Victoria University of Wellington
Te Whare Wānanga o te Ūpoko o te Ika a Māui

School of Mathematical and Computing Sciences
Te Kura Pangarau, Rorohiko

Emergent spacetimes

Matt Visser

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Overview:

Is “quantum gravity” even the right question?

It is increasingly plausible that Einstein's general relativity (like Euler's hydrodynamics), is “merely” a low-energy approximation to some radically different “fundamental” theory.

I will present a non-technical description of what might be going on, and what the prospects are for future progress.

Why "quantum gravity"?

It's a matter of principle:
We have two theories, quantum physics and Einstein's theory of gravity (general relativity), each of which works very well in isolation, and between them they cover 99% of everything we know about.

That is: We already do have a quite successful "theory of almost everything".

But the interface between these two theories is "awkward".

Why "quantum gravity"?

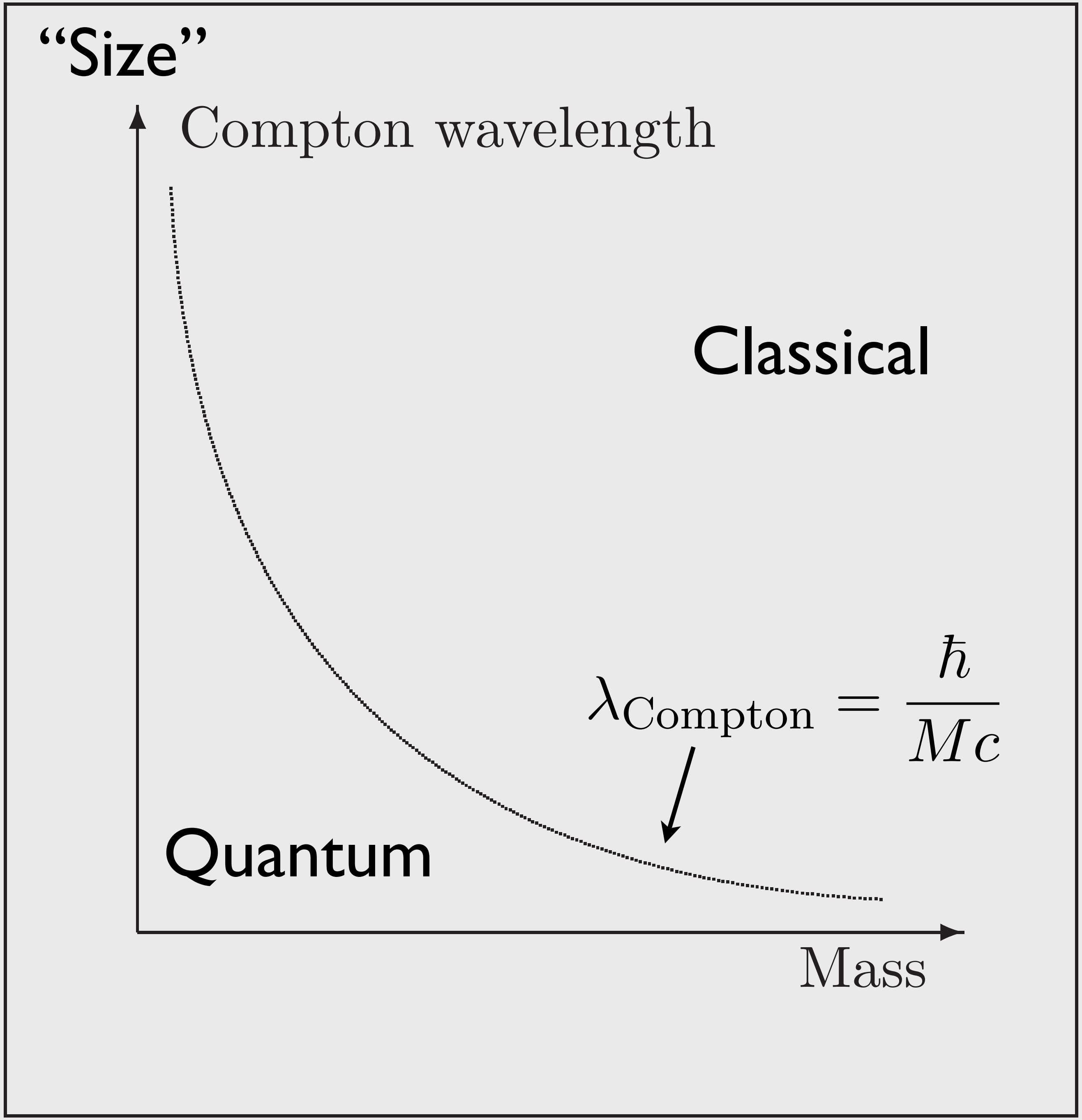
With what we already know we can make a good estimate of when the two theories will interact significantly.

That is: When will quantum physics become critical to understanding gravity, and when will gravity become critical to understanding quantum physics?

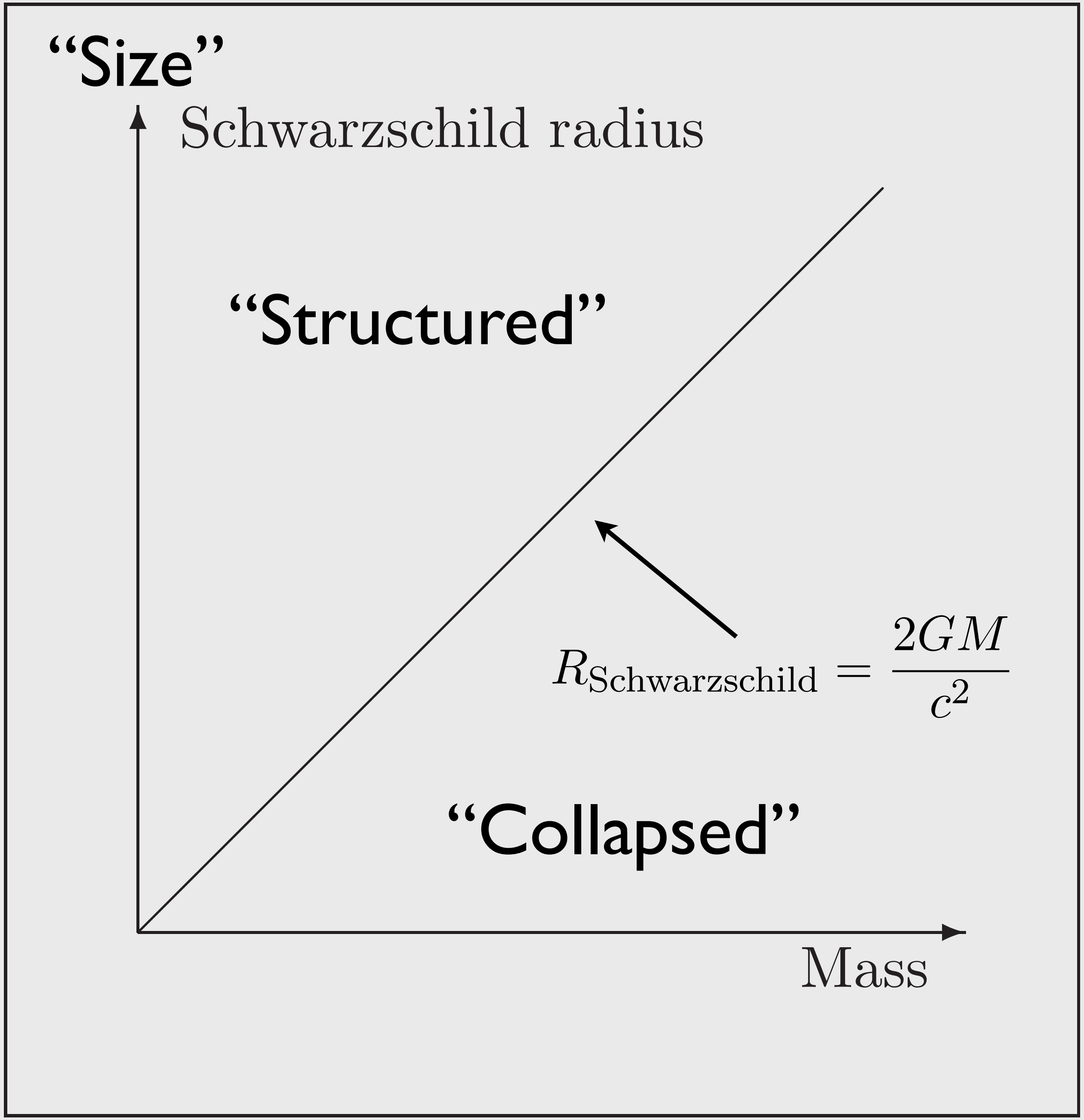
Answer: At the Planck scale, about 10,000,000,000,000,000,000 times [10^19] the mass of a Hydrogen atom.

For some purposes this is "big", for others "small".

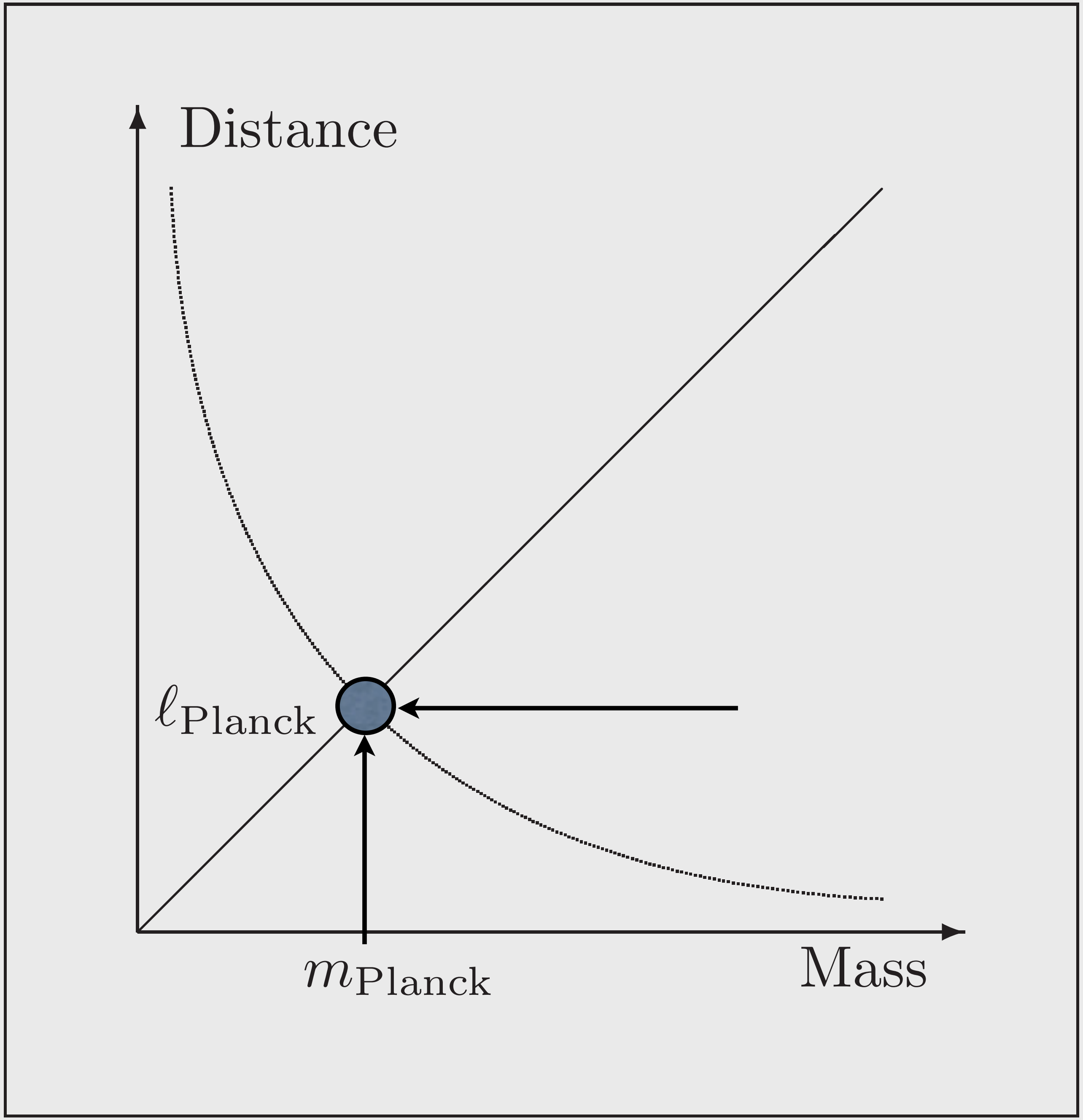
The “quantum gravity” frontier?



The "quantum gravity" frontier?



The "quantum gravity" frontier?

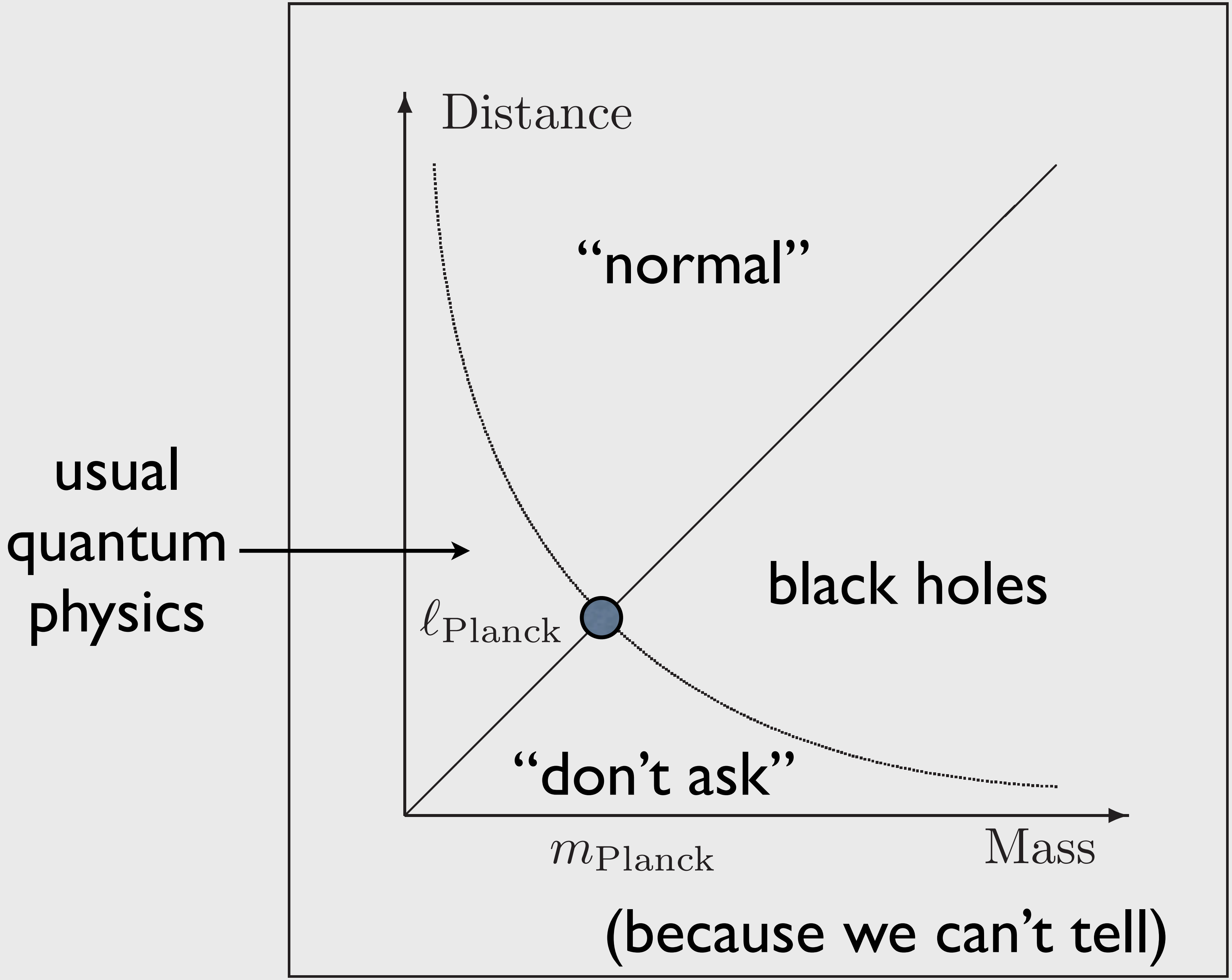


The "quantum gravity" frontier?

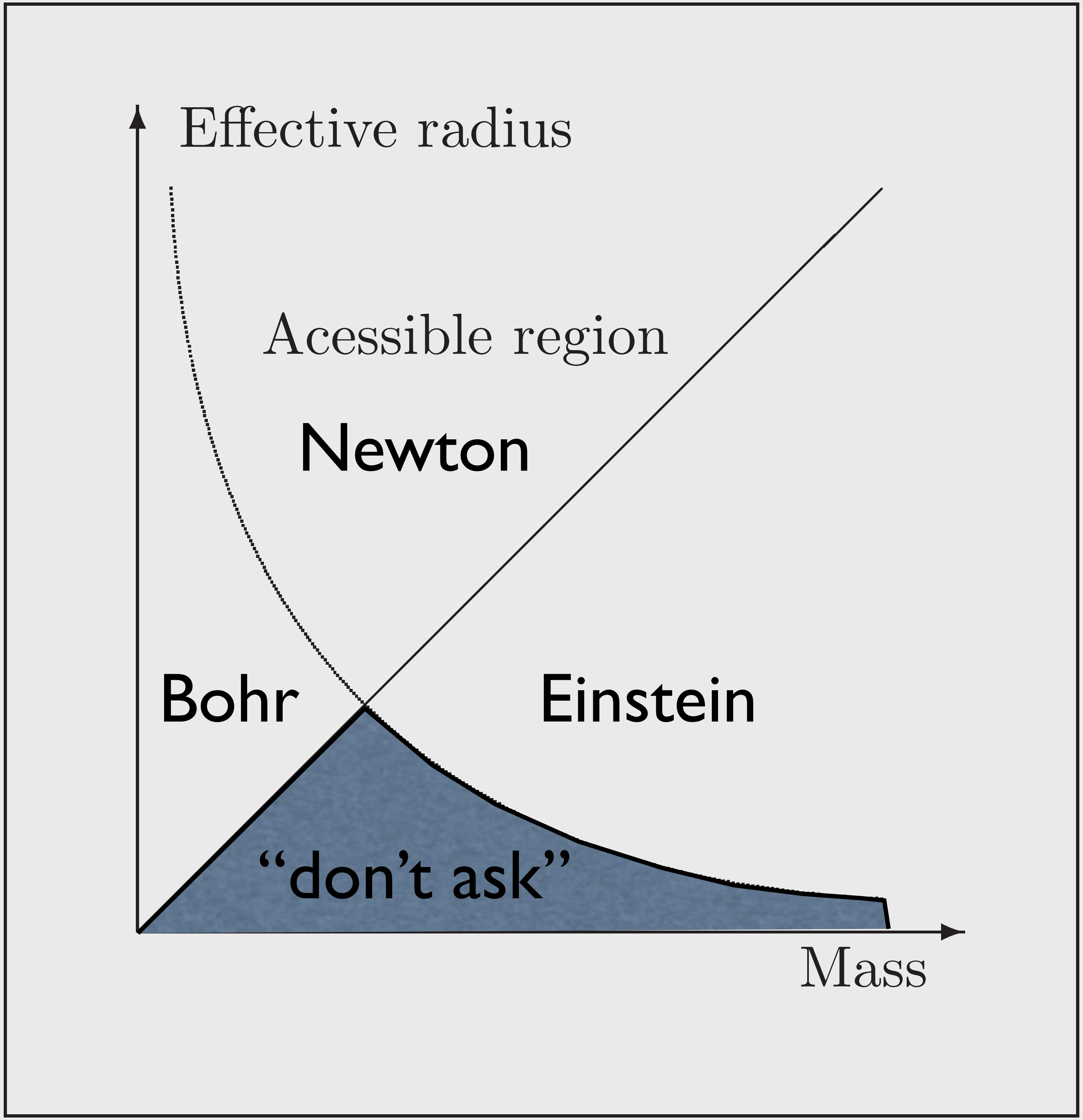
$$\ell_{\rm Planck} = \sqrt{\frac{\hbar\, G}{c^3}}$$

$$m_{\rm Planck} = \sqrt{\frac{\hbar\, c}{G}}$$

The "quantum gravity" frontier?



The "quantum gravity" frontier?



The "quantum gravity" frontier?

The Planck scale.

Symbol	Name	Value
m_{Planck}	Planck mass	2.18×10^{-8} kilogram 1.22×10^{19} GeV/c^2
E_{Planck}	Planck energy	1.22×10^{19} GeV
ℓ_{Planck}	Planck length	1.62×10^{-35} metres
T_{Planck}	Planck time	5.39×10^{-44} seconds

100,000,000,000,000,000,000 times smaller than the nucleus of an atom... [10^20]

But 10,000,000,000,000,000,000 more energy... [10^19]

The "quantum gravity" frontier?

"Bash and see" approach:

Direct probes --- particle accelerators
(Tevatron, LEP, RHIC, LHC)
only go up to roughly 100,000 [10^5]
times the mass of a Hydrogen atom...

We would like to probe 10,000,000,000,000,000,000
times the mass of a Hydrogen atom... [10^19]

That's a shortfall of 100,000,000,000,000 in energy...
[10^14]

Similarly, there's a shortfall of 100,000,000,000,000
[10^14] in our distance resolution...

The "quantum gravity" frontier?

This suggests a change in strategy:

--- Indirect tests (as much as possible)

Eg: tests for violation of symmetries
and/or conservation laws..

--- "Gedanken-experiments" (thought-experiments)

Eg: wormholes in spacetime...

--- "End run" physics (guess and then check)

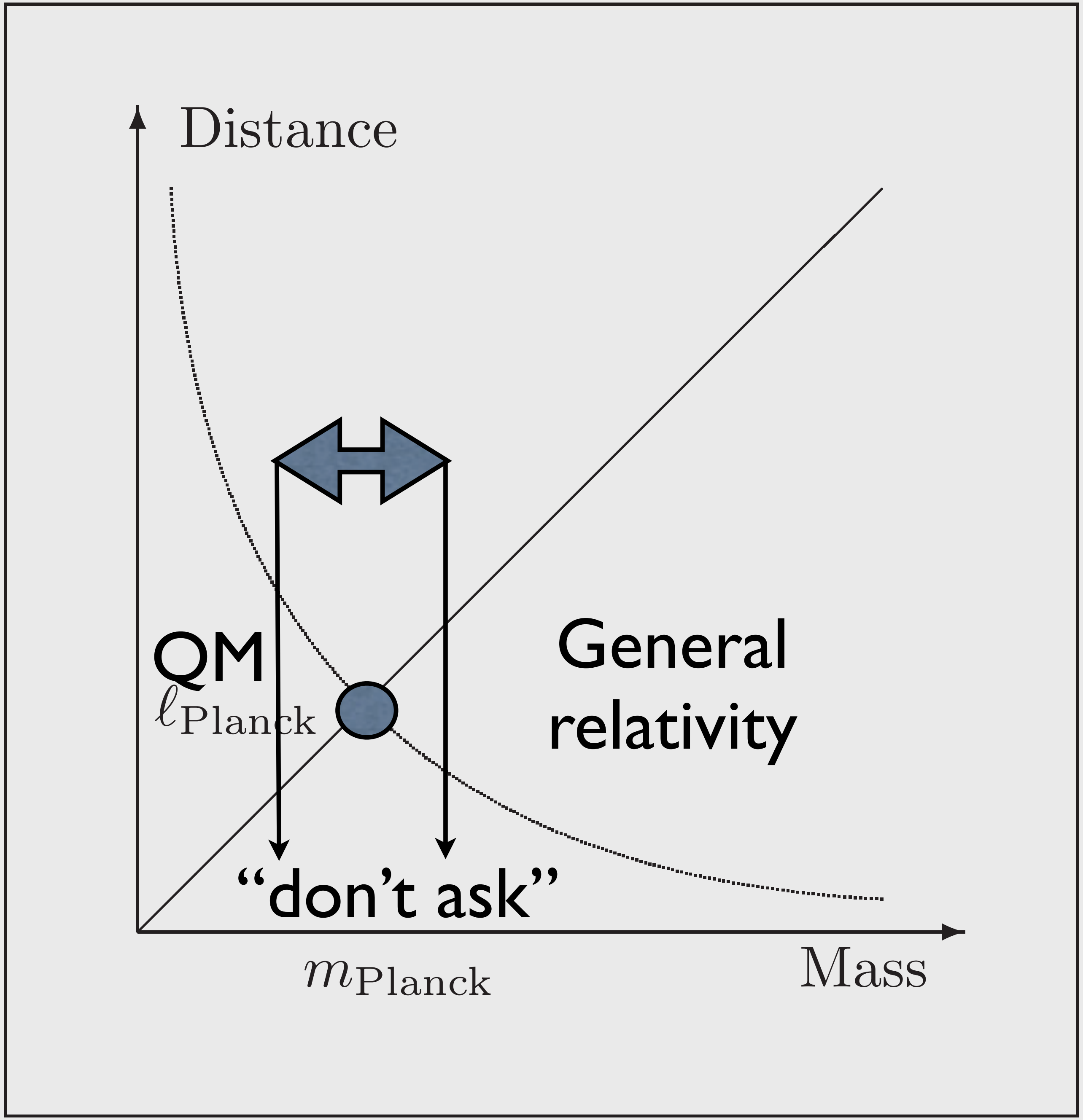
Two major routes to "quantum gravity"?

Force Einstein gravity into a quantum framework

Force quantum physics to lead you to Einstein gravity

Both have been tried,   with at best partial success.

Plus: there are a number of "minority opinions"...


Distance
QM
ℓ_{Planck}
General relativity
"don't ask"
m_{Planck}
Mass

Two major routes to "quantum gravity"?

Quantize gravity: eg: Loop quantum gravity

Gravitationalize quantum physics: eg: "strings"

"Strings" are not strictly speaking a "theory", they represent an enormous class of tentative hypotheses struggling to become a model, and then maybe a theory...

['t Hooft]

"Strings" are as yet a meta-model.

“Emergence”?

Maybe the real question should be:

What is the theory that in one limit gives you standard quantum physics and in another limit gives you standard Einstein gravity?

Can Einstein gravity and quantum physics be “emergent phenomena”?

“Emergence”!

“More is different”

The standard example of “emergence”
is fluid dynamics.

The short-distance theory is
quantum molecular dynamics,
which leads to the kinetic theory of fluids,
which leads to fluid dynamics.

==> The Euler equation and the continuity equation.

"Emergence"!

Euler:

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\, \vec{v} = \frac{-\vec{\nabla} p + \vec{f}}{\rho}$$

Continuity:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho\, \vec{v}) = 0$$

"mean-field" approximation

These equations only make sense at an "intermediate" level where it is possible to average out the random molecular motions...

So they are not "fundamental",
but that does not mean they are "trivial"...

“Emergence”!

Maybe the same thing happens for Einstein gravity?

Maybe we can obtain a “spacetime metric” by averaging over lots of random microscopic degrees of freedom?

Maybe the Einstein equations are no more “fundamental” than the Euler equations of fluid mechanics?

$$R_{ab} - \frac{1}{2} R\, g_{ab} = 8\pi G\, T_{ab}$$

“Emergence”!

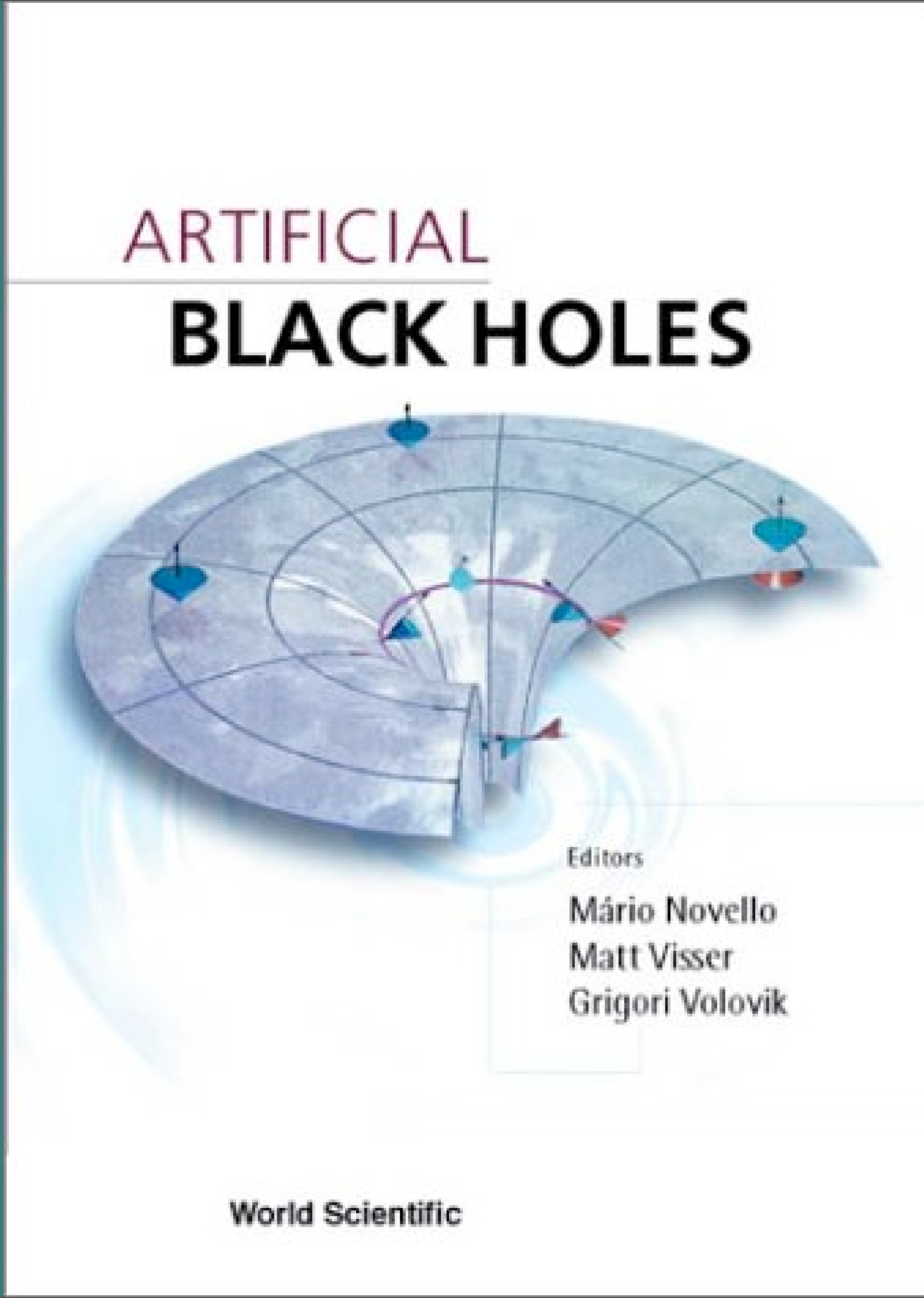
Only partial success at this stage...

Yes, we can in some situations get an “emergent spacetime metric”.

No, we cannot yet plausibly get anything resembling the Einstein equations...

(Of course, with enough wishful thinking...)

What have we done so far...



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Buy this book!

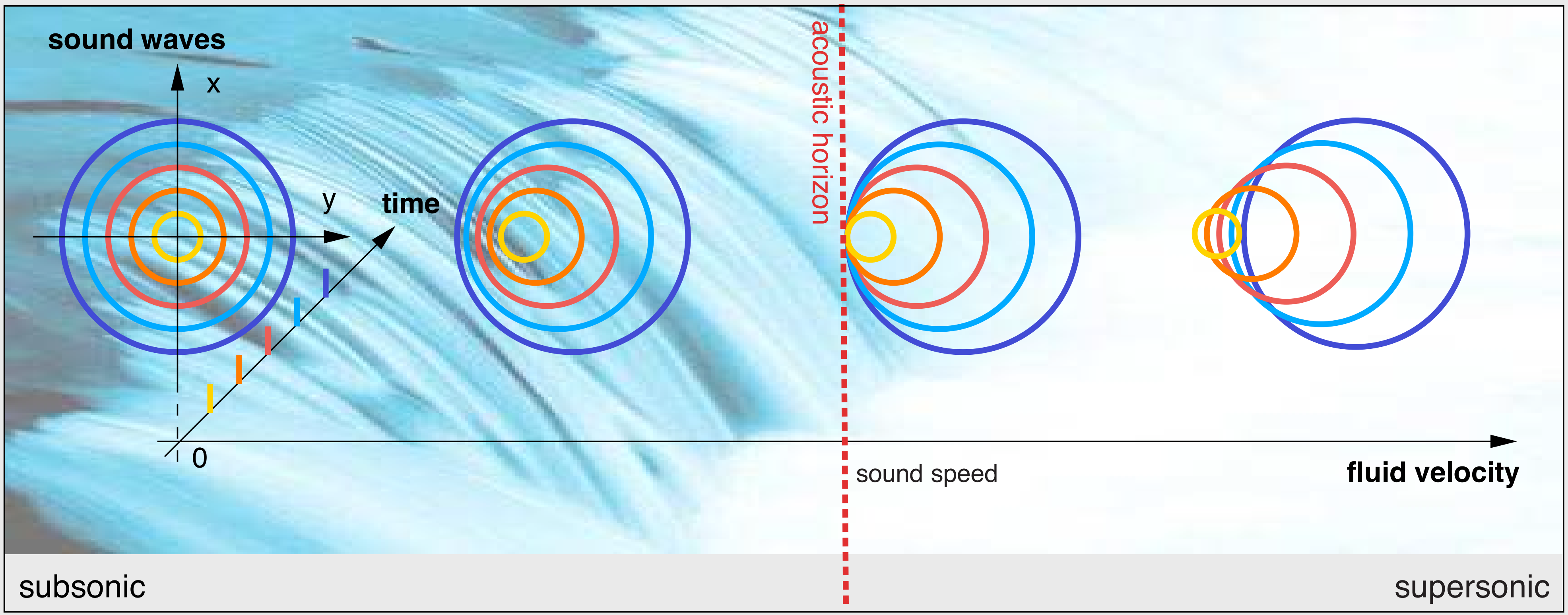
And I cherish more than anything else the Analogies, my most trustworthy masters.

They know all the secrets of Nature, and they ought least to be neglected in Geometry.

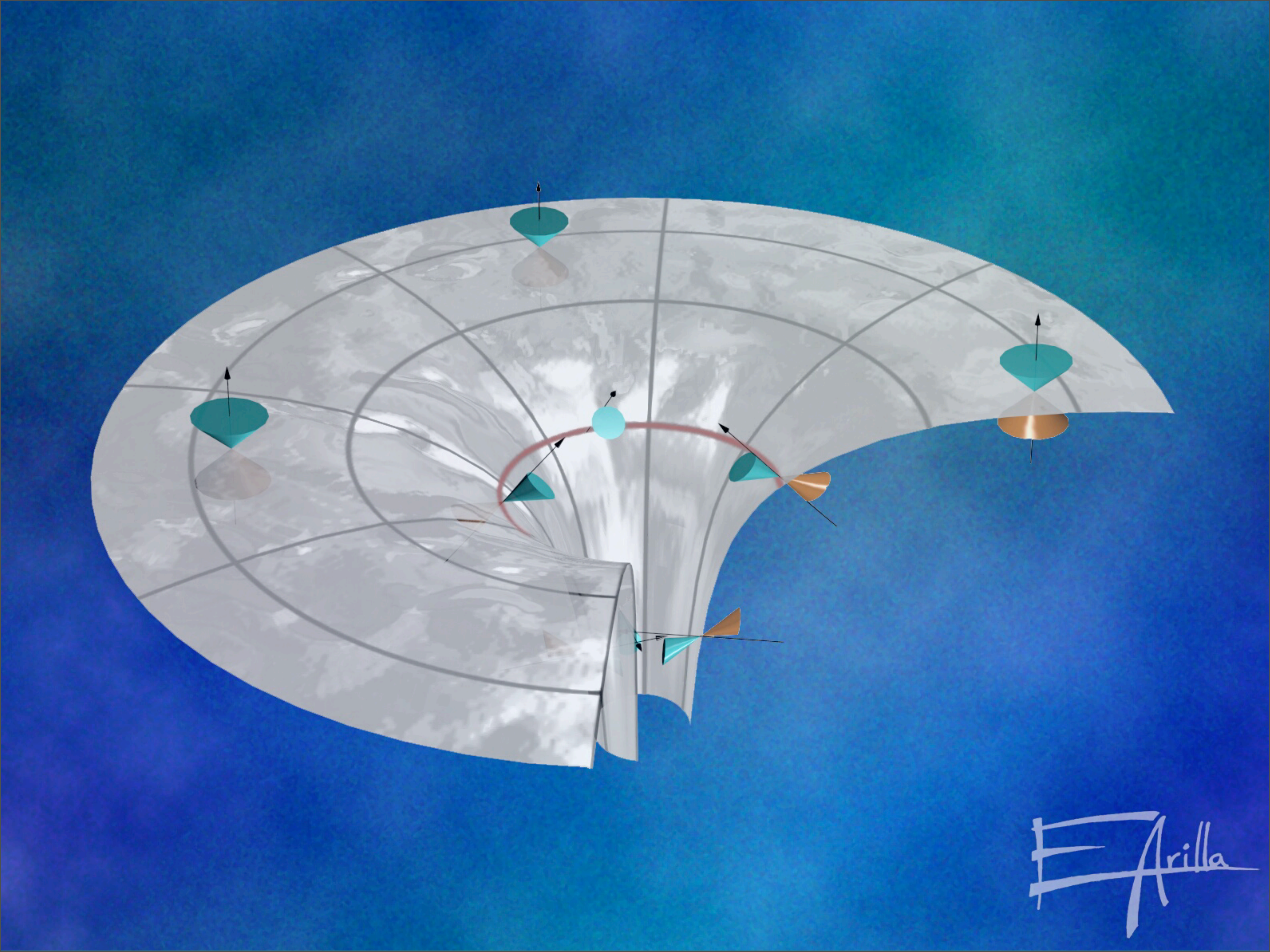
--- Johannes Kepler

Acoustic spacetime:

The simplest "analogue spacetimes" are the "acoustic spacetimes"...



Consider sound waves in a moving fluid... [Unruh]


EArilla

Key results:

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Acoustic propagation in fluids can be described in terms of Lorentzian differential geometry.

The acoustic metric depends algebraically on the fluid flow.

Acoustic geometry shares kinematic aspects of general relativity, but not the dynamics.

Einstein equations versus Euler equation.

In particular:
Acoustic black holes divorce kinematic aspects of black hole physics from the specific dynamics due to the Einstein equations.

Advanced features:

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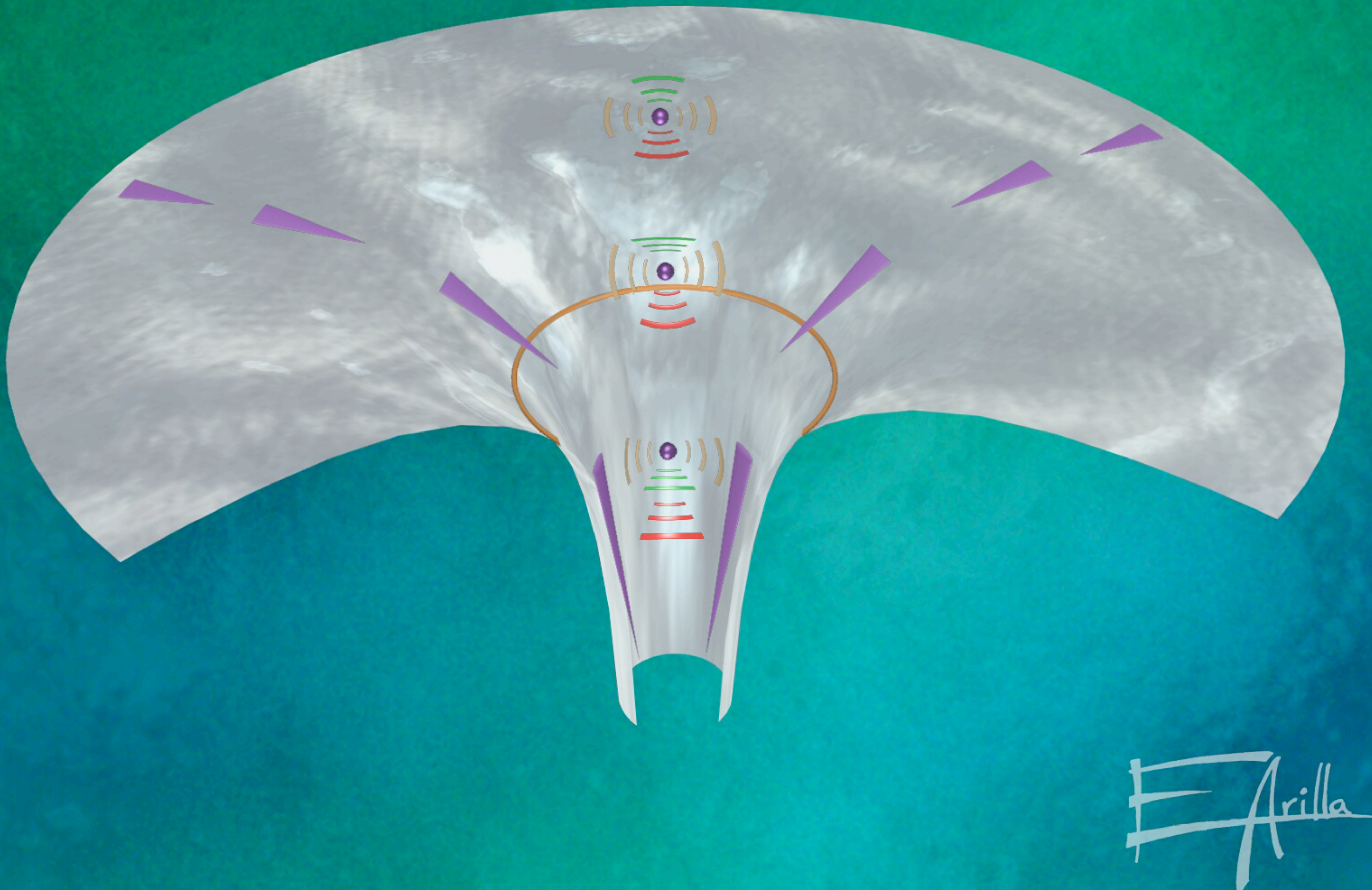
There are also other "analogue models" of general relativity, apart from the acoustic models.

Acoustic black holes have Hawking radiation without black hole entropy.

Hawking radiation is a purely kinematic effect that exists independent of whether or not the Lorentzian geometry obeys any particular geometrodynamics.

You do not need the Einstein equations to get Hawking radiation.

Acoustic perturbations do not “see” the physical metric --- they couple only to the acoustic metric.



Why bother?

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If you are a general relativist, this acoustic analogy gives you simple concrete physical models for curved spacetime.

If you are a fluid mechanic (or more generally a condensed matter physicist) the differential geometry of curved spacetimes gives you a whole new way of looking at sound (and other excitations).

Of course these analogue spacetimes can be greatly generalized: all you really need are well-defined characteristic speeds.

Physics examples:

There are numerous physical examples where we have direct experimental/observational evidence for acoustic metrics, up to and including acoustic horizons (dumb holes).

NB: "dumb" = "mute" (silent).

Main examples:

--- draining bathtub (acoustics and/or surface waves).
--- supersonic wind tunnels (Laval nozzles).
--- oscillating bubbles (acoustic apparent horizons).
--- Parker wind (stellar coronal outflow).
--- Bondi accretion.

Current status:

So far, these analogue spacetimes give you roughly half of general relativity.

You get the kinematics, up to and including curved spacetime quantum field theory.

You do not yet get a good justification for the Einstein equivalence principle.

You do not yet get the Einstein equations.

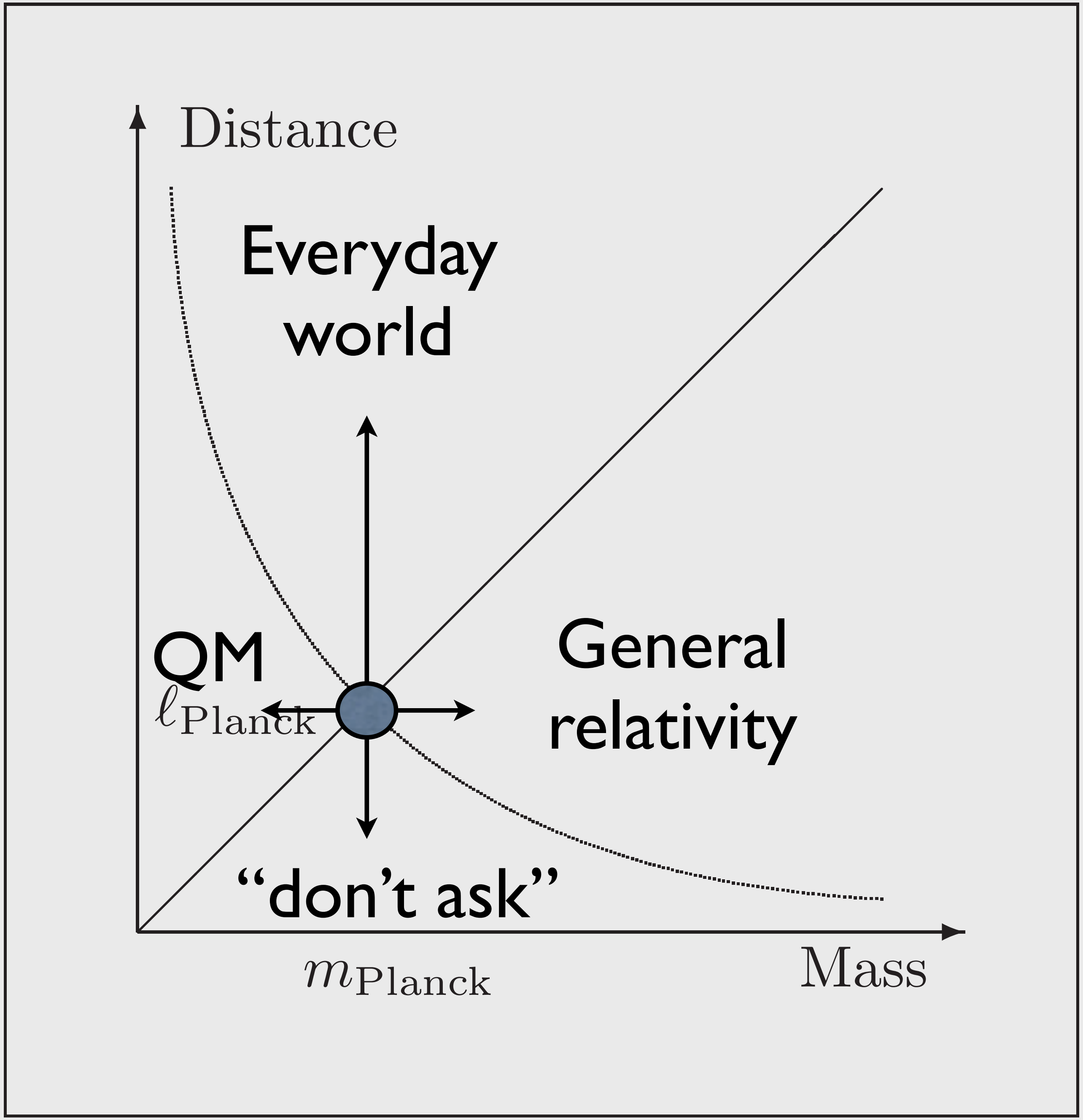
These are two really big issues...

For the future:

Two technical questions:

- Does "decoupling" lead to the Einstein equivalence principle?
- Does "decoupling" lead to the Einstein equations?

Decoupling seems necessary, and there are reasons to suspect that it might be sufficient.


Distance
Everyday world
QM
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"It is important to keep an open mind; just not so open that your brains fall out"

--- Albert Einstein