Baryogenesis from Exploding Primordial Black Holes

David Kaiser



Alexandra Klipfel (MIT)



Miguel Vanvlasselaer (Barcelona)

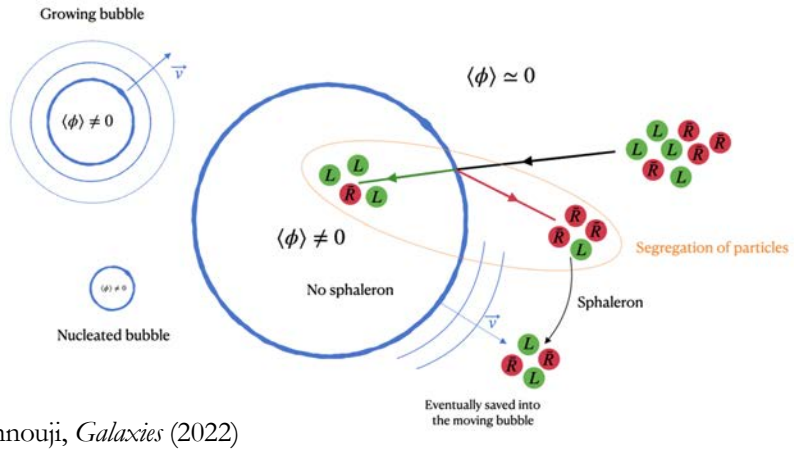


Sokratis Trifinopoulos (Northwestern)

arXiv:2603.15746
arXiv:2603.29024

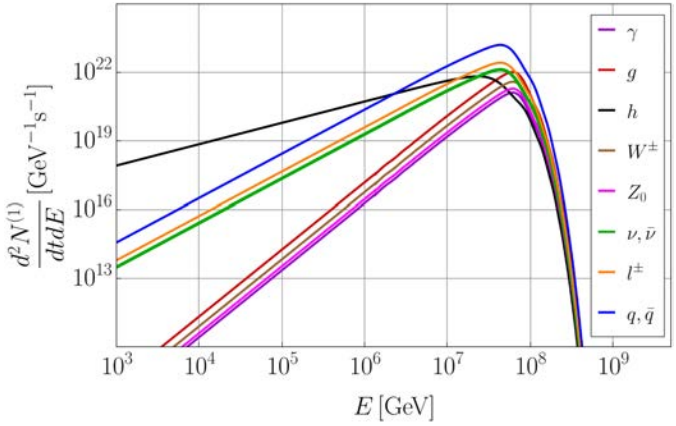
PBH amid the quark-gluon plasma
Image by Kaća Bradonjić

Electroweak Baryogenesis Review

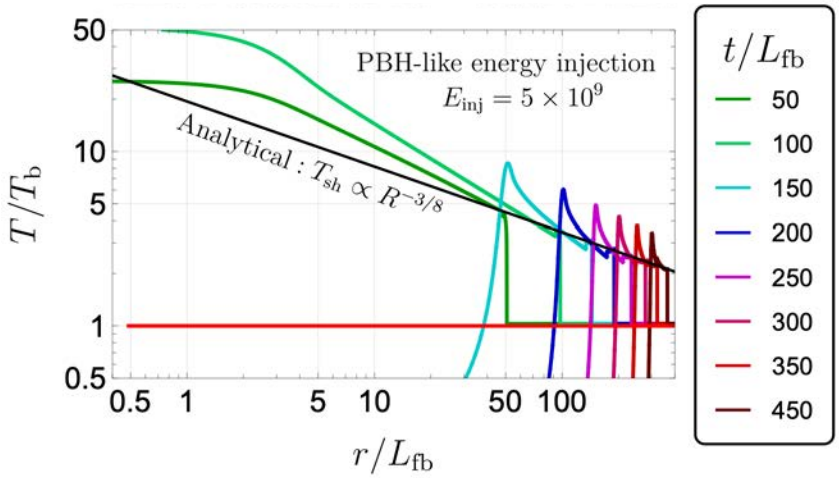


R. Gannouji, *Galaxies* (2022)

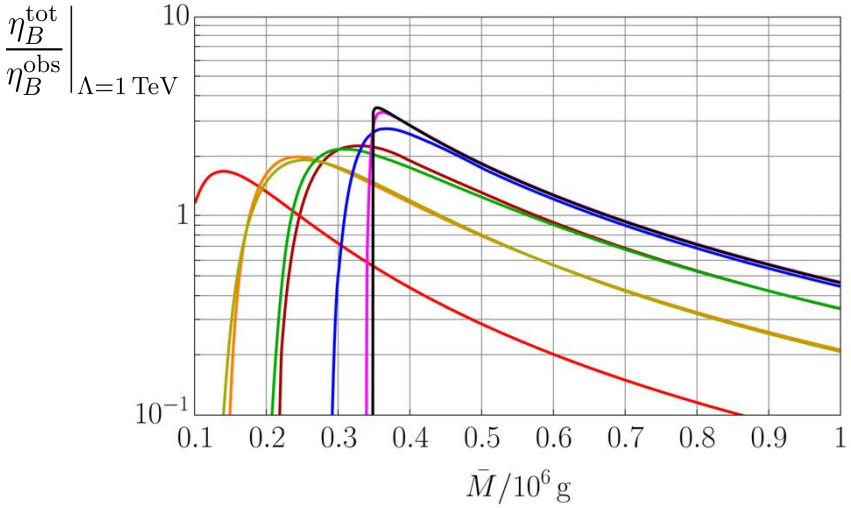
PBHs & Hawking Emission



PBH Explosions in the Quark-Gluon Plasma



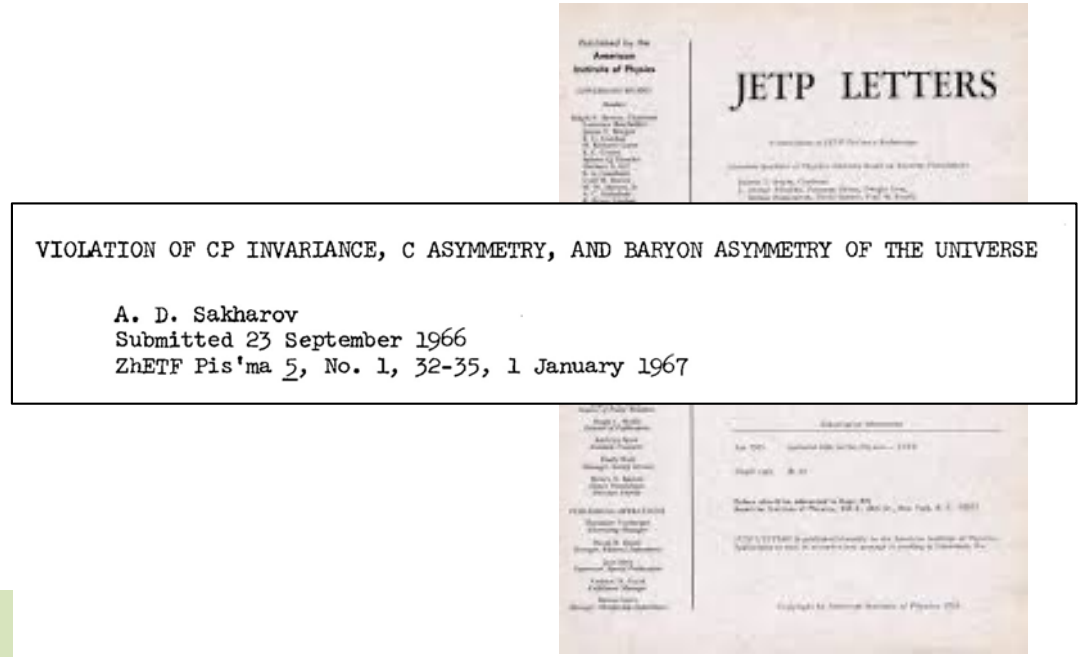
New Baryogenesis Mechanism



Electroweak Baryogenesis

The observed ***baryon asymmetry*** of the universe (BAU):

$$\eta_B^{\rm obs}\Big|_{\rm BBN} = \frac{n_B - n_{\bar{B}}}{s} = \frac{n_B}{7.04\, n_\gamma} = 8.65 \pm 0.09 \times 10^{-11}$$


JETP LETTERS

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

Sakharov conditions:

1. Out-of-equilibrium interactions
2. C and CP violation
3. Baryon number violation

The Standard Model can satisfy all three Sakharov conditions — but yields η_B ***exponentially below*** the observed value. Hence the need for ***some BSM physics***.

Electroweak Baryogenesis

Sakharov conditions:

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2. C and CP violation
3. Baryon number violation

Reviews: de Vries, Postma, van de Vis, arXiv:1710.04061, 2508.09989; Bodeker and Buchmuller, arXiv:2009.07294.

Typical EWBG scenario

- ***1st-order EW phase transition***: bubbles with broken-symmetric phase inside, unbroken phase outside.
- ***BSM*** CP-violating interactions at the bubble wall source ***chiral charge***.
- Baryon-number-violating ***sphaleron*** processes generate B within the unbroken phase.

Electroweak Baryogenesis

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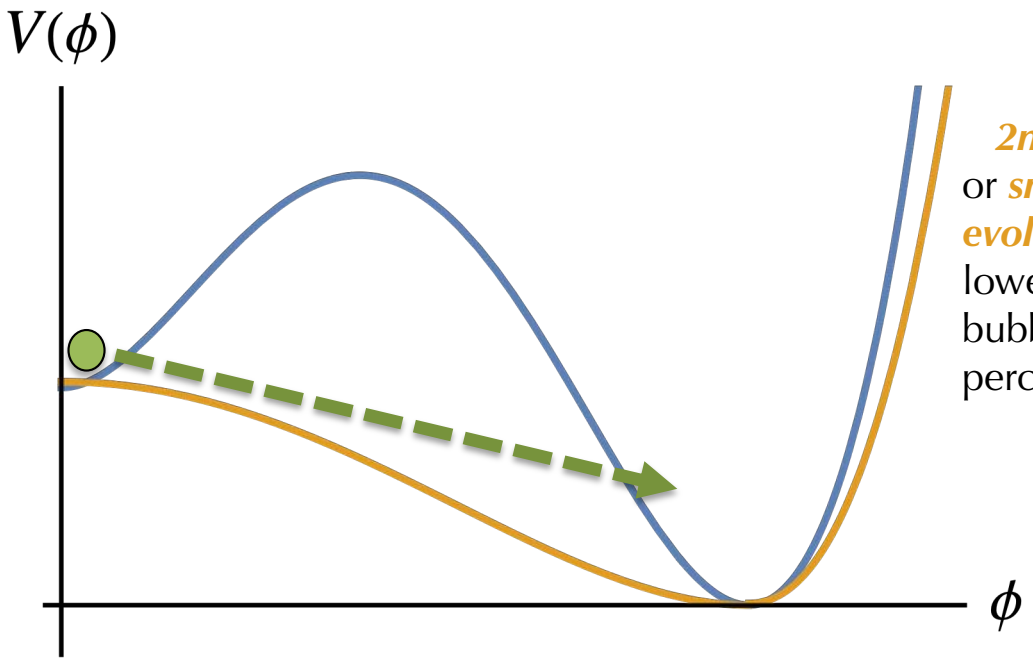
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1st-order phase transition: the field ***tunnels through a barrier*** to the lowest-energy state; ***bubbles*** of the broken-symmetry phase nucleate within a sea of "false vacuum" and eventually ***percolate***.



2nd-order phase transition or ***smooth crossover***: the field ***evolves smoothly*** to the lowest-energy state; no bubble nucleation or percolation.

Electroweak Baryogenesis

Typical EWBG scenario

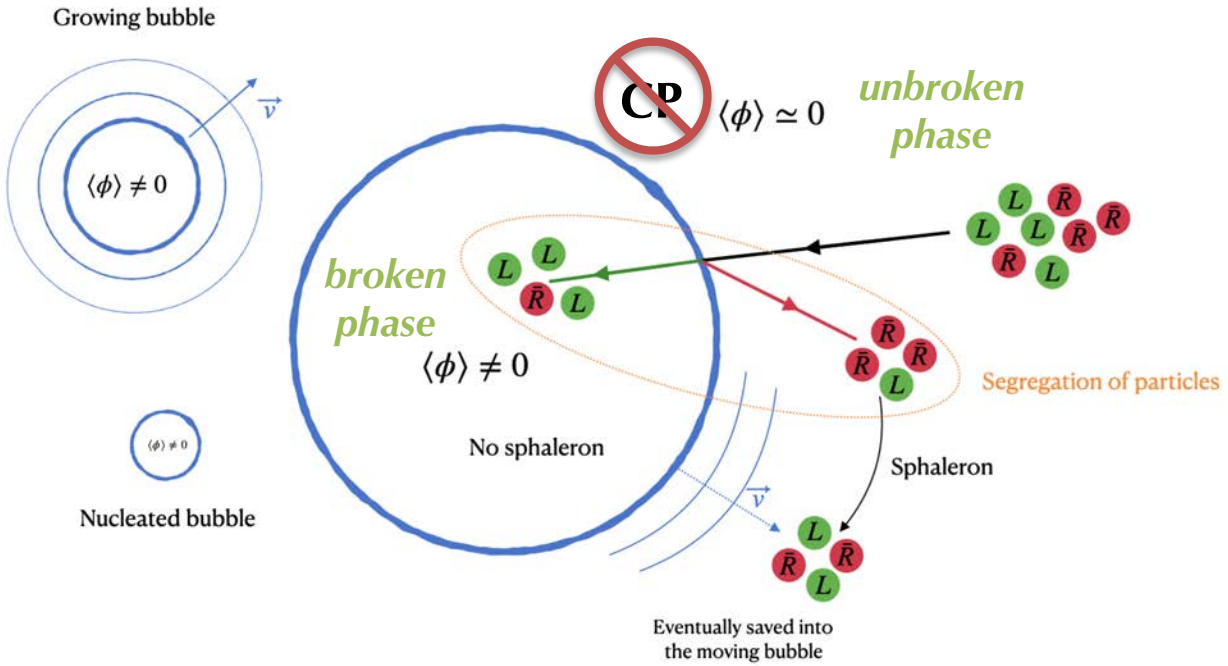
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R. Gannouji, *Galaxies* (2022)

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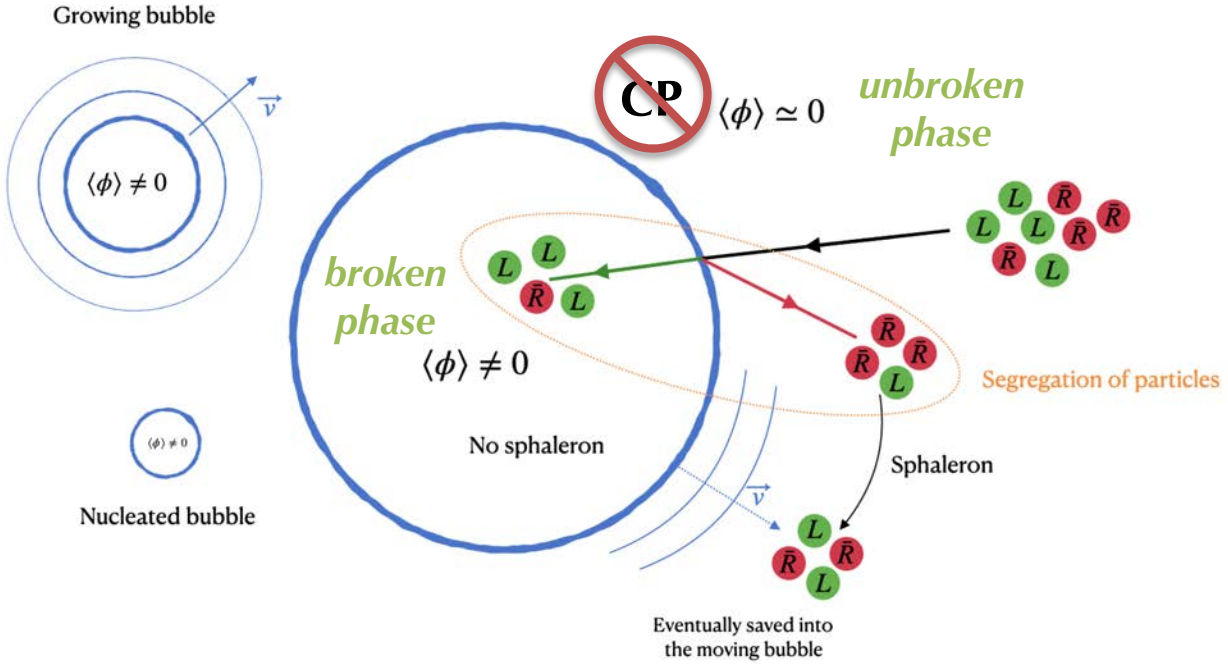
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If there were a strongly 1st-order phase transition:

Biggest obstacle for EWBG: As far as we know, the Standard Model EW phase transition was not 1st order. To produce $\eta_{B,\mathrm{obs}}$ requires ***BSM*** physics ***both*** to force a ***strongly 1st-order EWPT***, as well as to ***enhance chiral charge***.

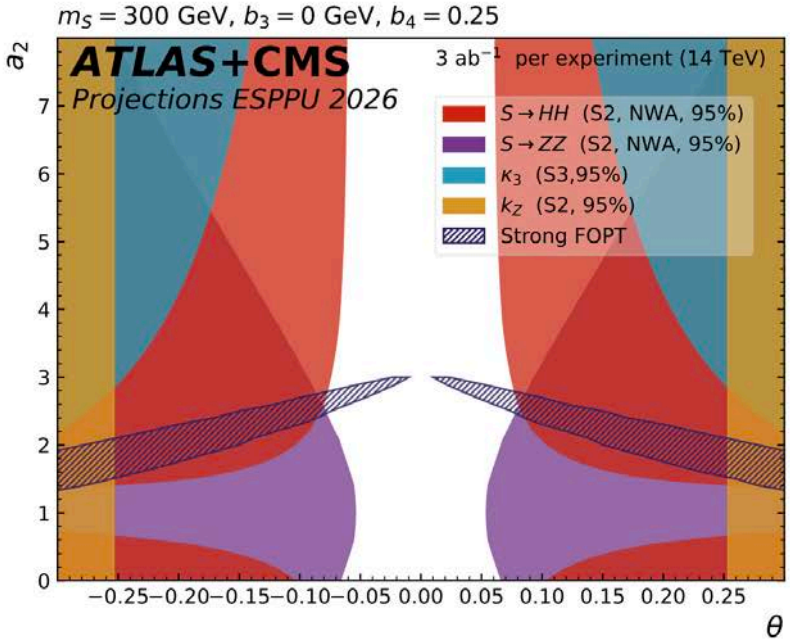


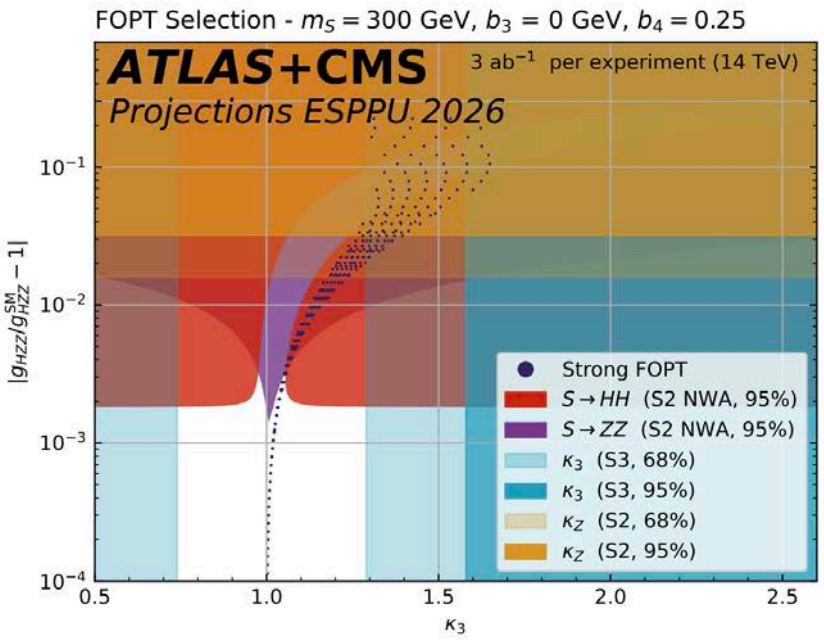
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Electroweak Baryogenesis

After 15 years of precision tests of the Standard Model Higgs sector, there is ***no evidence yet*** of BSM physics that could have driven a ***strongly 1st-order electroweak phase transition***. (Maybe data will come soon with HL-LHC and/or FCC…)

Moritz Bosse *et al.*, arXiv:2606.12533, 2607.12039



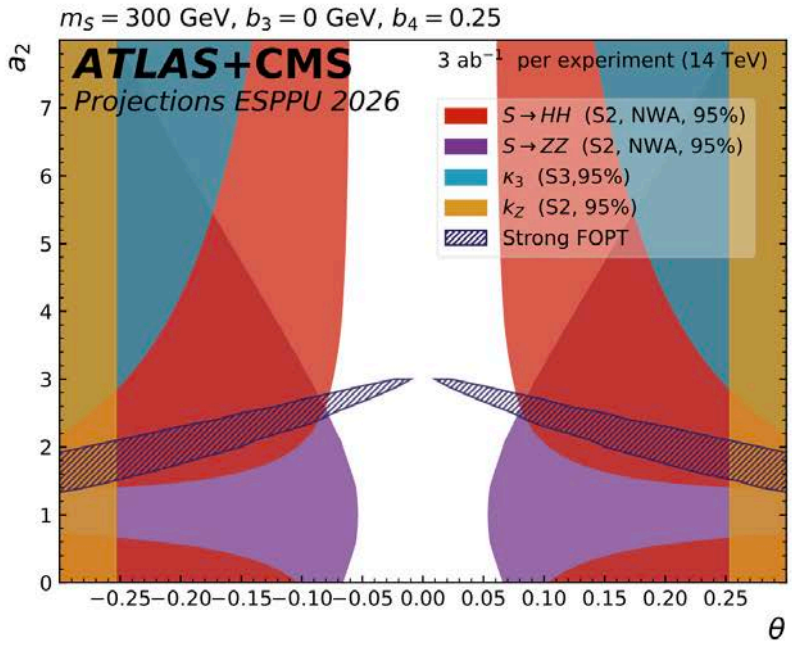


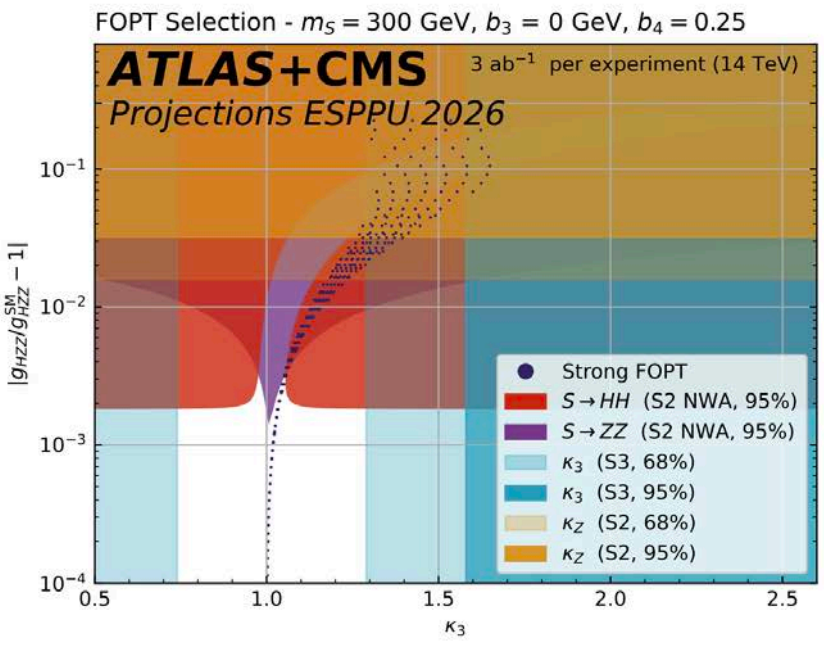
ATLAS + CMS, arXiv:2504.00672

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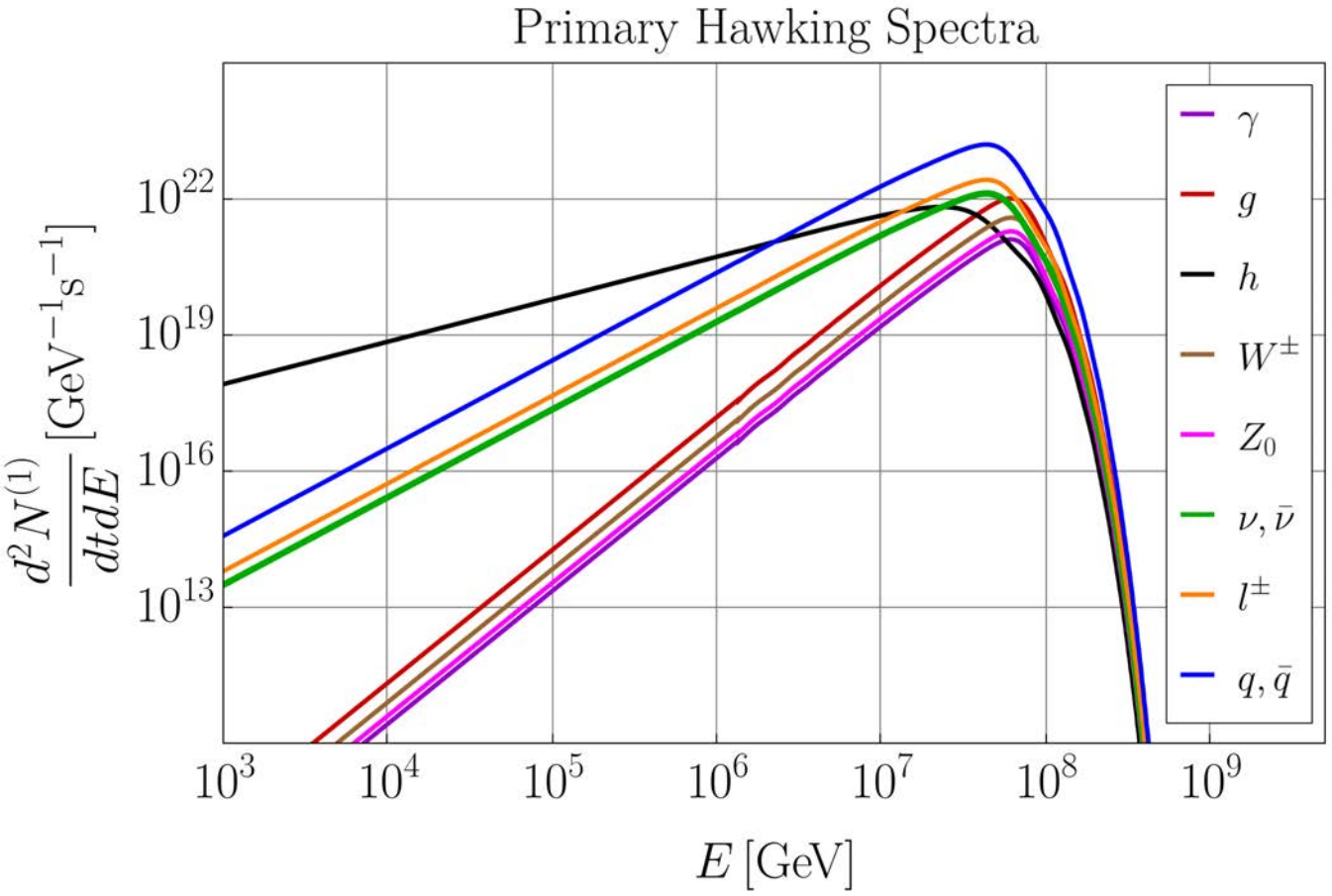




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Could PBHs create comparable conditions around the time of the electroweak phase transition, without requiring a strongly first-order phase transition or bubble nucleation?

PBHs & Hawking Emission



1970s: Early Ideas about PBHs

SOVIET ASTRONOMY – AJ VOL. 10, NO. 4 JANUARY-FEBRUARY, 1967

THE HYPOTHESIS OF CORES RETARDED DURING EXPANSION AND THE HOT COSMOLOGICAL MODEL

Ya. B. Zel'dovich and I. D. Novikov

Translated from Astronomicheskii Zhurnal, Vol. 43, No. 4,
pp. 758-760, July-August, 1966
Original article submitted March 14, 1966

Gravitational collapse of primordial overdensities into black holes, bypassing stellar evolution. That would open up a ***huge range*** of possible scales, since $M_{\rm PBH} \sim M_H(t_i)$, so could have $10^{-30}\, M_\odot \leq M_{\rm PBH} \leq 10^5\, M_\odot$.

Mon. Not. R. astr. Soc. (1971) **152,** 75–78.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

In contrast, black holes that form from stellar collapse have masses $M_{\rm BH} > M_\odot$.

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B. J. Carr and S. W. Hawking

Reviews: Green and Kavanagh, 2007.10722, Carr and Kühnel, 2006.02838, Escrivà, Kühnel, Tada, 2211.05767.

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An upper bound on the number of these objects can be set from the measurements by Sandage (**7**) of the deceleration of the expansion of the Universe. These measurements indicate that the average density of the Universe cannot be greater than about 10^{-28} g cm^{-2}. Since the average density of visible matter is only about 10^{-31} g cm^{-2}, it is tempting to suppose that the major part of the mass of the Universe is in the form of collapsed objects. This extra density could stabilize clusters of galaxies which, otherwise, appear mostly not to be gravitationally bound.

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$$\bar{M}(t_i) \simeq 0.2\, M_H(t_i)$$

Typical PBH mass at time of formation

Mass enclosed within a Hubble sphere

$$M_H(t) = \frac{t}{G} = 2 \times 10^5\, M_\odot \left(\frac{t}{1\,\mathrm{s}}\right)$$

From the Friedmann equation, we know how $M_H(t)$ evolved during the early universe.

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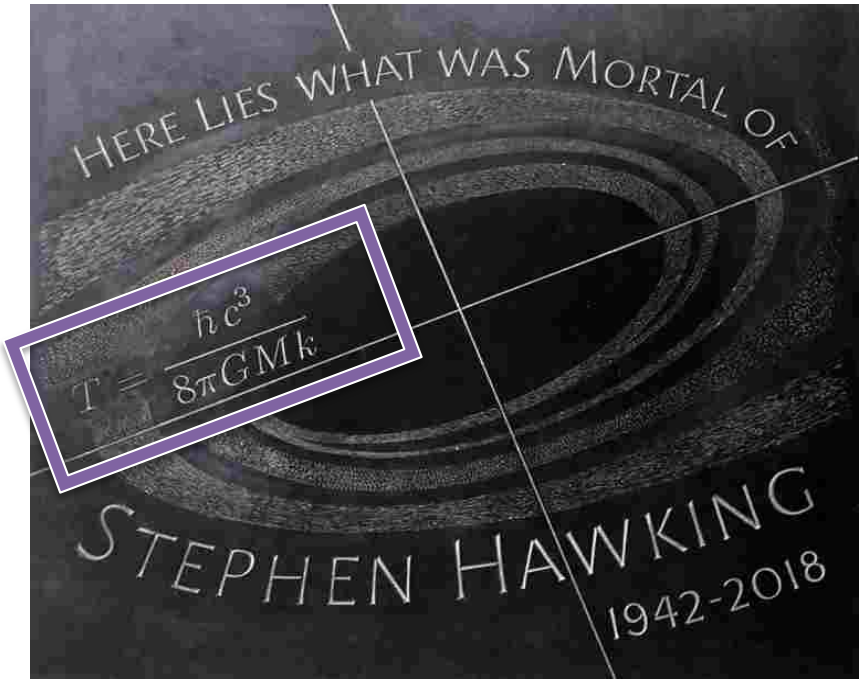
BLACK HOLES IN THE EARLY UNIVERSE

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Hawking Radiation

Black holes radiate as
(approximate) ***blackbodies***
with ***Hawking temperature***

$$T_H(M) = \frac{1}{8\pi G M} \simeq 10^{-20}\,\mathrm{GeV}\left(\frac{M_\odot}{M}\right)^*$$

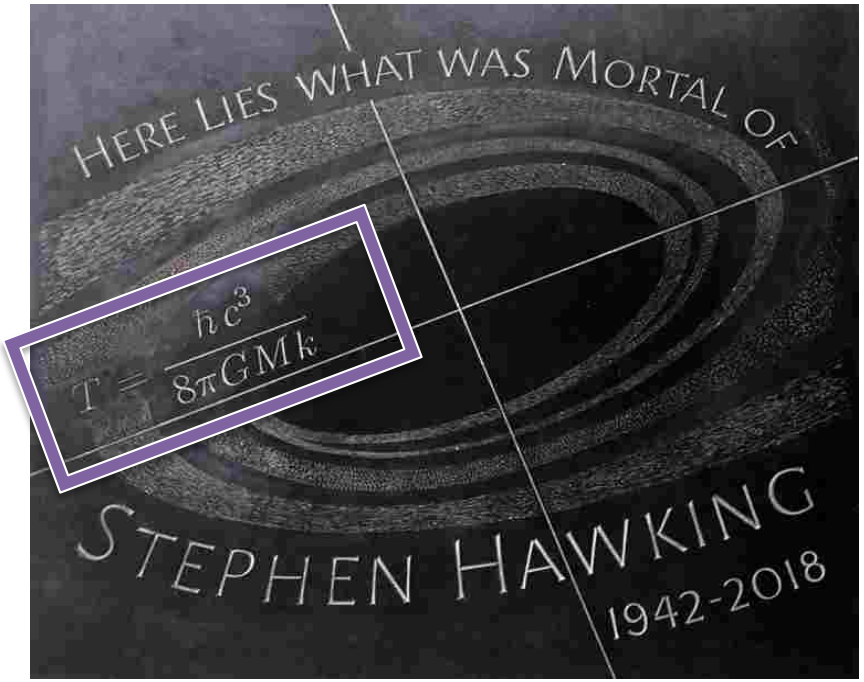


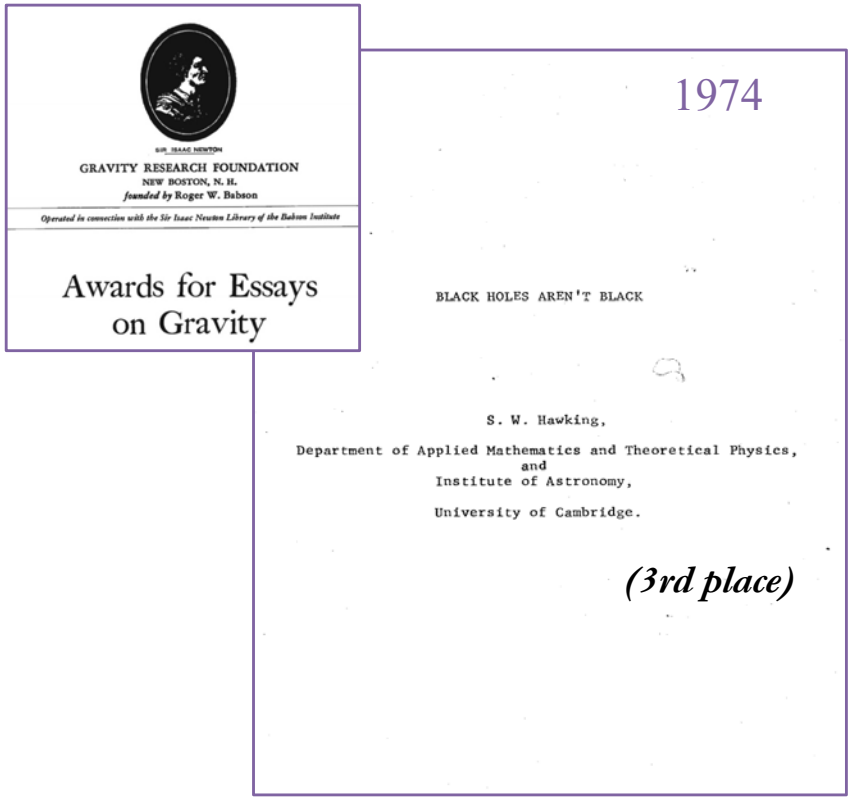
*The only hope of *ever* measuring Hawking radiation is if *PBHs exist!* See Klipfel & Kaiser, 2503.19227; 2506.14041; 2605.26204

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GRAVITY RESEARCH FOUNDATION
NEW BOSTON, N. H.
founded by Roger W. Babson

Operated in connection with the Sir Isaac Newton Library of the Babson Institute

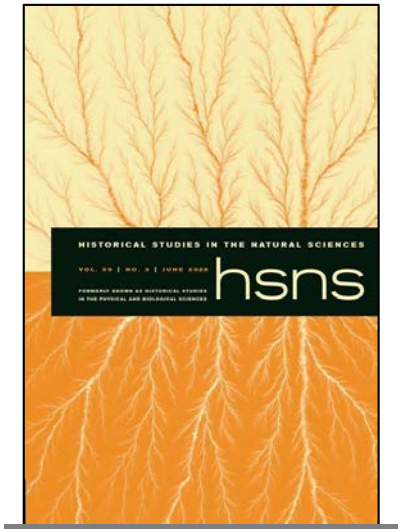
Awards for Essays on Gravity

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(3rd place)



48 no. 3 (2018): 338-379

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Black hole explosions?

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Department of Applied Mathematics and Theoretical Physics
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Institute of Astronomy
University of Cambridge

Nature Vol. 248 March 1 1974

Particle Creation by Black Holes

S. W. Hawking
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England

Commun. math. Phys. 43, 199—220 (1975)

See also D. Page, B. Carter, S. Teukolsky, G. Gibbons, J. MacGibbon, ...

Hawking Radiation

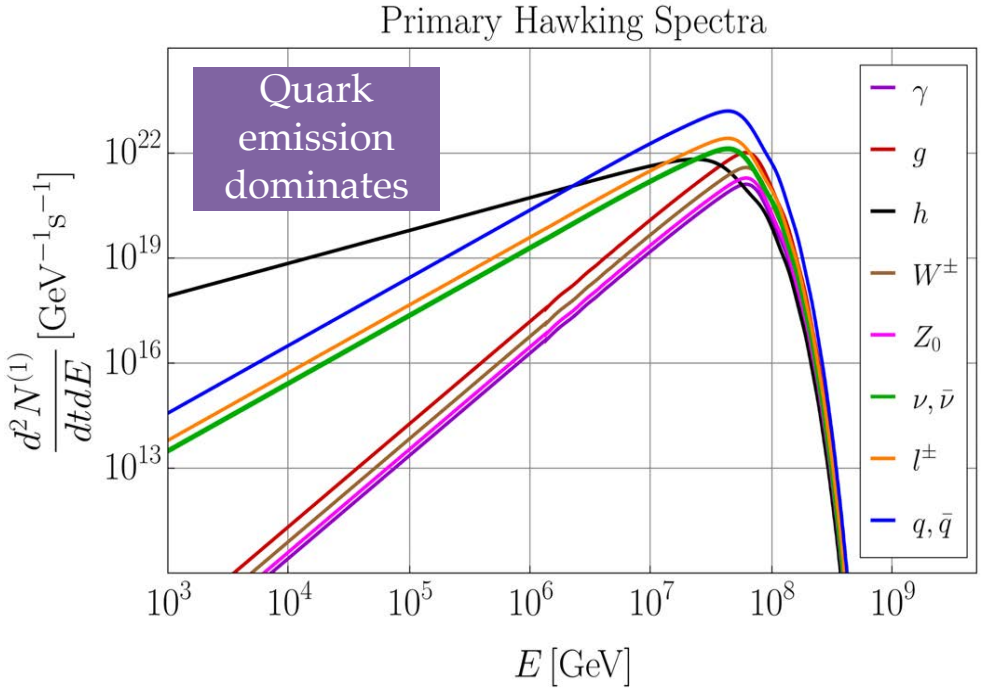
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"greybody factor"

$$\frac{d^2 N_j^{(1)}}{dt\,dE} = g_j \frac{\Gamma_{s_j}}{2\pi}\left[\exp\left(\frac{E}{T_H(M)}\right) - (-1)^{2s_j}\right]^{-1}$$

$M = 10^6\,\mathrm{g}$



See, e.g., Klipfel, Kaiser, arXiv:2503.19227, 2506.14041, 2601.05935, 2605.26204

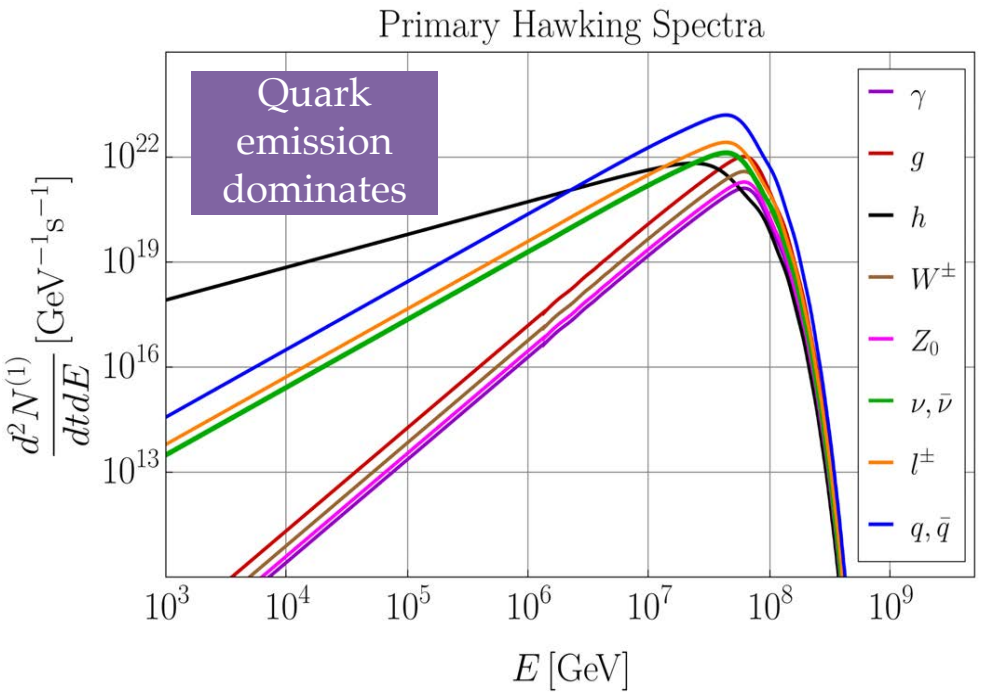
Figures by Alexandra Klipfel

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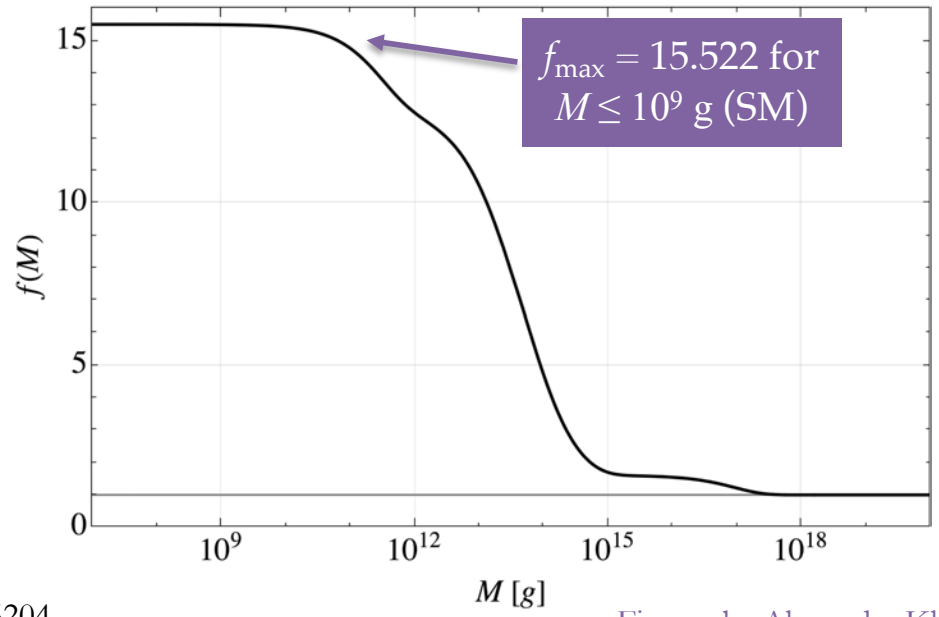
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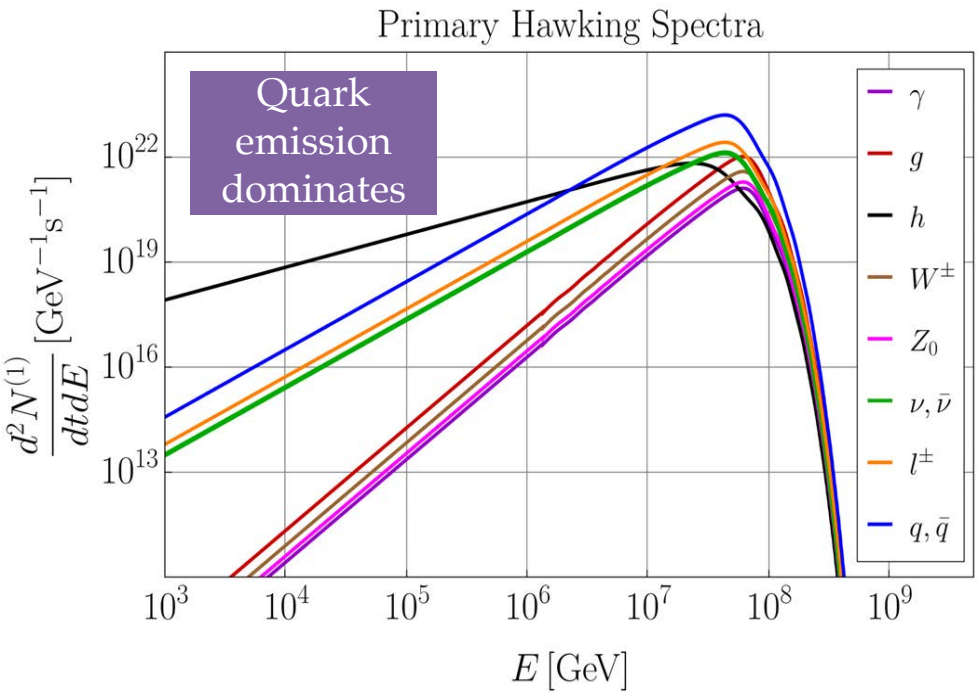


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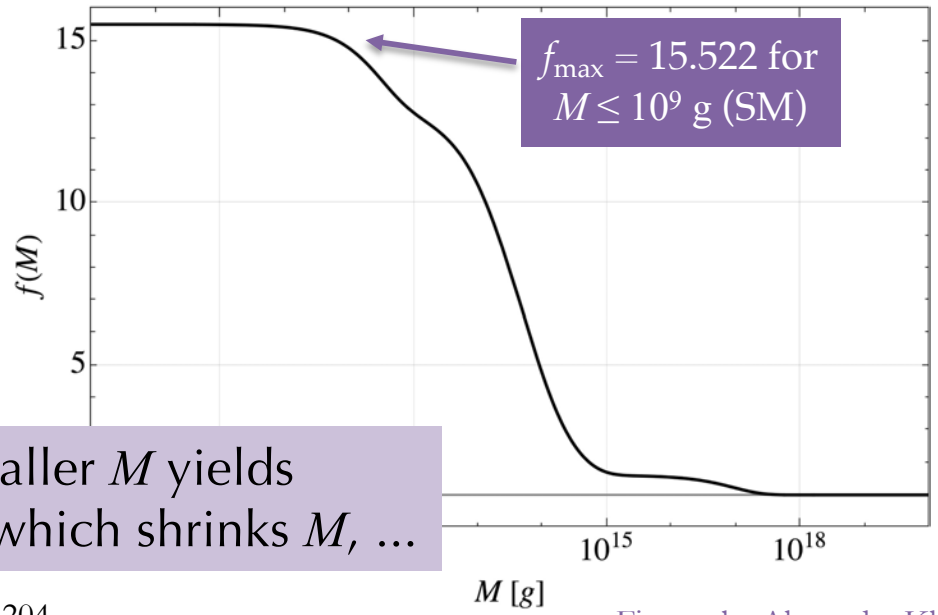
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A runaway process: smaller M yields more efficient emission, which shrinks M, ...

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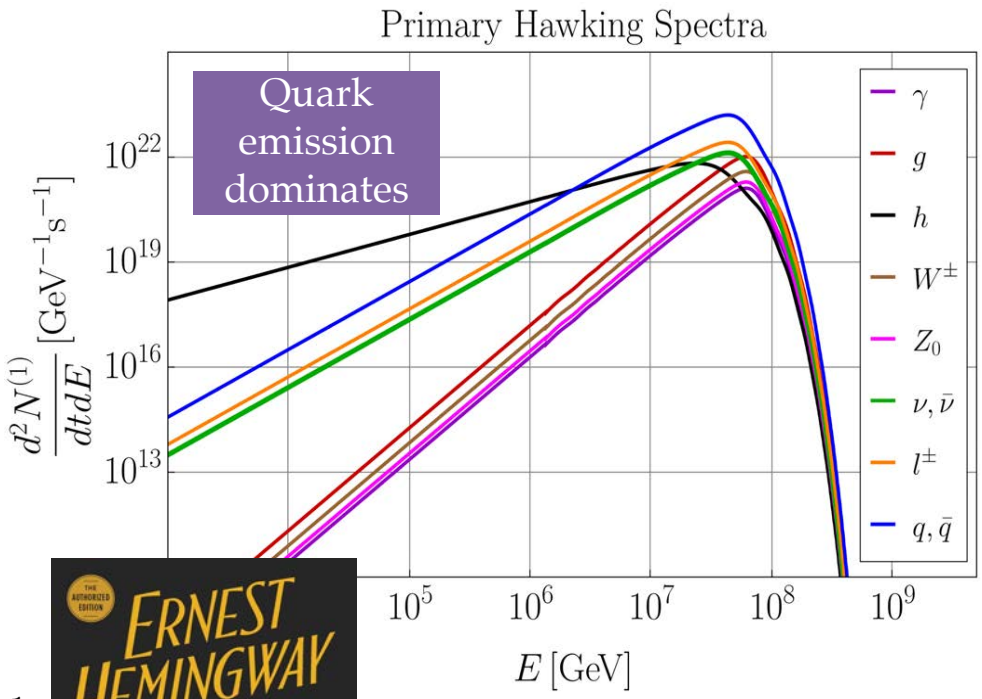
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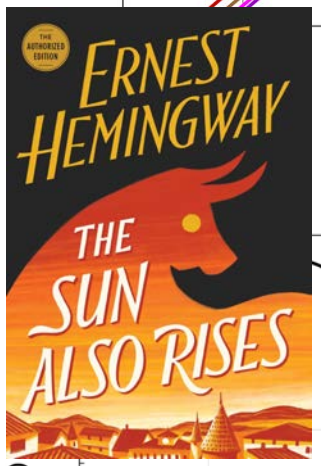
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"How do you go bankrupt? Two ways. Gradually, and then suddenly."

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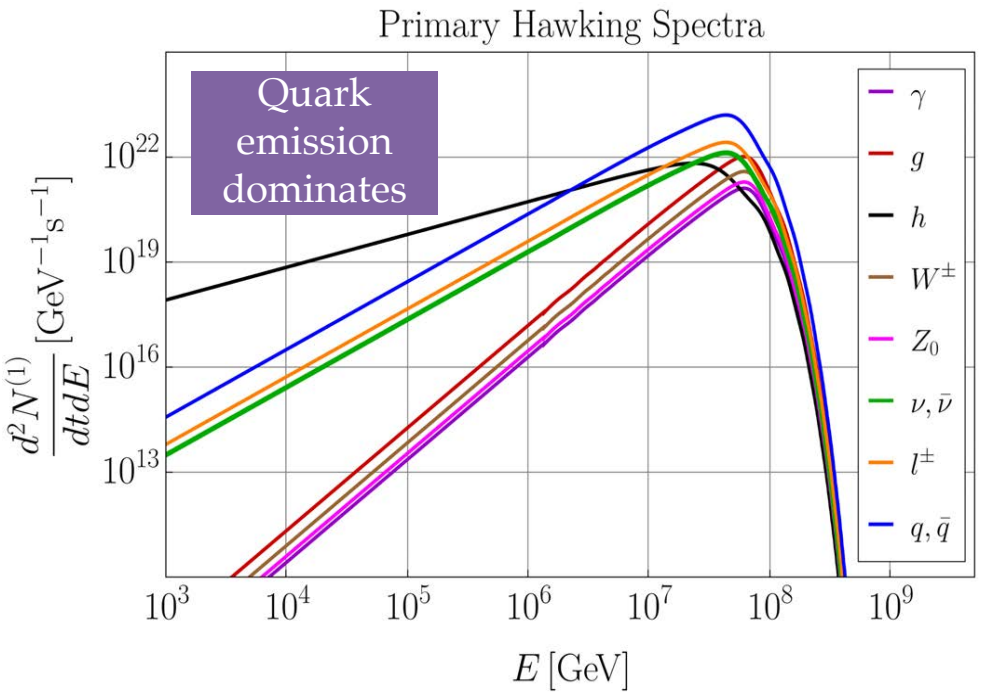
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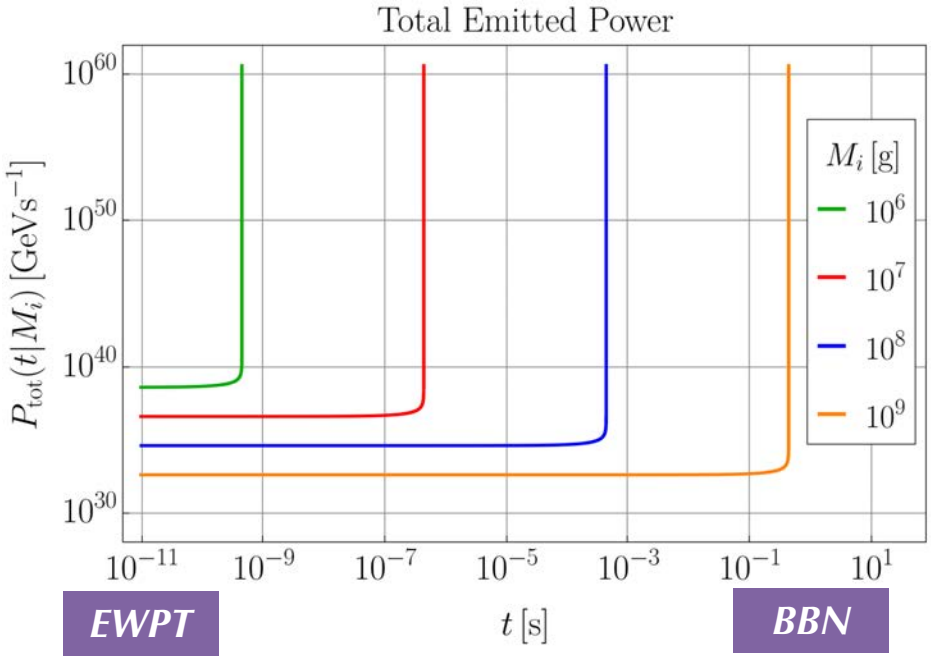
Lifetime:

$$\tau(M) = \frac{M^3}{3A f_{\max}} = 4.14 \times 10^{-10}\,\mathrm{s}\left(\frac{M}{10^6\,\mathrm{g}}\right)^3$$

Note : $M_{\mathrm{pl}} = 4.33 \times 10^{-6}\,\mathrm{g}$

$M = 10^6\,\mathrm{g}$





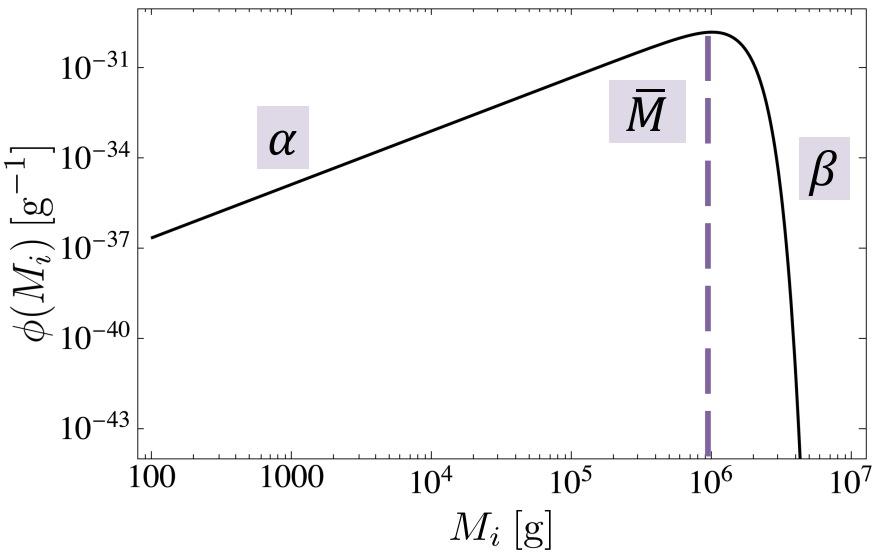
See, e.g., Klipfel, Kaiser, arXiv:2503.19227, 2506.14041, 2601.05935, 2605.26204

Figures by Alexandra Klipfel

PBH Population

PBHs generically form with a nontrivial ***number distribution:***

$$\phi(M_i) \equiv \frac{1}{n_{\mathrm{PBH},i}} \frac{dn_{\mathrm{PBH},i}}{dM_i} \sim \left(\frac{M_i}{\bar{M}}\right)^{\alpha-1} \exp\left[-\frac{(\alpha-1)}{\beta}\left(\frac{M_i}{\bar{M}}\right)^{\beta}\right]$$



The coefficients α, β depend on the ***statistics of the primordial curvature perturbations*** that trigger gravitational collapse, and also on the ***equation of state*** of the medium that undergoes collapse. For Gaussian perturbations that collapse within a radiation-dominated equation of state, several independent numerical simulations yield $\alpha = \beta = 2.78$.

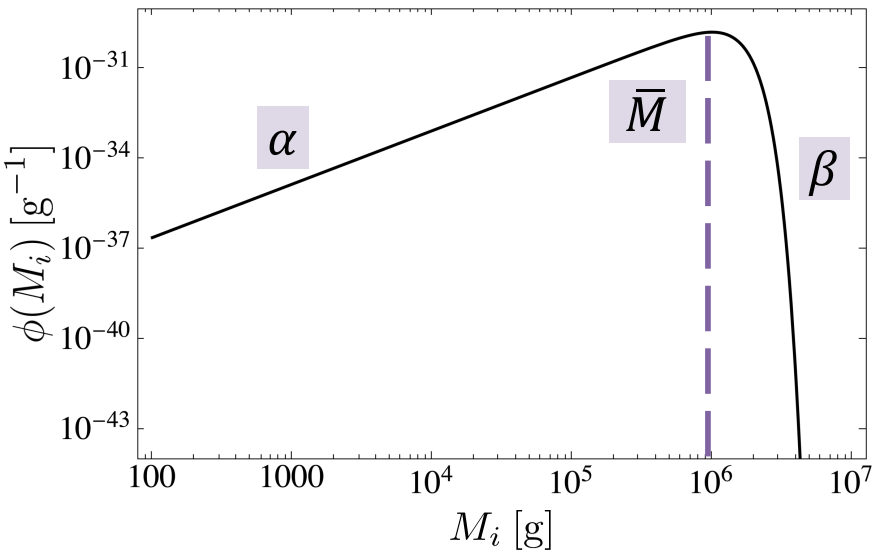
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As PBHs evaporate, the number distribution ***evolves over time***:

$$\phi(M,t) \simeq \frac{M^2\phi(M_i)}{(M^3+3Af_{\max}t)^{2/3}}$$

Low-mass tail: there will be a ***subpopulation*** of PBHs with $M \leq 3 \times 10^7$ g that will ***explode*** amid the early-universe quark-gluon plasma ($t < t_{\mathrm{QCD}} = 10^{-5}$ s).

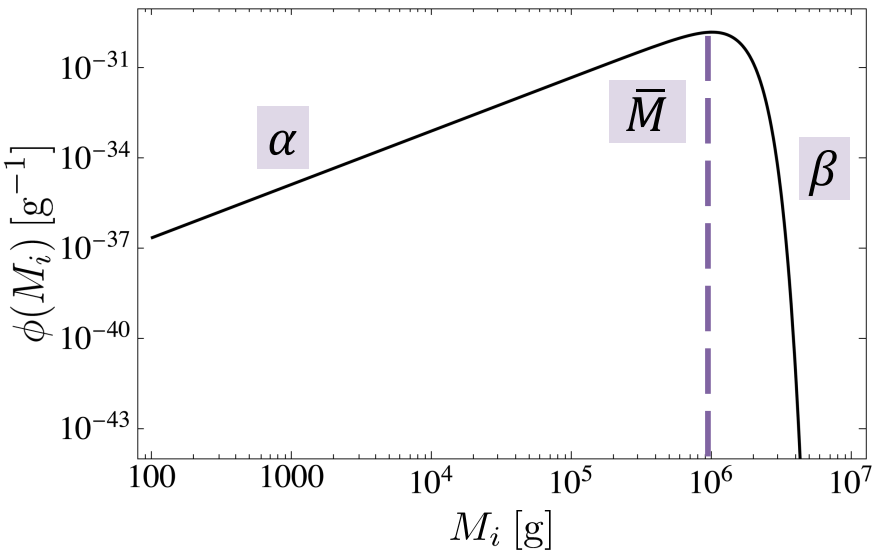
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Comoving PBH explosion rate:

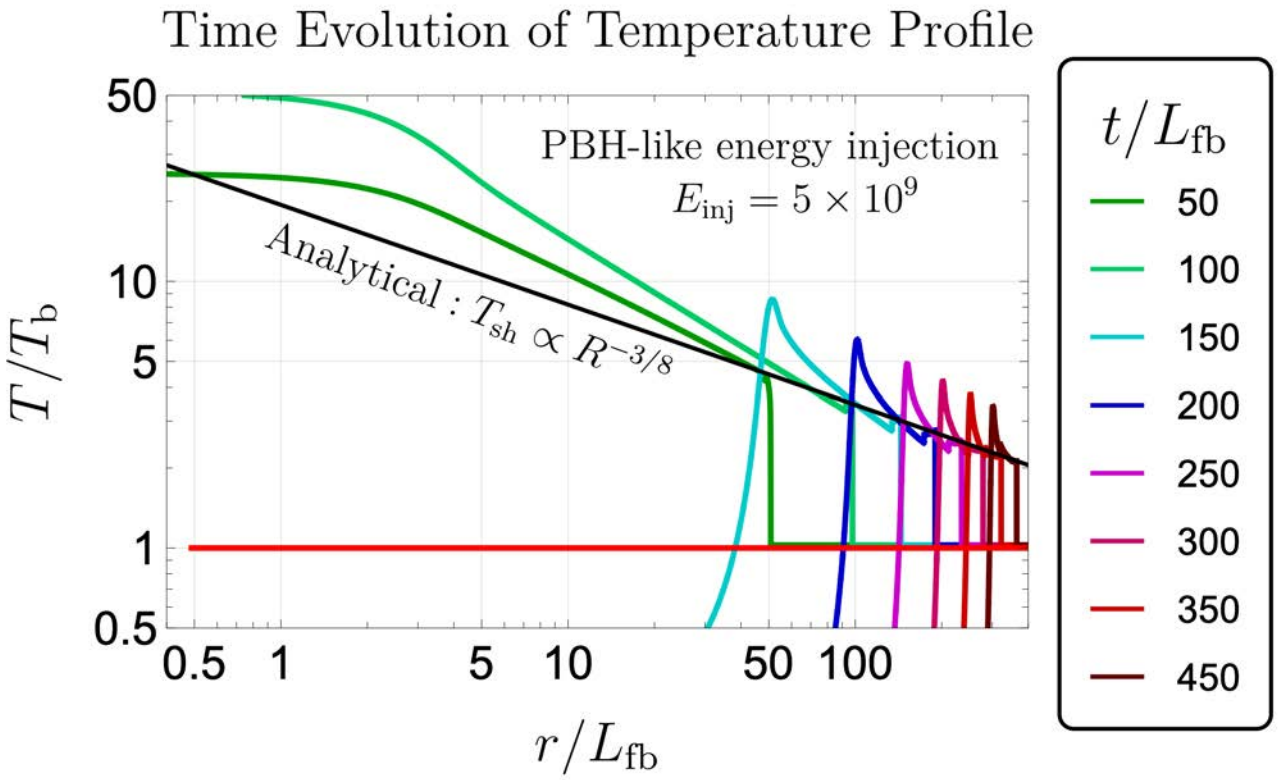
$$\frac{d\mathcal{N}^{\mathrm{co}}}{dt} = -n^{\mathrm{co}}_{\mathrm{PBH},i}\frac{d}{dt}\int_0^\infty dM\,\phi(M,t)$$

comoving initial PBH number density

Klipfel, Kaiser, arXiv:2503.19227, 2506.14041, 2601.05935, 2605.26204

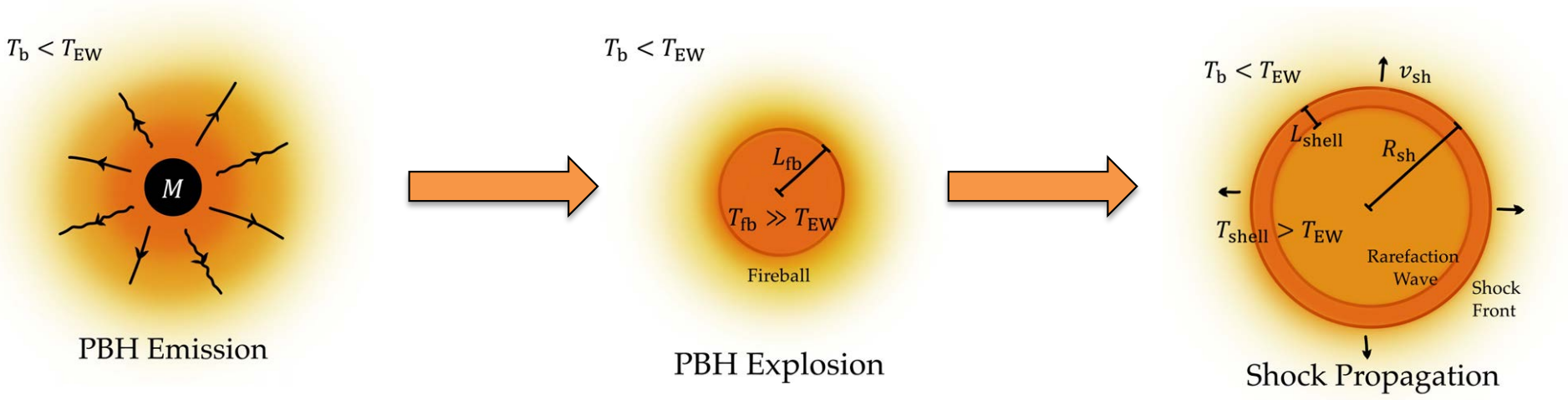
Figures by Alexandra Klipfel

PBH Explosions in the Quark-Gluon Plasma



Energy Injection into the QGP

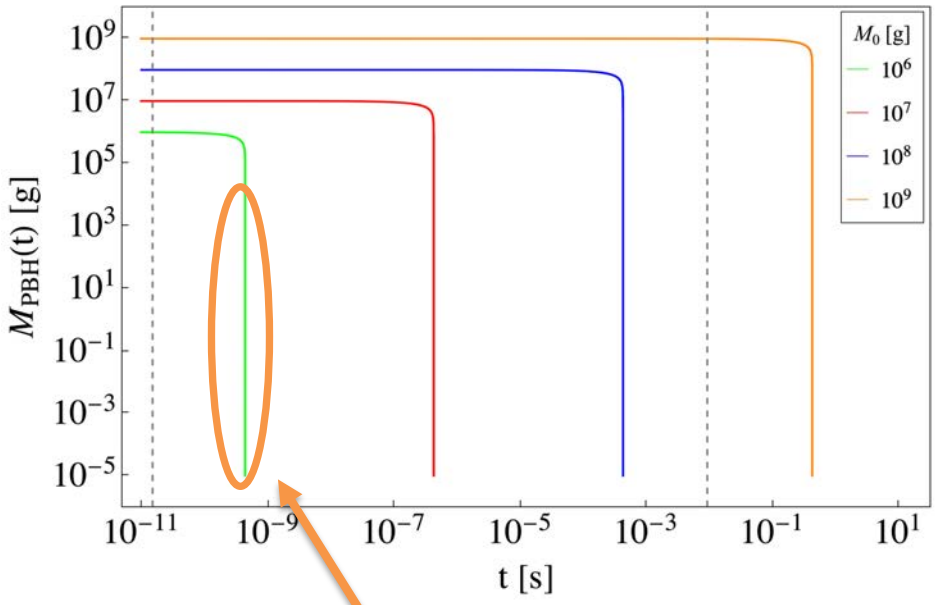
Three distinct processes, with three distinct time-scales:



Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2603.15746

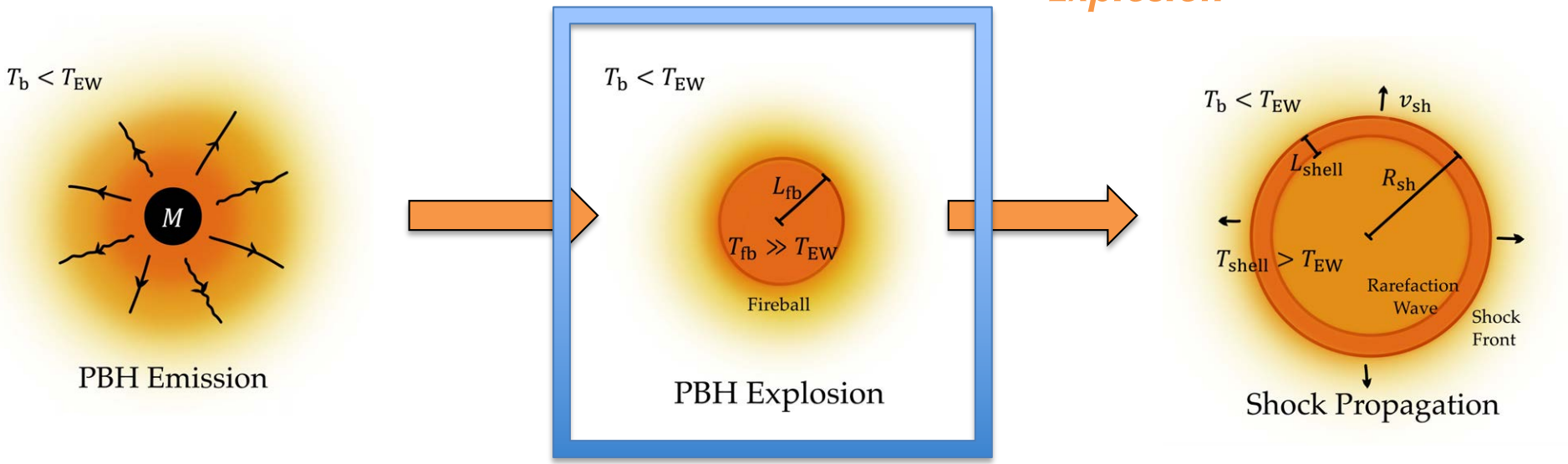
Figures by Alexandra Klipfel

Energy Injection into the QGP



"Instantaneous" Explosion

$$E_{\rm inj} = M_{\rm thres}$$



Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2603.15746

Figures by Alexandra Klipfel

Energy Injection into the QGP

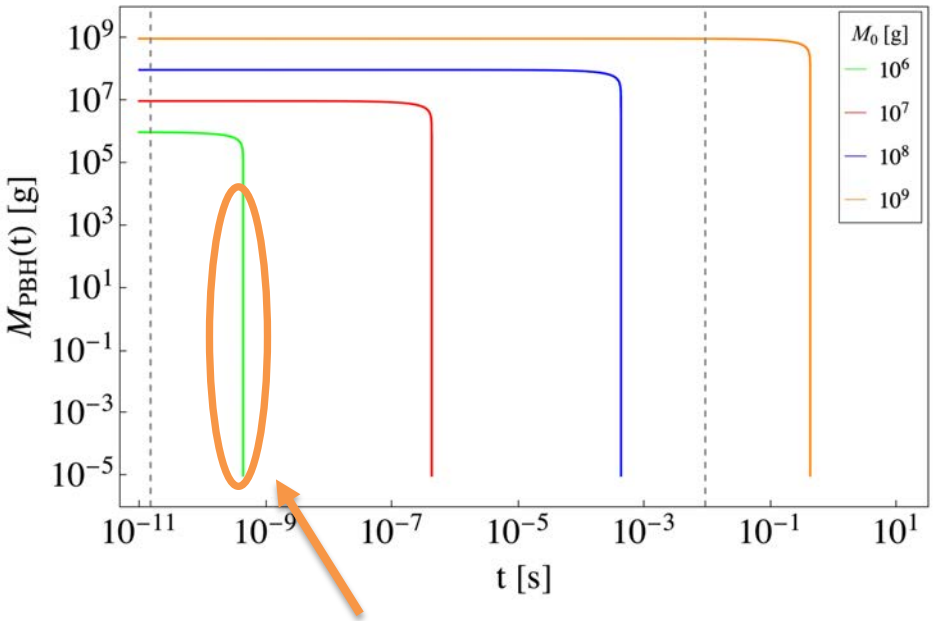
The ***maximum PBH mass*** that can be considered to ***explode quasi-instantaneously*** within the hot plasma must satisfy:

$$\tau(M) < t_{\text{advection}} < t_{\text{diffusion}}$$

PBH lifetime

timescale for energy redistribution via bulk fluid motion

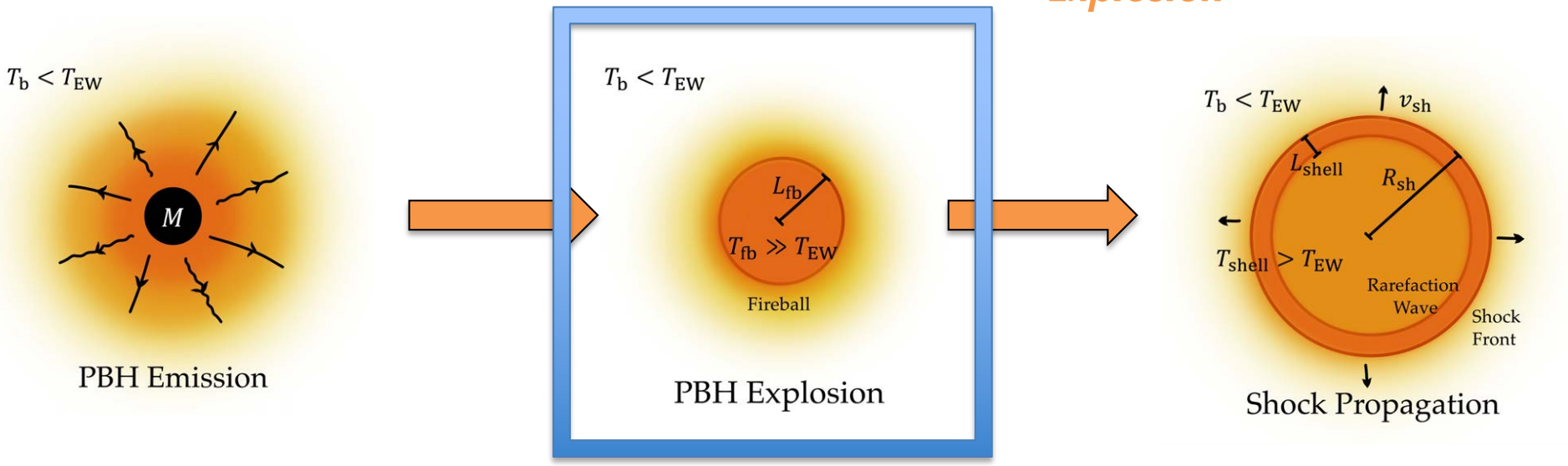
timescale for energy redistribution via collisions



When this condition is met, a ***shock*** will form and propagate within the plasma.

"Instantaneous" Explosion

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Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2603.15746

Figures by Alexandra Klipfel

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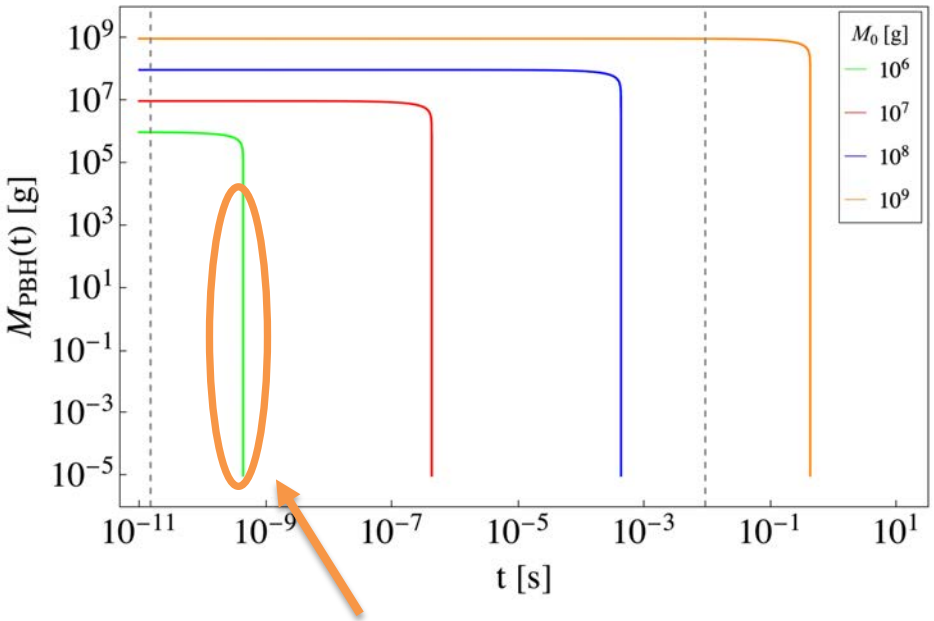
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Most Hawking-emitted particles are quarks and gluons. The ***Landau-Pomeranchuk-Migdal splitting rate*** sets the thermalization length-scale:

$$\Gamma_{\rm LPM}(k, T_{\rm b}) \simeq \alpha_s(T_{\rm b}) \sqrt{\frac{\hat{q}(T_{\rm b})}{2k}},$$

$$\hat{q}(T_{\rm b}) \simeq \alpha_s^2(T_{\rm b})\, T_{\rm b}^3 \ln(k/T_{\rm b})$$

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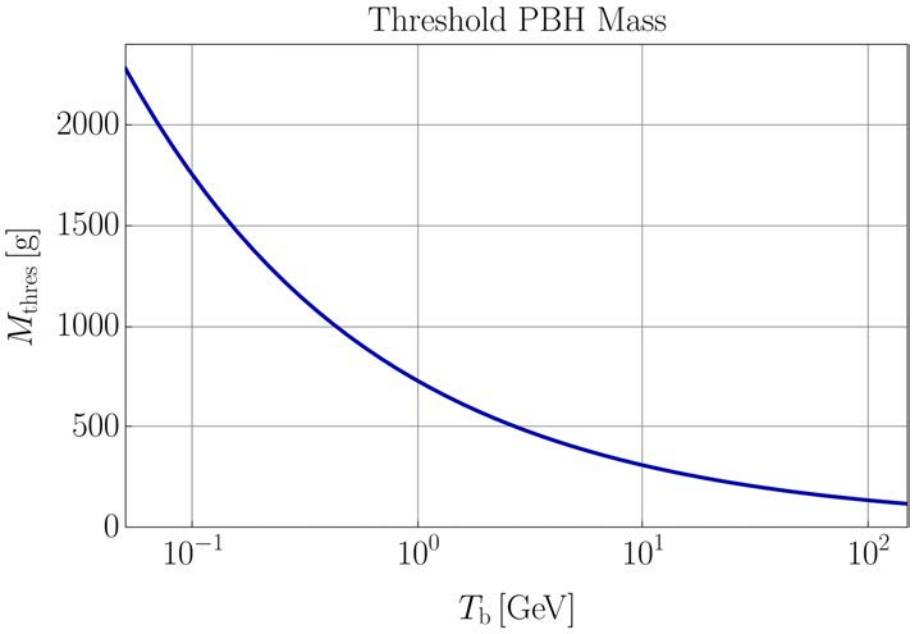
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The PBH ***threshold mass*** satisfies

$$\tau(M_{\rm thres}) = \Gamma_{\rm LPM}^{-1}(M_{\rm thres}, T_{\rm b})$$

The quasi-instantaneous injection of $E_{\rm inj} = M_{\rm thres}$ creates a ***fireball*** with initial radius

$$L_{\rm fb}(T_{\rm b}) = \Gamma_{\rm LPM}^{-1}(M_{\rm thres}, T_{\rm b})$$

Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2603.15746

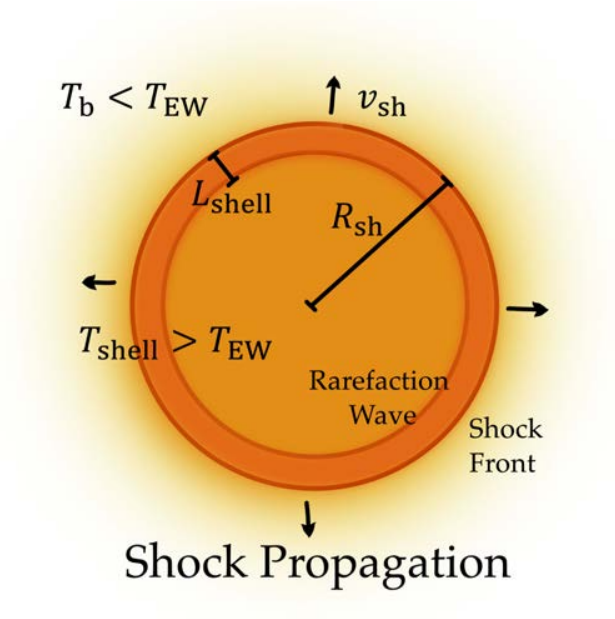
Figures by Alexandra Klipfel

Shock Propagation

Ultrarelativstic shock waves propagate outward.

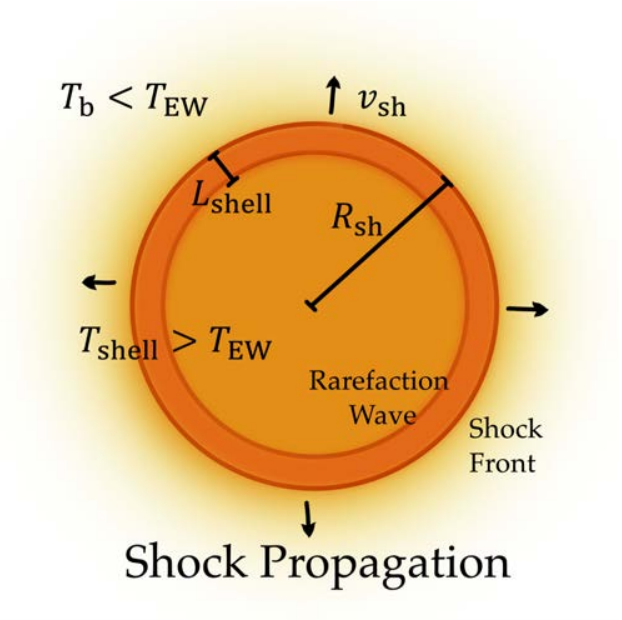
A ***superheated shell*** of fluid between the shock front and the rarefaction wave ***restores electroweak (EW) symmetry***.

Over time the shell ***cools*** via volume dilution as it expands.



Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2603.15746

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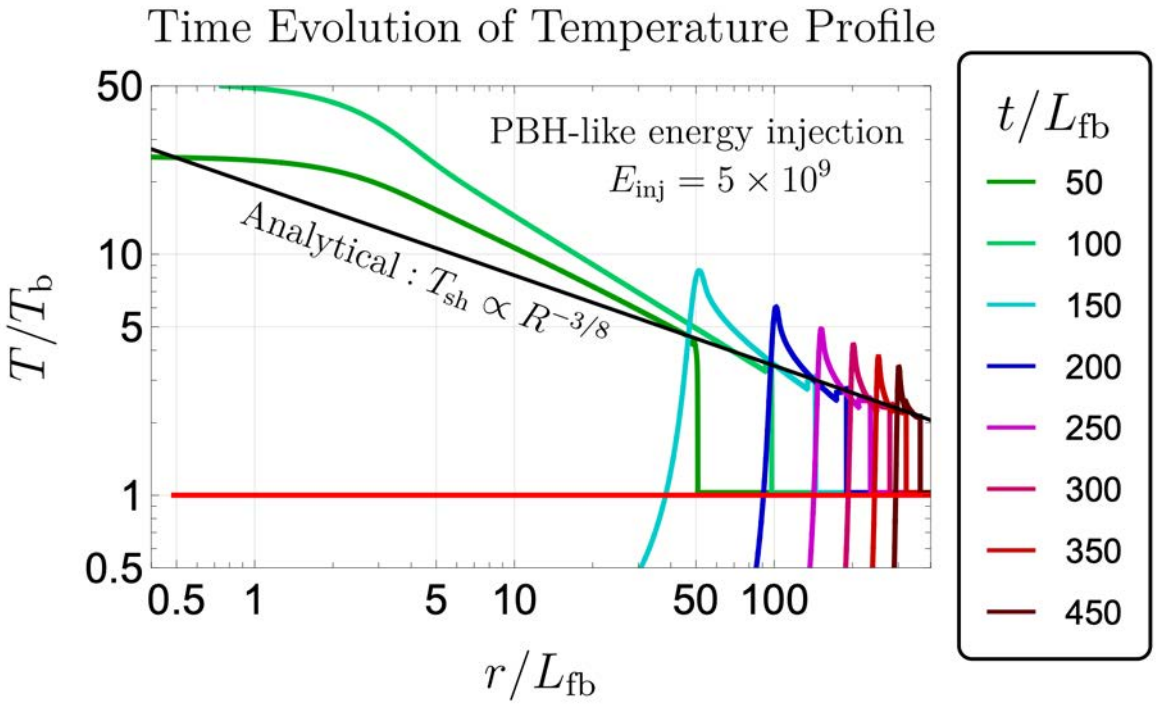
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Over time the shell ***cools*** via volume dilution as it expands.

The ***maximum radius*** of the shock wave when the shell temperature cools to the EW scale is

$$R_{\rm max}(T_{\rm b}) \simeq \left(\frac{K\, M_{\rm thres}(T_{\rm b})}{\rho_{\rm rad}(T_{\rm EW})} \right)^{1/3}$$

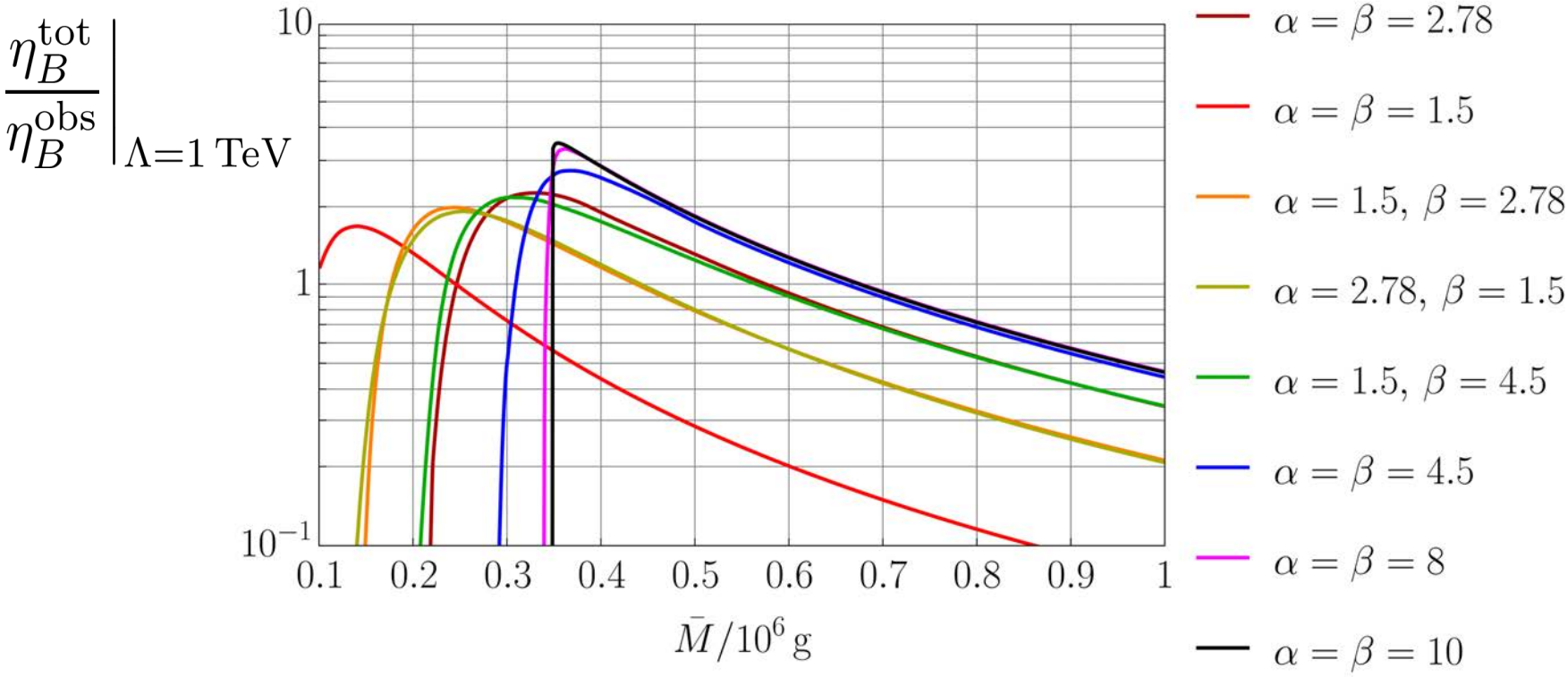
Our ***relativistic hydrodynamics simulations*** of PBH-like (extended) energy injection yield $K = 5$.



Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2603.15746

Plot by Miguel Vanvlasselaer

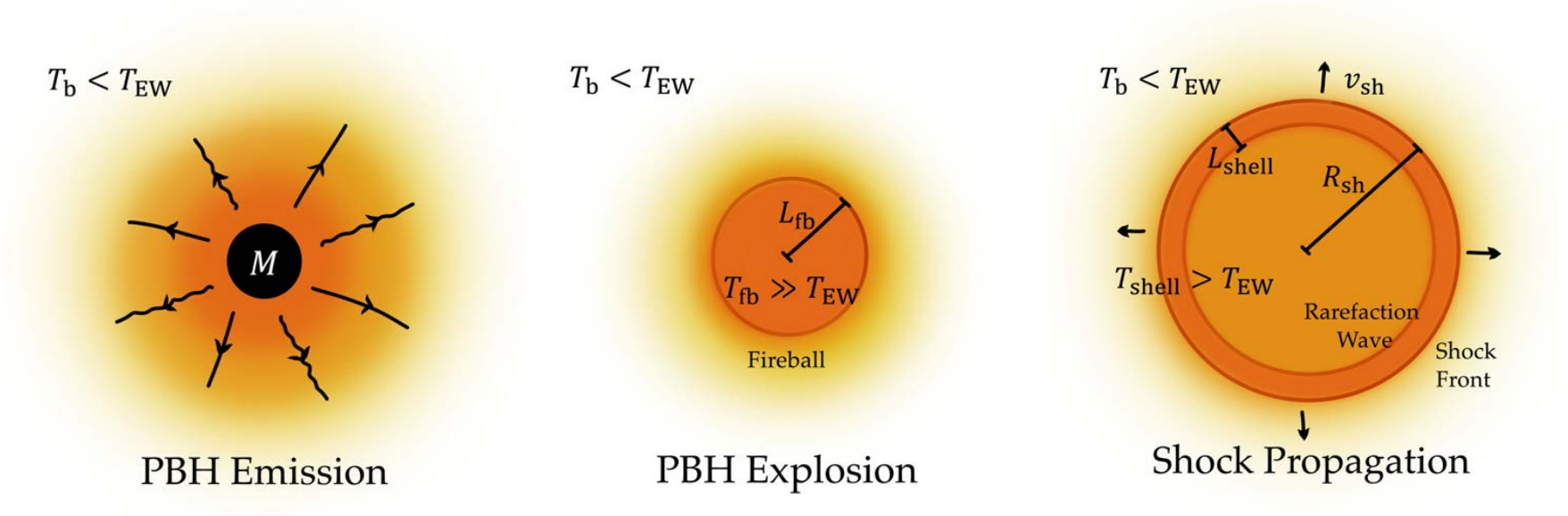
New Baryogenesis Mechanism



See also, e.g.,

Banks and Fischler, 1505.00472;
García-Bellido, Carr, and Clesse, 1904.02129, 1904.11482;
Flores, Kusenko, Pearce, and White, 2208.09789...

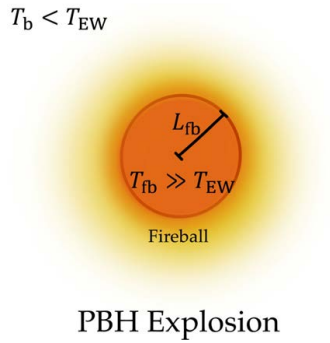
Baryogenesis from Exploding PBHs



Shock Fronts can mimic the features of interactions at bubble walls, ***without*** requiring a strongly 1st-order electroweak phase transition.

Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2604.29024

Baryogenesis from Exploding PBHs



PBH Explosion

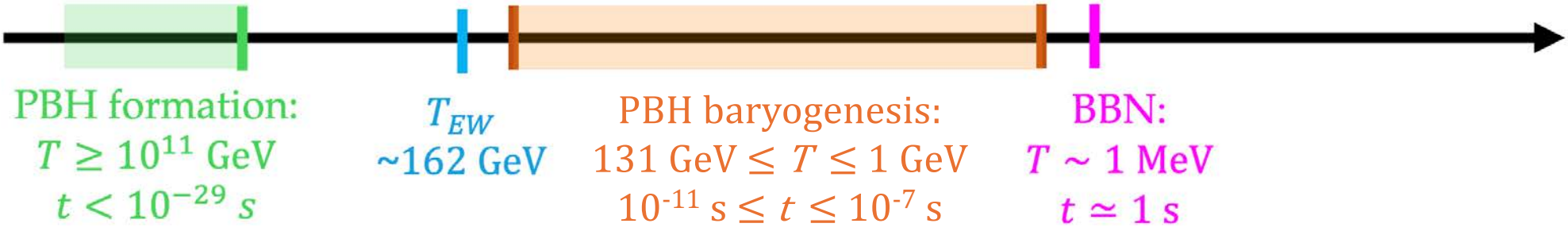
When do these explosions happen?

Start: Below T_{spha}, sphaleron transitions no longer efficiently wash out net B number.

$$T_{\rm start} = T_{\rm spha} \simeq 131\,{\rm GeV}$$

Stop: *Minimum background temperature* for EW symmetry breaking by fireball and shock:

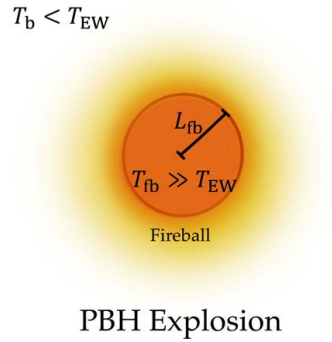
$$T_{\rm stop} \simeq 1\,{\rm GeV}$$



Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2604.29024

Figures by Alexandra Klipfel

Baryogenesis from Exploding PBHs



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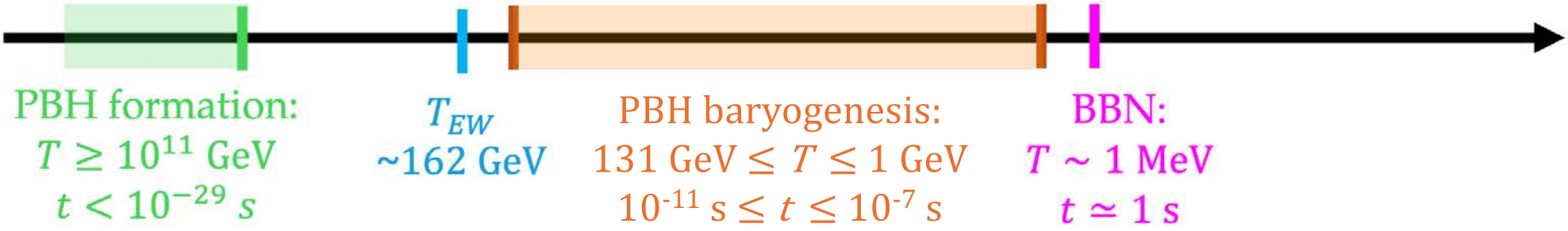
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PBH mass range of interest:

$$10^5\,{\rm g} \lesssim M_i \lesssim 10^8\,{\rm g}$$

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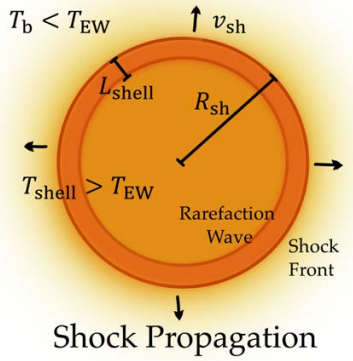
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Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2604.29024

Figures by Alexandra Klipfel

Baryogenesis from Exploding PBHs



BSM CP violation:

- ***Enhance*** baryon transition amplitudes across the shock-front shell
- New mechanism is ***agnostic*** regarding the exact CP-violating operator

Example:

$$\mathcal{O}_{\rm BSM} = \left(\bar{q}_L\, \tilde{H}\, t_R\right)\left(a + ib\gamma_5\right)\frac{\mathcal{S}}{\Lambda} + \text{h.c.}$$

$\mathcal{S}$: new singlet

Λ : scale of new physics

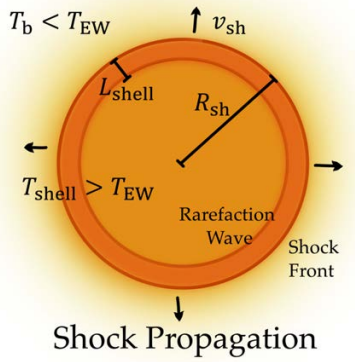
Espinosa, Gripaios, Konstandin, Riva, arXiv:1110.2876

Extends the SM with the addition of ***one new gauge singlet.***

Introduces ***CP-odd coupling*** between the Higgs field and the top quark following EW symmetry breaking.

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$$V \subset -\frac{|\mu_s^2|}{2}\mathcal{S}^2 + \frac{\lambda_s}{4}\mathcal{S}^4 + \frac{\lambda_{hs}}{4}h^2\mathcal{S}^2$$

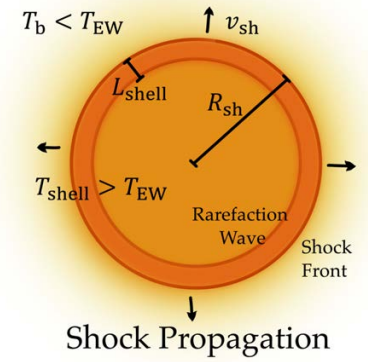
$$\begin{aligned} \langle \mathcal{S} \rangle &\to 0, h \to v_h(T_b) \quad \text{EW broken} \\ \langle \mathcal{S} \rangle &\to v_s(T_{\rm loc}), h = 0 \quad \text{EW symmetric} \end{aligned}$$

$$v_s(T_{\rm loc}) \sim 200\ \text{GeV}$$
$$\text{for } T_{\rm EW} \leq T_{\rm loc} \leq T_s.$$

Because $\langle \mathcal{S} \rangle = 0$ today, EDMs are only generated by loops, so this operator is consistent with present bounds for $\Lambda \gtrsim \mathcal{O}(1\,\text{TeV})$.

Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2604.29024

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Local baryon excess in region dV swept out by the expanding shock-front shell:

$$\frac{\eta_B^{\rm loc}}{\eta_B^{\rm obs}} \simeq 10b\left(\frac{v_s(T_{\rm loc})}{200\,\text{GeV}}\right)\left(\frac{1\,\text{TeV}}{\Lambda}\right)$$

BARYONET, arXiv:2510.21915

Total baryon number excess from a single PBH explosion:

$$N_B^{(1)}(T_{\rm b}) = \eta_B^{\rm loc}\, s(T_{\rm EW})\frac{4\pi}{3}R_{\rm max}^3(T_{\rm b})$$

Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2604.29024

Evolution of the Universe

To compute the total BAU, we need to know how the ***background temperature of the universe, $T_b(t)$, evolves over time***.

We allow for a ***transient period of PBH matter domination*** between t_i and $t_{\rm BBN}$ by introducing $\rho_{\rm PBH}(t_i) = \kappa_i\, \rho_{\rm rad}(t_i)\,, \quad \kappa_i \ll 1.$

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Evolution of the Universe

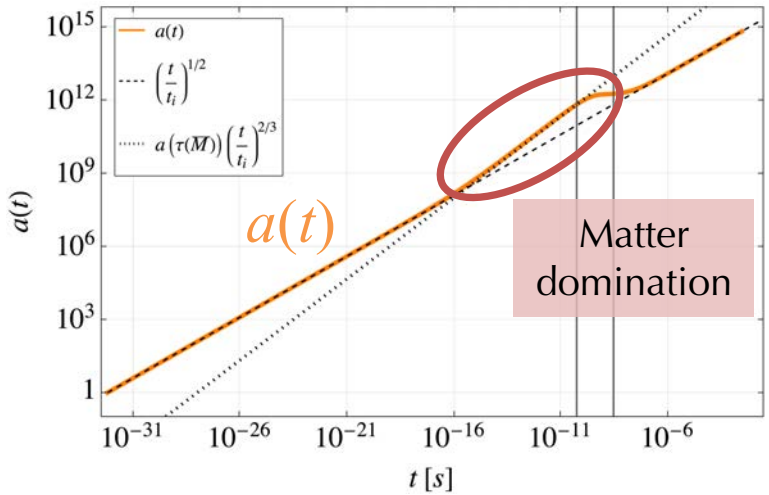
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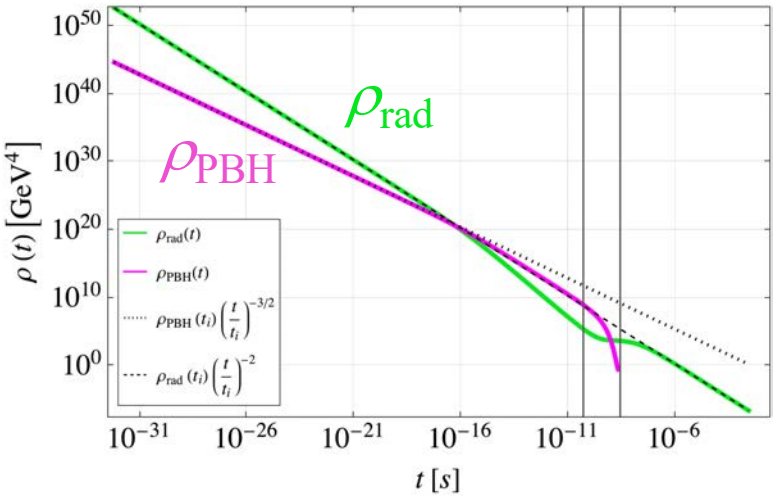
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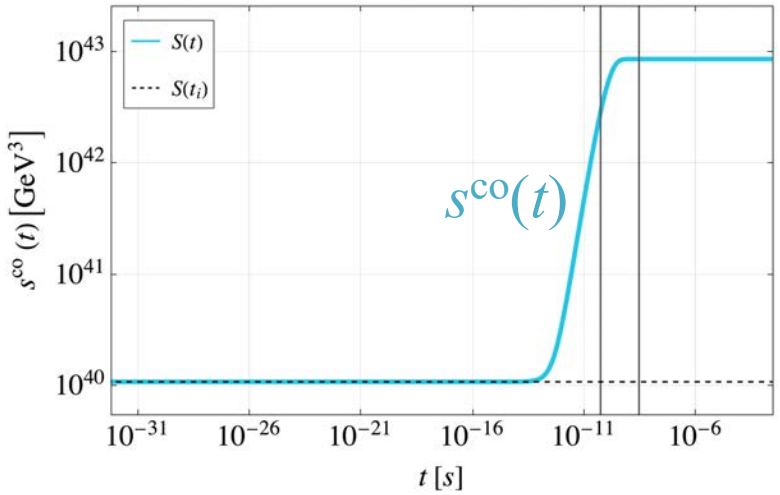
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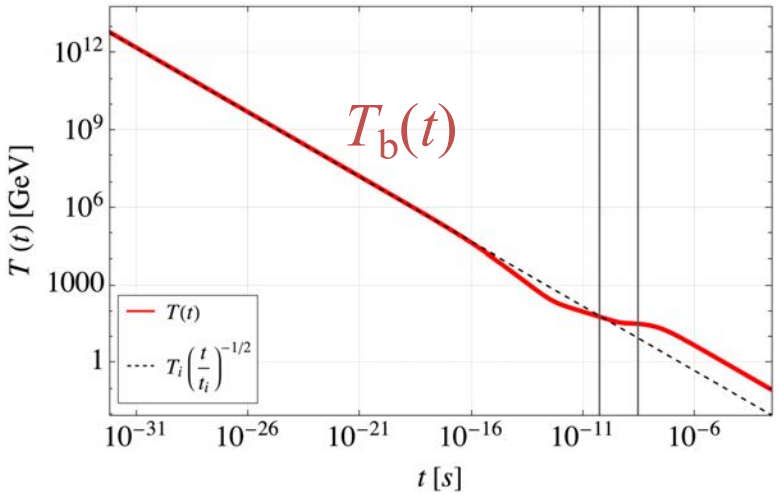
$\bar{M} = 10^{5.7}\,\mathrm{g}$

$\kappa_i = 10^{-8}$







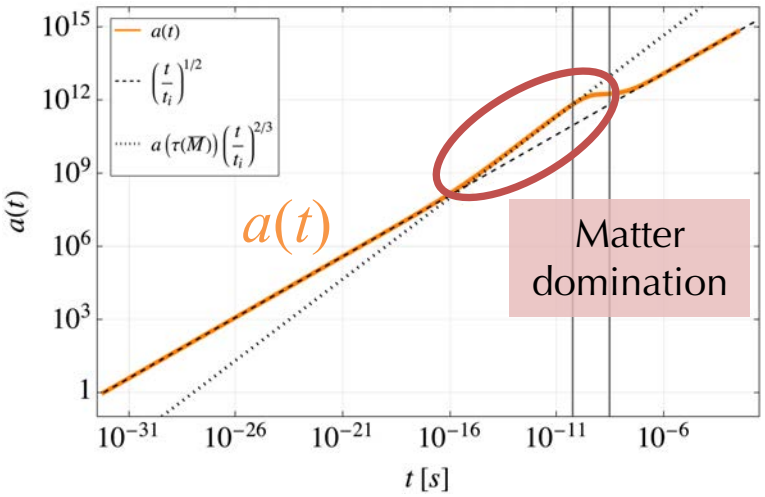


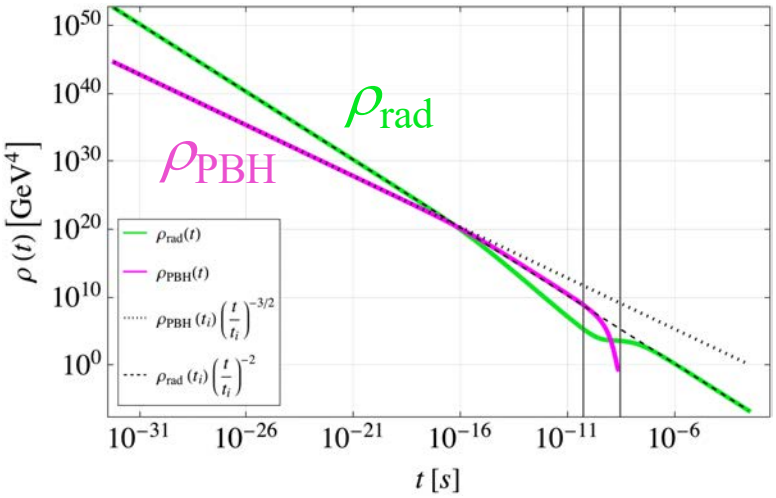
Evolution of the Universe

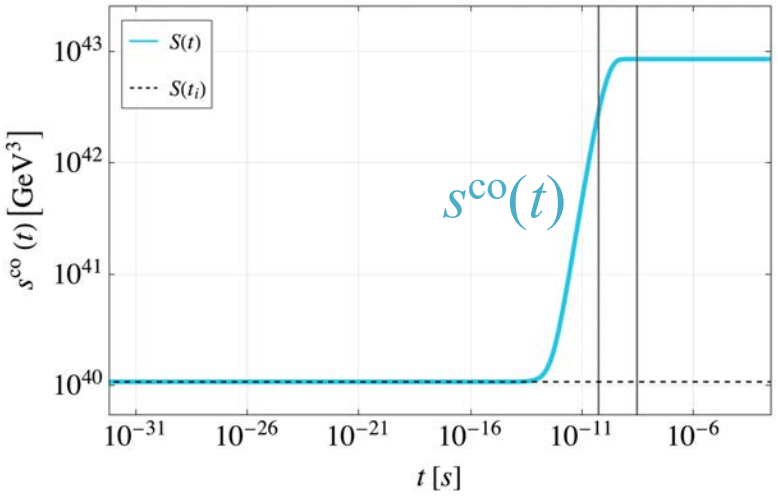
To compute the total BAU, we need to know how the ***background temperature of the universe, $T_b(t)$, evolves over time***.

We allow for a ***transient period of PBH matter domination*** between t_i and $t_{\rm BBN}$ by introducing $\rho_{\rm PBH}(t_i) = \kappa_i\, \rho_{\rm rad}(t_i)\,, \quad \kappa_i \ll 1.$

$$\alpha = \beta = 2.78$$
$$\bar{M} = 10^{5.7}\,\mathrm{g}$$
$$\kappa_i = 10^{-8}$$







Trade-off*:** increasing $\rho_{\rm PBH}(t_i)$ yields more PBH explosions (increasing n_B), while ***also increasing s (reducing η_B).

$$\eta_B^{\rm obs}\Big|_{\rm BBN} = \frac{n_B - n_{\bar{B}}}{s} = \frac{n_B}{7.04\, n_\gamma}$$
$$= 8.65 \pm 0.09 \times 10^{-11}$$

Baryon Asymmetry

Net comoving baryon excess number density:

net baryon excess per PBH explosion

$$n_B^{\mathrm{tot,co}} = \int_{t_{\mathrm{spha}}}^{t_{\mathrm{stop}}} dt\, N_B^{(1)}(t)\, \frac{d\mathcal{N}^{\mathrm{co}}(t)}{dt}$$

integrate explosions only over baryogenesis window

comoving PBH explosion rate

Total baryon asymmetry produced before the onset of BBN:

$$\eta_B^{\mathrm{tot}} = \frac{n_B^{\mathrm{tot,co}}}{s^{\mathrm{co}}(T_{\mathrm{BBN}})}$$

Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2604.29024

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Total baryon asymmetry produced before the onset of BBN:

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Recall:

$$N_B^{(1)} \simeq 10b \left(\frac{v_s(T_{\rm loc})}{200\,{\rm GeV}}\right)\left(\frac{1\,{\rm TeV}}{\Lambda}\right) \times s(T_{\rm EW})\,\frac{4\pi}{3} R^3(T_{\rm b})$$

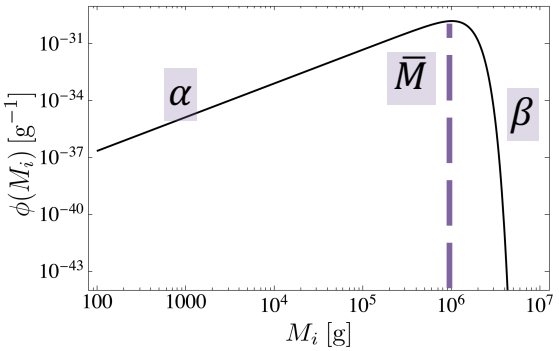
We parameterize the total BAU yield

$$Y \equiv \frac{\eta_B^{\rm tot}}{\eta_B^{\rm obs}} = \frac{10b}{(\Lambda/{\rm TeV})}\,\frac{v_s(T_{\rm loc})}{200\,{\rm GeV}}\,\frac{s(T_{\rm EW})}{s(T_{\rm BBN})} \times \int_{t_{\rm spha}}^{t_{\rm min}} dt \frac{4\pi}{3}\left[R_{\rm max}^{\rm EW}\right]^3 \frac{d\mathcal{N}^{\rm co}}{dt}$$

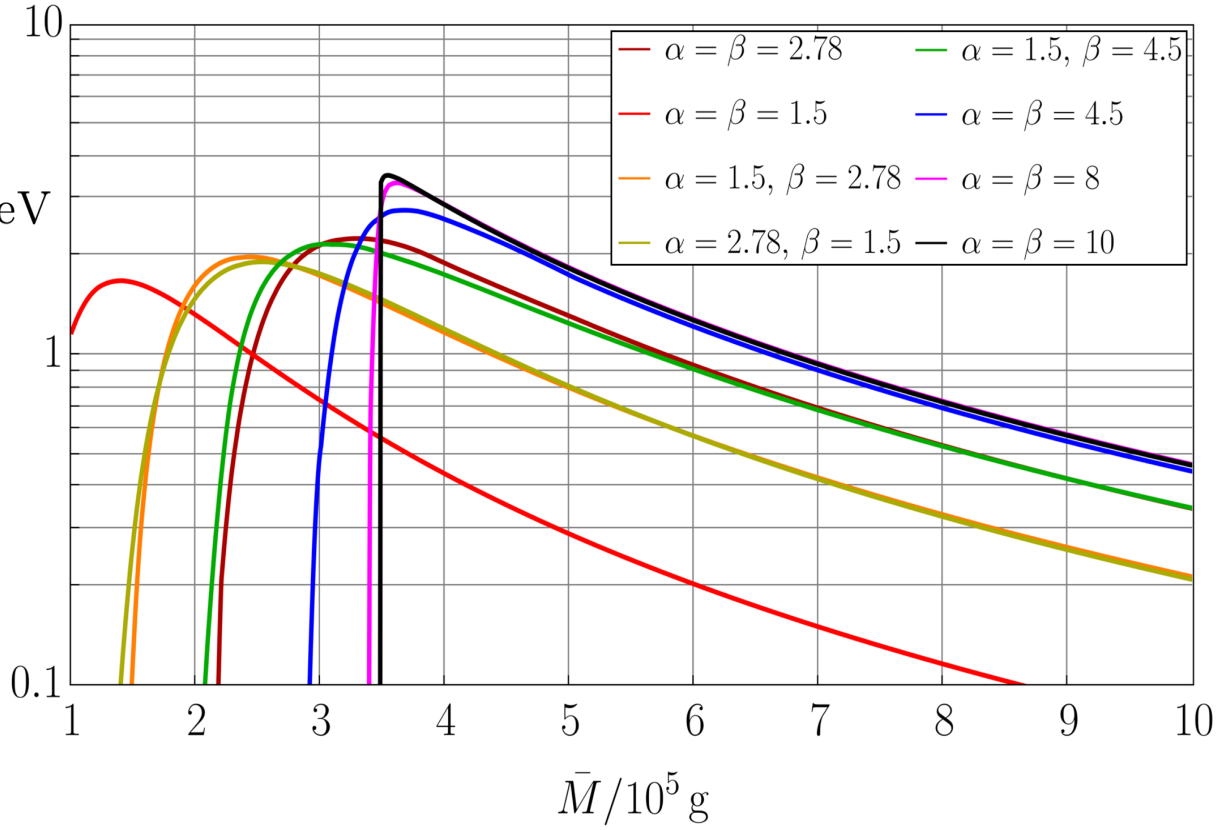
Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2604.29024

Baryon Asymmetry

$$Y \equiv \frac{\eta_B^{\rm tot}}{\eta_B^{\rm obs}} = \frac{10b}{(\Lambda/{\rm TeV})} \frac{v_s(T_{\rm loc})}{200\,{\rm GeV}} \frac{s(T_{\rm EW})}{s(T_{\rm BBN})} \times \int_{t_{\rm spha}}^{t_{\rm min}} dt \frac{4\pi}{3} \left[R_{\rm max}^{\rm EW}\right]^3 \frac{d\mathcal{N}^{\rm co}}{dt}$$



$$\left.\frac{\eta_B^{\rm tot}}{\eta_B^{\rm obs}}\right|_{\Lambda=1\,{\rm TeV}}$$



$b = 1$

$K = 5$

$\kappa_i = 10^{-8}$

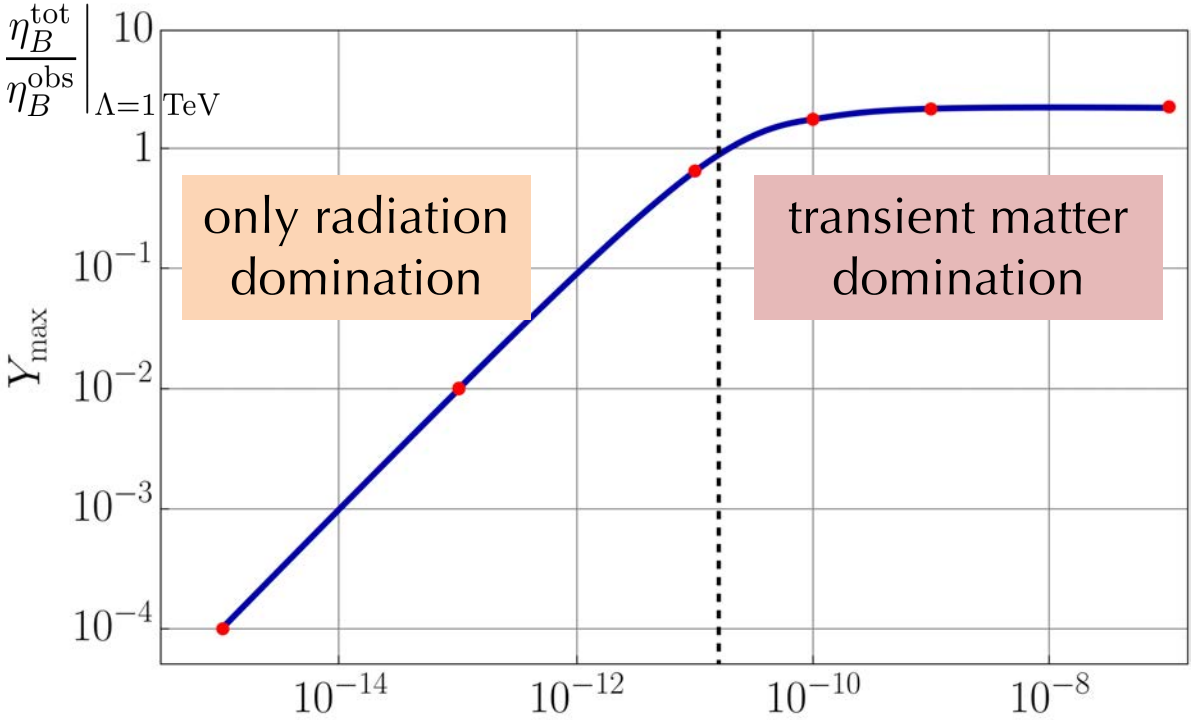
$$\frac{\eta_B^{\rm tot}}{\eta_B^{\rm obs}} \simeq 1 \ \text{for} \ \Lambda \sim \mathcal{O}(2-3\,{\rm TeV})$$

Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2604.29024

Baryon Asymmetry

$$Y \equiv \frac{\eta_B^{\rm tot}}{\eta_B^{\rm obs}} = \frac{10b}{(\Lambda/{\rm TeV})} \frac{v_s(T_{\rm loc})}{200\,{\rm GeV}} \frac{s(T_{\rm EW})}{s(T_{\rm BBN})} \times \int_{t_{\rm spha}}^{t_{\rm min}} dt \frac{4\pi}{3} \left[R_{\rm max}^{\rm EW}\right]^3 \frac{d\mathcal{N}^{\rm co}}{dt}$$

$$\alpha = \beta = 2.78$$



$$\kappa_i = \frac{\rho_{\rm PBH}(t_i)}{\rho_{\rm rad}(t_i)}$$

As we increase κ_i, the yield ***saturates*** from the increased ***entropy production***.

One cannot tune the initial PBH density arbitrarily to keep increasing Y (and thereby increase Λ).

The upper bound $\Lambda \sim \mathcal{O}({\rm TeV})$ implies that ***this scenario can be experimentally tested or constrained.***

Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2604.29024

Gravitational Wave Signature

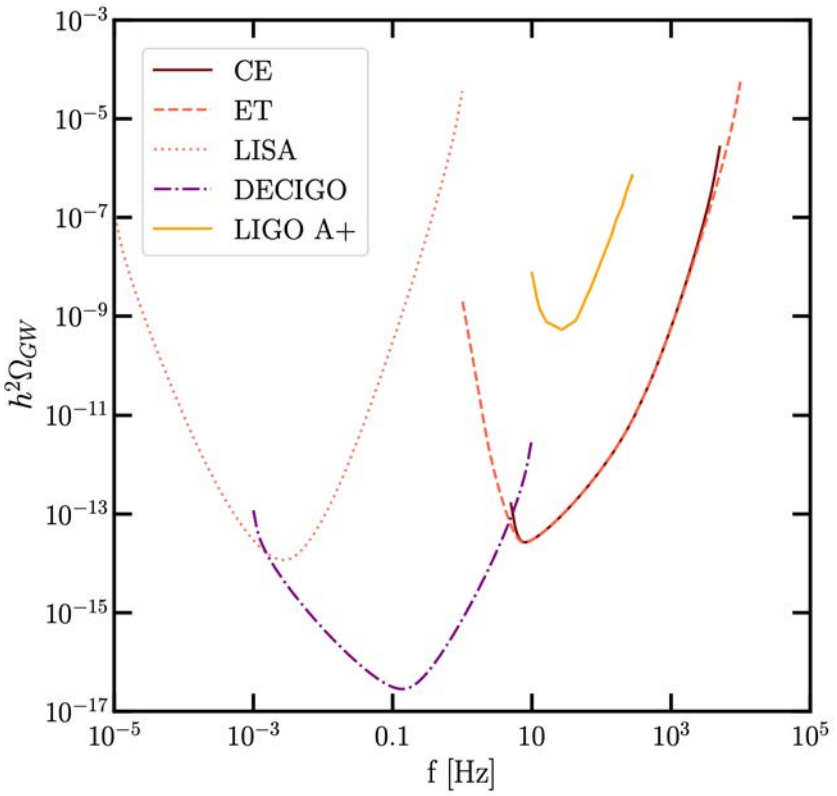


Figure by Wenzer Qin

The production of PBHs typically requires

$$\mathcal{P}_{\mathcal{R}}(k_{\rm pbh}) \gtrsim 10^{-3}$$

Such large-amplitude ***scalar*** perturbations will induce ***tensor*** perturbations at second-order: a ***stochastic gravitational-wave background (SGWB)***.

*Note: we have selected parameters such that ***shock waves do not collide***. So the SGWB signal we consider is ***not*** related to "bubble" (shock-wave) collisions, but rather from the fact that ***a population of PBHs had originally formed from scalar overdensities***.

Kohri and Terada, 1804.08577; Domènech, 2109.01398;
Qin, Geller, Balaji, McDonough, and Kaiser, 2303.02168

Gravitational Wave Signature

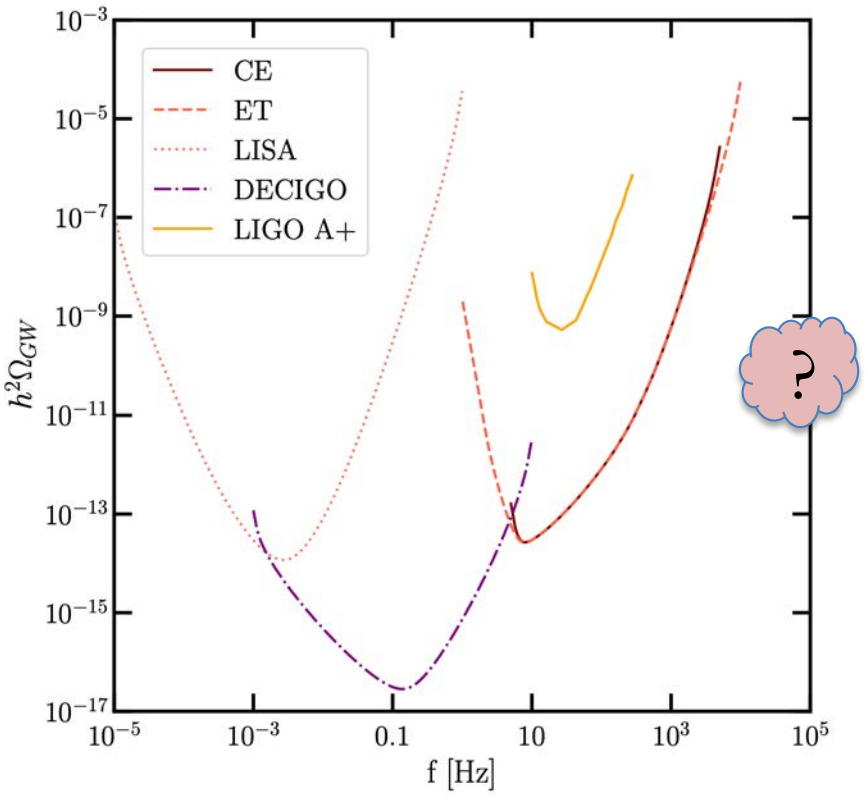


Figure by Wenzer Qin

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Such large-amplitude ***scalar*** perturbations will induce ***tensor*** perturbations at second-order: a ***stochastic gravitational-wave background (SGWB)***.

The present-day ***energy density*** of the SGWB for scalar perturbations that re-enter the Hubble radius during RD is

$$h^2\Omega_{\rm GW}(k_{\rm pbh}, t_0) \simeq 10^{-5}\,\mathcal{P}^2_{\mathcal{R}}(k_{\rm pbh})$$

For a population of PBHs with $\bar{M} \sim \mathcal{O}(10^5\,{\rm g})$, the SGWB would peak at $f_{\rm peak} \sim \mathcal{O}(10^2\,{\rm kHz})$.

Kohri and Terada, 1804.08577; Domènech, 2109.01398;
Qin, Geller, Balaji, McDonough, and Kaiser, 2303.02168

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https://doi.org/10.1007/s41114-021-00032-5

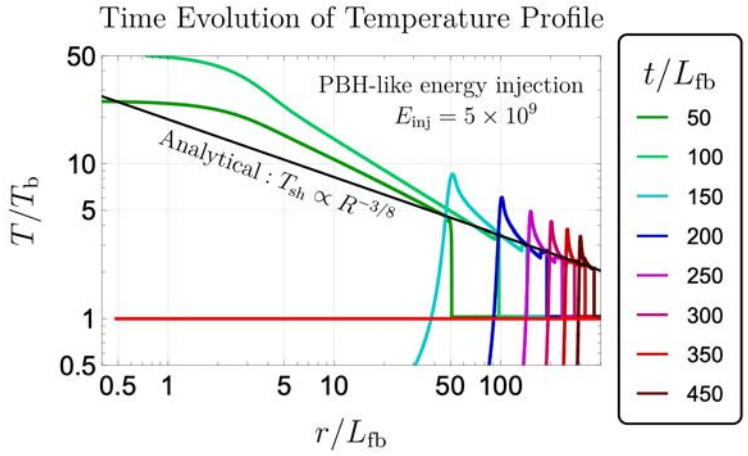
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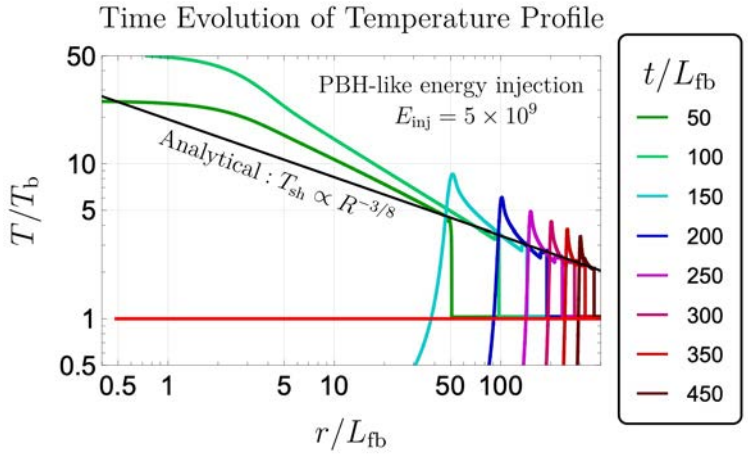
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Summary



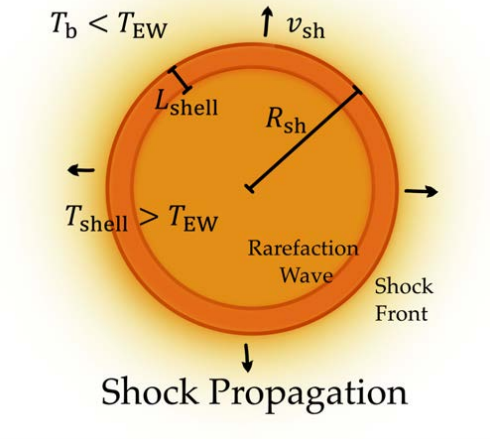
PBH explosions in the very early universe will generate ***shocks*** within the quark-gluon plasma. Such explosions will occur ***generically*** for extended PBH number distributions: ***some subpopulation*** will exist with $M_i \leq 3$ x 10^7 g.

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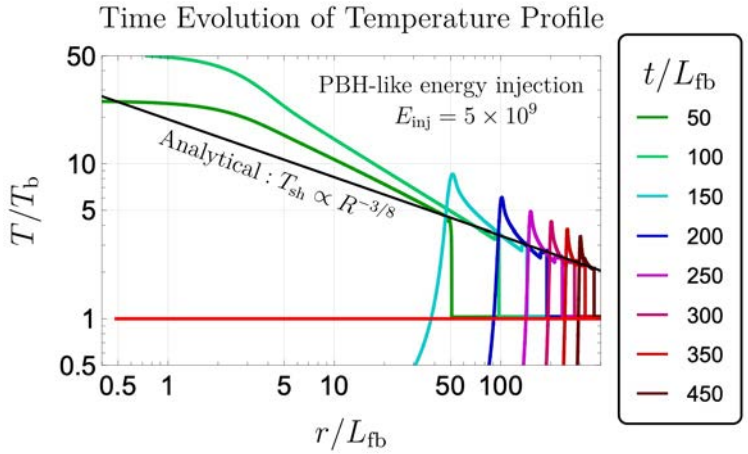


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The ***superheated shell*** of fluid between the shock front and the rarefaction wave will ***restore electroweak symmetry***. These expanding shock waves can ***mimic the behavior of bubbles*** from a strongly 1st-order phase transition.

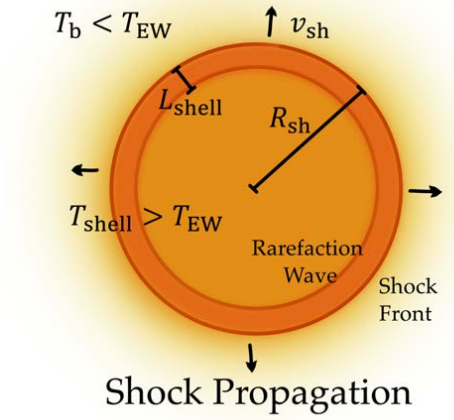


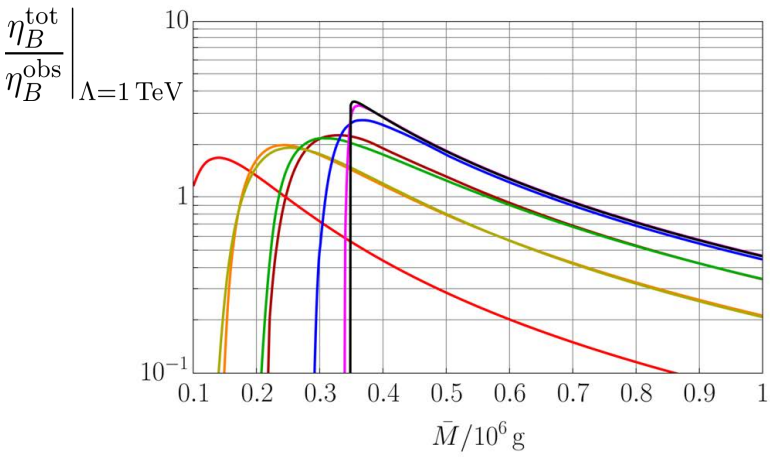
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PBH explosions in the very early universe will generate ***shocks*** within the quark-gluon plasma. Such explosions will occur ***generically*** for extended PBH number distributions: ***some subpopulation*** will exist with $M_i \leq 3 \times 10^7$ g.

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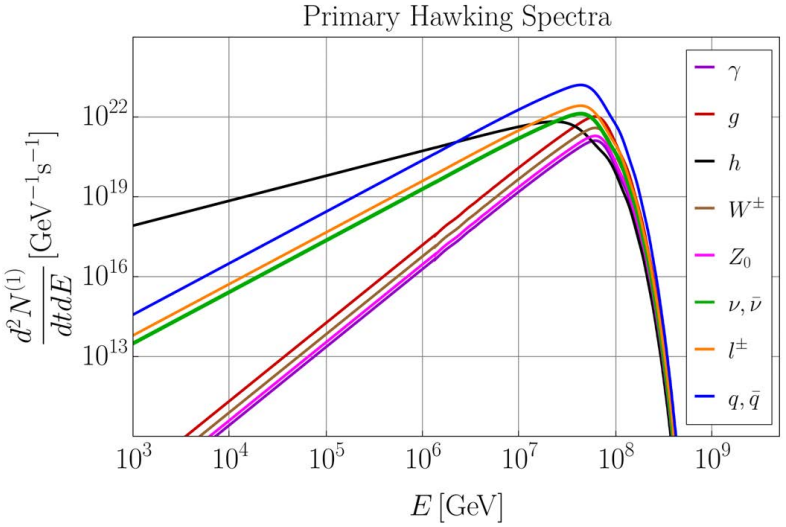


This ***new baryogenesis mechanism*** is ***agnostic*** to the BSM source of CP violation. A minimal dim-5 operator with one new scalar and $\Lambda \sim$ TeV can yield $\eta_B^{\rm obs}$. The ***BAU yield is robust to PBH model parameters***, and the mechanism could be ***tested*** with EW precision measurements and next-generation GW detectors.

BSM Effects and Hawking Emission

We assumed ***only SM degrees of freedom*** when computing the primary Hawking emission, and hence the rates of energy injection into the plasma and the PBH lifetimes.

Including the new BSM scalar field, with mass $m_s \sim 10^2$ GeV, shifts the Page factor $f_{\max}$ and PBH lifetime $\tau(M)$ by **~ 2%**, easily compensated by small shifts to other PBH parameters.



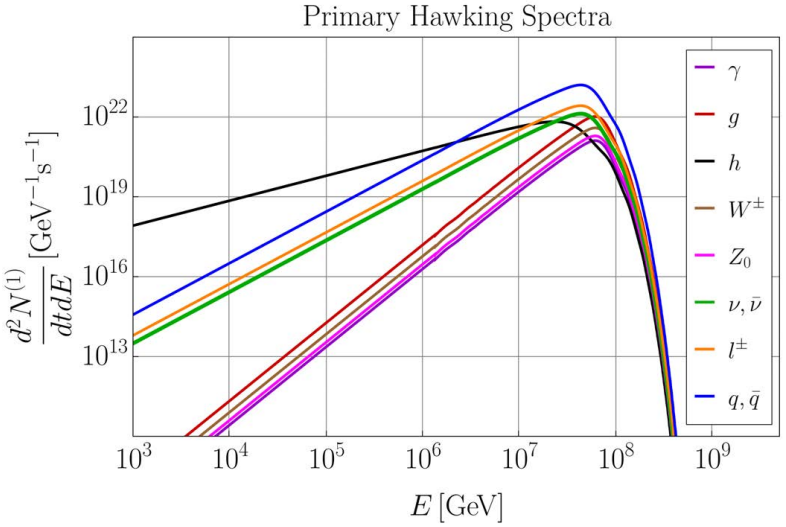
If ***many more*** BSM degrees of freedom exist at much higher energies, that would change the Hawking emission spectrum in (model-dependent) ways that might be measurable.

Baker and Thamm, arXiv:2105.10506, 2210.02805, 2512.19603

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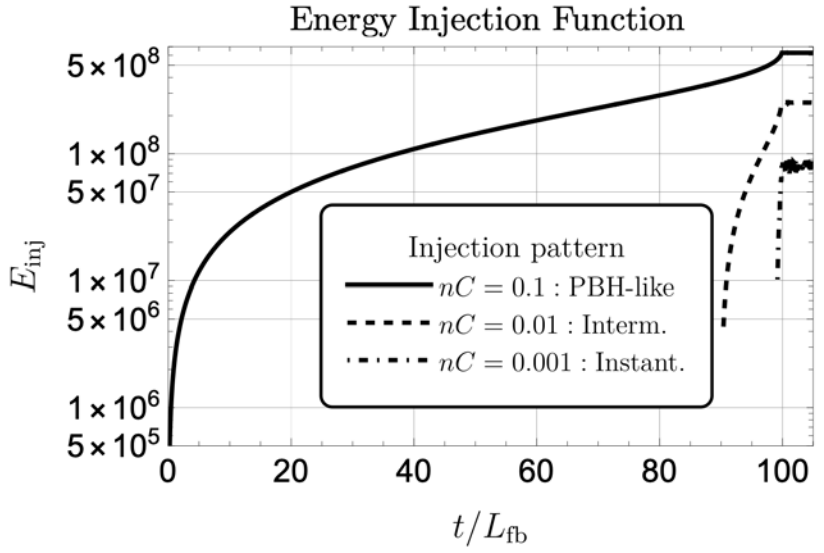
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Baker and Thamm, arXiv:2105.10506, 2210.02805, 2512.19603



Although the ***instantaneous power rate*** diverges as $P \sim (t - \tau)^{-2/3}$ close to the end of the PBH lifetime, the ***integrated power*** ($E_{\rm inj} \leq M_i$) remains finite. In our simulations, we truncate the active energy injection at $\tau(M_{\rm thres}) \sim L_{\rm LPM}$, which is effectively instantaneous on hydrodynamic timescales. This corresponds to $M_{\rm thres} \sim 10^3$ g ($\sim 10^8\ M_{\rm pl}$) and $\tau \sim 10^{-19}$ s ($\sim 10^{24}\ t_{\rm pl}$). So none of these results depends on extrapolating to (unknown) Planck–scale physics.

Evolution of the Universe

To compute the total BAU, we need to know how the ***background temperature of the universe, $T_b(t)$, evolves over time***.

We allow for a ***transient period of PBH matter domination*** between t_i and $t_{\rm BBN}$ by introducing $\rho_{\rm PBH}(t_i) = \kappa_i\, \rho_{\rm rad}(t_i)\,, \quad \kappa_i \ll 1.$

$$\left.\begin{aligned}
\dot\rho^{\rm co}_{\rm PBH}(t) &= -n^{\rm co}_{{\rm PBH},i} \int_0^M dM\, P_{\rm tot}(M)\, \phi(M,t),\\
\dot\rho^{\rm co}_{\rm rad}(t) &= -\dot\rho^{\rm co}_{\rm PBH}(t),\\
\dot s^{\rm co}(T) &= \frac{1}{T_{\rm b}} \dot\rho^{\rm co}_{\rm PBH}(t),\\
H^2(t) &= \frac{8\pi G}{3}\left[\rho^{\rm co}_{\rm PBH}(t)\, a^{-3}(t) + \rho^{\rm co}_{\rm rad}(t)\, a^{-4}(t)\right].
\end{aligned}\right\} \quad T_{\rm b}(t) = \left(\frac{45}{2\pi^2 g_*}\right)^{1/3} \frac{\left[s^{\rm co}(t)\right]^{1/3}}{a(t)}$$

Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser, arXiv:2604.29024



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Wenzer Qin
NYU postdoc



Thomas Steingasser
IFT Madrid postdoc

Production Mechanisms

Geller, Qin, McDonough, DK, *et al.*,
2205.04471, 2303.02168

Lorenzoni, Geller, DK, McDonough, *et al.*,
2504.13251, 2512.04199

Aurrekoetxea, Alves, DK, Guth, ***in prep.***

Medium Effects

Alonso-Monsalve and DK,
2309.15385, 2310.16877

Klipfel, Vanvlasselaer, Trifinopoulos, DK,
2603.15746, 2604.29024

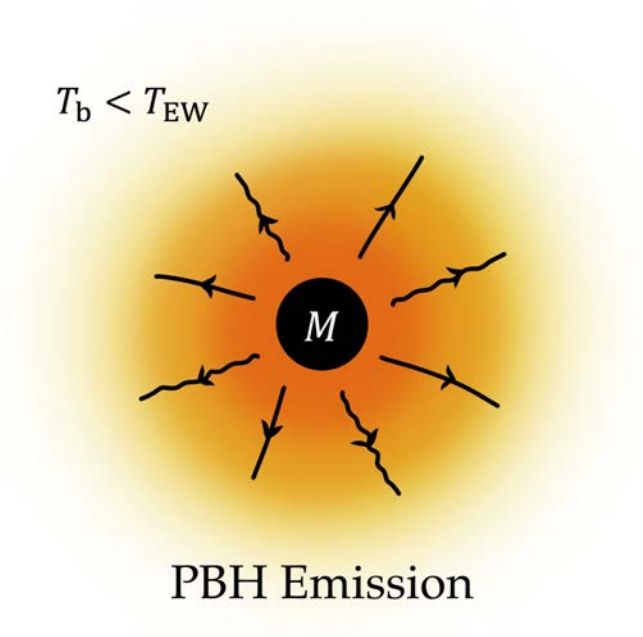
Detection Strategies

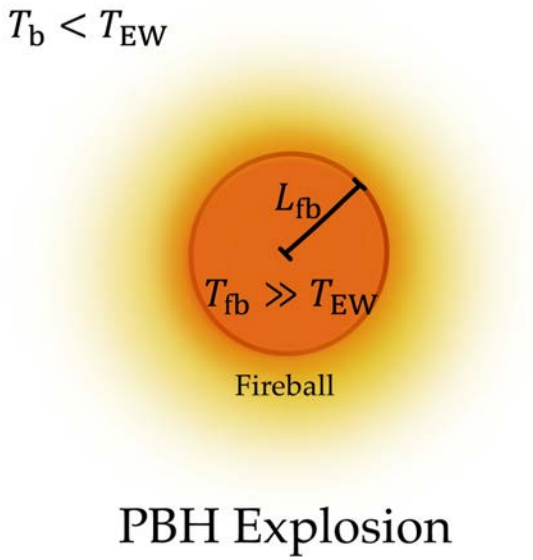
Tran, Geller, Lehmann, DK, ***2312.17217***

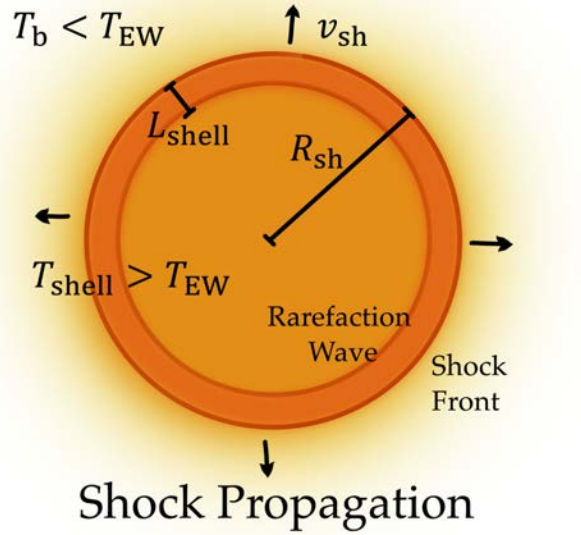
DeLorenci, DK, Patrick, *et al.*,
2405.08113, 2504.07517

Klipfel, Fisher, and DK, ***2503.19227, 2506.14041,2601.05935, 2605.26204***

Balaji, Cyr, Geller, DK, Lorenzoni, McDonough, Qin ***2604.xxxxx***







Figures by Alexandra Klipfel