A common origin of Baryons and Dark Matter via gravitational collapse of Primordial Black Holes

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Outline

- Introduction
  - LIGO Gravitational Waves from BH Binaries
  - Mass and Spin as a hint to PBH nature
- Novel scenario
  - Solar mass PBH form at quark-hadron trans.
  - Gravitational collapse of hot plasma induces Hot Spot EW baryogenesis at QCD
  - Similar density of Baryons and DM = PBH
  - Stochastic spectator field = QCD axion
- Overview and predictions
- Conclusions

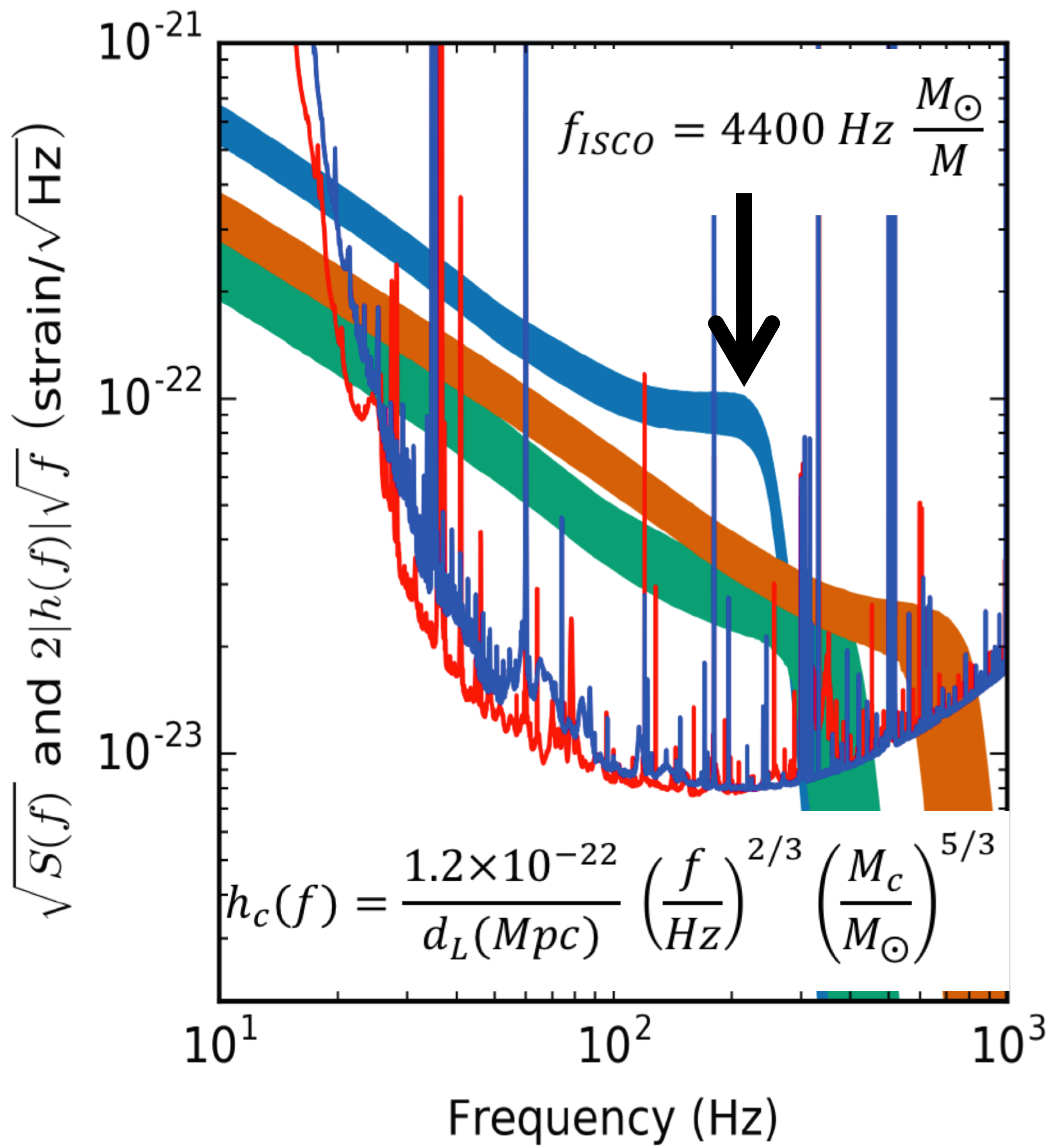
10 LVC BHB events (O1+O2) [many more in run O3]

LVC (2018)

Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	χ_{eff}	$M_{\mathrm{f}}/\mathrm{M}_\odot$	a_{f}	$E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9}\times10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3}\times10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5}\times10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5}\times10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1\times10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9}\times10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

TABLE III. Selected source parameters of the eleven confident detections. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of two waveform models for BBHs. For GW170817 credible intervals and statistical errors are shown for IMRPhenomPv2NRT with low spin prior, while the sky area was computed from TaylorF2 samples. The redshift for NGC 4993 from [87] and its associated uncertainties were used to calculate source frame masses for GW170817. For BBH events the redshift was calculated from the luminosity distance and assumed cosmology as discussed in Appendix B. The columns show source frame component masses m_i and chirp mass $\mathcal{M}$, dimensionless effective aligned spin χ_{eff}, final source frame mass M_f, final spin a_f, radiated energy E_{rad}, peak luminosity l_{peak}, luminosity distance d_L, redshift z and sky localization $\Delta\Omega$. The sky localization is the area of the 90% credible region. For GW170817 we give conservative bounds on parameters of the final remnant discussed in Sec. V E.

LVC BHB events



Given the present rate O1-O2
R ~ 20-120 events/yr/Gpc^3
soon O3 will have MANY events.

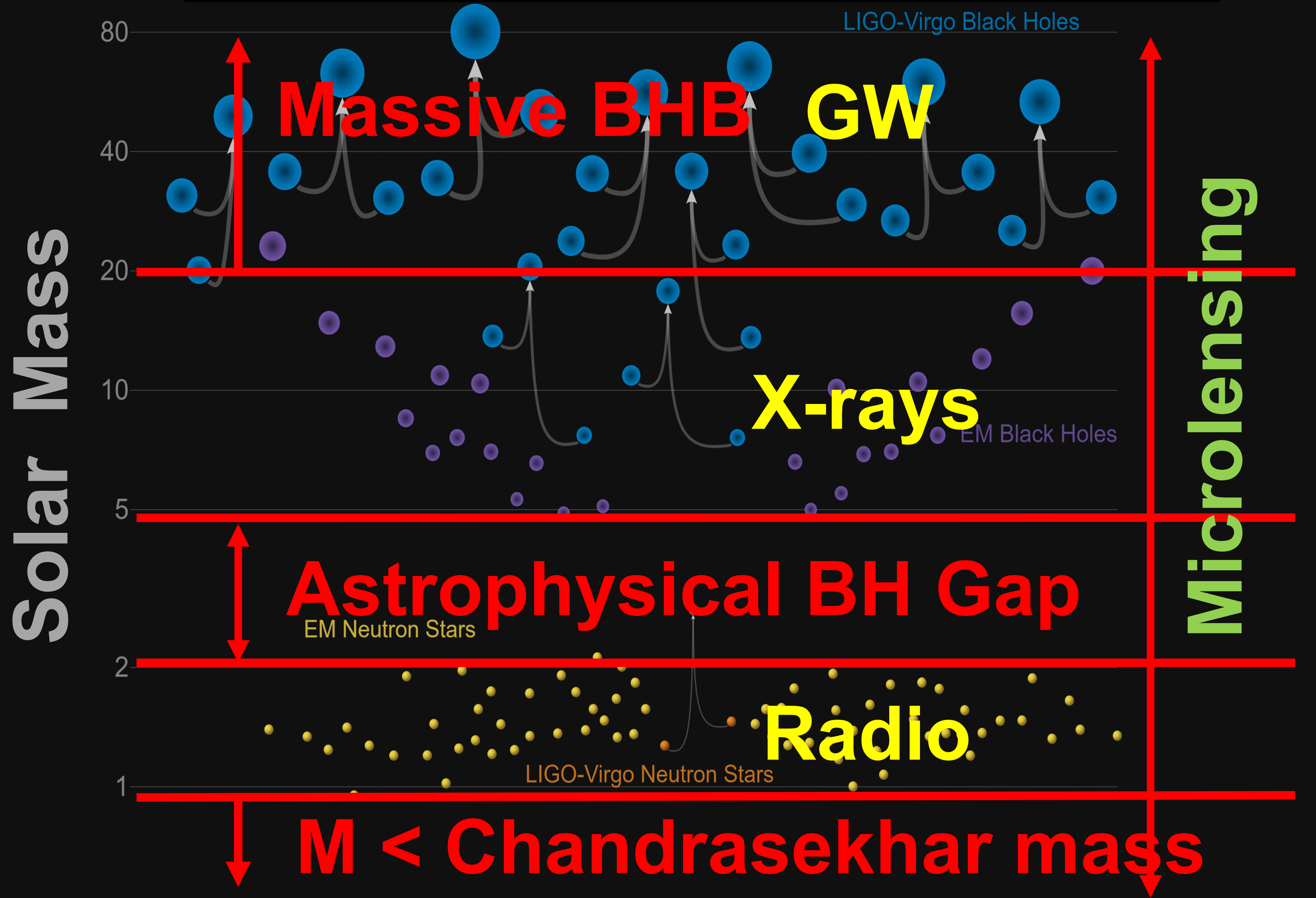
Will test lognormal distribution.
Observed rate of events is OK
with clustered wide-mass distr.

If LIGO detects a single BH with M < 1Msun it will necessarily be of primordial origin, not stellar.

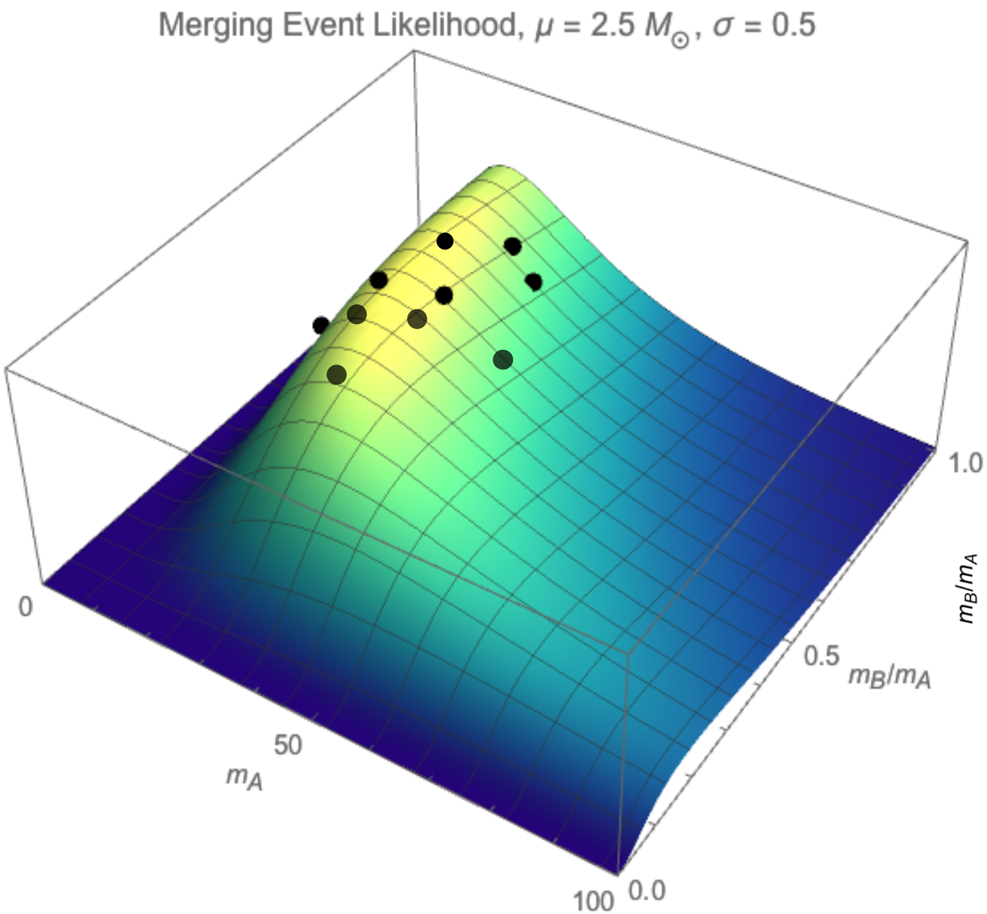
Chirp mass

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

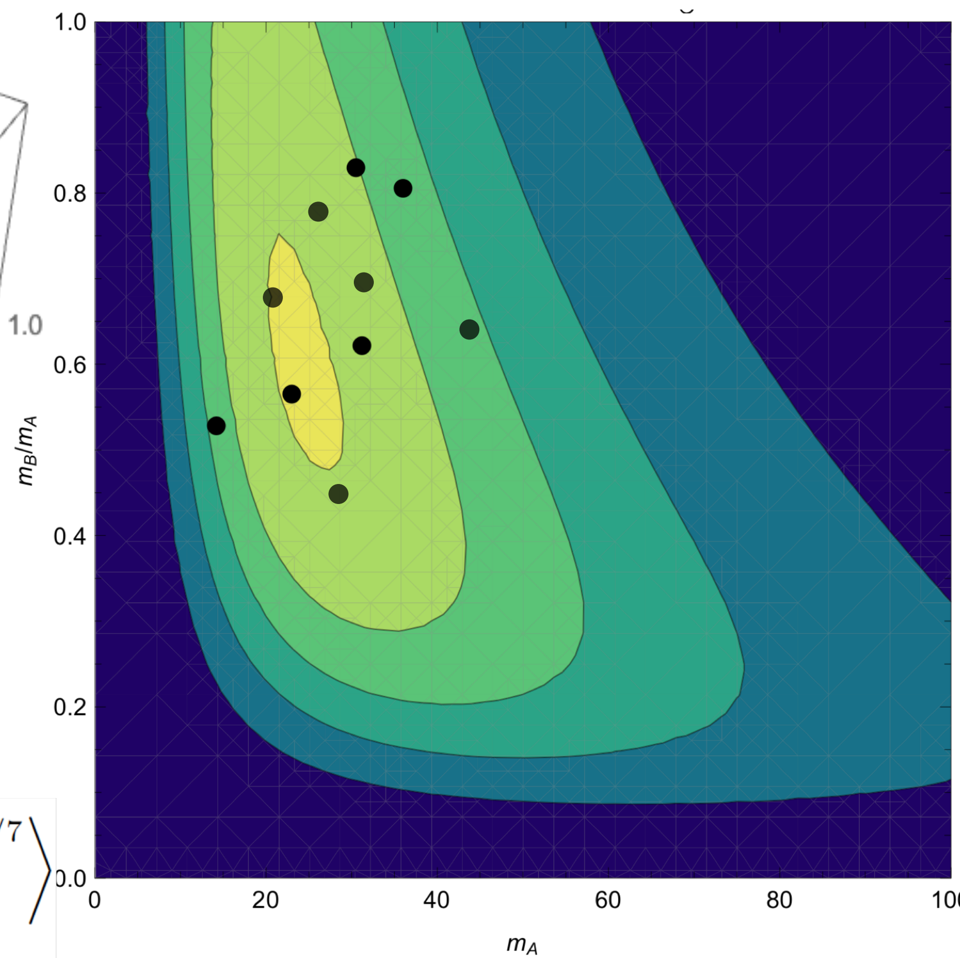
Black Holes and Neutron Stars



LVC BHB event rate



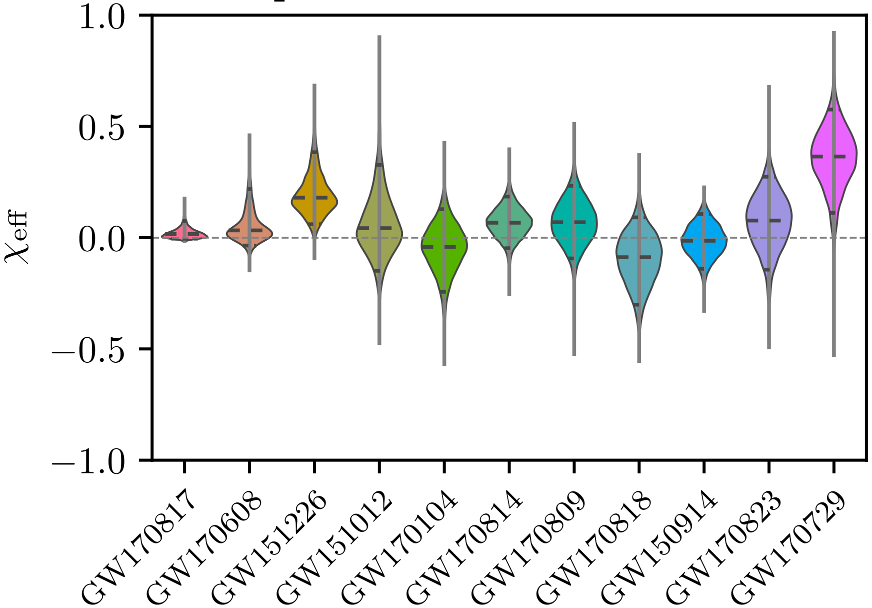
Clesse & JGB (2016-18)



$$\frac{\mathrm{d}\tau_{\mathrm{merg}}}{\mathrm{d}m_{\mathrm{A}}\mathrm{d}m_{\mathrm{B}}} \simeq 2.9\times10^{-9}\ \langle\delta^2_{\mathrm{PBH}}\rangle^{1/2}\left\langle\left(\frac{v}{20\ \mathrm{km/s}}\right)^{-11/7}\right\rangle \times\frac{\psi(m_{\mathrm{A}})\psi(m_{\mathrm{B}})(m_{\mathrm{A}}+m_{\mathrm{B}})^{10/7}}{2^{10/7}\ln^2(10)\ \rho^2_{\mathrm{DM}}(m_{\mathrm{A}})^{12/7}(m_{\mathrm{B}})^{12/7}}\ \mathrm{yr}^{-1}\mathrm{Gpc}^{-3},$$

$$\psi\equiv\frac{\mathrm{d}\rho(m_{\mathrm{PBH}})}{\mathrm{d}\log_{10}m_{\mathrm{PBH}}}=\frac{\rho_{\mathrm{DM}}}{\sqrt{2\pi\sigma^2}}\exp\left[-\frac{\log^2_{10}(m_{\mathrm{PBH}}/\mu)}{2\sigma^2}\right]$$

Spin distribution of LVC BHB

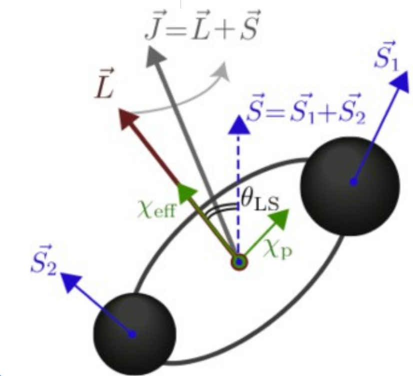


Effective aligned spin

$$\chi_{\rm eff} = \frac{m_1\,\chi_1 + m_2\,\chi_2}{m_1 + m_2}$$

$$\chi_i \equiv \frac{\vec{S}_i \cdot \vec{L}}{m_i^2}$$

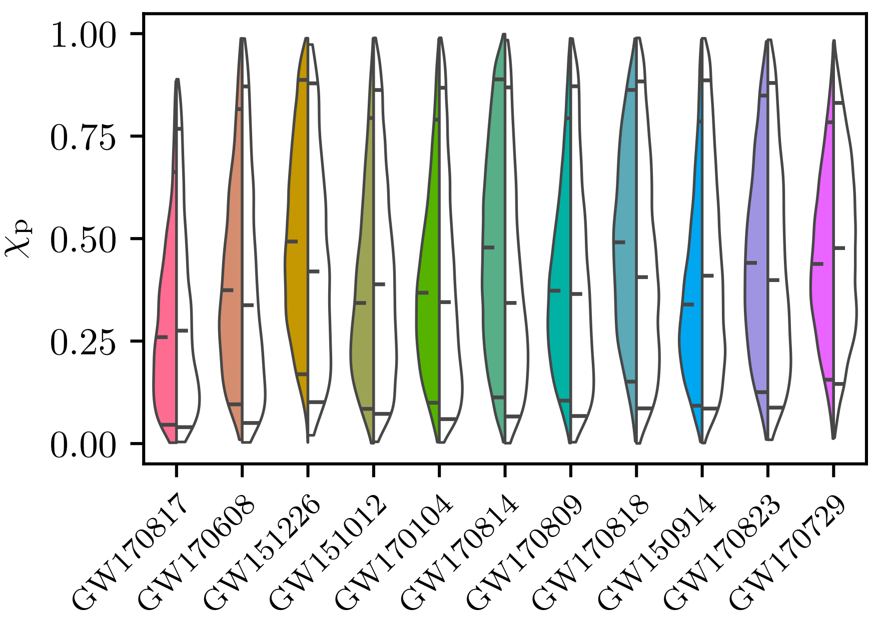
LVC (2018)



$$A_1 = 2 + 3m_2/2m_1$$

$$A_2 = 2 + 3m_1/2m_2$$

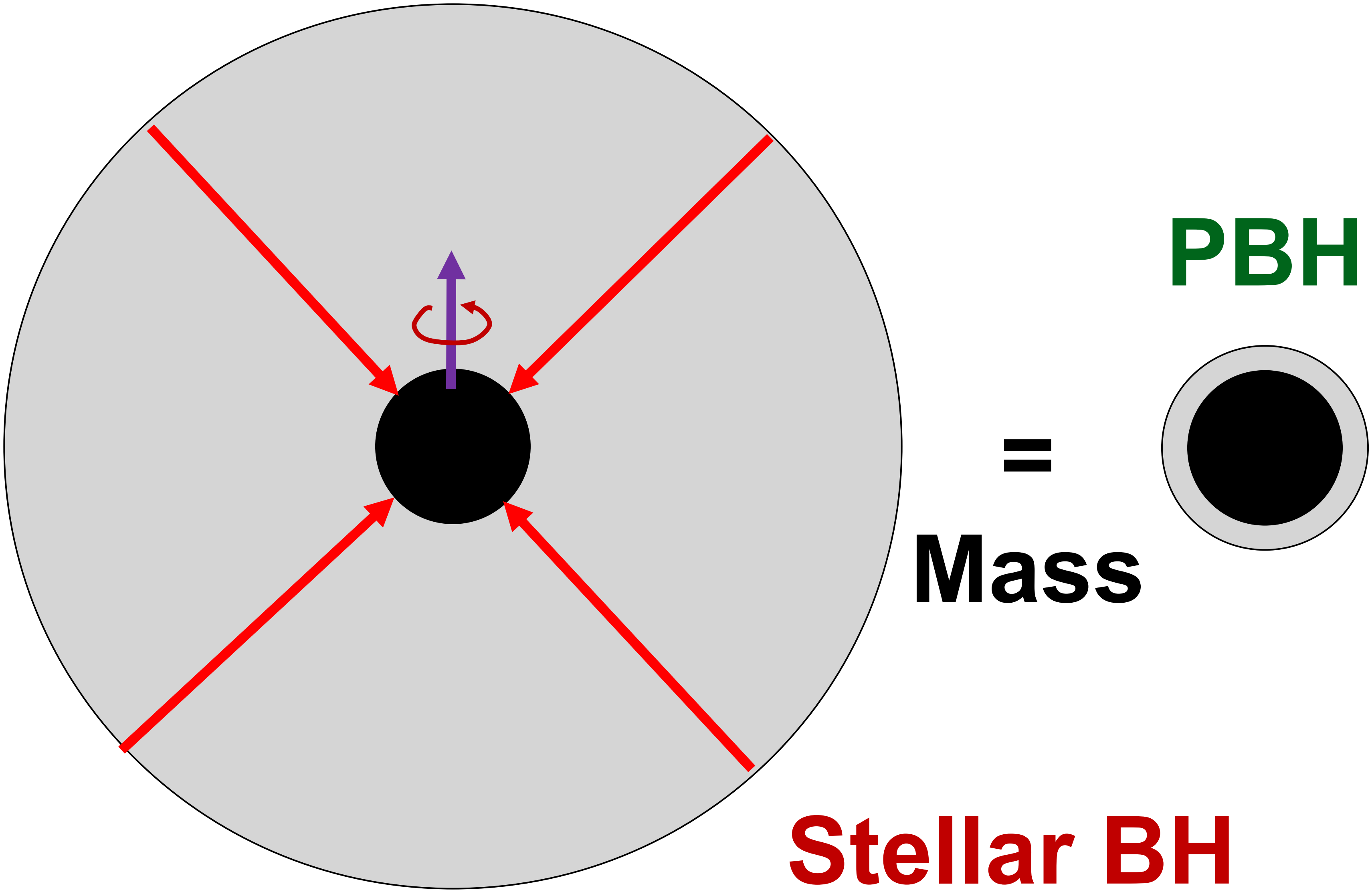
$$\chi_{\rm p} = \frac{\max(A_1\,m_1^2\,\chi_{1\perp},\, A_2\,m_2^2\,\chi_{2\perp})}{A_1\,m_1^2}$$



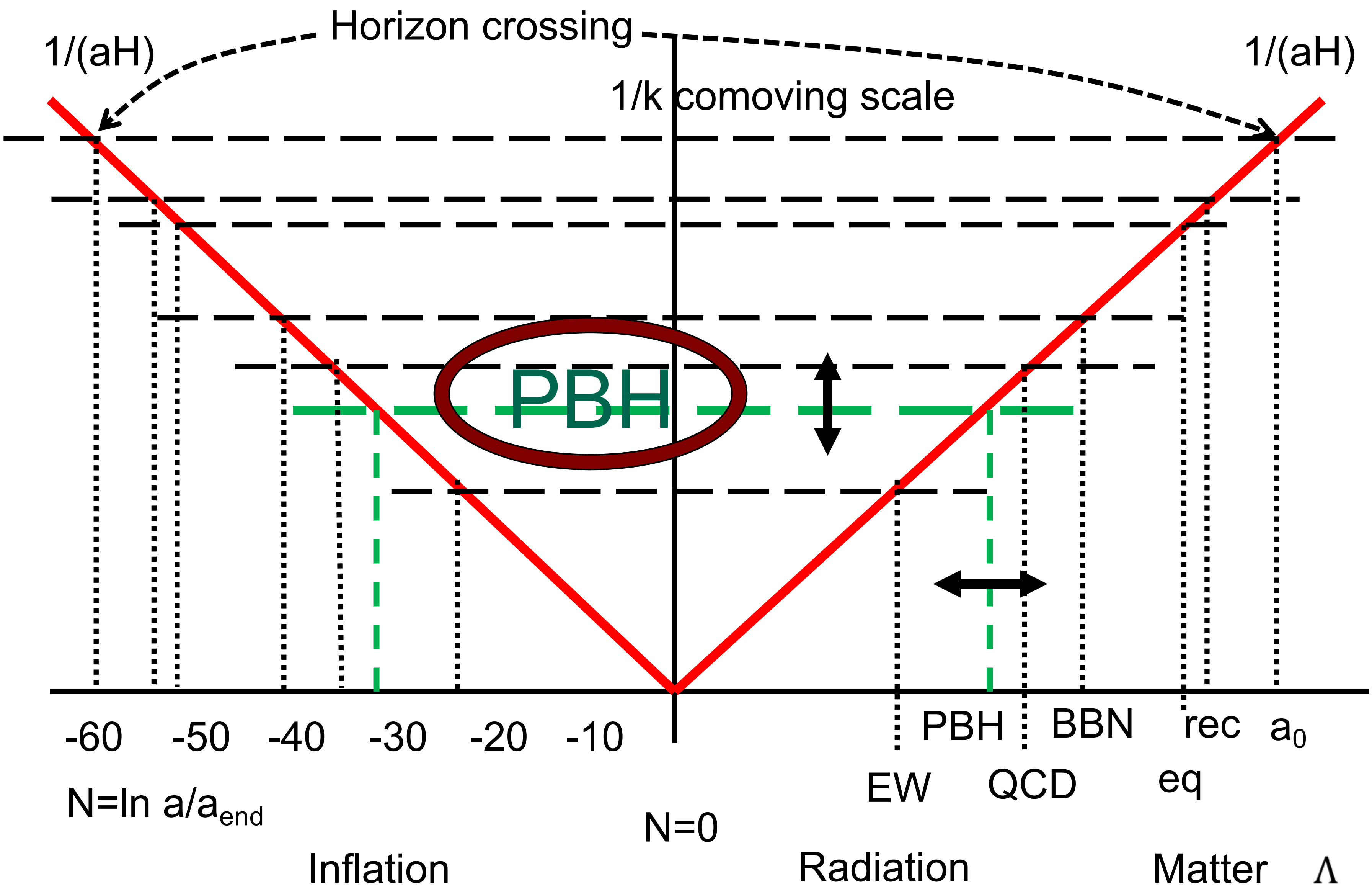
Effective precession spin

LVC (2018)

PBH are ~ spinless

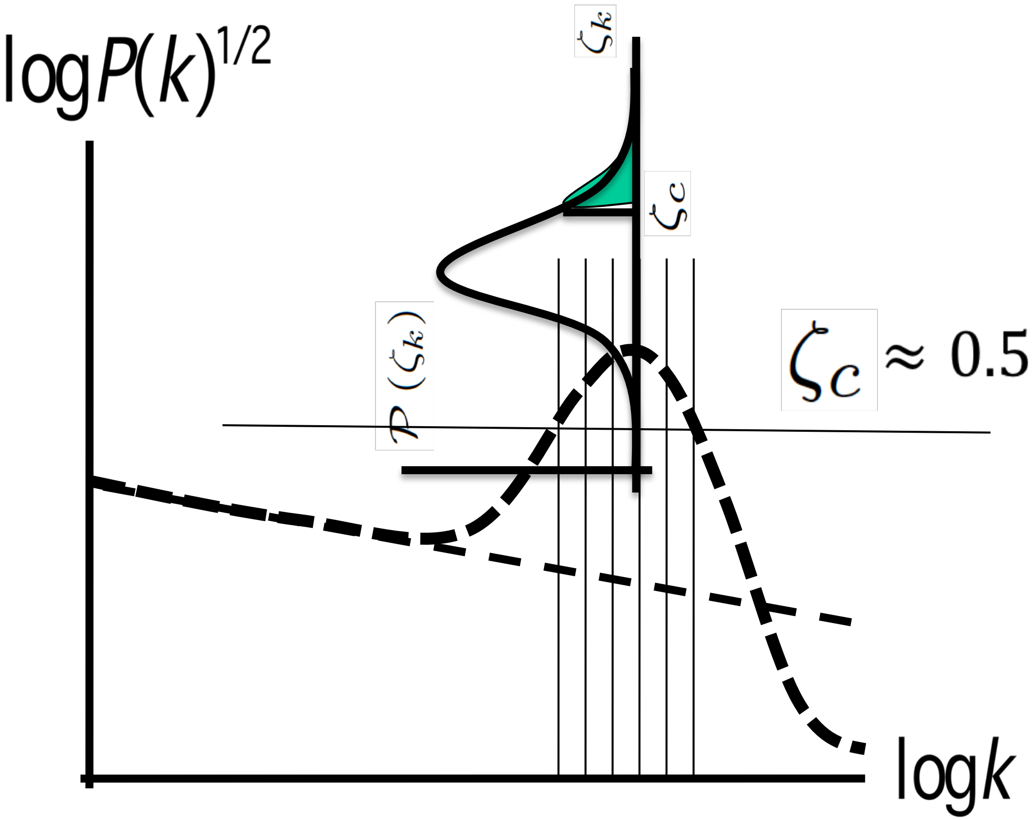


Inflation

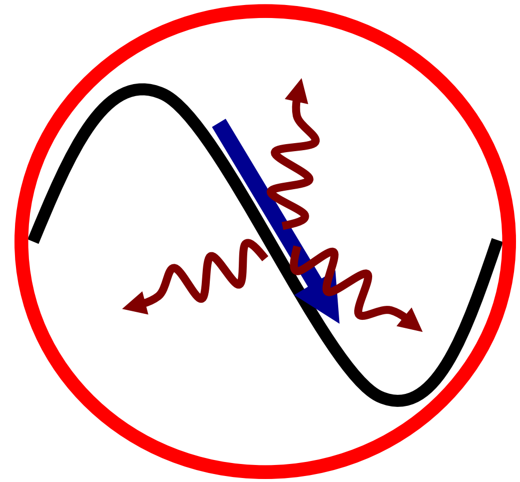


Horizon crossing
1/(aH)
1/(aH)
1/k comoving scale
PBH
-60
-50
-40
-30
-20
-10
N=ln a/a_end
N=0
EW
PBH
QCD
BBN
rec
eq
a_0
Inflation
Radiation
Matter
Λ

Gravitational Collapse of PBH



$$\beta^{\text{form}}(M_k) = \int_{\zeta_c}^{\infty} \mathcal{P}(\zeta_k)\, d\zeta_k$$



$$\boxed{M_{PBH} \approx 30 M_{\odot}\, e^{2(N-36)}}$$

$$\beta(N) = \begin{cases} \mathrm{Erfc}\left(\dfrac{\zeta_c}{\sqrt{2P_\zeta(N)}}\right), & \text{Gaussian statistics}, \\ \mathrm{Erfc}\left(\sqrt{\dfrac{1}{2} + \dfrac{\zeta_c}{\sqrt{2P_\zeta(N)}}}\right), & \chi^2 \ \text{statistics} \end{cases}$$

Origin of PBH mass

Chandrasekhar mass (Pauli exclusion)

$$M_{\rm Ch} = \frac{\omega}{\mu^2}\left(\frac{3\pi}{4}\right)^{1/2} \frac{M_{\rm P}^3}{m_{\rm p}^2} \simeq 1.4\, M_\odot$$

$$\omega = 2.018$$

μ is the number of electrons per nuclei (1 for hydrogen, 2 for helium)

Mass within the horizon at QCD

$$M_{\rm PBH} = \gamma\, \frac{4\pi}{3} \rho_{\rm r}\, d_{\rm H}^3 = \gamma\, \frac{3\sqrt{5}}{4\pi^{3/2}} \frac{x^2}{g_*^{1/2}(x)} \frac{M_{\rm P}^3}{m_{\rm p}^2} \simeq \ \text{few}\, M_\odot$$

$$x \equiv \frac{m_p}{T}$$

$$T \sim \Lambda_{\rm QCD} \sim 200\,{\rm MeV}$$

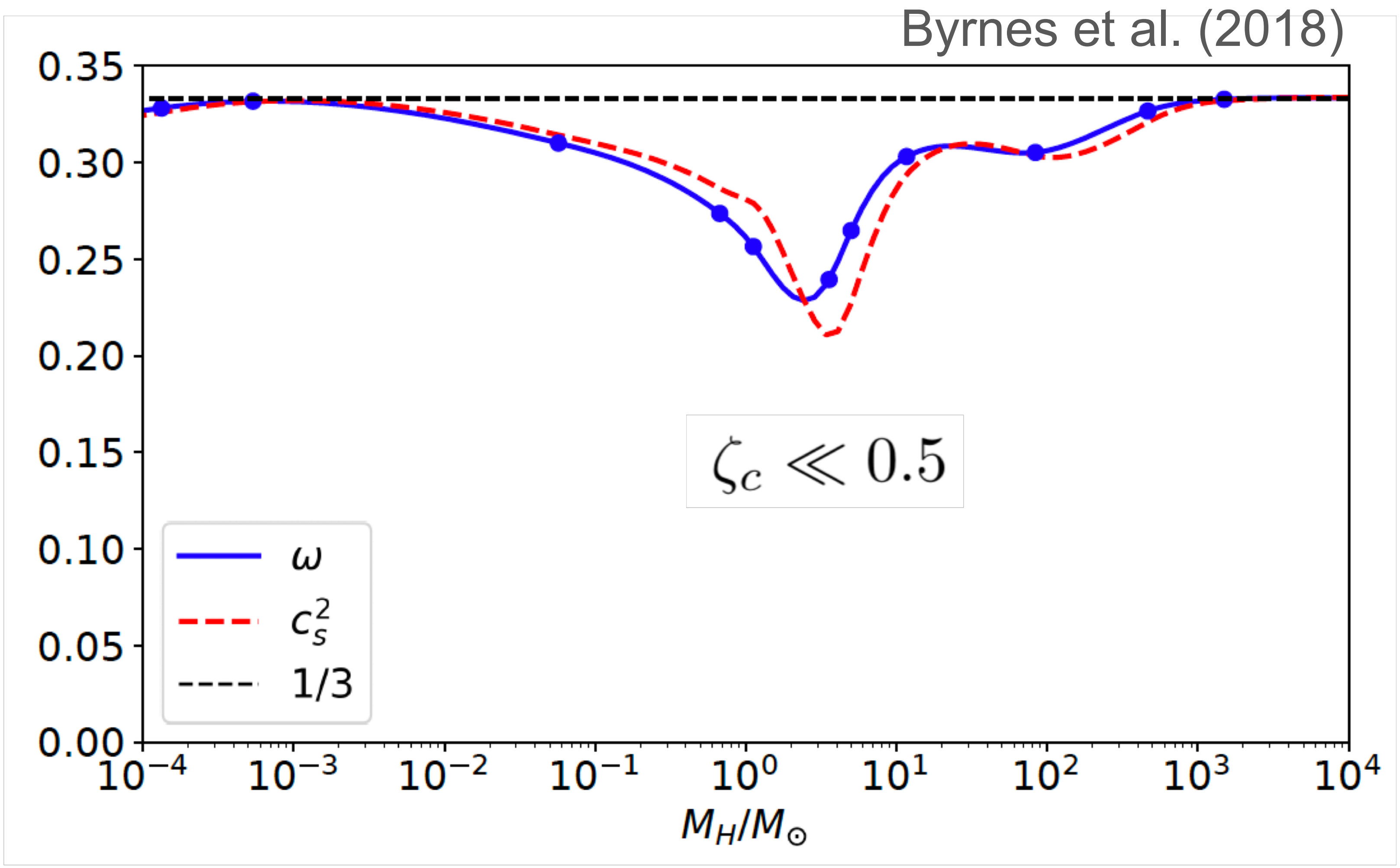
efficiency of collapse $\gamma \sim 0.2$

LIGO range!

Origin of PBH mass

Jedamzik (1997)

Softening the equation of state @ QCD



Matter-radiation equality

$$\frac{\Omega_{\rm M}}{\Omega_{\rm R}} = \frac{\Omega_{\rm B} + \Omega_{\rm DM}}{\Omega_{\rm R}} \simeq \frac{(1+\chi)\,\eta\,x}{1.4\,g_*(x)} \simeq \frac{1700}{g_*(z)}\,\frac{1+\chi}{1+z}$$

$$\eta = \frac{n_{\rm B}}{n_\gamma} \simeq 6\times 10^{-10}$$

$$T = T_0(1+z) \;\Rightarrow\; x = \frac{4\times 10^{12}}{1+z}$$

$$\chi = \frac{\Omega_{\rm DM}}{\Omega_{\rm B}}$$

$$1 + z_{\rm eq} = 3300\;(g_* = 3.36) \;\Rightarrow\; \chi \sim 5.5$$

Fraction domains @ PBH formation

$$\beta = \frac{\Omega_{\rm PBH}}{\Omega_{\rm R}} = f_{\rm PBH}\,\frac{\chi\,\Omega_{\rm B}}{\Omega_{\rm R}} \simeq f_{\rm PBH}\,\frac{\chi\,\eta\,x}{1.4\,g_*(x)}$$

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

$$x \sim 5 \;\Rightarrow\; \beta \sim \eta \sim 10^{-9} \quad \text{if}\;\; f_{\rm PBH} = 1$$

Is this a hint of a common origin?

$$T \sim \Lambda_{\mathrm{QCD}} \sim 200\,\mathrm{MeV} \quad \Rightarrow \quad \beta \sim \eta \sim 10^{-9} \quad \text{if} \quad f_{\mathrm{PBH}} = 1$$

Our scenario

We propose “hot spot” EWB associated with localized energy released during gravitational collapse at PBH formation in the quark-hadron transition

Electroweak baryogenesis @ QCD

Sakharov conditions: $\cancel{B}$, $\cancel{C}$, $\cancel{CP}$, non-equil.

$\cancel{CP}$ in the SM (CKM matrix)

$$V_{\rm CKM} = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix}$$

$$J = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \cdot K$$

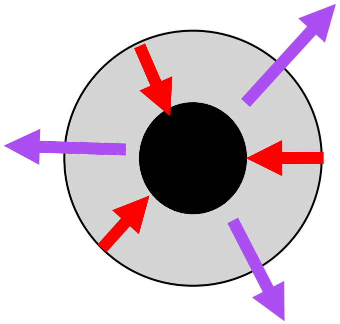
$$K = \mathrm{Im}\, V_{ii} V_{jj} V_{ij}^* V_{ji}^* = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin\delta = (3.06 \pm 0.2) \times 10^{-5}\,.$$

$$\delta_{\rm CP}(T) = \frac{J}{T^{12}} \simeq \left(\frac{20.4\,\mathrm{GeV}}{T}\right)^{12} K$$

Electroweak baryogenesis @ QCD

Out-of-equilibrium gravitational collapse

$$R_S = \frac{2GM_{\rm PBH}}{c^2} = \gamma\, d_H \;\Rightarrow\; \Delta K \simeq \left(\frac{1}{\gamma} - 1\right) M_{\rm hor} = \frac{1-\gamma}{\gamma^2} M_{\rm PBH}$$



$$n_p(x) = 1.59 \times 10^{40}\, x^{-3/2}\, e^{-x}\, {\rm cm}^{-3}$$

$$n_{\rm gas}(x) = 1.64 \times 10^{41}\, x^{-3}\, {\rm cm}^{-3}$$

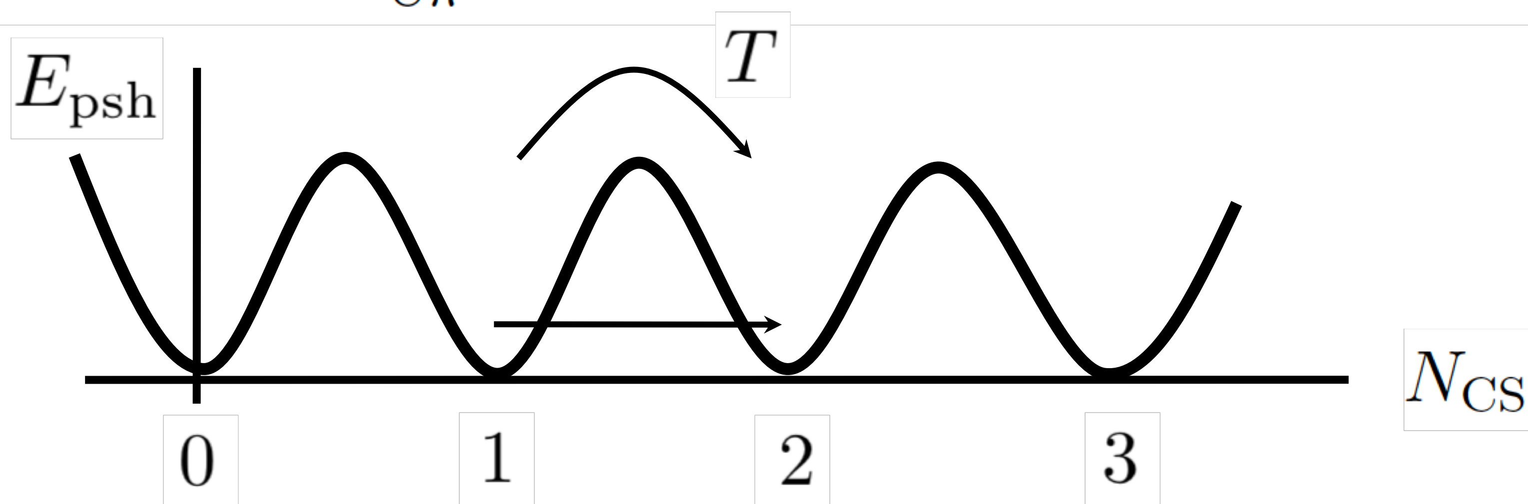
$$E_0 = \frac{\Delta K}{n_p\, \Delta V} \simeq \frac{1-\gamma}{\gamma^2(1-\gamma^3)} \frac{M_{\rm PBH}}{N_p} \simeq 10\; g_*(x)^{3/2}\, x^{-5/2}\, e^{x}\, {\rm GeV}$$

$$@\; x \sim 5\,, \quad \Delta K = \frac{3}{2} N_p k_{\rm B} T_{\rm eff} \;\Rightarrow\; k_{\rm B} T_{\rm eff} = \frac{2}{3} E_0 \simeq 1\, {\rm TeV}$$

Electroweak baryogenesis @ QCD

$\not{B}$ in the SM: Sphaleron transitions & chiral anomaly

$$\partial_\mu j^\mu_B = \partial_\mu j^\mu_L = \frac{3\alpha_W}{8\pi} F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \Longrightarrow \quad \Delta B = \Delta L = 3\Delta N_{\rm CS}$$



$$\Gamma_{\rm sph}(T) \sim \begin{cases} \alpha_W^4\, T^4\,, & T > 200\text{GeV} \\ \text{const.} \left(\frac{E_{\rm sph}}{T}\right)^3 m_W^4(T)\, e^{-\frac{E_{\rm sph}}{T}}\,, & T < 200\text{GeV} \end{cases}$$

Electroweak baryogenesis @ QCD

Putting all together

Asaka et al. (2004)

$$\eta \simeq \frac{7n_{\rm B}}{s} \simeq \frac{7n_{\rm parton}}{s} \times \Gamma_{\rm sph}(T_{\rm eff})\, V\, \Delta t \times \delta_{\rm CP}$$

$$s_{\rm gas} = \frac{2\pi^2}{45}\, g_{*S}\, T_{\rm th}^3 \quad @ \quad T_{\rm th} \ll T_{\rm eff}$$

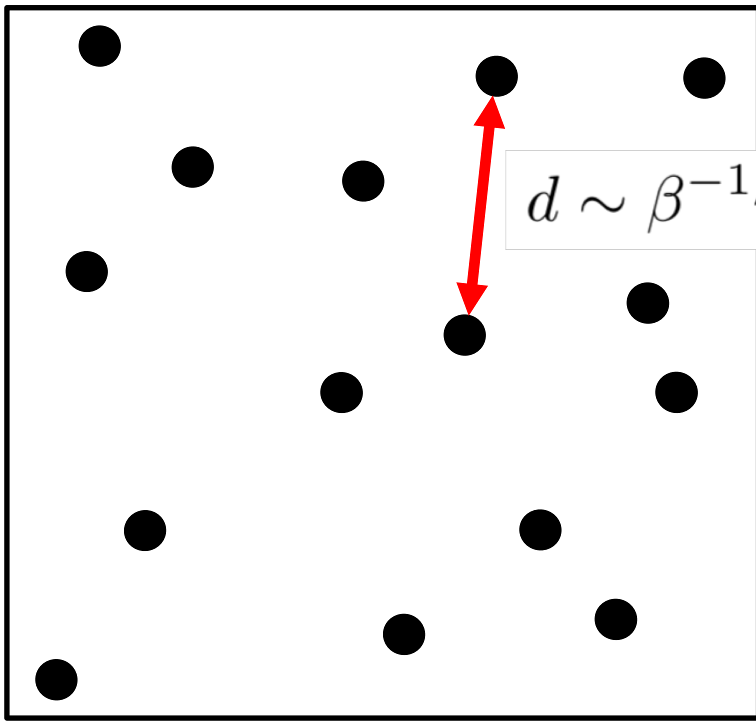
quenching the sphaleron transitions and preventing baryon washout.

$$\text{For} \quad x \gtrsim 5 \;\Rightarrow\; n_{\rm B} \sim n_\gamma \;\Rightarrow\; \eta^{\rm local} \sim 1$$

hot spots = Hubble domains that gravitational collapse to PBH

Electroweak baryogenesis @ QCD

Diffusion to the rest of the universe



$$d \sim \beta^{-1/3}\, d_H(t_{\rm QCD}) \sim 10^{-2} \text{ light seconds}$$

speed of sound $c_s = c/\sqrt{3}$

$$\eta^{\rm local} \sim 1 \;\Rightarrow\; \eta \sim \beta \sim 10^{-9}$$

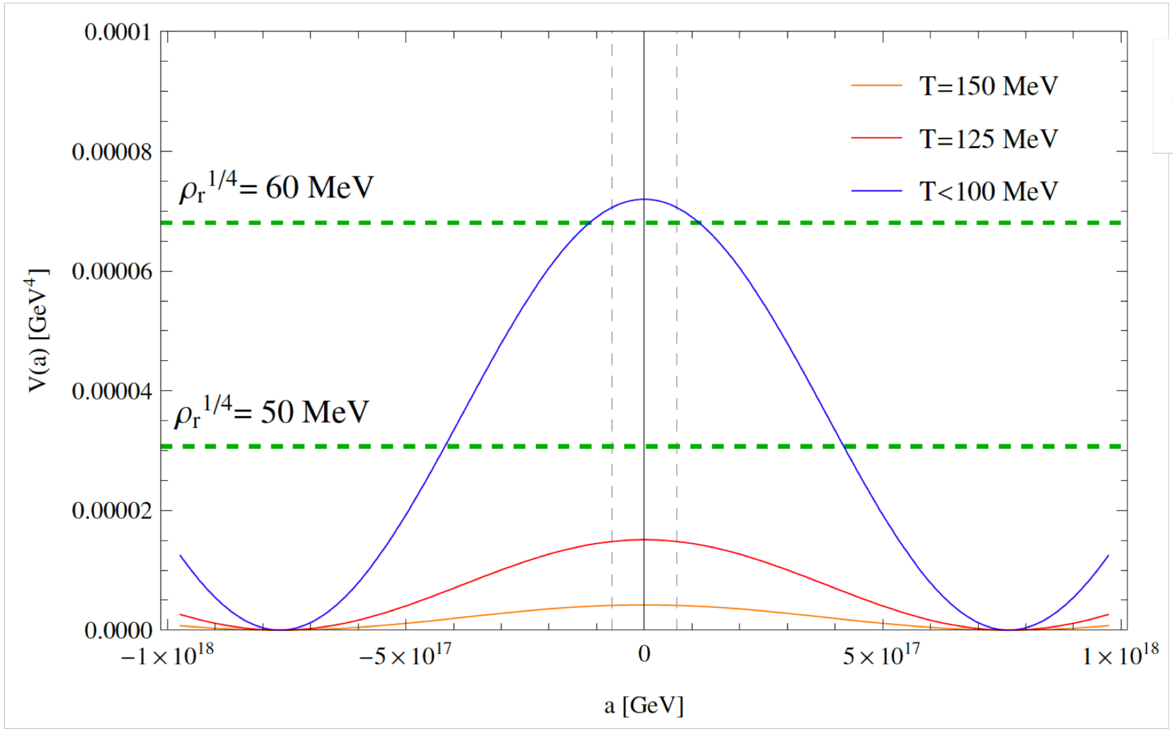
baryons diffuse until they uniformly distribute the original BAU to the rest of the universe well before nucleosynthesis ($t_{\rm BBN} \sim 1 - 180$ s)

Origin large curvature fluctuations

Stochastic spectator (curvaton) field

QCD axion (strong CP problem)

$$V(a) = m_a^{\rm eff}(T)^2\, f_a^2\, [1 + \cos(a/f_a)]$$



$$m_a^{\rm eff}(T)^2 = m_a^2\,(T/T_c)^{-7}$$

$$\text{for } T \gtrsim T_c \simeq 120\,\text{MeV}$$

$$= m_a^2 \quad \text{for} \quad T < T_c$$

Origin large curvature fluctuations

QCD axion as spectator field

$$m_a\, f_a \simeq m_\pi\, f_\pi \simeq (135\,\mathrm{MeV})^2$$

Those patches in which the axion remains at the top of its potential will dominate the energy density of the universe

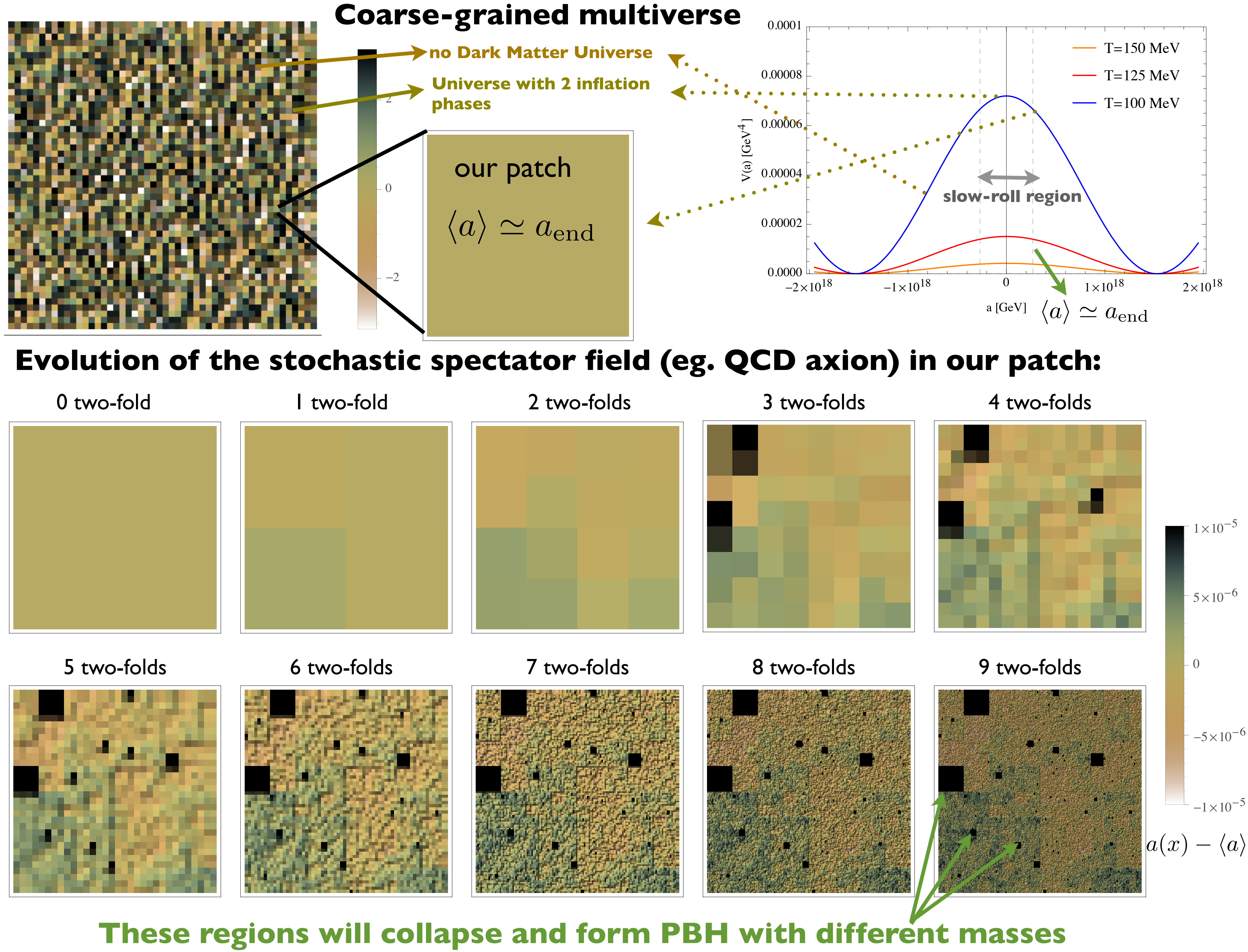
$$\text{for} \quad T < T_c = \left(\frac{60}{\pi^2 g_*}\, m_a^2\, f_a^2\right)^{1/4} \simeq 120\,\mathrm{MeV}$$

the axion will start rolling down the hill

inflating the universe until slow-roll ends at

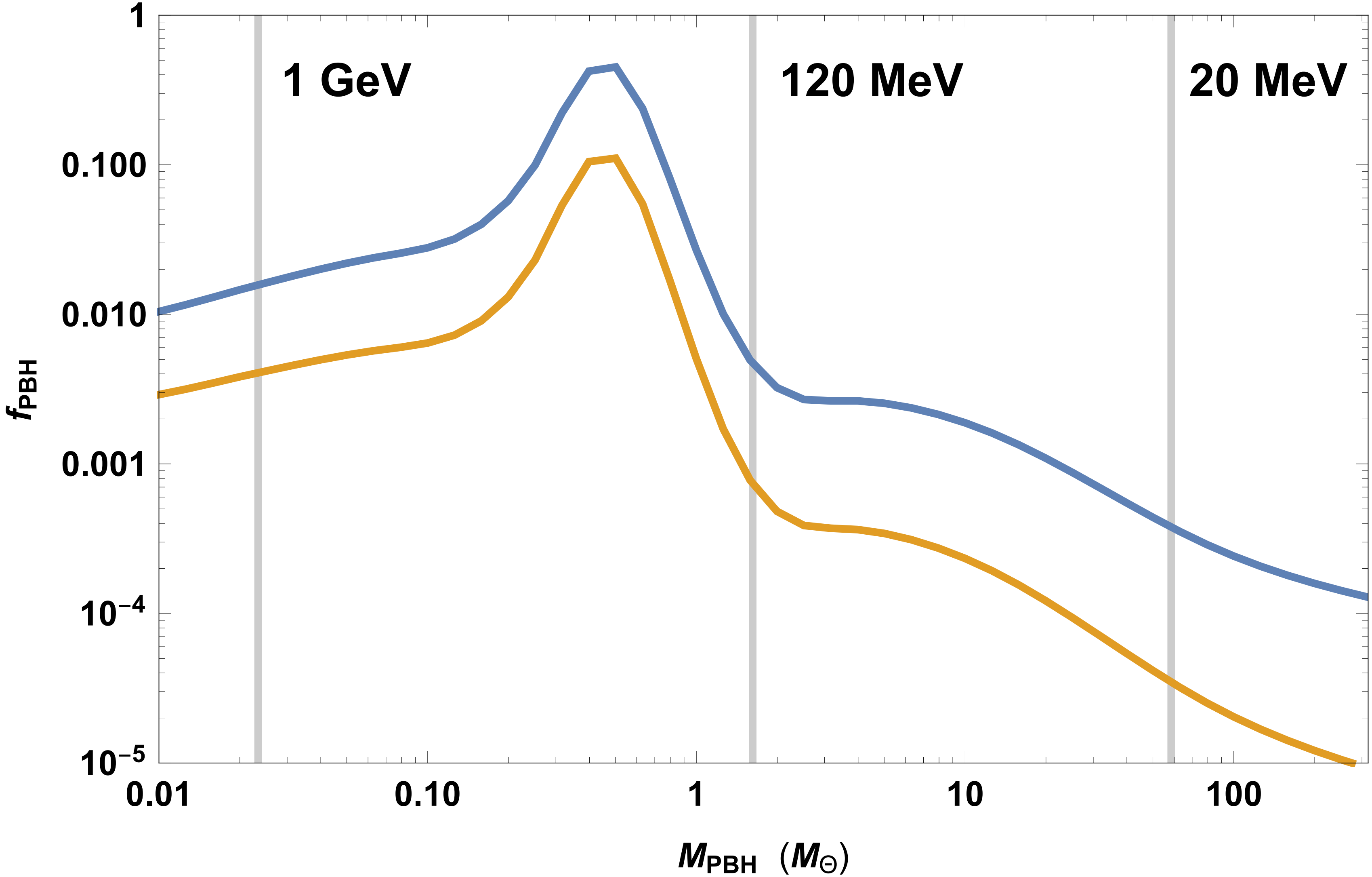
$$a_{\rm end} \simeq 2\sqrt{2}\, f_a^2/\bar{M}_P \ll f_a \qquad \bar{M}_P = M_P/\sqrt{8\pi}$$

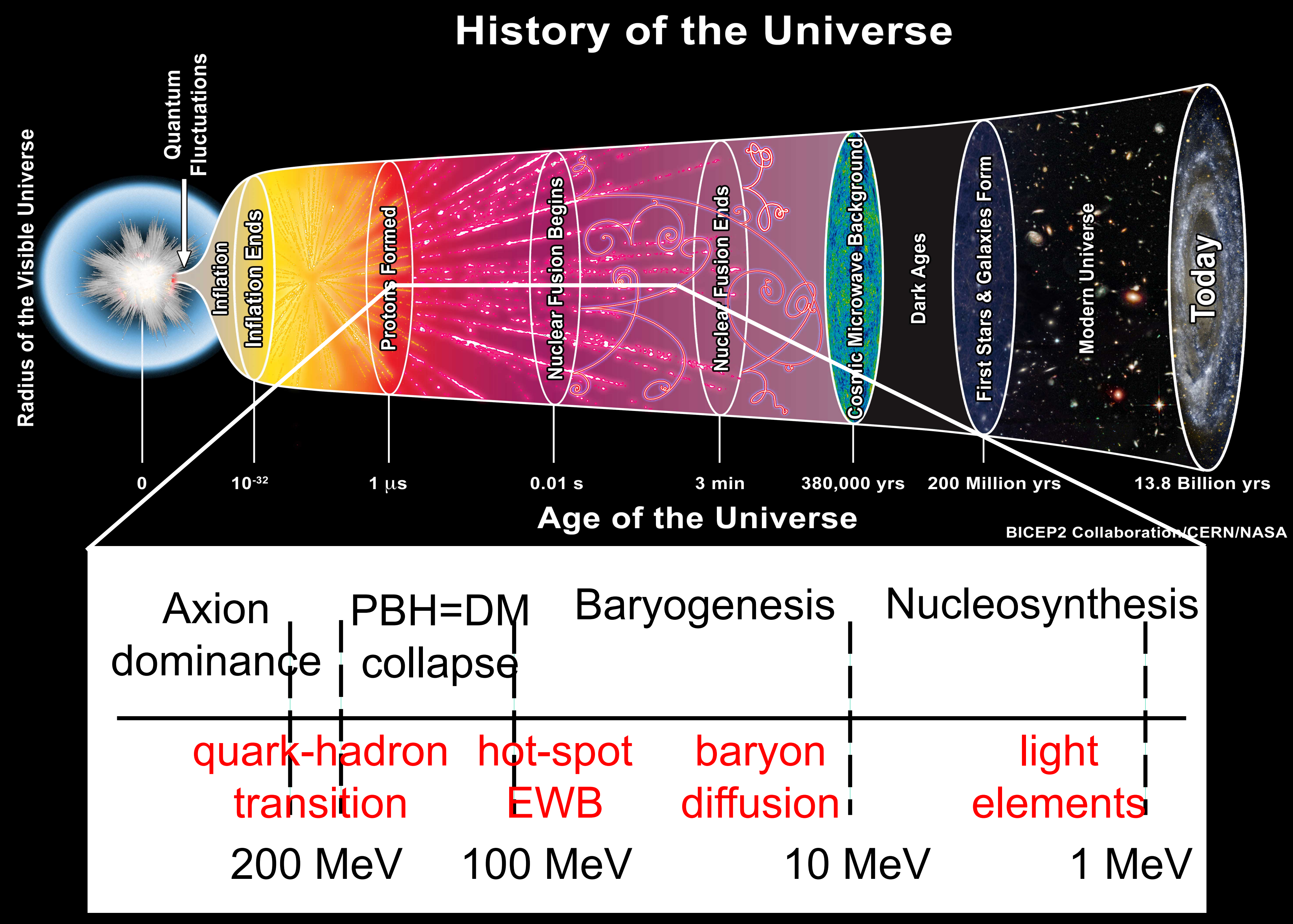
$$\Delta N \simeq \frac{f_a^2}{\bar{M}_P^2}\, \ln \frac{a_{\rm end}^2}{a_{\rm ini}^2} \lesssim 1.5 \text{ for } f_a \lesssim 0.1 \bar{M}_P$$



Coarse-grained multiverse
no Dark Matter Universe
Universe with 2 inflation phases
our patch
$\langle a \rangle \simeq a_{\rm end}$
2
0
−2
0.0001
0.00008
0.00006
0.00004
0.00002
0.0000
V(a) [GeV^4]
T=150 MeV
T=125 MeV
T=100 MeV
slow-roll region
-2×10^{18}
-1×10^{18}
0
1×10^{18}
2×10^{18}
a [GeV]
$\langle a \rangle \simeq a_{\rm end}$
Evolution of the stochastic spectator field (eg. QCD axion) in our patch:
0 two-fold
1 two-fold
2 two-folds
3 two-folds
4 two-folds
5 two-folds
6 two-folds
7 two-folds
8 two-folds
9 two-folds
1×10^{-5}
5×10^{-6}
0
-5×10^{-6}
-1×10^{-5}
$a(x) - \langle a \rangle$
These regions will collapse and form PBH with different masses

Predictions for PBH mass spectrum




History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10^-32
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA
Axion dominance
PBH=DM collapse
Baryogenesis
Nucleosynthesis
quark-hadron transition
hot-spot EWB
baryon diffusion
light elements
200 MeV
100 MeV
10 MeV
1 MeV

Conclusions

- SM physics can explain both DM and BAU.
- Smallness of BAU is due to the small number of Hubble domains that collapse to form PBH.
- The quark-hadron QCD transition triggers the collapse of PBH and BAU via “Hot spot” EWB.
- Dark matter density in the form of PBH is then of the same order as Baryon density.
- It also explains why PBH have masses ~ Msun.
- The predicted PBH mass distribution (features) could be measured by LIGO/Virgo in the near future.