Planck Stars

the final fate of
quantum non-singular black holes
and its
phenomenological consequences

Francesca Vidotto
UPV/EHU - Bilbao

SINGULARITIES OF GENERAL RELATIVITY
AND THEIR QUANTUM FATE
Warsaw - May 23rd, 2018

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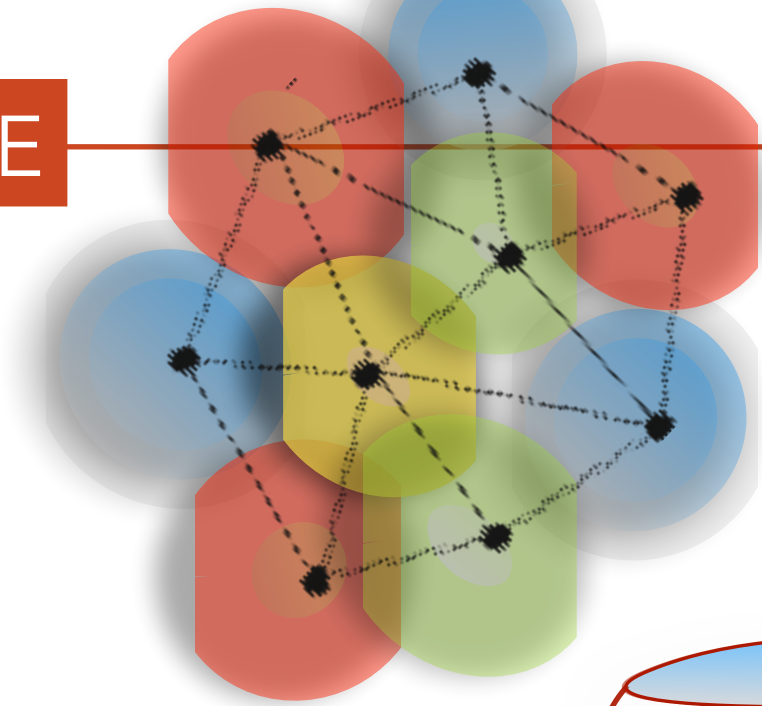
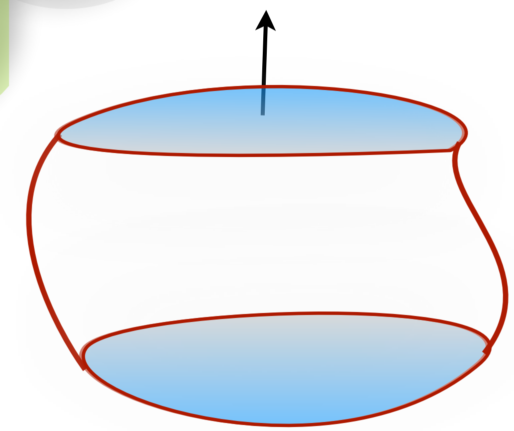
QUANTA OF SPACETIME





- It is a theory about quanta of spacetime
- Each quantum is Lorentz invariant
- The states are boundary states at fixed time $SL(2,\mathbb{C}) \to SU(2)$
- The physical phase space is spanned by SU(2) group variables $\vec{L}_l = \{L_l^i\}, i = 1, 2, 3$

  gravitational field operator (tetrad) SU(2) generators
- Geometry is quantized: $$A_\Sigma = \sum_{l\in\Sigma} \sqrt{L_l^i L_l^i}.$$
- $$V_R = \sum_{n\in R} V_n, \qquad V_n^2 = \frac{2}{9}\,|\epsilon_{ijk} L_l^i L_{l'}^j L_{l''}^k|$$
- Discrete spectra: minimal non-zero eigenvalue

QUANTIZATION OF THE CLASSICAL ACTION

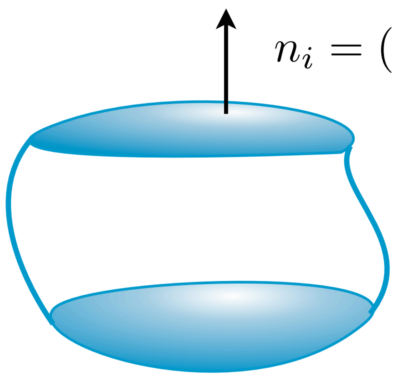
GR action $$S[e,\omega] = \int e \wedge e \wedge F^*[\omega] + \frac{1}{\gamma}\int e \wedge e \wedge F[\omega]$$ *(Holst term)*

BF theory $$S[e,\omega] = \int B[e] \wedge F[\omega]$$

Canonical variables $$\omega, \quad B = (e \wedge e)^* + \frac{1}{\gamma}(e \wedge e)$$

On the boundary $$n_i = e_i^a n_a \qquad n_i e^i = 0$$ $SL(2,\mathbb{C}) \to SU(2)$

$$B \to (K = nB, L = nB^*)$$



Simplicity constraint $$K = \gamma L$$

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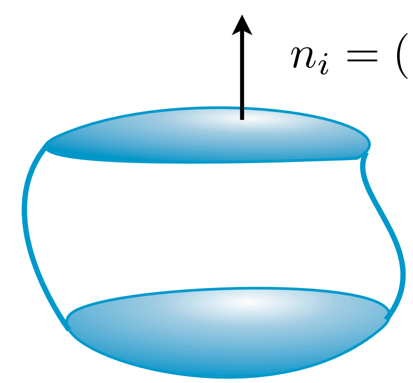


Simplicity constraint $$\hat{K} = \gamma \hat{L}$$

Boost generator   Rotation generator

Rovelli,Vidotto 1307.3228

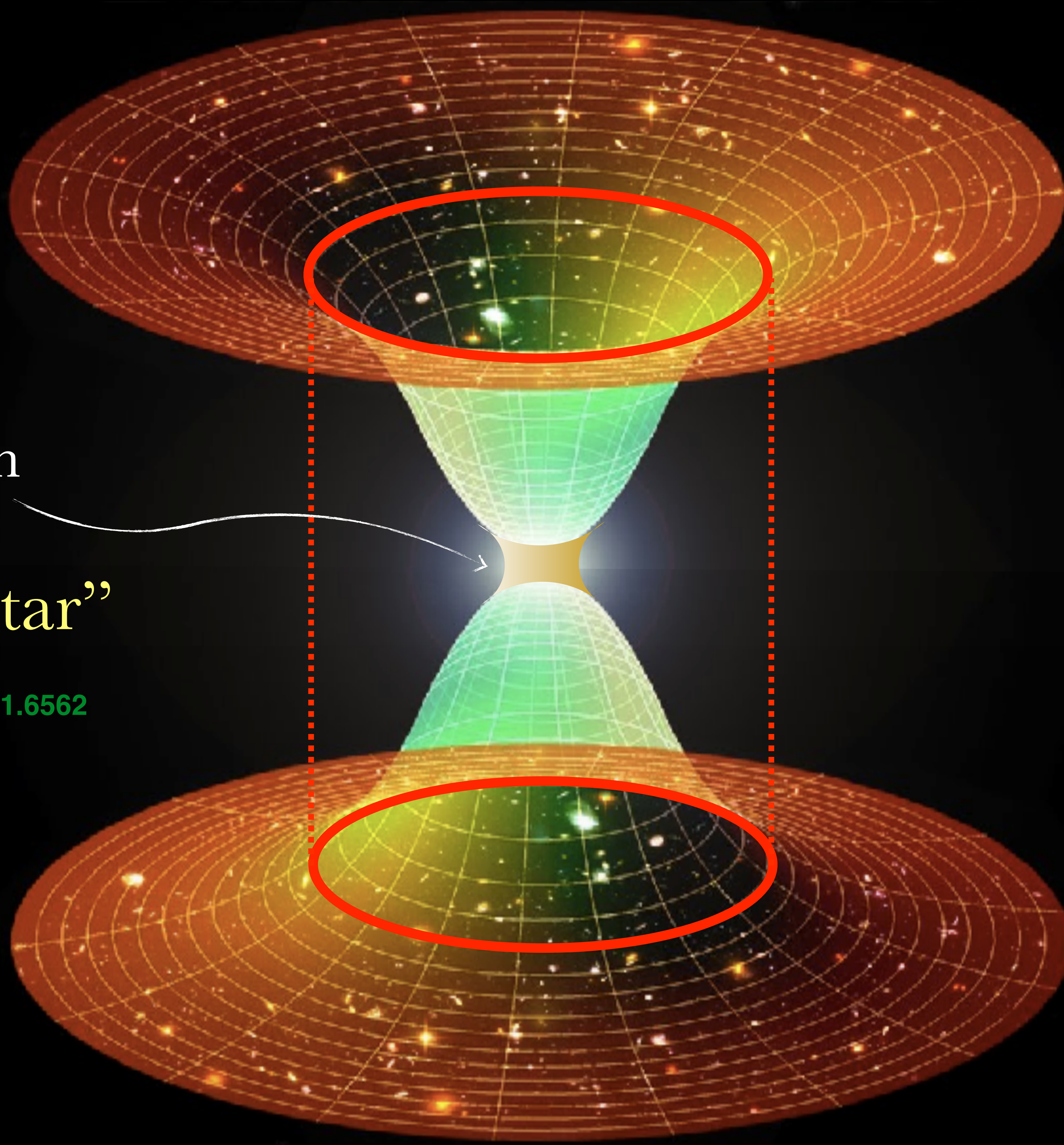
- Maximal acceleration: no curvature singularities!
  (spacetime can be geodesically incomplete for some artificially patched manifolds **Geroch '68***)*

BH EXPLOSION

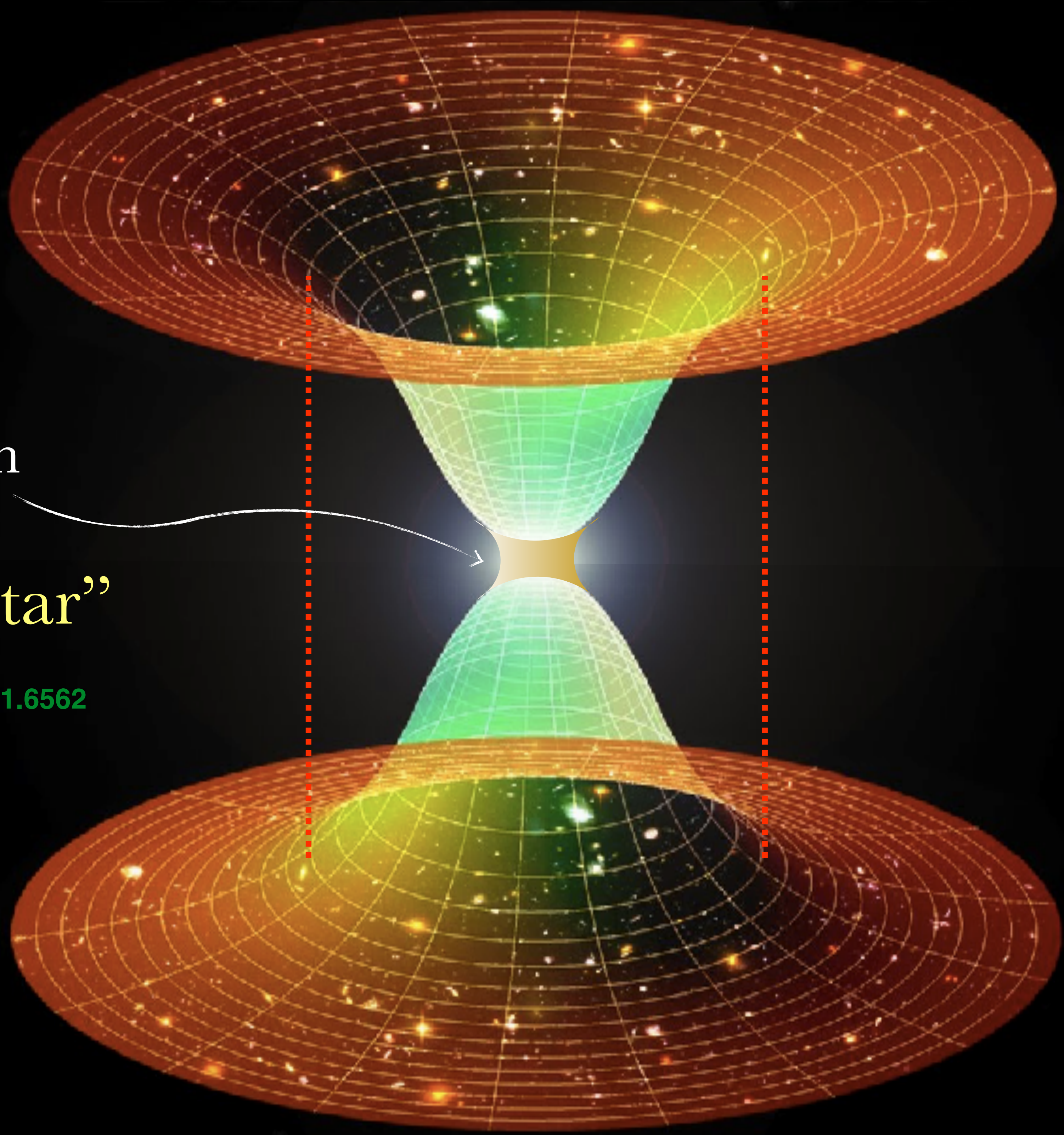
quantum
region

"Planck Star"

Vidotto, Rovelli 1401.6562



Black -to- White
tunnelling



quantum region

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Vidotto, Rovelli 1401.6562

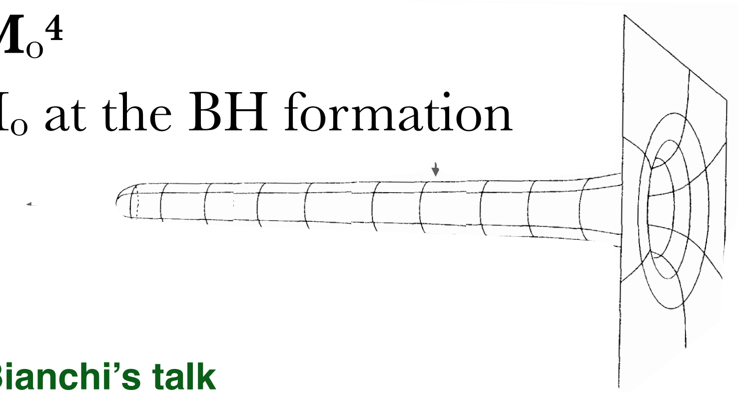
Black-to-White tunnelling


Scenario 1

WHITE HOLES AS REMNANTS 1

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

- **LARGE INTERNAL VOLUME ~ M_o^4**
  It depends only on the original mass M_o at the BH formation



Christodoulou, Rovelli 1411.2854
Bengtsson, Jakobsson 1502.01907
Ong 1503.08245
Christodoulou, De Lorenzo1604.07222

- **REMNANT LIFETIME ~ M_o^4** see Bianchi's talk
  Time needed for information to leak out from such a large volume trough the small WH surface.

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

Quintin, Brandenberger 1609.02556
Carr, Clifton, Coley 1704.02919

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

- **PAST LOW ENTROPY**
  Matter near thermal equilibrium: geometry has low entropy
  Only $1/T_H^2 \sim 10^{-120}$ of the volume of the universe was outside the remnants at the bounce!

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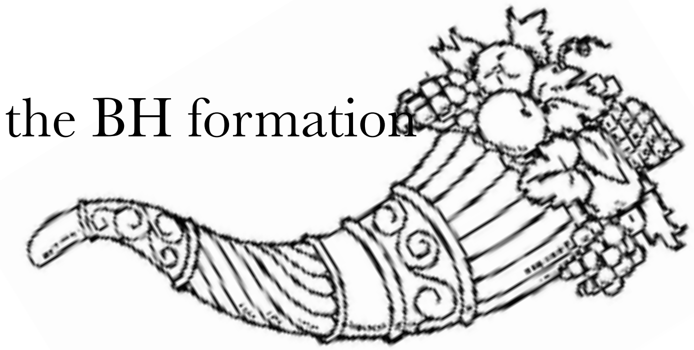

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Scenario 2

WHITE HOLES AS REMNANTS 2

Rovelli, Vidotto 1805.03872

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

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

- **PROCESSES**

$$|\psi\rangle = \begin{pmatrix} B(m,v) \\ W(m,v) \end{pmatrix}$$

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

$$H = \begin{pmatrix} m + 3\sqrt{3}\, i\pi m_o^2 \frac{\partial}{\partial v} - i\,\frac{\hbar^2}{m^2}\frac{\partial}{\partial m} & b\frac{\hbar}{m} \\ c\frac{\hbar}{m} e^{-m^2/\hbar} & m - 3\sqrt{3}\, i\pi m_o^2 \frac{\partial}{\partial v} \end{pmatrix}$$

- **STABILITY**

The minimal area yields a minimal mass!

$$\mu \equiv \frac{3^{\frac{1}{4}}}{2}\sqrt{\frac{\hbar}{G}} \qquad \Rightarrow \qquad H = \begin{pmatrix} \mu & \frac{b\hbar}{\mu} \\ \frac{a\hbar}{\mu} & \mu \end{pmatrix}$$

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

oscillation between black and white hole states


Scenario 3

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

- **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 background)

- Firewall argument
  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

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

Haggard, Rovelli 1407.0989

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Haggard, Rovelli 1407.0989

- Black-to-White Tunnelling
  - In the quantum world, things happen as soon as they can!
  - Indications from a full LQG computations.

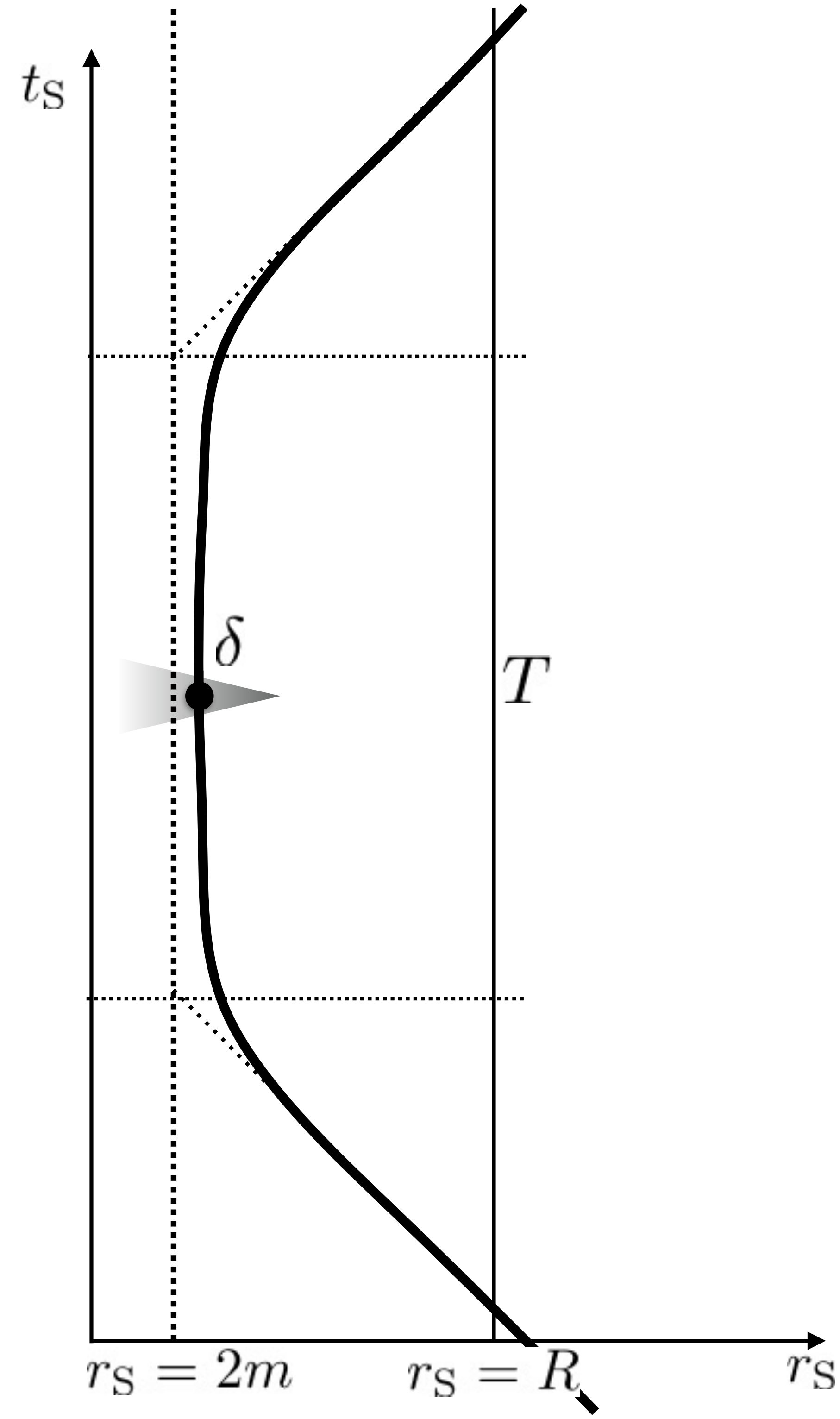
Chistodoulou, Rovelli, Speziale, Vilensky 1605.05268

NON-SINGULAR BLACK HOLES

- **QUANTUM REPULSION**
  Non-perturbative effect
  Effective theory: quantum repulsion

- **TIME DILATATION**
  Bounce time ~ M ~ ms for $M_\odot$
  Asymptotic time ~ $M^2 \sim 10^9$ for $M_\odot$

- **LIFETIME ~ M²**
  to be compared with the evaporation time ~ M^3
  (no information paradox)




Can we observe it?

PRIMORDIAL BLACK HOLES

- All black holes are subject to quantum effects.
- An explosion observed today, requires old black holes: primordial.

- (Quantum) PBH dark matter:
  - Today, black holes smaller than $m(t)|_{t=t_H}$ have already exploded.
  - It decreases with time.

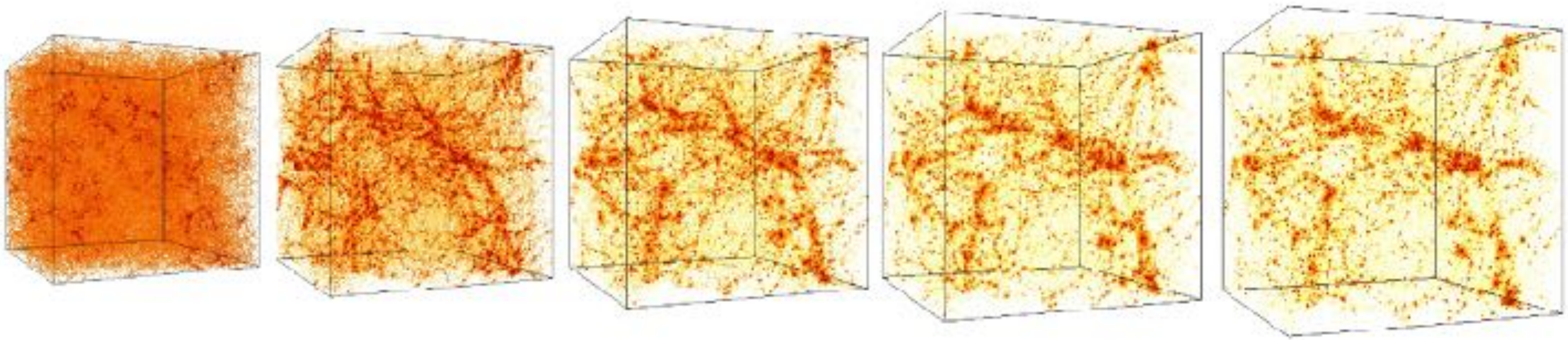
(but for later accretion/merging)

- Caution with constraints!
  - Constraints from Hawking evaporation do not apply.
  - PBH could exists, but not necessarily constitute all DM.

QUANTUM PRIMORDIAL BLACK HOLES AS DARK MATTER

- Structure formation

Bellomo, Bernal, Chluba, Cholis, Raccanelli, Verde, Vidotto WIP



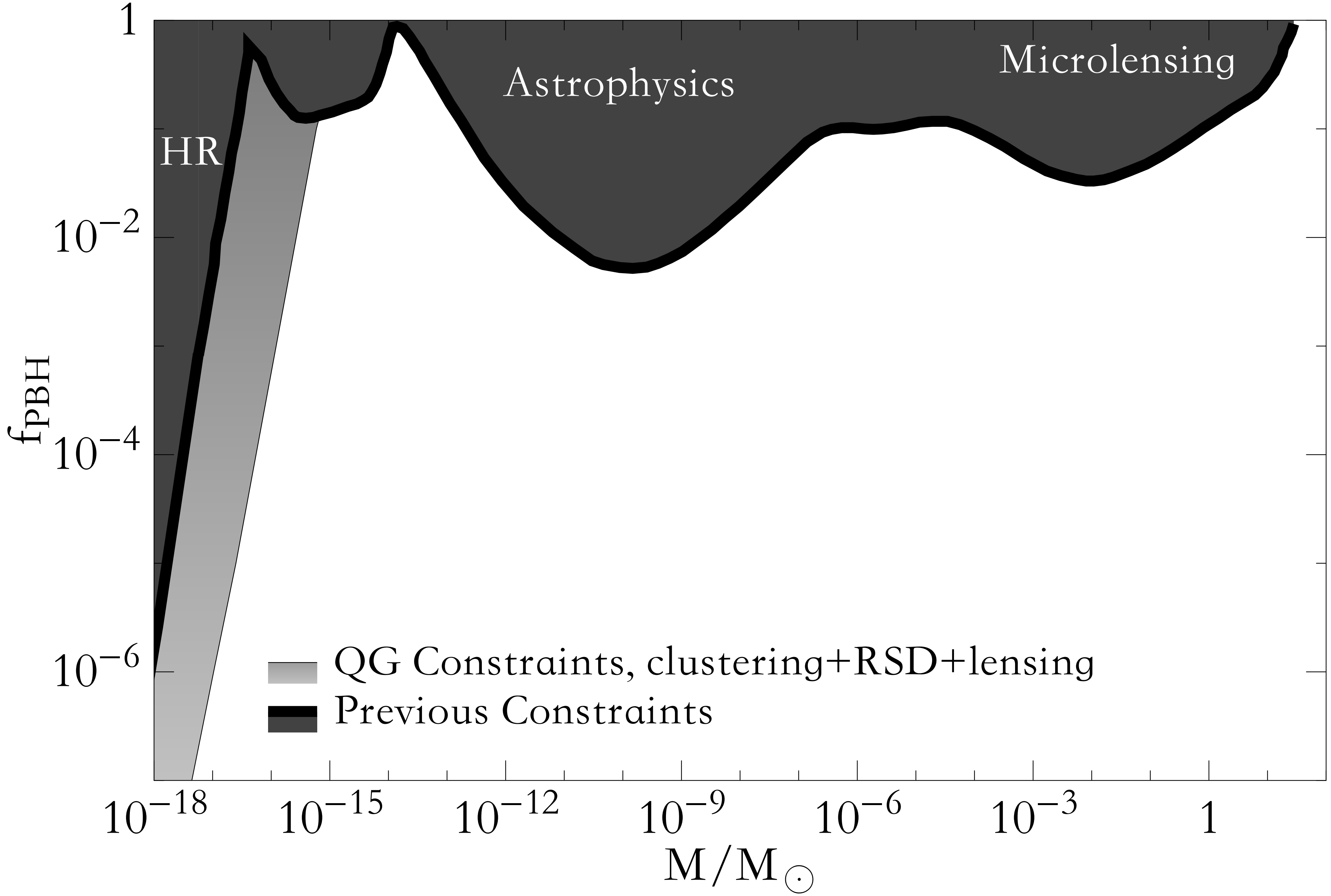
Result: Planck Stars compatible with constraints from early cosmology

- First stars & Supermassive black holes

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

EFFECTS IN THE LATE UNIVERSE

Raccanelli, Vidotto, Verde 1708.02588



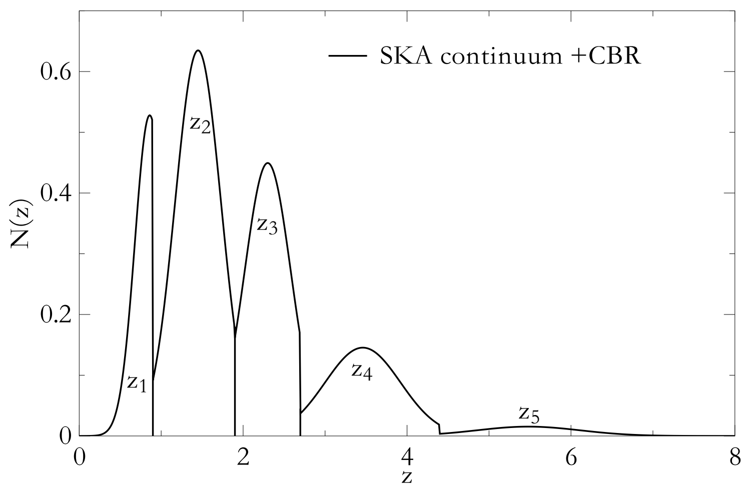
EFFECT ON GALAXY CLUSTERS

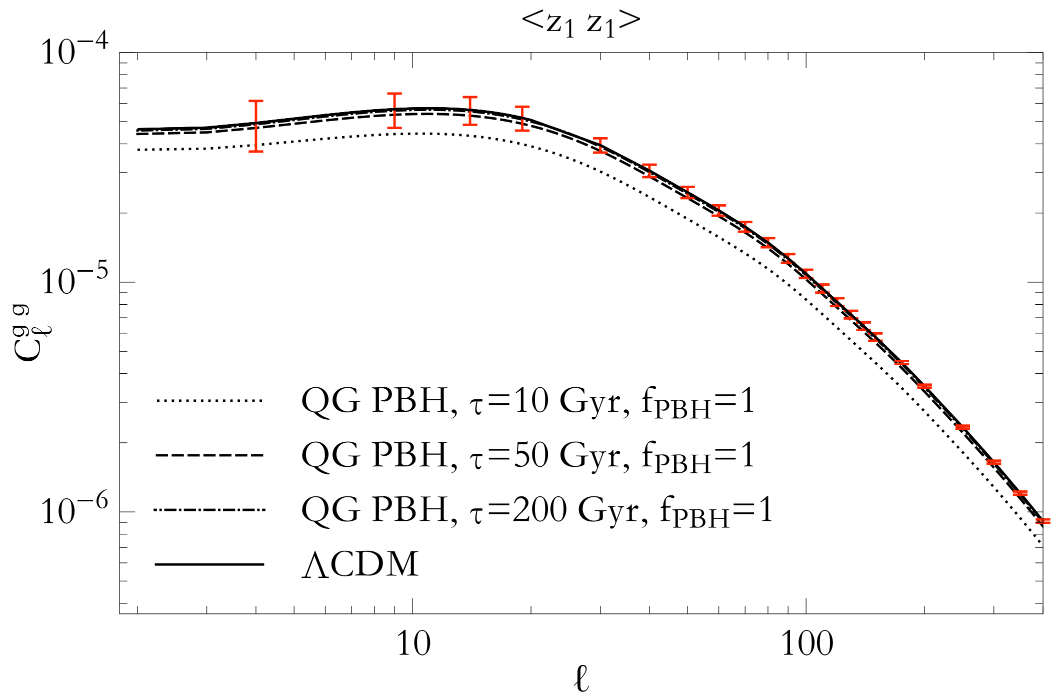
Raccanelli, Vidotto, Verde 1708.02588

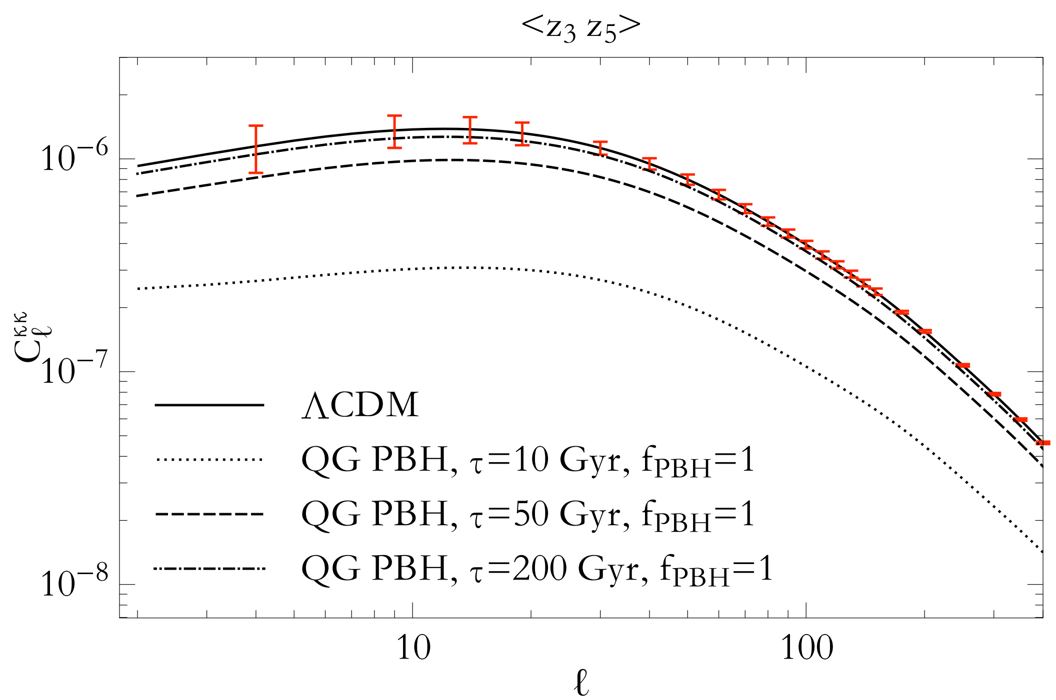
$$C_\ell^{XY}(z_i, z_j) = \left\langle a_{\ell m}^X(z_i)\; a_{\ell m}^{Y\,*}(z_j) \right\rangle$$

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

- Choice of redshift distribution:







EXPECTED SIGNALS

Barrau, Rovelli, Vidotto 1409.4031

- 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: $m = \sqrt{\frac{t_H}{4k}} \sim 1.2 \times 10^{23}$ kg $\qquad R = \frac{2Gm}{c^2} \sim .02$ cm
- **LOW ENERGY:** size of the source $\approx$ wavelength $\lambda_{predicted} \gtrsim .2$ cm (?)
- **HIGH ENERGY:** energy of the particle liberated $\approx Tev$
- **SYNCHROTRON EMISSION** Kavic &al. 0801.4023
- **GRAVITATIONAL WAVES**

FAST RADIO BURSTS

- fast process (few milliseconds)
- compact object: big flux $E = mc^2 \sim 1.7 \times 10^{47}$ erg

- **HIGH ENERGY** $\approx Tev$ → **REES' MECHANISM** Kavic &al. 0801.4023

- Electron-positron pairs traveling trough a magnetic field
- Repetition can be due to: • reflection of the signal due to plasm walls
  • region dense of PBH

- **LOW ENERGY:** size of the source $\approx$ wavelength $\lambda_{predicted} \gtrsim .2$ cm

- We may have missed a factor in our rough calculation!

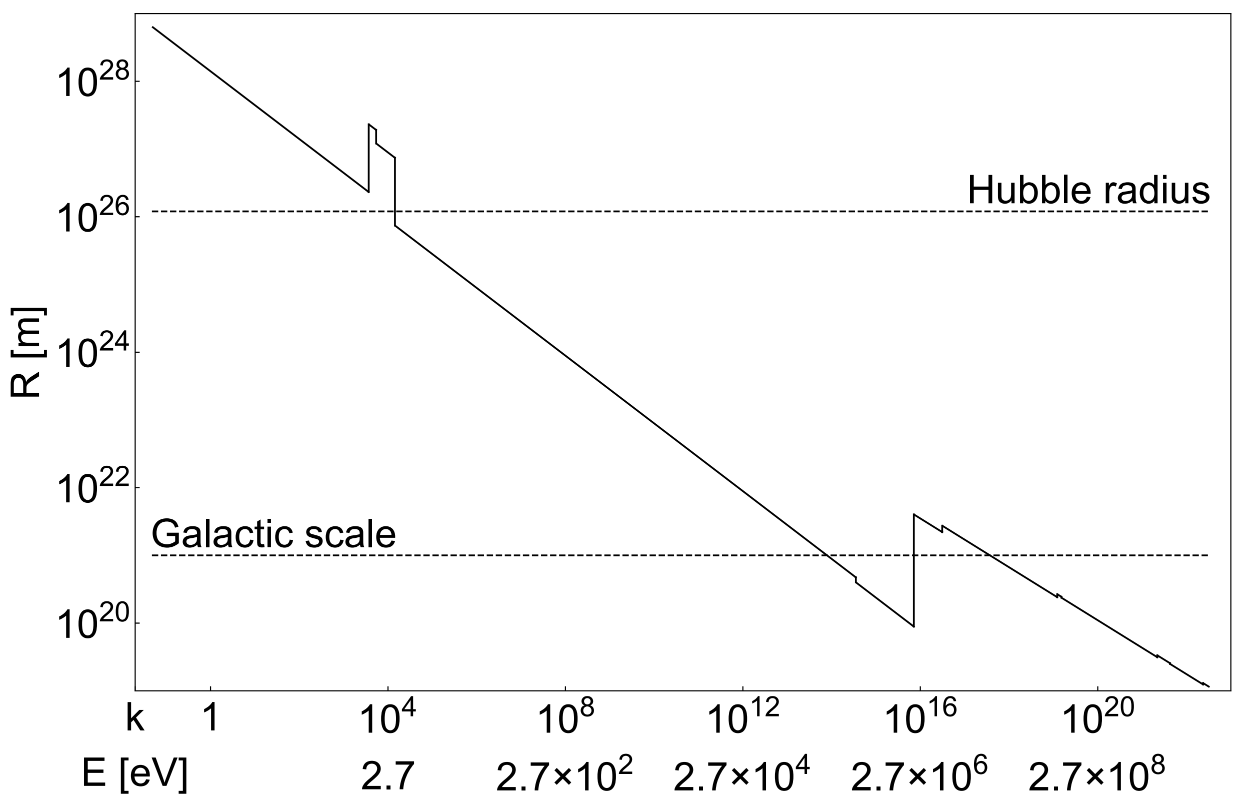
- We may be seeing only the a window in a distribution of event Barrau &al. 1801.03841

MAXIMAL DISTANCE

Barrau, Bolliet, Vidotto, Weimer 1507.1198

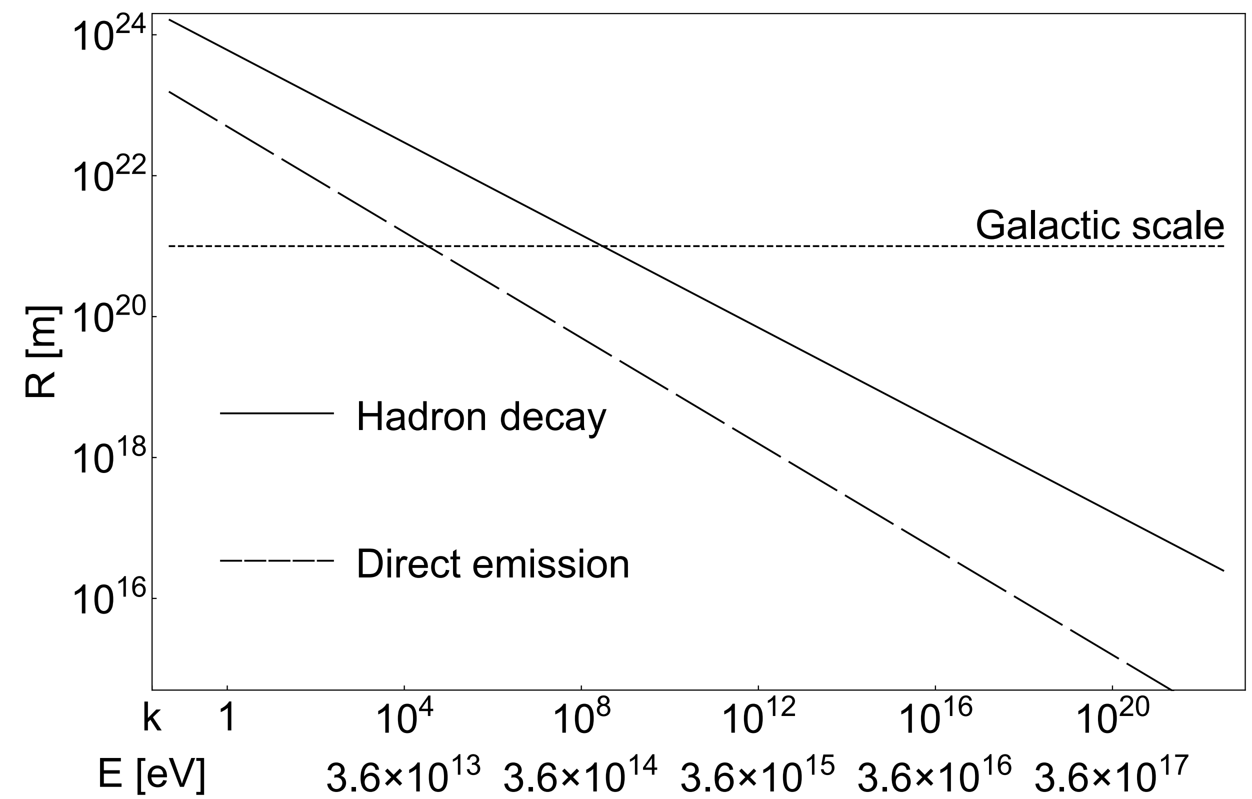
- shorter lifetime — smaller wavelength

Low energy channel



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

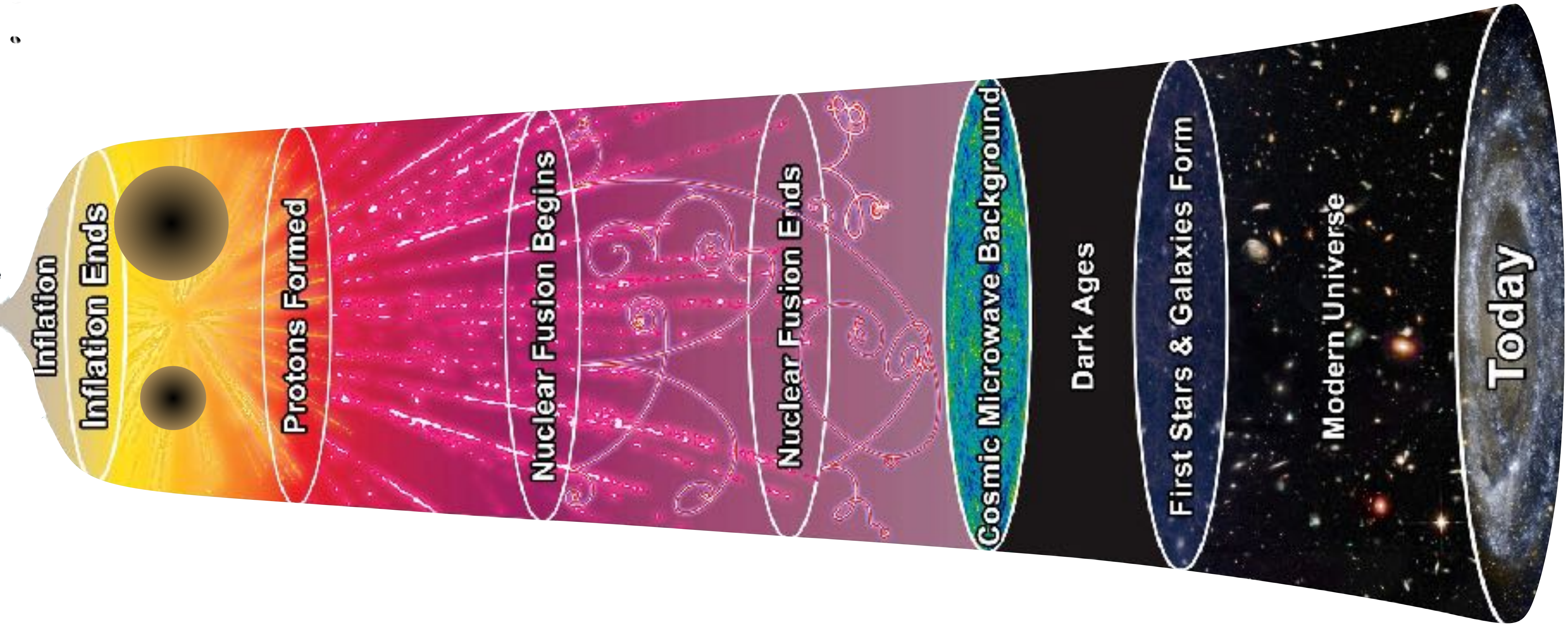
High energy channel



- PBH: mass - temperature relation
- different scaling

THE SMOKING GUN: DISTANCE/ENERGY RELATION

Low energy channel



- distant signals originated in younger and smaller sources

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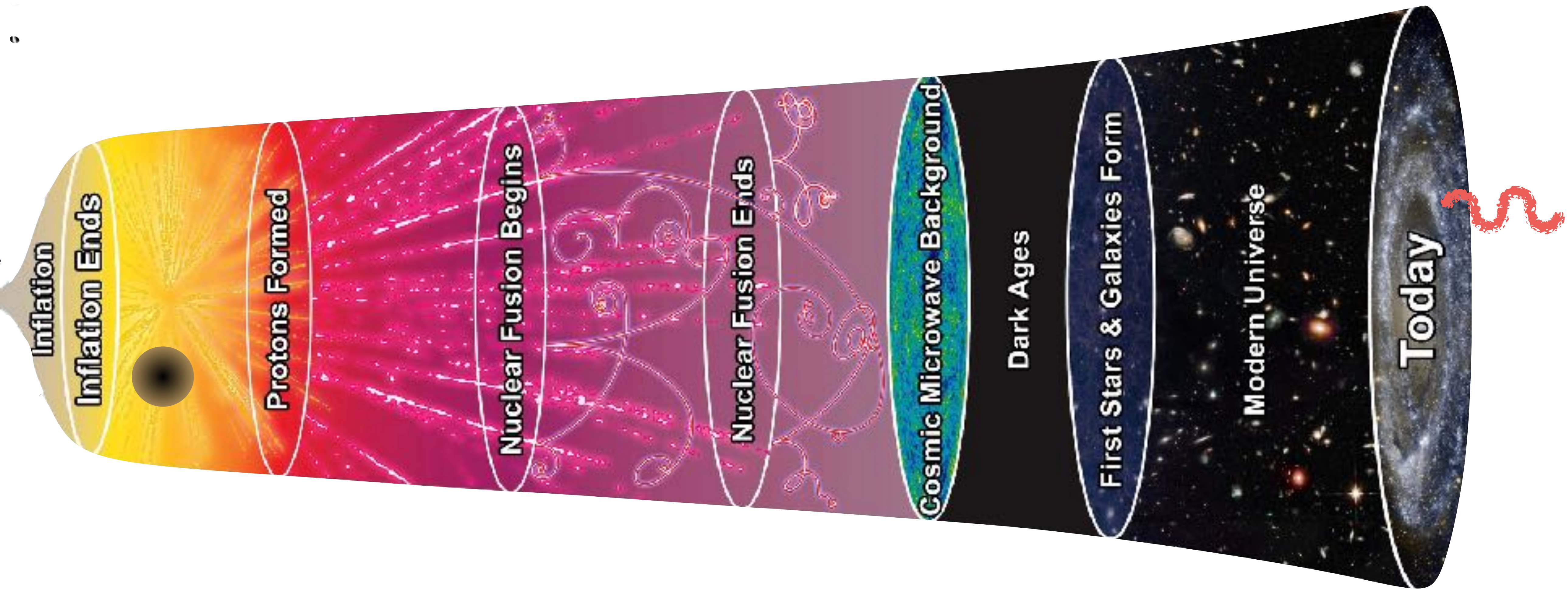

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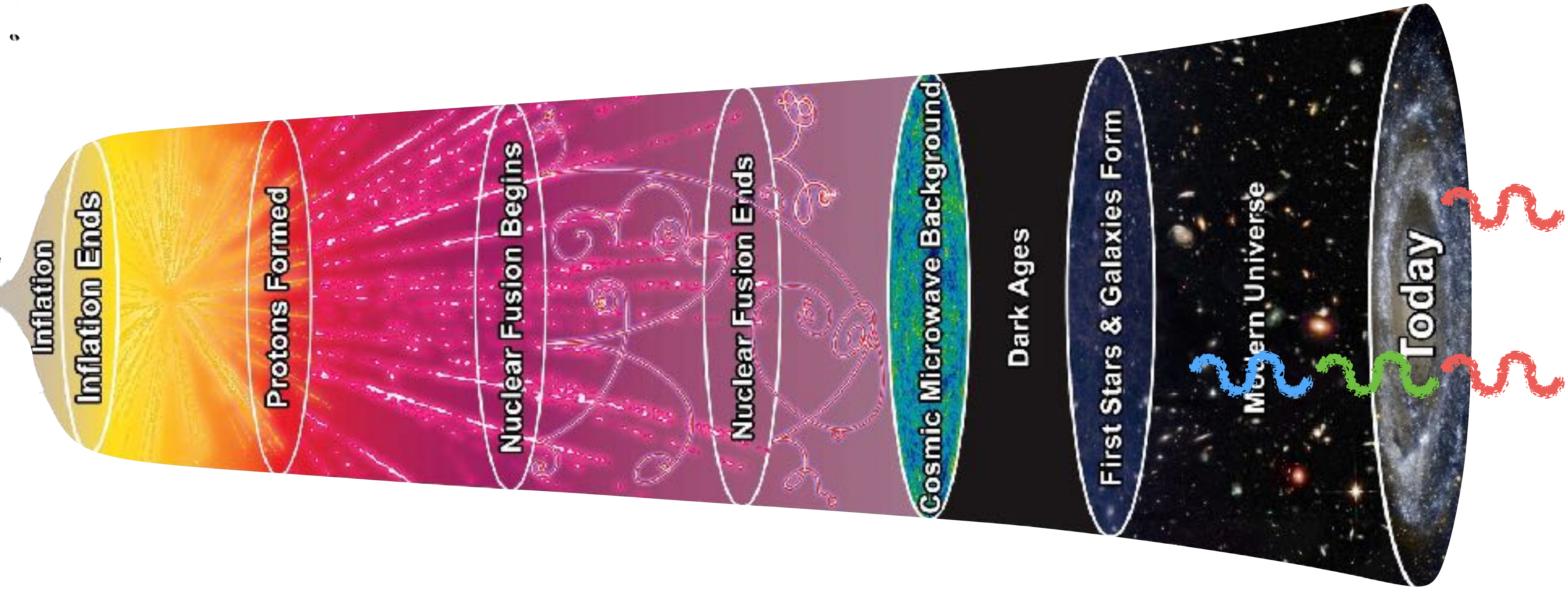

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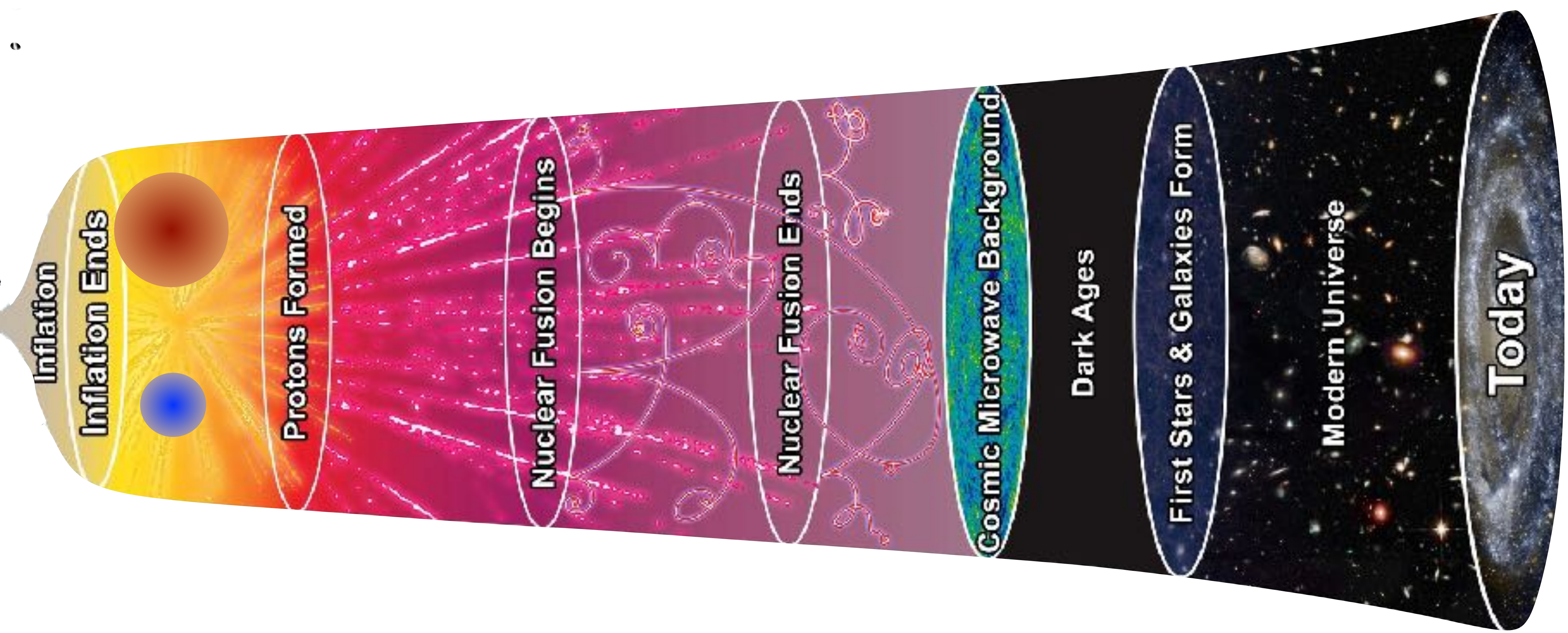

$M \sim M_H \sim t.$ $\qquad$ $t \sim 0.3 g_*^{-\frac{1}{2}} T^{-2}$

THE SMOKING GUN: DISTANCE/ENERGY RELATION

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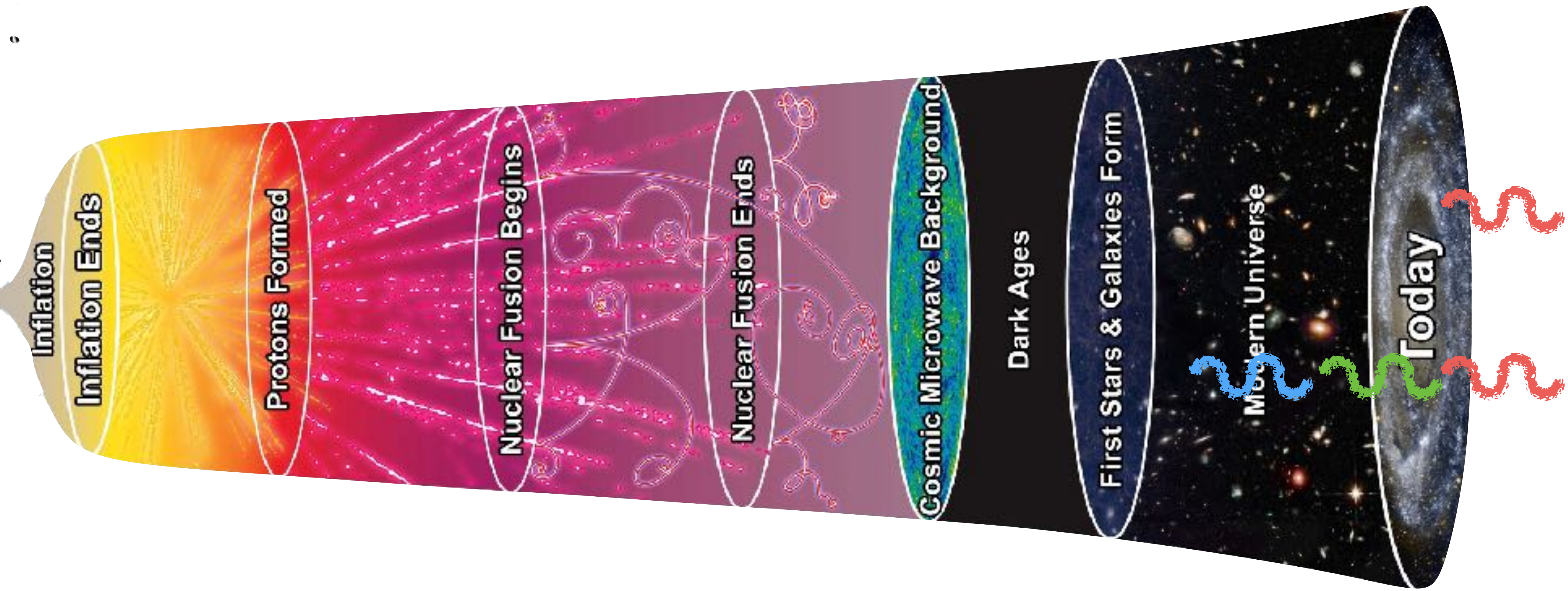
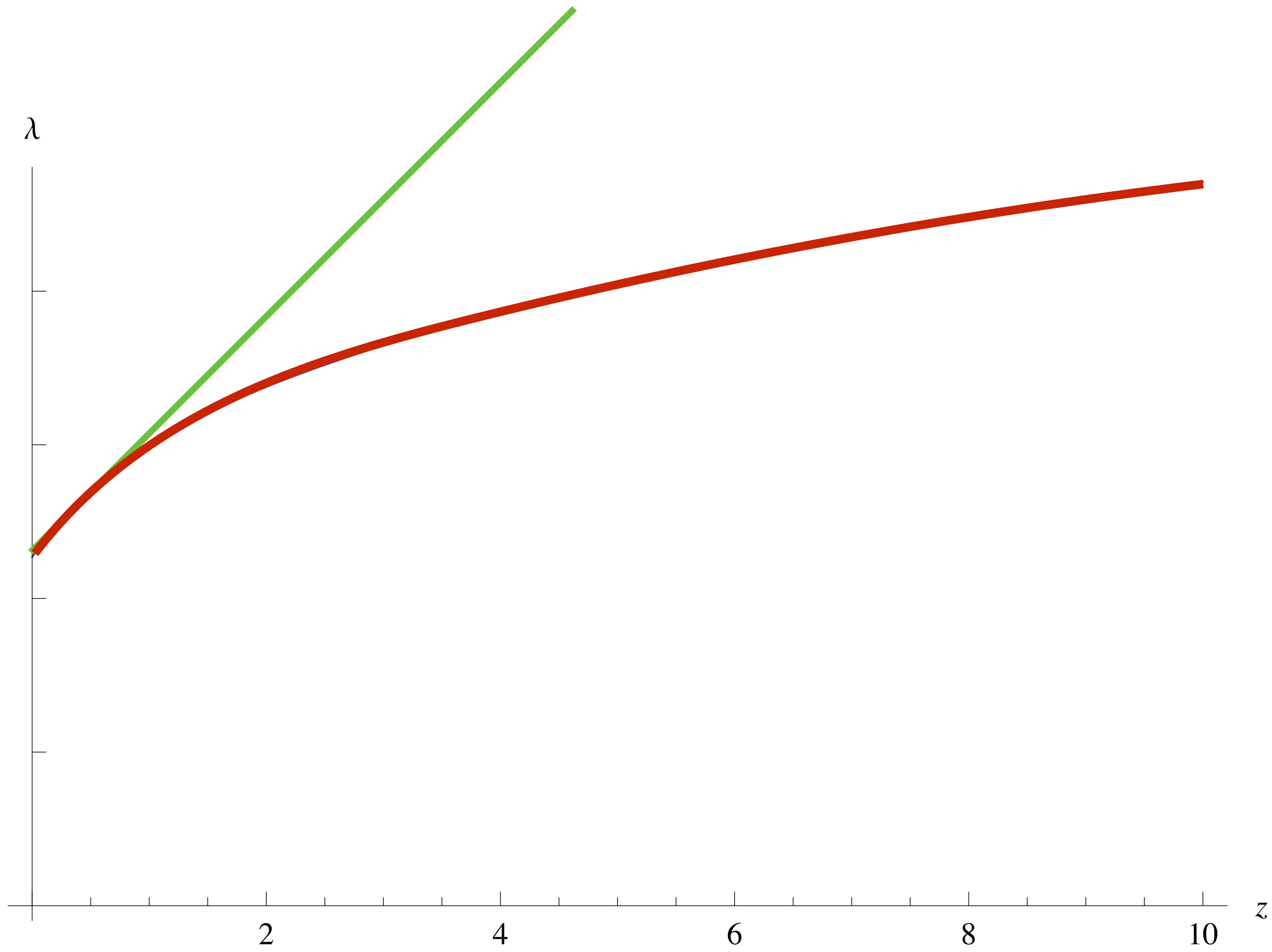


$$M \sim M_H \sim t$$

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

THE SMOKING GUN: DISTANCE/ENERGY RELATION

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



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

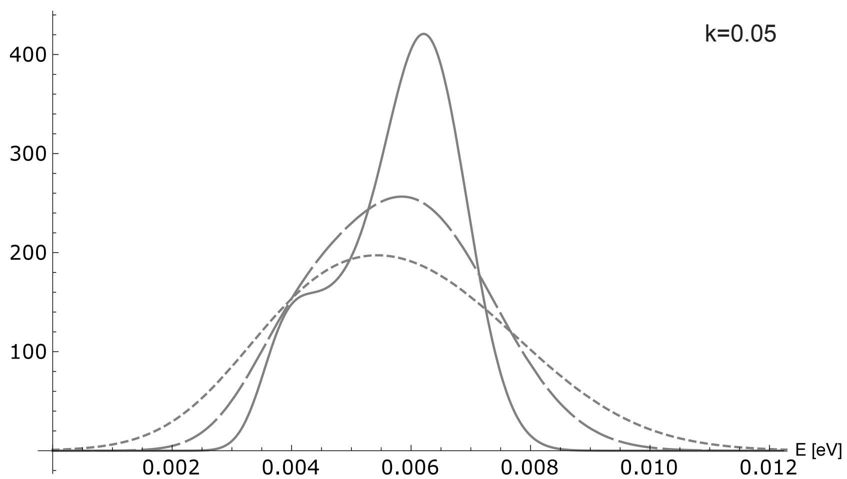
Barrau, Rovelli, Vidotto 1409.4031

INTEGRATED EMISSION

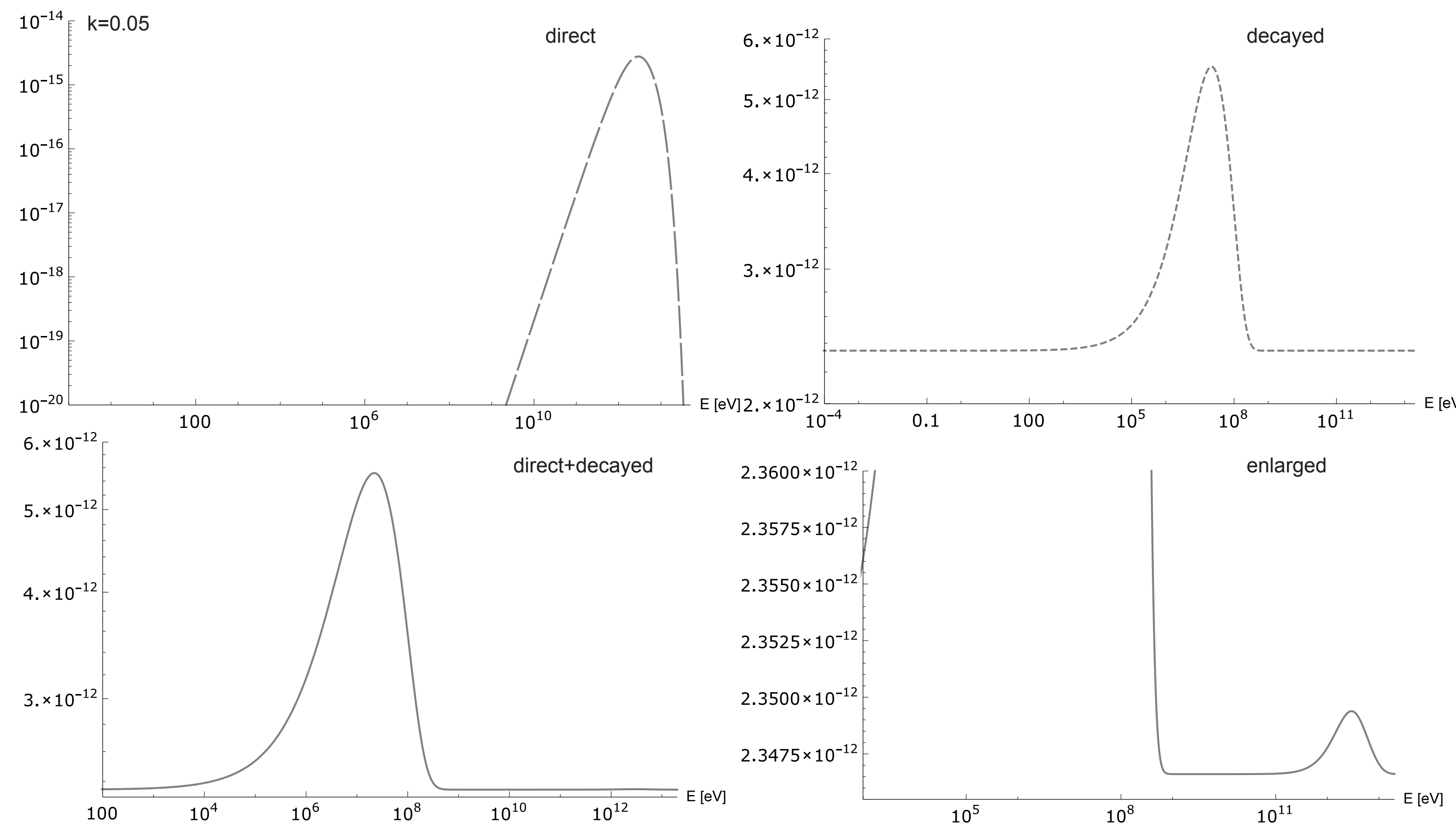
Barrau, Bolliet, Vidotto, Weimer 1507.1198

$$\tau \sim m^2$$

Low energy channel



High energy channel



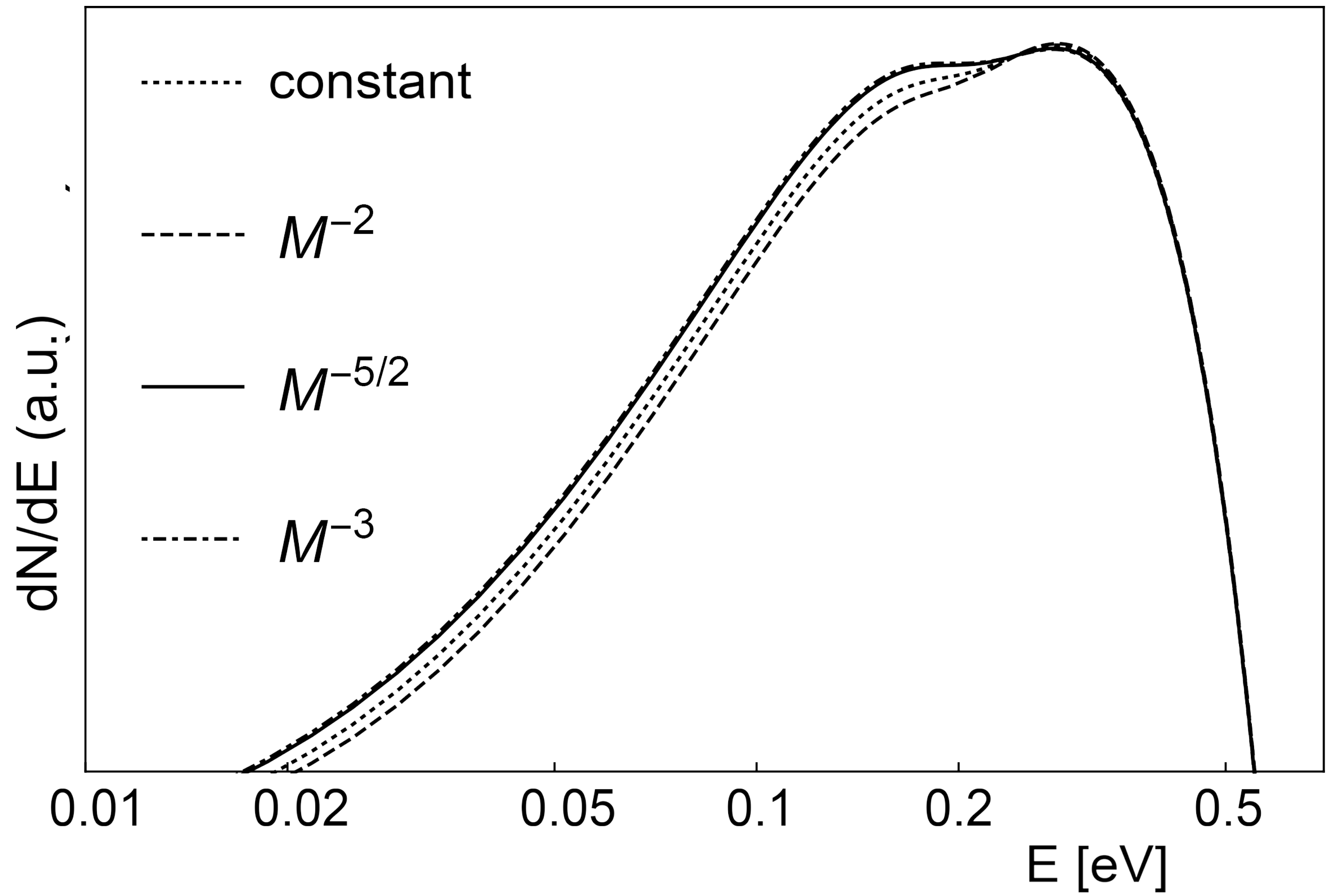
$$\frac{dN_{mes}}{dEdtdS} = \int \Phi_{ind}((1+z)E, R) \cdot n(R) \cdot Acc \cdot Abs(E, R) dR$$

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

PBH MASS SPECTRUM

$$n(R) = \int_{M(t)}^{M(t+\Delta t)} \frac{dn}{dMdV} dM \qquad n(R) \approx \frac{dn}{dMdV}\frac{\Delta t}{8k} \qquad \frac{dn}{dMdV} = \alpha M^{-1-\frac{1+3w}{1+w}}$$

Low energy channel



Different mass spectra gives qualitatively same diffuse emission…

SUMMARY ON REMNANTS

1. **BOUNCE²** : Bouncing BH in a Bouncing Universe

   - Planckian remnants pass trough the bounce and are viable dark matter

   - large "old" volume inside remnants make up all the volume of the universe

   * solve the problem with the Past Hypothesis in a perspectival manner

2. **REMNANTS AS DARK MATTER**

   * compatible with PBH formation at reheating

   * STABILITY OF THE REMNANTS via minimal area/mass

SUMMARY

1. PHENOMENOLOGY depends mainly on the lifetime

    given as a function of the mass: as short as $\mathbf{m^2}$

    * interesting to check prediction by different QG frameworks!

2. NEW EXPERIMENTAL WINDOWS for quantum gravity

    * new experimental window for quantum gravity

    - signals in the sub-mm, radio & TeV
    - direct detection & diffuse emission
    - peculiar energy distance relation

3. PRIMORDIAL BLACK HOLES

    - new features
    - Also for late-universe observations

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Fast Radio Bursts and White Hole Signals
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Phenomenology of bouncing black holes in quantum gravity: a closer look
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Fast radio bursts and the stochastic lifetime of black holes in quantum gravity
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Late Cosmo.

Quantum effects of Primordial Black Holes on Galaxy Clustering
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Remnants

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Eugenio Bianchi, Marios Christodoulou, Fabio D'Ambrosio, Hal Haggard, Carlo Rovelli
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