THE TIME MACHINE FACTORY CONFERENCE 2019
UNIVERSITÁ DI TORINO, 22 SEPTEMBER 2019

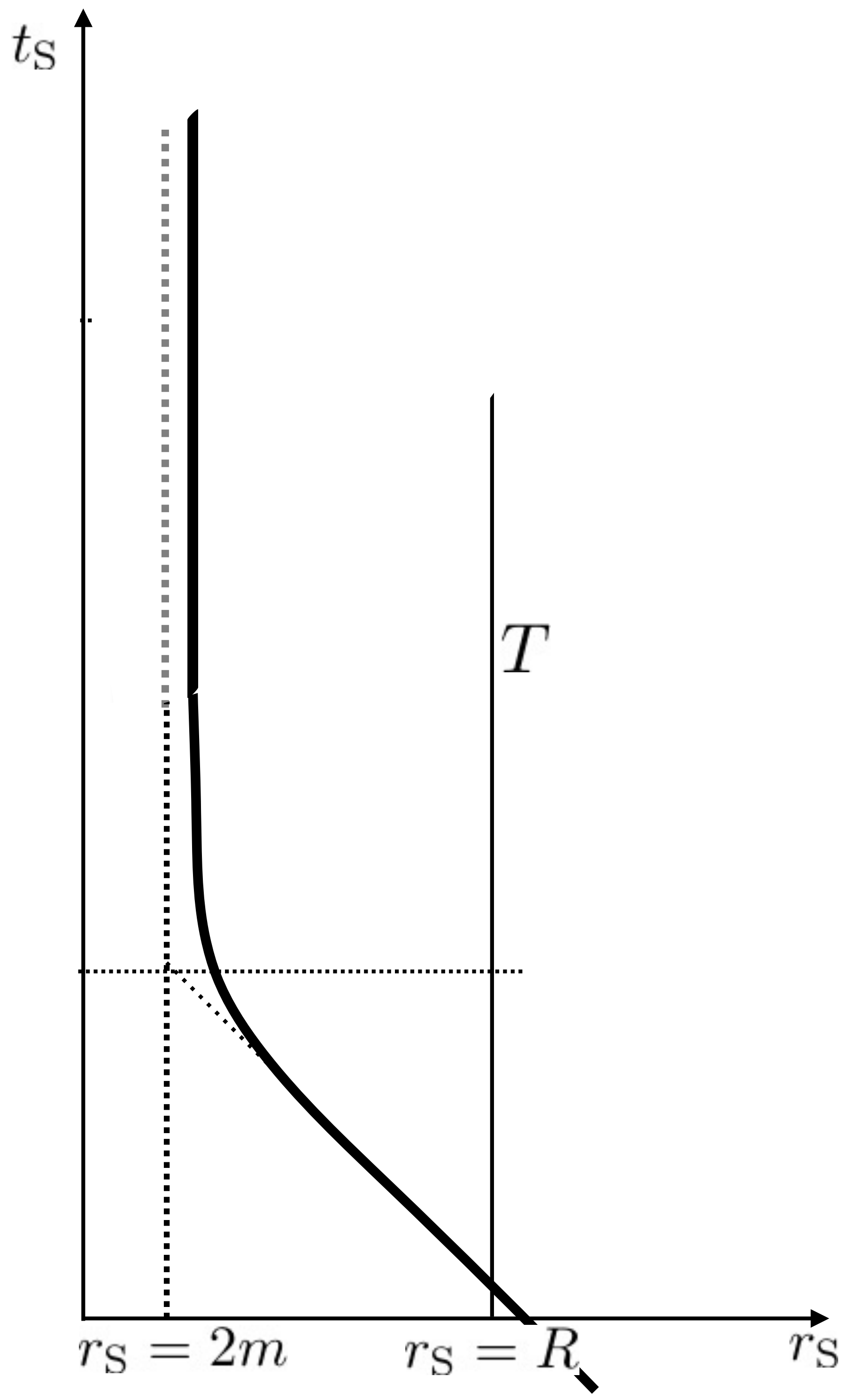

Illustration by Chris Gash

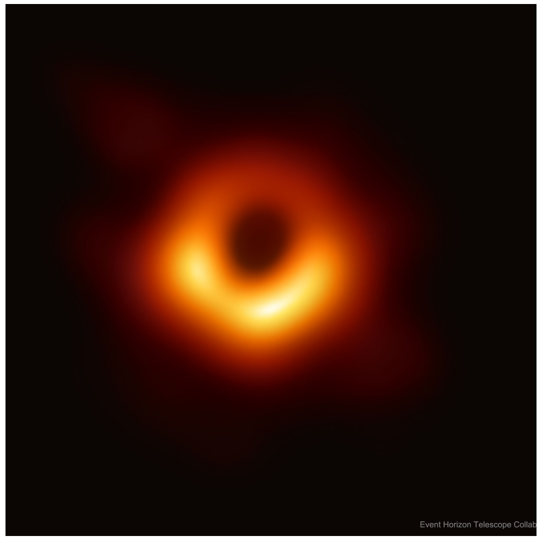
BLACK HOLES ARE TIME MACHINES

Francesca Vidotto

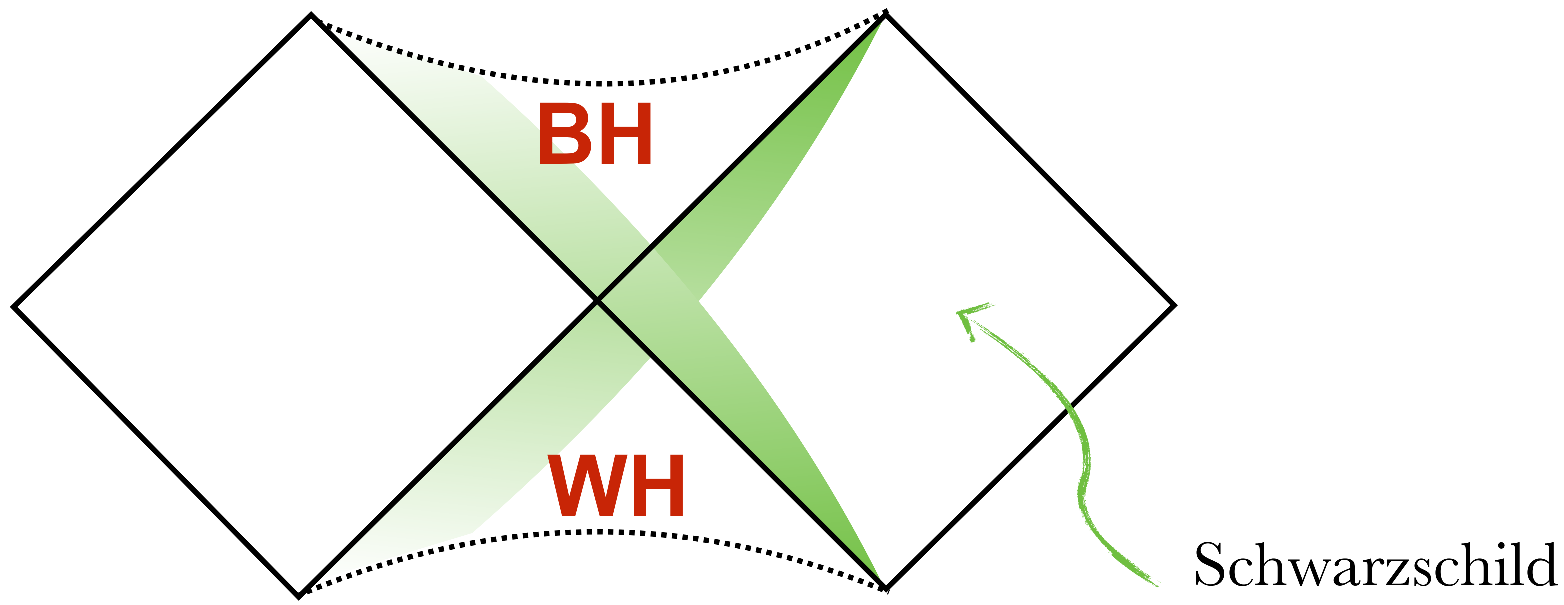
Western Ontario



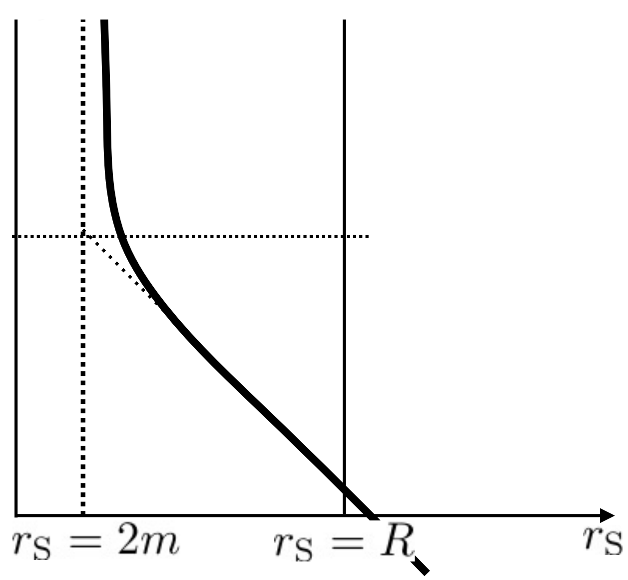

t_S
T
$r_S = 2m$
$r_S = R$
r_S

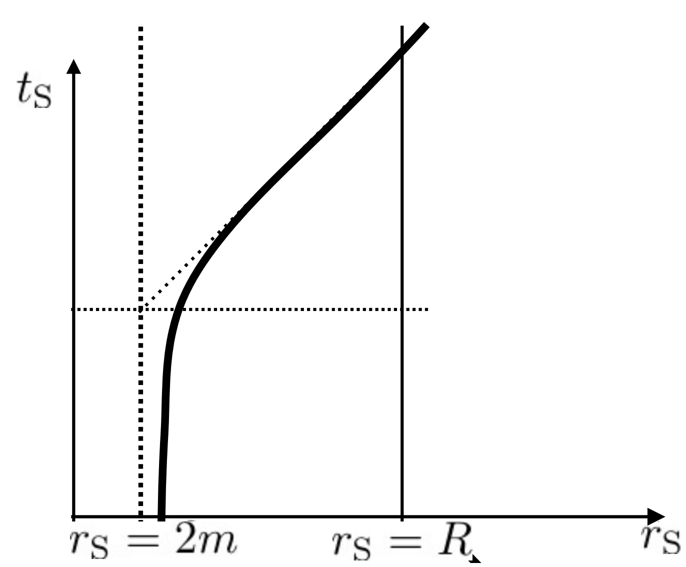


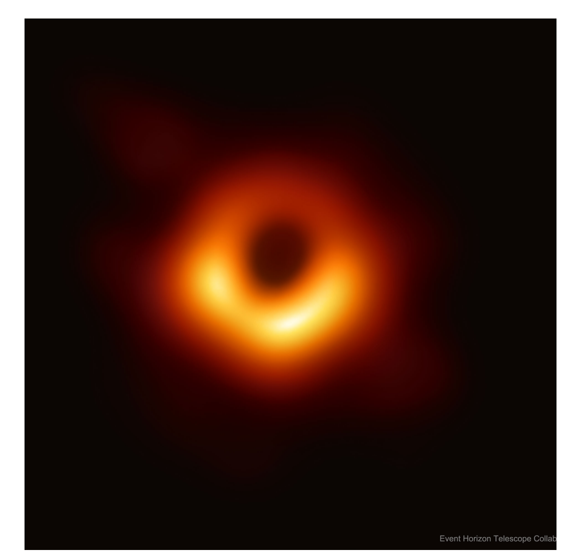
SCHWARZSCHILD IS BOTH BLACK AND WHITE



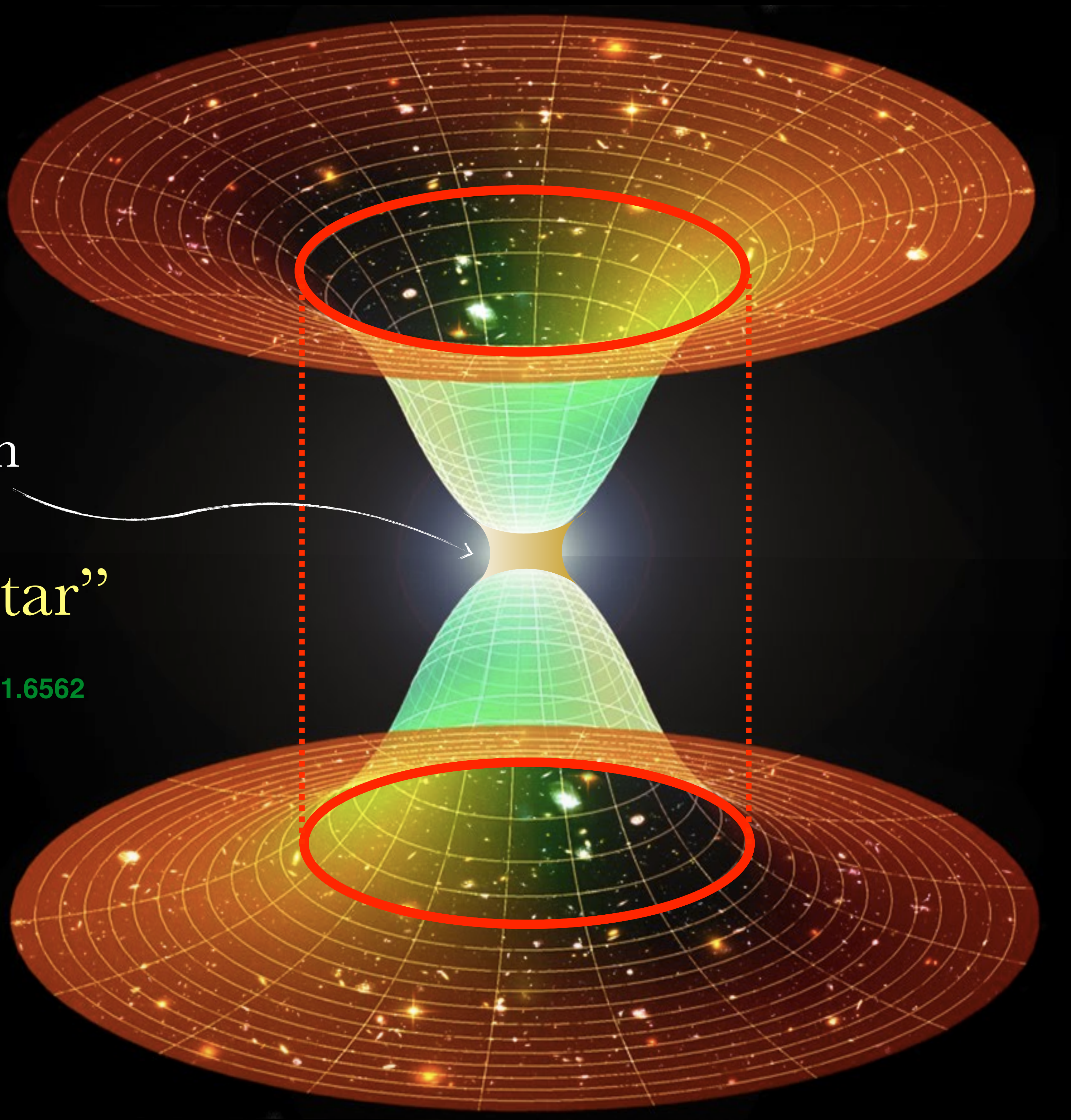
- White Holes and Black Holes shares the same Schwarzschild spacetime
- Only checking if matter is outgoing or ingoing they can be distinguished
- This could be practically impossible! A long time may be needed!







BH EXPLOSION



quantum region

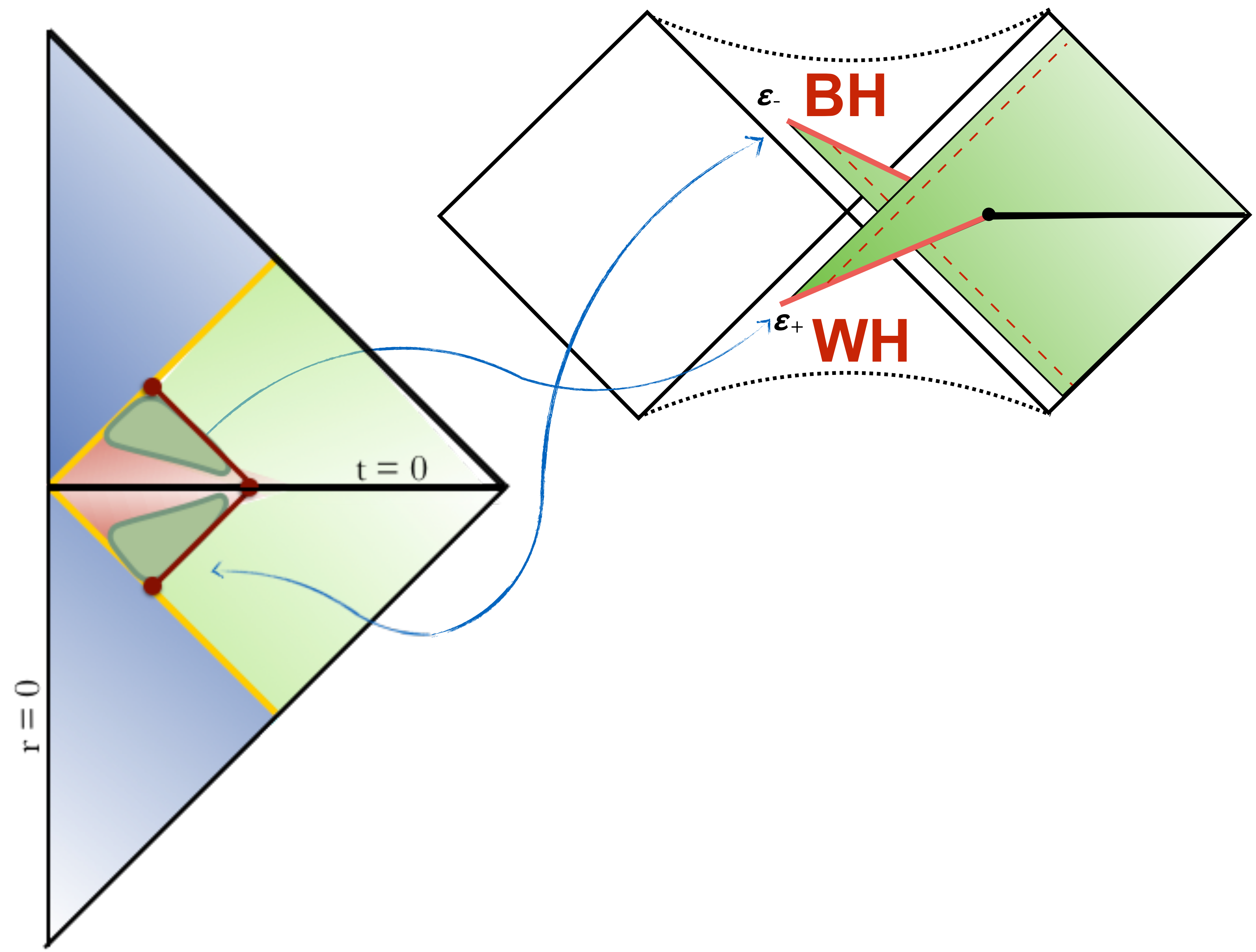
"Planck Star"

Vidotto, Rovelli 1401.6562

Black -to- White tunnelling

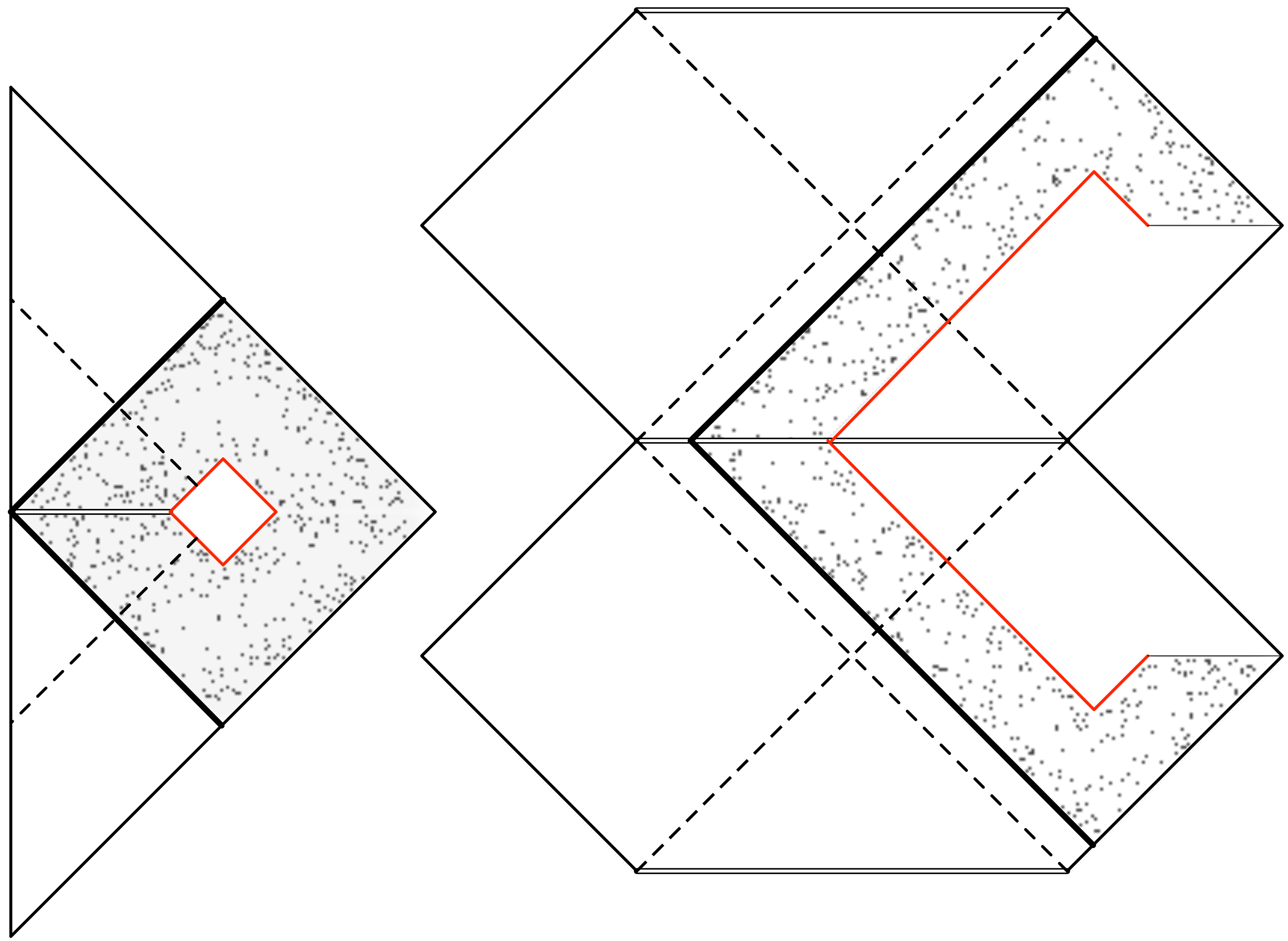
CAUSALITY

Haggard, Rovelli 1407.0989



WHITE HOLES AS REMNANTS

Bianchi, Cristodoulou, D'Ambrosio, Haggard, Rovelli 1802.04264



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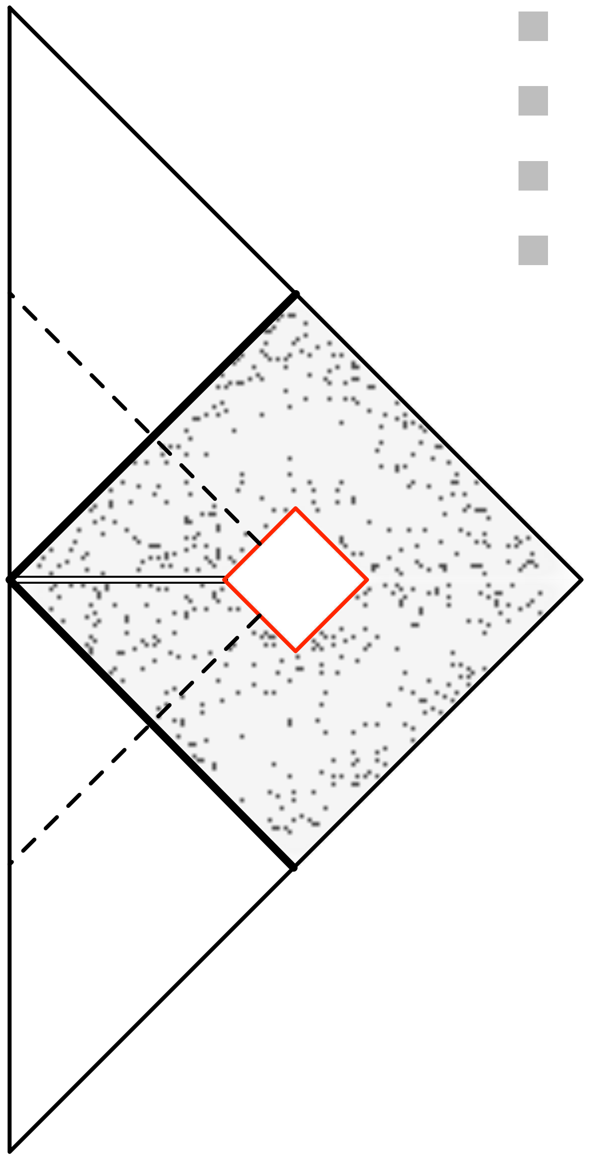
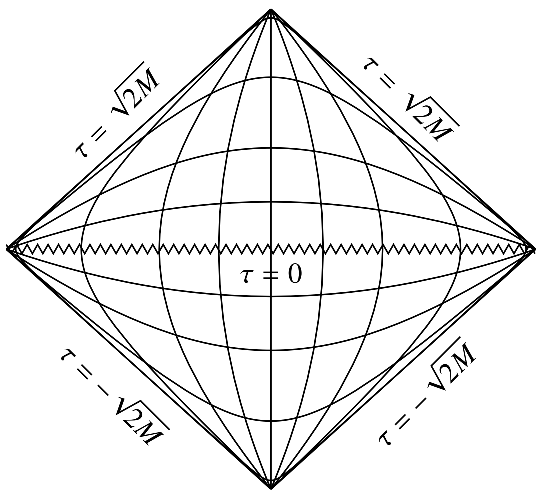


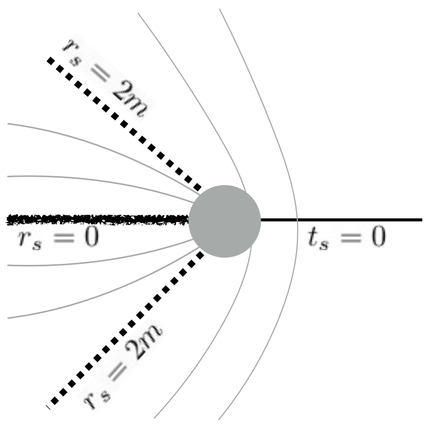
- Steps constructing the metric:
  - Entropy inside $S \sim m_o^2$
  - Slow release of inside information: almost stable remnant
  - Unitarity and energy considerations impose $\tau_R \sim m_o^4/\hbar^{3/2}$ Preskill 9209058
  - Stability under perturbations

- Internal transition:

Rovelli, Martin-Dussaud1803.06330
Ashtekar, Olmedo, Singh 1806.02406
Ashtekar, Olmedo, Singh 1806.00648
and more…

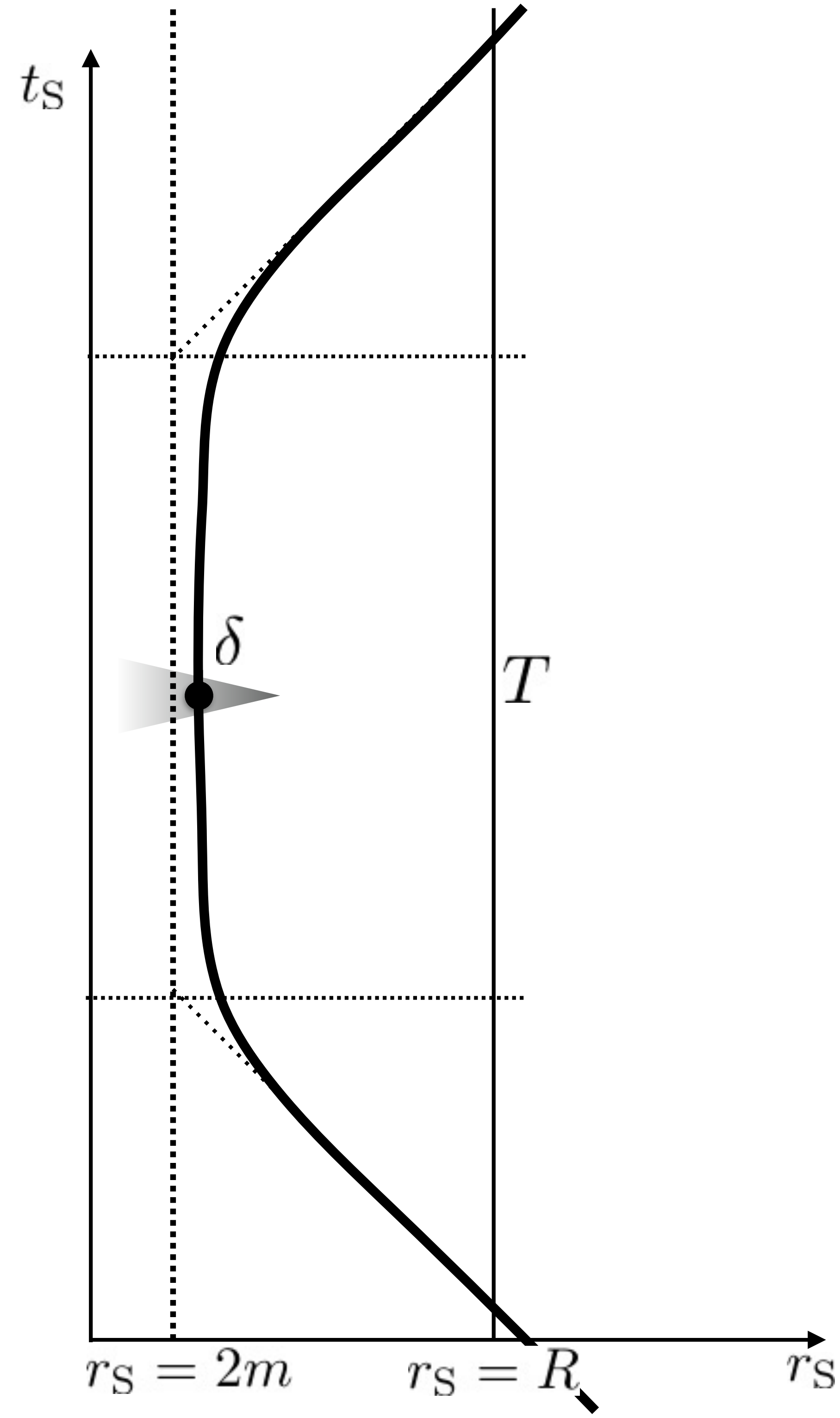


- External transition:



HOLES TIMES

- TRANSITION TIME ~ M^0 (PLANCKIAN)
- INTERNAL BOUNCE TIME ~ M
- EXTERNAL BOUNCE TIME
  - Death by evaporation ~ M^3
  - Earlier quantum instability ~ M^2
- REMNANT LIFETIME ~ M^4



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NON-PERTURBATIVE QUANTUM GRAVITY

Ingredients:

1. **General Relativity**

   * No modifications (Λ^+ included) but relax conditions on manifold

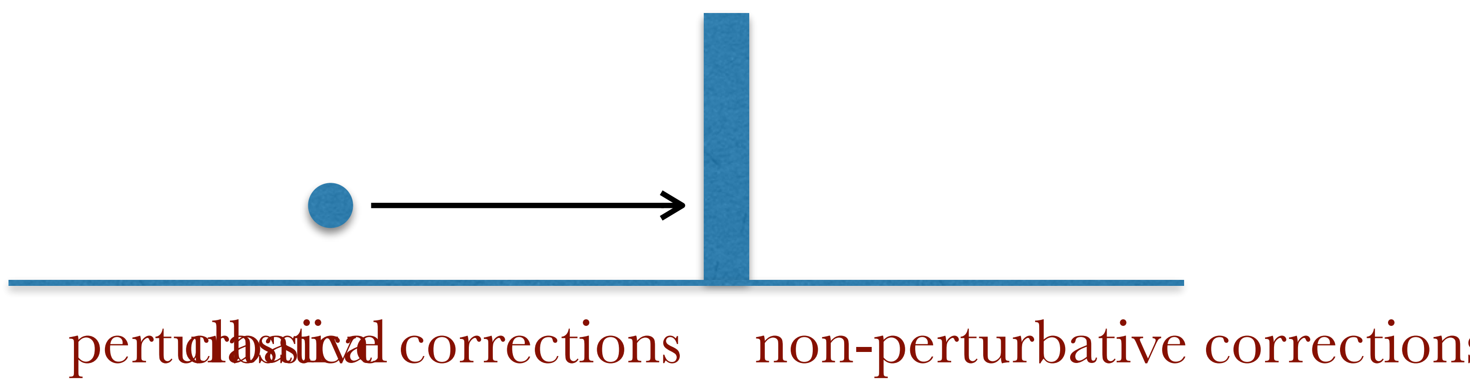
2. **Quantum Mechanics**

   * Violation of Einstein eq.s in a finite region $\Rightarrow$ NO central BH singularity

3. **Non-perturbative Methods**

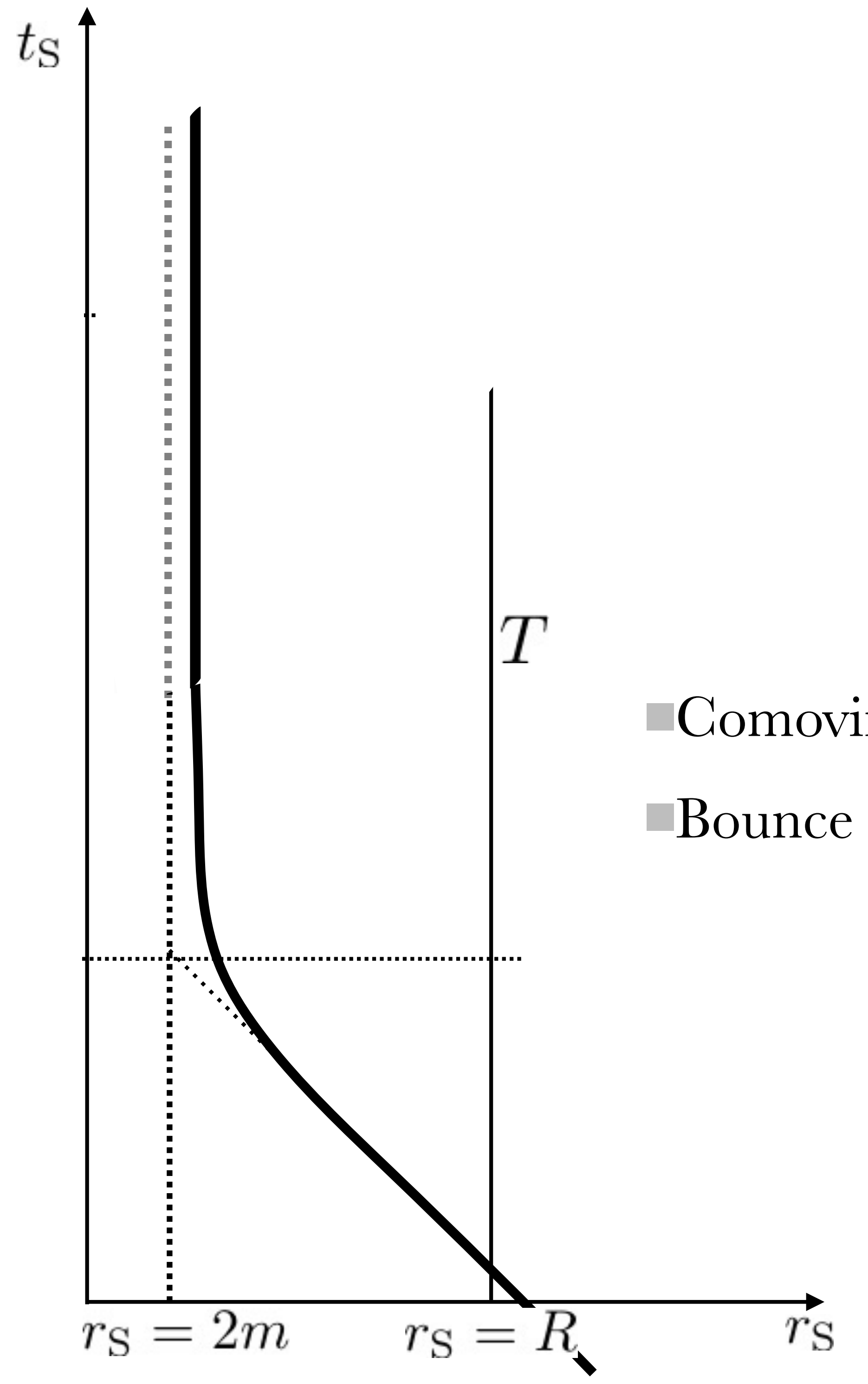
   * Effects that are not captured by standard QFT

   Example: TUNNELLING

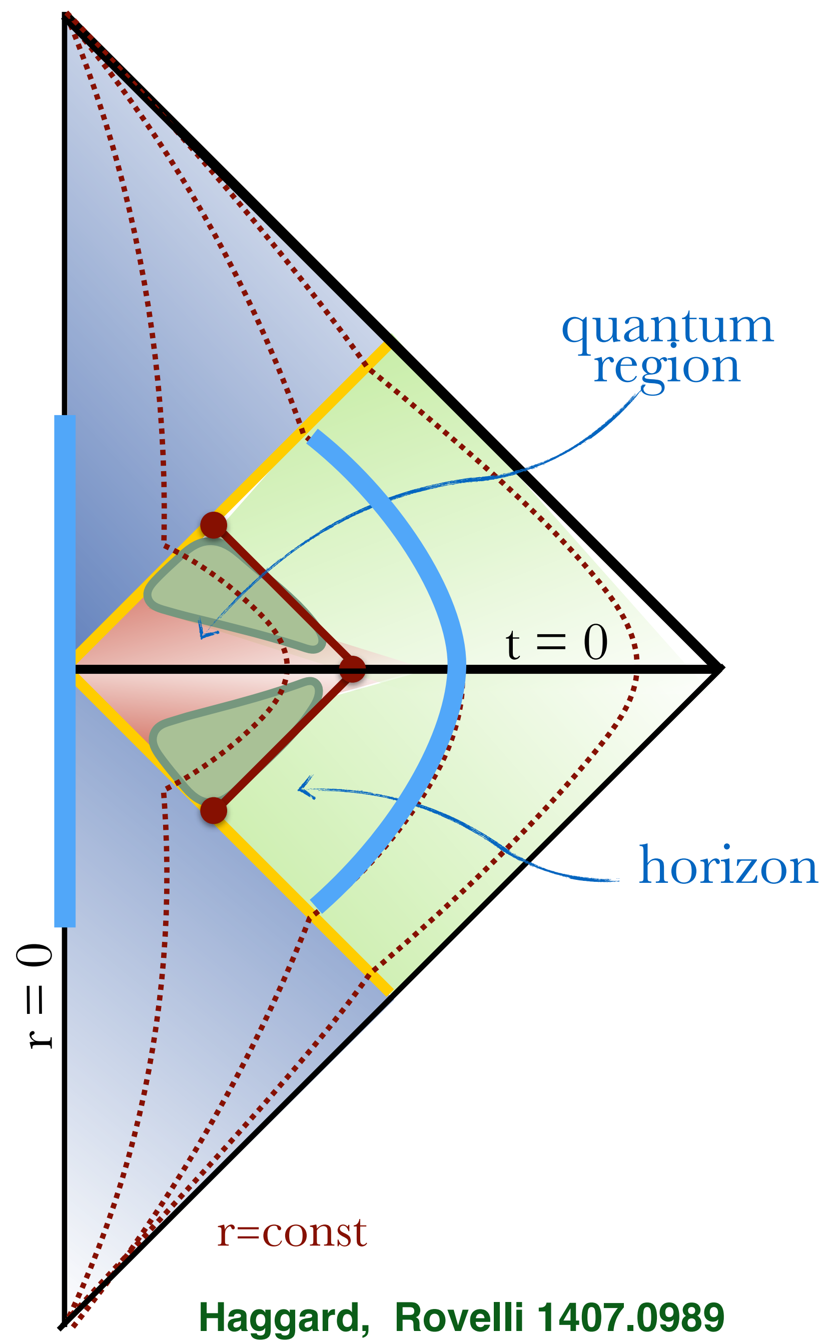


TIME DILATATION

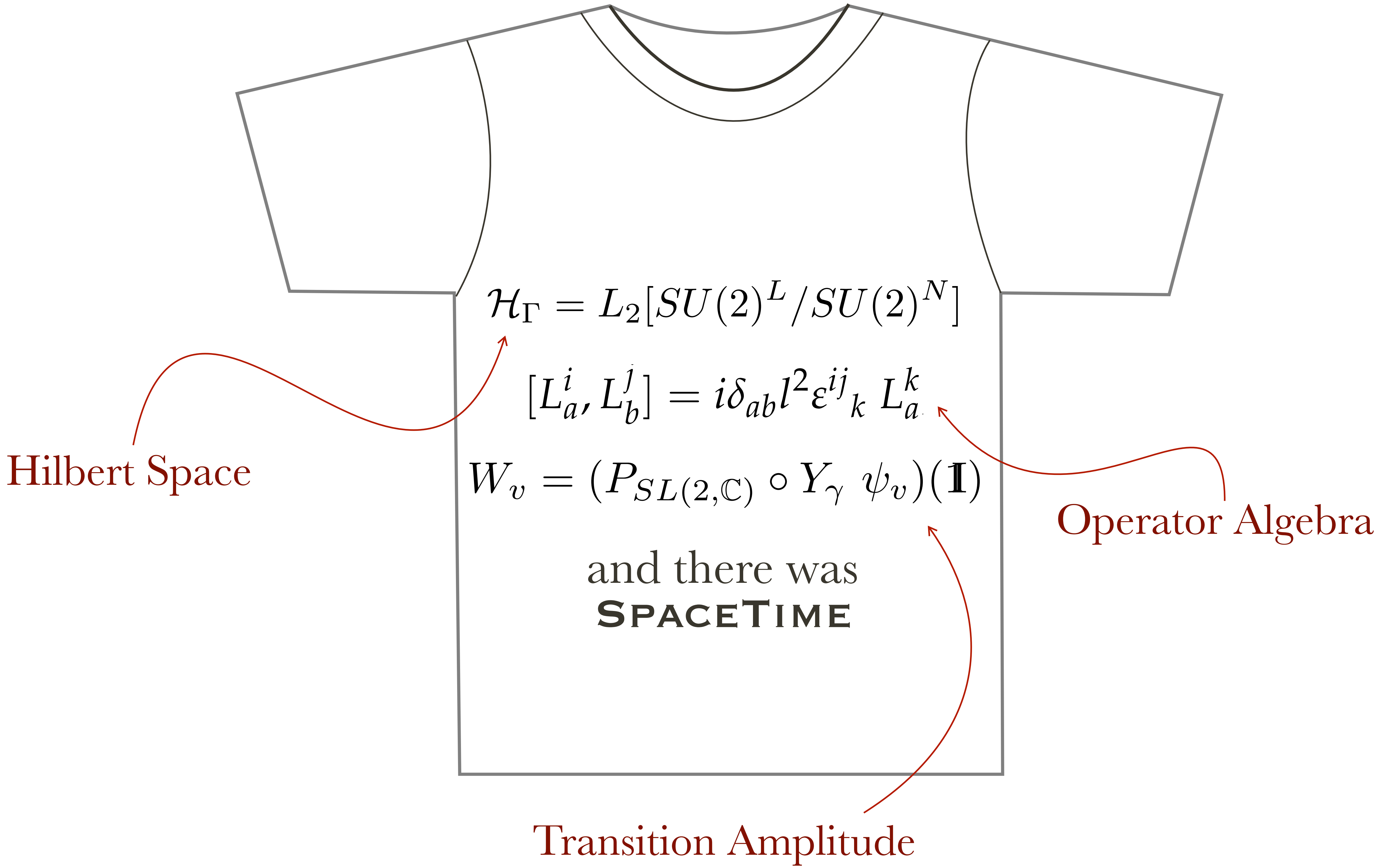
Vidotto, Rovelli 1401.6562



- Comoving time ~ M ~ ms for $M_\odot$
- Bounce time ~ $M^2 \sim 10^9$ years for $M_\odot$



Haggard, Rovelli 1407.0989

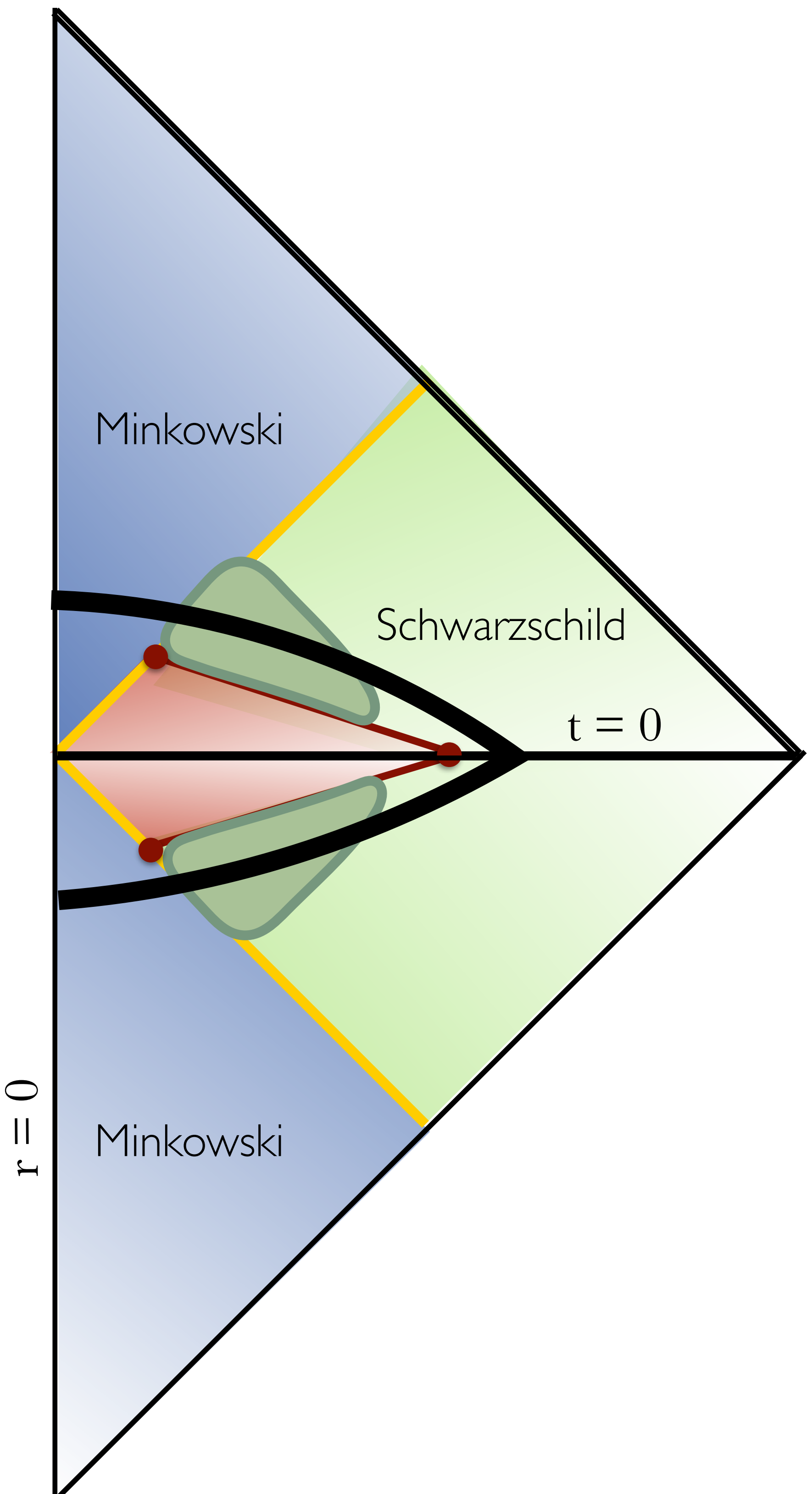


$$\mathcal{H}_\Gamma = L_2[SU(2)^L/SU(2)^N]$$

$$[L_a^i, L_b^j] = i\delta_{ab} l^2 \varepsilon^{ij}{}_k \, L_a^k$$

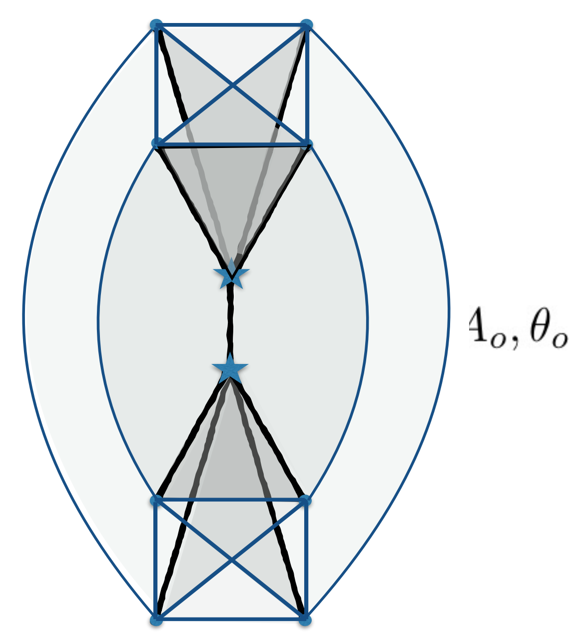
$$W_v = (P_{SL(2,\mathbb{C})} \circ Y_\gamma \; \psi_v)(\mathbb{1})$$

BOUNDARY STATE



- Boundary: B_3 U B_3 (joined on a S_2)
- Each B_3 can be triangulated by 4 isosceles tetrahedra
- The bulk can be approximated to first order by two 4-simplices joined by a tetrahedron

$$\Sigma = B_- \cup B_+$$



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Black hole explosions?

QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the length scale on which quantum fluctuations of the metric are expected to be of order unity. This means that the energy density of particles created by the gravitational field is small compared to the space-time curvature. Even though quantum effects may be small locally, they may still, however, add up to produce a significant effect over the lifetime of the Universe $\approx 10^{17}$ s which is very long compared to the Planck time $\approx 10^{-43}$ s.

The β_{ij} will not be zero because the time dependence of the metric during the collapse will cause a certain amount of mixing of positive and negative frequencies. Equating the two expressions for ϕ, one finds that the b_i, which are the annihilation operators for outgoing scalar particles, can be expressed as a linear combination of the ingoing annihilation and creation operators a_i and a_i^+

$$b_i = \sum_j \{\bar{\alpha}_{ij} a_j - \bar{\beta}_{ij} a_j^+\}$$

Thus when there are no incoming particles the expectation value of the number operator $b_i^+ b_i$ of the ith outgoing state is

$$< 0\_ \; |b_i^+ b_i| \; 0\_ > \; = \sum_j |\beta_{ij}|^2$$

The number of particles created and emitted to infinity in a gravitational collapse can therefore be determined by calculating the coefficients β_{ij}. Consider a simple example in which

Hawking evaporation: **m^3~10^{50}** Hubble time

Nature Vol. 248 March 1 1974 31

the collapse is spherically symmetric. The angular dependence of the solution of the wave equation can then be expressed in terms of the spherical harmonics Y_{lm} and the dependence on retarded or advanced time u, v can be taken to have the form $\omega^{-1/2}$ *exp* $(i\omega u)$ (here the continuum normalisation is used). Outgoing solutions $p_{lm\omega}$ will now be expressed as an integral over incoming fields with the same l and m:

$$p_\omega = \int \{\alpha_{\omega\omega'} f_{\omega'} + \beta_{\omega\omega'} \bar{f}_{\omega'}\} \, d\omega'$$

(The lm suffixes have been dropped.) To calculate $\alpha_{\omega\omega'}$ and $\beta_{\omega\omega'}$ consider a wave which has a positive frequency ω on I^+ propagating backwards through spacetime with nothing crossing the event horizon. Part of this wave will be scattered by the curvature of the static Schwarzschild solution outside the black hole and will end up on I^- with the same frequency ω. This will give a $\delta(\omega - \omega')$ behaviour in $\alpha_{\omega\omega'}$. Another part of the wave will propagate backwards into the star, through the origin and out again onto I^-. These waves will have a

Beckenstein[6] suggested on thermodynamic grounds that some multiple of κ should be regarded as the temperature of a black hole. He did not, however, suggest that a black hole could emit particles as well as absorb them. For this reason Bardeen, Carter and I considered that the thermodynamical similarity between κ and temperature was only an analogy. The present result seems to indicate, however, that there may be more to it than this. Of course this calculation ignores the back reaction of the particles on the metric, and quantum fluctuations on the metric. These might alter the picture.

Further details of this work will be published elsewhere. The author is very grateful to G. W. Gibbons for discussions and help.

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BLACK-HOLE LIFETIME

For something quantum to happens, semiclassical approximation must fail.

Typically in quantum gravity: high curvature Curvature ~ $(L_P)^{-2}$

Small effects can pile up: small probability per time unit gives a probable effect on a long time!

Typically in quantum tunneling: Curvature × (time) ~ $(L_P)^{-1}$

$$\frac{1}{m^2}\, T_b \sim 1$$

$\Longrightarrow$ the hole lifetime must be longer or of the order of ~ **m²**

Haggard, Rovelli 1407.0989

- Quantum Break Time Dvali, Gomez 1112.3359
- Black-to-White Tunnelling
  - In the quantum world, things happen as soon as they can!
  - Indications from a full LQG computations. Chistodoulou, Rovelli, Speziale, Vilensky 1605.05268

UNIVERSALITY OF BLACK HOLE EXPLOSION?

- **LARGE EXTRA DIMENSIONS**

  1st order topological phase transition from black string to black hole occurring because of the Gregory-Laflamme metrical instability

  Casadio and Harms 2000/01
  Gubser 2002, Kol 2002
  Gregory and Laflamme 2002

$$M_{\mathrm{BH}}^{(3+2n)/(1+n)}$$

- **BRANES**

  Large black holes localized on infinite Randall-Sundrum branes: period of rapid decay via Hawking radiation of CFT modes

  Emparana, Garcıa-Bellido, Kaloper 2003

Quantum effects shorten the lifetime of black holes!

FIREWALL NO-GO THEOREM

- Assumptions:
  Almheiri, Marolf, Polchinski, Sully 1207.3123
  - General Relativity: Equivalence Principle
  - Quantum Mechanics: Unitary Evolution
  - QFT in Curved Spacetime (fixed smooth background)

- Firewall argument
  See also Rovelli: "The Subtle Unphysical Hypothesis of the Firewall Theorem"
  after the Page time i.e. when about half of black-hole mass has evaporated particles emitted needs to break entanglement releasing an enormous energy

- Black Hole Lifetime
  Vidotto, Rovelli 1401.6562
  Quantum Gravity effects should manifest before the Page time
  $\Longrightarrow$ the hole lifetime must be shorter or of the order of $\sim \mathbf{m^3}$

- See also Quantum Break Time
  Dvali, Gomez 1112.3359


Scenario 3
FAST EXPLOSION

PRIMORDIAL BLACK HOLES

- PBHs are the least exotic beast in the dark universe zoo of theories
- PBHs are a viable DARK MATTER candidate

  * careful with old constraints in the literature!
- PBHs are interesting even if they are not all DARK MATTER

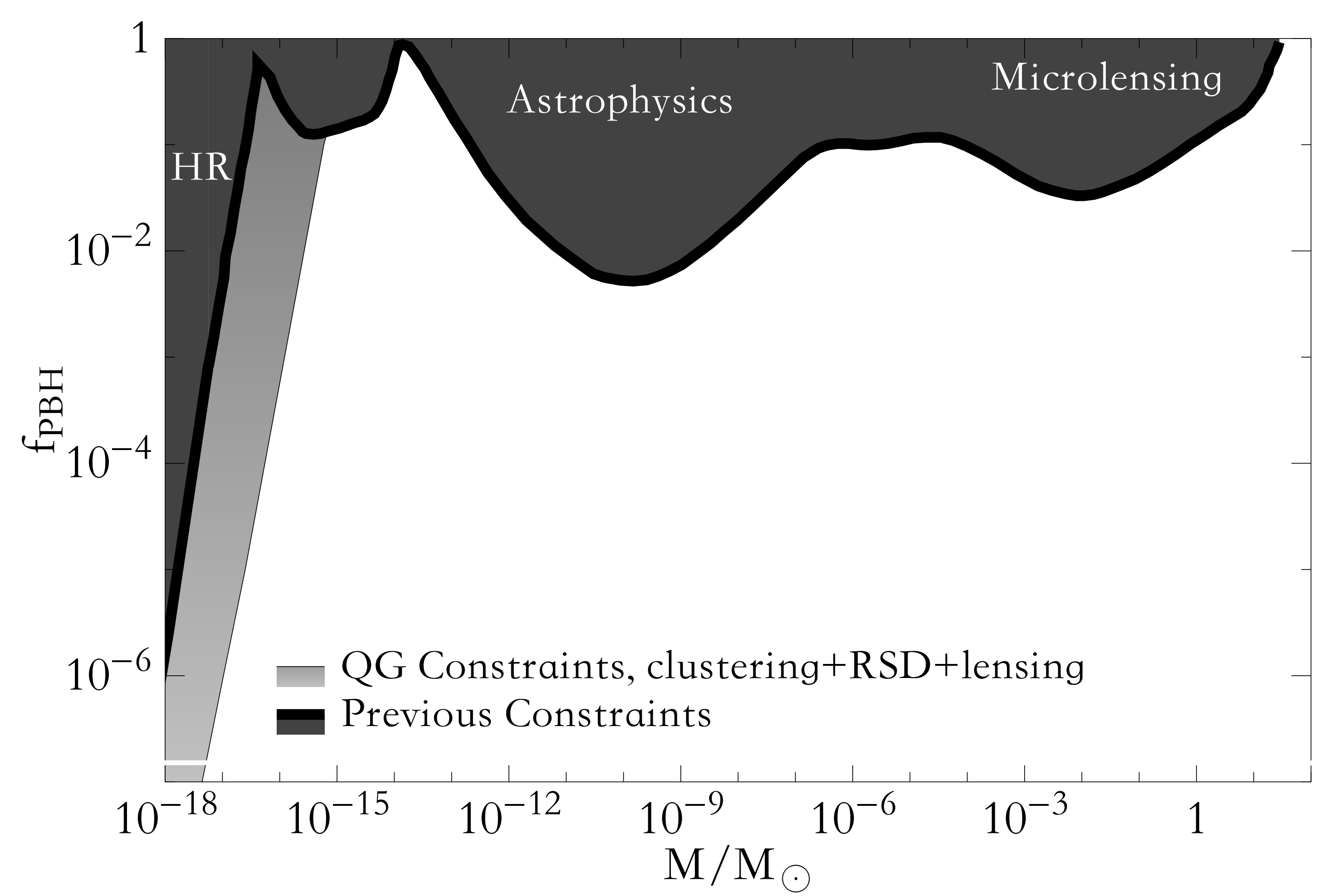
  * PBHs can be used to test **QUANTUM GRAVITY**

(QUANTUM) PBH DARK MATTER

- Today, black holes smaller than $m(t)|_{t=t_H}$ have already exploded.
- It decreases with time. *(but for later accretion/merging)*

- ## Caution with constraints!
  - Constraints from Hawking evaporation do not apply any more.
- ## Effects on late cosmology
  - Galaxy clusters surveys

Raccanelli, Vidotto, Verde 1708.02588



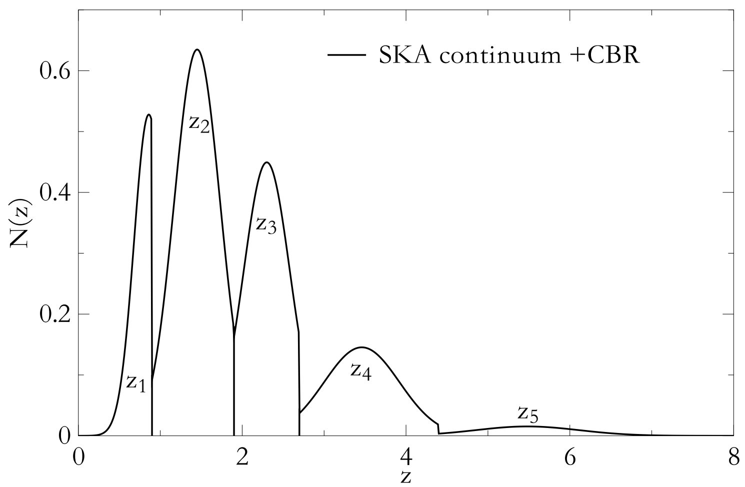
EFFECT ON GALAXY CLUSTERS

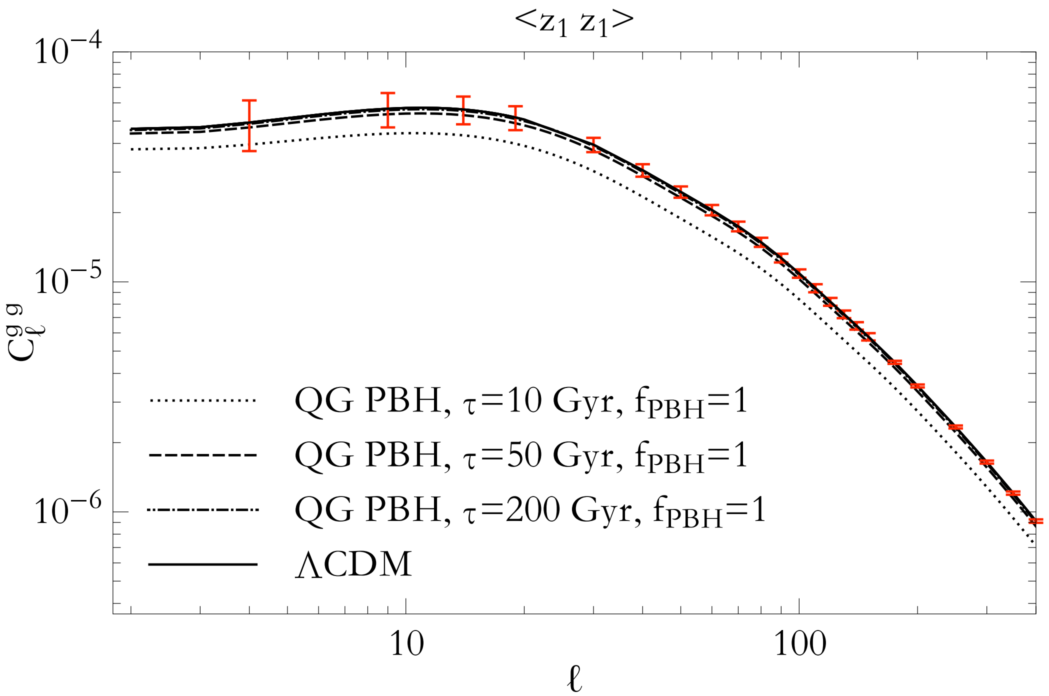
Raccanelli, Vidotto, Verde 1708.02588

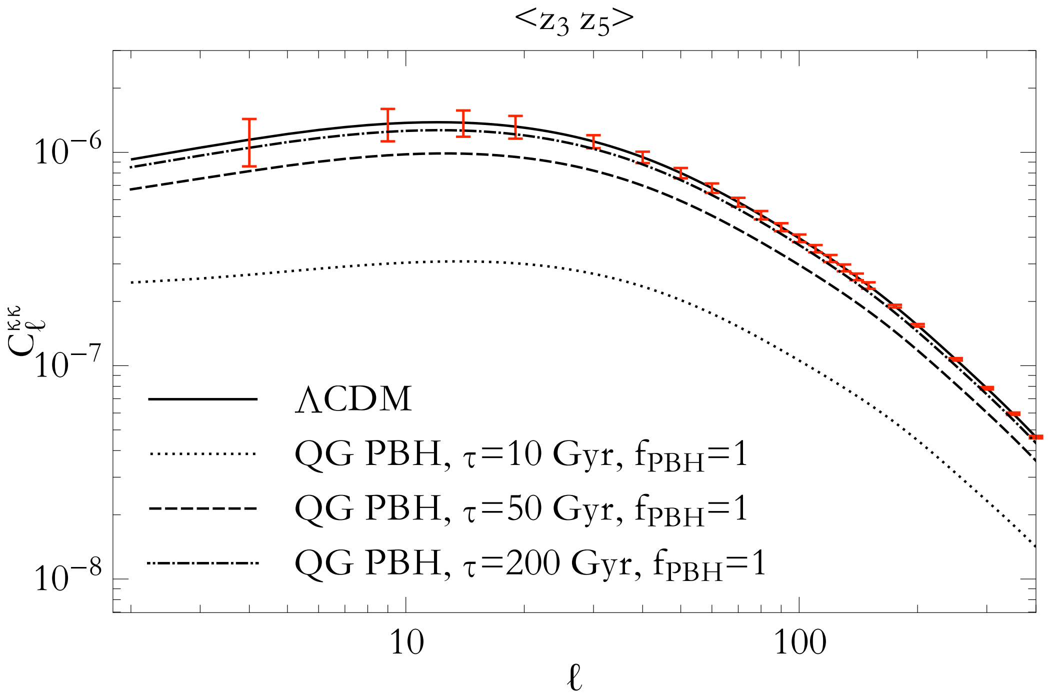
$$C_\ell^{XY}(z_i, z_j) = \left\langle a_{\ell m}^X(z_i)\ a_{\ell m}^{Y\,*}(z_j) \right\rangle$$

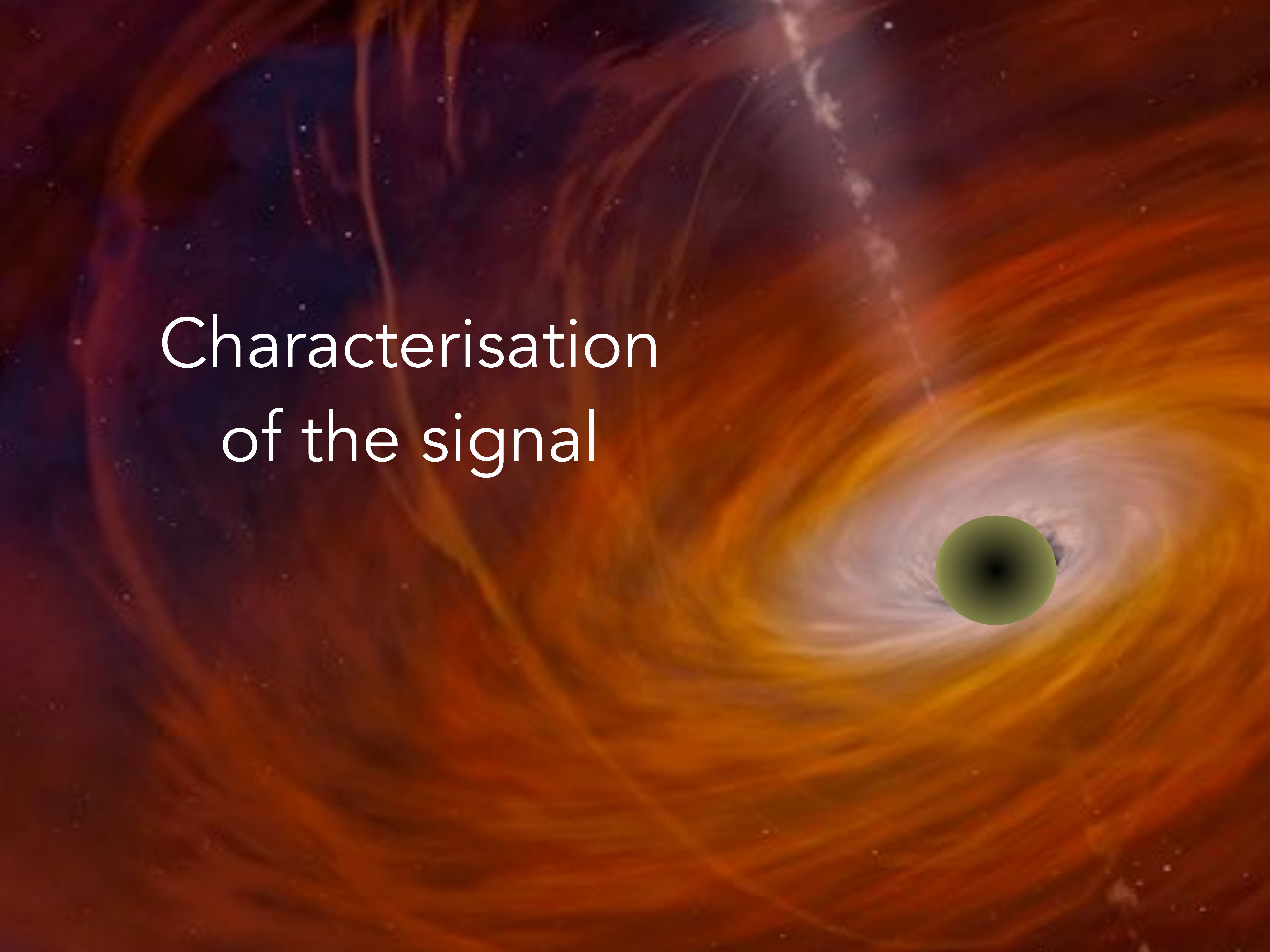
- angular positions and redshifts perturbed by peculiar velocities, gravitational lensing and potentials

- Choice of redshift distribution:








Characterisation
of the signal

PBH EXPLOSIONS

Vidotto 1811.08007

- fast process (few milliseconds?)
- the source disappears with the burst
- very compact object: big flux $E = mc^2 \sim 1.7 \times 10^{47}$ erg
- exploding today: $m = \sqrt{\frac{t_H}{4k}} \lesssim 1.2 \times 10^{23}$ kg $\qquad R = \frac{2Gm}{c^2} \lesssim .02$ cm
- ***HIGH ENERGY***: energy of the particle liberated $\approx Tev$
- **SYNCHROTRON EMISSION (REES' MECHANISM)**
- ***LOW ENERGY***: size of the source $\approx$ wavelength $\lambda_{predicted} \gtrsim .2$ cm

(the last two items are bracketed together:) **FRB** (?)

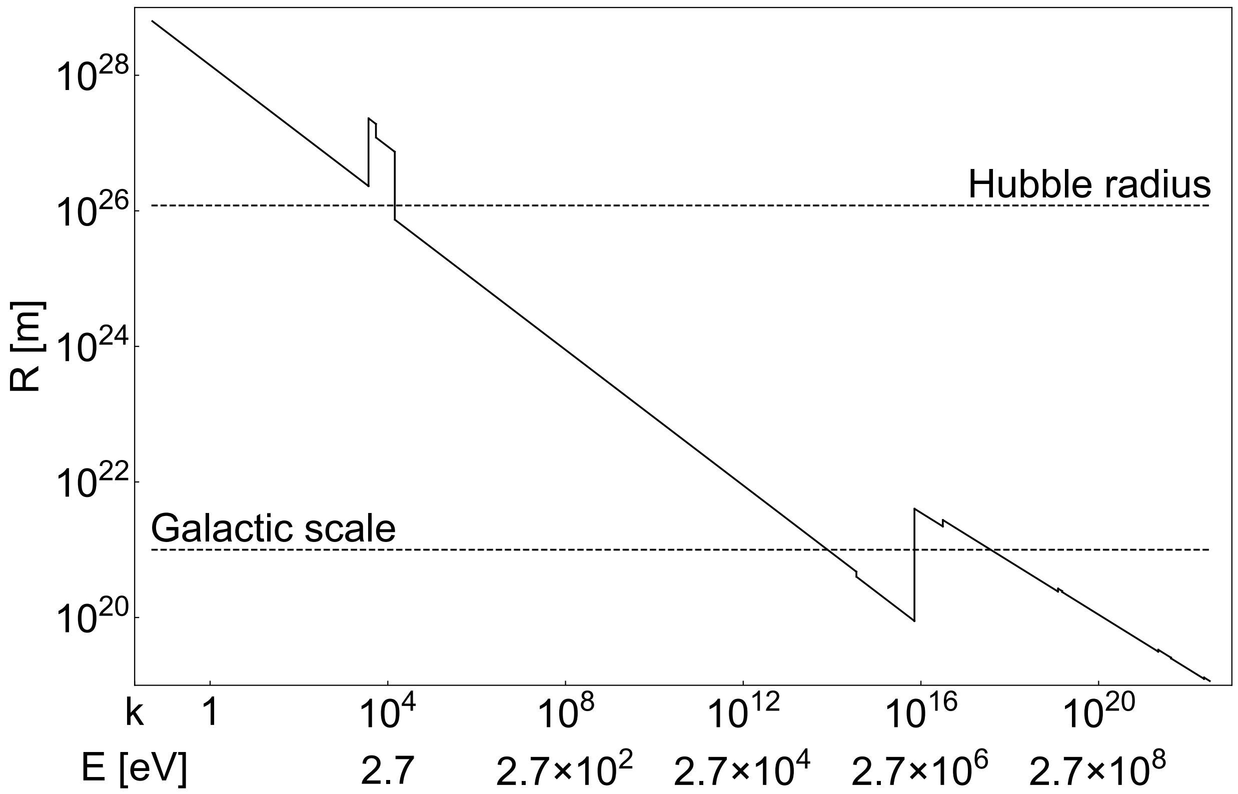
- **GRAVITATIONAL WAVES !!!**

MAXIMAL DISTANCE

Barrau, Bolliet, Vidotto, Weimer 1507.1198

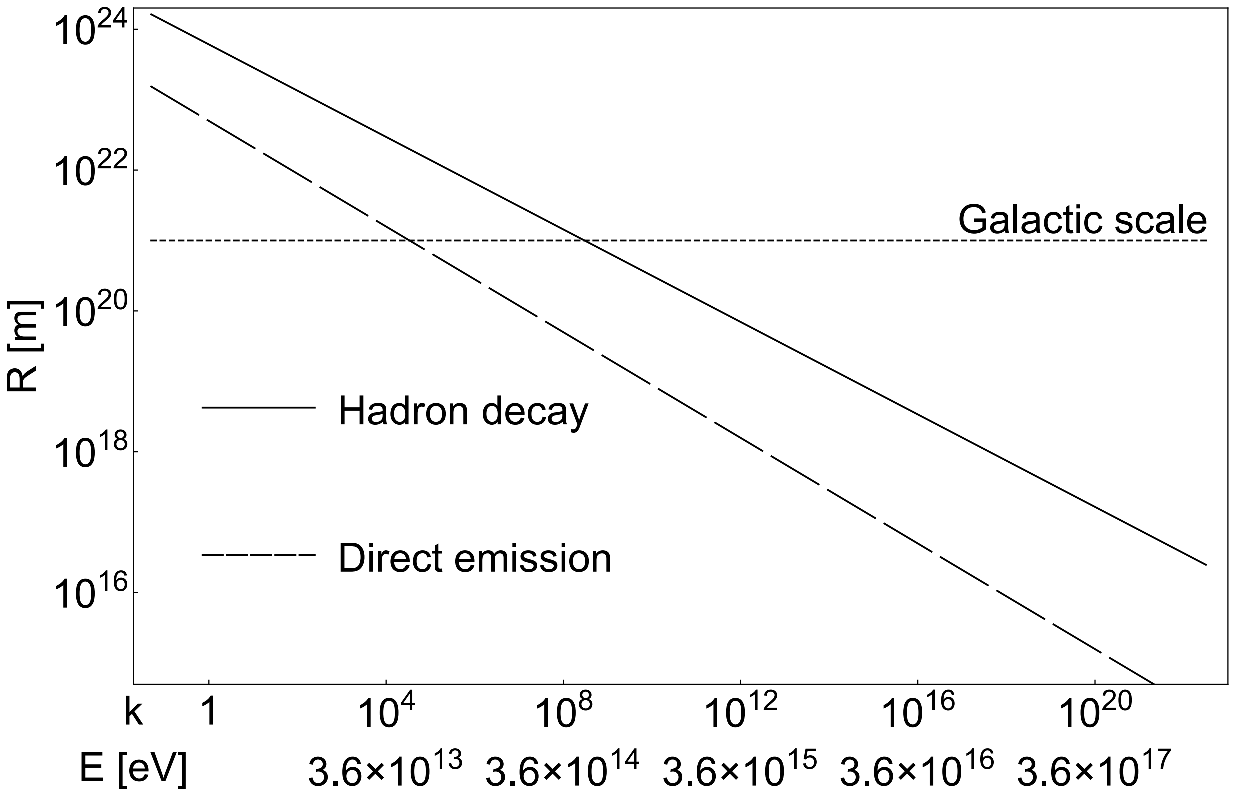
- shorter lifetime — smaller wavelength

Low energy channel



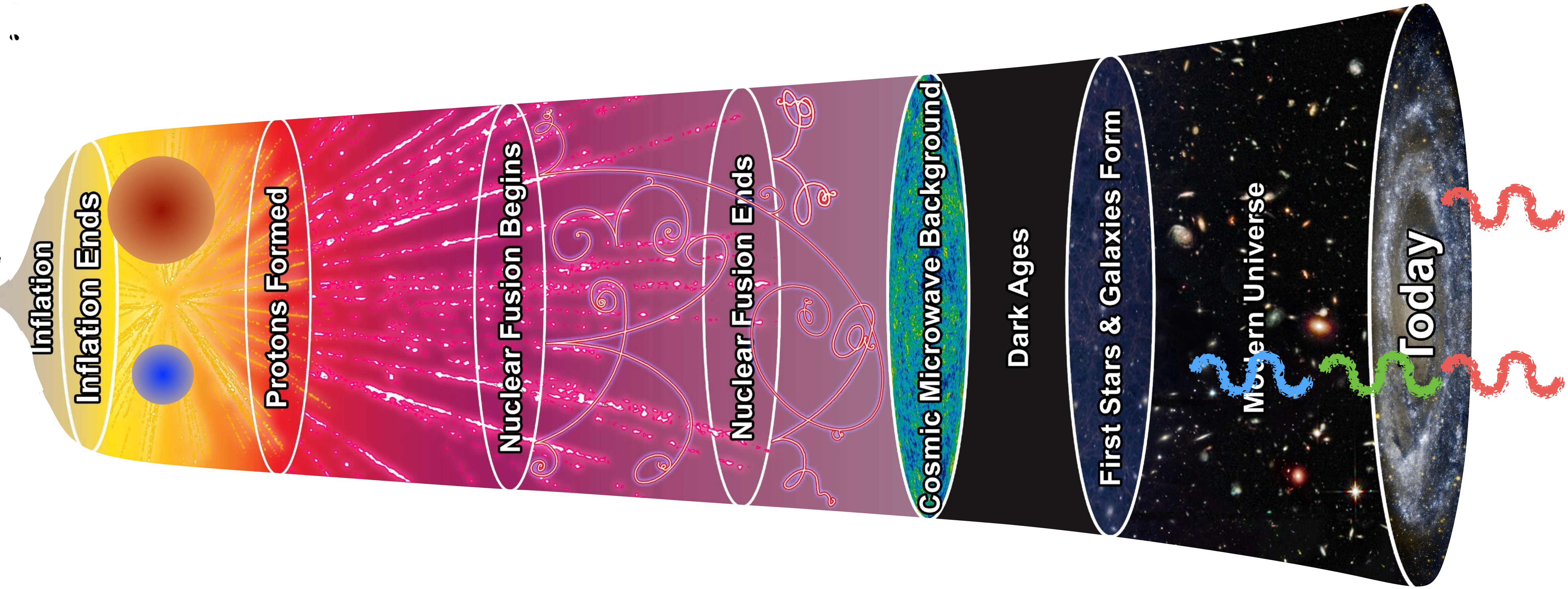
- detection of arbitrarily far signals
- better single-event detection

High energy channel



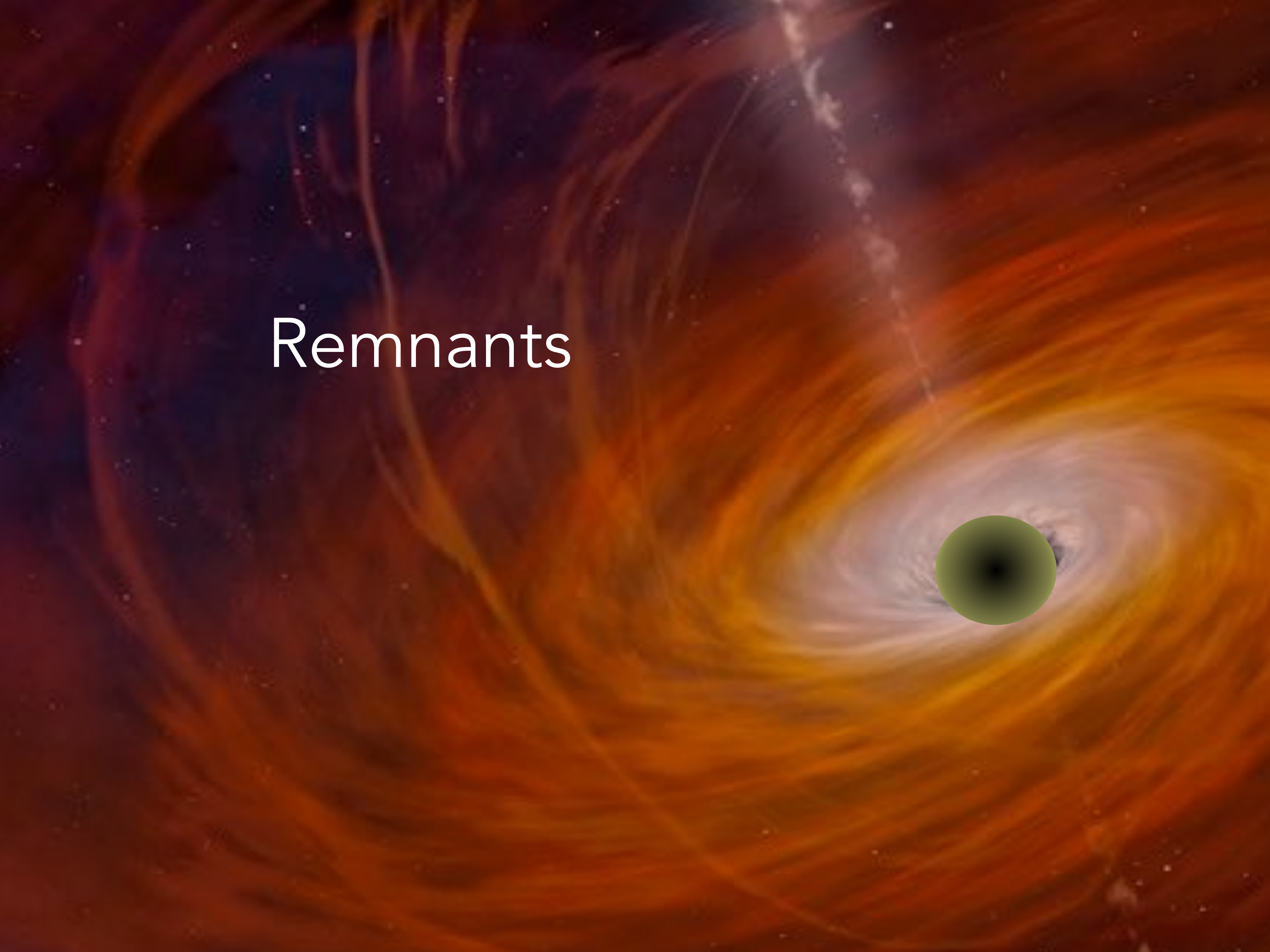
- PBH: mass - temperature relation
- different scaling

THE SMOKING GUN: DISTANCE/ENERGY RELATION



- distant signals originated in younger, smaller&hotter sources

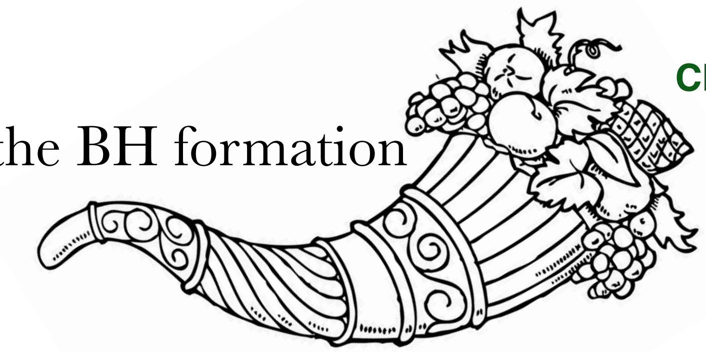
Remnants



QUANTUM EFFECTS MAKE REMNANTS STABLE

- **LARGE INTERNAL VOLUME ~ M_o^4**

  It depends only on the original mass M_o at the BH formation



Christodoulou, Rovelli 1411.2854
Christodoulou, De Lorenzo1604.07222

- **REMNANT LIFETIME ~ M_o^4**

  Time for information to leak out from such a large volume trough the small WH surface.

Bianchi, Cristodoulou, D'Ambrosio, Haggard, Rovelli 1802.04264

- **PROCESSES**

  1. BH volume increase & WH volume decrease
  2. White to black instability
  3. Hawking evaporation
  4. Black to white tunnelling

Rovelli, Vidotto 1805.03872

From the outside, at a finite time, no distinction between black and white holes

- **STABILITY**

  The minimal area yields a minimal mass!

$$|R\rangle = \frac{\sqrt{\frac{a}{b}}|B,\mu\rangle - |W,\mu\rangle}{\sqrt{1+\frac{a}{b}}}$$

oscillation between black and white hole states

DARK MATTER: REMNANTS FORMED AFTER INFLATION

Rovelli, Vidotto 1805.03872

- PBHs form at the reheating, evaporates and evolve in a long-living remnant

- **REMNANT LIFETIME COMPATIBLE WITH FORMATION AT REHEATING**

  $\mathbf{M_o}^4 \geq \mathbf{t}_{\rm Hubble}$
  $\mathbf{M_o}^3 < \mathbf{t}_{\rm Hubble}$ $\Rightarrow\ 10^{10} gr \leq \mathbf{M_o} < 10^{15} gr \ \Rightarrow\ 10^{-18} cm \leq R_o < 10^{-13} cm$

- **NUCLEOSYNTHESIS**

  BH evaporation should not modify D/H, Li6/Li7, and He3/D ratio

DARK MATTER: REMNANTS FROM BEFORE THE BOUNCE

Rovelli, Vidotto 1805.03224

- **BOUNCING BLACK HOLES IN A BOUNCING UNIVERSE**
  Planckian PBH remands from a previous eon (Penrose's EREBONS)
  Planck size particles can pass trough the bounce.

Quintin, Brandenberger 1609.02556
Carr, Clifton, Coley 1704.02919

- **PAST LOW ENTROPY**
  Matter near thermal equilibrium: geometry has low entropy
  A volume of the universe outside BH as low as only $1/T_H^2 \sim 10^{-120}$ of the total could have been outside the remnants at the bounce!

- **DARK MATTER**
  We want $\mathbf{M}_o^4 \geq \mathbf{t}_{\text{Hubble}}$ for them to survive till today.

- Inflation dilutes PBH: $\frac{1}{T_H^2} \sim \left(\frac{\dot{a}}{a}\right)^2 \sim \rho_M \qquad \rho_b \sim \rho T_H^3 \sim T_H \qquad V_{int} = \rho_b V_{WH} > T_H^2$

- **MATTER BOUNCE:** PBH as pressureless component

to conclude

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QG allows for Black-to-White tunnelling

* Mystery solved: this is how a BH dies!

* Instability possibly before Hawking evaporation time: new phenomenology

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REMNANTS AS DARK MATTER

* compatible with PBH formation at reheating

* stability via minimal area/mass

BOUNCE^2 : Bouncing BH in a Bouncing Universe