Quantum Gravity Signals

from primordial black holes

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Radboud University Nijmegen

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

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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HOW LONG IS THE BOUNCE FROM OUTSIDE?

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) ~ $(L_P)^{-1}$

⟹ the hole lifetime must be longer or of the order of ~ m^2

Upper limit:

Vidotto, Rovelli 1401.6562

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

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PRIMORDIAL BLACK HOLES EXPLOSIONS

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

Barrau, Rovelli, Vidotto 1409.4031

- **HIGH ENERGY:** energy of the particle liberated $\approx$ *formation temperature*
- fast process (few milliseconds?)
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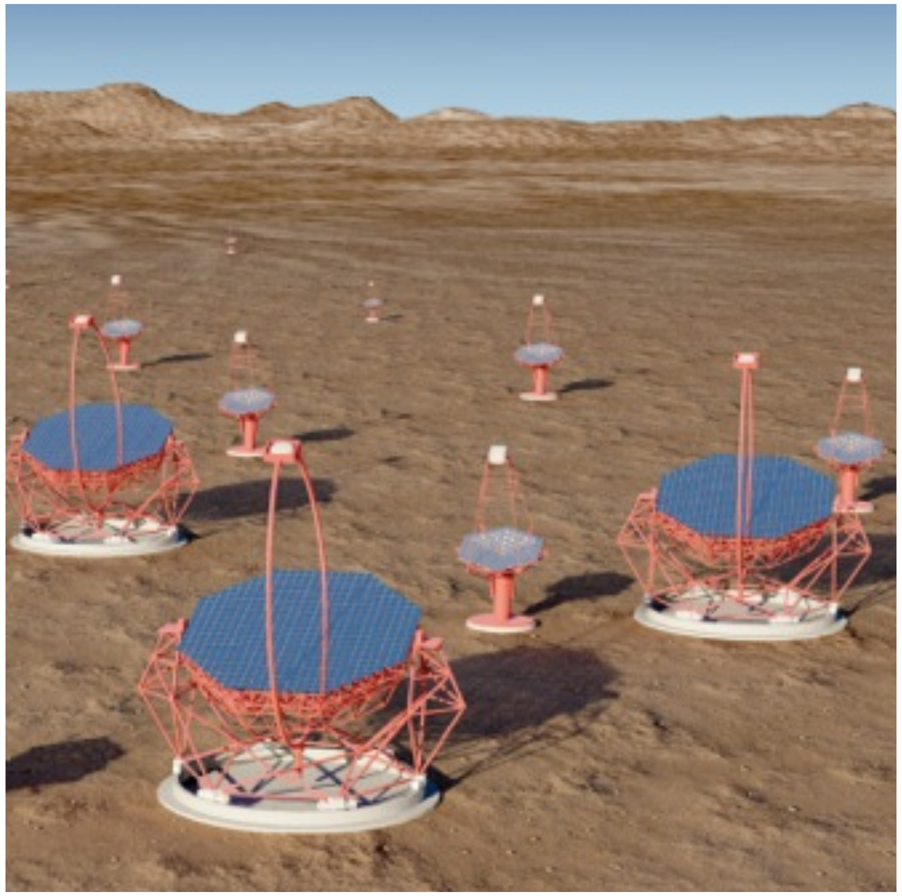
- the white hole should eject particles at the same temperature as the particles that felt in the black hole

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

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

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EXPONENTIAL DECAY: m^2 IS FAVORITE

- exploding now: $m = \sqrt{\frac{t_H}{4k}} \sim 1.2 \times 10^{23}$ kg $\quad R = \frac{2Gm}{c^2} \sim .02$ cm

- **LOW ENERGY:** size of the source ≈ 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 $\quad E = mc^2 \sim 1.7 \times 10^{47}$ erg

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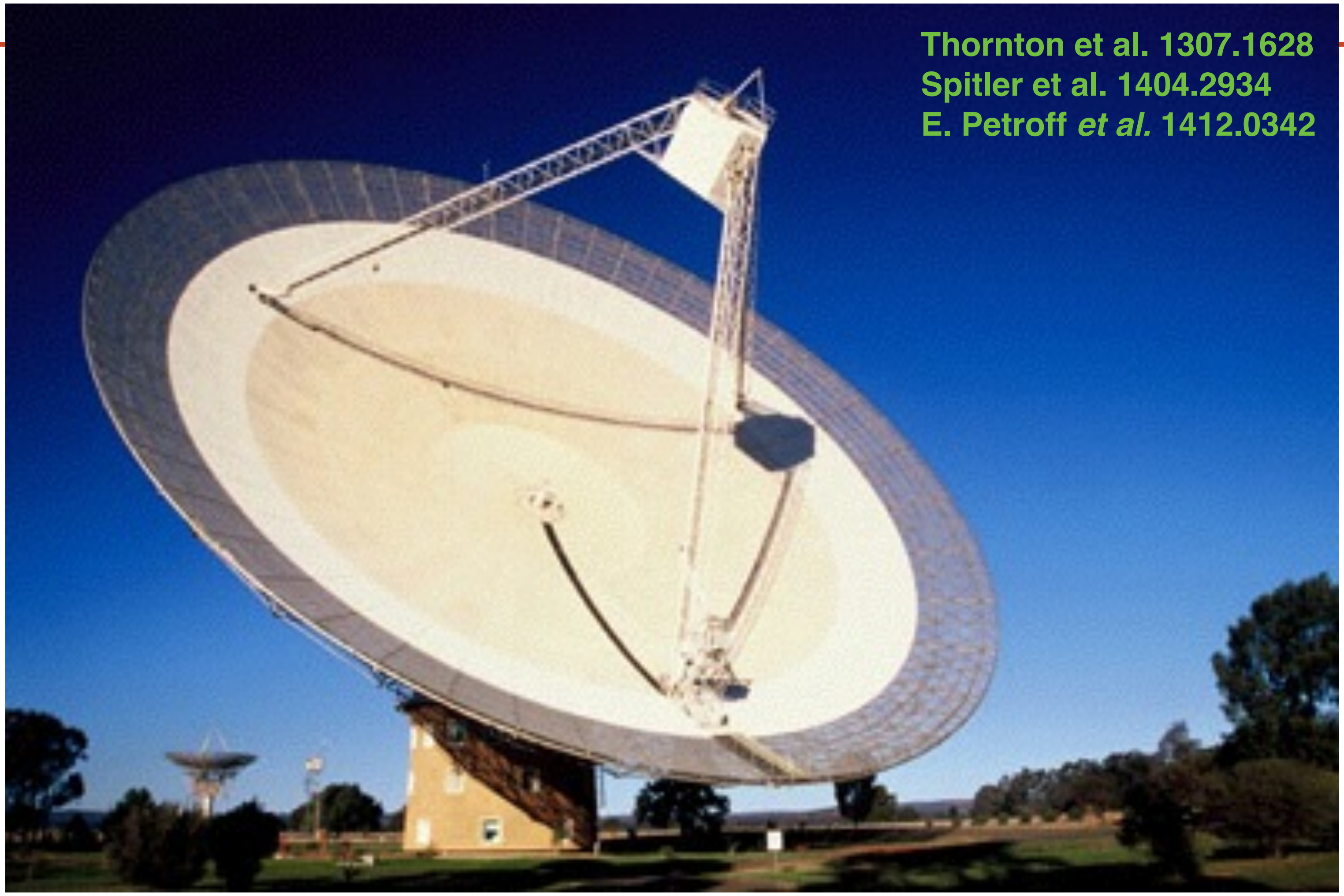
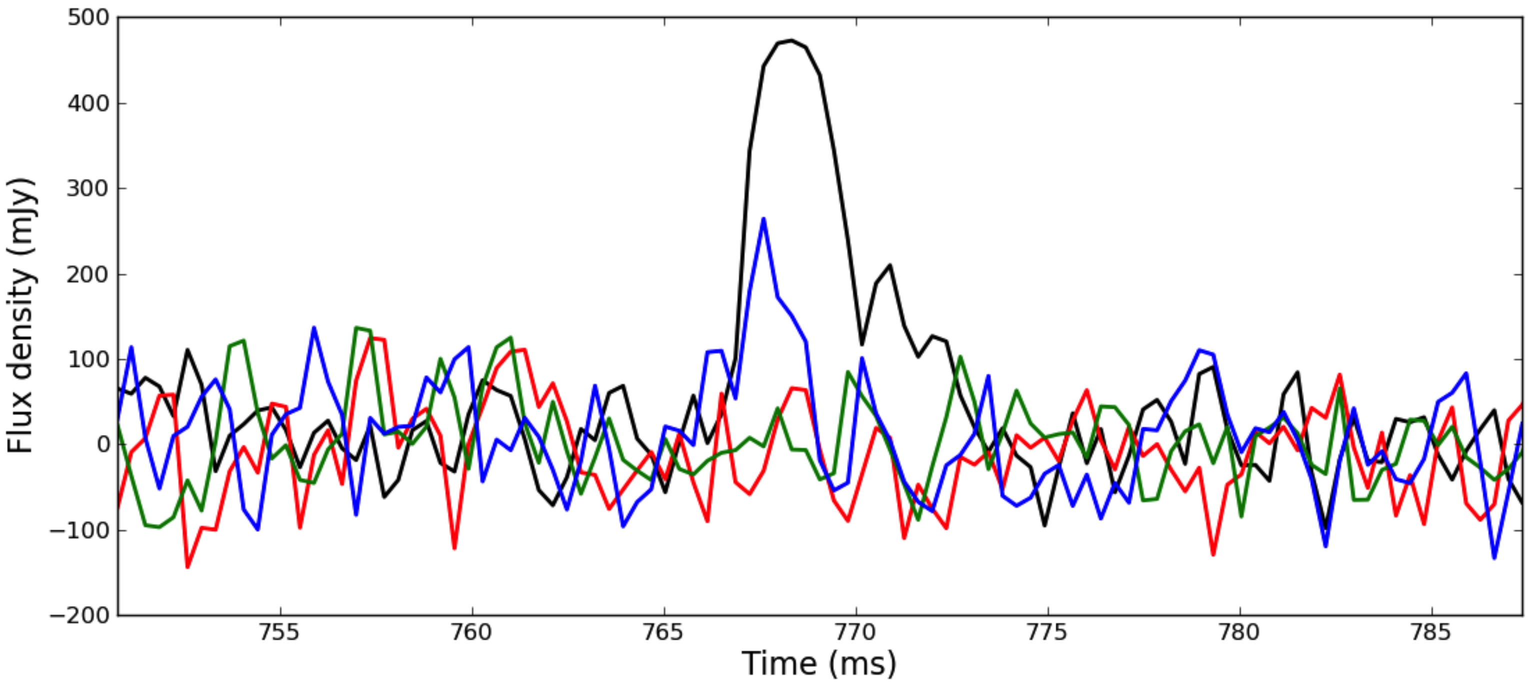
FAST RADIO BURSTS

Unknown source!

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





EXPONENTIAL DECAY: m^2 IS FAVORITE

- exploding now: $m = \sqrt{\frac{t_H}{4k}} \sim 10^{11}$ kg $\qquad R = \frac{2Gm}{c^2} \sim 10^{-14}$ cm
- **LOW ENERGY:** size of the source $\approx$ wavelength $\lambda_{predicted} \gtrsim GeV$
- **HIGH ENERGY:** energy of the particle liberated $\approx Tev$
- fast process (few milliseconds?)
- the source disappears with the burst
- very compact object: big flux $\qquad E = mc^2$

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MAXIMAL DISTANCE

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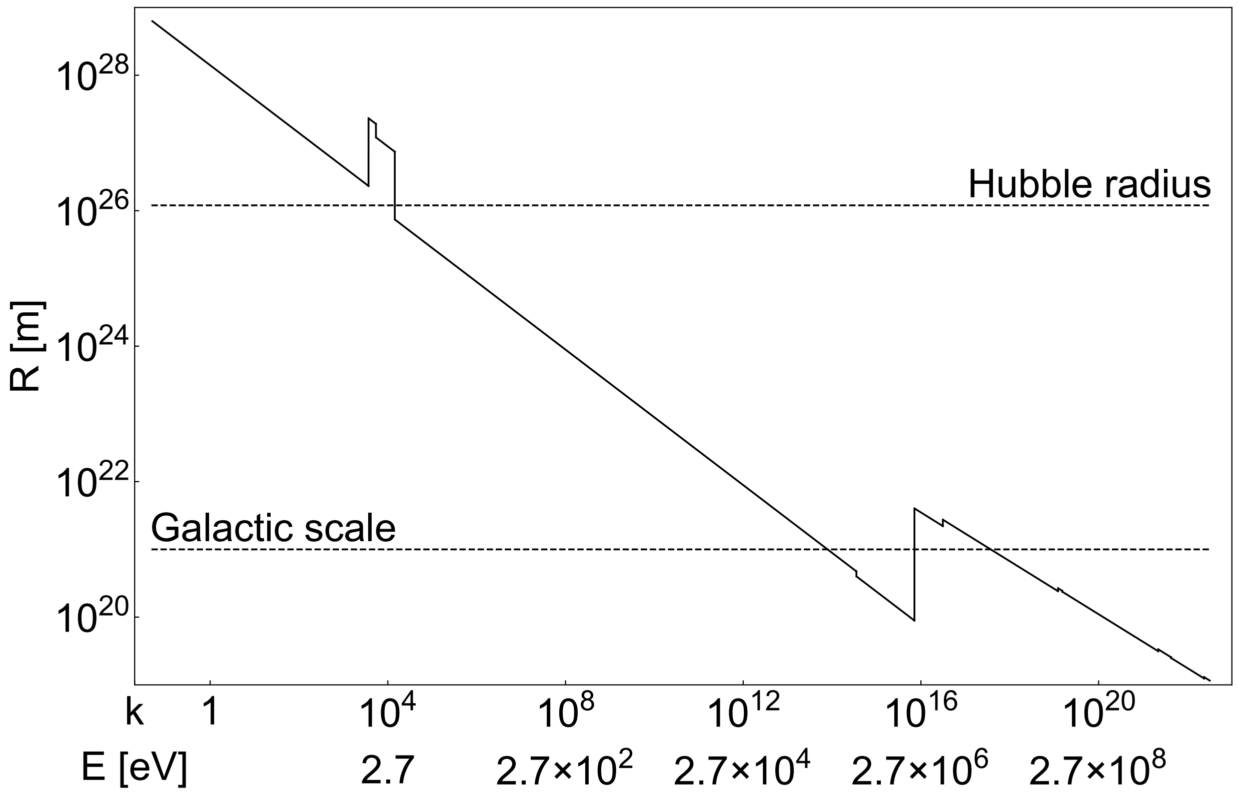
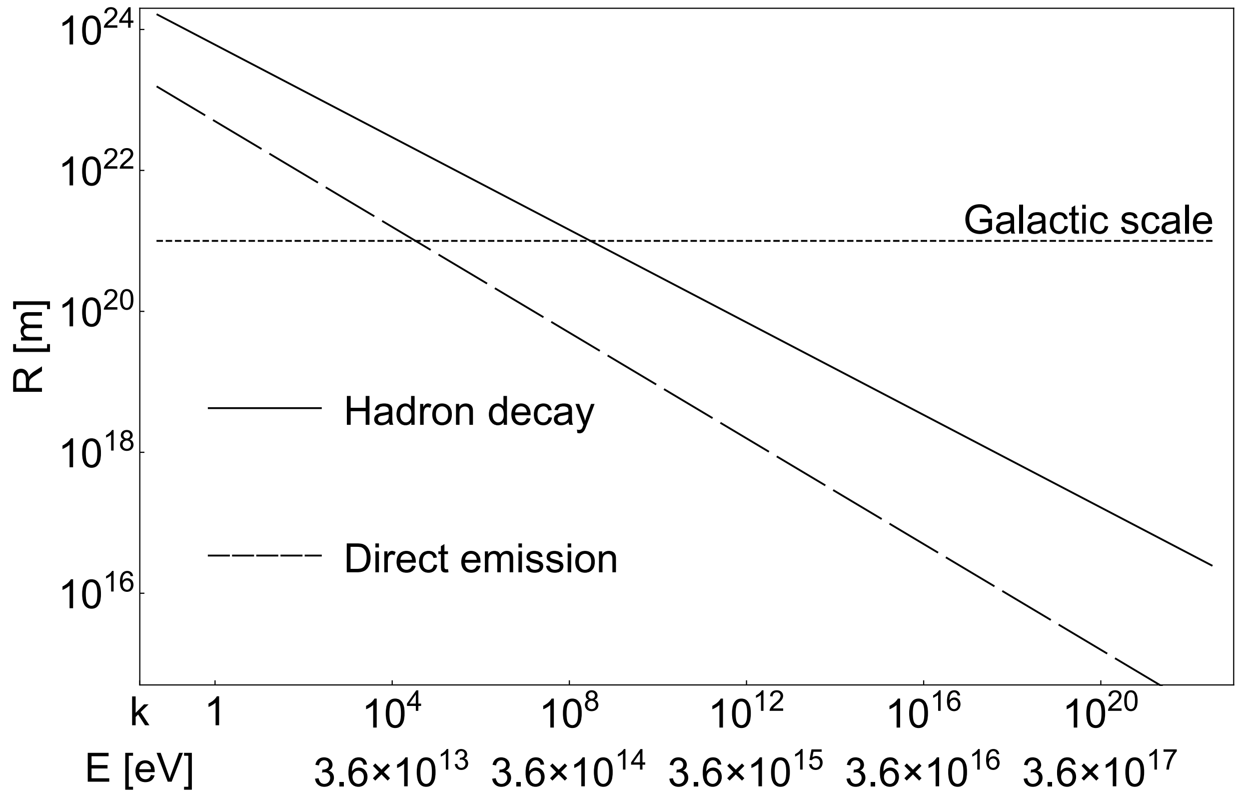
- shorter lifetime — smaller wavelength

Low energy channel



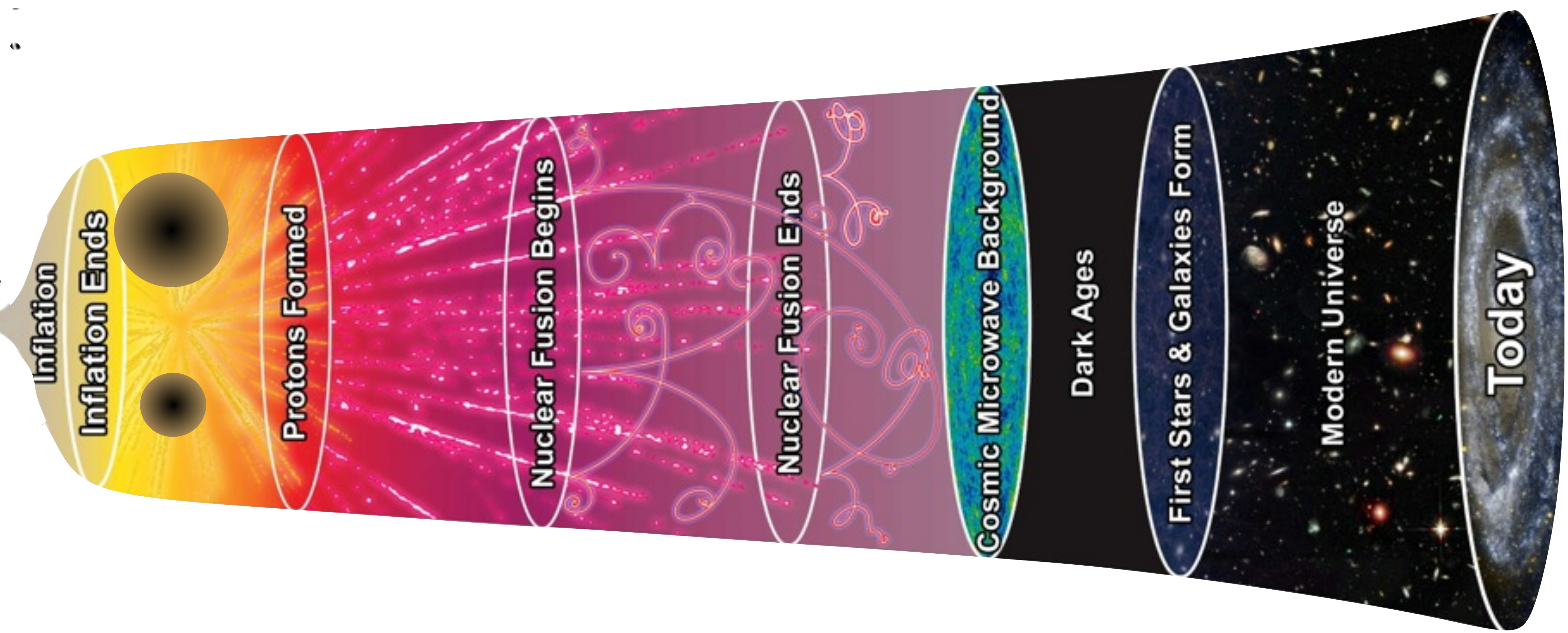
- detection of arbitrarily far signals
- better single-event detection

High energy channel



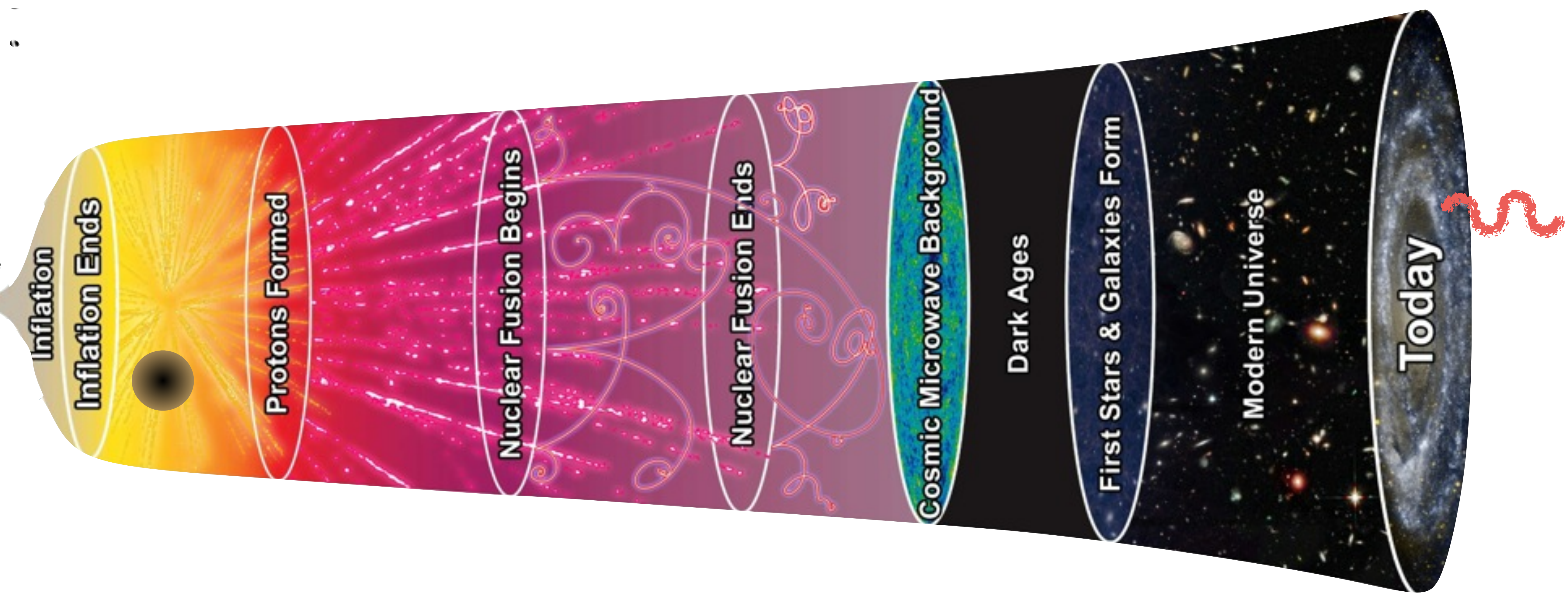
- PBH: mass - temperature relation
- different scaling

Low energy channel



- distant signals originated in younger and smaller sources

Low energy channel



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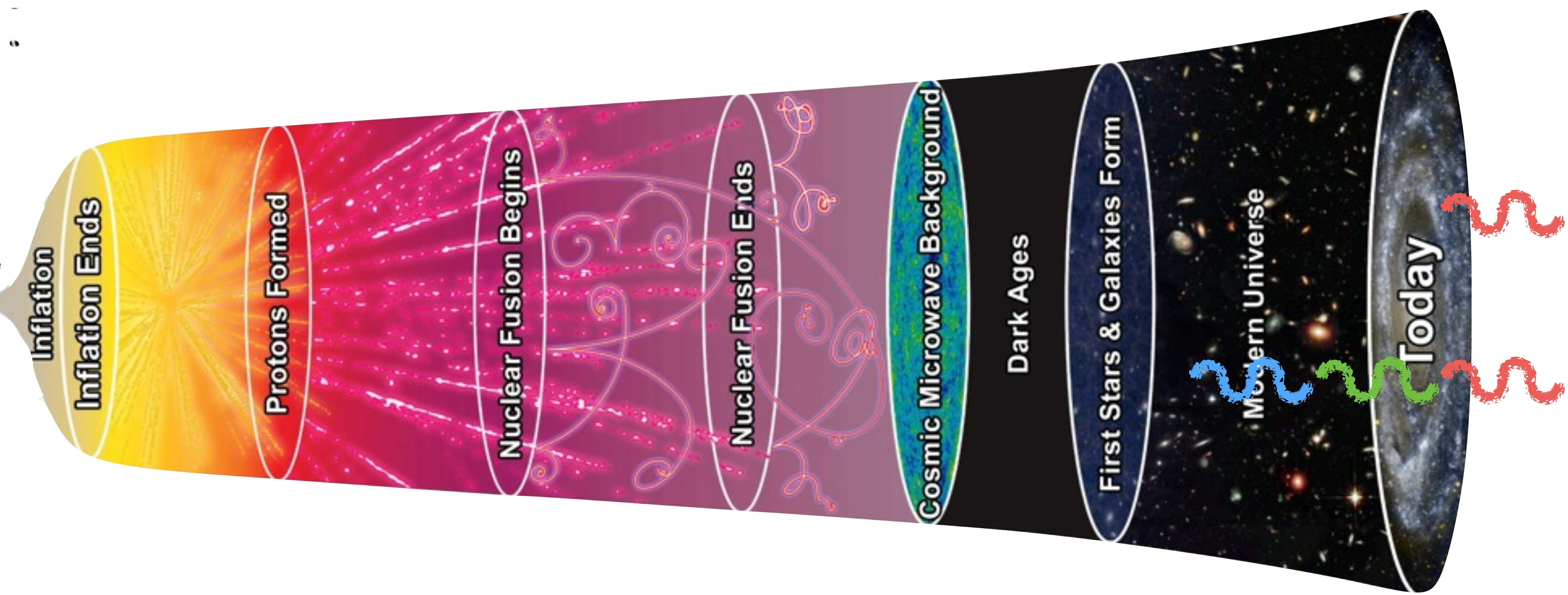

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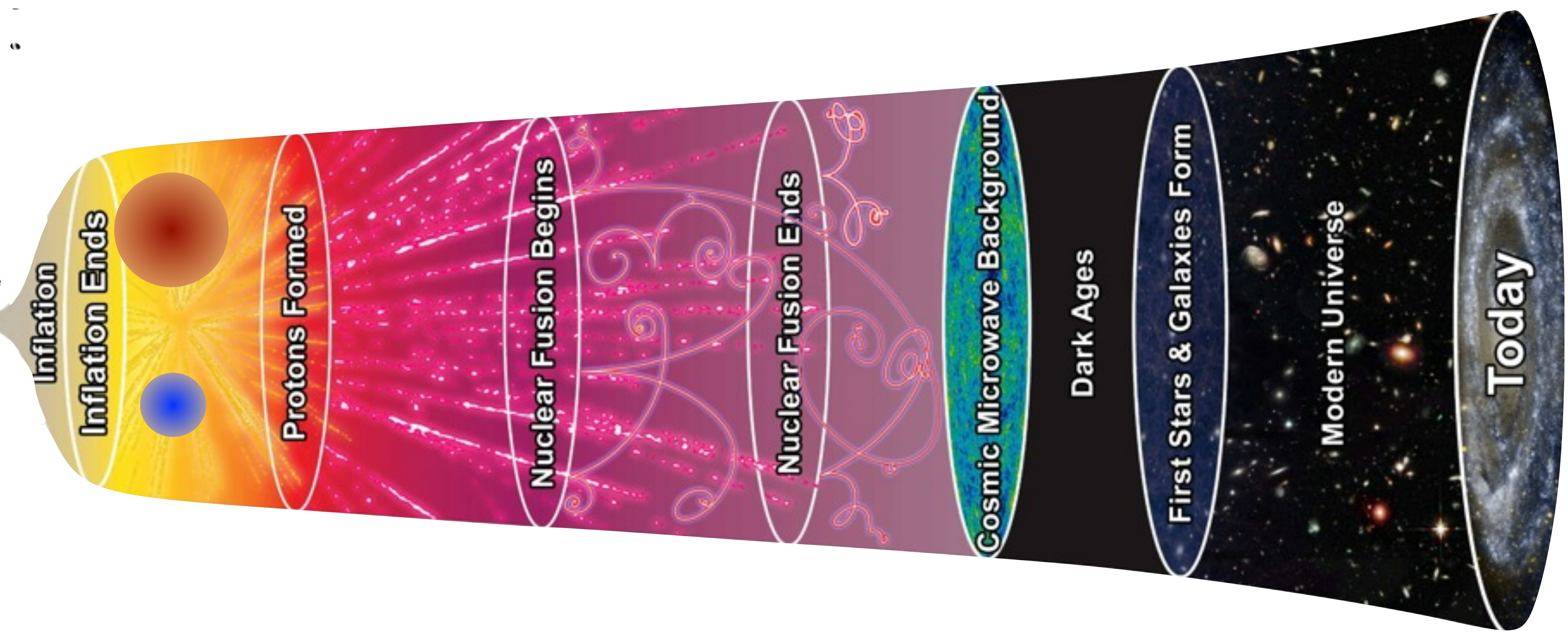
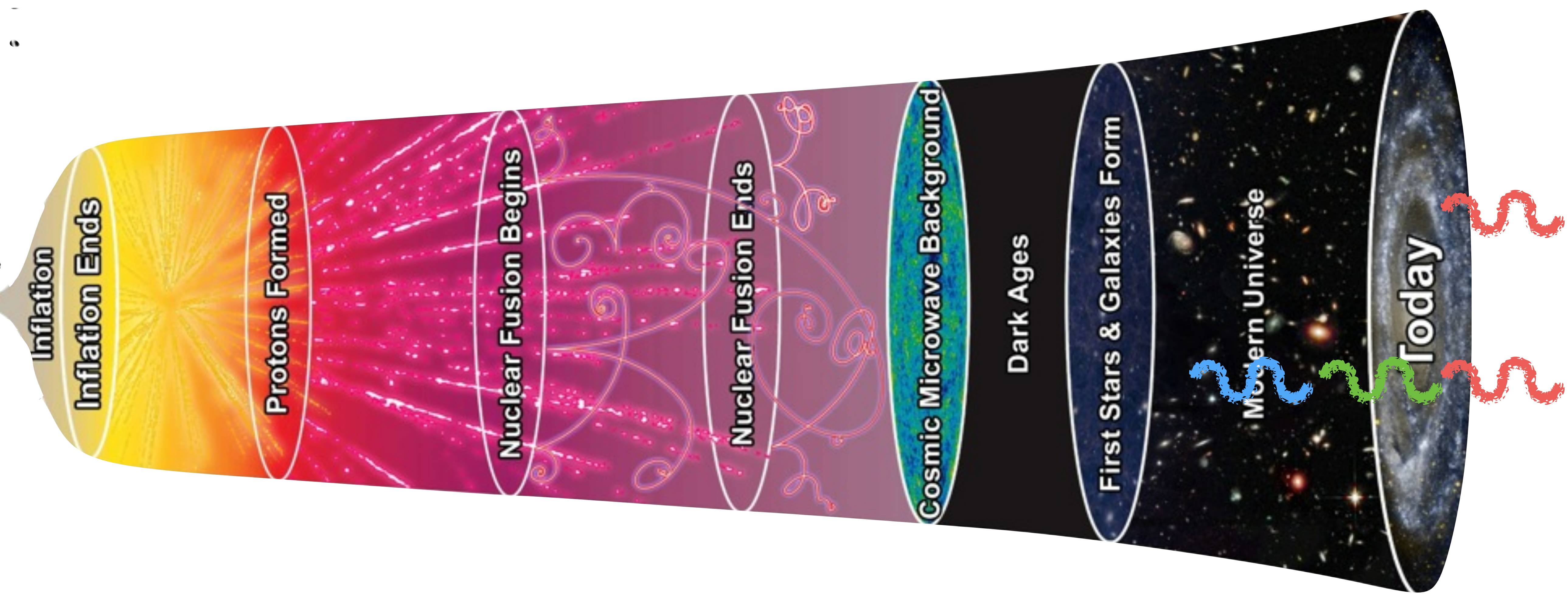


$$M \sim M_H \sim t$$

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

High energy channel



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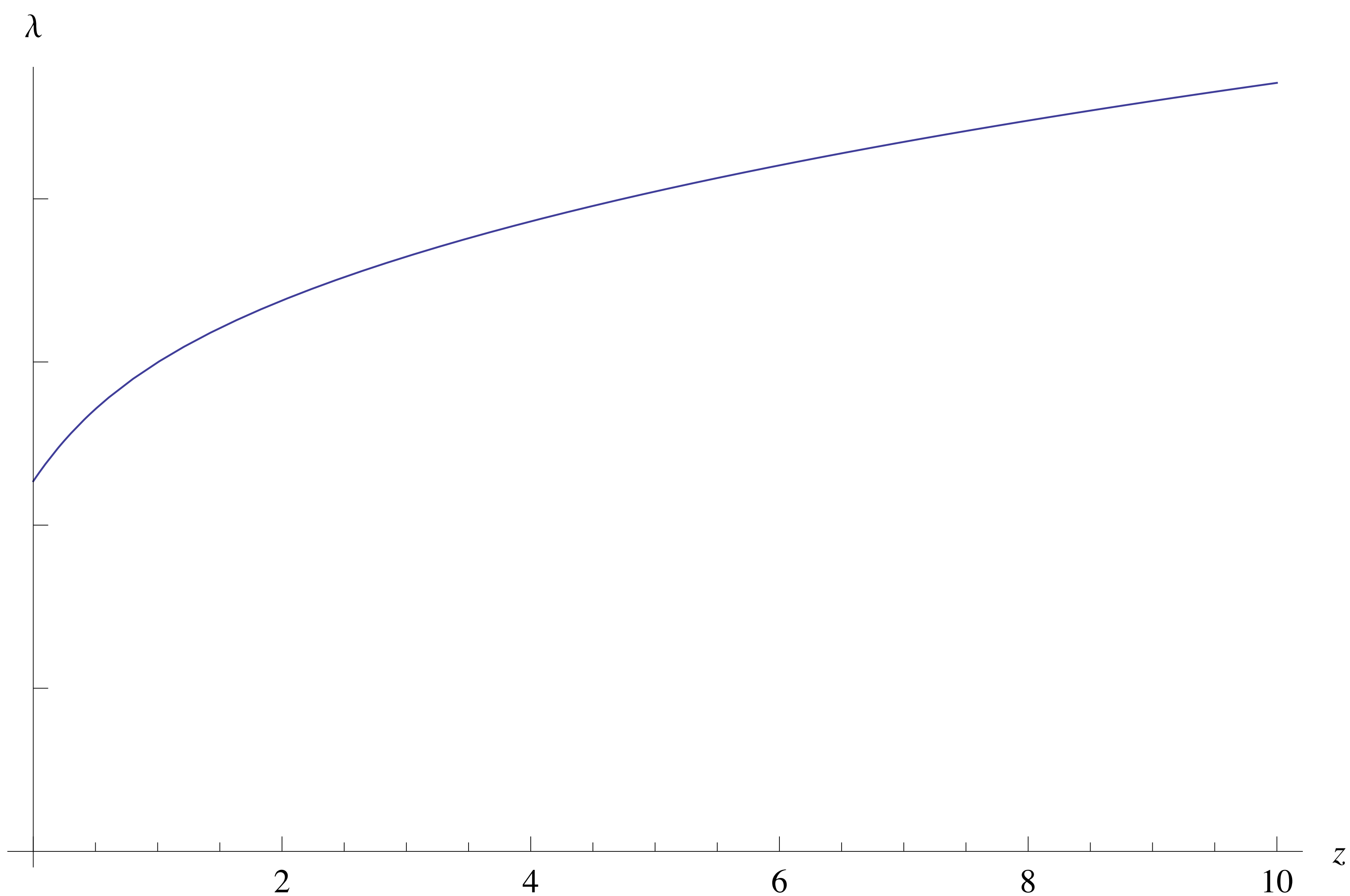
$$t \sim 0.3 g_*^{-\frac{1}{2}} T^{-2}$$

THE SMOKING GUN: DISTANCE/ENERGY RELATION

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

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



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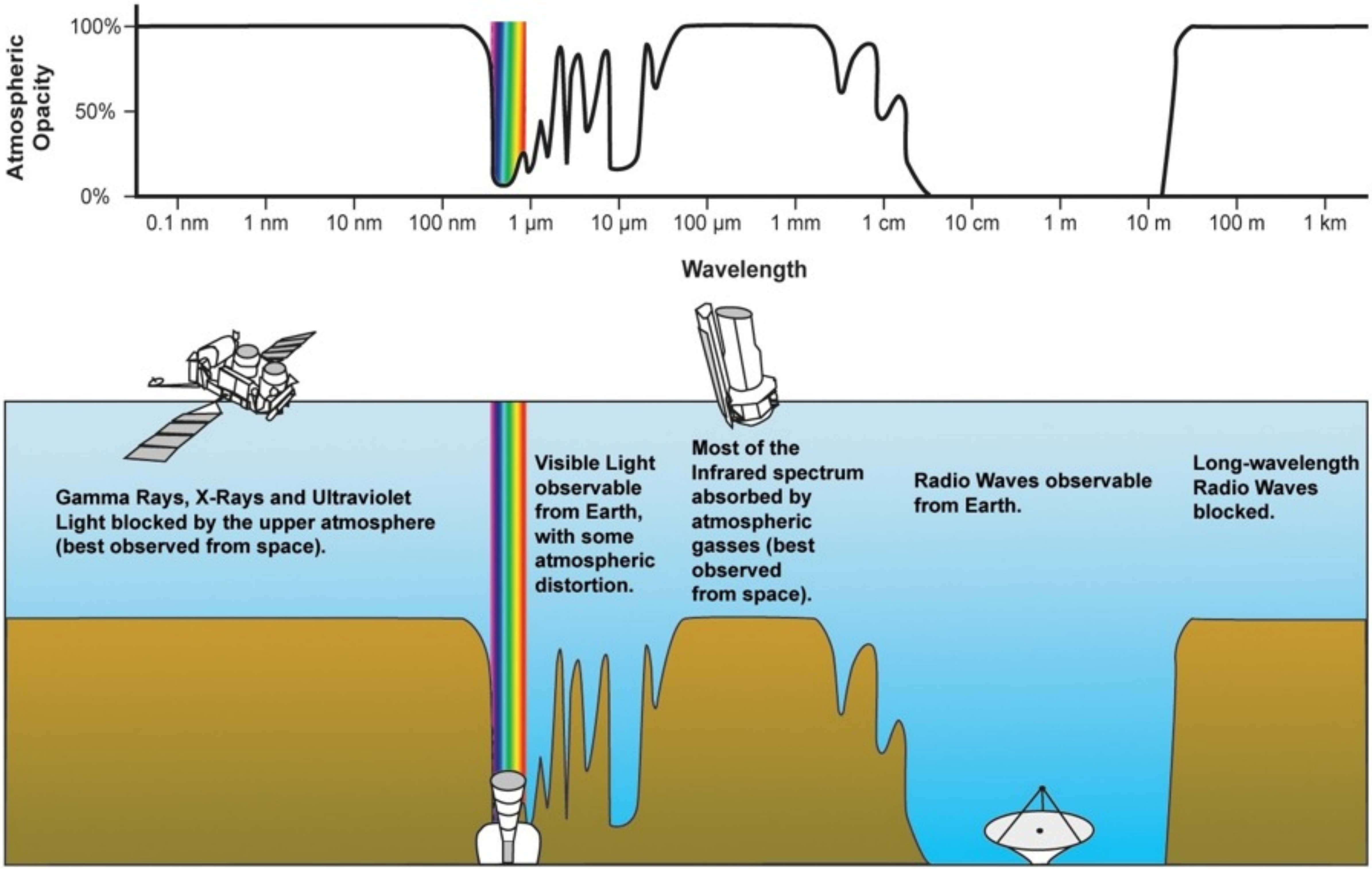
LIST OF FAST RADIO BURSTS

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 $\pm$ 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.

DETECTION ON EARTH?



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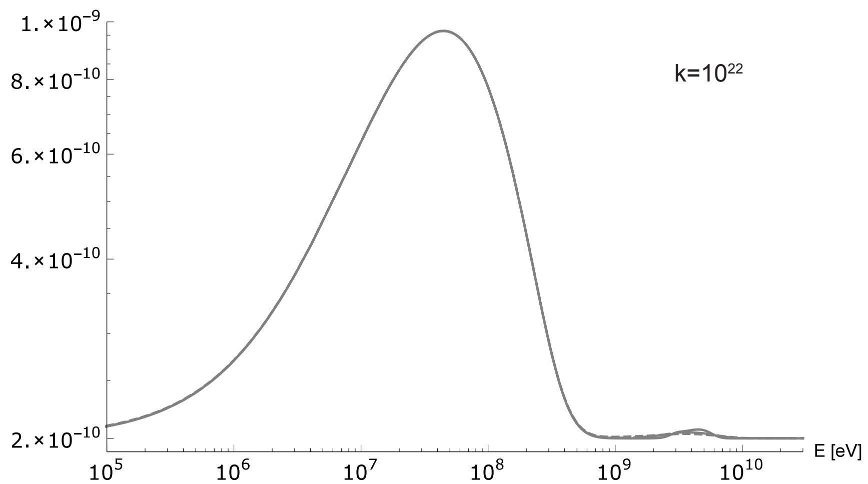
$$\tau \sim m^3$$

Low energy channel



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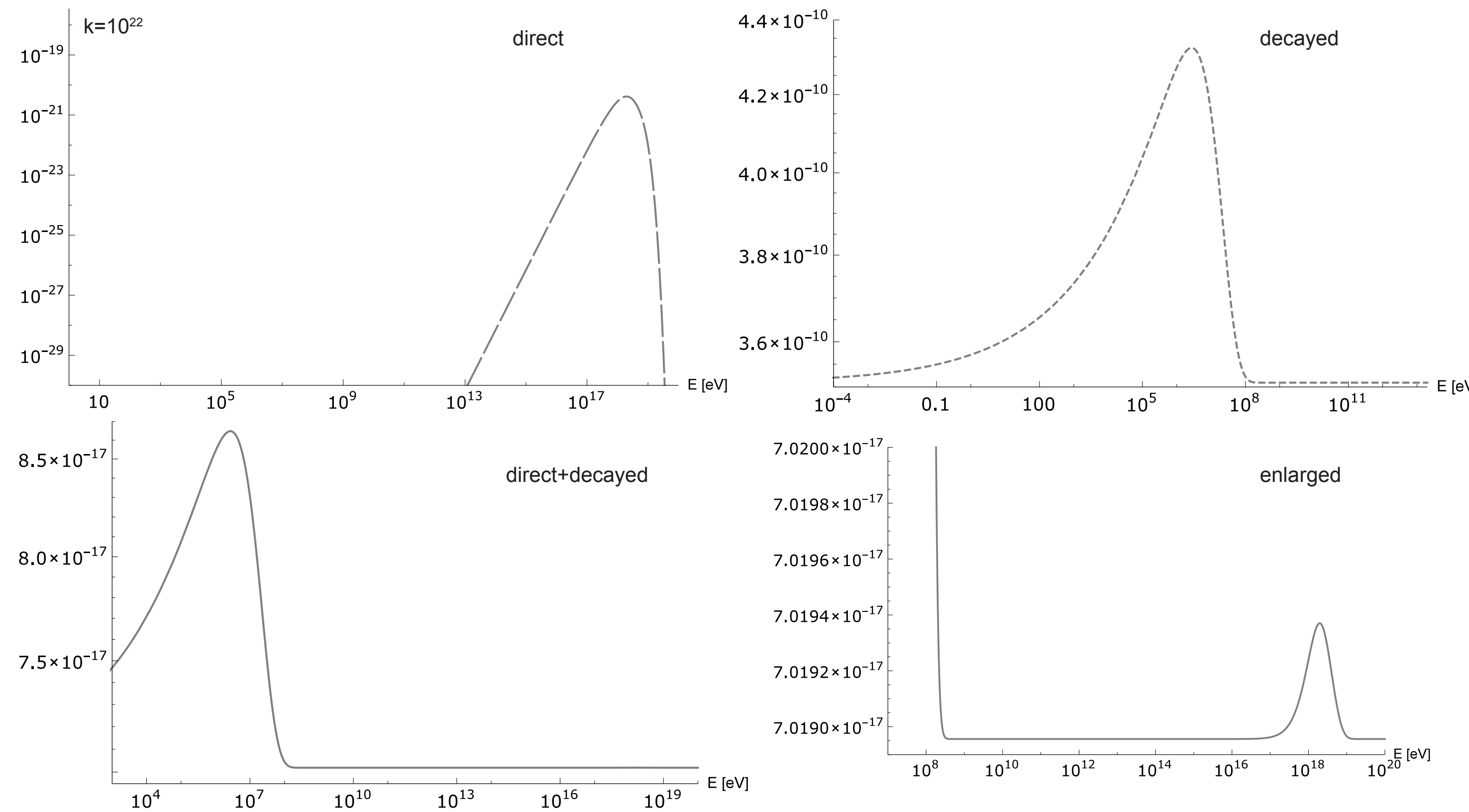

$$\frac{dN_{mes}}{dEdtdS} = \int \Phi_{ind}((1+z)E, R) \cdot n(R) \cdot Acc \cdot Abs(E, R) dR$$

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

INTEGRATED EMISSION

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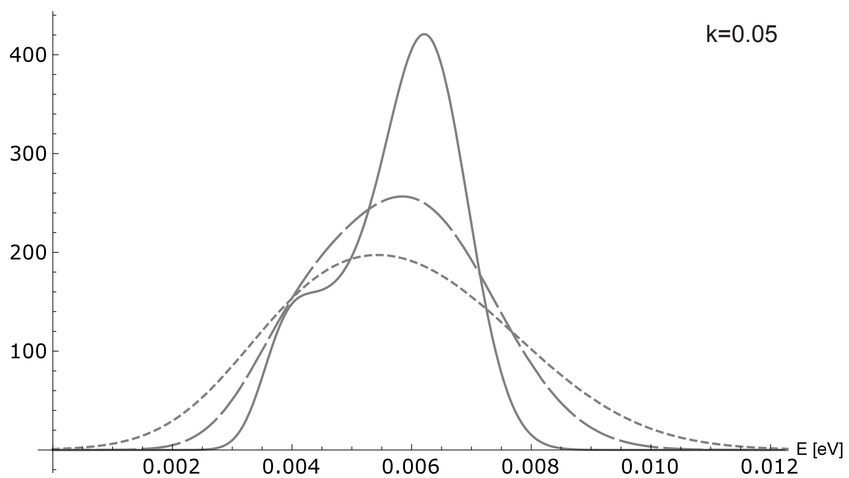
$$\tau \sim m^2$$

Low energy channel



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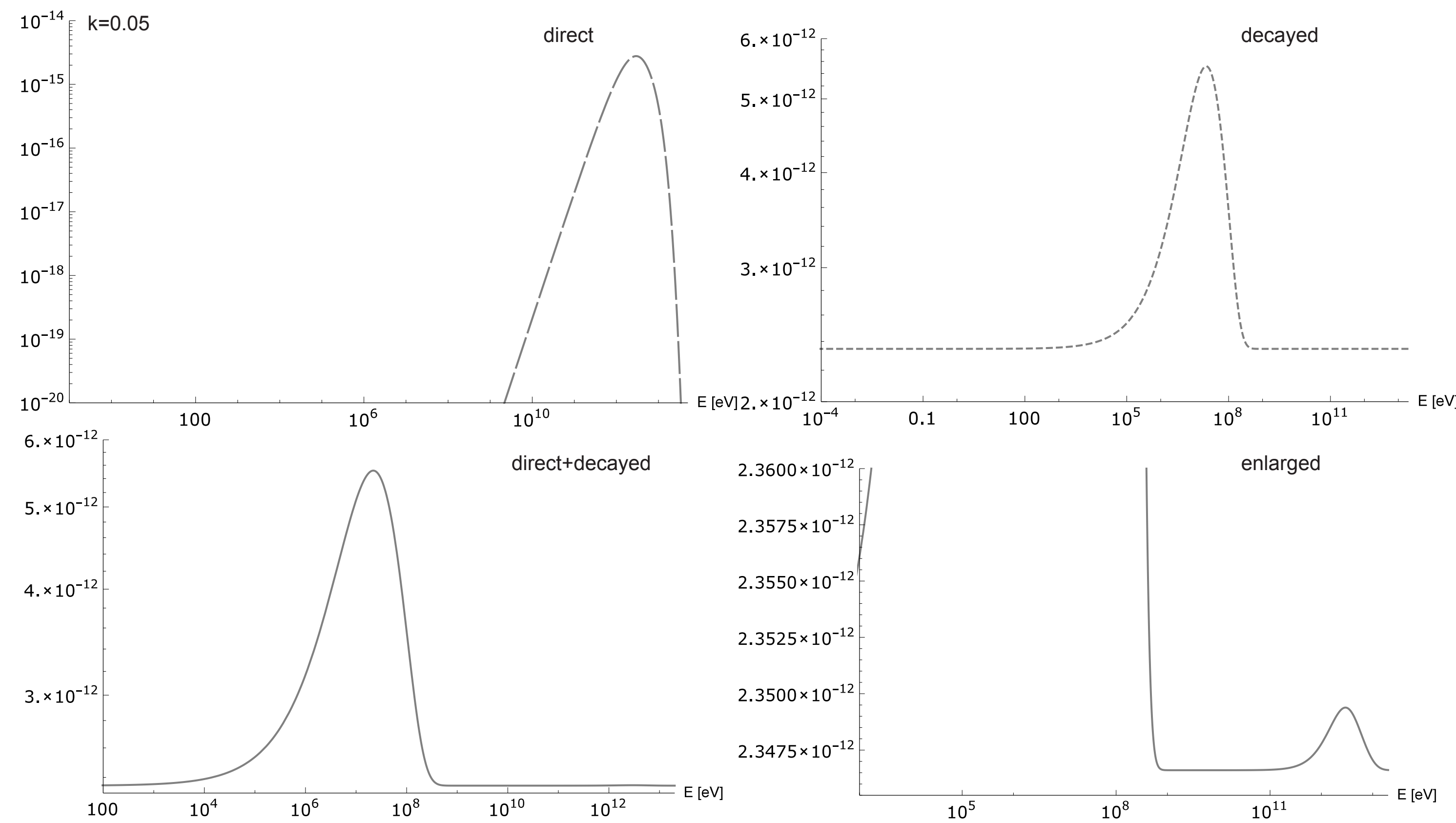

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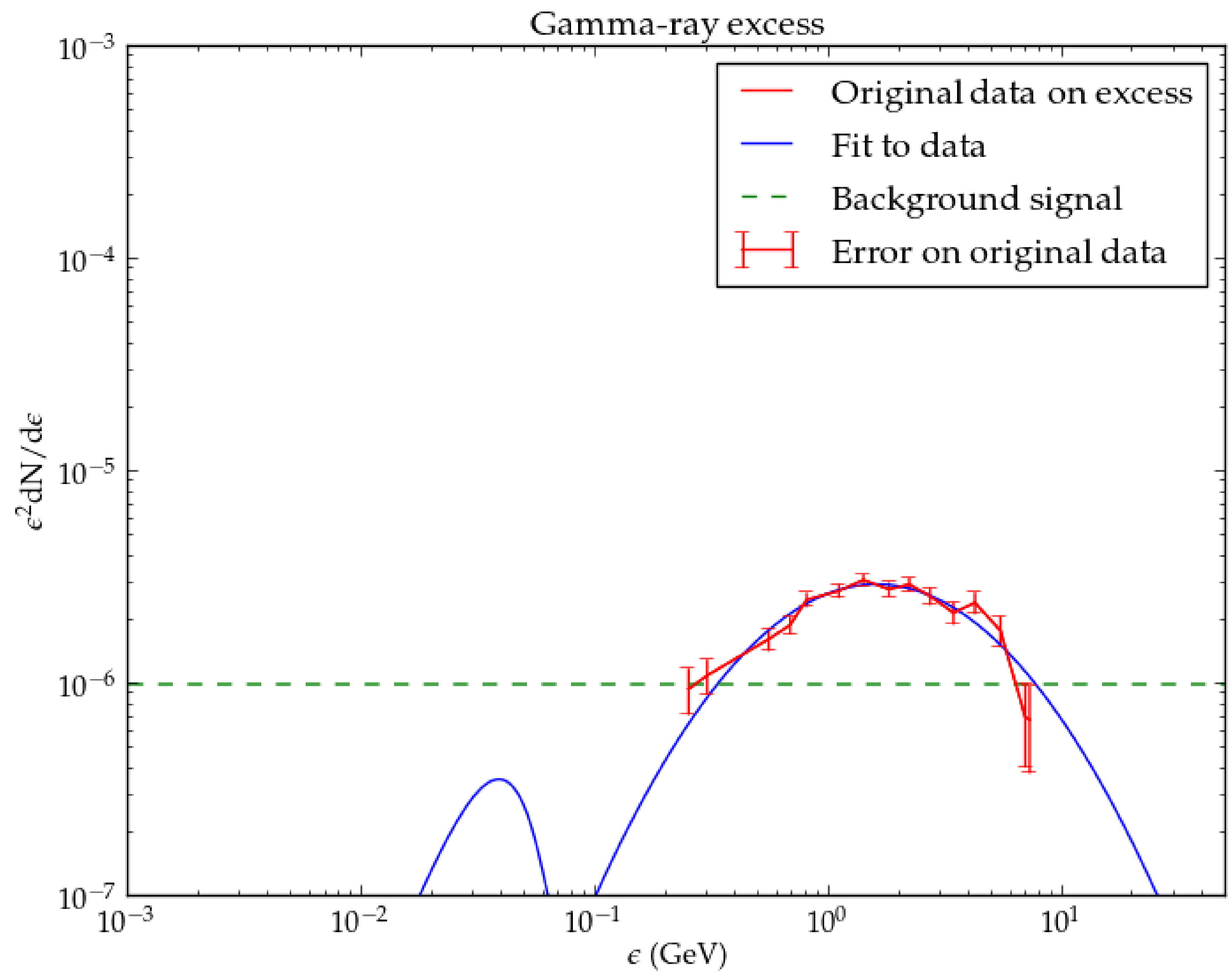
Schutten, Barrau, Bolliet, Vidotto 1606.08031

Low energy channel

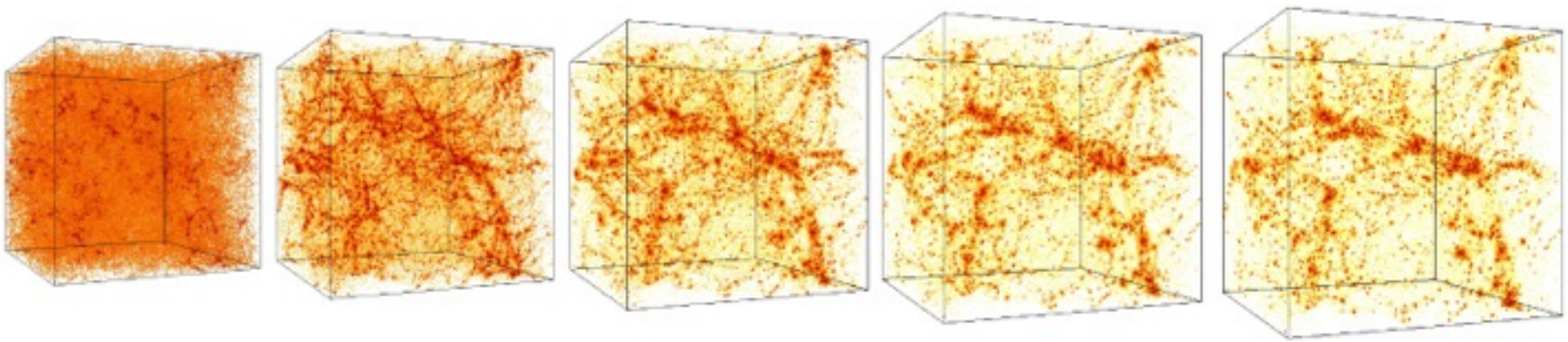
- Consider the longest possible lifetime of a quantum black hole.



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

- 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.

1. BLACK HOLE can be singularity free

   and they can tunnel into a white hole in a time $\sim m^2$

   * complete calculation available in LQG

2. PHENOMENOLOGY depends on mass and lifetime

   * new experimental window for quantum gravity

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

3. PRIMORDIAL BLACK HOLES

   - new features

SUMMARY

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what else
can change if black holes
explode this way?

arXiv:1401.6562
Planck stars
Carlo Rovelli, Francesca Vidotto
Int. J. Mod. Phys. D23 (2014) 12, 1442026

arXiv:1404.5821
Planck star phenomenology
Aurelien Barrau, Carlo Rovelli.
Phys. Lett. B739 (2014) 405

arXiv: 1409.4031
Fast Radio Bursts and White Hole Signals
Aurélien Barrau, Carlo Rovelli, Francesca Vidotto.
Phys. Rev. D90 (2014) 12, 127503

arXiv: 1507.1198
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

arXiv:1606.08031
Bouncing black holes in quantum gravity and the Fermi gamma-ray excess
Aurélien Barrau, Boris Bolliet, Francesca Vidotto, Marrit Schutten