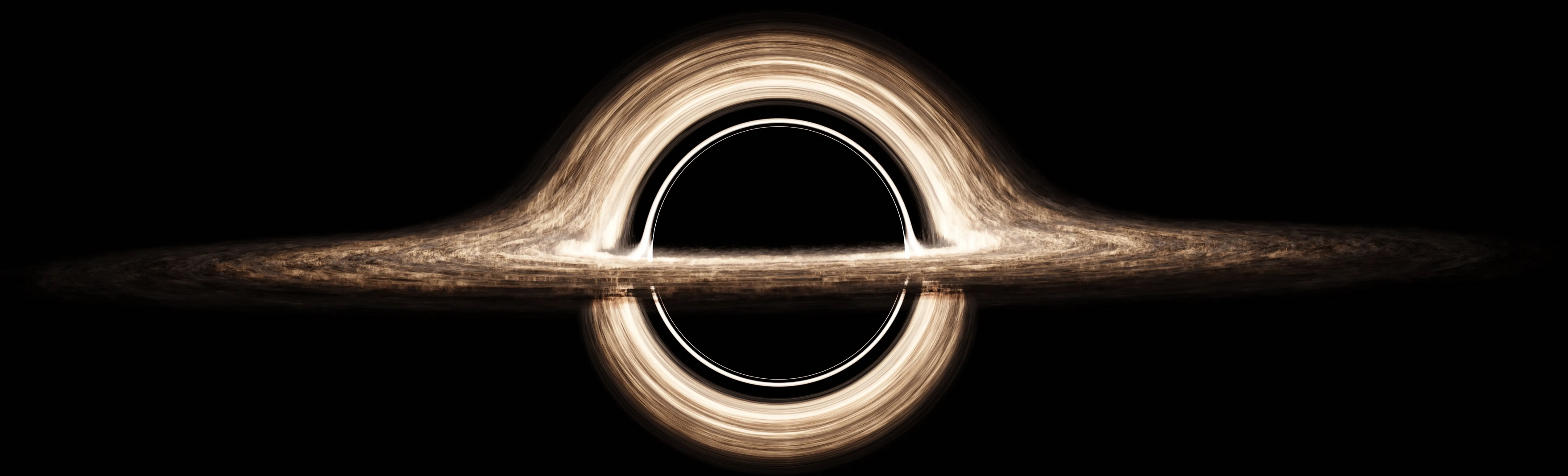
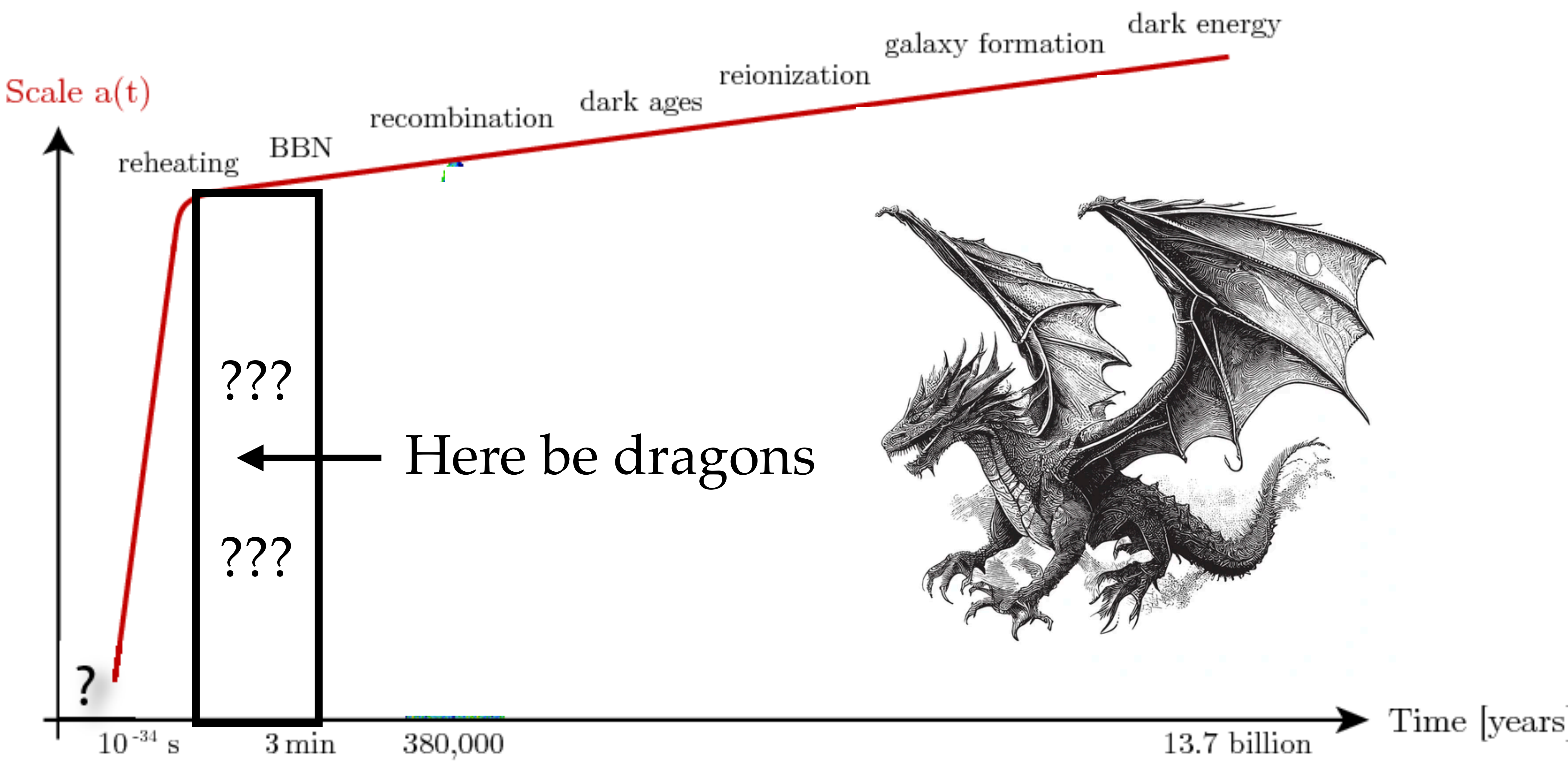
Primordial Black Holes & Particle Physics



Gordan Krnjaic
Fermilab + UChicago

Pheno Symposium 2026, University of Pittsburgh

Cosmic Timeline



Empirical data validates standard timeline from 1s - 13.7 Gyr

No data from earlier times, Wide range of possibilities for t < 1s

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

The existence of bodies with dimensions less than $R_g = 2GM/c^2$ at the early stages of expansion of the cosmological model leads to a strong accretion of radiation by these bodies. If further calculations confirm that accretion is catastrophically high, the hypothesis on cores retarded during expansion [3, 4] will conflict with observational data.

First ever paper on PBH argues they should not form under standard simple cosmological assumptions

Historical review: Carr, Green 2406.05736

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

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

(Communicated by M. J. Rees)

(Received 1970 November 9)

SUMMARY

It is suggested that there may be a large number of gravitationally collapsed objects of mass 10^{-5} g upwards which were formed as a result of fluctuations in the early Universe. They could carry an electric charge of up to ± 30 electron units. Such objects would produce distinctive tracks in bubble chambers and could form atoms with orbiting electrons or protons. A mass of 10^{17} g of such objects could have accumulated at the centre of a star like the Sun. If such a star later became a neutron star there would be a steady accretion of matter by a central collapsed object which could eventually swallow up the whole star in about ten million years.

Didn't deter Hawking, whose paper inspired later work on evaporation

Historical review: Carr, Green 2406.05736

Overview

Early Universe Formation

Hawking Evaporation

Black Hole Dominated Cosmology

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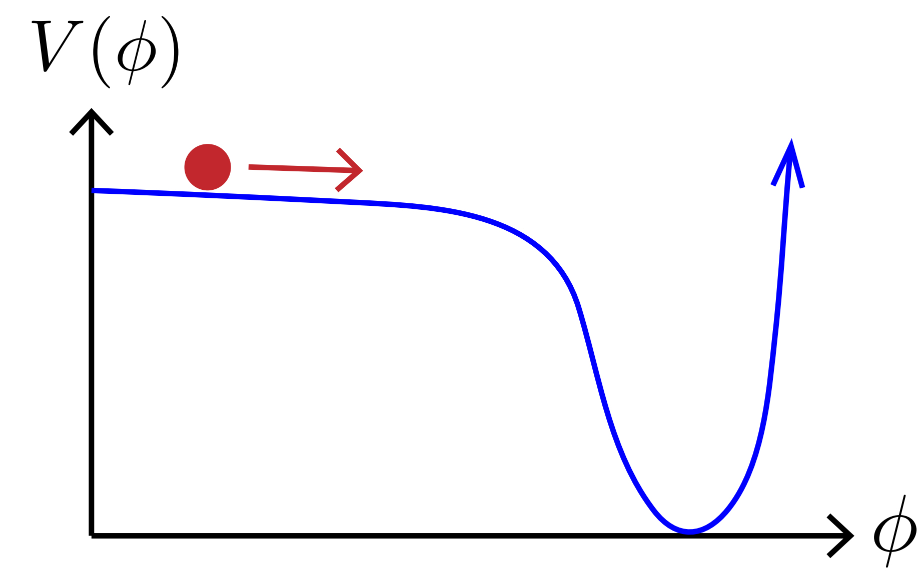
Inflation



Scalar field drives exponential expansion

$$a(t) \propto e^{H_i t} \qquad t \ll 1\,\mathrm{s}$$

Solves "horizon problem"

Why are causally disconnected CMB regions statistically identical?

Solves "flatness problem"

Spatial curvature generically dominates, but is observed to be negligible

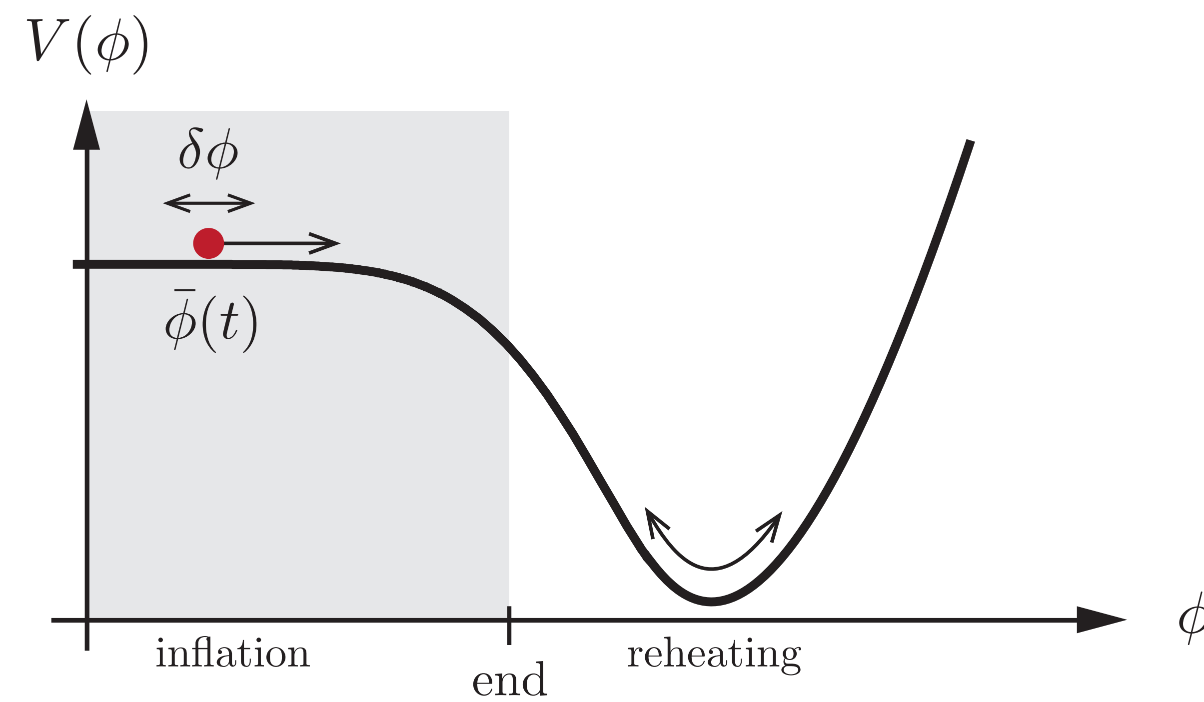
Solves "monopole problem"

GUTs predict large monopole density, which is not observed

Generates scalar and tensor perturbations from quantum fluctuations in ϕ

Discovered later, not the original motivation!

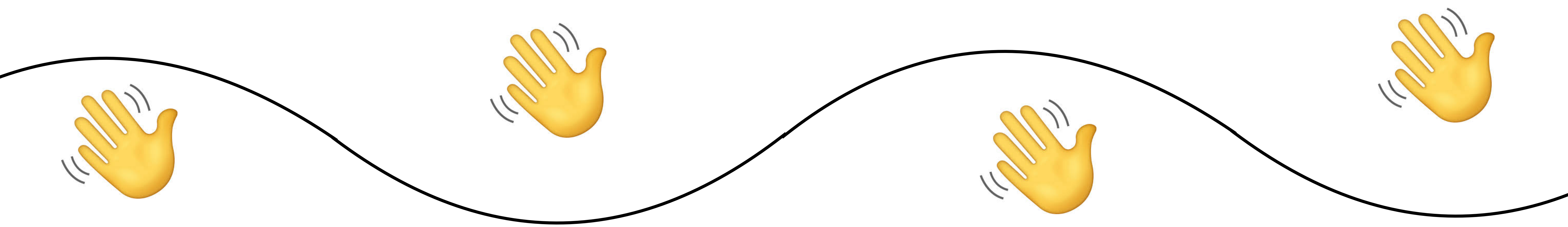
Primordial Fluctuations

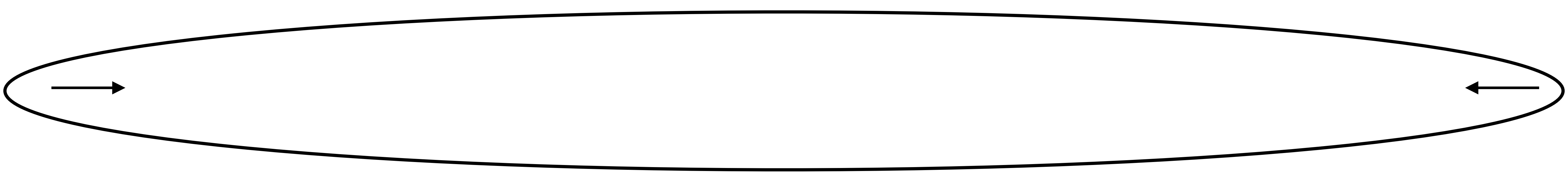


By Heisenberg uncertainty

$$\phi = \bar{\phi} + \delta\phi$$

inflation creates perturbations on all scales





During inflation, comoving horizon shrinks

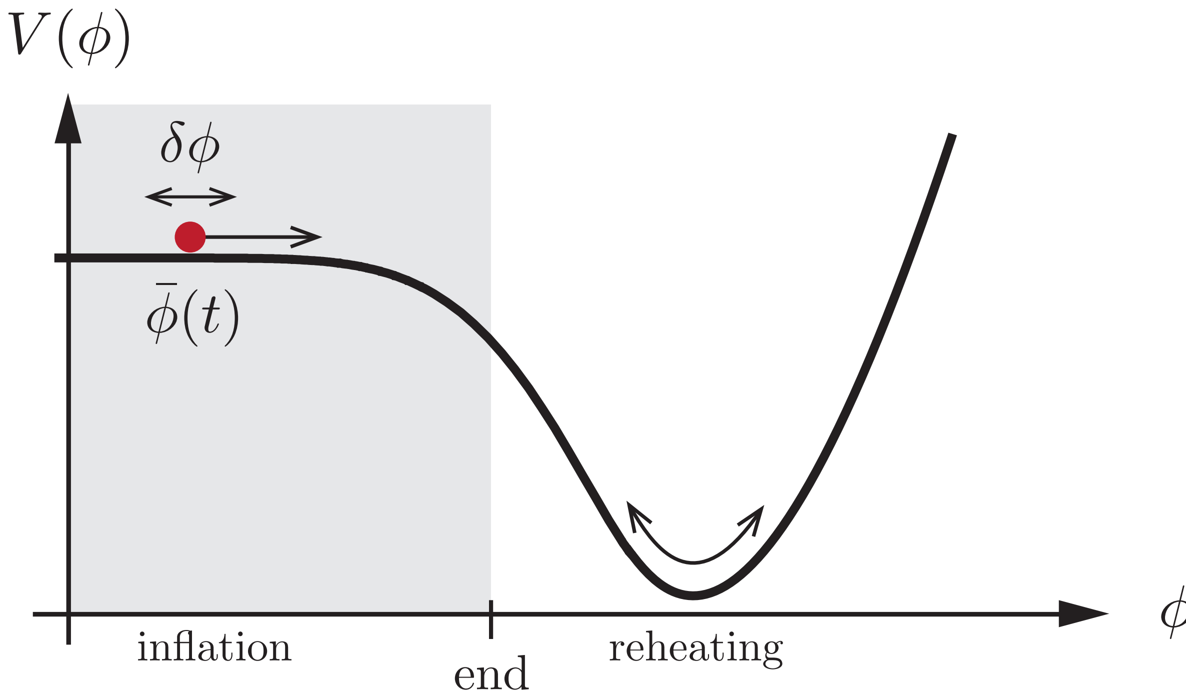
$$\frac{d}{dt}(aH)^{-1} < 0$$

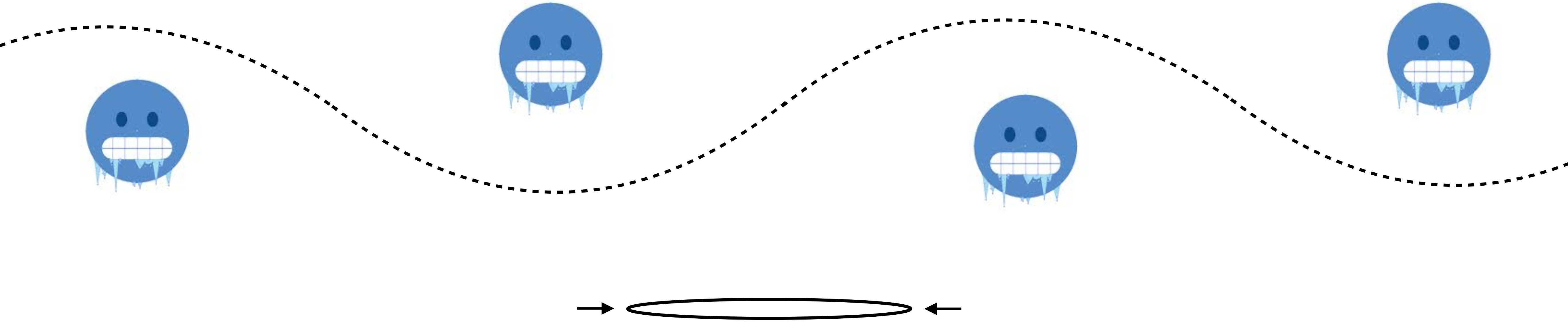
Primordial Fluctuations

By Heisenberg uncertainty

$$\phi = \bar{\phi} + \delta\phi$$

inflation creates perturbations on all scales





During inflation, comoving horizon shrinks

Perturbations frozen outside horizon

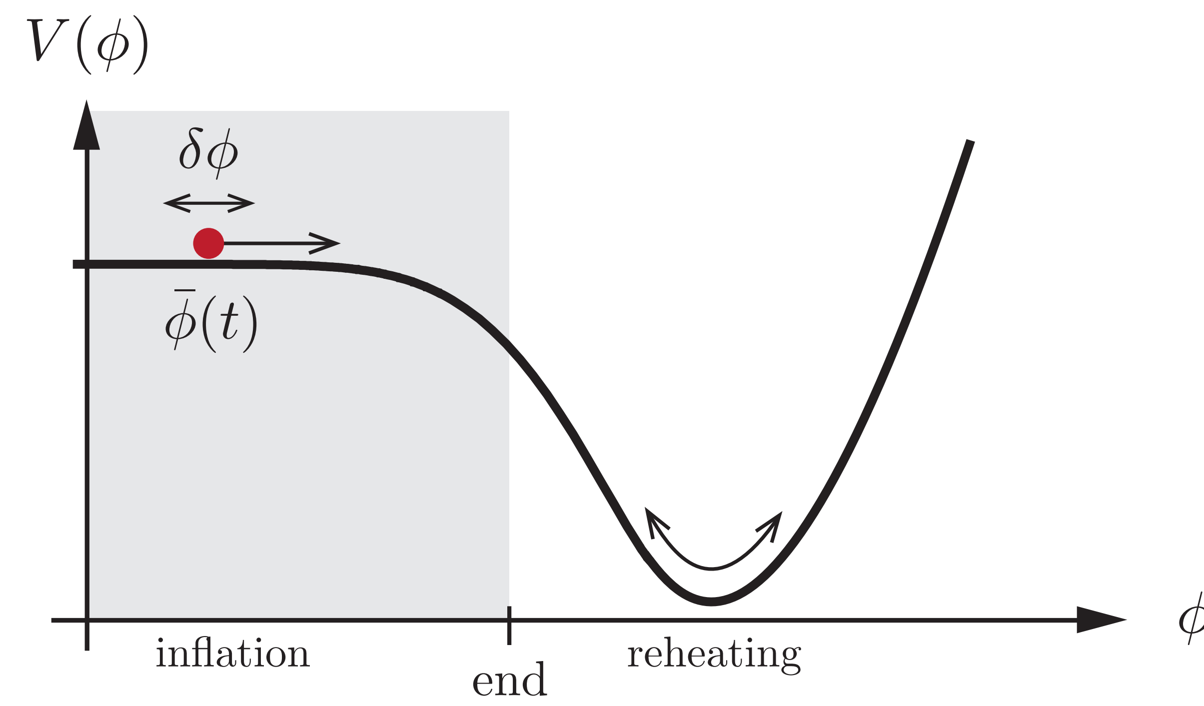
$$\frac{d}{dt}(aH)^{-1} < 0$$

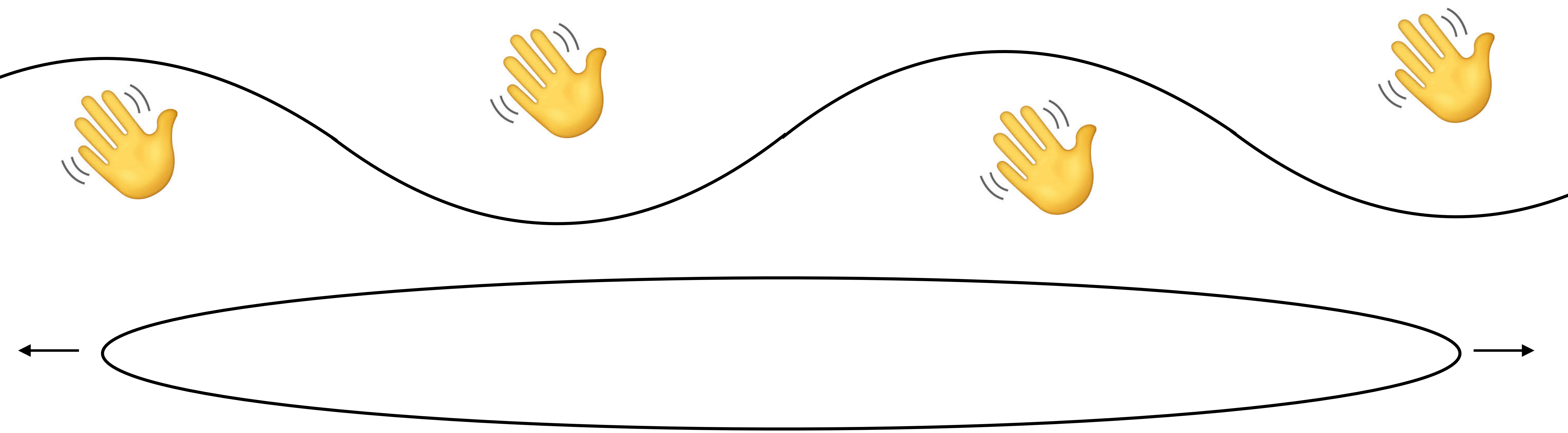
Primordial Fluctuations

By Heisenberg uncertainty

$$\phi = \bar{\phi} + \delta\phi$$

inflation creates perturbations on all scales



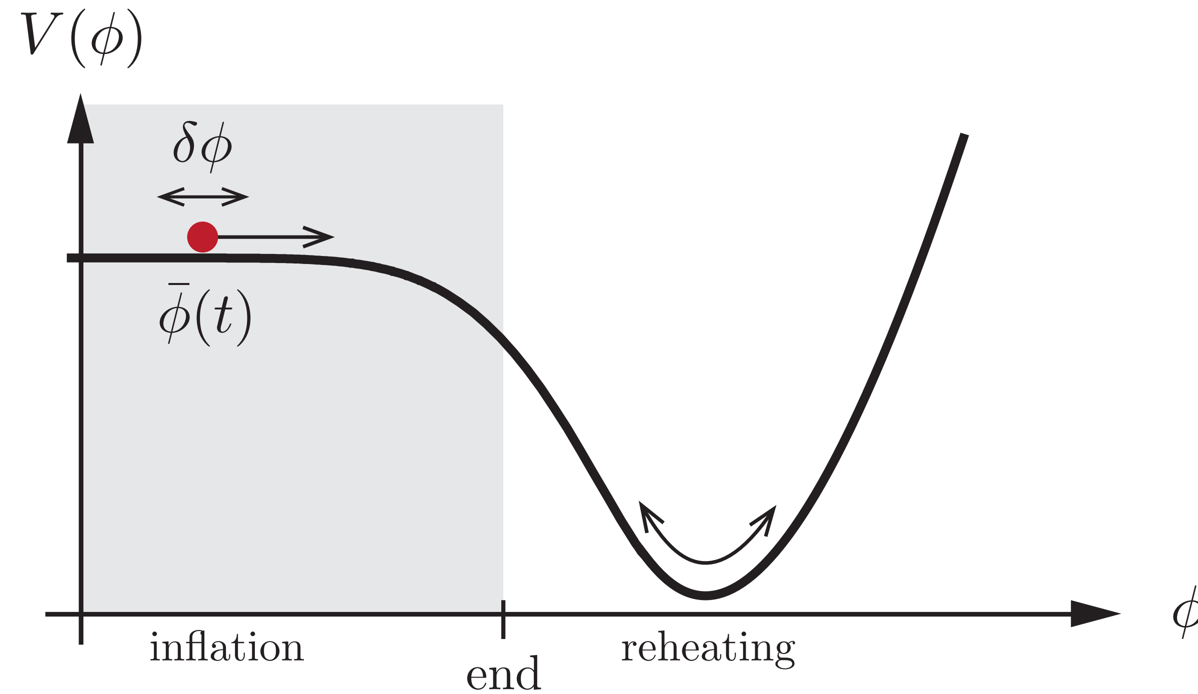


After inflation, horizon grows again

Perturbations evolve again at horizon re-entry

$$\frac{d}{dt}(aH)^{-1} > 0$$

Primordial Fluctuations

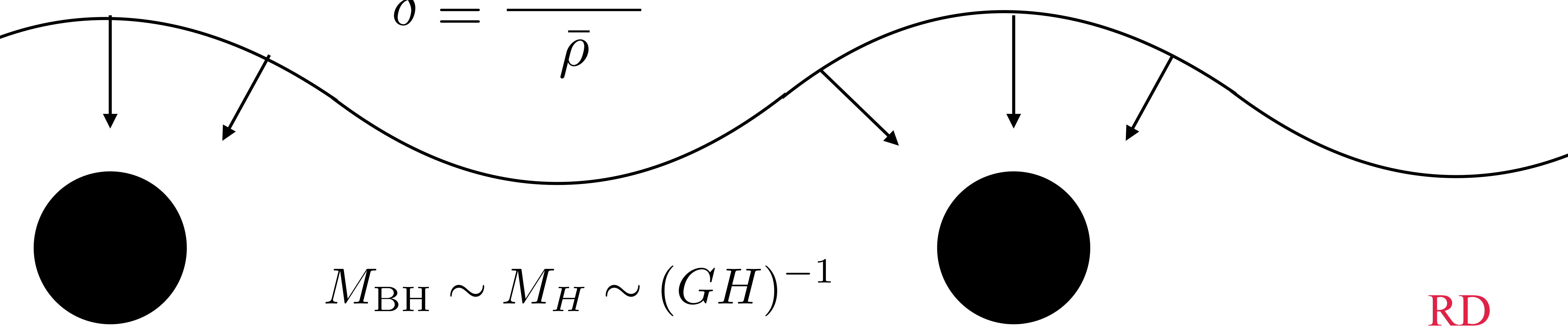


By Heisenberg uncertainty

$$\phi = \bar{\phi} + \delta\phi$$

inflation creates perturbations on all scales

$$\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}}$$



$$M_{\rm BH} \sim M_H \sim (GH)^{-1}$$

RD

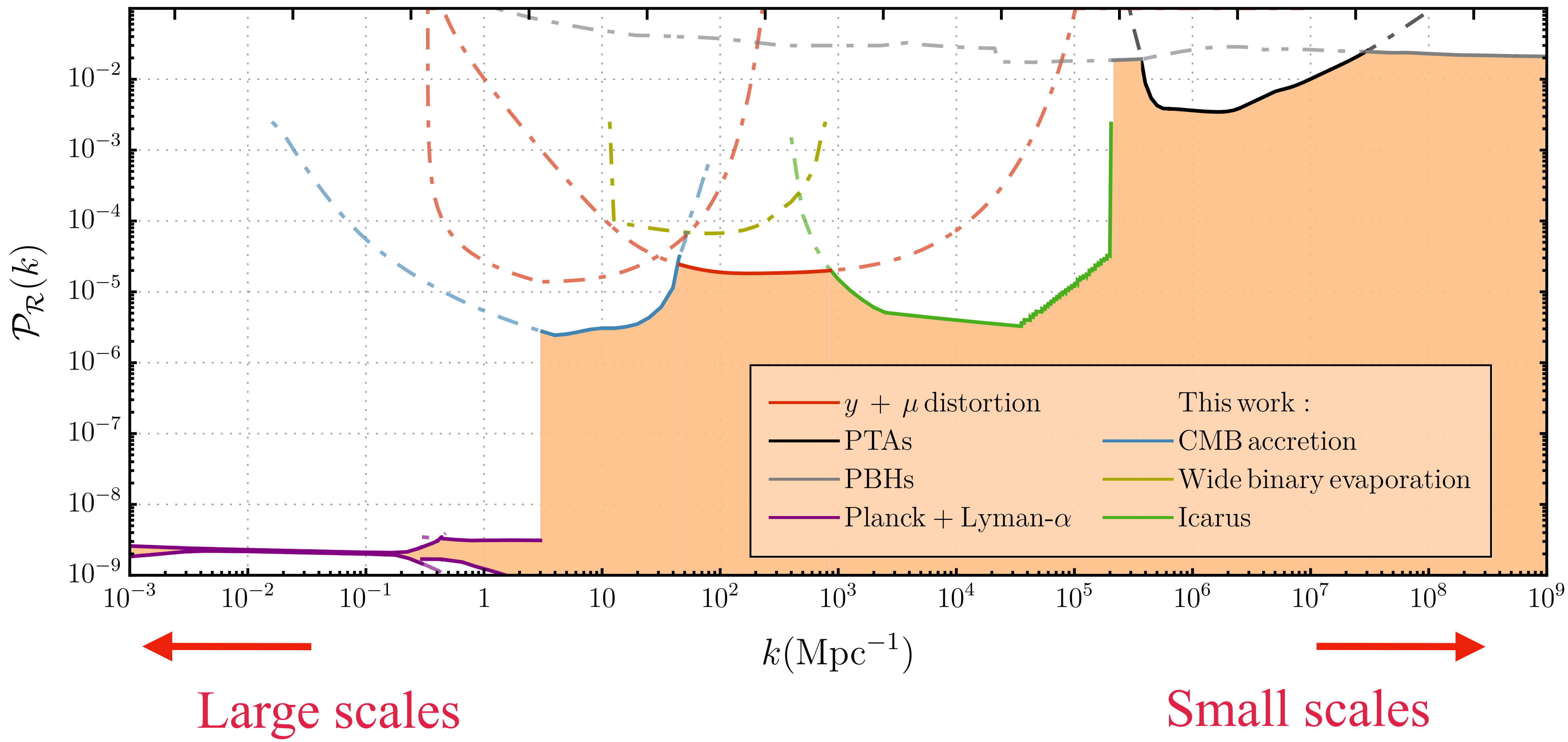
$$\delta_c = \sin^2\left(\frac{\pi\sqrt{w}}{1+3w}\right) \sim 0.4$$

If perturbation exceeds critical value
Hubble patch collapses to form PBH

Harada, Yoo, Kohri 1309.4201

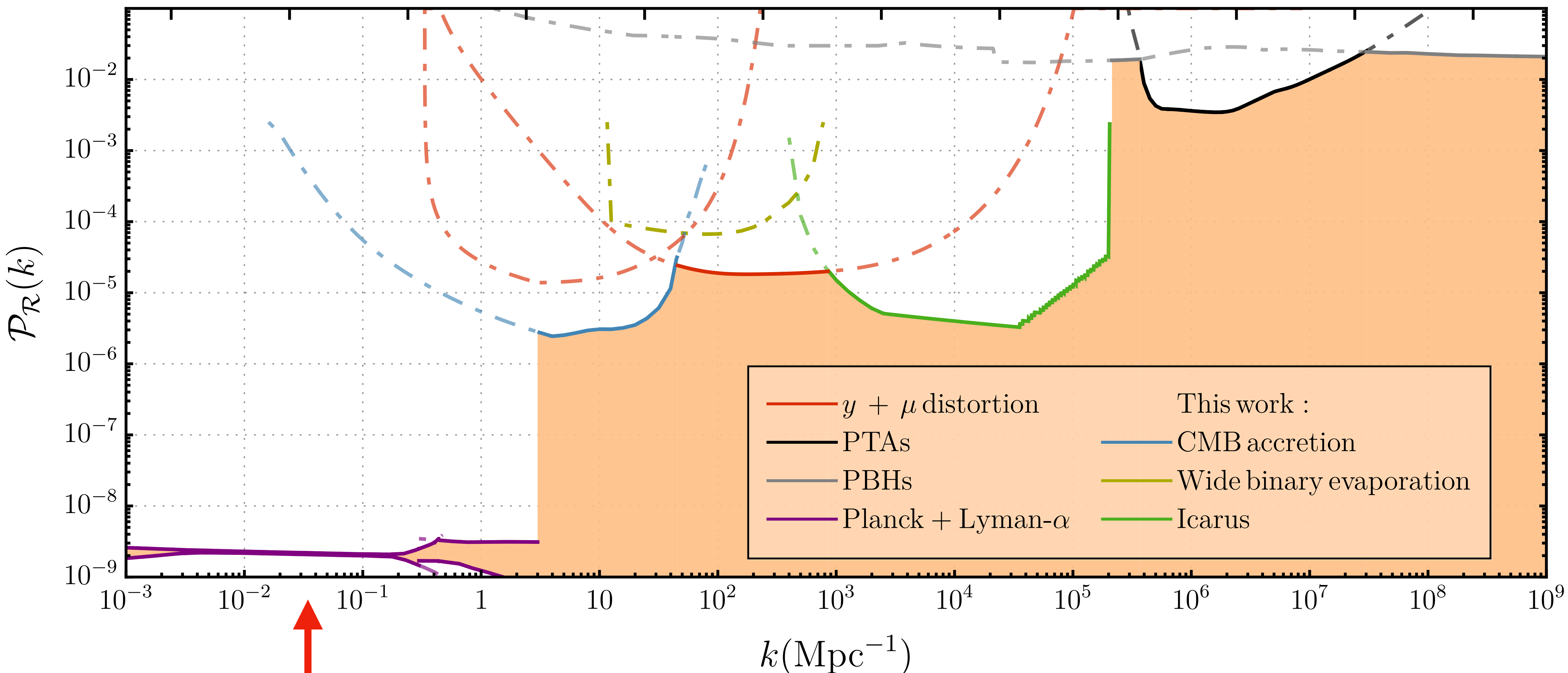
Primordial Fluctuations

Bringmann, Croon, Munoz 2506.20704



Primordial Fluctuations

Bringmann, Croon, Munoz 2506.20704



$$P_\mathcal{R} = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$$A_s = (2.10 \pm 0.05) \times 10^{-9}$$
$$n_s = 0.9649 \pm 0.0042$$
$$k_* = 0.05\,\mathrm{Mpc}^{-1}$$

Planck 2018

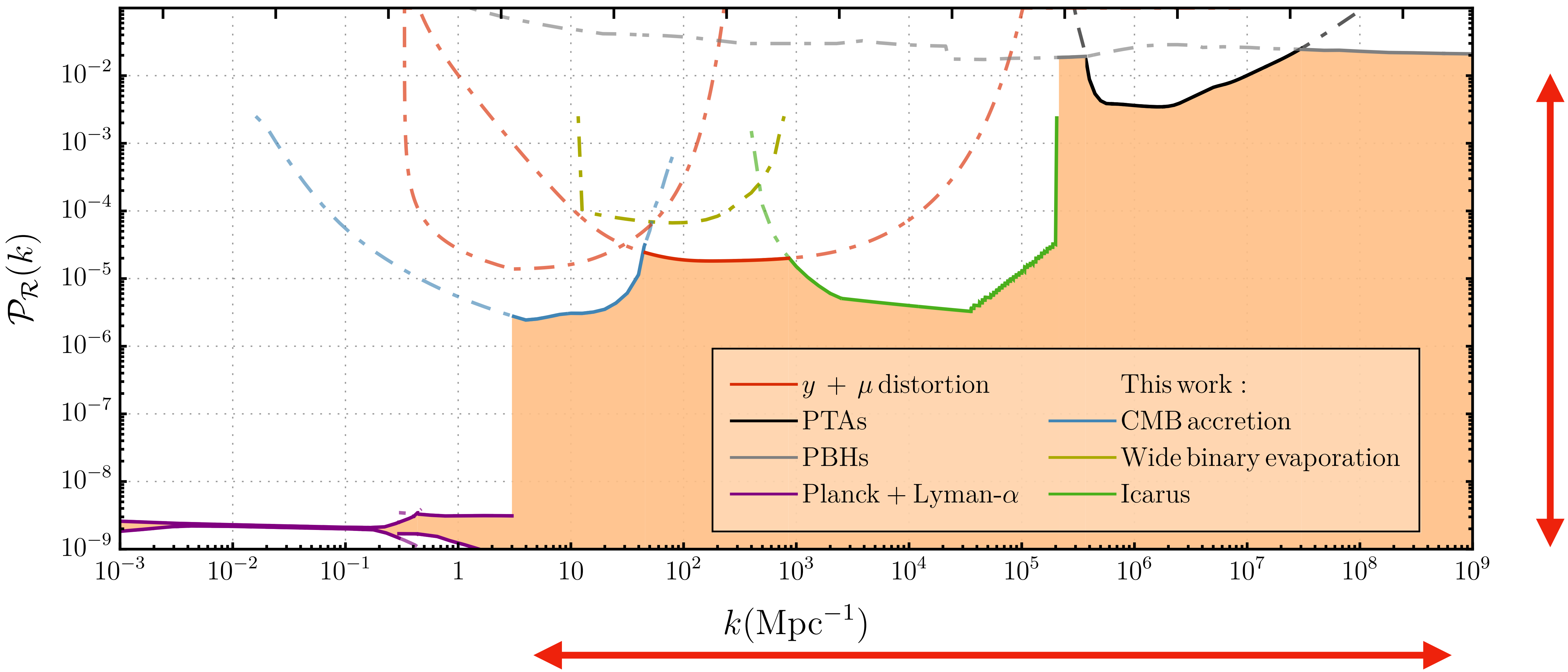
Measured to be ~ scale-invariant on CMB scales (> Mpc)

… no PBH formation in standard cosmology

Primordial Fluctuations

Green Kavanagh 2007.10722

Bringmann, Croon, Munoz 2506.20704



Universe can be much clumpier on small scales, allows PBH formation

$$\frac{\rho_{\rm PBH}}{\rho_{\rm tot}} \propto \int_{\delta_c}^{\infty} d\delta \exp\left(-\frac{\delta^2(R)}{2\sigma^2(R)}\right)$$

Abundance at formation

$$\sigma^2(R) \sim \int_0^{\infty} dk \mathcal{P}_{\mathcal{R}}(k)$$

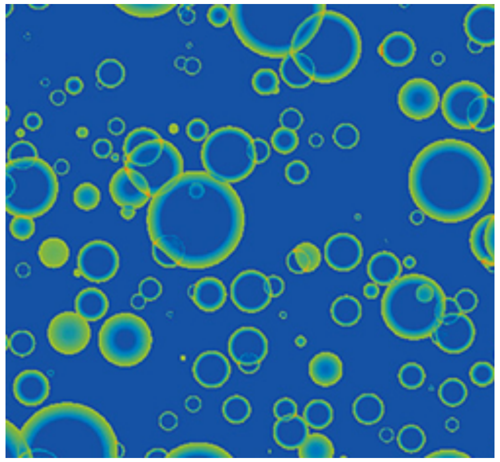
Power spectrum sets variance

Small Sample of Other Mechanisms

Phase Transitions

Nucleated bubbles collide and form PBH

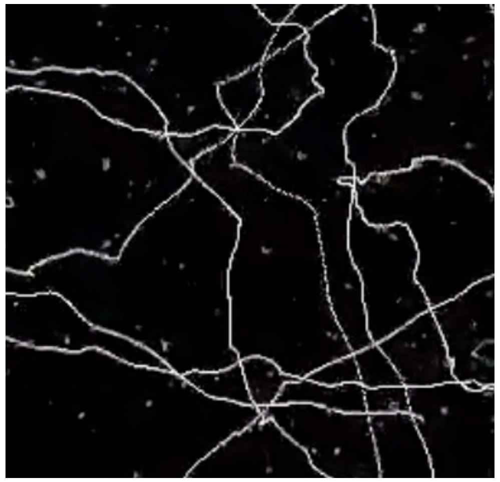
Kodama, Sasaki, Sato 1982   Kusenko, Sasaki, Takhistov, et al 2001.09160



Cosmic Strings

Strings form loops, which oscillate and contract to $R<Rs$

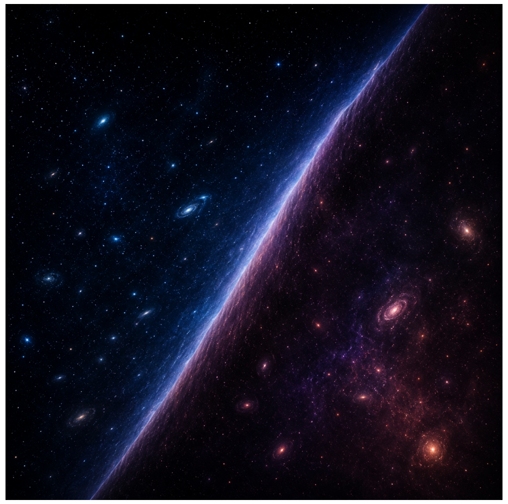
Kibble 1976, Hawking 1989, Polnarev, Zembowicz 1991



Domain Walls

Walls can lower energy by shrinking to $R<Rs$

Rubin, Khlopov, Sakharov 2000



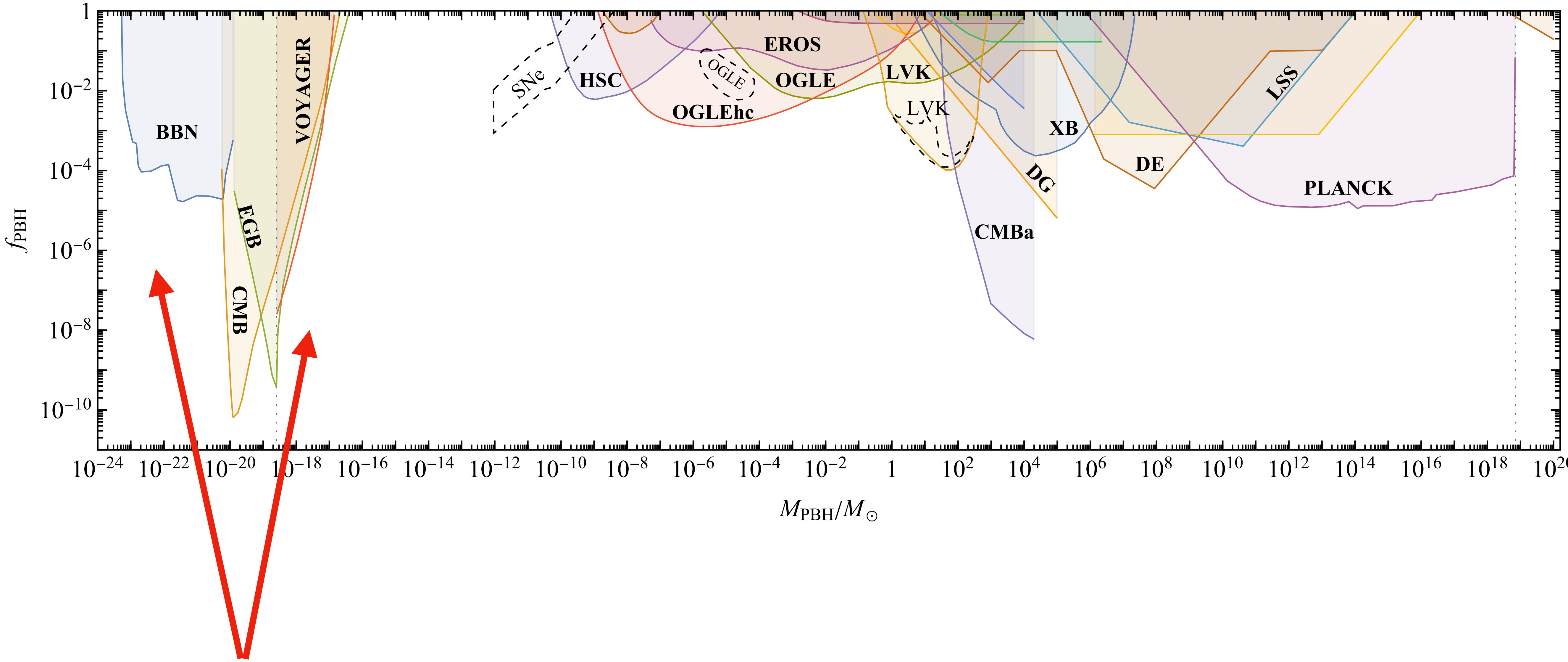
Q-Ball Collapse

Scalar condensate accretes and collapses to $R<Rs$

Cotner, Kusenko 1612.02529

Observational Status

Carr, Iovino, Perna, Vaskonen,Vermae 2601.06024

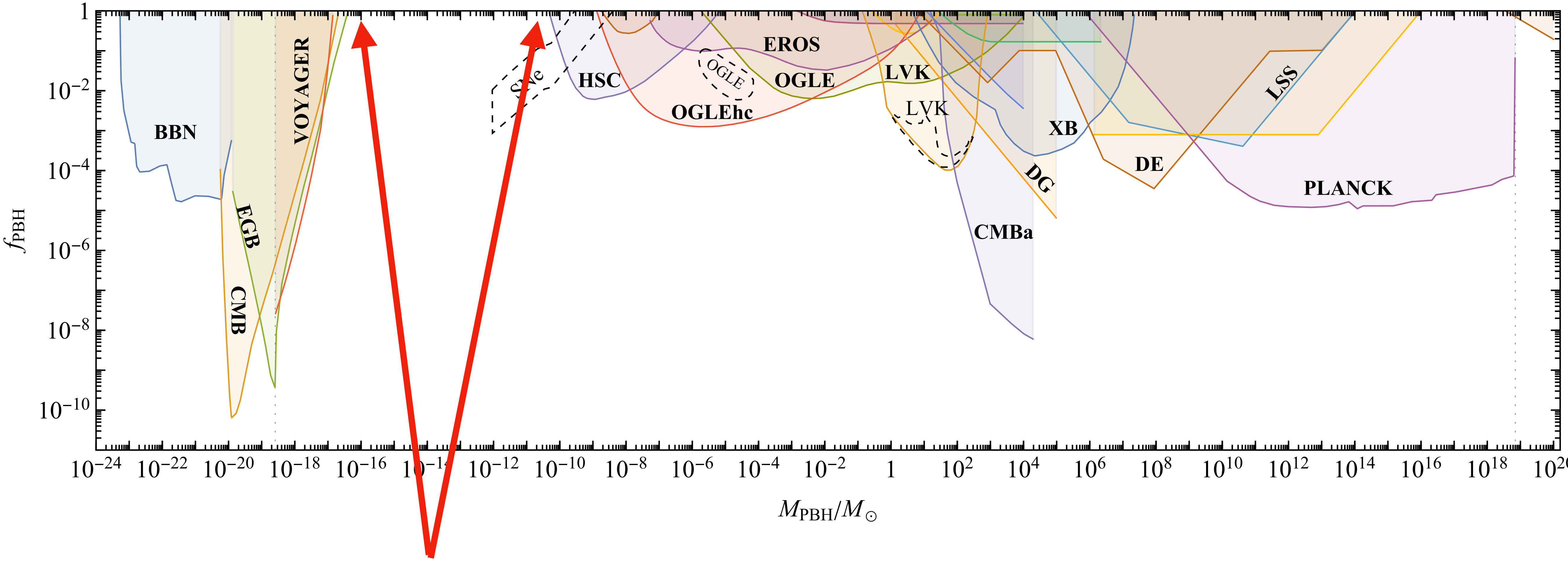


Cosmologically metastable PBH
Evaporation and energy injection limits

$$f_{\rm PBH} \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$

Observational Status

Carr, Iovino, Perna, Vaskonen,Vermae 2601.06024



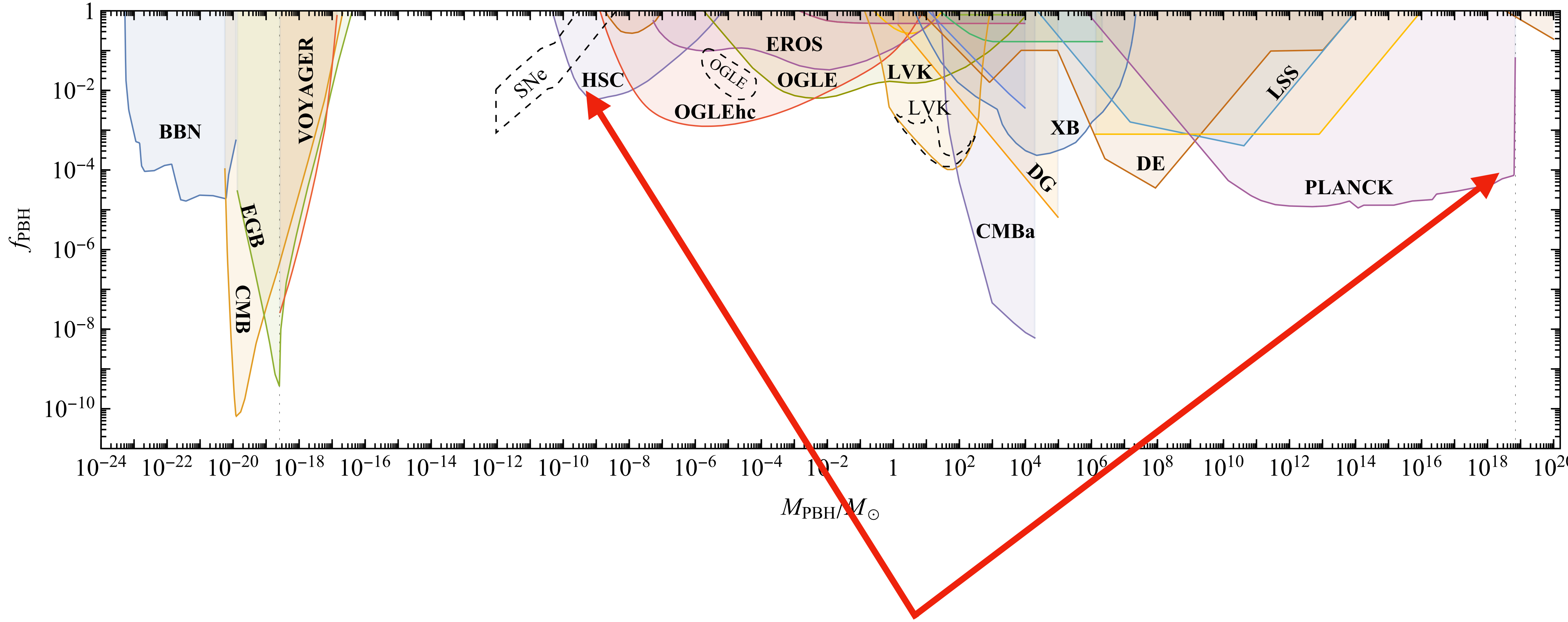
Cosmologically stable

Asteroid mass window: PBH can be all of the DM

$$f_{\rm PBH} \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$

Observational Status

Carr, Iovino, Perna, Vaskonen,Vermae 2601.06024



Cosmologically stable

Limits derive from astrophysics: lensing, GW, accretion…

$$f_{\mathrm{PBH}} \equiv \frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}}$$

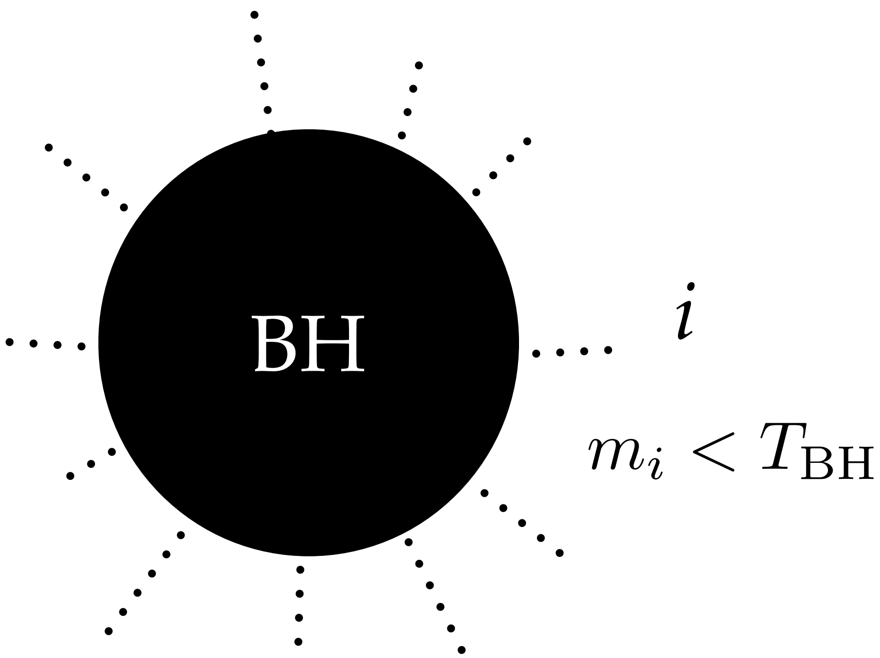
Overview

Early Universe Formation

Hawking Evaporation

Black Hole Dominated Cosmology

Hawking Evaporation



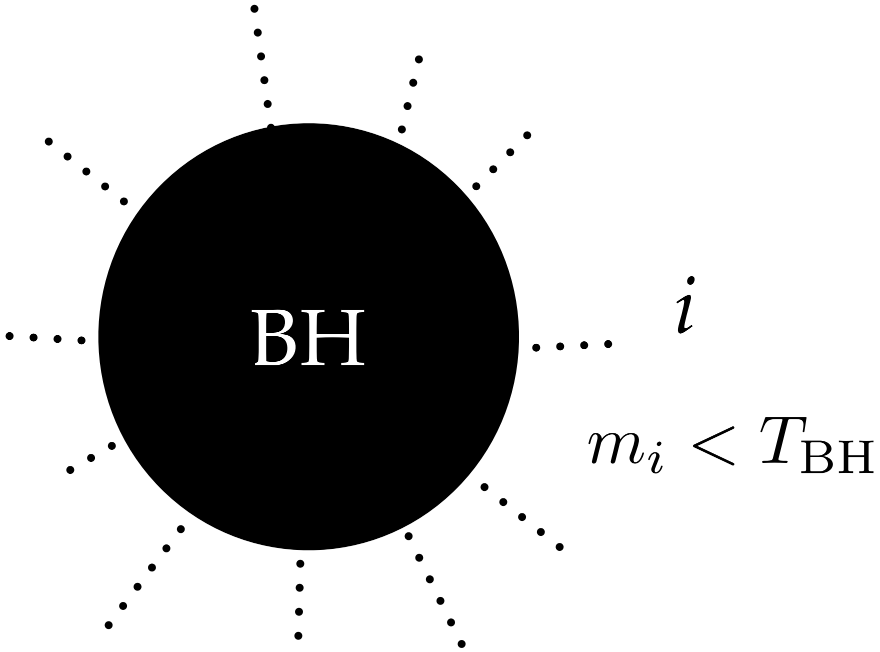
$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm BH}} \simeq 1.05 \times 10^{13}\,{\rm GeV}\left(\frac{\rm g}{M_{\rm BH}}\right)$$

Black holes emit particles with "gray body" spectrum set by Hawking temperature

$$i = {\rm SM} + {\rm DM} + {\rm axion} + \cdots$$

Hawking, Commun. Math. Phys. 43, 199 (1975)
Carr, Astrophys. J. 206, 8 (1976).
MacGibbon, Webber, Phys. Rev. D 41, 3052 (1990).

Hawking Evaporation



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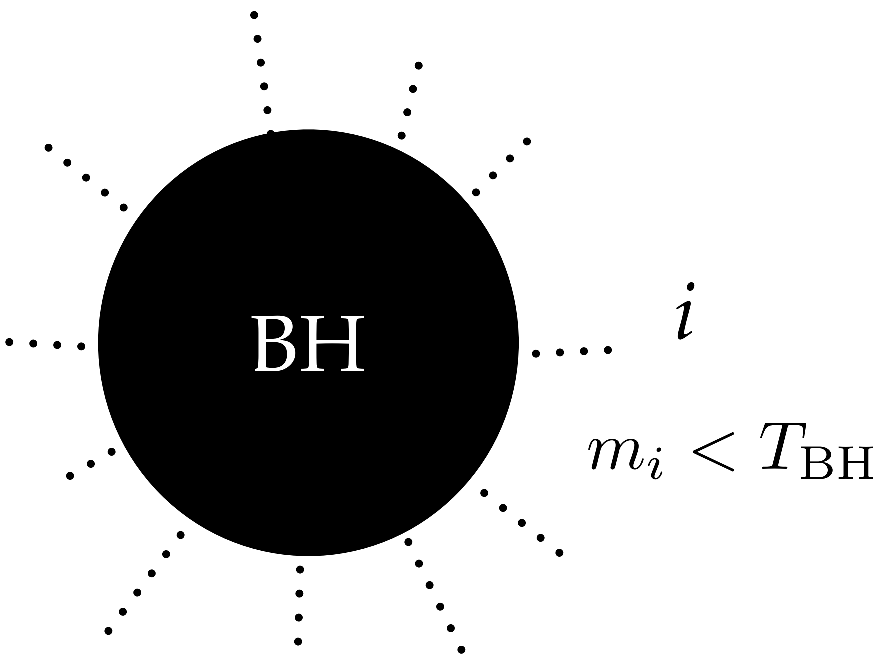
$$\frac{dM_{\rm BH}}{dt} = -\frac{\mathcal{G}\, g_{\star,H}(T_{\rm BH})\, M_{\rm Pl}^4}{30720\,\pi\, M_{\rm BH}^2} \simeq -7.6 \times 10^{24}\,{\rm g\,s}^{-1}\; g_{\star,H}(T_{\rm BH})\left(\frac{\rm g}{M_{\rm BH}}\right)^2$$

Equivalence principle: all species produced semi-democratically

Hawking, Commun. Math. Phys. 43, 199 (1975)
Carr, Astrophys. J. 206, 8 (1976).
MacGibbon, Webber, Phys. Rev. D 41, 3052 (1990).

Hawking Evaporation



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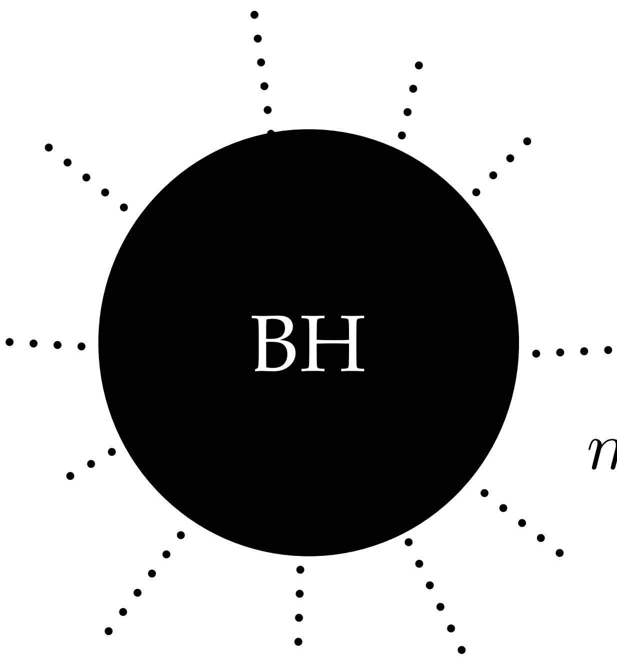
Gray-body factors

$$g_{\star,H}(T_{\rm BH}) \equiv \sum_i w_i g_{i,H} \quad , \quad g_{i,H} = \begin{cases} 1.82 & s = 0 \\ 1.0 & s = 1/2 \\ 0.41 & s = 1 \\ 0.05 & s = 2 \end{cases}$$

Hawking, Commun. Math. Phys. 43, 199 (1975)
Carr, Astrophys. J. 206, 8 (1976).
MacGibbon, Webber, Phys. Rev. D 41, 3052 (1990).

Hawking Evaporation



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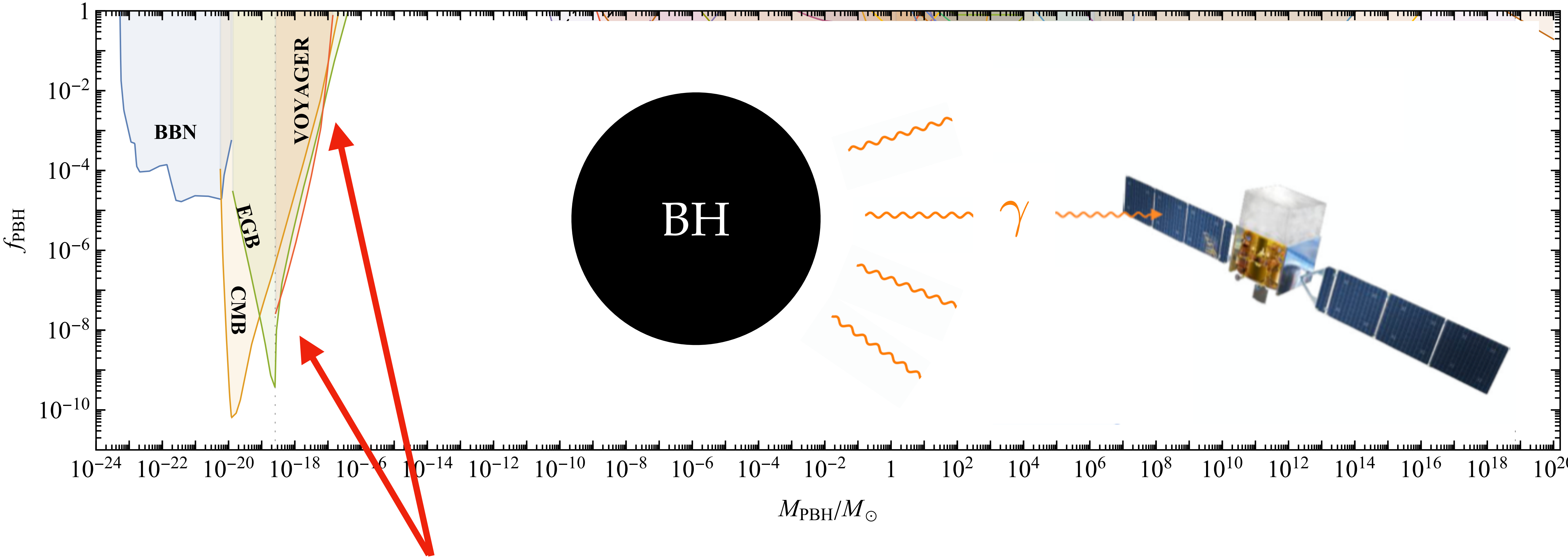
Lifetime highly sensitive to initial PBH mass

$$\tau_{\rm BH} = \int_0^{M_i} \frac{dM_{\rm BH}}{\dot{M}_{\rm BH}} \approx 4{\rm s} \left(\frac{M_i}{10^8\,{\rm g}}\right)^3$$

NB : $m_{\rm Pl} \sim$ mg

EM Particle Emission in Late Universe



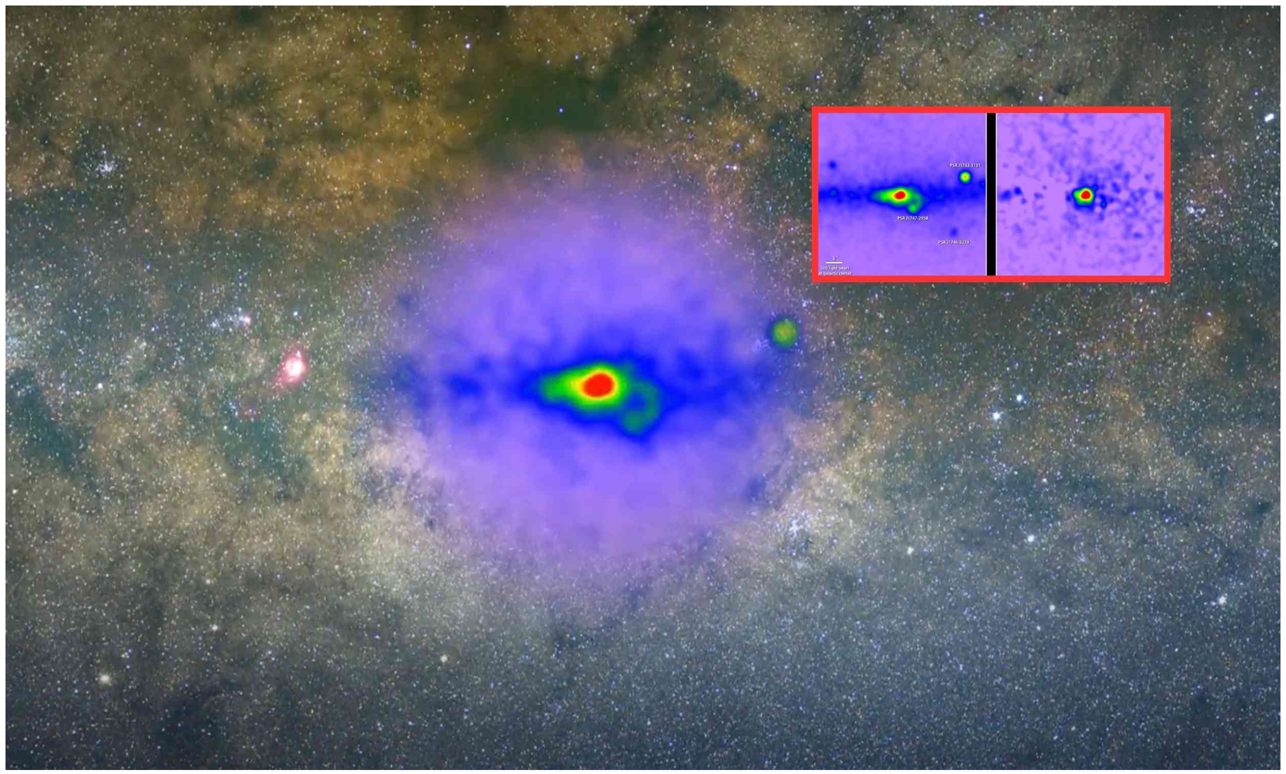
Near this edge, PBH lifetime ~ 10 Gyr with T ~ MeV

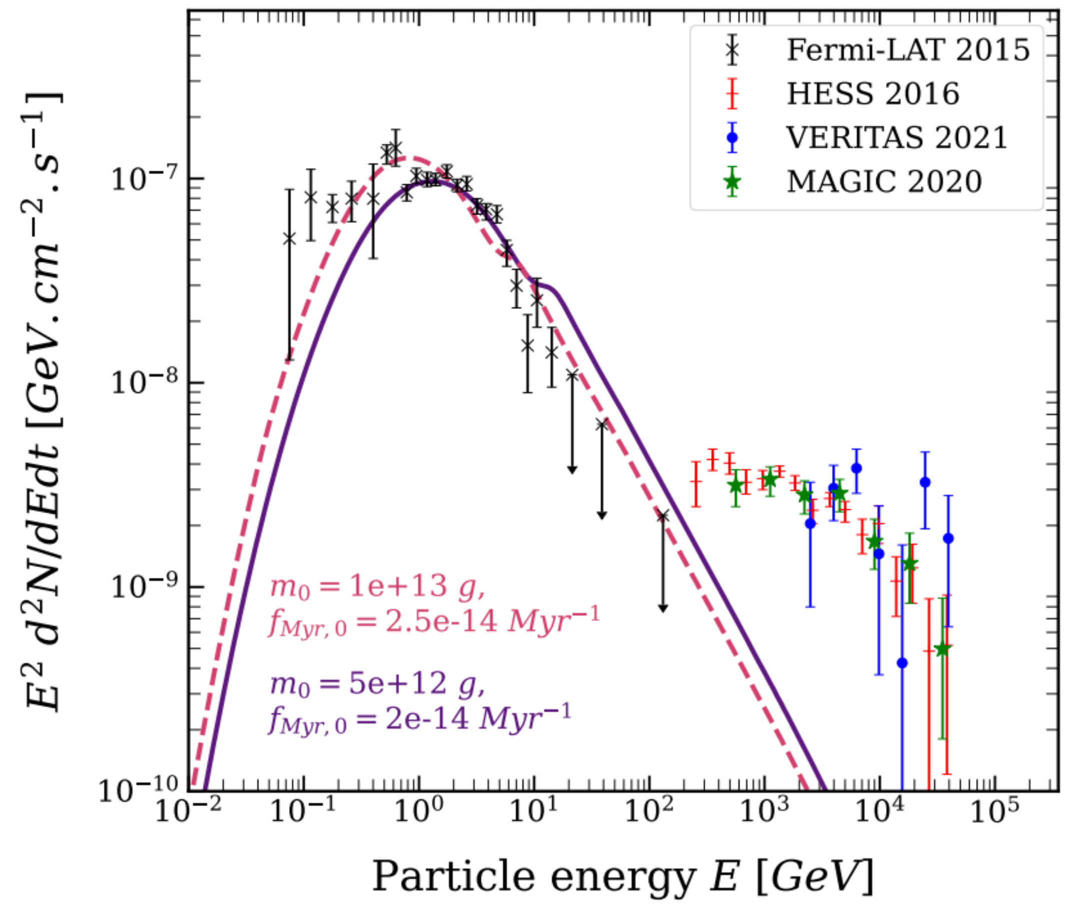
Emission of gamma rays, electrons, positrons, neutrinos

$$\Phi_\gamma^{\rm obs} > n_{\rm PBH} \int dt \frac{dN_\gamma}{dE_\gamma dt}$$

Carr (1975) Page, Hawking, (1976), MacGibbon, Carr (1989)

Galactic Center Excess?





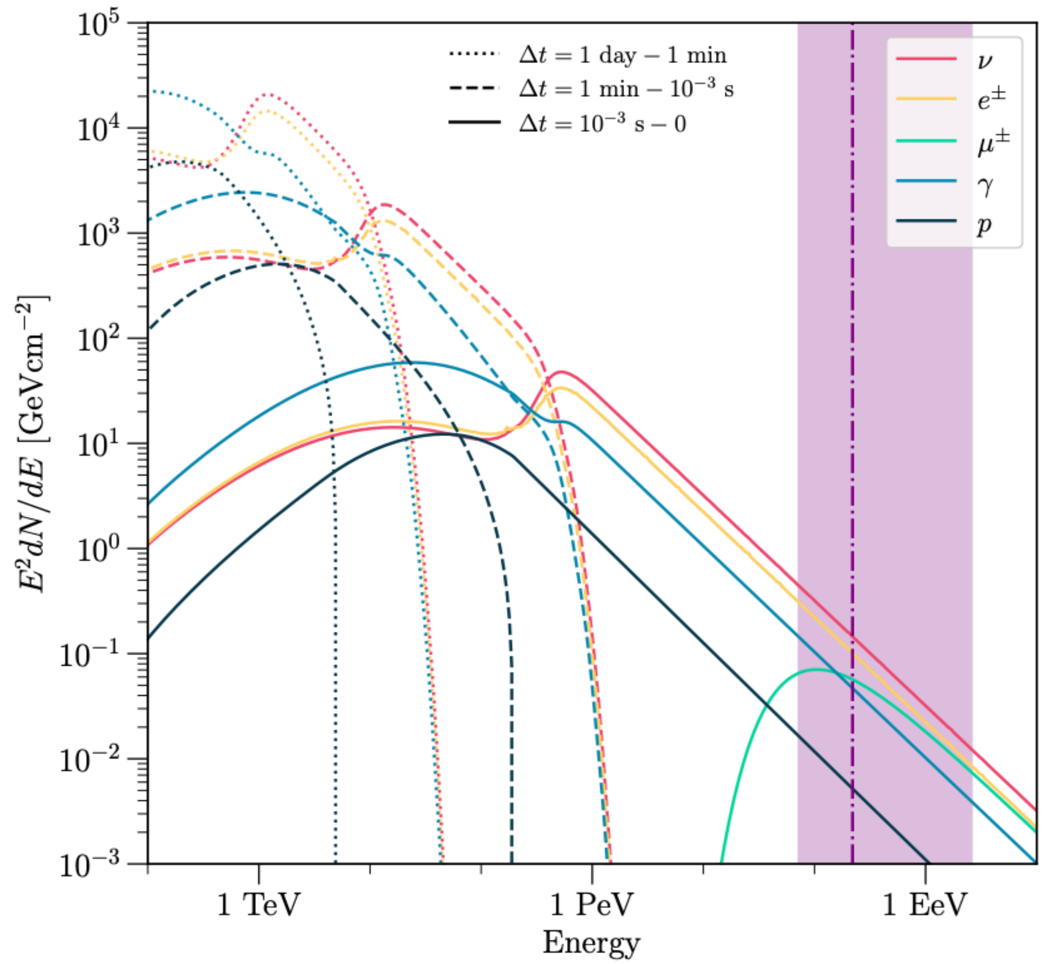
Longstanding excess of gamma rays in galactic center

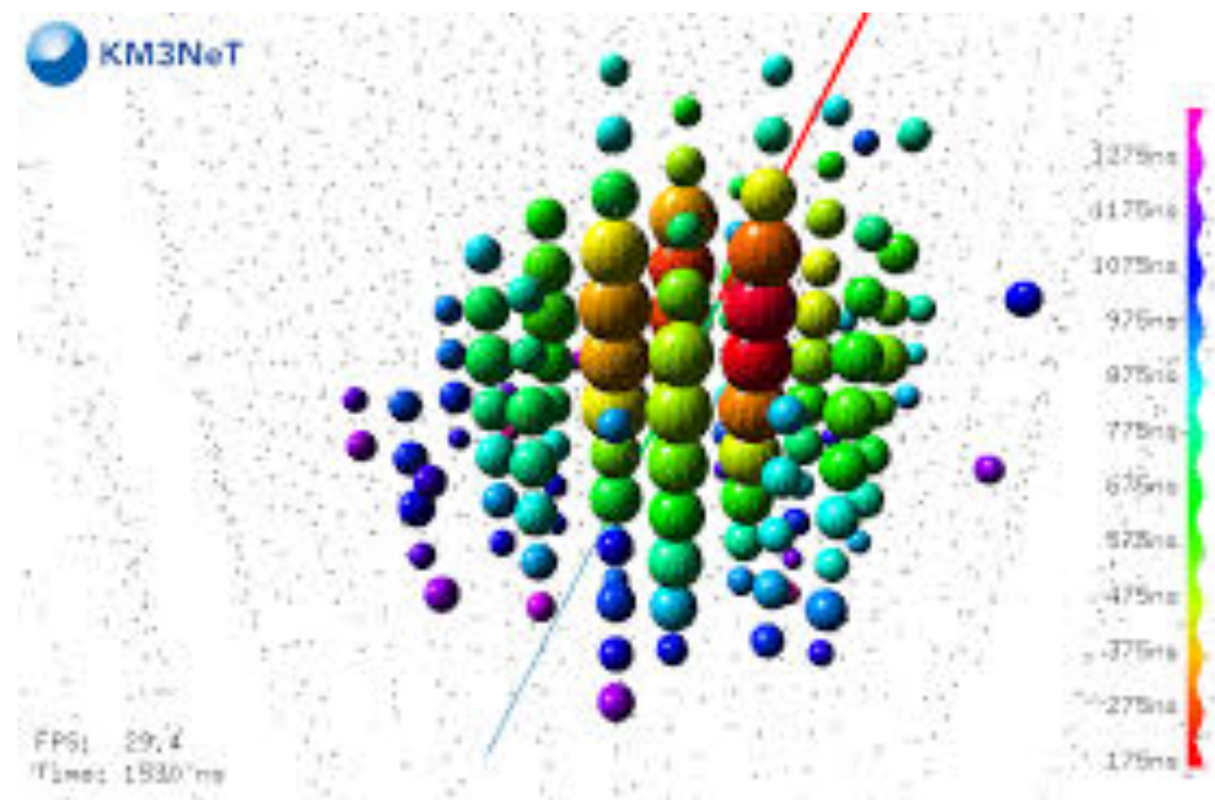
Spectrum of PBH evaporation products can match GCE
… but need late-time formation of fast-evaporating PBH

Picker, Kusenko, 2305.13434,

Flores, Kusenko 2008.12456

Neutrino Emission in the Late Universe





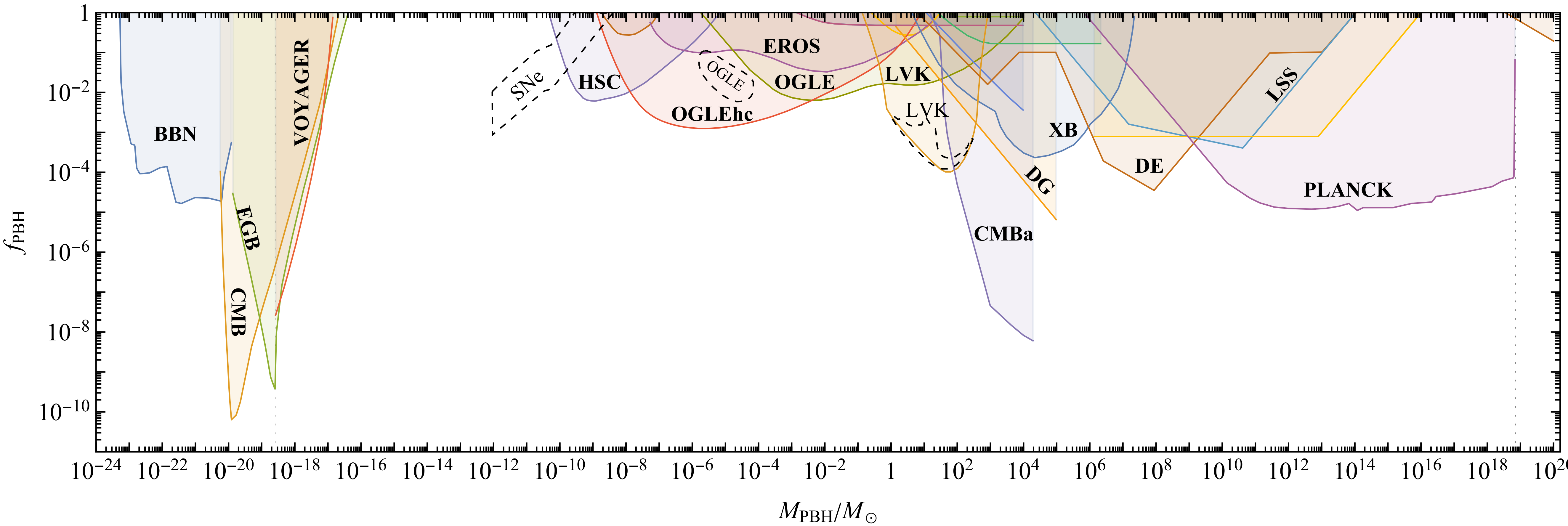
Evaporation near end of PBH life can emit high energy neutrinos.
If PBH sufficiently nearby, can explain ~ 100 PeV KM3NeT event

Klipfel, Kaiser 2503.19227

Some tension with EM particle fluxes

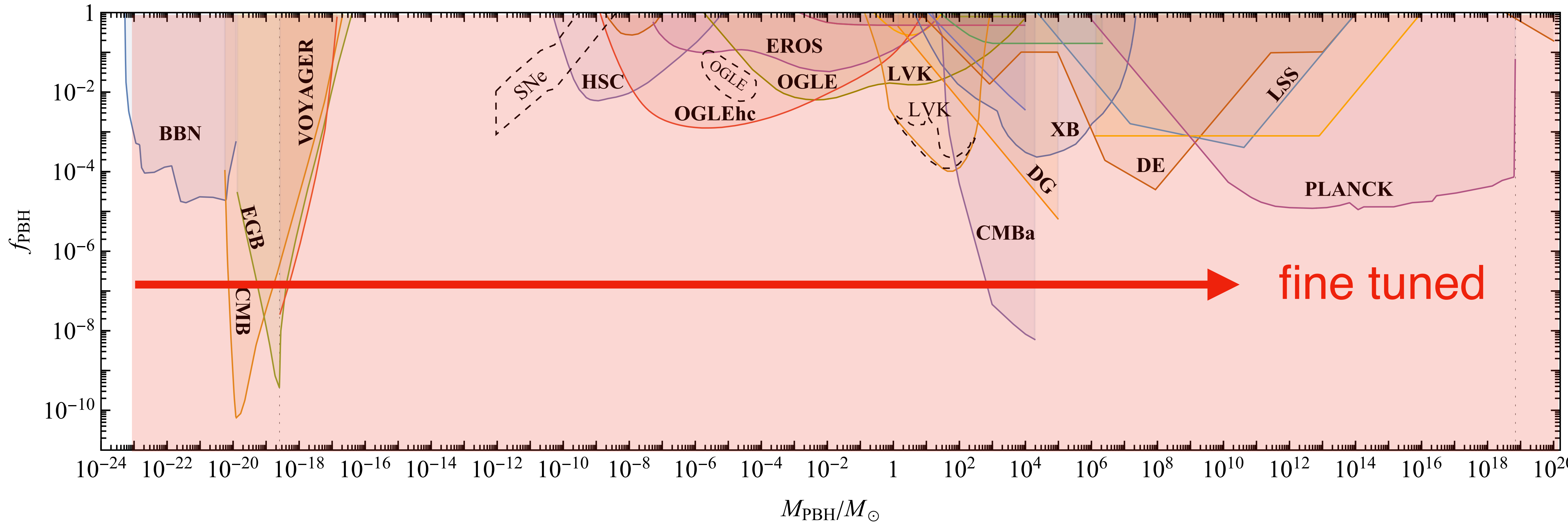
Airoldi, Alves, Perez-Gonzales, Salla, Funchal 2505.24666

There's Just One Problem…



PBH Always redshift like matter $\quad \rho_{\rm BH} \propto a^{-3} \implies \frac{\rho_{\rm BH}}{\rho_{\rm rad}} \propto a$

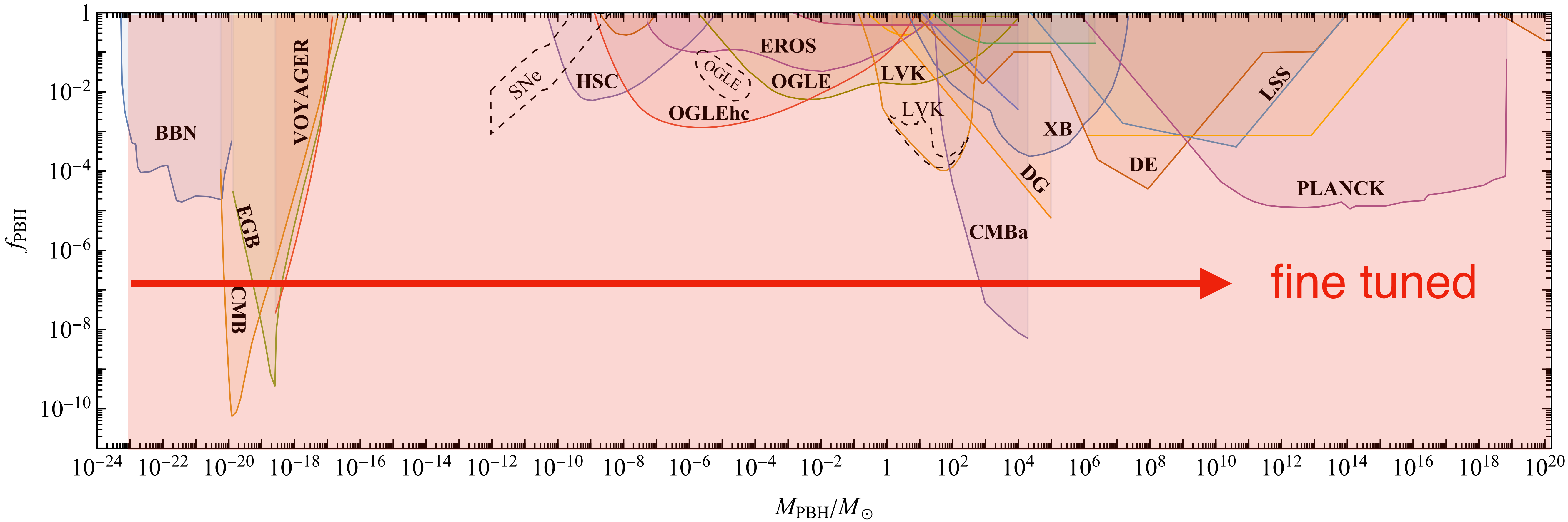
There's Just One Problem…



PBH Always redshift like matter $\rho_{\rm BH} \propto a^{-3} \implies \frac{\rho_{\rm BH}}{\rho_{\rm rad}} \propto a$

Need extremely fine-tuned initial abundance… ☹️

There's Just One Problem…

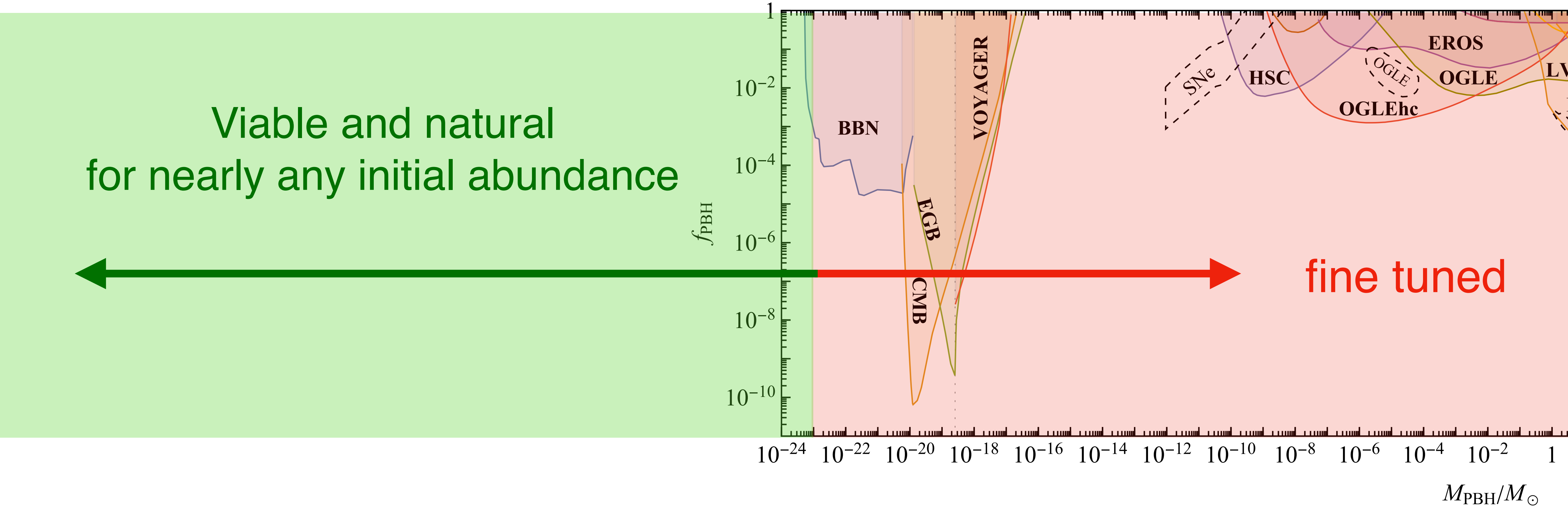


PBH Always redshift like matter $\quad \rho_{\rm BH} \propto a^{-3} \implies \frac{\rho_{\rm BH}}{\rho_{\rm rad}} \propto a$

Need extremely fine-tuned initial abundance… ☹️

"Never let a good crisis go to waste"
Rahm Emanuel (Former Chicago Mayor)

There's Just One ~~Problem~~…Opportunity!



If evaporation occurs before BBN, PBH can dominate the universe 😎

$$\tau_{\rm BH} \sim 1\,{\rm s}\left(\frac{M_{\rm BH}}{10^9\,{\rm g}}\right)^3$$

"When they go high, we go low"
Al Capone*

*probably

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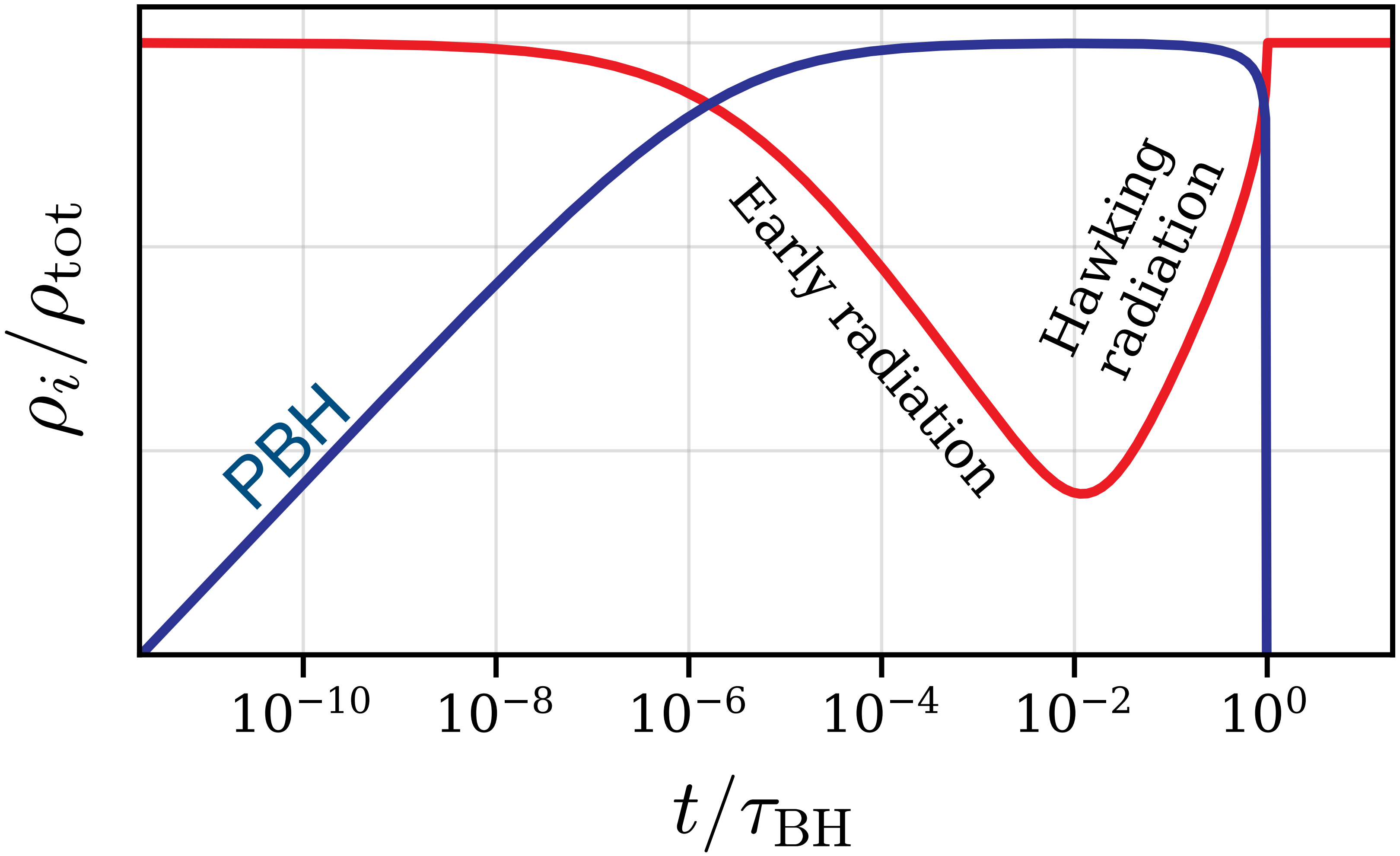
PBH Domination



1. Very light PBH naturally dominate universe (tiny abundance is enough!)

2. Hawking radiation thermalizes to restore thermal bath before BBN

3. Nearly every prediction is set by PBH mass

Morrison, Profumo, Yu 1812.10606

Hooper, GK, McDermott 1905.01301

PBH Domination

Boltzmann system

$$\dot{\rho}_{\mathrm{BH}} + 3H\rho_{\mathrm{BH}} = -\frac{\dot{M}_{\mathrm{BH}}}{M_{\mathrm{BH}}}\rho_{\mathrm{BH}}$$

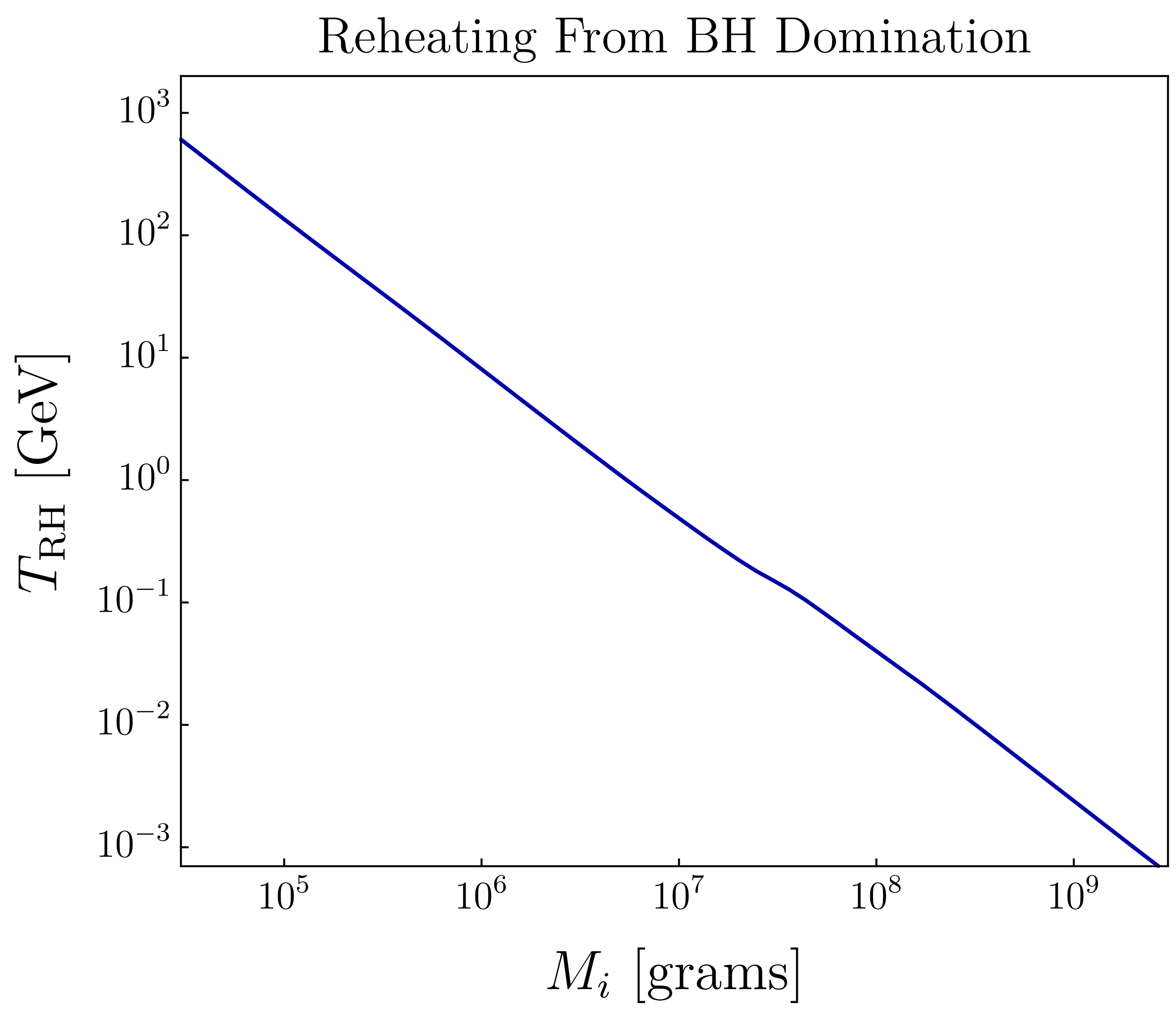
$$\dot{\rho}_R + 4H\rho_R = +\frac{\dot{M}_{\mathrm{BH}}}{M_{\mathrm{BH}}}\rho_{\mathrm{BH}}$$

Hubble rate matter dominated

$$H \approx \sqrt{\frac{8\pi G\rho_{\mathrm{BH}}}{3}} = \frac{2}{3t}$$

At evaporation time $t = \tau_{\mathrm{BH}}$

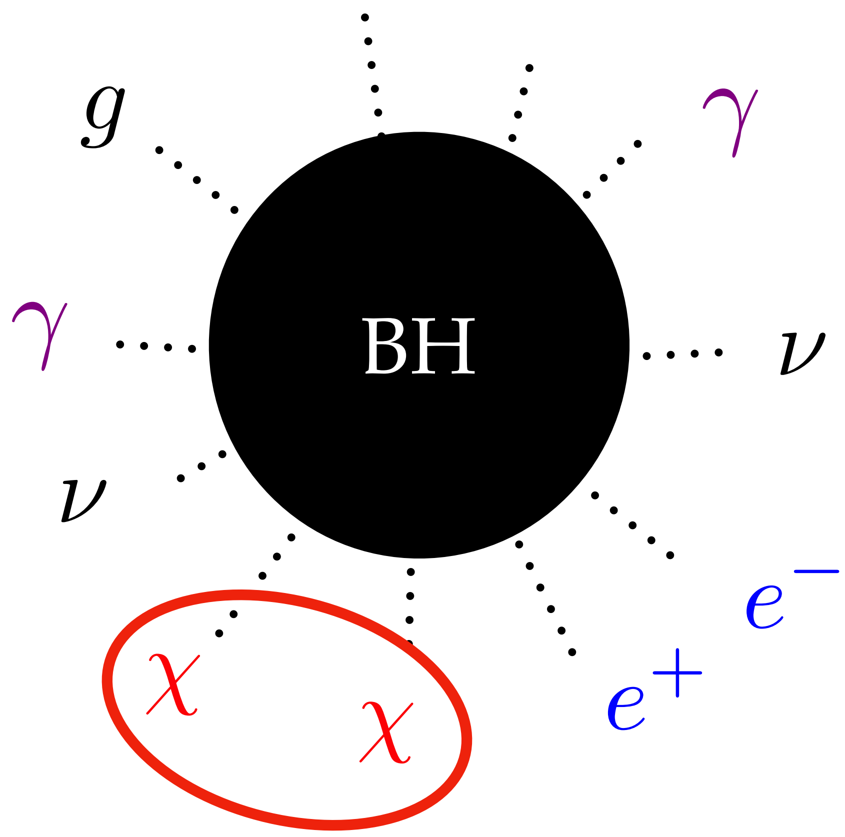
$$\rho_{\mathrm{BH}} \approx \rho_R \implies \frac{2}{3\tau_{\mathrm{BH}}} \sim \frac{T_{\mathrm{RH}}^2}{M_{\mathrm{Pl}}}$$



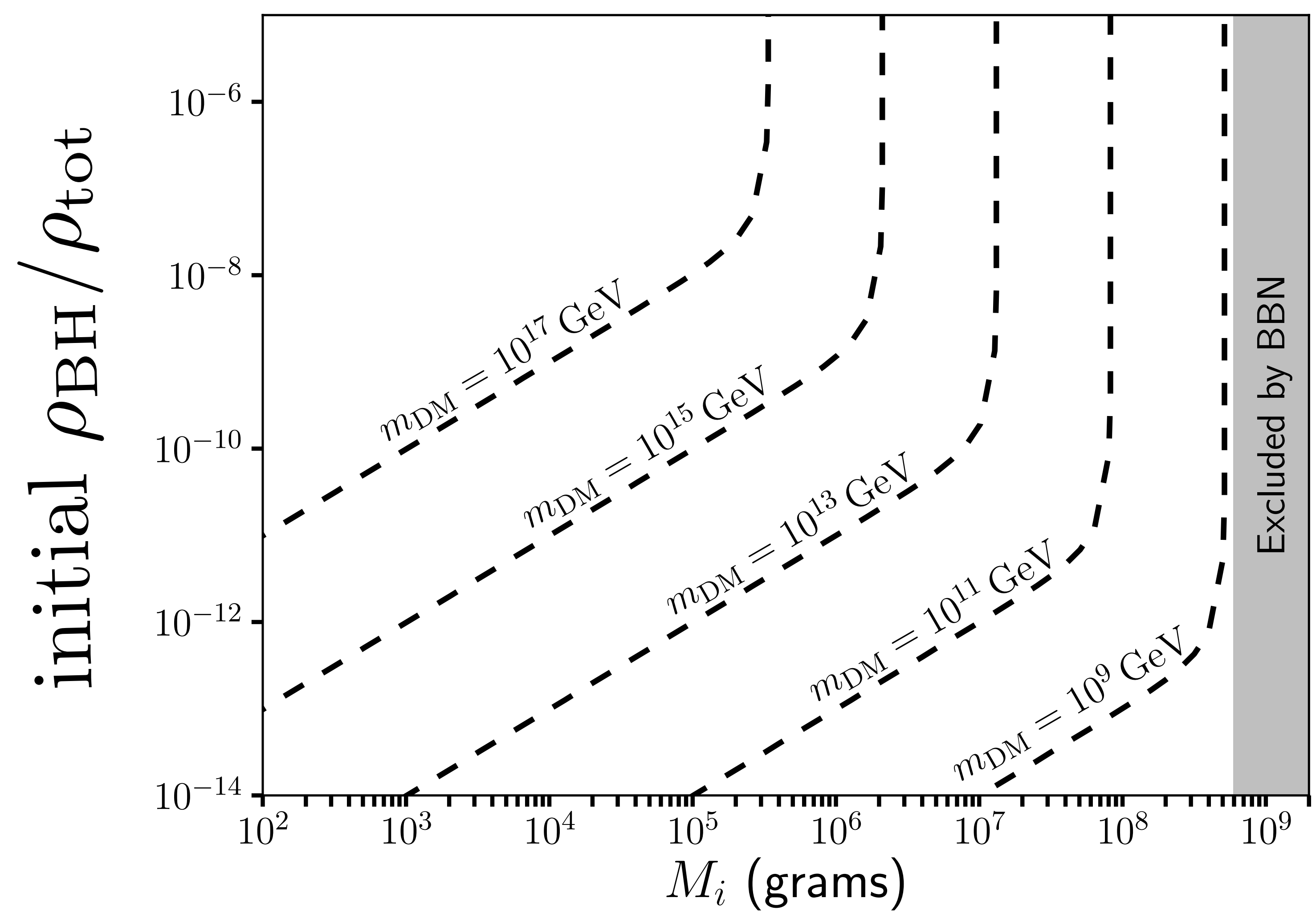
$$\tau_{\mathrm{BH}} \propto M_{\mathrm{BH}}^3$$

Hooper, GK, McDermott 1905.01301

Dark Matter From PBH Domination



DM from Hawking radiation



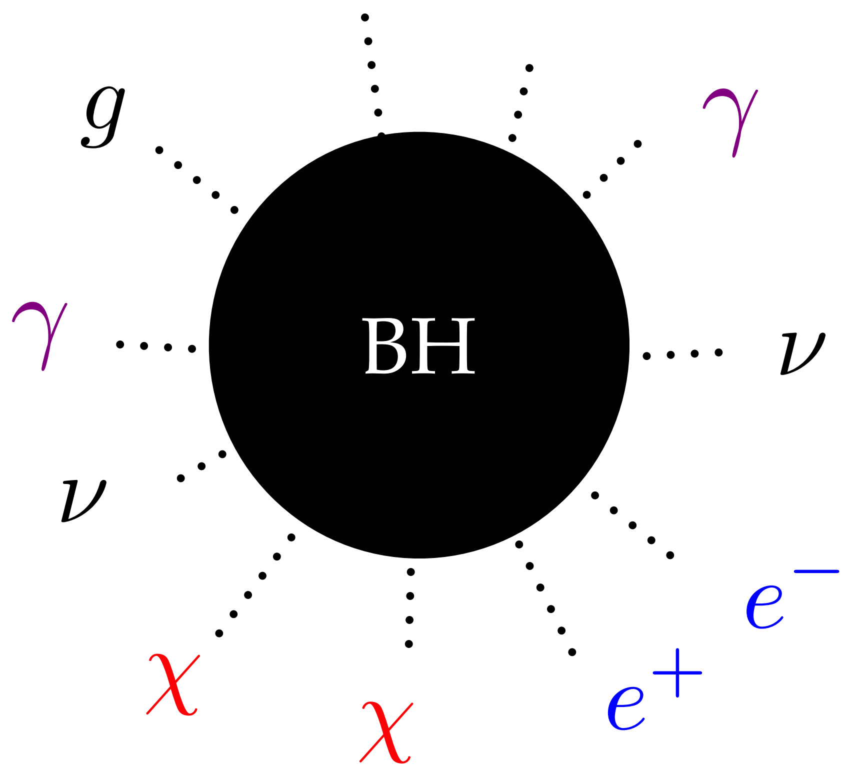
Assumes DM does not thermalizes with surrounding plasma

Requires ultra-heavy DM mass scale $> 10^9$ GeV

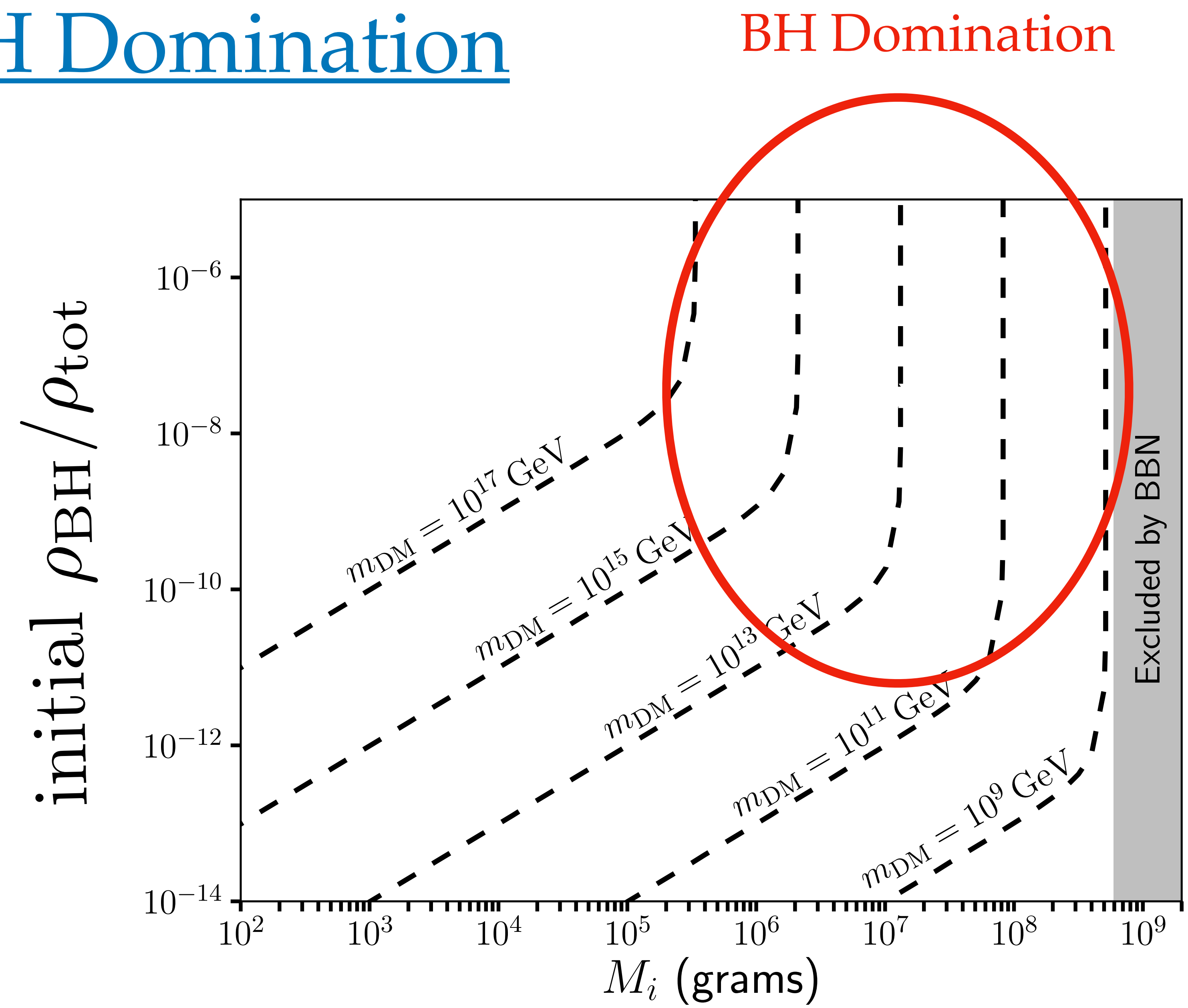
Morrison, Profumo, Yu 1812.10606

Hooper, GK, McDermott 1905.01301

Dark Matter From PBH Domination



DM from Hawking radiation



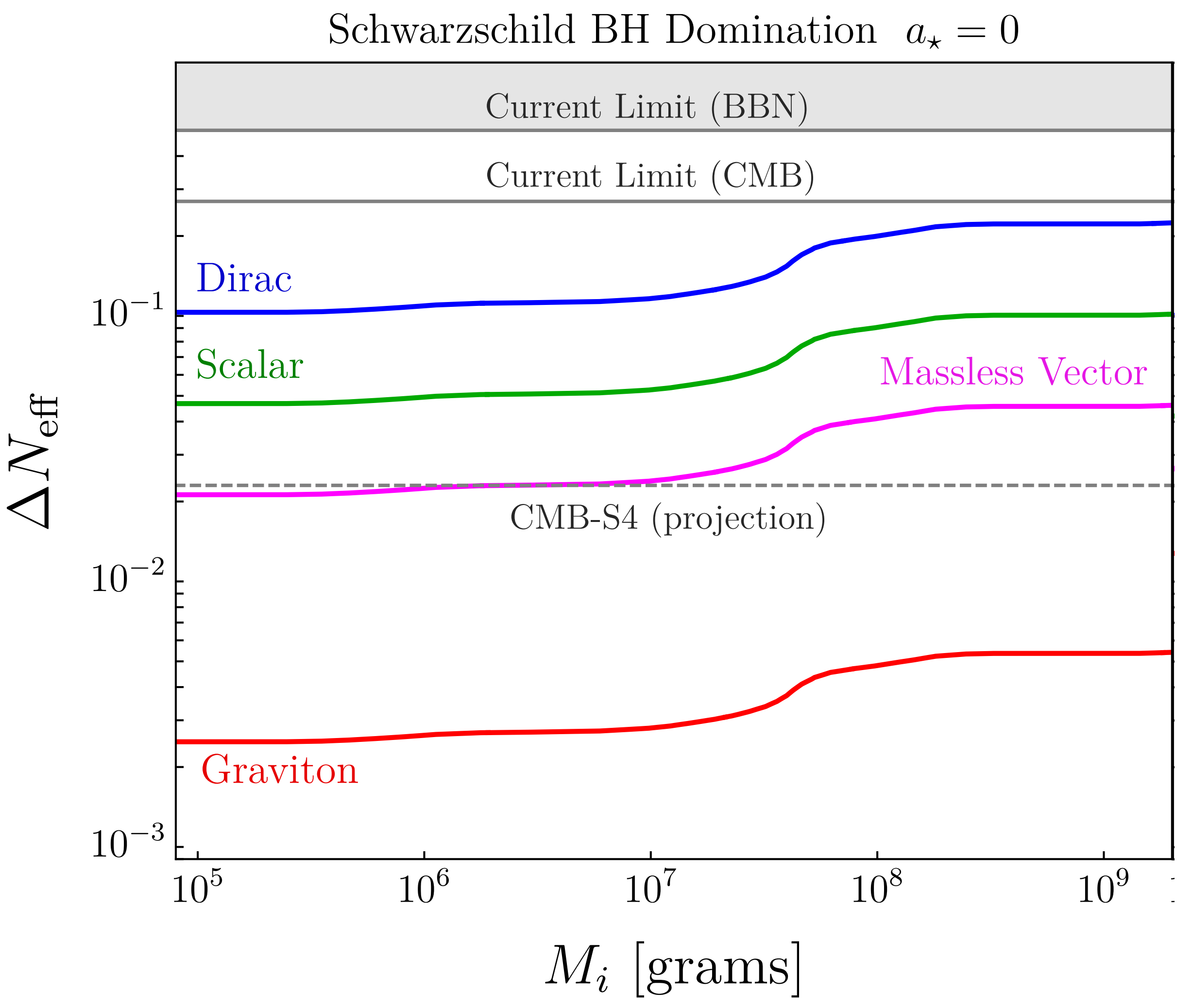
Assumes DM does not thermalizes with surrounding plasma

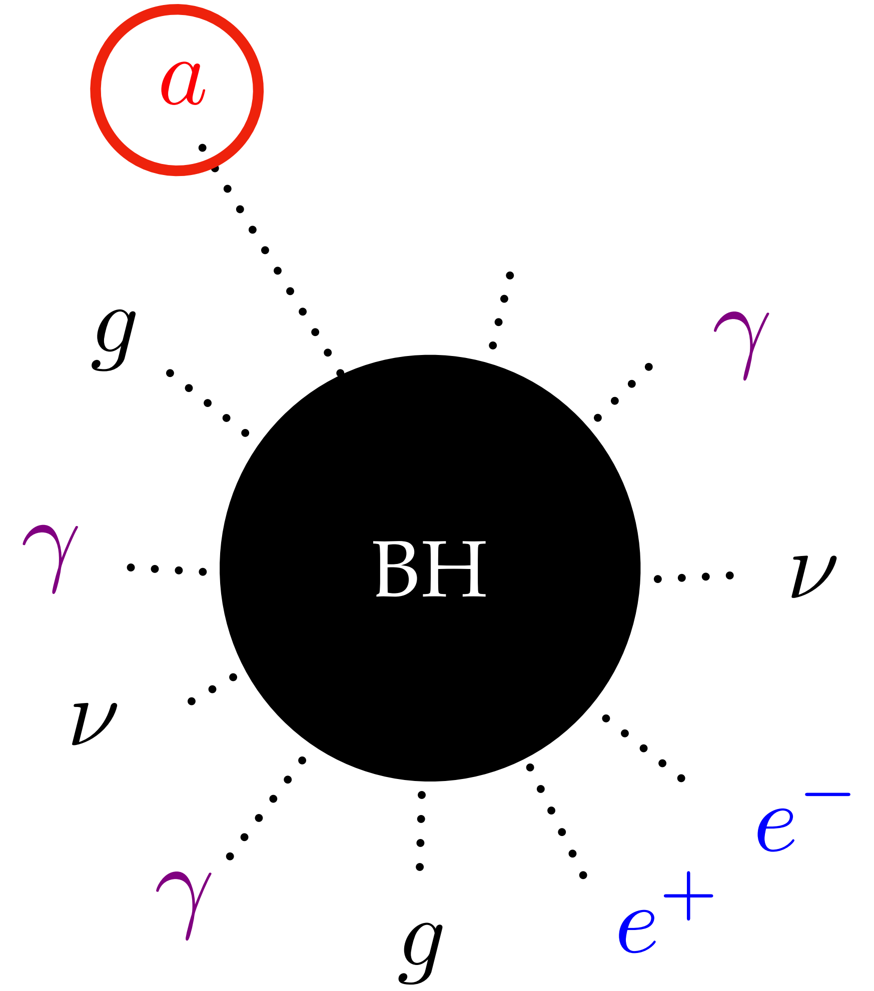
Requires ultra-heavy DM mass scale $> 10^9$ GeV

Morrison, Profumo, Yu 1812.10606

Hooper, GK, McDermott 1905.01301

Dark Radiation From PBH Domination



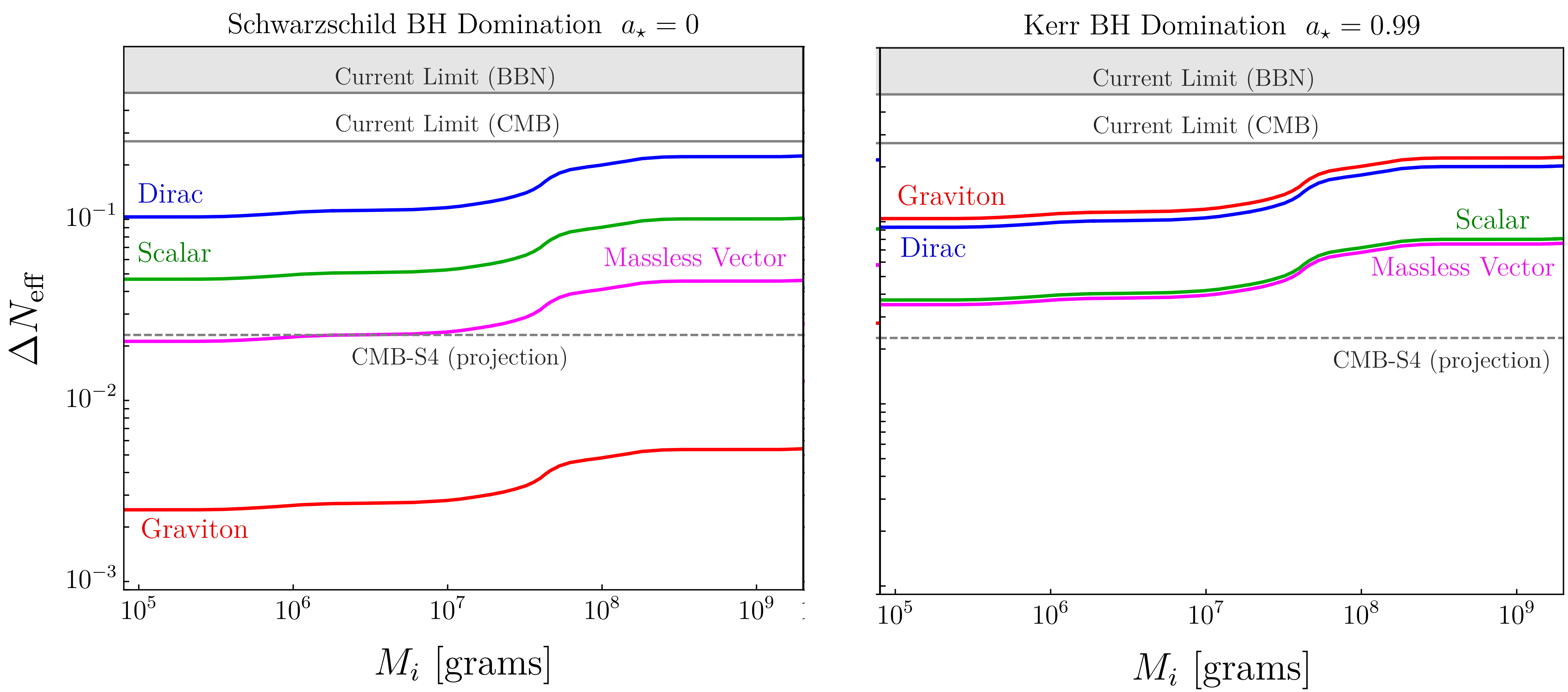


Hawking evaporation produces all known **and unknown** particles
Light new particles contribute to present-day radiation density

$$\Delta N_{\rm eff} = \frac{\rho_{\rm DR}}{\rho_{\nu_i} + \rho_{\bar{\nu}_i}}$$

Hooper, GK, McDermott 1905.01301

Dark Radiation From PBH Domination

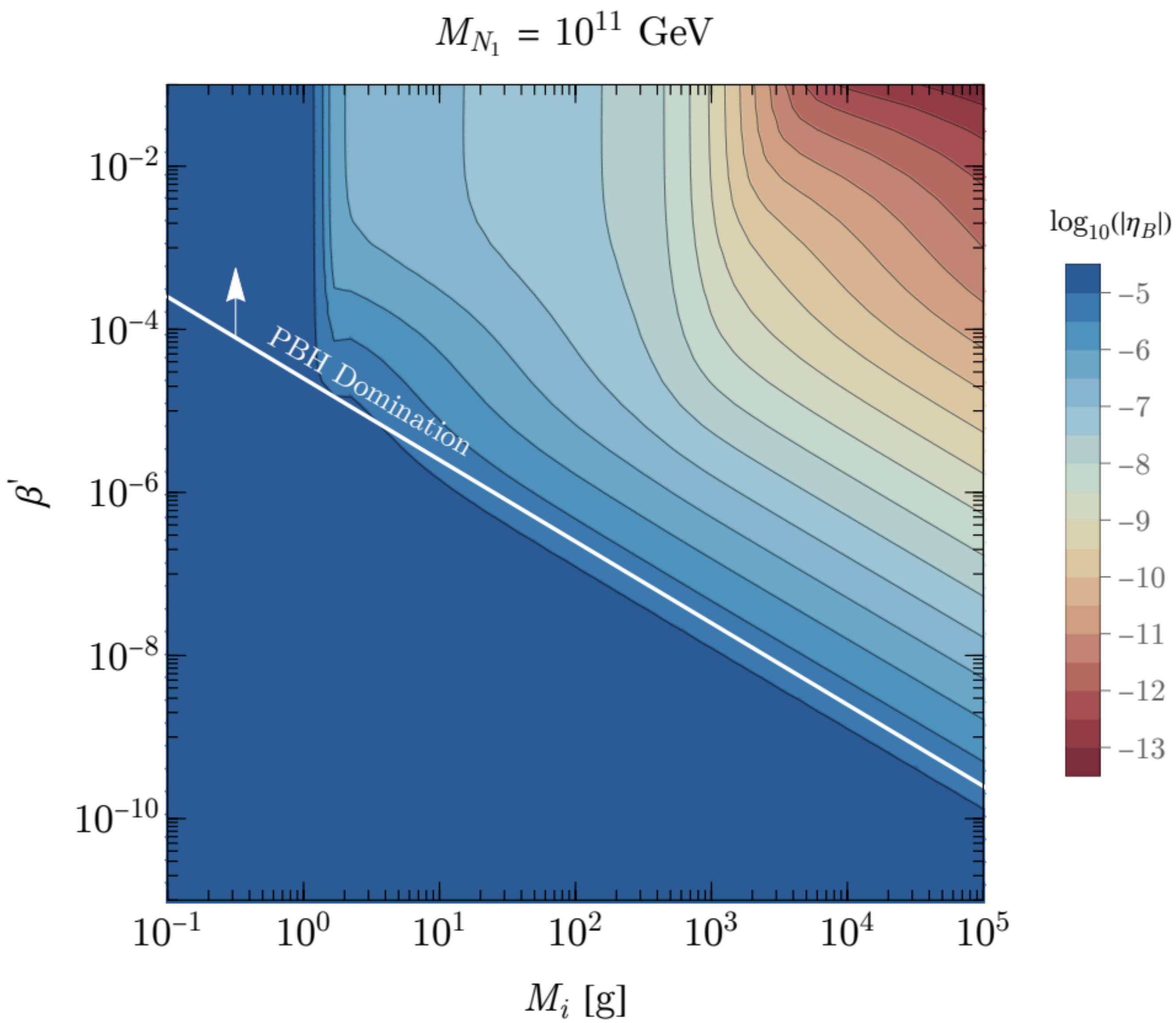


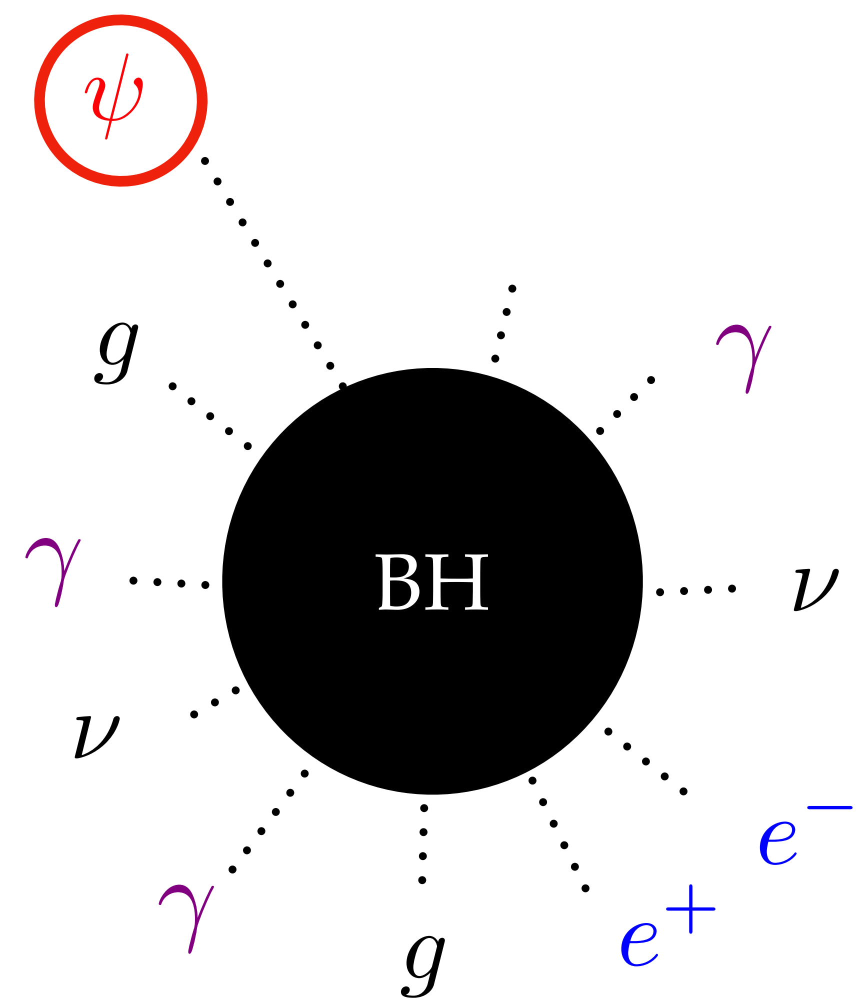
If the PBH have large spin, they produce a hot graviton background

$$\Delta N_{\rm eff} = \frac{\rho_{\rm DR}}{\rho_{\nu_i} + \rho_{\bar{\nu}_i}}$$

Hooper, GK, McDermott 1905.01301 Hooper, GK, March-Russell, McDermott, Petrosian-Byrne 2004.00618

Baryogenesis From PBH Domination





PBH evaporation injects heavy particles out of equilibrium

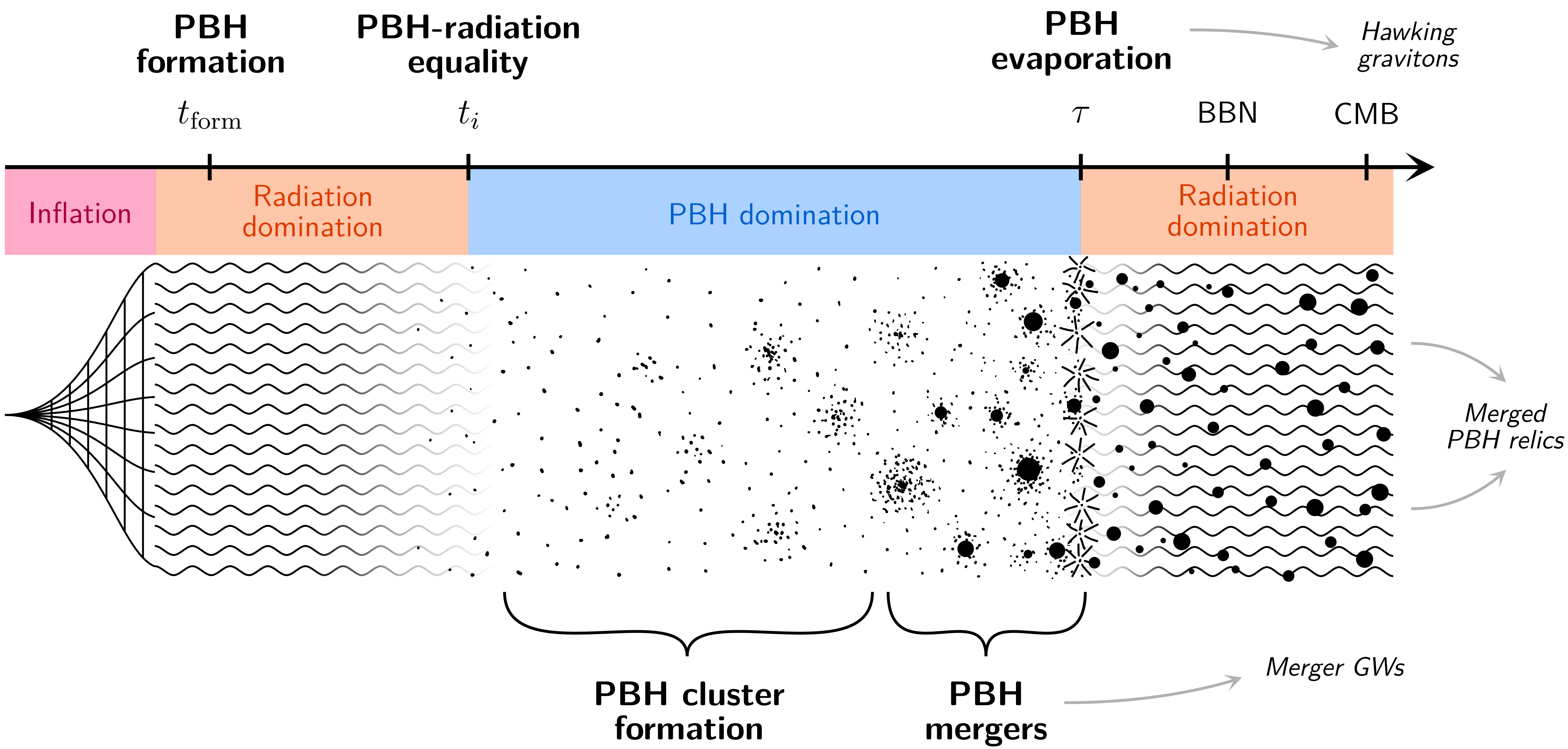
Baryon/lepton violating decays occur without washout $T_{\rm BH} \gg T_{\rm RH}$

Rescues GUT baryogengesis and low-scale leptogenesis

Baumann, Steinhardt, Turok 0703250
Hooper, GK, 2010.01134

Perez-Gonzales, Turner 2010.03565
Klipfel, Vanvlasselaer, Trifinopoulos, Kaiser 2603.29024

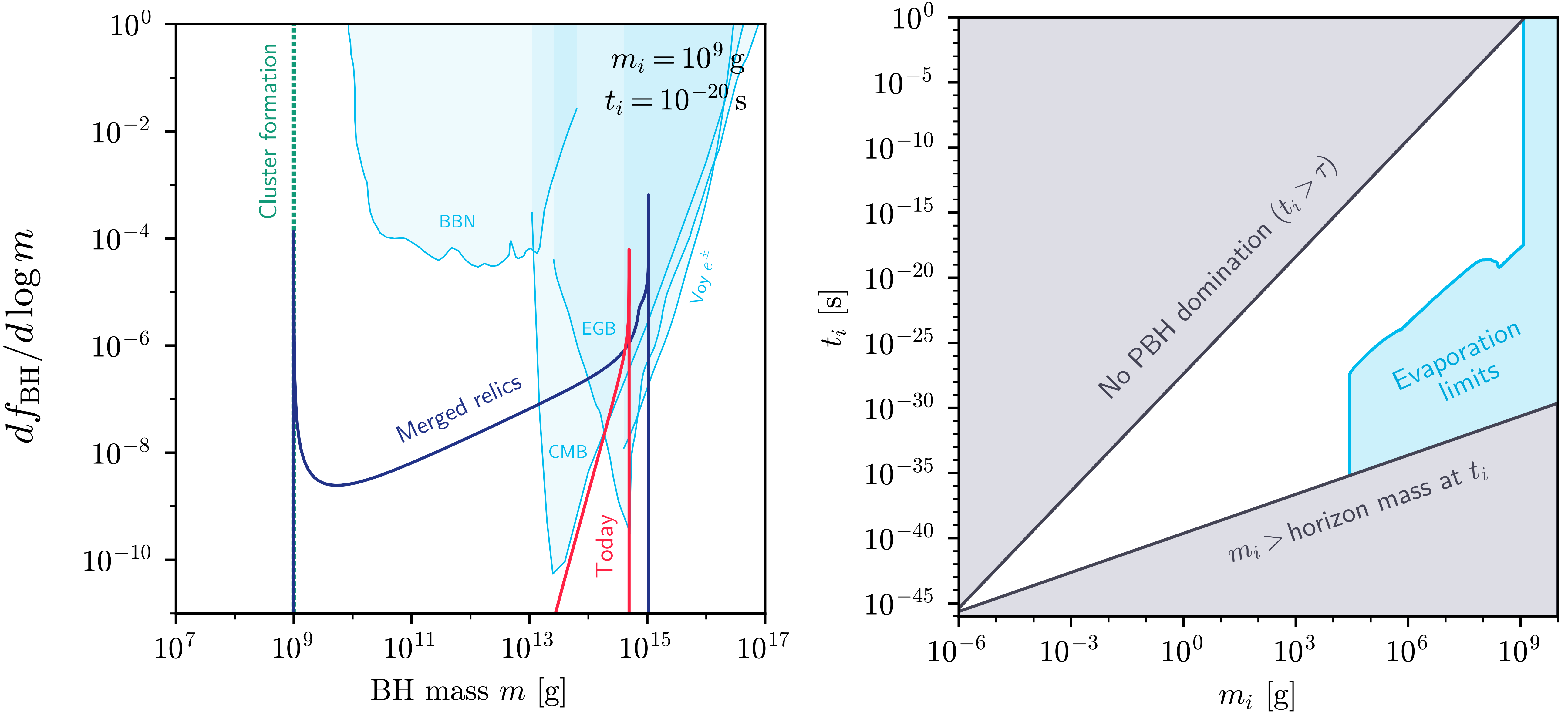
Mergers During PBH Domination



During early matter domination, perturbations grow, haloes form
PBH can cluster and merge to become more massive (longer lived)

Holst, GK, Xiao 2412.01890

Mergers During PBH Domination



During early matter domination, perturbations grow, haloes form
PBH can cluster and merge to become more massive (longer lived)

Holst, GK, Xiao 2412.01890

First limits on this cosmology

Overview

Early Universe Formation

Hawking Evaporation

Black Hole Dominated Cosmology

Are PBH the only compact objects we can make?

Primordial *Neutron Stars?*

Q: What prevents neutron star formation in early universe?

Primordial *Neutron Stars?*

Q: What prevents neutron star formation in early universe?

A: In standard cosmology, not enough baryon number inside horizon

$$M_B = \frac{4\pi m_p s Y_B}{3H^3} \approx 0.3 M_\odot \left(\frac{Y_B}{10^{-10}}\right)\left(\frac{500\,\mathrm{keV}}{T}\right)^3$$

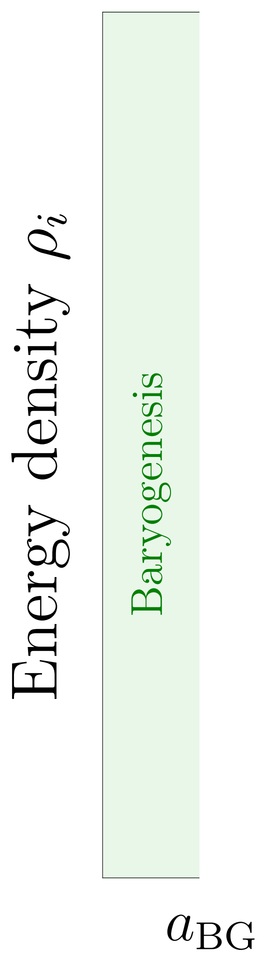
Baryonic mass inside causal horizon

Baryon-entropy ratio

Need *much* larger baryon number than we observe

… but this is possible with Affleck-Dine baryogenesis

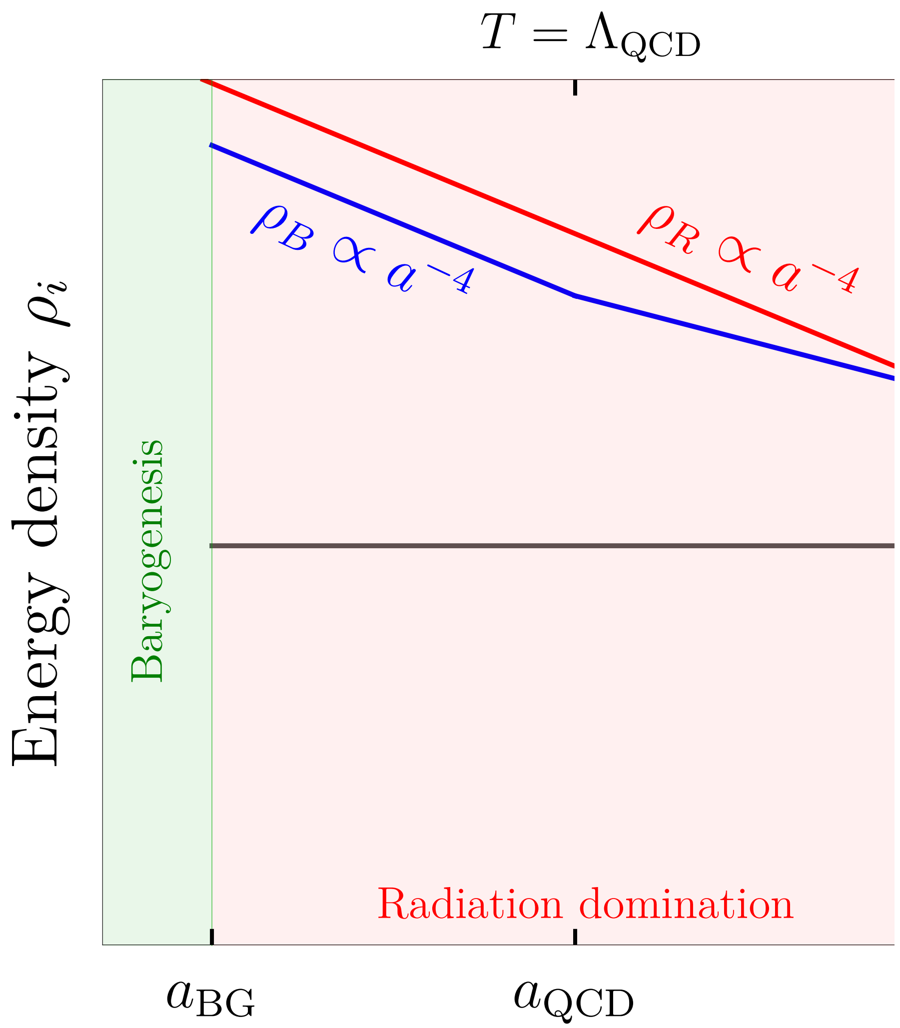
Primordial *Neutron Stars*



Step 1: baryogengesis initially creates $Y_B = \dfrac{n_B}{s} \gg 10^{-10}$

GK, Rocha, Xiao 2604.08651

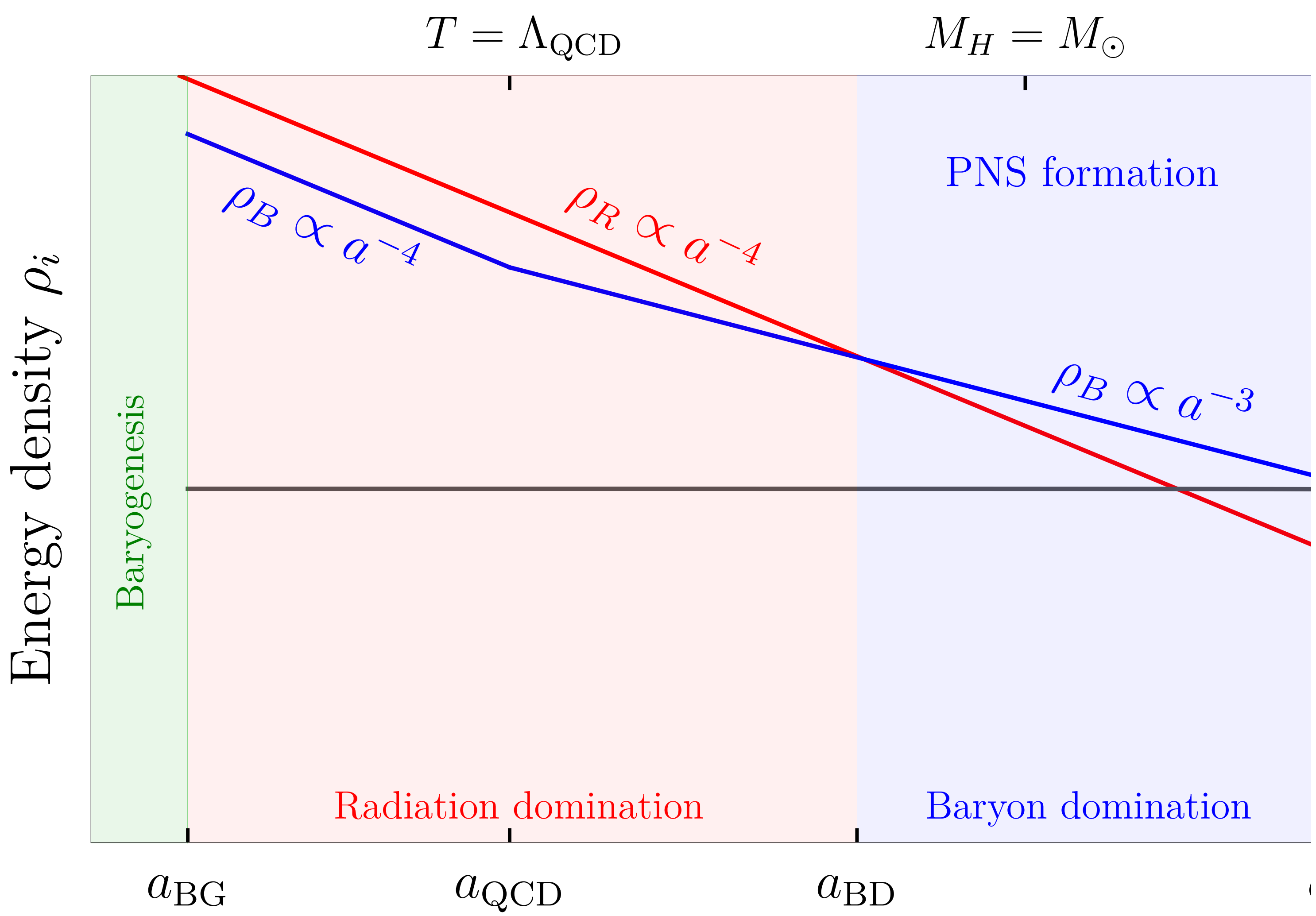
Primordial *Neutron Stars*

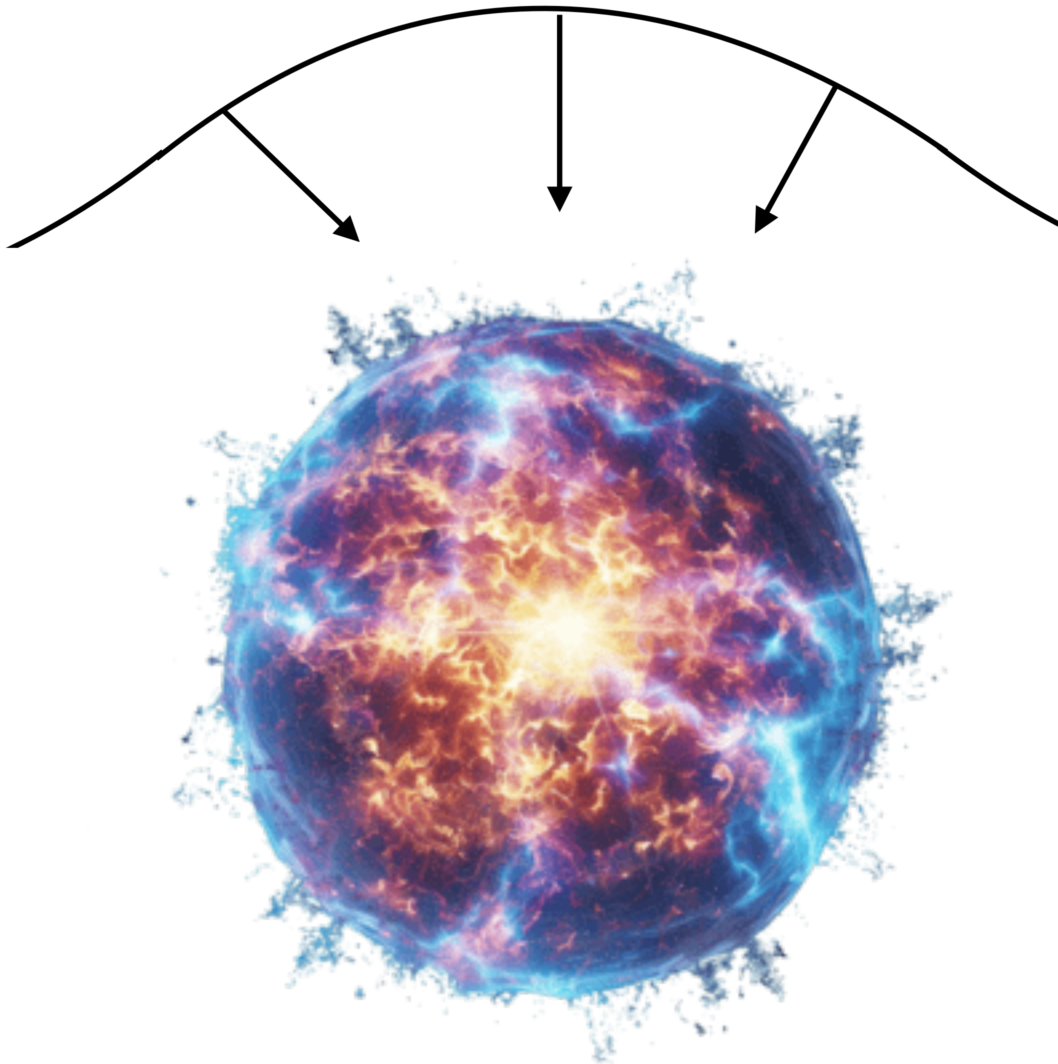


Step 2: confinement occurs, baryons become non-relativistic

GK, Rocha, Xiao 2604.08651

Primordial *Neutron Stars*



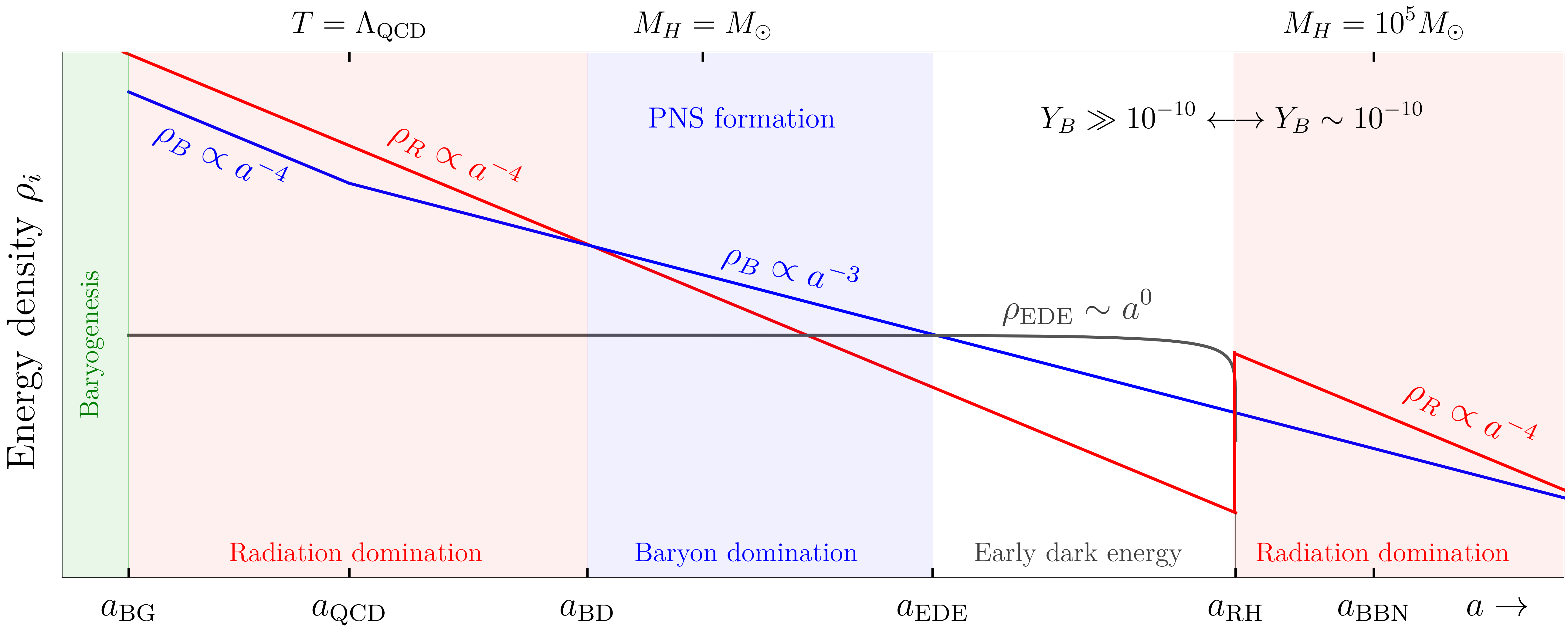


$$\delta_c^{\rm PNS} < \delta < \delta_c^{\rm PBH}$$

Step 3: baryons dominate universe when horizon contains ~ 1 solar mass
fluctuations just below PBH threshold form **neutron stars** instead

GK, Rocha, Xiao 2604.08651

Primordial *Neutron Stars*

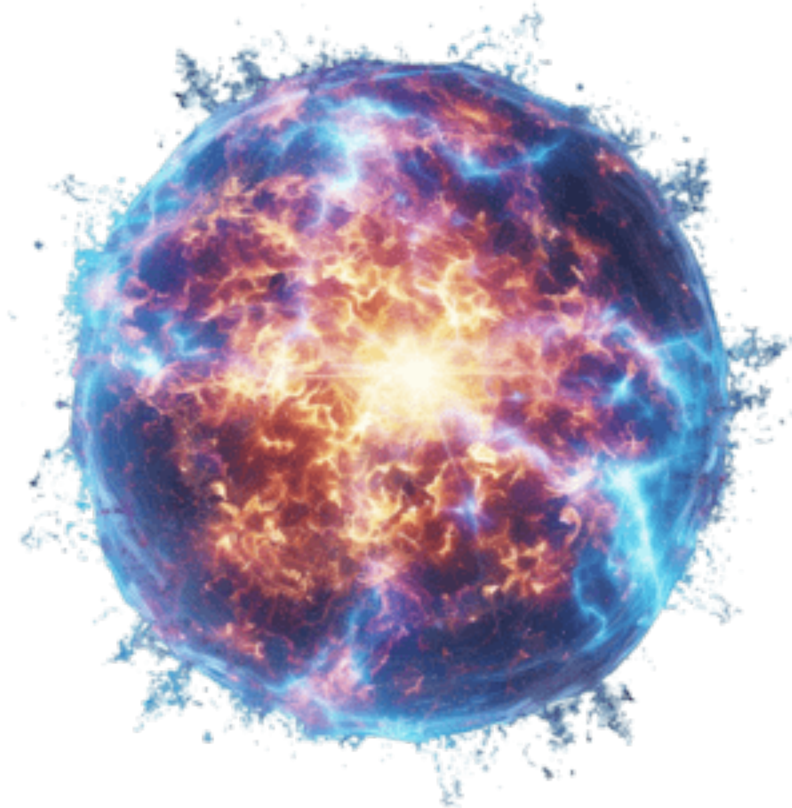


Step 4: entropy dump restores observed baryon asymmetry $Y_B \sim 10^{-10}$

reheats universe below confinement temp, neutron stars survive

GK, Rocha, Xiao 2604.08651

Primordial *Neutron Stars*



Small magnetic field

non-stellar collapse, no initial seed field

Low temperature

Tracks CMB over cosmic time, generically cold

Distributed in halo like dark matter

May be more abundant than conventional neutron stars

Smoking gun: sub-solar mass

Can be as light as ~ 0.1 solar mass from QCD

GK, Rocha, Xiao 2604.08651

See Duncan Rocha's talk

Conclusion: PBH are particle fountains

Many formation mechanisms

Collapsing density perturbations, phase transitions, defects…

Indirect detection: late-time Hawking evaporation

Fluxes of photons, neutrinos, electrons positrons

Connections to KM3NeT, galactic center excess

PBH dominated cosmology

Attractor solution, simple & predictive

Make dark matter, dark radiation, baryogengesis

Primordial neutron stars

May also form if universe temporarily had a large baryon asymmetry

Thanks!