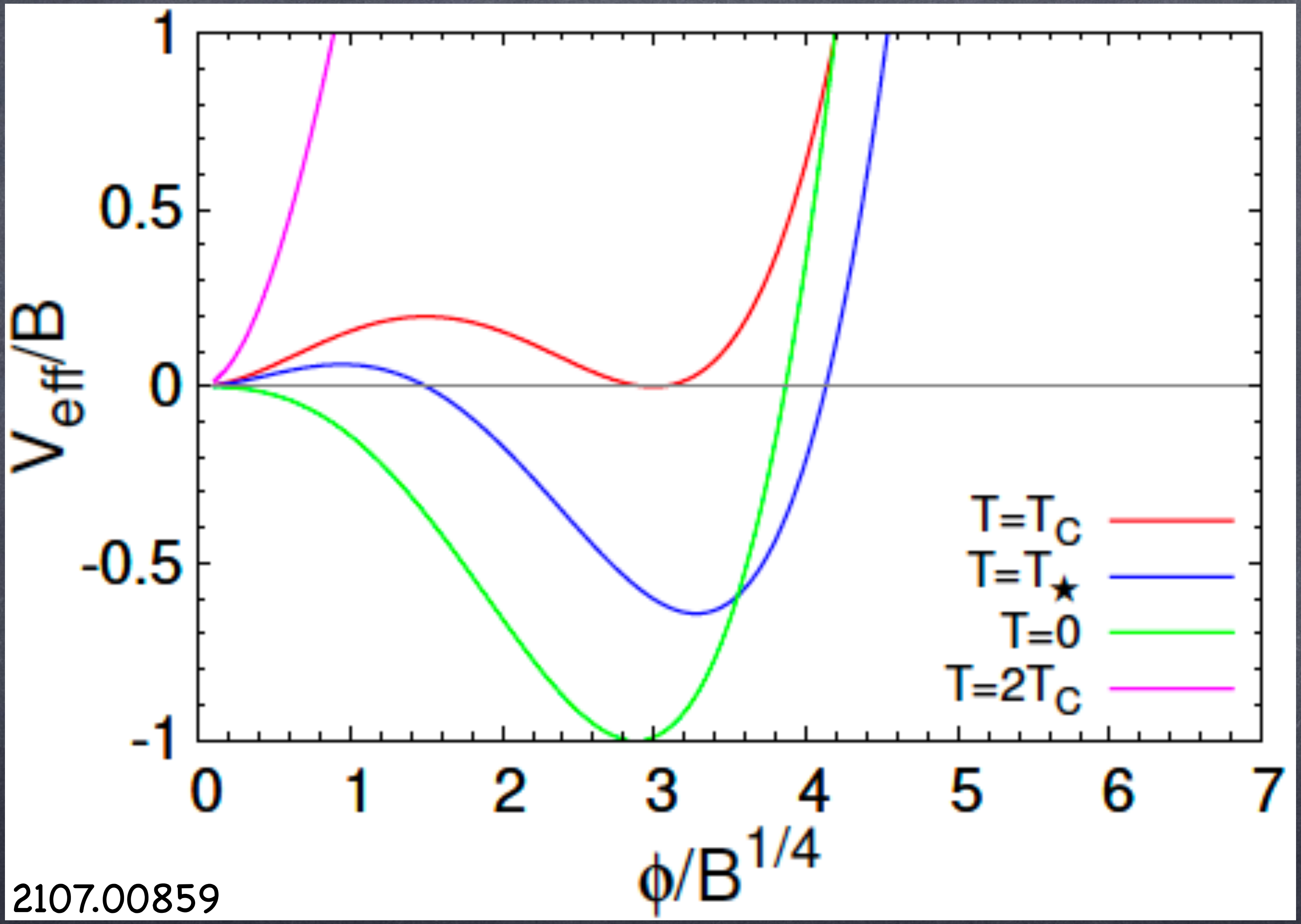
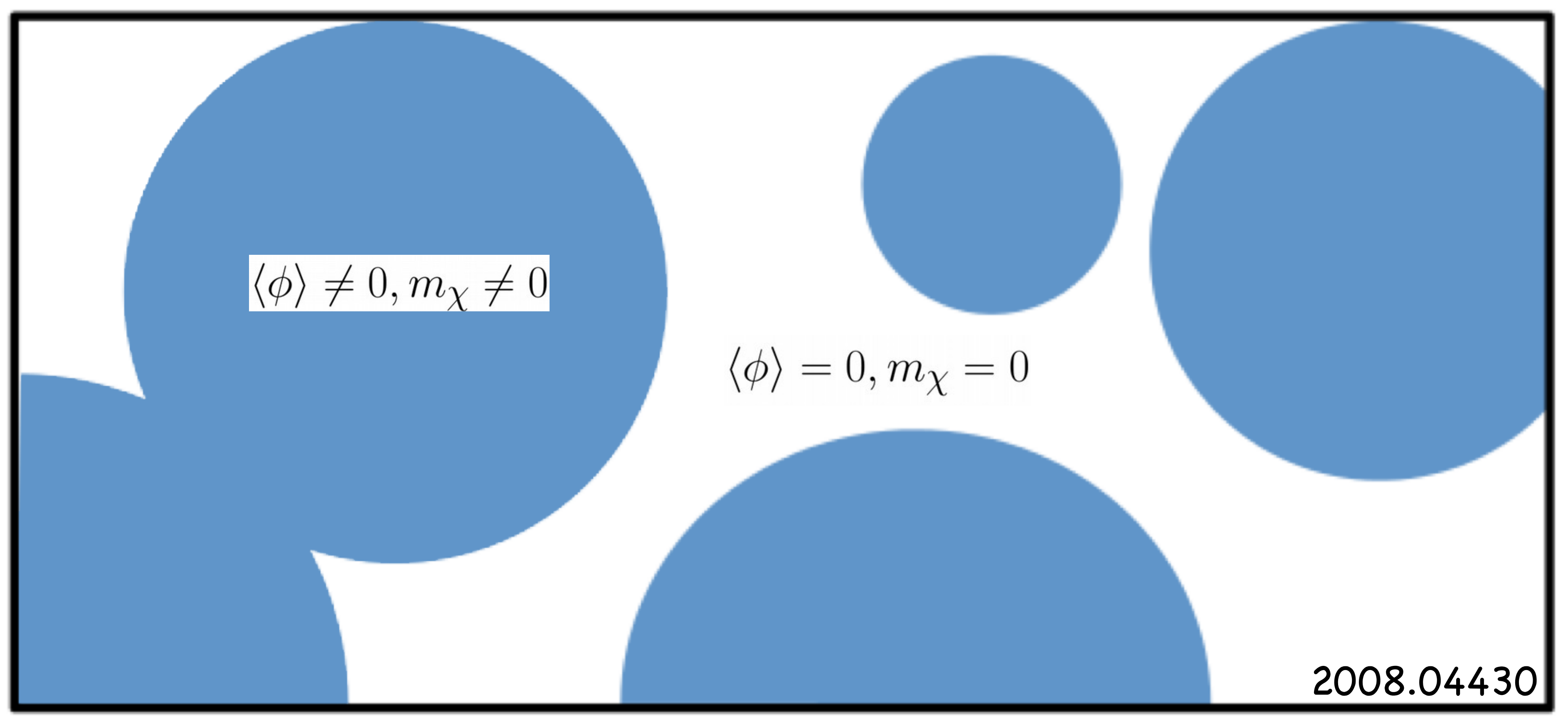
Correlated signals of first-order phase transitions in dark sectors

Macroscopic dark matter from a FOPT

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



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



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

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:

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

- ... 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

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

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

Parameters that determine GW signal

$$T_\star \, ,$$

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
$B^{1/4}/\text{keV}$	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}
$T_{\text{SM}\star}/\text{keV}$	1.41	100.0	64.5	128.1	164.8	169.5	427.8	1601
$T_\star/\text{keV}$	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
$M_{\text{FB}}/M_\odot$	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}
$R_{\text{FB}}/R_\odot$	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
$\Omega_{\text{FB}}h^2$	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

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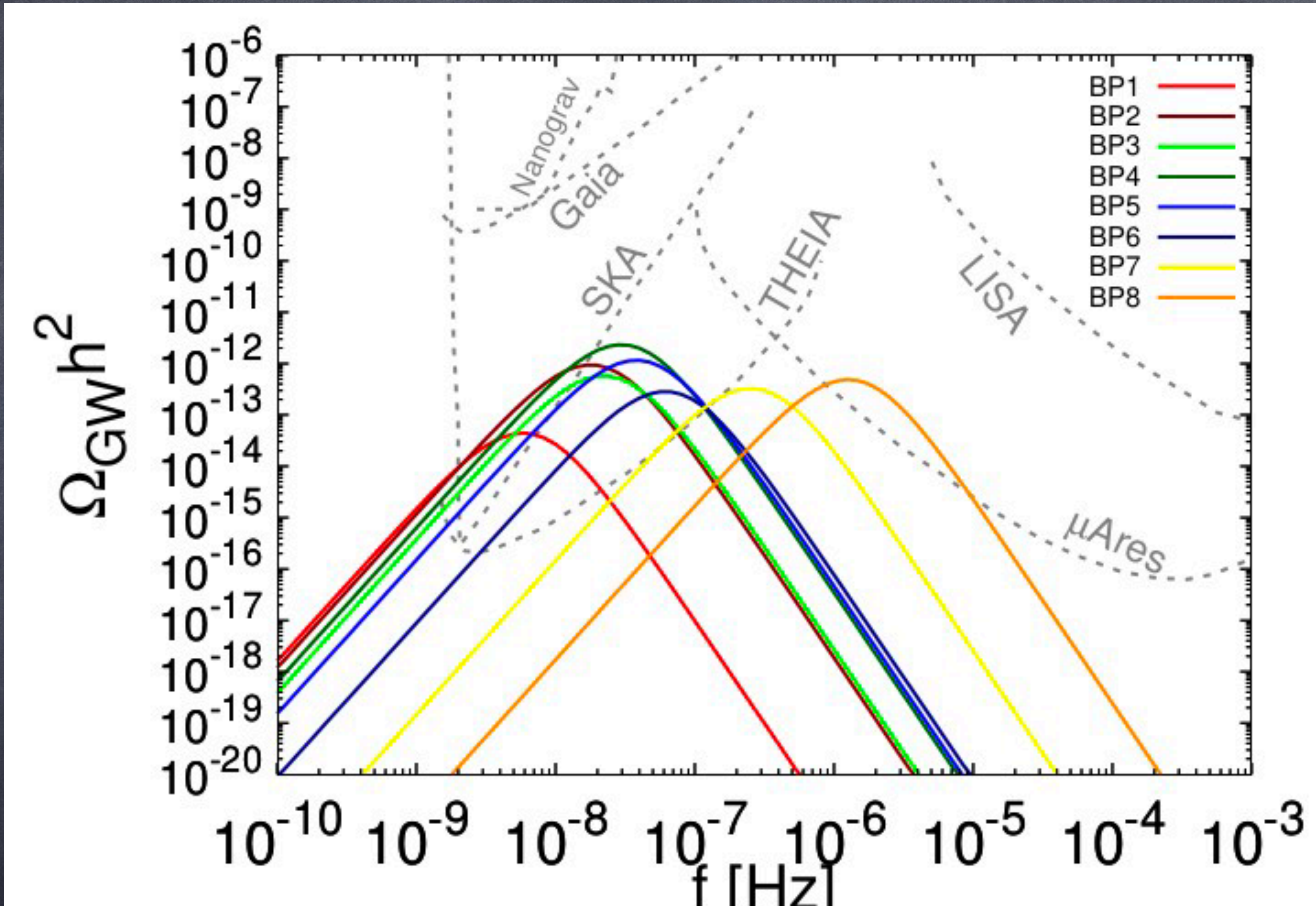
Gravitational wave signal



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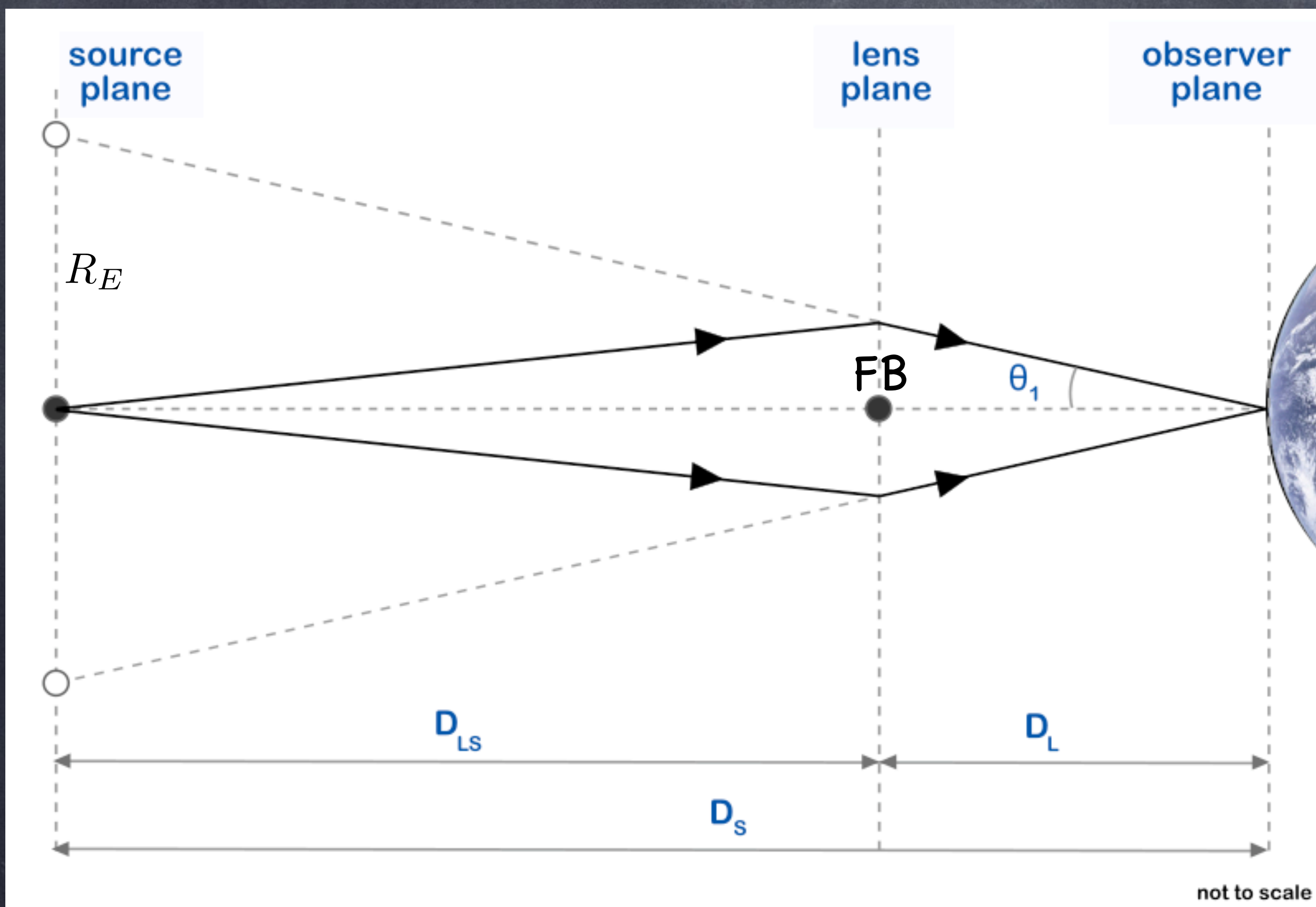
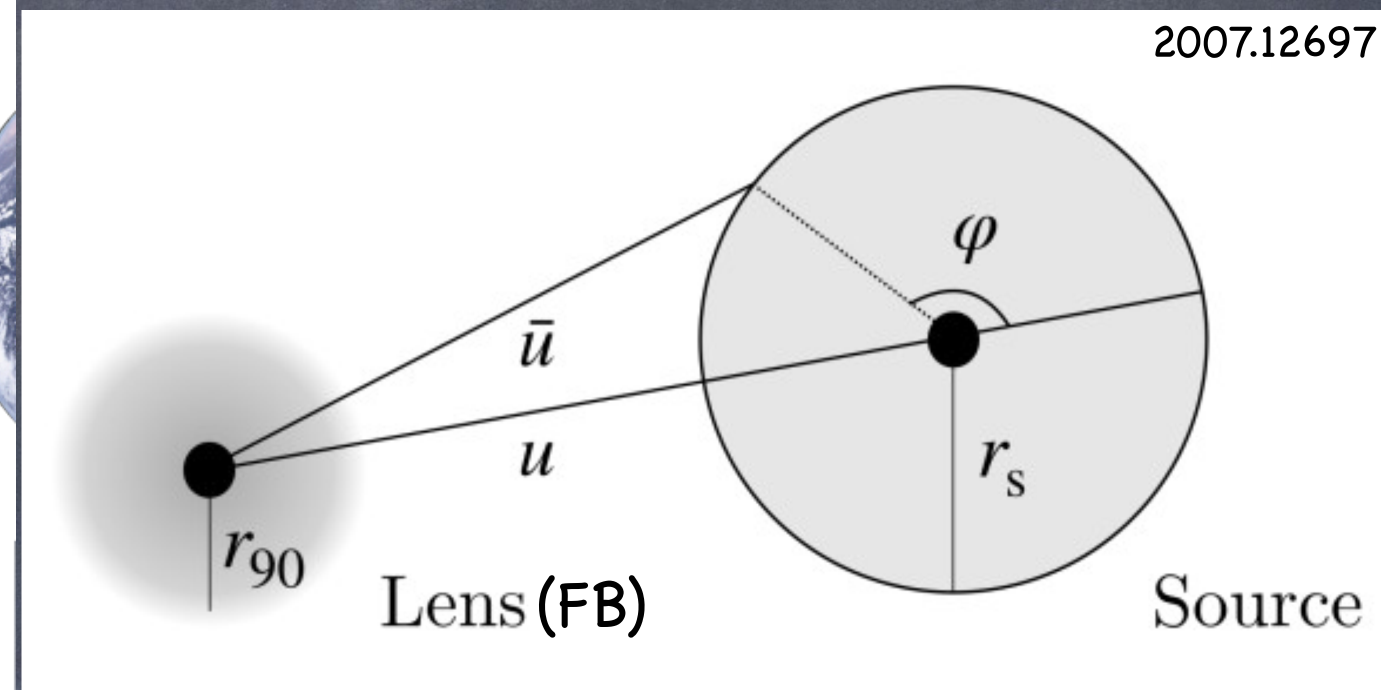
Microlensing



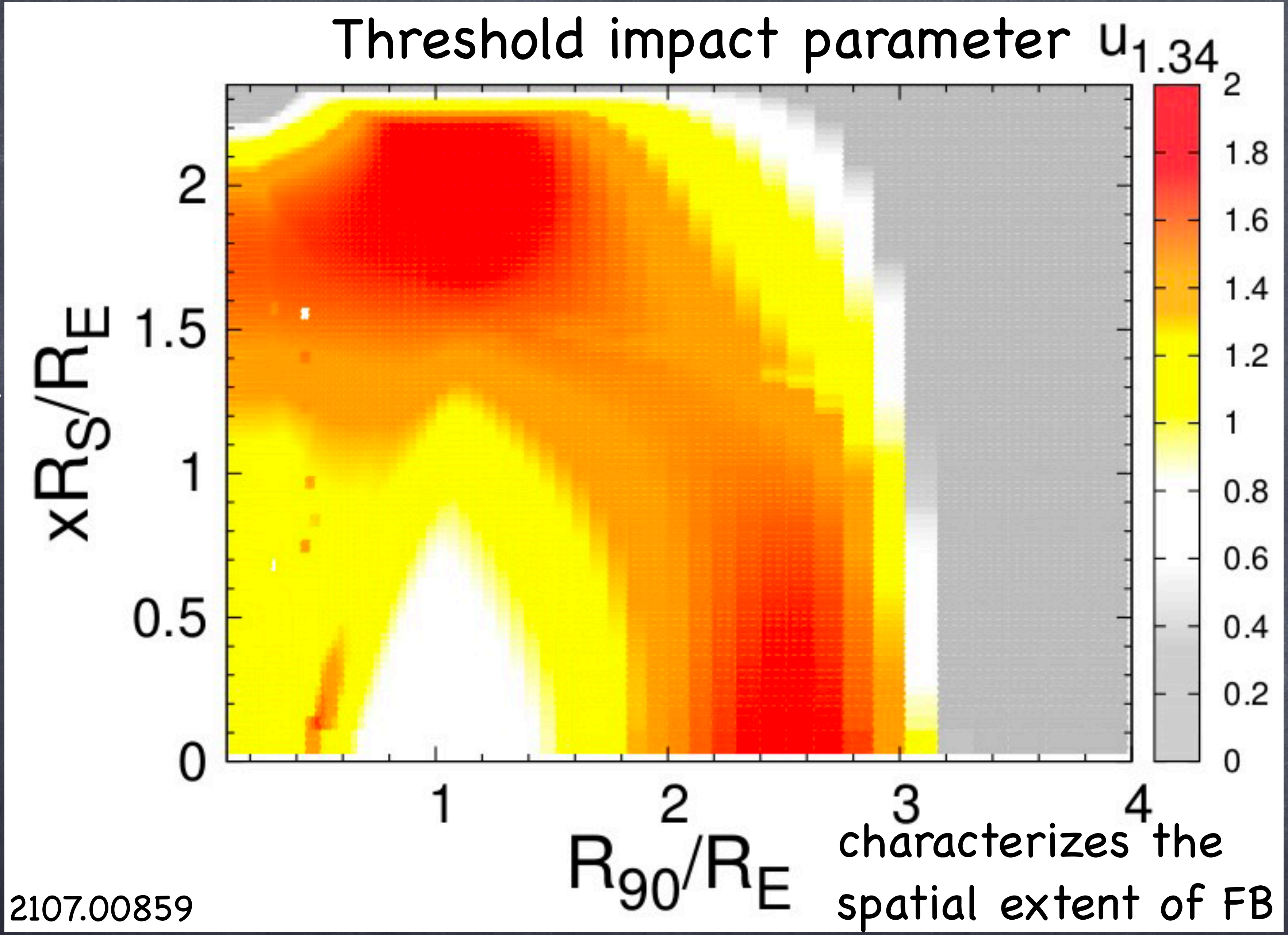
Finite lens and finite source



Magnification (transient brightening) by a point lens by a point source:

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

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



projected source radius

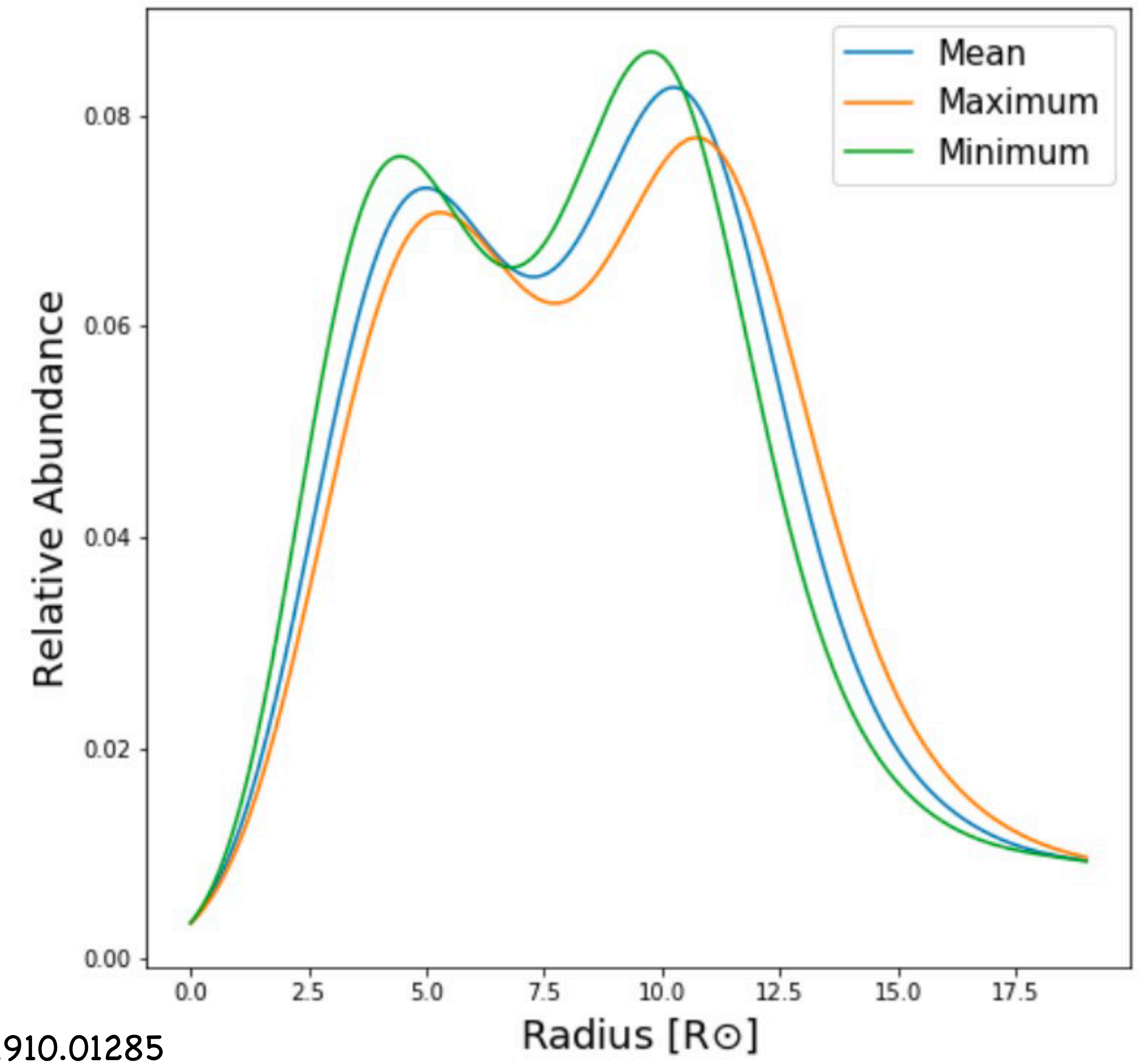
pt lens & pt source

characterizes the spatial extent of FB

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



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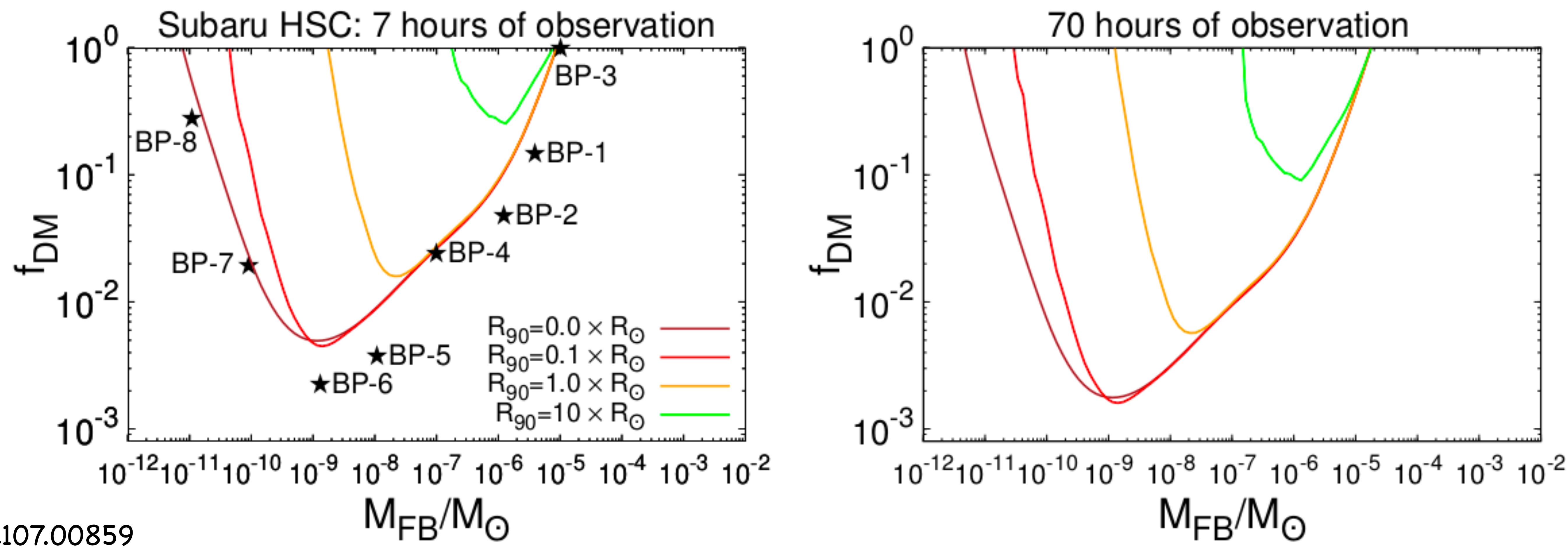
Microlensing survey of the M31 galaxy



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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,

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

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$\beta/H_\star$	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}
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ΔN_{eff}	0.391	0.226	0.248	0.394	0.497	0.425	0.261	0.408

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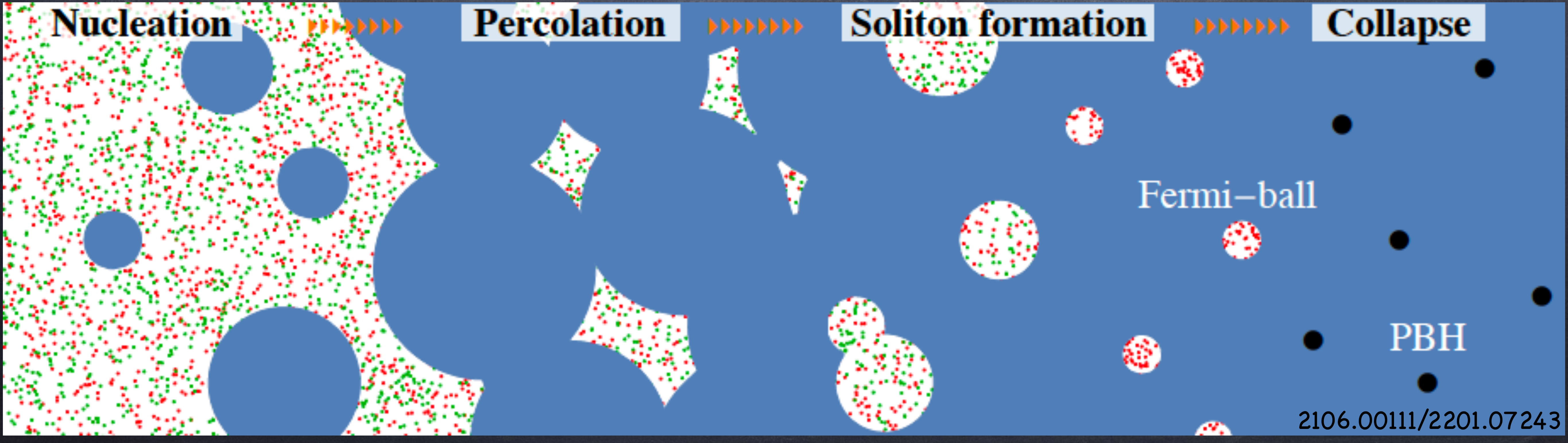
Fermi ball collapse to primordial black hole

- Yukawa interaction length increases as T falls
- (Negative) Yukawa energy can dominate and cause FB to collapse

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



A = 0.1	BP-1	BP-2	BP-3	BP-4	BP-5	BP-6
λ	0.097	0.177	0.084	0.198	0.198	0.077
$B^{1/4}/\text{MeV}$	37.89	16.55	3.412	1.843	0.286	2.411
C/MeV	0.551	1.329	0.054	0.260	0.047	0.022
D	1.257	0.138	0.413	0.750	0.794	0.286
g_χ	0.031	0.020	0.187	0.240	0.118	0.164
η_χ	4.97×10^{-9}	4.67×10^{-11}	3.81×10^{-13}	9.40×10^{-16}	1.47×10^{-18}	9.26×10^{-17}
$T_{\text{SM}\star}/\text{MeV}$	29.81	53.46	7.821	2.939	0.440	4.979
$T_\star/\text{MeV}$	18.72	36.89	3.156	1.126	0.157	2.908
T_f/MeV	19.73	37.13	3.338	1.343	0.214	3.071
T_ϕ/MeV	17.72	21.64	2.737	0.800	0.077	2.361
$S_3(T_\star)/T_\star$	156	161	165	170	180	170
$M_{\text{PBH}}/M_\odot$	3.18×10^{-16}	1.08×10^{-16}	1.07×10^{-17}	1.07×10^{-18}	3.91×10^{-19}	3.99×10^{-20}
Q_{FB}	5.02×10^{42}	1.77×10^{42}	1.14×10^{42}	2.06×10^{41}	4.48×10^{41}	5.00×10^{39}
β'	3.83×10^{-17}	2.02×10^{-19}	8.01×10^{-23}	3.43×10^{-26}	5.45×10^{-30}	1.01×10^{-27}
α	1.26×10^{-2}	1.72×10^{-3}	2.78×10^{-3}	9.23×10^{-3}	1.81×10^{-2}	1.14×10^{-2}
$\beta/H_\star$	1.42×10^{4}	2.55×10^{3}	4.22×10^{3}	2.86×10^{3}	1.90×10^{3}	2.74×10^{3}
v_w	0.840	0.694	0.845	0.935	0.968	0.843
$\Omega_{\text{PBH}}h^2$	0.108	9.73×10^{-4}	1.15×10^{-6}	1.54×10^{-9}	2.03×10^{-13}	7.94×10^{-29}
ΔN_{eff}	0.413	0.406	0.087	0.114	0.165	0.379

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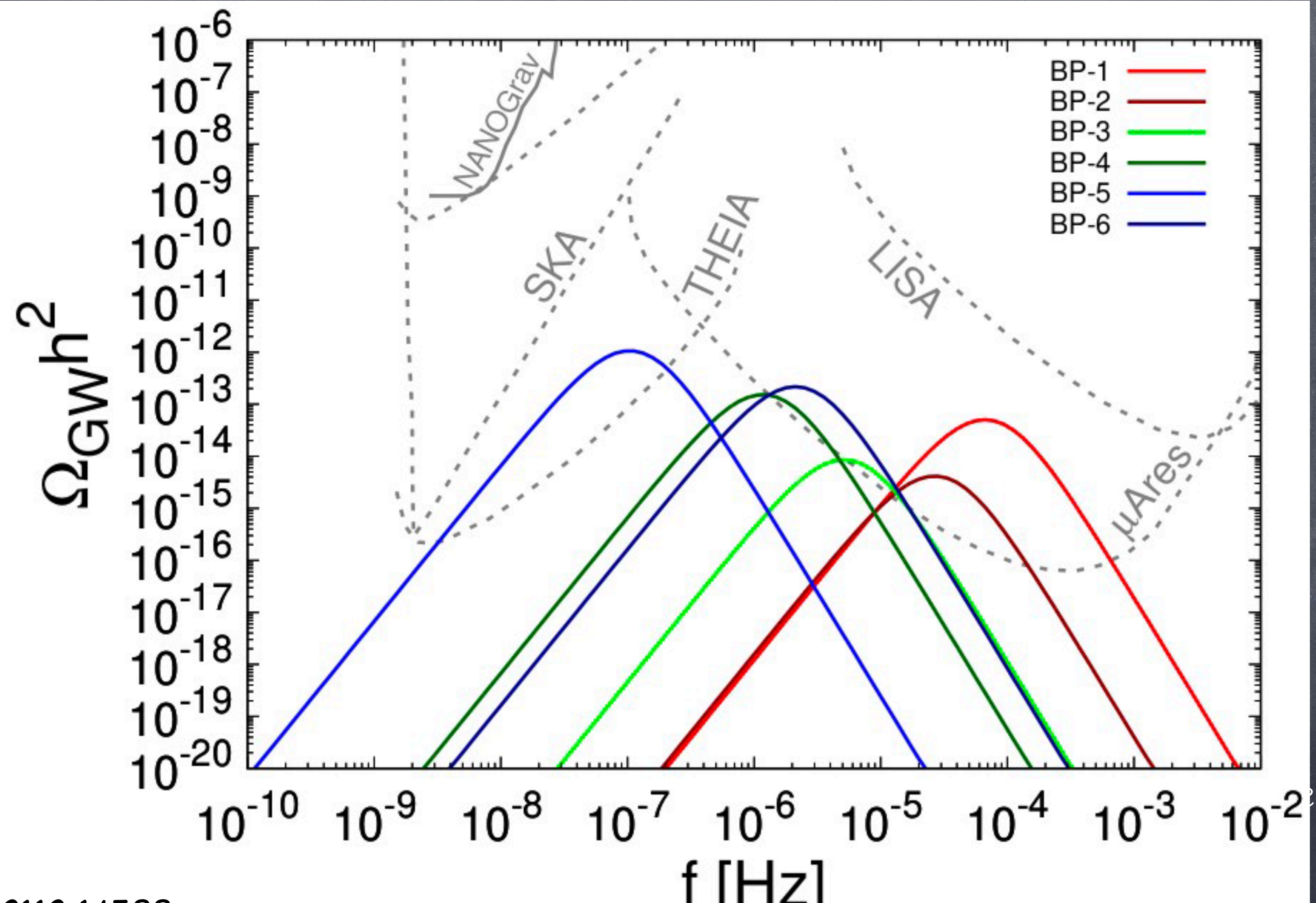

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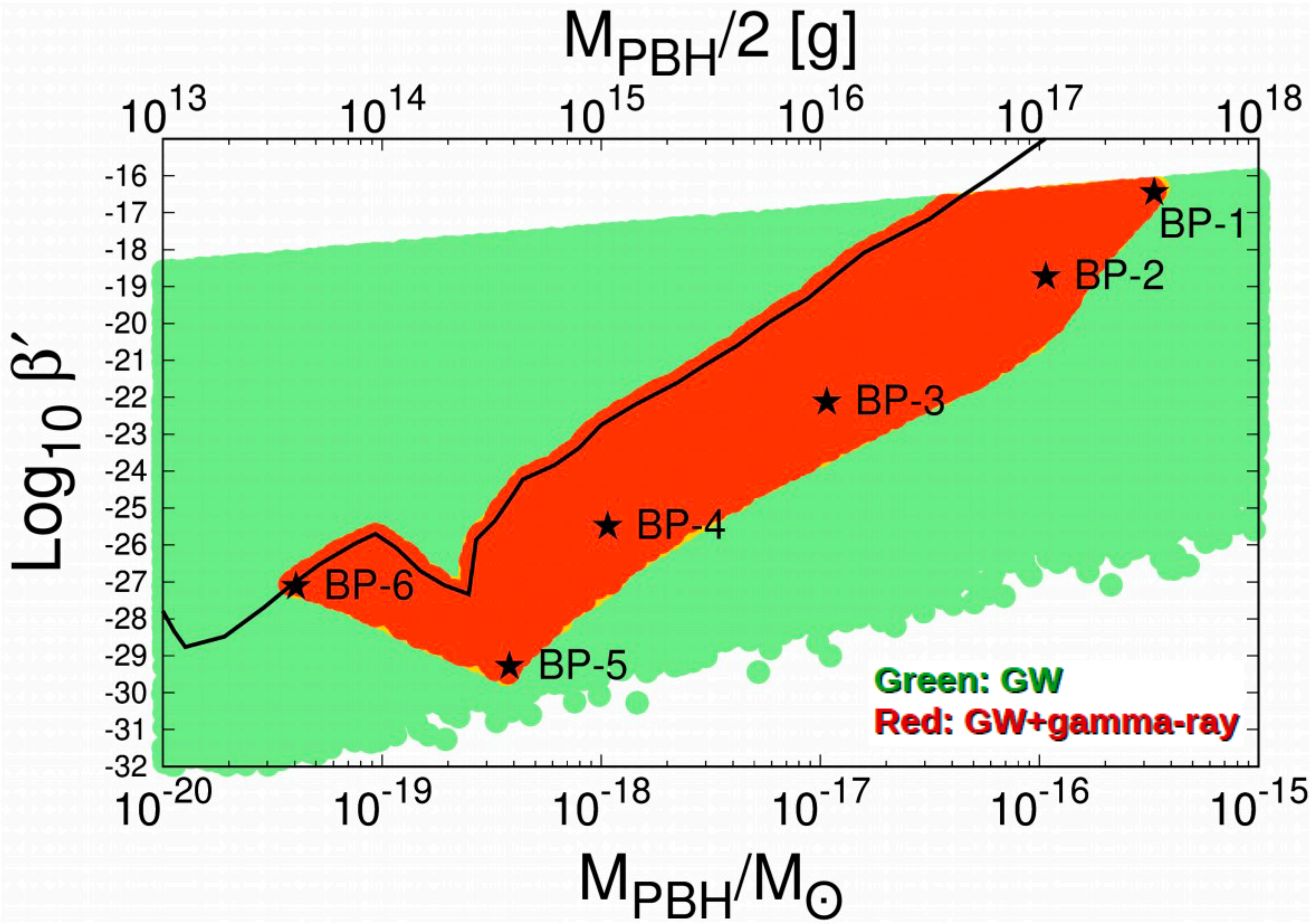
1612.01443

- 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



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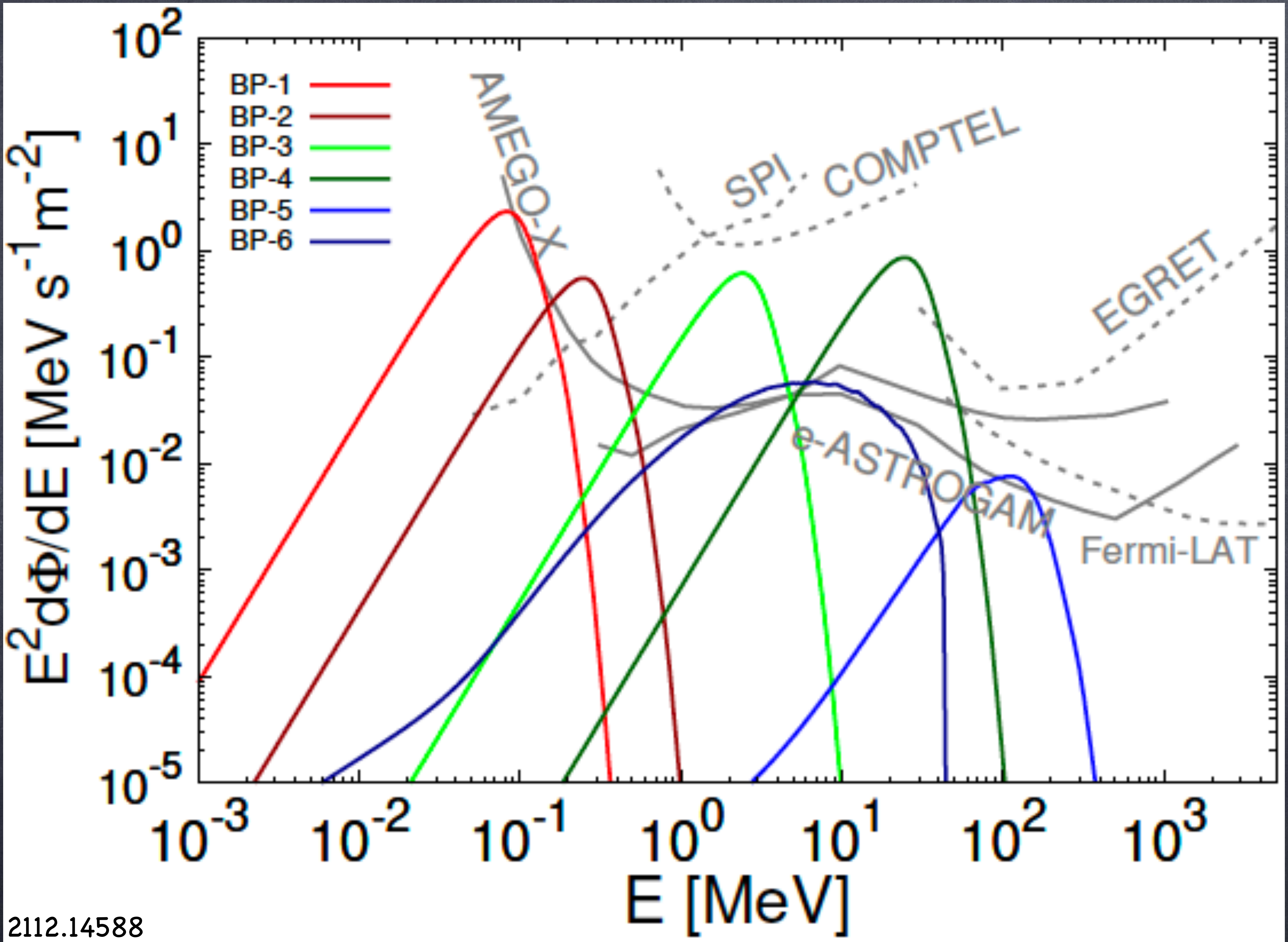
BP-1
BP-2
BP-3
BP-4
BP-5
BP-6
AMEGO-X
SPI
COMPTEL
EGRET
e-ASTROGAM
Fermi-LAT
$E^2 d\Phi/dE$ [MeV s^{-1}m^{-2}]
E [MeV]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
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10^{0}
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10^{3}

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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 $10^{-13} M_\odot \lesssim M_{\mathrm{FB}} \lesssim 10^{-3} M_\odot$
- 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 $10^{-20} M_\odot \lesssim M_{\mathrm{FB}} \lesssim 10^{-15} M_\odot$

- Correlated observations of GWs $(10^{-7}\ \mathrm{Hz} - 10^{-4}\ \mathrm{Hz})$ at THEIA/muAres and extragalactic gamma-rays at AMEGO-X/eASTROGAM, can be made

- A measurable amount of dark radiation is also typically expected