BHs and compact objects in LV gravity

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Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN

- Why LV gravity?
- BHs in LV gravity
- Compact objects in LV gravity











Kent Yagi
Princeton

WHY are we interested on Lorentz Violations in Gravity?

- Why not?

Is Nature really Lorentz invariant?

Precision tests in the matter sector
Gravitational physics is mostly tested in the non-relativistic limit
(Local tests in the solar system, large scale cosmology)

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- Quantum Gravity

Hořava Gravity

Can provide a UV completion for GR
Formulated as a standard field theory

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At low energies $$\mathscr{L} = \mathscr{L}_2 + \cancel{\mathscr{L}_4} + \cancel{\mathscr{L}_6}$$

BHs in $\mathcal{L}_2$

$$S = -\frac{1}{16\pi G}\int d^4x\sqrt{|g|}\left(R + K^{\alpha\beta}_{\mu\nu}\nabla_\alpha U^\mu \nabla_\beta U^\nu + \lambda(U_\mu U^\mu - 1)\right),$$

$$K^{\alpha\beta}_{\mu\nu} = c_1 g^{\alpha\beta}g_{\mu\nu} + c_2\delta^\alpha_\mu\delta^\beta_\nu + c_3\delta^\alpha_\nu\delta^\beta_\mu + c_4 U^\alpha U^\beta g_{\mu\nu}$$

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Generically propagates a vector and a scalar

There is a combination of couplings such that only the scalar propagates

- The limit of HG $\qquad c_1 - c_3 = c_\omega \to \infty$

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This action has stationary and spherically symmetric solutions of the form

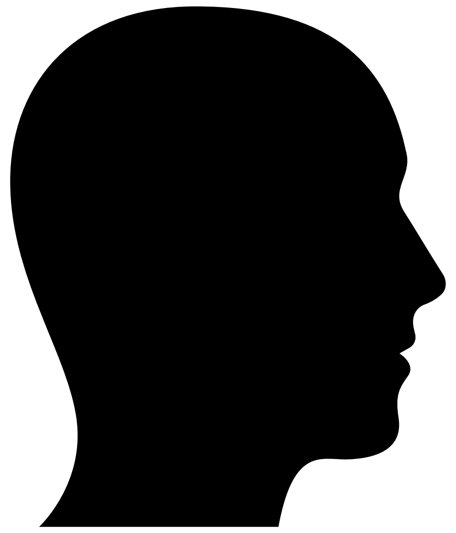
$$ds^2 = F(r)dt^2 - \frac{B(r)^2}{F(r)}dr^2 - r^2 dS_2$$

$$U_\mu dx^\mu = \frac{1 + F(r)A(r)^2}{2A(r)}dt + \frac{B(r)}{2A(r)}\left(\frac{1}{F(r)} - A(r)^2\right)dr$$

$$U_\mu = \frac{\partial_\mu \Theta}{\sqrt{|\partial_\alpha\Theta\partial^\alpha\Theta|}}$$

Jacobson PRD 64 (2001) 024028

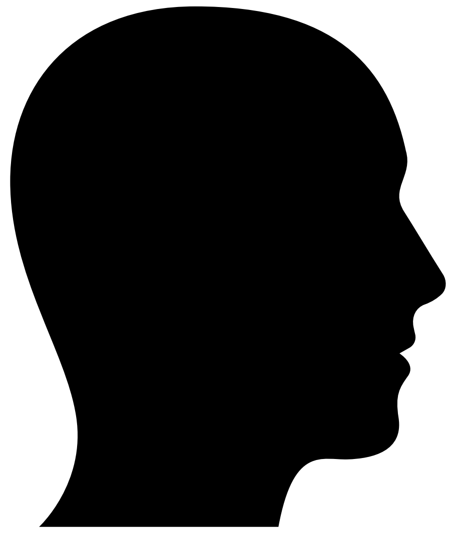
Berglund, Bhattacharyya, Mattingly, Phys.Rev.D 85 (2012) 124019



But if the theory is Lorentz violating, the Horizon has no meaning!

$$\mathscr{L}_{\text{matter}} \sim \partial_t^2 - c^2\partial_x^2 + \frac{a_4}{\Lambda^2}\partial_x^4 - \frac{a_6}{\Lambda^4}\partial_x^6$$

$$\omega^2 = k^2\left(c^2 + \frac{a_4}{\Lambda^2}k^2 + \ldots\right)$$



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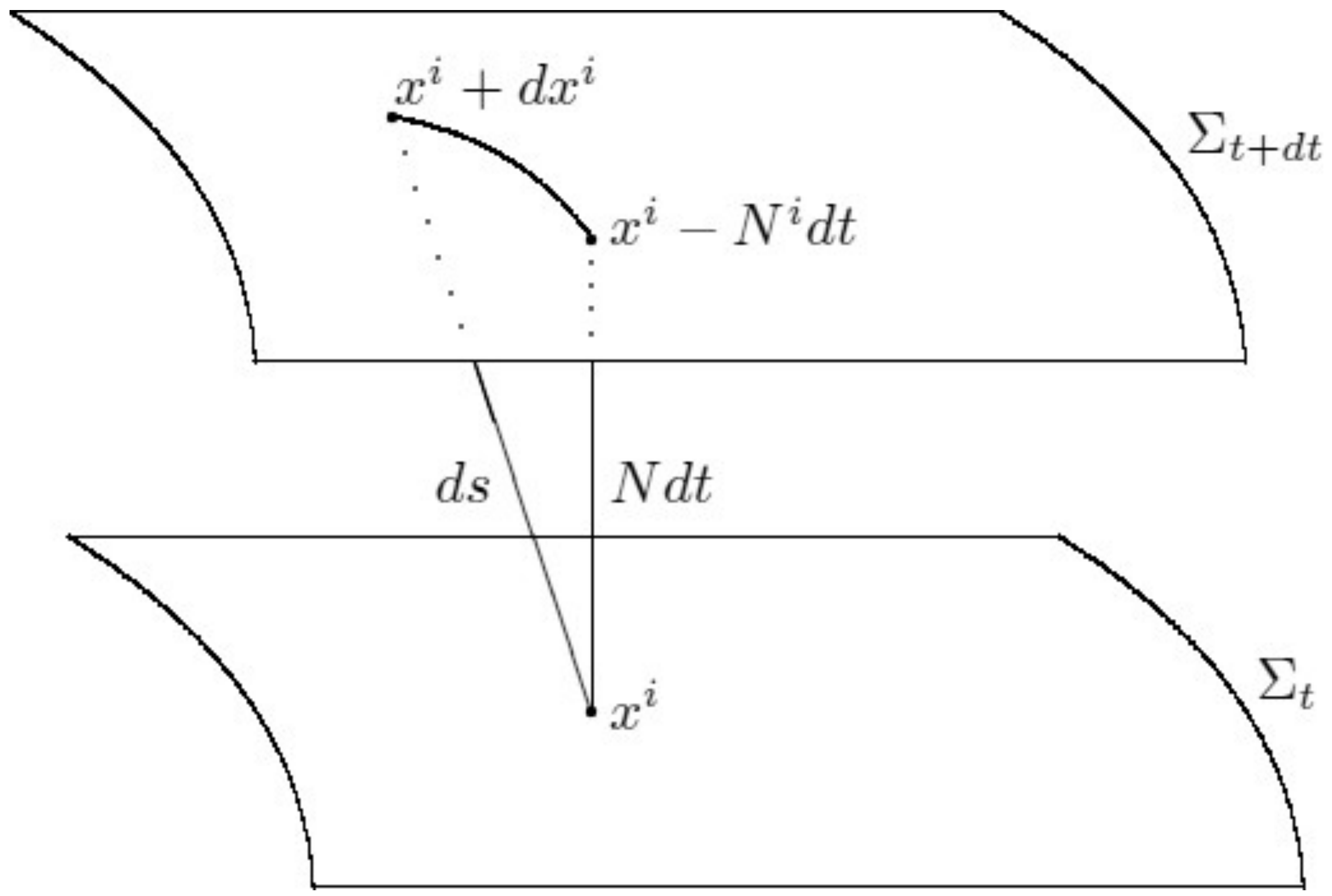

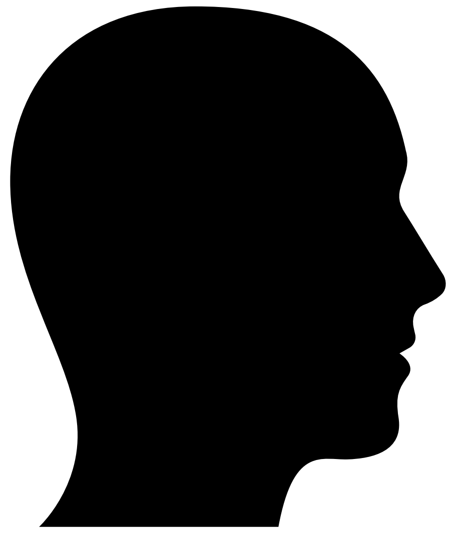

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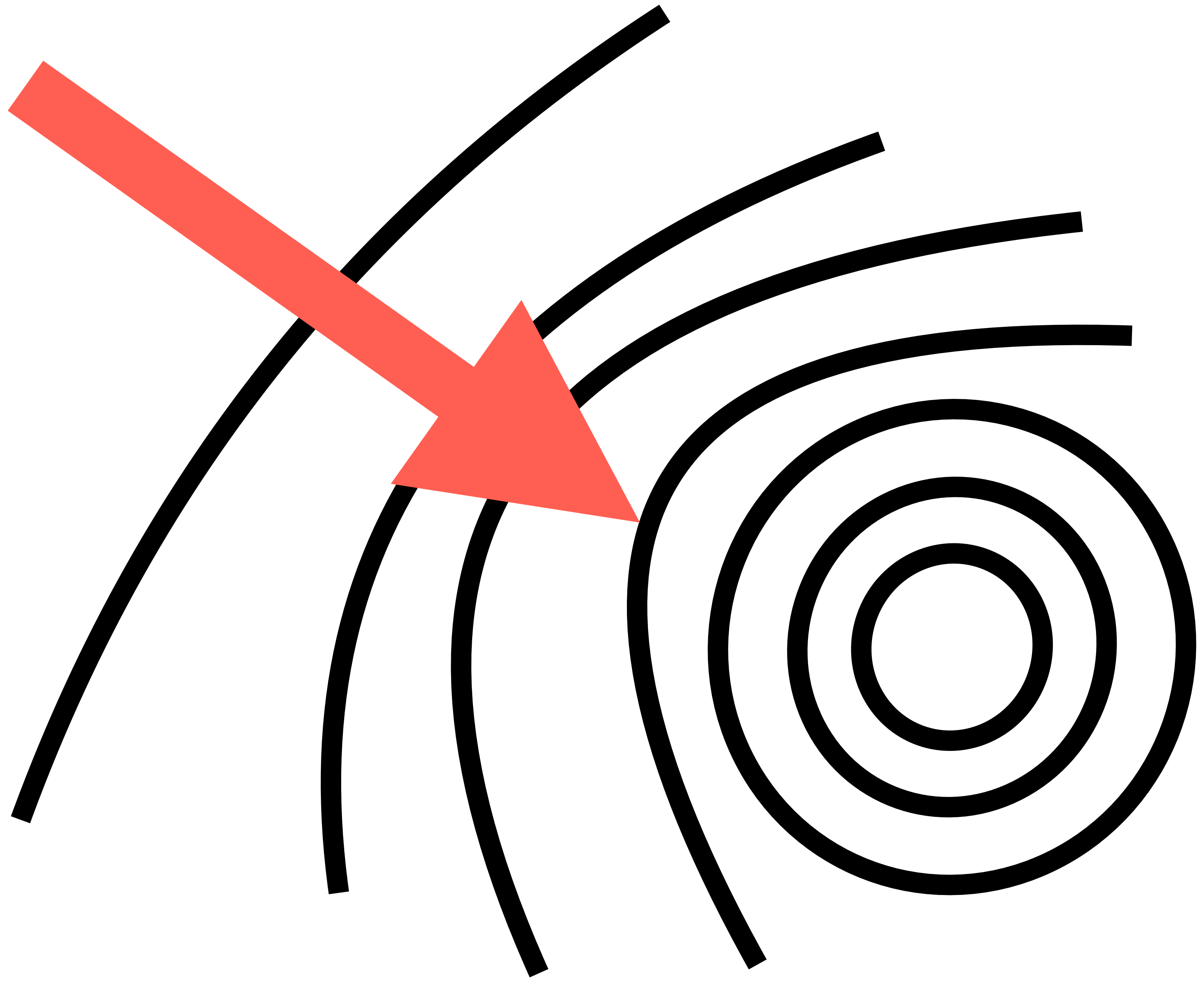

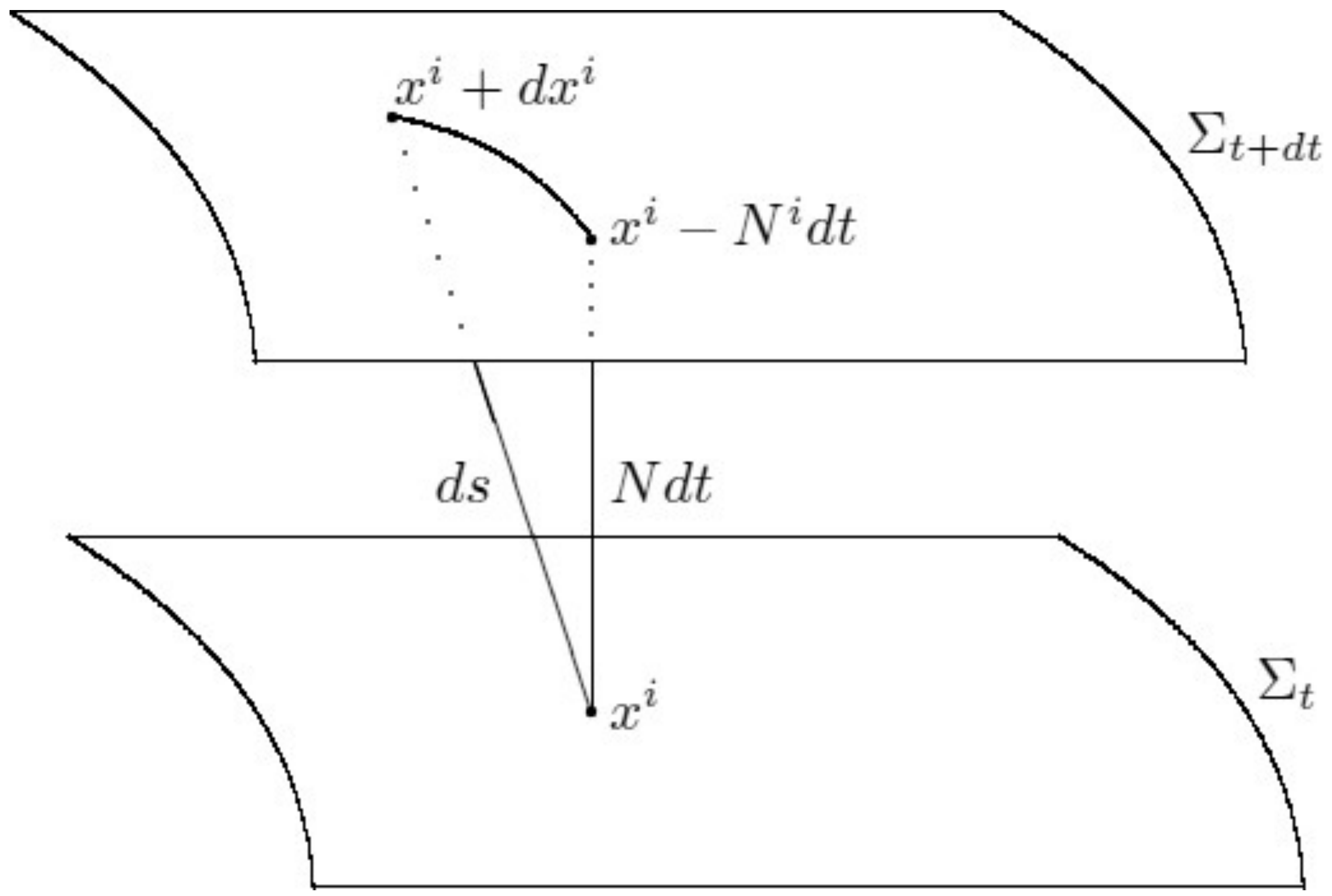

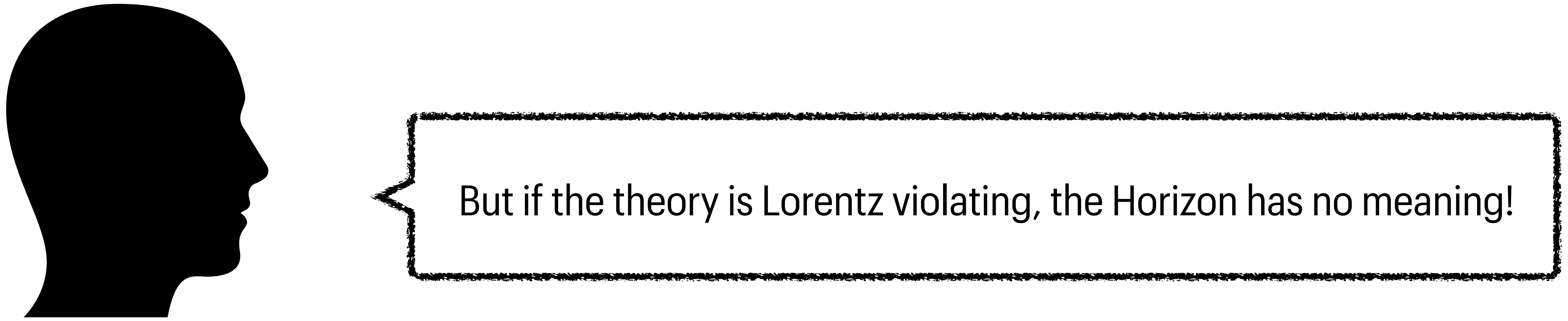

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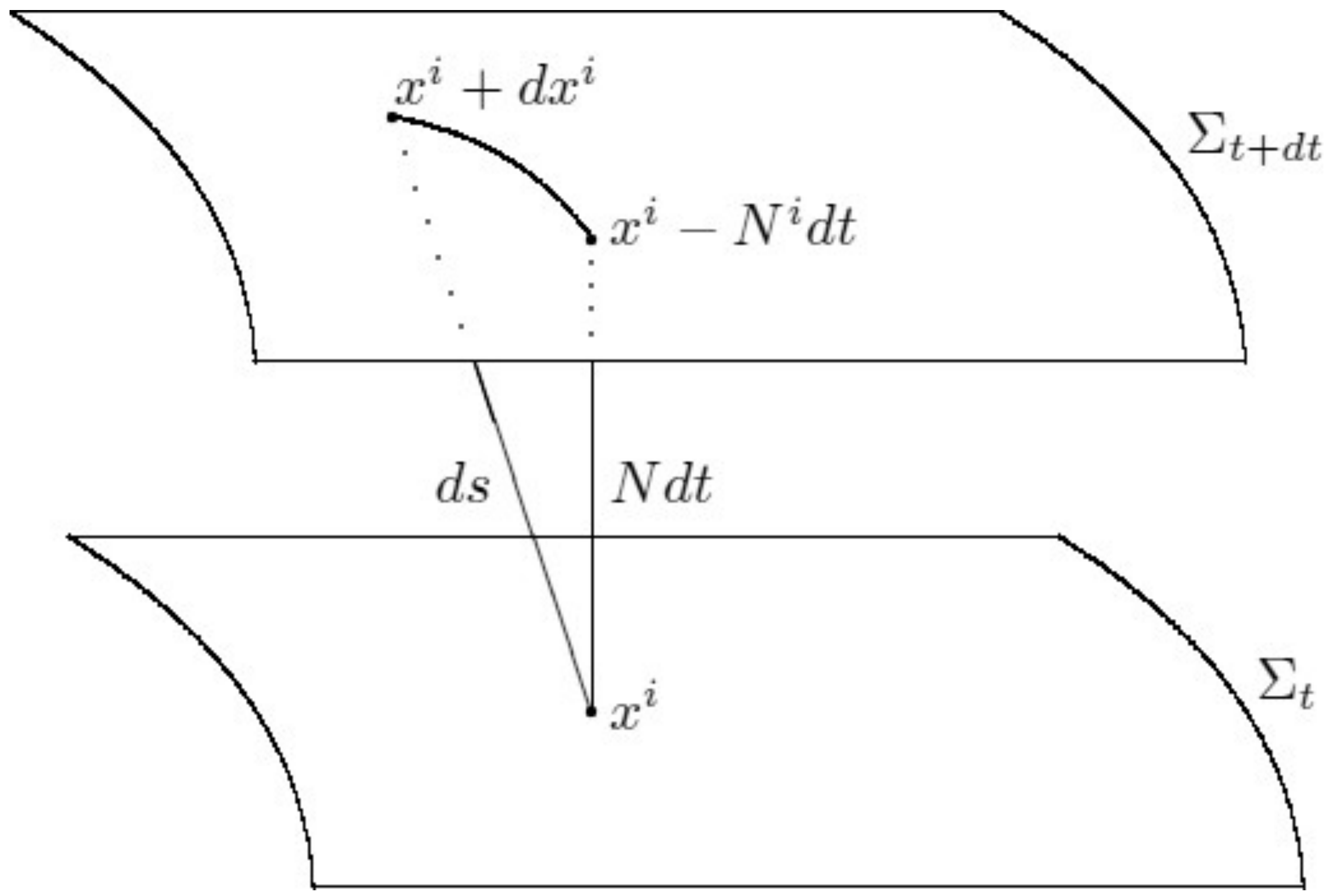
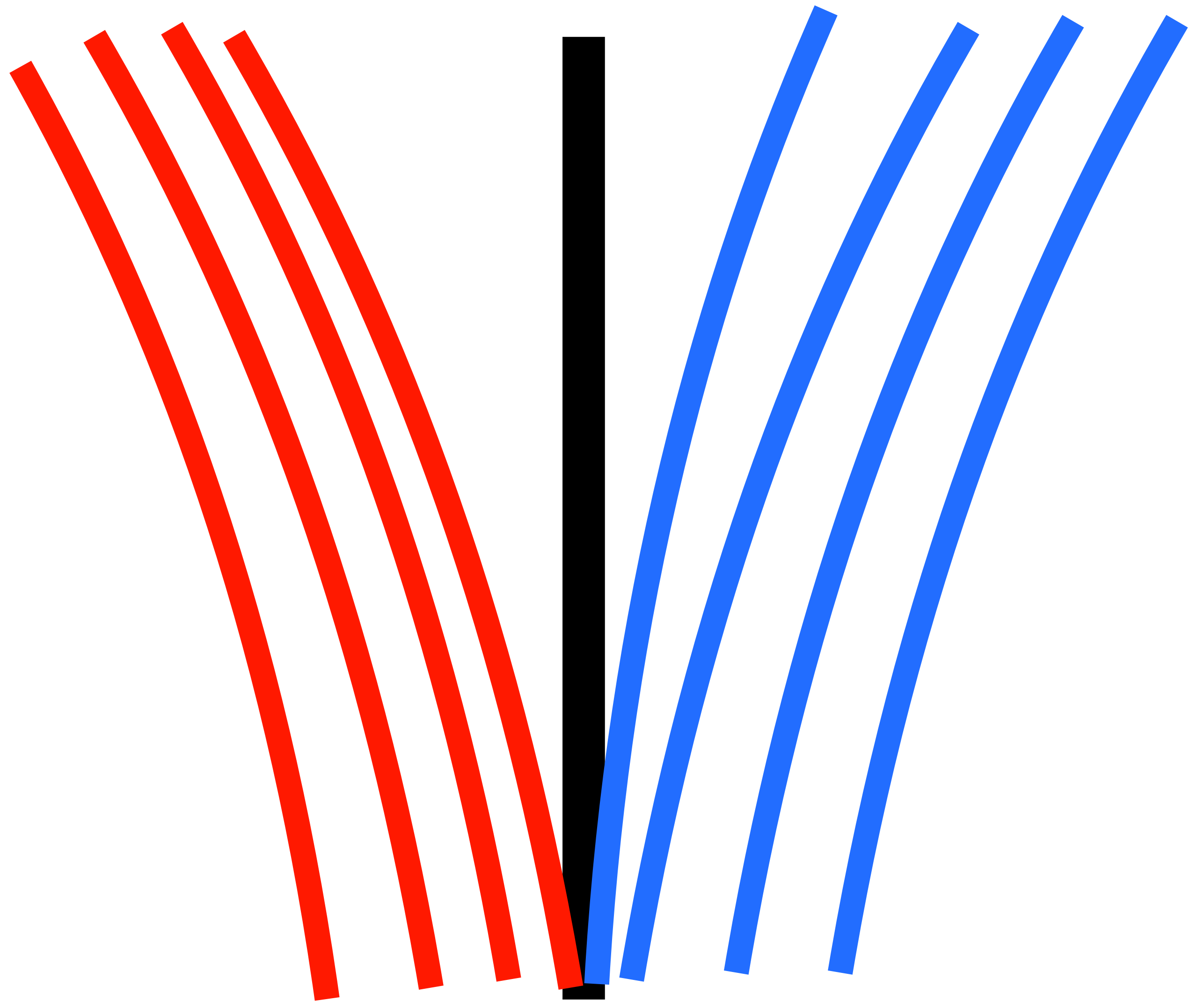
Universal Horizon

$$N = (\chi \cdot U) = 0$$





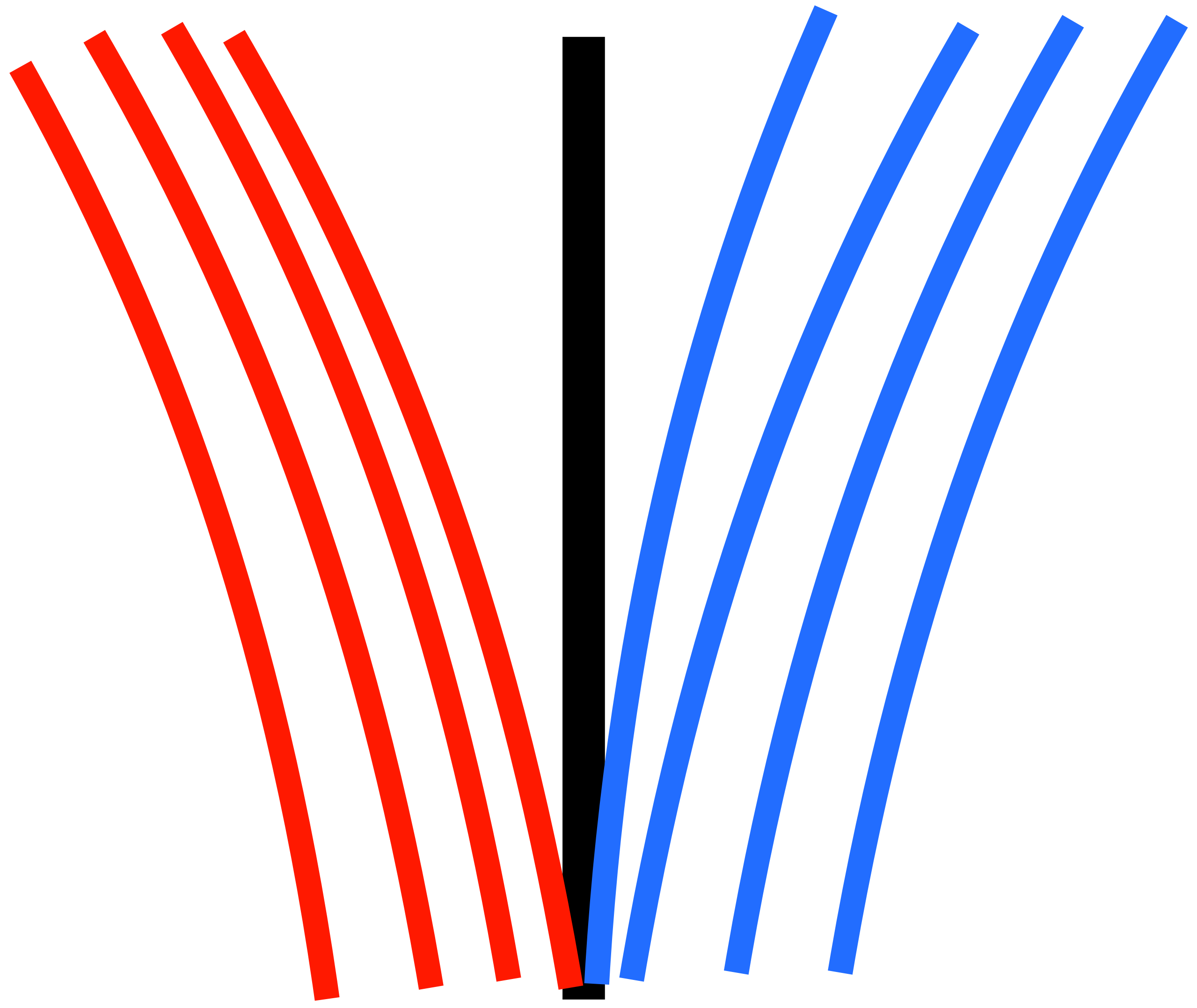
The peeling close to the UH mimics that of rays in the event horizon of a GR black hole

↓

Thermodynamics

$$T = \frac{n-1}{n}\frac{\kappa_{\rm UH}}{\pi}$$

$$\mathscr{L}_{\rm matter} \sim \partial_t^2 - c^2\partial_x^2 + \frac{a_4}{\Lambda^2}\partial_x^4 + \ldots + \frac{a_{2n}}{\Lambda^{2n-2}}\partial_x^{2n}$$



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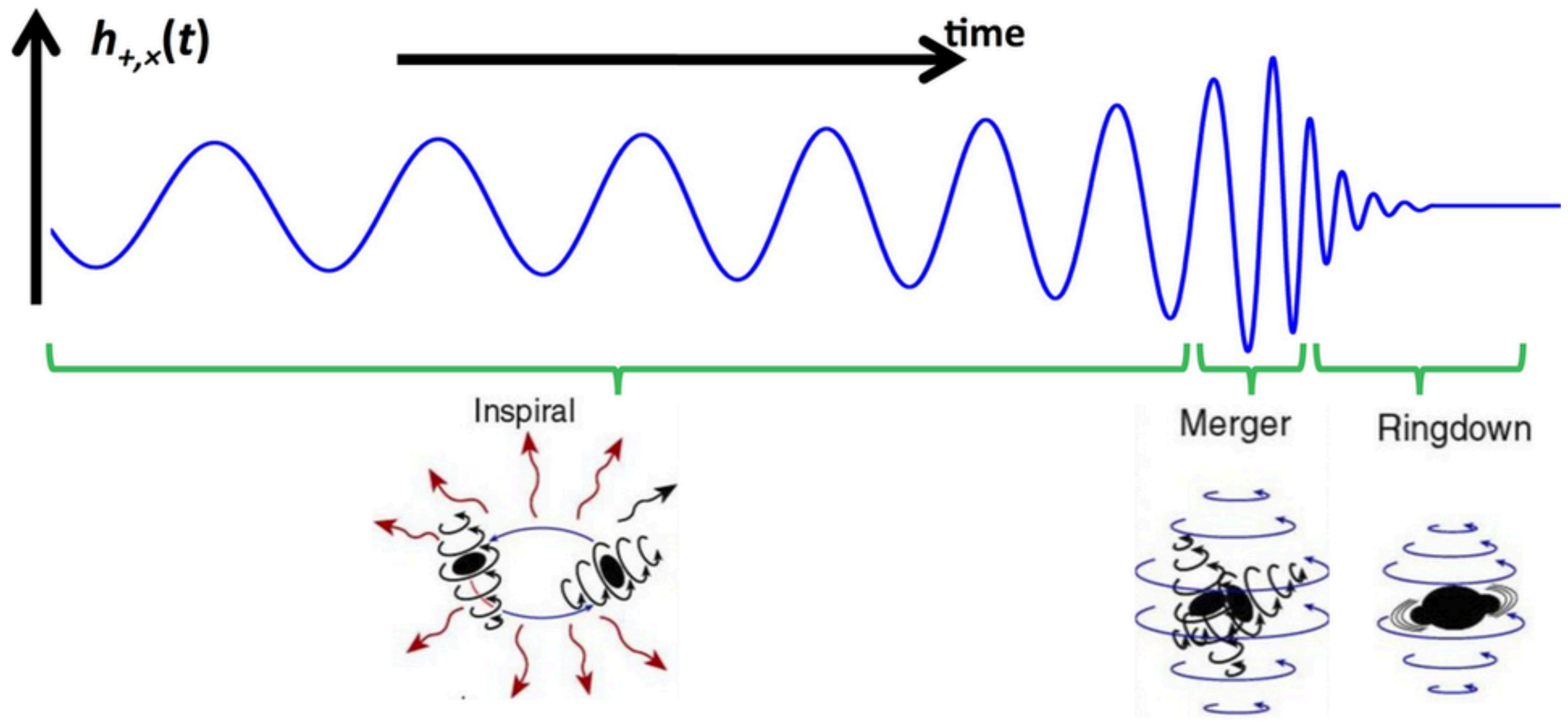
- We have confirmed this result
  - By collapsing a shell

    H-V, Liberati, Santos-García, JHEP 04 (2021) 255
  - By studying the peeling and causal structure close to the UH

    Del Porro, H-V, Liberati, Schneider, PRD 105 (2022) 10, 104009
  - By studying quantum tunnelling through the horizon

    Del Porro, H-V, Liberati, Schneider, 2207.08848

Observability?

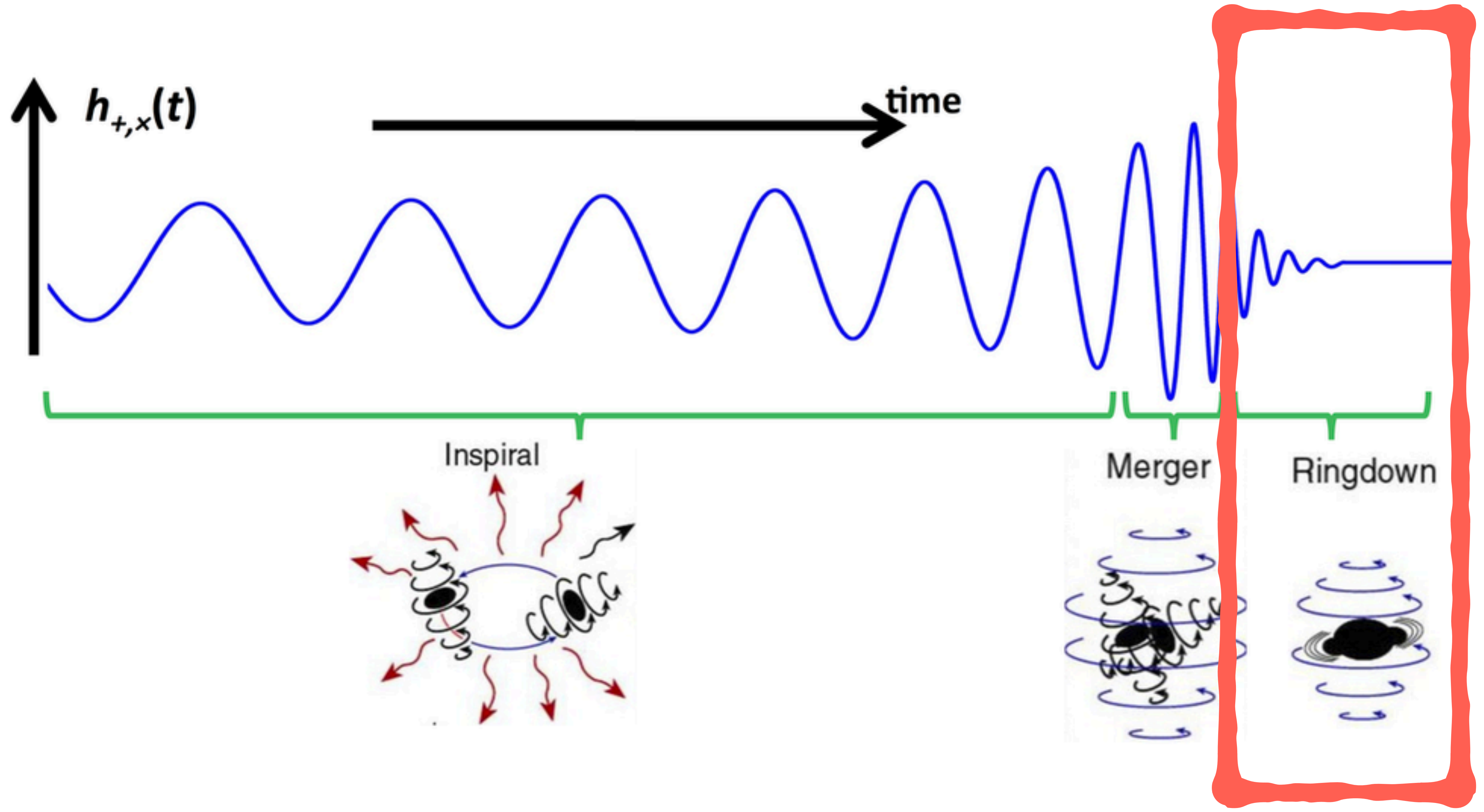


Franchini, H-V, Barausse PRD 103 (2021) 8, 084012

Observability?

The ringdown signal can always be decomposed in terms of QNMs

We focus on the HL limit



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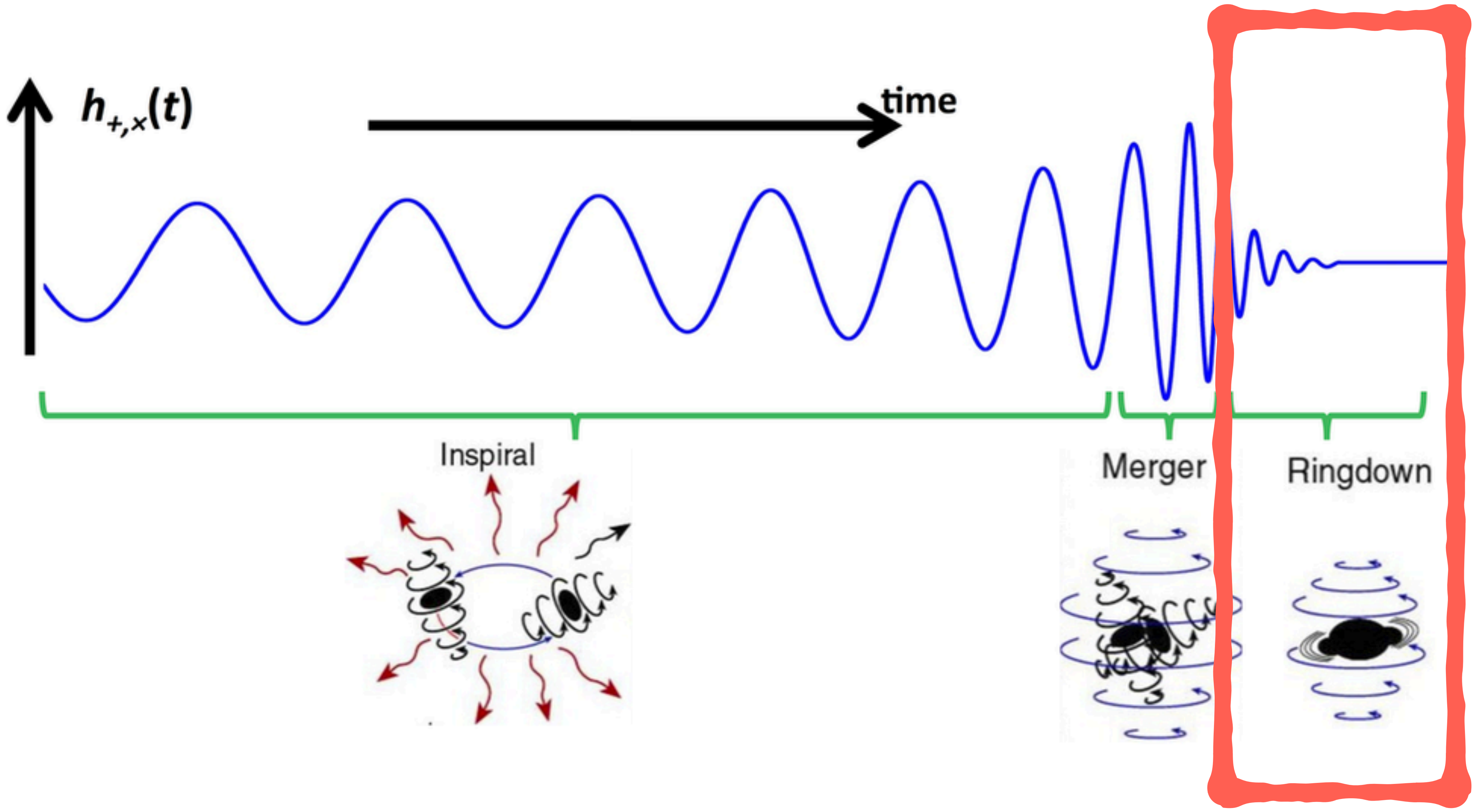
We focus on the HL limit

$$\frac{d^2Q}{dr^2} + Q\left[\omega^2 - V_{\rm odd}\right] = 0$$

$$\frac{d^2\Psi}{dr^2} + \Psi\left[\omega^2 - V_{\rm even}\right] = 0$$

$$\frac{d^2\phi}{dr^2} - \phi V_{\rm scalar} = J[h]$$



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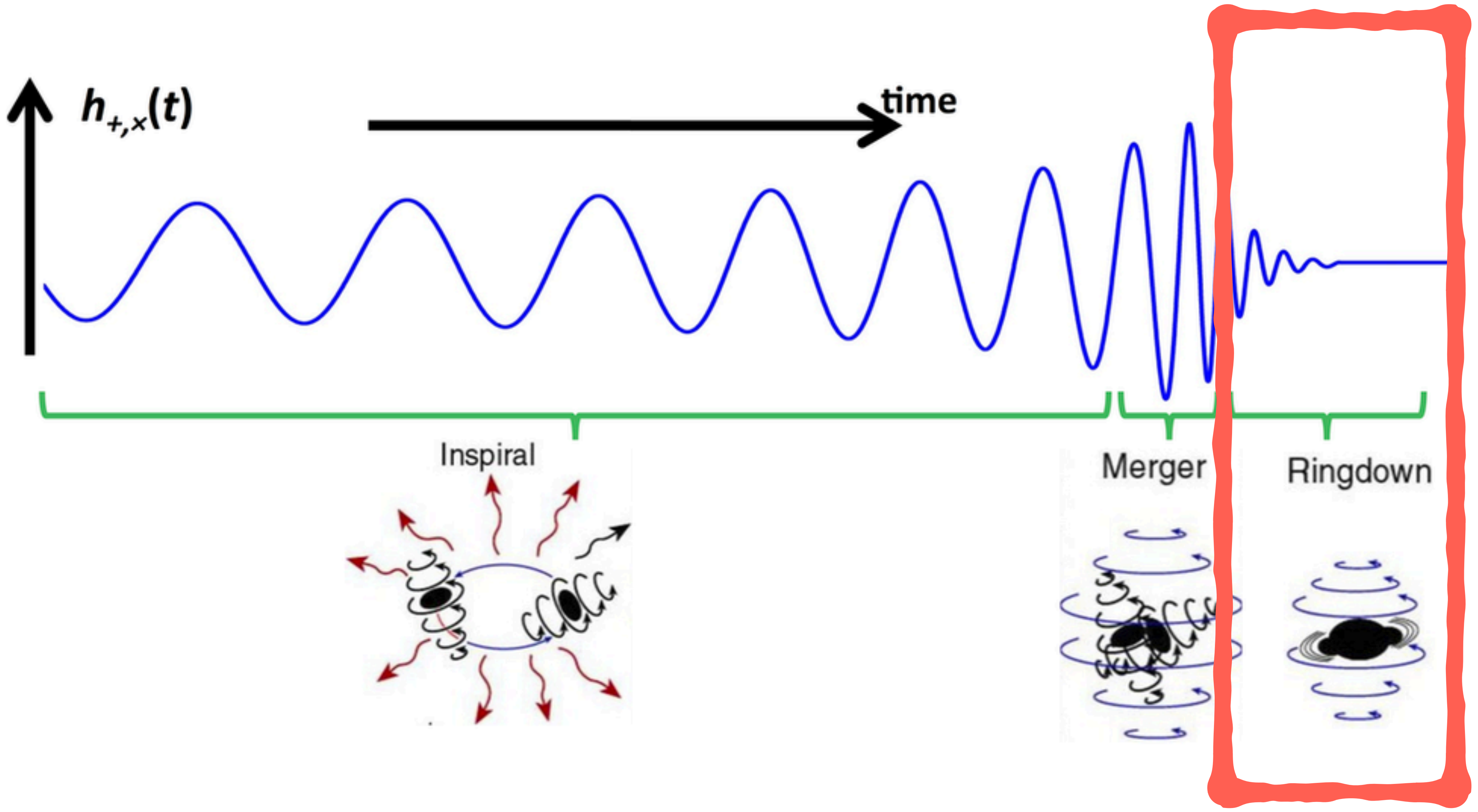

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Identical to GR!!

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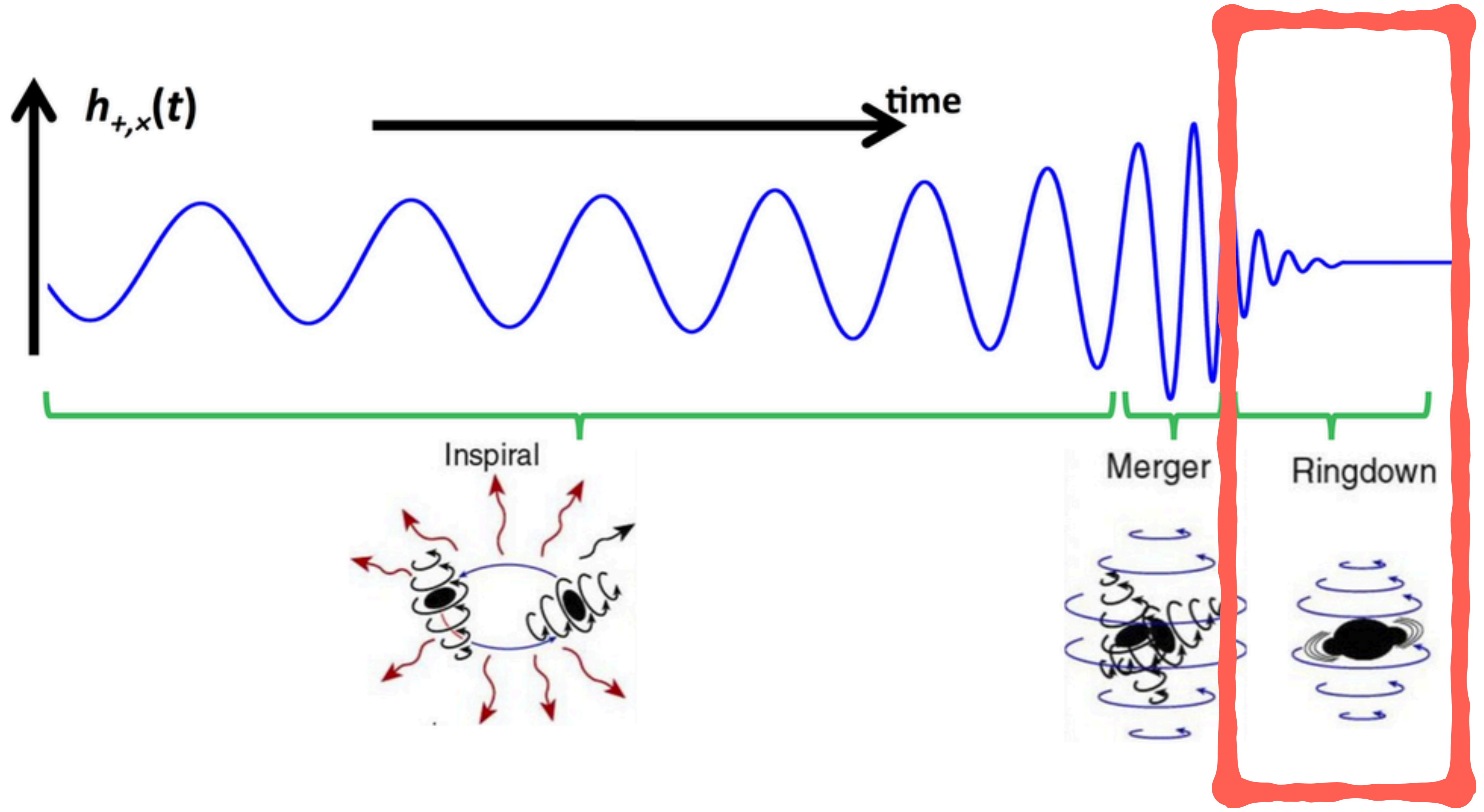

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We need LV matter. But that's hard...

Franchini, H-V, Barausse PRD 103 (2021) 8, 084012

Compact objects (aka neutron stars) in LV gravity

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left(-R - K^{\alpha\beta}_{\mu\nu}\nabla_\alpha U^\mu \nabla_\beta U^\nu - \lambda(U^\mu U_\mu - 1)\right)$$

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Gupta, H-V, Blas, Barausse, Cornish, Yagi, Yunes CQG 38 (2021) 19, 195003

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- GW propagate at c=1 $\quad c_1 + c_3 = 0$
- Solar system tests $\quad 3c_2 = c_\theta \leq \mathcal{O}(1)$
- The limit of HG $\quad c_1 - c_3 = c_\omega \to \infty$

- Violations of the strong equivalence principle

In modified theories of Gravity, compact objects do not move on geodesics of the metric

In the point particle approximation this is parametrised by sensitivities

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$$S = -\int d\tau\ m(\gamma), \qquad m(\gamma) = m_0 \left[1 + \sigma(1-\gamma) + \ldots\right], \qquad \sigma = \left.\frac{d\log m(\gamma)}{d\log\gamma}\right|_{\gamma=1}$$

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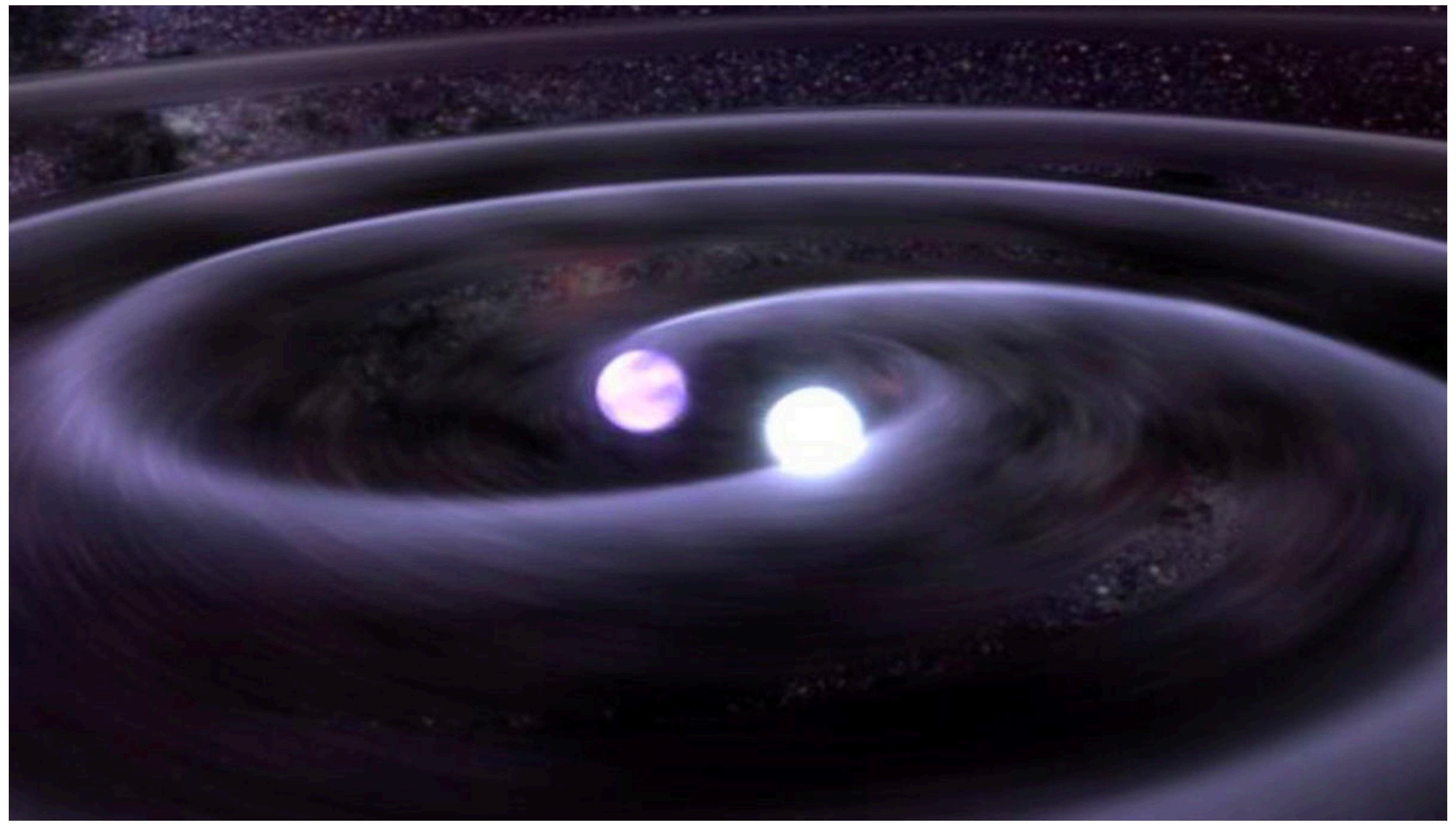
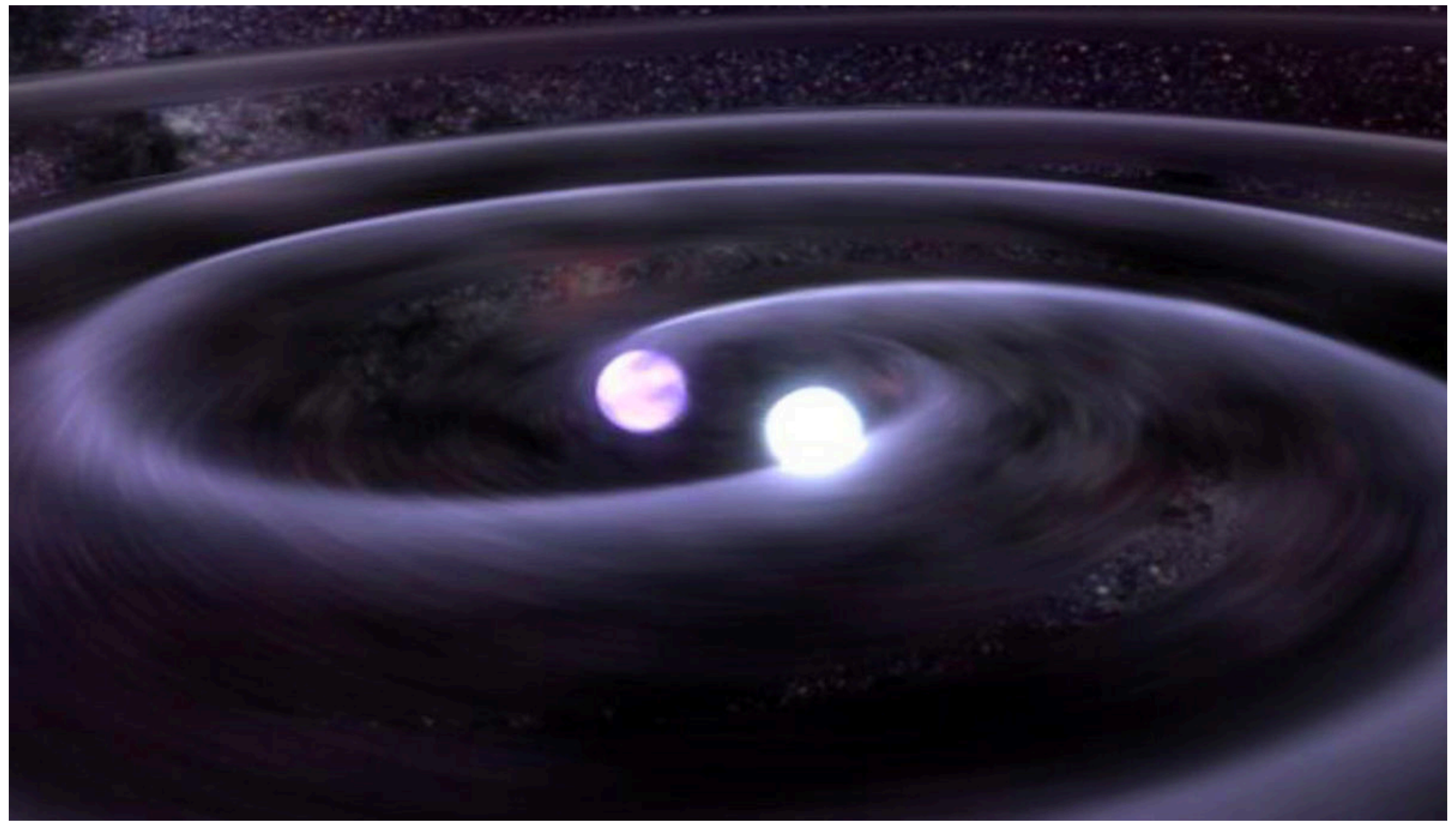
The sensitivities also control the emission of gravitational waves in binary systems of compact objects i.e. binary pulsars



- As pulsars move the period of the orbit change due to emission of GW

$$\frac{\dot{E}_b}{E_b} = 2\left\langle \left(\frac{\mathcal{G}_{12} G m_1 m_2}{r^3}\right) \left\{ \frac{32}{5}(\mathcal{A}_1 + \mathcal{S}\mathcal{A}_2 + \mathcal{S}^2\mathcal{A}_3) v_{21}^2 \right.\right.$$
$$+ (s_1 - s_2)^2 \left[\mathcal{E} + 2\mathcal{D}[w^2 - (\boldsymbol{w}\cdot\boldsymbol{n})^2] + \frac{18}{5}\mathcal{A}_3\, w^2 + \left(\frac{6}{5}\mathcal{A}_3 + 36\mathcal{B}\right)(\boldsymbol{w}\cdot\boldsymbol{n})^2\right]$$
$$\left.\left. - (s_1 - s_2)\,\frac{24}{5}(\mathcal{A}_2 + 2\mathcal{S}\mathcal{A}_3)(\boldsymbol{w}\cdot\boldsymbol{v}_{21}) \right\}\right\rangle,$$



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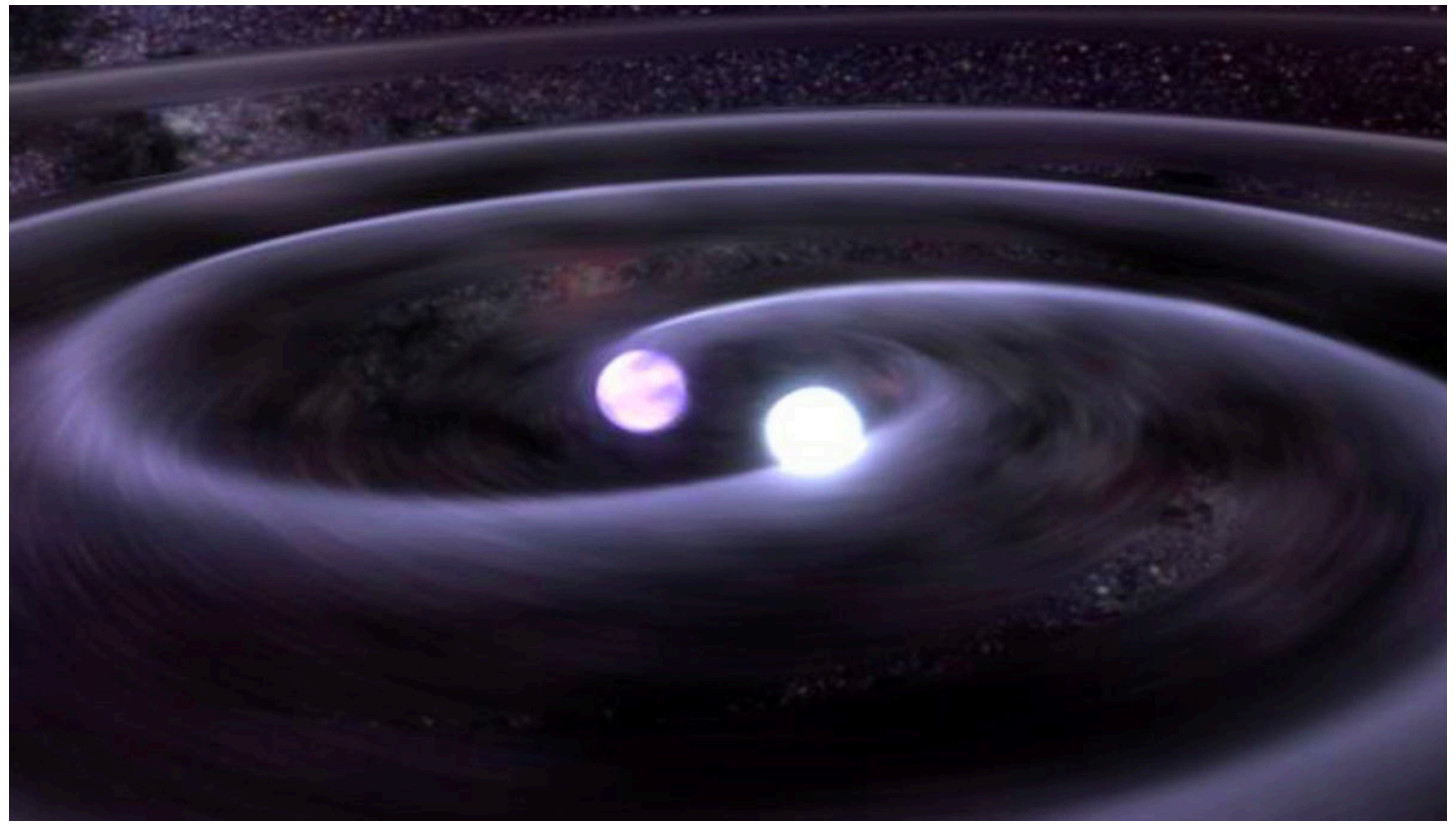

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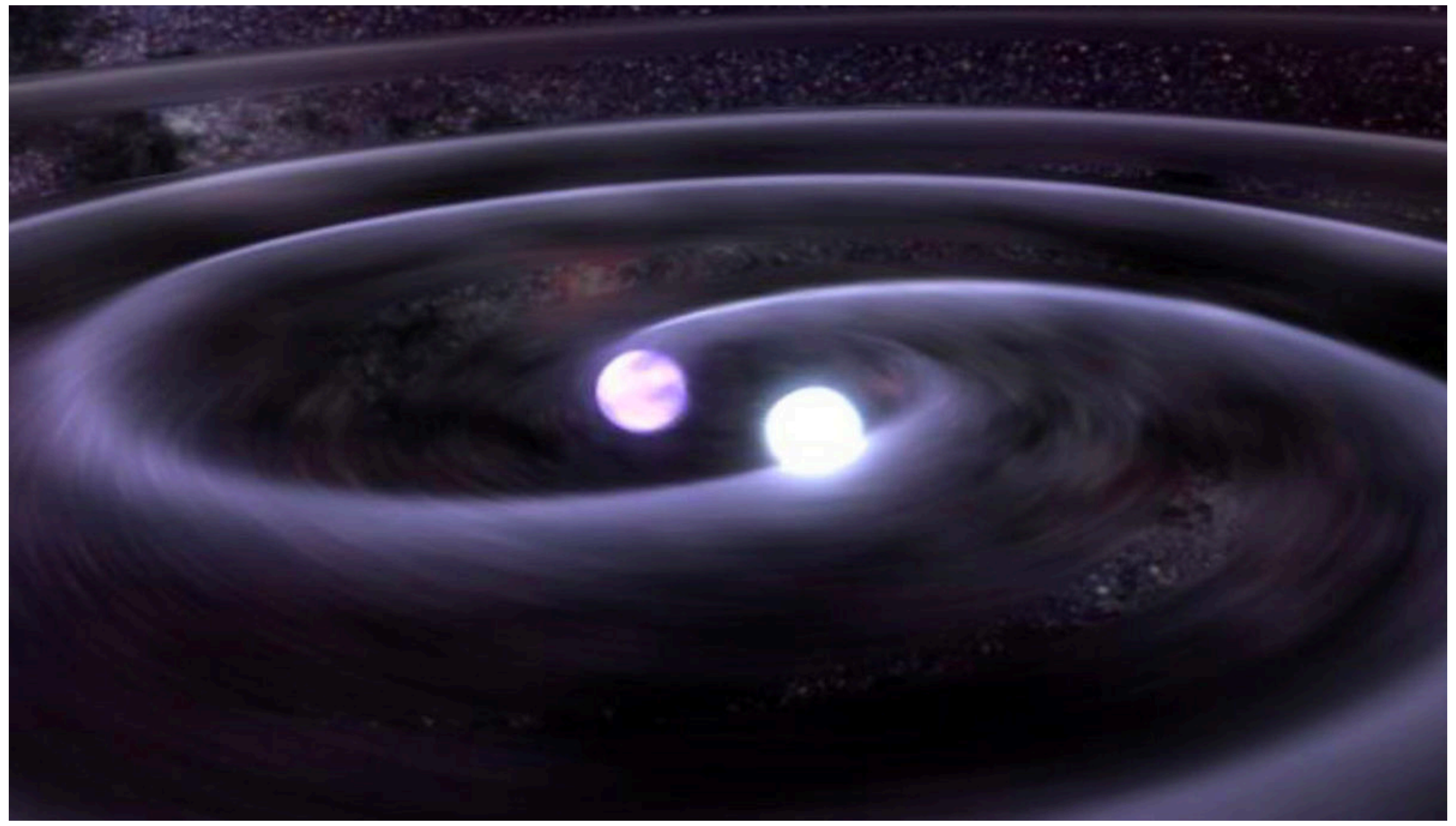

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- **However, instead of the c_i couplings, we use a different parametrization**

$\alpha_1, \alpha_2, c_\omega,$ ~~c_σ~~

There are some phenomenological constraints on the æther coupling constants as discussed in Sec. 2, i.e., $|\alpha_1| \lesssim 10^{-4}$, $|\alpha_2| \lesssim 10^{-7}$ (Solar system constraints), $\alpha_1 < 0$, $\alpha_1 < 8\alpha_2 < 0$ and $c_\omega > -\alpha_1/2$ (positive energy, absence of vacuum Cherenkov radiation and gradient instabilities) and $c_\sigma \lesssim 10^{-15}$ (GW constraint).* Using these pre-existing constraints and by determining if the estimated value of $\dot{P}_b$ lies within the range $\dot{P}_b^{\text{obs}} \pm \delta \dot{P}_b^{\text{obs}}$ (Table 1), we determine the consistency of points in the parameter space with observations.

Pulsar System	$m_1(M_\odot)$	$m_2(M_\odot)$	P_b (days)	$\dot{P}_b^{\rm obs}$
PSR J1738+0333[35]	$1.46^{+0.06}_{-0.05}$	$0.181^{+0.008}_{-0.007}$	0.3547907398724(13)	$-25.9(3.2) \times 10^{-15}$
PSR J0348+0432 [6]	2.01(4)	0.172(3)	0.102424062722(7)	$-0.273(45) \times 10^{-12}$
PSR J1012+5307 [21] [51]	1.64(0.22)	0.16(0.02)	0.60467272355(3)	$-1.5(1.5) \times 10^{-14}$
PSR J0737-3039 [50]	1.3381(7)	1.2489(7)	0.10225256248(5)	$-1.252(17) \times 10^{-12}$

+ triple system PSR J0337+1715

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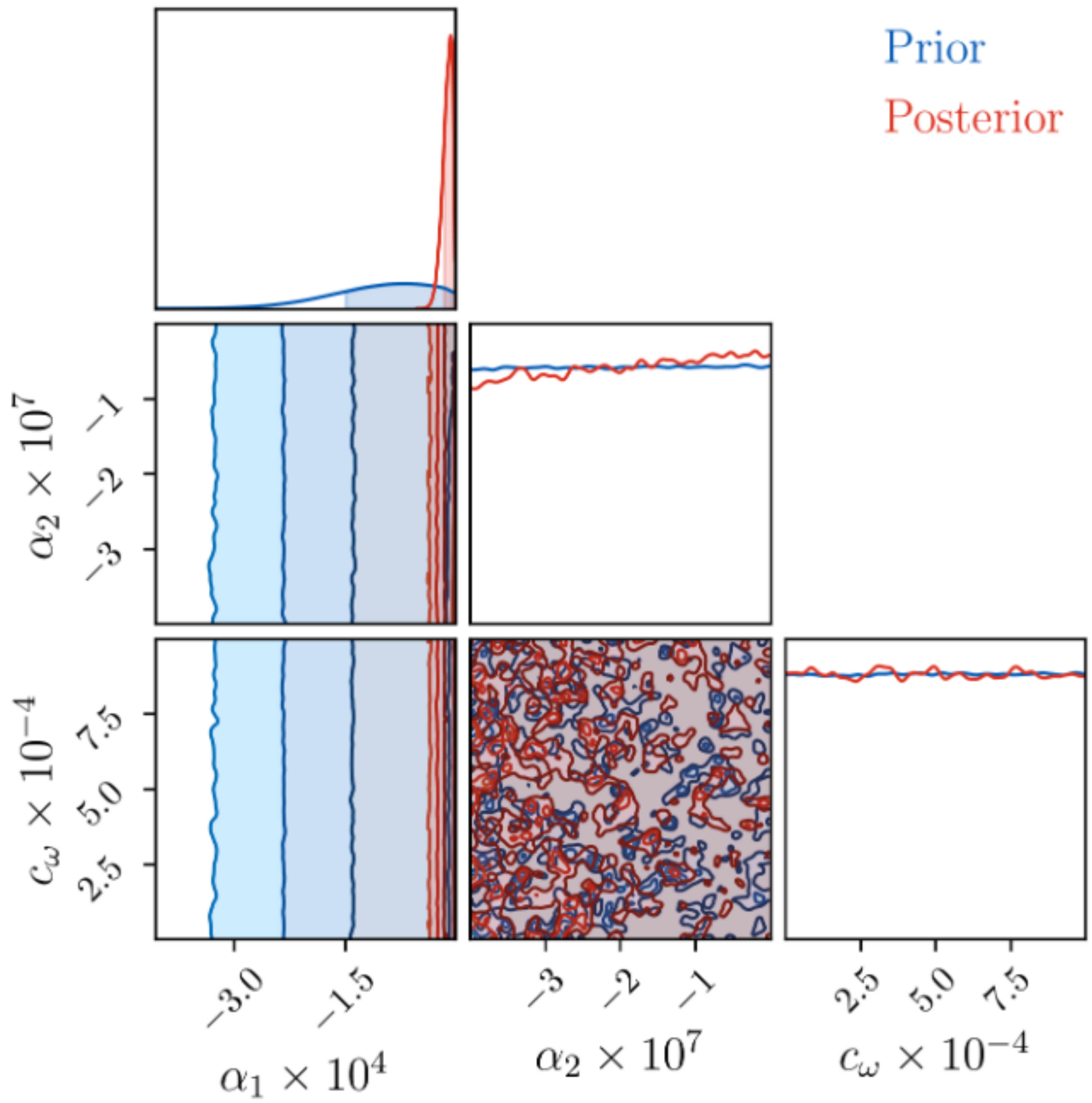
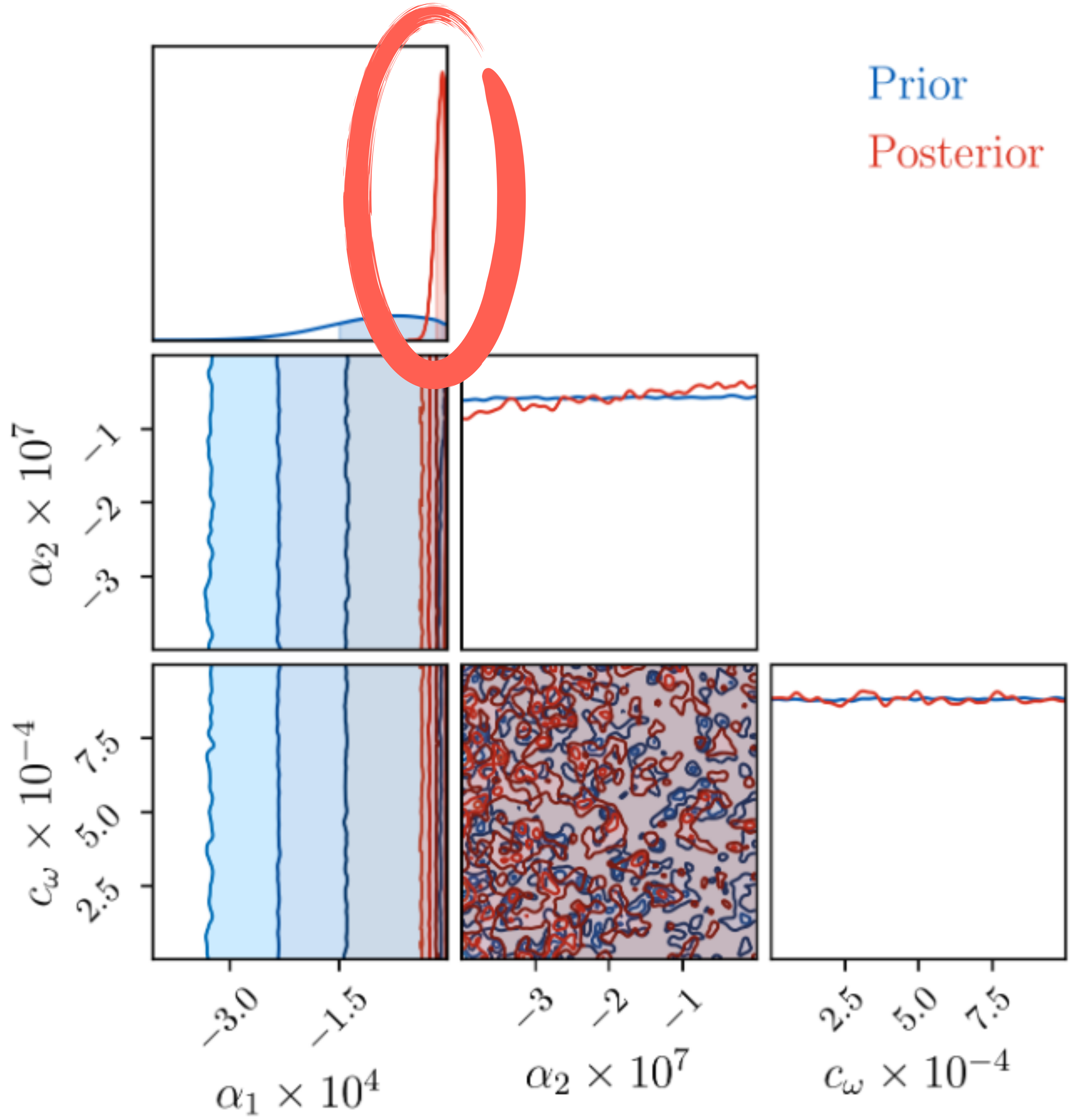


Prior
Posterior
$\alpha_2 \times 10^7$
$c_\omega \times 10^{-4}$
$\alpha_1 \times 10^4$
$\alpha_2 \times 10^7$
$c_\omega \times 10^{-4}$
−3.0
−1.5
−3
−2
−1
2.5
5.0
7.5



Prior
Posterior
$\alpha_2 \times 10^7$
−1
−2
−3
$c_\omega \times 10^{-4}$
7.5
5.0
2.5
−3.0
−1.5
$\alpha_1 \times 10^4$
−3
−2
−1
$\alpha_2 \times 10^7$
2.5
5.0
7.5
$c_\omega \times 10^{-4}$

Conclusions

- Bhs in Hořava gravity reinforce the link between horizons and thermodynamics
    - Although LV seems to dilute the concept of horizon, this is not true for this specific family of theories.
- Observations constrain the space of parameters
    - However, there is still room for non-trivial deviations from LI in the gravitational sector
    - QNMs will not distinguish between GR and HG
    - We have improved the bounds on the c_i’s an order of magnitude