Primordial Black Hole Domination

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PITT PACC Workshop:
Non-Standard Cosmological Epochs
and Expansion Histories

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Outline:

Primordial Black holes (PBHs)
History
Motivations

light PBHs and:
Dark Matter
Dark Sectors
Dark Radiation
Baryogenesis

PBHs and Gravitational Waves

PBHs: BHs formed in the early Universe through a non-stellar way

Zel'dovich and Novikov 1960s
Hawking 1970s
Hawking and Carr 1970s

Why PBHs?

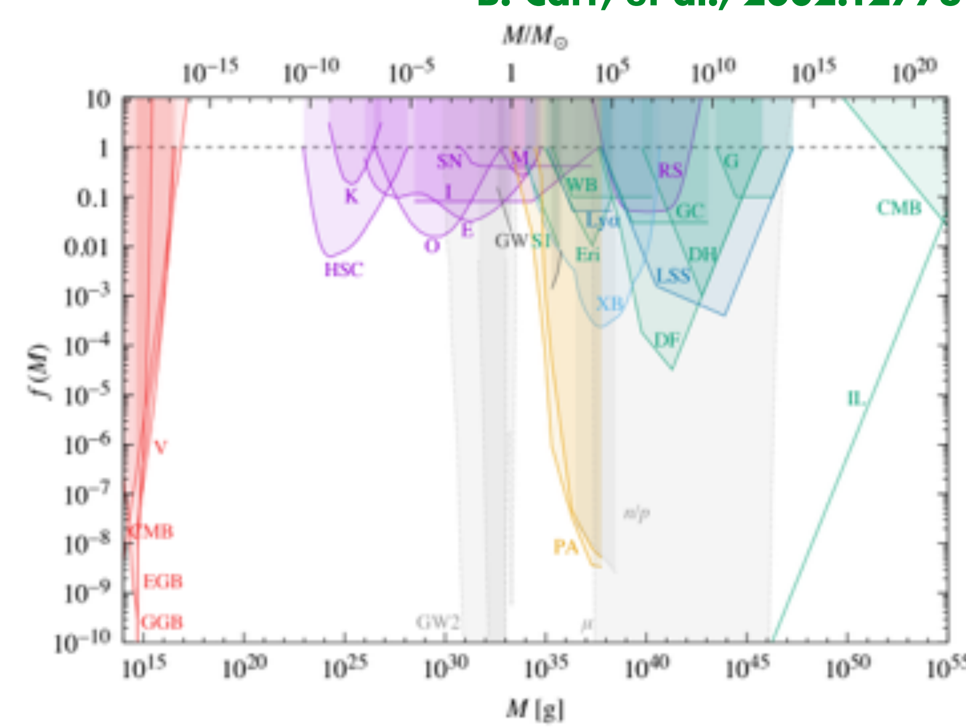
Formation mechanism provides information about the early Universe

Can alter the evolution of the Universe (Non-Standard Cosmologies, Stasis)

Provide a Gravitational production channel for (heavy) particles via Hawking evaporation

Provide a DM candidate which (unlike WIMPs, axions, sterile neutrinos,...) is NOT a new particle (however their formation does usually require Beyond the Standard Model physics, e.g. inflation).

B. Carr, et al., 2002.12778



Formation mechanism:

Collapse of primordial overdensities (standard scenario)
Collapse of topological defects
Particle Trapping by Bubble Walls
Scalar Fifth Force
Scalar-Field Fragmentation
Confinement (heavy quarks)

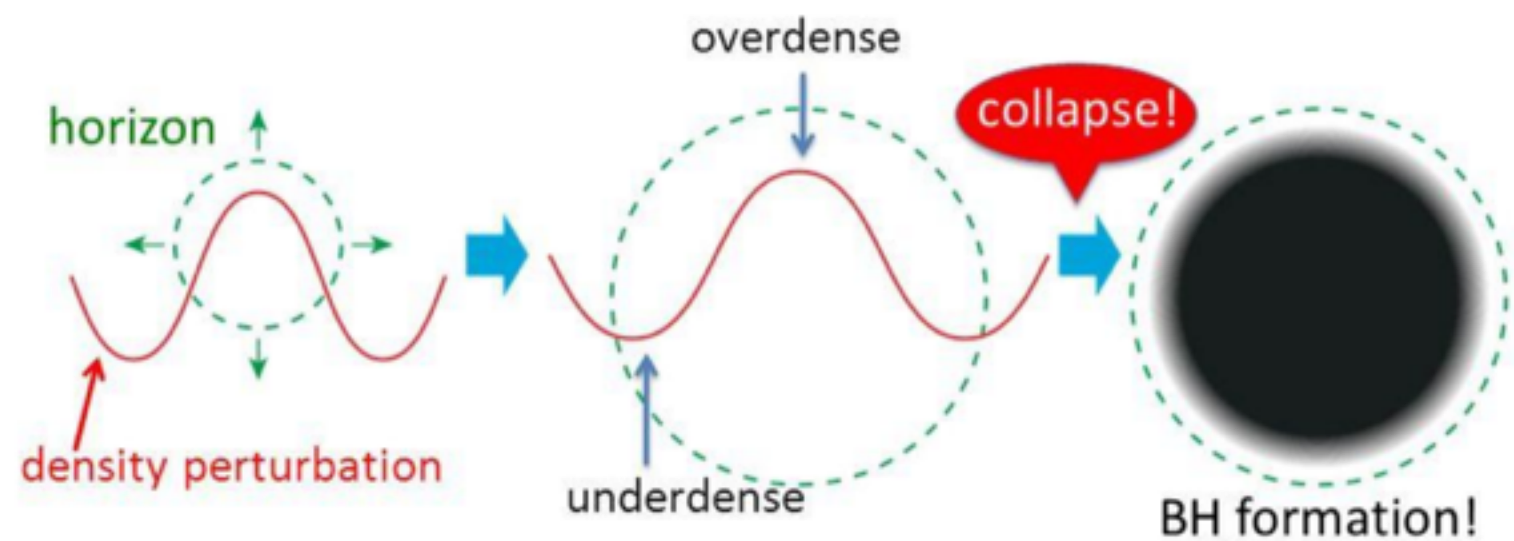
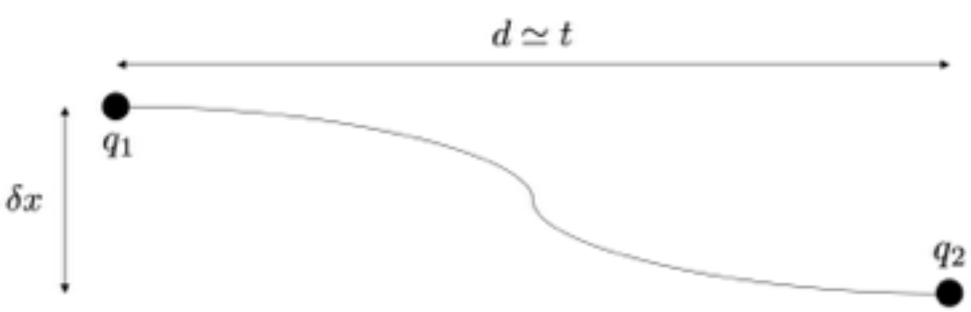
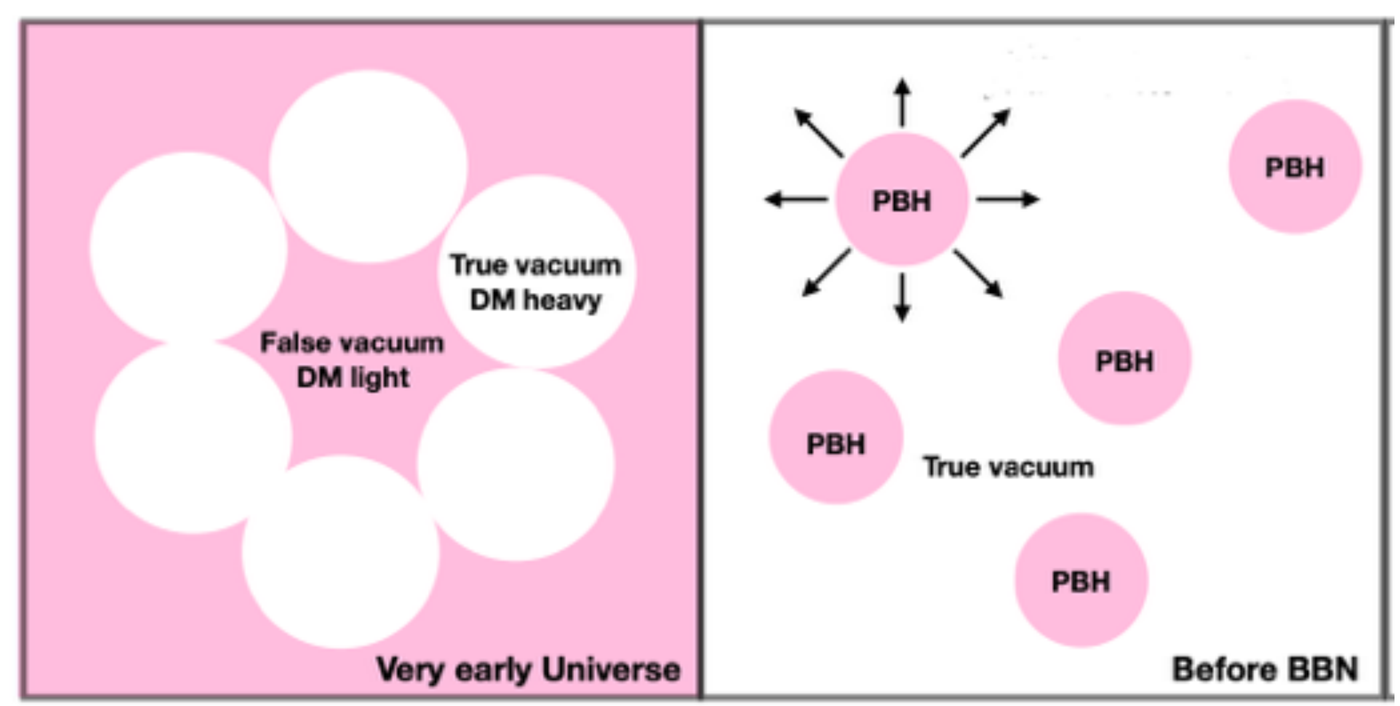


image credit: https://slideplayer.com/slide/7773485/



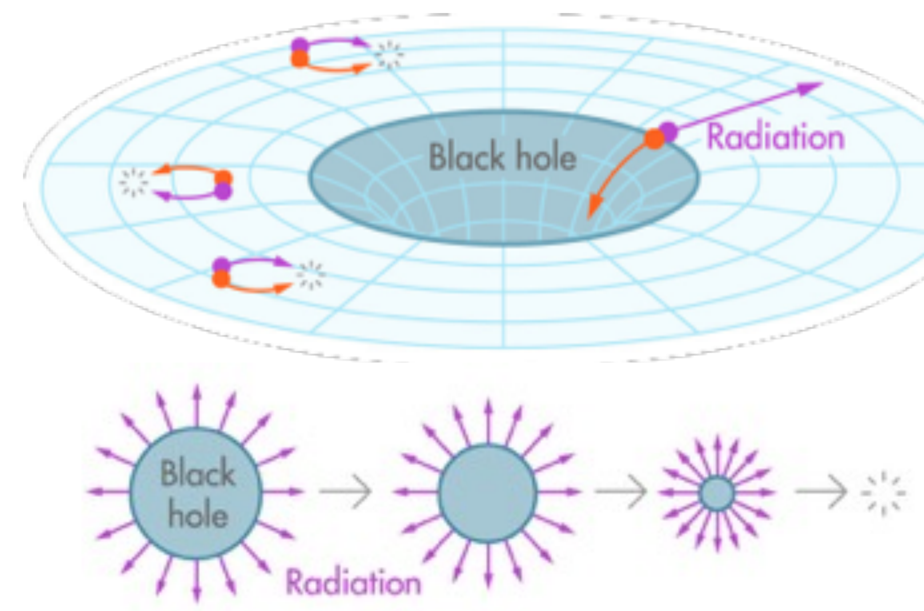


BHs can be described by:
mass, spin, charge

mass and spin: a wide range,
monochromatic or extended distribution
(depending on formation mechanism, cosmological epoch, ...)

Hawking Evaporation of Kerr BHs:

image credit: Quantamagazine



$$T_{\rm K} = \frac{1}{2\pi}\left(\frac{r_+ - M_{\rm BH}}{r_+^2 + a^{*2}M_{\rm BH}^2}\right)$$

$$a^* \equiv L/M_{\rm BH}^2$$

$$r_+ \equiv M_{\rm BH}(1+\sqrt{1-a^{*2}})$$

$$\frac{d^2N_i}{dtdE} = \frac{1}{2\pi}\frac{\Gamma_{s_i}^{l,m}}{e^{E'/T_{\rm K}} - (-1)^{2s_i}}$$

$$E' \equiv E - m\Omega = E - ma^*/2r_+$$

$$\frac{dM_{\rm BH}}{dt} = -\frac{f(M_{\rm BH},a^*)}{M_{\rm BH}^2}\,,$$

$$\frac{da^*}{dt} = \frac{a^*\left[2f(M_{\rm BH},a^*) - g(M_{\rm BH},a^*)\right]}{M_{\rm BH}^3}$$

Page factors

$$f(M_{\rm BH},a^*) \equiv M_{\rm BH}^2 \int_0^{+\infty}\sum_i\sum_{\rm dof}\frac{E}{2\pi}\frac{\Gamma_{s_i}^{l,m}(E,M_{\rm BH},a^*)}{e^{E'/T_{\rm K}} - (-1)^{2s_i}}dE\,,$$

$$g(M_{\rm BH},a^*) \equiv \frac{M_{\rm BH}}{a^*}\int_0^{+\infty}\sum_i\sum_{\rm dof}\frac{m}{2\pi}\frac{\Gamma_{s_i}^{l,m}(E,M_{\rm BH},a^*)}{e^{E'/T_{\rm K}} - (-1)^{2s_i}}dE$$

numerical tools:

`BlackHawk` Arbey, Auffinger1905.04268

Simpler case: Schwarzschild BHs (ignoring grabbed factors)

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M_{\rm BH}} \simeq 10^{13}\left(\frac{1\,{\rm g}}{M_{\rm BH}}\right)\,{\rm GeV}$$

$$\frac{d^2 u_i(E,t)}{dt dE} = \frac{g_i}{8\pi^2}\frac{E^3}{e^{E/T_{\rm BH}} \pm 1}$$

$$M(t) = M_i\left(1 - \frac{(t-t_i)}{\tau}\right)^{1/3}, \qquad \tau = \frac{10240\pi}{g_*(T_{\rm BH})}\frac{M_i^3}{M_{\rm Pl}^4} \qquad \tau(M = 10^{15}\,{\rm g}) \sim \tau_{\rm Univ.}$$

bosons:

$$N_i = \frac{120\,\zeta(3)}{\pi^3}\frac{g_i}{g_*(T_{\rm BH})}\frac{M_{\rm BH}^2}{M_{\rm Pl}^2}, \qquad T_{\rm BH} > m_i$$

$$N_i = \frac{15\,\zeta(3)}{8\pi^5}\frac{g_i}{g_*(T_{\rm BH})}\frac{M_{\rm Pl}^2}{m_i^2}, \qquad T_{\rm BH} < m_i$$

fermions: $N_F = \frac{3}{4}\frac{g_F}{g_B}N_B$

mass range in this talk:

$$0.1\,{\rm g} \lesssim M_{\rm BH} \lesssim 10^9\,{\rm g}$$

CMB: constraint on the size of Horizon at the end of inflation

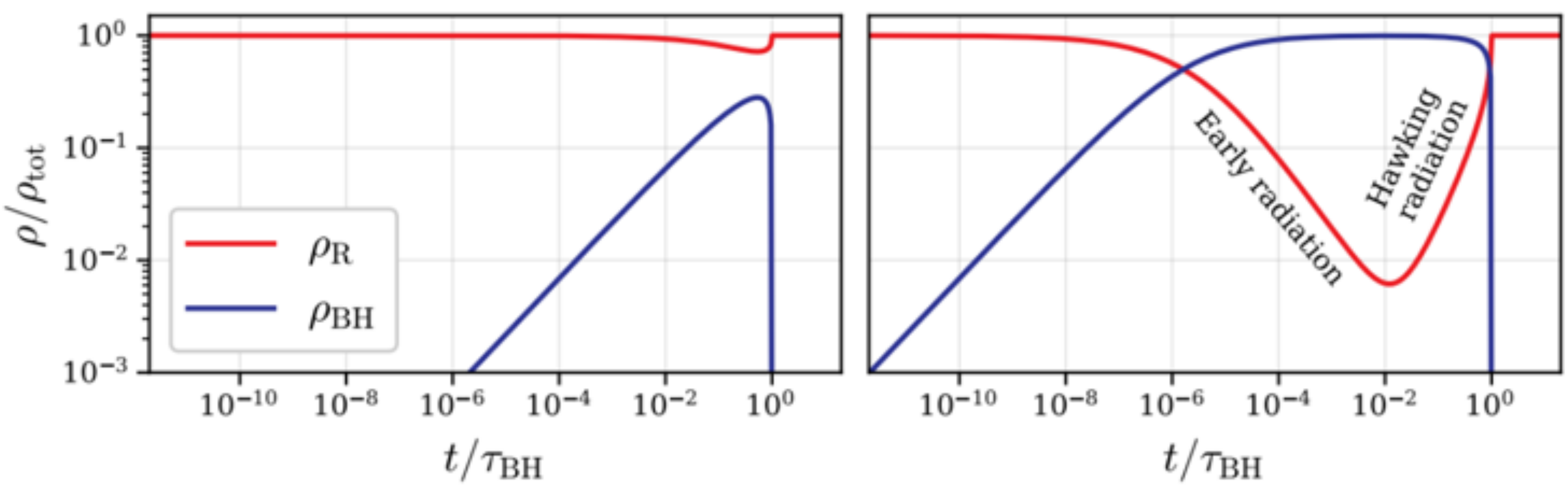
$H_I \lesssim 10^{-5} M_{\rm Pl}$ (*Planck*)

evaporate before **BBN**

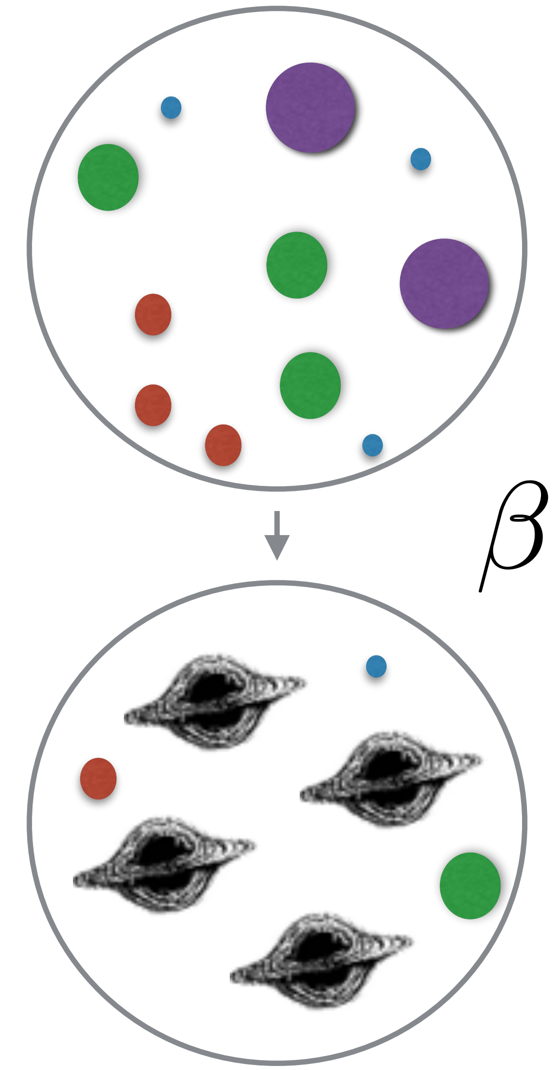
Not constrained by cosmology

PBH Energy Content:

initial abundance of PBHs $\beta \equiv \frac{\rho_{\rm PBH}(t_i)}{\rho_{\rm rad}(t_i)}$



C. J. Shallue, J. B. Munoz, G. Z. Krnjaic 2406.08535



$\rho_{\rm PBH} \propto a^{-3}, \quad \rho_{\rm rad} \propto a^{-4}$ $\qquad \rho_{\rm PBH}(t_{\text{early-eq}})/\rho_{\rm rad}(t_{\text{early-eq}}) \sim 1$

$t_{\text{early-eq}} \lesssim t_{\rm eva}$

critical initial abundance

$$\beta_{\rm crit} \sim \frac{M_{\rm Pl}}{M_{\rm BH}}$$

$\beta < \beta_{\rm crit}$ evaporation happens in a RD Universe

$\beta \geq \beta_{\rm crit}$ evaporation happens in a MD (PBH dominated) Universe (PBHs reheat the Universe)

Dark Matter Production

if DM only interacts gravitationally:

D. Baumann, P. J. Steinhardt, N. Turok, 0703250
T. Fujita, et. al., 1401.1909
R. Allahverdi, J. Dent, J. Osinski, 1711.10511
O. Lennon, et. al., 1712.07664
L. Morrison, S. Profumo and Y. Yu, 1812.10606
D. Hooper, G. Krnjaic, S. D. McDermott, 1905.01301

Assuming PBHs with monochromatic mass function,
formed during RD,
with a mass of the order of the Horizon mass at formation time:

evaporation in a RD Universe: $\beta < \beta_{\rm crit}$

$$\Omega_\chi h^2 \simeq 7.3 \times 10^7 \beta \left(\frac{g_*(T_i)}{106.8}\right)^{-1/4} \left(\frac{\gamma}{0.2}\right)^{1/2} \left(\frac{m_\chi}{\rm GeV}\right) \left(\frac{g_\chi}{g_*(T_{\rm BH})}\right) \left(\frac{M_{\rm BH}}{M_{\rm Pl}}\right)^{1/2}, \qquad T_{\rm BH} > m_\chi$$

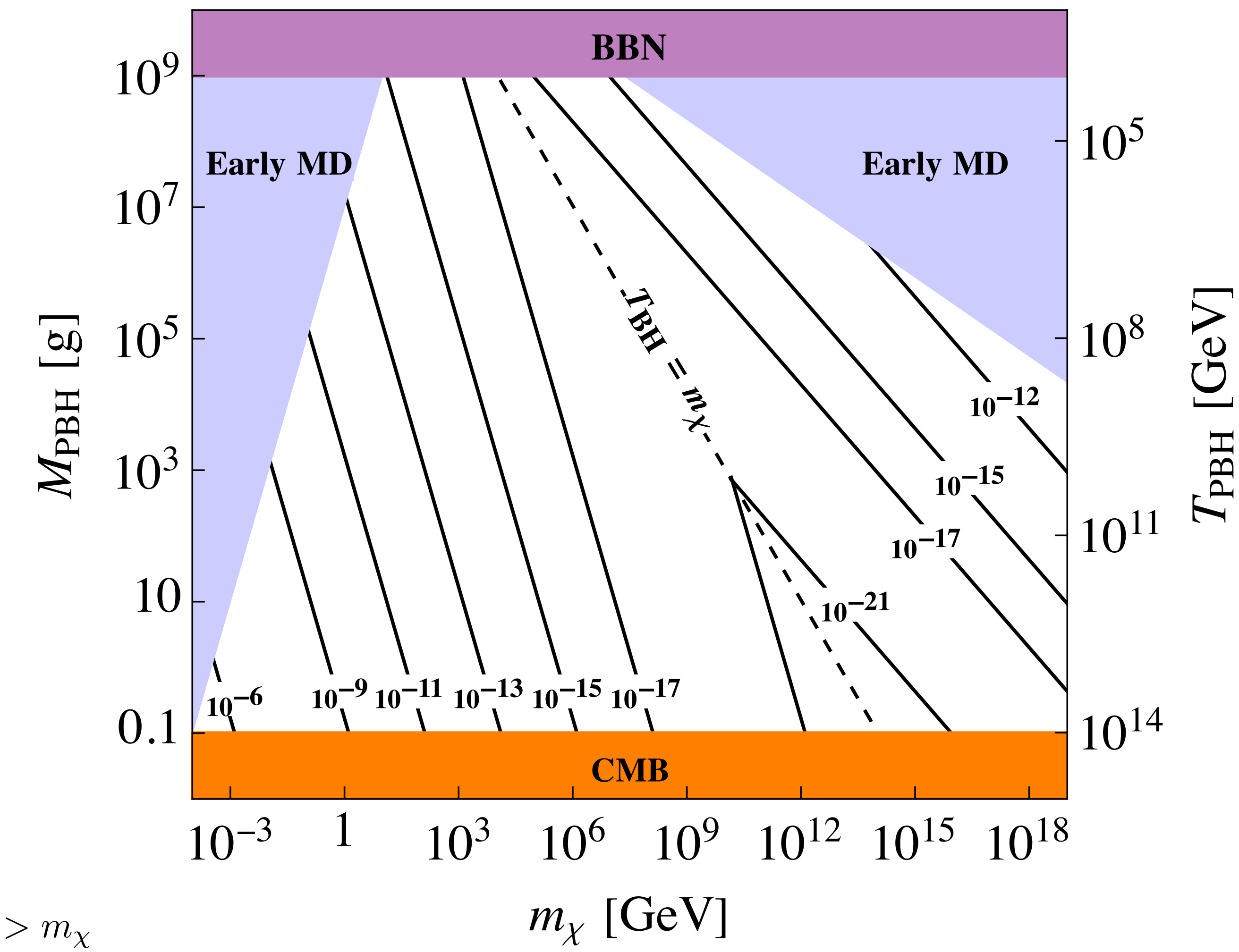
$$\Omega_\chi h^2 \simeq 1.2 \times 10^5 \beta \left(\frac{g_*(T_i)}{106.8}\right)^{-1/4} \left(\frac{\gamma}{0.2}\right)^{1/2} \left(\frac{m_\chi}{\rm GeV}\right) \left(\frac{g_\chi}{g_*(T_{\rm BH})}\right) \left(\frac{M_{\rm Pl}^7}{M_{\rm BH}^3 m_\chi^4}\right)^{1/2}, \qquad T_{\rm BH} < m_\chi$$

evaporation in MD Universe: $\beta \geq \beta_{\rm crit}$

$$\Omega_\chi h^2 \simeq 1.1 \times 10^7 \left(\frac{g_*(T_{\text{eva-BH}})}{106.8}\right)^{1/4} \left(\frac{g_\chi}{g_*(T_{\rm BH})}\right) \left(\frac{m_\chi}{\rm GeV}\right) \left(\frac{M_{\rm Pl}}{M_{\rm BH}}\right)^{1/2}, \qquad T_{\rm BH} > m_\chi$$

$$\Omega_\chi h^2 \simeq 1.7 \times 10^4 \left(\frac{g_*(T_{\text{eva-BH}})}{106.8}\right)^{1/4} \left(\frac{g_\chi}{g_*(T_{\rm BH})}\right) \left(\frac{m_\chi}{\rm GeV}\right) \left(\frac{M_{\rm Pl}^9}{M_{\rm BH}^5 m_\chi^4}\right)^{1/2}, \qquad T_{\rm BH} < m_\chi$$

In this case the yield is independent of initial abundance of PBHs.



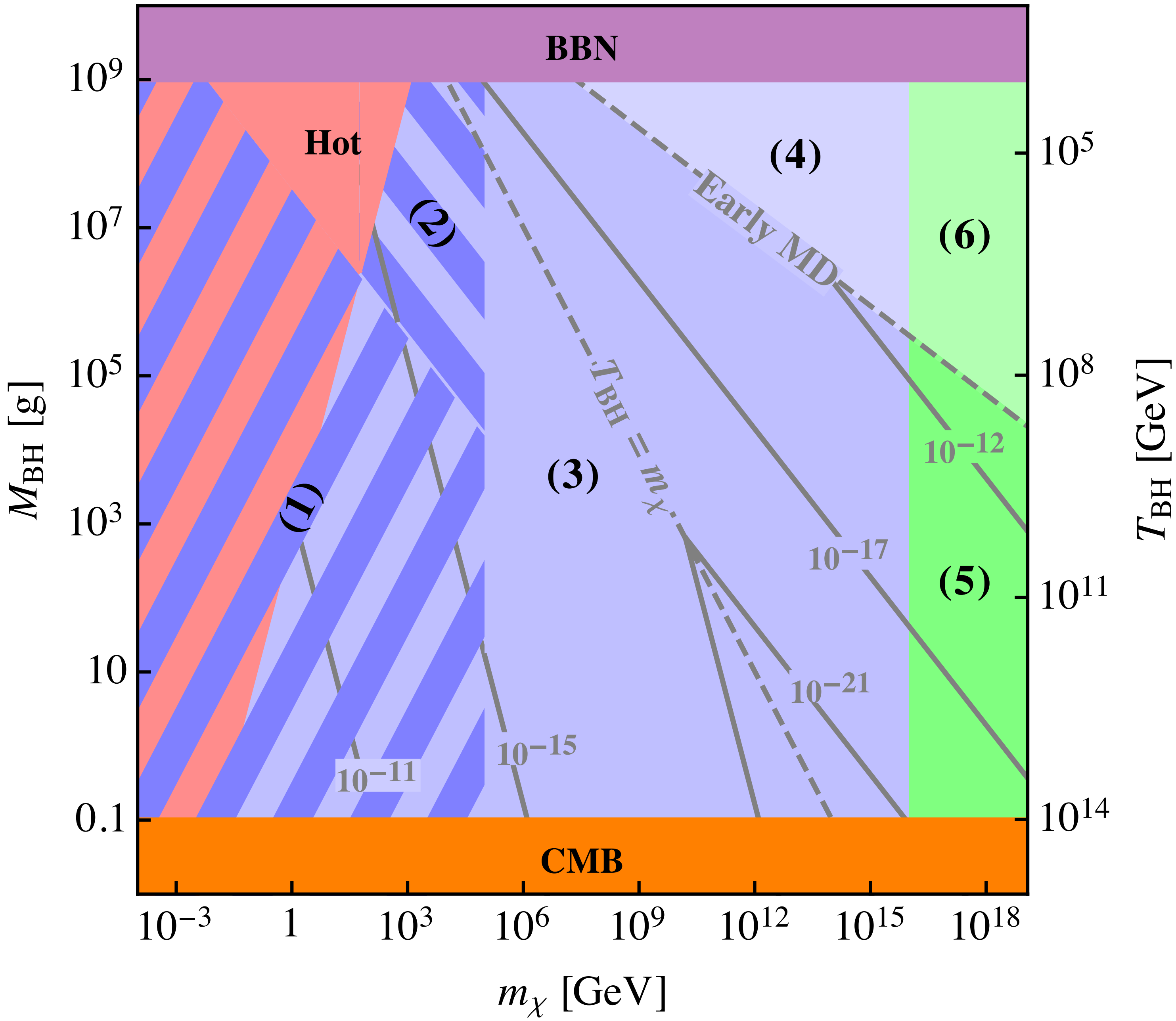
Light DM can be hot

Adding non-gravitational interactions:
Interplay between PBH evaporation and other DM production mechanism

- Freeze-out (WIMP, SIMP)
- Freeze-in
- or other gravitational production channels:
  Gravitational production of superheavy DM

$$\Omega_\chi^{\rm SM}(m_\chi, \lambda) + \Omega_\chi^{\rm PBH}(m_\chi, M_{\rm PBH}, \beta) \leq \Omega_{\rm CDM}$$

PBHs can affect DM models.



Sources of Dark Matter:

(1): freeze−out only

(2): freeze−out and/or PBH

(3): freeze−in and/or PBH

(4): freeze−in required plus PBH

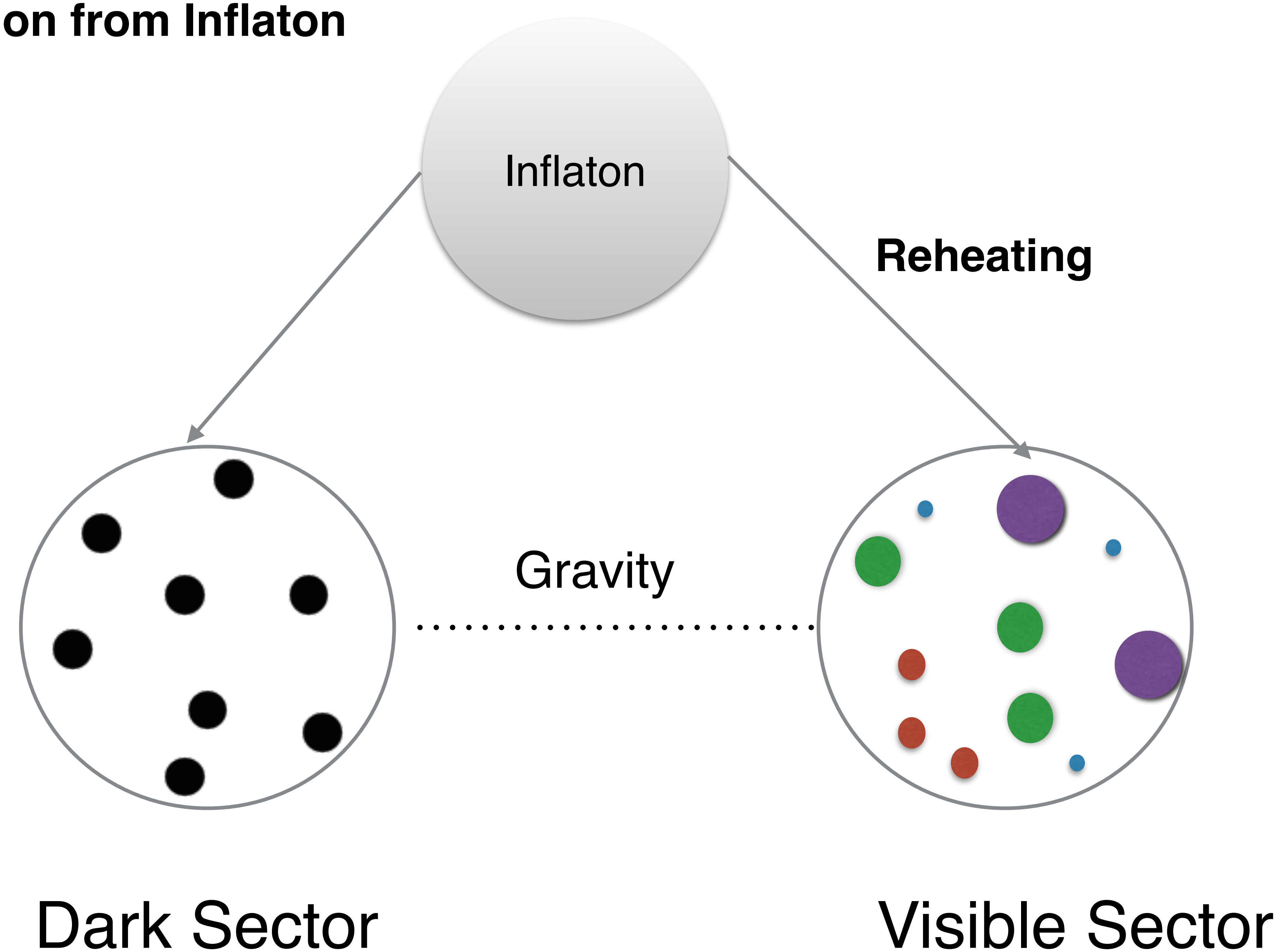
(5): WIMPZILLA and/or PBH

(6): WIMPZILLA required plus PBH

Paolo Gondolo, Pearl Sandick, BSE, 2020

Populating a Dark Sector (Asymmetric Reheating)

Direct Production from Inflaton



issue: two sectors can exchange inflaton and thermalize

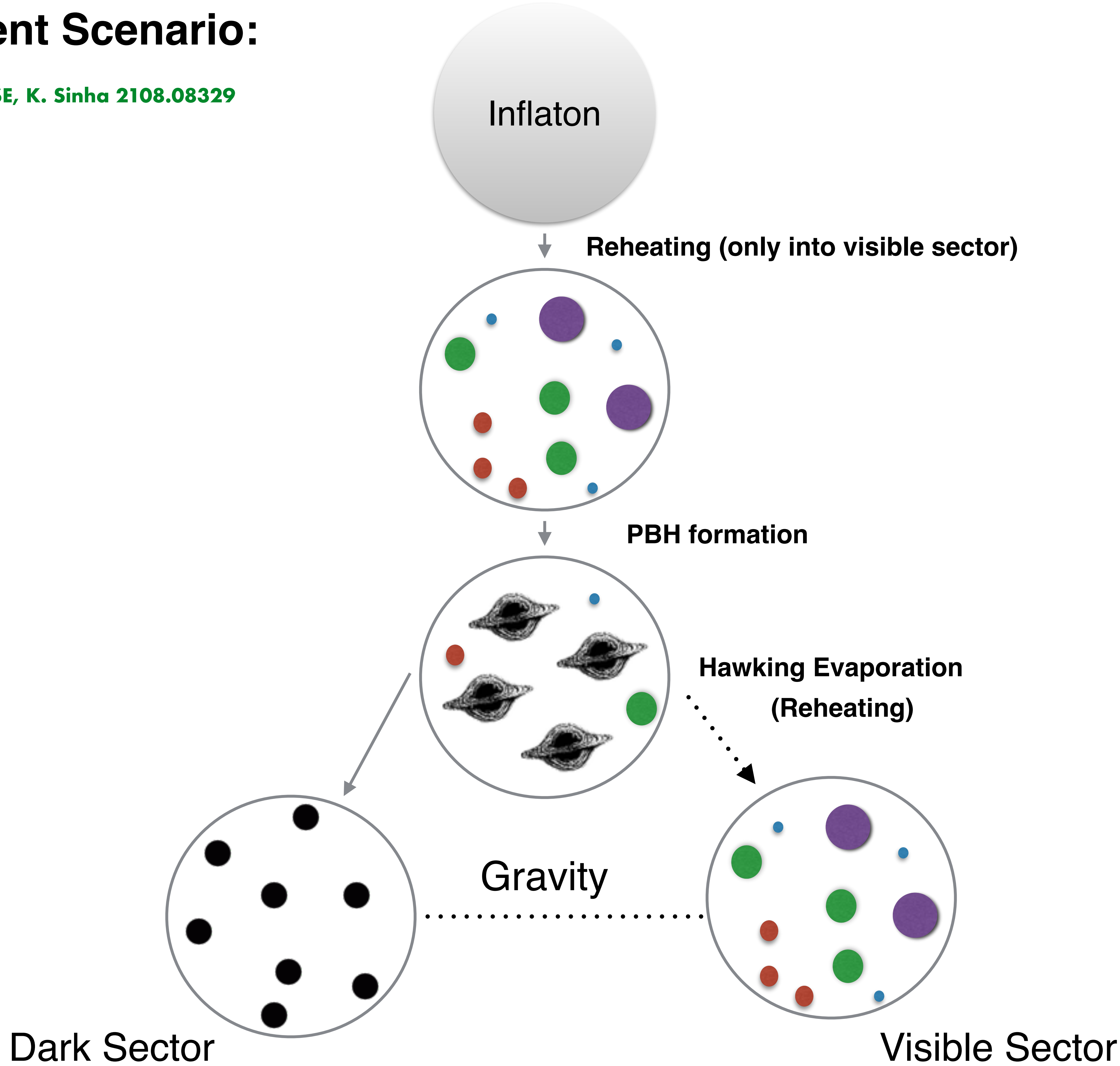
P. Adshead, Y. Cui, J. Shelton, 1604.02458

E. Hardy, J. Unwin, 1703.07642

P. Adshead, P. Ralegankar, J. Shelton,1906.02755

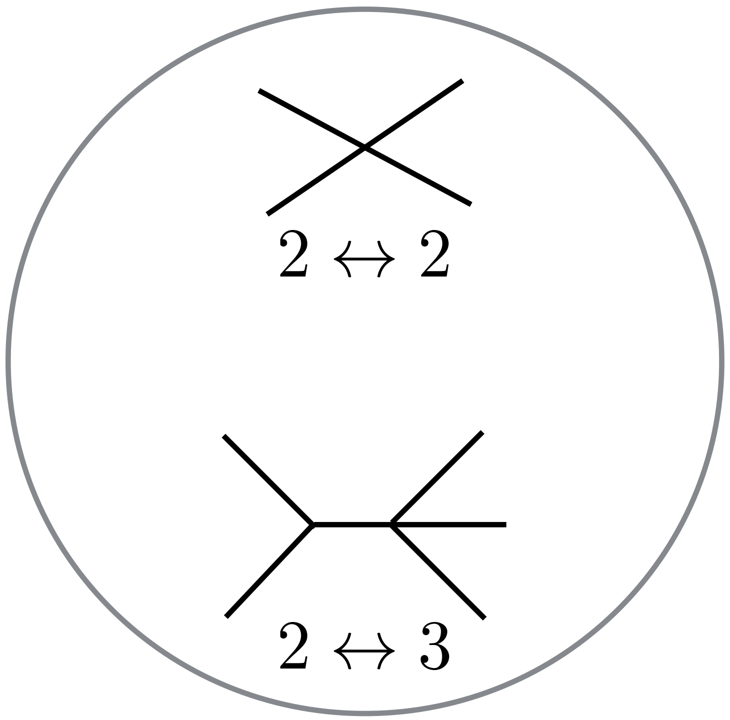
A different Scenario:

P. Sandick, BSE, K. Sinha 2108.08329



Populating a self-interacting dark sector by relativistic and far from equilibrium particles:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{1}{2}m_\chi^2\chi^2 - \frac{m_\chi\lambda}{3!}\chi^3 - \frac{\lambda^2}{4!}\chi^4, \qquad 1 \lesssim \lambda \lesssim 4\pi$$

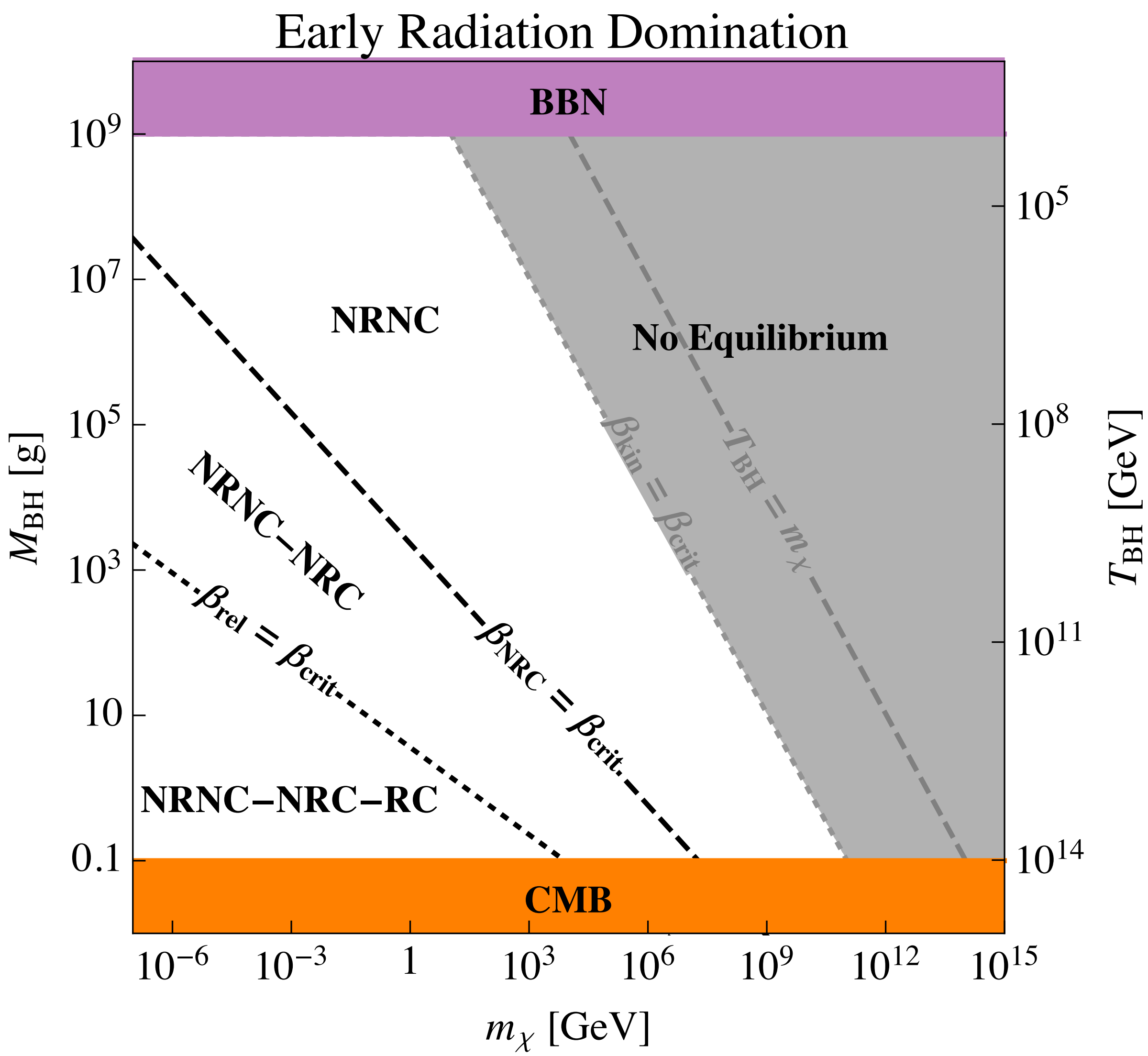


Dark Sector

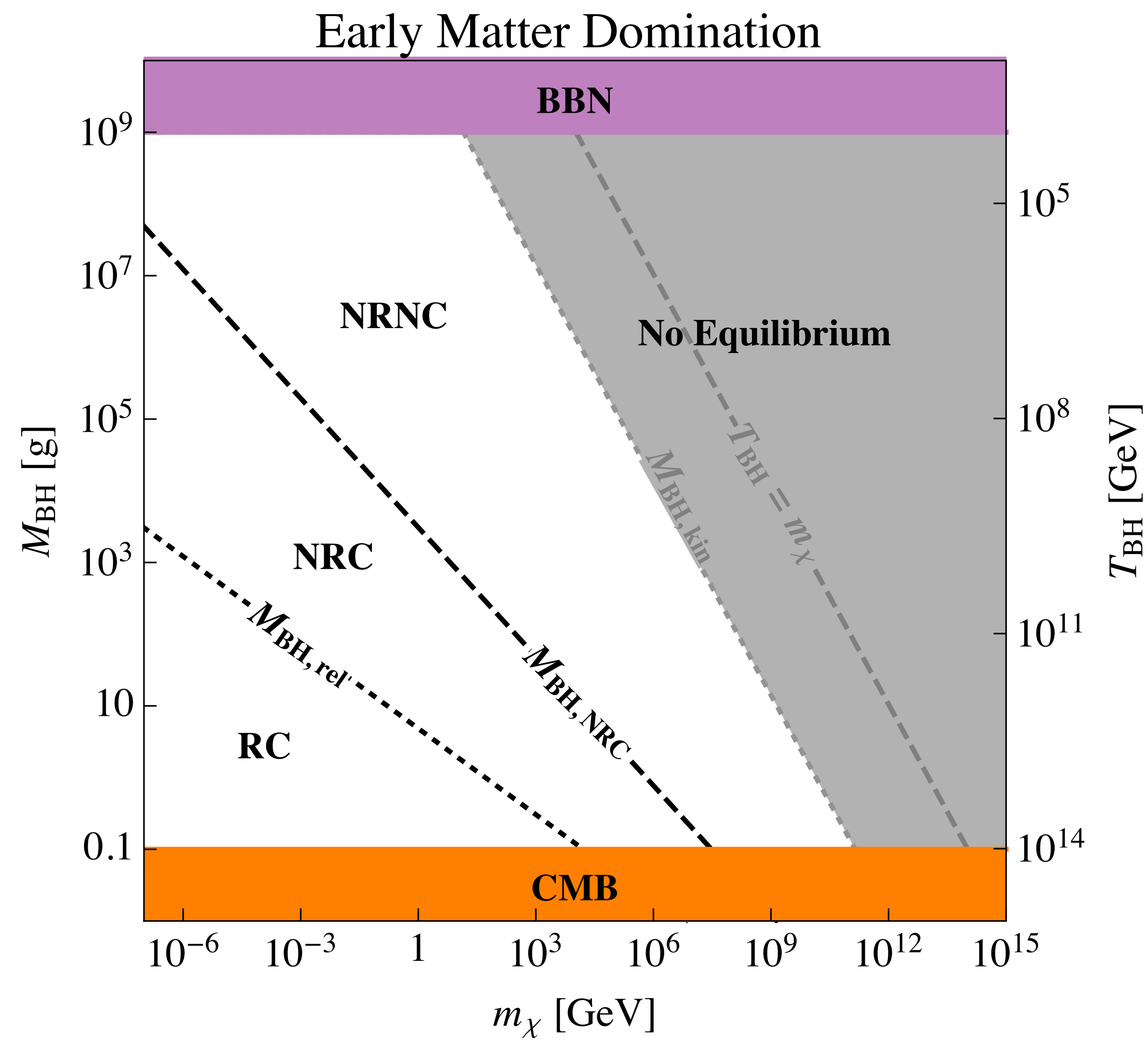
kinetic equilibrium
Chemical equilibrium
Cannibalism/decoupling (freeze-out)

Thermal History	Early Radiation Domination	Early Matter Domination
NRNC (non-relativistic, no cannibalism)	$\beta_{\text{kin}} \lesssim \beta \lesssim \beta_{\text{NRC}}$	$M_{\text{BH, NRC}} \lesssim M_{\text{BH}} \lesssim M_{\text{BH, kin}}$
NRC (non-relativistic, cannibalism)	$\beta_{\text{NRC}} \lesssim \beta \lesssim \beta_{\text{rel}}$	$M_{\text{BH, rel}} \lesssim M_{\text{BH}} \lesssim M_{\text{BH, NRC}}$
RNC (relativistic, no cannibalism)	$\beta_{\text{rel}} \lesssim \beta \lesssim \beta_{\text{RC}}$	$M_{\text{BH, RC}} \lesssim M_{\text{BH}} \lesssim M_{\text{BH, rel}}$
RC (relativistic, cannibalism)	$\beta_{\text{RC}} \lesssim \beta \lesssim \beta_{\text{crit}}$	$M_{\text{BH}} \lesssim M_{\text{BH, RC}}$

Thermal Histories



$\beta < \beta_{\rm crit}$



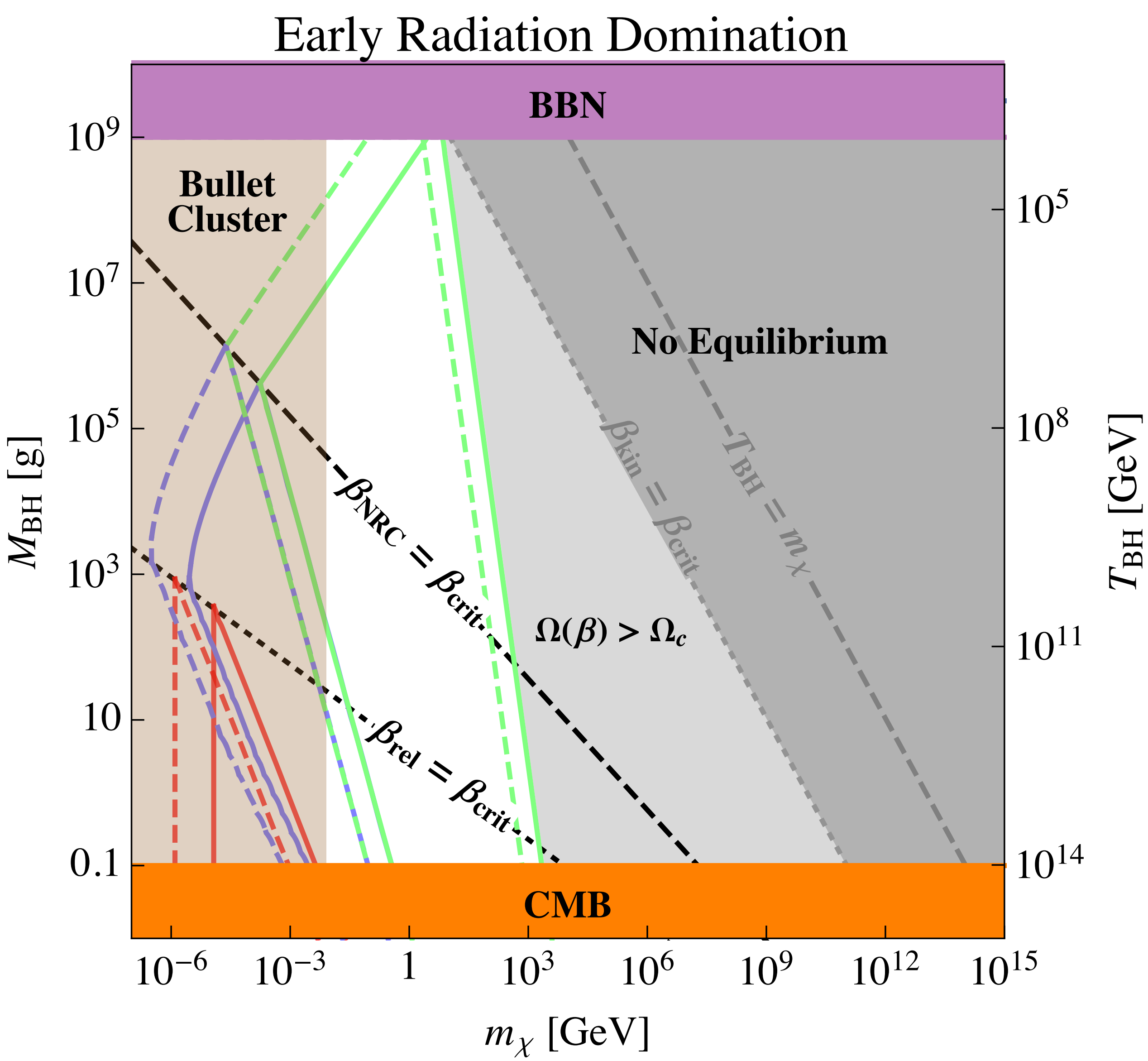
$\beta \geq \beta_{\rm crit}$

P. Sandick, BSE, K. Sinha 2108.08329

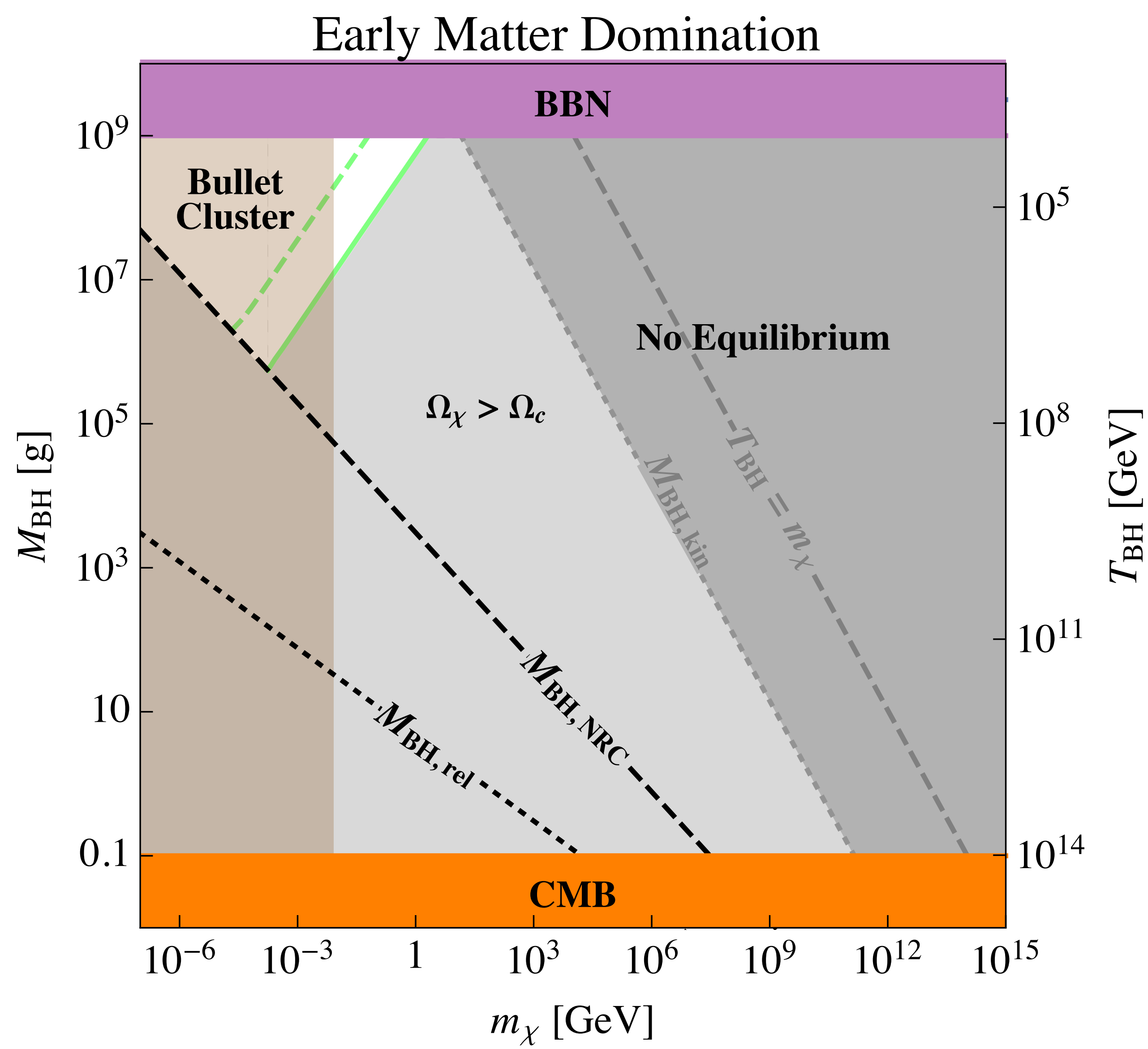
$T_{\rm BH} < m_\chi$ no equilibrium

relativistic: cannibalism is inevitable

Constraints: relic abundance, Bullet Cluster



$\beta < \beta_{crit}$



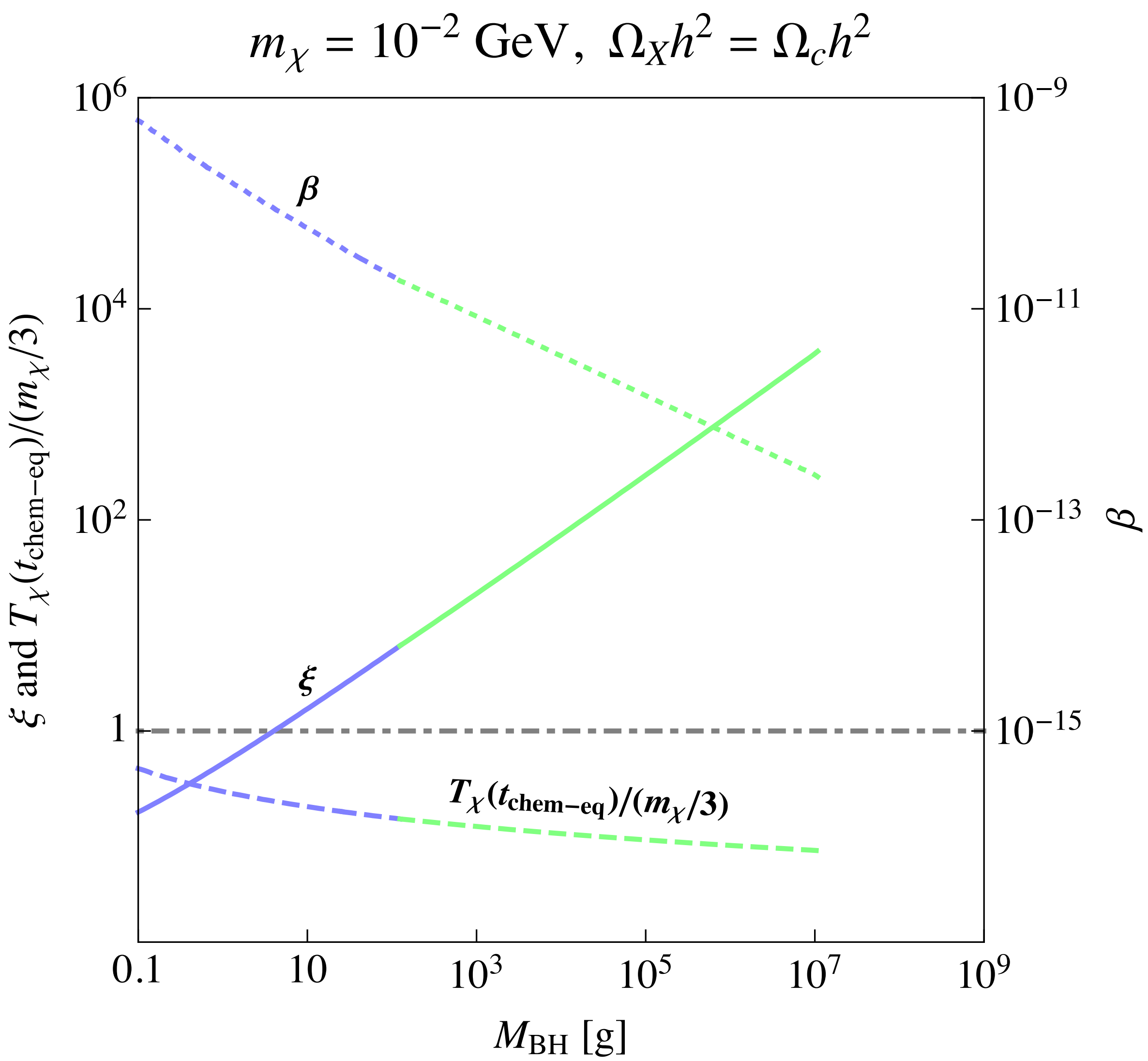
$\beta \geq \beta_{crit}$

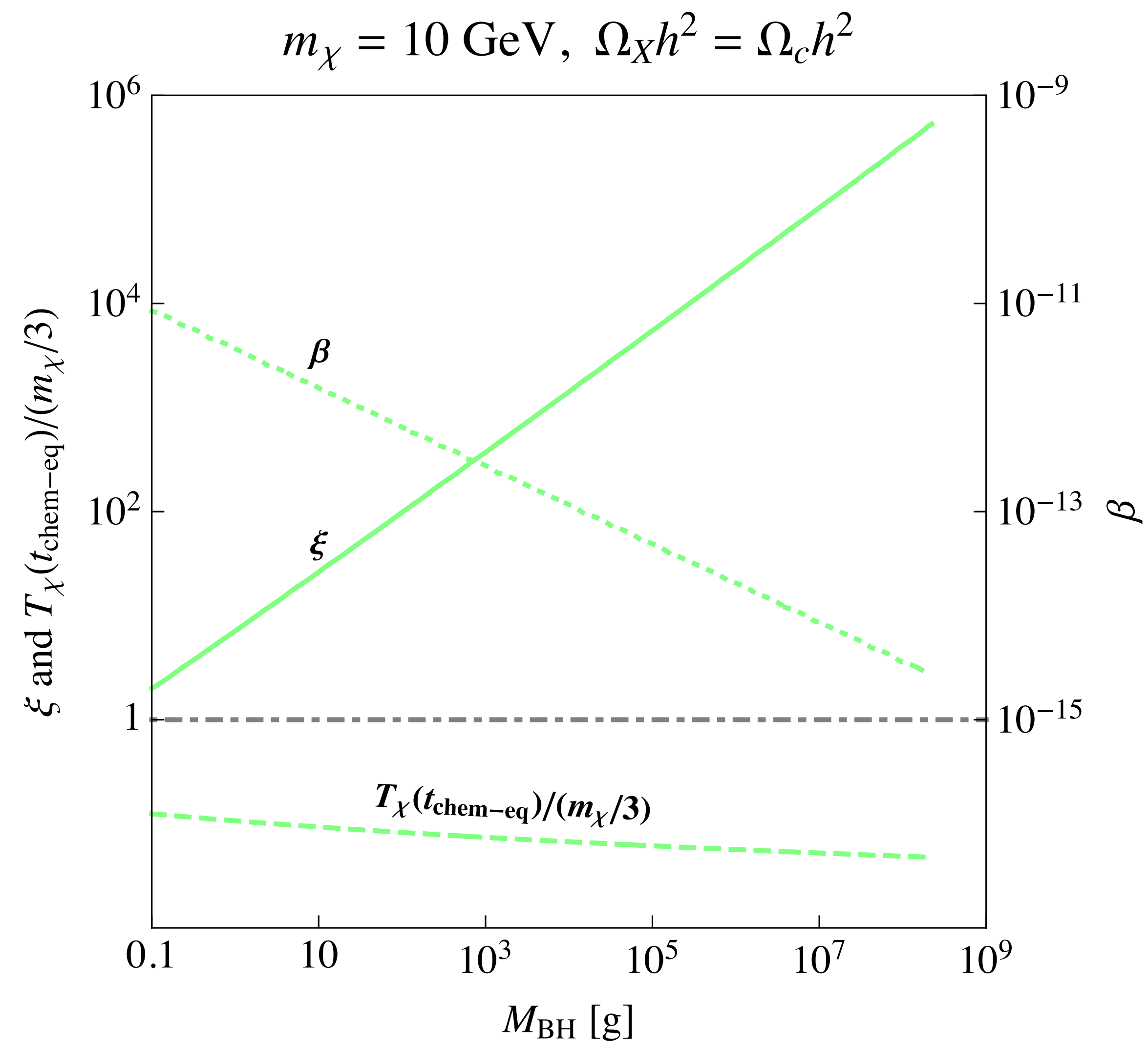
NRNC

NRC

RC

Dark Sector Temperature:





P. Sandick, BSE, K. Sinha 2108.08329

$$\xi = \frac{T_\chi(t_{\rm chem-eq})}{T_V(t_{\rm chem-eq})}$$

Dark Radiation

PBHs can impact cosmology by emitting massless particles

the effective number of relativistic degrees of freedom $\Delta N_{\rm eff}$

massless particle: graviton

Spinning BHs have enhanced emission of particles with higher spin.

Graviton is spin 2!

How large is the spin of PBHs?
Depends on the formation mechanism and environment:

formation in RD: small angular momentum

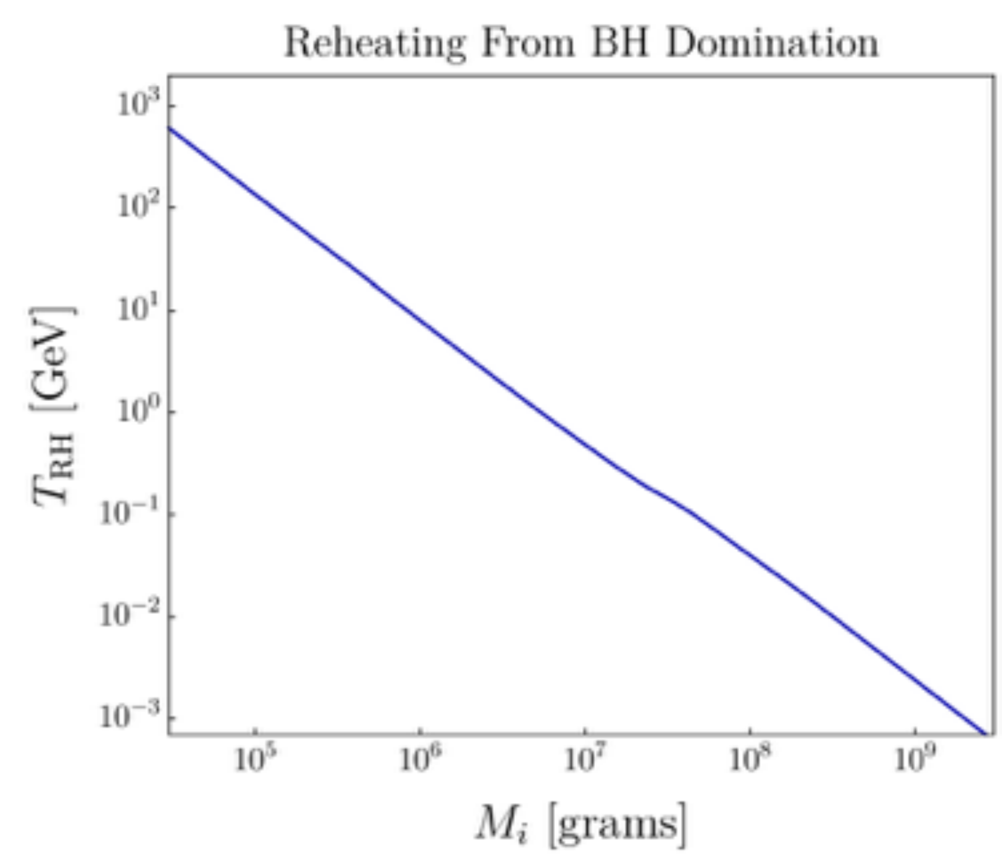
formation in MD: tidal forces and density fluctuations can make collapsing regions non-spherical, which can lead to very large PBH spins

merger also gives rise to high spin.

The effect becomes important for PBH domination, when PBH evaporation reheats the Universe.

$$\Delta N_{\rm eff} = \frac{\rho_{\rm DR}(t_{\rm EQ})}{\rho_{\rm R}(t_{\rm EQ})}\left[N_\nu + \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\right] \qquad N_\nu = 3.046$$

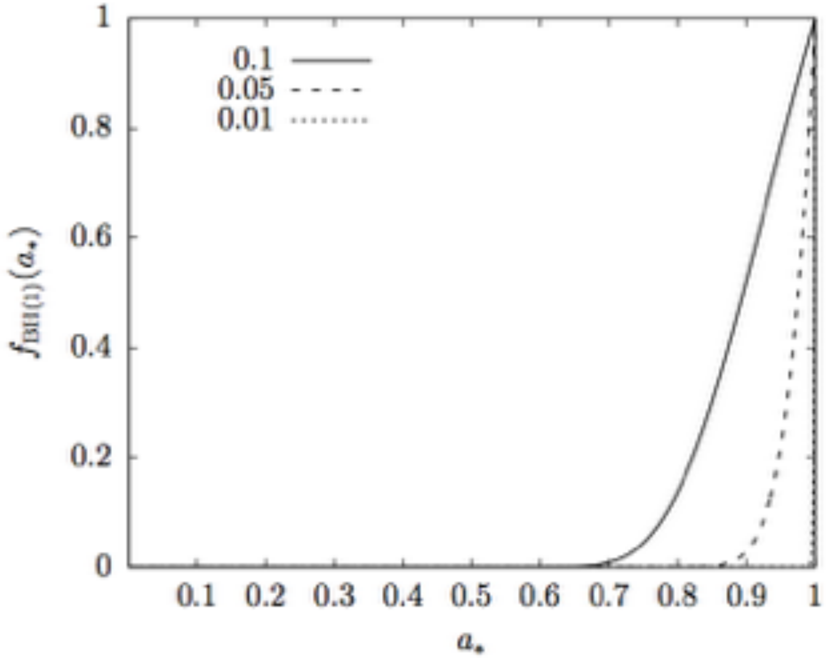
$$\frac{\rho_{\rm DR}(t_{\rm EQ})}{\rho_{\rm R}(t_{\rm EQ})} = \frac{\rho_{\rm DR}(t_{\rm RH})}{\rho_{\rm R}(t_{\rm RH})}\left(\frac{g_*(T_{\rm RH})}{g_*(T_{\rm EQ})}\right)\left(\frac{g_{*,S}(T_{\rm EQ})}{g_{*,S}(T_{\rm RH})}\right)^{4/3}$$



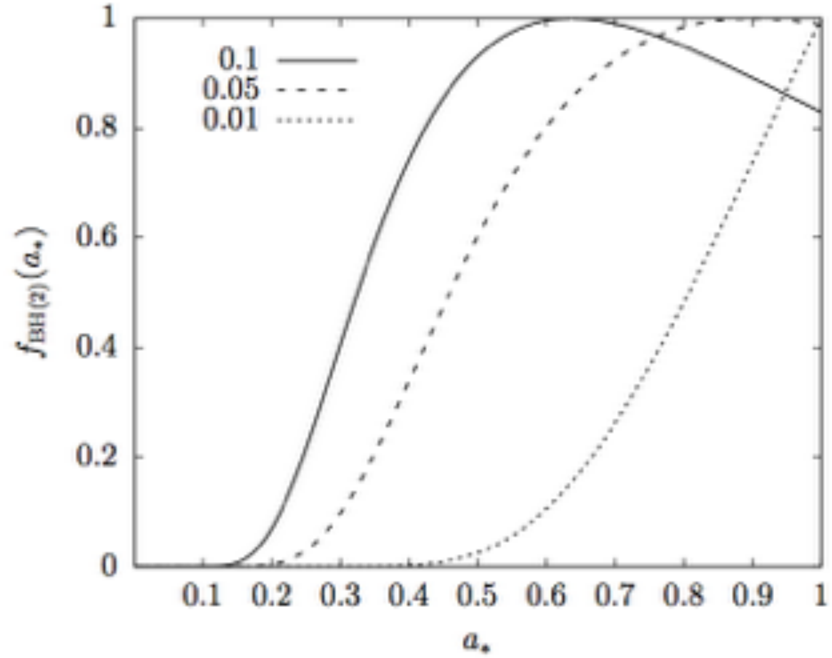
Spin distribution

Harada, Yoo, Kohri, Nakao 1707.03595

EMDE: 1st order



EMDE: 2nd order



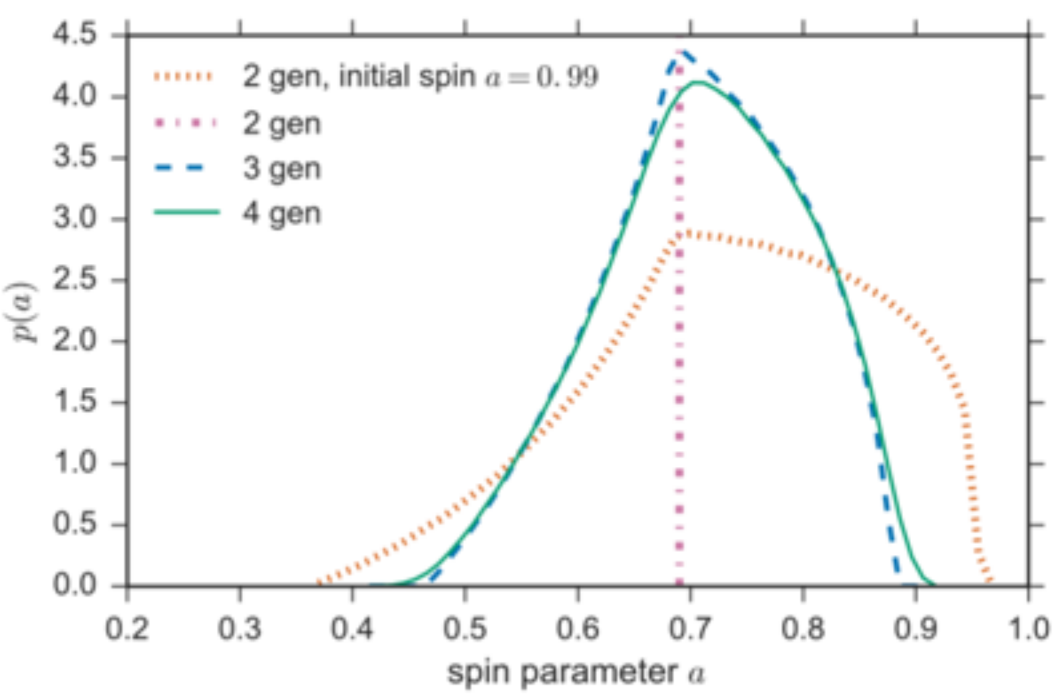
spin distribution is a function of the mean variance of the density perturbations at horizon entry

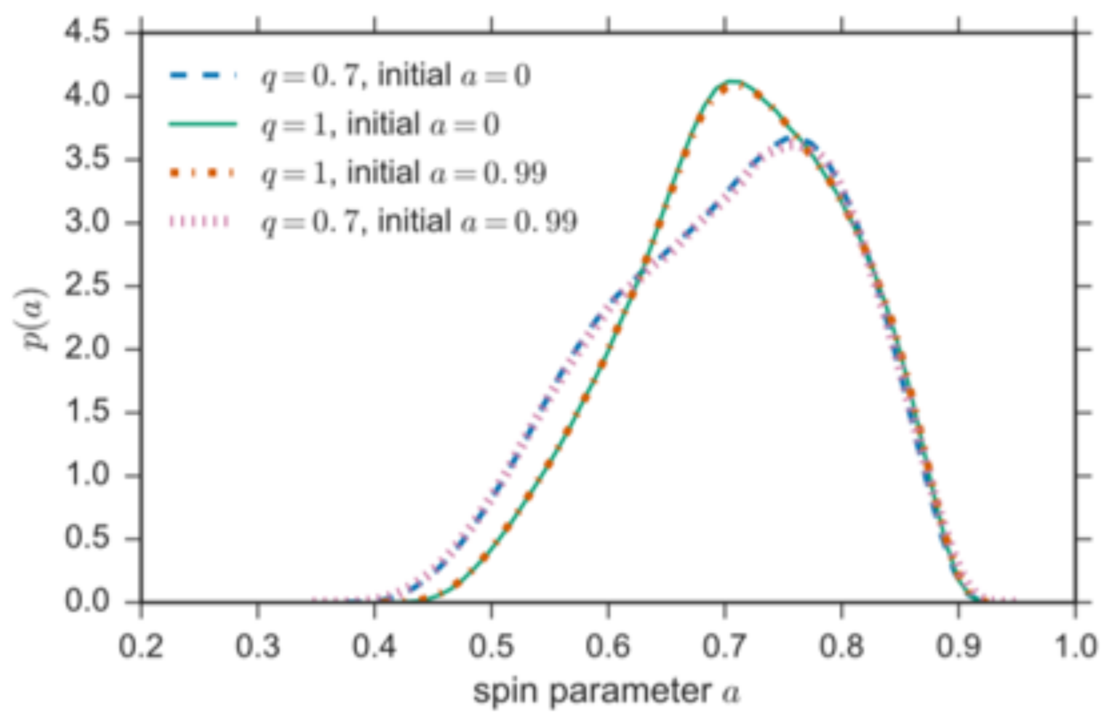
$$\sigma_{\rm H} = \langle \delta_s(t_{\rm H})^2 \rangle^{1/2}$$

1st order: deviation of the boundary of the volume from a sphere.

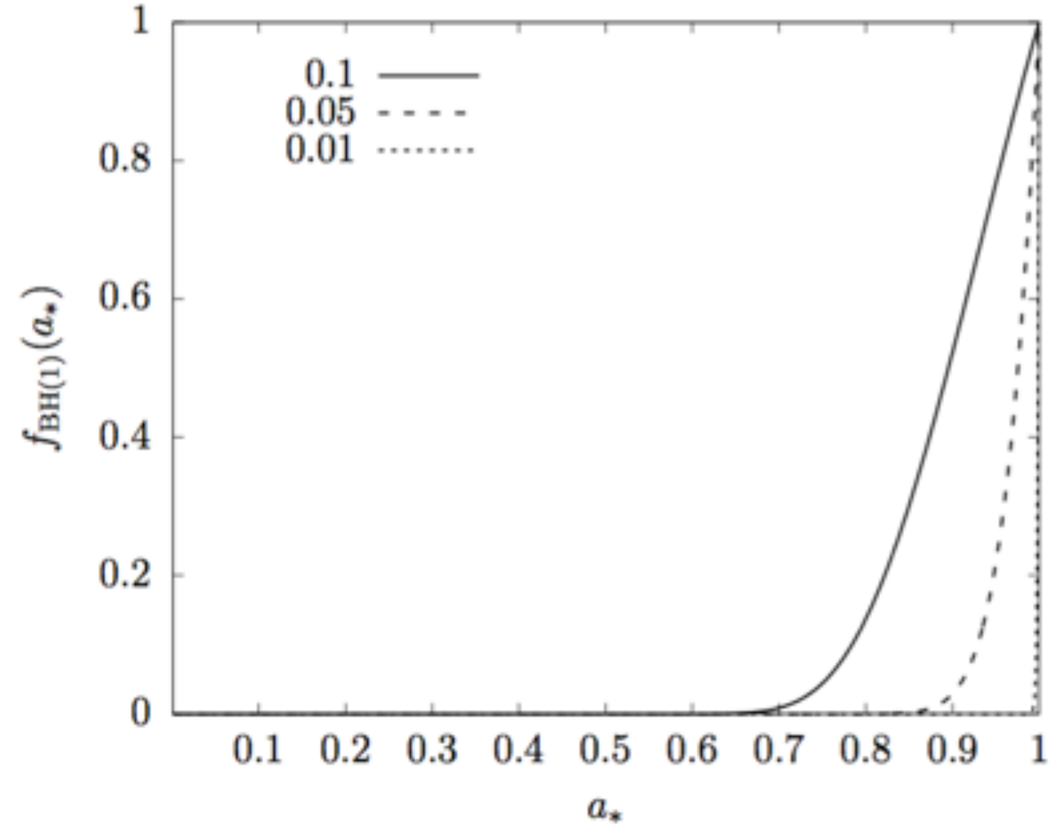
2nd order: density fluctuations in the comoving region.

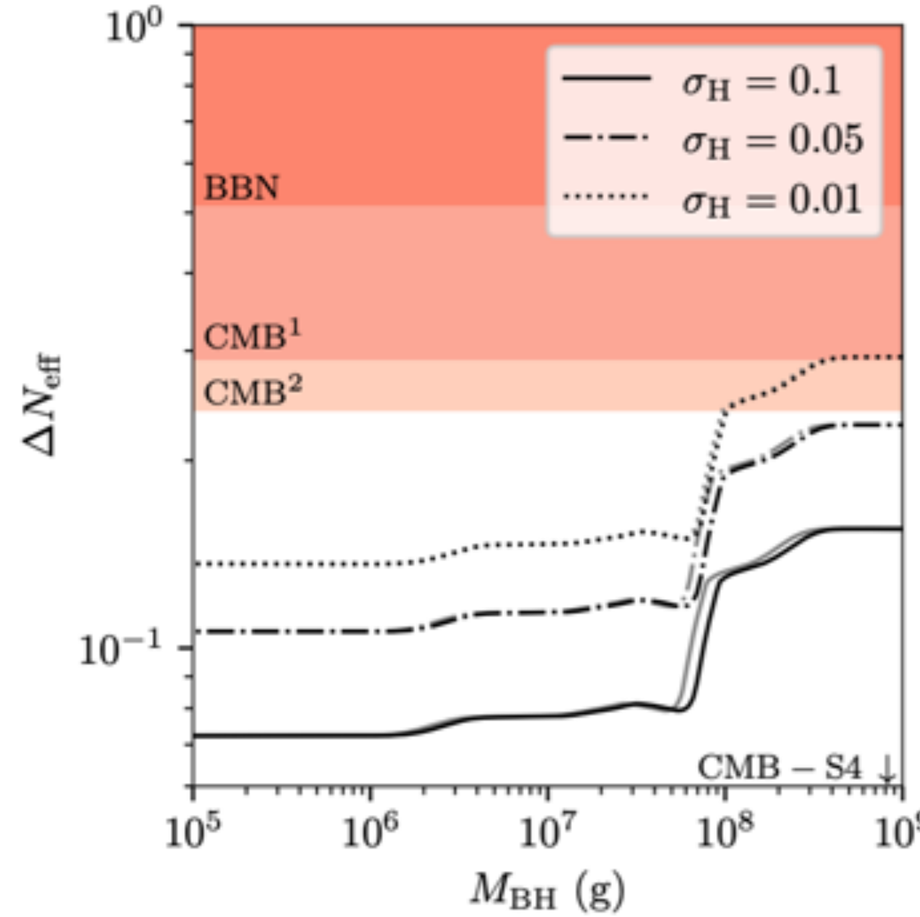
Fishbach, Holz, Farr 1703.06869



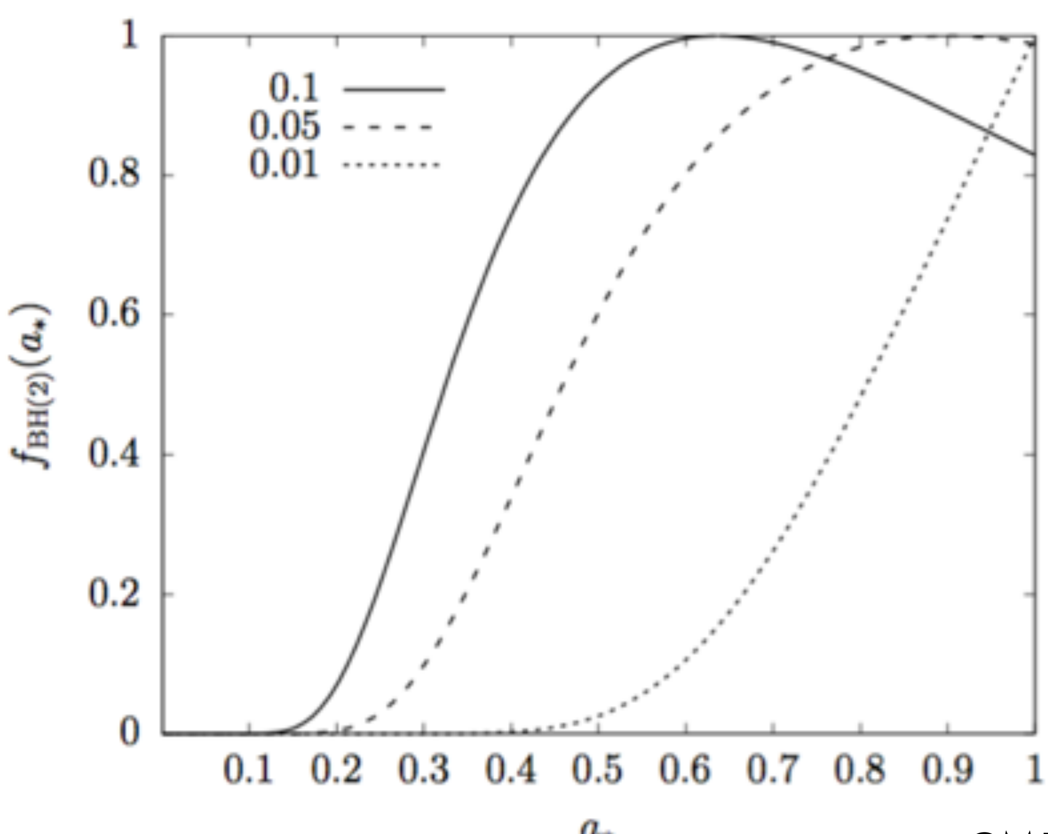


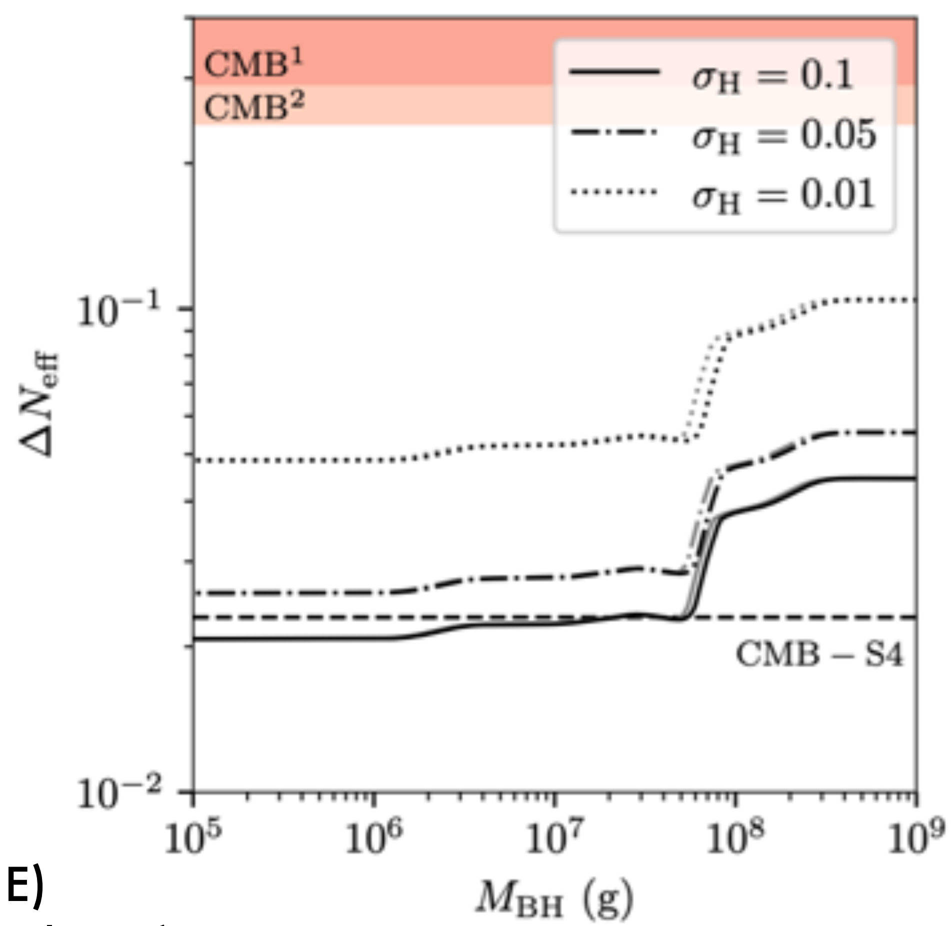
1st order





2nd order

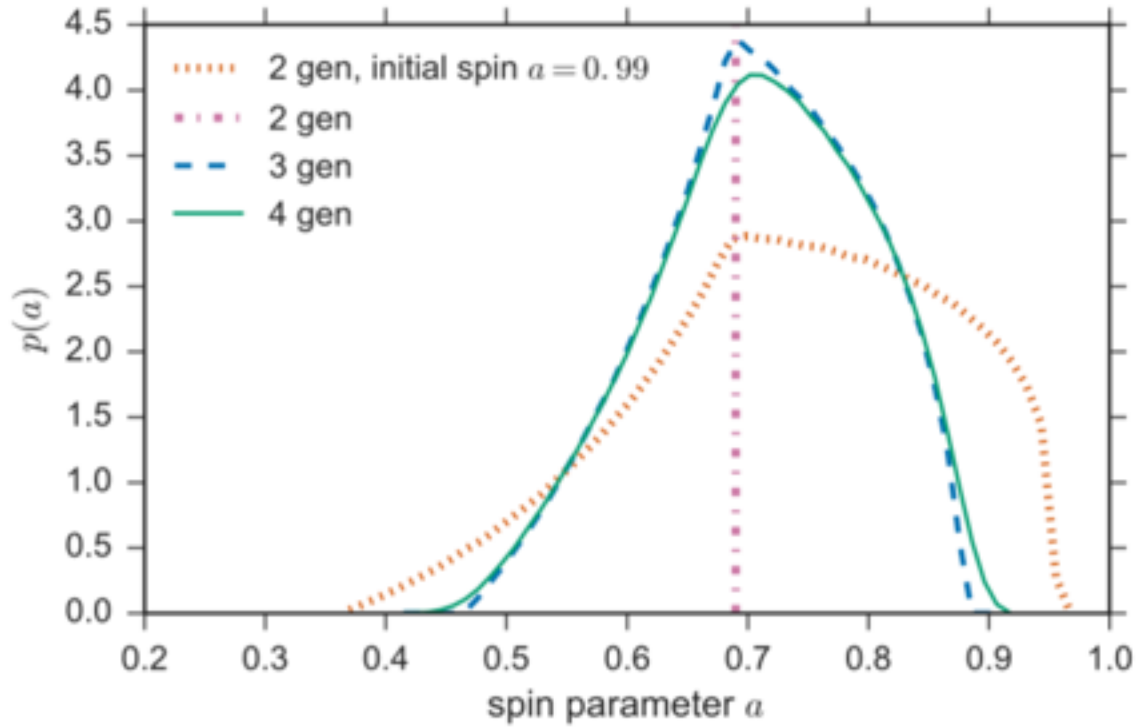


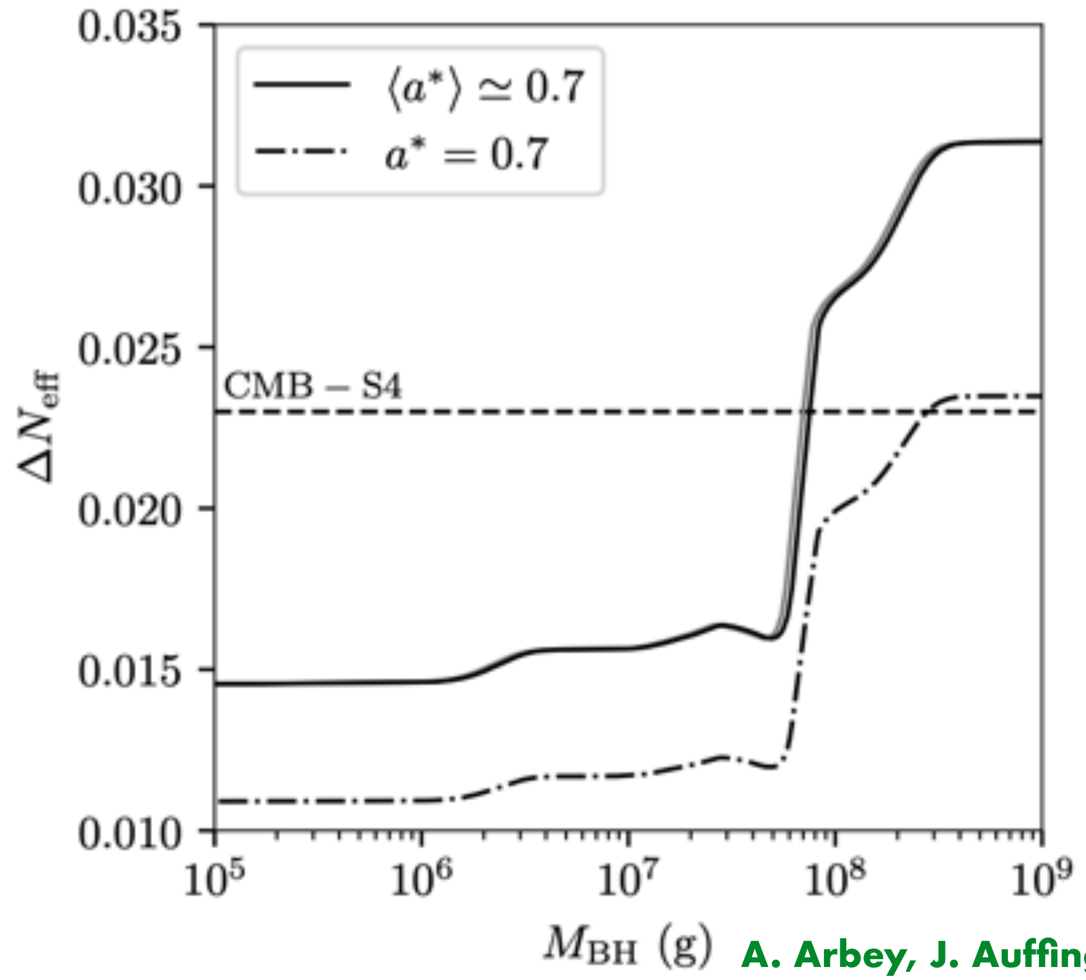


A. Arbey, J. Auffinger, P. Sandick, BSE, K. Sinha, 2104.04051

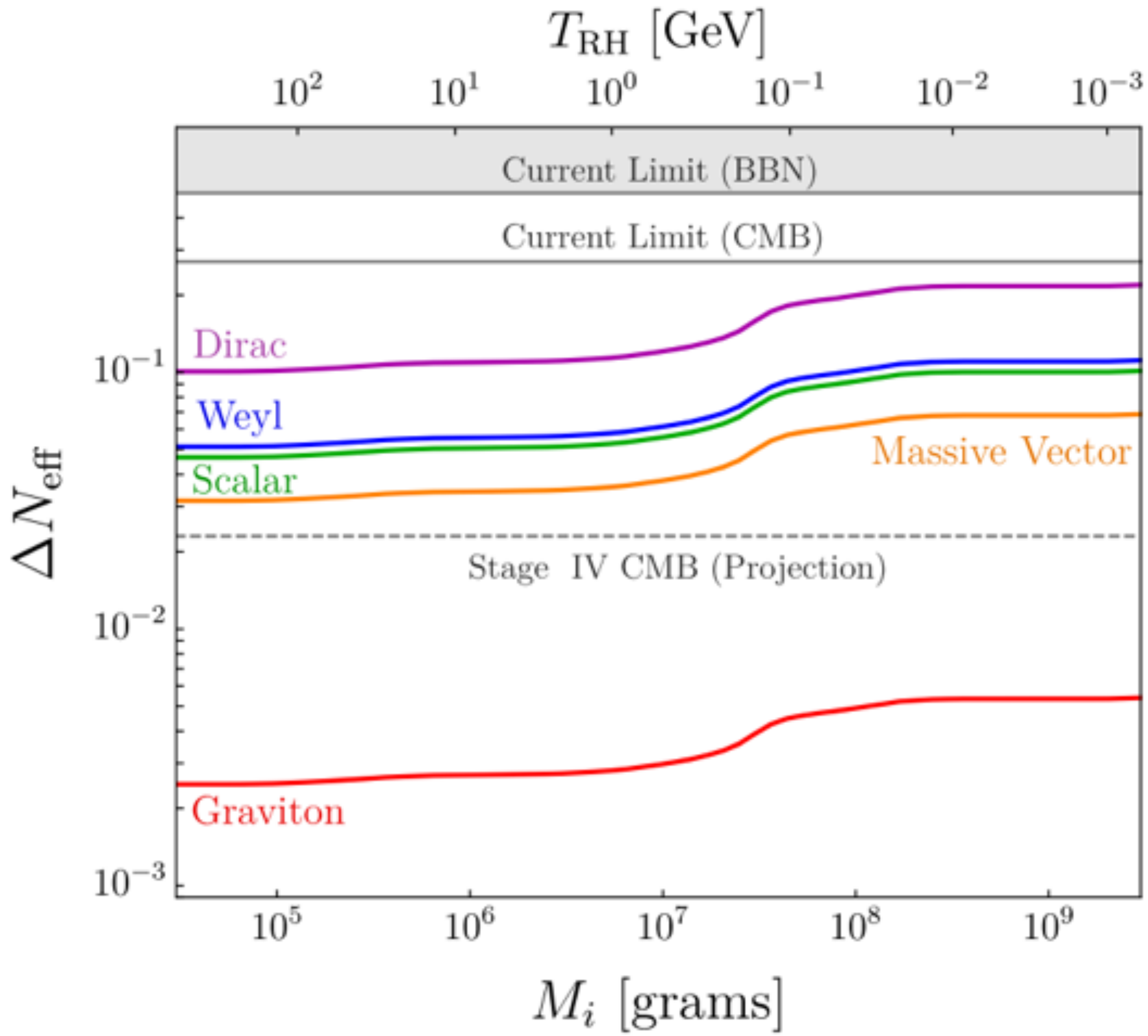
CMB1(TT+low E)
CMB2(TT,TE,EE+low E)

Inspirals:





A. Arbey, J. Auffinger, P. Sandick, BSE, K. Sinha, 2104.04051



O. Lennon, et. al., 1712.07664

D. Hooper, G. Krnjaic, S. D. McDermott, 1905.01301

regardless of reheating temperature

light and feebly-coupled scalars

$$N_{\rm axion} \lesssim 7$$

Baryogenesis

PBHs produce a BSM particle X that has baryon number

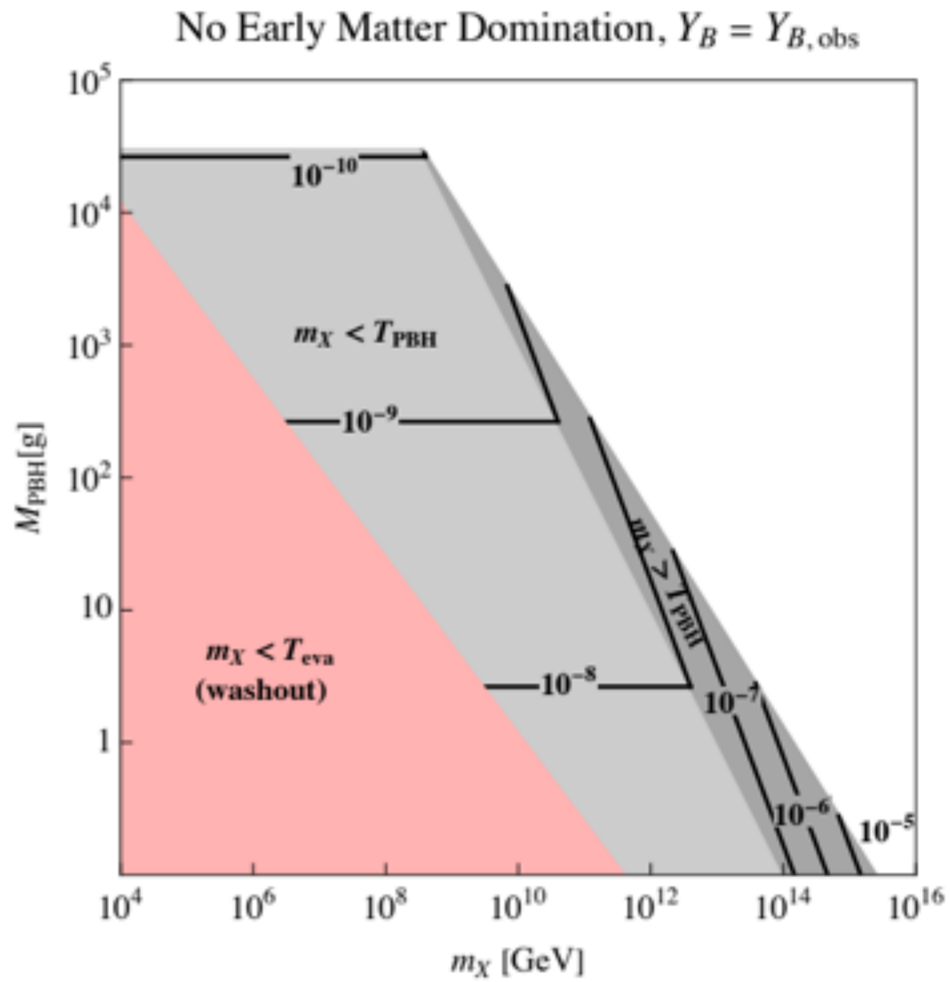
and CP violating decays to the SM.

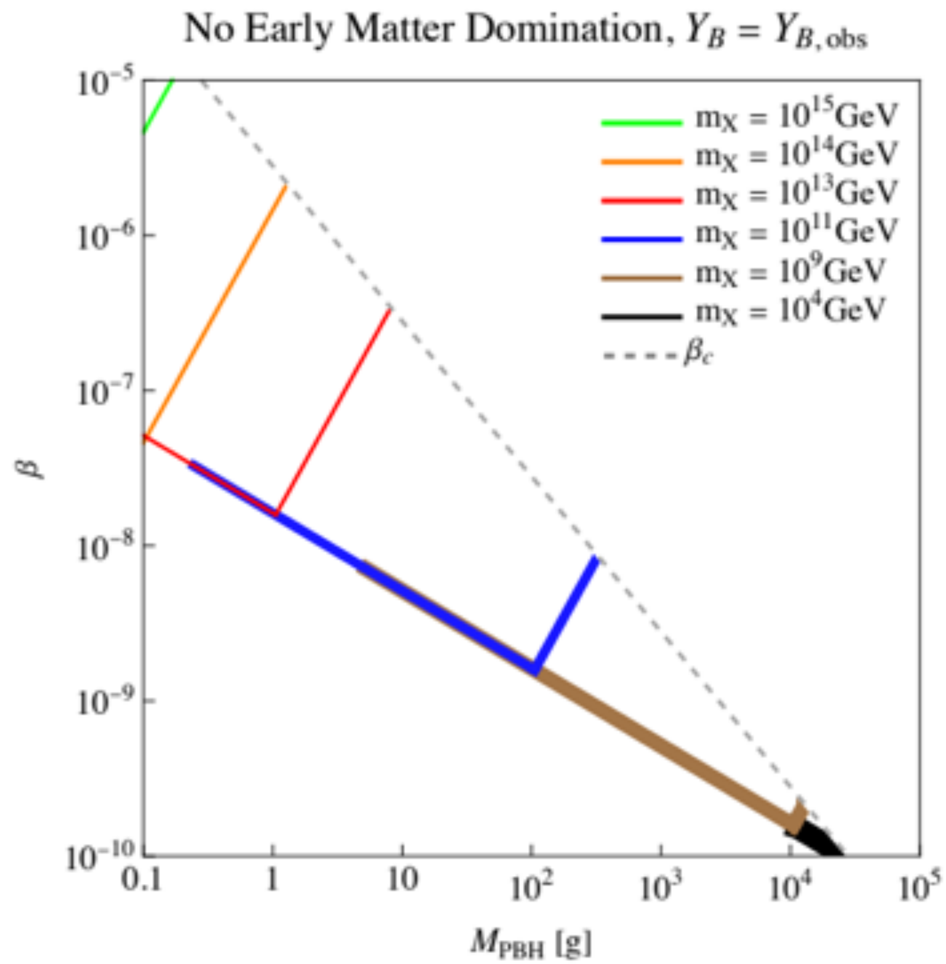
$$\gamma_{CP} = \sum_i B_i \frac{\Gamma(X \to f_i) - \Gamma(\bar{X} \to \bar{f}_i)}{\Gamma_X}$$

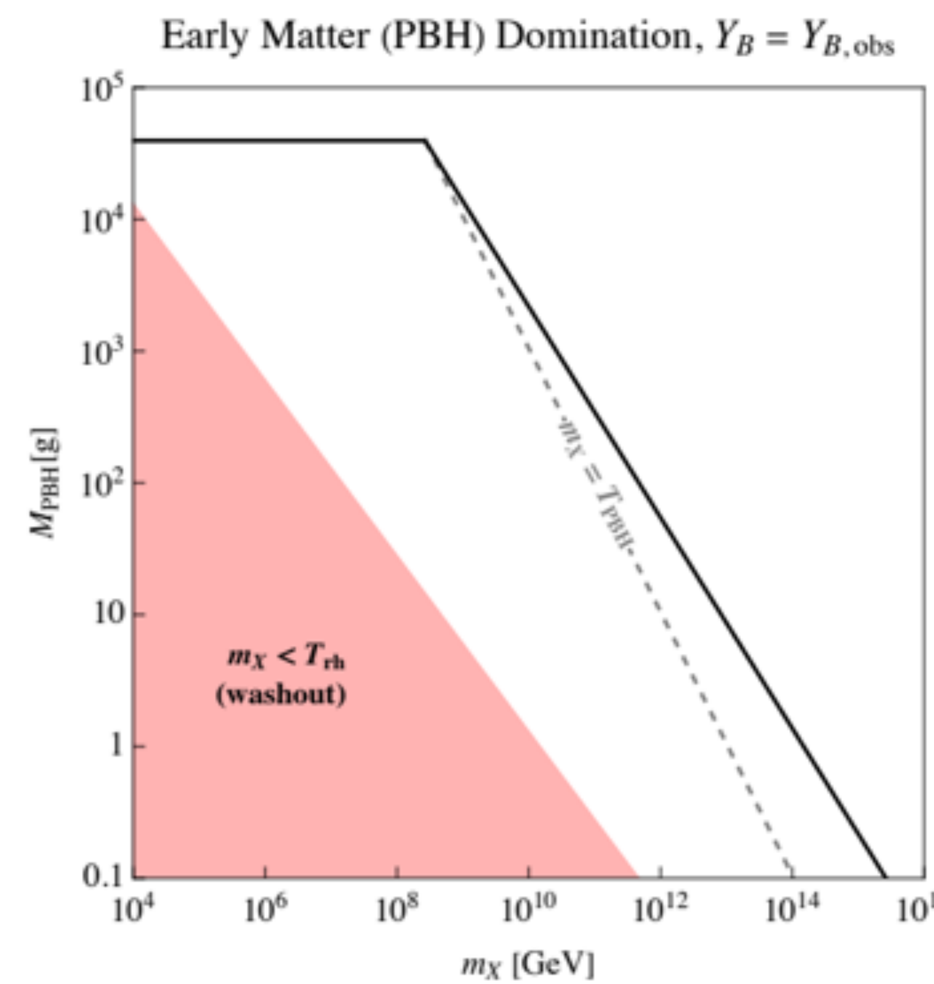
$$\gamma_{CP} \sim \frac{1}{16\pi^2}$$

$$Y_B = \frac{n_B(t_0)}{s(t_0)} = \gamma_{CP} \frac{n_X(t_{\text{eva}})}{s(t_{\text{eva}})}$$

$$Y_B = \frac{n_B}{s} \simeq 8.7 \times 10^{-11}$$







T. C. Gehrman, BSE, K. Sinha, T. Xu, 2211.08431

Gravitational Waves from PBHs

GWs associated with PBH formation:

scalar induced GWs from primordial overdensities

first order phase transition ...

GWs from PBH binary mergers

J. L. Zagorac, R. Easther, and N. Padmanabhan,1903.05053

GWs from Hawking evaporation

R. Anantua, R. Easther, and J. T. Giblin, 0812.0825

A. D. Dolgov and D. Ejlli, 1105.2303

R. Dong, W. H. Kinney, and D. Stojkovic, 1511.05642

A. Ireland, S. Profumo and J. Scharnhorst, 2302.10188

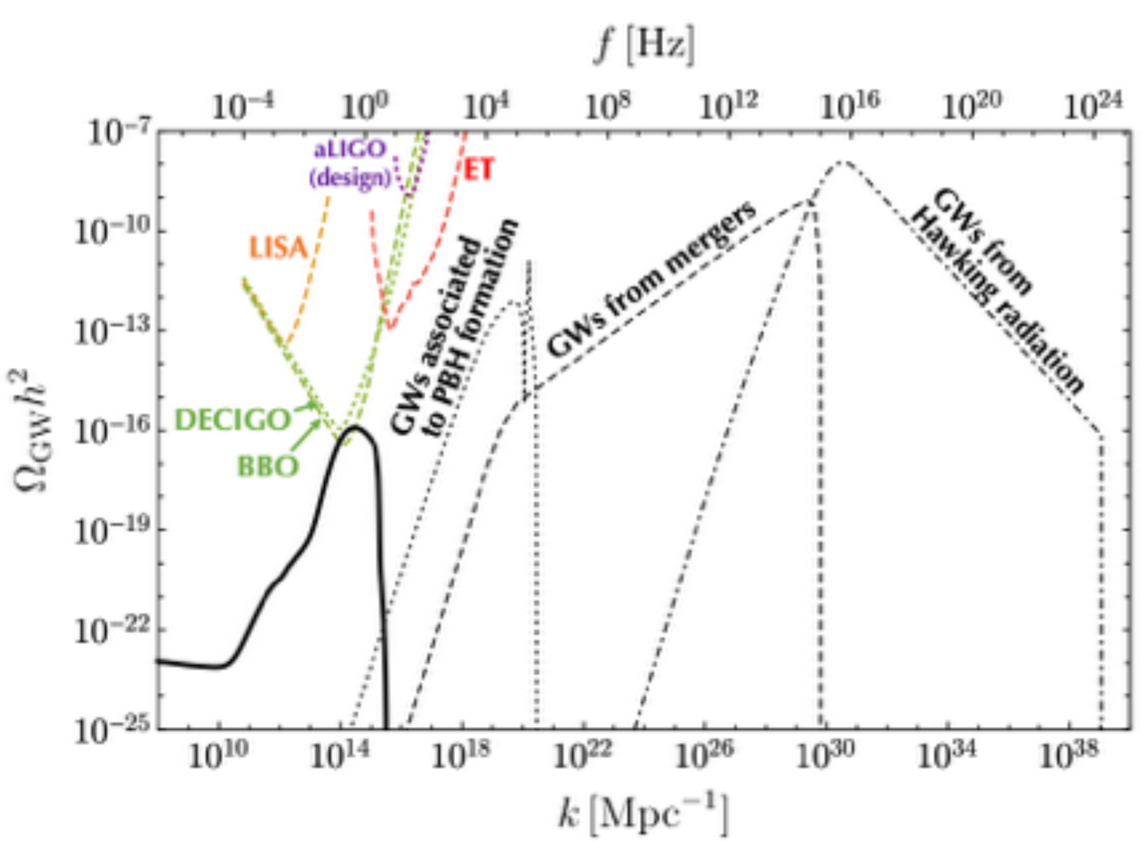
GWs amplified by PBH reheating:

sudden transition from EMD to RD enhance the production of induced GWs

(due to fast oscillations of sub-horizon scalar modes)

K. Inomata, K. Kohri, T. Nakama, and T. Terada ,1904.12879

M. Pearce, L. Pearce, G. White, C. Balazs, 2311.12340



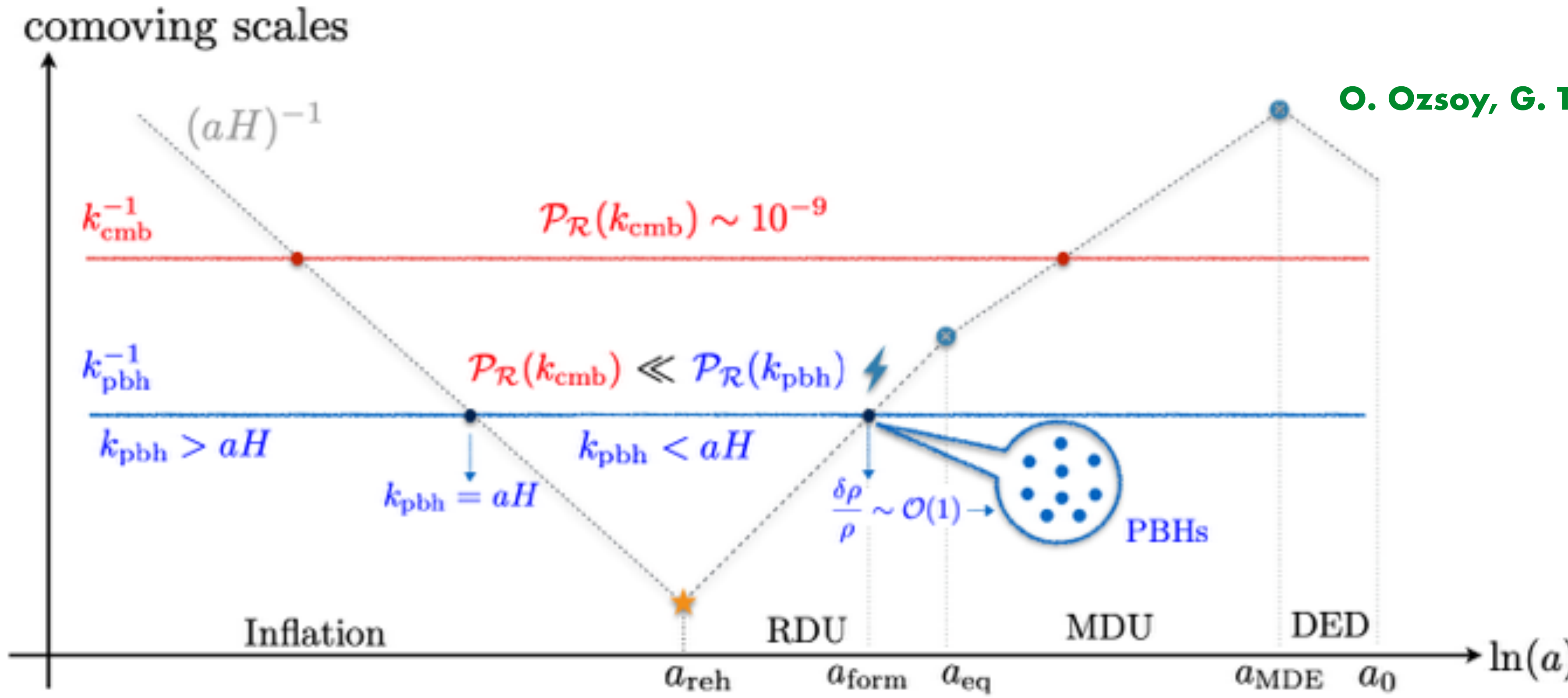
$$M_{\rm PBH,i} = 10^4\,{\rm g} \text{ and } \beta = 10^{-7}$$

(PBHs domination)

K. Inomata, et. al., 2003.10455

GW from formation mechanism:

Collapse of primordial overdensities (standard scenario): induce GWs at the second order



O. Ozsoy, G. Tasinato, 2301.03600

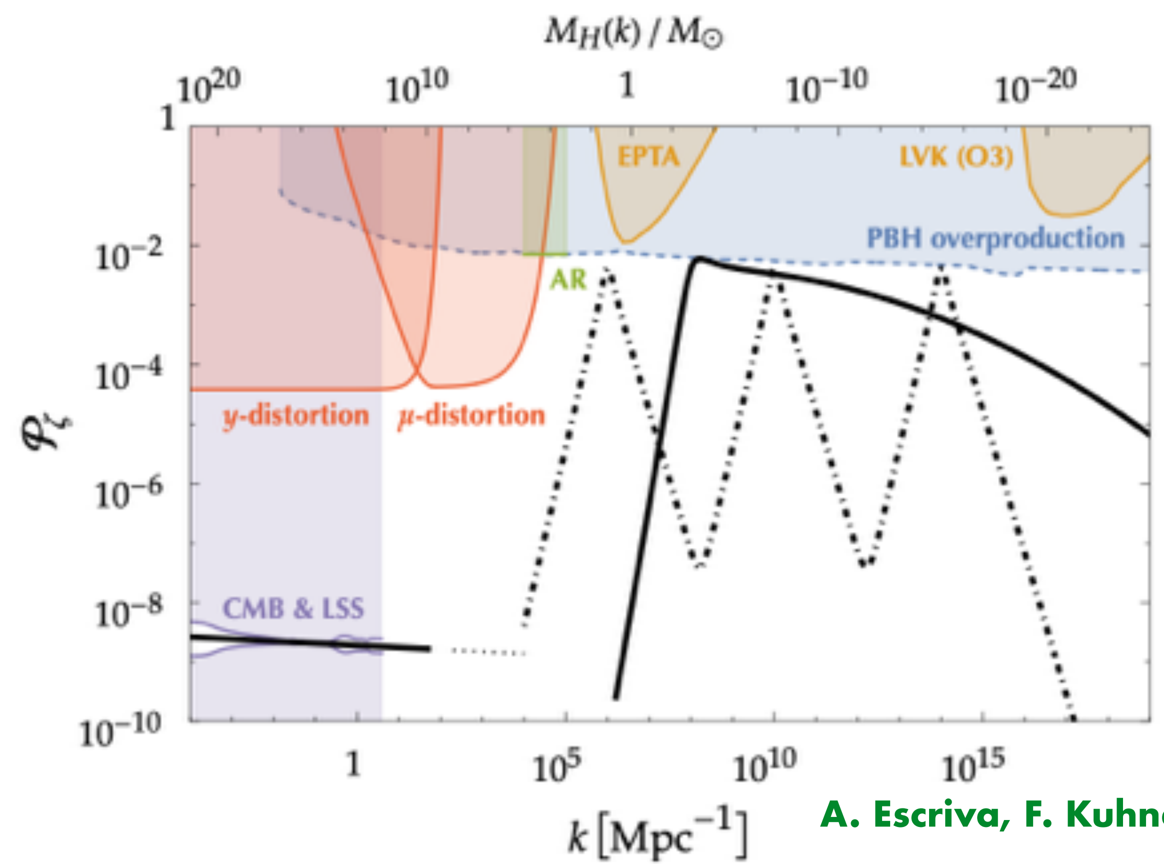
$$\delta\varphi_i \sim \delta\varphi_p \times \delta(\ln(k/k_p))$$

$$h_k'' + 2\mathcal{H}h_k' + k^2 h_k \approx k_p^2 \delta\varphi_p^2$$

$$f_{\rm peak} = \frac{k_p}{2\pi} \sim 10^{-15} \left(\frac{k_p}{\rm Mpc^{-1}}\right) \rm Hz$$

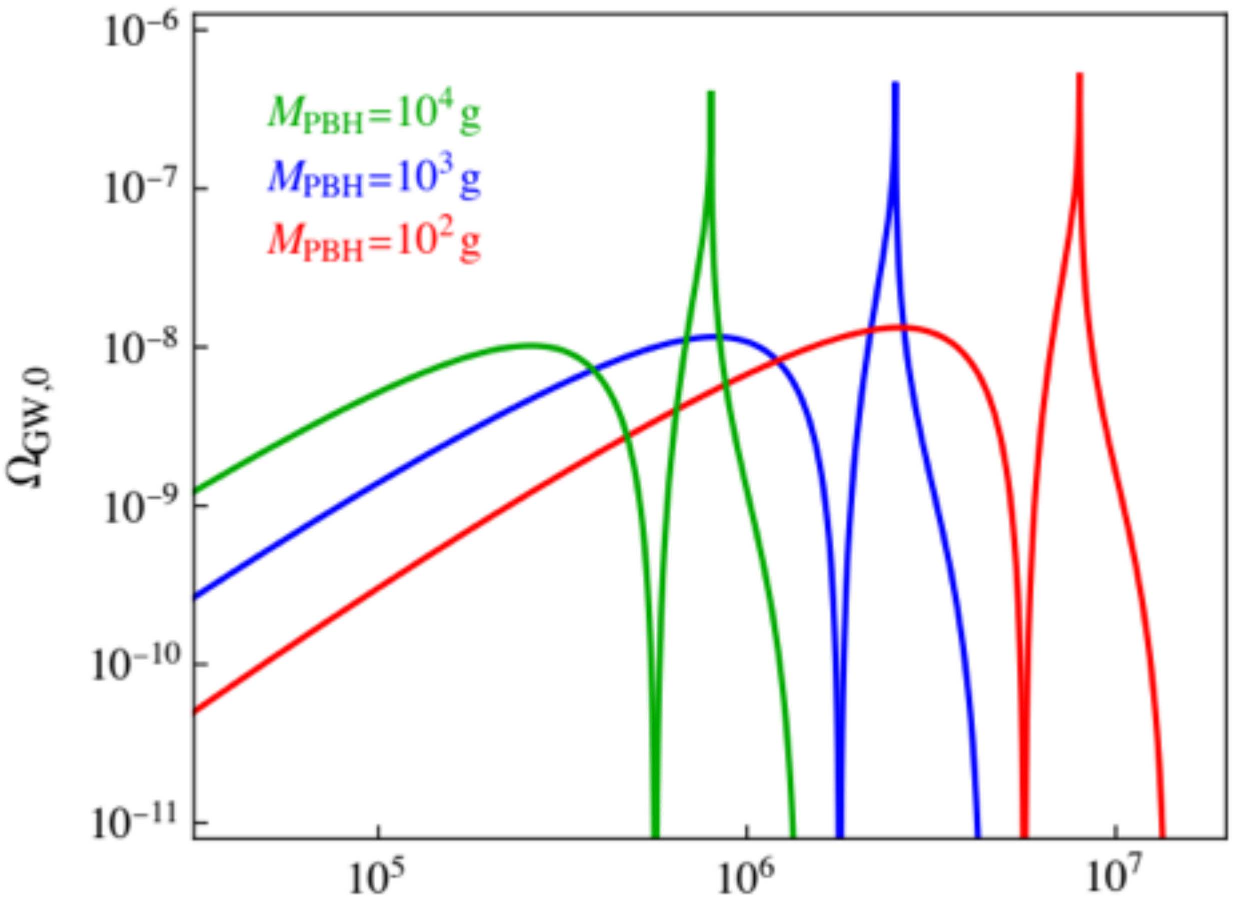
$$M_{\rm BH} \sim M_H(k = aH) \sim \frac{1}{k^2}$$

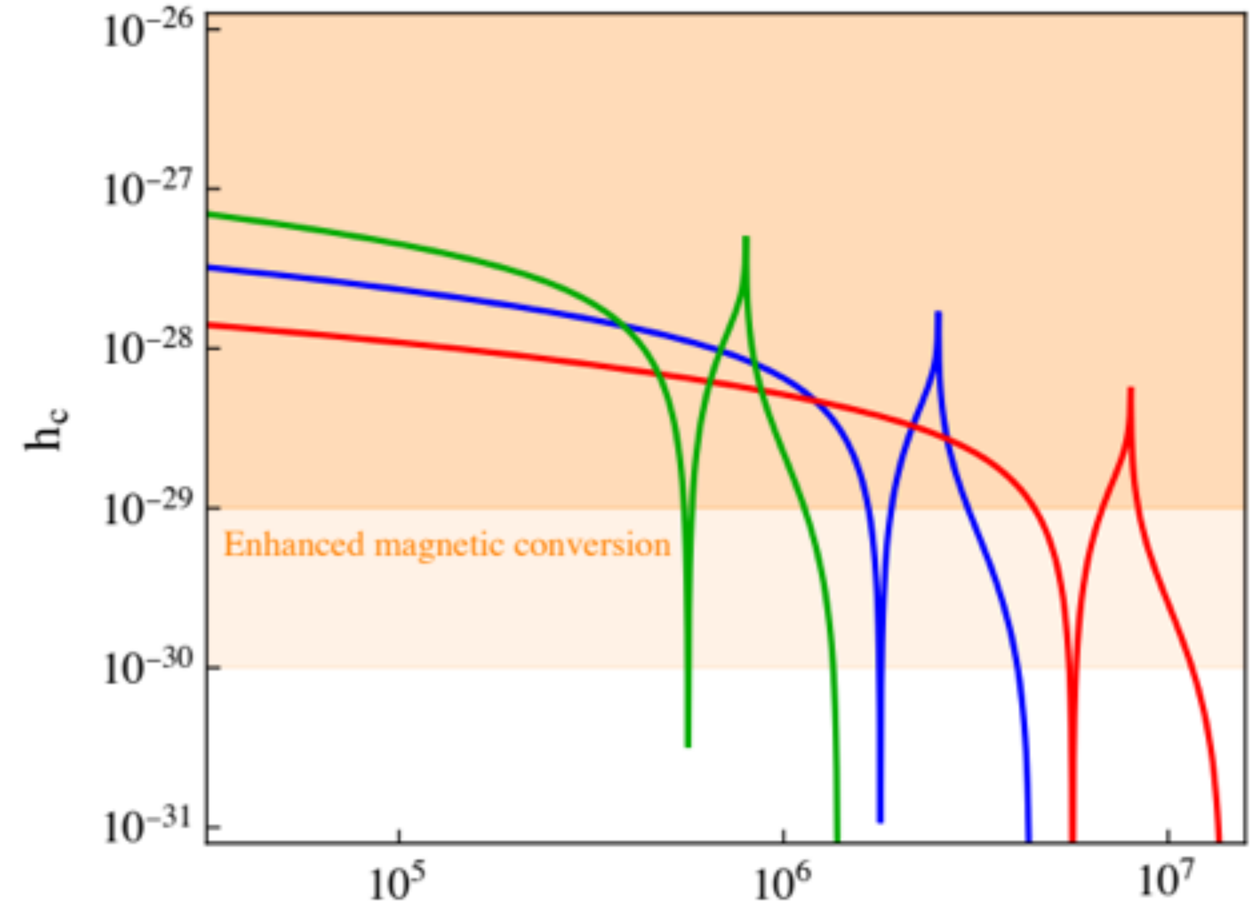
$$f_{\rm GW}^{\rm peak} \simeq 2.82 \times \left(\frac{M_{\rm PBH}}{10^4\ \rm g}\right)^{-\frac{1}{2}} \rm MHz.$$



A. Escriva, F. Kuhnel, Y. Tad 2211.05767

GWs and Baryogenesis:





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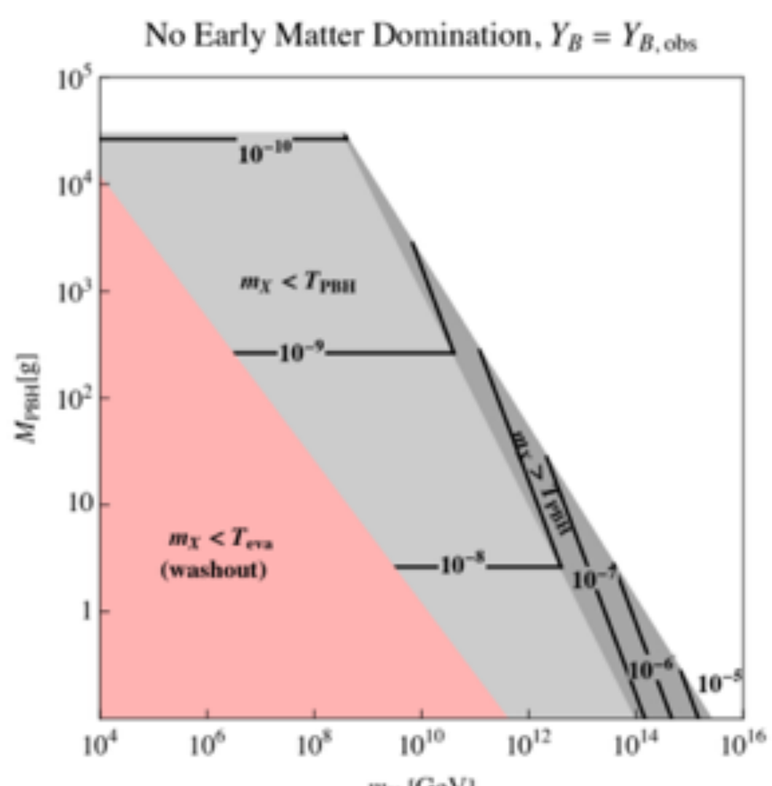
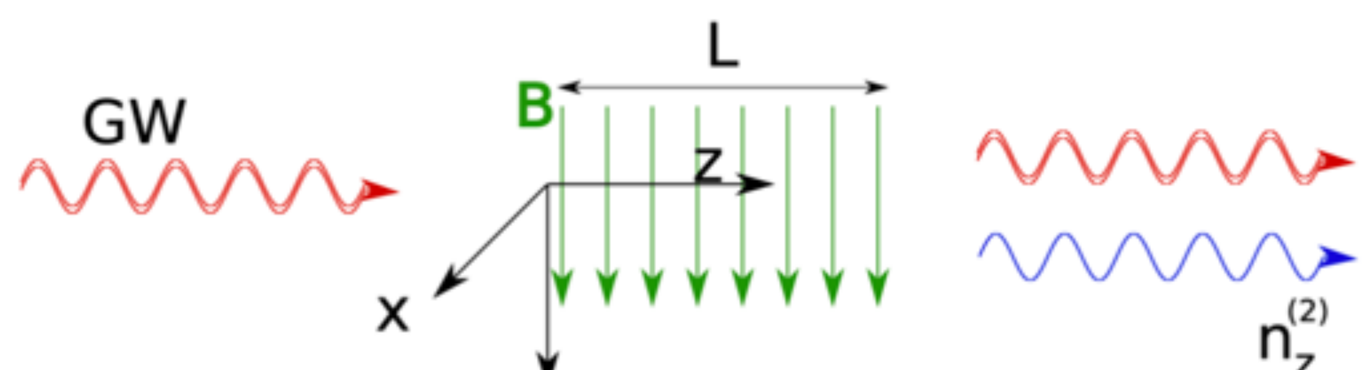


Probing baryogenesis by MHz-GHz GWs

detection proposal: the inverse Gertsenshtein effect



F.Y. Li, et. al., 0909.4118

A Ringwald, J. Schütte-Engel, C. Tamarit, 2011.04731

Summary

PBHs:

provide important information about the early Universe.
Also provide a gravitational production channel.

lead to non-standard cosmologies.

can be used to probe EMDEs.

populate dark sectors with interesting thermal histories.

associated with high frequency GWs.

Backup Slides

$$\delta = \delta\rho/\rho$$

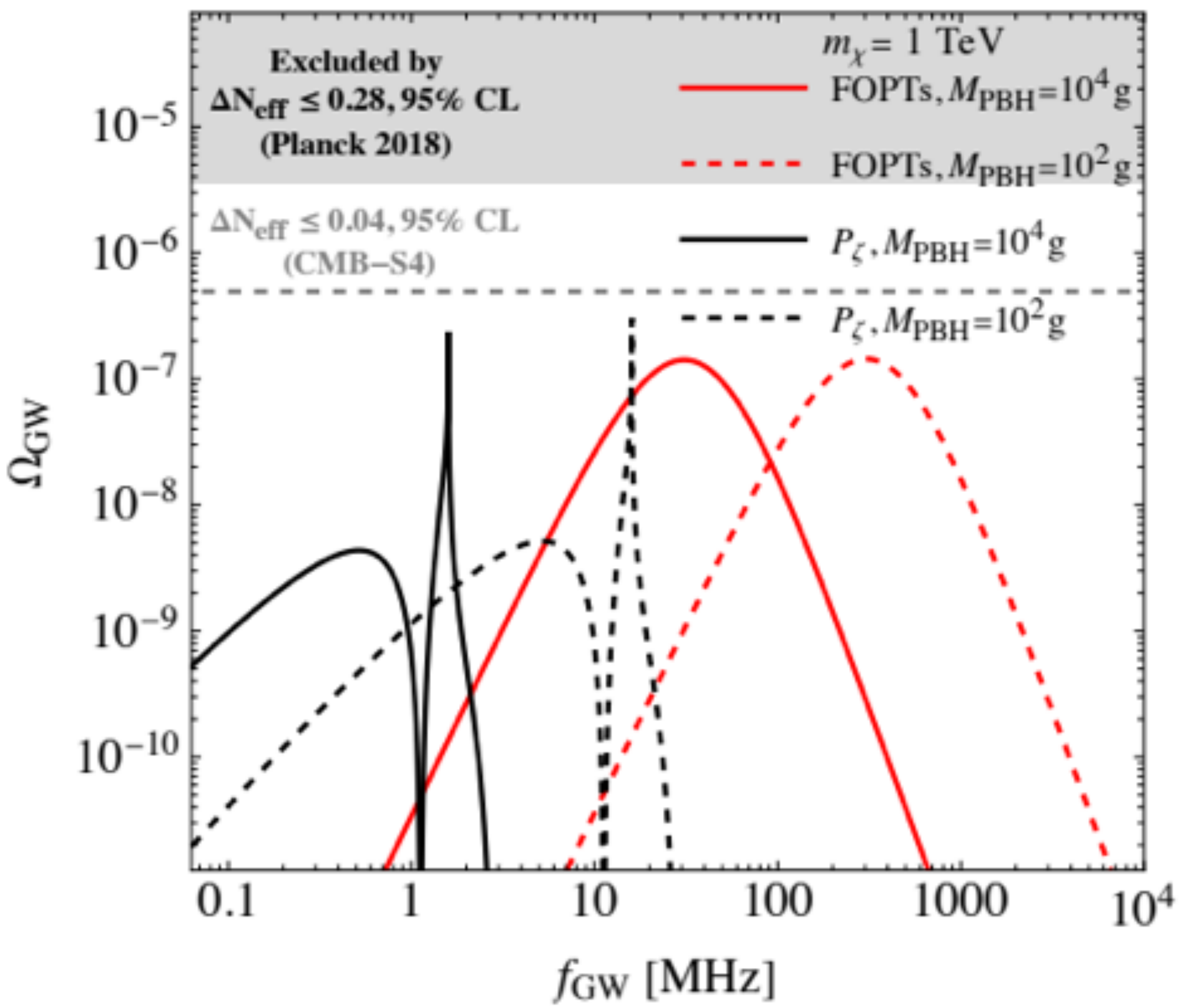
$$p(\delta) = \frac{1}{\sqrt{2\pi}\sigma_0}\, e^{-\frac{\delta^2}{2\sigma_0^2}}.$$

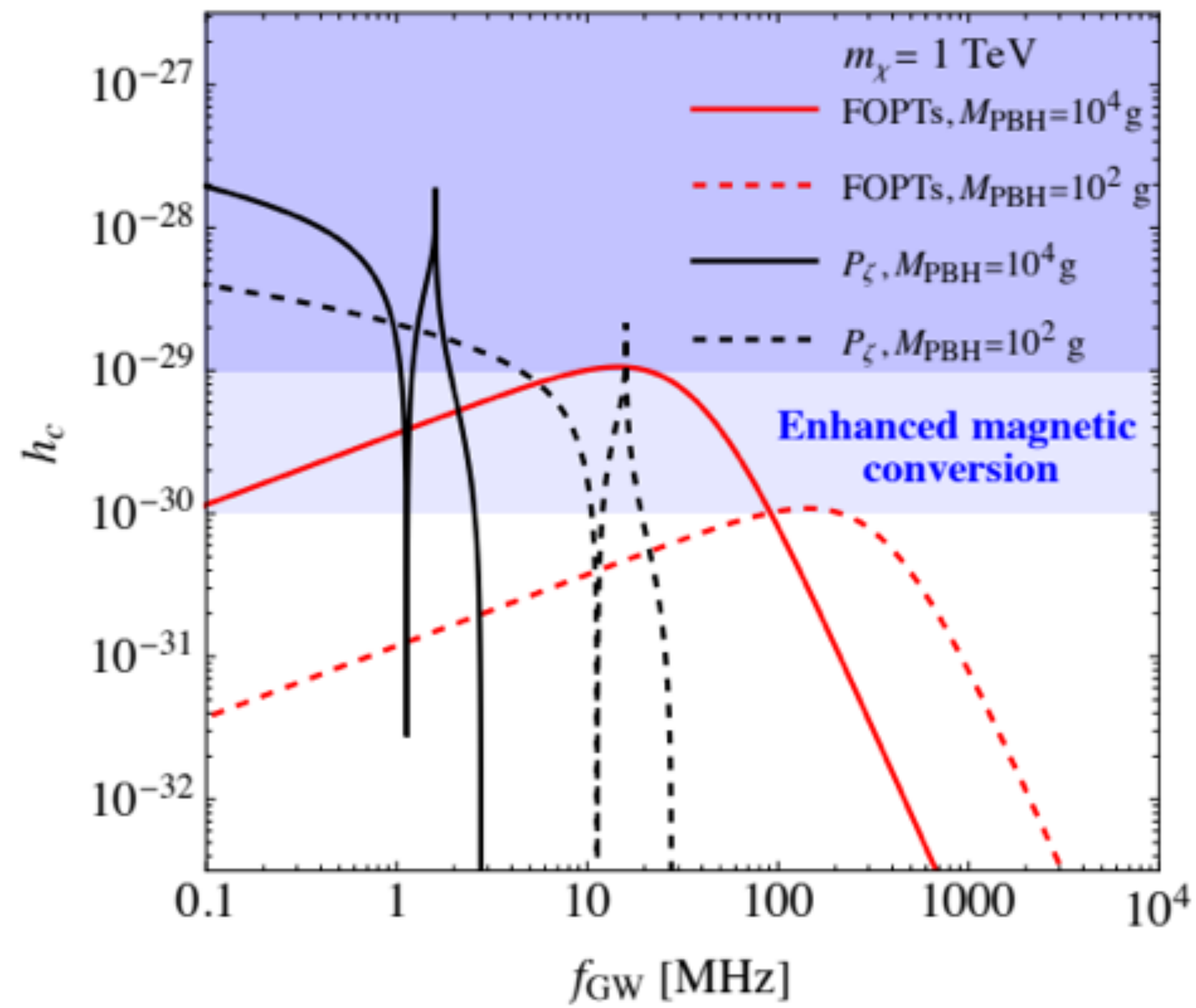
$$\sigma_0^2(k = R^{-1}) = \int_0^\infty \frac{\mathrm{d}k'}{k'} \frac{16}{81} (k'R)^4 W^2(k', R) P_\zeta(k')$$

$$\beta_{\mathrm{PBH}} = \gamma \int_{\delta_c}^\infty d\delta\, \frac{1}{\sqrt{2\pi}\sigma_0} e^{-\frac{\delta^2}{2\sigma_0^2}} \qquad \delta_c = c_s^2$$

$$= \frac{\gamma}{2}\, \mathrm{Erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma_0}\right).$$

$$\delta(\vec{x}, t) \simeq \frac{2(1+w)}{(5+3w)} \frac{\nabla^2 \mathcal{R}(\vec{x})}{(aH)^2} + \ldots \quad \Longrightarrow \quad \delta_k \simeq -\frac{4}{9} \left(\frac{k}{aH}\right)^2 \mathcal{R}_k$$





T. C. Gehrman, BSE, K. Sinha, T. Xu,2304.09194