Dumb Holes and Bayesian Confirmation

Stephan Hartmann (MCMP/LMU Munich)

with R. Dardashti (Hannover), K.Thébault (Bristol) & E. Winsberg (USF)

April 27, 2017

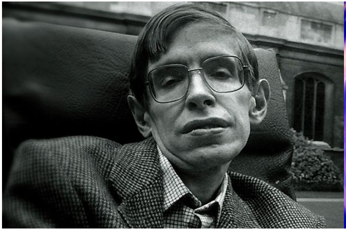
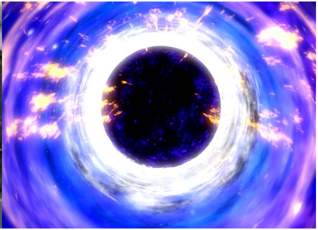
1975: Hawking derives a semi-classical result associating a radiative flux to black hole event horizons: black holes are hot!

Commun. math. Phys. 43, 199—220 (1975)

Particle Creation by Black Holes

S. W. Hawking
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England

Received April 12, 1975

Testing this prediction of gravitational Hawking radiation is virtually impossible – the temperature is of the order of billionths of a kelvin.

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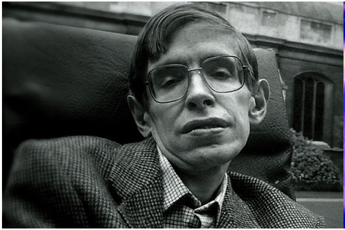
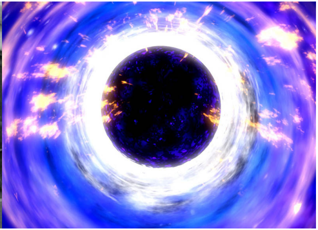




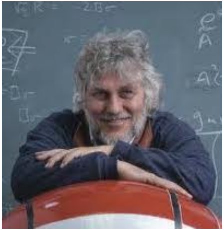
1981: Inspired by the analogy with sound waves in a waterfall, Unruh shows that Hawking's semi-classical arguments can be applied to sonic horizons in fluids: 'dumb holes' are hot!

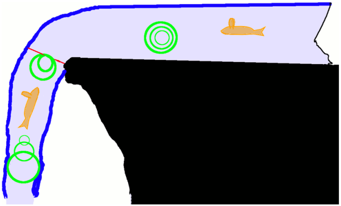
PHYSICAL REVIEW LETTERS

VOLUME 46 25 MAY 1981 NUMBER 21

Experimental Black-Hole Evaporation?

W. G. Unruh
Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada
(Received 8 December 1980)





From the outset such analog models were constructed with the idea of experimental testing of Hawking's prediction. However, water proved too noisy a medium to detect quantum effects.

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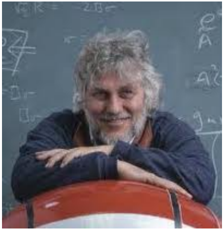

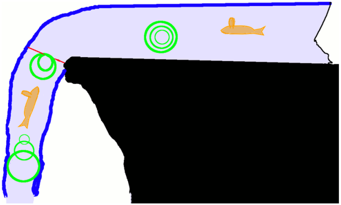

2016: Jeff Steinhauer reported the experimental observation of Hawking radiation in a Bose-Einstein condensate acoustic analog black hole.

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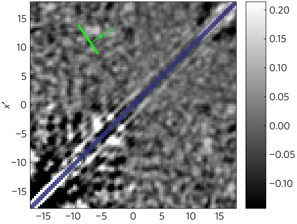
PUBLISHED ONLINE: 15 AUGUST 2016 | DOI: 10.1038/NPHYS3863

Observation of quantum Hawking radiation and its entanglement in an analogue black hole

Jeff Steinhauer



The Steinhauer result was met with worldwide press excitement, with newspaper reports (of varying quality) in many countries and even speculation that Hawking would be awarded the Nobel prize on the basis of the Steinhauer experiments.

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Science & Environment

Simulated black hole experiment backs Hawking prediction

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The Israeli Research That's Bringing Stephen Hawking Closer to the Nobel Prize

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DAILY NEWS 15 August 2016

Black hole made in the lab shows signs of quantum entanglement

The response of physicists was more mixed, with excitement about the technical achievement of the dumb hole experiment tempered by scepticism as to the consequences for black holes.

"...an amusing feat of engineering that won't teach us anything about black holes"

–Daniel Harlow (Harvard)

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What Sonic Black Holes Say About Real Ones

Can a fluid analogue of a black hole point physicists toward the theory of quantum gravity, or is it a red herring?

What can we learn from such *analog experiments*?

Can they provide us with *evidence* of a similar type to that provided by conventional experiments?

In particular, are there circumstances in which they be taken to provide *inductive support* for conclusions about astrophysical black holes?

Plan of Talk

1. Bayesian Confirmation Theory
2. Hawking Radiation and Multiple Realiziablity
3. Validating Analog Experiments
4. Bayesian Analysis

1. Bayesian Confirmation Theory

Confirmation and Corroboration

- Empirical data are relevant for the assessment of scientific theories and scientific theories should account for the empirical phenomena in their domain. After all, they are empirical theories, and not just pieces of mathematics.
- Empirical data E ("evidence") confirm or disconfirm a given theory H. This means that we have **a good reason to belief in the truth of H** and therefore a good reason to apply the theory in the future.
- But what does it exactly mean that E confirms H? How can this relation be explicated? To address this question, we will look at two confirmation theories developed by philosophers of science.
- Before, however, we consider Popper's falsificationism. Popper was an anti-inductivist: For him, a theory can never be confirmed. It can only be **corroborated** which – importantly – has no implications for our beliefs in the theory's expected future performance.

Theory Assessment I: Popper's Falsificationism

- According to ***naive falsificationism***, a theory or hypothesis H is corroborated if an empirically testable prediction of H obtains. Otherwise it is falsified and should be rejected and replaced by an alternative theory.
- N.B.: More sophisticated versions of falsificationism have the same problem as naive falsificationism, and so I won't discuss them here.
- It is important to note that, according to falsificationism, a theory can only be corroborated empirically. Hence, **a Popperian cannot make sense out of analog corraboration** (at least not in a straight forward way). It is not an acceptable way to empirically justify a theory.

Theory Assessment II: The Hypothetico-Deductive Model

- According to the ***hypothetico-deductive model***, a theory or hypothesis H is confirmed by a piece of evidence E iff E is predicted by H (i.e. if E is a deductive consequence of H) and if E is observed.
- Also here, a theory or hypothesis can only be confirmed empirically and it is hard to imagine how a defender of the hypothetico-deductive model can make sense out of analog confirmation.
- The HD-model has a number of other well-known problems, e.g.
  1. **The Tacking Problem:** If E confirms H, then it also confirms $H \wedge X$. Note that X can be a completely irrelevant proposition. This is counter-intuitive.
  2. **Degrees of confirmation:** Some evidence confirms a theory or hypothesis more than other evidence. However, according to the hypothetico-deductive model, we can only make the qualitative inference that E confirms H (or not).

Theory Assessment III: Bayesian Confirmation Theory

- According to ***Bayesian Confirmation Theory***, a theory or hypothesis H is confirmed by a piece of evidence E iff the observation of E raises the (subjective) probability of H.
- Scientists attach a degree of belief (= a probability) to a theory or hypothesis and change ("update") it in the light of new evidence.
- Reasons are provided why this is a rational procedure (e.g. Dutch Book arguments).
- What evidence? An observed instance of a law, testimony,...
- How should one update? **Conditionalization** (at least in many cases): The posterior probability of H (i.e. $P'(\mathrm{H})$) follows from the *prior probability* of H (i.e. $P(\mathrm{H})$), the *likelihood* of the evidence (i.e. $P(\mathrm{E}|\mathrm{H})$) and the *expectancy* of the evidence (i.e. $P(\mathrm{E})$):

Bayes Theorem

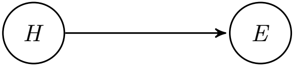
$$P'(\mathrm{H}) := P(\mathrm{H}|\mathrm{E}) = \frac{P(\mathrm{E}|\mathrm{H}) \cdot P(\mathrm{H})}{P(\mathrm{E})}$$

Discussion

- Bayesian Confirmation Theory can be applied in a straightforward way to empirical testing, i.e. to the case where a direct **deductive or inductive consequence E of H** is observed.
- Note that Bayesian Confirmation Theory accounts for the fact that some evidence confirms a hypothesis better than another piece of evidence. One way to measure the degree of confirmation is by using the **difference measure** $d(\mathrm{H},\mathrm{E}) := P(\mathrm{H}|\mathrm{E}) - P(\mathrm{H})$.
- What is more, it turns out that the Bayesian machinery is flexible enough to also model indirect ways of confirming theories and we will later see how this works for analog confirmation.

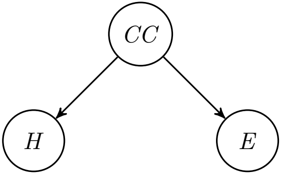
Bayesian Networks

1. Direct confirmation



- Specify the prior $P(H)$ and the likelihoods $P(E|H)$ and $P(E|\neg H)$.

2. Indirect confirmation



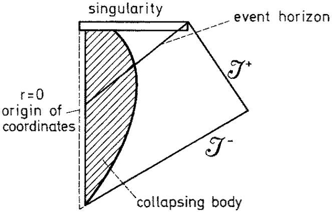
- Specify the prior $P(CC)$ and the likelihoods $P(E|CC)$, $P(E|\neg CC)$, $P(H|CC)$ and $P(H|\neg CC)$.
- The "common cause" CC shields off H from E: Learning E if CC is known does not change the probability of H.

2. Hawking Radiation and Multiple Realiziablity

Gravitational Hawking Effect

– In the semi-classical approach to gravity that Hawking's original calculation takes place we consider a *quantum field* propagating within a *classical spacetime* and assume there is no backreaction.

– For this modelling framework to be valid it is assumed that we are considering quanta of wavelengths much larger than the Planck length.



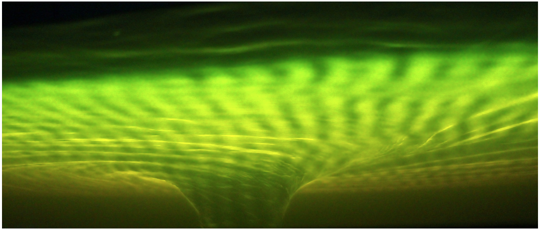
Gravitational Hawking Effect

$$\frac{\text{Semi-Classical Gravity}}{\text{Quantum Gravity}}$$

Gravitational Hawking Effect

$$\frac{\text{Long Wavelength}}{\text{Planck Wavelength}}$$

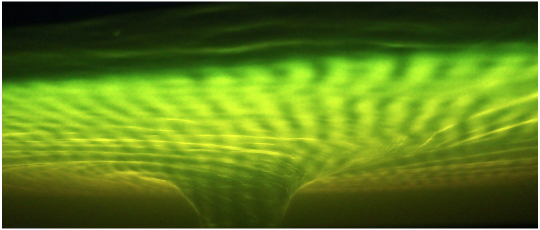
The Fluid Mechanical Hawking Effect



– Sound is a small vibratory or wavelike disturbance in a medium. The classical acoustic model of a fluid is as a continuous, compressible, inviscid medium. Sound is then a longitudinal oscillatory motion with small amplitude within the medium.

– Propagation of sound in a fluid can be understood as being governed by an *effective acoustic spacetime*: acoustic perturbations couple only to the effective acoustic spacetime and not to the physical spacetime within which the fluid exists.

The Fluid Mechanical Hawking Effect



- One is able to stretch the fluid/gravity connection even further and consider *both* classical and quantum mechanical acoustic phenomena within the fluid using the same equations as for radiative phenomena within a black hole spacetime.
- The relevant calculation for the acoustic case proceeds in *precisely* the same manner as the Hawking calculation only with the quantum field corresponding to sound, and late time flux from the 'dumb hole' being made up of phonons (the quanta of sound).

Hydrodynamic Hawking Effect

Continuum Hydrodynamics

Molecular Hydrodynamics

Hydrodynamic Hawking Effect

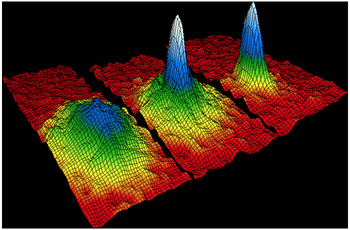
$$\frac{\text{Long Wavelength}}{\text{Molecular Wavelength}}$$

Bose-Einstein Condensation

– A Bose-Einstein condensate (BEC) is an exotic form of matter that Bose (1924) and Einstein (1924,1925) predicted to exist for a gas of atoms when cooled to a sufficiently low temperature.

– In 1995, the experimental demonstration of the existence of a BEC was provided using supercooled dilute gases of alkali atoms.

– The crucial observation was a sharp increase in the density of the gas at a characteristic frequency of the lasers used for cooling.



The BEC Hawking Effect

nature physics

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Observation of quantum Hawking radiation and its entanglement in an analogue black hole

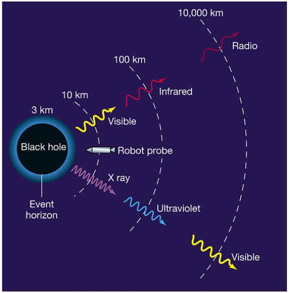
Jeff Steinhauer

- Doing quantum analog experiments on sound in a fluid has proved impossible in practice. Rather in the Steinhauer experiments a Bose-Einstein condensate (BEC) was used.
- The key point is that the theoretical model of the BEC has the same syntactic form as that used by Hawking: in particular we have an effective spacetime, an acoustic horizon and a late time phonon flux.

Multiple Realizability?

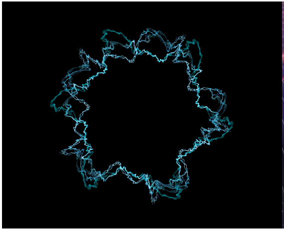
- There are now a huge number of potential analog realisations of the Hawking effect: phonons in superfluid liquid helium, ‘slow light’ in moving media, traveling refractive index interfaces in nonlinear optical media, laser pulses in nonlinear dielectric medium…
- To realize the Hawking effect it seems it is sufficient to have: i) a classical (effective) background with quantum fields living on it; and ii) an (effective) geometry with an (effective) causal horizon.

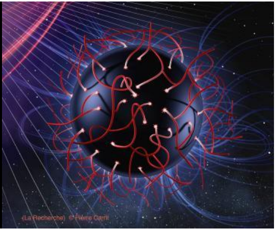
'Trans-Planckian' Problem



In the standard calculation of the Hawking temperature exponential gravitational red-shift means that the black hole radiation detected at late times (i.e. the outgoing particles) must be taken to correspond to extremely high frequency radiation at the horizon.

‘Trans-Planckian’ Problem





Such a ‘trans-Planckian’ regime is the dominion of theories of quantum gravity, and is thus well beyond the domain of applicability of the modelling framework we are using.

‘Trans-Planckian’ Problem

- This problem with ‘trans-Planckian’ modes has a direct analog in the BEC case.
- There will be a similar trans-Planckian regime in which the Hawking type model breaks down for any other analog realisation: *condensed matter models are never valid to arbitrarily small length scales!*

BEC Hawking Effect

Hydrodynamic BEC

Gross-Pitaevskii BEC

$$\frac{\text{Long Wavelength}}{\text{Healing Wavelength}}$$

Model Limitations

Semi-Classical Gravity	Continuum Hydrodynamics	Hydrodynamic BEC
Quantum Gravity	Molecular Hydrodynamics	Quantum Field Theory

Model Limitations

Hawking Effect	Hawking Effect	Hawking Effect
Quantum Gravity	Molecular Hydrodynamics	Quantum Field Theory

Universality of the Hawking Effect

PHYSICAL REVIEW D **71,** 024028 (2005)

Universality of the Hawking effect

William G. Unruh[1] and Ralf Schützhold[2]

[1]*Canadian Institute for Advanced Research Cosmology and Gravity Program, Department of Physics & Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, British Columbia, Canada V6T 1Z1*

[2]*Institut für Theoretische Physik, Technische Universität Dresden, D-01062 Dresden, Germany*

(Received 3 August 2004; published 24 January 2005)

This is where the 'universality' results of Unruh and Schützhold are crucial: they show that the Hawking effect does not, to lowest order, depend on the details of underlying physics, given certain modelling assumptions.

Universality of the Hawking Effect

Semi-Classical Gravity	Continuum Hydrodynamics	Hydrodynamic BEC
———————	———————	———————
Quantum Gravity	Molecular Hydrodynamics	Quantum Field Theory

Universality of the Hawking Effect

$$\frac{\text{Hawking Effect}}{\text{Quantum Gravity}} \qquad \frac{\text{Hawking Effect}}{\text{Molecular Hydrodynamics}} \qquad \frac{\text{Hawking Effect}}{\text{Quantum Field Theory}}$$

Universality of the Hawking Effect

Hawking Effect	Hawking Effect	Hawking Effect
$\uparrow\uparrow\uparrow\uparrow$	$\uparrow\uparrow\uparrow\uparrow$	$\uparrow\uparrow\uparrow\uparrow$
Quantum Gravity	Molecular Hydrodynamics	Quantum Field Theory

Universality as Multiple Realizability

– Batterman (2000) influentially argued that we can understand the universality of critical phenomena in condensed matter systems as an instance of multiple realizability.

– Although his analysis focuses upon asymptotics/RG techniques there is no obvious necessary connection between such techniques and the general features characteristic of 'universality as multiple realizability' that he isolates (cf. Butterfield 2011).

Universality as Multiple Realizability

Following Batterman (2000, p.123) the two characteristic features of universality (as multiple realizability) are:

1. Details of microstructure of a given token system are largely irrelevant for describing behaviour generically exhibited by members of the system type.
2. Many different system types, with physically distinct microstructure (e.g. fluids and magnets), exhibit the same behaviour.

Universality as Multiple Realizability

Adapting this account to the case in hand, the universality of the Hawking Effect is established by the Unruh and Schützhold result, in that:

1. Details of 'trans-Planckian' structure of a given (analog) black hole system are largely irrelevant for describing thermal behaviour generically exhibited by the associated causal horizons – i.e. Hawking radiation.
2. Many different realisations of the (analog) black hole system, with distinct 'trans-Planckian' structure (e.g. black holes and BECs), have causal horizons that exhibit Hawking radiation.

Universality as Multiple Realizability

In this precise sense we can say that, provided the conditions of Unruh and Schützhold universality argument are satisfied, the Hawking effect is an example of universality as multiple realizability.

3. Validating Analog Experiments

Validating Experiments

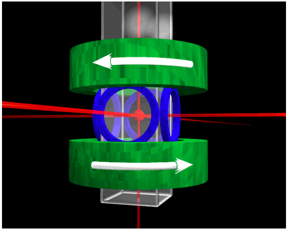
We can make an important distinction between two different types of validation in the context of experimental science:

- An experimental result is **internally valid** when the experimenter is genuinely learning about the actual system they are manipulating – when, that is, the system is not being unduly disturbed by outside interferences.
- An experimental result is **externally valid** when the information learned about the system being manipulated is relevantly probative about the class of systems that are of interest to the experimenters.

Bose-Einstein Condensation

– A Bose-Einstein condensate (BEC) is an exotic form of matter the existence of which was first experimentally demonstrated in 1995 using a supercooled dilute gas of Alkali atoms.[1]

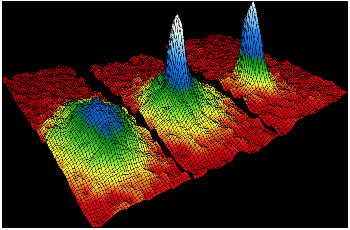
– In the experiment of Anderson et al. (1995) a sample of ^{87}Rb atoms was cooled in a magneto-optical trap. It was then loaded into a magnetic trap and further cooled by evaporation.



[1] Here we are following the excellent discussion of Franklin, https://plato.stanford.edu/entries/physics-experiment/app3.html

Bose-Einstein Condensation

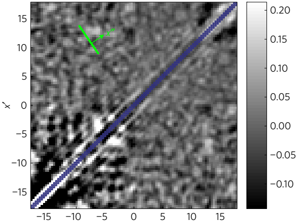
- The trap was then removed and the sample was illuminated with laser light and the resulting shadow of the cloud was imaged, digitized, and stored.
- The crucial observation, that confirmed the sample to be in a Bose-Einstein condensate phase, was a sharp increase in density at a characteristic frequency of the lasers used to assist cooling.



Validating Experiments

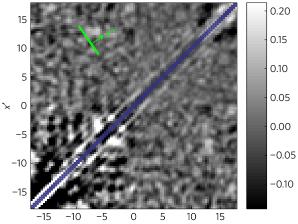
- The internal validity of the experiments relates to the question of whether or not the results obtained genuinely reflect the fact that the particular supercooled dilute gases of alkali atoms experimented upon were behaving as a BEC.
- The external validity of the experiments relates to the question of whether or not the inferences regarding the particular *source systems* experimented upon (particular supercooled dilute gases of alkali atoms) can be reliably generalised to the wide class of *target systems* that the theory of BECs refers to.

The Technion Experiments



– In his landmark experiment Steinhauer used a BEC of ^{87}Rb atoms confined radially by a narrow laser beam.
– The horizon was created by a very sharp potential step which is swept along the BEC at a constant speed.
– Significantly the length scales are such that the hydrodynamic description of a BEC is appropriate: the width of the horizon is of the order or a few times bigger than the healing length.

The Technion Experiments



- The main experimental result consists of an aggregate correlation function computed based upon an ensemble of 4,600 repeated experiments which were conducted over six days.
- Given some reasonable assumptions (for example modes at different frequency are assumed to be independent of each other) the experiments can be interpreted as establishing an ‘entanglement witness’ to Hawking radiation in BEC.

Internal Validation

- Was Steinhauer genuinely learning about the physics of the particular sonic horizon within the particular ^{87}Rb BEC that he was manipulating?
- Various sources of internal validation are apparent from the description of the experimental set up given, not least the repetition of the experimental procedure nearly five thousand times.
- Given this, the evidence gained from the experiments conducted can be categorised as of the appropriate epistemic type to be used to confirm specific statements regarding the particular BEC that was experimented upon.

External Validation (Conventional)

- Can the particular sonic horizon that was constructed, within the particular ^{87}Rb BEC, stand in for a wider class of BEC systems?
- For example, all BEC sonic horizons within the realm of validity of the hydrodynamic approximation to the Gross-Pitaevskii equation, regardless of whether the relevant systems have been (or even could be) constructed on earth.
- Given this set of systems obeys the ‘reasonable assumptions’ of the Steinhauer experiments, such as modes at different frequency are assumed to be independent of each other, then we can also externally validate the experiments in the conventional sense.

External Validation (Analogue)

- We claim that theoretical arguments for the universality of Hawking radiation can function as external validation for the Steinhauer experiments.
- That is, such arguments give us a *theoretical basis* to take the source system of the Technion experiments to stand in for a wider class of target systems, including astrophysical black holes.
- We then claim, that given such external validation, analogue experiments can confer inductive support to hypotheses regarding target systems that we are not directly manipulating such as astrophysical black holes.

Validating Analog Experiments

– The key question in the *epistemology of analog experimentation* is then whether there are arguments that can provide external validation of the analog experiments *qua* analog experiments.

– By this I mean in addition to the necessary conventional external validation, can we provide arguments that the relevant source systems ‘stand-in’ for the target systems to which the analogical relationship refers.

– In our case, can we provide arguments that dumb holes can ‘stand-in’ for astrophysical black holes?

Validating Analog Experiments

- If accepted, the theoretical universality arguments of Unruh and Schützhold would function as external validation for the Steinhauer experiments, given we interpret them as establishing Hawking radiation as multiple realizable.
- That is, they give us a *theoretical basis* to take the source system of the Steinhauer experiments to stand in for a wider class of target systems, including astrophysical black holes.

4. Bayesian Analysis

Analogy and Confirmation

- Some authors suggest that arguments by analogy can only establish the *plausibility* of a conclusion, and with it grounds for further investigation (Salmon 1990, Bartha (2010).
- Hesse (1964), on the other hand, suggests that we can incorporate confirmatory arguments by analogy within Carnap's confirmation theory.

Analogy and Confirmation

- From a Bayesian perspective, however, conventional arguments by analogy seem to fall foul of the old evidence problem: information encapsulated in an analogical argument must reasonably be taken to be part of the background knowledge, and thus cannot be confirmatory in Bayesian terms (Bartha 2010, 2013).
- **This point is simply irrelevant to the case of analog experimentation since the evidence we gain is new empirical evidence.**

Confirmation via Analog Experimentation

We can model confirmation via (externally validated) analog experimentation in Bayesian confirmation theory as follows:

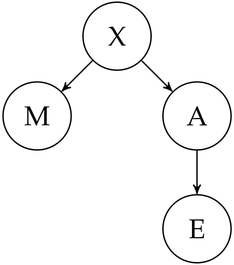
– Call E the proposition that BEC Hawking radiation is detected.

– Call A the proposition that the hydrodynamic BEC model is empirically adequate.

– Call M the proposition that the semi-classical gravitational model is empirically adequate.

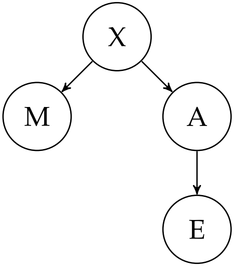
– Call X the proposition that Unruh and Schützhold arguments establish the Hawking effect as an example of universality as multiple realizability (as defined earlier).

Confirmation via Analog Experimentation



The inferential relationships between universality, the two models, and the evidence allows us to draw the Bayesian network above. That $P(E|A) > P(E|\bar{A})$ is true by definition.

Confirmation via Analog Experimentation

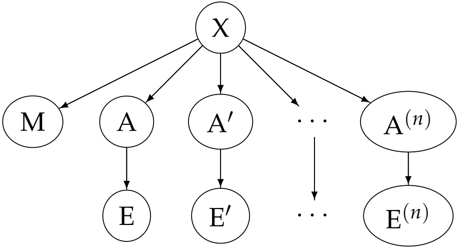


Universality as multiple realizability directly implies $P(M|X) > P(M|\bar{X})$ and $P(A|X) > P(A|\bar{X})$ since, for each model, it establishes the empirical irrelevance of the trans-Planckian physics not modelled.

Confirmation via Analog Experimentation

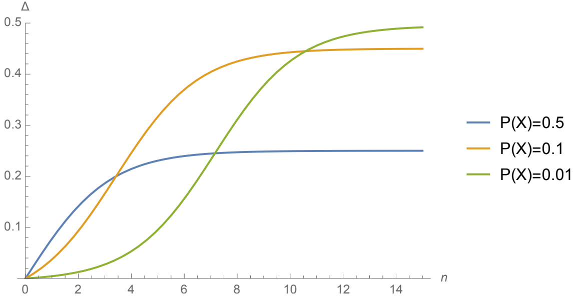
- Given the structure of this network, it is straight-forward to prove that $P(M|E) > P(M)$ provided $0 < P(X) < 1$.
- Provided we assign a non-zero (or one) prior probability to universality, evidence for BEC Hawking radiation confirms gravitational Hawking radiation in a Bayesian sense.

Confirmation via Analog Experimentation



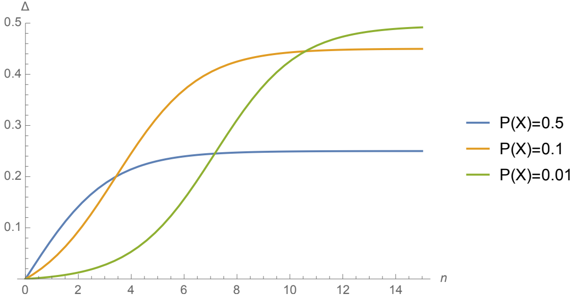
The network can be generalised to the case of an arbitrary number of *independent* analog systems.

Saturation of Confirmation



We can then model the process of gaining more and more evidence from independent analog systems up to a *saturation point* where the quantity $\Delta^{(n)} = P(M|E, E', ..., E^{(n)}) - P(M)$ stops growing.

Saturation of Confirmation



A further interesting feature that we can examine is the speed with which the saturation point is approached. The higher the prior probability of X, the quicker the saturation point is reached.

Saturation of Confirmation

- This result is in tune with scientific intuitions. At the moment we have only one implementation of a source system for the Hawking effect: the BEC in the Steinhauer experiments.
- Given initial confidence in the universality arguments, if another different implementation of a source system displaying the Hawking effect was achieved, that should surely radically increase the belief in the astrophysical Hawking effect.
- However, once a few such examples were constructed, one would quickly stop gaining new insight.

Saturation of Confirmation

- Conversely, given initial skepticism regarding the universality arguments, a second implementation of the dumb hole source system would not radically increase the belief in the astrophysical Hawking effect.
- Furthermore, in such circumstances it would only be after a diverse and extensive range of implementations of source systems that one would stop believing that new examples gave new information.

Epistemology of Analog Experimentation

- We intend these results to be the steps in an 'epistemology of analog experimentation'.
- We think that the evaluation of analog experimentation is dependent upon the availability of arguments for external validation.
- We are planning to consider further detailed case studies of analog experimentation with a view to finding whether there are arguments for external validation (or not).

For more details see:

1. Radin Dardashti, Stephan Hartmann, Karim Thébault, and Eric Winsberg: Confirmation via Analog Simulation: A Bayesian Analysis, *http://philsci-archive.pitt.edu/12221/*.
2. Karim Thébault: What Can We Learn From Analog Experiments?, *http://philsci-archive.pitt.edu/12484/*.
3. Radin Dardashti, Karim Thébault, and Eric Winsberg: Confirmation via Analog Simulation: What Dumb Holes Could Tell us about Gravity, *The British Journal for the Philosophy of Science* (2017).

Thanks!

Universality of the Hawking Effect

In more general terms, Unruh and Schützhold suggest that the Hawking effect will be insensitive to the details of the trans-Planckian physics provided the following three conditions obtain:

a. Local Lorentz invariance is broken at the Planck scale via the introduction of the freely falling preferred frame.

b. The Planckian excitations are assumed to start off in their ground state with respect to the freely falling frame.

c. The evolution of the modes is assumed to be adiabatic (i.e. the Planckian dynamics is supposed to be much faster than all external (sub-Planckian) variations)