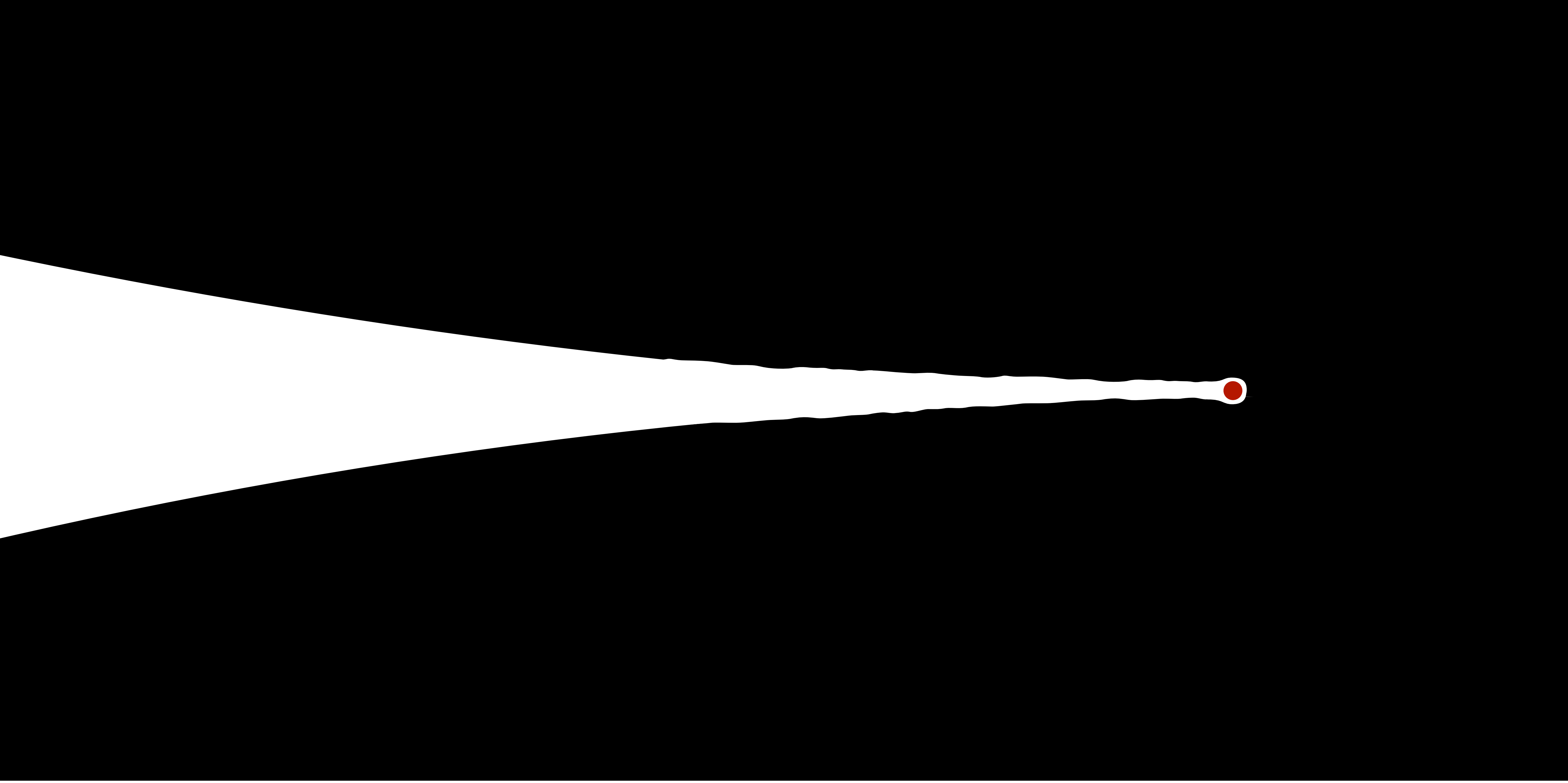


Black holes in regular gravitational theories

From Black Holes to the Cosmos: Matt Visser's journey through space and time

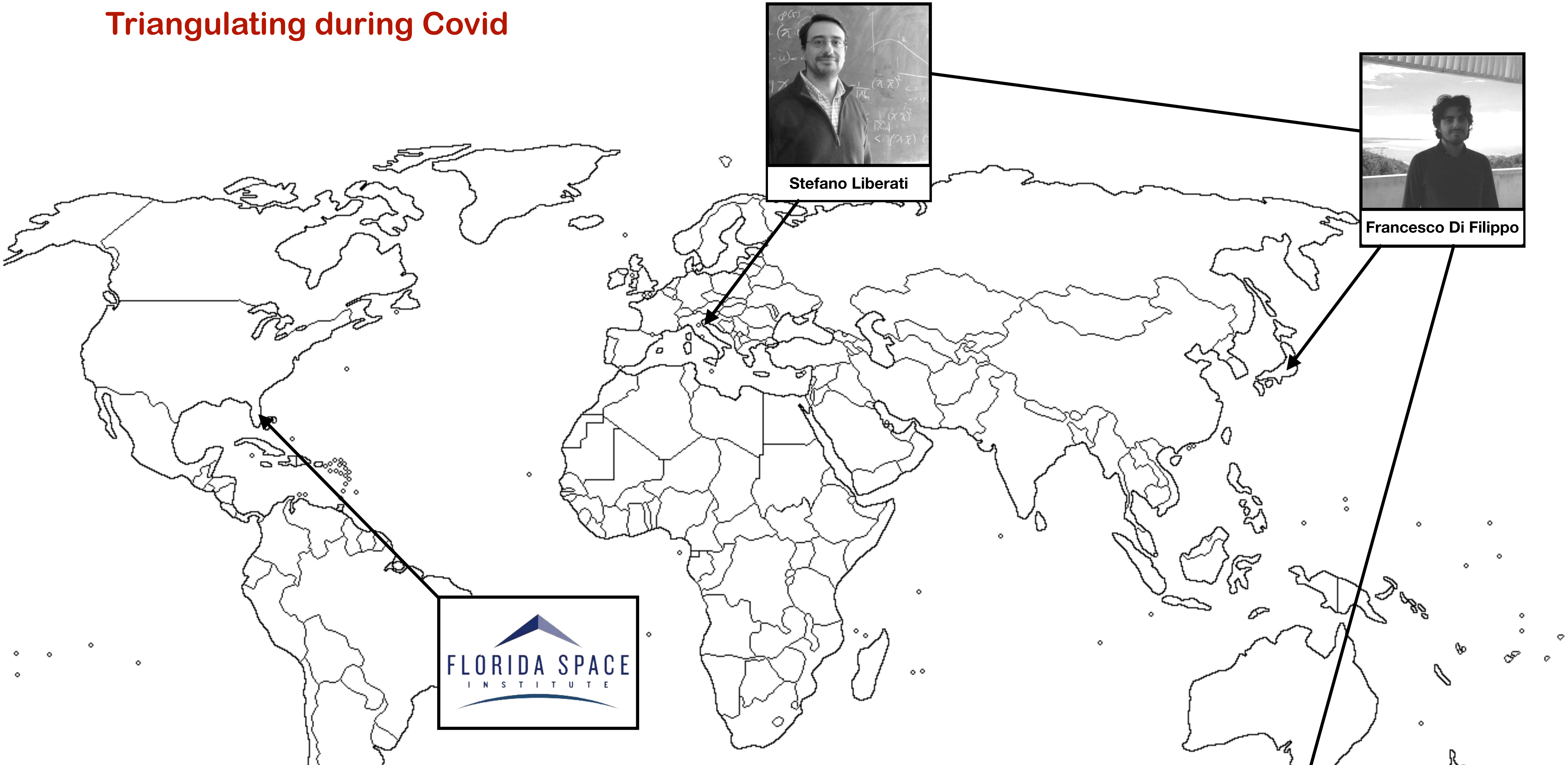
24-28 August 2026, SISSA (Trieste)

INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA

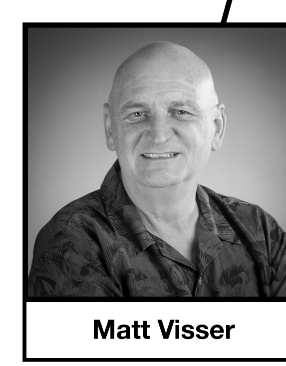
Raúl Carballo-Rubio

Instituto de Astrofísica de Andalucía (IAA-CSIC), Spain

Triangulating during Covid



Orlando, FL, USA *	EDT (UTC -4)	Mon, 24 Aug 2026	21:00	😐
Trieste, Italy *	CEST (UTC +2) 6 hour(s) ahead	Tue, 25 Aug 2026	03:00	☹
Kyoto, Japan	JST (UTC +9) 13 hour(s) ahead	Tue, 25 Aug 2026	10:00	🙂
Wellington, New Zealand	NZST (UTC +12) 16 hour(s) ahead	Tue, 25 Aug 2026	13:00	🙂



Outline

Motivation

An agnostic (effective) approach to the dynamics of regular black holes

Applications

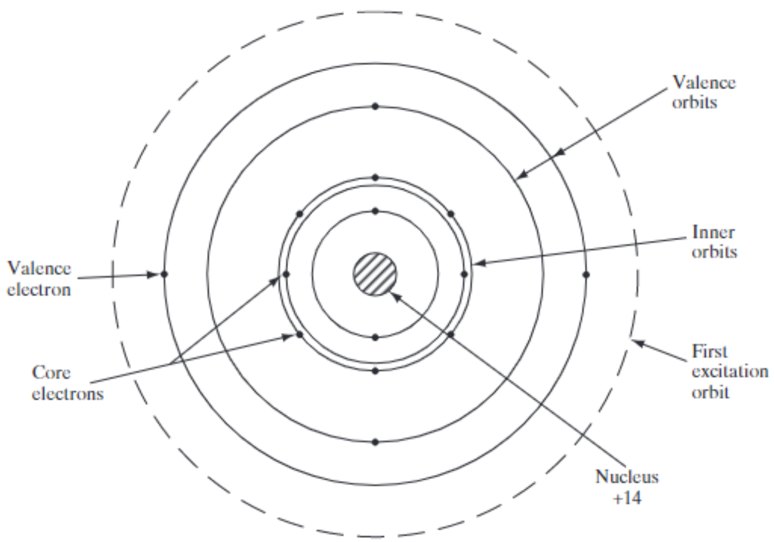
Conclusions

Motivation
Regular black holes

Regular black holes are the best-motivated alternative to classical black holes.

[RCR, F. Di Filippo, S. Liberati, M. Visser *et al.*, JCAP 05 (2025) 003]

Can be understood as semiclassical models (in analogy with the Bohr model of the hydrogen atom).



Substantial challenge: lack of dynamical solutions.

All classical works on the subject based on kinematics: assume either static spacetimes or spacetimes with prescribed time evolution.

[J. Bardeen (1968), S. A. Hayward, Phys. Rev. Lett. 96 (2006) 031103, +++]

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An agnostic (effective) approach to the dynamics of regular black holes

Three steps

Step 1: stay humble (spherical symmetry).

Step 2: use as minimal input as possible (symmetries + locally Cartesian centre).

Step 3: calculate!

An agnostic (effective) approach to the dynamics of regular black holes

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Step 1: stay humble (spherical symmetry).

→ **metric:** $g_{\mu\nu}(y)\mathrm{d}y^{\mu}\mathrm{d}y^{\nu} = q_{ab}(x)\mathrm{d}x^{a}\mathrm{d}x^{b} + r^{2}(x)\gamma_{ij}\mathrm{d}\theta^{i}\mathrm{d}\theta^{j}$

→ **coordinates:** $\{y^0, y^1, y^2, y^3\} = \{x^0, x^1, \theta^2, \theta^3\}$

(arbitrary dimensions straightforward to implement)

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→ **2D Horndeski:** exploit "duality" to describe second-order dynamics

[RCR, Nature Commun. 17 (2026) 1]

$$\mathscr{G}^{(\boldsymbol{\alpha},\boldsymbol{\beta})}_{\mu\nu}(q, r) = 8\pi T_{\mu\nu}$$

An agnostic (effective) approach to the dynamics of regular black holes

2D Horndeski recap

Lagrangian:

→ **starting expression (4D → 2D):**

$$\mathcal{L} = H_2(r,\chi) - H_3(r,\chi)\Box r + H_4(r,\chi)\mathcal{R} - 2\partial_\chi H_4(r,\chi)\left[(\Box r)^2 - \nabla^a\nabla^b r\nabla_a\nabla_b r\right]$$

→ **definition:** $\chi = \nabla_a r \nabla^a r$

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$$\mathscr{E}_{ab}(q,r) = \frac{1}{\sqrt{-q}}\frac{\delta\mathcal{L}}{\delta q^{ab}} = \boldsymbol{\beta}\nabla_a\nabla_b r - q_{ab}\left(\frac{1}{2}\boldsymbol{\alpha} + \boldsymbol{\beta}\Box r\right) + \left(\partial_\chi\boldsymbol{\alpha} - \partial_r\boldsymbol{\beta}\right)\nabla_a r \nabla_b r$$

$$\mathscr{F}(q,r) = \frac{1}{\sqrt{-q}}\frac{\delta\mathcal{L}}{\delta r} = -\boldsymbol{\beta}\mathcal{R} + 2\partial_r\boldsymbol{\beta}\Box r + \partial_r\boldsymbol{\alpha} + 2\partial_\chi\boldsymbol{\beta}\left[(\Box r)^2 - \nabla_a\nabla_b r \nabla^a\nabla^b r\right]$$

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"Free" functions:

→ **two functions:** $\boldsymbol{\alpha}(r,\chi)$ **and** $\boldsymbol{\beta}(r,\chi)$

→ **general relativity:** $\boldsymbol{\alpha}_{\mathrm{GR}} = 2(1-\chi)$ **and** $\boldsymbol{\beta}_{\mathrm{GR}} = -2r$

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$$\mathscr{G}^{(\boldsymbol{\alpha},\boldsymbol{\beta})}_{\mu\nu} = \frac{1}{r^2}\mathscr{E}_{ab}\delta^a_\mu\delta^b_\nu - \frac{1}{4}r\mathscr{F}\gamma_{ij}\delta^i_\mu\delta^j_\nu$$

An agnostic (effective) approach to the dynamics of regular black holes

Definition of the generalized Einstein tensor

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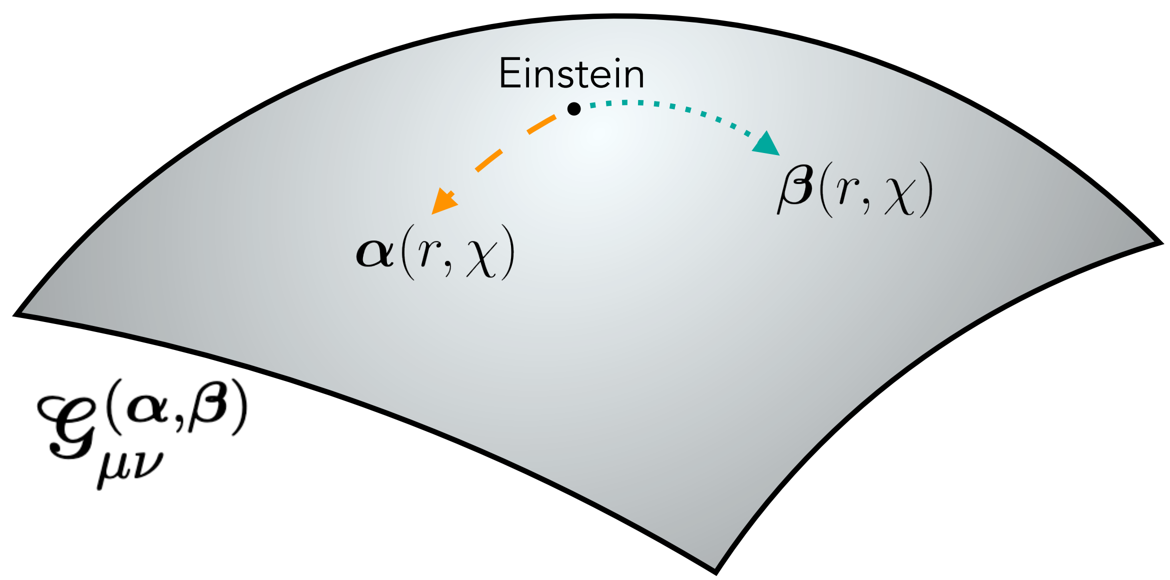
Properties:

→ relative factor: conservation

→ overall factor: general relativity: $\boldsymbol{\alpha}_{\rm GR} = 2(1-\chi)$ and $\boldsymbol{\beta}_{\rm GR} = -2r$

→ space of tensors depending on two functions: $\boldsymbol{\alpha}(r,\chi)$ and $\boldsymbol{\beta}(r,\chi)$



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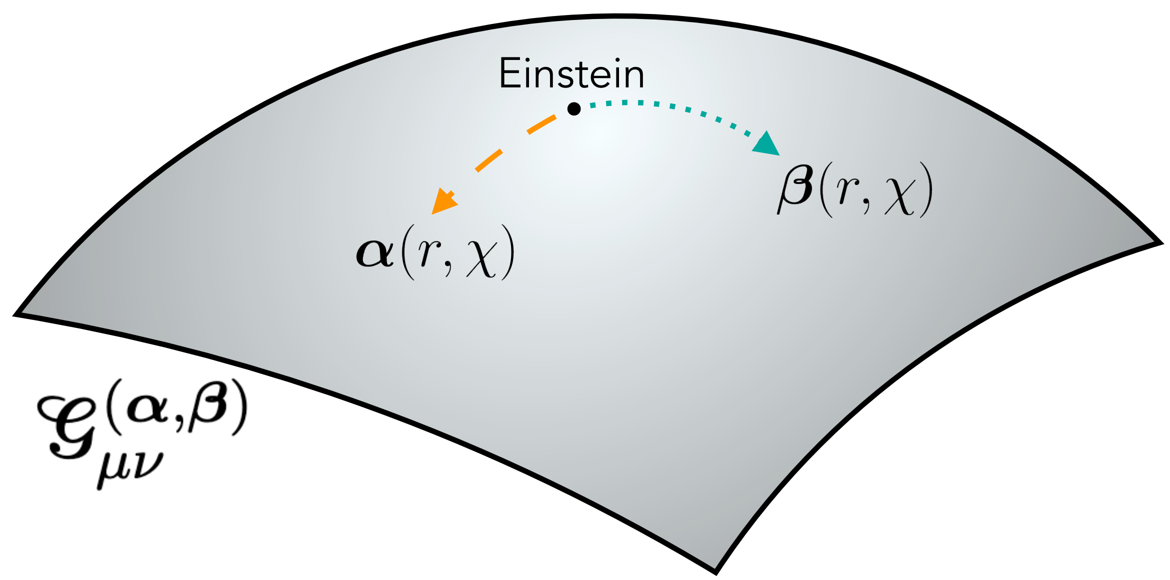

- **locally Cartesian centre: same behavior in the centre as general relativity**

[F. Thaalba, J. Arrechea and S. Liberati, 2608.02481]

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Applications

List of growing literature

Regular Vaidya solutions.
[V. Boyanov and RCR, Phys. Rev. Lett. 136 (2026) 17, 171403]

Describing renormalization-group improvement.
[J. Borissova and RCR, JCAP 05 (2026) 023]

Constructing four-dimensional covariant actions.
[J. Borissova and RCR, Phys. Rev. D 113 (2026) 12, 124004; J. Borissova, Phys. Rev. D 113 (2026) 12, 124088]

Regularity and geodesic completeness in the presence of charge and matter fields.
[J. Arrechea, RCR and M. Visser, Phys.Rev.D 114 (2026) 2, 024081; RCR, C. Coviello and V. Vellucci, 2607.07831; F. Thaalba, J. Arrechea and S. Liberati, 2608.02481]

Thermodynamics of regular black holes.
[J. Borissova, 2604.24101]

Regularity in cosmological settings.
[J. Borissova and J. Magueijo, JCAP 07 (2026) 045]

Static bounces and wormholes.
[J. Mazza, 2608.02771]

Formation of inner-extremal regular black holes.
[J. Borissova, 2608.02908]

Bonus: unified description of previous independent results.
[J. Ziprick and G. Kunstatter, Phys. Rev. D 82 (2010) 044031; J. Barenboim, A. V. Frolov and G. Kunstatter, Phys. Rev. Res. 6 (2024) 3, L032055 & Phys. Rev. D 111 (2025) 10, 104068; P. Bueno, P. A. Cano, R. A. Hennigar and Á. J. Murcia, Phys. Rev. Lett. 134 (2025) 18, 181401 & Phys. Rev. D 112 (2025) 6, 064039]

Applications

Birkhoff's theorem

For generic α and β, vacuum solutions are static and depend on a single continuous integration constant (the mass). Violations require either additional degrees of freedom, higher derivatives, or non-localities that survive in spherical symmetry.

[RCR, Nature Commun. 17 (2026) 1; G. Kunstatter, H. Maeda and T. Taves, Class. Quant. Grav. 33, 105005 (2016)]

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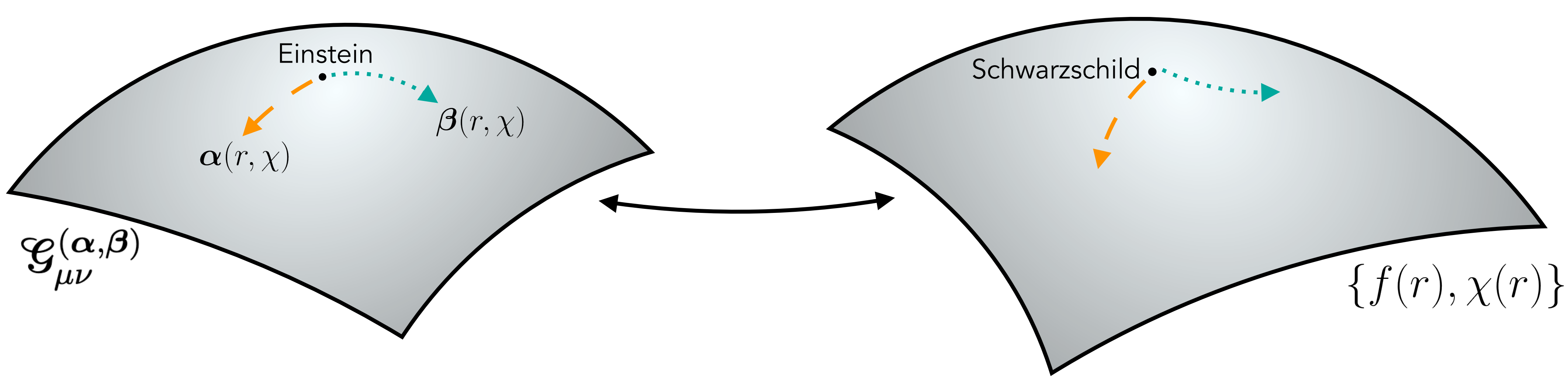
Sketch of the proof:

→ **choose coordinates** $\{x^0, x^1\} = \{t, r\}$

→ $g_{\mu\nu}(y)\mathrm{d}y^\mu \mathrm{d}y^\nu = -f(t,r)\mathrm{d}t^2 + \chi^{-1}(t,r)\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2$

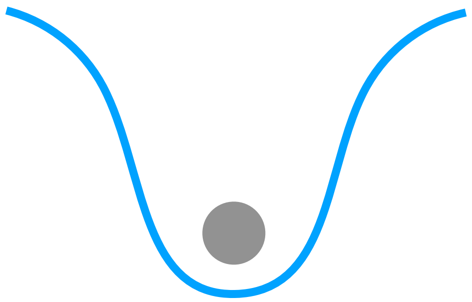
→ **vacuum solutions of** $\mathscr{G}^{(\boldsymbol{\alpha},\boldsymbol{\beta})}_{\mu\nu} = 0$ **must be static and given by:**

$$\frac{\mathrm{d}\chi}{\mathrm{d}r} = -\frac{\boldsymbol{\alpha}(r,\chi)}{\boldsymbol{\beta}(r,\chi)} \qquad f(r) = \chi(r)\exp\left[2\int \mathrm{d}r \frac{(\partial_\chi \boldsymbol{\alpha} - \partial_r \boldsymbol{\beta})}{\boldsymbol{\beta}}\right]$$



Applications

Regularizing vacuum solutions



Conditions for bounded curvature:

[RCR, F. Di Filippo, S. Liberati and M. Visser, Phys.Rev.D 101 (2020) 084047]

$$f\big|_{r=0} = 1\,, \qquad \partial_r f\big|_{r=0} = 0$$

Equivalently, from Birkhoff's theorem:

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$$\boldsymbol{\alpha}(r,\chi) \sim \frac{1}{r^p}\,, \qquad \boldsymbol{\beta}(r,\chi) \sim \frac{1}{r^{p+1}}\,, \qquad p \geq 1$$

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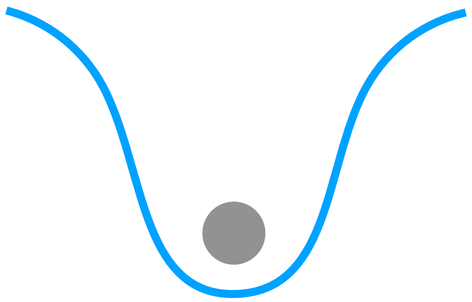

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Not satisfied by general relativity:

$$\boldsymbol{\alpha}_{\rm GR}(r,\chi_{\rm Sch}) = 2(1-\chi_{\rm Sch}) = \frac{4M}{r}\,, \qquad \boldsymbol{\beta}_{\rm GR}(r,\chi_{\rm Sch}) = -2r$$

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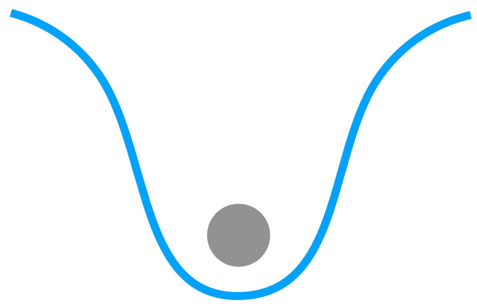

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Satisfied by Bardeen and Hayward, interpreted as vacuum solutions:

$$\boldsymbol{\alpha}_{\mathrm{B}}(r,\chi) = 2\,(1-\chi)\,\frac{\sqrt{r^2+\ell^2}\,(r^2-2\ell^2)}{r^3}\,, \quad \boldsymbol{\beta}_{\mathrm{B}}(r,\chi) = -\frac{2\,(r^2+\ell^2)^{3/2}}{r^2}$$

$$\boldsymbol{\alpha}_{\mathrm{H}}(r,\chi) = \frac{2\left[r^4 - 3\ell^2 r^2\,(1-\chi)\right](1-\chi)}{\left[r^2-\ell^2\,(1-\chi)\right]^2}\,, \quad \boldsymbol{\beta}_{\mathrm{H}}(r,\chi) = -\frac{2r^5}{\left[r^2-\ell^2\,(1-\chi)\right]^2}$$

Applications

New constraints: charged and dynamical solutions

Bardeen does not satisfy conditions for locally Cartesian centre, leading to pathologies (e.g. singular diluted stars or ill-defined dynamical evolutions).

[J. Arrechea, RCR and M. Visser, Phys.Rev.D 114 (2026) 2, 024081; F. Thaalba, J. Arrechea and S. Liberati, 2608.02481]

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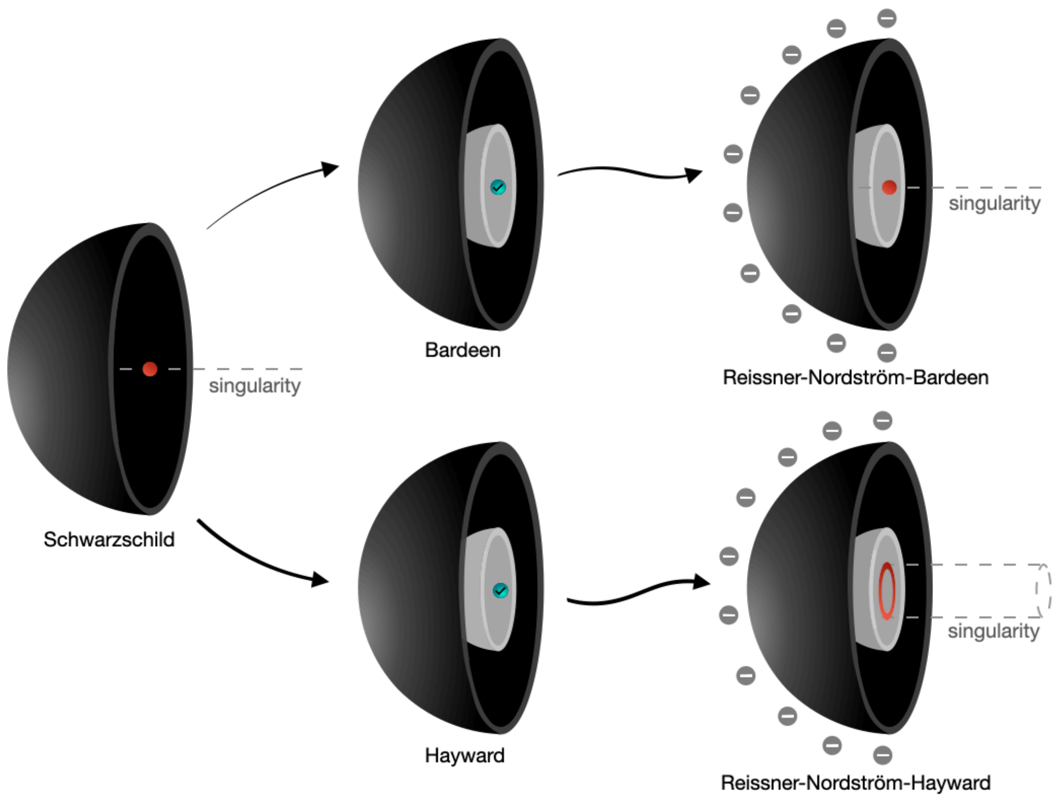

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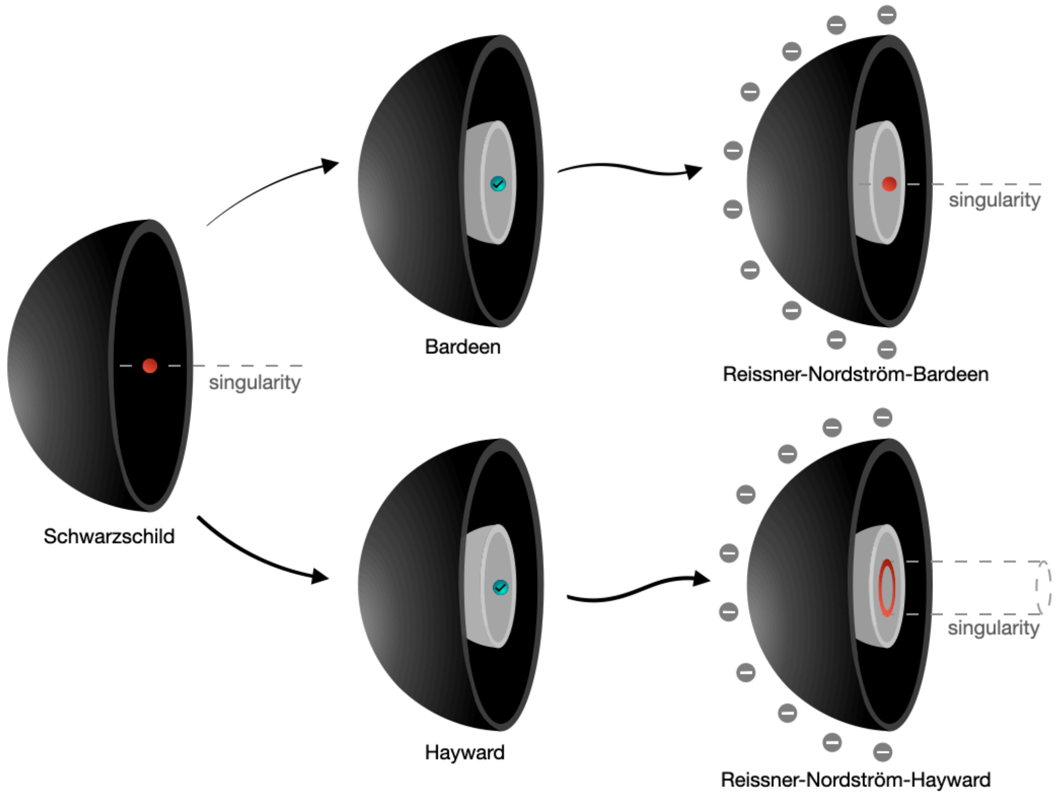

Coupling to time-dependent matter induces additional centre conditions.

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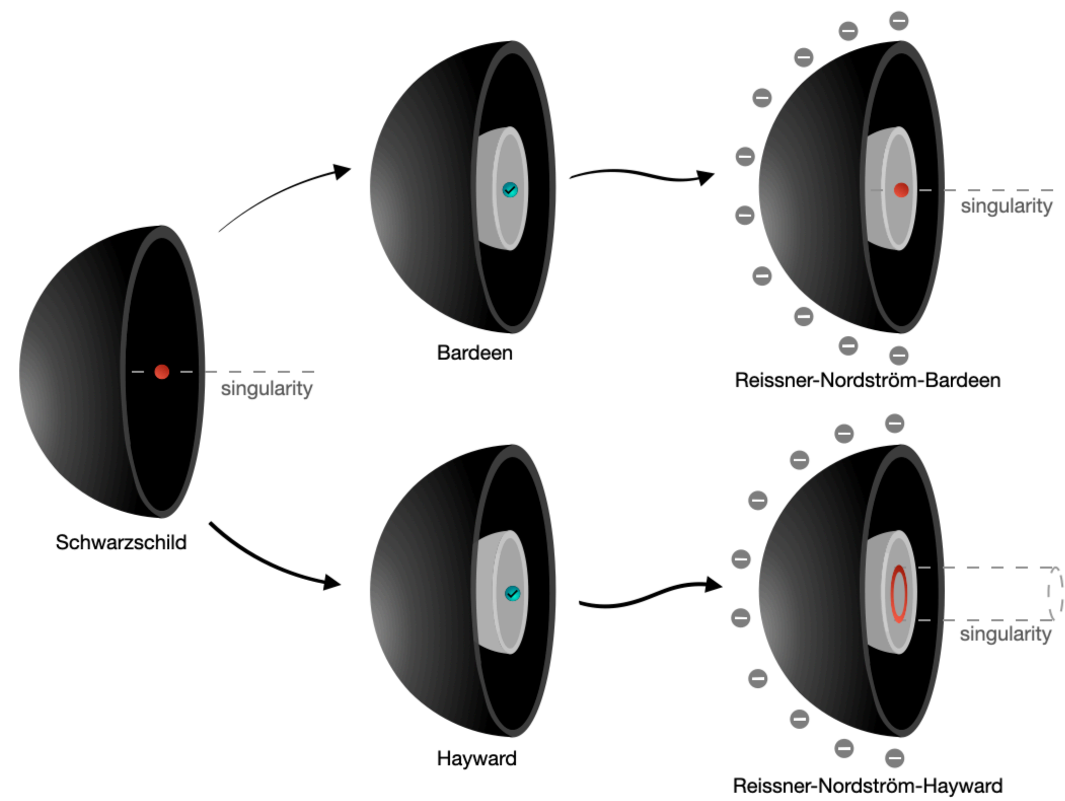

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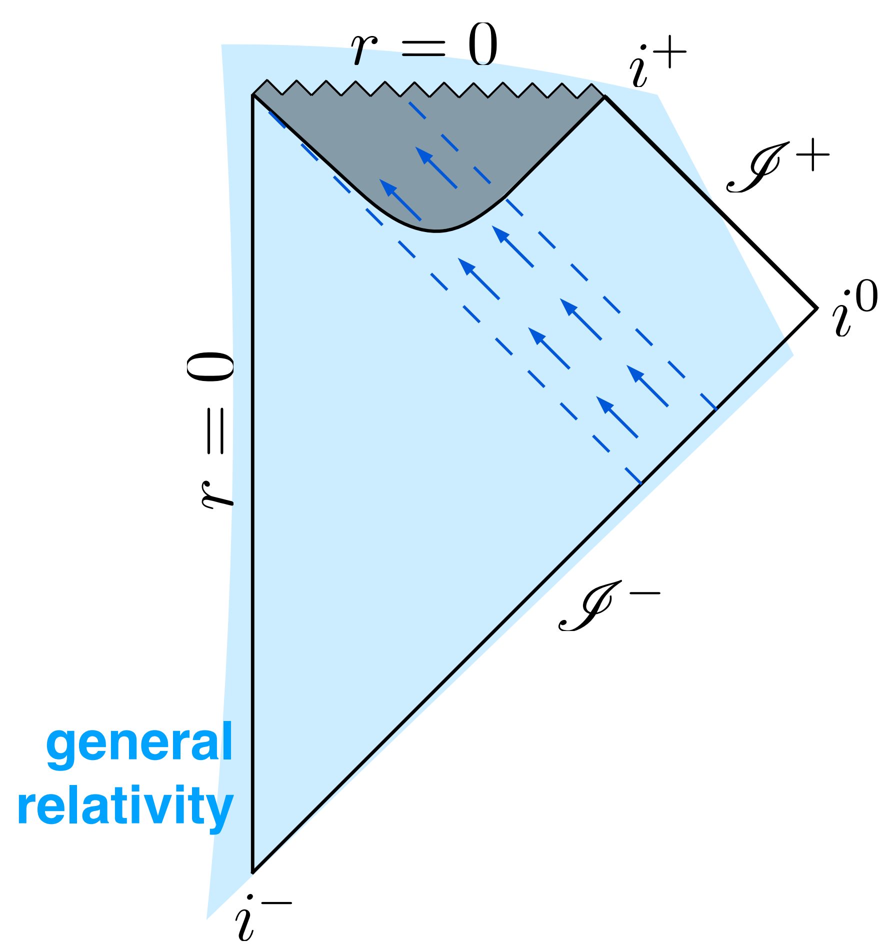
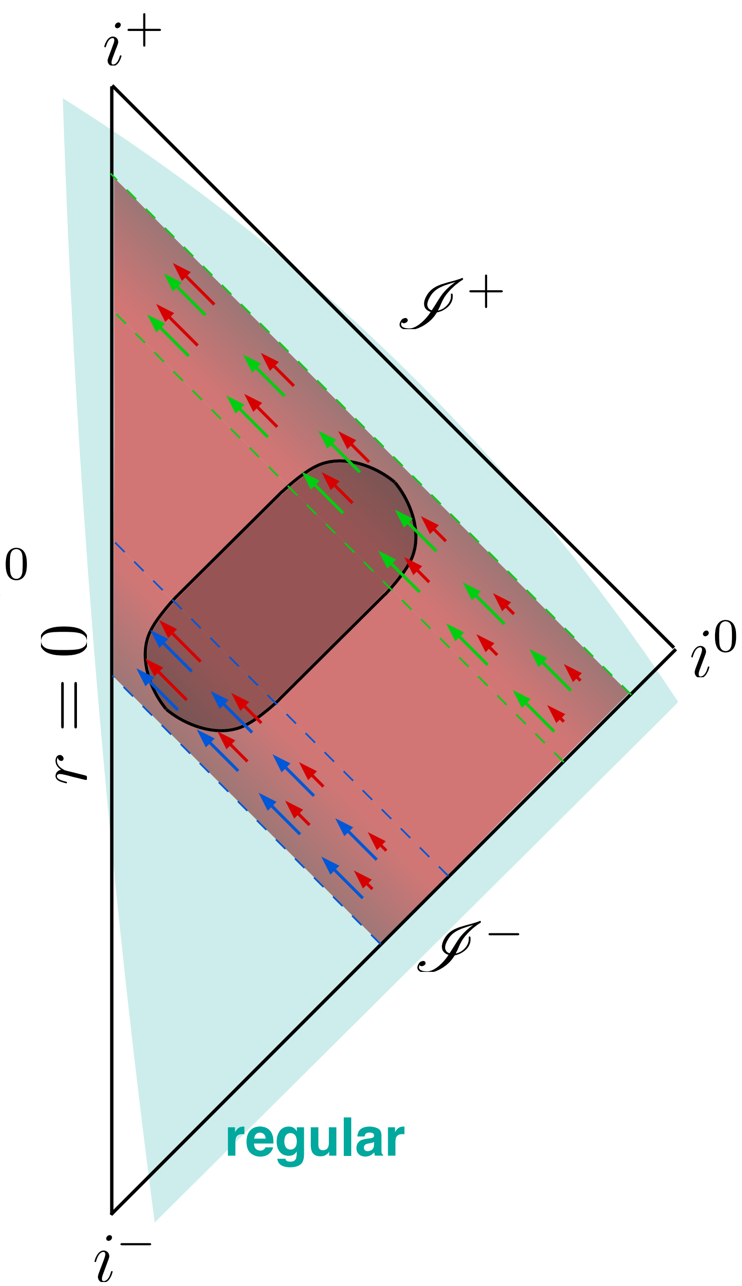
	Bardeen	Hayward	Bardeen 2.0	Hayward 2.0
Parity	❌	👍	👍	👍
Charged	❌	❌	👍	👍
Centre	❌	👍	❌	👍

Applications

Formation and evaporation of regular black holes

Hayward proposed time-dependent geometries with no curvature singularities and no information loss.
[S. Hayward, Phys. Rev. Lett. 96, 031103 (2006)]





Implemented as solutions of the master field equations, thus demonstrating that the formation and disappearance of black holes with no curvature singularities can be described by suitable field equations.
[V. Boyanov and RCR, Phys. Rev. Lett. 136 (2026) 17, 171403]

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Conclusions

Research into regular black holes is entering a new phase:
from geometric model-building to dynamical descriptions based on field equations.

Facilitated by a set of Einstein-like master field equations
encapsulating all possible second-order dynamics of spherically symmetric spacetimes.

Including matter fields (scalar, Maxwell, perfect fluids, …) leads
to novel constraints on the space of consistent theories and geometries.

From “anything goes” in geometric model-building
to limited possibilities.

All ingredients to construct fully dynamical picture
of formation and evaporation of (spherically symmetric) regular black holes.

Thank you very much!