From black holes to fundamental gravity and back: analogue gravity and the harmonic background paradigm

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Matt Visser's journey through space and time! 24-28 August 2026

IAA INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA

EXCELENCIA SEVERO OCHOA

All my work has been inspired in one way or another by Matt's

But more importantly …

In my view, Matt's friendship has been a gentle breeze that destiny sent my way to help me find a truly fulfilling life

Outline

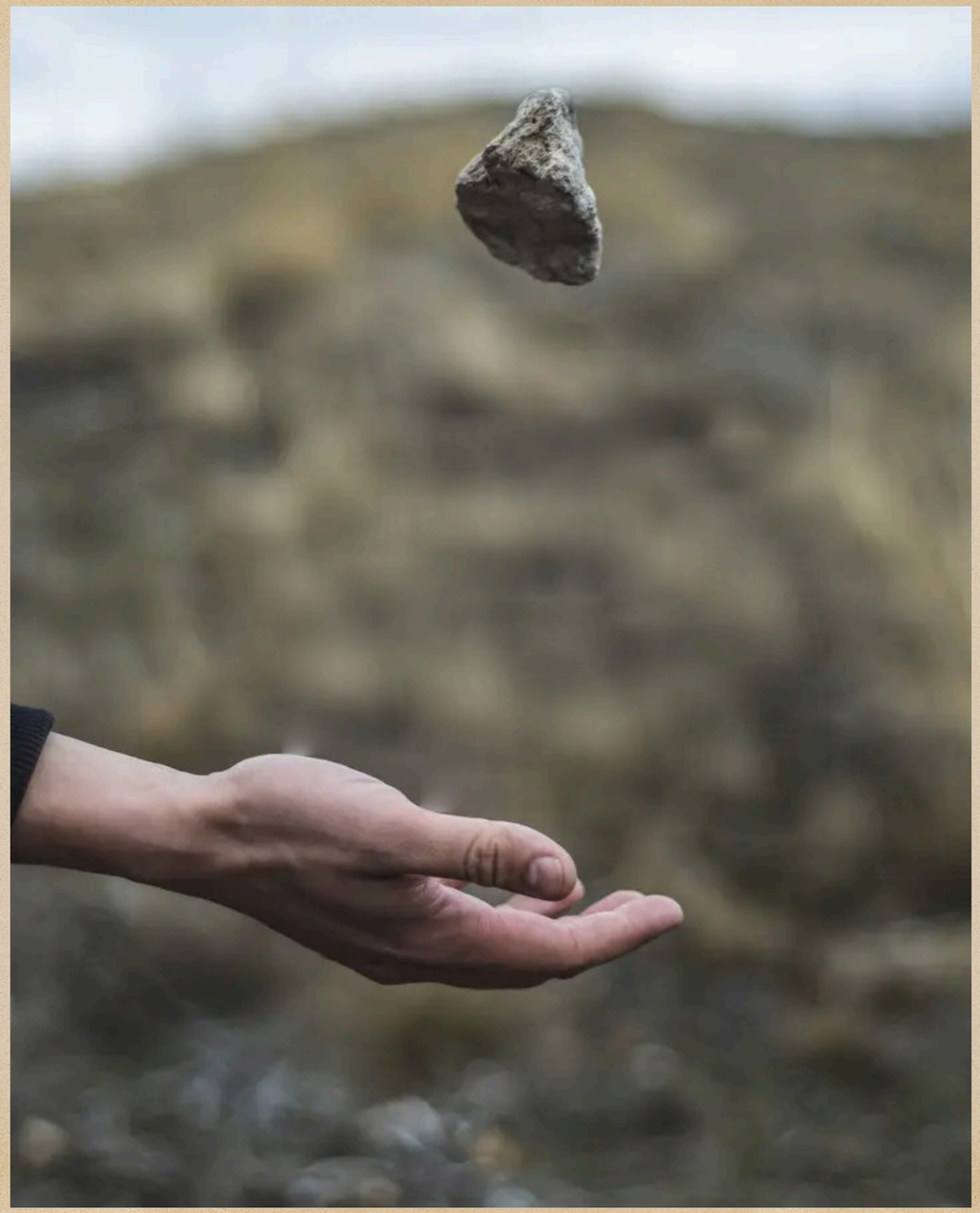
- Personal road map: from black holes to fundamentals and back; Einstein unfinished revolution.
- Analogue and Emergent gravity
- The Harmonic Background Paradigm: an alternative paradigm to describing gravitational phenomena
- A way out from black holes and their problems?

Einstein unfinished revolution

- General Relativity (GR) is fantastic in characterising gravitational effects outside large lumps of matter (by GR I mean "Einstein eqs. + energy condition")
- Inside matter, GR is just built as an effective macroscopic (mean field) theory. It is not so well tested, but there are not good reasons to expect it to be adequate to describe configurations where gravity does not play a significant role at the microscopic level
- On the other hand, we should not expect GR to be adequate to describe situations where gravity plays a role in the very microscopic interactions within the material content

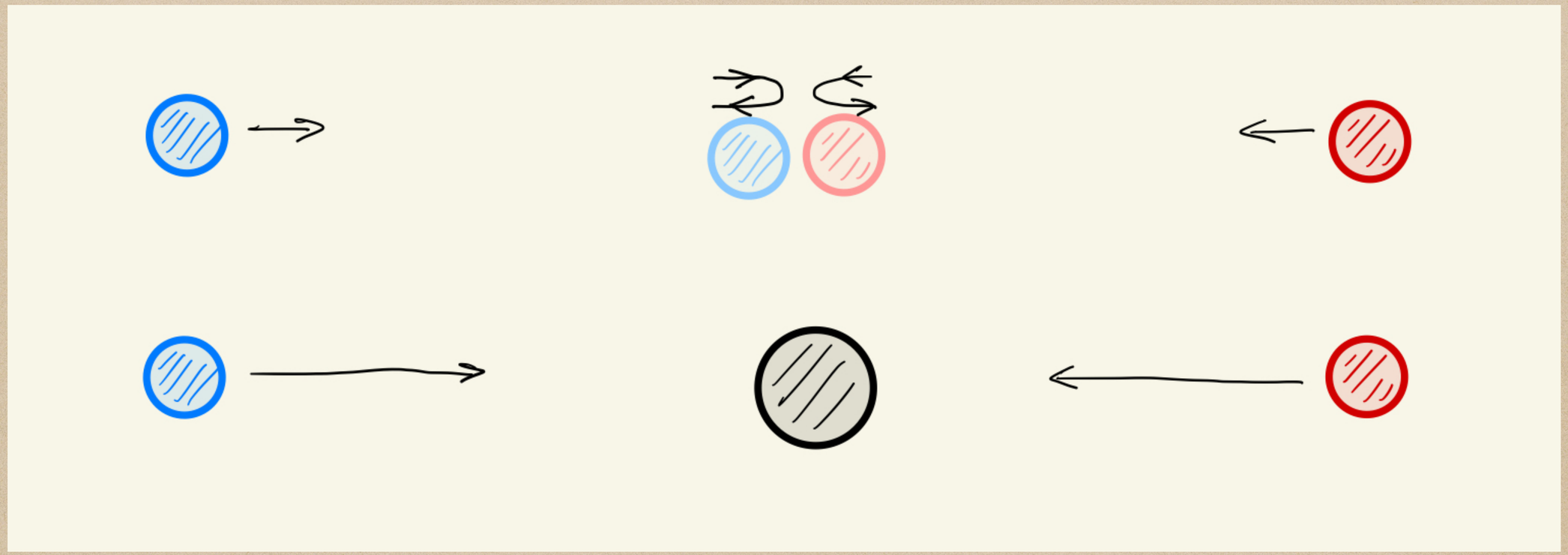
- We could maintain an effective spacetime picture, but then at Planckian matter densities it is reasonable to expect that the effective matter violates some energy conditions (Gliner 1965)
- On the other hand, in many respects standard GR can be seen as a refinement of Newton gravitational theory. As such, it should keep some of its properties (of course nobody knows which ones, for certain)
- Among the differences between Newton's and Einstein's gravity there is one that in my mind overshadows the rest: its clear breaking of the time-inversion symmetry when horizons appear (leaving aside cosmological considerations)

The most basic gravitational experience



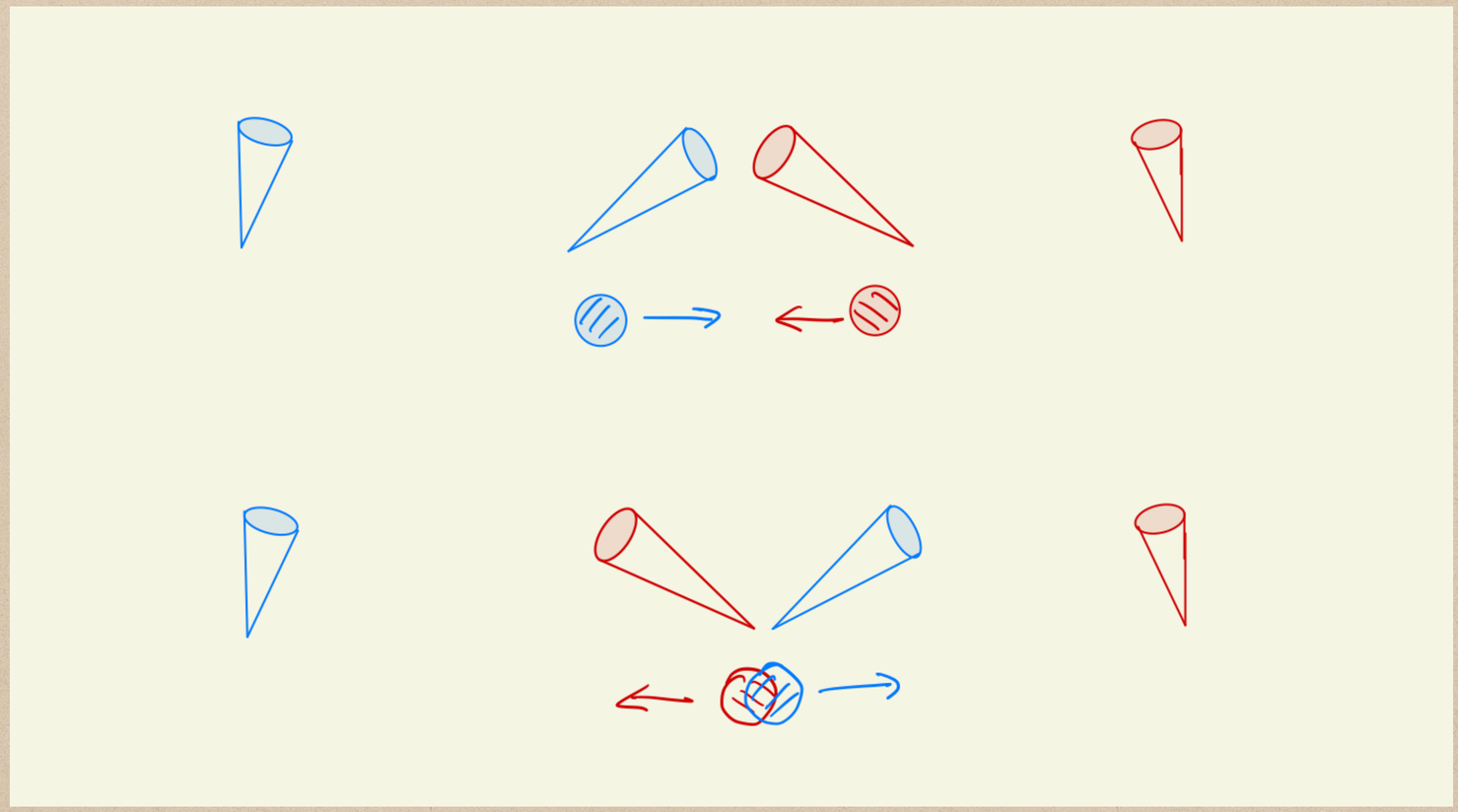
Also in GR: there is a white hole solution for any black hole solution

Head on collision and the hoop conjecture



Two-particle interaction

Locally, some "causal-cone exchange" might happen



But how does this "exchange" propagates outwards?

Three potential mechanisms of communication

- Theories with (superluminal) dispersion: Analogue and Emergent gravity
- Semiclassical gravity (i.e. effective stress-energy clouds violating energy conditions)
- Fundamental underlying causality beside the effective causality provided by the GR metric (i.e. Bi-metricity and potential gravity's switch off)

Emergent gravity from Galilean physics

- Ubiquitous emergence of relativistic systems in condensed-matter-like systems
- The problem: Einstein eqs. from condensed-matter-like systems?
- Galilean structure as the simplest fiducial space and time; an organisation tool/scaffolding
- Asses the viability of emergence of gravity from Galilean many-body quantum systems

- We have worked out completely emergence of electromagnetism and partially, Yang-Mills, and linear gravity

CB, R. Carballo-Rubio, LJ. Garay, New J.Phys. 16 (2014) 12, 123028; CB, R. Carballo-Rubio, F. Di Filippo, LJ. Garay, JHEP 1610, 084 (2016); CB, R. Carballo-Rubio, LJ. Garay, G. García-Moreno, Appl. Sciences 11 (2021) 18, 8763; CB, R. Carballo-Rubio, LJ. Garay, G. García-Moreno, Phys. Rev. D104 (2021) 2, 025017; CB, Gil Jannes, Gen. Rel. Grav. 56 (2024) 10, 116

Main ingredients:

i) Order parameters close to the vacuum (P and D condensation)

ii) Emergence of Lorentz invariance from Fermi points

Main result: Lorentz invariance can lead to the emergence of gauge symmetries

Logic:

i) Start from a theory with all the Lorentz invariant terms (not gauge invariant)

ii) Impose what appears as a natural truncation of the space of solutions

iii) Then, the truncated theory happens to be indistinguishable from a gauge theory

Harmonic Background Paradigm

It all started with the revision of a collateral debate…

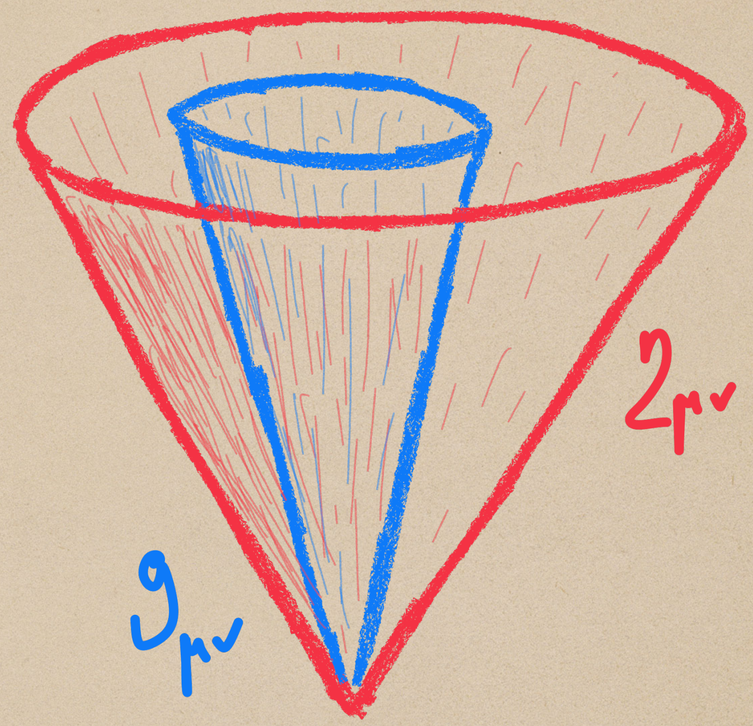
Visser-Bassett-Liberati (VBL) (Nucl. Phys. B Proc.Suppl. 88, 267, 2000)

vs Gao-Wald controversy

(Class. Quant. Grav. 17, 4999, 2000)

Can gravity be described as a theory of deformed causality with

$[g] \leq [\eta]$?



- VBL answer YES, under some conditions:

1. Weak gravity $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
2. Harmonic condition $\partial_\mu(h^{\mu\nu} - \frac{1}{2}\eta^{\mu\nu}h) = 0$
3. Absence of free incoming waves

$$\Box h_{\mu\nu} = -16\pi \bar{T}_{\mu\nu} \qquad \bar{T}_{\mu\nu} = T_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} T$$

$$h_{\mu\nu}(\mathbf{x}, t) = h_{\mu\nu}^{\text{in-phys}} + h_{\mu\nu}^{\text{in-gauge}} + 16\pi \int d^3y \frac{\bar{T}_{\mu\nu}(\mathbf{y}, \bar{t})}{|\mathbf{x} - \mathbf{y}|} \qquad \bar{t} = t - |\mathbf{x} - \mathbf{y}|$$

$l^\mu l^\nu h_{\mu\nu} \geq 0$ If $l^\mu l^\nu T_{\mu\nu} \geq 0$ Background Null Energy Condition

l^μ Null with respect the flat metric

- Gao-Wald reply that cone hierarchy is highly gauge dependent and so of no physical significance
- Starting from one $h_{\mu\nu}$ one can generate $\bar{h}_{\mu\nu} = h_{\mu\nu} + 2\nabla_{(\mu}\xi_{\nu)}$ which among other things can open up the causal cones
- They are absolutely correct on this. However, the VBL result can also be correct and physically relevant if interpreted in a different paradigm.

Gravitational paradigms

- GR is typically discussed within the Geometrical paradigm or within the Field-theoretical paradigm.
- Since Rosen works in the 40's it is known that gravity can alternatively be seen as a gauge theory of a tensorial object $h_{\mu\nu}$ over a flat background
- This paradigm is not as different from the geometric paradigm as one might think

Harmonic background paradigm

- We propose a third paradigm (to linear level):

1. There is a genuine flat background spacetime $\eta_{\mu\nu}$
2. Gravity is a unique restricted tensorial quantity $h_{\mu\nu}$:

$$\nabla_\mu(h^{\mu\nu} - \frac{1}{2}\eta^{\mu\nu}h) = 0,$$

3. There is not incoming waves of any sort at infinity
4. There exists a cone hierarchy $[g] \leq [\eta]$

- The restrictions on $h_{\mu\nu}$ are equivalent to select a unique flat background geometry
- We are not considering these restrictions as a gauge fixing, but as proper physical restrictions on what represents actually the gravitational field
- Our idea has strong resonances with Fock's harmonic coordinate system (The theory of space, time and gravitation 1959)

- In our proposal everything is covariant, meaning that one can use whatever system of coordinates one likes to describes the physics
- What we are eliminating is the identification of the group of coordinate changes with a dynamical gauge group. This is possible once assumed the existence of a fundamental causality besides the effective one

Why gravity is attractive in weak gravity situations?

- One can invert the logical direction of the VBL result
- Within the Harmonic background paradigm gravity can only act producing effective causal cones inside the Minkowski ones
- Then, for consistency this implies that $T_{\mu\nu}l^{\mu}l^{\nu} \geq 0$ (Background null energy condition)
- The obstruction to exit the fundamental causality makes matter to have a positive energy content when no strong gravity is present

Some additional observations

- Once the effective cones are well inside the Minkowskian there is not reason why effective matter should be only attractive
- The relation Energy condition /causality is stablished only at the linear level, precisely where the proofs are rigorous
- The construction is compatible with the emission of GW: they are generated by sources inside spacetime

Some conceptual advantages:

- One to one identification between background and effective spacetimes: e.g. a geodesic of g corresponds to a single curve in η
- There exists a proper stress-energy tensor for the gravitational energy (there is not gauge invariance problem)
- The GR behaviour is less isolated in theory space (e.g. Massive gravities, Rosen gravity, …)
- One can frame interesting novel extensions to the GR behaviour

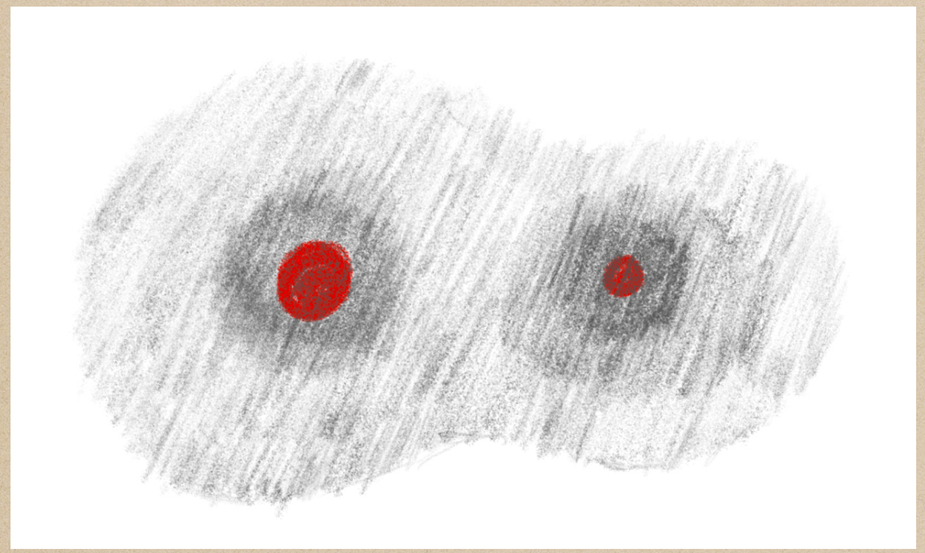
Extension to the full non-linear regime?

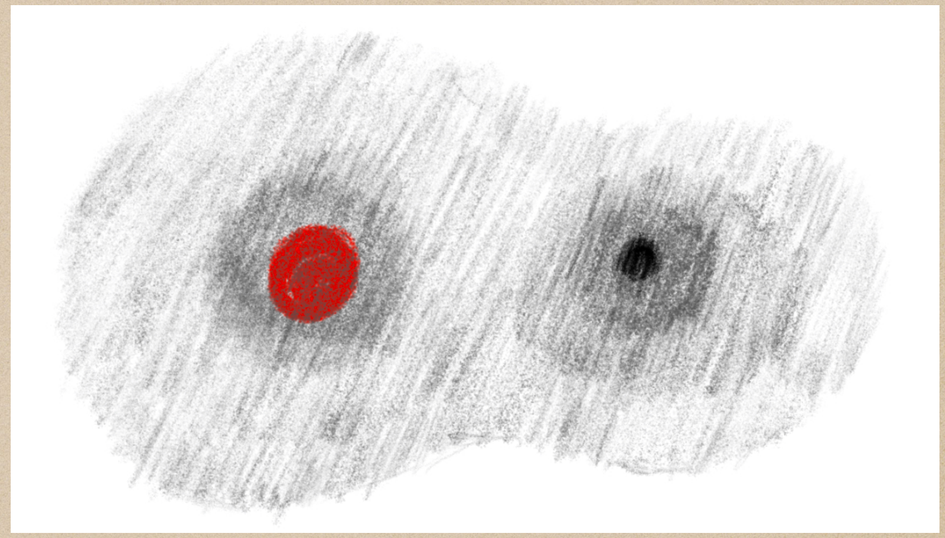
$$h_{\mu\nu}(\mathbf{x},t) = 16\pi \int d^3y \frac{\bar{T}^{\mathrm{T}}_{\mu\nu}(\mathbf{y},\bar{t})}{|\mathbf{x}-\mathbf{y}|}$$

$$T^{\mathrm{T}}_{\mu\nu} = T^{\mathrm{G}}_{\mu\nu} + T^{\mathrm{I}}_{\mu\nu} + T^{\mathrm{M}}_{\mu\nu}$$

- We need that the total SET integrated in the past light cone of the flat metric is always positive (a semi-average background null energy condition)

Positive energy theorem …





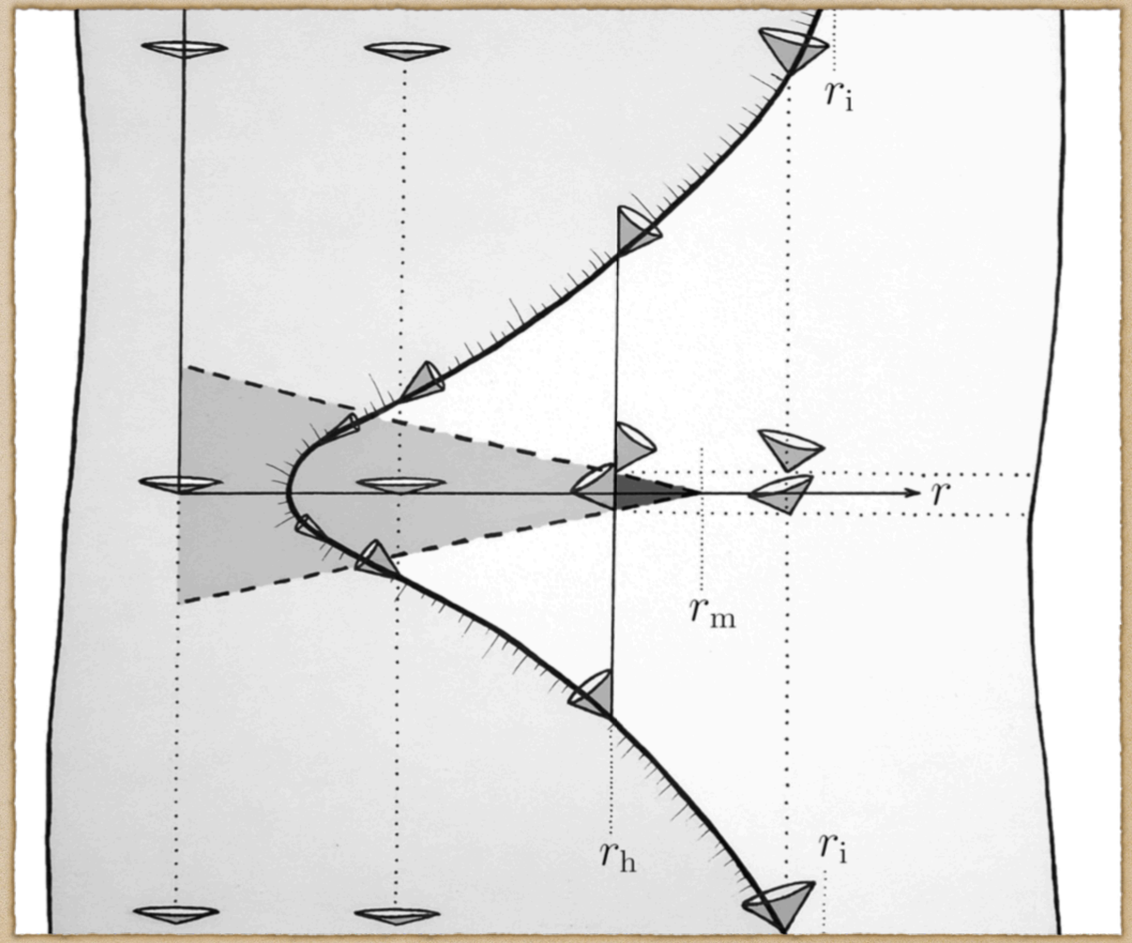
… but in a local version

A way-out of Black holes and their problems

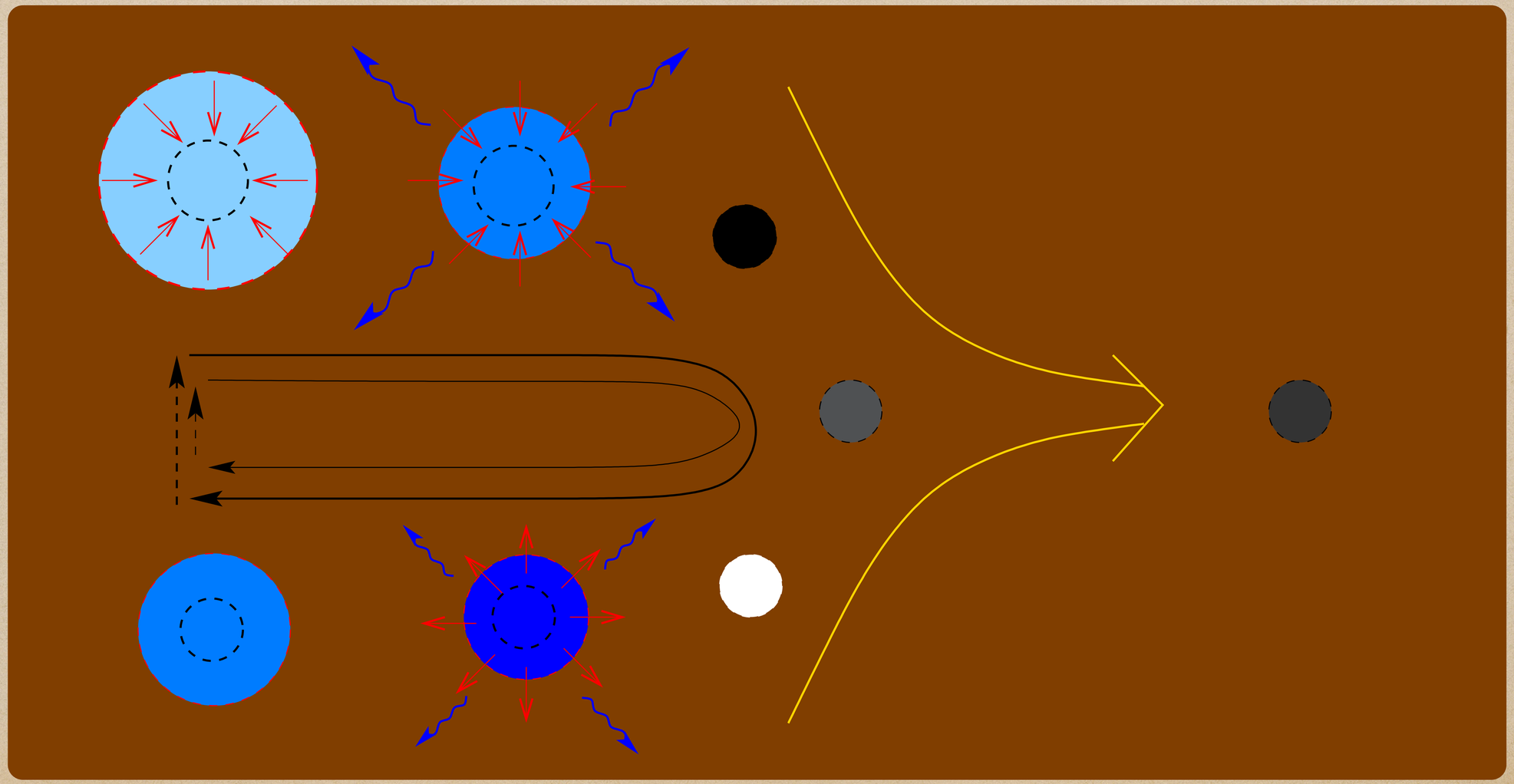
Within the HBP it is not difficult to consider a way-out to the problems associated with gravitational collapse

Switch-off of gravity in gravitational collapse

- Collapse could proceed with a transient black hole to white hole transition
- At some energy scale the order parameter representing gravity might dissolve leaving the η causality
- After some bounces the geometry should settle into an ultracompact object



Black-hole white-hole oscillations

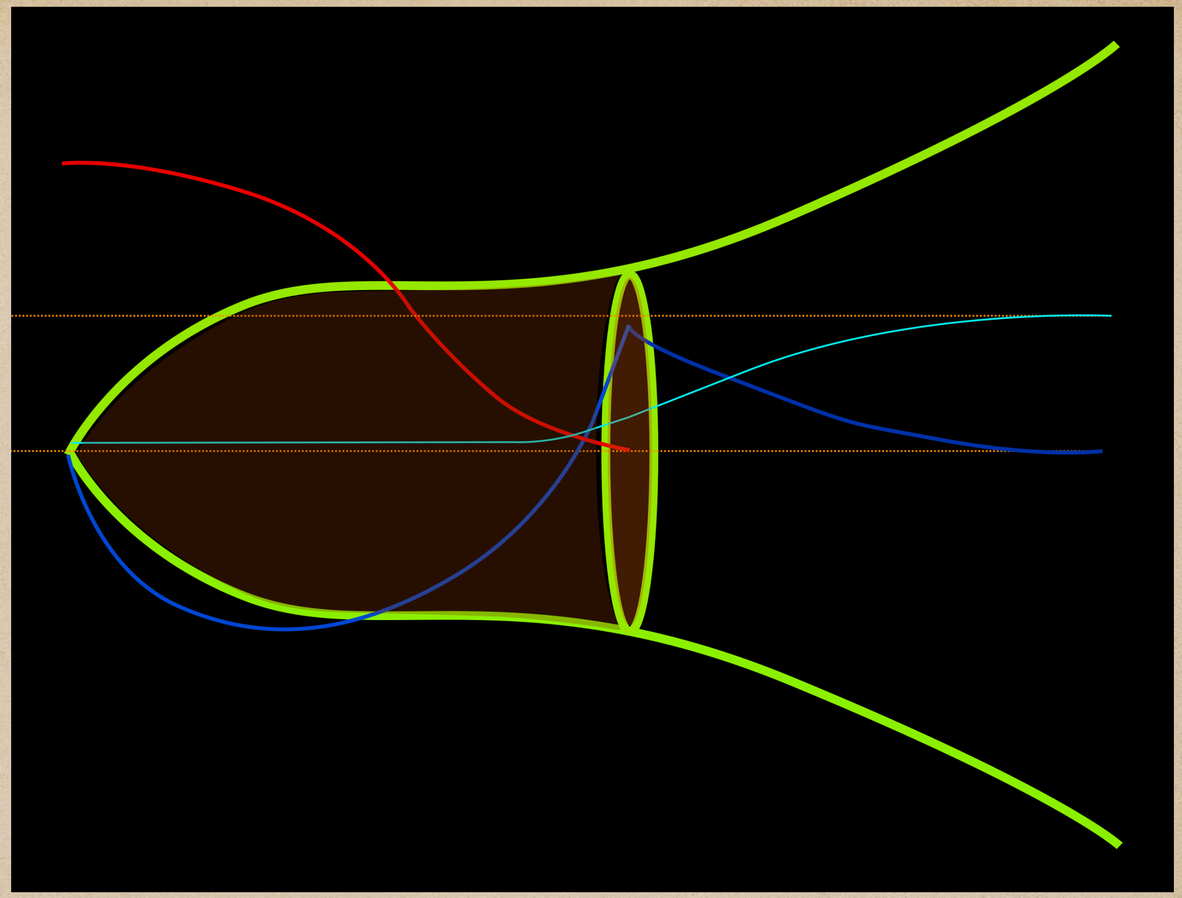


Semiclassical approach

- The previous ideas do also have strong resonances with semiclassical gravity analyses
- On the one hand, semiclassical gravity appears to support ultracompact stellar configurations
- On the other hand, it appears to favor black-hole oscillations

Semiclassical stars

- Semiclassical gravity allows for static stellar configurations arbitrarily surpassing the Buchdahl compactness limit



Arrechea et al Scien. Reports; PRD

Trapped regions

and

anti-trapped regions

Boyanov's PhD +

Class.Quant.Grav. 43 (2026) 2, 025007

Barenboim et al, Phys.Rev.Res. 6 (2024) 3, L032055

Conclusions and final remarks

- The viability of a emergent gravity theory is not rule out, quite the opposite (work in progress)
- A crucial ingredient is the emergent nature of diffeomorphisms (this appears to bypass Weinberg-Wittem theorem and other obstacles)
- Physics strongly linked to (global) Lorentz invariance

- We have cleared up the VBL / GaoWald controversy: both are correct but starting from different paradigms for gravitational phenomena
- The standard field theoretic paradigm does not give actual prominence to the background metric
- Instead, we propose what we call the Harmonic background paradigm
- A consequence of assuming this paradigm is that matter has to be attractive in standard weak-field situations

- The Harmonic Background Paradigm is well suited to model process such as a gravity switch-off at high matter densities.
- The existence of a more fundamental causality could avoid what in my view is the main problem of GR
- It can help making GR closer to Newtonian gravity than it is typically assumed

Happy 70s Matt!!