Quantum Black Holes

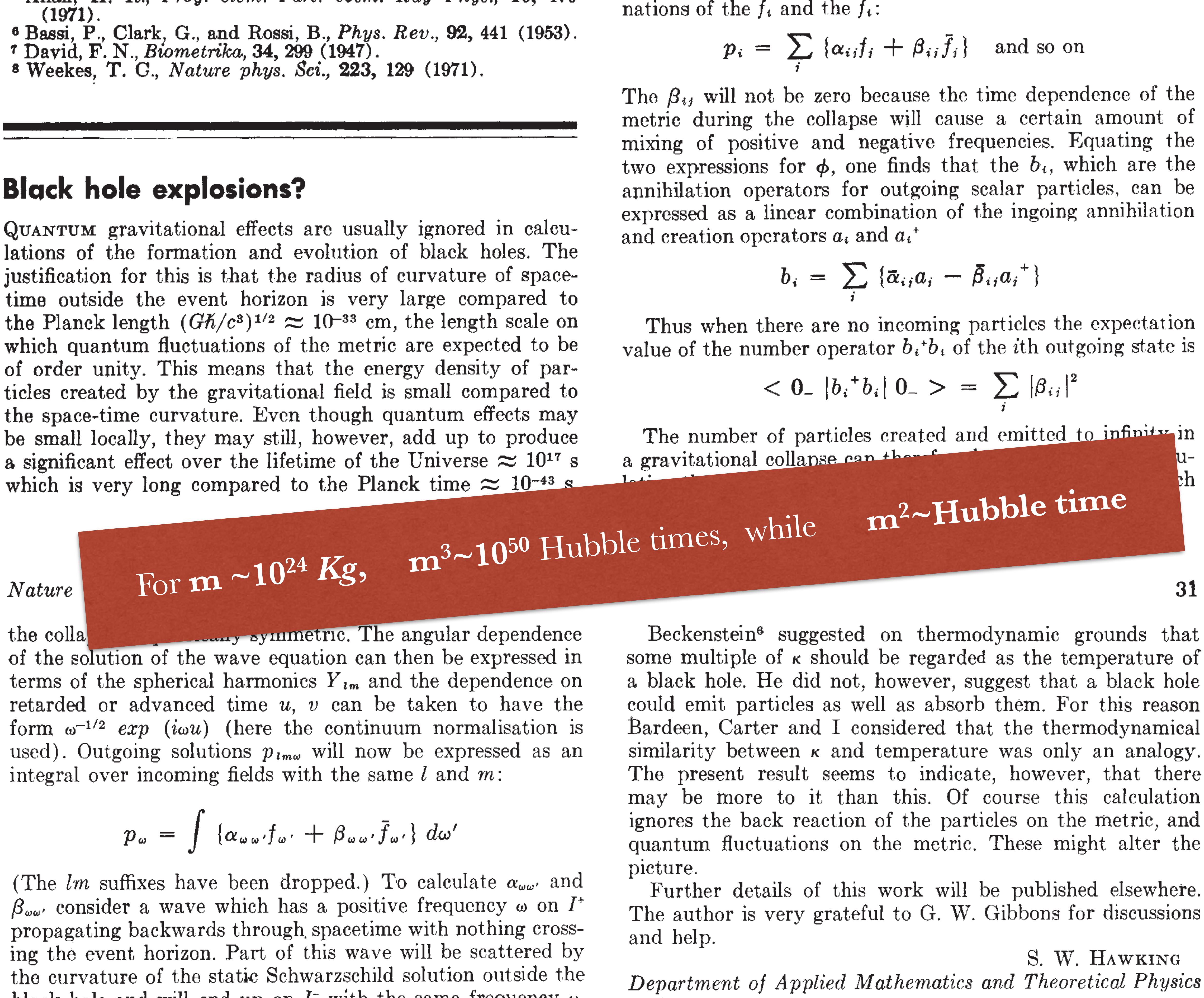
theory & phenomenology

Francesca Vidotto

II FLAG MEETING
Trento - June 7th, 2016

Netherlands Organisation for Scientific Research

Radboud University Nijmegen



(1971).

[6] Bassi, P., Clark, G., and Rossi, B., *Phys. Rev.*, **92**, 441 (1953).

[7] David, F. N., *Biometrika*, **34**, 299 (1947).

[8] Weekes, T. C., *Nature phys. Sci.*, **223**, 129 (1971).

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.

nations of the f_i and the $\bar{f}_i$:

$$p_i = \sum_j \{\alpha_{ij} f_j + \beta_{ij} \bar{f}_j\} \quad \text{and so on}$$

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 the

For **m ~10**^{24} ***Kg***, **m**^{3}**~10**^{50} Hubble times, while **m**^{2}**~Hubble time**

Nature

31

the colla

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

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.

S. W. HAWKING

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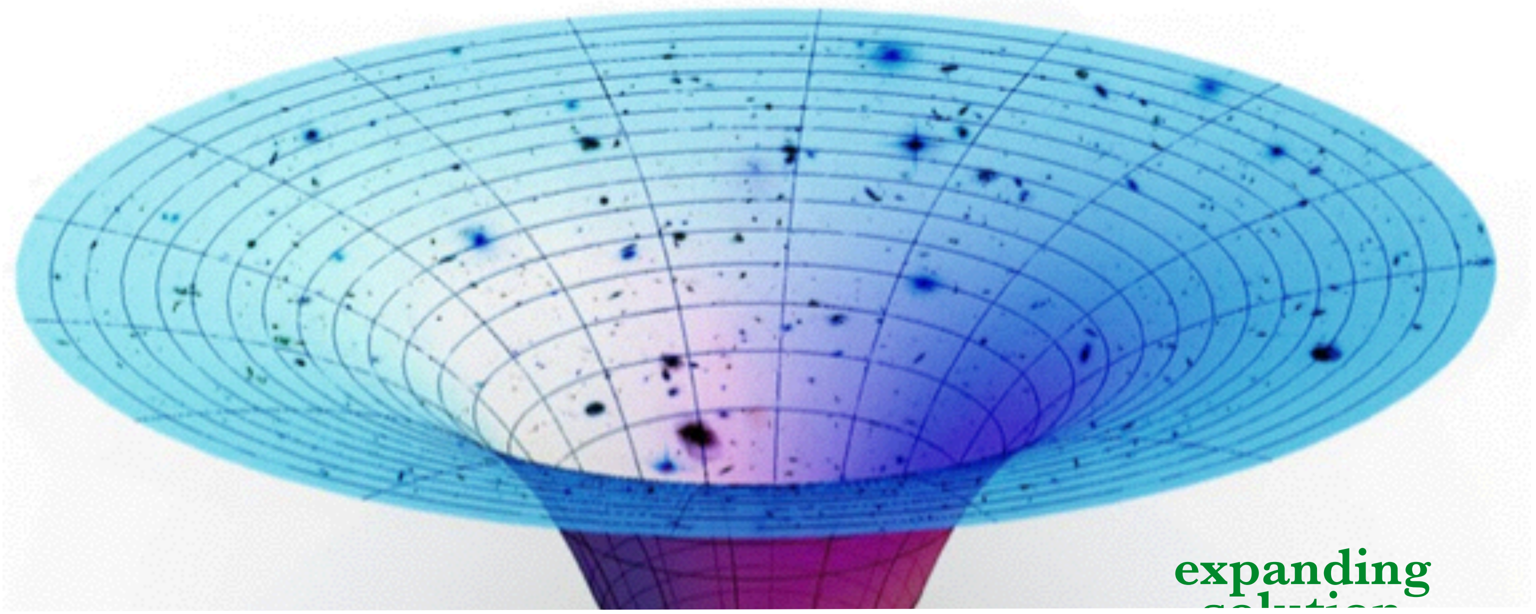
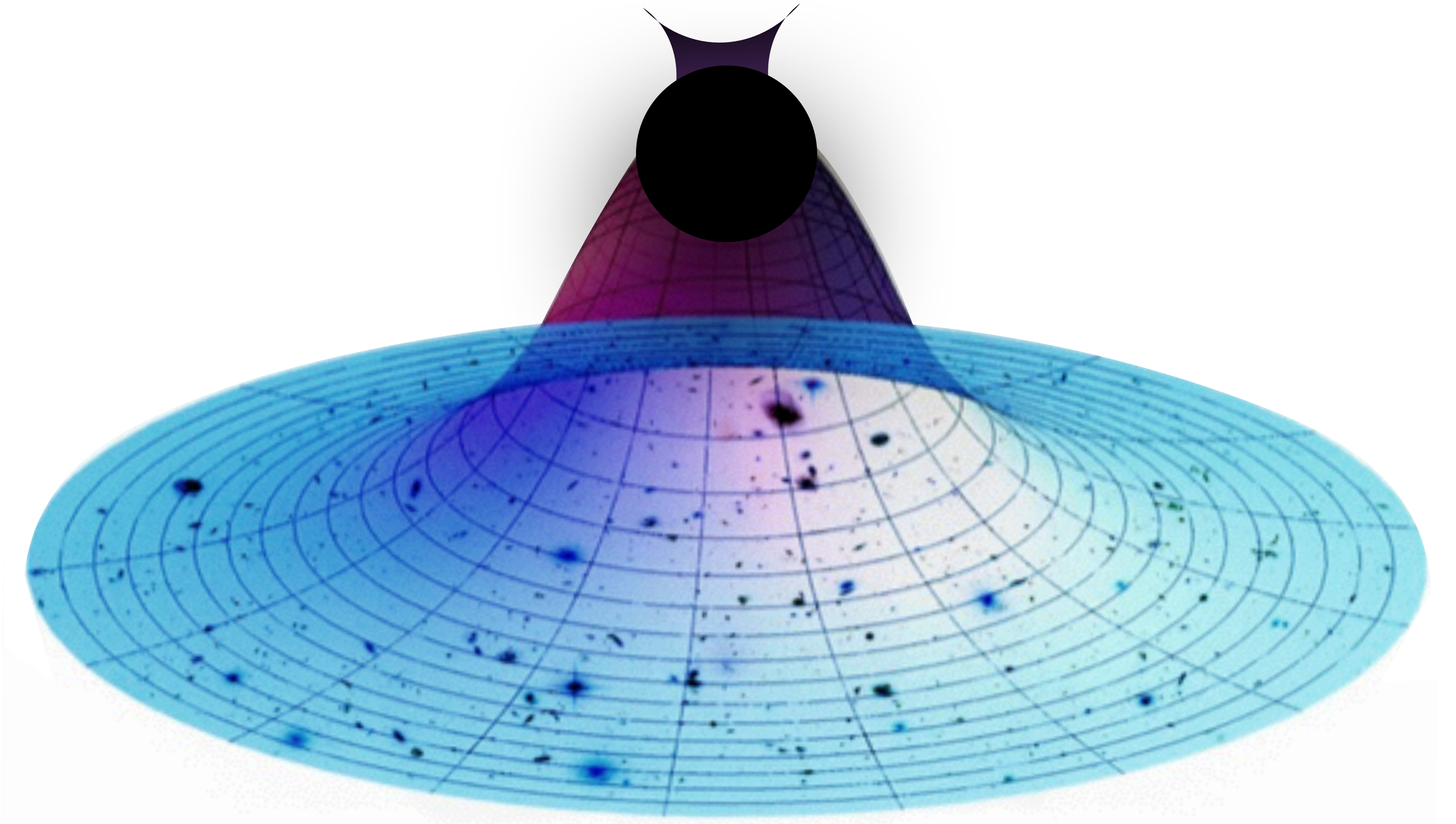
LOOP QUANTUM COSMOLOGY INSPIRATION

- Effective repulsive force
  - Planck density
- Size ≫ Planck length
  - $r_b \sim \frac{m}{m_P} \ell_P$
- Quantum Tunneling
  - superposition





contracting
solution

See works by Barrau, De Lorenzo, Haggard, Christodoulou, Vilensky Rovelli, Speziale, Vidotto…

See also related works by Bianchi, Smerlak, Perez, Gosh, Frodden, Gambini, Pullin…

Bonanno, Reuter hep-th/0002196
Alkofer, D'Odorico, Saueressig, Vidotto 1503.06472

NON-SINGULAR BLACK HOLES

- **NON-PERTURBATIVE EFFECT**

  Effective theory: quantum repulsion

  Quantum effects piling outside the horizon

- **TIME DILATATION**

  Bounce time ~ M ~ ms for $M_\odot$

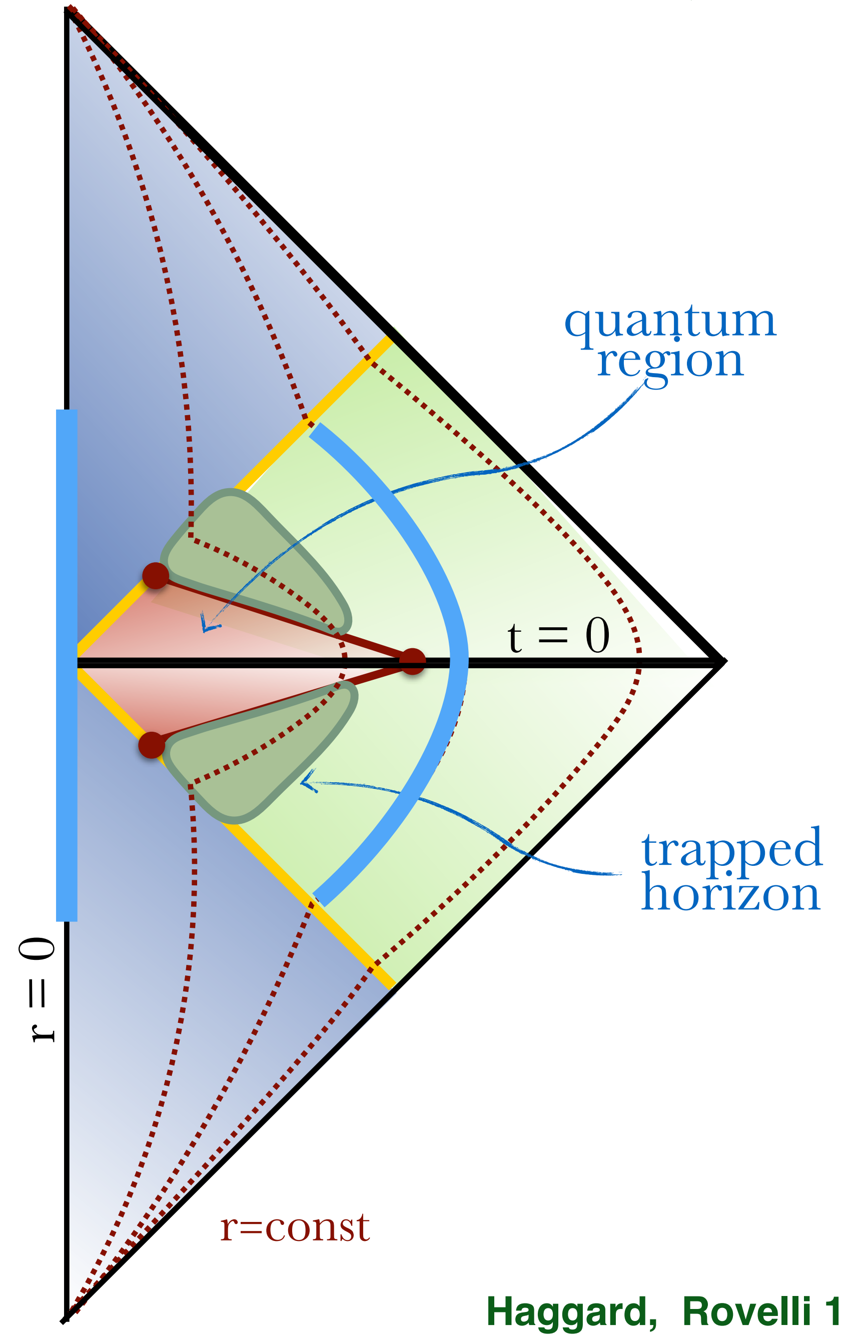
  Asymptotic time ~ $M^2 \sim 10^9$ for $M_\odot$

- **LIFETIME ~ M^2**

  to be compared with the evaporation time ~ M^3

  (no information paradox)

Vidotto, Rovelli 1401.6562



Haggard, Rovelli 1407.0989

HOW LONG IS THE BOUNCE FROM OUTSIDE?

- **Upper limit:**

Vidotto, Rovelli 1401.6562

Firewall argument (Almheiri, Marolf, Polchinski, Sully):"something" unusual must happen before the Page time (~ 1/2 evaporation time)

⟹ the hole lifetime must be shorter or of the order of ~ $\mathbf{m^3}$

- **Lower limit:**

Haggard, Rovelli 1407.0989

For something quantum to happens, semiclassical approximation must fail.

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

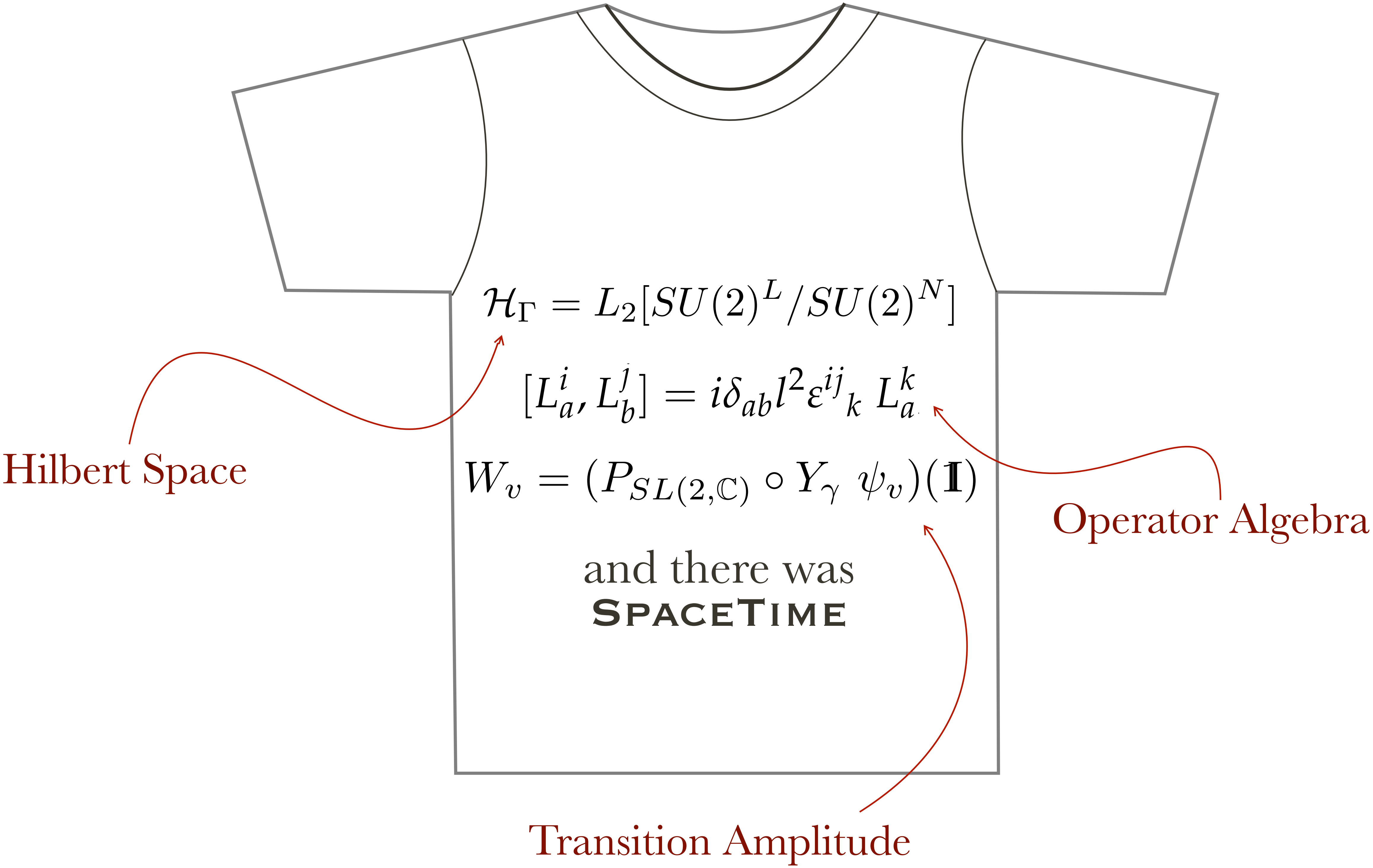
Small effects can pile up: small probability per time unit gives a probable effect on a long time!

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

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

⟹ the hole lifetime must be longer or of the order of ~ $\mathbf{m^2}$

LOOP QUANTUM GRAVITY



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

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

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

and there was
SPACETIME

Hilbert Space

Operator Algebra

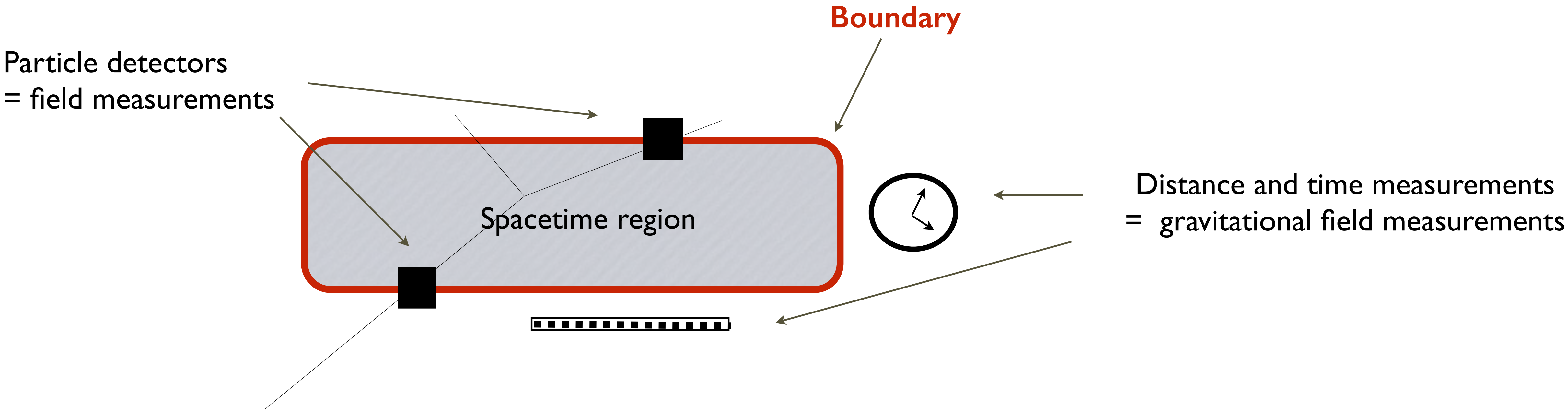
Transition Amplitude

A PROCESS AND ITS AMPLITUDE

Boundary state $\Psi = \psi_{in} \otimes \psi_{out}$

Amplitude $A = W(\Psi)$

Quantum system
=
Spacetime region



Boundary

Particle detectors
= field measurements

Spacetime region

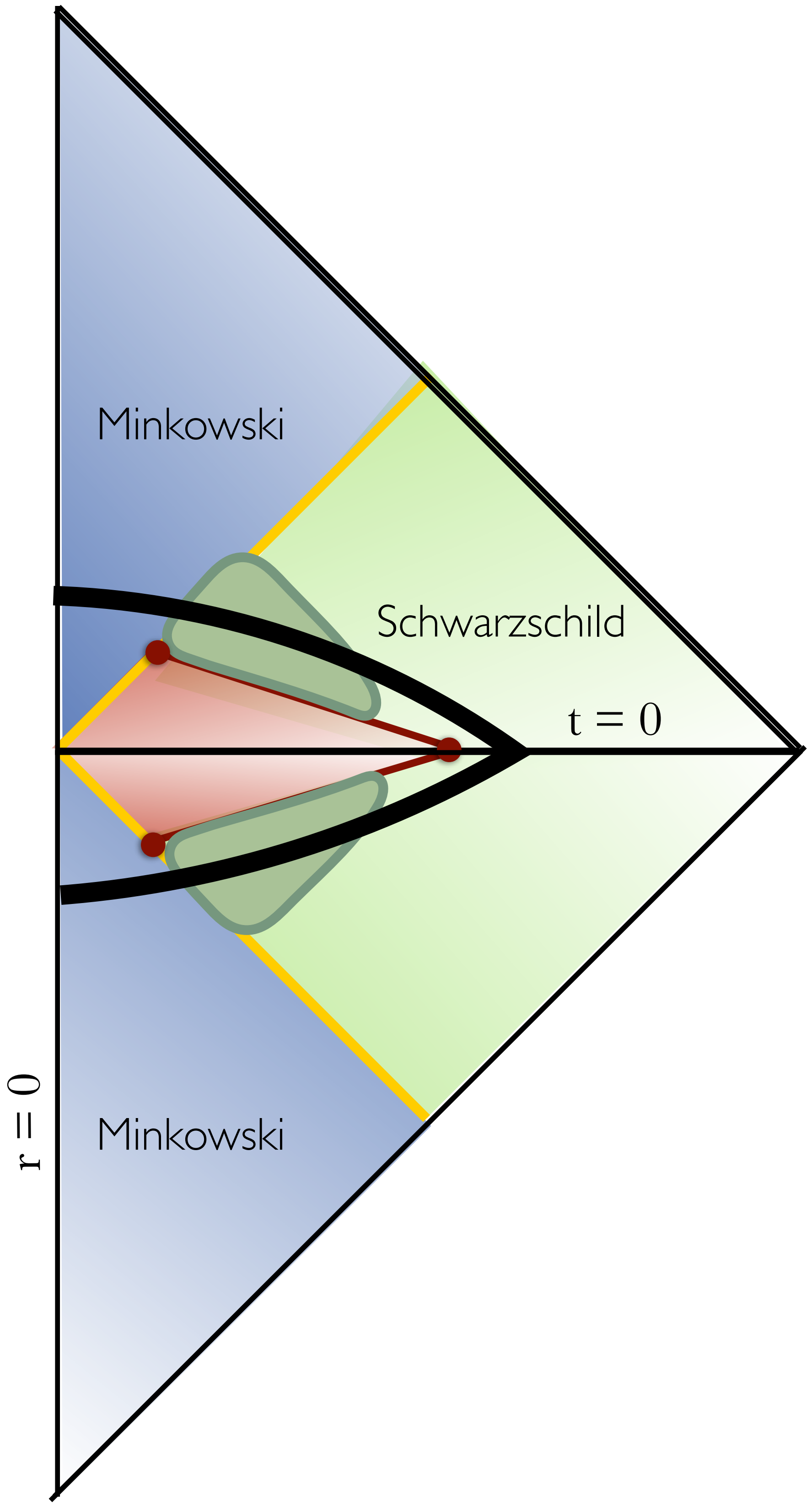
Distance and time measurements
= gravitational field measurements

In GR, distance and time measurements are field measurements like any other one:

they are part of the **boundary data** of the problem

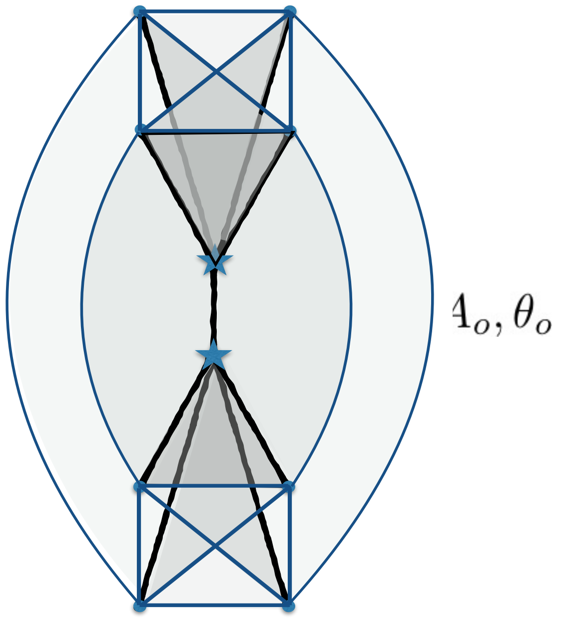
Boundary values of the gravitational field = **geometry of box surface** = **distance and time separation** of measurements

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

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



BLACK HOLE LIFETIME

$$W(m,T) = \sum_{\{j_\ell\}} w(m,T,j_\ell) \sum_{\{J_{\mathtt{n}}\},\{K_{\mathtt{n}}\},\{l_\ell\}} \left(\bigotimes_{\mathtt{n}} N^{J_{\mathtt{n}}}_{\{j_{\mathtt{n}}\}}(\{\nu_{\mathtt{n}}\},\{\alpha_{\mathtt{n}}\})\; f^{J_{\mathtt{n}},K_{\mathtt{n}}}_{\{j_{\mathtt{n}}\}\{l_{\mathtt{n}}\}} \right) \left(\bigotimes_{\mathtt{n}} i^{K_{\mathtt{n}},\{l_{\mathtt{n}}\}} \right)_{\Gamma}$$

$$w(m,T,j_\ell) = c(m) \prod_\ell d_{j_\ell}\, e^{-\frac{1}{2\eta_\ell}\left(j_\ell - \frac{(2\eta_\ell^2 - 1)}{2}\right)^2} e^{i\gamma\zeta_\ell j_\ell} \quad , \; \eta_\ell^2 \sim m^2$$

T ~ m²

$$f^{K_{\mathtt{n}},J_{\mathtt{n}}}_{\{j_{\mathtt{n}}\}\{l_{\mathtt{n}}\}} \equiv d_{J_{\mathtt{n}}}\; i^{J_{\mathtt{n}},\{j_{\mathtt{n}}\}}_{\{\overrightarrow{p}_{\mathtt{n}}\}} \left(\int dr_{\mathtt{n}} \frac{\sinh^2 r_{\mathtt{n}}}{4\pi} \overrightarrow{\bigotimes_{\ell \in \mathtt{n}}} d_{j_\ell l_\ell p_\ell}(r_{\mathtt{n}}) \right) i^{K_{\mathtt{n}},\{l_{\mathtt{n}}\}}_{\{\overleftarrow{p}_{\mathtt{n}}\}}\; d_{K_{\mathtt{n}}}$$

$$\int_0^{\tau(m)} P(m,T)\, dT = 1 - \frac{1}{e}$$

PRIMORDIAL BLACK HOLES EXPLOSIONS

- exploding now: $m(t)\big|_{t=t_H}$ $R = \frac{2Gm}{c^2}$

- **LOW ENERGY:** size of the source $\approx$ wavelength $\lambda_{predicted}$
- **HIGH ENERGY:** energy of the particle liberated $\approx Tev$

- fast process (few milliseconds?)
- the source disappears with the burst
- very compact object: big flux $E = mc^2$

Barrau, Rovelli, Vidotto 1409.4031

EXPONENTIAL DECAY: m^2 IS FAVORITE

- exploding now: $m = \sqrt{\frac{t_H}{4k}} \sim 1.2 \times 10^{23}$ kg $R = \frac{2Gm}{c^2} \sim .02$ cm
- **LOW ENERGY:** size of the source $\approx$ wavelength $\lambda_{predicted} \gtrsim .05$ cm
- **HIGH ENERGY:** energy of the particle liberated $\approx Tev$
- 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

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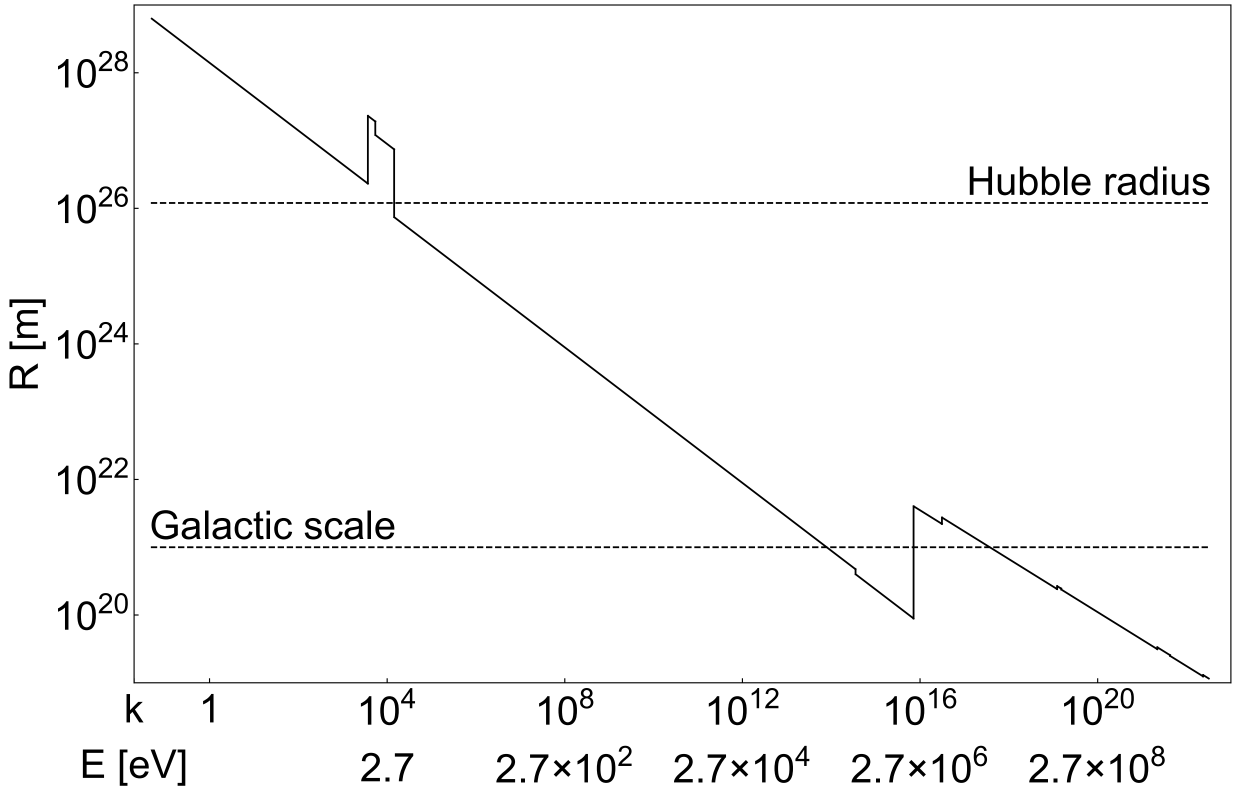
MAXIMAL DISTANCE

Barrau, Bolliet, Vidotto, Weimer 1507.1198

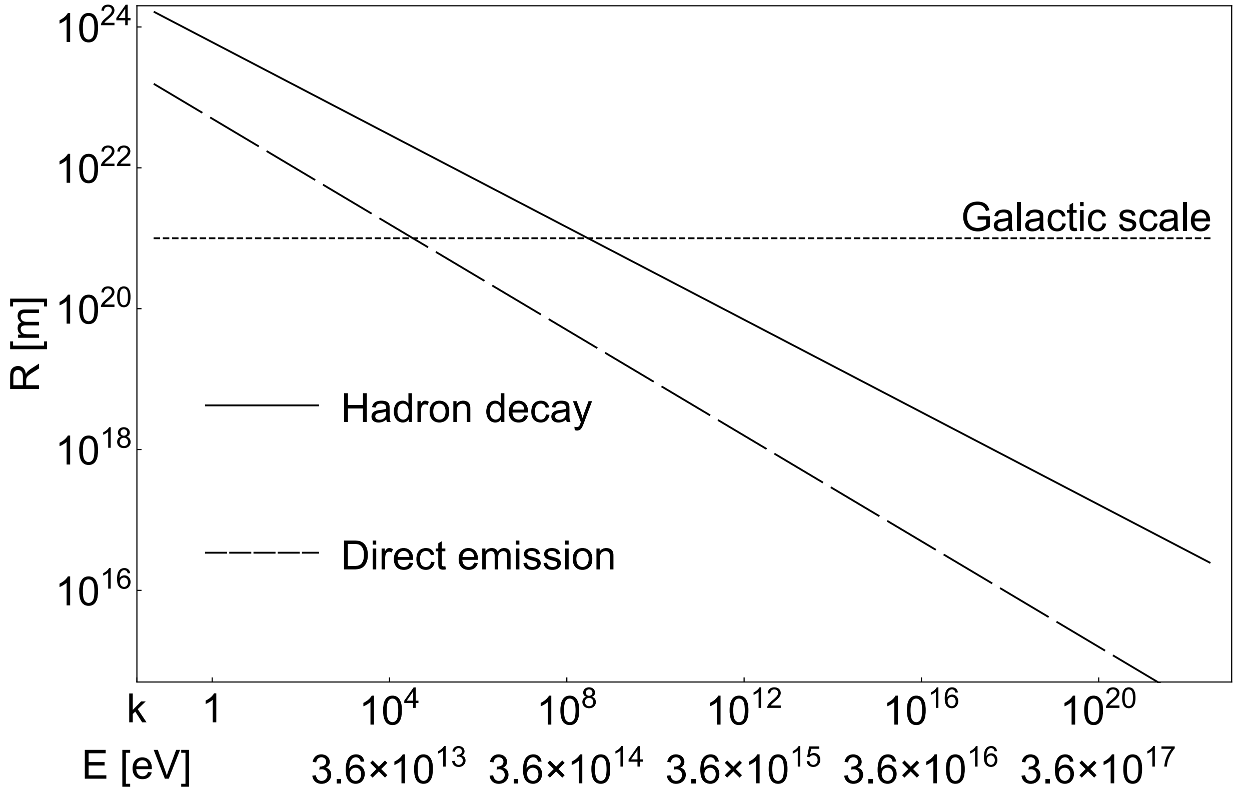
- shorter lifetime — smaller wavelength

Low energy channel



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

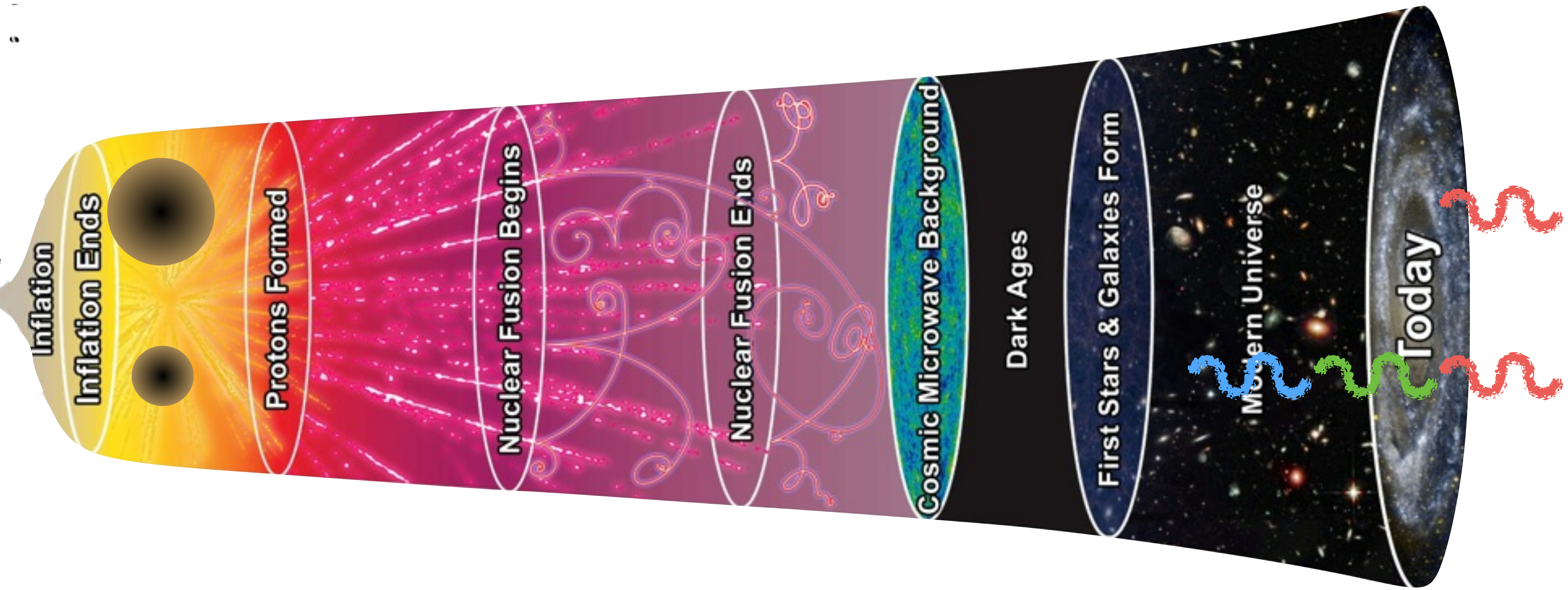
High energy channel



- PBH: mass - temperature relation
- different scaling

THE SMOKING GUN: DISTANCE/ENERGY RELATION

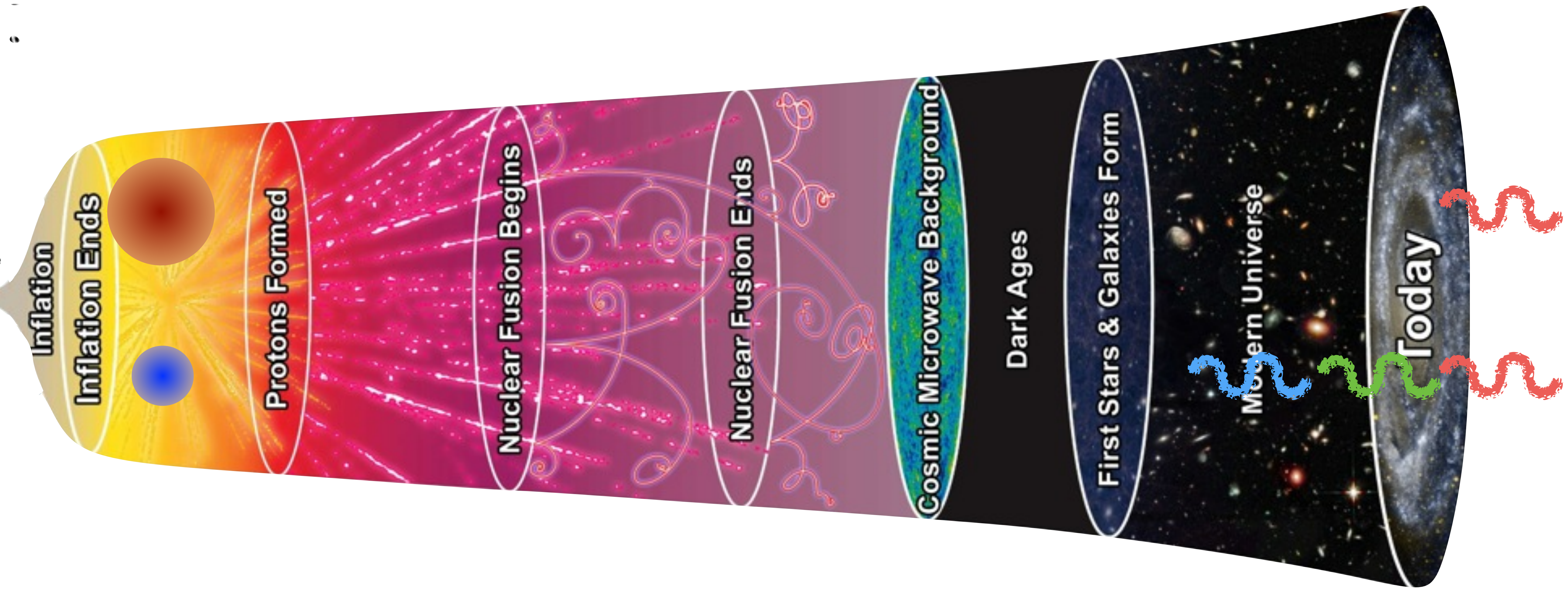
Low energy channel



- distant signals originated in younger and smaller sources

THE SMOKING GUN: DISTANCE/ENERGY RELATION

High energy channel

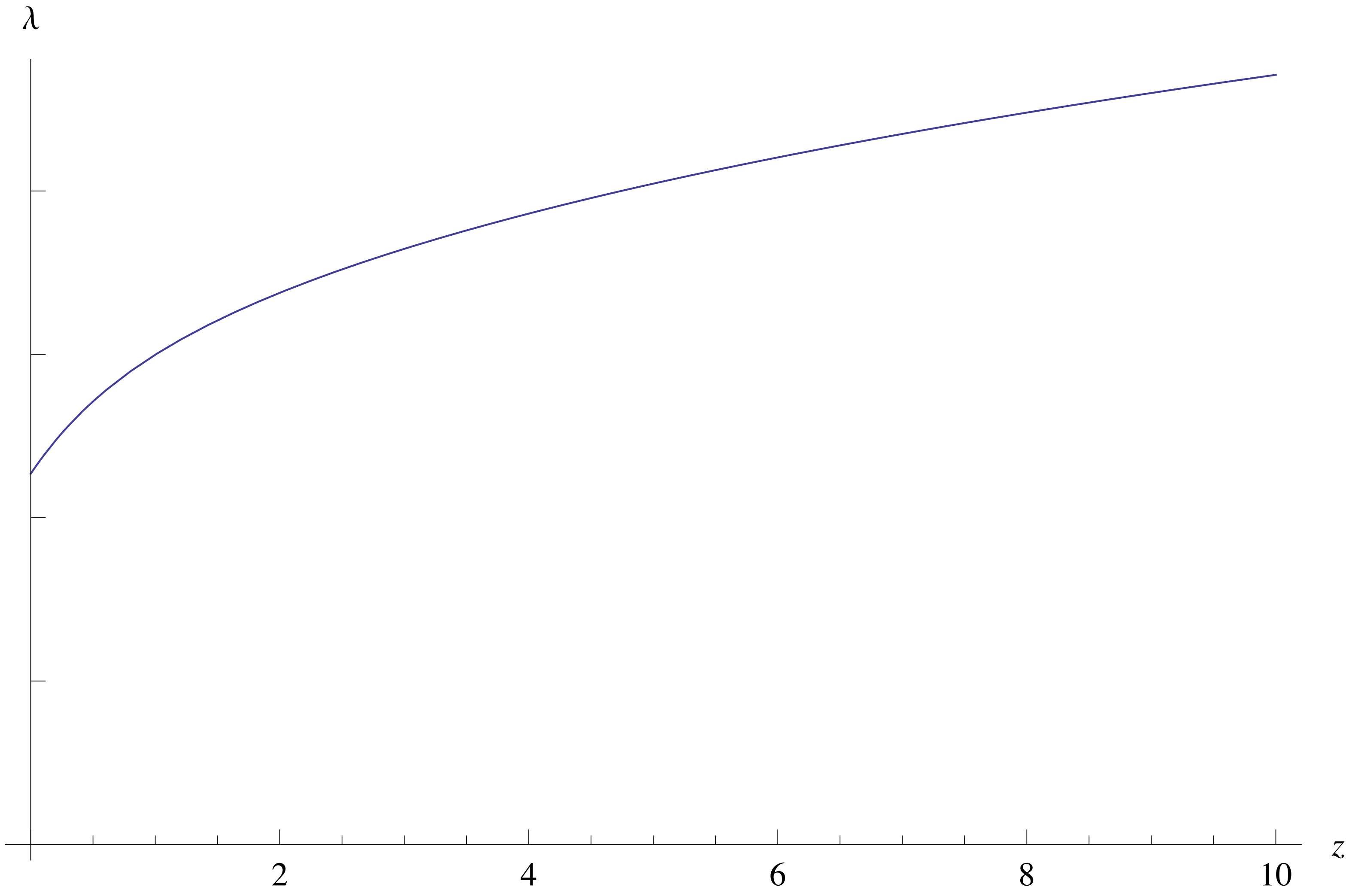


$$M \sim M_H \sim t$$

$$t \sim 0.3 g_*^{-\frac{1}{2}} T^{-2}$$

THE SMOKING GUN: DISTANCE/ENERGY RELATION

$$\lambda_{obs}^{other} = (1+z)\lambda_{emitted}^{other} \quad \longrightarrow \quad \lambda_{obs} \sim \frac{2Gm}{c^2}(1+z)\sqrt{\frac{H_0^{-1}}{6\,k\Omega_\Lambda^{1/2}}\ \sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{1/2}(z+1)^{-3/2}\right]}$$



- distance ∝ 1/wave length
- taking into account the redshift the resulting function is very slowly varying

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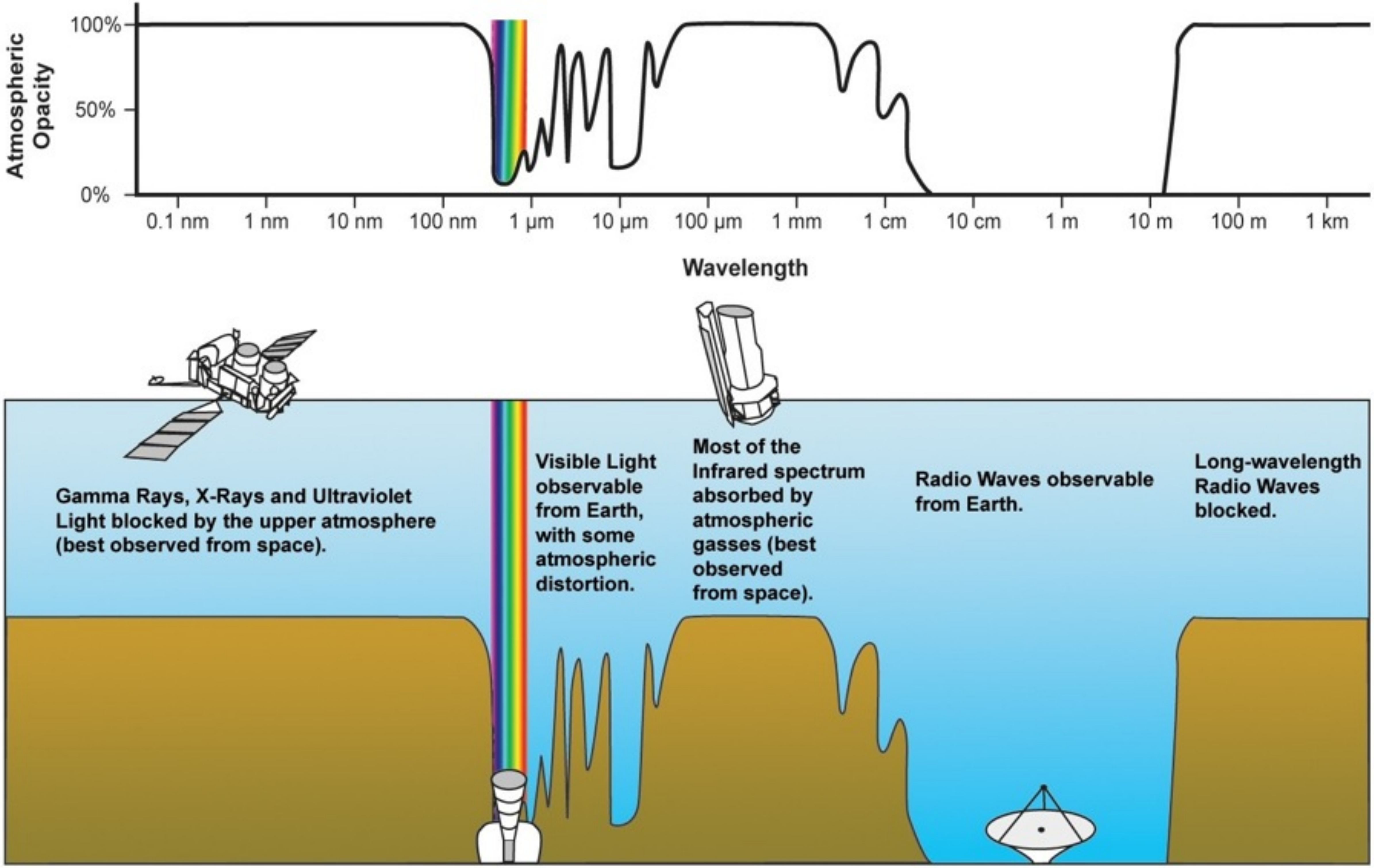
DETECTION ON EARTH?



Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

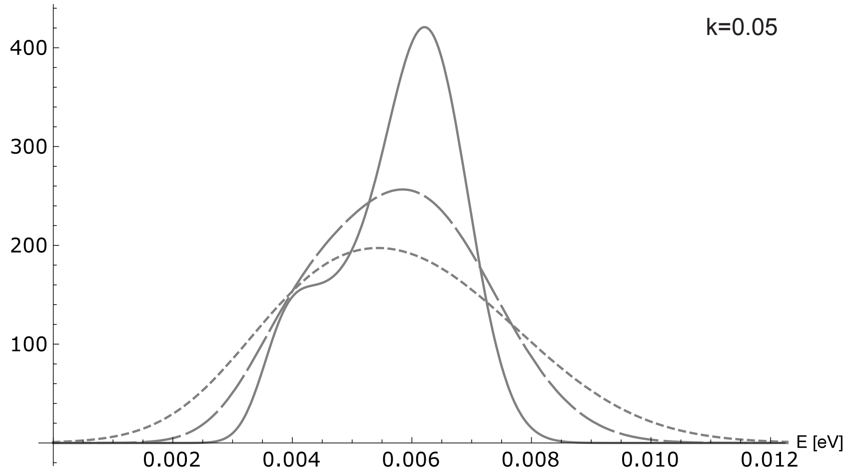
Long-wavelength Radio Waves blocked.

INTEGRATED EMISSION

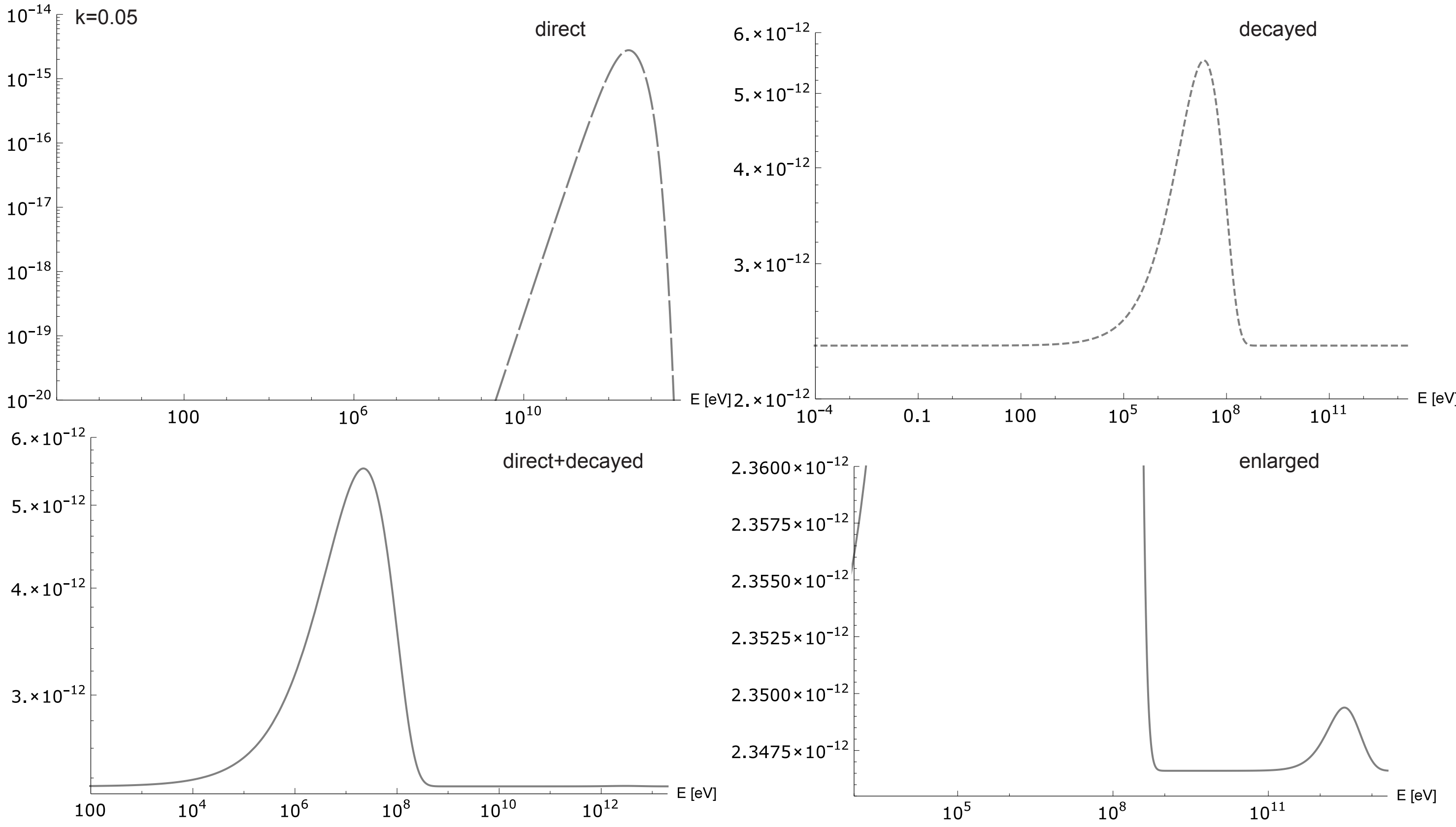
Barrau, Bolliet, Vidotto, Weimer 1507.1198

$$\tau \sim m^2$$

Low energy channel



High energy channel



$$\frac{dN_{mes}}{dEdtdS} = \int \Phi_{ind}((1+z)E,R)\cdot n(R) \cdot Acc\cdot Abs(E,R)dR$$

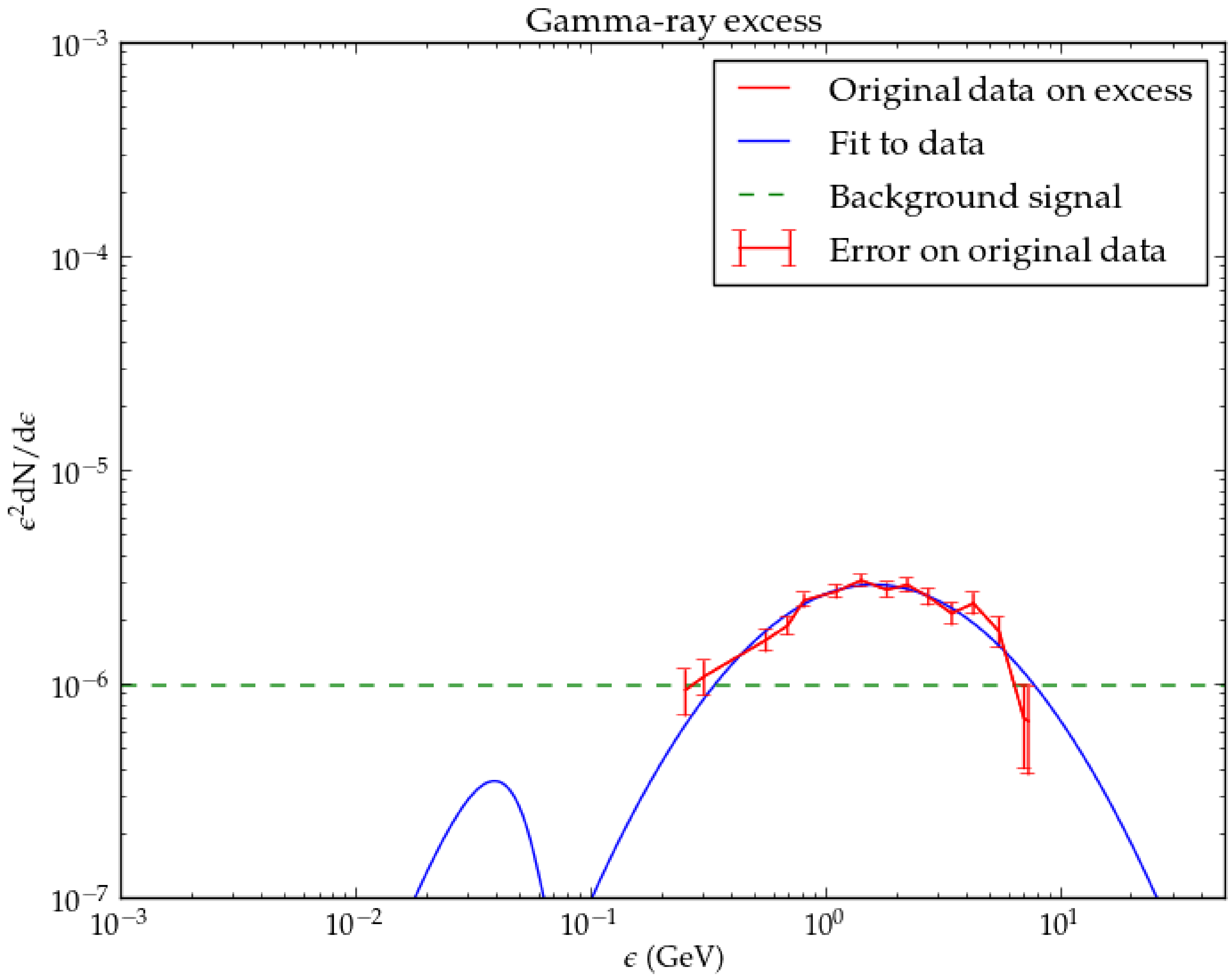
- characteristic shape: distorted black body
- depends on how much DM are PBL

GeV FERMI EXCESS

Schutten, Barrau, Bolliet, Vidotto, to appear

Low energy channel

- Consider the longest possible lifetime of a quantum black hole.

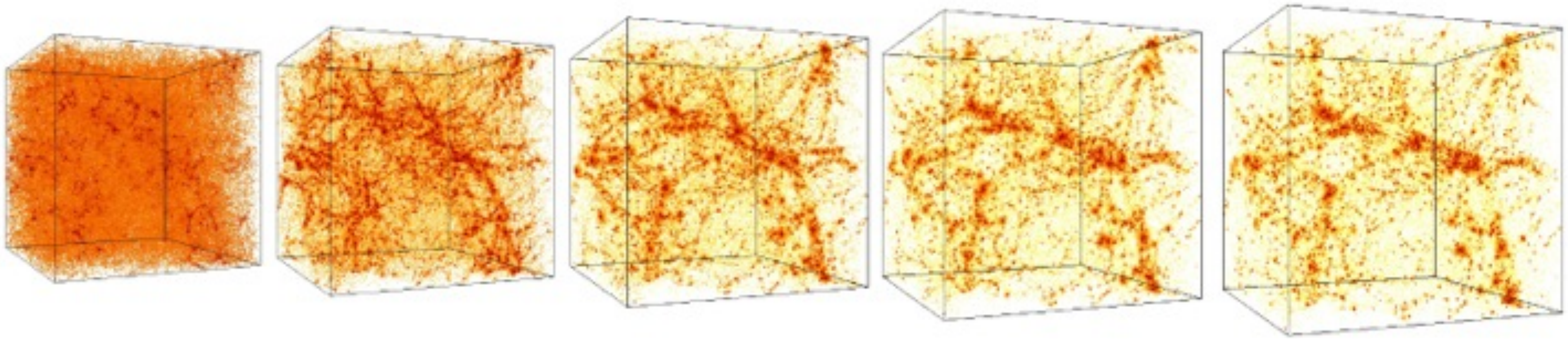


- Number of secondary gamma-rays is higher than the number of primary gamma-rays, but their spectral energy density is much lower.

QUANTUM PRIMORDIAL BLACK HOLES AS DARK MATTER

- Structure formation

Raccanelli, Chluba, Cholis, Vidotto WIP



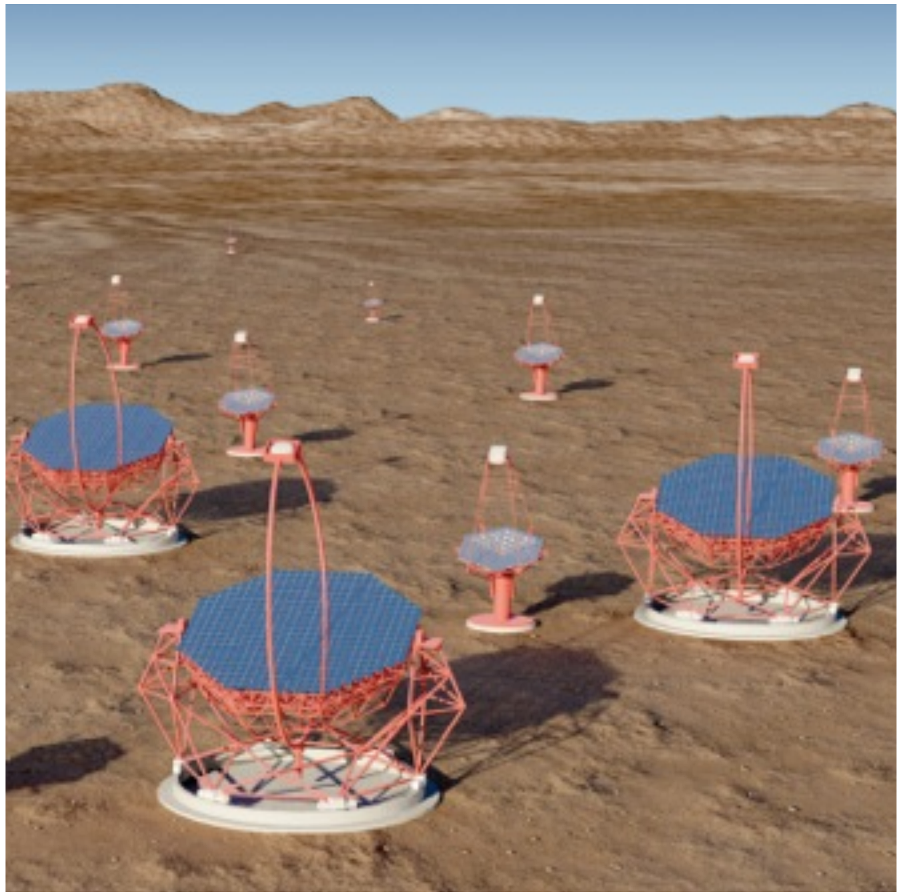
- First stars & Supermassive black holes

Bambi, Freese, Vidotto WIP

  - Primordial black holes inside first-generation stars can provide the seeds for supermassive black holes.

TeV EMISSION

- the white hole should eject particles at the same temperature as the particles that felt in the black hole
- limited horizon due to absorption ~ 100 million light-years / z=0.01
- Short Gamma Ray Burst ?



- telescopes spanning large surfaces needed (CTA?)

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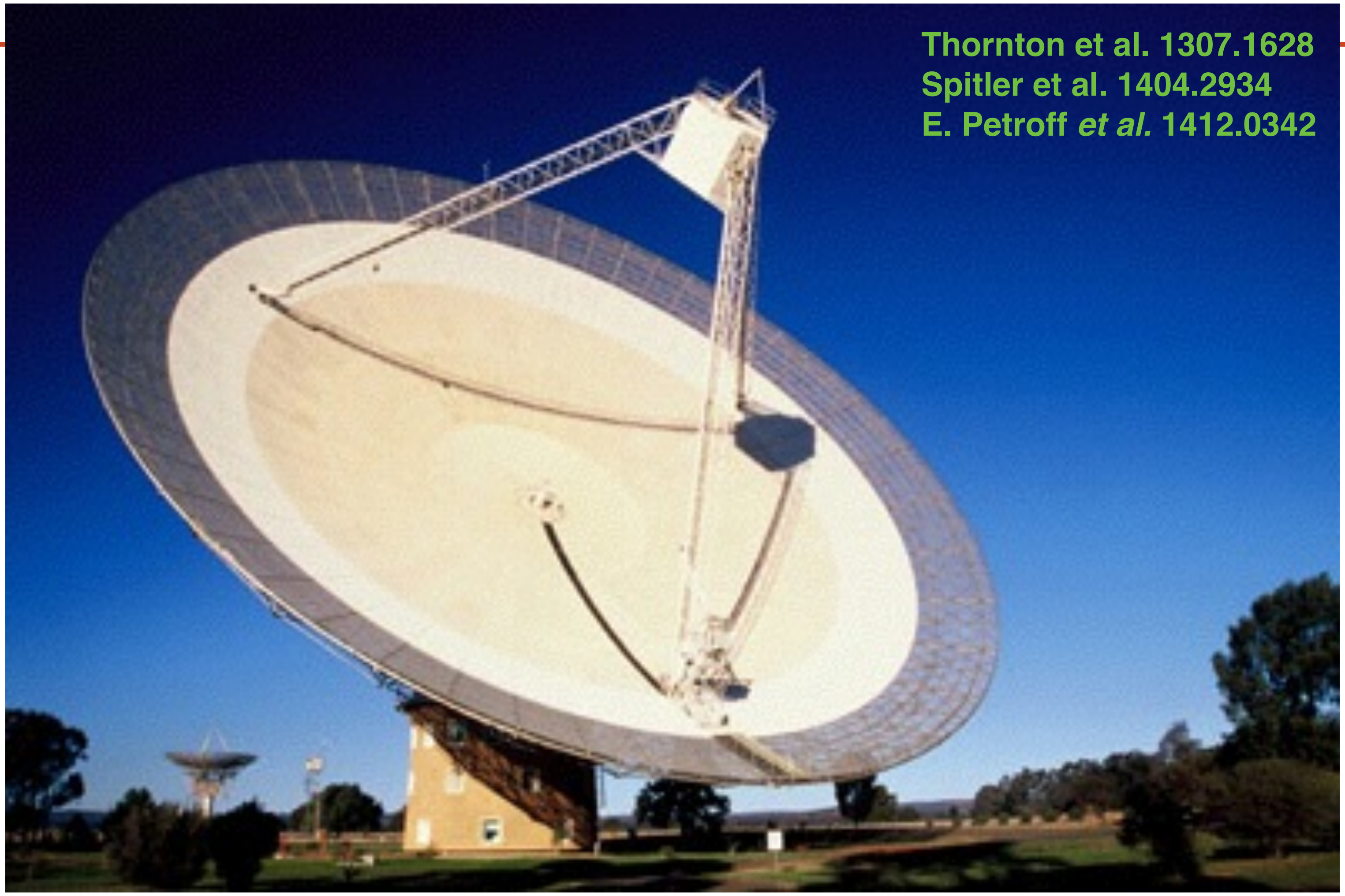
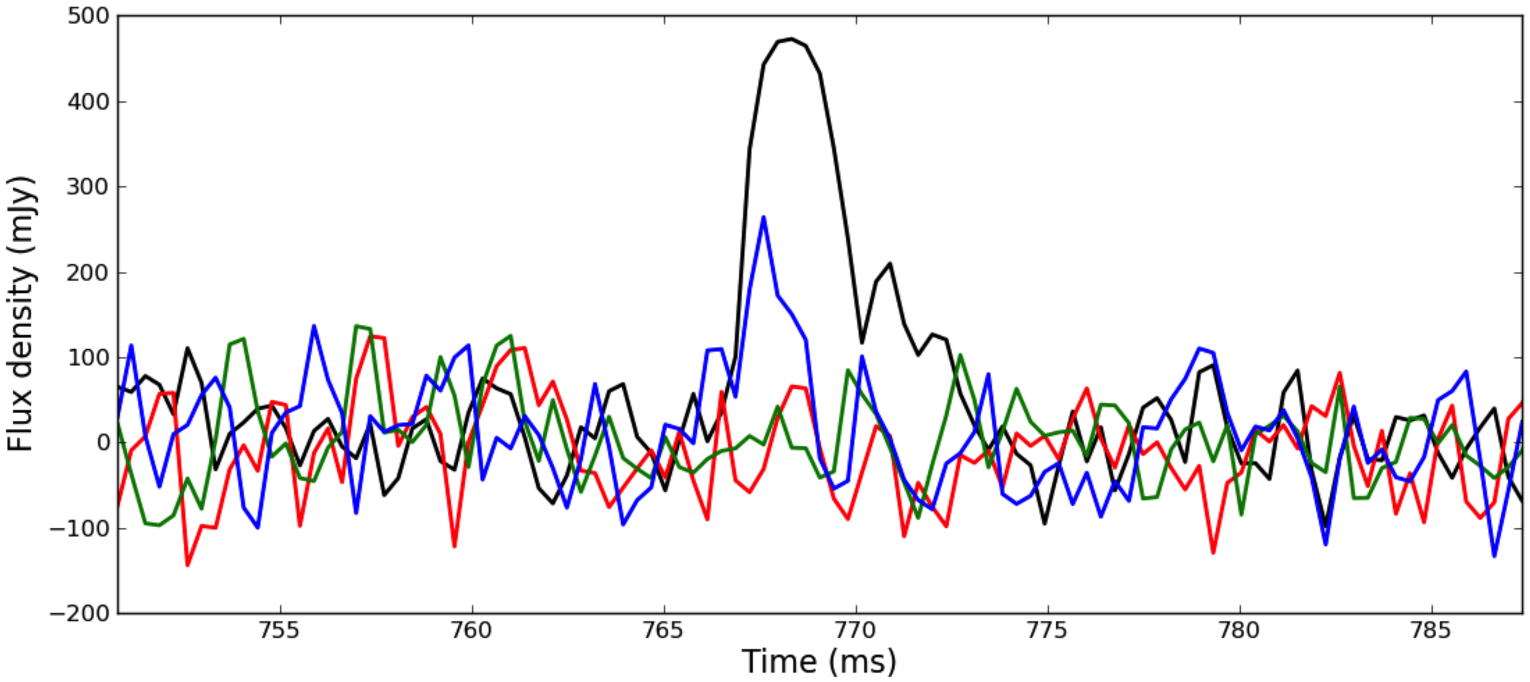
FAST RADIO BURSTS

Unknown source!

- Short
  - Observed width $\simeq$ milliseconds
- No Long GRB associated
  - No Afterglow
- Punctual
  - No repetition
- Enormous flux density
  - Energy $\lesssim 10^{38}$ erg
- Likely Extragalactic
  - Dispersion Measure: $z \lesssim 0.5$
- 10^4 event/day
  - A pretty common object?
- Circular polarization
  - Intrinsic



Thornton et al. 1307.1628
Spitler et al. 1404.2934
E. Petroff *et al.* 1412.0342



FAST RADIO BURSTS

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- $\lambda \approx 20$ cm → size of the source $\approx$ $\lambda_{predicted} \gtrsim .02$ cm
- Short
  - Observed width ≃ milliseconds → fast process
- No Long GRB associated
  - No Afterglow → Very short GRB ? gravitational waves ?
- Punctual
  - No repetition → the source disappears with the burst
- Enormous flux density
  - Energy ≲ 10^{38} erg → very compact object $\longrightarrow 10^{47}$ erg
- Likely Extragalactic
  - Dispersion Measure: $z \lesssim 0.5$ → peculiar distance/energy relation
- 10^4 event/day
  - A pretty common object?

Are they bouncing Black Holes?

- Circular polarization
  - Intrinsic

LIST OF FAST RADIO BURSTS

name	date	RA	dec	DM	width	peak	notes
FRB 010724	2001/07/24	01h18′	-75°12′	375	4.6	30	"Lorimer Burst"
FRB 010621	2001/06/21	18h52′	-08°29′	746	7.8	0.4	
FRB 110220	2011/02/20	22h34′	-12°24′	944.38	5.6	1.3	
FRB 110627	2011/06/27	21h03′	-44°44′	723.0	<1.4	0.4	
FRB 110703	2011/07/03	23h30′	-02°52′	1103.6	<4.3	0.5	
FRB 120127	2012/01/27	23h15′	-18°25′	553.3	<1.1	0.5	
FRB 011025	2001/10/25	19h07′	-40°37′	790	9.4	0.3	
FRB 121002	2012/10/02	18h14′	-85°11′	1628.76	2.1; 3.7	0.35	double pulse 5.1 ms apart
FRB 121002	2012/10/02	18h14'	-85°11'	1629.18	<0.3	>2.3	
FRB 121102	2012/11/02	05h32′	33°05'	557	3.0	0.4	by Arecibo radio telescope
	2015	05h32′~	33°05'~	557~			10 repeat bursts: 6 bursts in 10 minutes, 3 bursts weeks apart.
FRB 131104	2013/11/04	06h44′	-51°17′	779.0	<0.64	1.12	'near' Carina Dwarf Spheroidal Galaxy
FRB 140514	2014/05/14	22h34′	-12°18′	562.7	2.8	0.47	21 ± 7 per cent (3σ) circular polarization
FRB 090625	2009/06/25	03h07'	-29°55′	899.6	<1.9	>2.2	
FRB 130626	2013/06/26	16h27'	-07°27'	952.4	<0.12	>1.5	
FRB 130628	2013/06/28	09h03'	+03°26'	469.88	<0.05	>1.2	
FRB 130729	2013/07/29	13h41'	-05°59'	861	<4	>3.5	
FRB 110523	2011/05/23	21h45'	-00°12'	623.30	1.73	0.6	700-900 MHz at Green Bank radio telescope, detection of both circular and linear polarization.
FRB 150418	2015/04/18	07h16'	−19° 00′	776.2	0.8	2.4	Detection of linear polarization. The origin of the burst is disputed.

SUMMARY

1. **BLACK HOLE** can be singularity free

   and they can tunnel into a white hole in a time ~m^2

   * complete calculation available in LQG

2. **PHENOMENOLOGY** depends on mass and lifetime

   * new experimental window for quantum gravity

   - IR radio & TeV
   - direct detection & diffuse emission
   - peculiar energy distance relation

3. PRIMORDIAL BLACK HOLES

   - new features

what else
can change if black holes
explode this way?

MAIN PAPERS

Planck Stars

Planck stars
Carlo Rovelli, Francesca Vidotto
Int. J. Mod. Phys. D23 (2014) 12, 1442026

Classical metric

Black hole fireworks: quantum-gravity effects outside the horizon spark black to white hole tunneling
Hal Haggard, Carlo Rovelli
Phys. Rev. D.92.104020.

Improved Black Hole Fireworks: Asymmetric Black-Hole-to-White-Hole Tunneling Scenario
Tommaso De Lorenzo, Alejandro Perez
arXiv:1512.04566

Phenomenology

Planck star phenomenology
Aurelien Barrau, Carlo Rovelli.
Phys. Lett. B739 (2014) 405

Phenomenology of bouncing black holes in quantum gravity: a closer look
Aurélien Barrau, Boris Bolliet, Francesca Vidotto, Celine Weimer
JCAP 1602 (2016) no.02, 022

Fast Radio Bursts

Fast Radio Bursts and White Hole Signals
Aurélien Barrau, Carlo Rovelli, Francesca Vidotto.
Phys. Rev. D90 (2014) 12, 127503

LQG lifetime calculation

Computing a Realistic Observable in Background-Free Quantum Gravity: Planck-Star Tunnelling-Time from Loop Gravity
Marios Chistodoulou, Carlo Rovelli, Simone Speziale, Ilya Vilensky.
ArXiv: 1605.05268