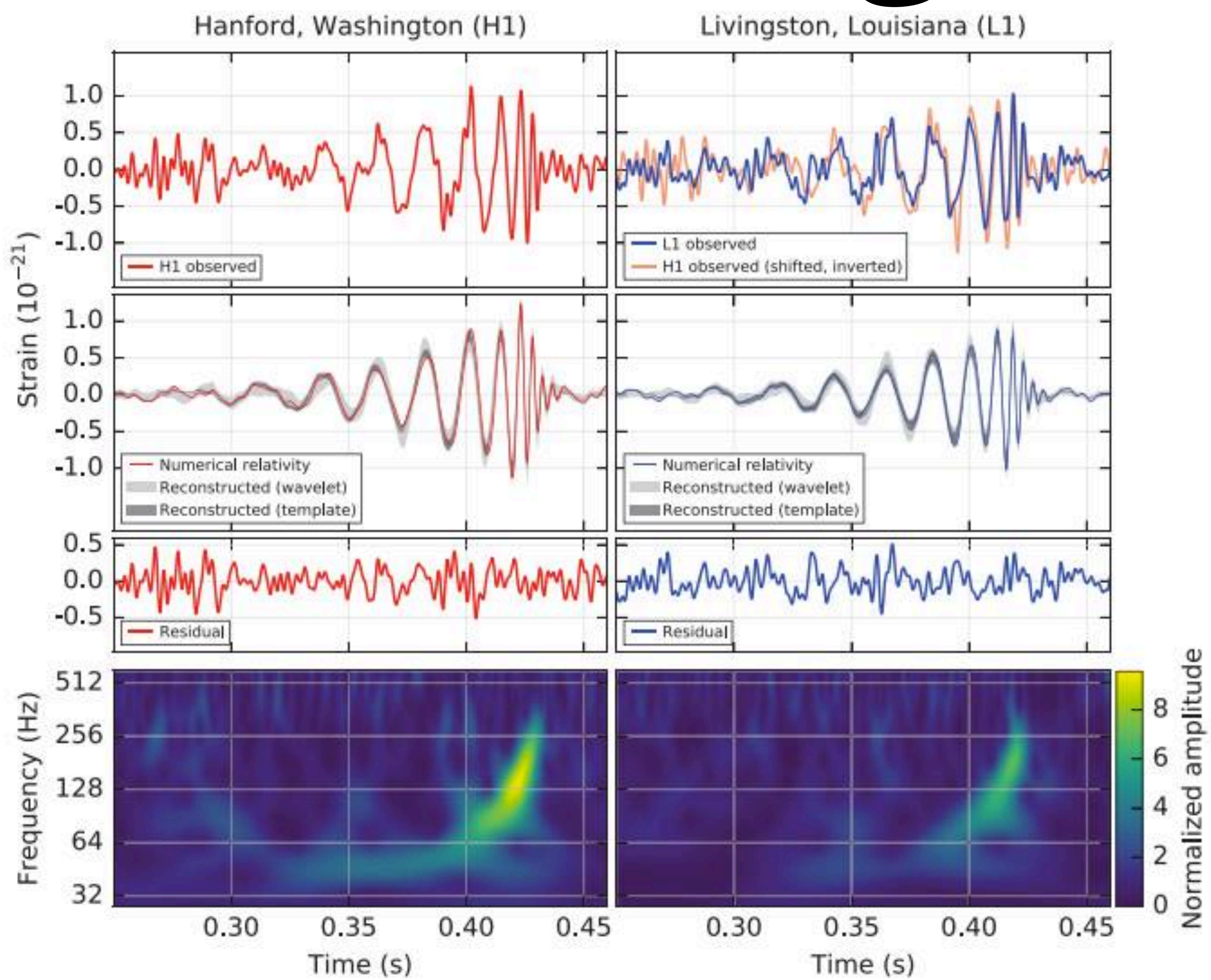
A new era has begun



PART I: Motivations

Consider a system with characteristic mass ***M*** and size ***L***.

$$\Phi \equiv \frac{G_N M}{L}$$

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It is a measure of the Newtonian gravitational potential

$$\phi(r) = -\frac{G_N M}{r}$$

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$$\mathcal{S} = -m \int ds$$

$$ds = \sqrt{g_{\mu\nu} dx^\mu dx^\nu}$$

↓

$$g_{\mu\nu} = (-1,1,1,1)$$

$$ds = dt\sqrt{1 - v^2}$$

free particle in special relativity

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$$\mathcal{S} = -m \int ds$$

$$ds = \sqrt{g_{\mu\nu} dx^\mu dx^\nu}$$

$$\downarrow \quad F(r) = -m\phi(r)$$

$$g_{00} = 1 + 2\phi(r)$$

$$g_{0i} = 0$$

$$g_{ij} = \delta_{ij}$$

PART I: Motivations

Consider a system with characteristic mass ***M*** and size ***L***.

$$ds^2 = -\left(1 - \frac{2G_N M}{r}\right) dt^2 + \frac{dr^2}{\left(1 - \frac{2G_N M}{r}\right)} + r^2 d\Omega^2$$

$$\left[\frac{2G_N M}{r}\right] \sim \Phi$$

$$\frac{1}{\left(1 - \frac{2G_N M}{r}\right)} = 1 + \frac{2G_N M}{r} + \dots$$

PART I: Motivations

Consider a system with characteristic mass ***M*** and size ***L***.

$$\Phi_{\rm Sun} \simeq 10^{-6}$$

$$\Phi_{\rm BH} = 1/2$$

For a BH, $L = 2G_N M$

PART I: Motivations

Consider a system with characteristic mass M and size L.

The parameter Φ is very useful in defining the validity of the Newtonian approximation.

It is not fundamental in characterizing a gravitational field in Einstein's theory. Indeed, the Einstein field equation are written in terms of the Ricci scalar and the Ricci tensor all of which measure the curvature of the field and not its potential.

Consider a system with characteristic mass ***M*** and size ***L***.

$$\mathscr{R}^{1/2} \equiv \sqrt{\frac{G_N M}{L^3}}$$

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The inverse of the characteristic curvature length scale of the system

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The inverse of the characteristic curvature length scale of the system

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu} \overset{[T] \sim M/L^3}{\Longrightarrow} [R] \sim \mathcal{R}$$

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$$\mathscr{R}^{1/2} \equiv \sqrt{\frac{G_N M}{L^3}}\,, \quad [R] = \mathscr{R}$$

example

$$\mathcal{S} = \frac{1}{16\pi G_N}\int d^4x\, R$$

$\alpha \lesssim 1/\mathscr{R}^{1/2}$: For a given system, we are probing GR down to typical length of order $\alpha \sim 1/\mathscr{R}^{1/2}$

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$$\mathcal{S} = \frac{1}{16\pi G_N} \int d^4x \, R \left(1 + \alpha^2 R\right)$$

$\alpha \lesssim 1/\mathscr{R}^{1/2}$: For a given system, we are probing GR down to typical length of order $\alpha \sim 1/\mathscr{R}^{1/2}$

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$$\mathscr{R}^{1/2} \equiv \sqrt{\frac{G_N M}{L^3}}$$

$$\alpha_{\rm Sun} \sim 1/\mathscr{R}^{1/2}_{\rm Sun} \sim 5 \times 10^8\,{\rm km}$$

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$$\mathscr{R}^{1/2} \equiv \sqrt{\frac{G_N M}{L^3}}$$

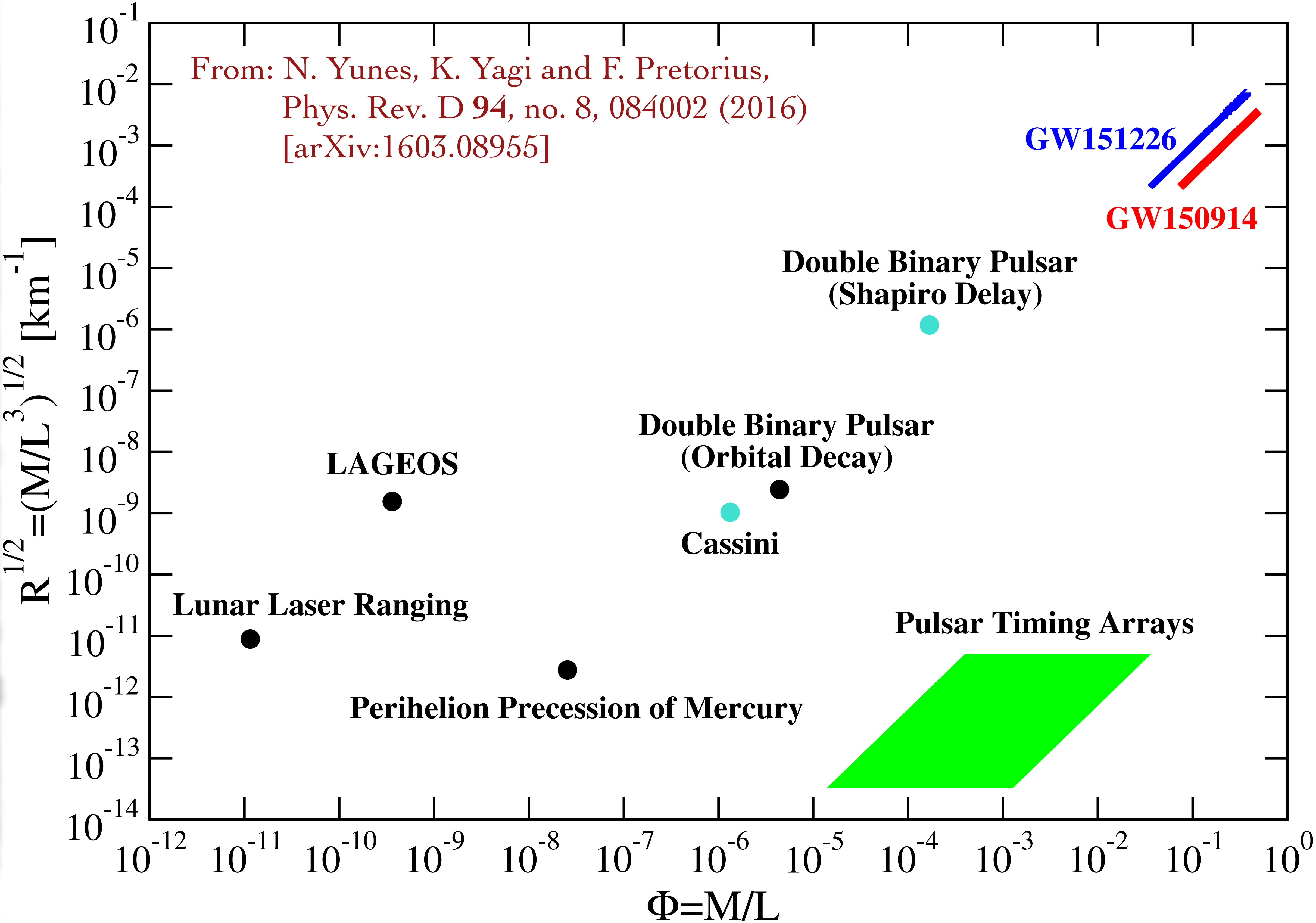
$$\alpha_{\rm BH} \sim 1/\mathscr{R}_{\rm BH}^{1/2} \sim 1/G_N M$$

$G_N = 1/M_{\rm P}^2$

$l_{\rm P} = 1/M_{\rm P}$

$$\alpha_{\rm BH} \sim l_{\rm P} \left(\frac{M}{M_{\rm P}} \right)$$

PART I: Motivations



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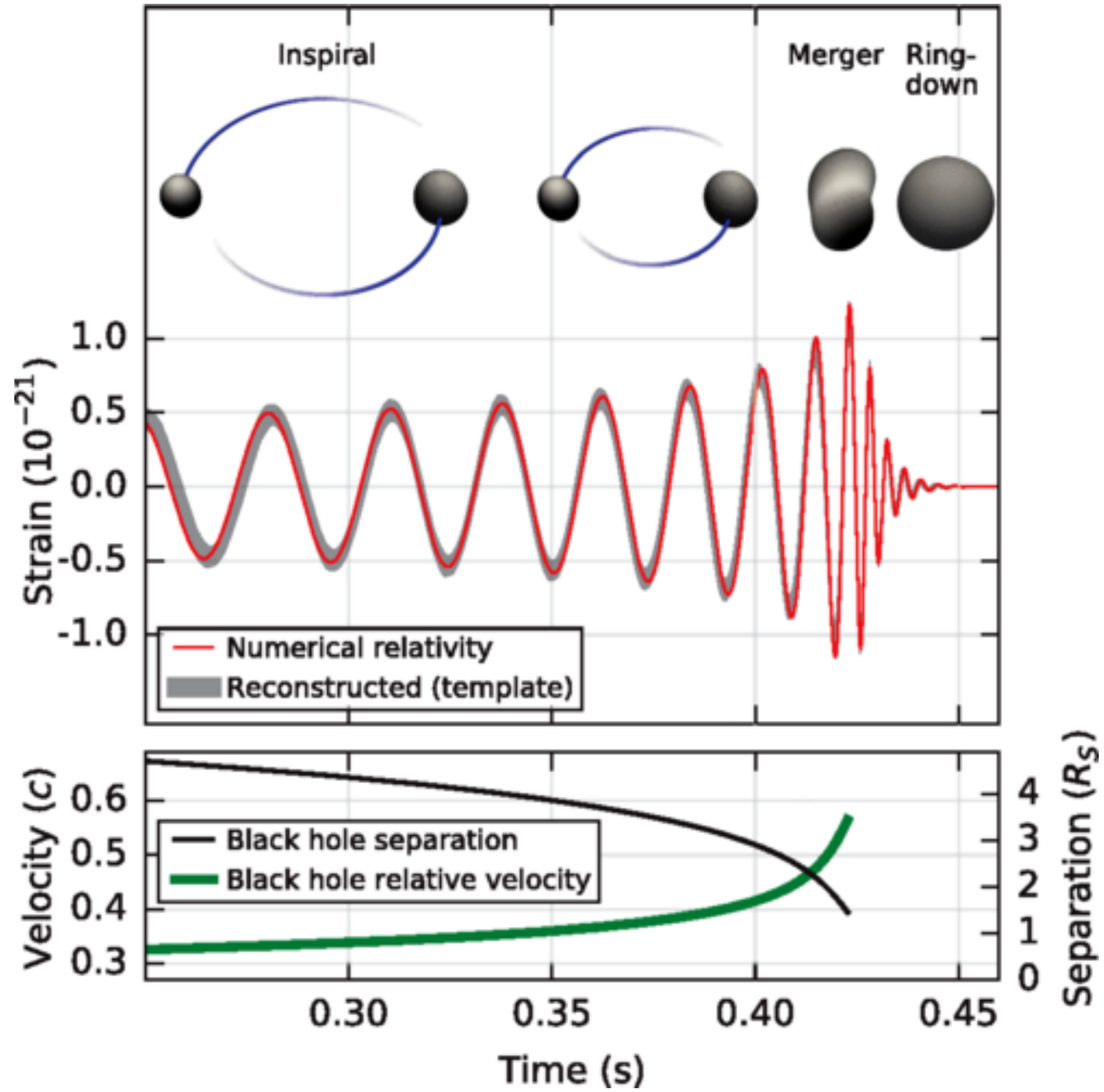
<u>Inspiral phase</u>: The compact objects are well separated with respect to the total mass.



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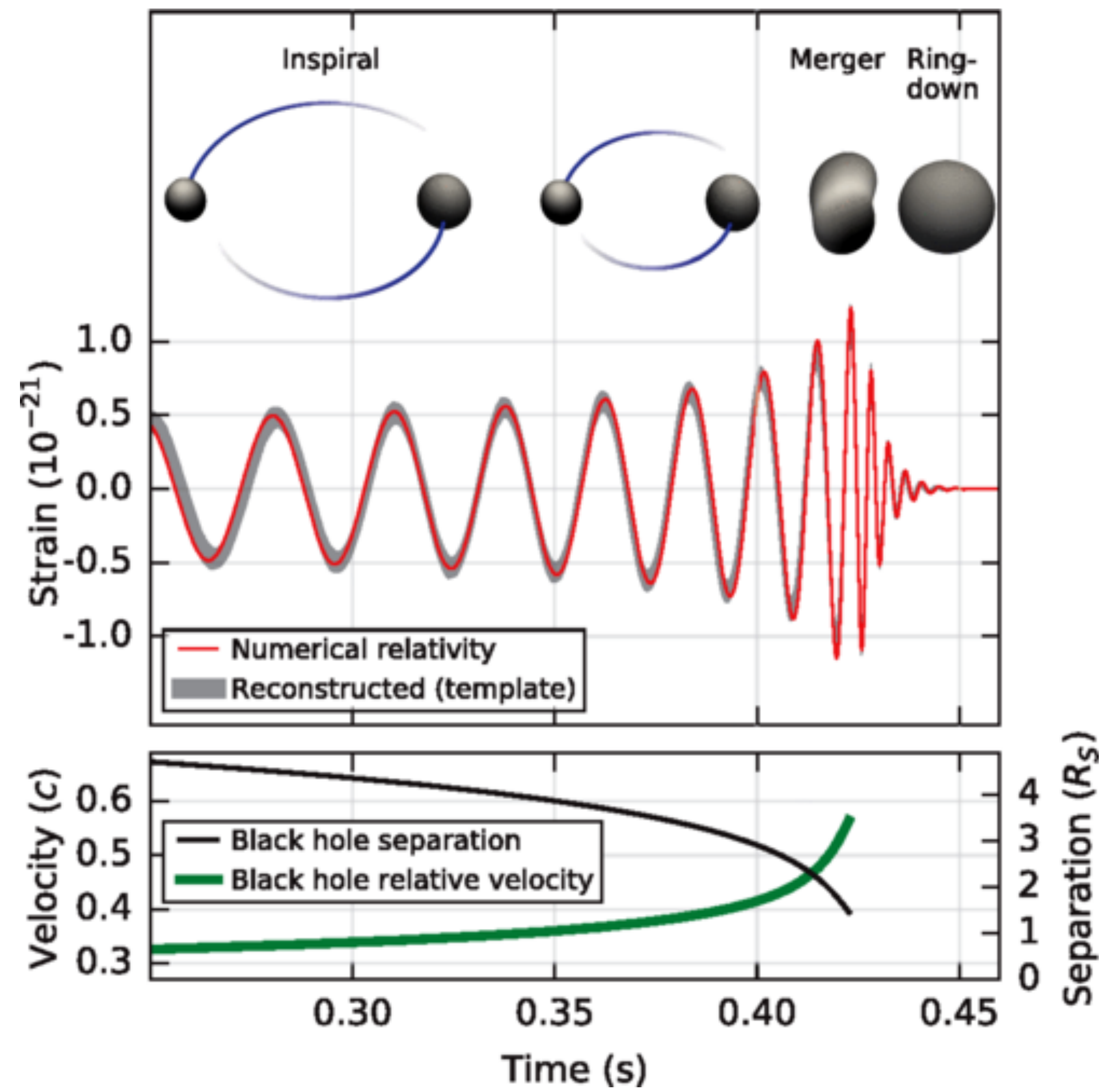
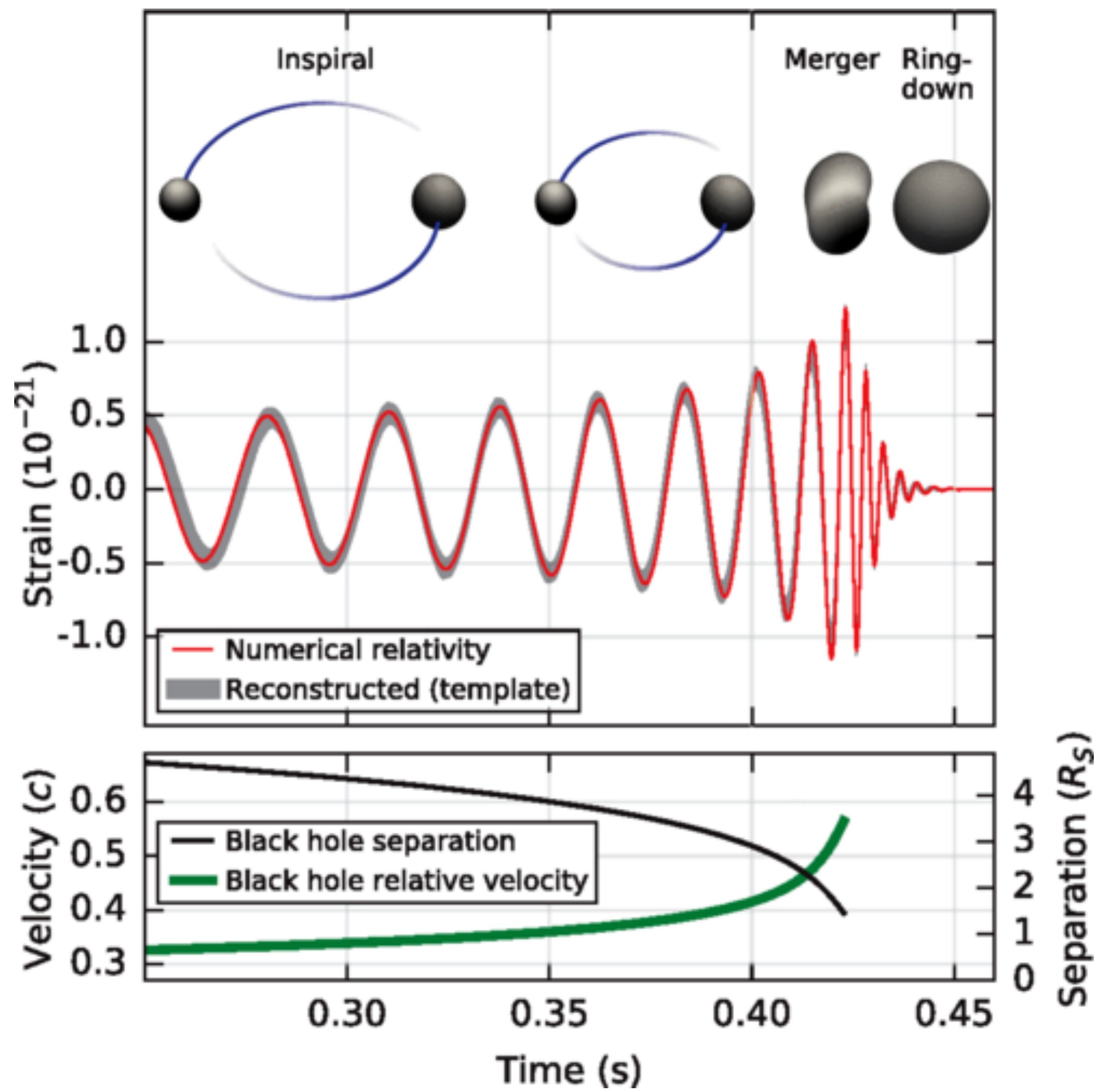
Plunge & merger: The compact objects are very close to each other and velocities approach the speed of light. The two objects coalesce.



PART I: Motivations

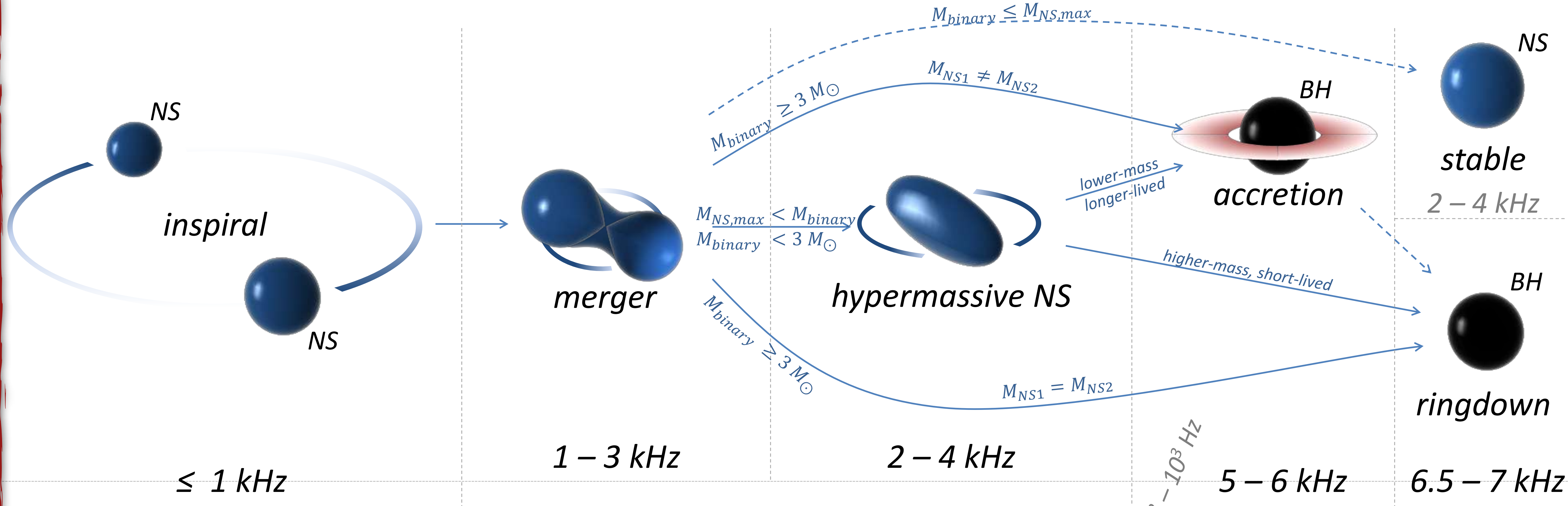
Ringdown: The highly distorted remnant formed after merger oscillates, radiating away any deformations and relaxes to a stationary state.



This classification is clean in concept, and applies to both BH-BH and NS-NS merger.

PART I: Motivations

From: I. Bartos, P. Brady and S. Marka, Class. Quant. Grav. **30**, 123001 (2013) [arXiv:1212.2289]



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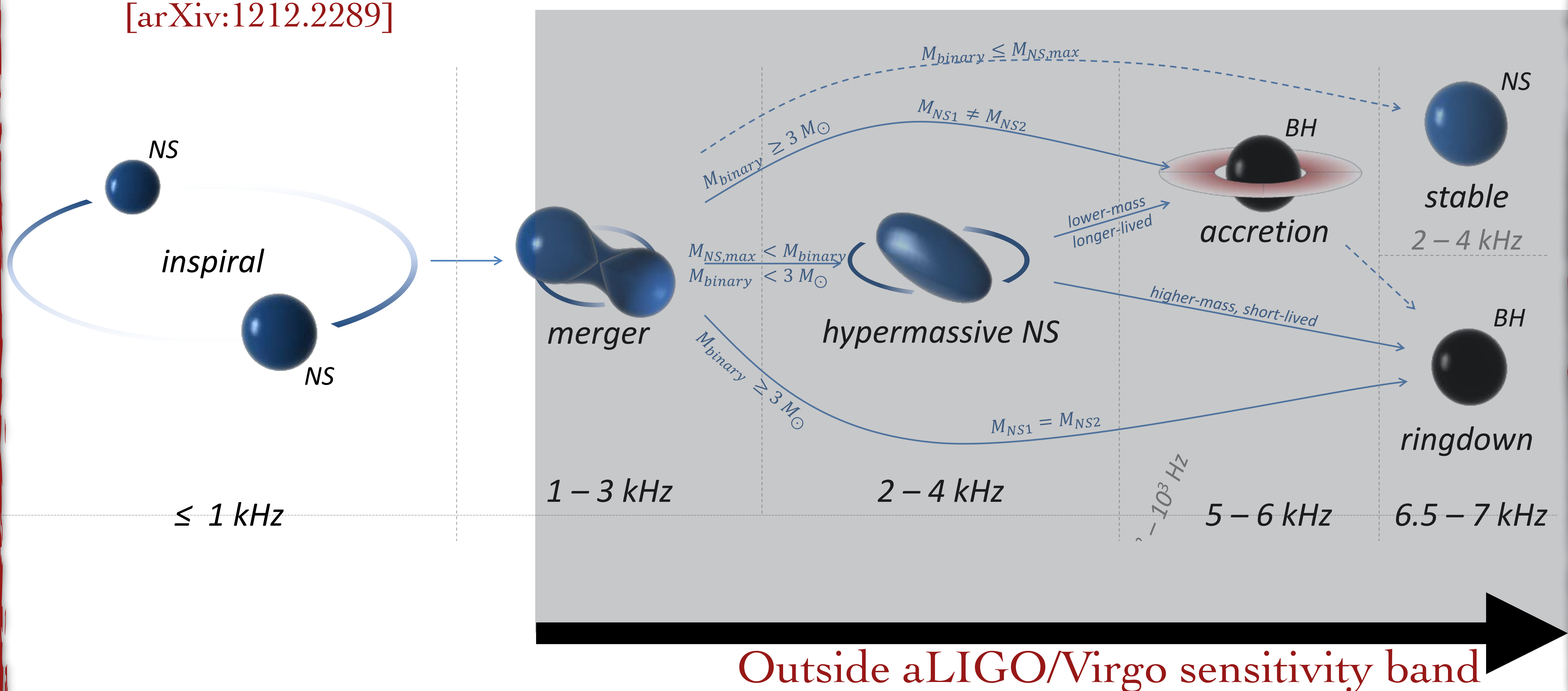
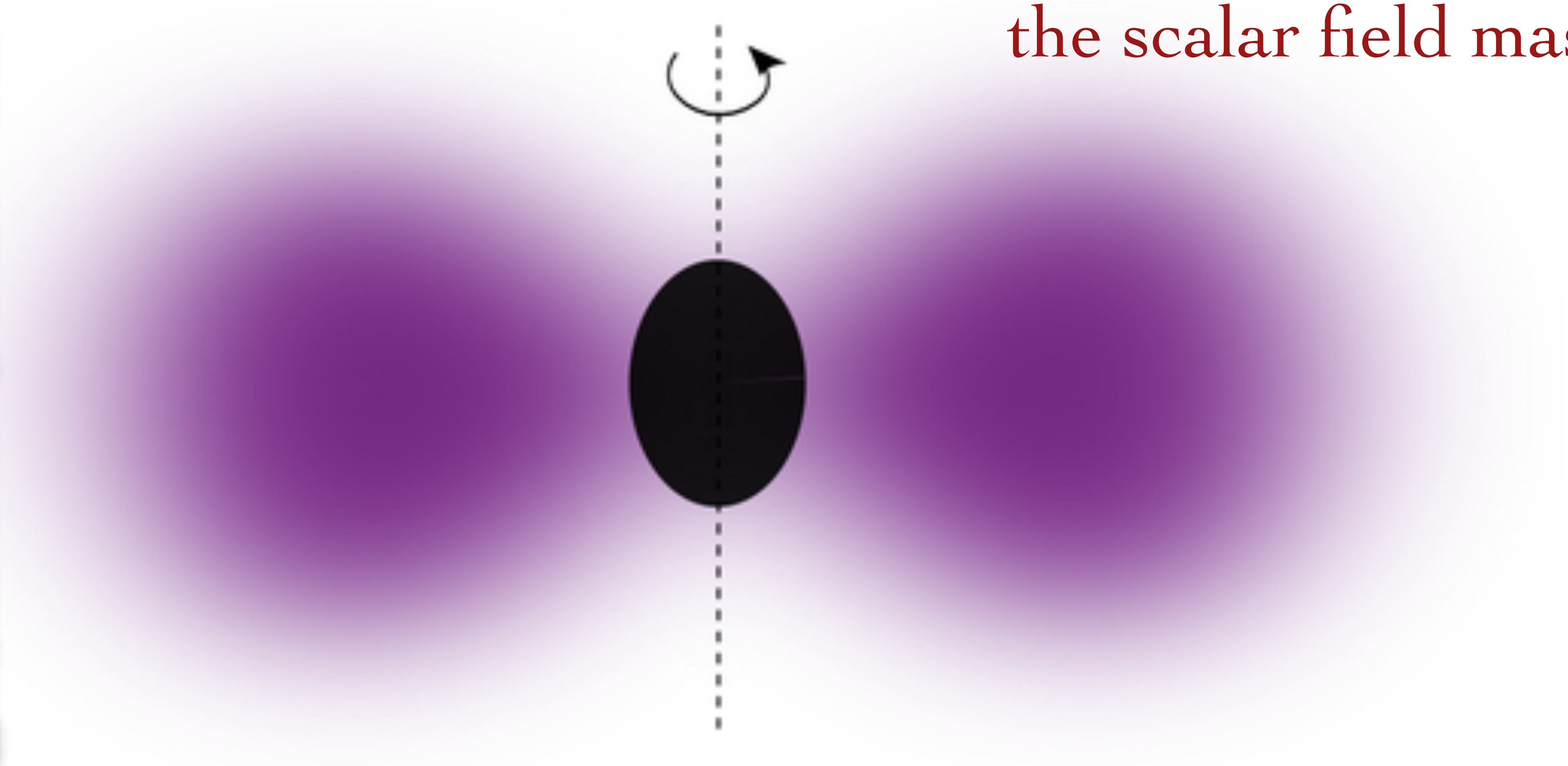


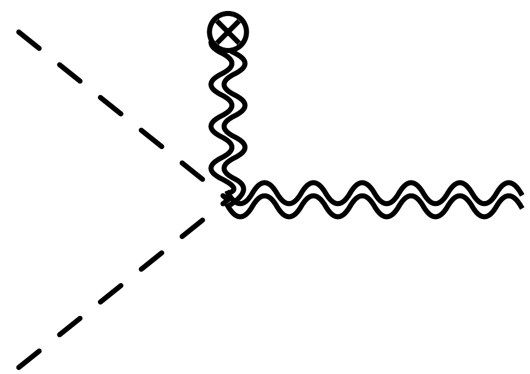
What we can learn from gravitational waves?

Black hole as “particle detector”

GW as a probe for new <u>light and weakly-coupled</u> (dark) particles

The condensate is dissipated through the emission of GWs (with frequency set by the scalar field mass)

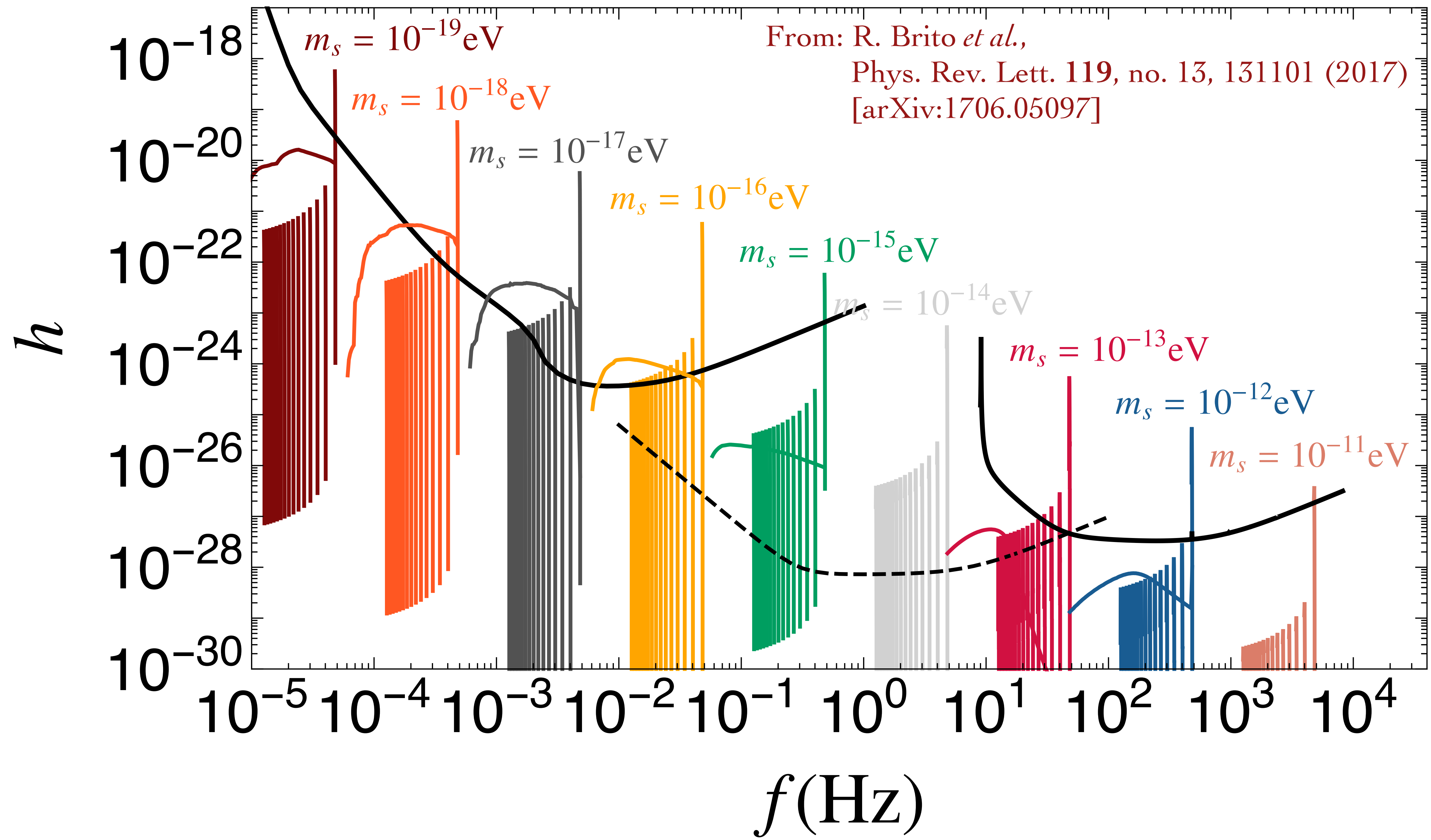




$$M \approx 6.7 \left(\frac{10^{-12}\,\mathrm{eV}}{m} \right) M_{\odot}$$

$$\frac{m}{10^{-12}\,\mathrm{eV}} \simeq 240\,\mathrm{Hz}$$

Black hole as "particle detector"



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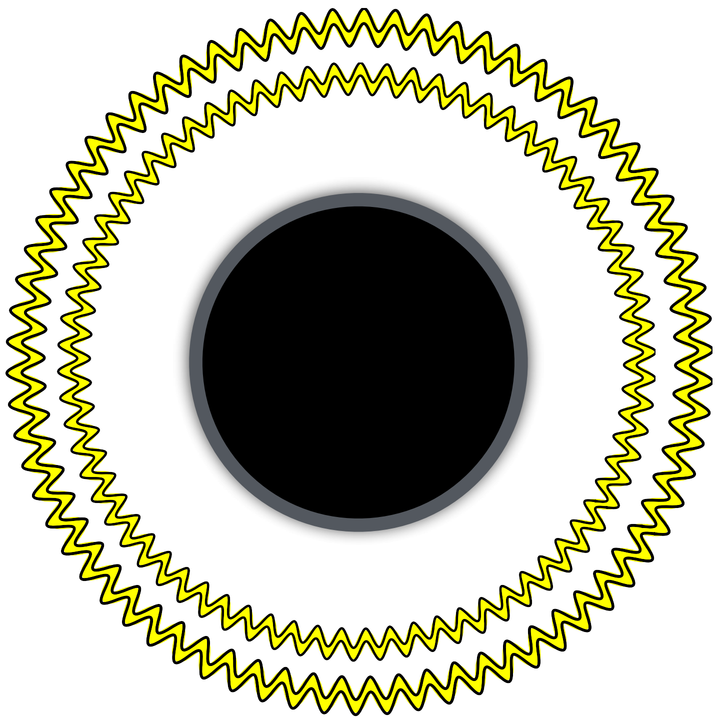
Gravitational wave "echoes"

GW as a probe for deformation of the black hole event horizon compared to GR predictions



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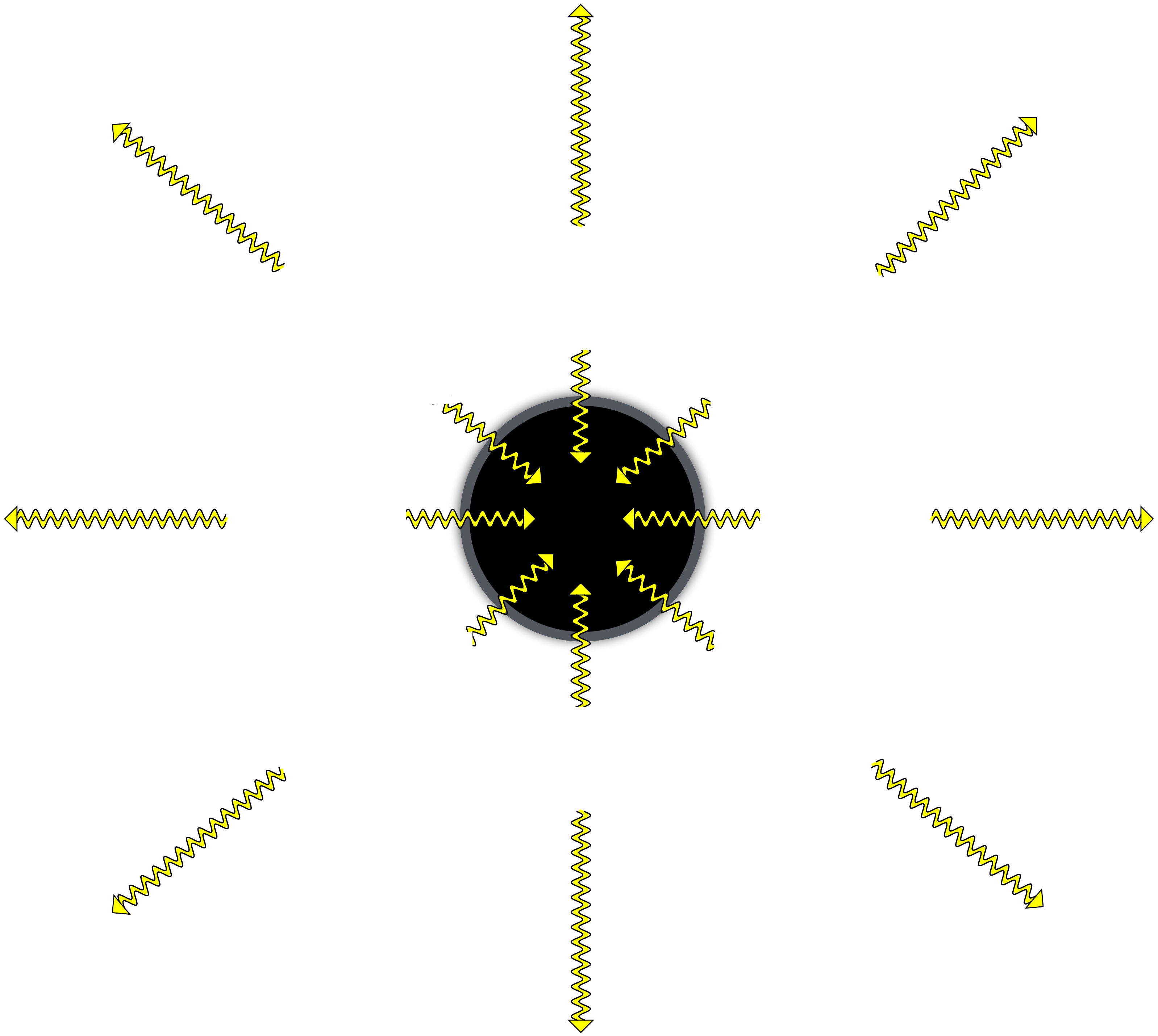

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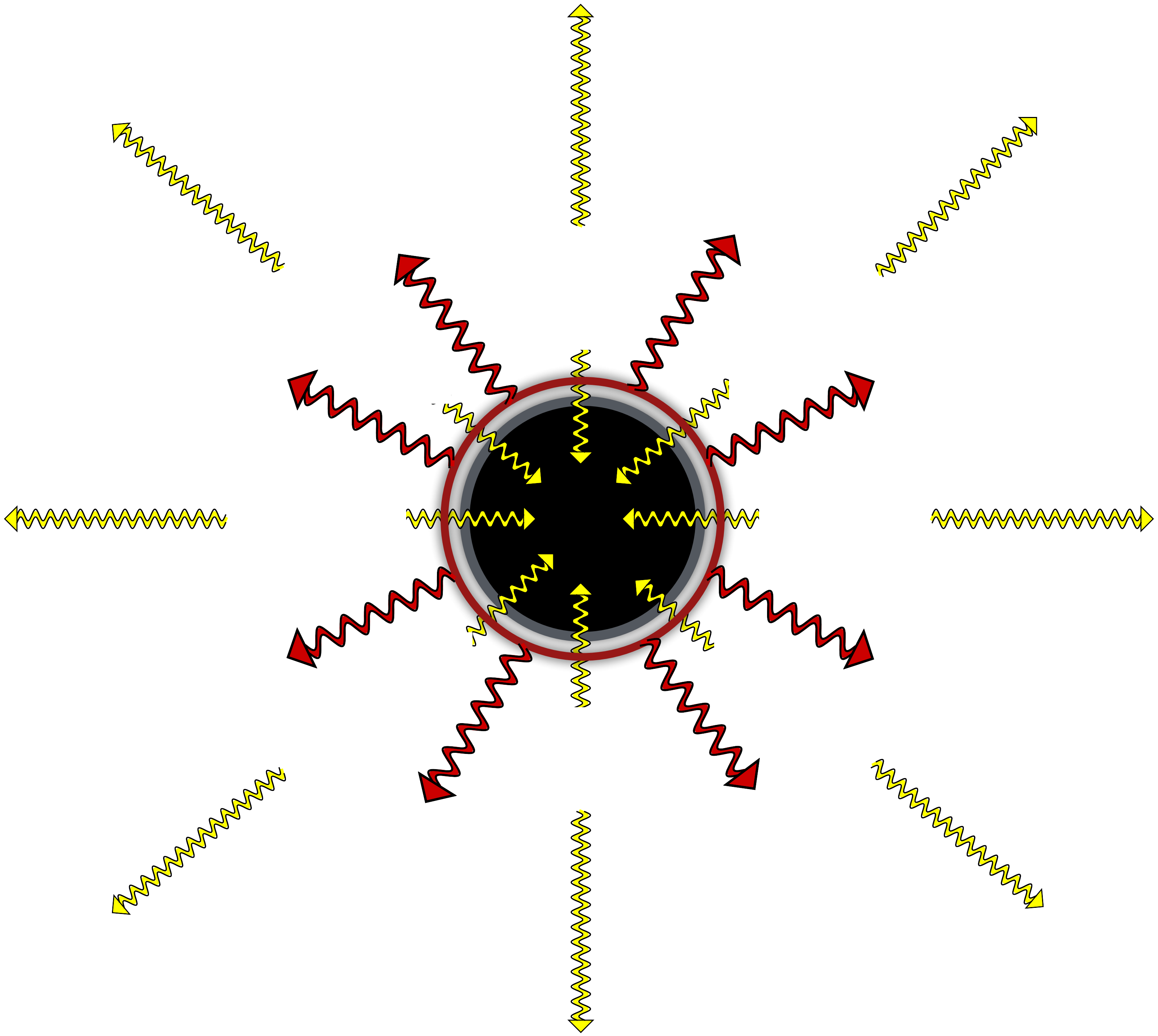

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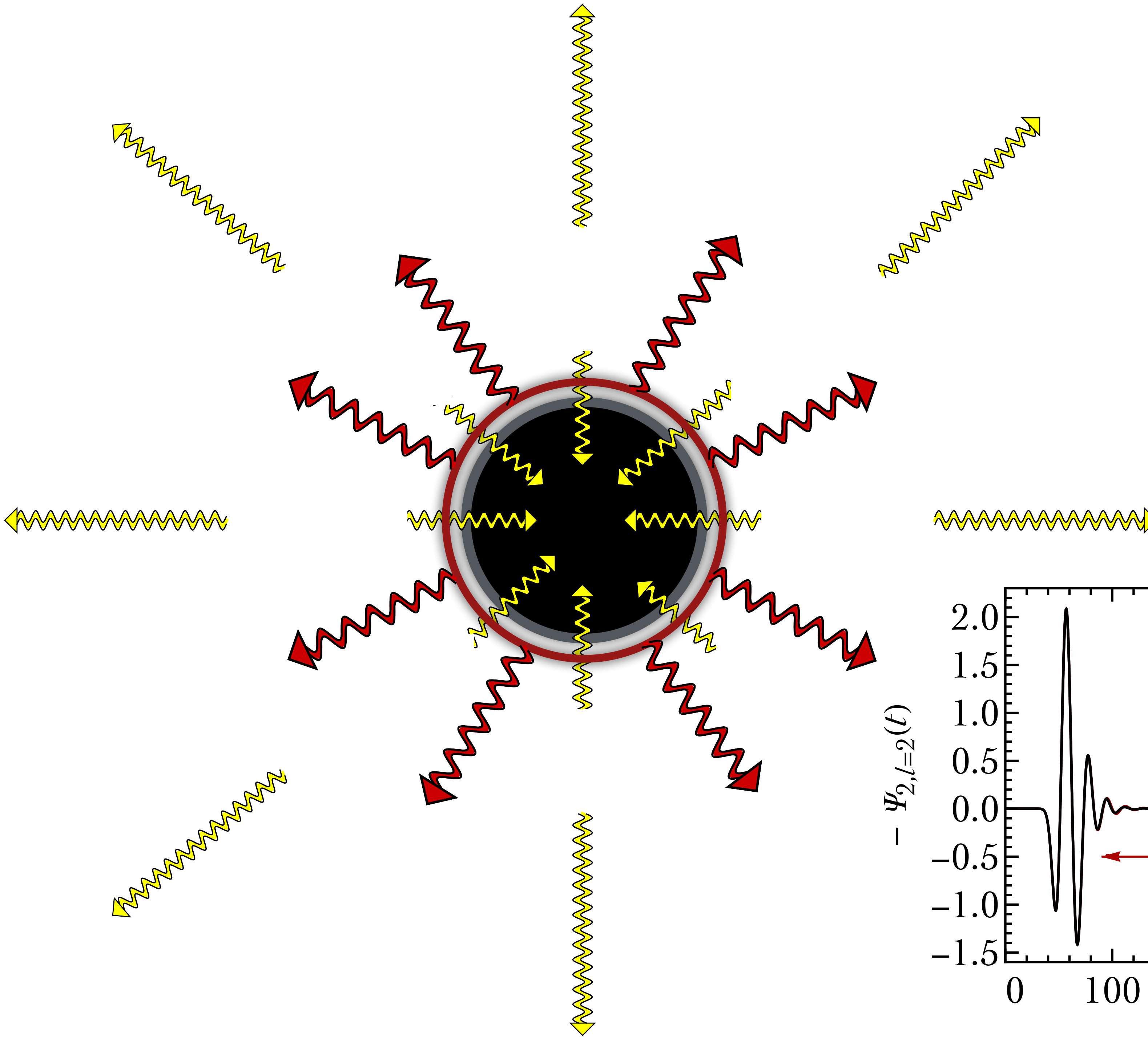
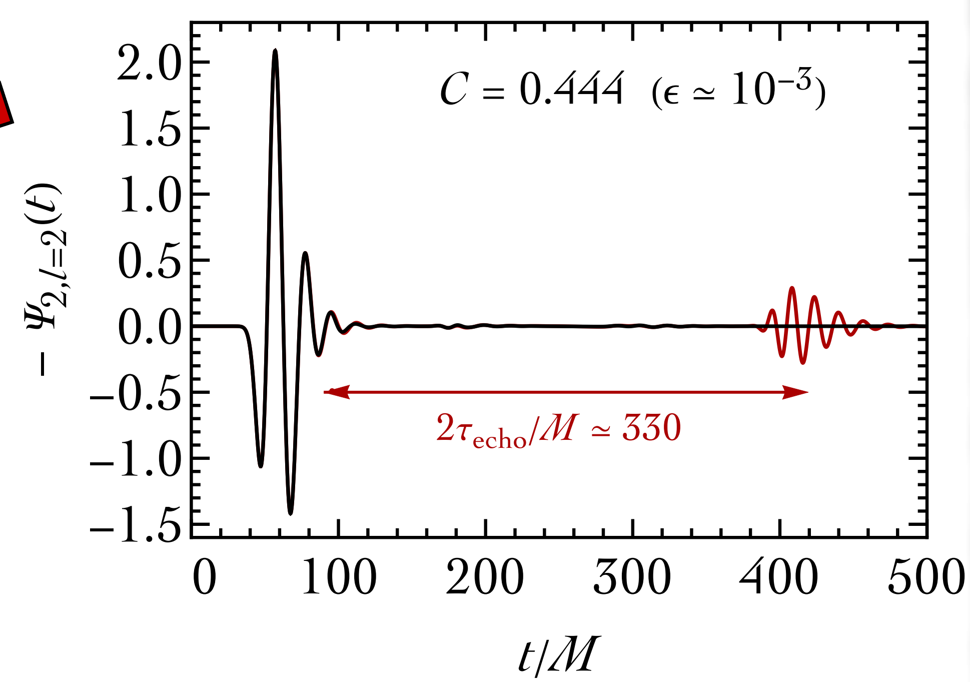
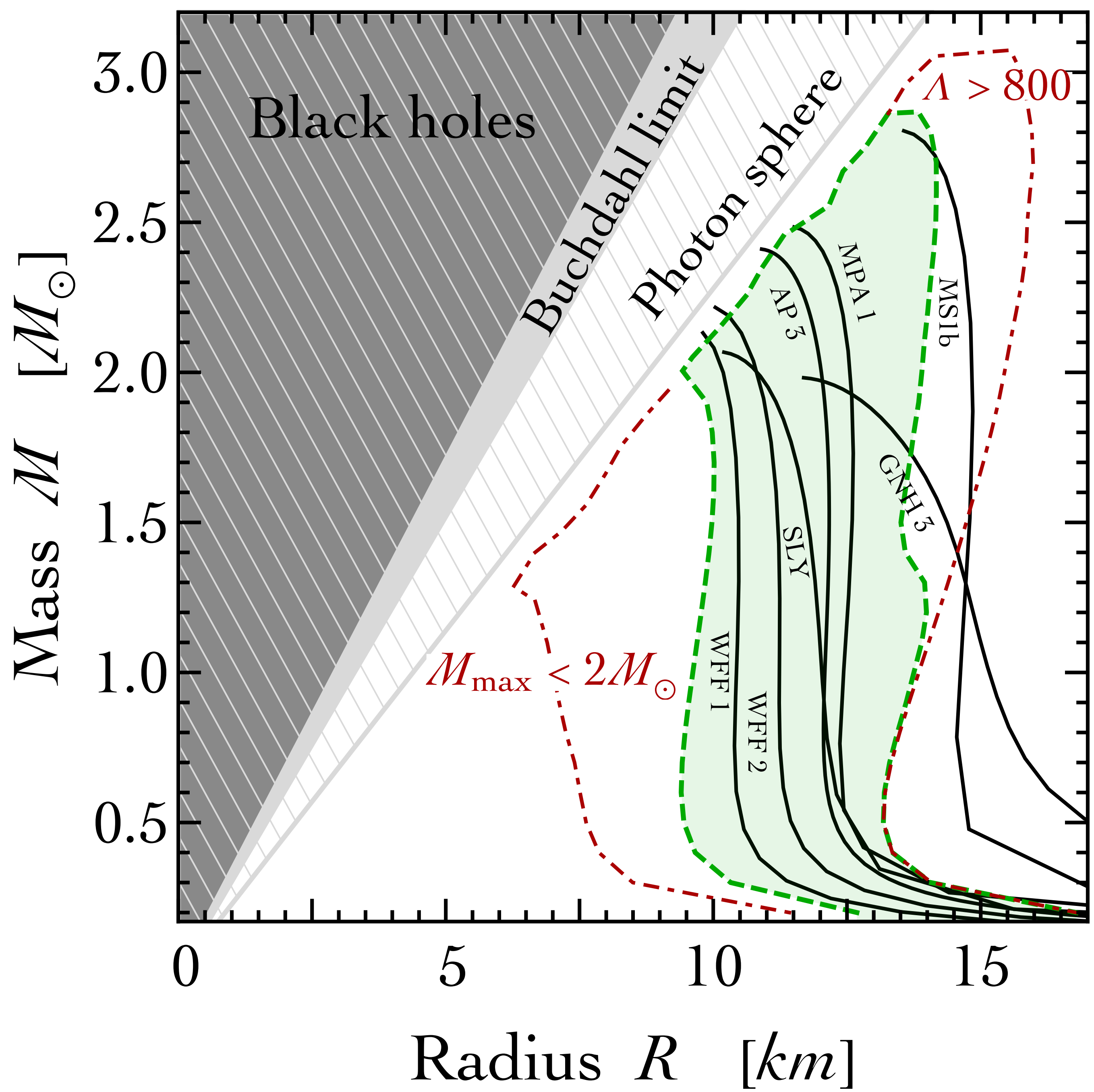




Neutron star EoS

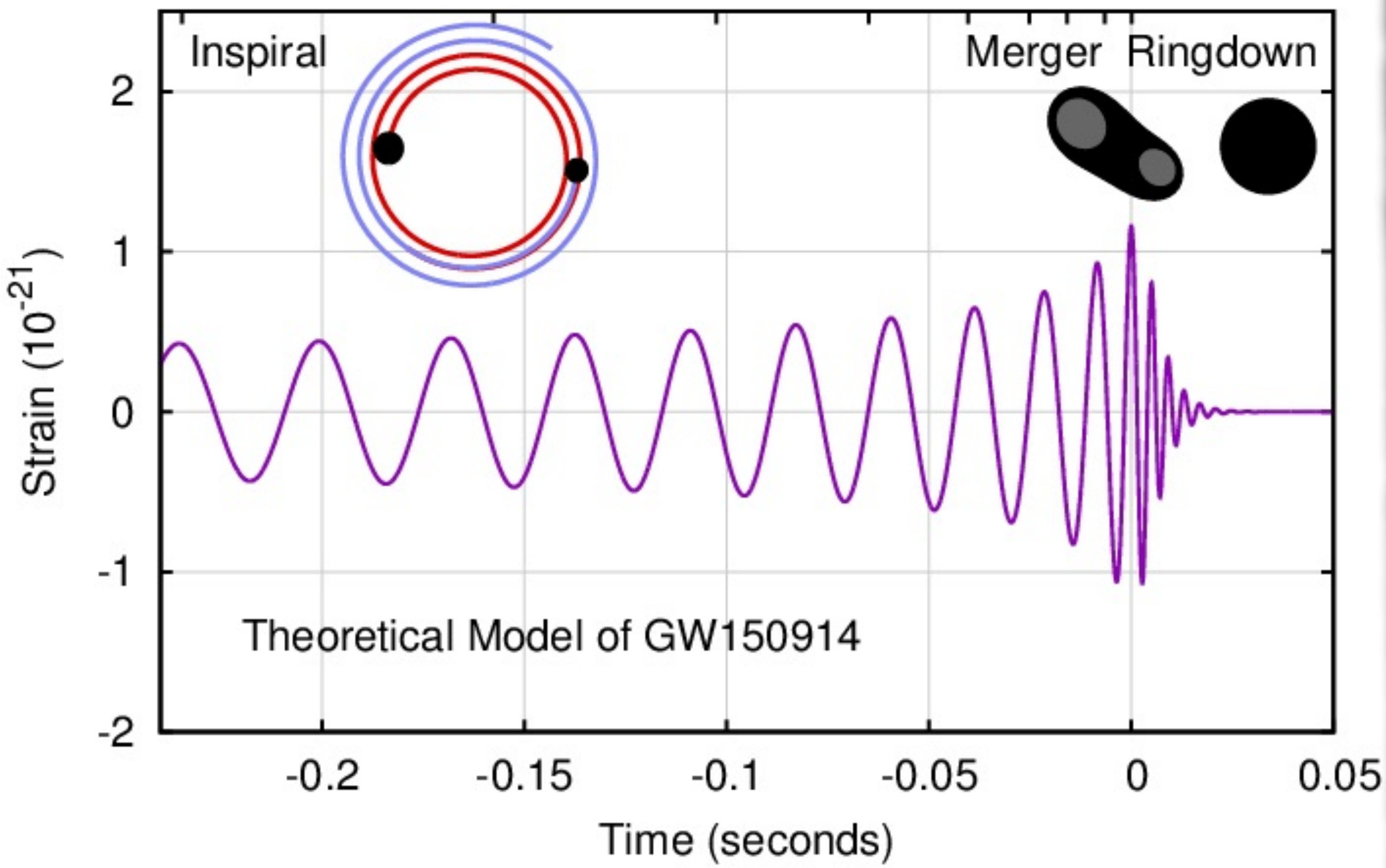
The details of the NS internal structure (and hence its EoS) become important as the orbital separation approaches the size of the bodies



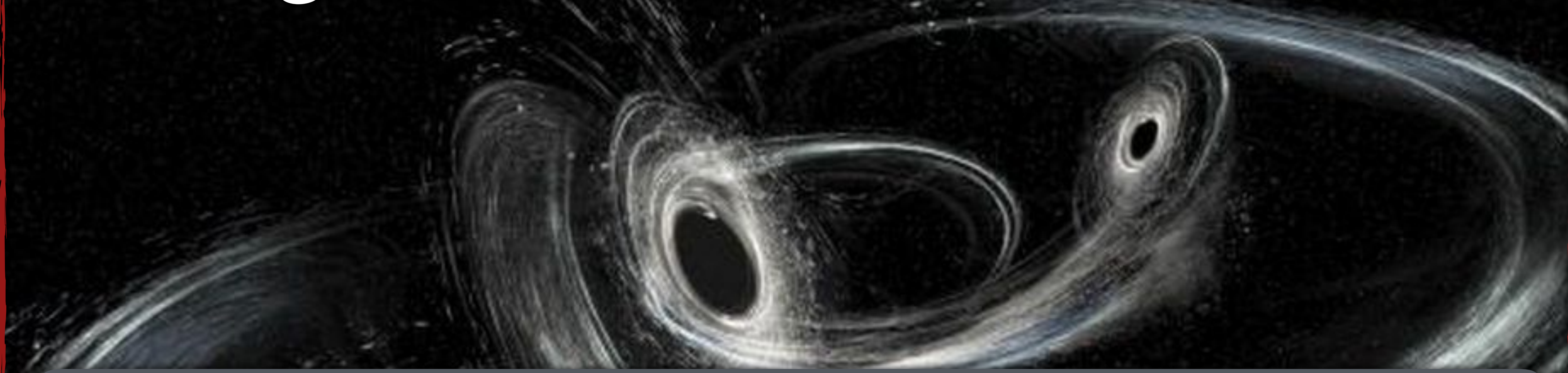
Scattering amplitude

Challenge: two-body problem in General Relativity

Post-newtonian expansion: expansion in v/c



What we can learn from gravitational waves?



"Gravity is the weakest force in Nature."

PART II: Phenomenology

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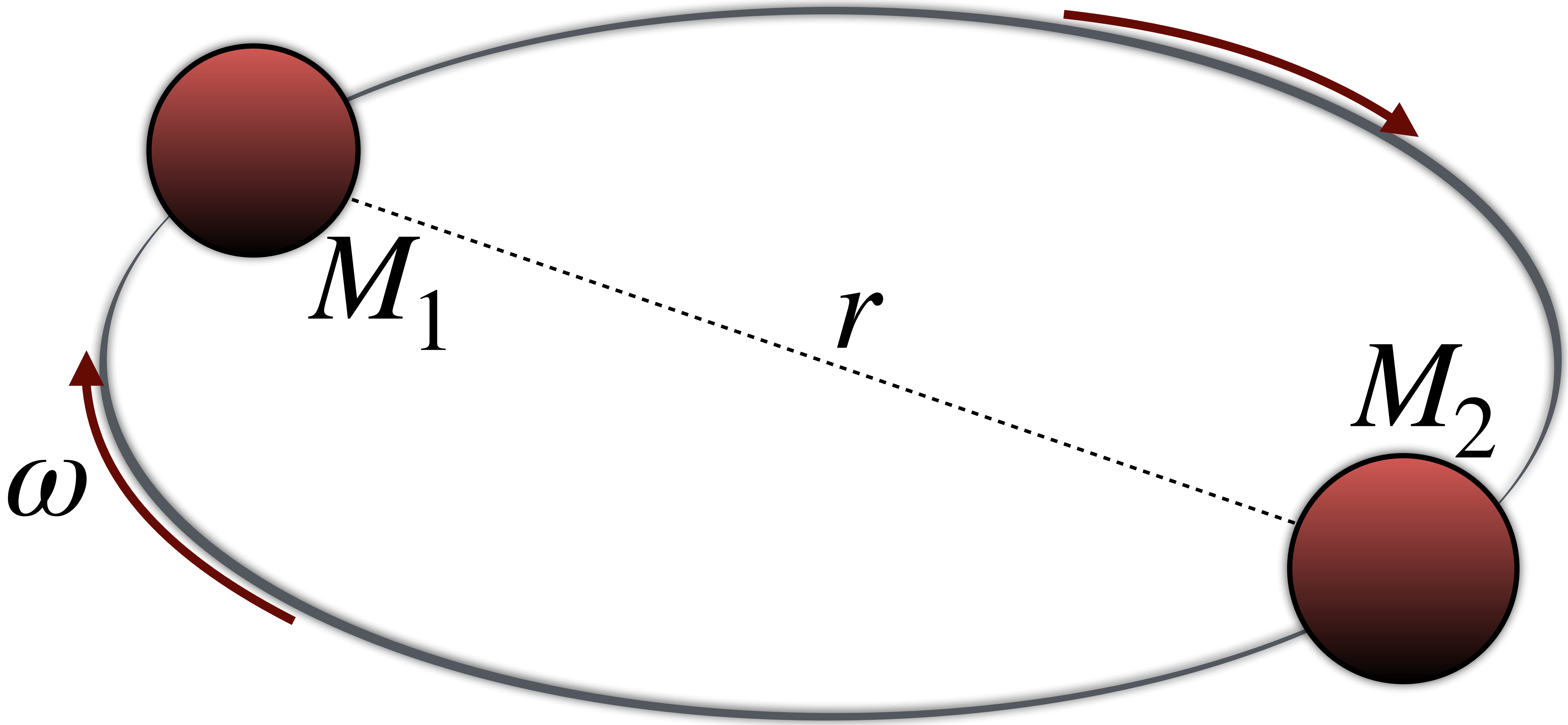
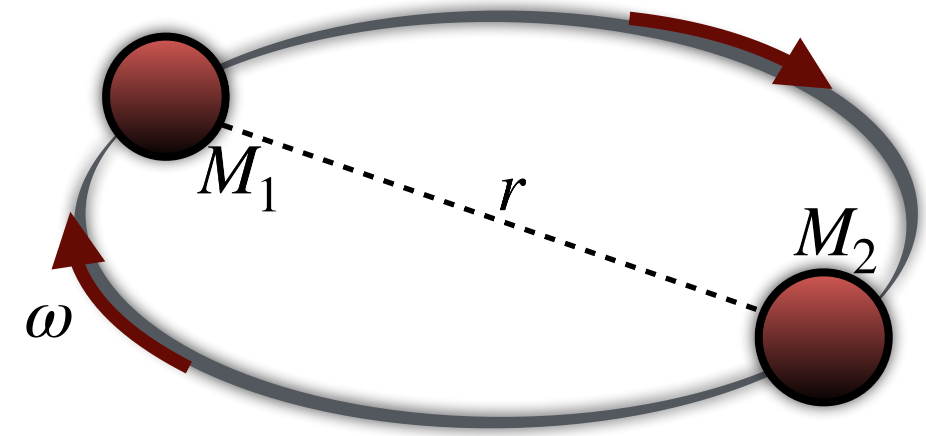


PART II: Phenomenology

$$\omega = \frac{G_N(M_1 + M_2)}{r^3}$$



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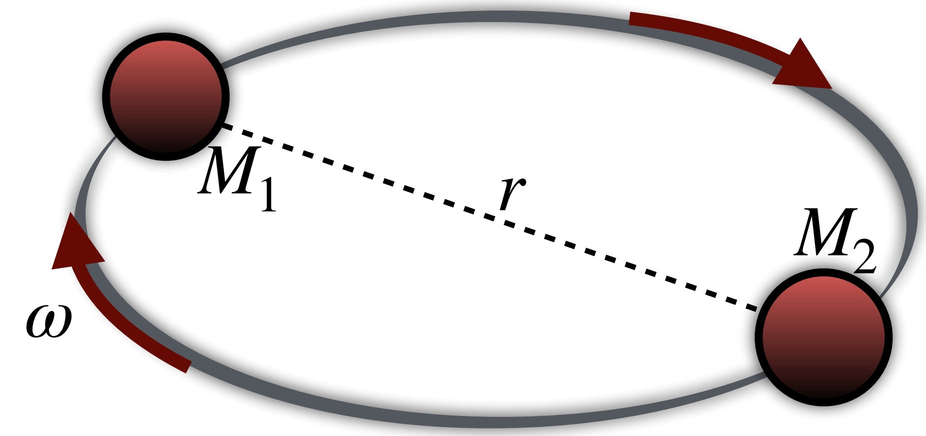

$$\frac{dE_{\text{tot}}}{dt} = -\mathscr{P}_{\text{GW}}$$

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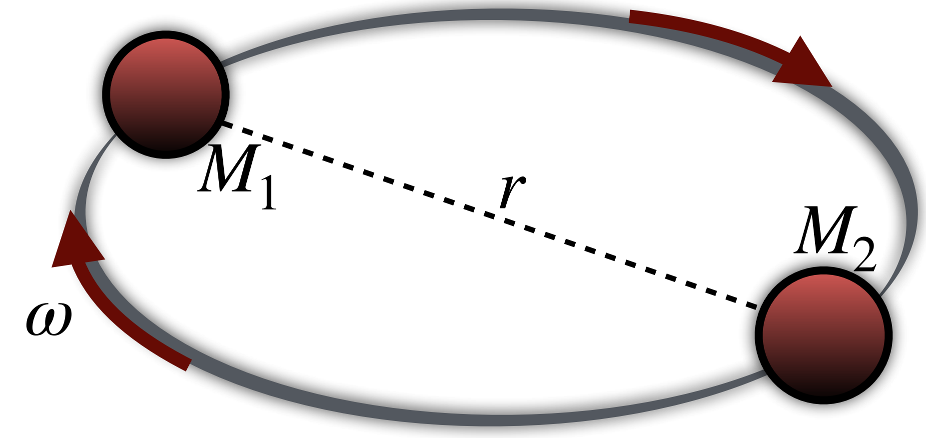
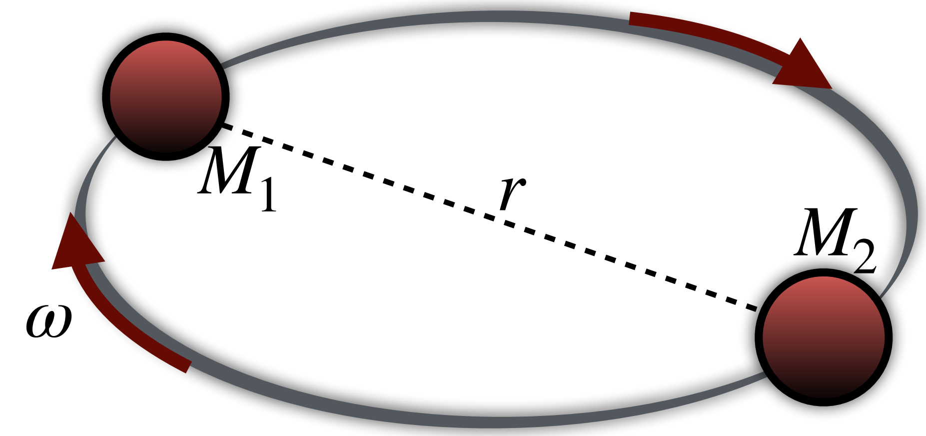


$$\frac{dE_{\rm tot}}{dt} = -\mathscr{P}_{\rm GW}$$

$$\mathscr{P}_{\rm GW} = \frac{32 G_N \mu^2 \omega^6 r^4}{5}$$

$$E_{\rm tot} = -\frac{G_N \mu (M_1 + M_2)}{r} + \frac{1}{2}\mu r^2 \omega^2$$

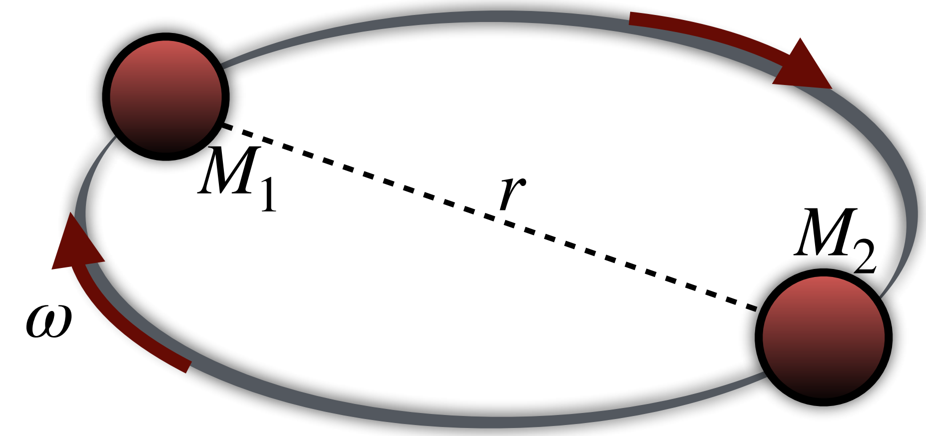
PART II: Phenomenology



$$\frac{d\omega}{dt} = \frac{96}{5}\left(G_N M_C\right)^{5/3} \omega^{11/3}$$

PART II: Phenomenology

$$M_C \equiv \mu^{3/5}(M_1 + M_2)^{2/5} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$$



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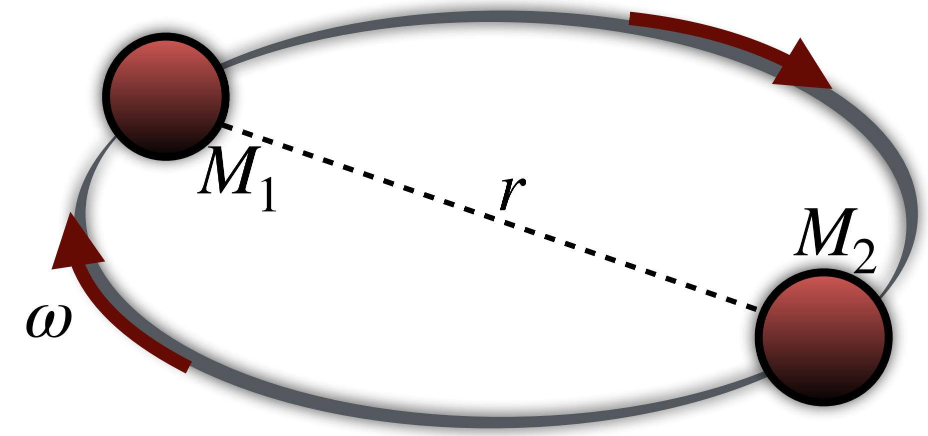
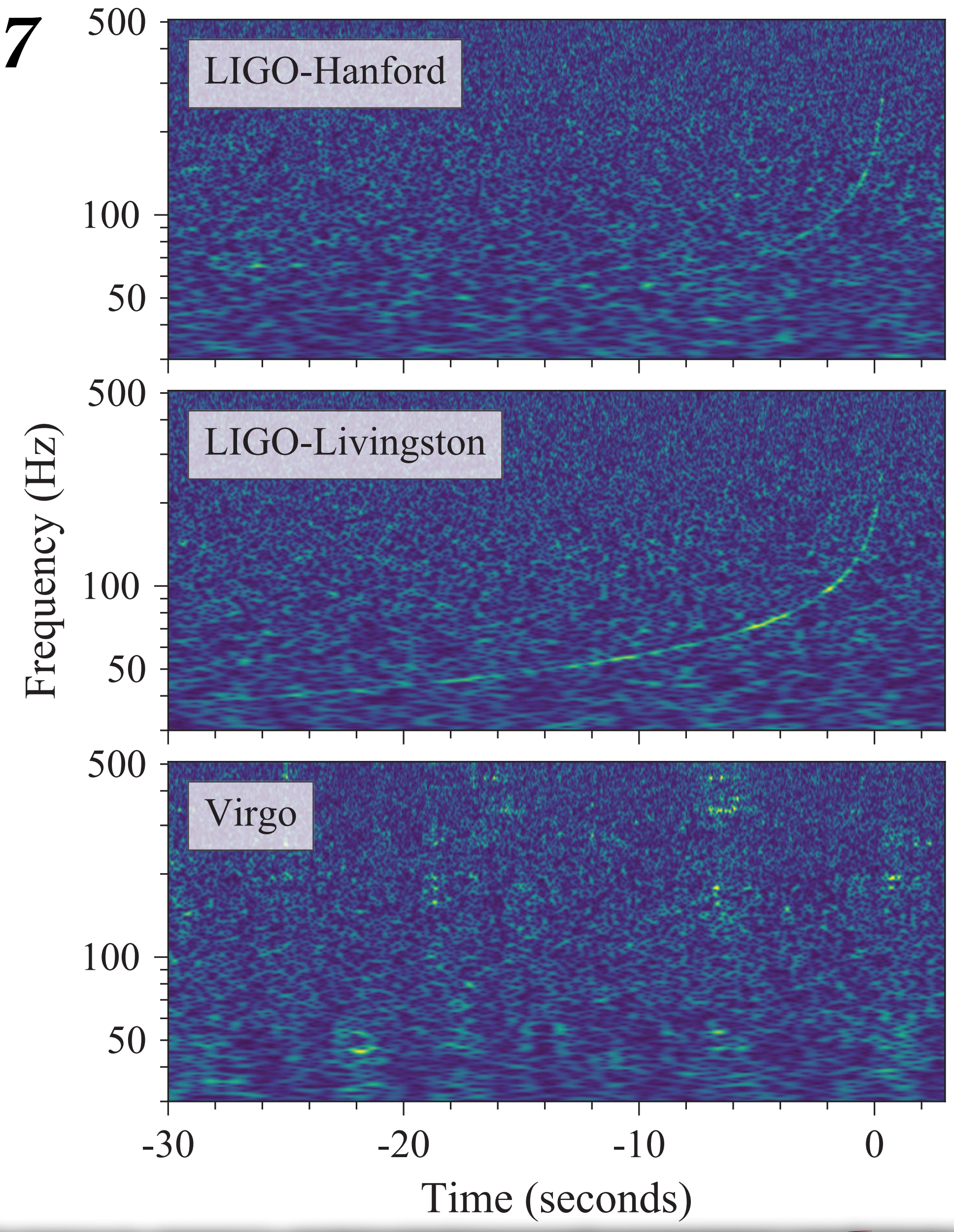


GW170817



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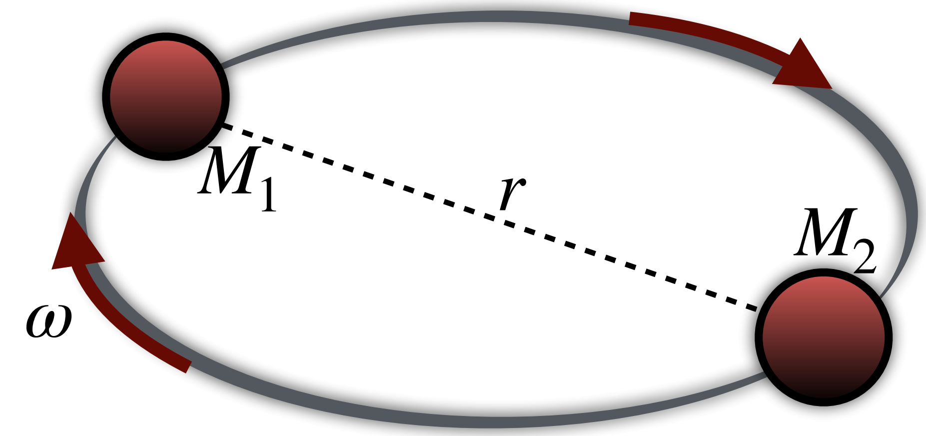

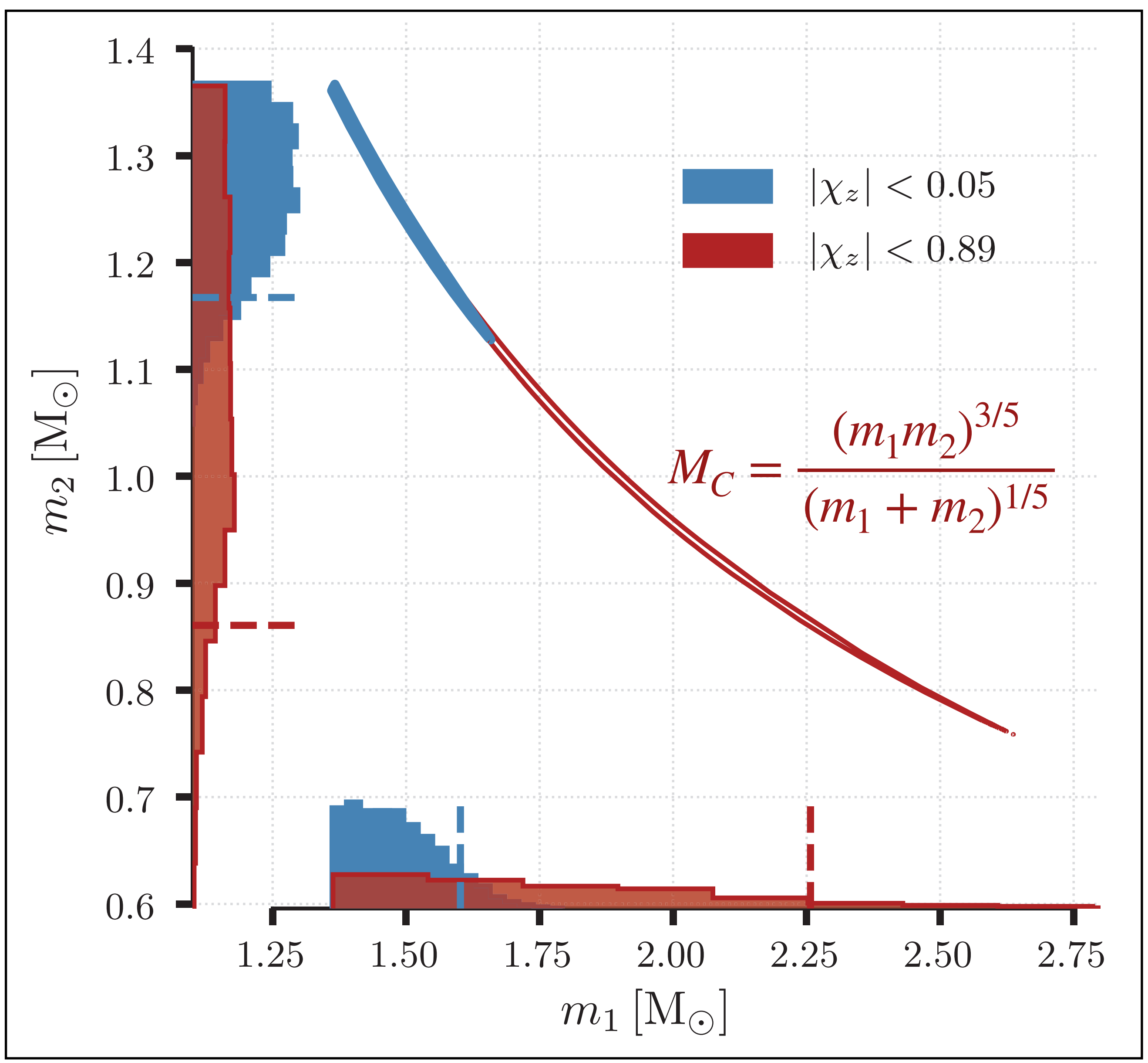

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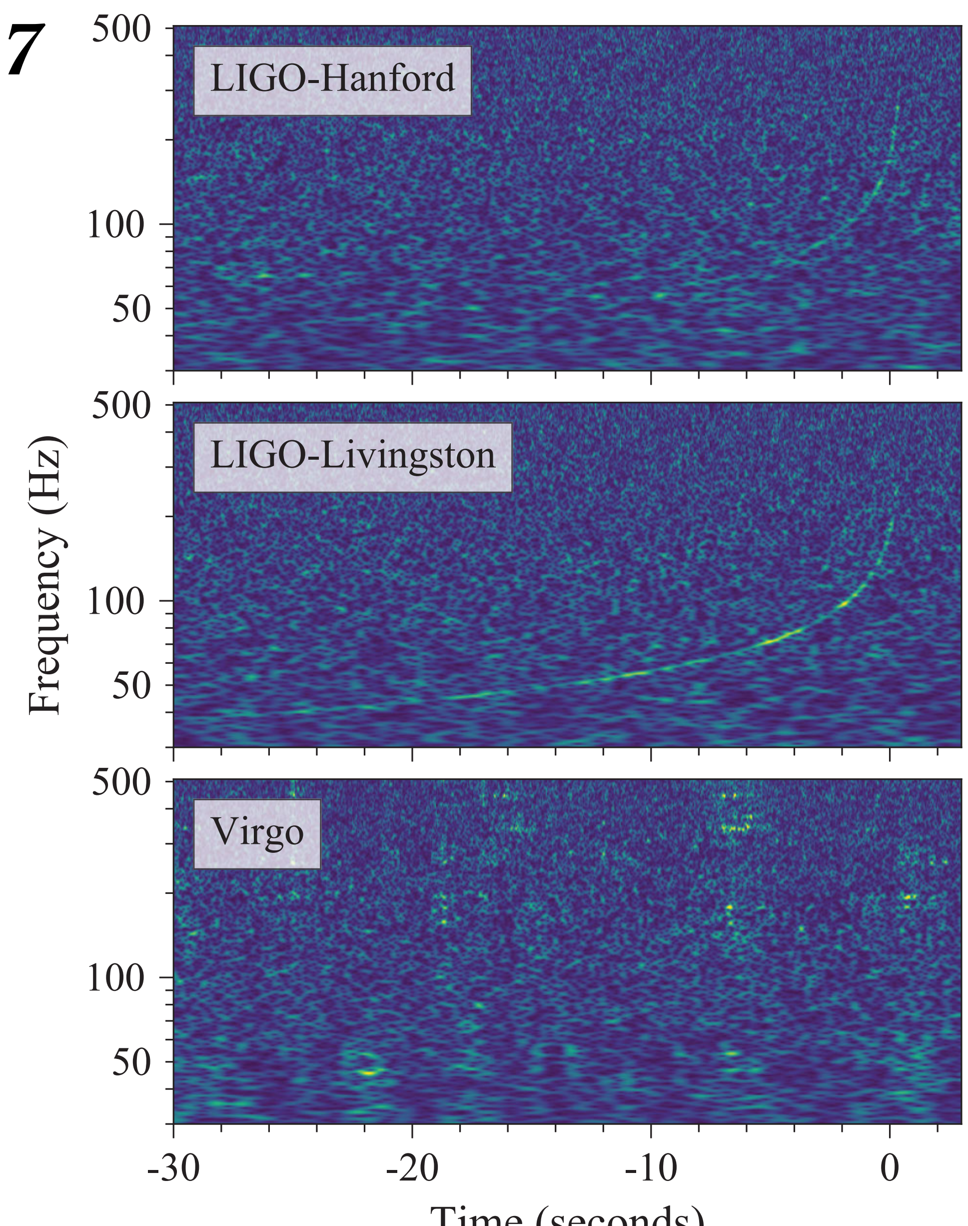
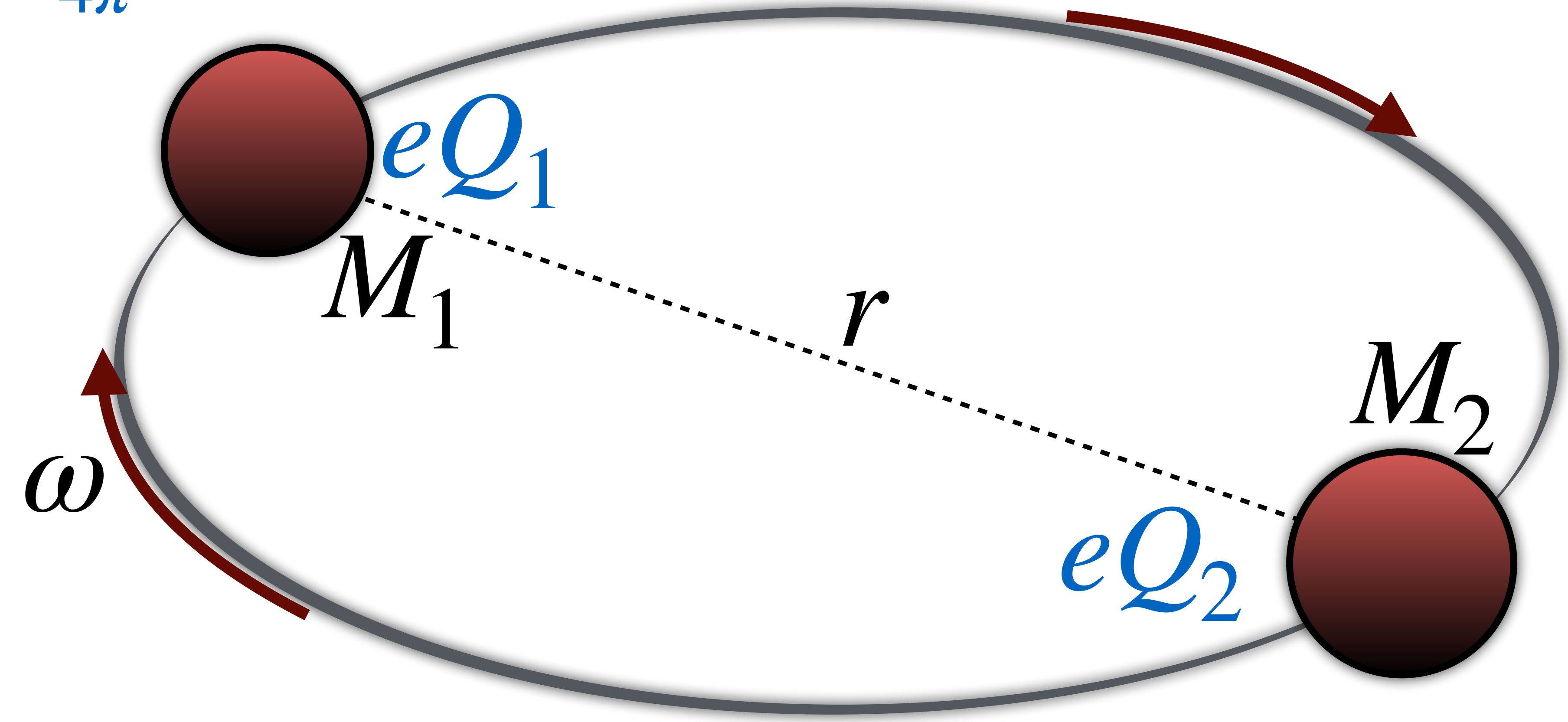


PART II: Phenomenology

$$\alpha \equiv \frac{e^2}{4\pi}$$



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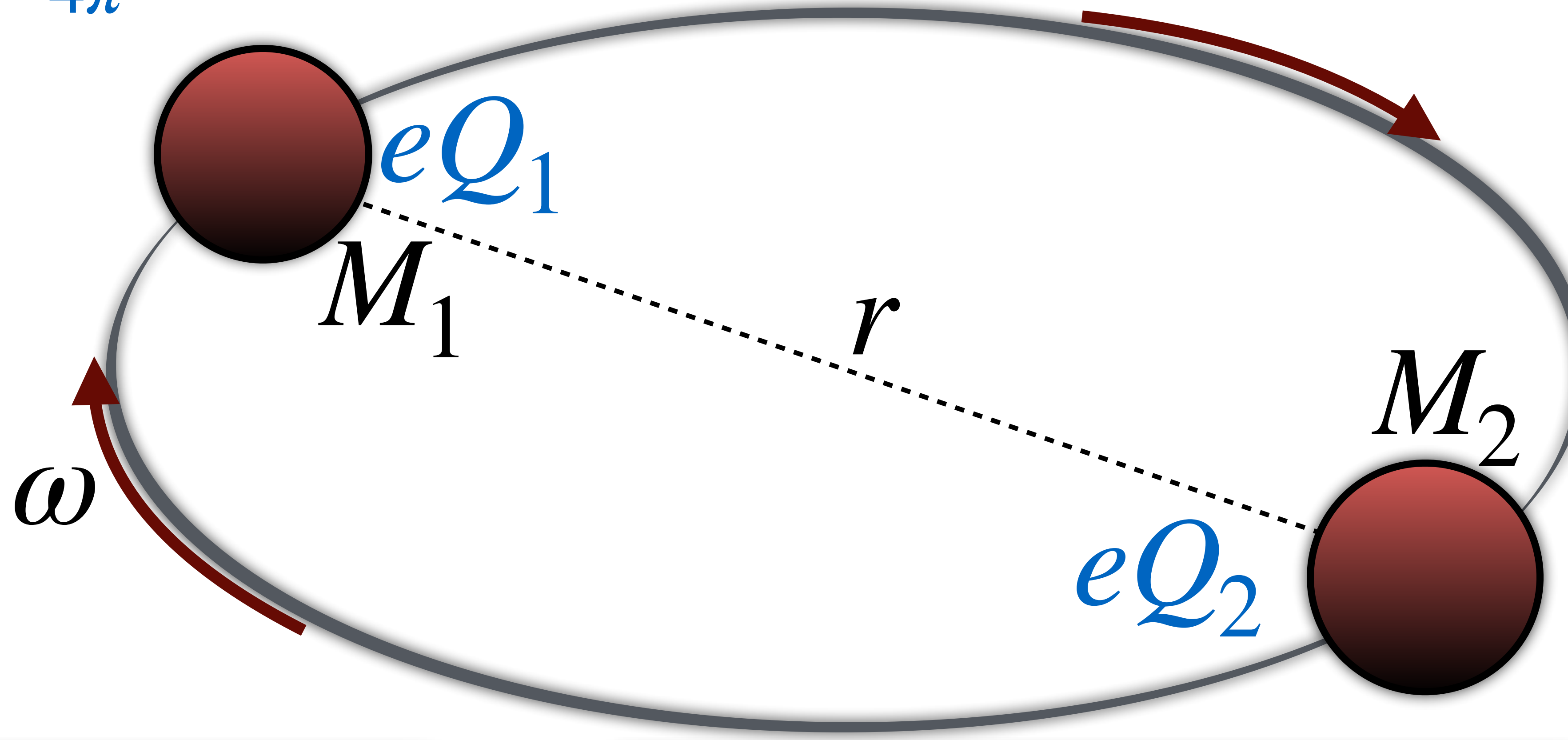


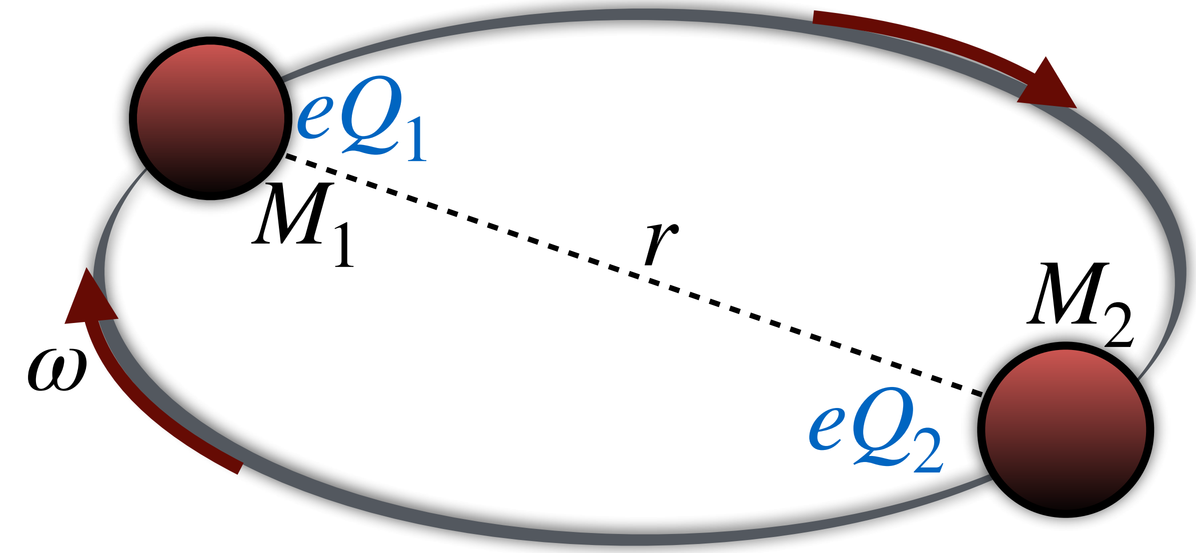
$$V(r) = -\frac{G_N M_1 M_2}{r} + \frac{\alpha Q_1 Q_2}{r}$$

$$\frac{dE_{\rm tot}}{dt} = -\mathscr{P}_{\rm GW} - \mathscr{P}_{\rm dark}$$

$$\mathscr{P}_{\rm dark} = \frac{2\alpha\gamma^2\omega^4 r^2}{3}$$

PART II: Phenomenology

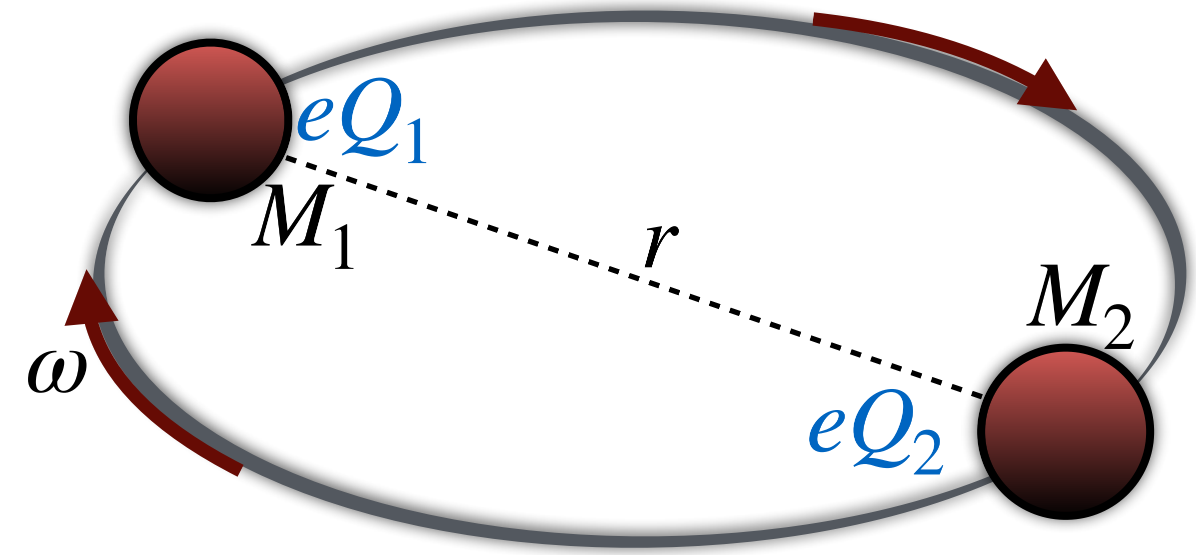
Radiation requires some acceleration of the source



Expansion in multiple of the radiation field at far distance

	Gravitational radiation	**Electromagnetic radiation**
Monopole	✗ Forbidden by conservation of mass	✗ Forbidden by conservation of charge
Dipole	✗ A dipole depends on the displacement of the center of mass from some fixed point. The velocity of the center of mass is simply given by the total momentum divided by the total mass.	✓ (N.B.: unless the charge-to-mass ratio is the same for all the particles)
Quadrupole	✓	✓

PART II: Phenomenology

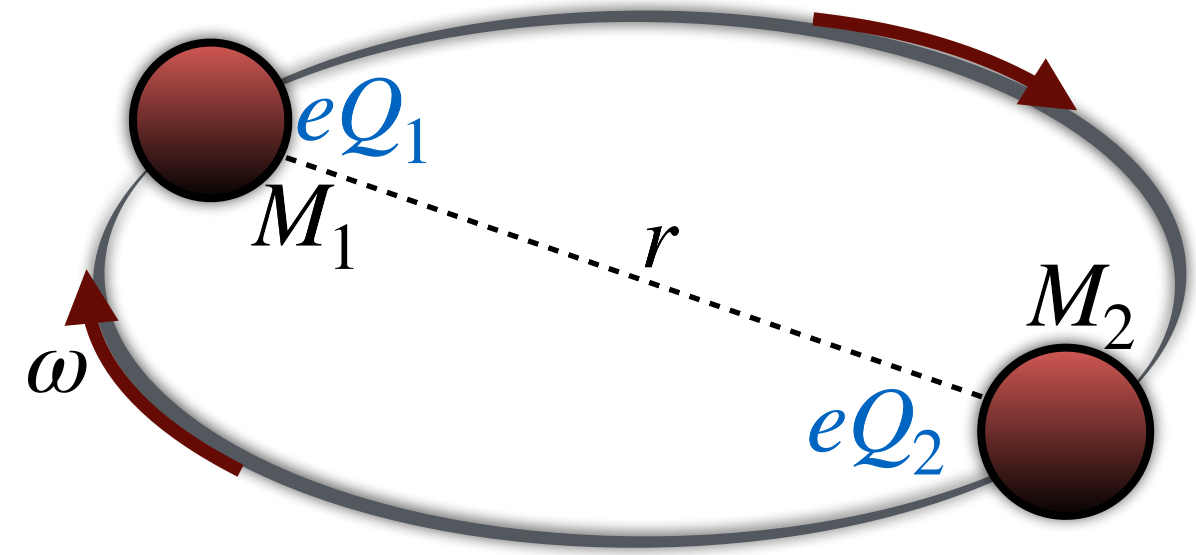


$$\frac{d\omega}{dt} = \frac{96}{5}\left(G_N M_C\right)^{5/3}\omega^{11/3}\left(1 - \frac{\alpha Q_1 Q_2}{G_N M_1 M_2}\right)^{2/3} + 2\alpha\mu\omega^3\left|\frac{Q_1}{M_1} - \frac{Q_2}{M_2}\right|^2$$

PART II: Phenomenology

$$\tilde{\alpha} \equiv \frac{\alpha Q_1 Q_2}{G_N M_1 M_2} = \frac{\alpha Q_1 Q_2}{10^{76}}$$

(with $M_{1,2} = 1.25\, M_\odot$)



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Correction to quadrupole emission

Dipole radiation

PART II: Phenomenology

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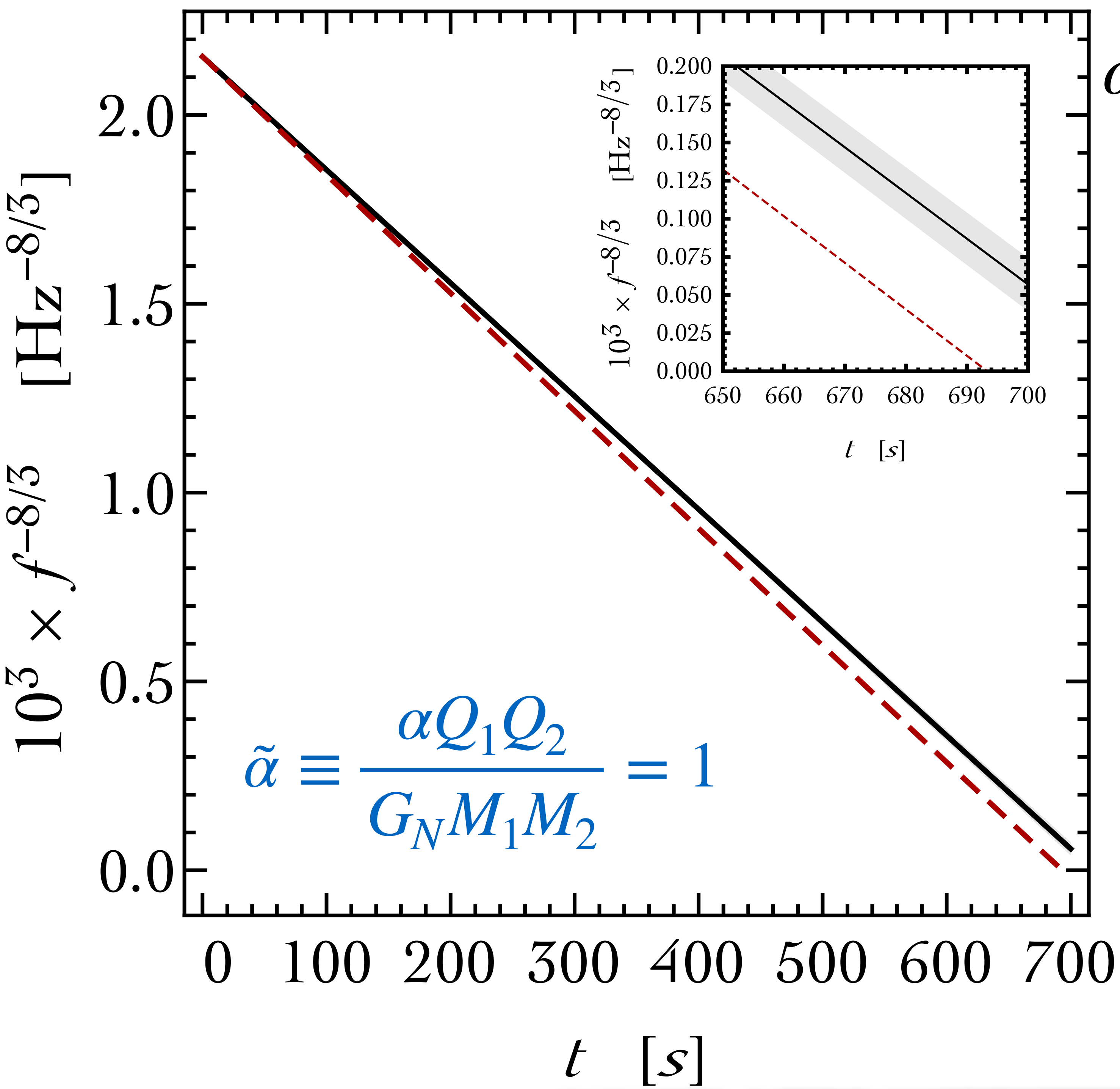
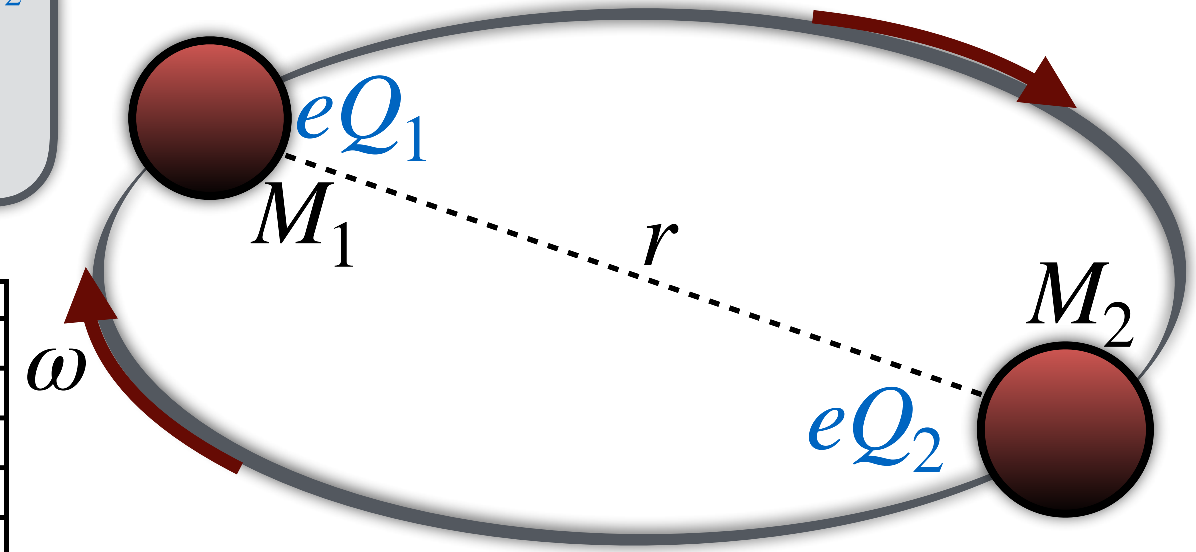


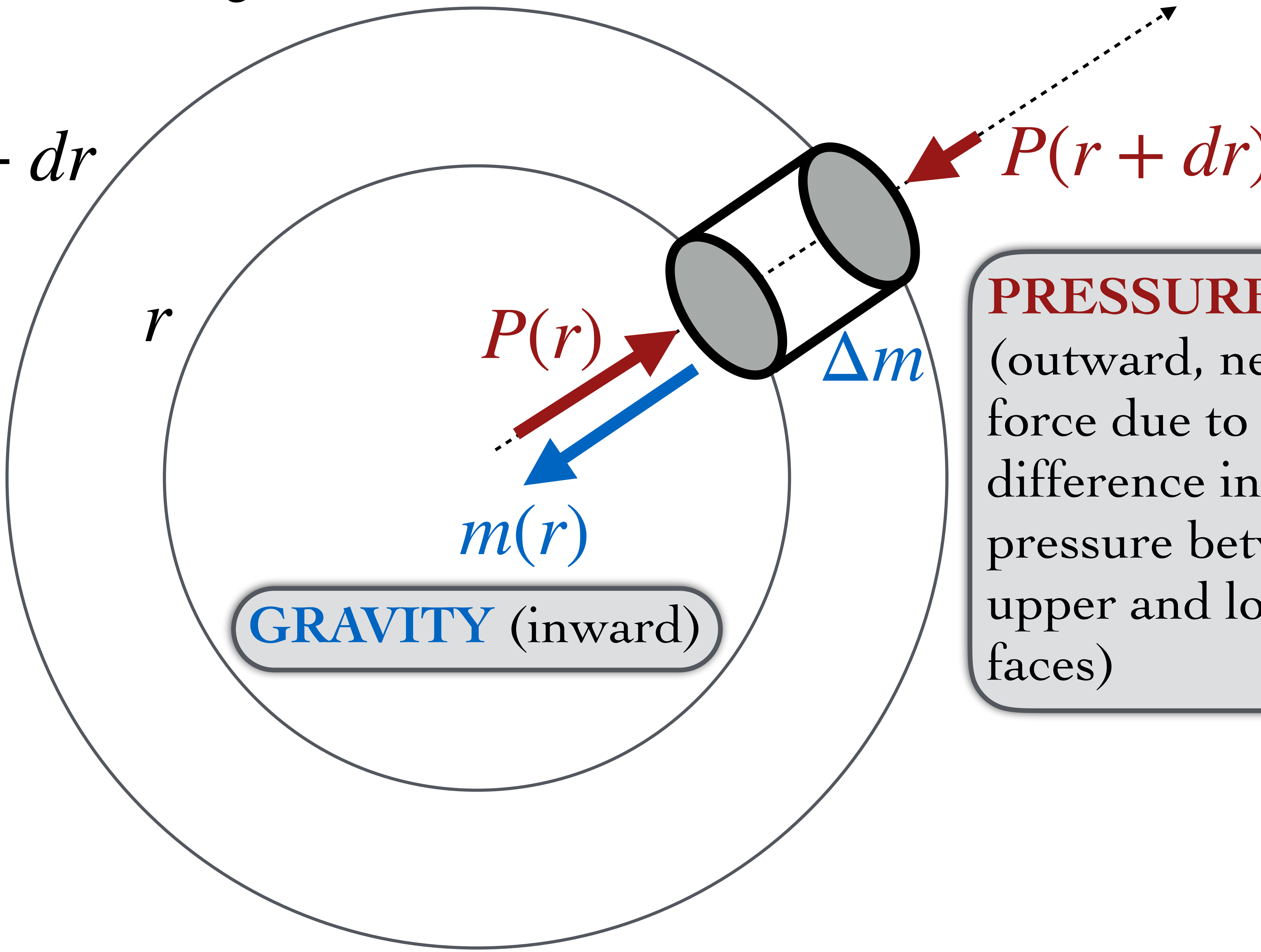


assuming 0.1 % error on M_C

$$\tilde{\alpha} \gtrsim 10^{-2}$$

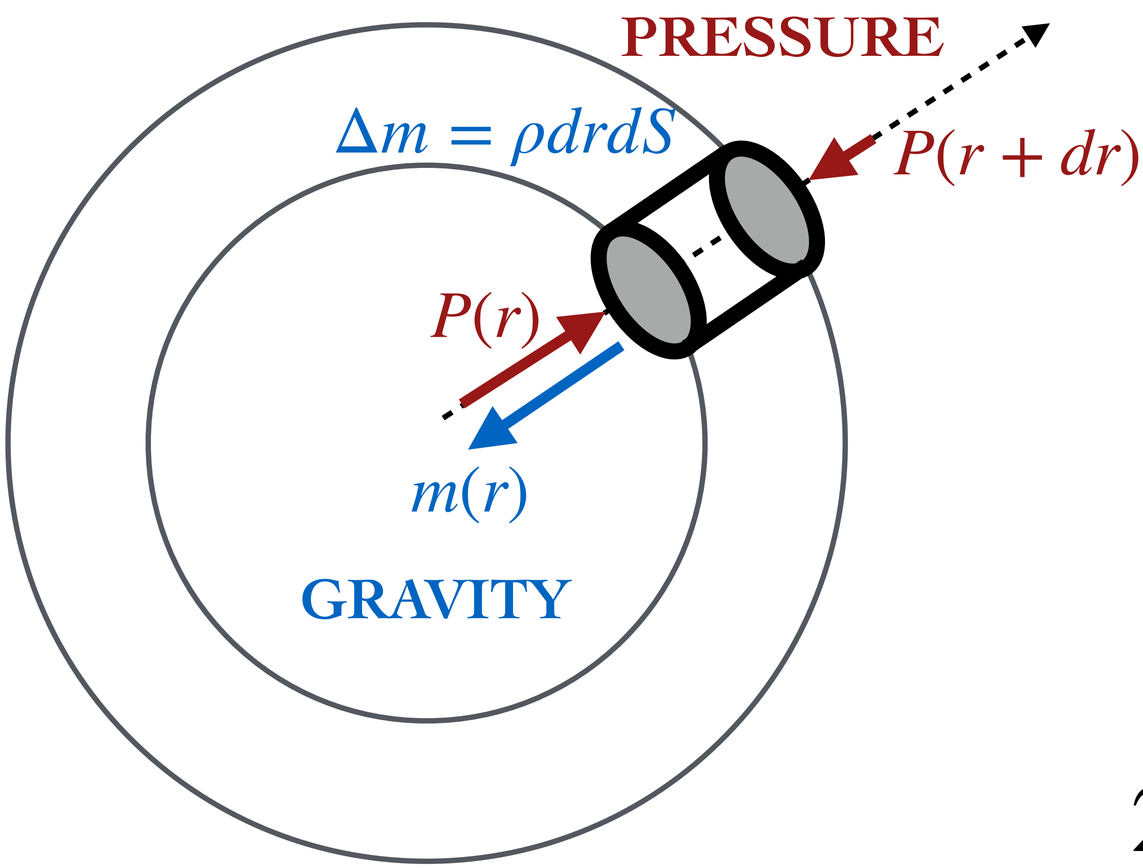
PART II: Phenomenology

Radial forces acting on the infinitesimal element



PRESSURE (outward, net force due to difference in pressure between upper and lower faces)

PART II: Phenomenology



2^{nd} equation of stellar structure
(hydrostatic equilibrium)

$$\frac{dP}{dr} = -\frac{G_N \rho m}{r^2}$$

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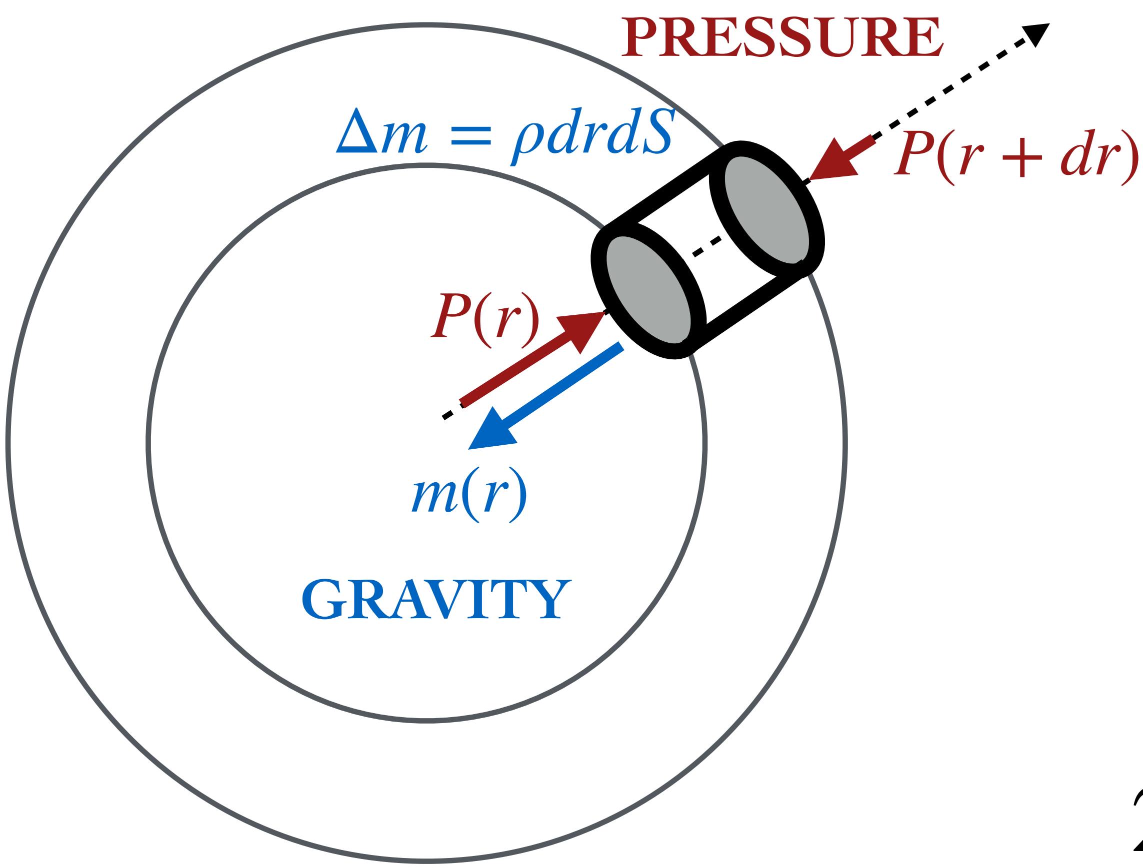

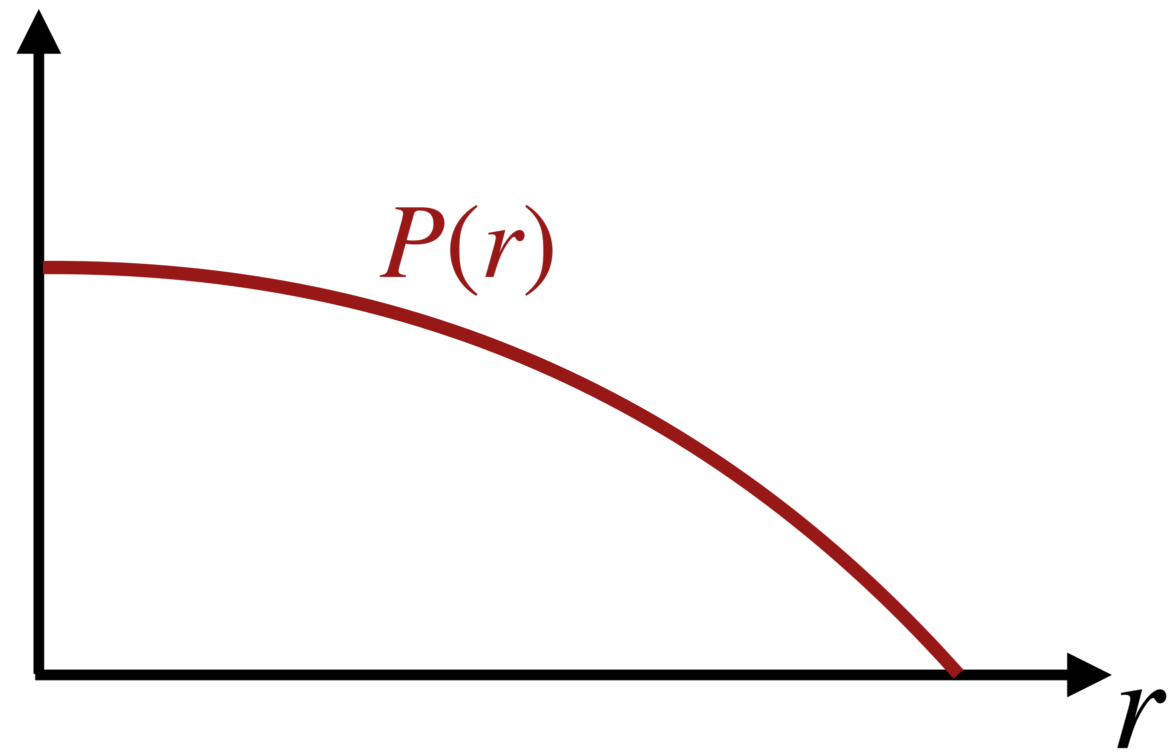

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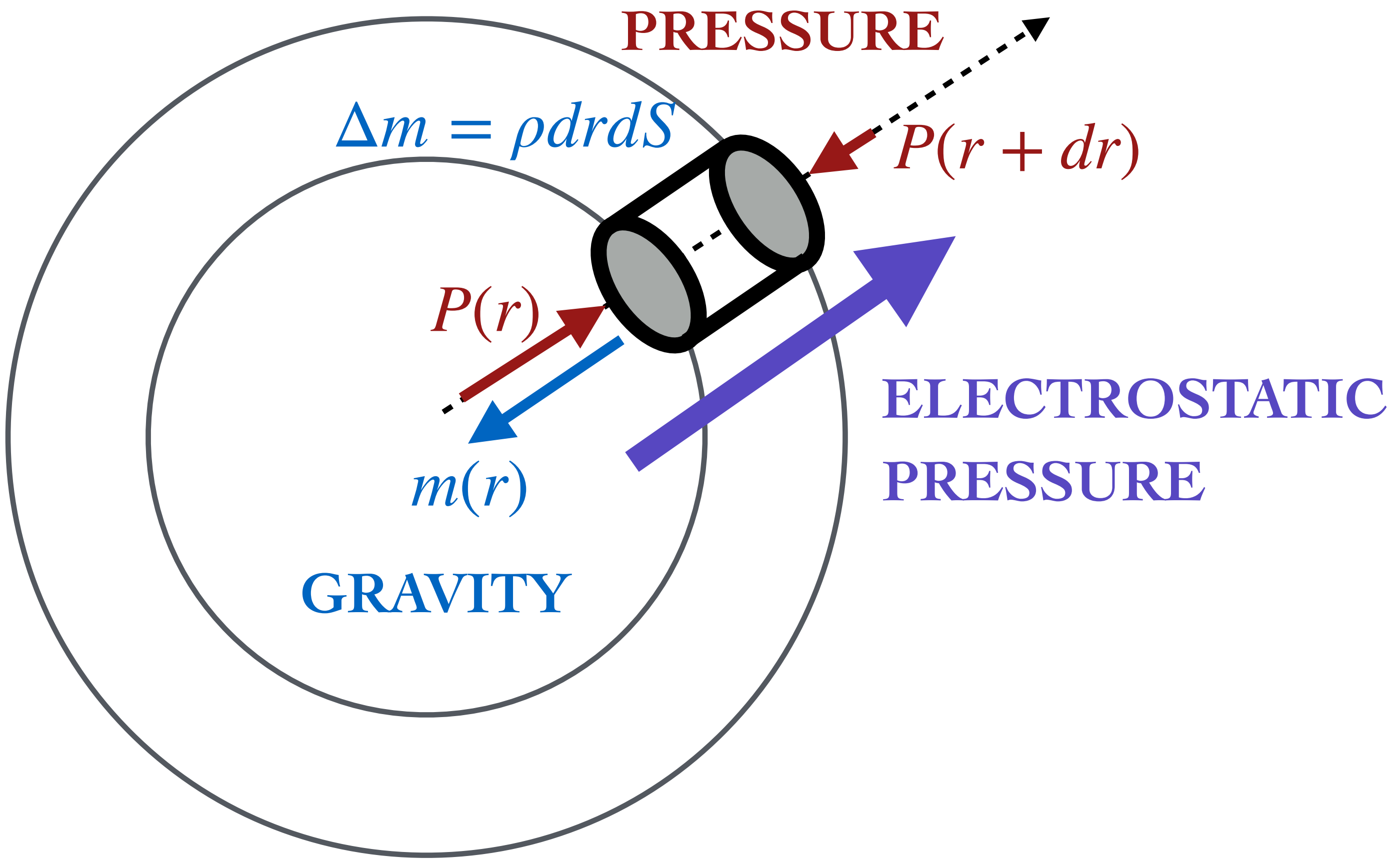
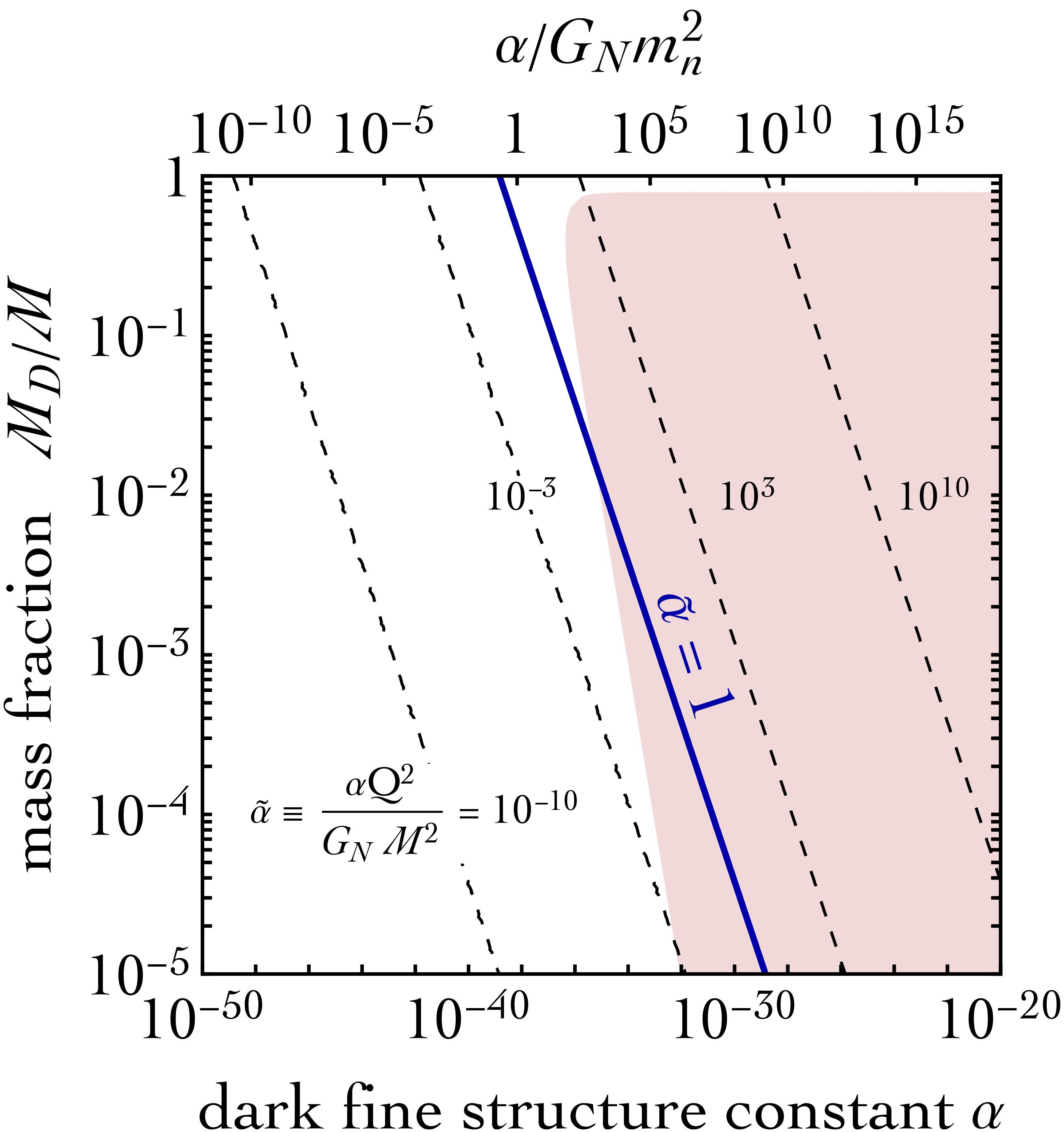


$$E(r) = \frac{Q(r)}{4\pi r^2}$$

$$\frac{dP}{dr} = -\frac{G_N \rho}{r^2}\left(m - 2\pi r^3 E^2\right)$$

PART II: Phenomenology



PART III: Theory

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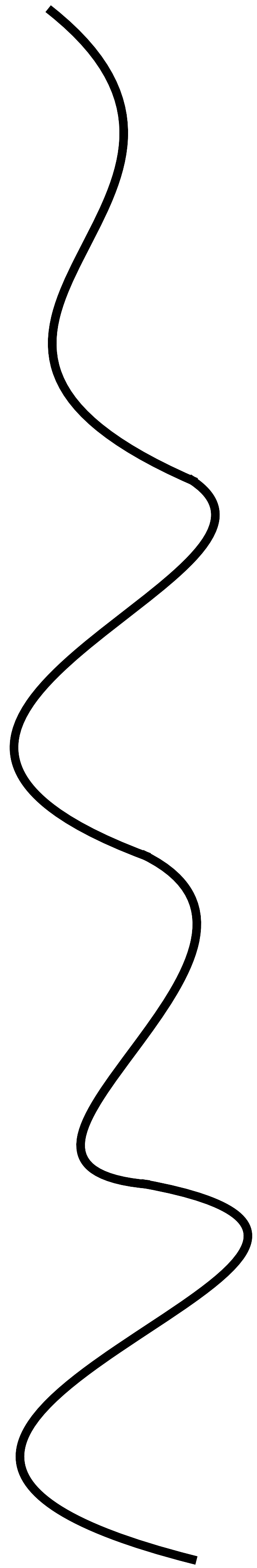
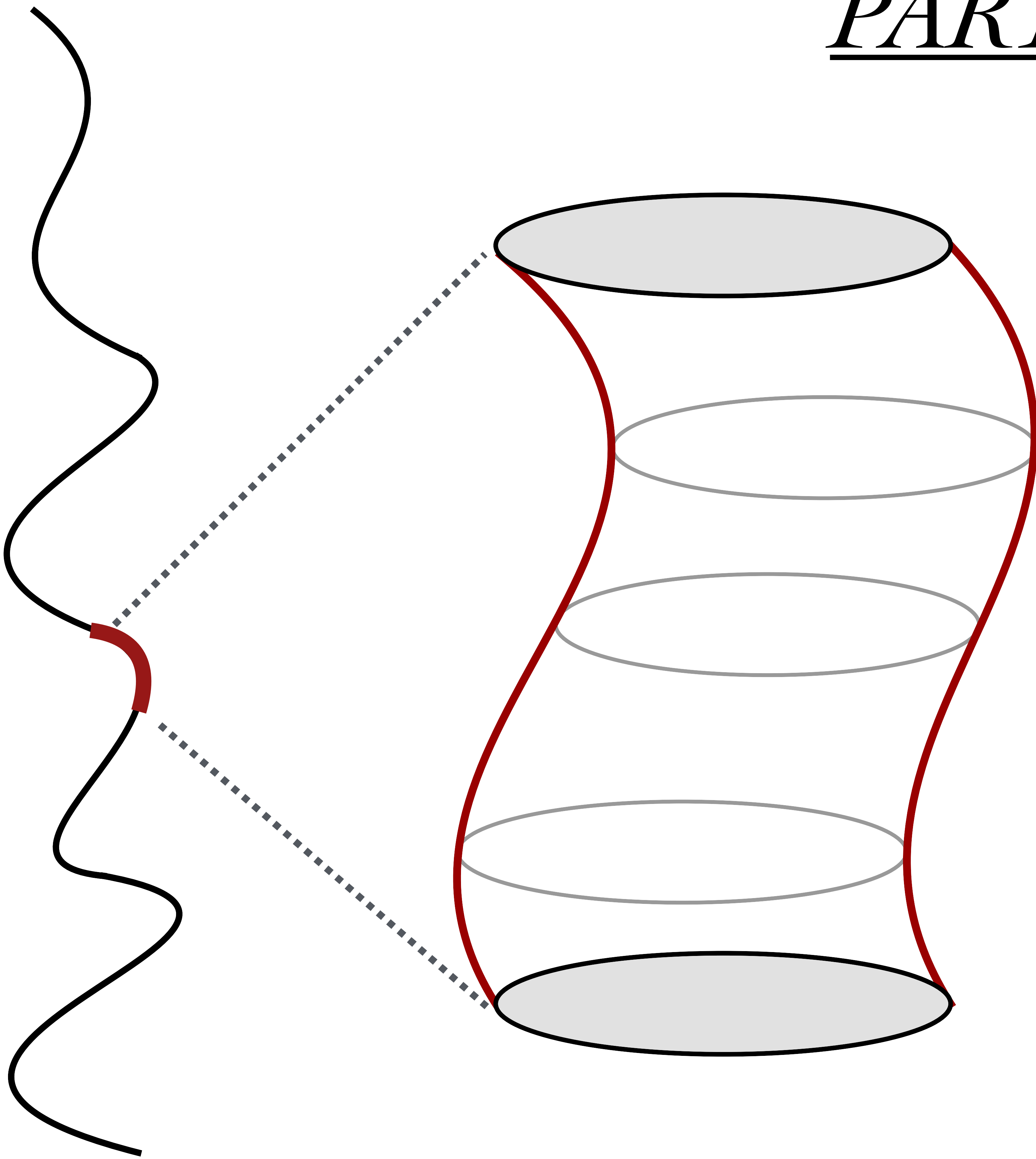


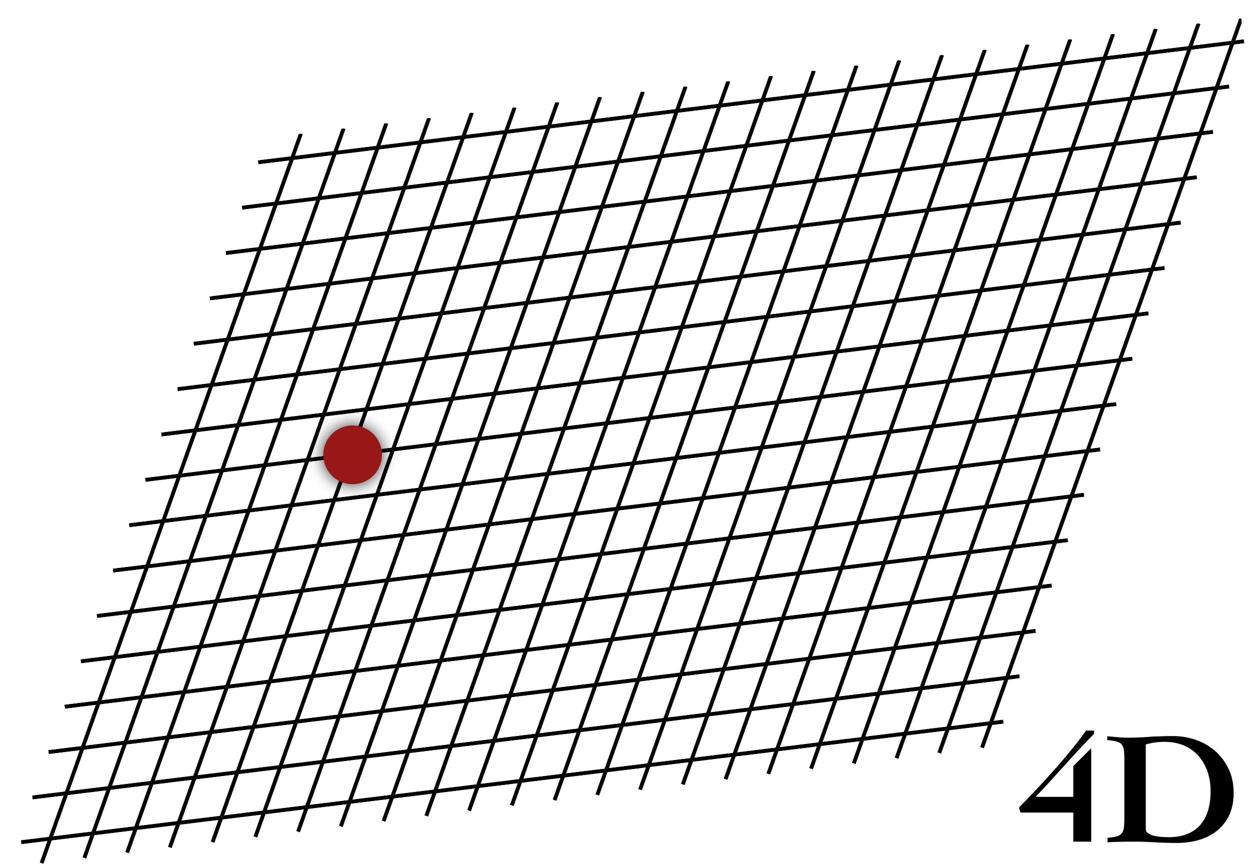
Consider a space that consists of a long, thin tube. Viewed from far distance, the tube looks like a one-dimensional line.

PART III: Theory



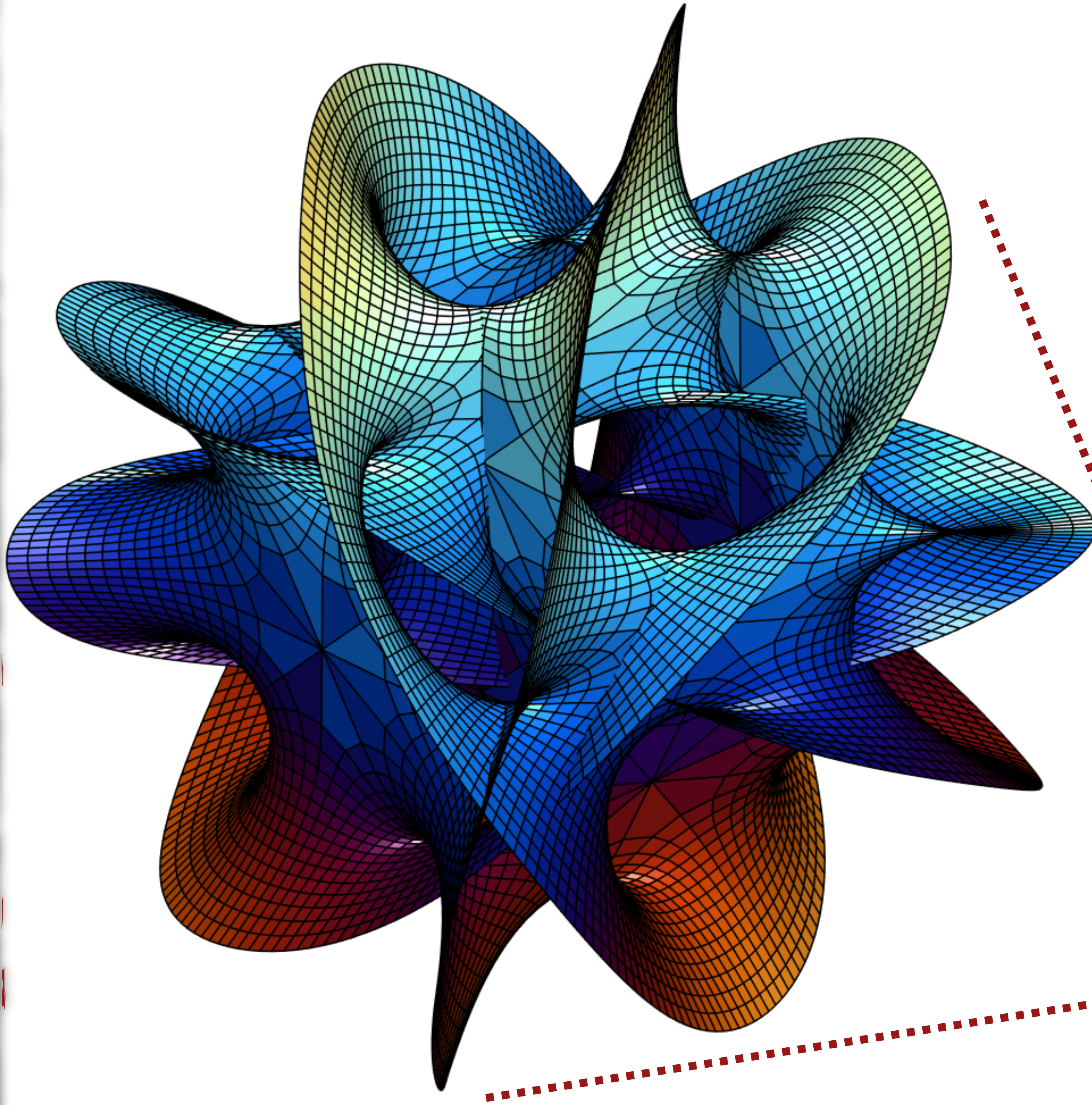
Under high magnification, the cylindrical shape becomes apparent. Each point on the line is revealed to be a one-dimensional circle of the tube.

PART III: Theory

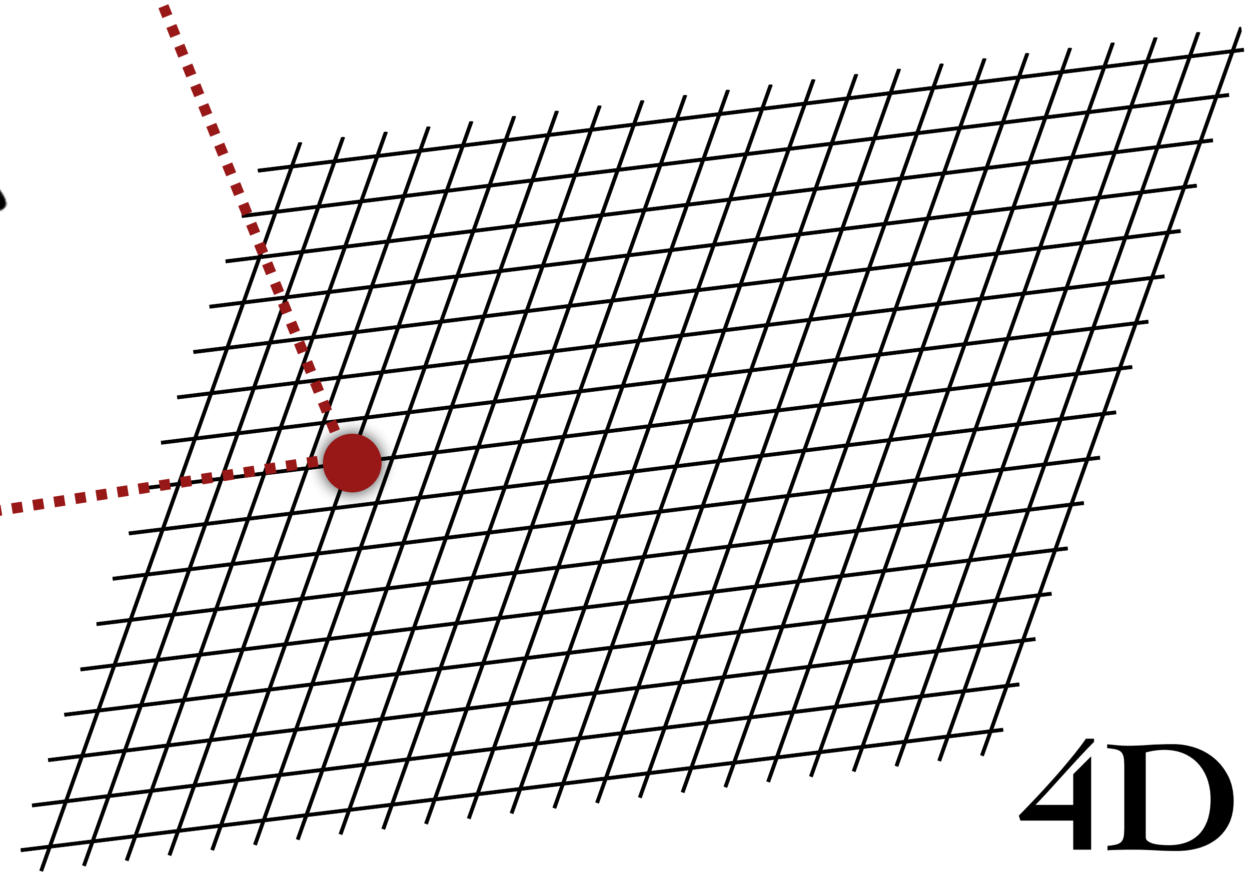


4D

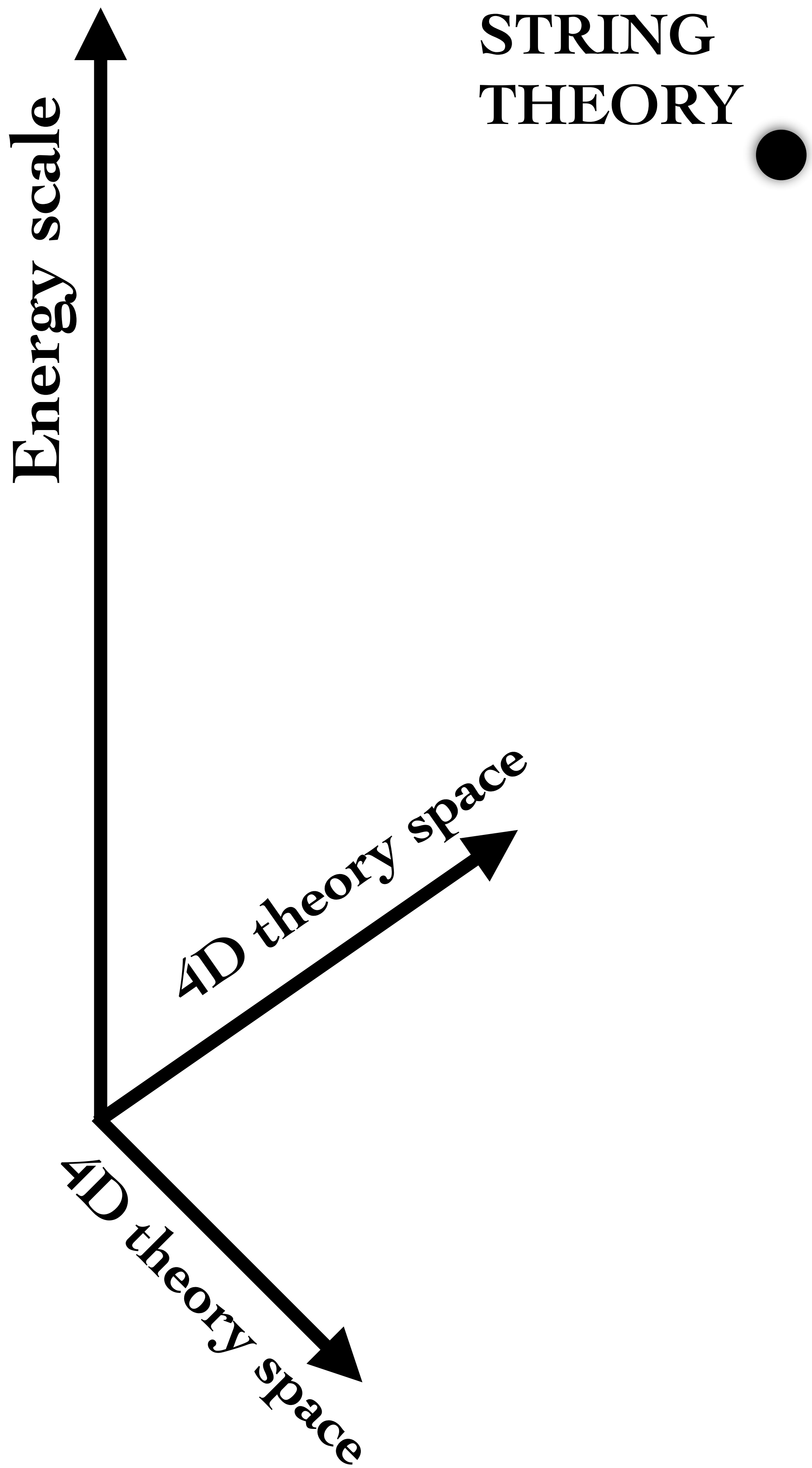
PART III: Theory



Our world has six extra dimensions, every point of our familiar space hides an associated tiny six-dimensional space. The physics that is observed depends on the size and the structure of the manifold.

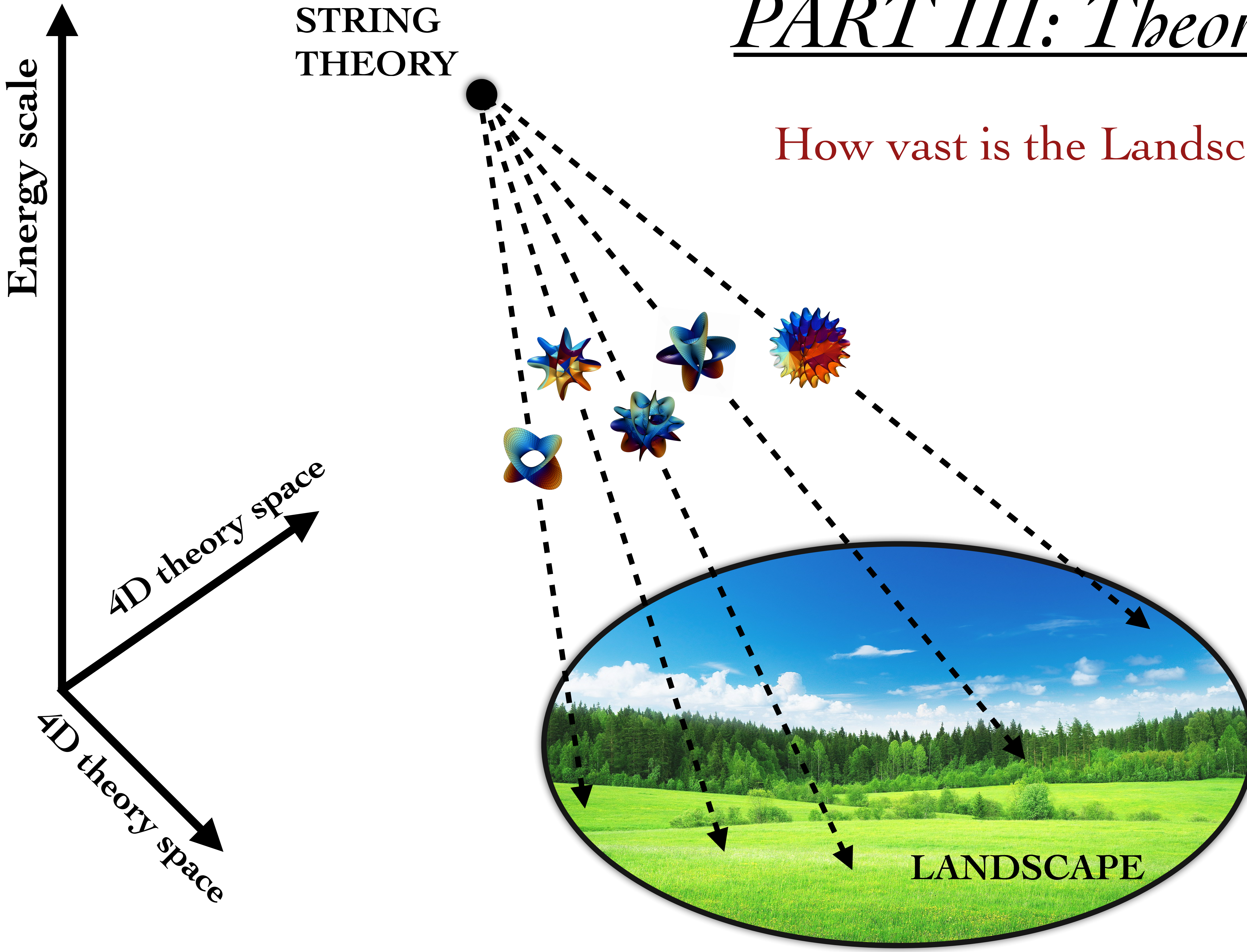


PART III: Theory

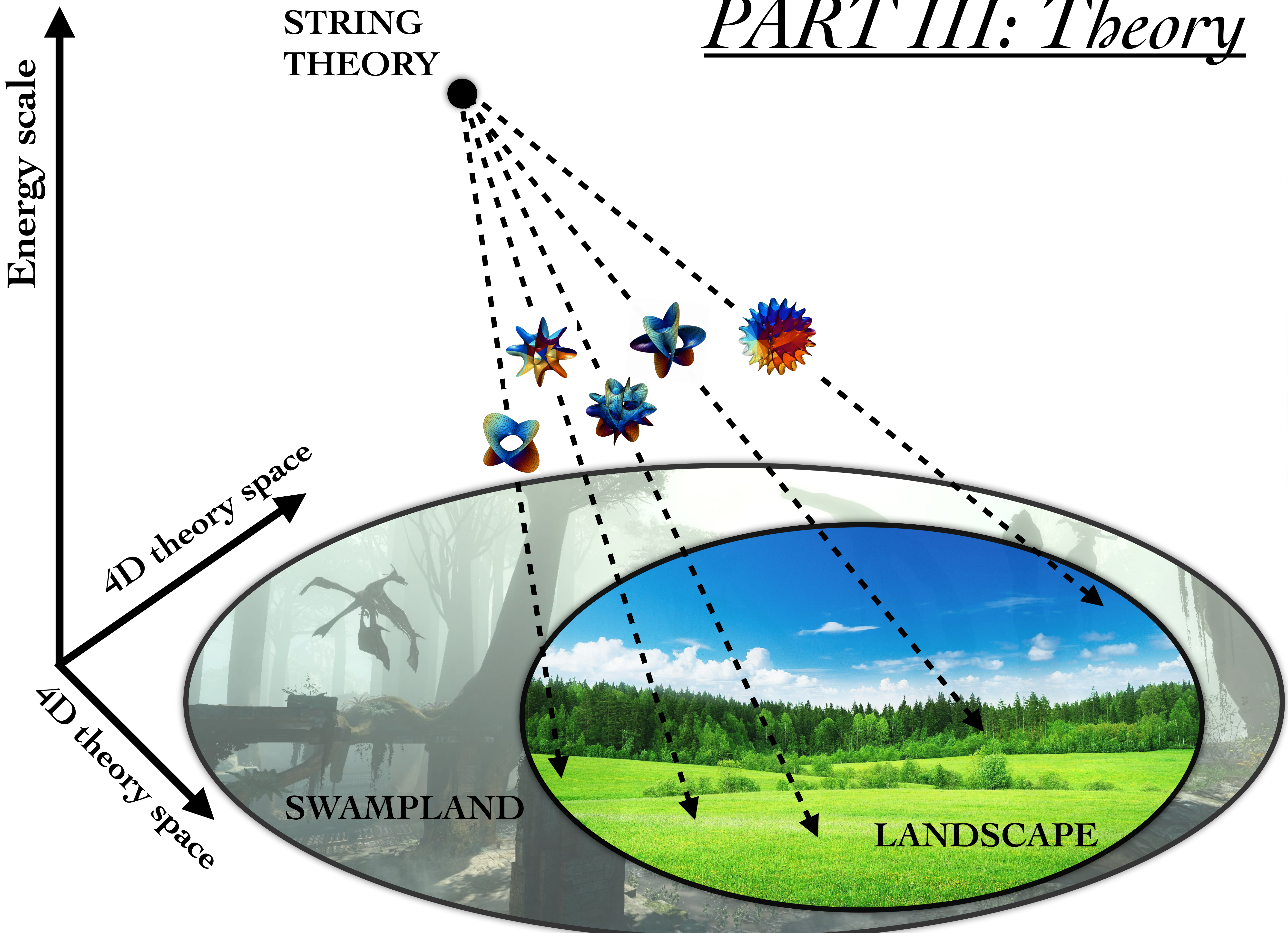


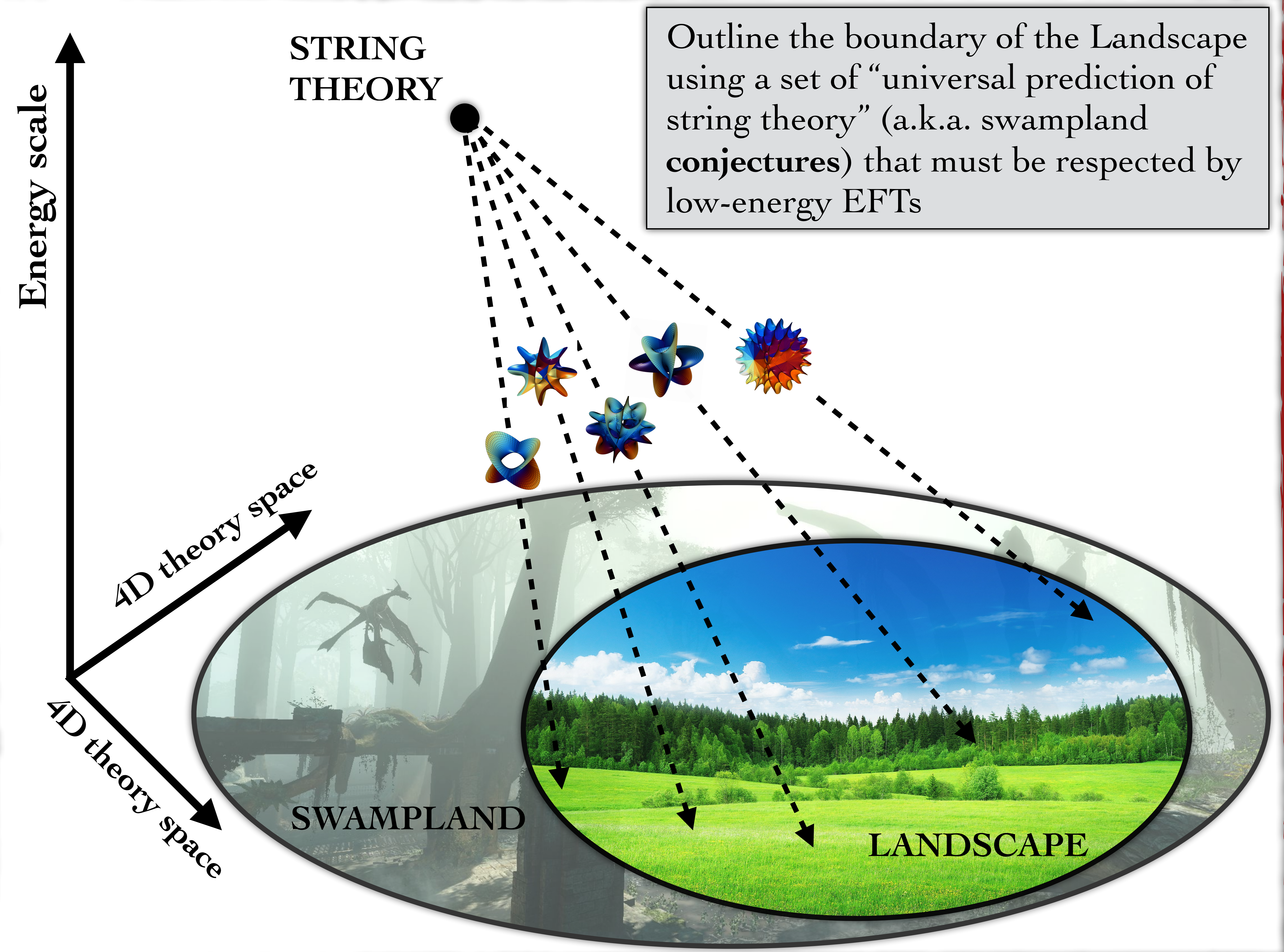
PART III: Theory

How vast is the Landscape?

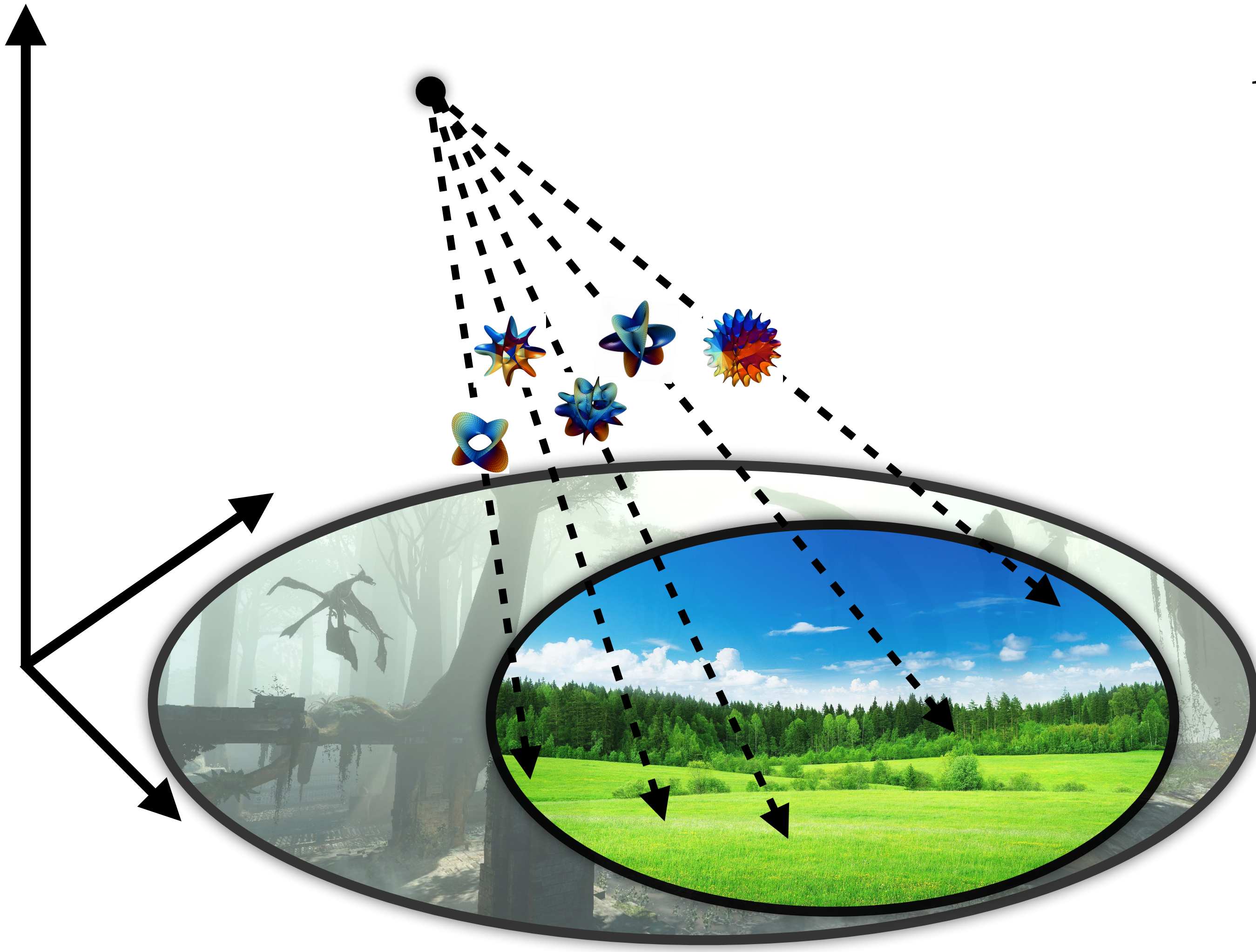


PART III: Theory




Outline the boundary of the Landscape using a set of "universal prediction of string theory" (a.k.a. swampland **conjectures**) that must be respected by low-energy EFTs
STRING THEORY
Energy scale
4D theory space
4D theory space
SWAMPLAND
LANDSCAPE

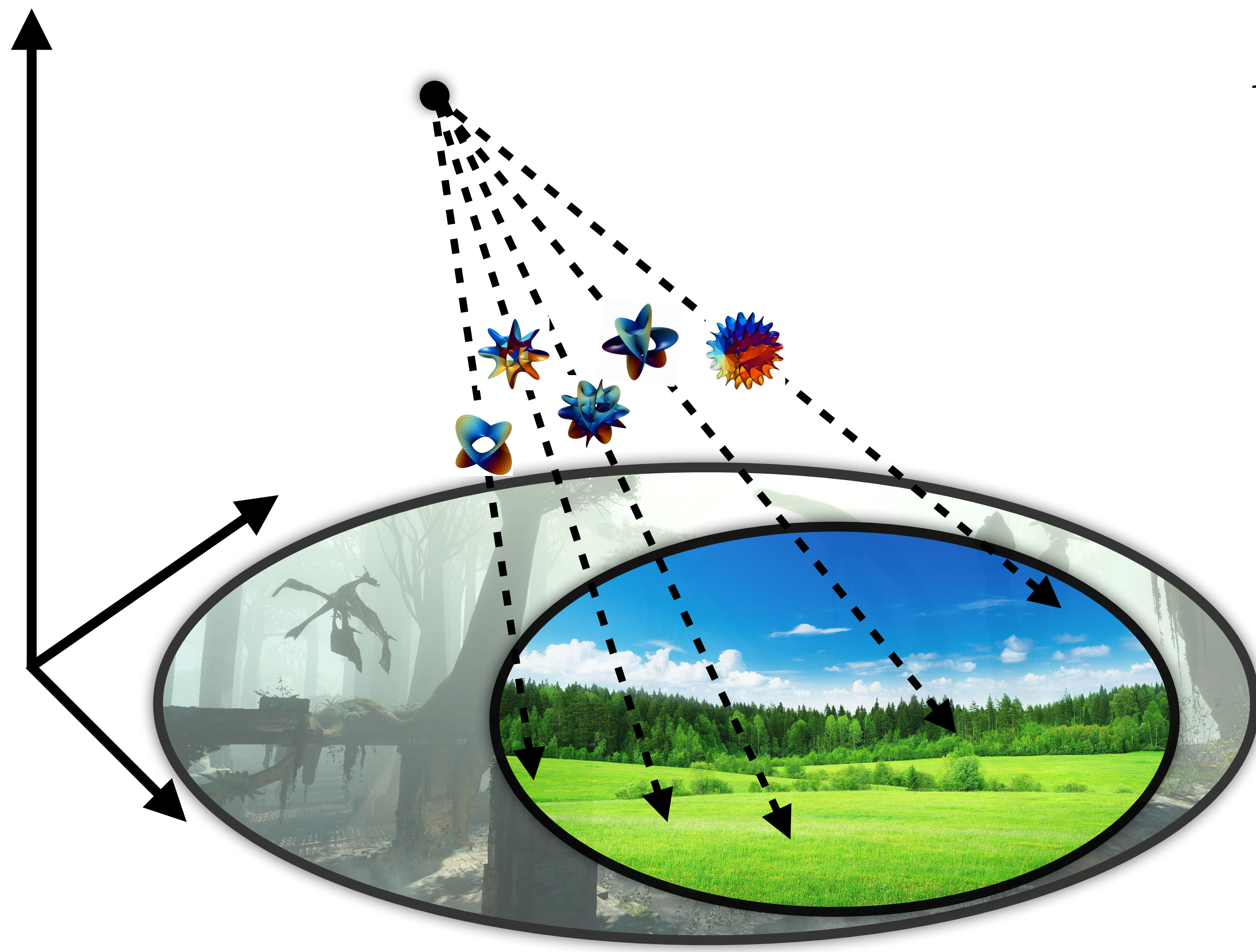
PART III: Theory



$$\mathcal{S} = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G_N} + \mathcal{L}_{\rm SM} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \ldots \right)$$

U(1) **dark**

PART III: Theory



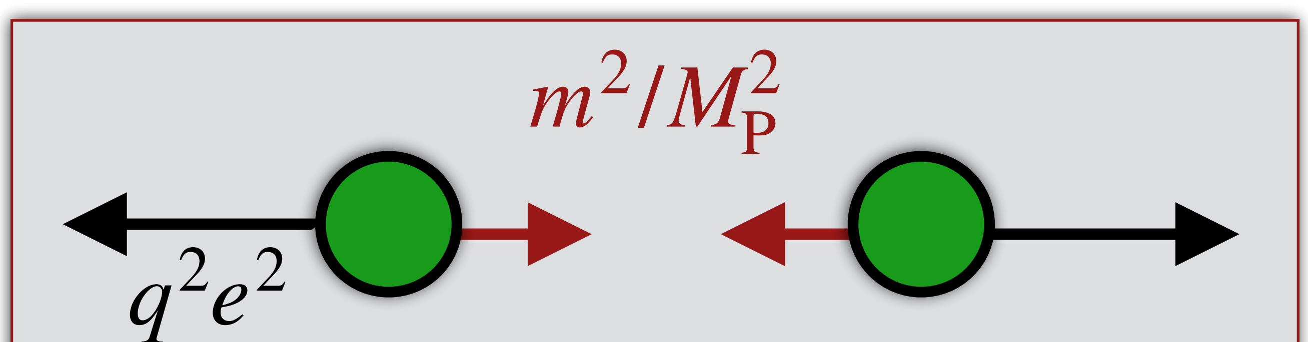
Weak Gravity Conjecture

There must exist at least one state with charge qe larger than its mass m in Planck units

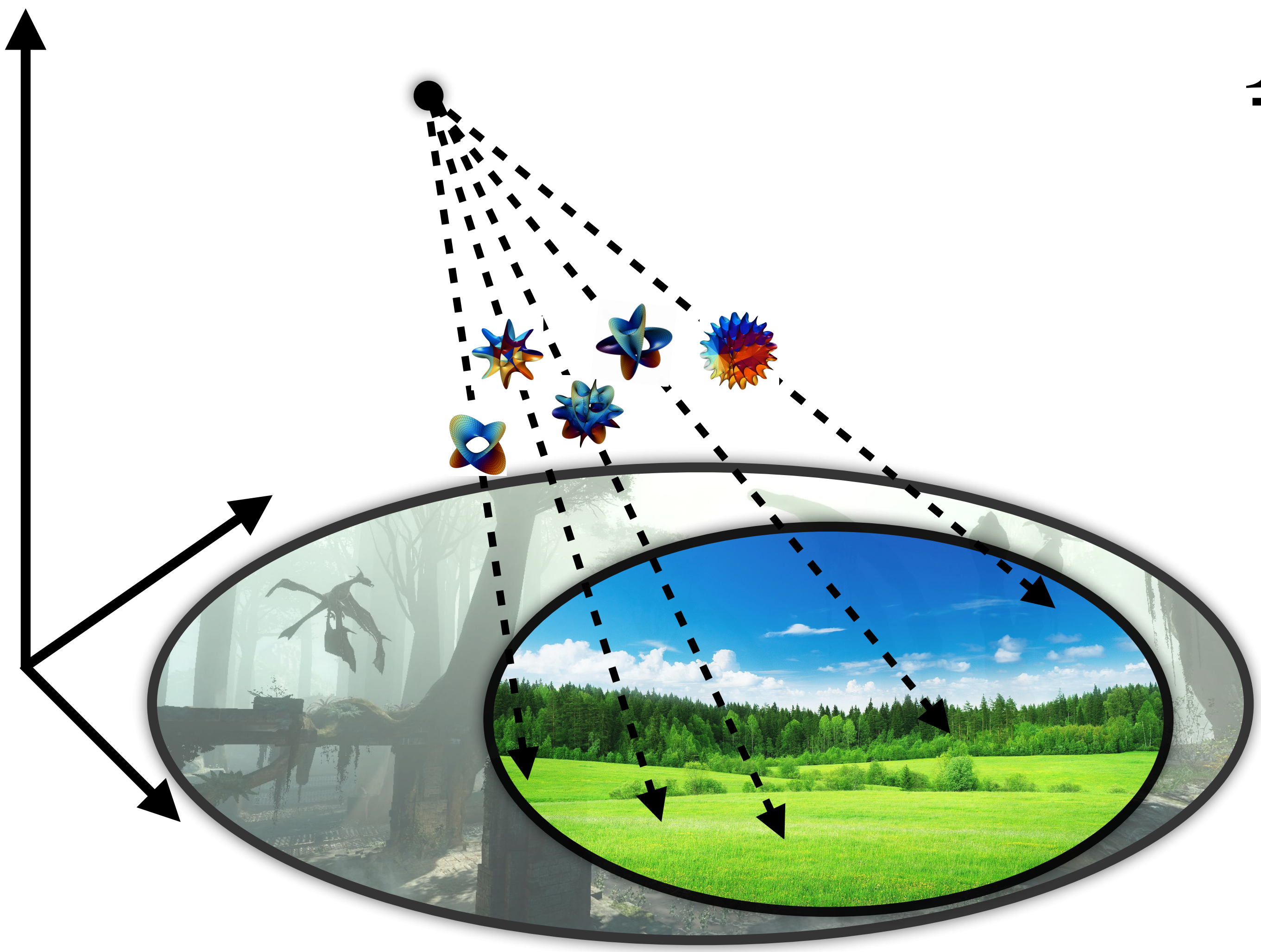
$$qe > \frac{m}{M_{\rm P}}$$

$$\mathcal{S} = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G_N} + \mathcal{L}_{\rm SM} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \ldots \right)$$

U(1) **dark**



PART III: Theory



Weak Gravity Conjecture

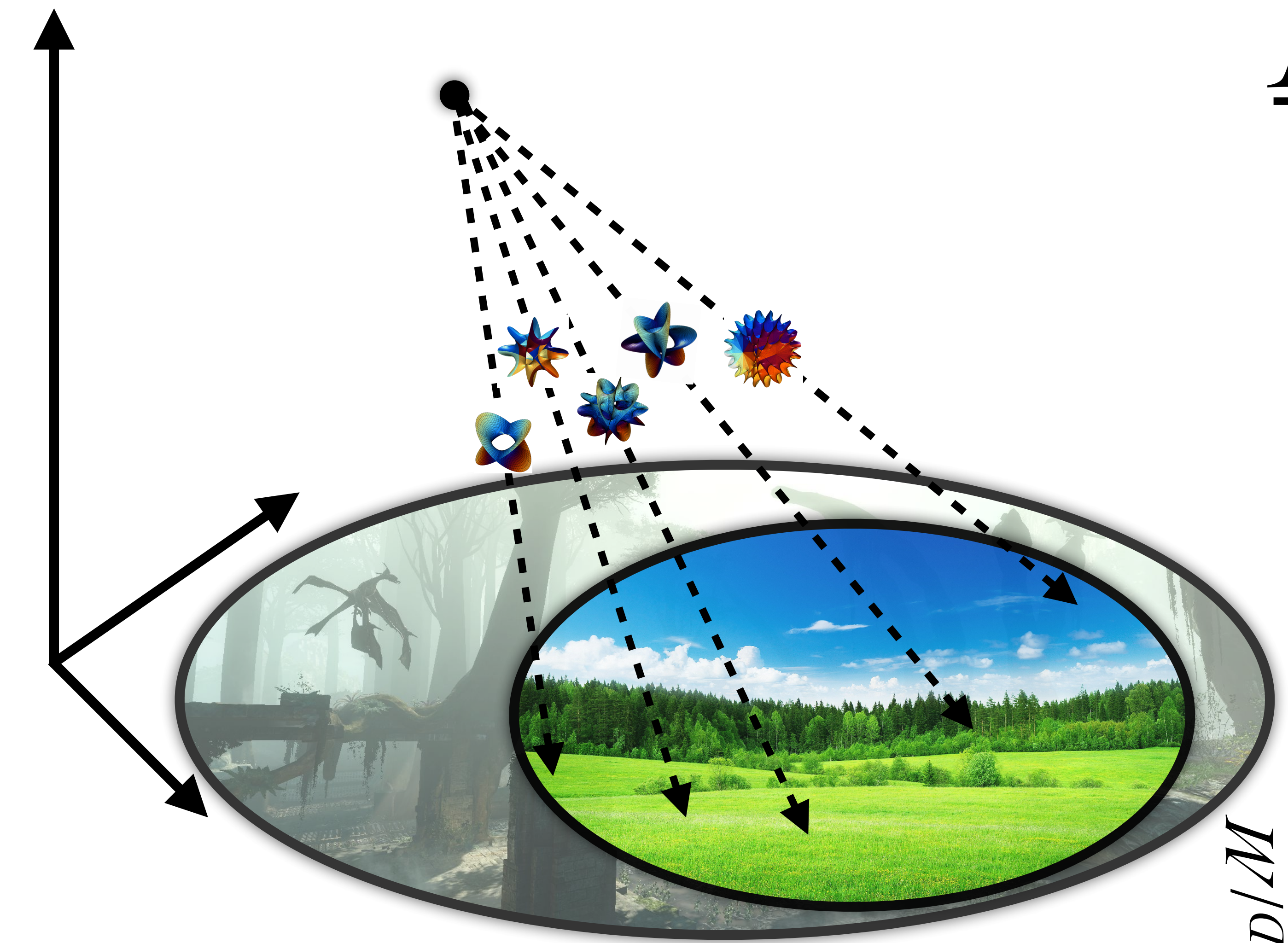
There must exist at least one state with charge qe larger than its mass m in Planck units

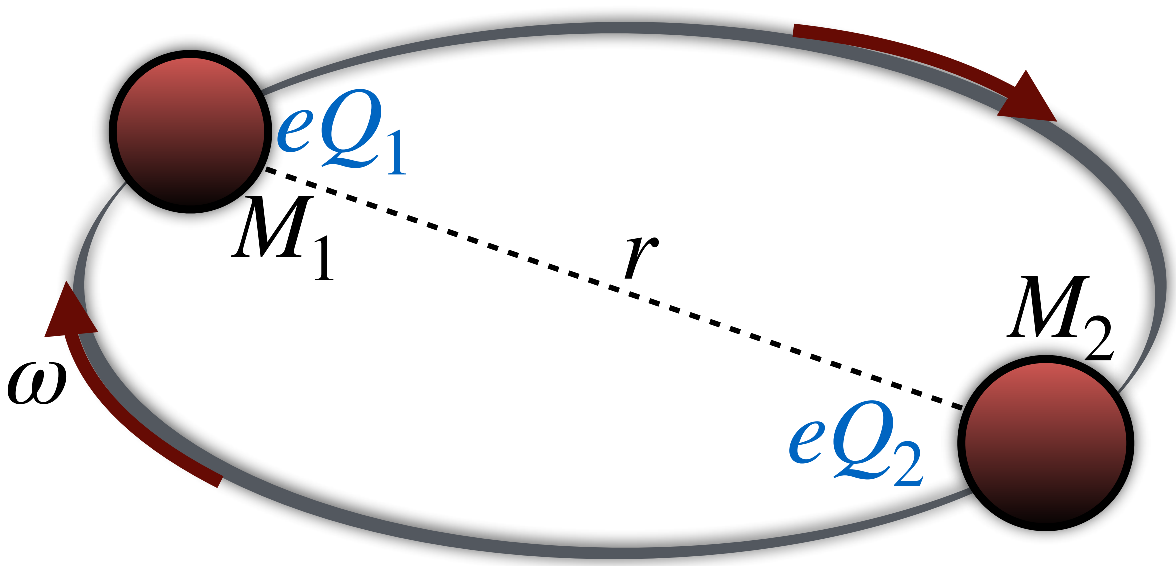
$$qe > \frac{m}{M_{\rm P}}$$

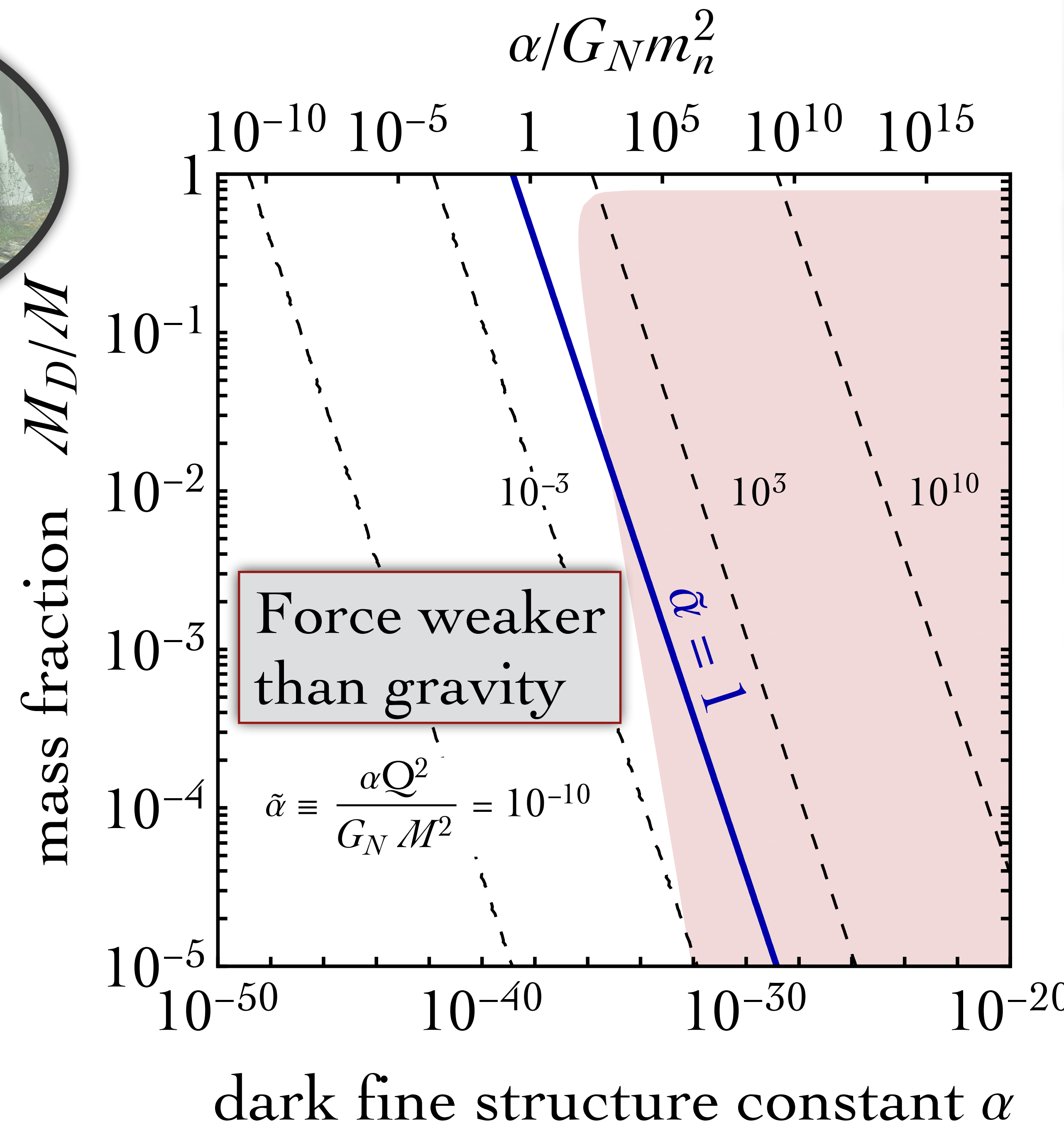
It is tempting to generalize it…

"Gravity is the weakest force in Nature."

PART III: Theory

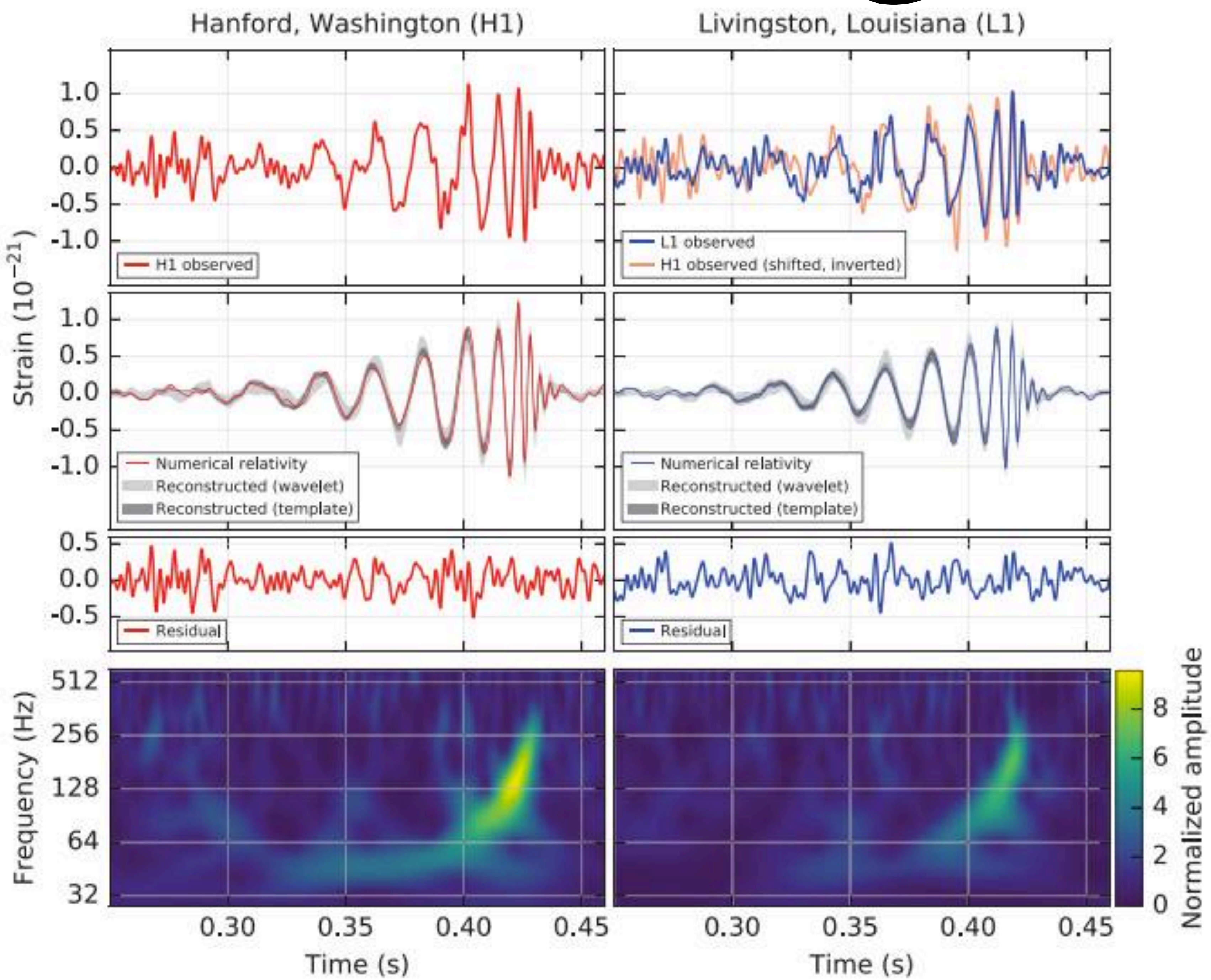






PART IV: Conclusions

A new era has begun



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Bonus Material

$$n \to Q_U + Q_D + Q_D$$

$$\underbrace{937.900\ \text{MeV}}_{\text{decay of } ^9\text{Be closed}} < 2m_D + m_U < \underbrace{m_n = 939.565\ \text{MeV}}_{\text{decay kin. open}}$$