GW and LSS signatures of Primordial Black Holes as Dark Matter

GW from Early Universe

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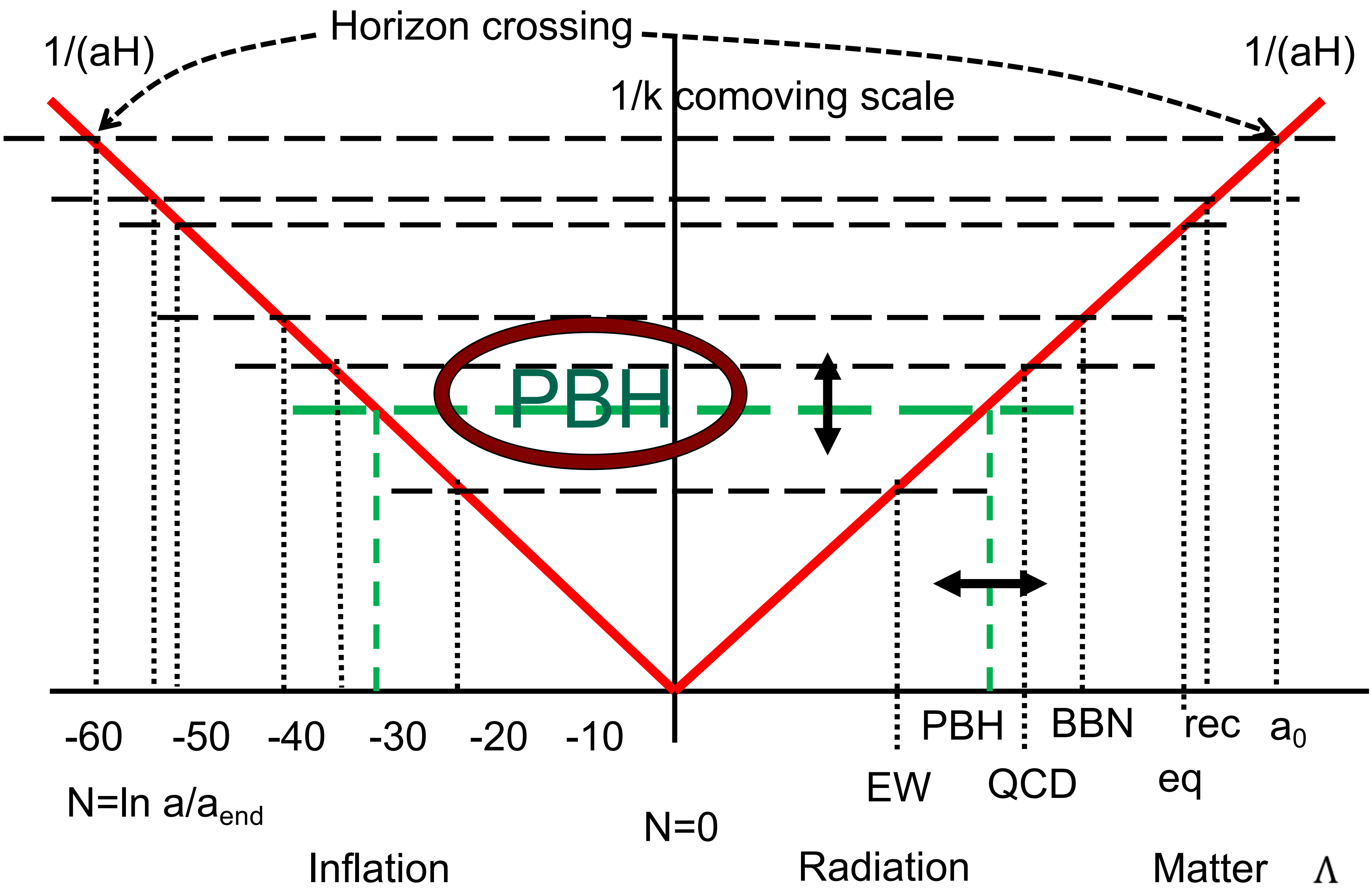
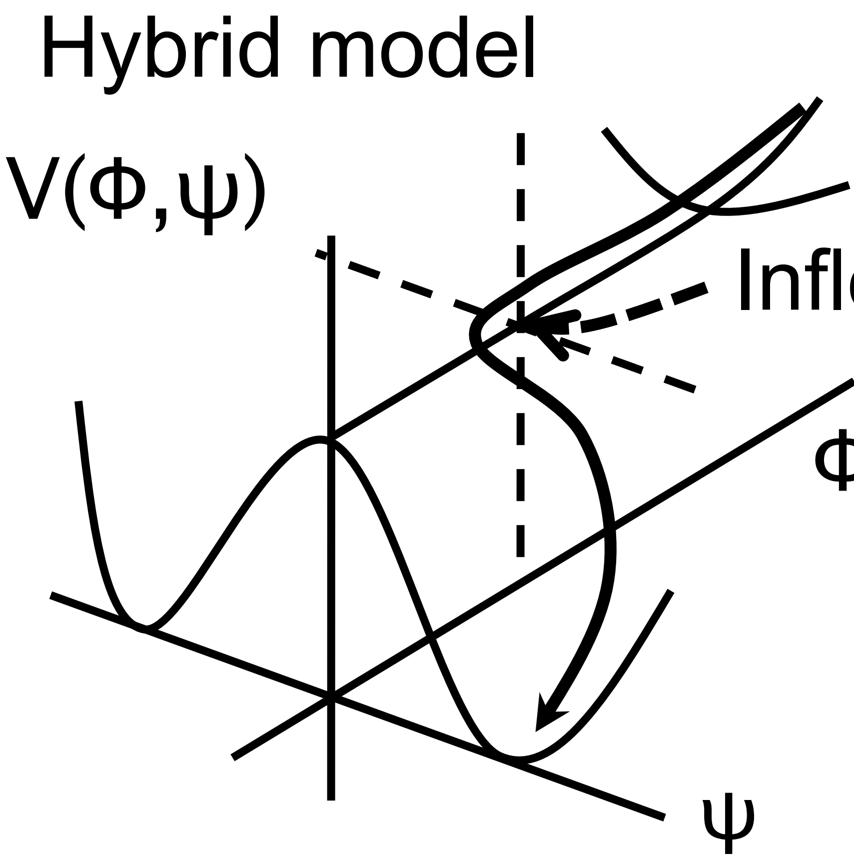
Outline

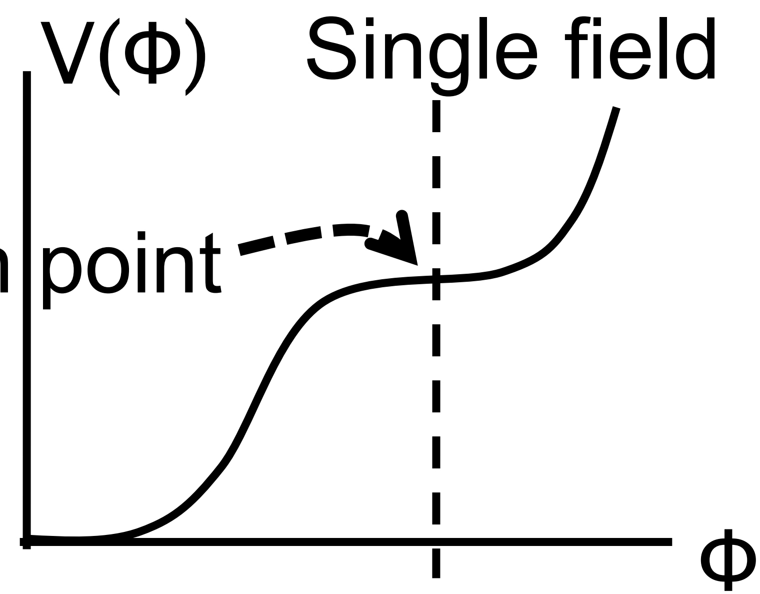
Observational Cosmology only requires QM, GR and the SM of particle physics

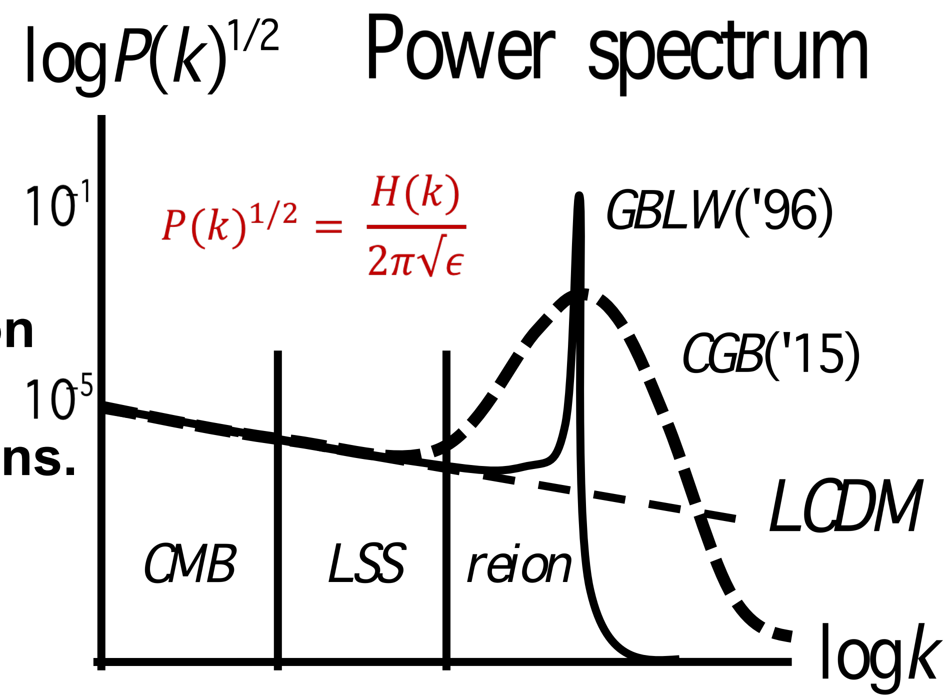
- Thermal history of the Universe
- GW signatures of PBH as DM
- Hot Spot Electroweak Baryogenesis
- Early Galaxy Formation
- Long duration microlensing events
- PBH clustering and constraints
- Conclusions

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



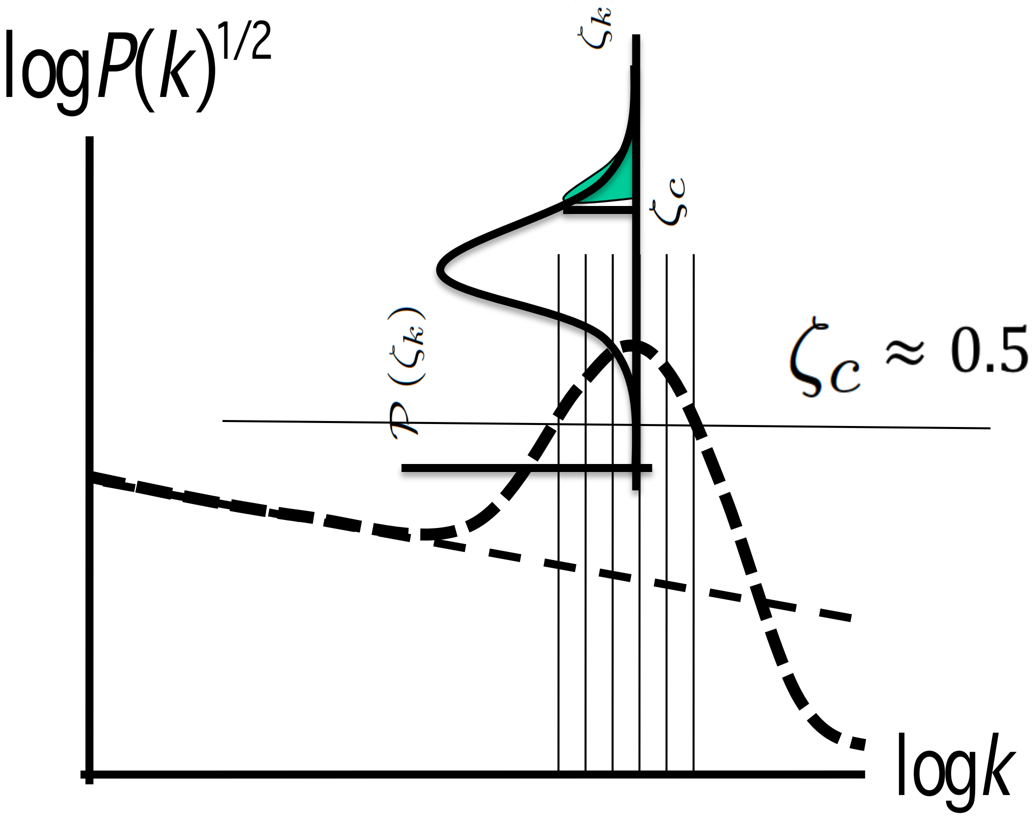




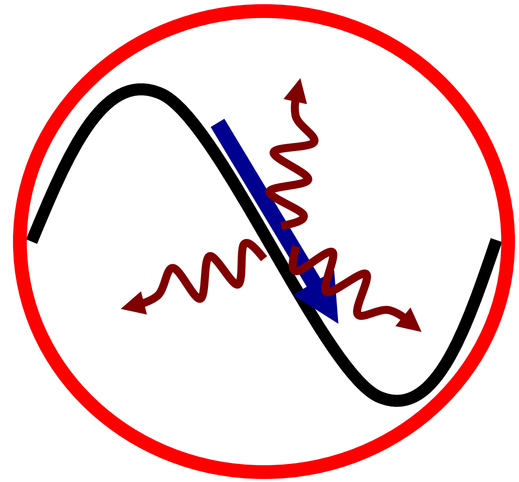
Quantum fluctuations during inflation may have enough amplitude to generate large curvature perturbations.

Quantum diffusion makes a narrow peak become a broad peak in k.

Gravitational Collapse of PBH



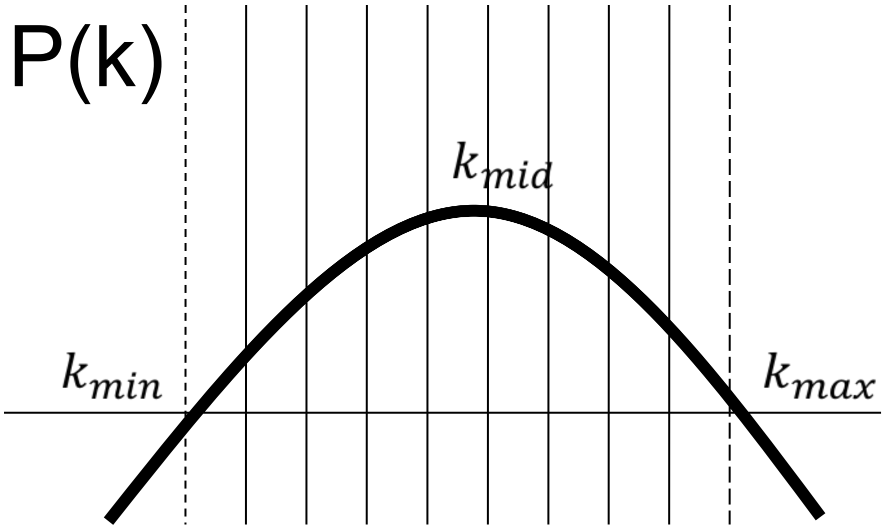
$$\beta^{\text{form}}(M_k) = \int_{\zeta_c}^{\infty} \mathcal{P}(\zeta_k)\, d\zeta_k$$



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

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

Clustering properties of PBH



$$\beta(\nu) = \mathrm{erfc}\left(\nu/\sqrt{2}\right) \simeq \sqrt{\frac{2}{\pi}}\,\frac{e^{-\nu^2/2}}{\nu}$$

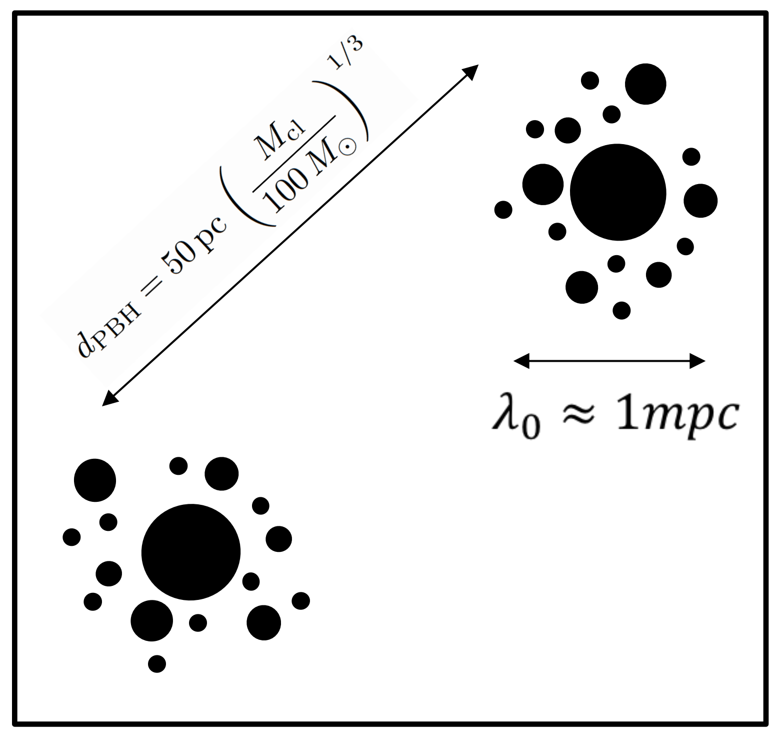
$$N_{\rm cl} = \frac{10}{7}\,\beta(\nu)\,e^{3\nu^2/4} \sim 2000 \qquad \nu = \frac{\zeta_c}{\sigma_k} \approx 6$$

Poisson statistics

$$\lambda(z_f) = \frac{d_H(z_f)}{\beta(z_f)^{1/3}} \sim 1.2\times 10^5~\mathrm{km}\,\left(\frac{6\times 10^{11}}{1+z_f}\right)^{5/3}$$

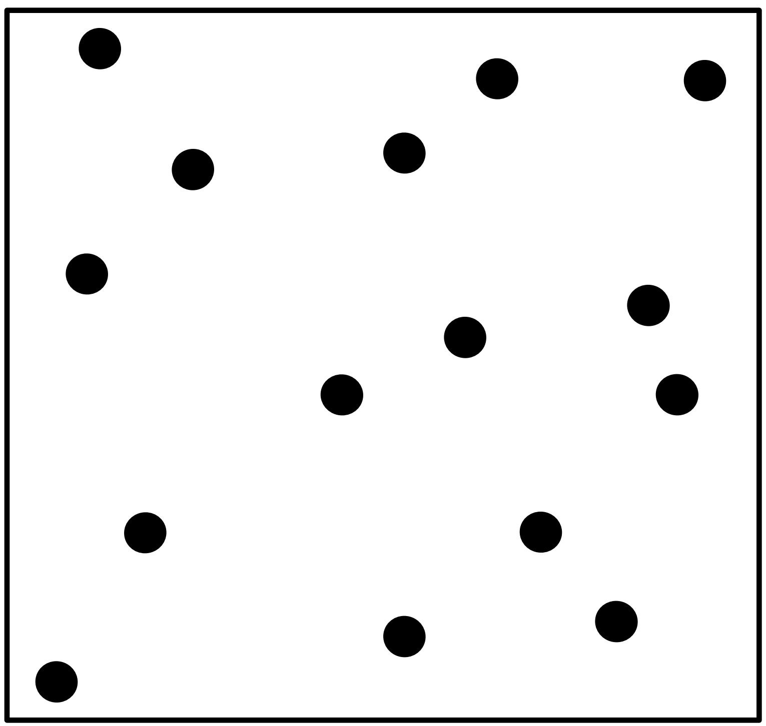
$$\beta(z_f) \sim 3\times 10^{-9}\,\left(\frac{6\times 10^{11}}{1+z_f}\right)$$

$$M_{\rm PBH} \sim 20\,M_\odot\,\left(\frac{6\times 10^{11}}{1+z_f}\right)^2$$

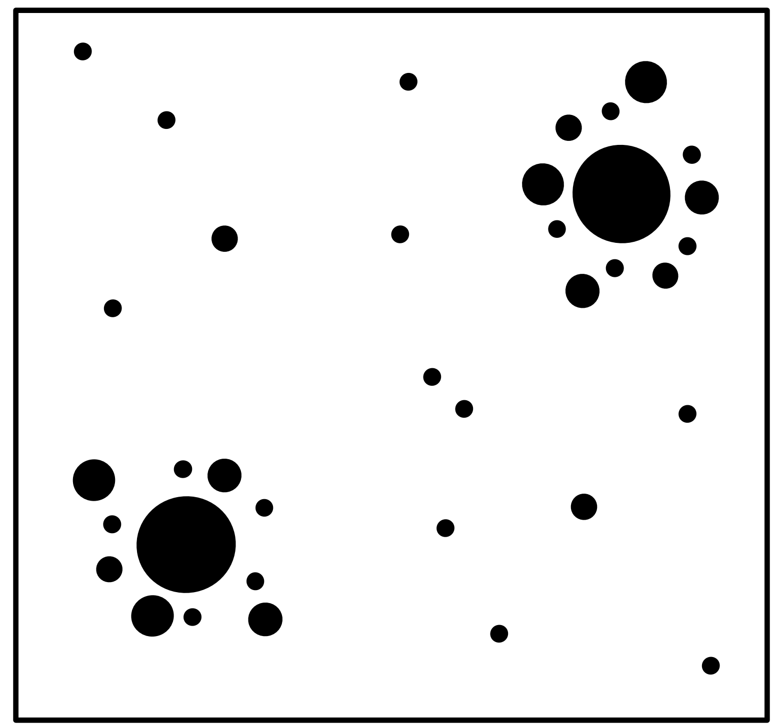


Inflationary predictions

- Wide mass distribution JGB & Clesse (2017)
- Clusters of PBH: N_{cl} ~100-1000 , comoving size ~1mpc



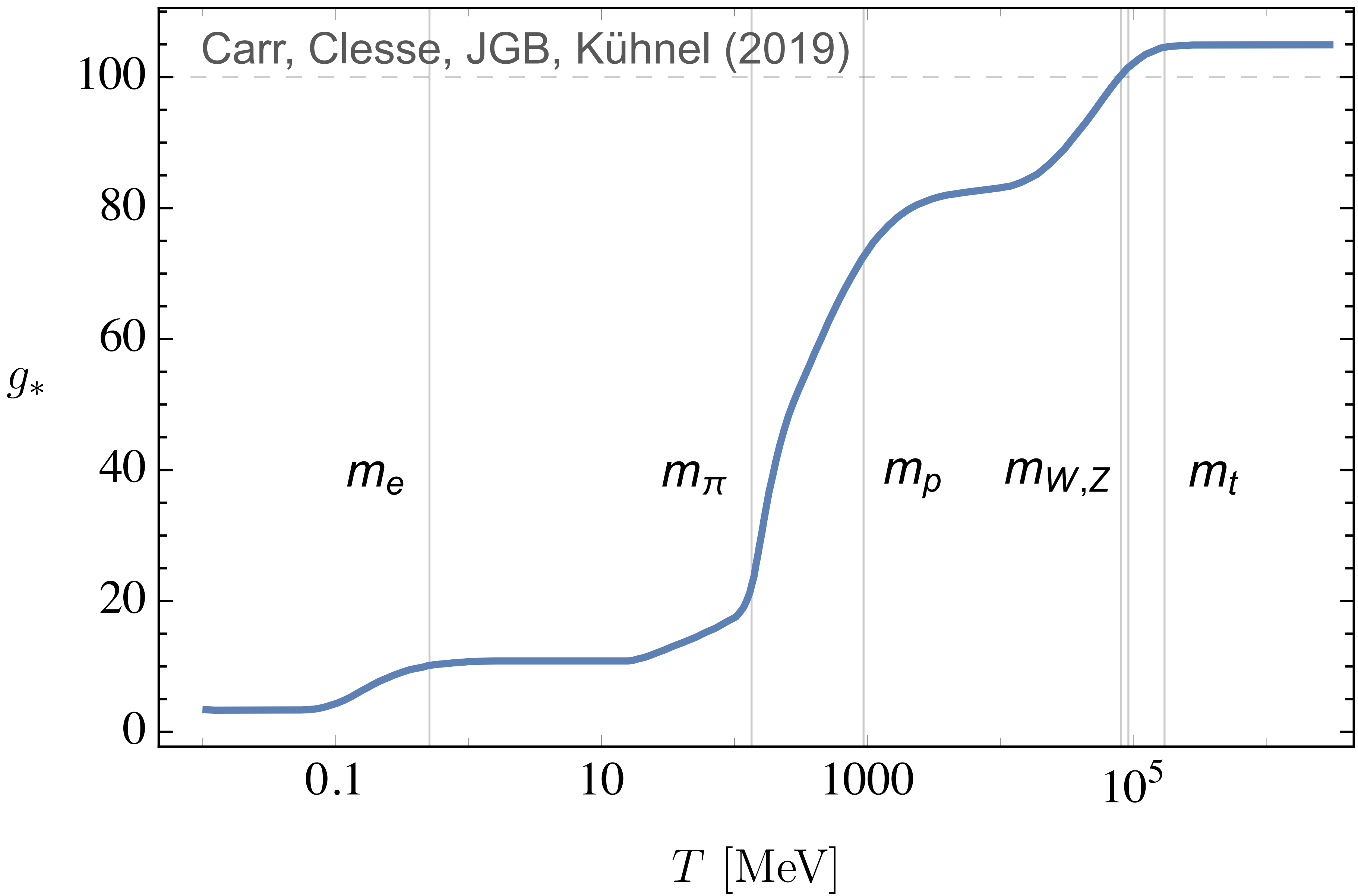
uniform single-mass
is already ruled out



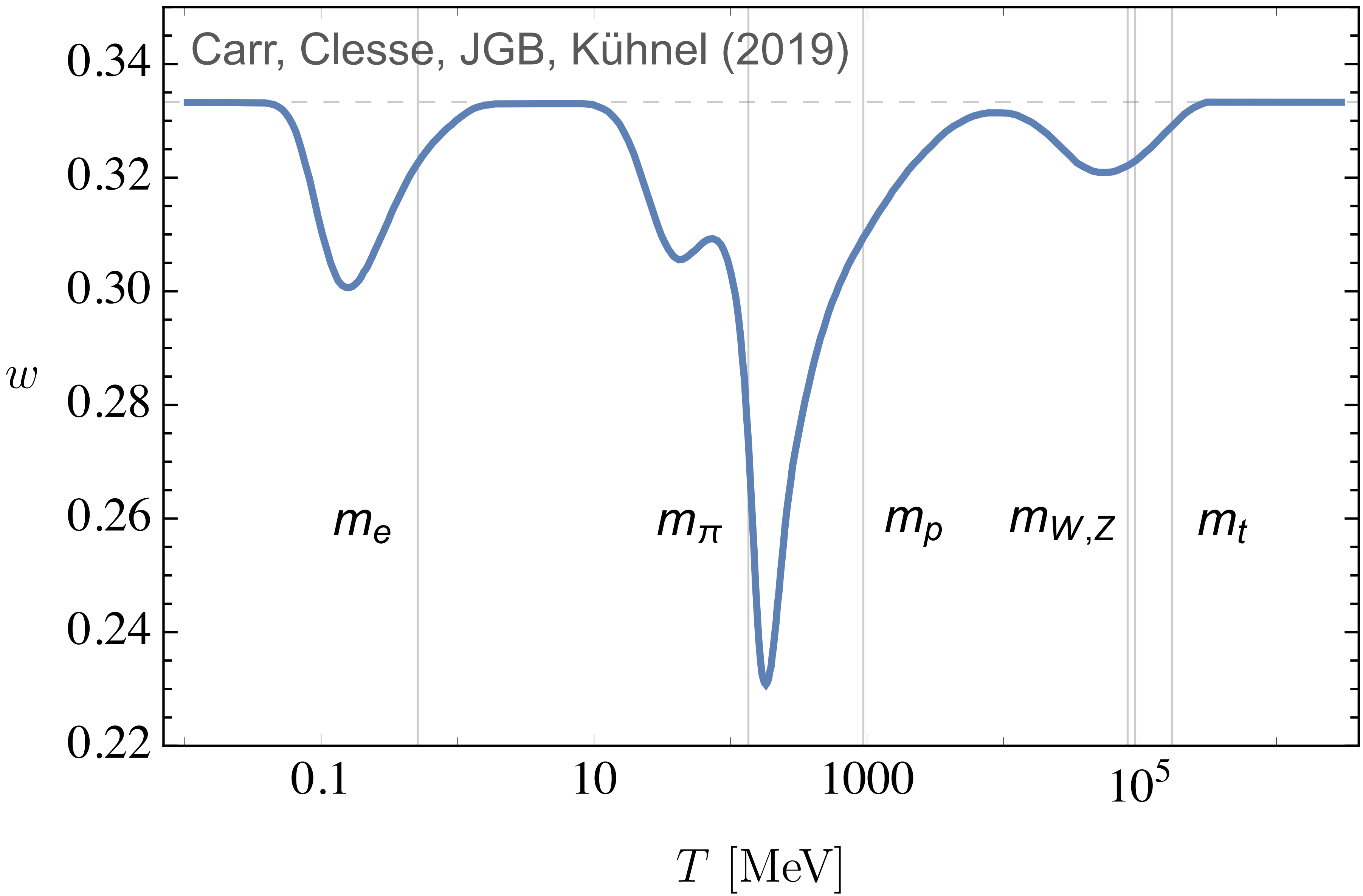
clustered wide-mass
is still viable

Thermal History Universe

Thermal history of the universe

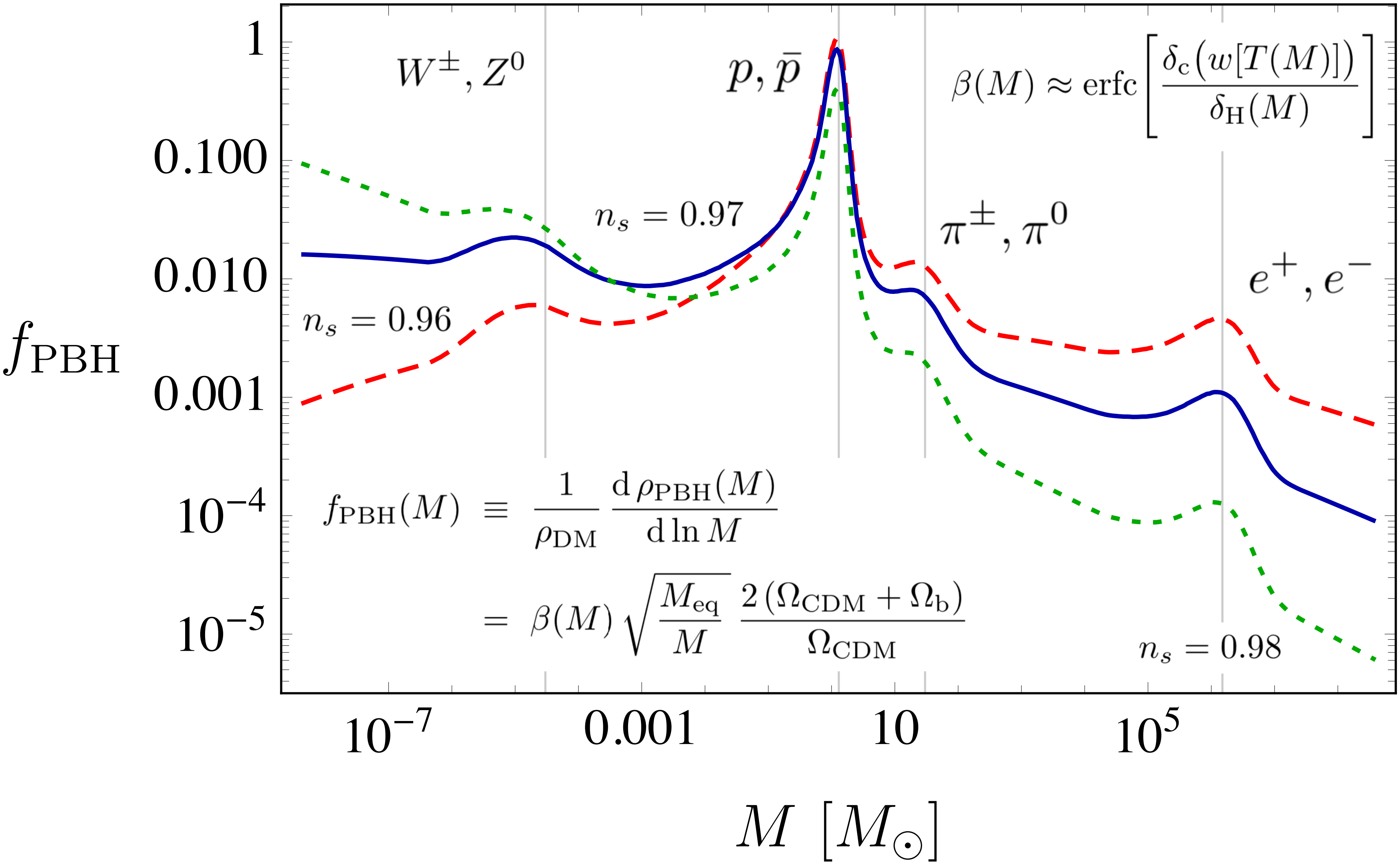


Thermal history of the universe



Predictions for PBH mass spectrum

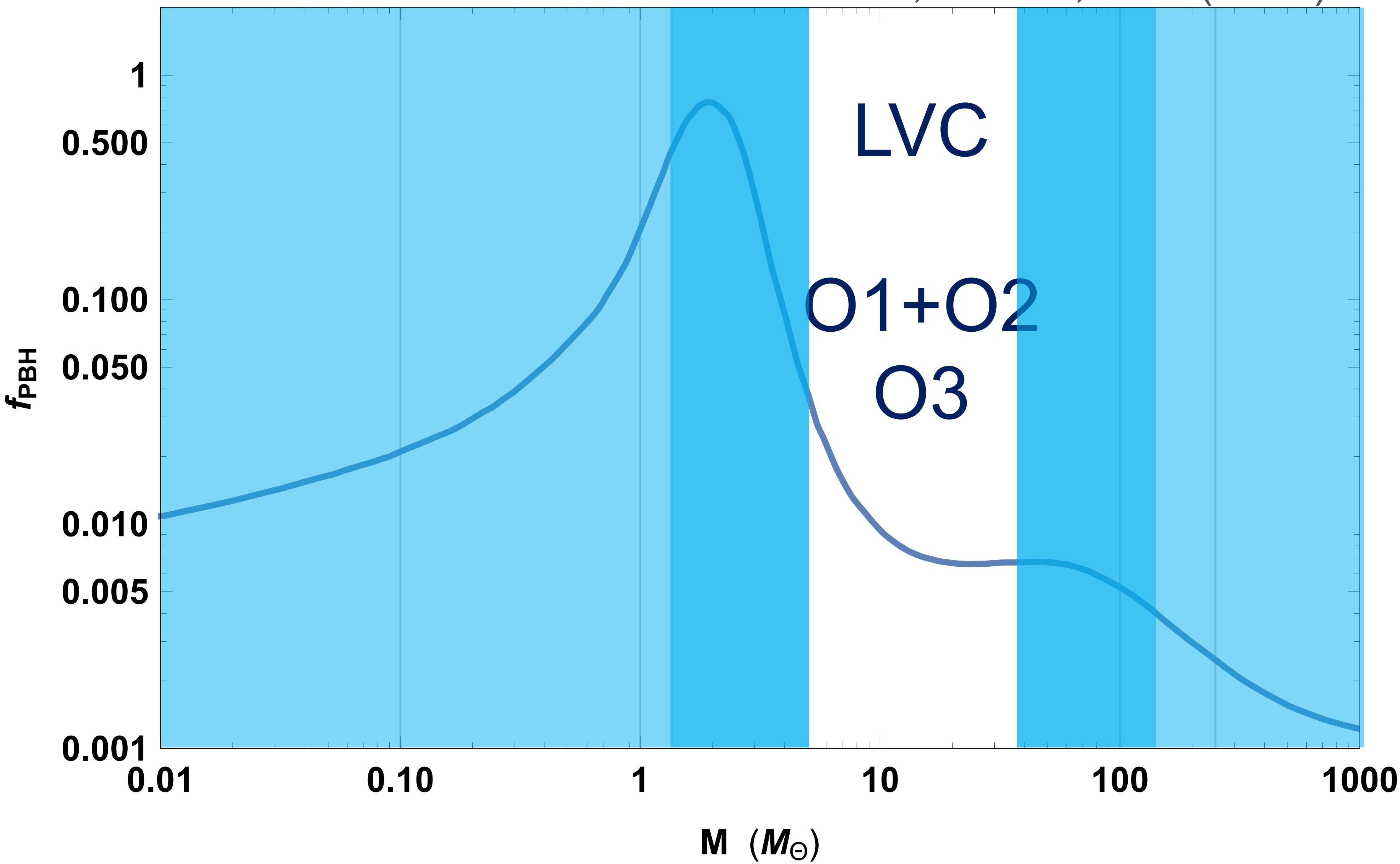
Carr, Clesse, JGB, Kühnel (2019)



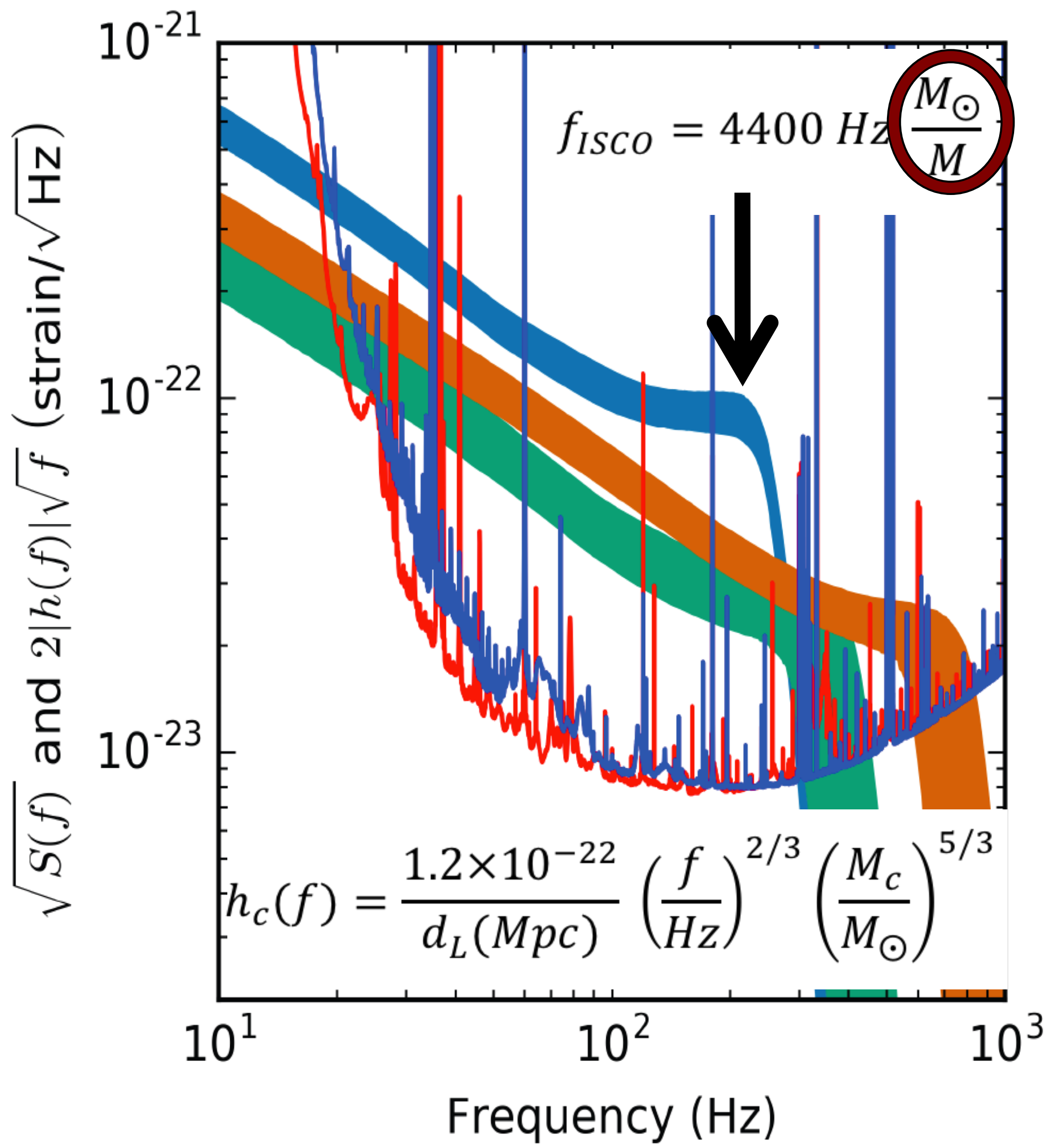
GW signatures of PBH as DM

Predictions for PBH mass spectrum

Carr, Clesse, JGB (2019)



LVC BBH events



Given the present rate O1-O2
R ~ 20-100 events/yr/Gpc^3
O3 has MANY more events.

LVC test BH mass distribution.

If LIGO detects a single BH with M < 1 Msun or M > 100 Msun it will necessarily be of primordial origin, not stellar.

Chirp mass

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

10 LVC BBH events (O1+O2)

LVC GWTC-1 (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

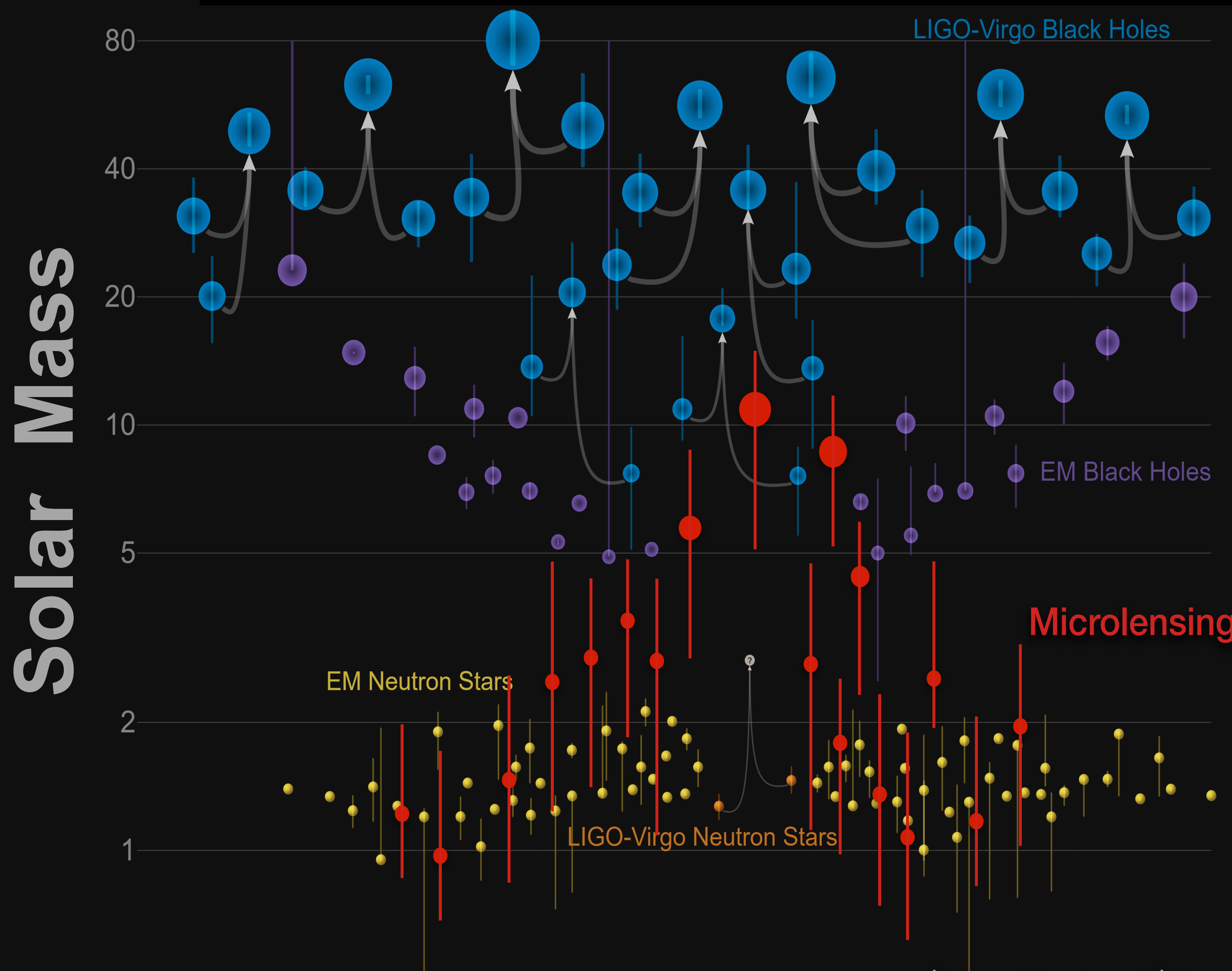
TABLE III. Selected source parameters of the eleven confident detections. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of two waveform models for BBHs. For GW170817 credible intervals and statistical errors are shown 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.

23 LVC BBH candidate events (O3)

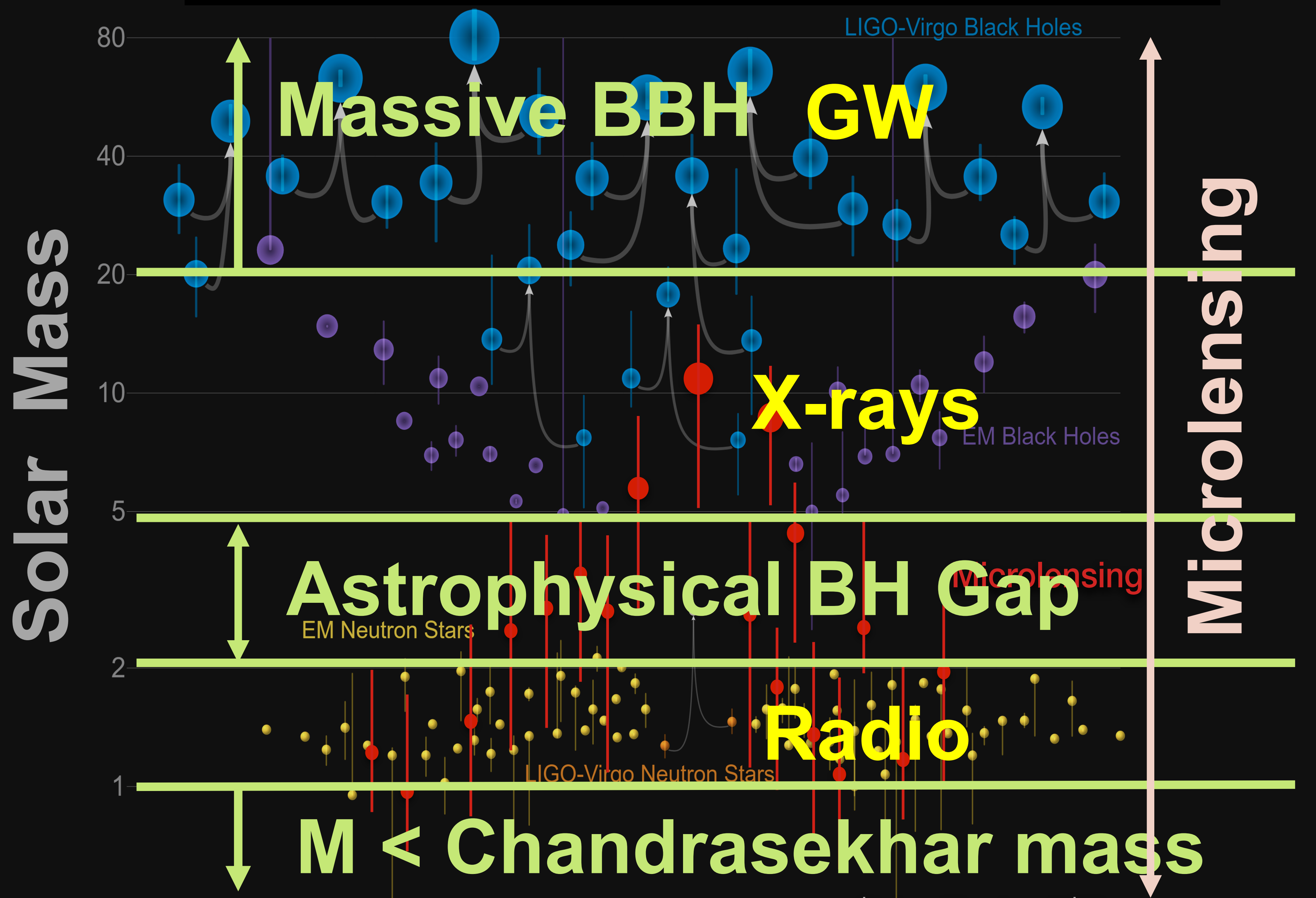
Latest — as of 3 September 2019 15:53:49 UTC

UID	Labels
S190901ap	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190829u	PE_READY ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190828l	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190828j	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190822c	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190816i	PE_READY ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190814bv	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190808ae	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190728q	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190727h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190720a	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190718y	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190707q	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190706ai	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190701ah	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190630ag	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190602aq	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190524q	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190518bb	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190513bm	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190512at	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190503bf	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT

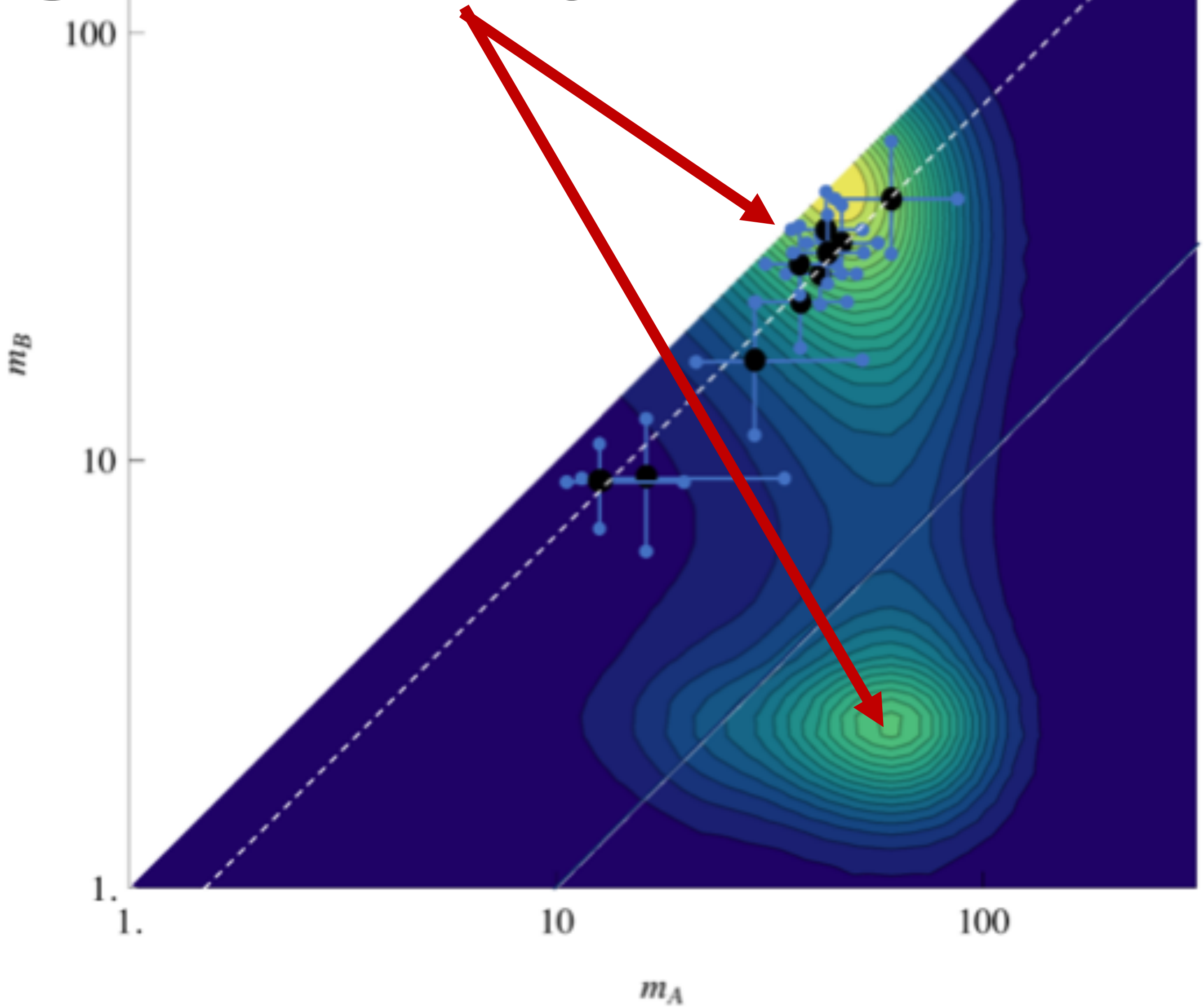
Black Holes and Neutron Stars



Black Holes and Neutron Stars

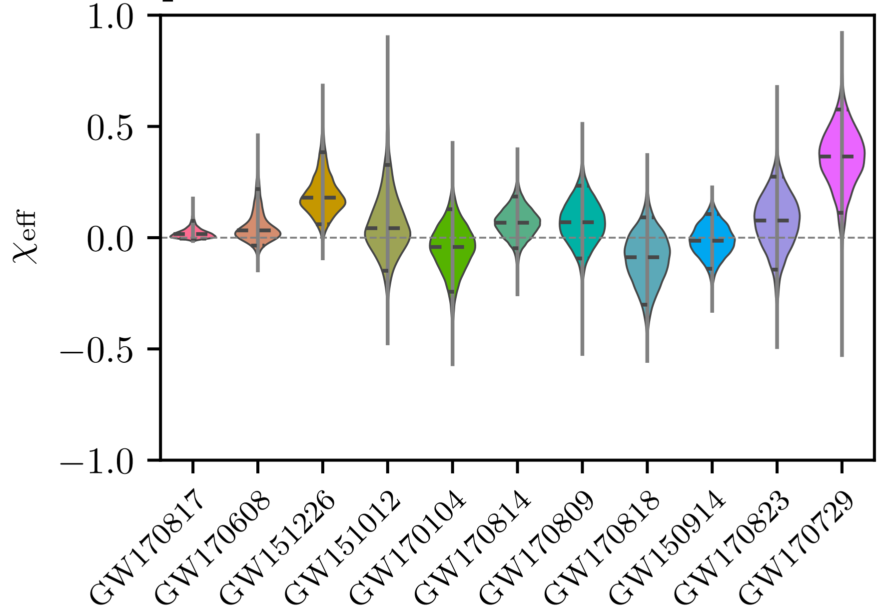


Rate of merger events @ LIGO-Virgo



Carr, Clesse, JGB, Kühnel (2019)

Spin distribution of GWTC-1 BBH

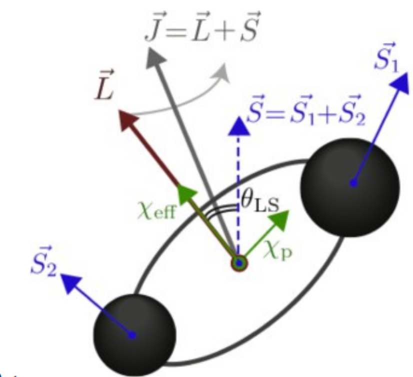


Effective aligned spin

LVC GWTC-1 (2018)

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

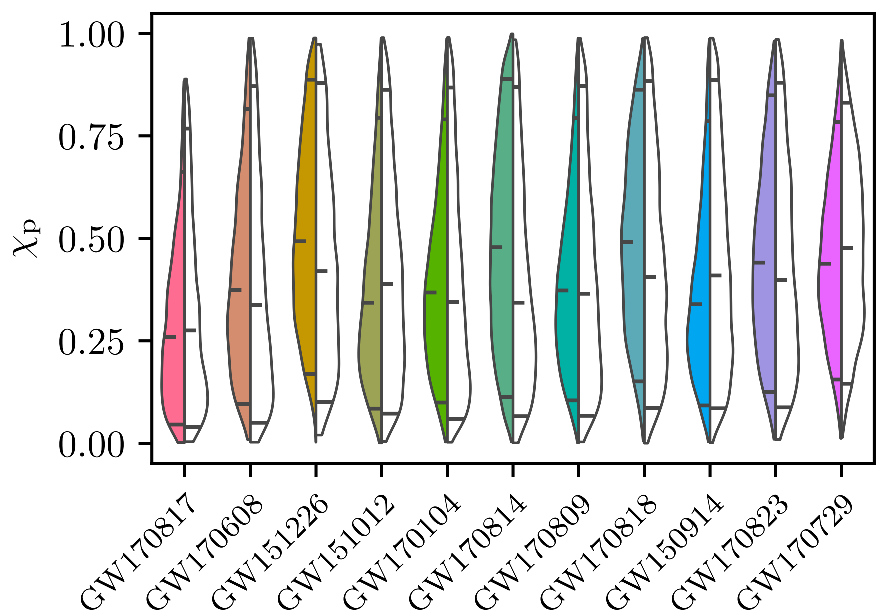
$$\chi_i \equiv \frac{\vec{S}_i \cdot \vec{L}}{m_i^2}$$



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

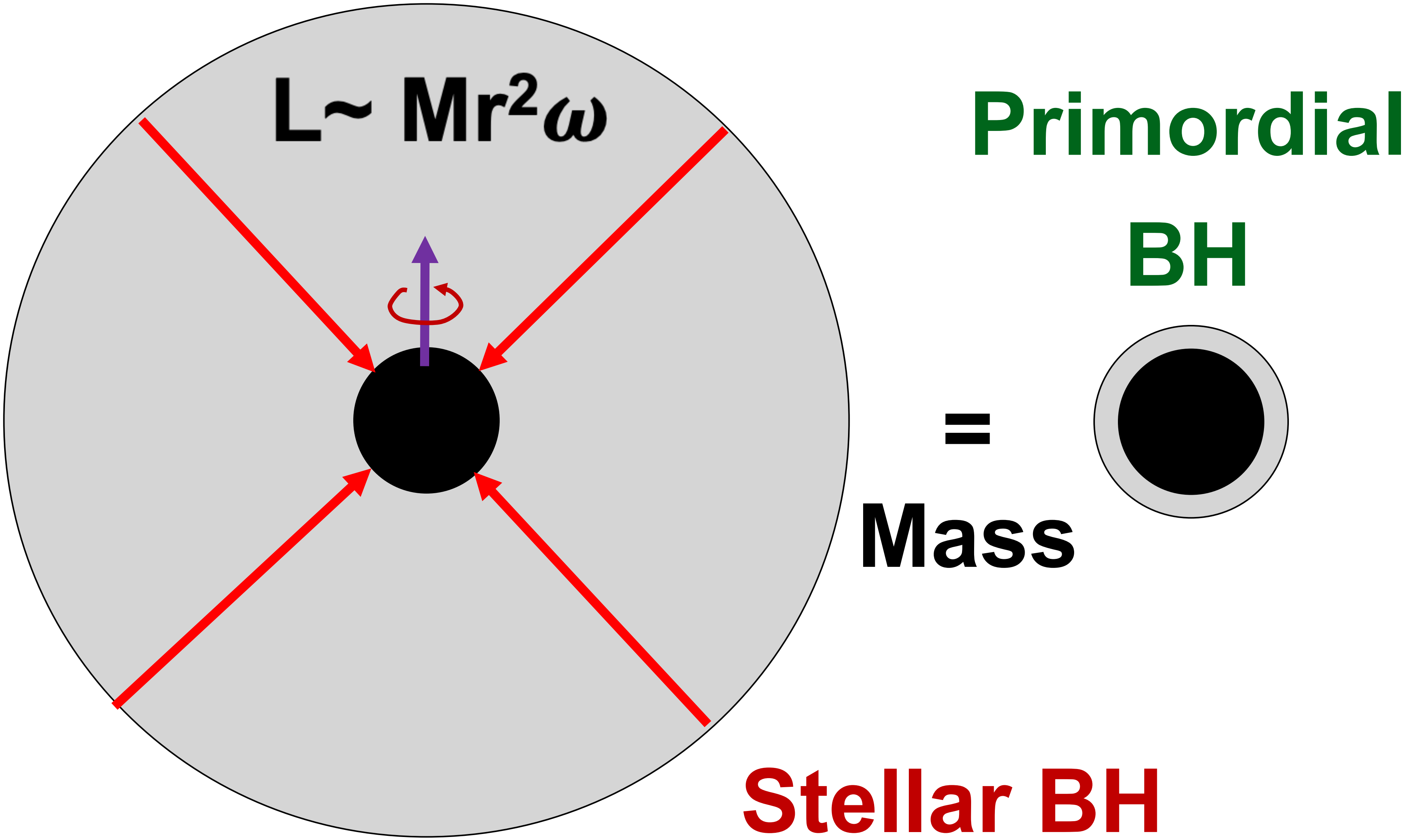
$$A_2 = 2 + 3m_1/2m_2$$

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



Effective precession spin

PBH are ~ spinless



Primordial Black Holes

- Could ALL advLIGO-Virgo events be PBH?
- Why do they have masses similar to stellar masses?
- If they were PBH, do they constitute ALL of the DM?
- Why is Omega_DM ~ Omega_B within factor 5?
- Why is   n_DM ~ 10^(-9) n_photon ?
- How do they modify galaxy formation?
- Can we distinguish their effect on LSS?
- Can we detect PBH with microlensing events?
- etc…

Origin of PBH mass

Chandrasekhar mass (Pauli exclusion pple)

$$M_{\rm Ch} = \frac{\omega}{\mu^2}\left(\frac{3\pi}{4}\right)^{1/2}\frac{M_{\rm P}^3}{m_{\rm p}^2} \simeq 1.4\, M_\odot \qquad \omega = 2.018$$

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

Mass within the horizon at QCD (causality)

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

$$x \equiv \frac{m_p}{T} \qquad T \sim \Lambda_{\rm QCD} \sim 200\,{\rm MeV}$$

LIGO range!

efficiency of collapse $\gamma \sim 0.2$

Hot Spot Electroweak Baryogenesis

Matter-radiation equality

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

$$\eta = \frac{n_{\rm B}}{n_\gamma} \simeq 6\times 10^{-10} \qquad T = T_0(1+z) \;\Rightarrow\; x = \frac{4\times 10^{12}}{1+z}$$

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

Fraction domains @ PBH formation

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

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

Is this a hint of a common origin?

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

Our scenario

JGB, Carr, Clesse (2019)

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: $\not{B}$, $\not{C}$, $\not{CP}$, non-equil.

$\not{CP}$ in the SM (CKM matrix)

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

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

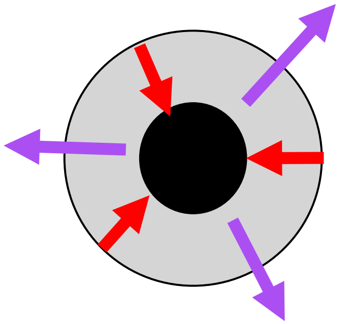
$$K = \mathrm{Im}\, V_{ii} V_{jj} V_{ij}^* V_{ji}^* = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin\delta = (3.06 \pm 0.2) \times 10^{-5}\,.$$

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

Electroweak baryogenesis @ QCD

Out-of-equilibrium gravitational collapse

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



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

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

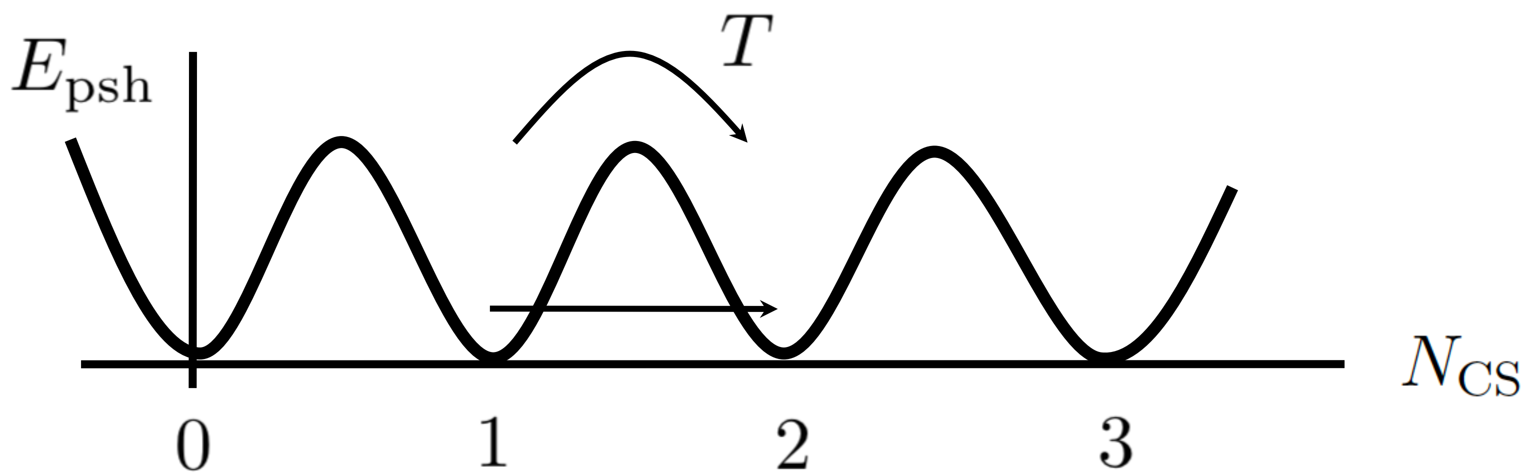
$$E_0 = \frac{\Delta K}{n_p\, \Delta V} \simeq \frac{1-\gamma}{\gamma^2(1-\gamma^3)} \frac{M_{\rm PBH}}{N_p} \simeq 10\; g_*(x)^{3/2}\, x^{-5/2}\, e^{x}\, {\rm GeV}$$

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

Electroweak baryogenesis @ QCD

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

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



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

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.

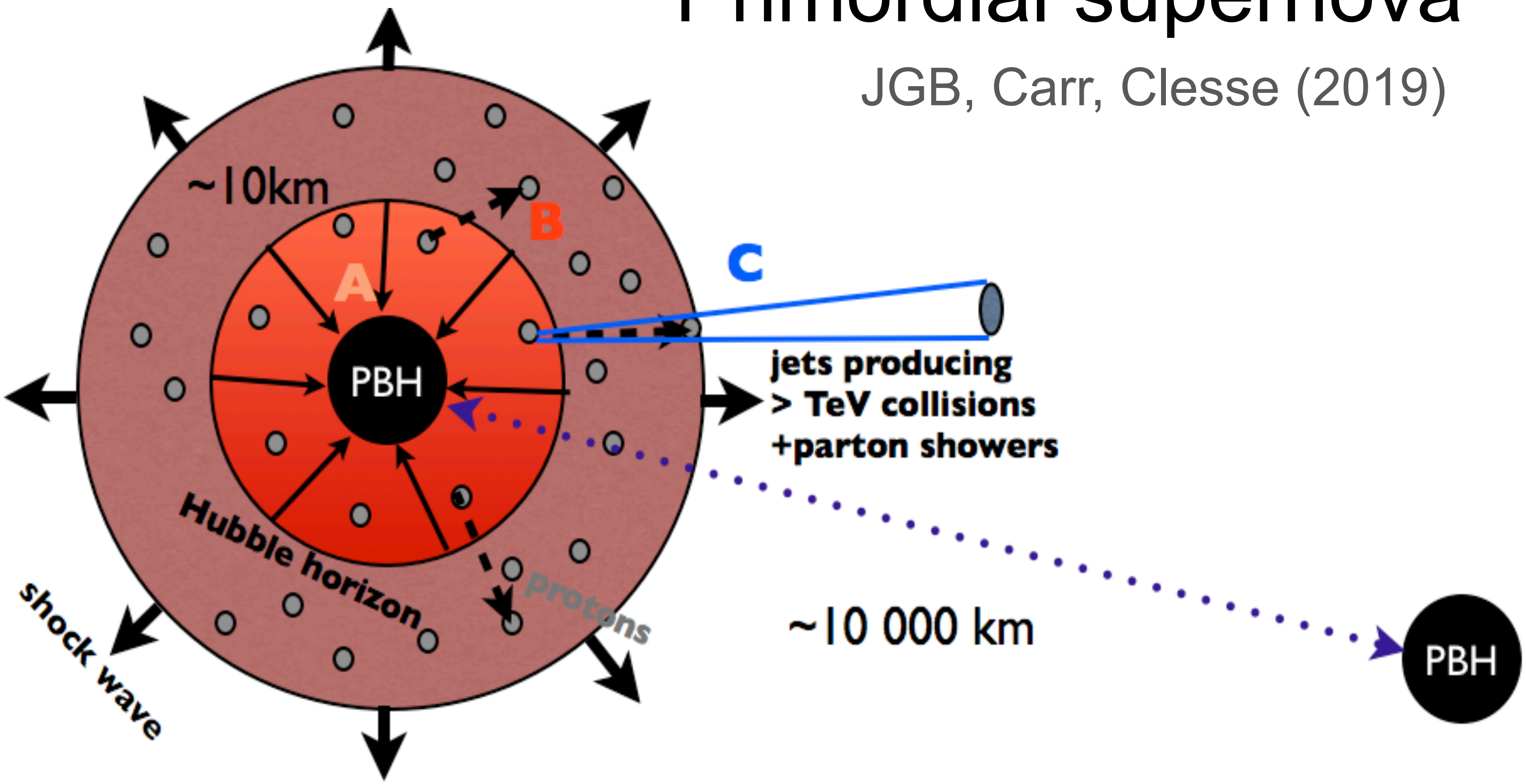
$$\text{For} \quad x \gtrsim 5 \;\Rightarrow\; n_{\rm B} \sim n_\gamma \;\Rightarrow\; \eta^{\rm local} \sim 1$$

hot spots = Hubble domains that gravitational collapse to PBH

Electroweak baryogenesis @ QCD

“Primordial supernova”

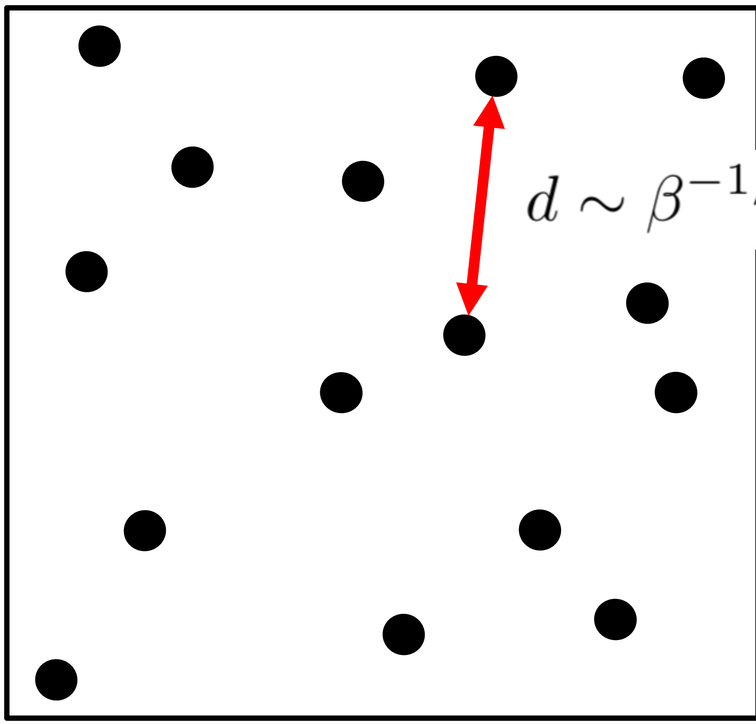
JGB, Carr, Clesse (2019)



Electroweak baryogenesis @ QCD

Baryons irradiate to the rest of the universe

JGB, Carr, Clesse (2019)

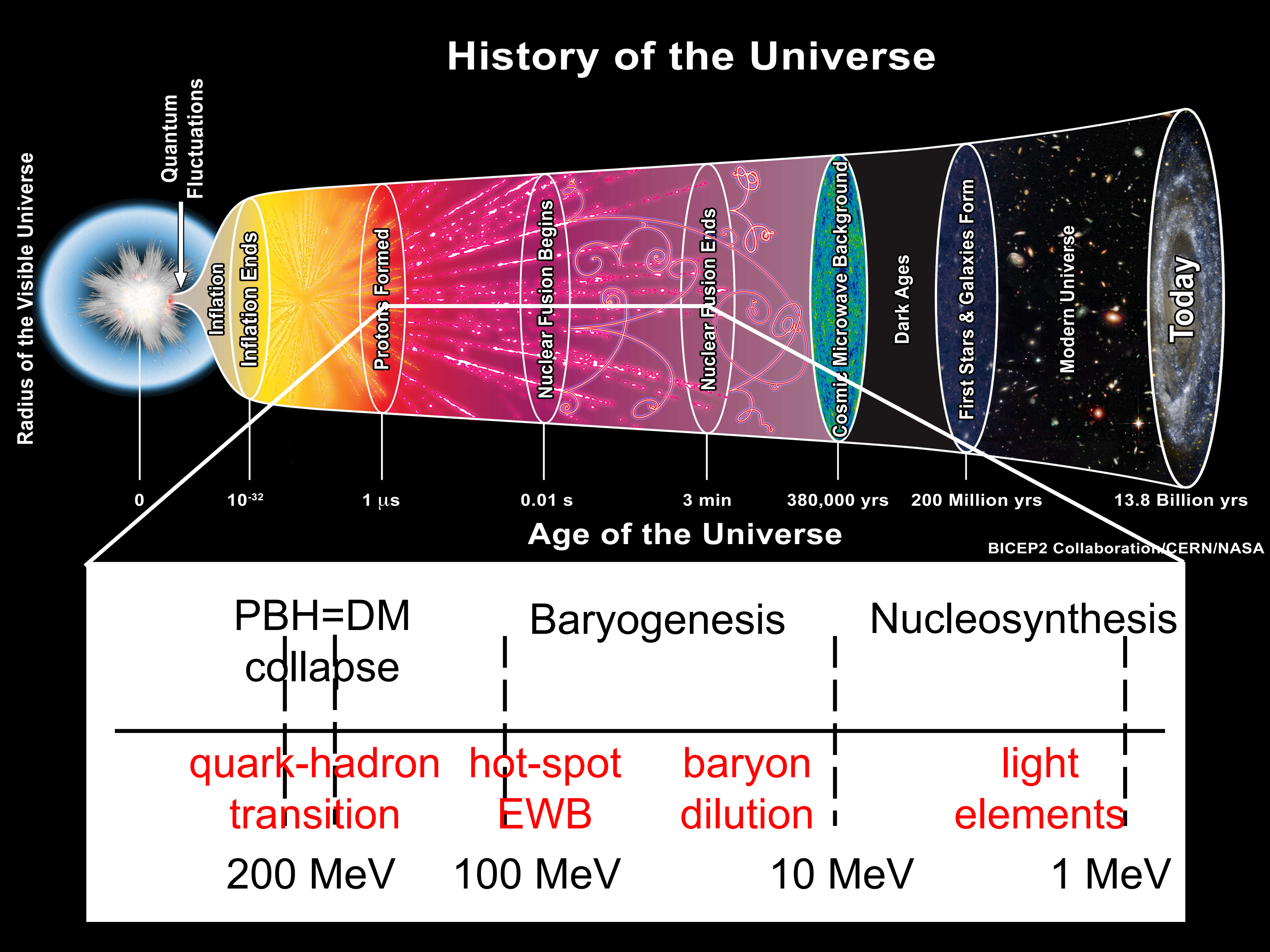


$$d \sim \beta^{-1/3}\, d_H(t_{\rm QCD}) \sim 10^{-2} \text{ light seconds}$$

at the speed of light

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

baryons radiate away from hot spot until they uniformly distribute the original BAU to the rest of the universe well before BB Nucleosynthesis ($t_{\rm BBN} \sim 1 - 180$ s)



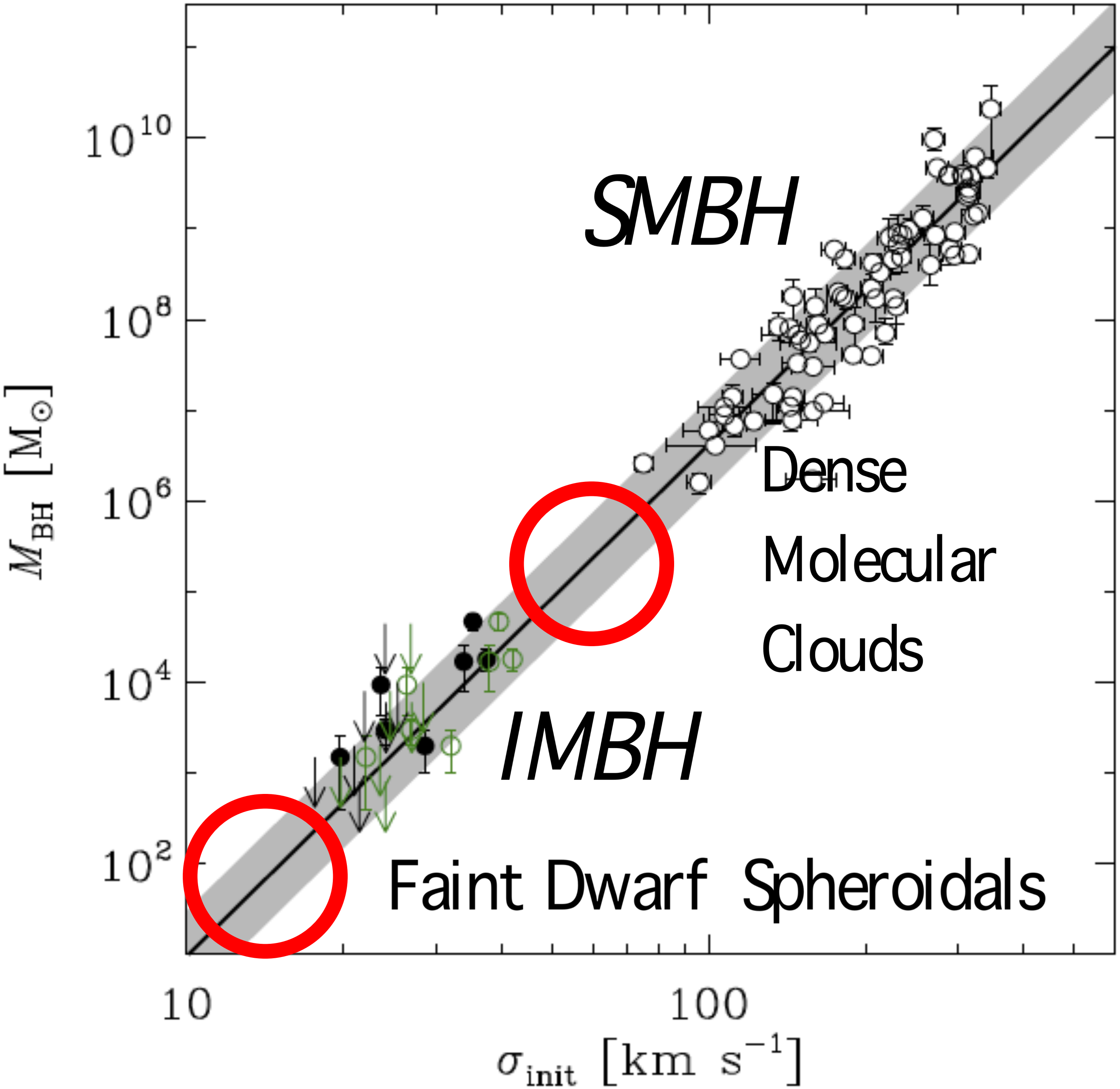
History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10^-32
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs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

Early Galaxy Formation

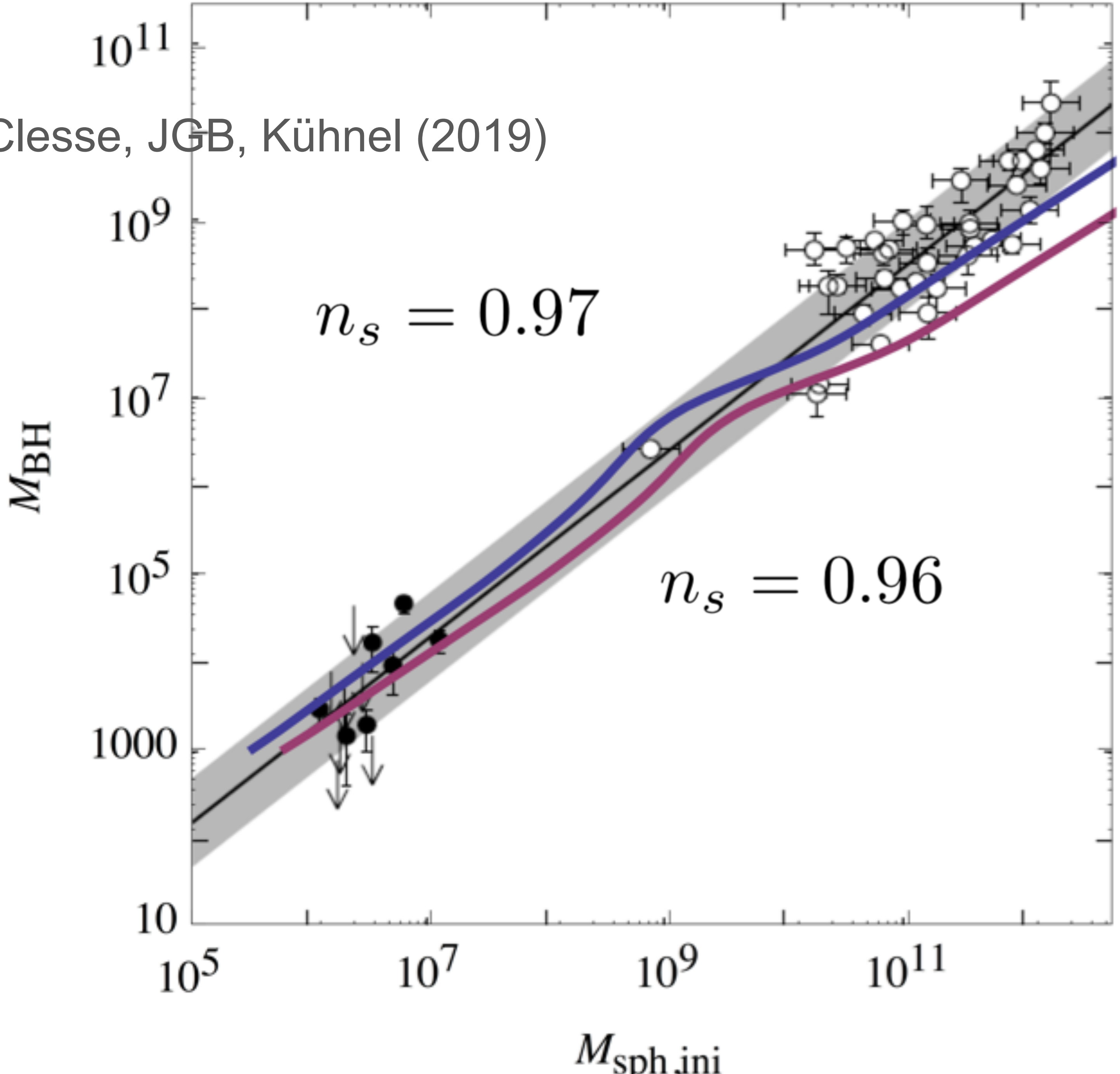
Massive PBH = seeds of structure

- Massive primordial black holes with $10^{-2}\ M_{\odot} < M_{PBH} < 10^{2}\ M_{\odot}$, which cluster and merge and could resolve some of the most acute problems of ΛCDM paradigm.
- ΛCDM N-body simulations never reach the 100 $M_{\odot}$ particle resolution, so for them PBH is as good as PDM.
- PBH DM paradigm naturally incorporates all properties of collisionless CDM scenario on large scales but differs on small scales.

Kruijssen et al. (2013)

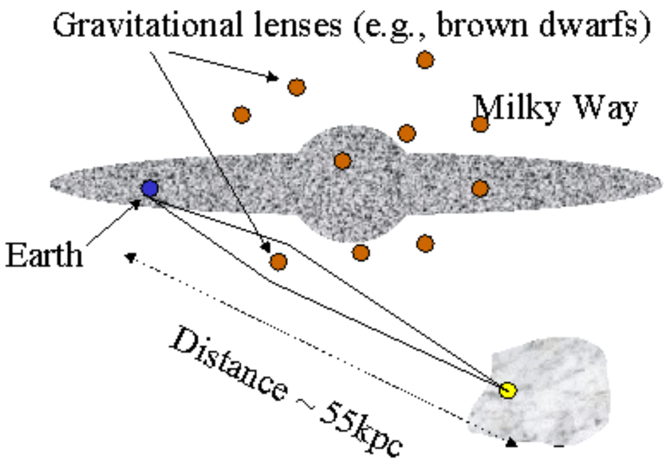


Carr, Clesse, JGB, Kühnel (2019)



Long duration microlensing events EROS, OGLE

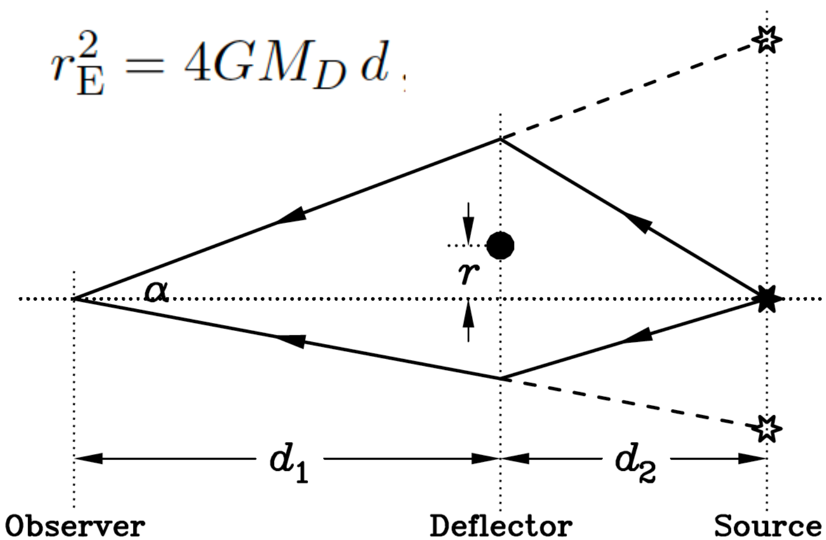
Microlensing



$$A = \frac{2+u^2}{u\sqrt{4+u^2}} \qquad u = \frac{r}{r_E}$$ amplification

$$\overline{Dt} = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v}$$ average $\frac{1}{2}$ crossing

$$r_E^2 = 4GM_D\, d$$



$$d = \frac{d_1 d_2}{d_1 + d_2}$$

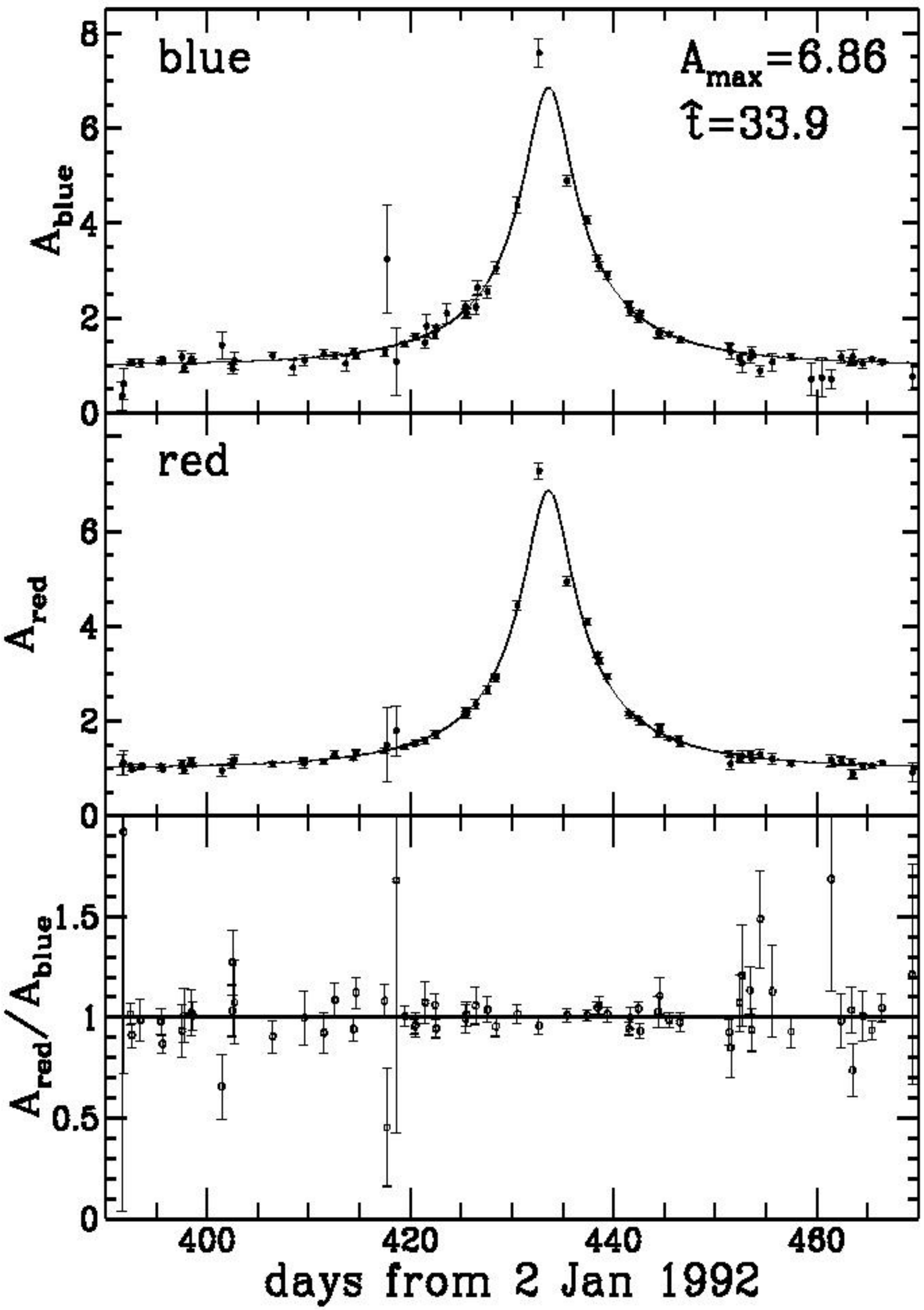
$M_D = 100\,M_\odot$ => $\overline{Dt} = 4$ years

$M_D = 10\,M_\odot$ => $\overline{Dt} = 1.23$ years

$M_D = 1\,M_\odot$ => $\overline{Dt} = 5$ months

$M_D = 0.1\,M_\odot$ => $\overline{Dt} = 1.5$ months

$M_D = 0.01\,M_\odot$ => $\overline{Dt} = 2$ weeks



Alcock et al. (2005)

symmetric

$$A_{max} = 7.20 \pm 0.09$$

achromatic

$$\frac{A_{red}}{A_{blue}} = 1.00 \pm 0.05$$

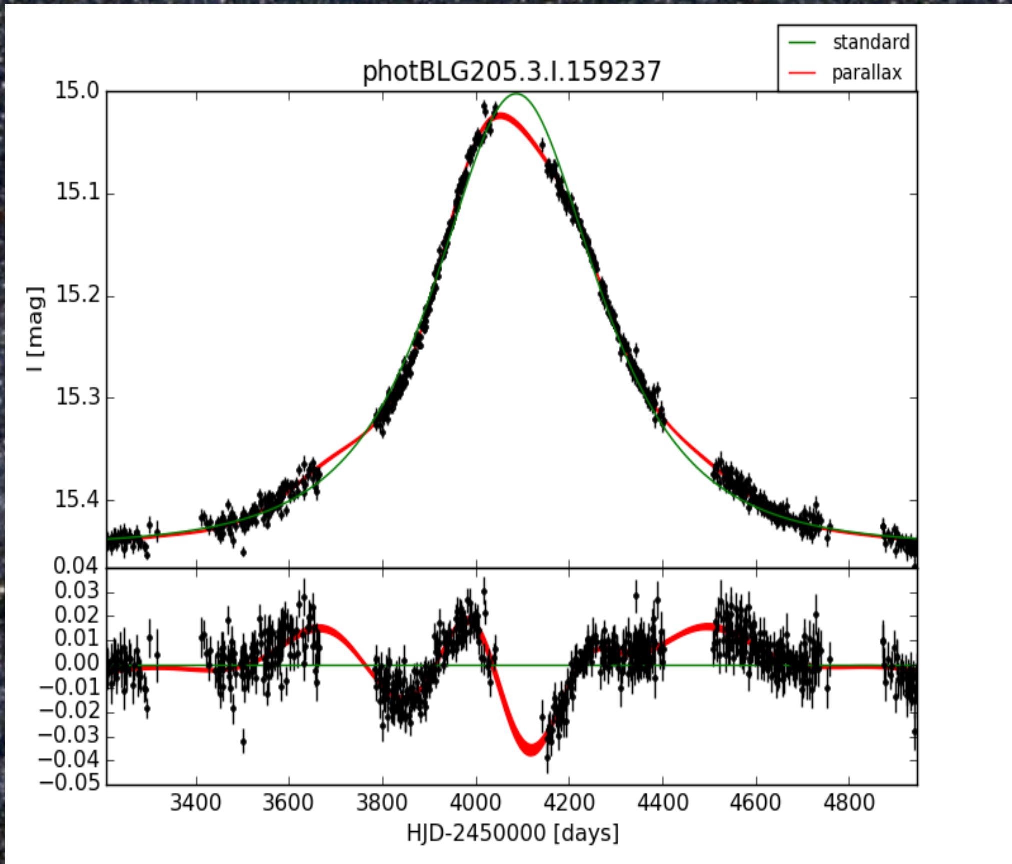
unique

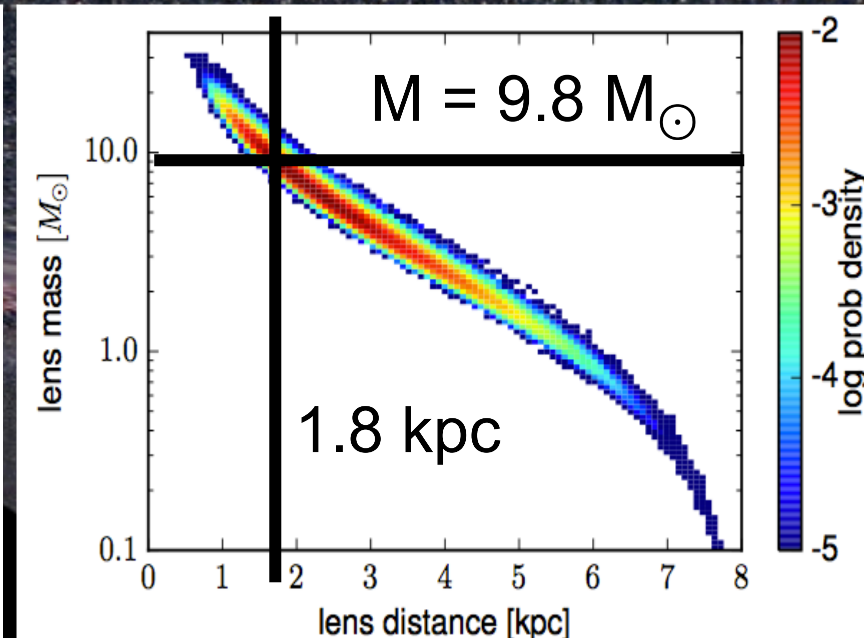
$$t = 34.8 \pm 0.2 \, \text{days}$$

$$M_D = 0.1\, M_{\odot}$$

OGLE3-UL-PAR-02 - candidate BH

Wyrzykowski (2016)





OGLE photometry
from 2001-2008
and microlensing model

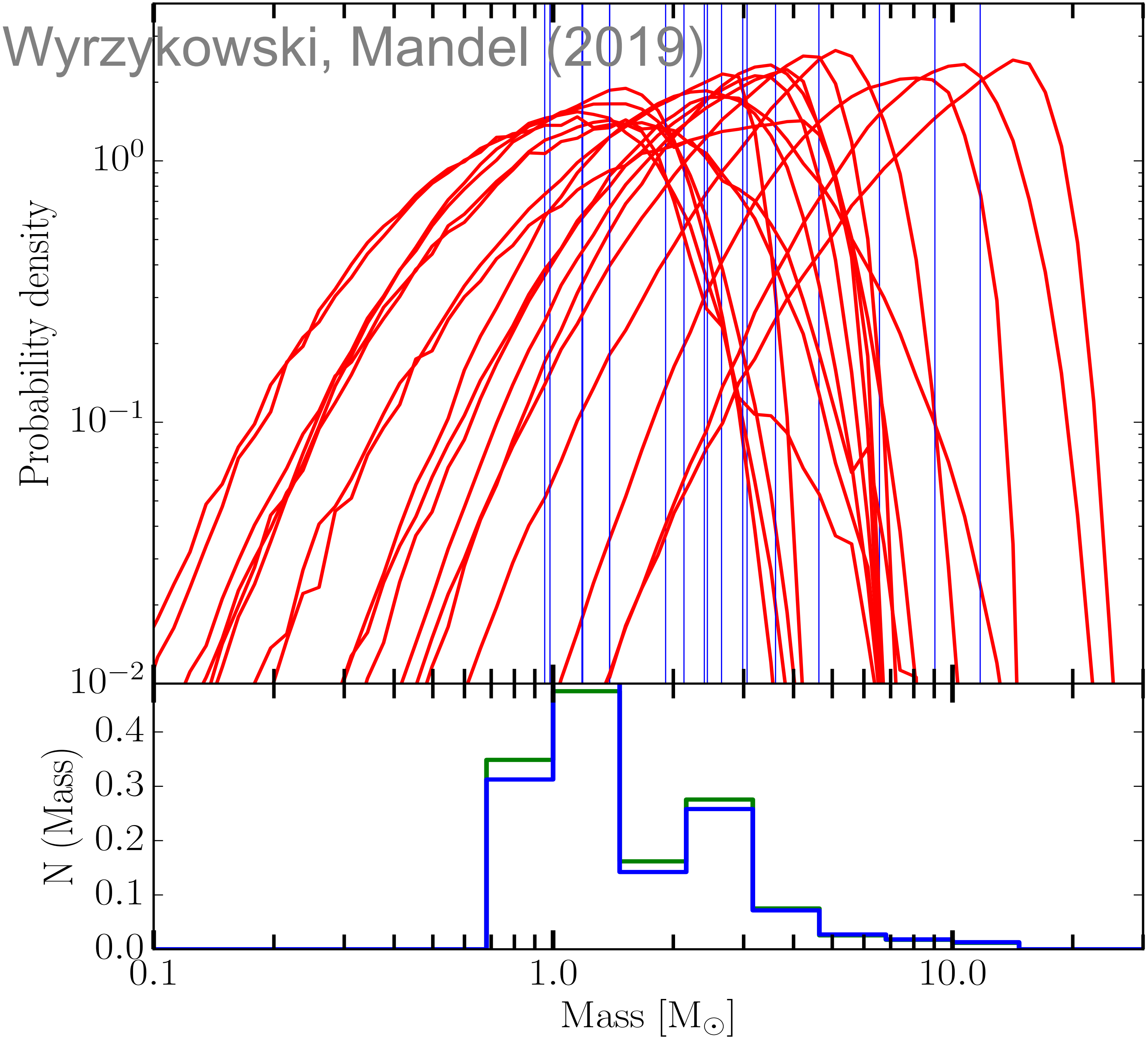
Mass, Distance (degenerated estimate)

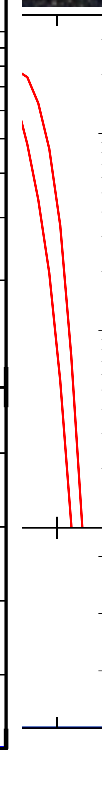
• usin

• only

• new

Wyrzykowski, Mandel (2019)

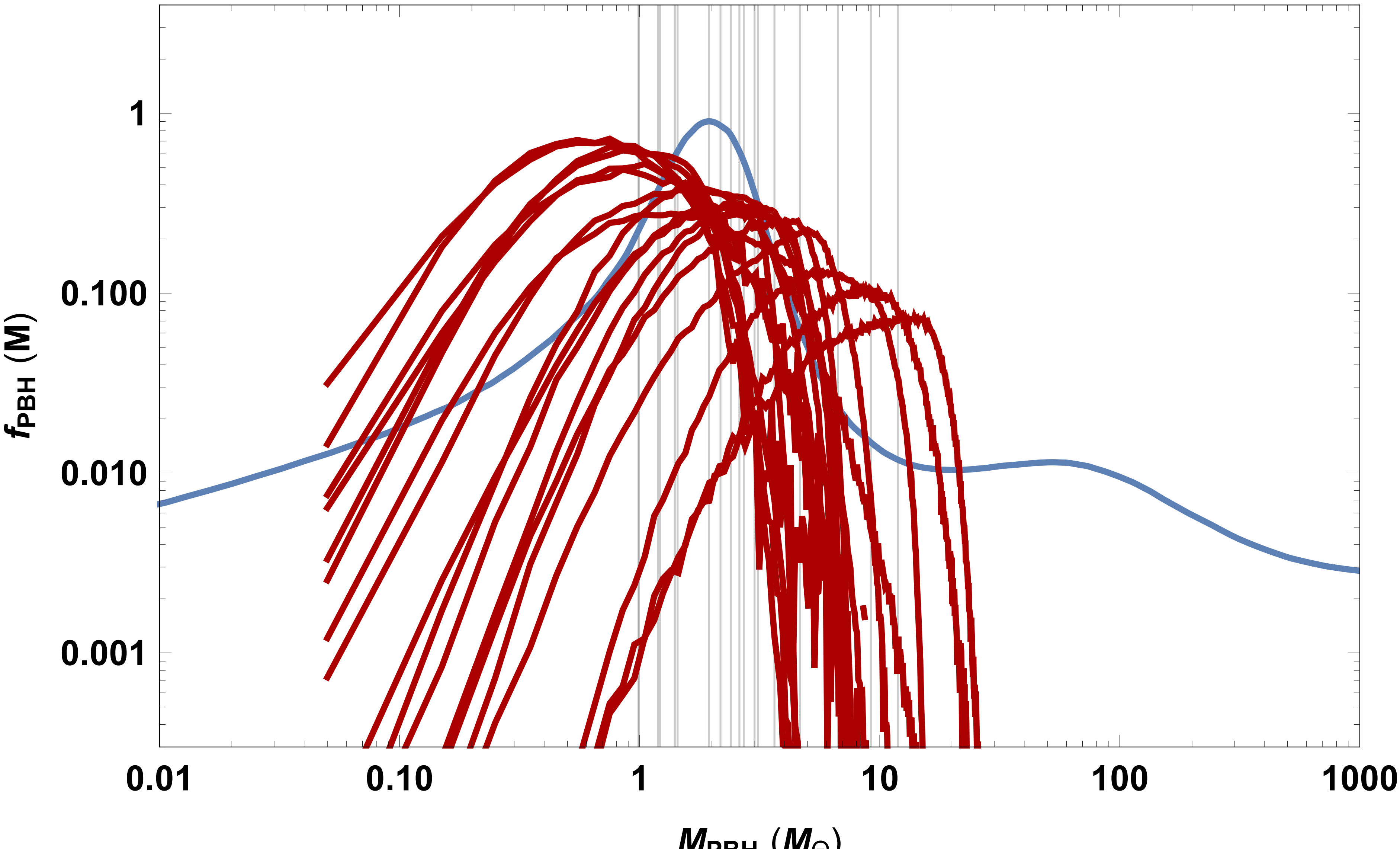




Wyrz

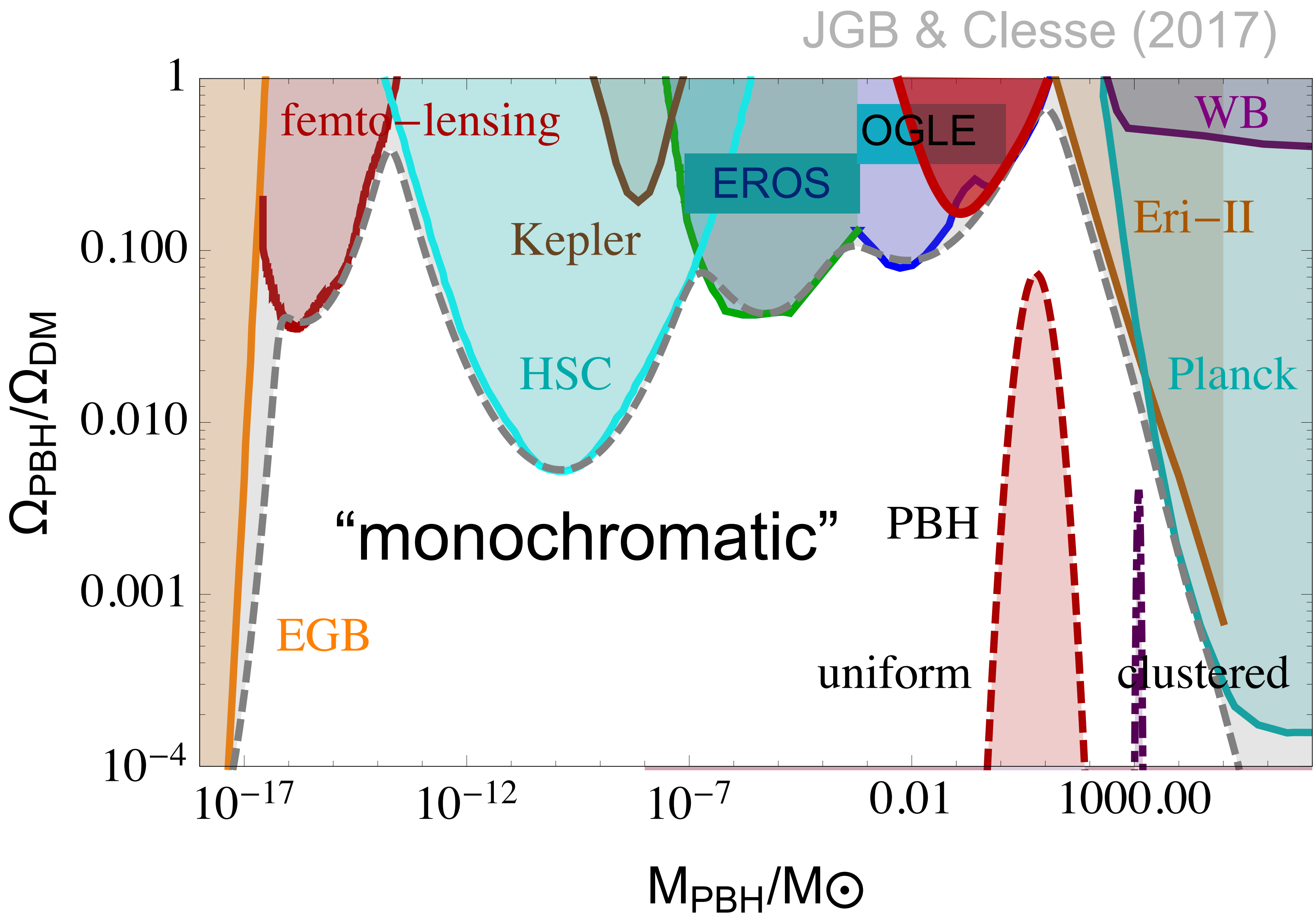
z Wyrzykowski

Wyrzykowski, Mandel (2019)

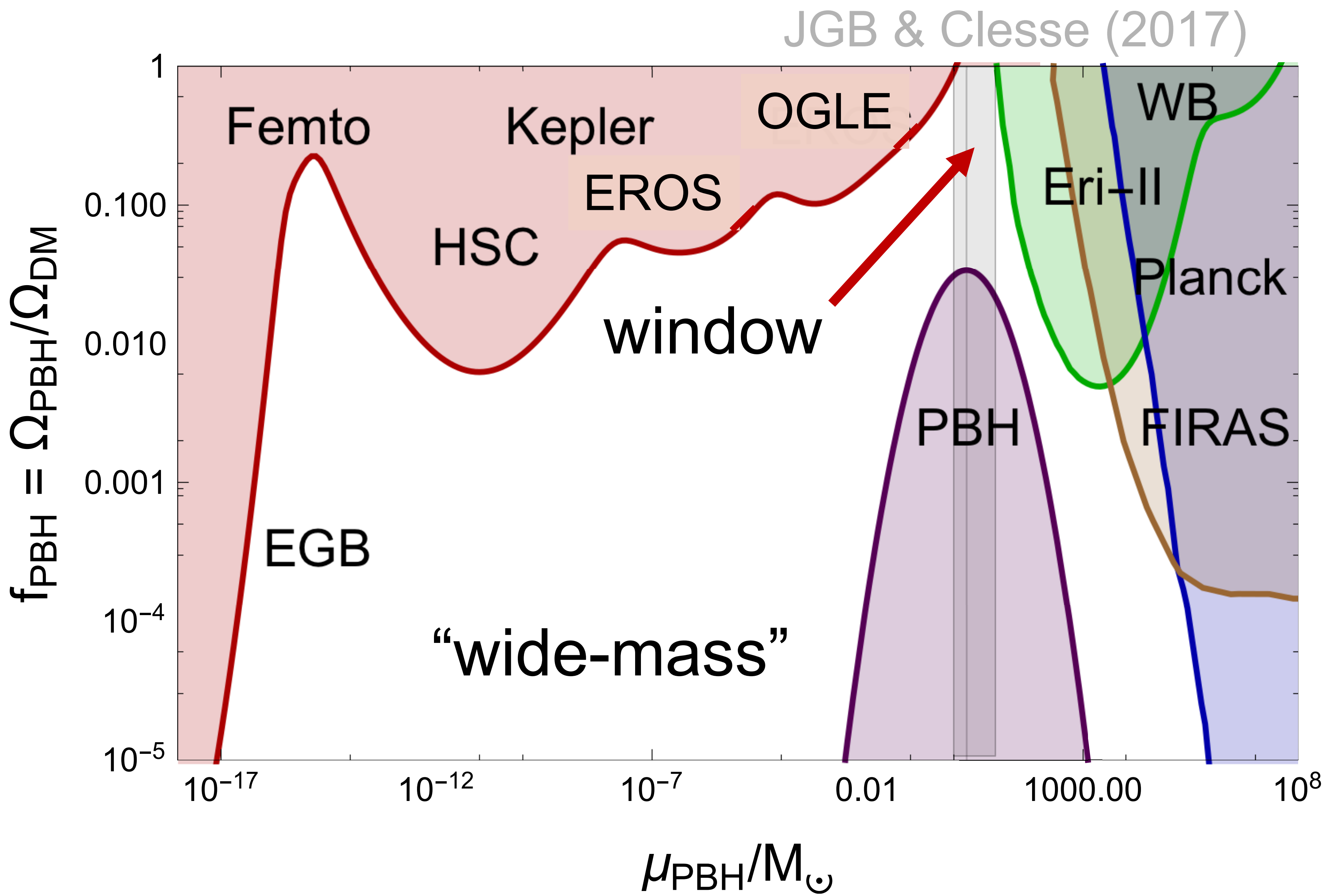


Summary Constraints on PBH

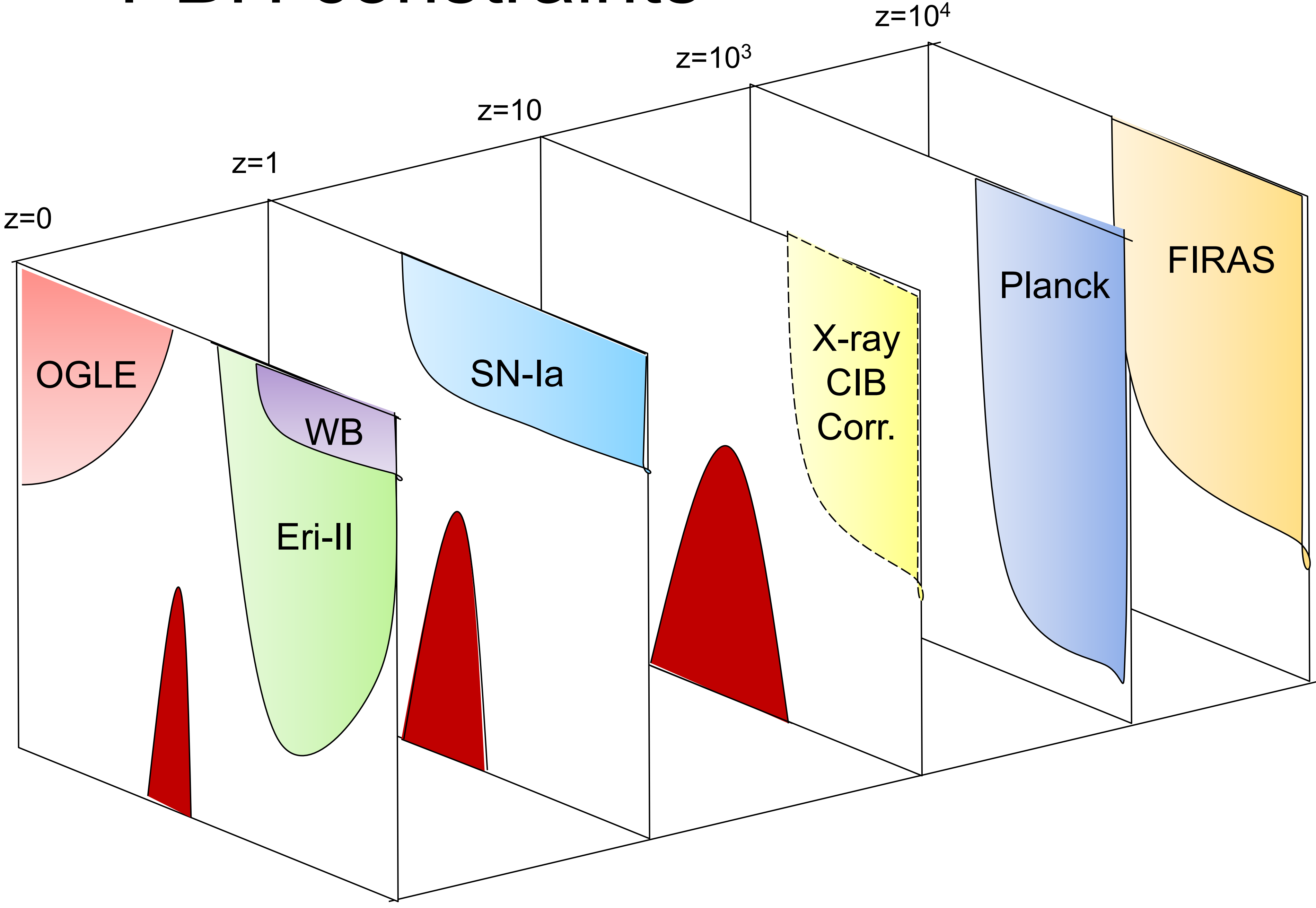
PBH constraints



PBH constraints



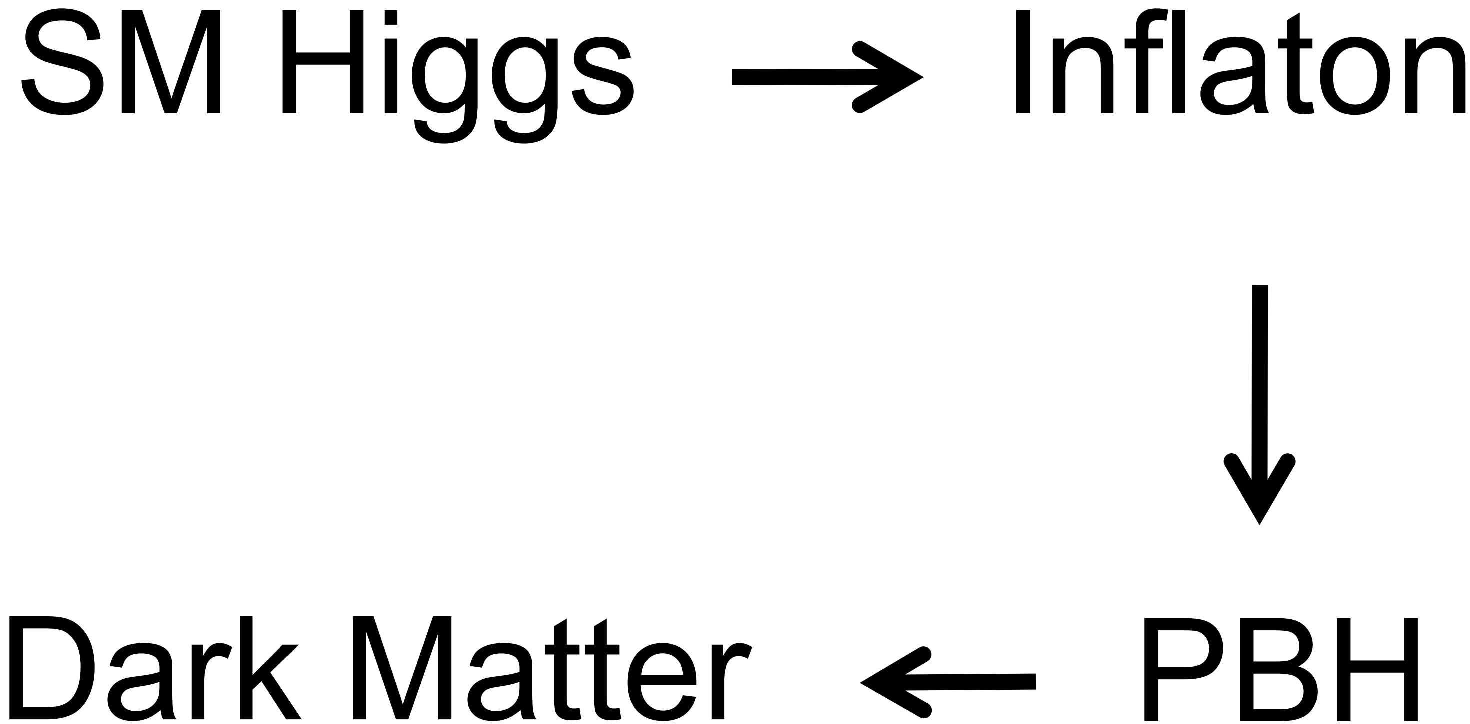
PBH constraints



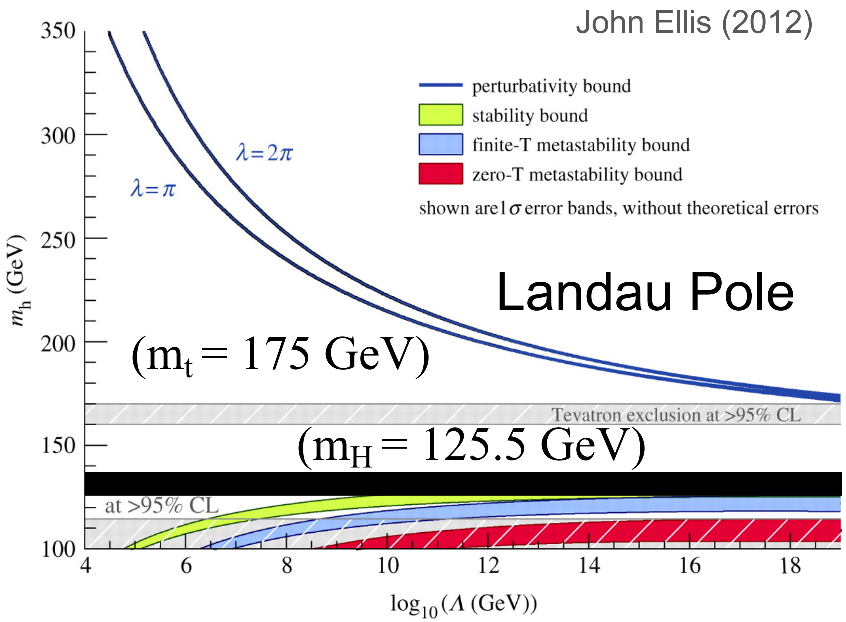
Conclusions

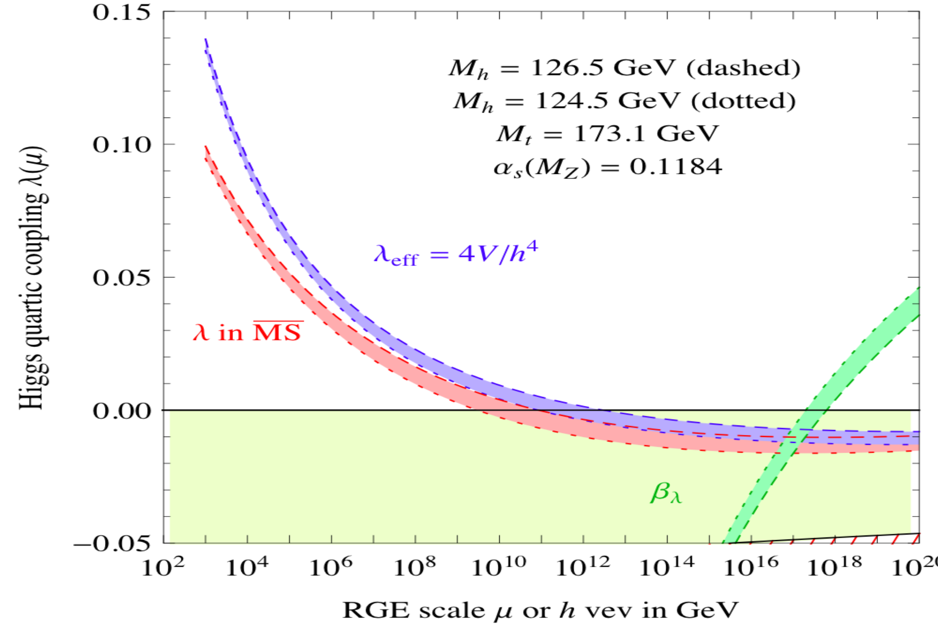
- SM physics can explain both DM and BAU.
- Smallness of BAU is due to the small number of Hubble domains that collapse to form PBH.
- The quark-hadron QCD transition triggers the collapse of PBH and BAU via "Hot spot" EWB.
- Dark matter density in the form of PBH is then of the same order as Baryon 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.

Critical Higgs Inflation


SM Higgs
Inflaton
PBH
Dark Matter

John Ellis (2012)





Ezquiaga, JGB, Ruiz Morales (2017)

$$S=\int d^4x\sqrt{g}\left[\left(\frac{1}{2\kappa^2}+\frac{\xi(\phi)}{2}\phi^2\right)R-\frac{1}{2}(\partial\phi)^2-\frac{1}{4}\lambda(\phi)\phi^4\right]$$

$$\lambda(\phi) \;=\; \lambda_0 + b_\lambda \ln^2(\phi/\mu)\ ,$$

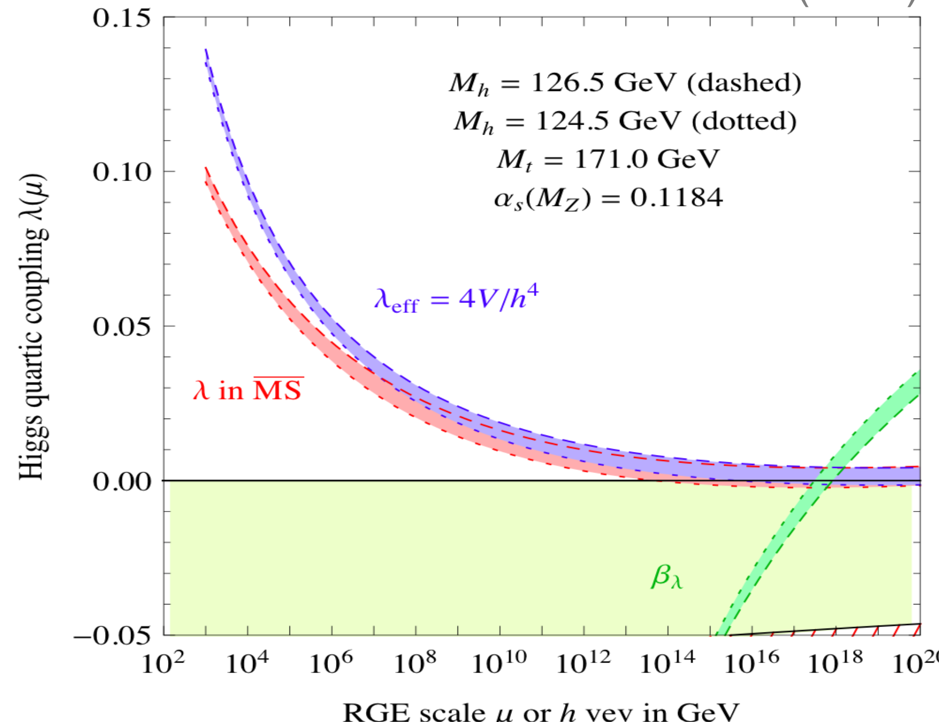
$$\xi(\phi) \;=\; \xi_0 + b_\xi \ln(\phi/\mu)\ ,$$

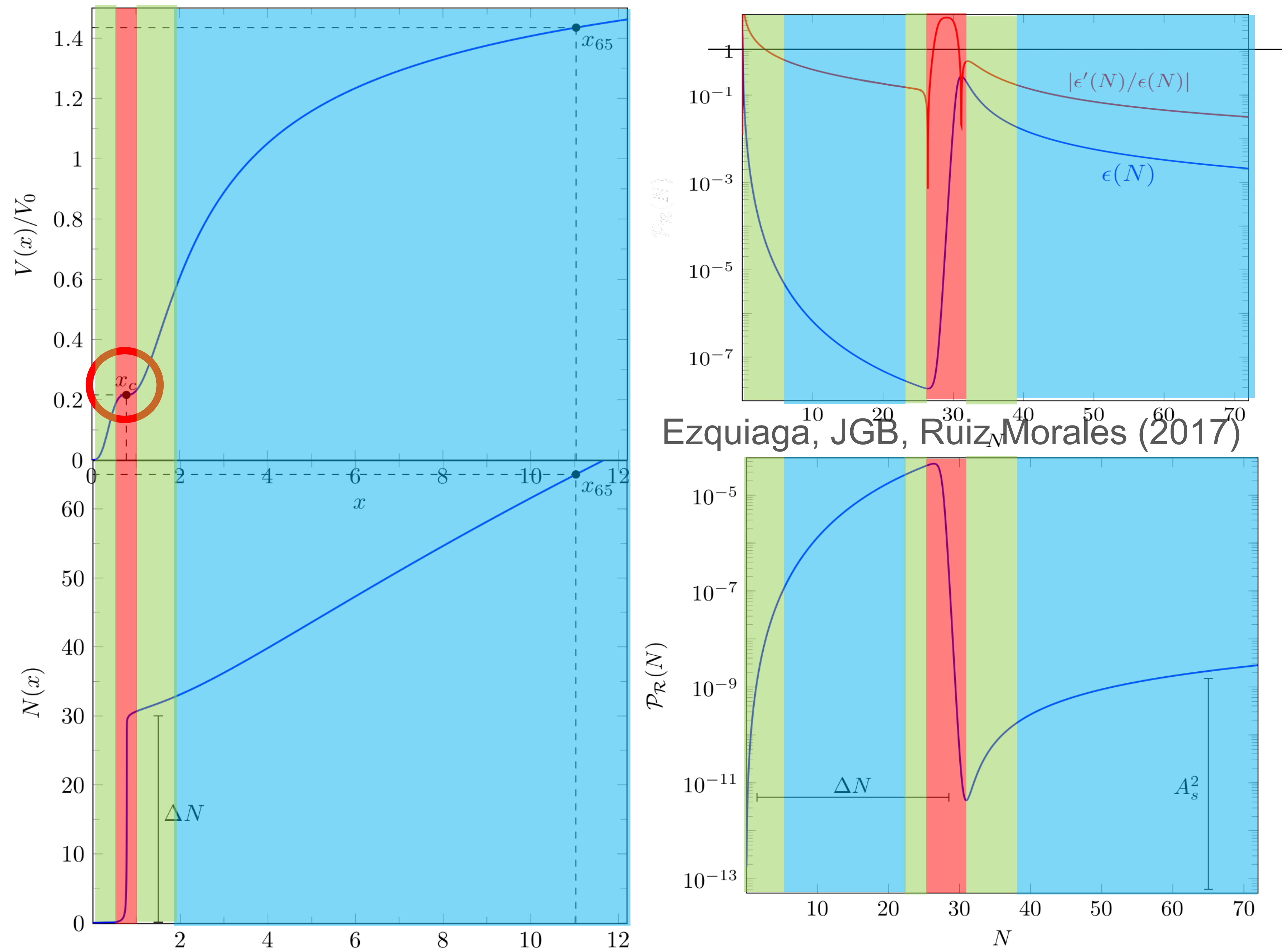
$$\frac{d\varphi}{d\phi}=\frac{\sqrt{1+\xi(\phi)\,\phi^2+6\,\phi^2\,(\xi(\phi)+\phi\,\xi'(\phi)/2)^2}}{1+\xi(\phi)\,\phi^2}$$

$$V(x)=\frac{V_0\,(1+a\,\ln^2 x)\,x^4}{(1+c\,(1+b\,\ln x)\,x^2)^2} \qquad x\,=\,\phi/\mu$$

$V_0=\lambda_0\mu^4/4,\ a=b_\lambda/\lambda_0,\ b=b_\xi/\xi_0$ and $c=\xi_0\,\kappa^2\mu^2$

Buttazzo et al (2014)





Ezquiaga, JGB, Ruiz Morales (2017)

Primordial Spectrum PBH

JGB, Ruiz Morales (2017)