A Visser's guide to the edge of spacetime

An emergency talk

Matt at 70:
a tour of the strangest corners of gravity.

Stefano Liberati · SISSA & IFPU, Trieste

DECLARATION OF CONFLICT OF INTEREST

I am the worst possible person to give this talk

Conference etiquette says the opening speaker presenting an overview, in this case of 45 years of Matt’s research, should be impartial.

However, I have co-authored seventy-four papers with the man, over twenty-eight years, across two hemispheres and at least three entirely different subjects.

What follows is therefore not a complete or unbiased survey (and assembled in a hurry, at that!).
It is an unusually long and unusually public stream of consciousness, delivered with slides.

416 **(~30k citations)**
records on INSPIRE under Matt's name

74
of them with mine on them too

1998 → 2026
and the most recent arrived last month

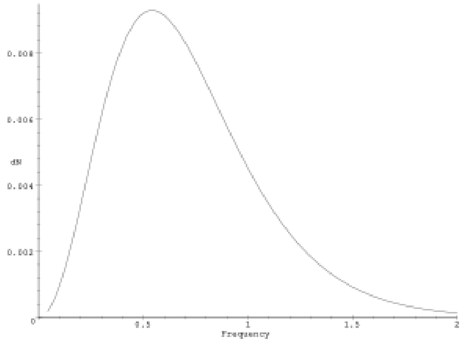
I wasn’t supposed to give this talk and
I confess that, writing it, I felt like a tour guide who keeps turning up in the holiday photographs!

00

It started with a glowing bubble

Before the wormholes, before the horizons, before any of the grand geometry: a flask of water, a loudspeaker, and a light nobody could explain.

Sonoluminescence, or how to begin a friendship by vindicating a Nobel laureate's last great idea



1 The puzzle

Trap a bubble of gas in water, drive it with kHz sound, and every acoustic cycle it collapses and flashes: of order a million optical photons, PHz, blue-white, in well under a nanosecond, with clockwork regularity. Nobody could say where the light came from.

2 Schwinger's proposal

Julian Schwinger, 1992: this is the dynamical Casimir effect. Change the refractive index faster than the QED vacuum can follow, and zero-point modes are converted into real, on-shell photons. The air in the bubble is not glowing; it is the vacuum.

3 What we actually did

We stopped admiring the idea and computed it: explicit Bogoliubov coefficients for the QED vacuum of a collapsing dielectric bubble: sudden approximation first, then honest finite-volume geometry, plus a two-photon-correlation test to tell thermal light from squeezed.

4 The verdict

The photons are there in the formalism, and so is the spectrum. But only if the refractive index changes on femtosecond timescales. So, things can work if the mechanism is not based on the bubble collapse timescale but on a sudden change in the bubble refractive index when the bubble hits its minimal radius.

Our first joint investigation took five hard-fought papers, and went against the mainstream. Twenty-eight years later, we are still writing papers together. Bad habits die hard…

Phys. Rev. Lett. 83 (1999) 678 · Phys. Rev. D 61 (2000) 085023 & 085024 · J. Phys. A 33 (2000) 2251 · Phys. Lett. A 271 (2000) 308

WHAT THE BUBBLE WAS REALLY FOR

We came for the glow. We stayed for the geometry.

collapsing bubble	→	mode mixing	→	Bogoliubov β ≠ 0	→	now rename n → $g\_\{\mu\nu\}$
n(t, x) changes fast		in and out vacua disagree		real photons from nothing		and it is Hawking's calculation

- **The disguise.** A moving dielectric is a curved spacetime wearing a lab coat; Gordon knew it in 1923. We (and others) rediscovered it while chasing a light bulb.

$$g_{\mu\nu} = \Omega^2 \left\{-1 \oplus g_{ij}\right\} \qquad g^{ij} = \left[\left\{\frac{\mu^{1/2}\,\epsilon\,\mu^{1/2}}{\det(\mu\,\epsilon)}\right\}^{1/2}\right]^{ij}.$$

- **The transferable skill.** Everything we built for the bubble (mode decomposition, sudden approximations, thermality tests) is the standard toolkit for quantum fields on a dynamical background.
- **The consequence.** Within two years we had stopped writing about bubbles and started writing about acoustic horizons. Same equations, better press coverage.

Moral: Sonoluminescence was a Trojan horse. Analogue gravity climbed out of it.

A career that only makes sense read sideways

Read chronologically Matt's career looks like that of someone with ADHD.
Read as a network it is one expanding web of knowledge often coming back to the same tools and methods, just for different problems.

1980s · quantum fields first

Berkeley, particle theory, one-loop effective actions, zeta functions and the Casimir effect.
Gravity came later; the field-theory instincts never left.

1990s · building the exotic

Traversable wormholes made calculable, thin shells, stability, chronology protection, dirty black holes — and the 1995 monograph that gave a whole community its vocabulary.

2000s · gravity in a bucket

Acoustic horizons, Bose–Einstein condensates, emergent Lorentzian geometry, varying-c cosmology, cosmography. Spacetime becomes something you can, in principle, order from a catalogue.

2010s–20s · the inside job

Regular black holes, black bounces, inner-horizon instabilities, Kerr in myriad coordinates and the Visser test for modified gravity: is it new physics, or GR in disguise? E.g. Rastall gravity, including its unimodular limit, provides a striking example.

Energy conditions link wormholes to cosmology; horizons link the black holes to the bathtub.
The threads keep crossing because it was always one thread.

01

Energy conditions

The fine print underneath the singularity theorems, the shortcuts, and every cosmic history you have ever been shown.

NEC: $T_{\mu\nu}k_{\mu}k_{\nu} \geq \ 0.$

WEC: $T_{\mu\nu}u_{\mu}u_{\nu} \geq 0$

SEC: $\left(T_{\mu\nu} - ½T\,g_{\mu\nu}\right)u_{\mu}u_{\nu} \geq 0$

ANEC: $\int T_{\mu\nu}k_{\mu}k_{\nu}d\lambda \geq 0.$

Four short inequalities — and almost every theorem you believe rests on one of them.

The hypothesis is the physics, not the small print

CONDITION	WHAT IT SAYS	WHAT IT BUYS YOU	WHAT OPENS UP WHEN IT FAILS
NEC	$T_{\mu\nu} k_\mu k_\nu \geq 0$	null focusing	wormholes · warp drives
WEC	$T_{\mu\nu} u_\mu u_\nu \geq 0$	non-negative local energy	dirty-black-hole bounds
SEC	$(T_{\mu\nu} - ½T g_{\mu\nu}) u_\mu u_\nu \geq 0$	timelike focusing	bounces · cosmic acceleration
ANEC	$\int T_{\mu\nu} k_\mu k_\nu d\lambda \geq 0$	averaged null focusing	topological censorship

Everyone quotes the singularity theorems and chronology conjectures.
Matt is one of the few who reads the assumptions out loud, slowly, in front of witnesses.

Quantise the field and the hierarchy starts to sag

A scale anomaly is enough

Matt showed that a nonzero scale anomaly suffices to obstruct the averaged null energy condition. No special system is required: the anomaly is already present for free conformally coupled quantum fields in a generic curved spacetime.

"In a generic four-dimensional spacetime with a nonzero scale anomaly, a conformally coupled quantum field cannot obey a renormalization-scale-independent ANEC."

The vacuum has opinions

Boulware, Hartle–Hawking, Unruh: static exterior, thermal equilibrium, evaporating hole. Same spacetime, three stress tensors, three different verdicts on the classical conditions.

State-dependence, everywhere

If $\langle T_{\mu\nu} \rangle$ depends on the state, so does the fate of every global theorem whose hypothesis it is supposed to satisfy. The fine print turns out to be negotiable.

Semiclassical gravity, promoted

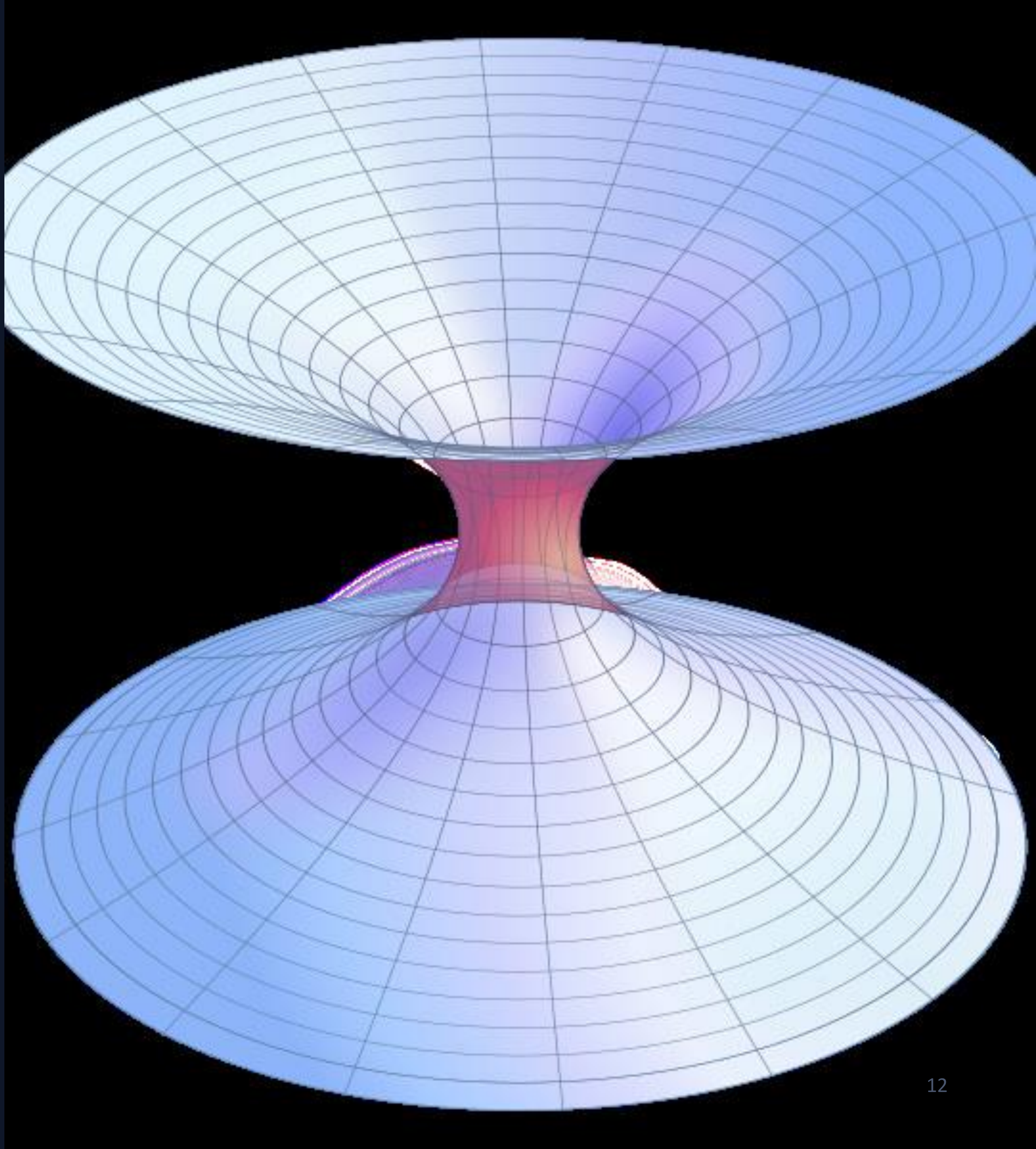
It stops being a small correction to a classical picture and becomes the diagnostic instrument the thing that tells you when the classical picture was never entitled to its conclusion.

Classical energy conditions are what quantum field theory violates on its way to work.

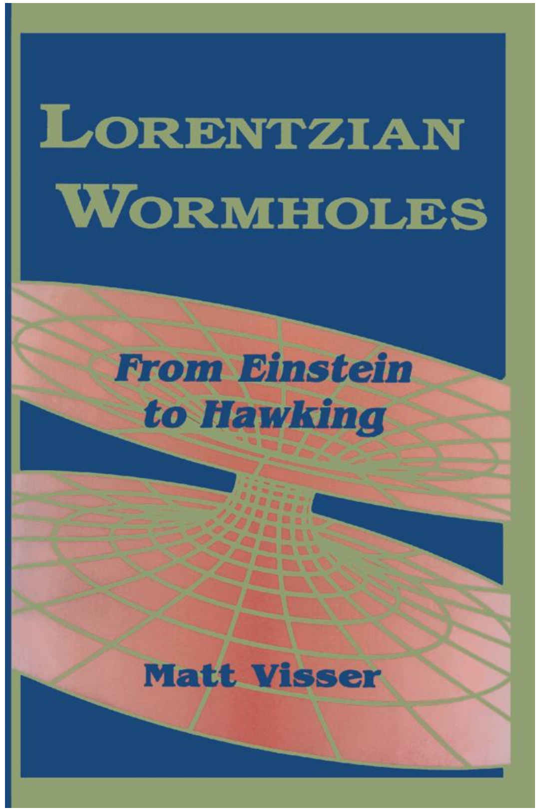
02

Exotic geometries

Wormholes, shortcuts,
and the discipline of always asking what they cost.



Wormholes became laboratories, not loopholes



- **Construct.** Cut-and-paste and thin-shell geometries that make traversability explicit rather than aspirational. You can write the metric down; you can also write down the bill.
- **Test.** Linear stability analysis turns an appealing picture into a dynamical system with modes that may or may not survive. With Eric Poisson, he related stability issues to the (linearised) equation of state of the exotic matter located at the throat.
- **Observe.** Lensing and causal signatures connect the geometry to things a telescope could in principle disagree with.
- **Synthesise.** Lorentzian Wormholes: From Einstein to Hawking (1995) — the book that gave a scattered subject a shared technical language and gave a generation of students something to hide from their supervisors.

The achievement was methodological:
Folklore replaced by systematic calculation.

The throat tells you exactly where the bill is paid and how much it comes to

flare-out	→	$R_{\mu\nu}k_\mu k_\nu < 0$	→	$T_{\mu\nu}k_\mu k_\nu < 0$
minimum area at the throat		null rays defocus		the null energy condition breaks

With David Hochberg, the result was made generic, static and dynamic, and without leaning on spherical symmetry.

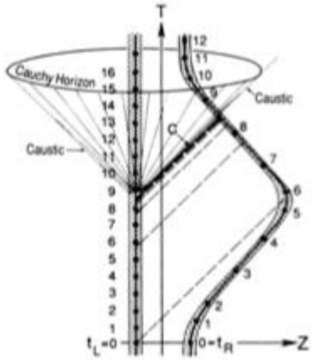
It is geometry, not topology, that does the talking, and the violation is localised at or near the throat rather than smeared over the whole spacetime.

- **Why this is the archetype.** Define the object geometrically, find the local condition it forces, then convert that condition into a statement about stress-energy. Three steps, no metaphysics.

- **Why it mattered.** 'Wormholes need exotic matter' stopped being folklore and became a theorem with a postcode.

You cannot talk your way past a wormhole throat.
The curvature sends you a toll and an invoice.
Still, this may seem just an engineering problem…

Build a shortcut and causality walks into the room



relative motion/grav.redshiift
time shift between the mouths

→

closed loop
causal self-contact

→

backreaction
chronology protection?

…, taken seriously

… that the universe protects … he quantum stress tensor … e the trouble is supposed to … it was actually doing there.

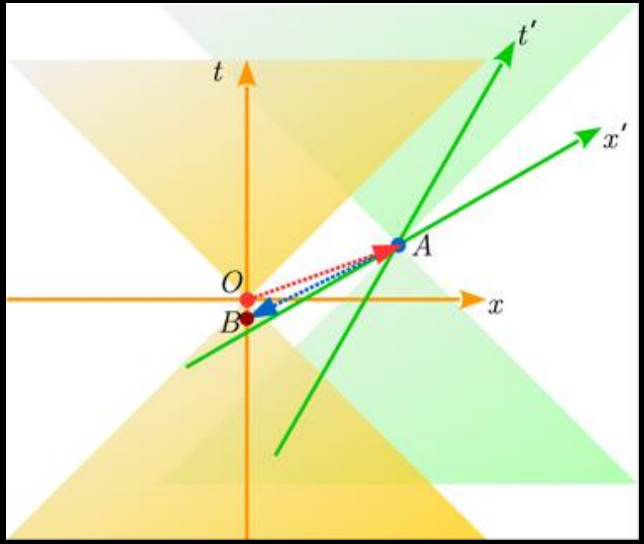
The reliability horizon

The sharper question is not when the divergence arrives, but when we stop being allowed to believe the calculation. Two-point correlation functions inevitably become ill-defined or singular on the Cauchy/chronology horizons, causing the expectation value of the RSET to blow up. (Kay–Radzikowski–Wald theorem).

Matt's garden shed…
(For the youngsters, this is a TARDIS from the BBC sci-fi series Doctor Who.
Matt was one of the "Time Lords" interviewed in an episode of the BBC's Horizon documentary series.)

The universe may or may not protect chronology.
Semiclassical gravity, it turns out, gives up first.

Faster than c is not the same as backwards in time



"Relativity forbids superluminal signalling" is folklore, not a theorem.
von Ignatowsky derivation of SR: needs only homogeneity and isotropy of space, the relativity principle, and a pre-causality condition. It produces an invariant speed C as a structural constant (not a priori c_light). It does not produce a speed limit. Faster-than-C signalling contradicts none of the postulates.

A signal that outruns light

Take the antitelephone argument seriously and watch which ingredient does the work. It is not the speed. It is the assumption that the same superluminal law holds in every inertial frame.

→

No preferred frame → paradox

With no definite speed relative to any rest frame, a boost reverses the ordering on the return leg and the causal loop closes. It is the boost invariance assumption, not the superluminality, that leads to the causal loop.

→

A preferred frame → no paradox

Give the signal a definite speed relative to some frame and there is a frame in which it only ever moves forward in time. Stable causality (a global t with ∇t timelike) then excludes closed causal curves outright.

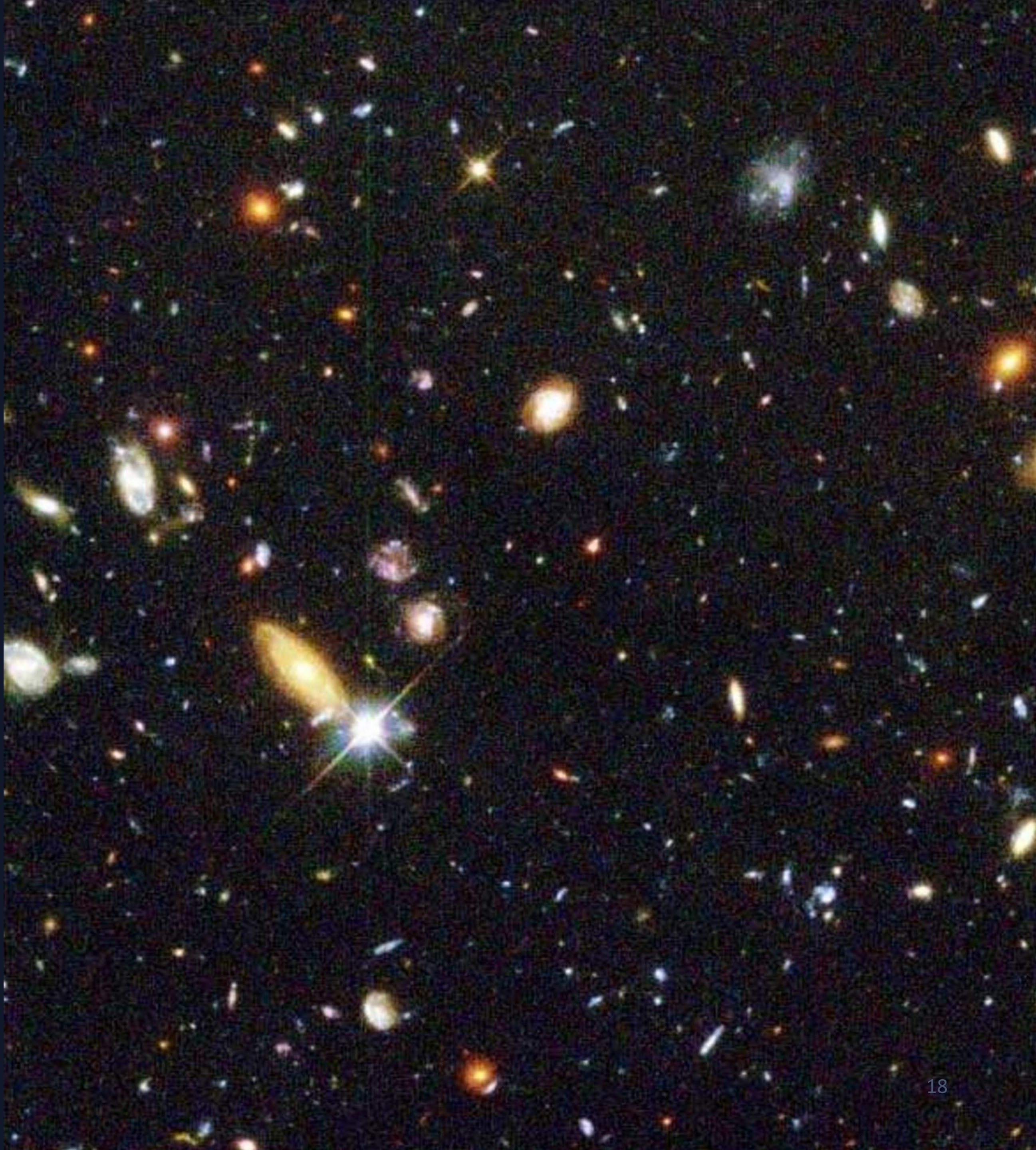
Superluminal signalling does not violate causality. Lorentz-invariant superluminal signalling does. Almost everyone quotes the first sentence while meaning the second.

Faster-than-c signals, special relativity, and causality, gr-qc/0107091, Annals Phys. 298 (2002) 167 · Scharnhorst effect at oblique incidence, quant-ph/0010055, Phys. Rev. D 63 (2001) 085003

03

Cosmology,
and everything after

Expansion measured before it is explained — and a research map that has never once agreed to stay inside a single field.



Variable speed of light cosmology?

By 2000, variable-speed-of-light cosmology was being offered as a rival to inflation. The proposals had a habit of varying c by decree and moving on briskly, before anyone could ask what it was varying with respect to.

THE QUESTION EVERYONE STEPPED OVER

Hard breaking

Mutilate Lorentz and diffeomorphism invariance by hand, and "the speed of light changed" becomes a statement about your choice of units rather than about the universe. The variation carries no invariant meaning.

Soft (covariant) breaking

Let a field χ pick out the frame instead. The equations stay Lorentz invariant; the state does the breaking. Now the question has an answer and the model stays compatible with Einstein gravity and low-energy particle physics.

WHAT IT ACTUALLY BUYS YOU

✓ **The kinematic puzzles — solved.** The horizon problem and its relatives fall to VSL exactly as neatly as they fall to inflation.

✗ **Flatness — not solved.** In their pure form these models violate no energy condition, and flatness needs the strong energy condition to fail. The assumption doing the work in inflation was never the expansion, it was the SEC violation.

→ **Heterotic: VSL plus inflation.** If χ contributes to dark energy as CDM or quintessence you inherit real observational handles: modified lensing, birefringence, drifting constants, and rotation of the polarisation plane of distant light.

The result worth having was neither "VSL works" nor "VSL fails". It was finding out precisely which cosmological puzzle each assumption had quietly been solving all along.

Dedicated to the memory of Dennis Sciama. · *Geometrodynamics of variable speed of light cosmologies, astro-ph/0001441, Phys. Rev. D 62 (2000) 103518*

Cosmic acceleration reopens all the same questions

bang

$a \to 0$. The classic. Everything diverges and everybody agrees to stop calculating.

bounce

a finite, with $\dot{a} = 0$ and $\ddot{a} > 0$. Requires SEC and NEC to look the other way.

rip

$a \to \infty$ in finite time. The universe tears itself up on a schedule.

sudden

a finite, but a higher derivative diverges. Nothing dramatic happens to the size of the universe; something dramatic happens anyway.

With Céline Cattoën, the whole zoo (bangs, bounces, crunches, rips, sudden singularities, extremality events) was classified purely by the behaviour of the scale factor and its derivatives.
Kinematics classifies the event; only afterwards does dynamics get to say whether your favourite theory permits it.

One of Matt's obsessions: Classify first, believe later.
It is astonishing how many cosmological arguments this simple ordering dissolves.

Cosmography: measure the expansion before explaining it

$$a(t) = a_0[1 + H_0\Delta t - \tfrac{1}{2}\, q_0 H_0{}^2 \Delta t^2 + \tfrac{1}{6}\, j_0 H_0{}^3 \Delta t^3 + {}^1/{}_{24}\, s_0 H_0{}^4 \Delta t^4 + \cdots]$$

H · rate

How fast. The one everybody argues about at conferences, loudly.

q · deceleration

Whether the expansion is speeding up. Sign matters more than value.

j · jerk

The first coefficient that starts to discriminate between models.

s · snap

Where the data runs out and the honesty has to begin.

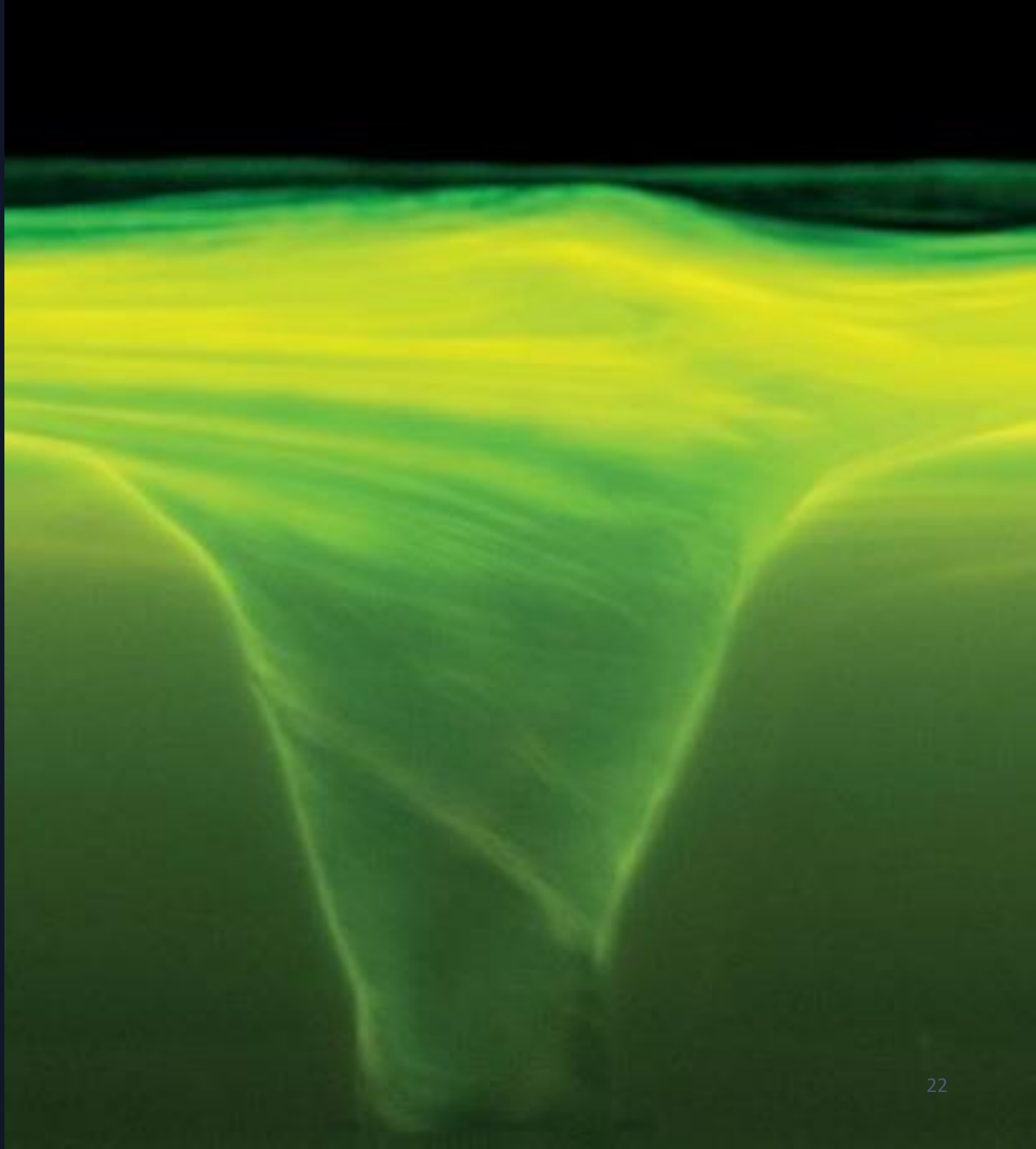
Expand the scale factor and the luminosity distance without first choosing a gravity theory or an equation of state. With Céline Cattoën, Matt also showed how much the answer depends on which distance variable and which redshift parametrisation you happened to pick. We have recently explored cosmography beyond FRW as well. This is exactly the kind of thing nobody (especially cosmologists) wants to hear.

Separate what you measured from what you assumed, and a surprising number of cosmological certainties become negotiable.

04

Analogue & emergent gravity

When sound, light and cold atoms quietly inherit the mathematics of spacetime — and start answering questions we could not otherwise ask.



Sound can inherit a spacetime, and does not need permission

$$ds^2 \propto -(c_s^2 - v^2)dt^2 - 2v \cdot dxdt + dx^2$$

subsonic

$|v| < c_s$ · sound can still swim upstream

→

the horizon

$|v| = c_s$ · the last point of no return

→

supersonic

$|v| > c_s$ · trapped, and it does not know it

For an irrotational, barotropic fluid the linearised sound field obeys a curved-spacetime wave equation exactly. Matt did not start the field, but his 1998 paper provided a first systematic treatment of analogue horizons, ergoregions, surface gravity and Hawking-like emission, all in a fluid you could in principle buy.

A fish that swims past the sonic point cannot warn its companions outside.
This is, formally, the entire black-hole causal structure in a bathtub.

Barceló, Liberati, Visser:
Living Rev.Rel. 8 (2005) 12, *Living Rev.Rel.* 14 (2011) 3 gr-qc/0505065 [gr-qc], *Living Rev.Rel.* 29 (2026) 1, 2

Models OF gravity, or models FOR gravity?

What analogues genuinely reproduce

An effective metric governing wave propagation. Horizons, with trapping, redshift and mode conversion. The kinematics of quantum field theory in curved spacetime, including particle production and Hawking-like emission. None of this is metaphor; it is the same equation.

What they honestly do not

Einstein's dynamics: the medium obeys its own equations of motion, not the field equations. Universal coupling: different modes may see different metrics. And nothing here is quantum gravity: the analogy is a probe, not an identity, though it can still teach us a great deal about gravity.

The limitation is the insight. For example, the UV completion in analogue gravity taught us about the robustness of Hawking radiation and allowed us to observe it! Also, exactly because the correspondence is exact for kinematics and absent for dynamics, an analogue experiment tells you precisely which phenomena were only ever geometry plus quantum fields, and which ones genuinely require gravity to be gravity.

We set out to simulate gravity and ended up with a serious argument about what gravity is. This is our kind of occupational hazard.

Emergence turns the usual hierarchy upside down

background	→	linearise	→	effective metric	→	quantise
any non-trivial classical solution		normal modes of the perturbations		a Lorentzian geometry nobody put in by hand		an effective action with gravitational terms

- **Classical physics → geometry.** Linearise a generic field theory about a background and a Lorentzian metric appears whether or not you wanted one. Geometry is what perturbations always see.
- **Quantum fluctuations → dynamics.** Quantise those perturbations and the induced effective action contains gravitational terms, in the spirit of Sakharov. Dynamics is what the fluctuations pay for. Alternatively in relativistic BEC you can recover a geometrodynamics pretty close to Nordstrom gravity.
- **The moral.** This does not prove gravity is emergent. It shows why emergence is structurally unsurprising and why low-energy universality, not microscopic resemblance, is the language to argue in.

If spacetime is hydrodynamics, then asking what it is made of is like asking a wave what it is made of. Interesting, but not the first question you should ask.

BECs became laboratories for emergent cosmology

06

Relativity emerges

A two-component condensate supports massless and massive phonons sharing an infrared light cone. Quantum pressure exposes high-energy Lorentz violation. (this wa salso with me)

07

The condensate expands

Varying the scattering length realizes an analogue FRW universe. Truncated-Wigner simulations recover cosmological particle creation.

09

Rainbow spacetime

Microscopic dispersion makes the metric momentum dependent: low-energy modes feel expansion; the extreme ultraviolet hardly does.

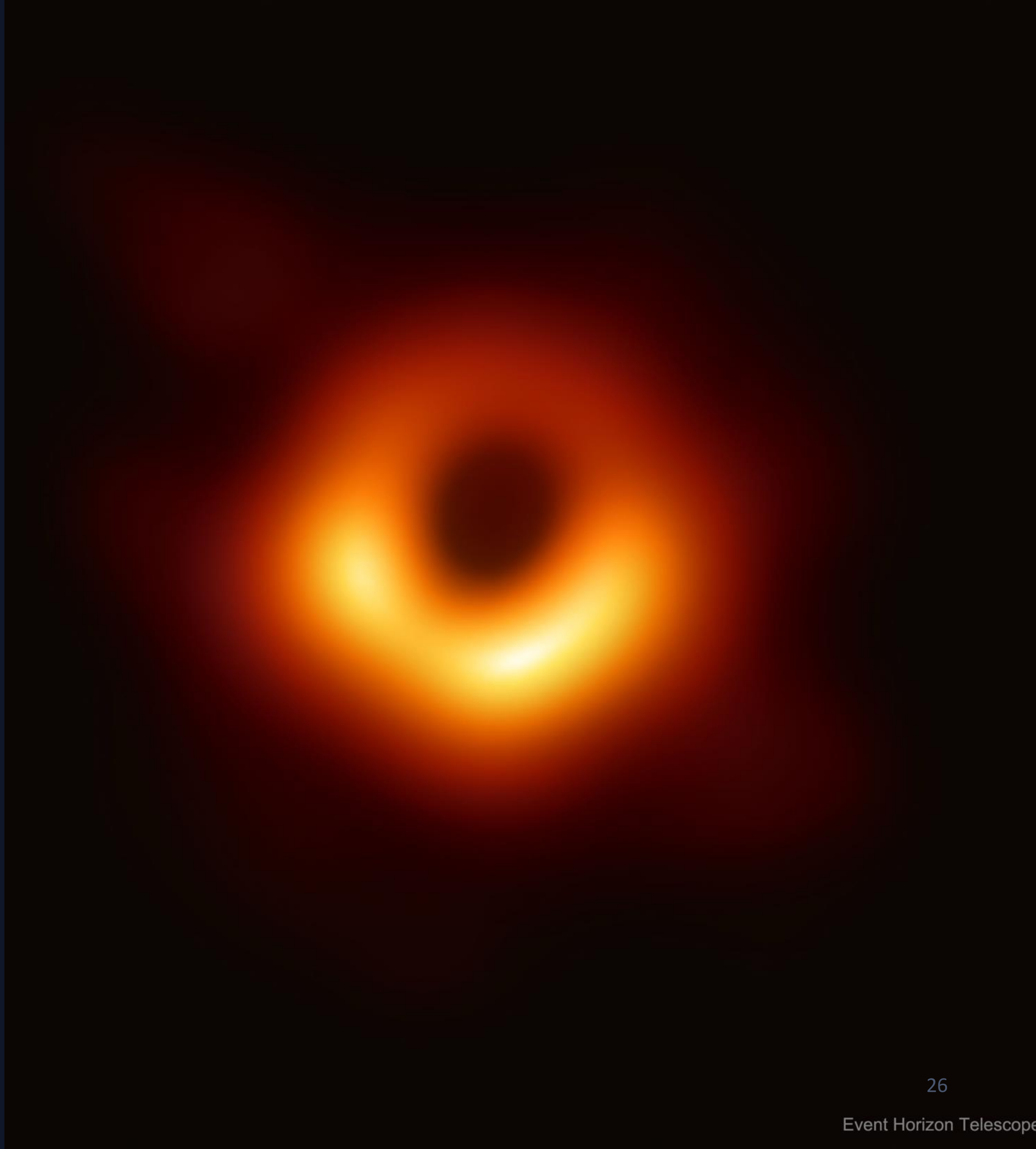
CQG 23 (2006) 3129–3154 · PRA 76 (2007) 033616 · CQG 26 (2009) 065012

Atoms provide the microphysics; geometry, Lorentz symmetry and particle production emerge above it.

05

Horizons

Thermodynamics, radiation, and the many ways a one-way surface can matter — including by not being there.



Event Horizon Telescope

Dirty black holes: thermodynamics after the cleaners left

The idealisation

Textbook black-hole thermodynamics assumes an isolated hole in vacuum: a spacetime with the surroundings tidied away.
Real ones have furniture…

The result

Surround the hole with classical matter and, under the relevant energy condition, the Hawking temperature is suppressed relative to a vacuum hole of the same horizon area. The matter changes the redshift, and the redshift is the thermometer.

Entropy, reframed

Companion work recast the entropy contribution as a surface term: the area law survives the mess, and the route to it becomes considerably more transparent.

Why it counts

The cleanest theorems in physics are usually stated for the cleanest systems. Showing they survive contact with dirt is what turns an elegant result into a robust one.

'Dirty' is Matt's word, not mine.
He has a gift for "barely legal" titles that referees cannot forget.

Visser: Phys.Rev.D 46 (1992) 2445–2451 + 7 publications with Boonserm, Martin, Medvedev et al.

Hawking radiation does not require a stationary black hole or even a trapped region

collapse		exponential peeling		large, sustained redshift		approx. thermal flux
no completed horizon needed	→	affine parameters drift apart	→	over a long enough interval	→	you get the radiation anyway

- **Necessary:** an approximately exponential relation between the affine parameters, i.e. peeling, maintained for long enough. That is the whole engine. This can be realized by a slowly evolving ($\dot{\kappa}/\kappa^2 \ll 1$) horizon or a collapse approaching horizon formation exponentially slow.
- **Not necessary:** a permanent trapped region, an event horizon, or a singularity waiting at the end of it.
- **The payoff:** non-singular collapse can radiate like a black hole without ever setting up the information-loss paradox in the first place. The flux was never the problem.

Be careful about mentioning event or Cauchy (or any global) horizons to Matt if you do not want to meet the Incredible Hulk.

Kerr became a place where everyone had to meet

The point

Rotating geometry is where exact solutions, wave propagation, horizon physics and astrophysical interpretation are all forced into the same room and made to agree.

The volume

The Kerr Spacetime: Rotating Black Holes in General Relativity (2009), edited with David Wiltshire and Susan Scott. Editing is a contribution: it makes a hard spacetime navigable for the next generation.

The obsession

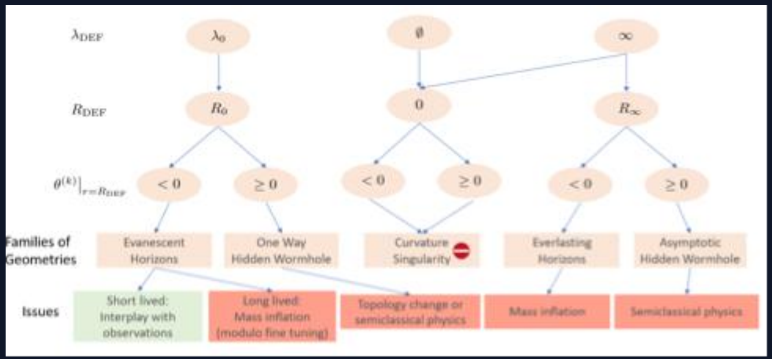
How to simulate full Kerr. Describe Kerr in several coordinate systems. 1) Kerr 2) Kerr-Schild 3) Boyer-Lindquist 3) Rational polynomial 4) Doran. If a coordinate system exists, Matt has probably tried to describe Kerr in it.

The joint chapters

Painlevé–Gullstrand versus Kerr, and the Gordon form — two of ours, and two more reminders that a good coordinate system is a physical statement in disguise.

Normal people collect stamps. Matt collects coordinate charts for the Kerr metric.

Round three: we went back for the inside of black holes



1 Are regular black holes viable?

Replace the singularity with a core and you inherit an inner horizon. But inner horizons are restless. Mass inflation and semiclassical instabilities turn a cure into a runaway geometry.

2 Geodesic completeness, honestly

A systematic classification of what a non-singular spacetime can actually look like: regular cores, horizonless ultracompact objects, bounces, and which of them survive their own instabilities.

3 Confronting observation

Constraints from the Event Horizon Telescope, from infrared limits on thermalising surfaces, from LISA. The exotic finally has to file a tax return.

Twenty-odd joint papers in eight years, and the most recent arrived just this month. The pattern from 1998 is entirely intact: construct the sharpest object, find the assumption carrying the result, then check what observation is willing to tolerate.

At seventy, most people revisit their greatest hits. Matt went back to singularities to see whether they could be talked out of existence.

Seventy is just like crossing the horizon of a SMBH: you cannot come back (and probably you still end up spaghettified), but hey! there are still plenty of mysteries to be uncovered!

Happy birthday, Matt!
and thank you for twenty-eight years of the best kind of argument!