Quantum Insights on Primordial Black Holes *as Dark Matter*

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Dark Side of the Universe
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THE DARK SIDE OF GRAVITY

Caution: not a complete list!

- DARK ENERGY
  - Cosmological Constant (or more complicated GR modification)
  - Gravitational Backreaction see Buchert's talk
  - Quantum Gravity: Spacetime Discreteness Perez, Sudarsky, Bjorken 1804.07162
  - …
- DARK MATTER
  - Mond, Mimetic Gravity and other classical modification of GR
  - Bimetric Gravity see Henry-Couannier's talk
  - N-body Equivalence Principle Alexander, Smolin 1804.09573
  - Quantum Gravity: Minimal Acceleration Smolin 1704.00780
  - Emergent Gravity Verlinde 1611.02269
  - …
  - **Primordial Black Holes** see also Garcia-Bellido's talk

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**

IN THIS TALK: QUANTUM GRAVITY

1. QG makes PBH remnants stable

   * Quantum Gravity: minimal aerea

2. QG cures GR singularities

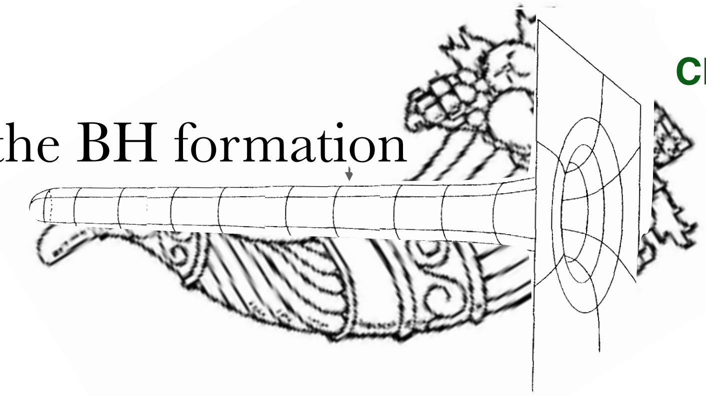
   * NO central BH singularity, NO cosmological singularity: instead a bounce

3. QG allows for Black-to-White tunnelling

   * Decay happens faster than the Hawking evaporation: new phenomenology

3 different scenarios discussed in this talk

QUANTUM EFFECTS MAKE REMNANTS STABLE



Christodoulou, Rovelli 1411.2854
Christodoulou, De Lorenzo1604.07222

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

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

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

Rovelli, Vidotto 1805.03872

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

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


Scenario 1
REHEATING
Remnants

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**

$\mathbf{M}_o{}^4 \geq \mathbf{t}_{\text{Hubble}}$

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

- **NUCLEOSYNTHESIS**

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


Scenario 2
BIG BOUNCE
Remnants

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.

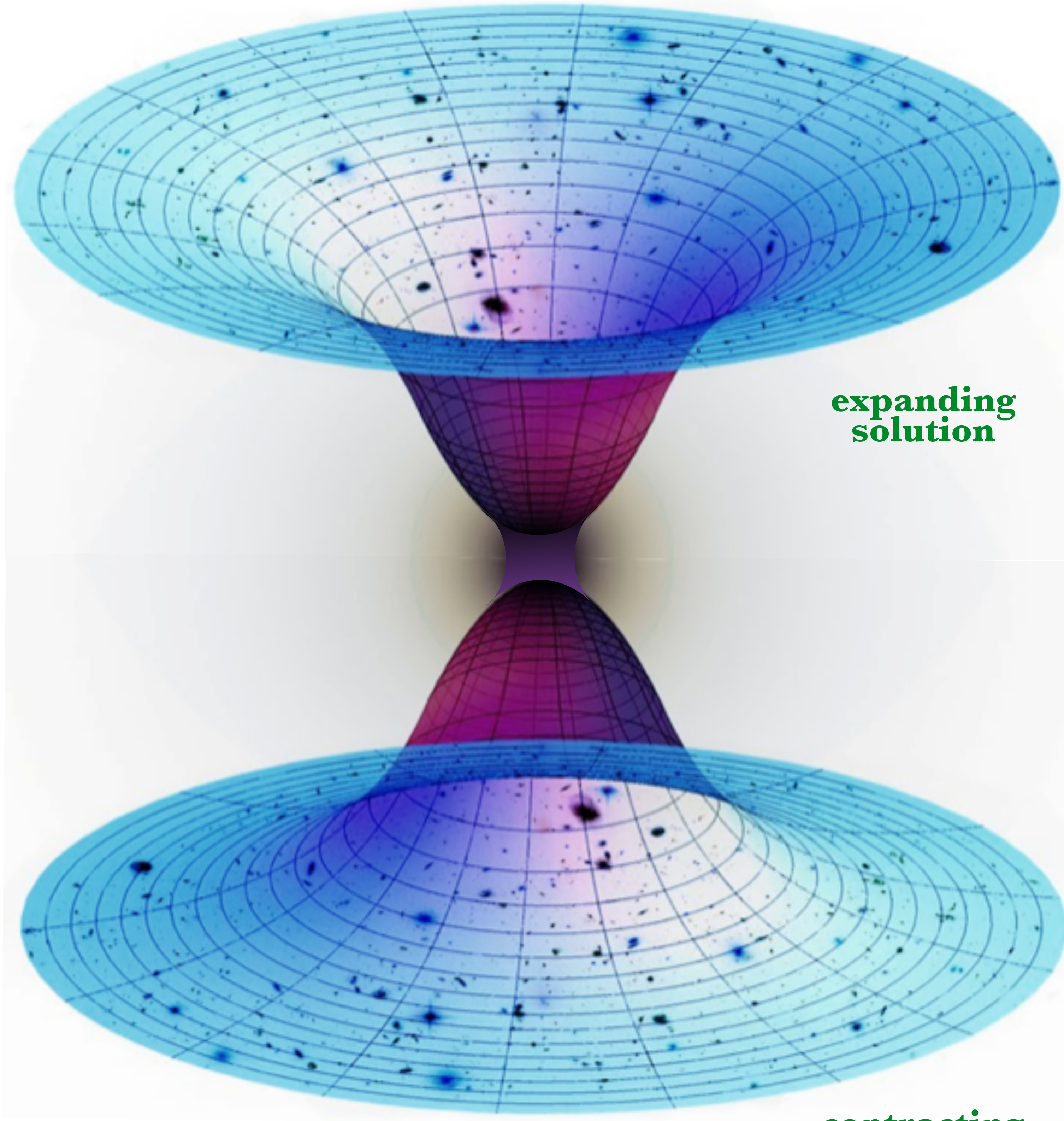
- Inflation dilutes PBH: $\frac{1}{T_H^2} \sim \left(\frac{\dot{a}}{a}\right)^2 \sim \rho_M \qquad \rho_b \sim \rho T_H^3 \sim T_H \qquad V_{int} = \rho_b V_{WH} > T_H^2$

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

QUANTUM BOUNCE

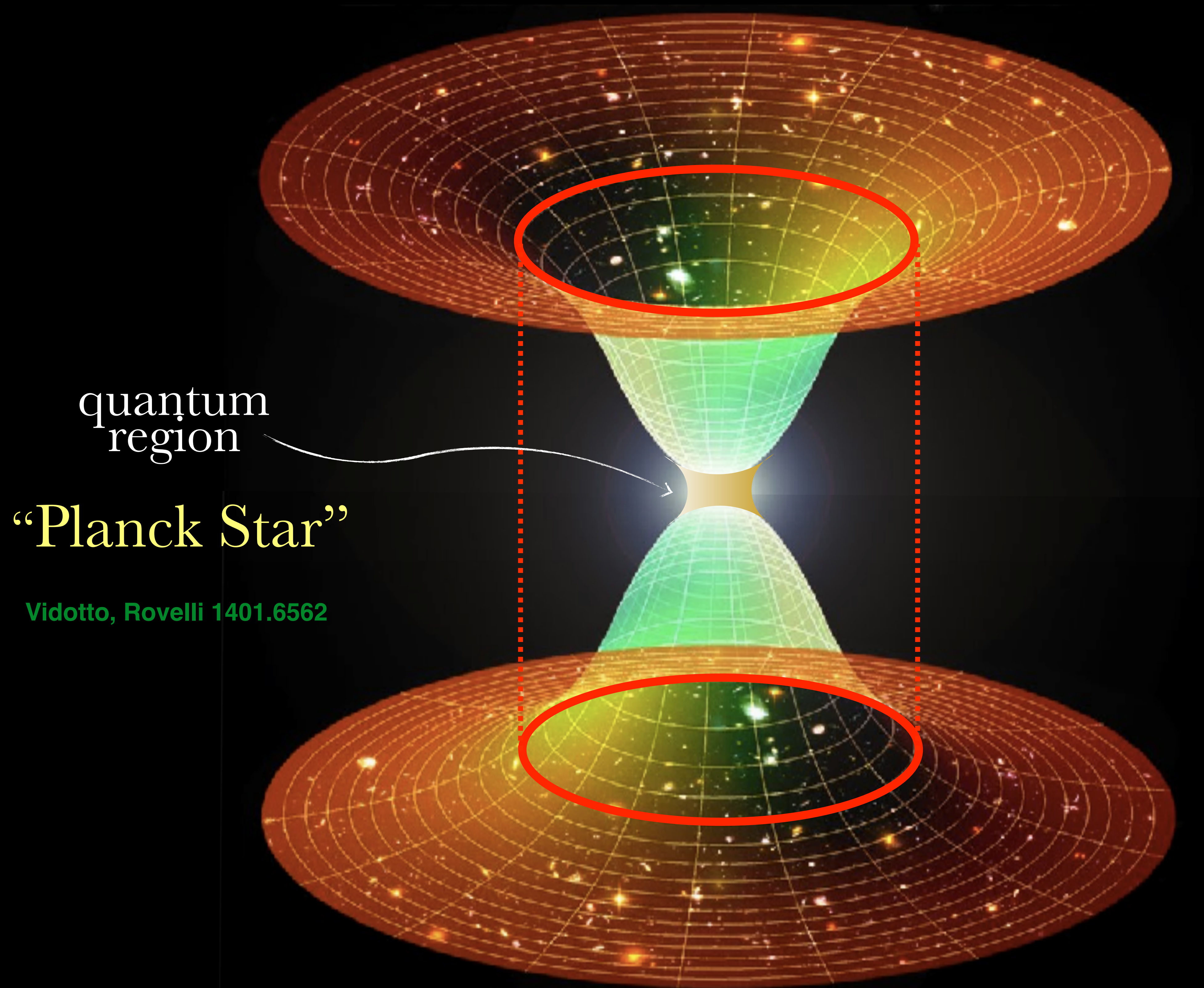
- Quantum Tunneling
  - superposition
- Effective repulsive force
  - Planck density
- Size $\gg$ Planck length
  - $V_b \sim \frac{m}{m_P}\, \ell_P^3 \approx 10^{24} cm^3$
- Phenomenology
  - signature in the CMB

pre-big-bang accessible



see Ashtekar,Barrau for a review 1504.07559

BH EXPLOSION



Black -to- White
tunnelling


Scenario 3
FAST EXPLOSION

QUANTUM EFFECTS SHORTEN BH LIFETIME

- Black Hole Lifetime
  Vidotto, Rovelli 1401.6562
  Quantum Gravity effects should manifest before the Page time (firewalls!)
  $\Longrightarrow$ the hole lifetime must be **shorter** or of the order of $\sim$ **m³**

- Black-to-White Tunnelling
  Minimal time for quantum effects to appear on the horizon:
  Curvature × (time) ~ $(L_P)^{-1}$
  $\Longrightarrow$ the hole lifetime must be **longer** or of the order of $\sim$ **m²**
  $$\frac{1}{m^2} T_b \sim 1$$

- See also Quantum Break Time Dvali, Gomez 1112.3359

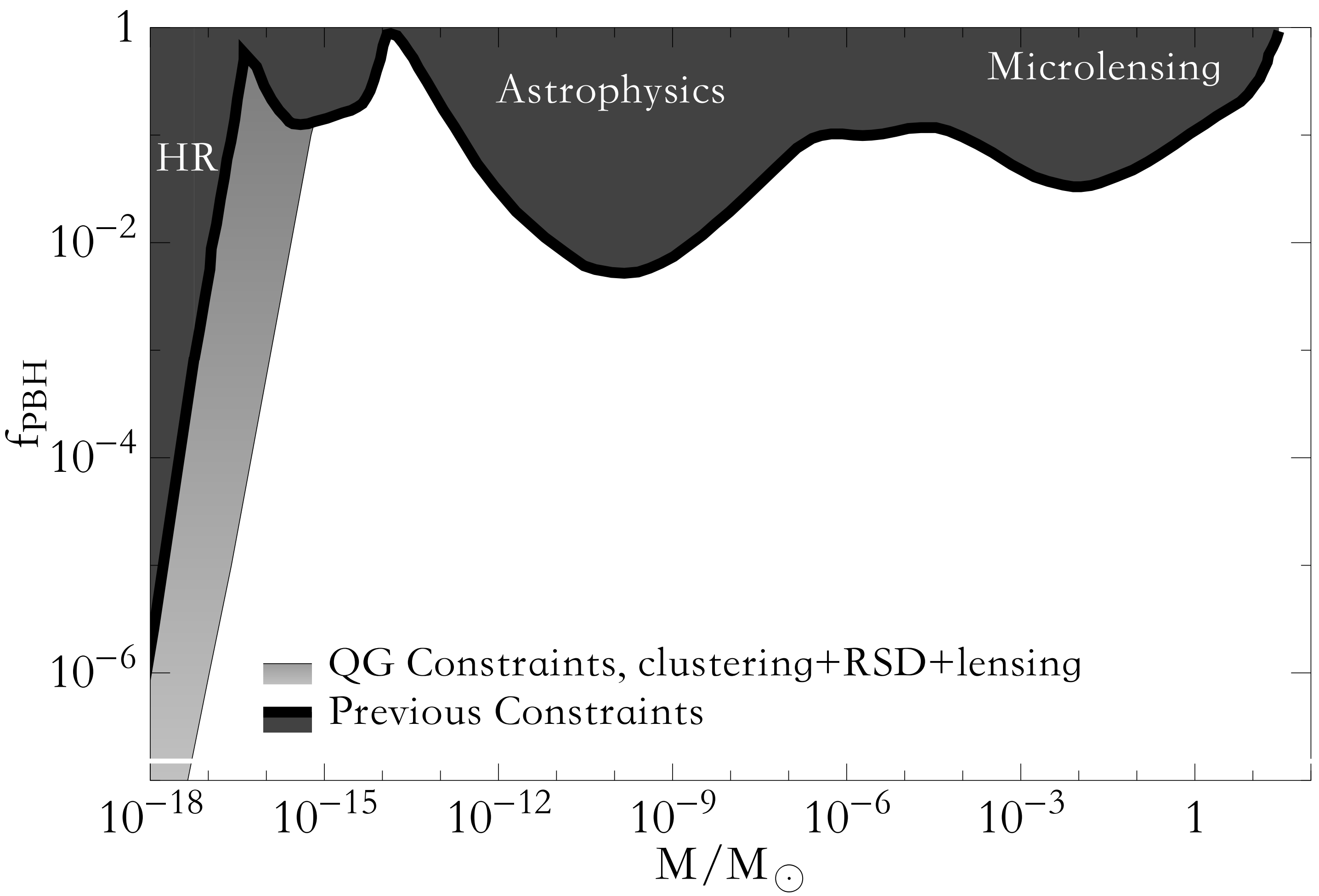
- Other BH instabilities? From large extra dimensions? From infinite branes? Gubser 2002, Kol 2002
  Emparan, García-Bellido, Kaloper 2003

(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



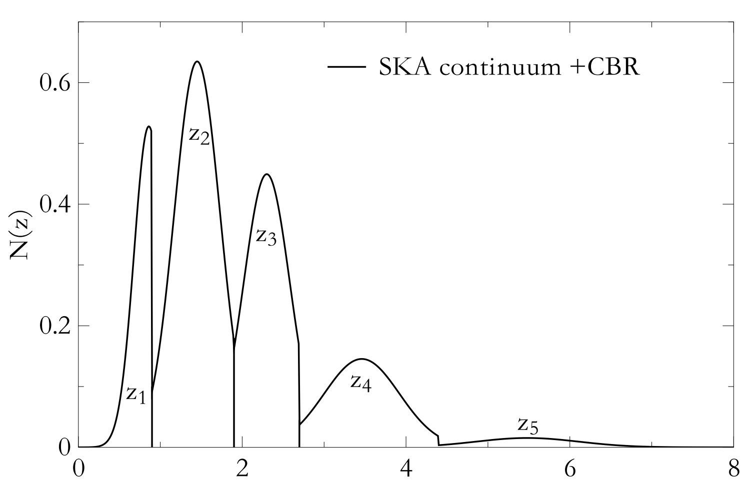
EFFECT ON GALAXY CLUSTERS

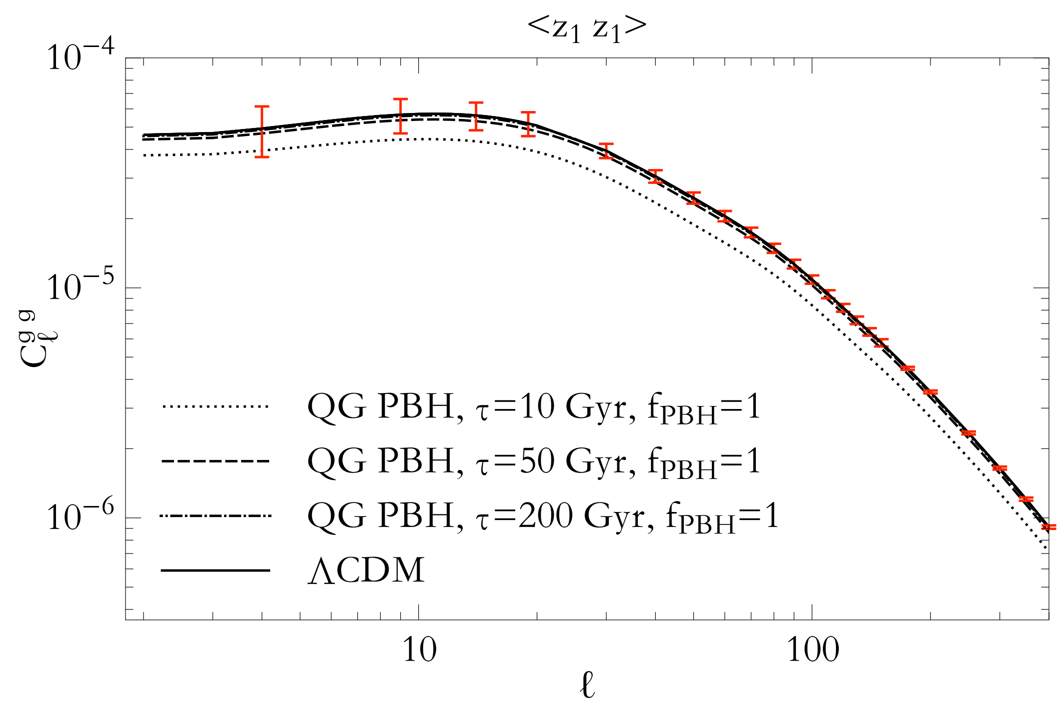
Raccanelli, Vidotto, Verde 1708.02588

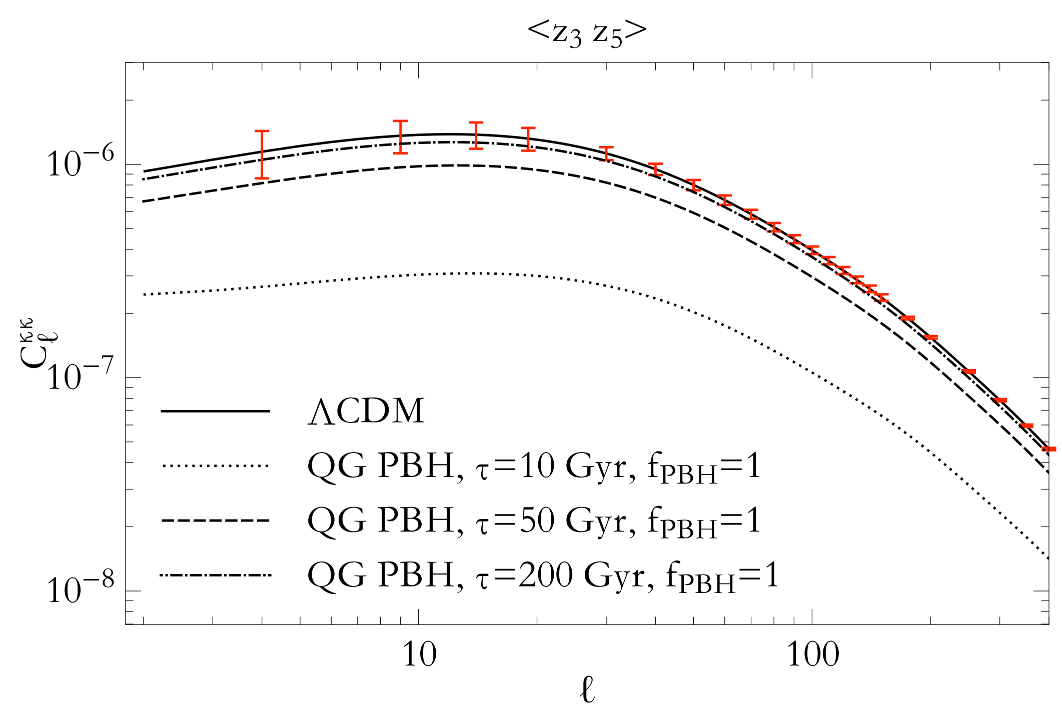
$$C_\ell^{XY}(z_i, z_j) = \left\langle a_{\ell m}^X(z_i)\ a_{\ell m}^{Y\,*}(z_j) \right\rangle$$

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

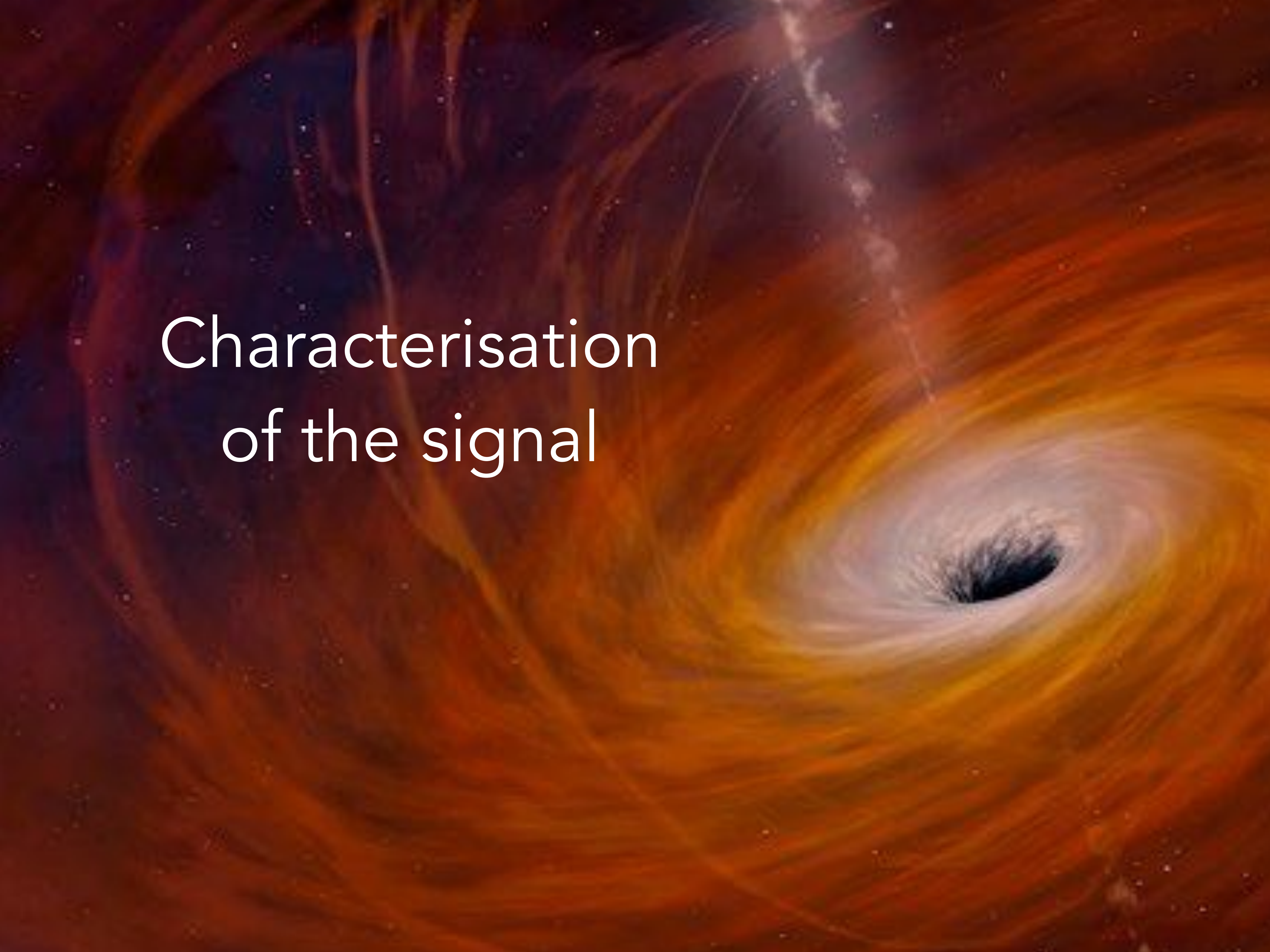
- Choice of redshift distribution:







Characterisation of the signal



PBH EXPLOSIONS

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 $\quad R = \frac{2Gm}{c^2} \sim .02$ 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!

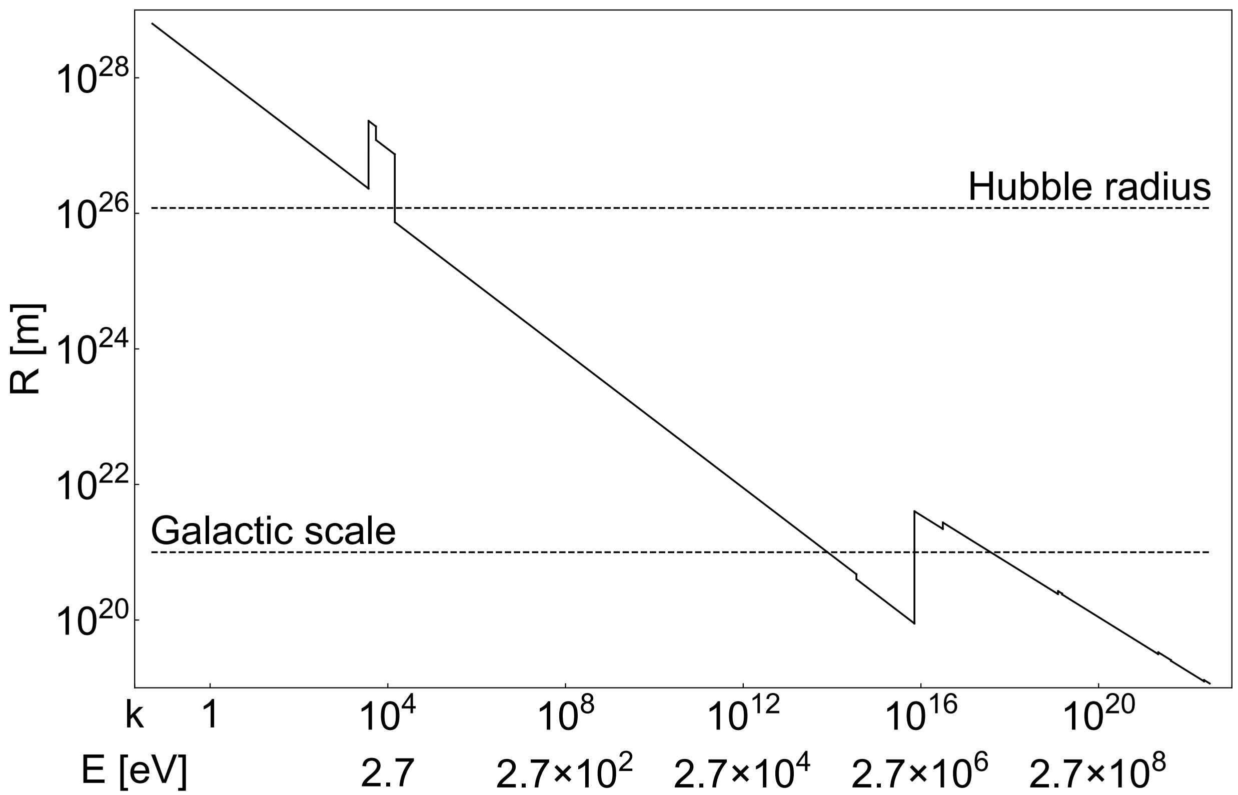
- We may be seeing only the a window in a distribution of event **Barrau &al. 1801.03841**

MAXIMAL DISTANCE

Barrau, Bolliet, Vidotto, Weimer 1507.1198

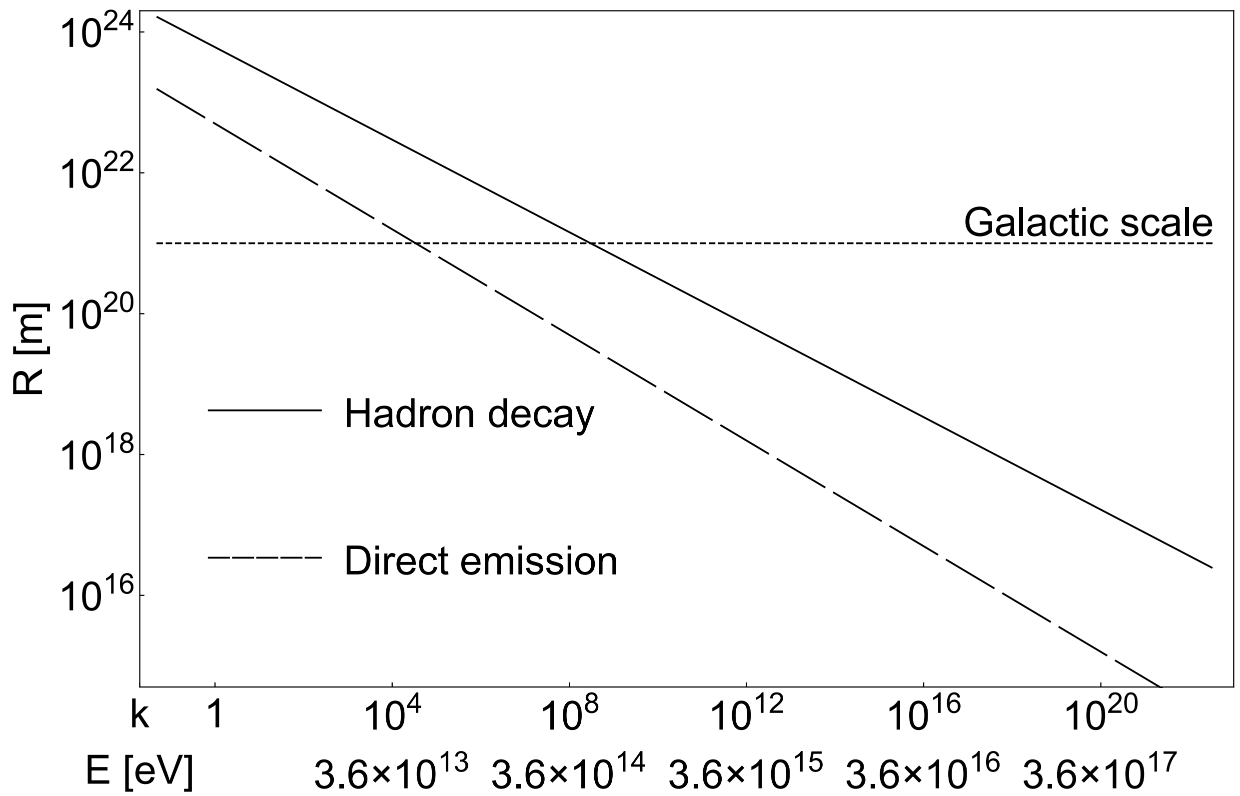
- shorter lifetime — smaller wavelength

Low energy channel



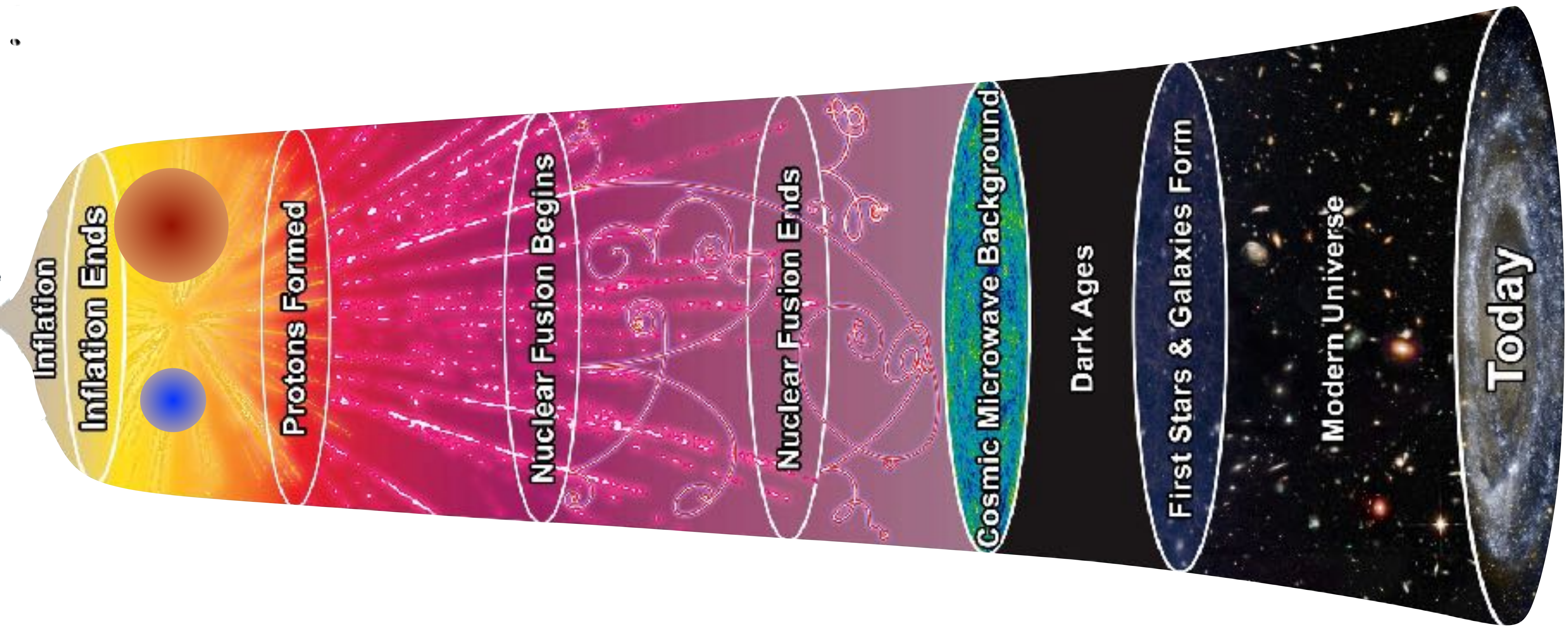
- detection of arbitrarily far signals
- better single-event detection

High energy channel



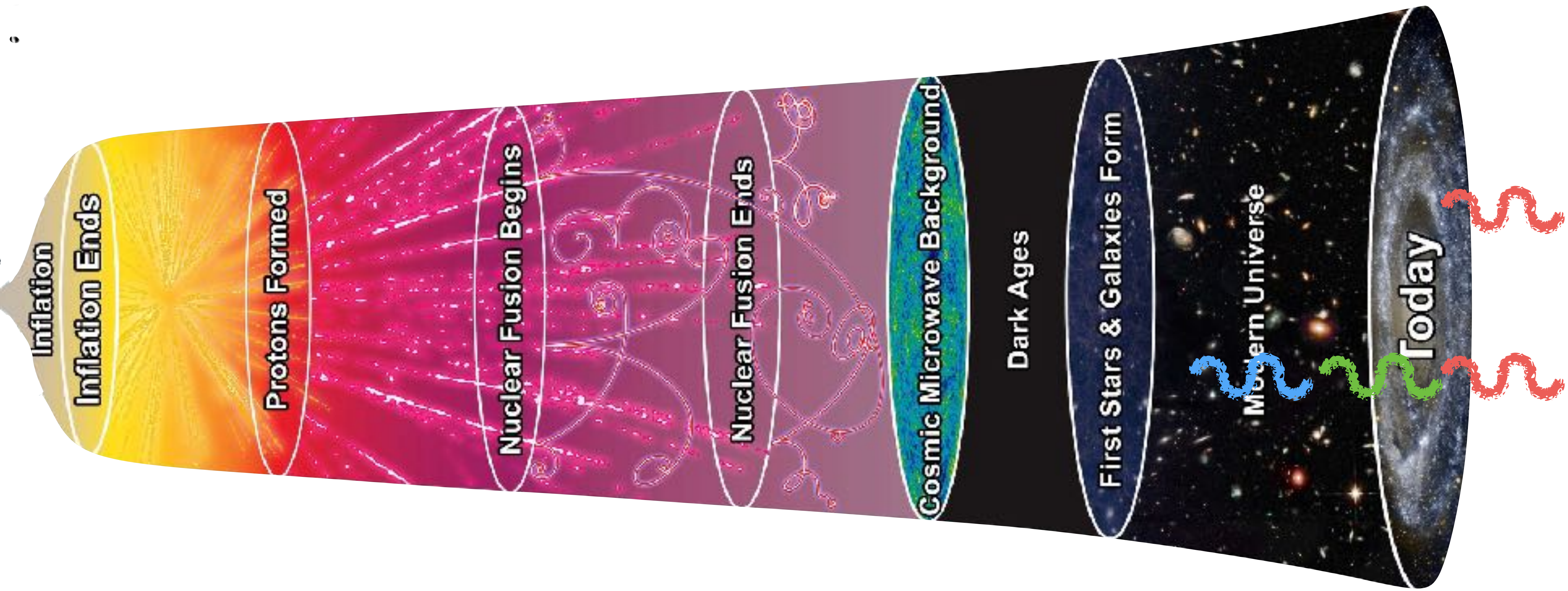
- PBH: mass - temperature relation
- different scaling

THE SMOKING GUN: DISTANCE/ENERGY RELATION



- distant signals originated in younger, smaller&hotter sources

THE SMOKING GUN: DISTANCE/ENERGY RELATION

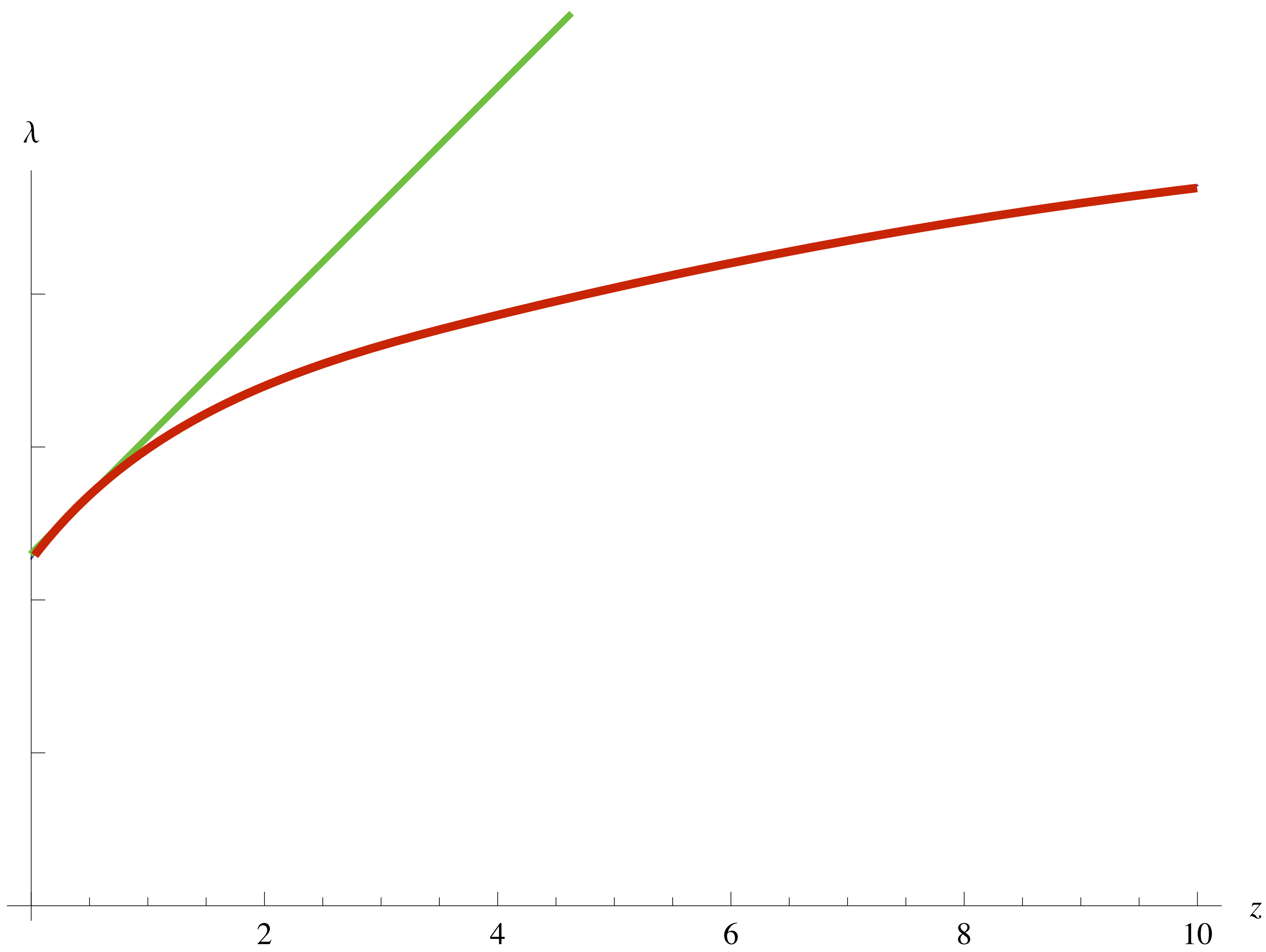


- distant signals originated in younger, smaller&hotter sources

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



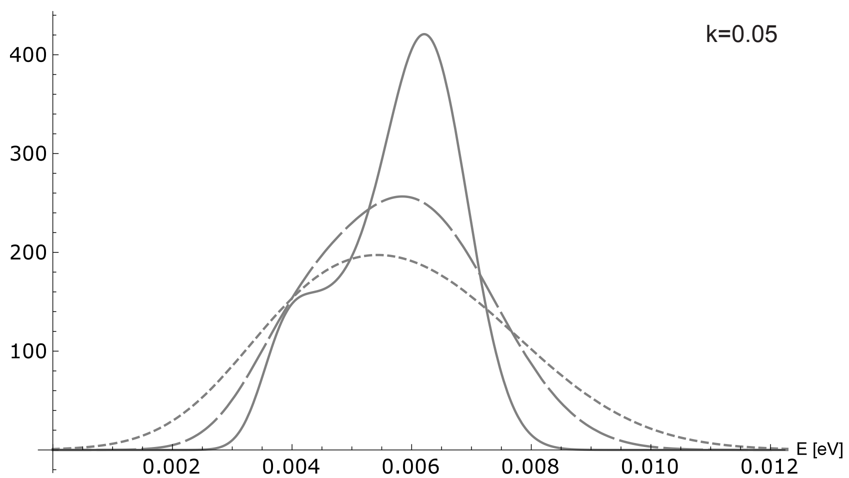
Barrau, Rovelli, Vidotto 1409.4031

INTEGRATED EMISSION

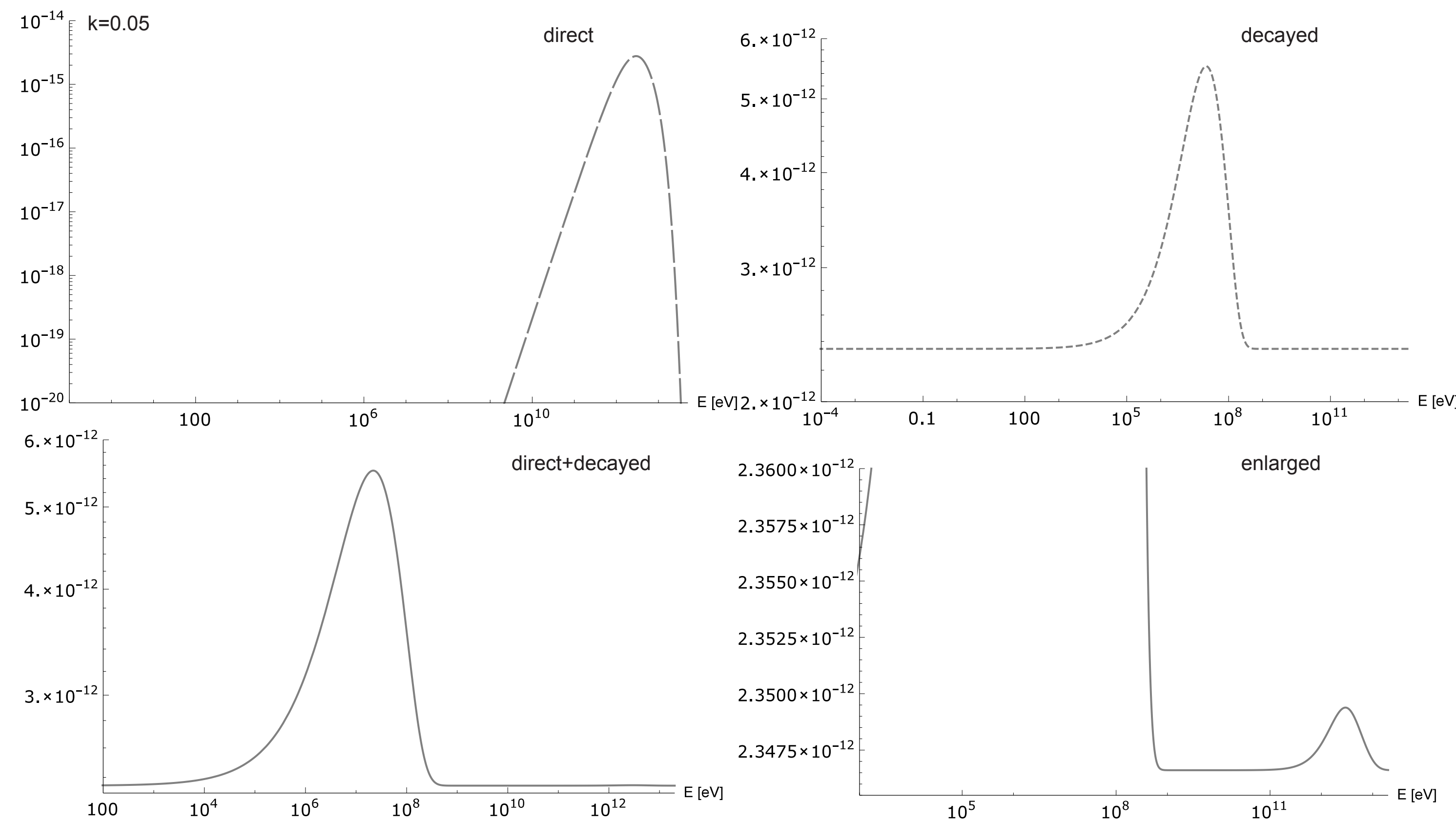
Barrau, Bolliet, Vidotto, Weimer 1507.1198

$$\tau \sim m^2$$

Low energy channel



High energy channel



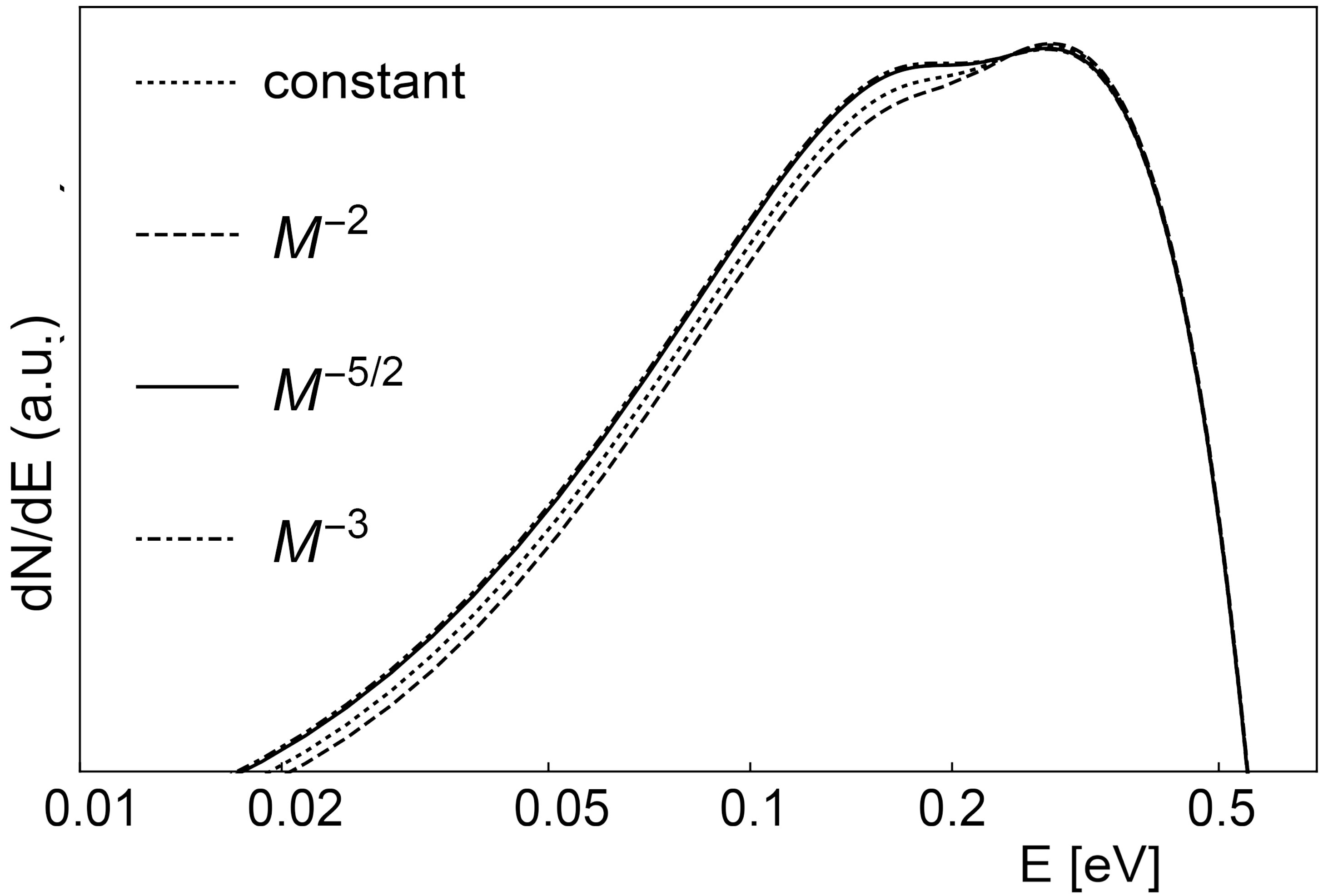
$$\frac{dN_{mes}}{dEdtdS} = \int \Phi_{ind}((1+z)E,R)\cdot n(R) \cdot Acc \cdot Abs(E,R)dR$$

- 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…


to conclude

SUMMARY ON REMNANTS

1. REMNANTS AS DARK MATTER
   * compatible with PBH formation at reheating
   * stability via minimal area/mass

2. BOUNCE² : Bouncing BH in a Bouncing Universe
   - their presence in the contracting phase yields n_s scale invariance
   - large "old" volume inside remnants make sense of the Past Hypothesis

3. FAST EXPLODING PBH
   - phenomenology depends on the lifetime as short as $\mathbf{m^2}$
   - new experimental window for quantum gravity
   - signals in the sub-mm, radio & TeV
     - direct detection & diffuse emission
     - peculiar energy distance relation
     - also late-universe observations

what else can change if black holes explode this way?

MAIN REFERENCES

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Planck stars
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Planck star phenomenology
Aurelien Barrau, Carlo Rovelli.
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Nature Astronomy, March'17, comment

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

White Holes as Remnants: A Surprising Scenario for the End of a Black Hole
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e-Print: arXiv:1802.04264

Small black/white hole stability and dark matter
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e-Print: arXiv:1805.03872

Erebons

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Carlo Rovelli, Francesca Vidotto.
e-Print: arXiv:1805.03224