Black Holes Are True Vacuum Nurseries

Louis Hamaide – 12/23

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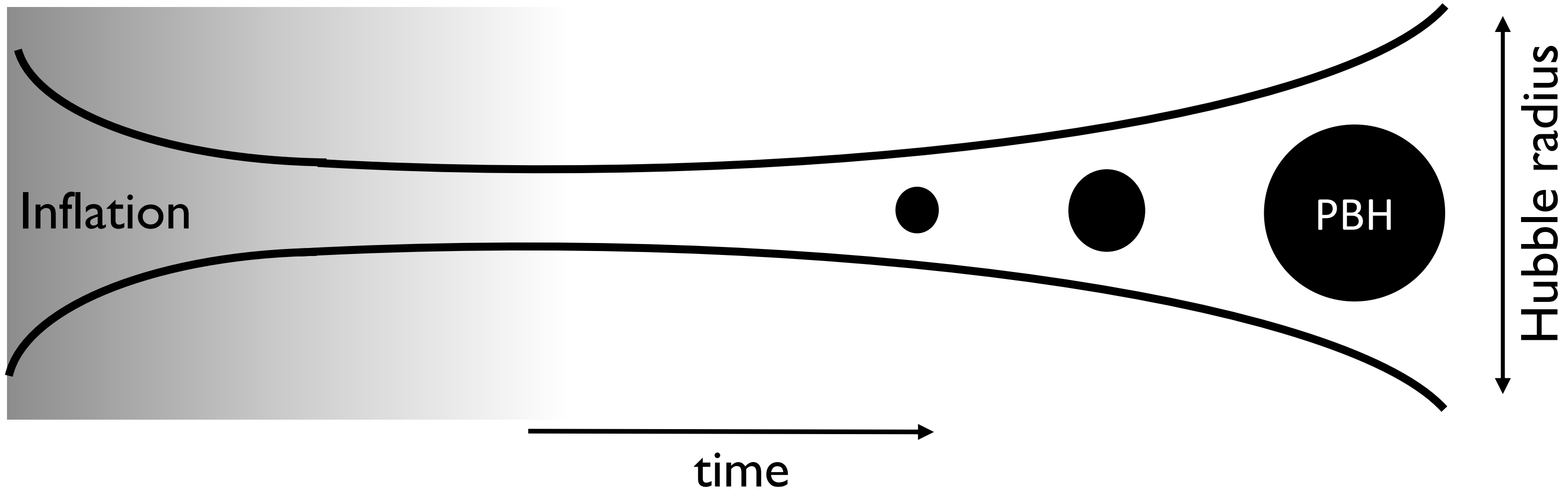
Based on *arxiv 2311.01869*

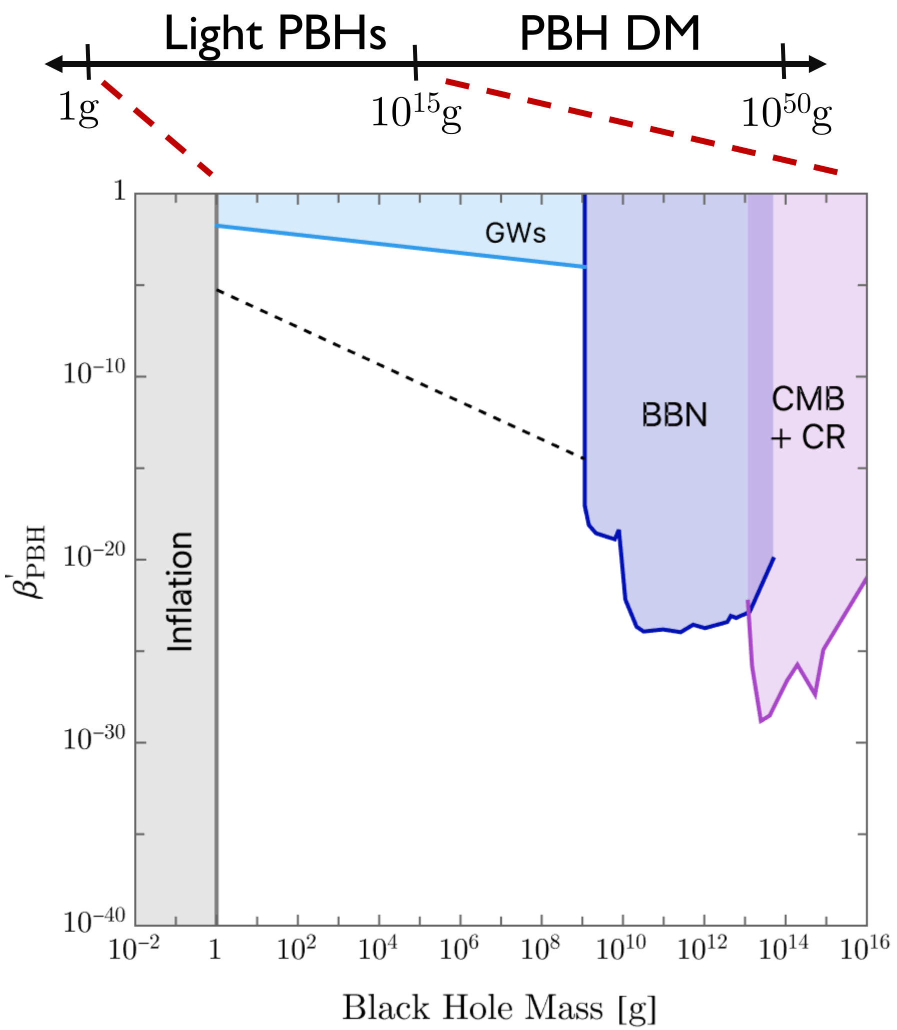
Intro to (Light) PBHs (1/2)

- Primordial black holes form from the collapse of large overdensities in the early universe. Estimated O(1) of the horizon mass necessary to bring about collapse. Thus as horizon size increases after inflation, and $M_{PBH} \propto T^{-2} \propto t$
- Collapsing modes have information about inflaton power spectrum. PBHs larger than $\sim 10^{15}$g have not yet evaporated today
- PBHs very popular part of the cosmologist's toolkit: can be dark matter if not evaporated



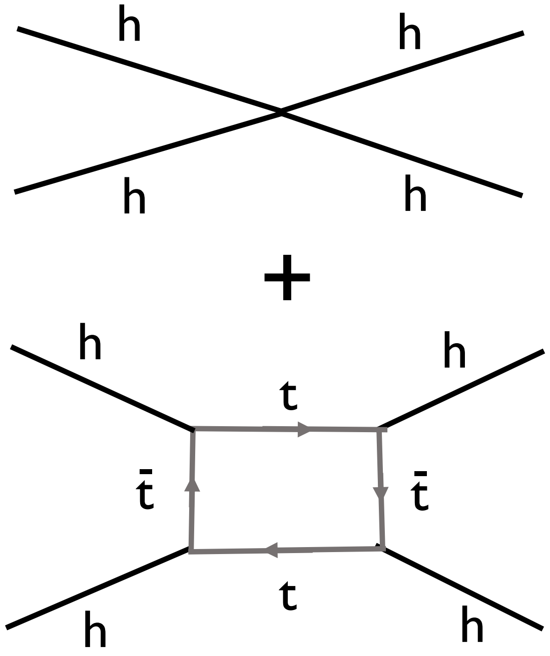
Introduction to light PBHs (2/2)

- PBHs can form in a large range of masses, and would have evaporated today if initially $<10^{15}$g
- Bounds exist already in this region, although the region 1g - 10^9g is more difficult to probe because effects from PBH evaporation are harder to detect
- Given the energies involved, these masses are windows into new physics, and are mostly constrained by GWs
- Light PBH ($<10^9$g) evaporation has been proposed as a DM production mechanism, or used in baryogenesis

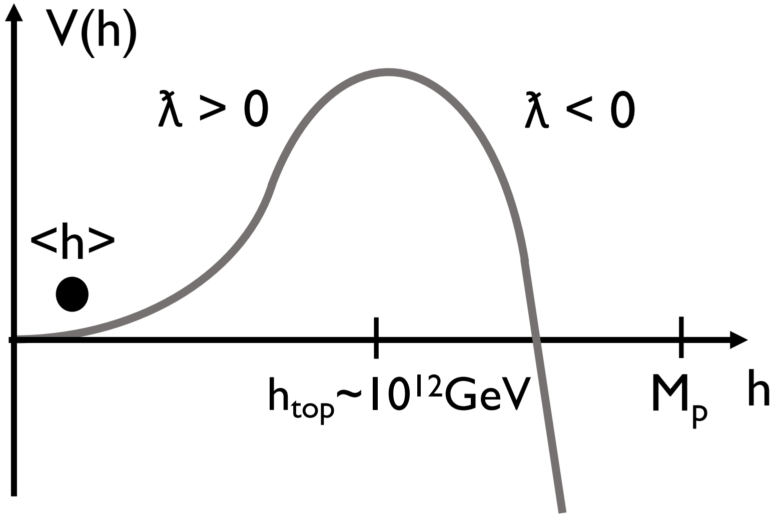


Introduction to Higgs Metastability

- Higgs potential quartic term receives largest (loop renormalization) corrections at large energies from Yukawa interactions with top quark – depends on measured top quark mass
- We can use latest LHC values of SM constants to find **metastability** (@ **2 sigma**)
- Current day Higgs vacuum decay rates imply stability on timescales much longer than age of universe



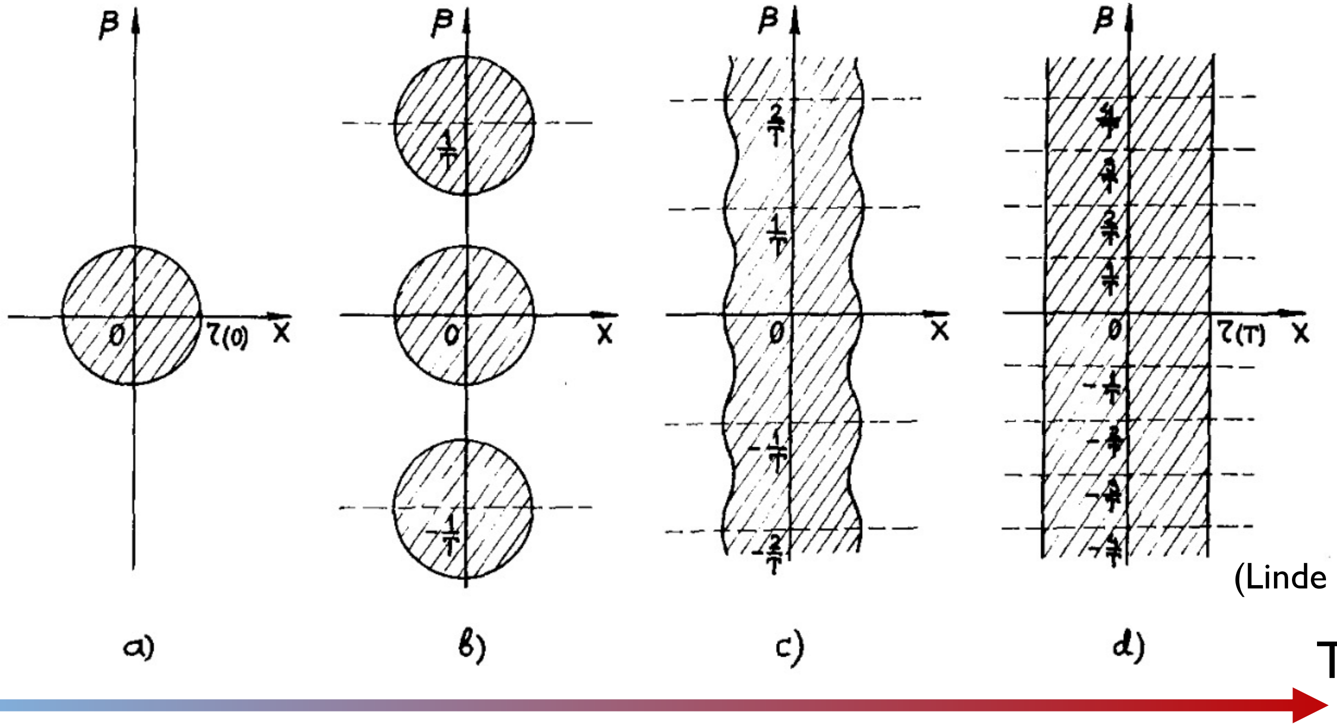
$$V(h) = \tilde{\lambda}(h)\, h^4$$



Introduction to FVDs (1/3)

- Taking $t \rightarrow i\tau$ in the path integral from FV to TV gives $e^{iS} \rightarrow e^{-S_E}$ where $S_E = \int d\tau dx^3 H(h(\tau, x^3))$ is the Euclidean action, which is positive and which we minimize
- τ is periodic in the complex plane with period $\beta = 1/T$. Two options (limits) for vacuum decay appear:

τ-dependent solutions remain e^{-S_E}, Euclidean action extremized



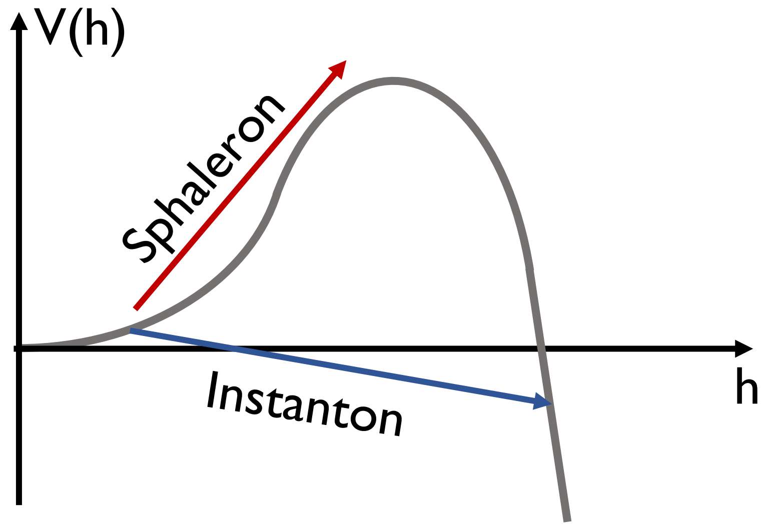
(Linde 1981)

τ-independent solutions gives $e^{-\beta E}$, where E = bubble energy

Introduction to FVDs (2/3)

- For τ-independent solutions (high T) this corresponds to thermal fluctuation solution or "sphaleron"
- For τ-dependant solutions (low T) this corresponds to a tunnelling solution or "instanton"

Tunnelling	Fluctuations
h is τ-dependent & β periodic	h is τ-independent
4d action extremized	3d action (i.e. energy) extremized
Solution is O(4) symmetric	Solution is O(3) symmetric



- Linde found decay rate of FV: $\Gamma \propto S^{3/2}e^{-S}$ for decays with 3D symmetry

Note: bubble action is *maximized*

Introduction to FVDs (3/3)

- Several authors have contributed to the study of FVDs in the presence of gravity – we show a quick summary here:

	Coleman	Coleman + de Lucia	Linde
Instantons (T=0)	✓	✓	x
Gravitational effects	x	✓	x
Sphalerons (T>0)	x	x	✓
Black holes ($T=T_{BH}$)	x	x	x

Introduction to FVDs (3/3)

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	Coleman	Coleman + de Lucia	Linde	Gregory + Moss
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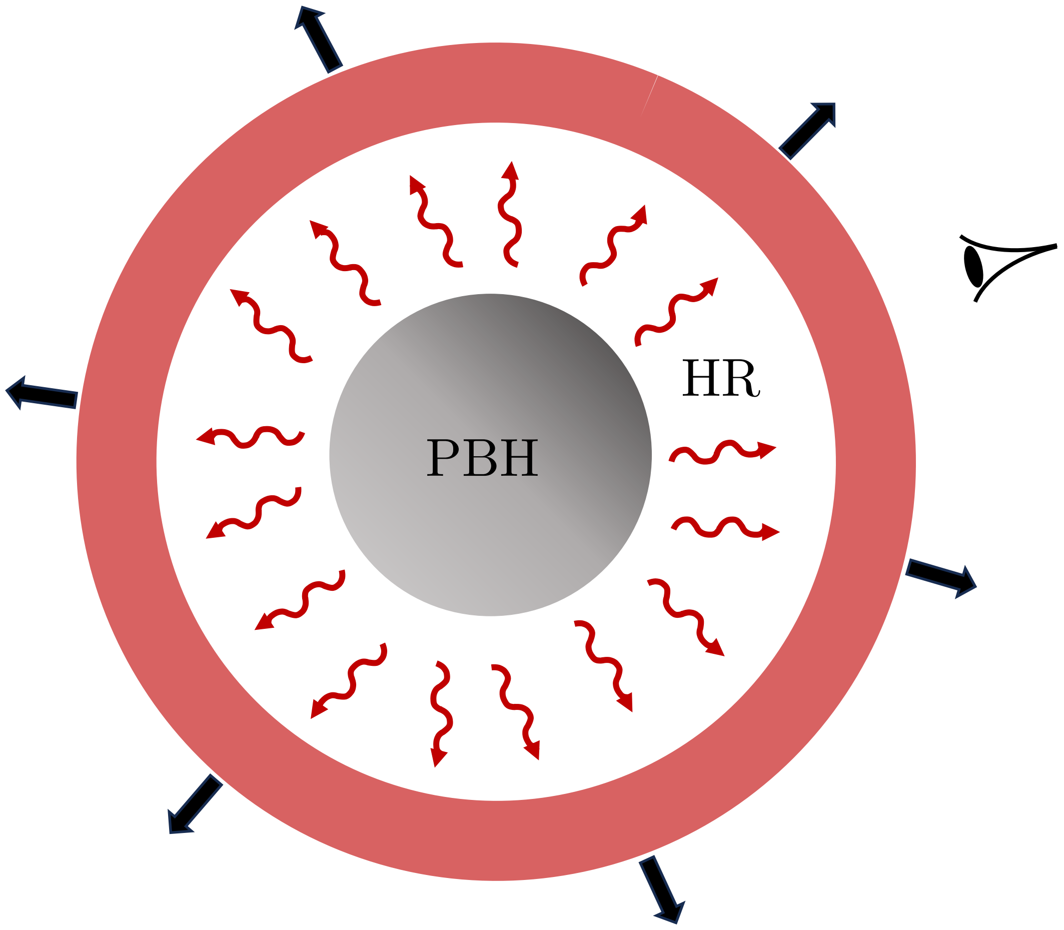
Sphalerons (T>0)	✗	✗	✓	✓
Black holes ($T=T_{BH}$)	✗	✗	✗	✓

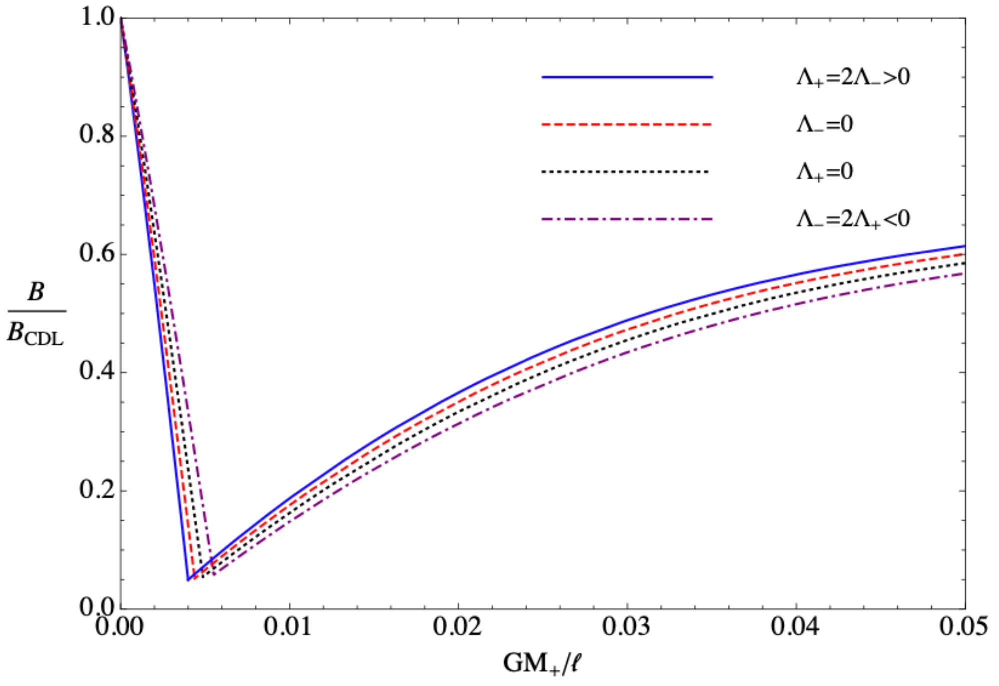
Black Holes as Bubble Nucleators (1/7)

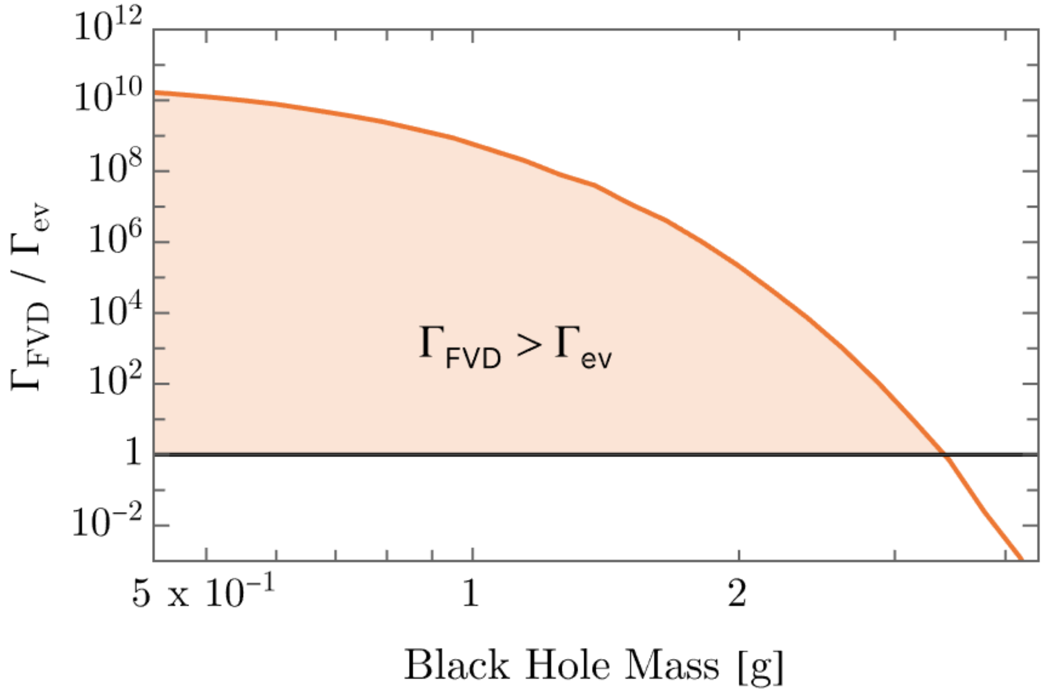
- Higgs vacuum has been found to be stable at low energies today (i.e. with instantons) and in flat early universe (with sphalerons)
- However decay rate would increase for lower bubble energies → curvature inhomogeneities considered for this purpose
- PBHs are natural candidates and have temperatures which can reach instability scale. As PBH evaporates it can contribute energy to the bubble if high enough temperature
- Phase transitions would leave observable imprint



Black Holes as Bubble Nucleators (2/7)

- First calculations of the action in the presence of a black hole, using high temperature sphalerons, confirm energy is lower than flat space sphaleron, motivating further study:





Gregory & Moss (2015 & 2017)

Black Holes as Bubble Nucleators (3/7)

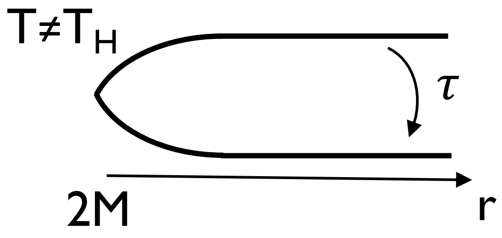
- Gregory & Moss[1] calculated the action of a Higgs decay in the presence of a black hole, using the high temperature sphalerons:

$$S_b\,[T] = \beta \int dx^3 \sqrt{-g} \left(-\frac{R}{16\pi G} + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi + V(\phi) \right)$$

where the natural choice of periodicity is $\beta = 8\prod \mathrm{M}$, i.e. the black hole temperature.

- When taking arbitrary β we must account for conical deficits:

$$S_b\,[T] \supset -\frac{\beta_H - \beta}{\beta_H}\frac{\mathcal{A}}{4G} + \mathcal{O}(\epsilon)$$



which are due to extrinsic curvature at the horizon (corrections depend on smoothing scale)

[1]preprint 1503.077331

Black Holes as Bubble Nucleators (4/7)

- Conical deficits cancel the β contributions from the bulk:

$$S_b\,[T] \supset \beta(M_+ - M_-) = \beta E_{\text{bubble}}$$

- The resulting action is a simple expression:

$$S_b\,[T] = \frac{\mathcal{A}_+}{4G} - \frac{\mathcal{A}_-}{4G}$$

which crucially doesn't depend on the background temperature since $S_b\,[T] = S_b[T_H]$

- Although the action is the same for all temperatures, the decay rate (prefactor) for arbitrary temperature is **different from Hartle-Hawking**:

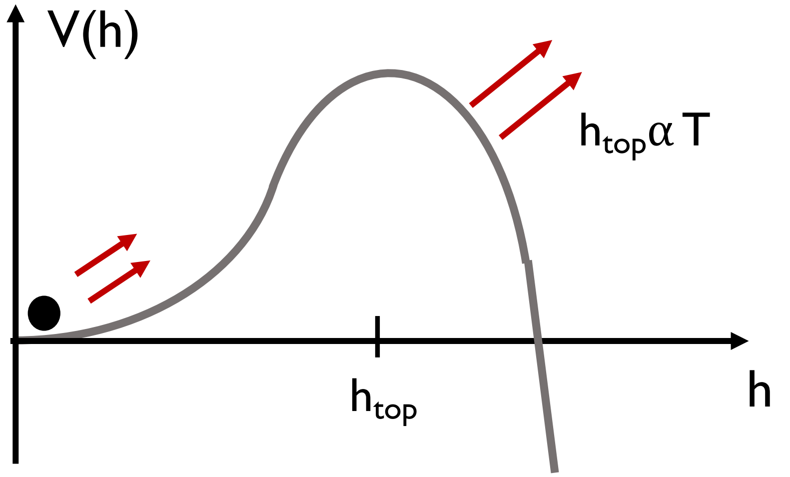
$$\Gamma_{\text{FVD}}(T) \;\approx\; T\left(\frac{S_b[T_H]}{2\pi}\right)^{1/2} \exp\left(-S_b[T_H]\right)$$

Black Holes as Bubble Nucleators (5/7)

Caveats/issues

- Strumia[1] noted thermal loop corrections to the Higgs potential must also be taken into account, which increase the action (i.e. suppress the decay rate) at high temperature
- For small (i.e. hot, above metastable scale) black holes in equilibrium with the plasma (Hartle-Hawking vacuum), the effect is large:

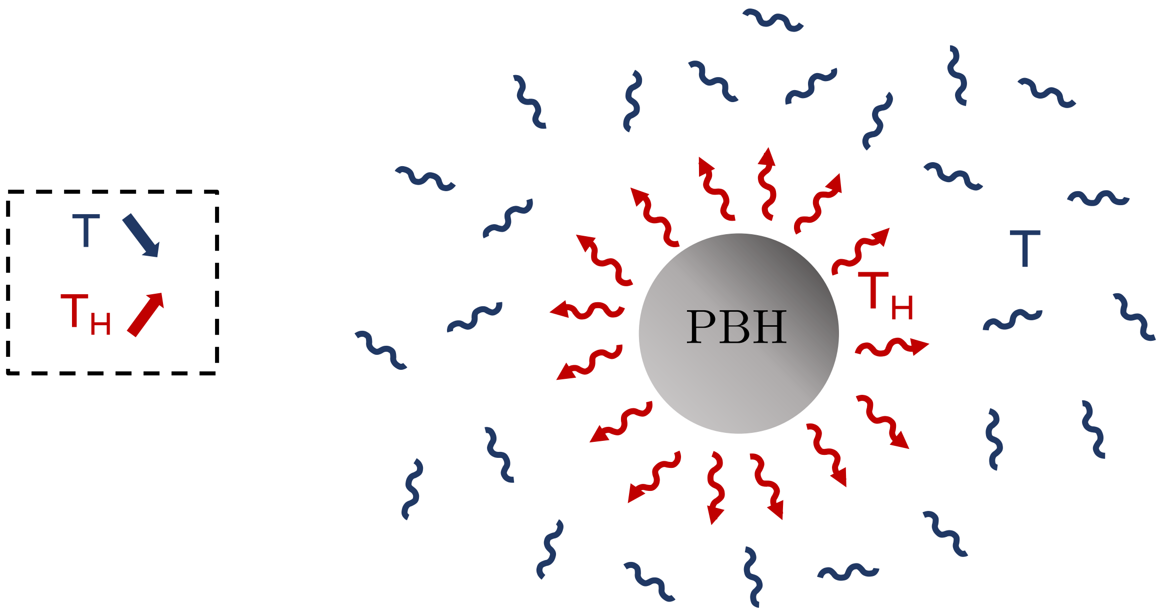
$$S_b = \beta\, E_{bubble} \approx \beta\, h_{top} \sim \beta\, T \sim \text{cst.}$$



[1]preprint 2209.05504

Black Holes as Bubble Nucleators (6/7)

- Euclidean formalism requires thermalized plasma around the black hole, however evaporating black holes are not in equilibrium (Unruh vacuum)
- Gregory & Moss results were calculated for Hartle-Hawking vacuum (equilibrium), but cooling universe not at $T = T_H$ during most of evaporation (or often not long enough when it is)
- However radiation can interact with plasma → need more careful study of thermal history



Black Holes as Bubble Nucleators (7/7)

- Several authors have contributed to the study of FVDs in **black hole** backgrounds in the presence of gravity – we show a (non-extensive) summary here:

PBHs	Gregory + Moss	Strumia
Hartle-Hawking	✓	✗
Conical deficits	✓	✗
Thermal corrections	✗	✓
Prefactor (non HH)	✗	✗

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Thermal corrections	✗	✓	✓
Prefactor (non HH)	✗	✗	✓

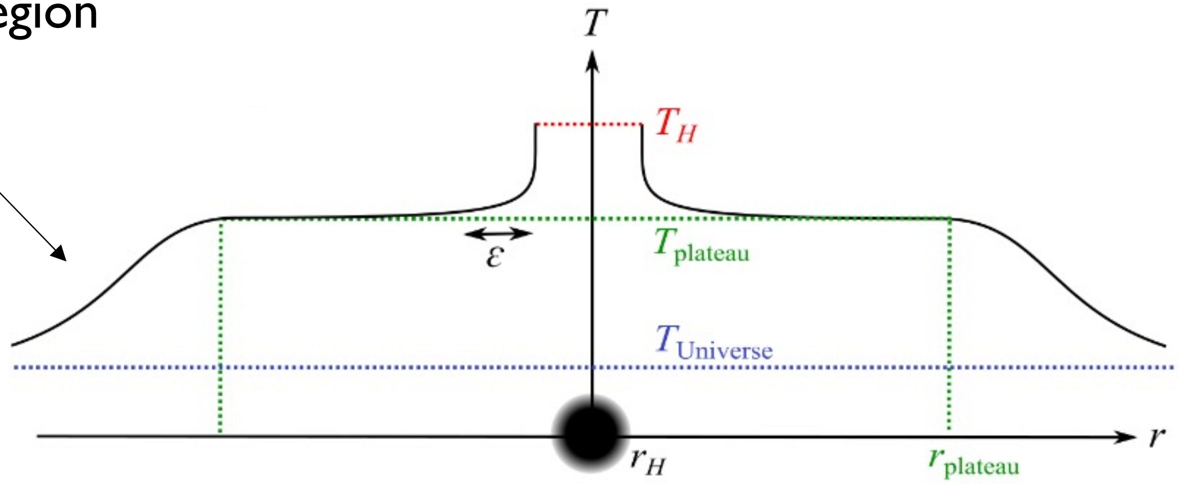
Hot Spots Around PBHs (1/3)

Is there a path forward ?

- He, Kohri, Matsui & Yamada recently computed the energy deposition rate (thermalization time) of Hawking radiation into the surrounding plasma using the LPM effect:

$$\Gamma(T) \sim \alpha^2 T \sqrt{\frac{T}{T_H}}$$

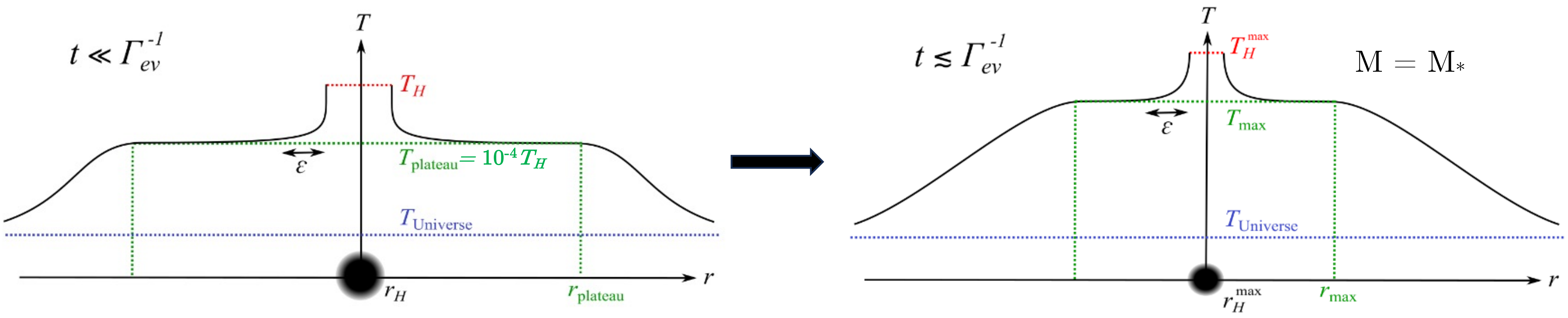
- For thermalization rates much faster than evaporation, heating of "hot spot" in plasma will occur
- This yields a homogeneous inner region of radius: $r_{cr}(M_{ini}) \sim 10^8 \, \mathrm{M_{BH}}$ and temperature $\mathrm{T} = 10^{-4} \, \mathrm{T_H}$ and and a diffusion region



Hot Spots Around PBHs (2/3)

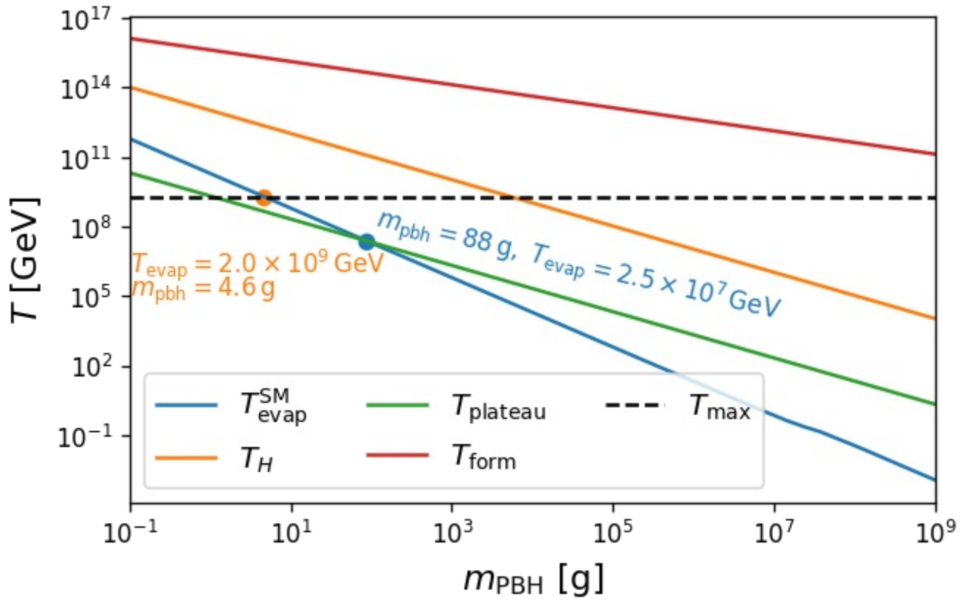
Is there a path forward ?

- Below M_* ~ 0.8g deposition rates lower than evaporation rate. Then hot spot doesn't form, or existing hot spot diffuses away
- Until M_* hot spot follows evaporation of black hole, so Euclidean formalism valid. For all $M>M_*$ hot spot radius is larger than the bubble radius



Introduction to light PBHs (3/3)

- We can account for cases where the universe has $\mathrm{T > T_H}$ where we ignore $\mathrm{T_H}$
- For M_{BH} > 4g hot spots form at some point during evaporation, while for smaller masses the universe's temperature dominates. For M_{BH} > 88g , the hot spot forms toward the end of the BH evaporation only



Introduction to light PBHs (3/3)

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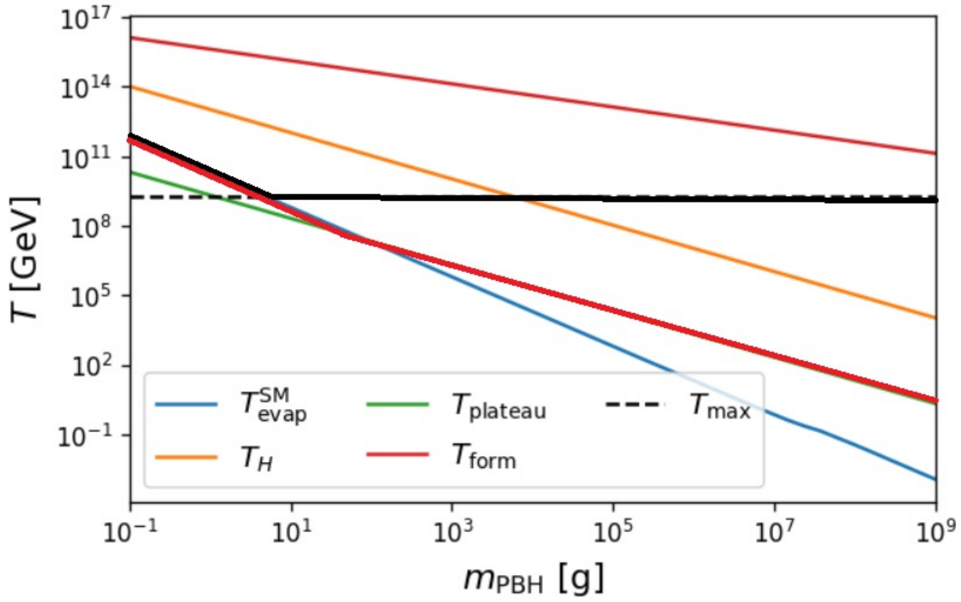
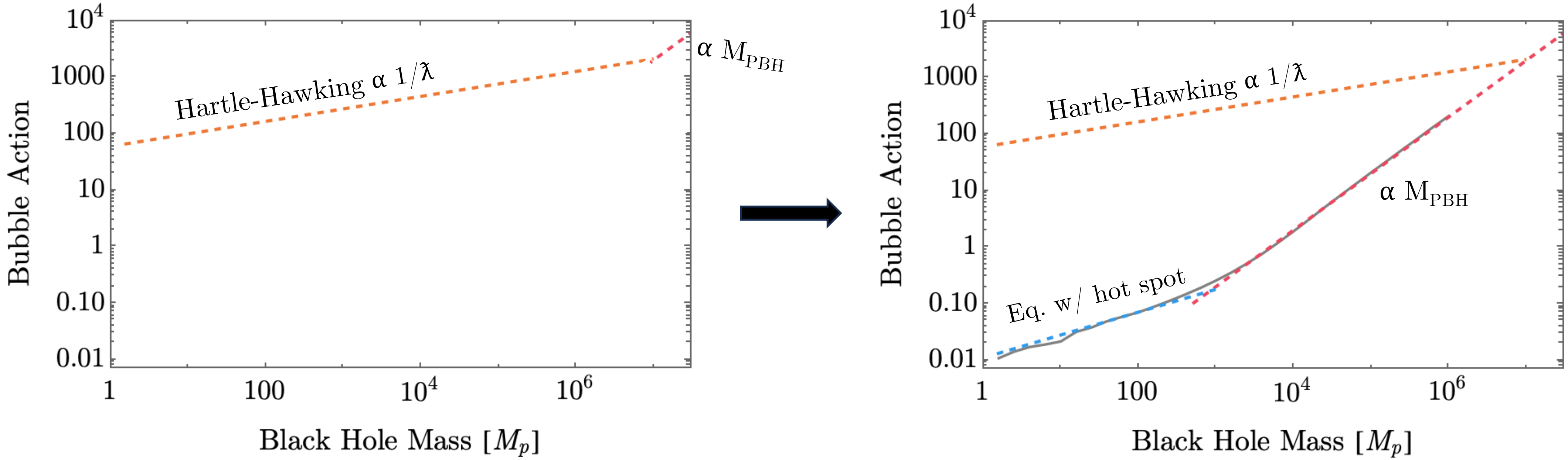
- For M_{BH} > 4g hot spots form at some point during evaporation, while for smaller masses the universe's temperature dominates. For M_{BH} > 88g , the hot spot forms toward the end of the BH evaporation only
- We can choose either the (red, conservative) to take $Max(T_{BH}(M_i), T_{evap})$ since universe cools fastest before t_{ev} , or (black) the $Max(T_{max}, T_{evap})$ assuming the hot spot has heated to T_{max} and Euclidean formalism is valid



FVD rate around PBHs (1/2)

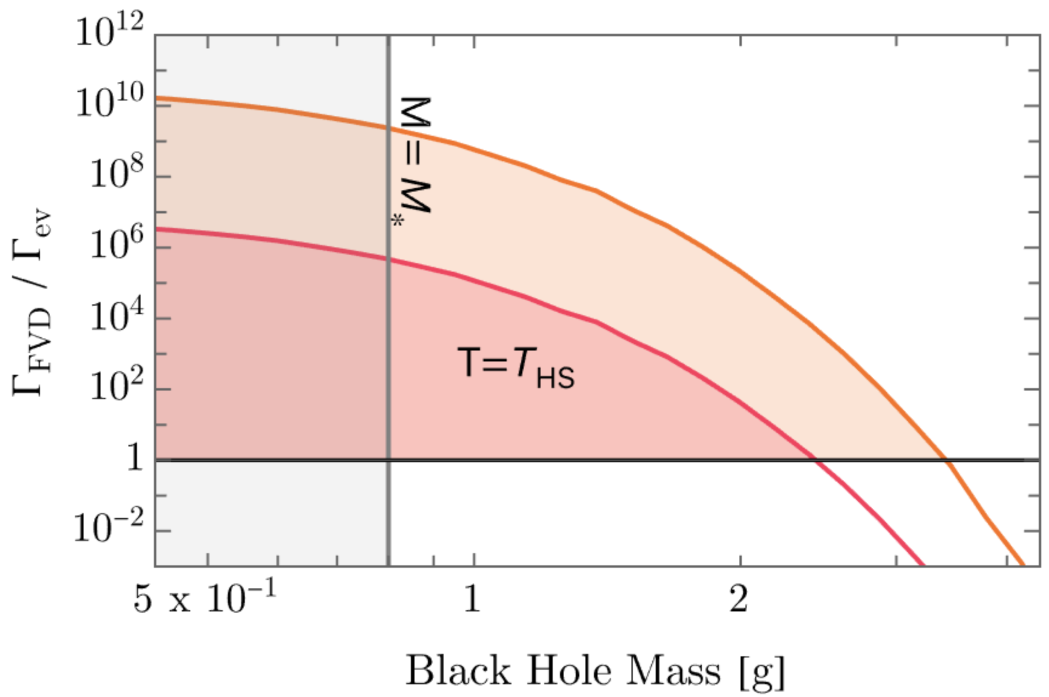
- Assuming the hotspot form, vacuum decay can now occur inside these: energy is calculated using thermal fluctuations from (relatively low) T_{HS}, while temperature in front of action is $T_H >> T_{HS}$
- Thus thermal fluctuations dominate for lower PBH mass, i.e. $S_b[T_H, T] \approx S_b[T_H]$ and decay rate is:

$$\Gamma_{\rm FVD}(T) \approx T \left(\frac{I_{\rm b}[T_H]}{2\pi} \right)^{1/2} \exp\left(-I_{\rm b}[T_H]\right)$$



Hot Spots Around PBHs (2/2)

- Hot spots create ideal conditions for FVD: if T_{HS} is too low or too high phase transition doesn't occur
- For T_{HS} too high (~10^3 higher) the thermal fluctuations become dominant again, while for T_{HS} too low (~10^{-3}) the prefactor pushes the decay ratio below the region where Euclidean formalism is valid (ratio>>1)



Bounds on PBHs

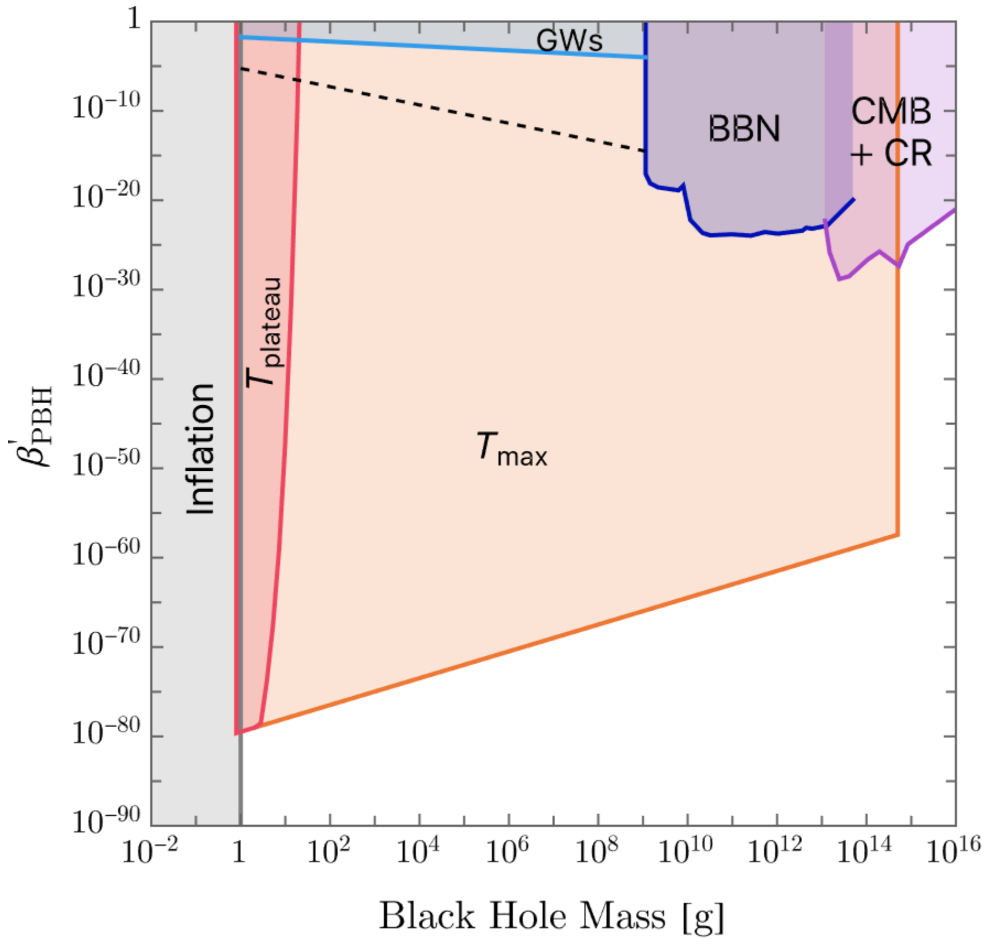
- Since the decay ratio $\Gamma_{\rm FVD} \,/\, \Gamma_{\rm ev} >> 1$ we can use:

  $P_{\rm FVD} \equiv 1 - e^{-\Gamma_{\rm FVD}\Delta t} \sim 1$ where $\Delta t \sim \Gamma_{\rm ev}^{-1}$
- We can use $\Gamma_{\rm FVD} \,/\, \Gamma_{\rm ev}(\mathrm{M}_*)$ to exclude any PBH which evaporated in our current Hubble horizon

  → very stringent constraints :

$$\beta_{\rm PBH} \lesssim 5 \times 10^{-80} \left(\frac{M}{M_\star}\right)^{3/2}$$

- Conservative constraints assume Euclidean formalism only valid at $\Gamma_{\rm FVD} \,/\, \Gamma_{\rm ev}\,(\mathrm{M_i})$
- Further work must solve exact temperature profile, as action depends strongly on near horizon region
- Higgs stabilization at high energy could allow light PBHs

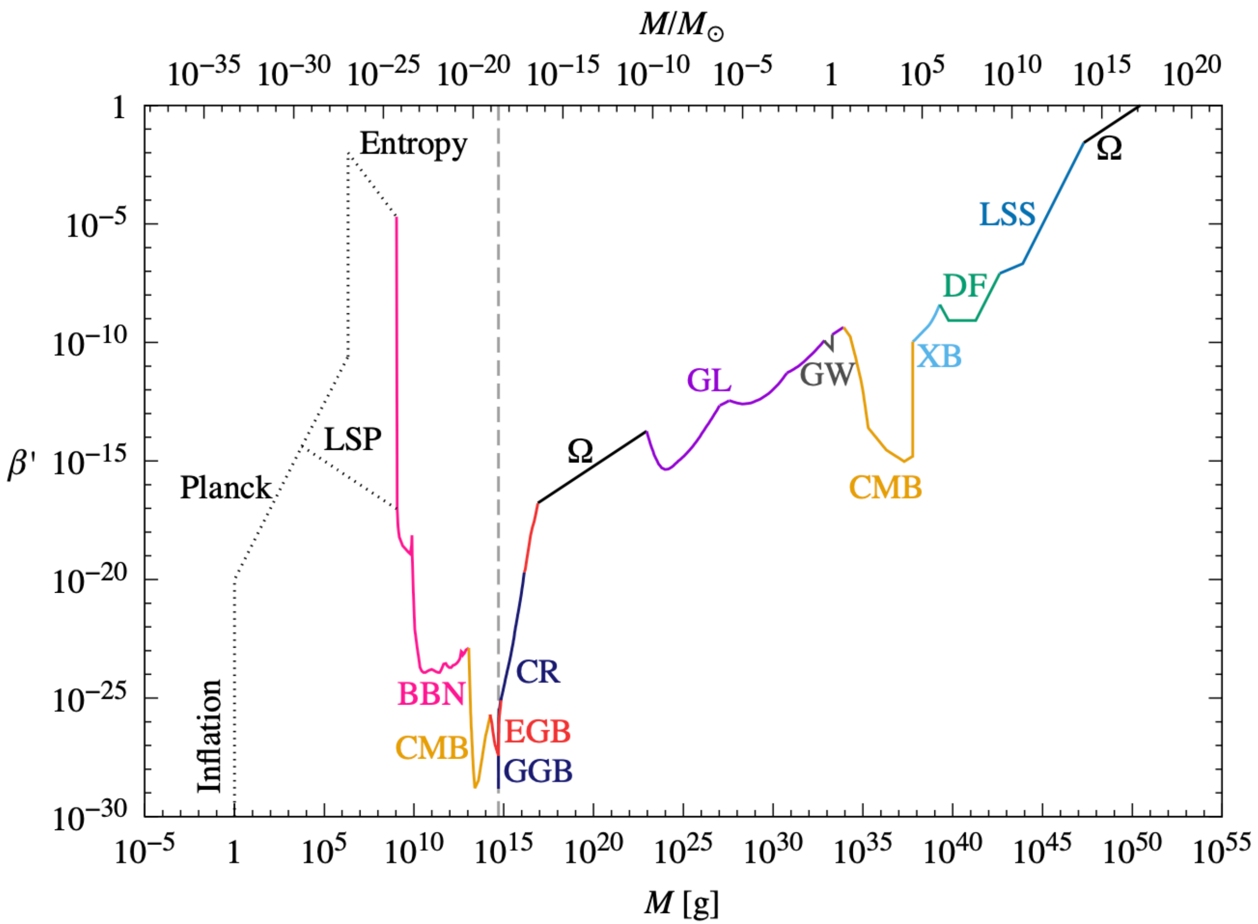


Conclusions

- PBHs are of theoretical interest and not highly constrained below 10^{10}g
- Light PBHs provide a seed to create FVD of metastable Higgs but difficult to produce without PBHs due to thermal fluctuations
- Hot spots around PBHs tends to destabilize the vacuum
- Studying light PBHs means one needs to address metastability first
- We can now apply this to metastability in DM and/or other BSM scenarios!

Thank you!

Back-up



$M/M_\odot$
10^{-35} 10^{-30} 10^{-25} 10^{-20} 10^{-15} 10^{-10} 10^{-5} 1 10^{5} 10^{10} 10^{15} 10^{20}
1
10^{-5}
10^{-10}
β' 10^{-15}
10^{-20}
10^{-25}
10^{-30}
Entropy
Ω
LSS
DF
XB
GL
GW
Ω
LSP
Planck
CMB
CR
BBN
EGB
CMB
GGB
Inflation
10^{-5} 1 10^{5} 10^{10} 10^{15} 10^{20} 10^{25} 10^{30} 10^{35} 10^{40} 10^{45} 10^{50} 10^{55}
M [g]

Back-up

Finally, we estimate the temperature profile $T(r)$ around a PBH in Regime (i). For a given time t, the region inside $r < r_{\rm d}(t, T(r_{\rm d}))$ is expected to be equilibrated by the efficient diffusion over that length scale. In equilibrium, the total energy flux at any radius should be the same and is equal to the flux of Hawking radiation. For a shell at $r < t_{\rm th}(T_{\rm H,ini}, T)$, all the energy flux from the PBH is carried by the Hawking radiation itself, and hence the temperature inside $r < t_{\rm th}(T_{\rm H,ini}, T)$ should not have the gradient but be homogeneous. Note that this critical radius is given by

$$r_{\rm cr}(M_{\rm ini}) \equiv t_{\rm th}(T_{\rm H,ini}, T) \simeq 6 \times 10^7 \left(\frac{\alpha}{0.1}\right)^{-6} \left(\frac{g_*}{106.75}\right) \left(\frac{g_{H*}}{108}\right)^{-1} T_{\rm H,ini}^{-1}, \tag{3.14}$$

where we use Eq. (3.12) to estimate the homogeneous temperature of the core region $r \lesssim t_{\rm th}$. This is al-