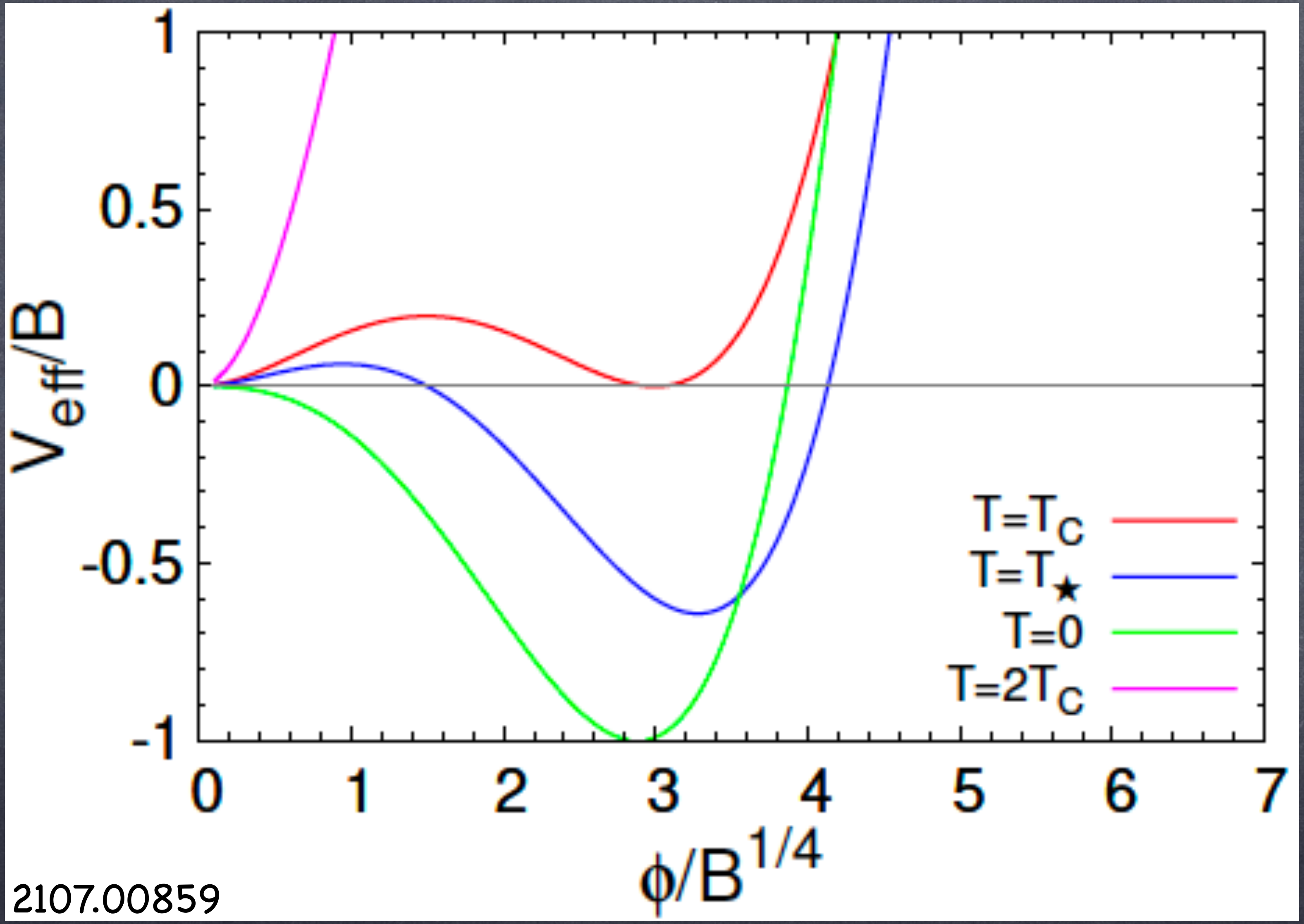
Correlated signals of first-order phase transitions in dark sectors

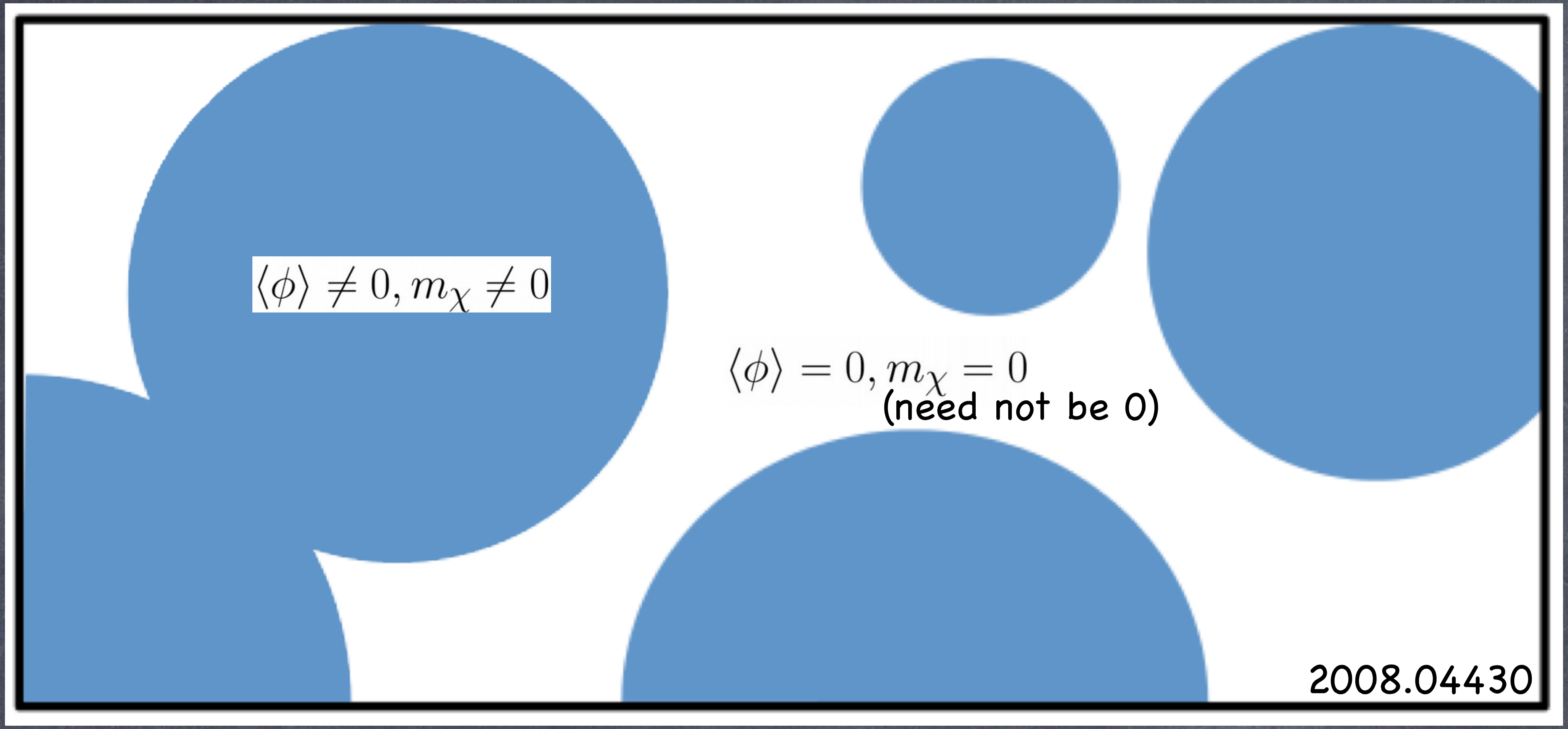
Macroscopic dark matter from a FOPT

$$\mathcal{L} \supset -g_\chi \phi \bar{\chi}\chi - V_{\text{eff}}(\phi, T)$$



2107.00859

$$V_{\text{eff}}(\phi, T) = D(T^2 - T_0^2)\phi^2 - (AT + C)\phi^3 + \frac{\lambda}{4}\phi^4$$



$$m_\chi = g_\chi \langle\phi\rangle \gg T_c$$

Conditions needed (2008.04430):

- Dirac fermion must have large mass gap in true and false vacuum (so that it gets trapped in the false vacuum)

- Must have charge asymmetry η_χ during FOPT (so that an excess remains after pair annihilation that can aggregate to form macroscopic Fermi balls)

- Must carry a conserved global U(1)_Q (so that FB attains stability by accumulating Q-charge)

- FBs start to form at $T_\star$ as the false vacuum shrinks and separates into smaller volumes

- Below a critical volume of the false vacuum bubble, a true vacuum bubble does not nucleate inside it, and FB formation takes over

- With one FB per critical volume, the number density at formation is given by the bubble nucleation rate per unit volume and the bubble wall velocity:

$$n_{\rm FB}\big|_{T_\star} \sim \left(\frac{\Gamma(T_\star)}{v_w}\right)^{3/4}$$

- … and dilutes as matter

- Net Q charge is the # of fermions in FB: $Q_{\rm FB} = \eta_\chi (s/n_{\rm FB})_{T_\star}$

FB energy

$$E_{\mathrm{FB}} \simeq \frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3} \frac{Q_{\mathrm{FB}}^{4/3}}{R} - \frac{3g_\chi^2}{8\pi}\frac{Q_{\mathrm{FB}}^2 L_\phi^2}{R^3} + \frac{4\pi}{3}\Delta V(T) R^3$$

- Fermi-gas kinetic energy

- Yukawa potential energy (can be neglected only if interaction length L_ϕ is small compared to the mean separation of fermions $n_\chi^{-1/3}$)

- Potential energy difference in true and false vacua

FB mass ($\propto Q_{\mathrm{FB}}$) and radius ($\propto Q_{\mathrm{FB}}^{1/3}$) obtained by minimizing the FB energy wrt radius. FB has a uniform density profile

Stability

- FB must be stable against decay i.e., dark fermion has smaller energy inside FB than outside
- FB must be stable to fission i.e., a more massive FB is energetically favored for a given total charge: M(Q1 + Q2) < M(Q1) + M(Q2)

$$\frac{dM_{\mathrm{FB}}}{dQ_{\mathrm{FB}}} < m + g_\chi \langle \phi \rangle \,, \qquad \frac{d^2 M_{\mathrm{FB}}}{dQ_{\mathrm{FB}}^2} < 0$$

Parameters that determine GW signal

temp at which fraction of space in false vacuum is 1/e

$$T_\star \, ,$$

strength of FOPT

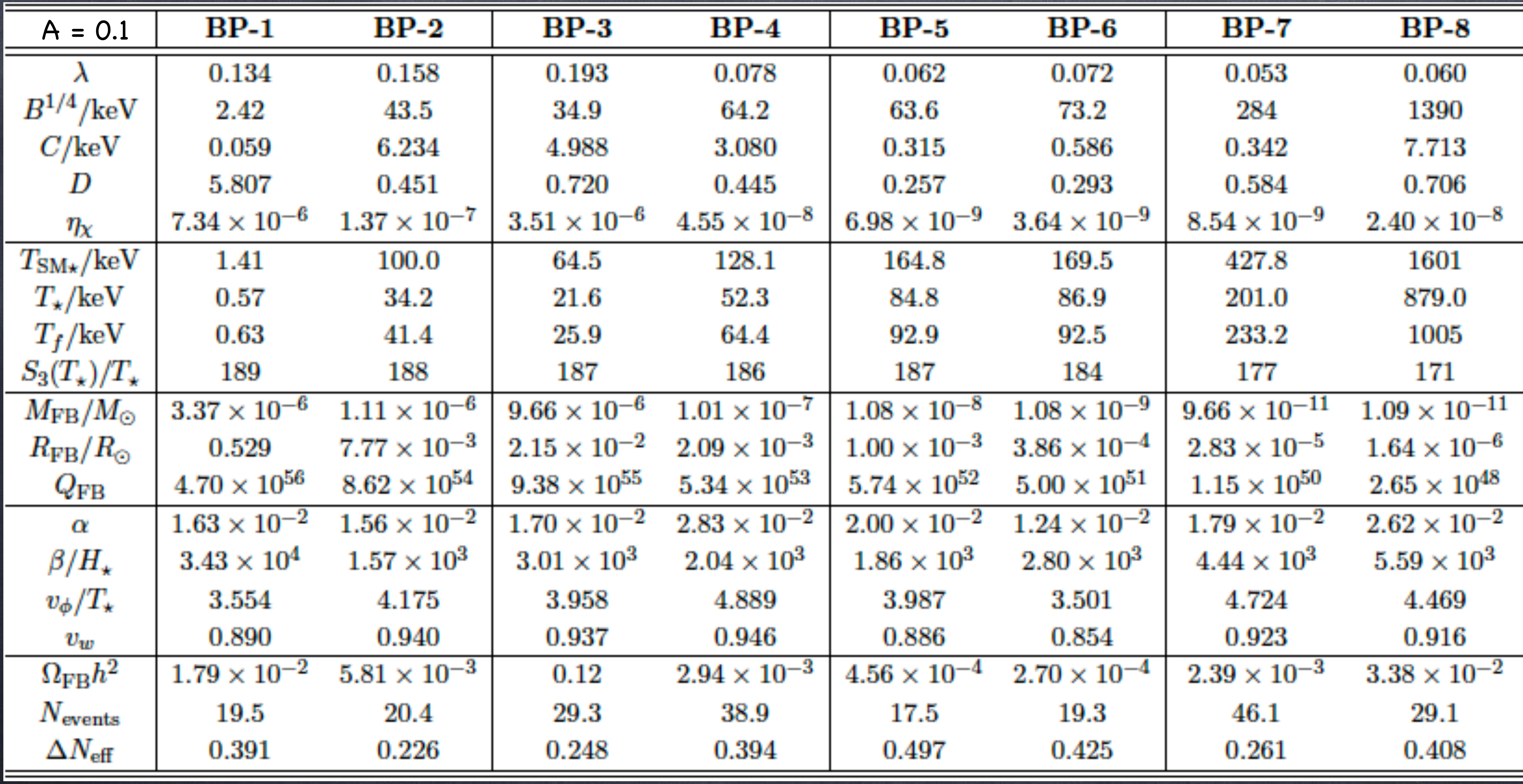
$$\alpha \equiv \frac{\left(1 - T\frac{\partial}{\partial T}\right)\Delta V_{\rm eff}|_{T_\star}}{\rho(T_\star)} \, , \quad \rho \equiv \pi^2 g_\star T^4/30$$

inverse duration

$$\frac{\beta}{H_\star} \simeq T_\star \frac{d(S_3/T)}{dT}\bigg|_{T_\star}$$

$$v_w$$

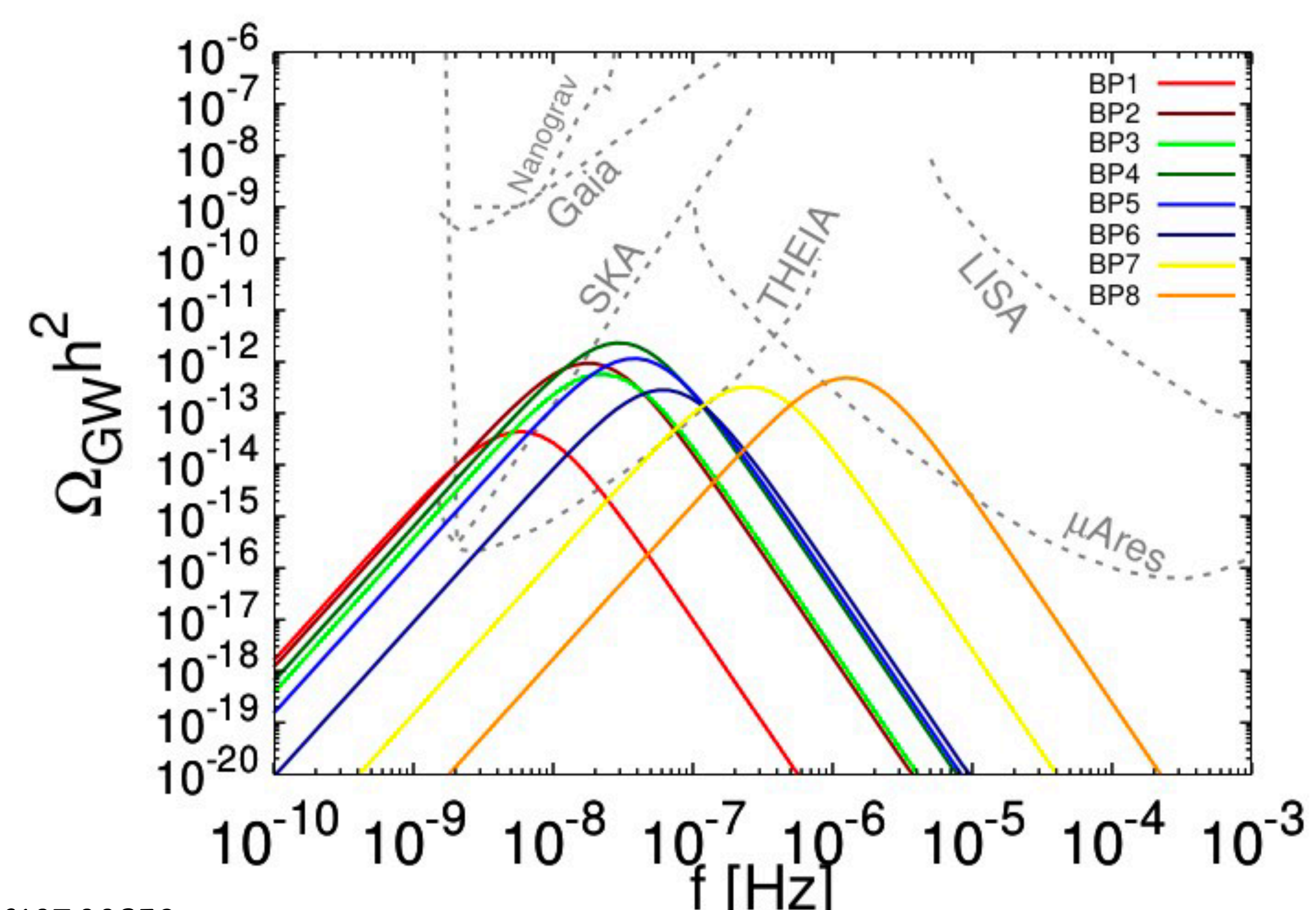
Sound waves give the dominant contribution



A = 0.1	**BP-1**	**BP-2**	**BP-3**	**BP-4**	**BP-5**	**BP-6**	**BP-7**	**BP-8**
λ	0.134	0.158	0.193	0.078	0.062	0.072	0.053	0.060
$B^{1/4}/\mathrm{keV}$	2.42	43.5	34.9	64.2	63.6	73.2	284	1390
C/keV	0.059	6.234	4.988	3.080	0.315	0.586	0.342	7.713
D	5.807	0.451	0.720	0.445	0.257	0.293	0.584	0.706
η_χ	7.34×10^{-6}	1.37×10^{-7}	3.51×10^{-6}	4.55×10^{-8}	6.98×10^{-9}	3.64×10^{-9}	8.54×10^{-9}	2.40×10^{-8}
$T_{\mathrm{SM}\star}/\mathrm{keV}$	1.41	100.0	64.5	128.1	164.8	169.5	427.8	1601
$T_\star/\mathrm{keV}$	0.57	34.2	21.6	52.3	84.8	86.9	201.0	879.0
T_f/keV	0.63	41.4	25.9	64.4	92.9	92.5	233.2	1005
$S_3(T_\star)/T_\star$	189	188	187	186	187	184	177	171
$M_{\mathrm{FB}}/M_\odot$	3.37×10^{-6}	1.11×10^{-6}	9.66×10^{-6}	1.01×10^{-7}	1.08×10^{-8}	1.08×10^{-9}	9.66×10^{-11}	1.09×10^{-11}
$R_{\mathrm{FB}}/R_\odot$	0.529	7.77×10^{-3}	2.15×10^{-2}	2.09×10^{-3}	1.00×10^{-3}	3.86×10^{-4}	2.83×10^{-5}	1.64×10^{-6}
Q_{FB}	4.70×10^{56}	8.62×10^{54}	9.38×10^{55}	5.34×10^{53}	5.74×10^{52}	5.00×10^{51}	1.15×10^{50}	2.65×10^{48}
α	1.63×10^{-2}	1.56×10^{-2}	1.70×10^{-2}	2.83×10^{-2}	2.00×10^{-2}	1.24×10^{-2}	1.79×10^{-2}	2.62×10^{-2}
$\beta/H_\star$	3.43×10^{4}	1.57×10^{3}	3.01×10^{3}	2.04×10^{3}	1.86×10^{3}	2.80×10^{3}	4.44×10^{3}	5.59×10^{3}
$v_\phi/T_\star$	3.554	4.175	3.958	4.889	3.987	3.501	4.724	4.469
v_w	0.890	0.940	0.937	0.946	0.886	0.854	0.923	0.916
$\Omega_{\mathrm{FB}}h^2$	1.79×10^{-2}	5.81×10^{-3}	0.12	2.94×10^{-3}	4.56×10^{-4}	2.70×10^{-4}	2.39×10^{-3}	3.38×10^{-2}
N_{events}	19.5	20.4	29.3	38.9	17.5	19.3	46.1	29.1
ΔN_{eff}	0.391	0.226	0.248	0.394	0.497	0.425	0.261	0.408

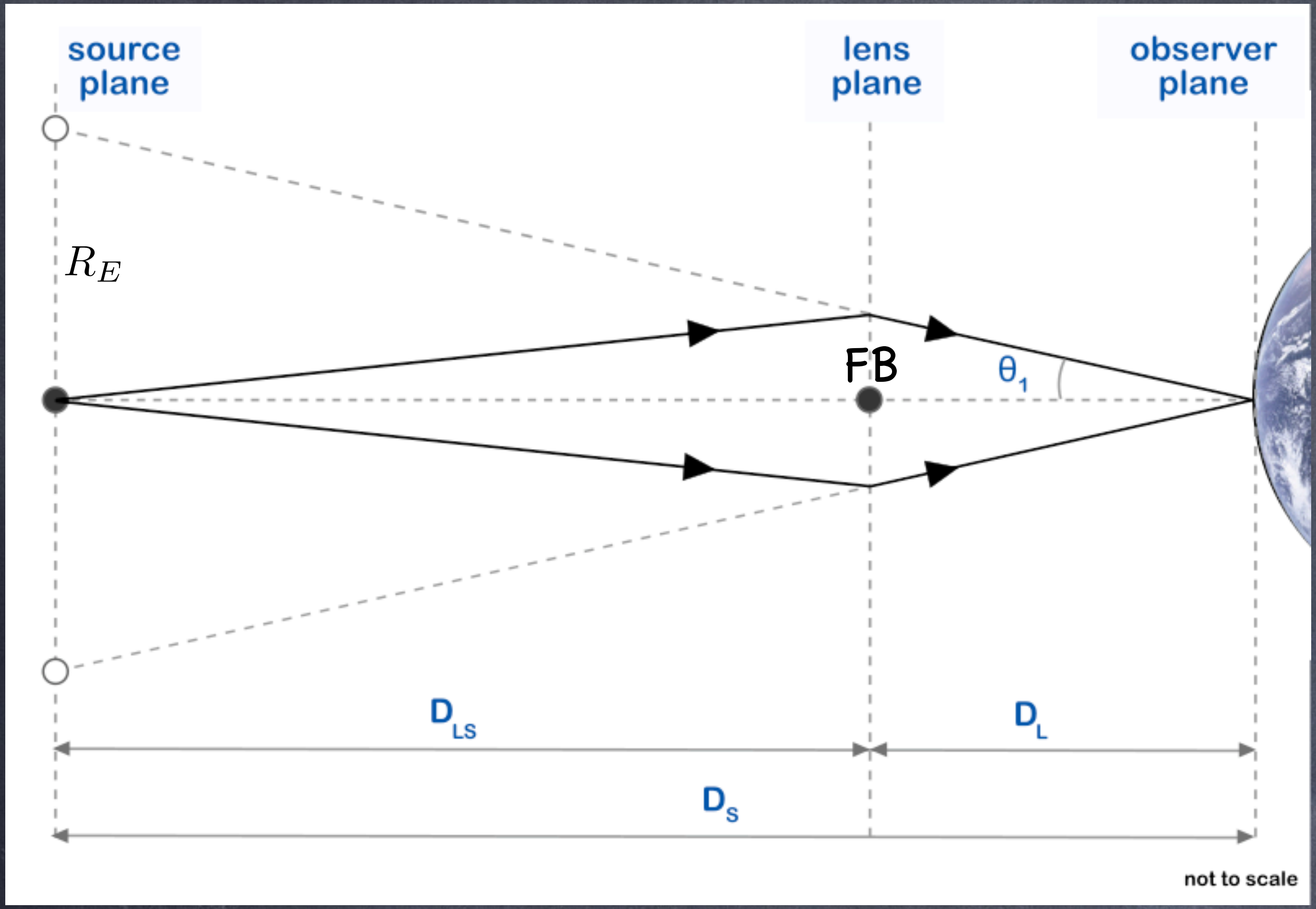
2107.00859

Gravitational wave signal

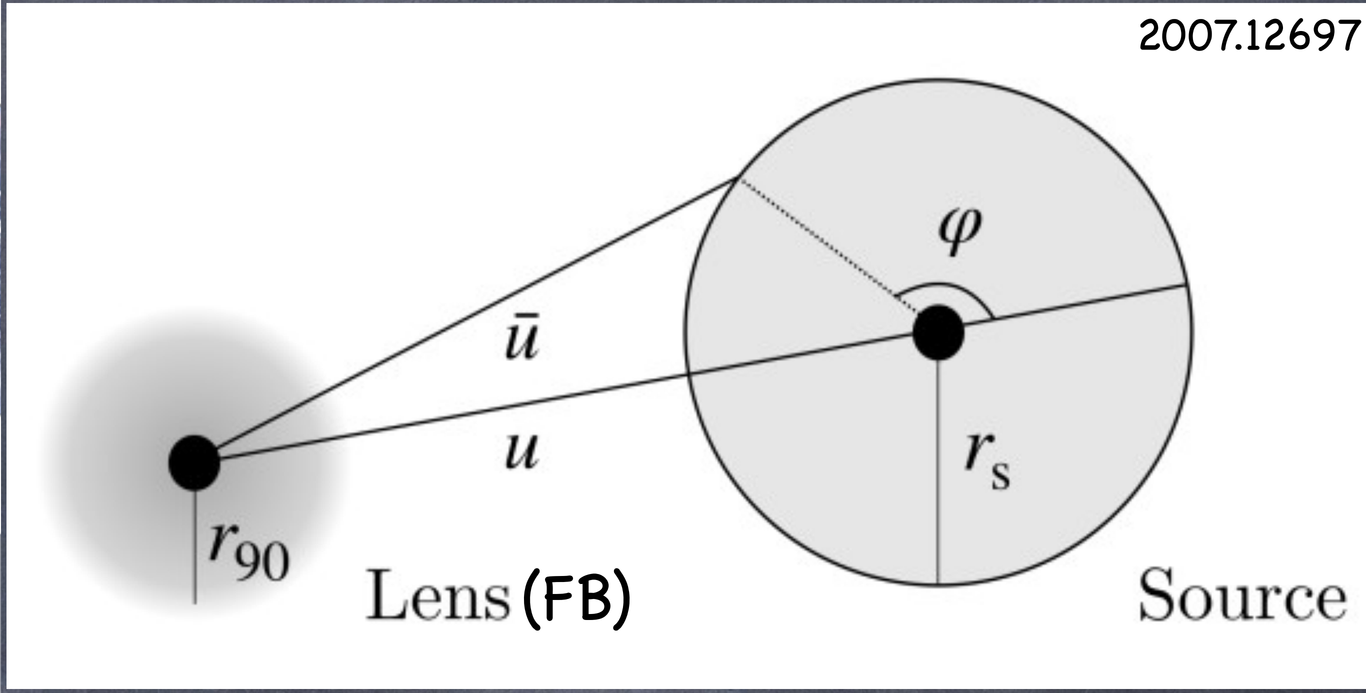


2107.00859

Microlensing



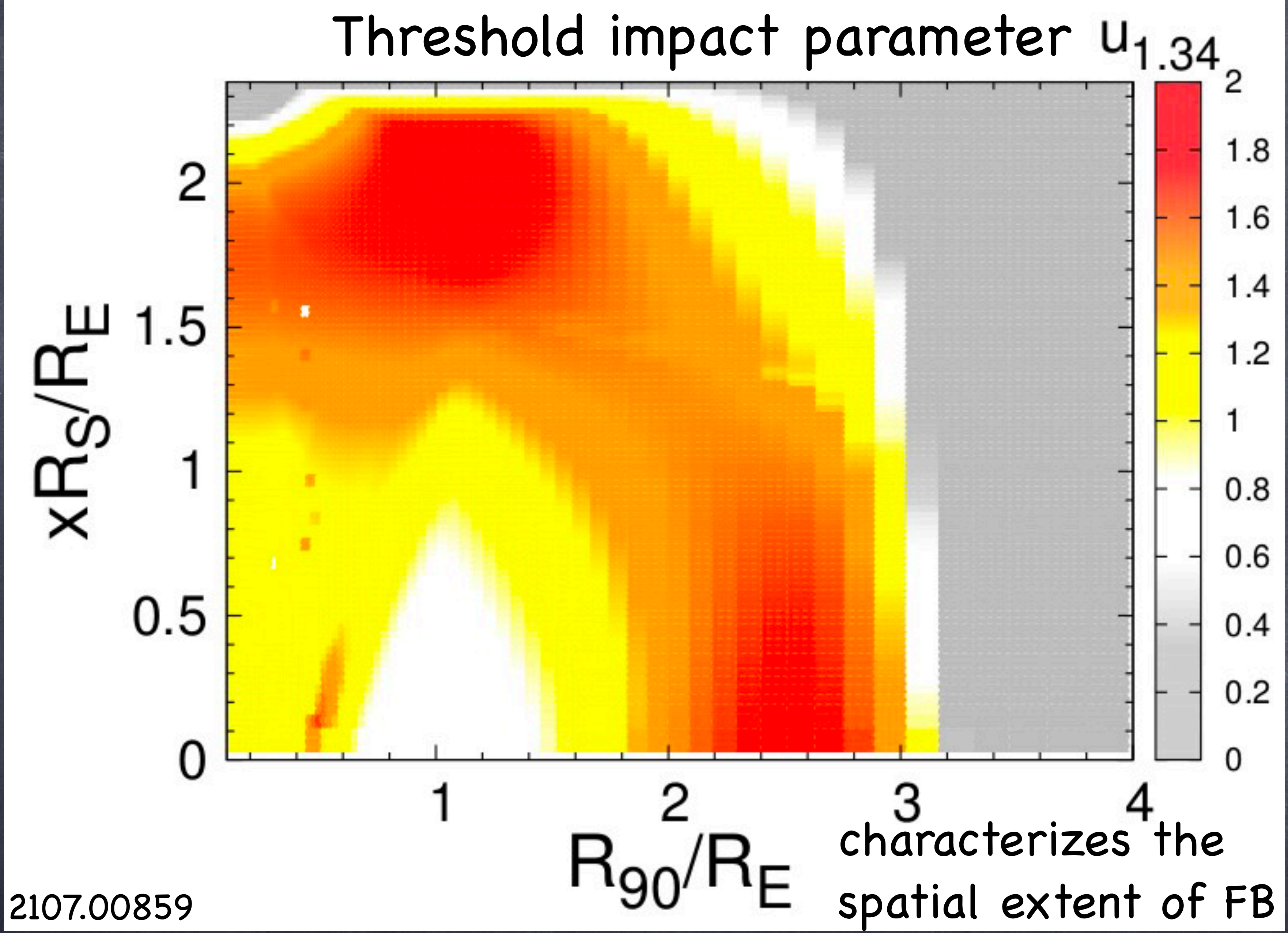
Finite lens and finite source



If angular separation of images is too small, magnification (transient brightening) is observed. Magnification by a point lens of a point source:

$$\mu = \frac{u^2+2}{u\sqrt{u^2+4}} \to 1.34 \quad \text{for} \quad u = 1$$

$\mu(u \leq u_{1.34}) \geq 1.34$


Threshold impact parameter $u_{1.34}$

projected
source
radius

pt lens & pt source

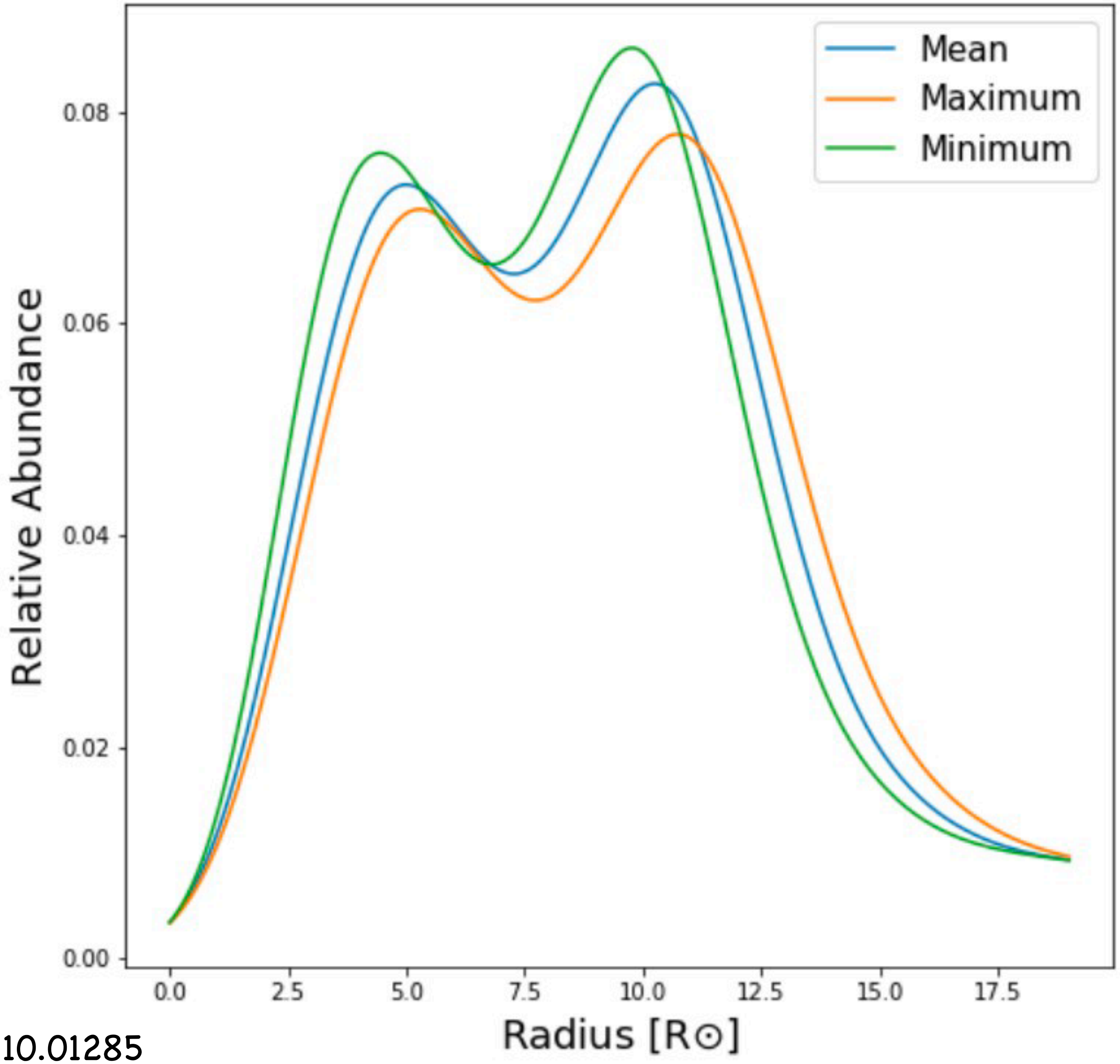
characterizes the
spatial extent of FB

2107.00859

Event rate/source star depends on threshold impact param via

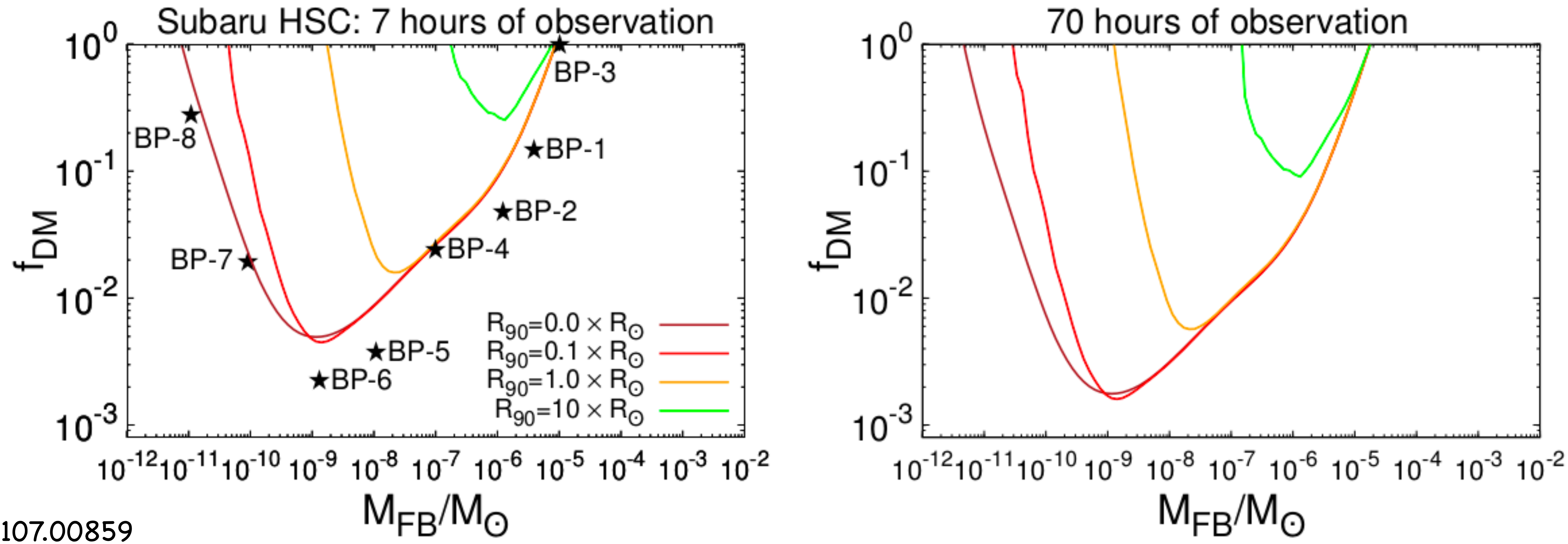
$$v_E(x) = 2u_{1.34}(x)R_E(x)/t_E \quad \text{where} \quad x = D_L/D_S$$

Radius distribution of stars in M31



1910.01285

Microlensing survey of the M31 galaxy

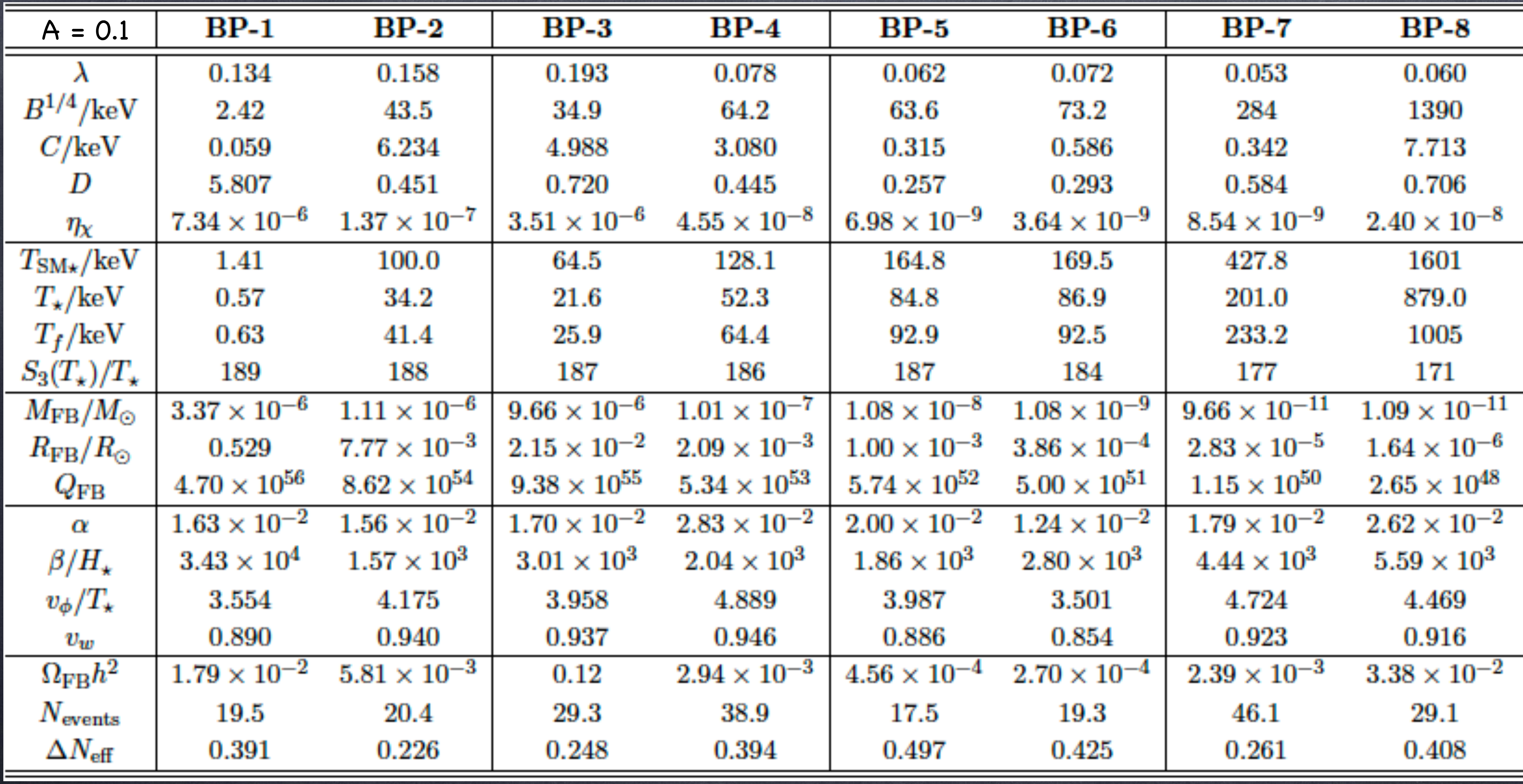


2107.00859

Extra relativistic degrees of freedom

- Dark sector is partially thermalized via gravitational interactions with SM sector
- Latent heat converted to dark radiation during FOPT heats the dark sector from $T_\star$ to T_f
- Effective # of extra neutrino species after the FOPT depends sensitively on $T_f/T_{\mathrm{SM}\star}$
- For temperatures below 60 keV,

$$\Delta N_{\mathrm{eff}} \simeq 9.9(T_f/T_{\mathrm{SM}\star})^4$$



A = 0.1	**BP-1**	**BP-2**	**BP-3**	**BP-4**	**BP-5**	**BP-6**	**BP-7**	**BP-8**
λ	0.134	0.158	0.193	0.078	0.062	0.072	0.053	0.060
$B^{1/4}/\mathrm{keV}$	2.42	43.5	34.9	64.2	63.6	73.2	284	1390
C/keV	0.059	6.234	4.988	3.080	0.315	0.586	0.342	7.713
D	5.807	0.451	0.720	0.445	0.257	0.293	0.584	0.706
η_χ	7.34×10^{-6}	1.37×10^{-7}	3.51×10^{-6}	4.55×10^{-8}	6.98×10^{-9}	3.64×10^{-9}	8.54×10^{-9}	2.40×10^{-8}
$T_{\mathrm{SM}\star}/\mathrm{keV}$	1.41	100.0	64.5	128.1	164.8	169.5	427.8	1601
$T_\star/\mathrm{keV}$	0.57	34.2	21.6	52.3	84.8	86.9	201.0	879.0
T_f/keV	0.63	41.4	25.9	64.4	92.9	92.5	233.2	1005
$S_3(T_\star)/T_\star$	189	188	187	186	187	184	177	171
$M_{\mathrm{FB}}/M_\odot$	3.37×10^{-6}	1.11×10^{-6}	9.66×10^{-6}	1.01×10^{-7}	1.08×10^{-8}	1.08×10^{-9}	9.66×10^{-11}	1.09×10^{-11}
$R_{\mathrm{FB}}/R_\odot$	0.529	7.77×10^{-3}	2.15×10^{-2}	2.09×10^{-3}	1.00×10^{-3}	3.86×10^{-4}	2.83×10^{-5}	1.64×10^{-6}
Q_{FB}	4.70×10^{56}	8.62×10^{54}	9.38×10^{55}	5.34×10^{53}	5.74×10^{52}	5.00×10^{51}	1.15×10^{50}	2.65×10^{48}
α	1.63×10^{-2}	1.56×10^{-2}	1.70×10^{-2}	2.83×10^{-2}	2.00×10^{-2}	1.24×10^{-2}	1.79×10^{-2}	2.62×10^{-2}
$\beta/H_\star$	3.43×10^{4}	1.57×10^{3}	3.01×10^{3}	2.04×10^{3}	1.86×10^{3}	2.80×10^{3}	4.44×10^{3}	5.59×10^{3}
$v_\phi/T_\star$	3.554	4.175	3.958	4.889	3.987	3.501	4.724	4.469
v_w	0.890	0.940	0.937	0.946	0.886	0.854	0.923	0.916
$\Omega_{\mathrm{FB}}h^2$	1.79×10^{-2}	5.81×10^{-3}	0.12	2.94×10^{-3}	4.56×10^{-4}	2.70×10^{-4}	2.39×10^{-3}	3.38×10^{-2}
N_{events}	19.5	20.4	29.3	38.9	17.5	19.3	46.1	29.1
ΔN_{eff}	0.391	0.226	0.248	0.394	0.497	0.425	0.261	0.408

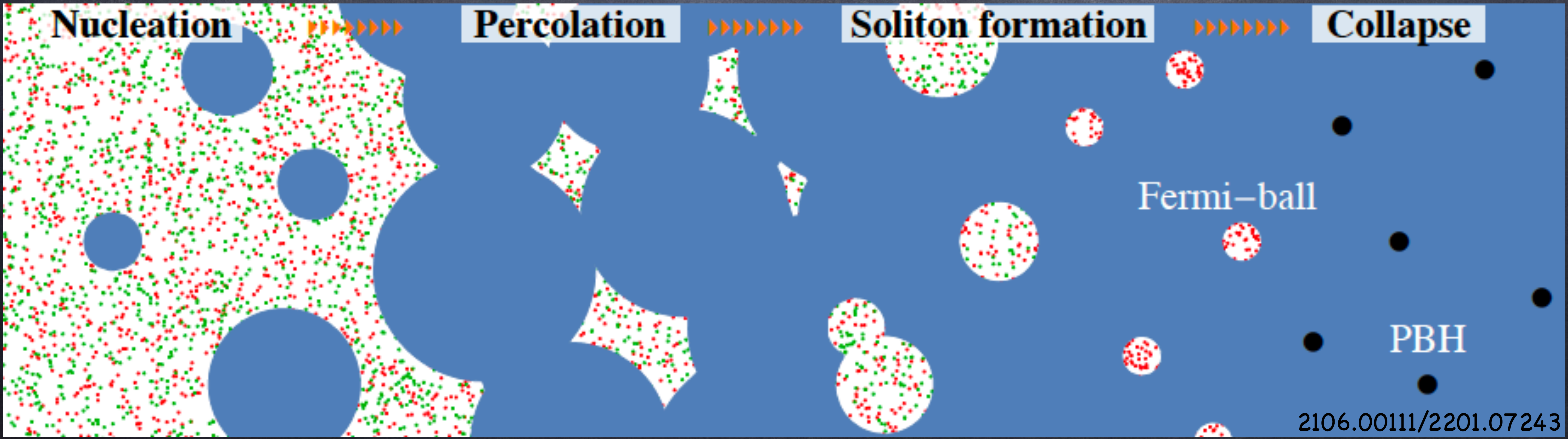
2107.00859

Fermi ball collapse to primordial black hole

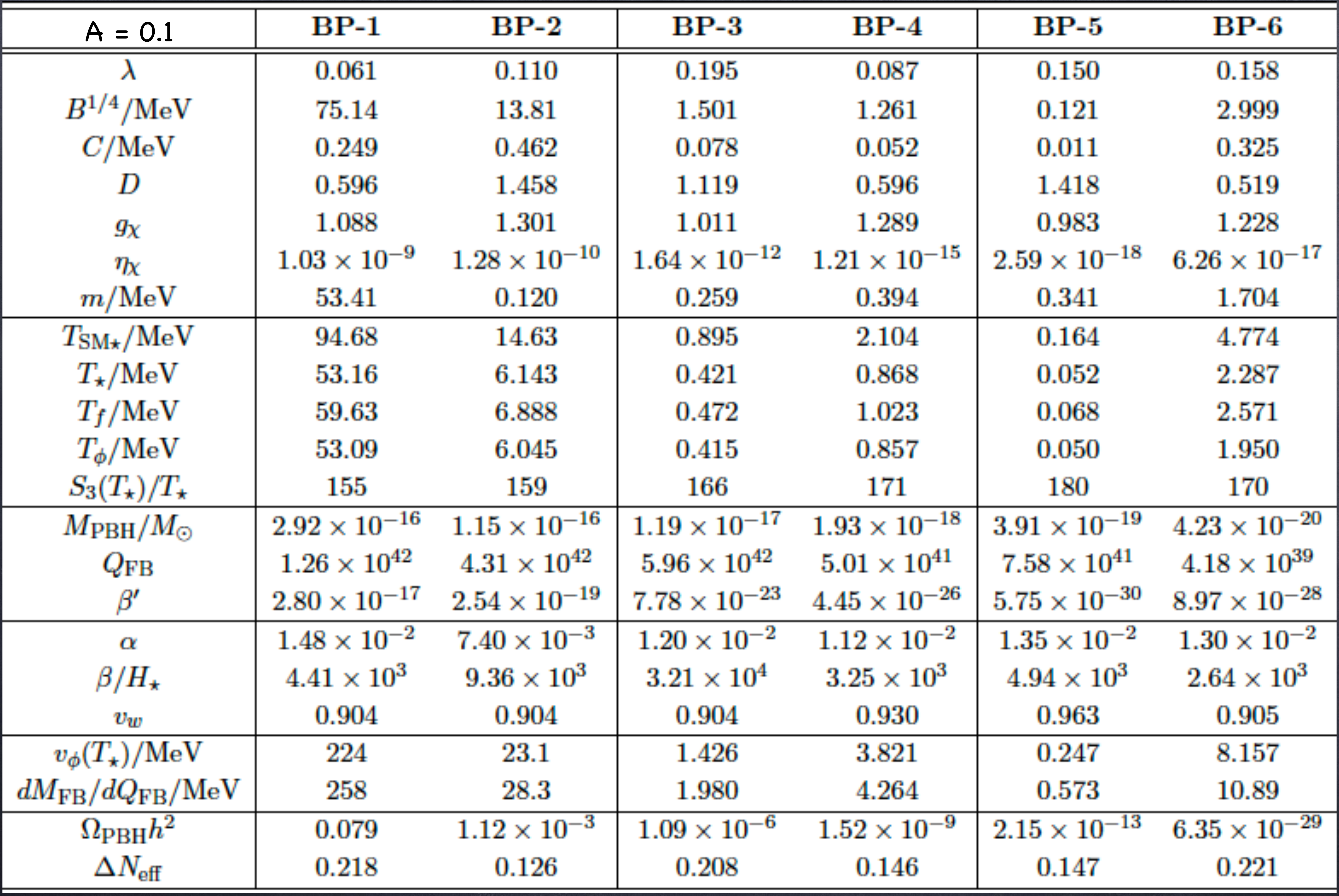
- Yukawa interaction length increases as T falls

- (Negative) Yukawa energy can dominate and cause FB to collapse

$$L_\phi \gtrsim R_{\rm FB}/Q_{\rm FB}^{1/3}$$

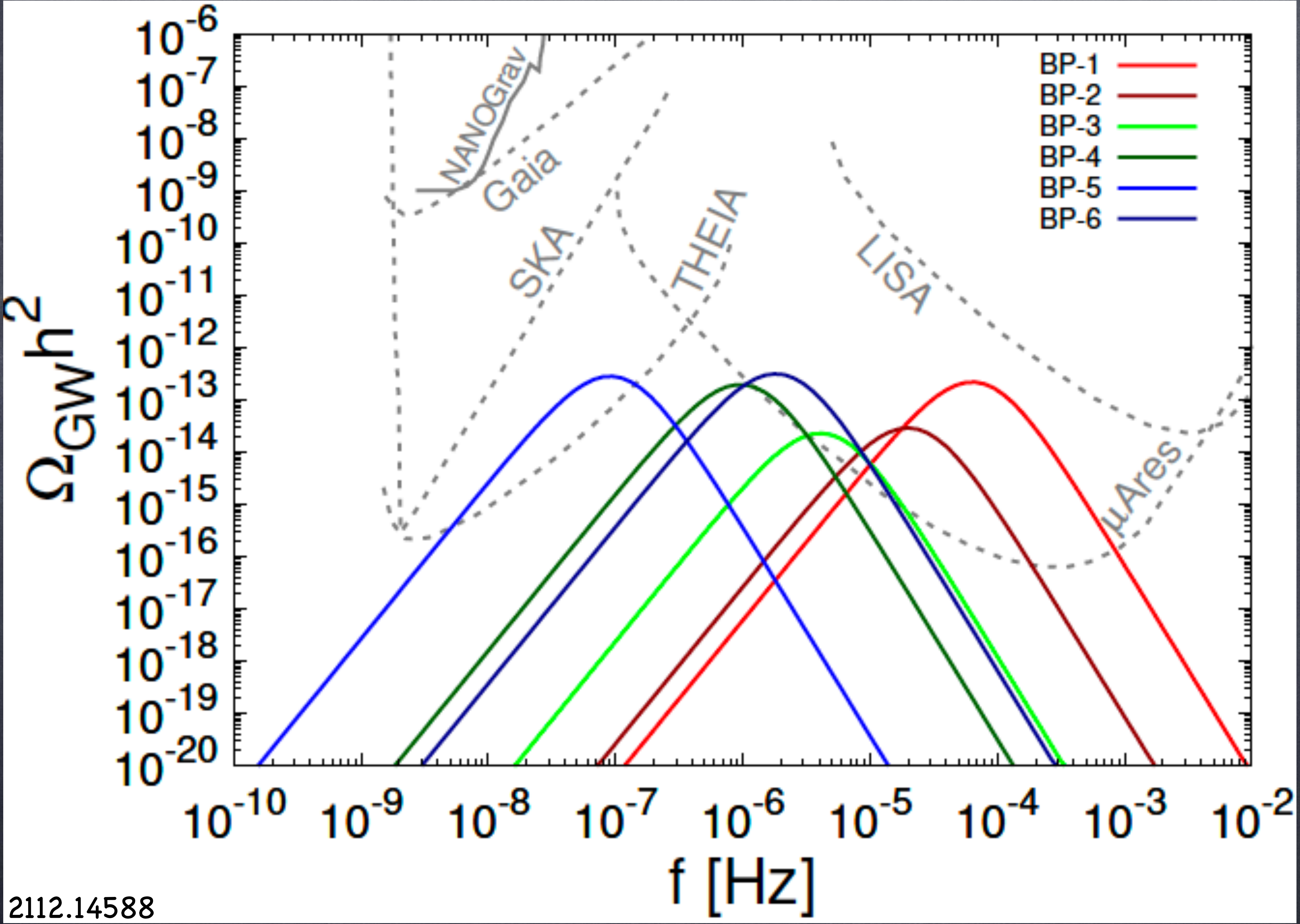


2106.00111/2201.07243



A = 0.1	BP-1	BP-2	BP-3	BP-4	BP-5	BP-6
λ	0.061	0.110	0.195	0.087	0.150	0.158
$B^{1/4}/\mathrm{MeV}$	75.14	13.81	1.501	1.261	0.121	2.999
C/MeV	0.249	0.462	0.078	0.052	0.011	0.325
D	0.596	1.458	1.119	0.596	1.418	0.519
g_χ	1.088	1.301	1.011	1.289	0.983	1.228
η_χ	1.03×10^{-9}	1.28×10^{-10}	1.64×10^{-12}	1.21×10^{-15}	2.59×10^{-18}	6.26×10^{-17}
m/MeV	53.41	0.120	0.259	0.394	0.341	1.704
$T_{\mathrm{SM}\star}/\mathrm{MeV}$	94.68	14.63	0.895	2.104	0.164	4.774
$T_\star/\mathrm{MeV}$	53.16	6.143	0.421	0.868	0.052	2.287
T_f/MeV	59.63	6.888	0.472	1.023	0.068	2.571
T_ϕ/MeV	53.09	6.045	0.415	0.857	0.050	1.950
$S_3(T_\star)/T_\star$	155	159	166	171	180	170
$M_{\mathrm{PBH}}/M_\odot$	2.92×10^{-16}	1.15×10^{-16}	1.19×10^{-17}	1.93×10^{-18}	3.91×10^{-19}	4.23×10^{-20}
Q_{FB}	1.26×10^{42}	4.31×10^{42}	5.96×10^{42}	5.01×10^{41}	7.58×10^{41}	4.18×10^{39}
β'	2.80×10^{-17}	2.54×10^{-19}	7.78×10^{-23}	4.45×10^{-26}	5.75×10^{-30}	8.97×10^{-28}
α	1.48×10^{-2}	7.40×10^{-3}	1.20×10^{-2}	1.12×10^{-2}	1.35×10^{-2}	1.30×10^{-2}
$\beta/H_\star$	4.41×10^{3}	9.36×10^{3}	3.21×10^{4}	3.25×10^{3}	4.94×10^{3}	2.64×10^{3}
v_w	0.904	0.904	0.904	0.930	0.963	0.905
$v_\phi(T_\star)/\mathrm{MeV}$	224	23.1	1.426	3.821	0.247	8.157
$dM_{\mathrm{FB}}/dQ_{\mathrm{FB}}/\mathrm{MeV}$	258	28.3	1.980	4.264	0.573	10.89
$\Omega_{\mathrm{PBH}}h^2$	0.079	1.12×10^{-3}	1.09×10^{-6}	1.52×10^{-9}	2.15×10^{-13}	6.35×10^{-29}
ΔN_{eff}	0.218	0.126	0.208	0.146	0.147	0.221

2112.14588

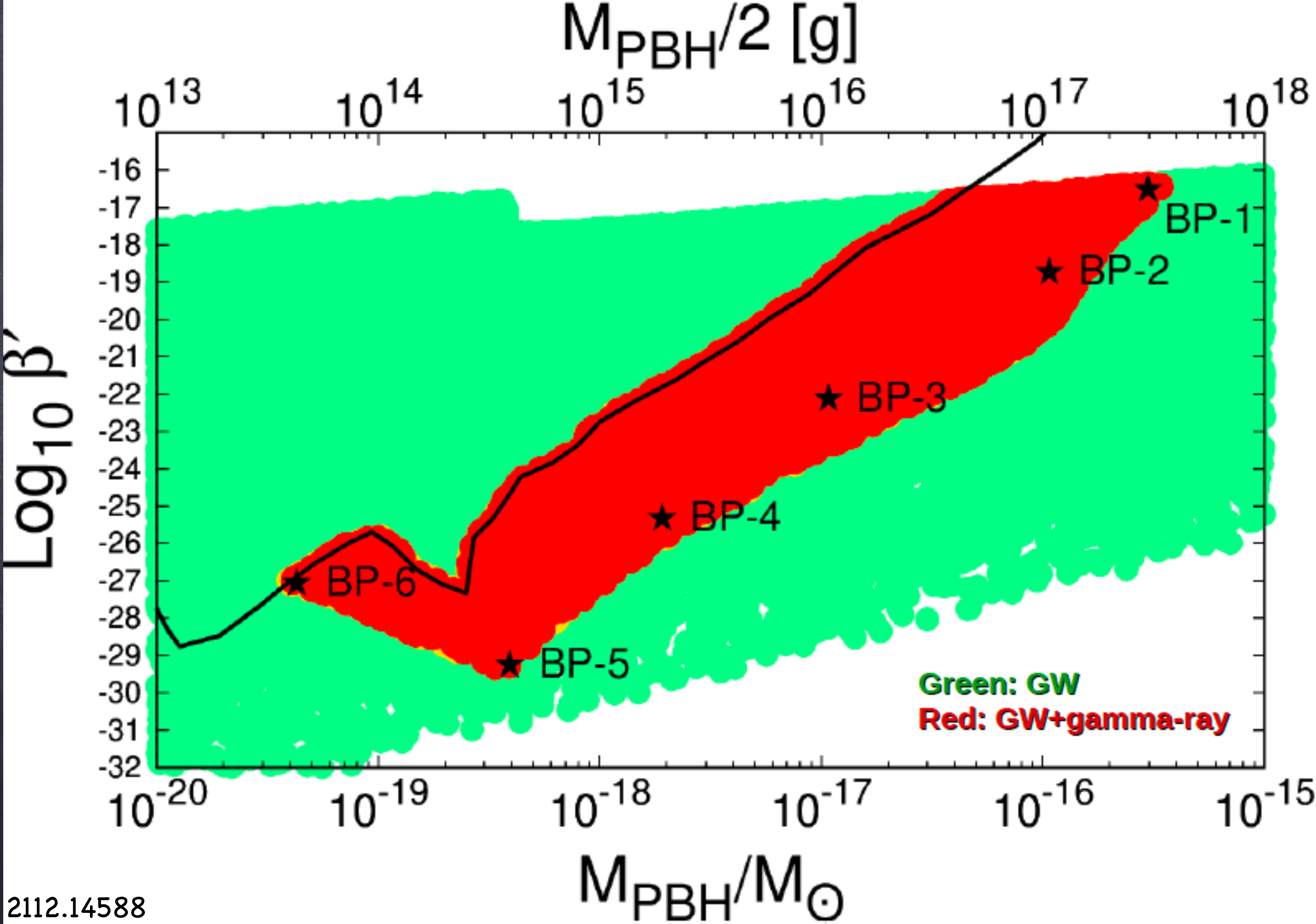


$\Omega_{GW}h^2$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
f [Hz]
NANOGrav
Gaia
SKA
THEIA
LISA
μAres
BP-1
BP-2
BP-3
BP-4
BP-5
BP-6

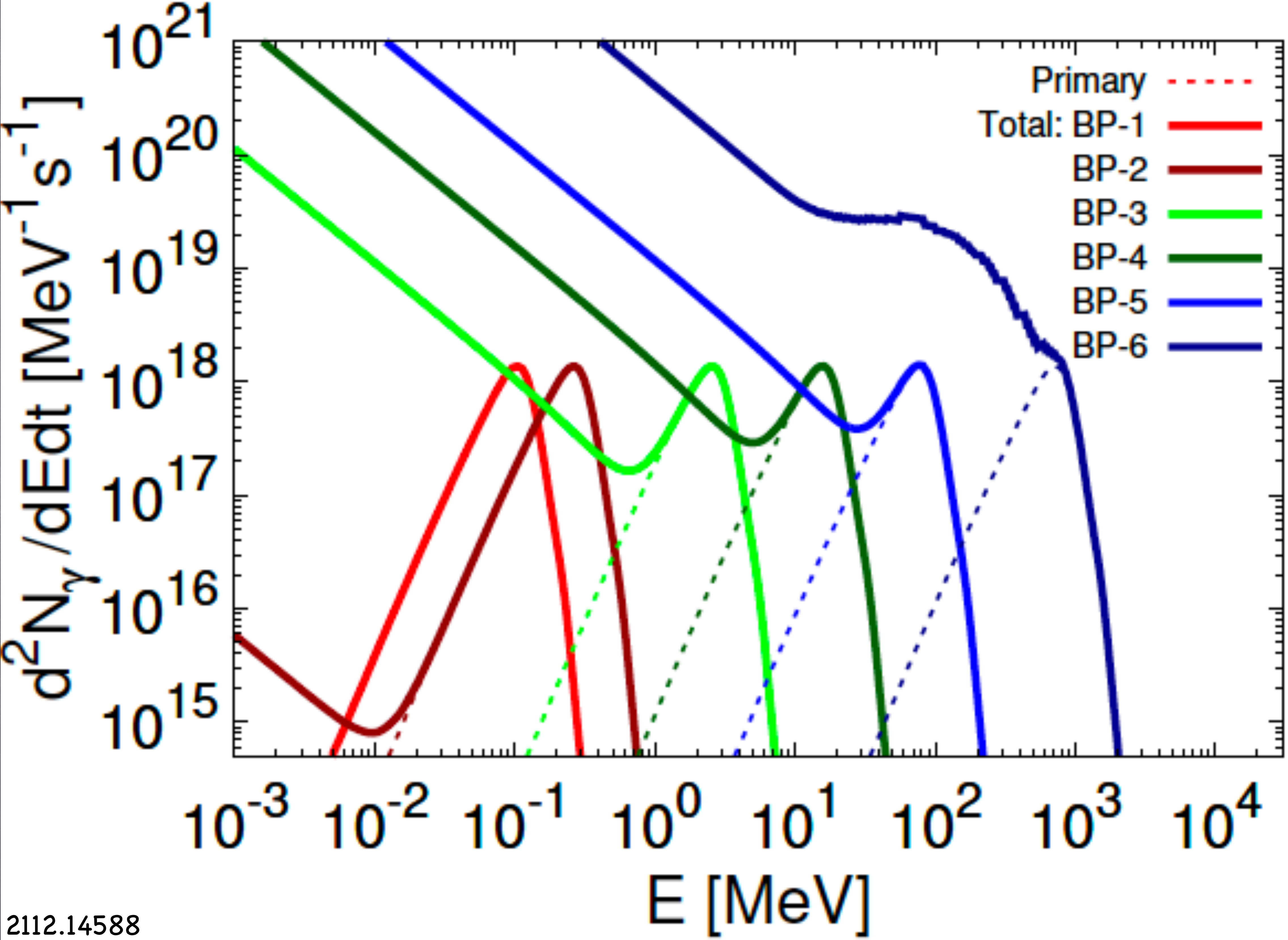
2112.14588

- Since FBs have a monochromatic mass function, so do the PBHs
- PBH formation will not conserve Q charge of FB and PBH will evaporate as a Schwarzschild BH
- Hawking evaporation of PBH produces all particles with mass below the PBH temperature
- Will focus on extragalactic gamma-ray background

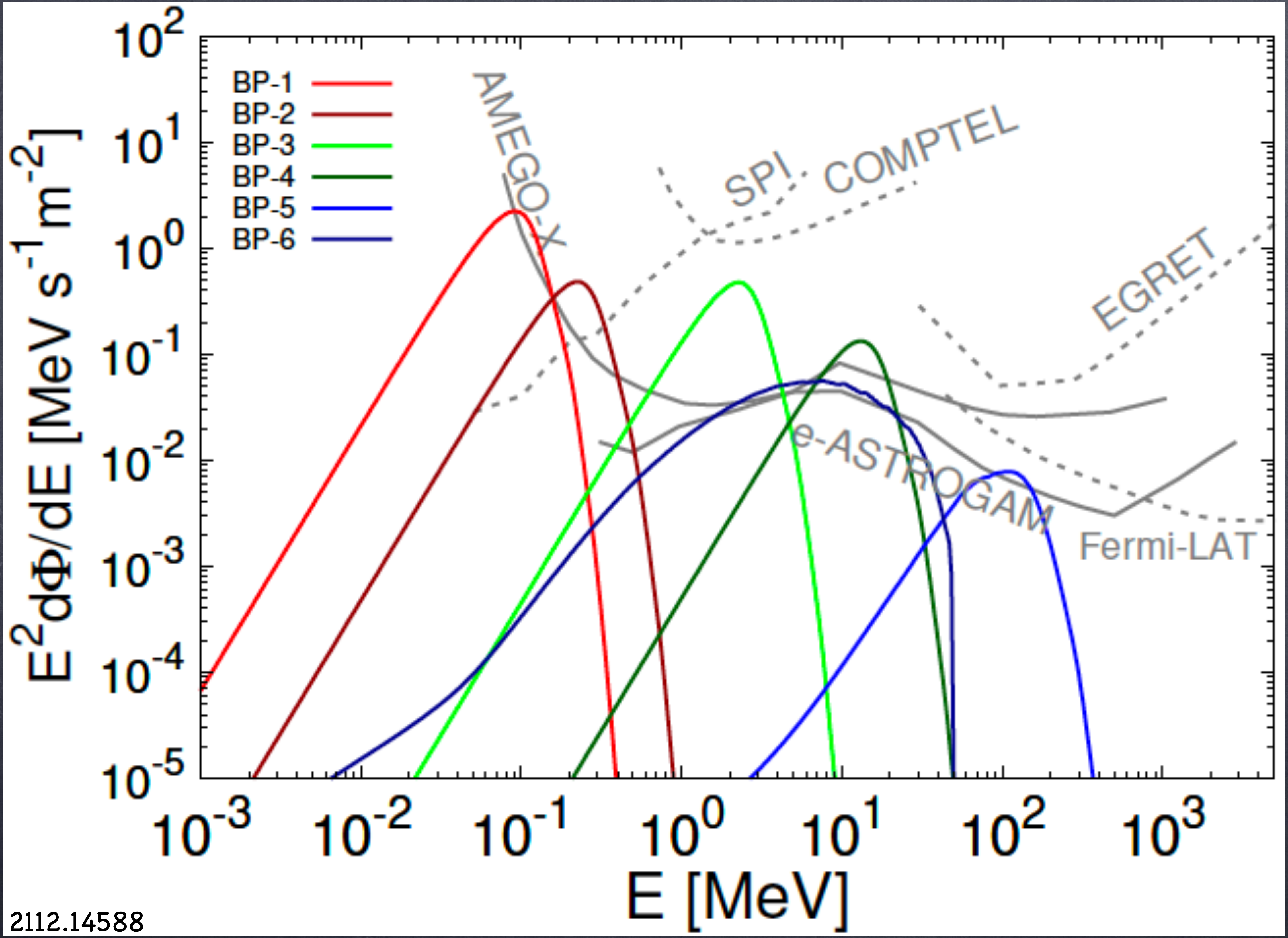
Measure of fraction of energy density in PBHs at formation



2112.14588


$d^2N_\gamma/dEdt$ [MeV^{-1}s^{-1}]
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
E [MeV]
Primary
Total: BP-1
BP-2
BP-3
BP-4
BP-5
BP-6

2112.14588


BP-1
BP-2
BP-3
BP-4
BP-5
BP-6
AMEGO-X
SPI
COMPTEL
EGRET
e-ASTROGAM
Fermi-LAT
$E^2 d\Phi/dE$ [MeV s^{-1}m^{-2}]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
E [MeV]

2112.14588

Summary

- Macroscopic Fermi balls can be produced in the false vacuum during FOPT
- Vacuum energy $1 \lesssim B^{1/4}/\mathrm{keV} \lesssim 10^3$ give FBs of mass $10^{-13} M_\odot \lesssim M_{\rm FB} \lesssim 10^{-3} M_\odot$
- Correlated observations of GWs $(10^{-9}\ \ \mathrm{Hz} - 10^{-5}\ \ \mathrm{Hz})$ at SKA/THEIA/muAres and microlensing at Subaru-HSC, can be made

- If the Yukawa force is strong enough FBs can collapse to PBHs
- Vacuum energy $0.1 \lesssim B^{1/4}/\mathrm{MeV} \lesssim 10^4$ gives PBHs of mass $10^{-20} M_\odot \lesssim M_{\rm PBH} \lesssim 10^{-15} M_\odot$
- Correlated observations of GWs $(10^{-7}\ \mathrm{Hz} - 10^{-4}\ \mathrm{Hz})$ at THEIA/muAres and extragalactic gamma-rays at AMEGO-X/e-ASTROGAM, can be made
- A measurable amount of dark radiation is also typically expected