Searching for Primordial Black Holes with Gravitational Waves

Iberian GW Meeting, Braga, 8th June 2022

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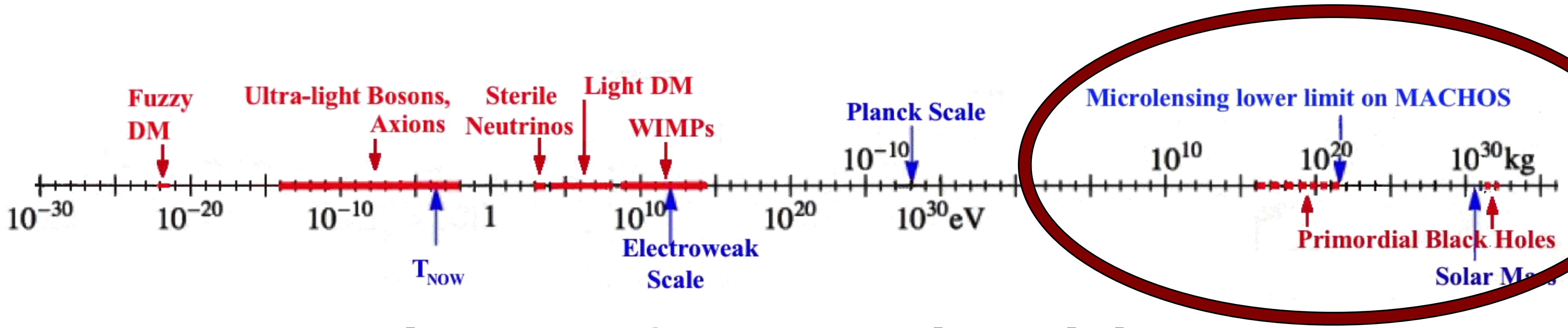
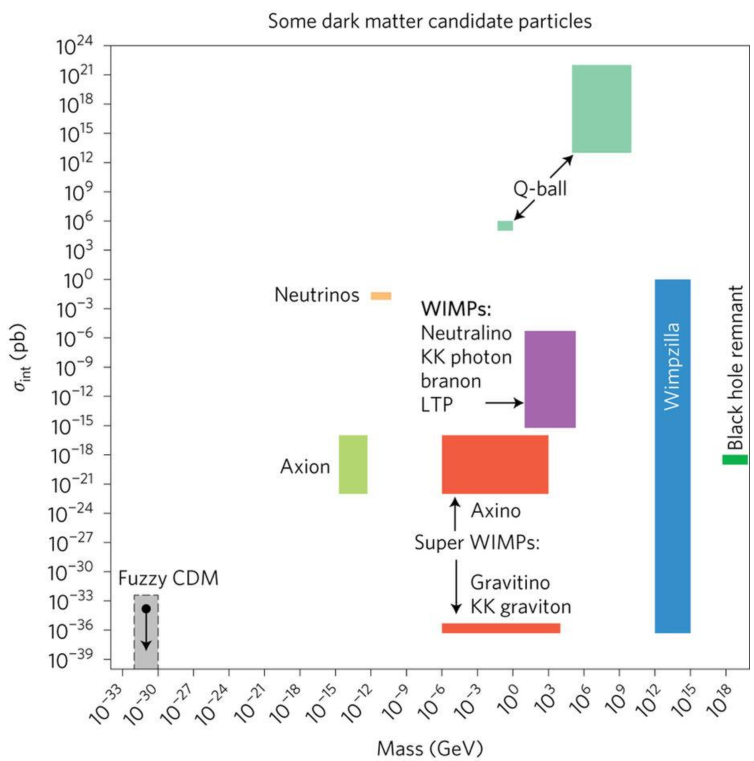
IFT-UAM/CSIC Madrid

What is Dark Matter?

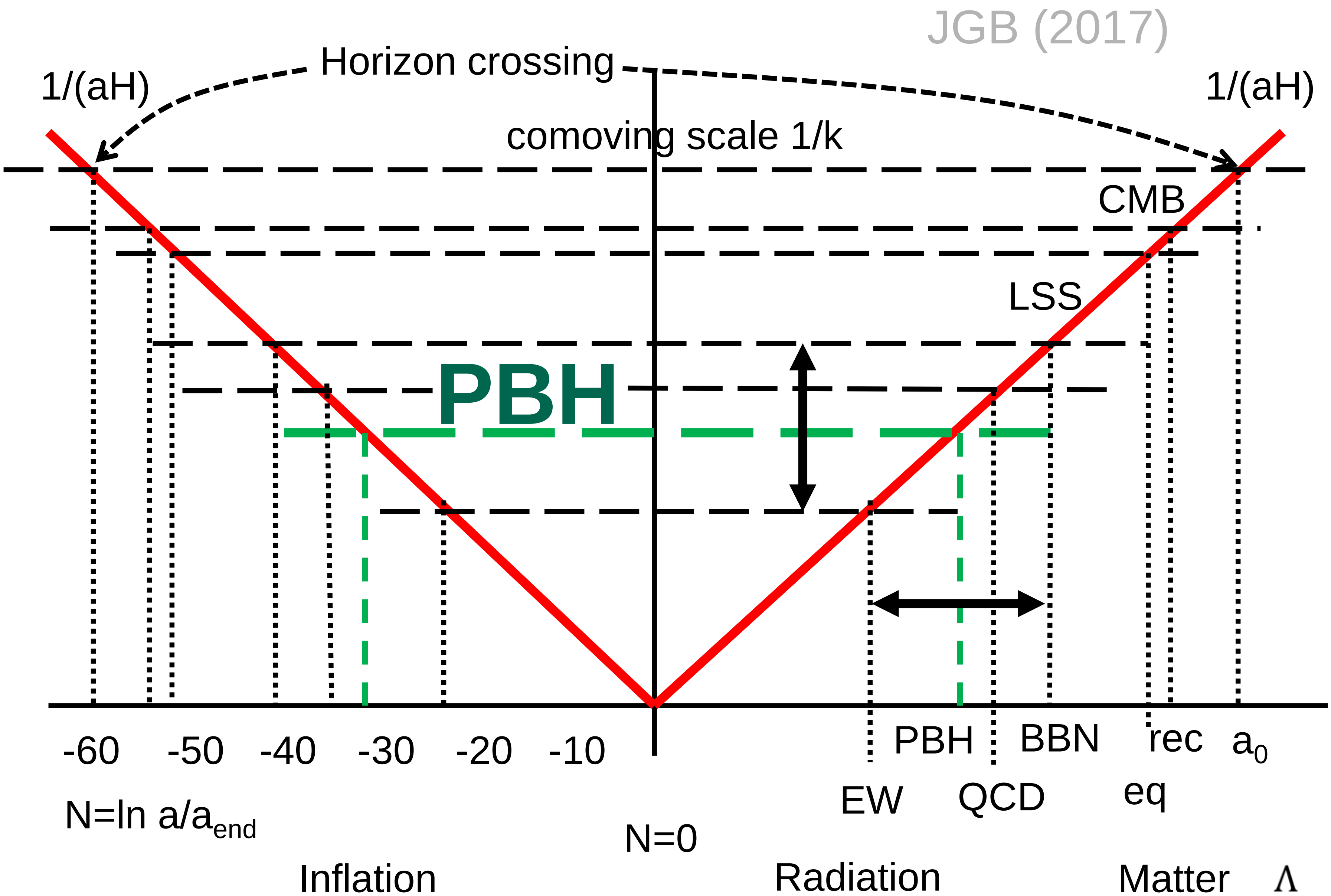


90 orders of magnitud in mass

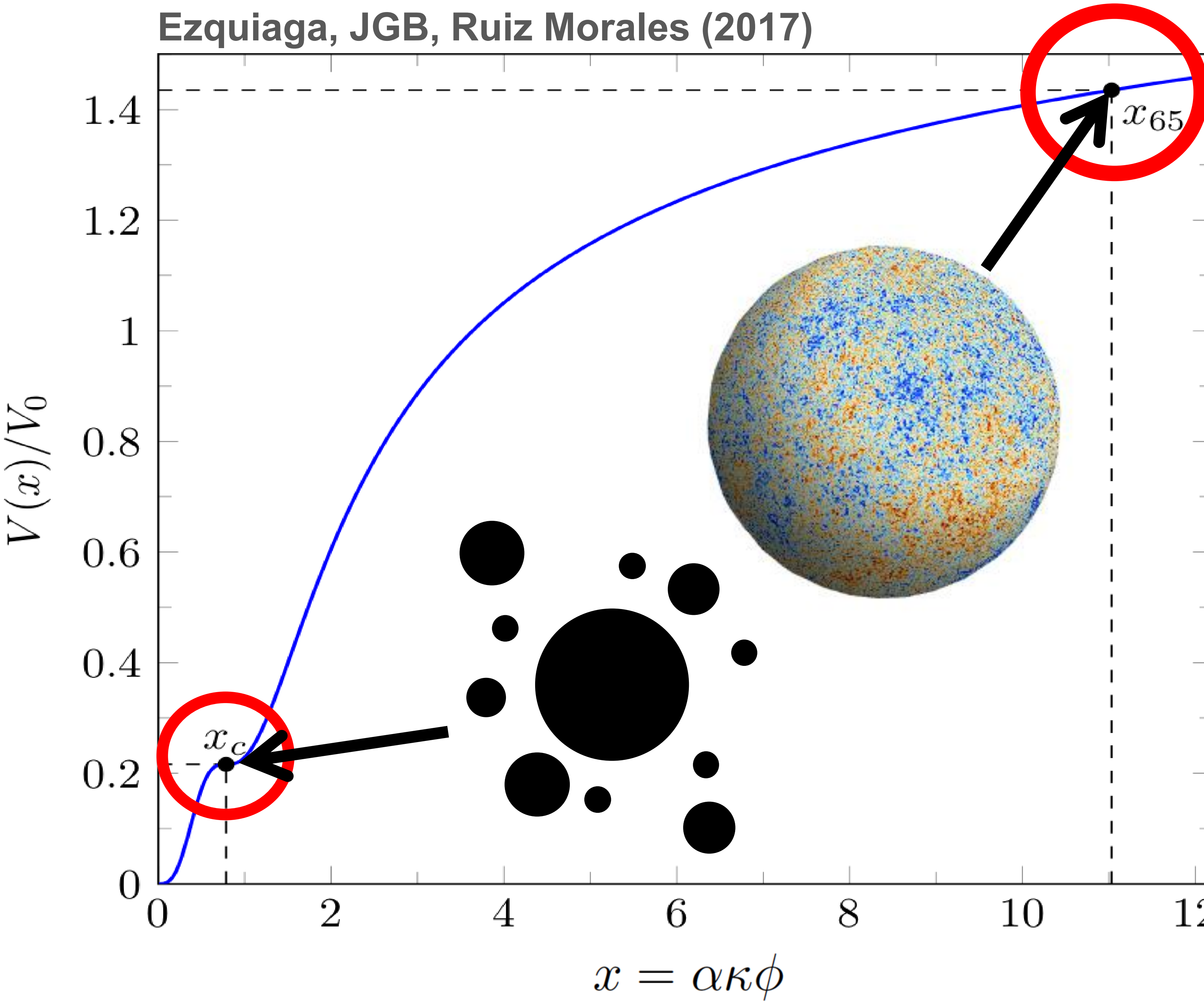


80 orders of magnitud in strength

Inflation

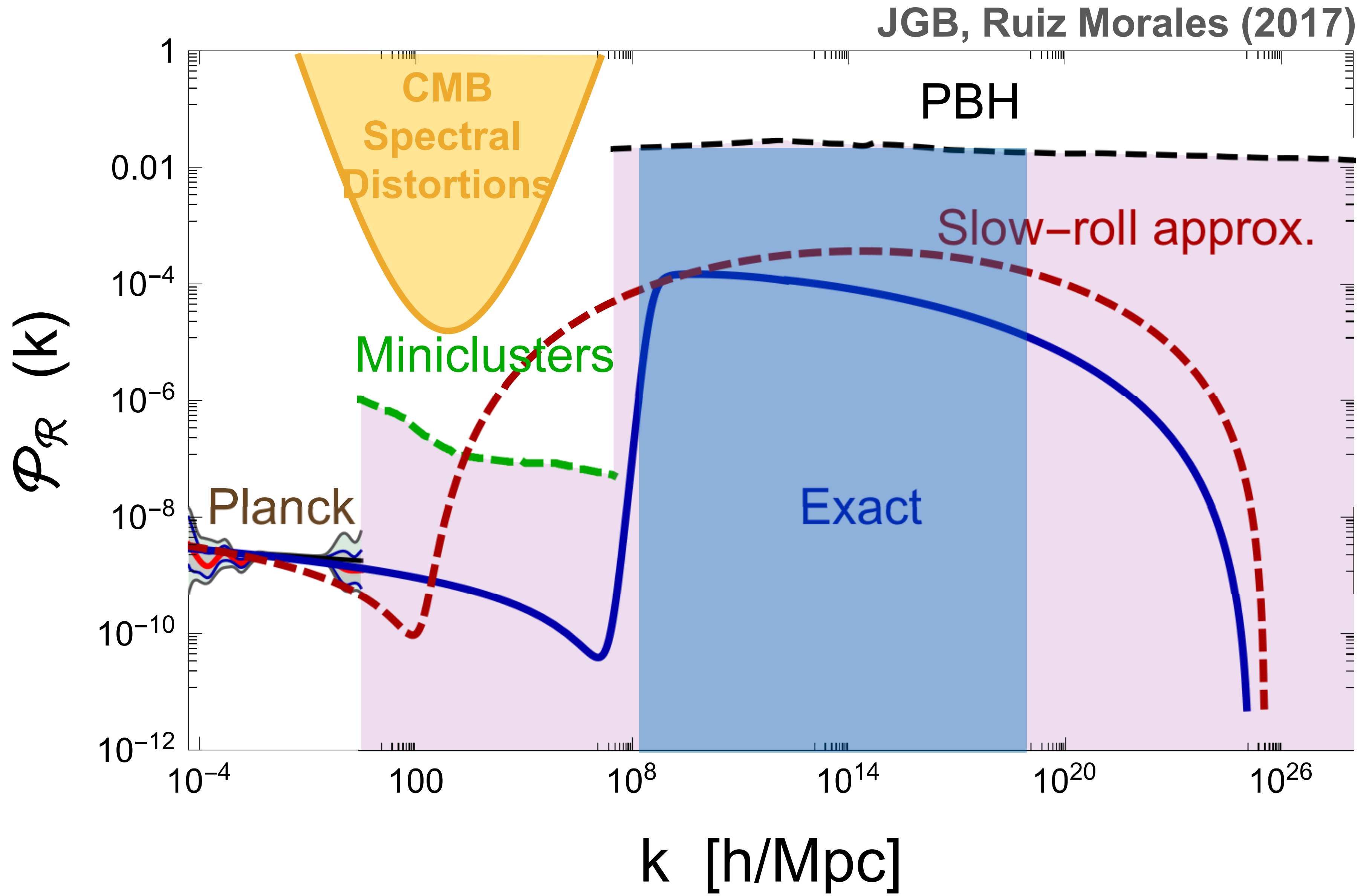


JGB (2017)
Horizon crossing
1/(aH)
1/(aH)
comoving scale 1/k
CMB
LSS
PBH
-60
-50
-40
-30
-20
-10
PBH
BBN
rec
a_0
N=ln a/a_{end}
EW
QCD
eq
N=0
Inflation
Radiation
Matter
Λ



Ezquiaga, JGB, Ruiz Morales (2017)
$V(x)/V_0$
$x = \alpha\kappa\phi$
x_c
x_{65}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
2
4
6
8
10
12

Primordial Spectrum PBH



Critical Higgs Inflation

Standard Model Lagrangian

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi) + \xi |\phi|^2 R$$

Ezquiaga, JGB, Ruiz Morales (2017)

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

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

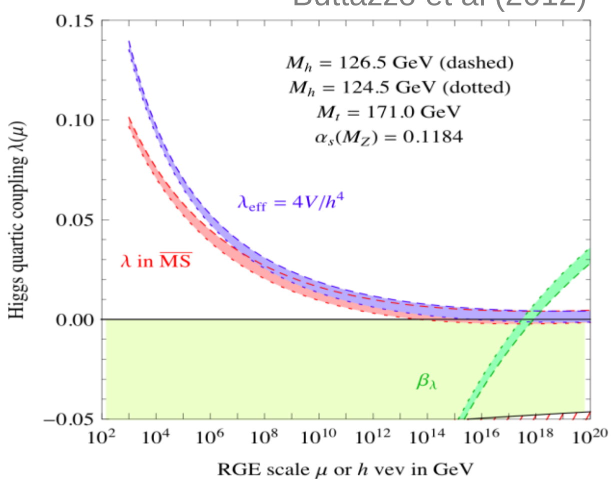
$$\xi(\phi) \;=\; \xi_0 + b_\xi \ln (\phi/\mu) \;,$$

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

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

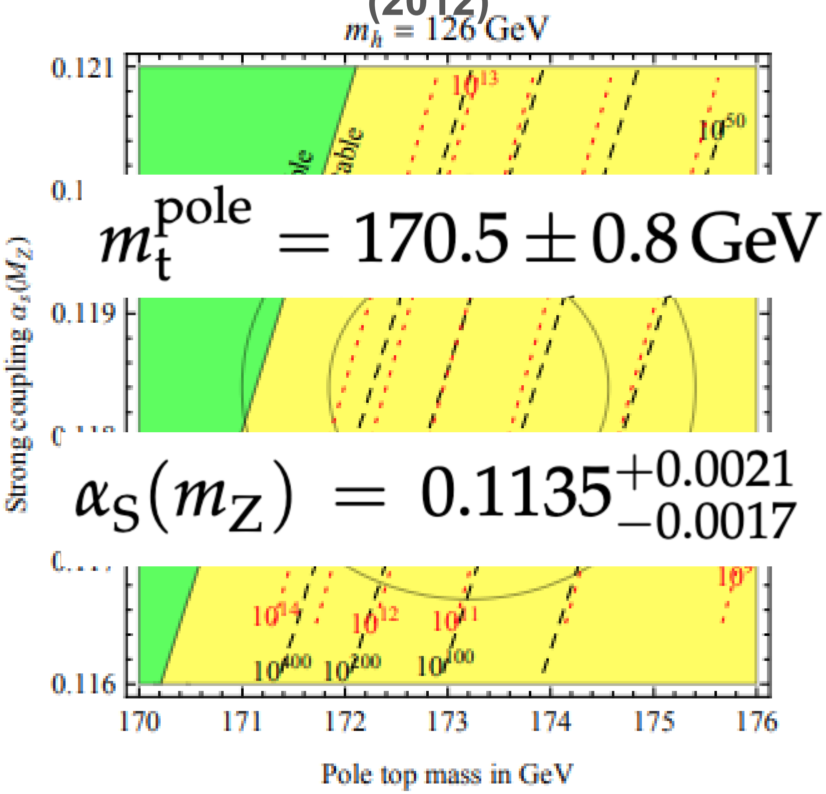
$$V_0 = \lambda_0 \mu^4/4,\ a = b_\lambda/\lambda_0,\ b = b_\xi/\xi_0 \text{ and } c = \xi_0\, \kappa^2 \mu^2$$

Buttazzo et al (2012)



EW vacuum meta-stability

Buttazzo et al. (2012)

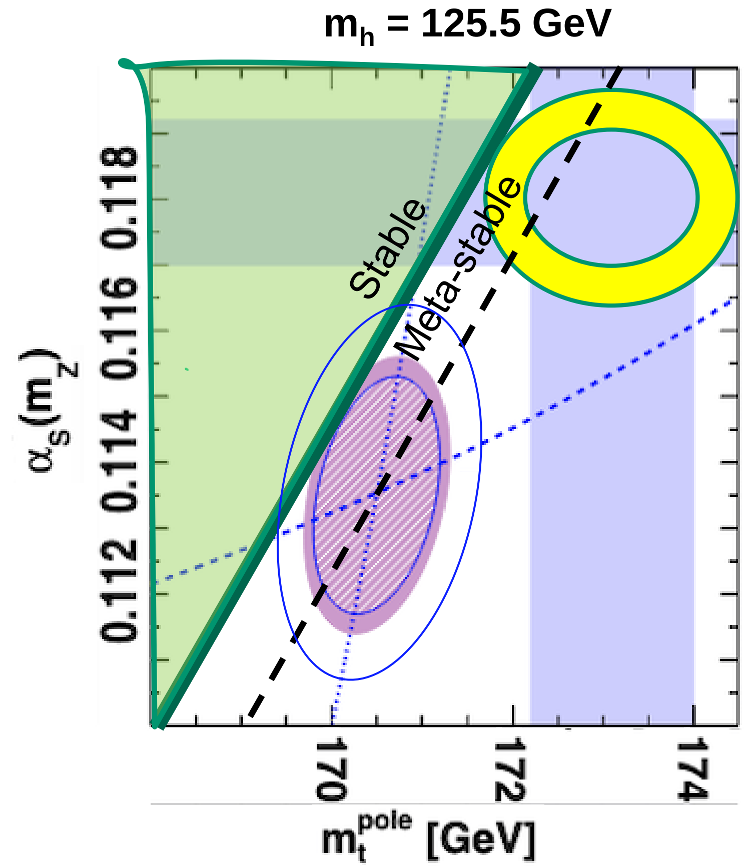


$$m_t^{\text{pole}} = 170.5 \pm 0.8\,\text{GeV}$$

$$\alpha_S(m_Z) = 0.1135^{+0.0021}_{-0.0017}$$

https://arxiv.org/pdf/1112.3022.pdf

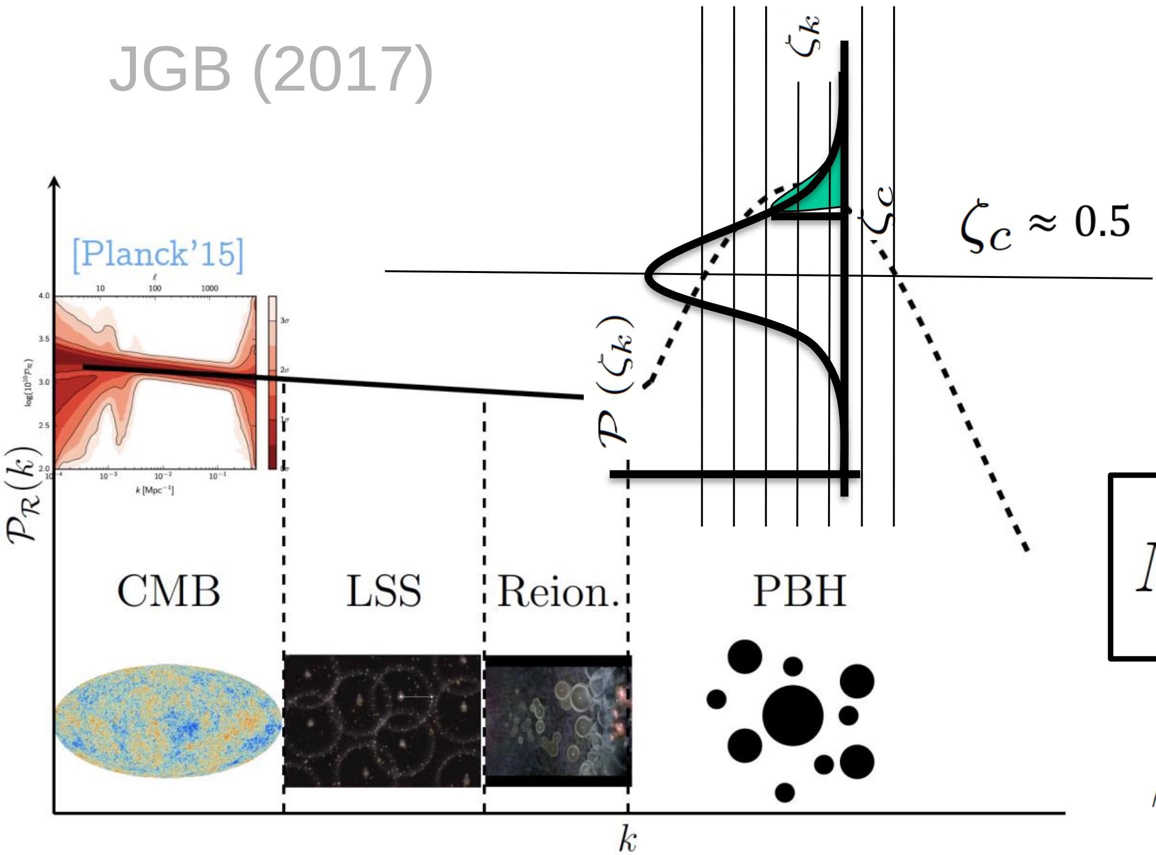
CMS Collab. (2020)

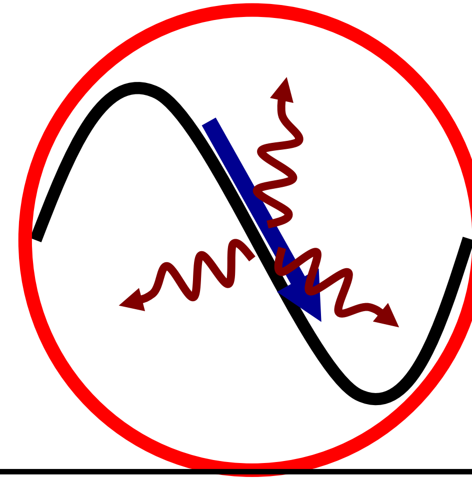


https://arxiv.org/abs/1904.05237

Gravitational Collapse of PBH

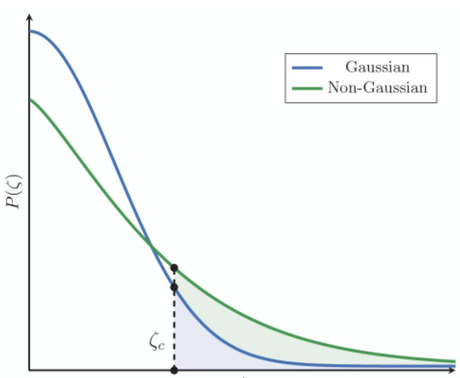
JGB (2017)





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

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



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

Stochastic δN - formalism

Coarse-grained curvature perturbation

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t) e^{2\zeta(t,\mathbf{x})} \delta_{ij} \mathrm{d}x^i \mathrm{d}x^j \qquad \zeta_{\mathrm{cg}}(\mathbf{x}) = \delta N_{\mathrm{cg}}(\mathbf{x}) = \mathcal{N}(\mathbf{x}) - \langle \mathcal{N} \rangle$$

$$\frac{1}{M_{\mathrm{pl}}^2} \frac{\mathrm{d}}{\mathrm{d}\mathcal{N}} P_{\mathbf{\Phi}}(\mathcal{N}) = \left(-\sum_i \frac{v_{\phi_i}}{v} \frac{\partial}{\partial \phi_i} + v \sum_i \frac{\partial^2}{\partial \phi_i^2} \right) \cdot P_{\mathbf{\Phi}}(\mathcal{N})$$

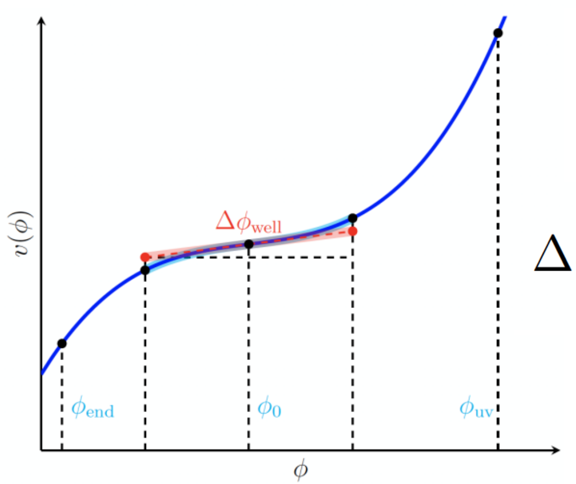
Fokker-Planck Diffusion Eq.

Determined by the poles of the characteristic function

$$P_\phi(\mathcal{N}) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-it\mathcal{N}} \chi_{\mathcal{N}}(t,\phi) dt = \sum_n a_n(\phi)\, e^{-\Lambda_n \mathcal{N}}$$

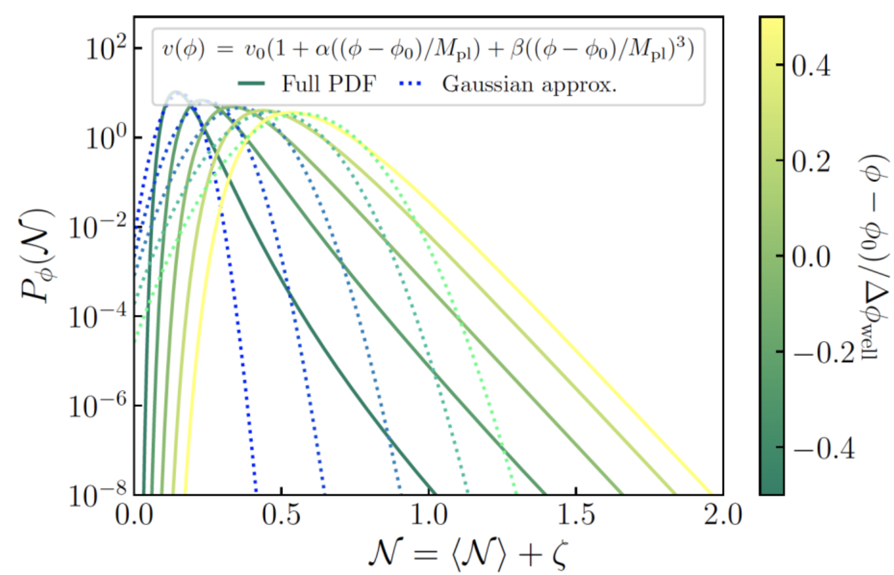
$$\chi_{\mathcal{N}}(t,\phi) = \sum_n \frac{a_n(\phi)}{\Lambda_n - it} + \text{regular func}$$

Ezquiaga, JGB, Vennin (2019)



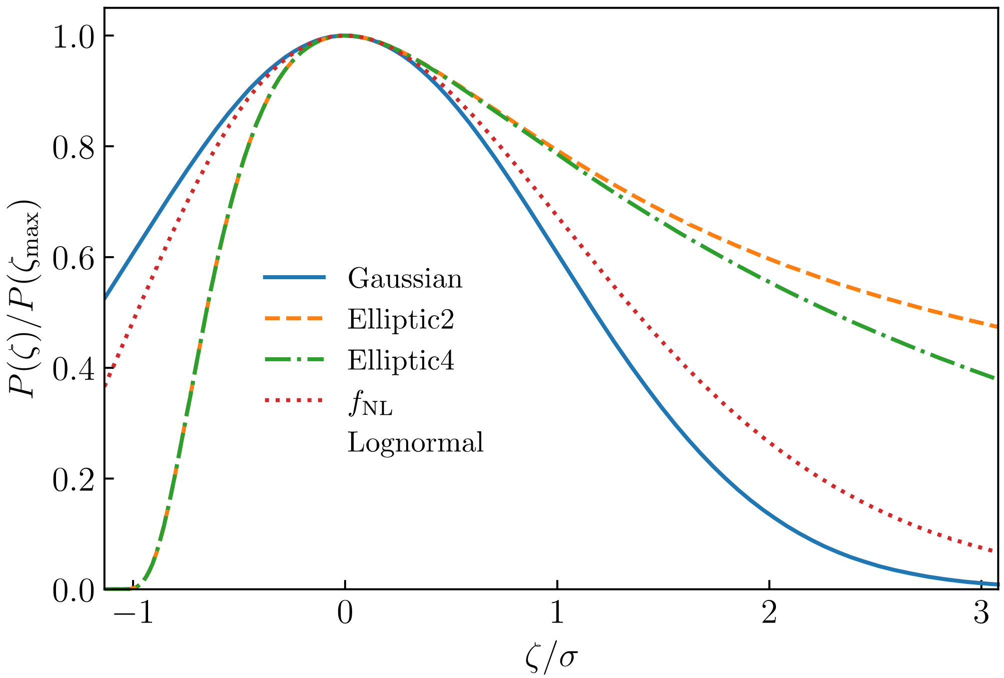
$$\alpha \gg (v_0^2 \beta)^{1/3}$$

$$\Delta\phi_{\mathrm{well}} \simeq 2 M_{\mathrm{pl}} \sqrt{\frac{\alpha}{3\beta}}$$



Quantum Diffusion @ CMB & LSS

Ezquiaga, JGB, Vennin (2022)



$$P_2(\zeta_k) = -\frac{\pi}{2\mu^2}\vartheta_2'\left(\frac{\pi\alpha_k}{2}, e^{-\frac{\pi^2}{\mu^2}\mathcal{N}_k}\right)$$

$$P_4(\zeta_k) = \frac{\pi}{2\mu^2\alpha_k}\vartheta_4'\left(\frac{\pi\alpha_k}{2}, e^{-\frac{\pi^2}{\mu^2}\mathcal{N}_k}\right)$$

$$\zeta(x) = \zeta_{\rm G}(x) + \frac{3}{5} f_{\rm NL}\left[\zeta_{\rm G}^2(x) - \sigma_{\rm G}^2(x)\right]$$

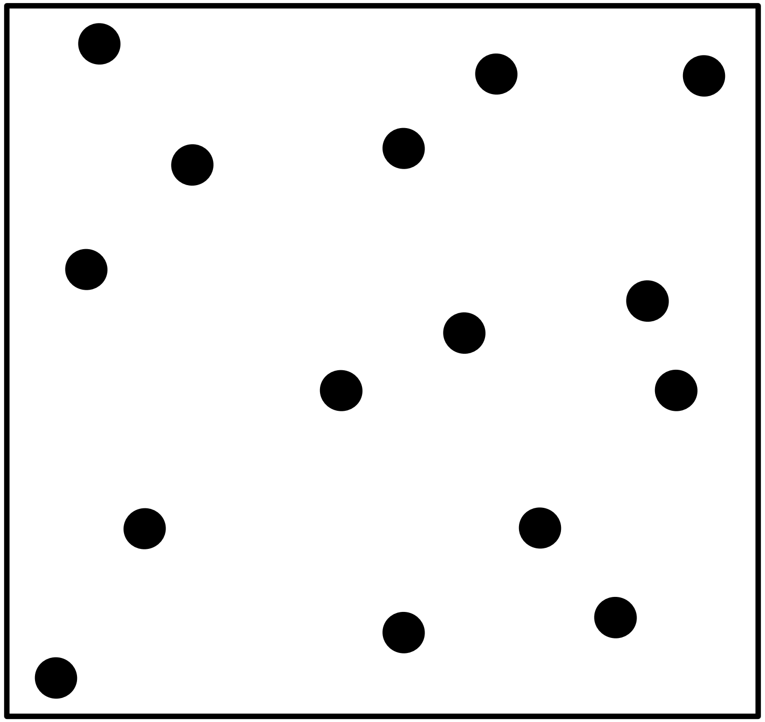
$$\mathrm{LN}(x,\rho,\sigma) = \frac{1}{\rho\,\sigma\sqrt{2\pi}}\exp\left[-\frac{\ln(x/\rho)^2}{2\sigma^2} - \frac{\sigma^2}{2}\right]$$

$$\mathrm{G}(x,\rho,\sigma_{\rm G}) = \frac{1}{\sigma_{\rm G}\sqrt{2\pi}}\exp\left[-\frac{(x-\rho)^2}{2\sigma_{\rm G}^2}\right]$$

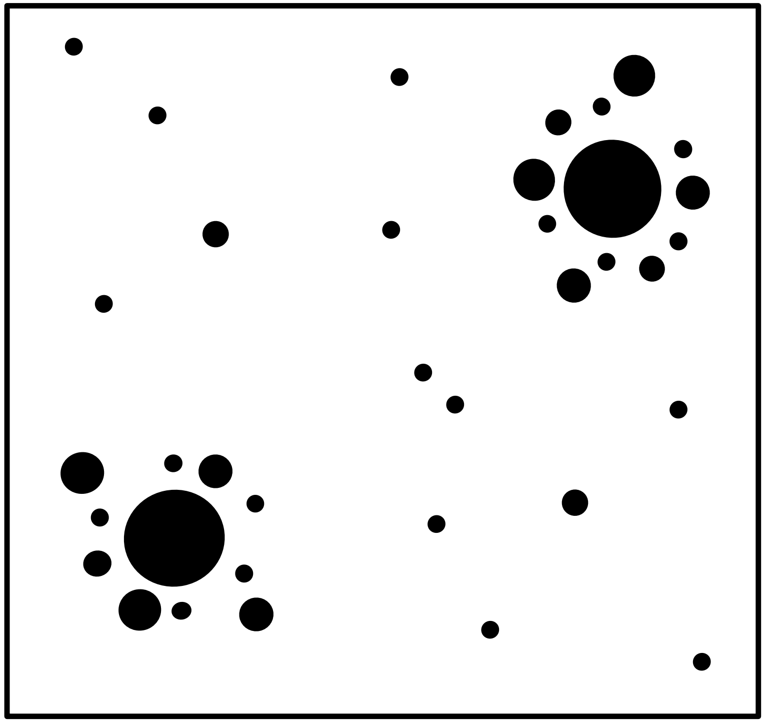
$$P_{\rm NL}(\zeta) = \frac{1}{\sqrt{2\pi\sigma_{\rm G}^2\Delta}}\left[e^{-\frac{25(\sqrt{\Delta}-1)^2}{72 f_{\rm NL}^2\sigma_{\rm G}^2}} + e^{-\frac{25(\sqrt{\Delta}+1)^2}{72 f_{\rm NL}^2\sigma_{\rm G}^2}}\right]$$

where $\Delta(\zeta) = 1 + \frac{12}{5} f_{\rm NL}\zeta + \frac{36}{25} f_{\rm NL}^2\sigma_{\rm G}^2.$

Spatial Distribution PBH



- Monochromatic
- Uniformly distributed

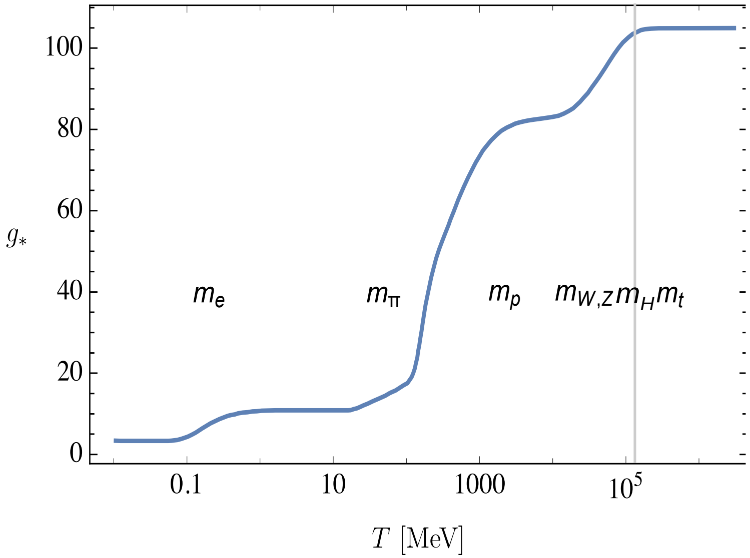


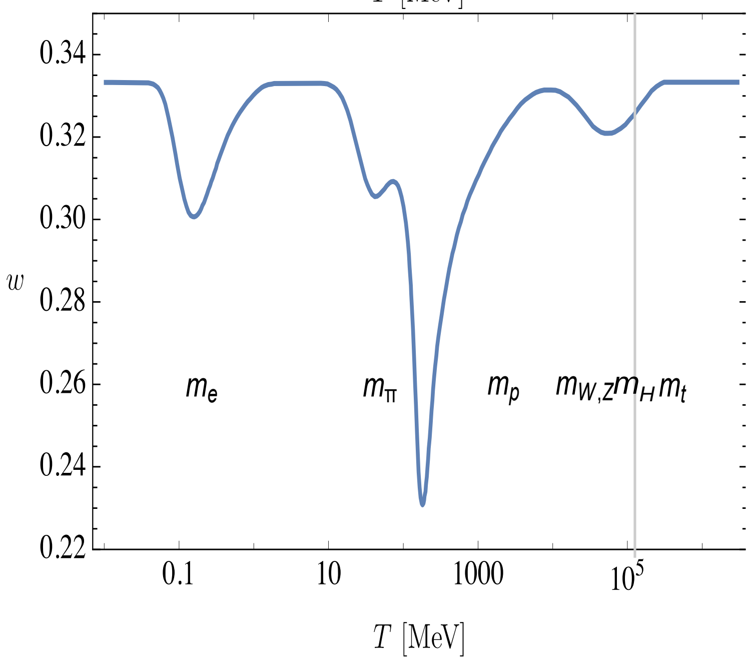
- Broad range masses
- PBH clusters

JGB (2017)

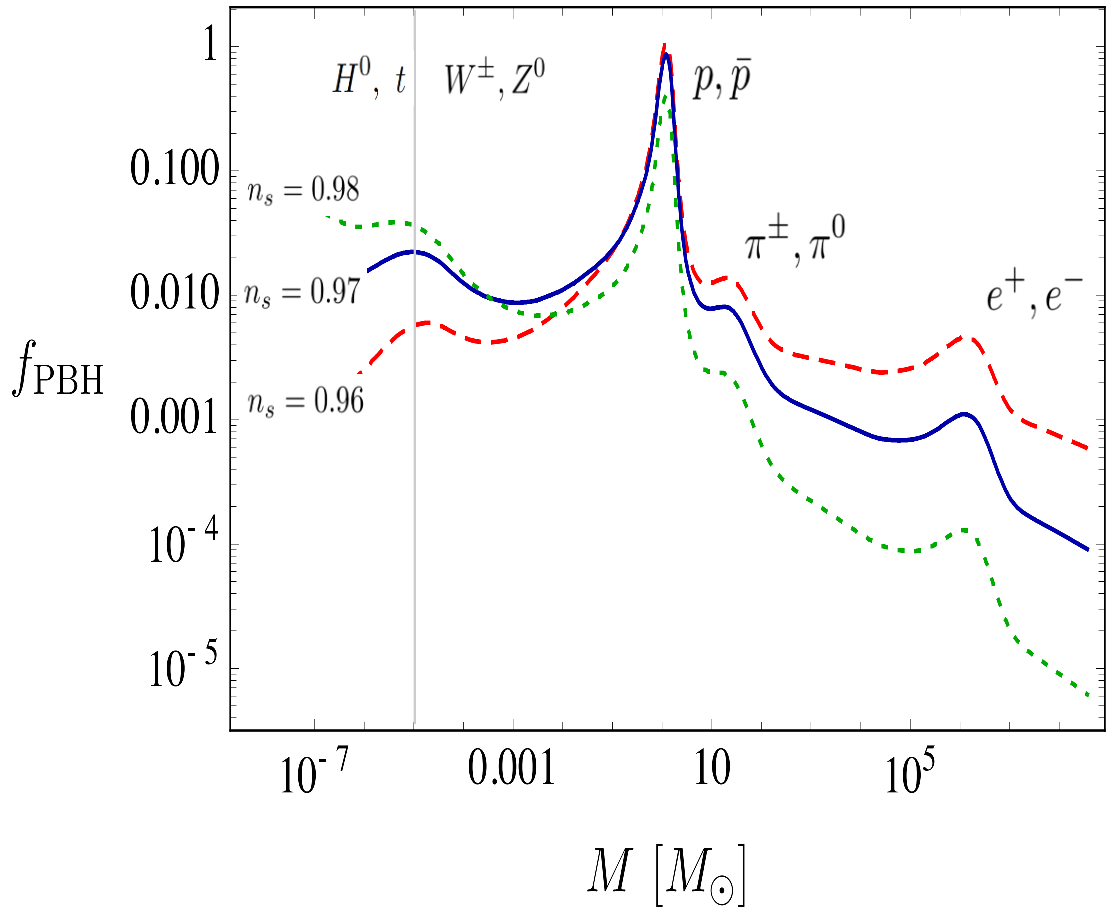
Thermal history of the universe

Carr, Clesse, JGB, Kühnel (2019)





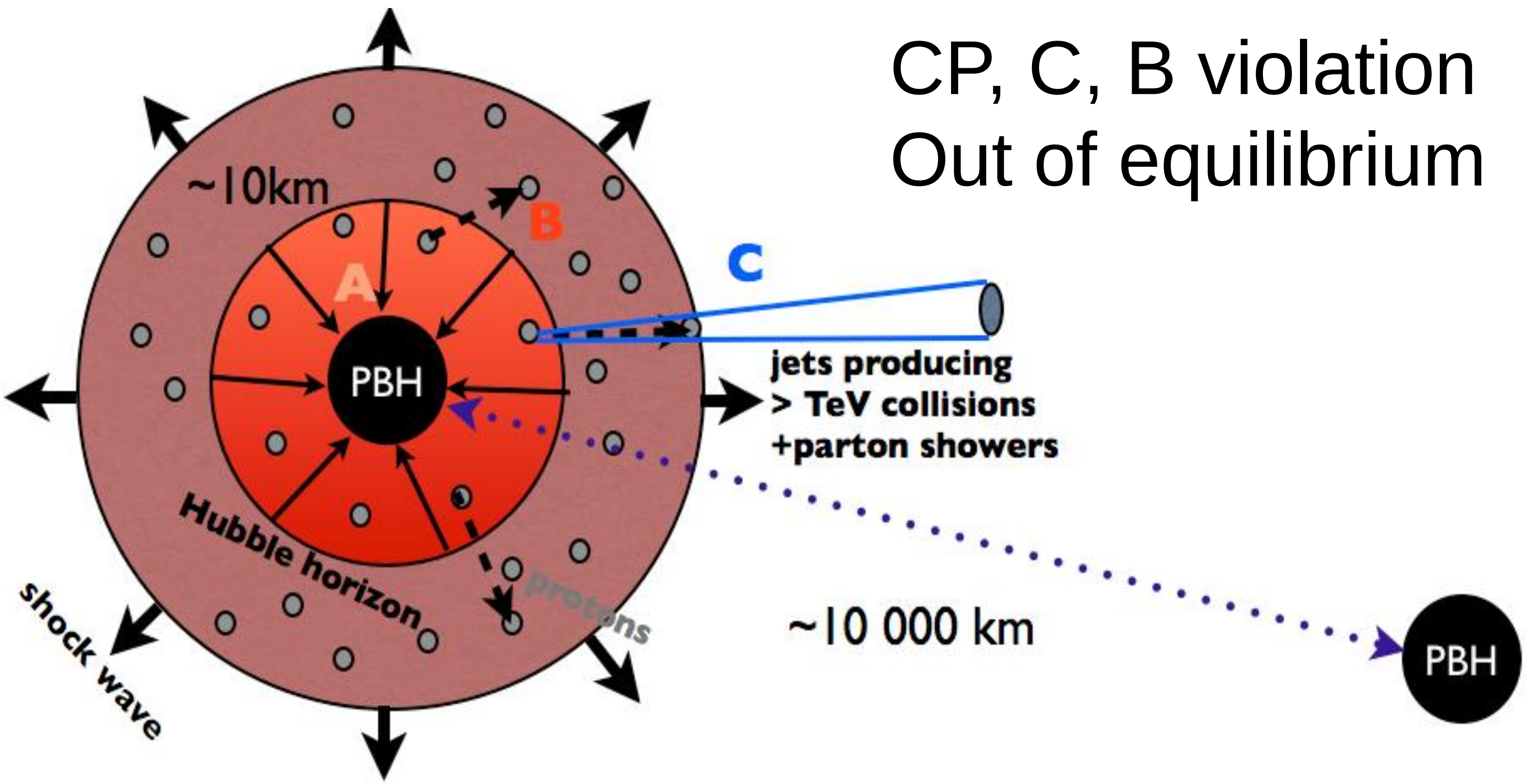
PBH mass spectrum



Electroweak baryogenesis @ QCD

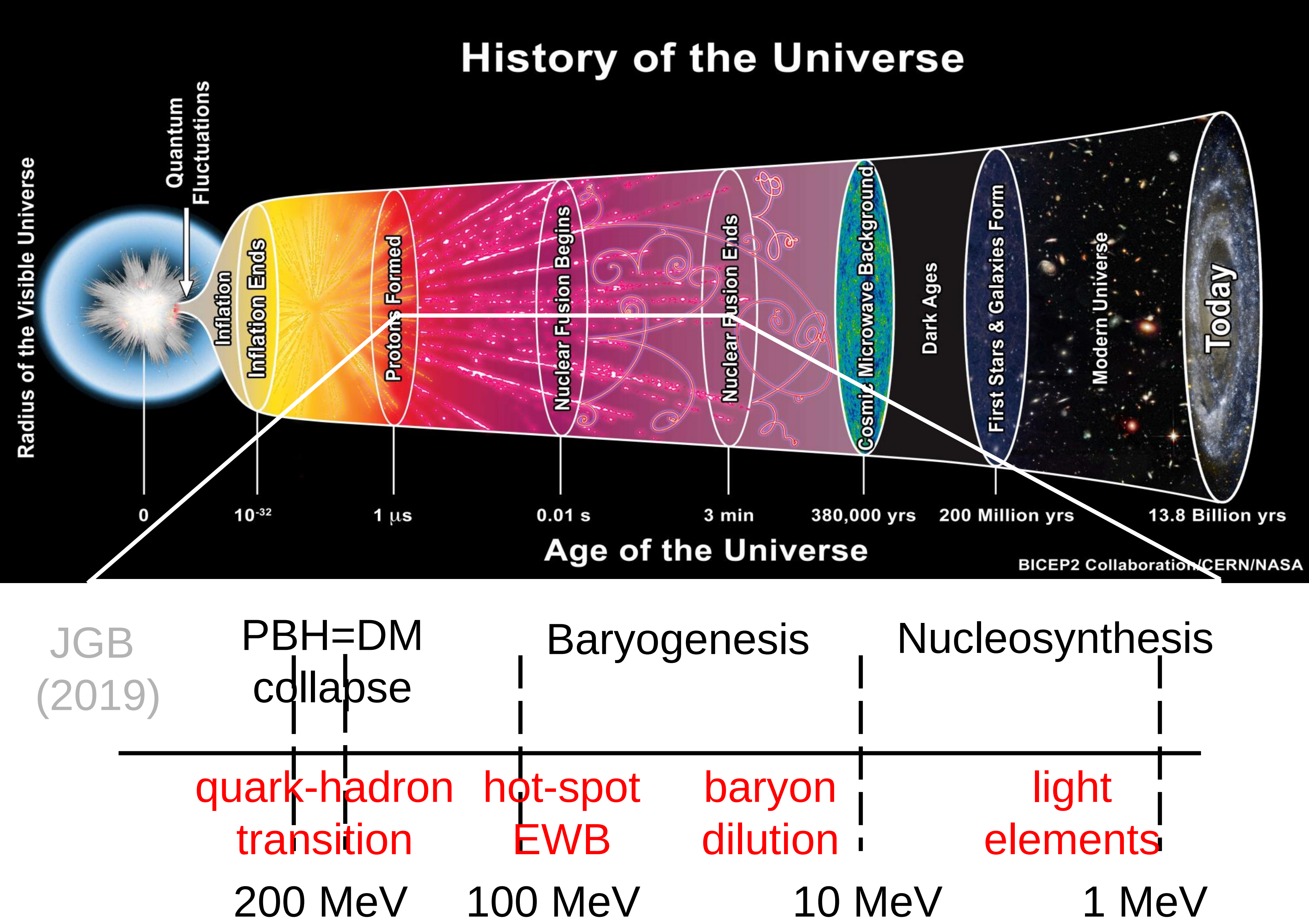
"Primordial supernova"

JGB, Carr, Clesse (2019)



Sakharov conditions:

CP, C, B violation
Out of equilibrium


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
JGB (2019)
PBH=DM collapse
Baryogenesis
Nucleosynthesis
quark-hadron transition
hot-spot EWB
baryon dilution
light elements
200 MeV
100 MeV
10 MeV
1 MeV

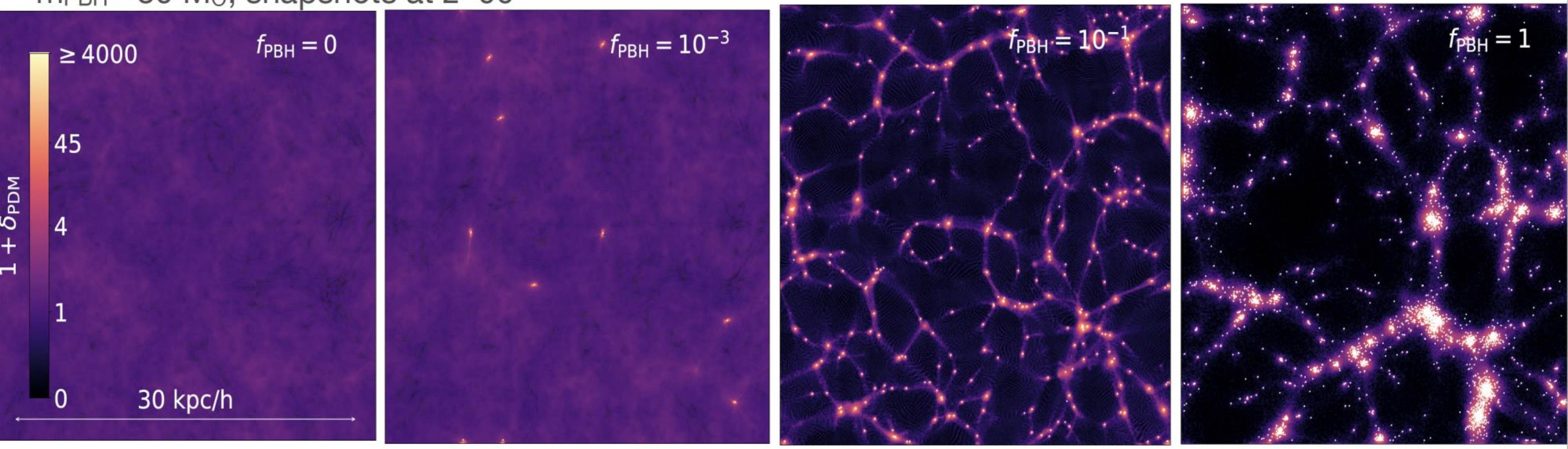
Clesse (2021)

Can (stellar-mass) PBHs be the dark matter?

Poisson in a PBH sea...

N-body simulations by Inman & Ali-Haimoud, 1907.08129

m_{PBH}= 30 $M_\odot$, snapshots at z=99



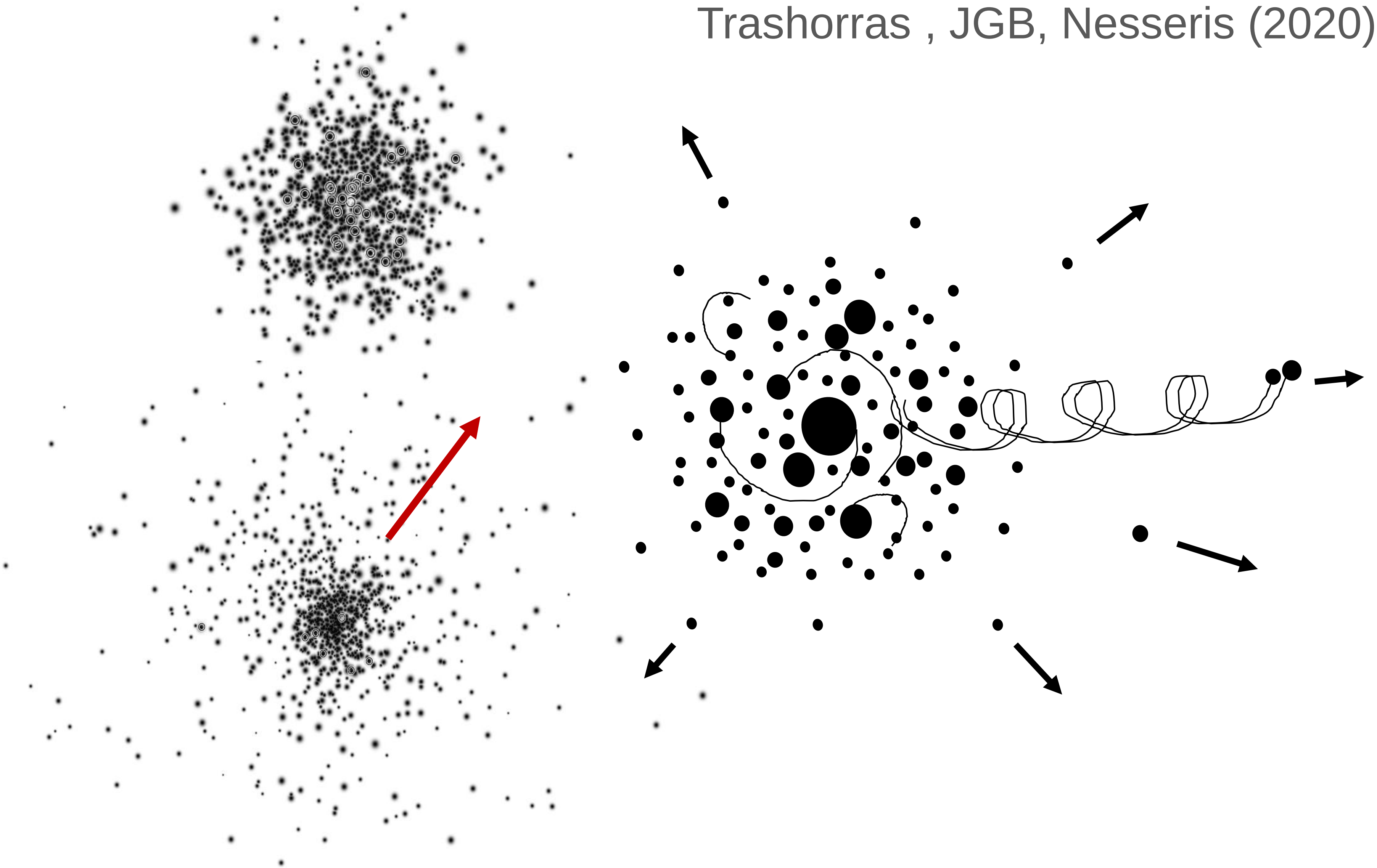
Halos of 10^6 - 10^7 $M_\odot$

On small scales, completely different than particle-CDM !

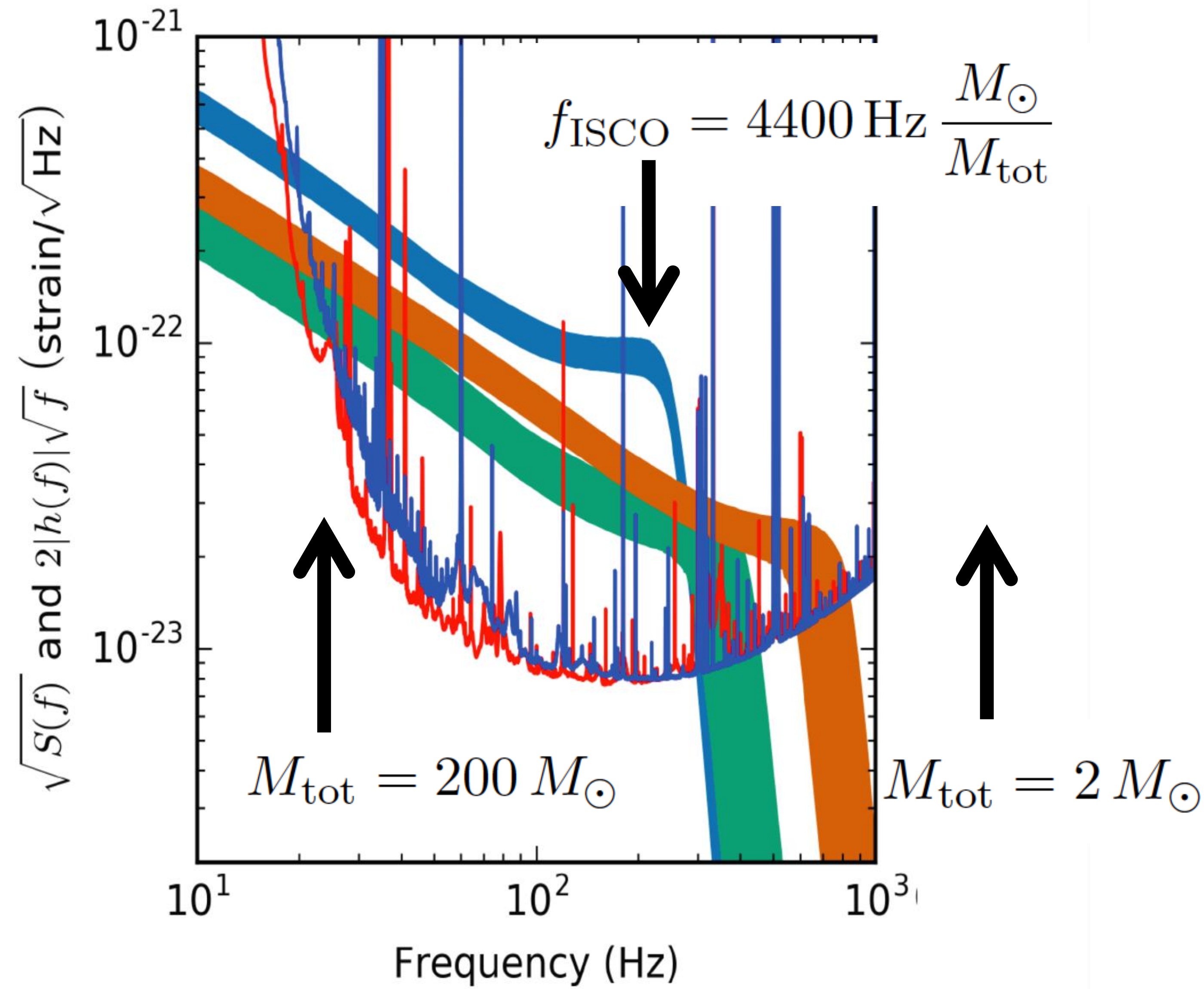
Potential implications for 21cm, recombination, etc... [Hasinger+20]

PBH clusters

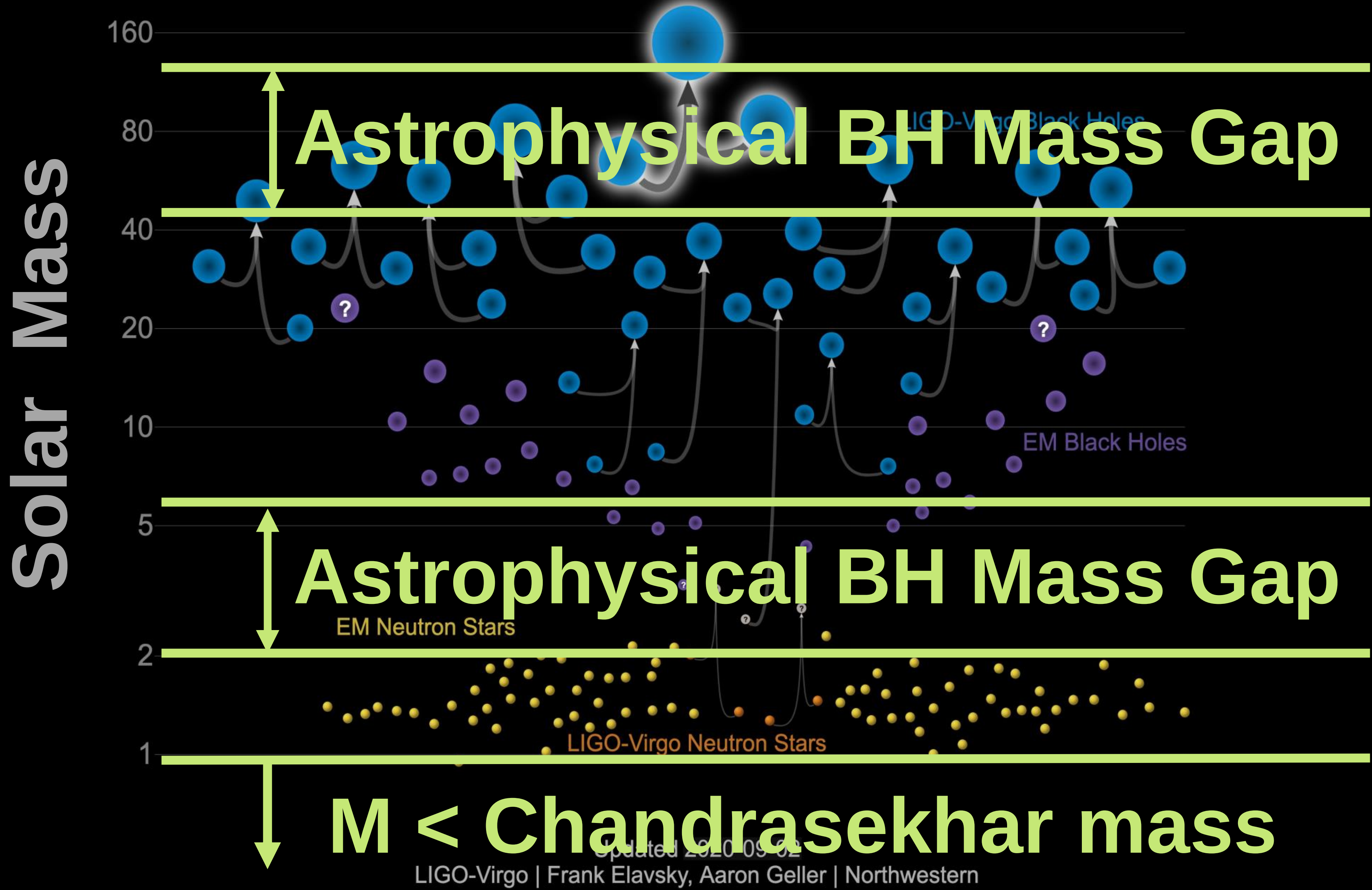
Trashorras , JGB, Nesseris (2020)



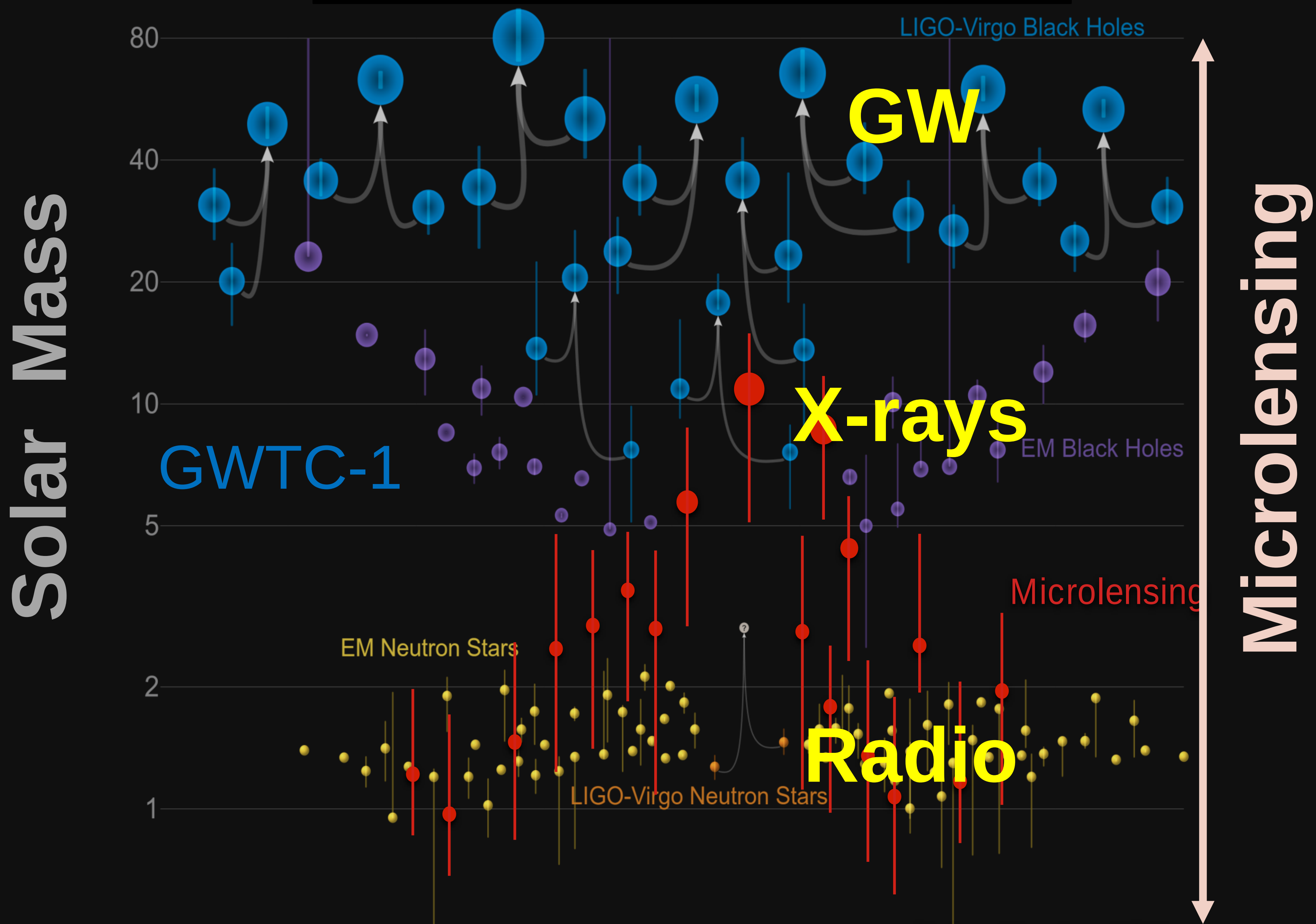
LVC BBH events



Black Holes and Neutron Stars

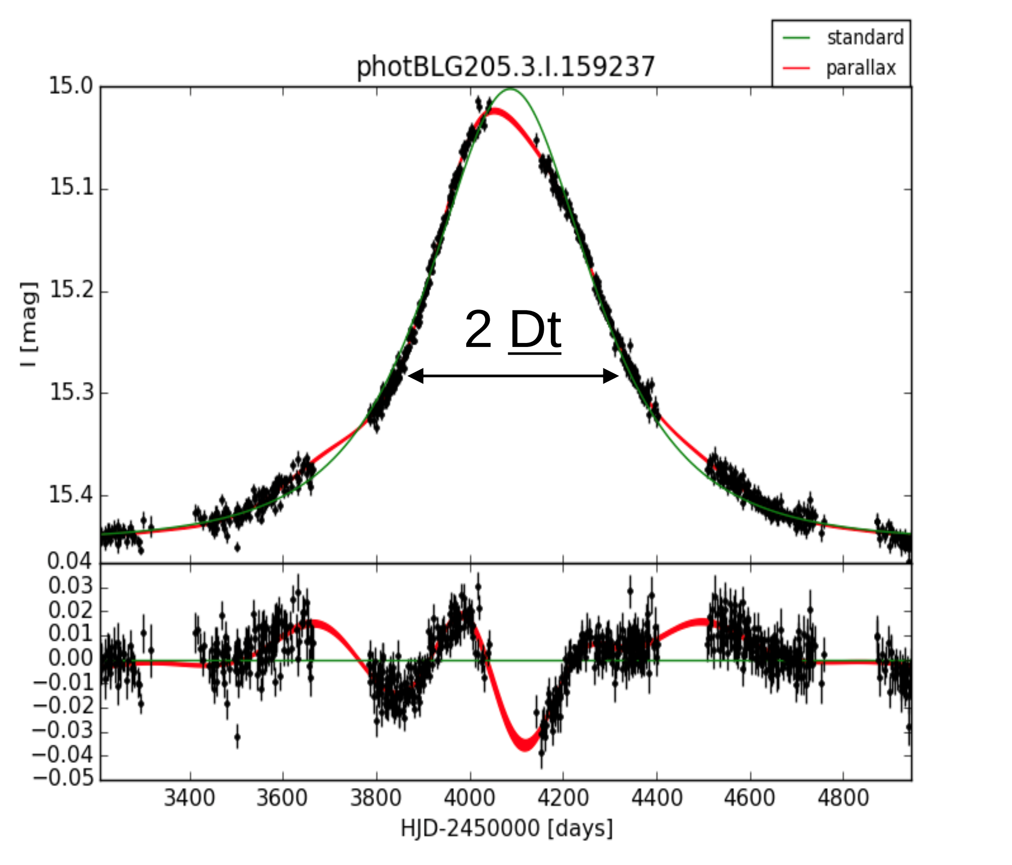


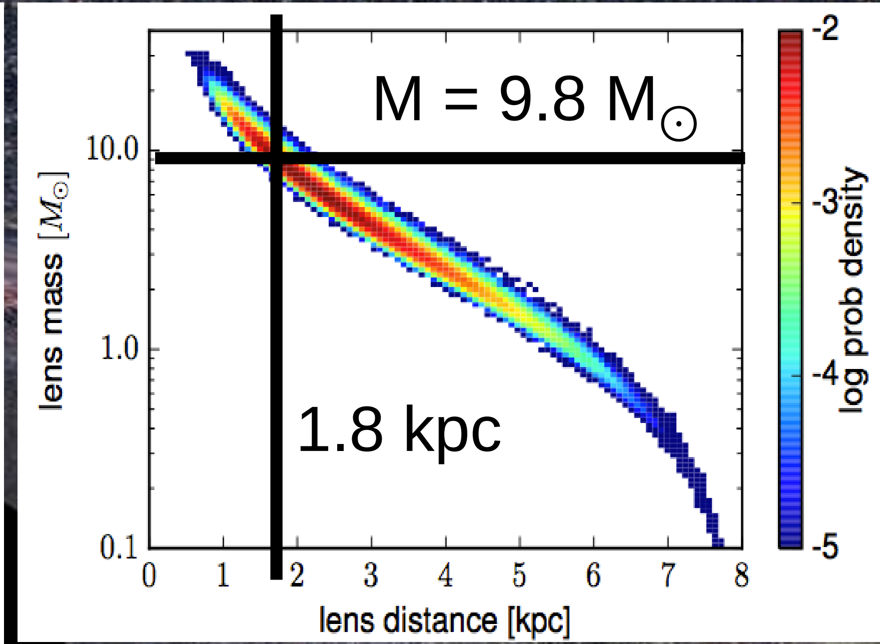
Black Holes and Neutron Stars



Wyrzykowski (2016)

OGLE3-UL-PAR-02 - candidate BH



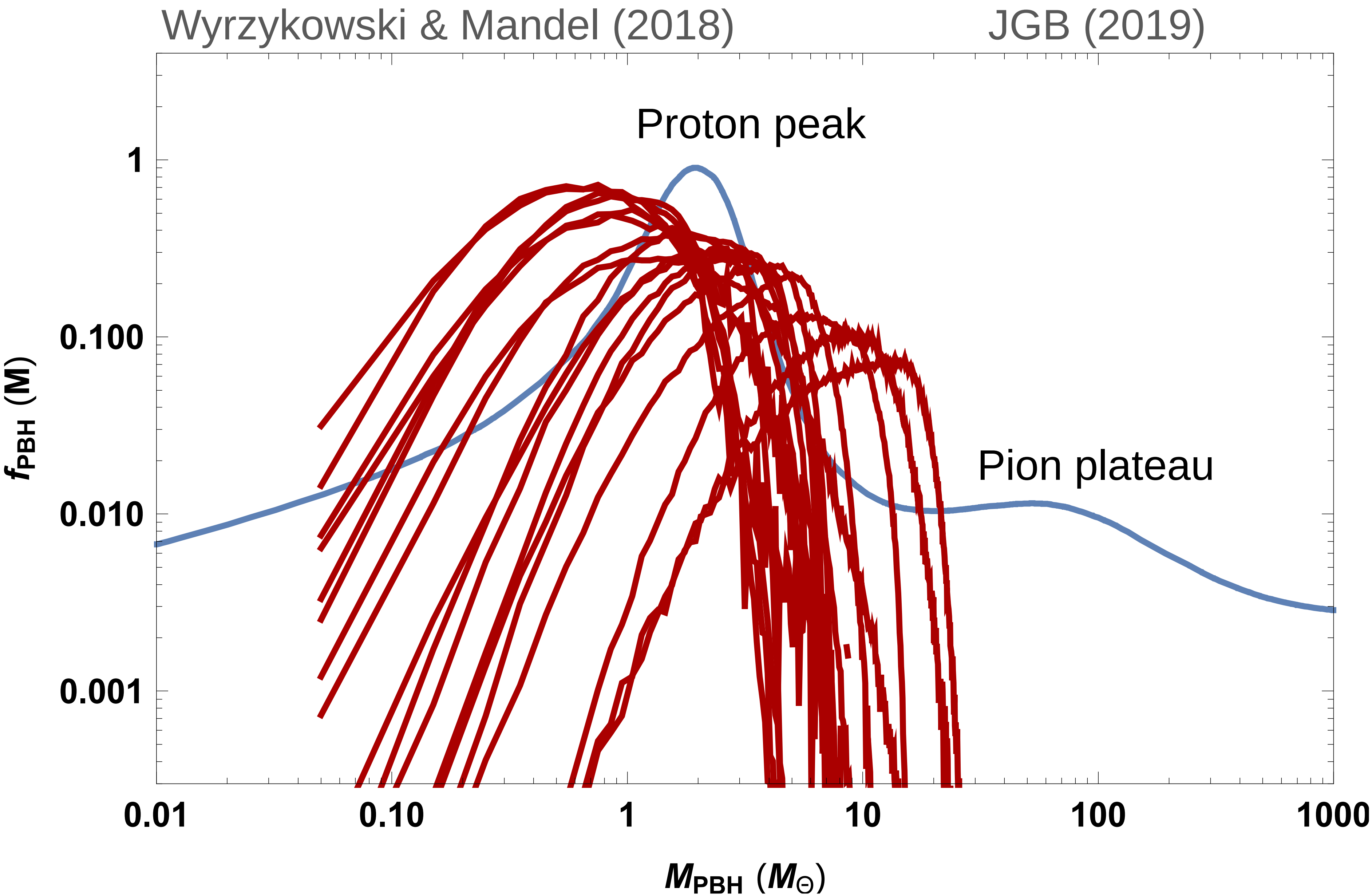


$$\overline{Dt} = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v}$$

OGLE photometry
from 2001-2008
and microlensing model

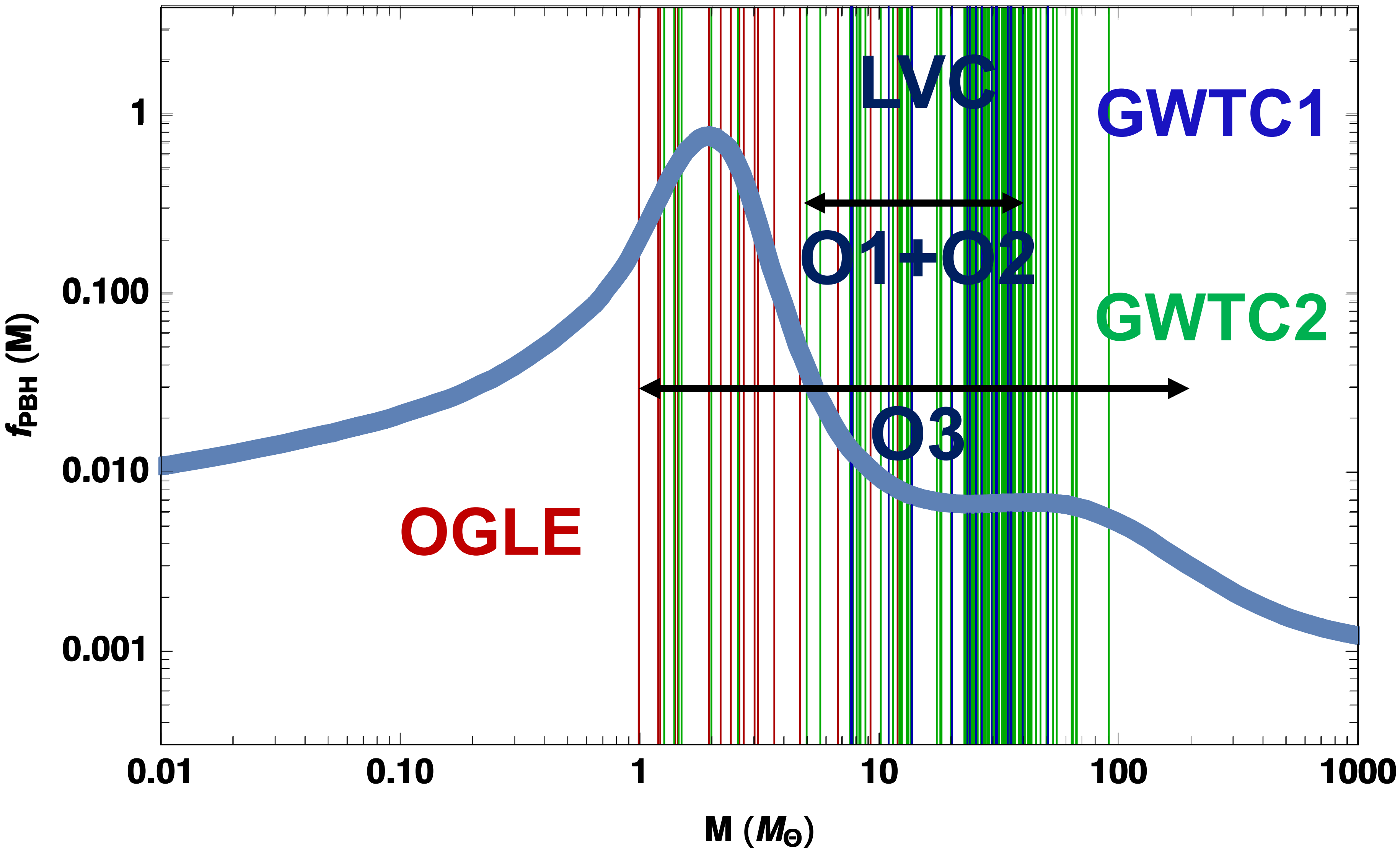
Mass, Distance (degenerated estimate)

Primordial Black Holes & OGLE

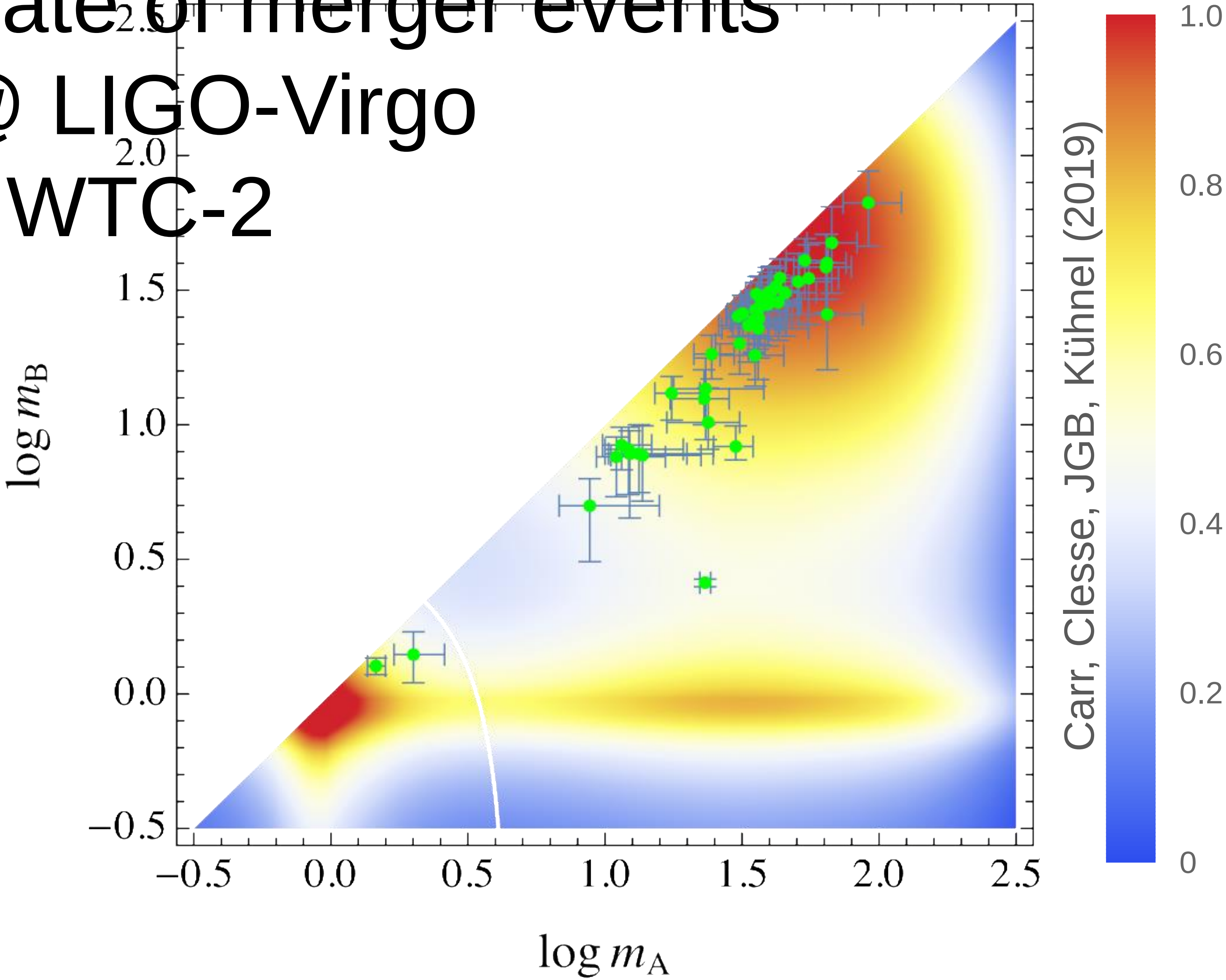


Model prediction: mass spectrum

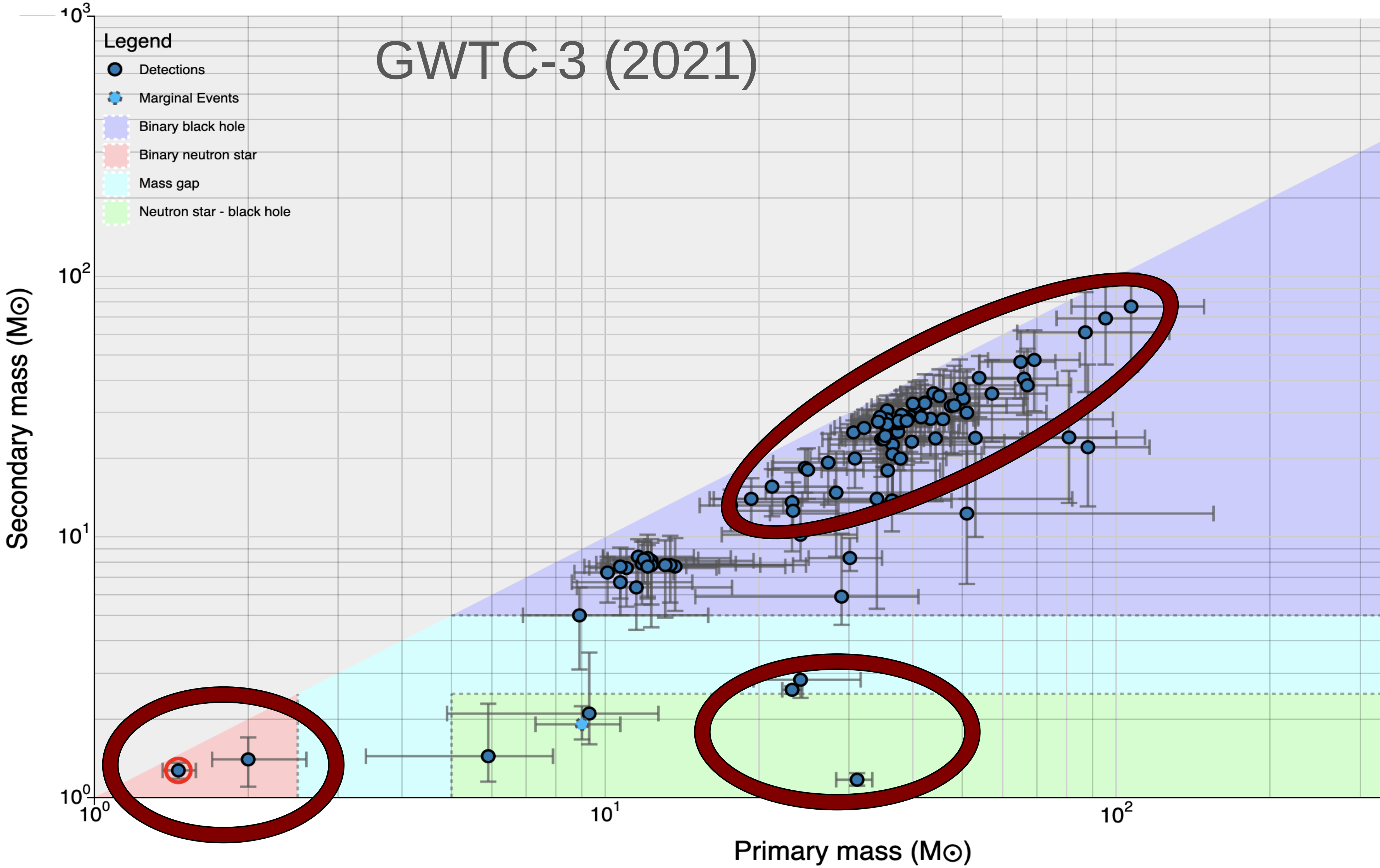
JGB, Clesse (2020)



Rate of merger events
@ LIGO-Virgo
GWTC-2

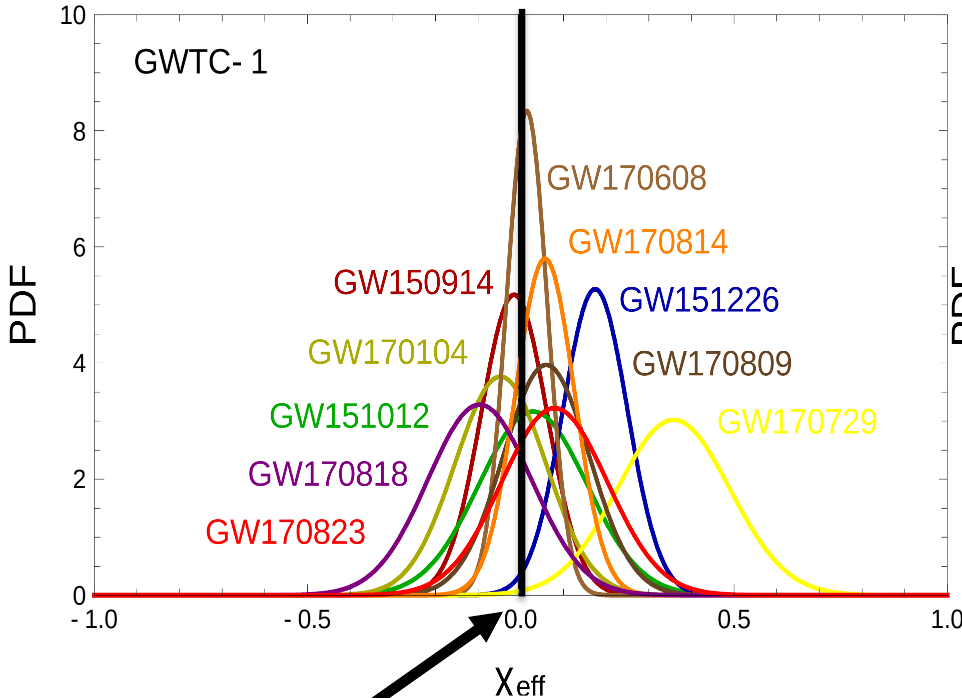


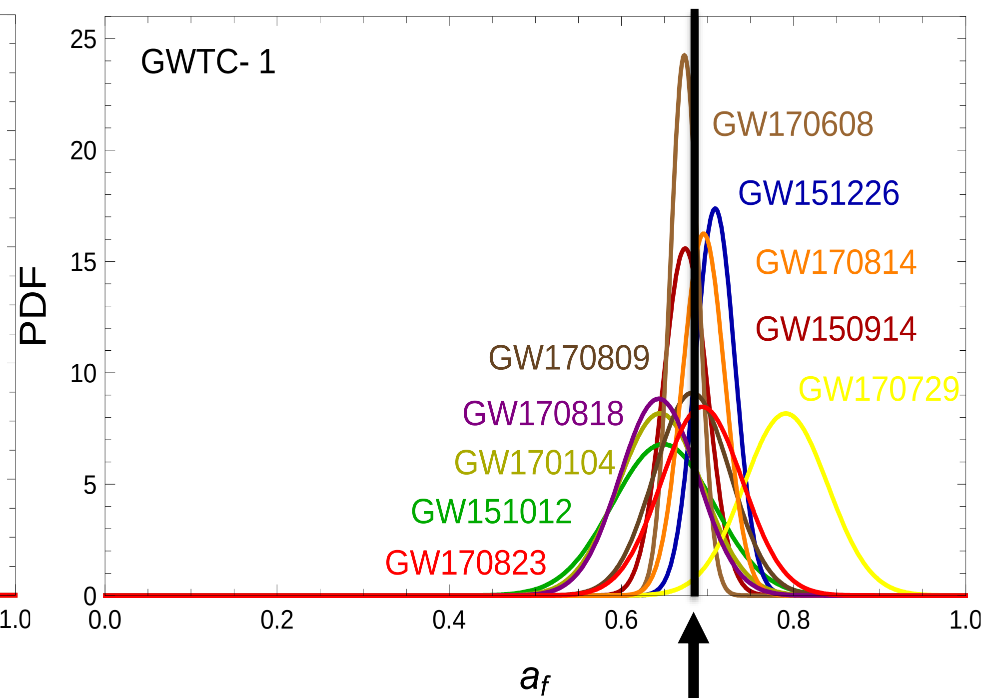
Primary and secondary masses



Effective & Final Spin

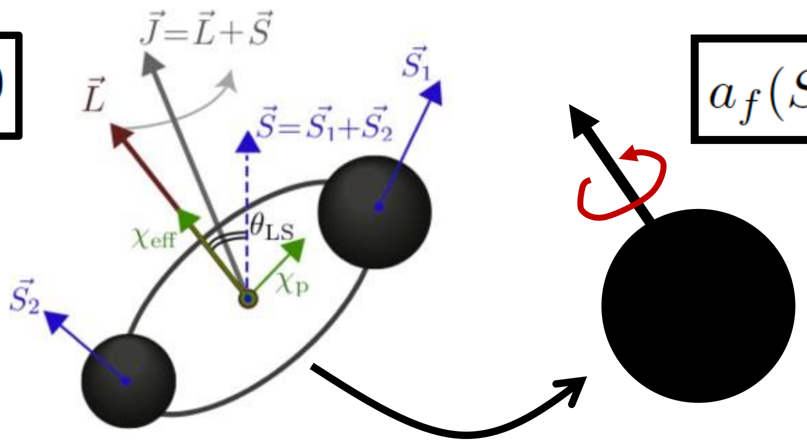
JGB (2019)





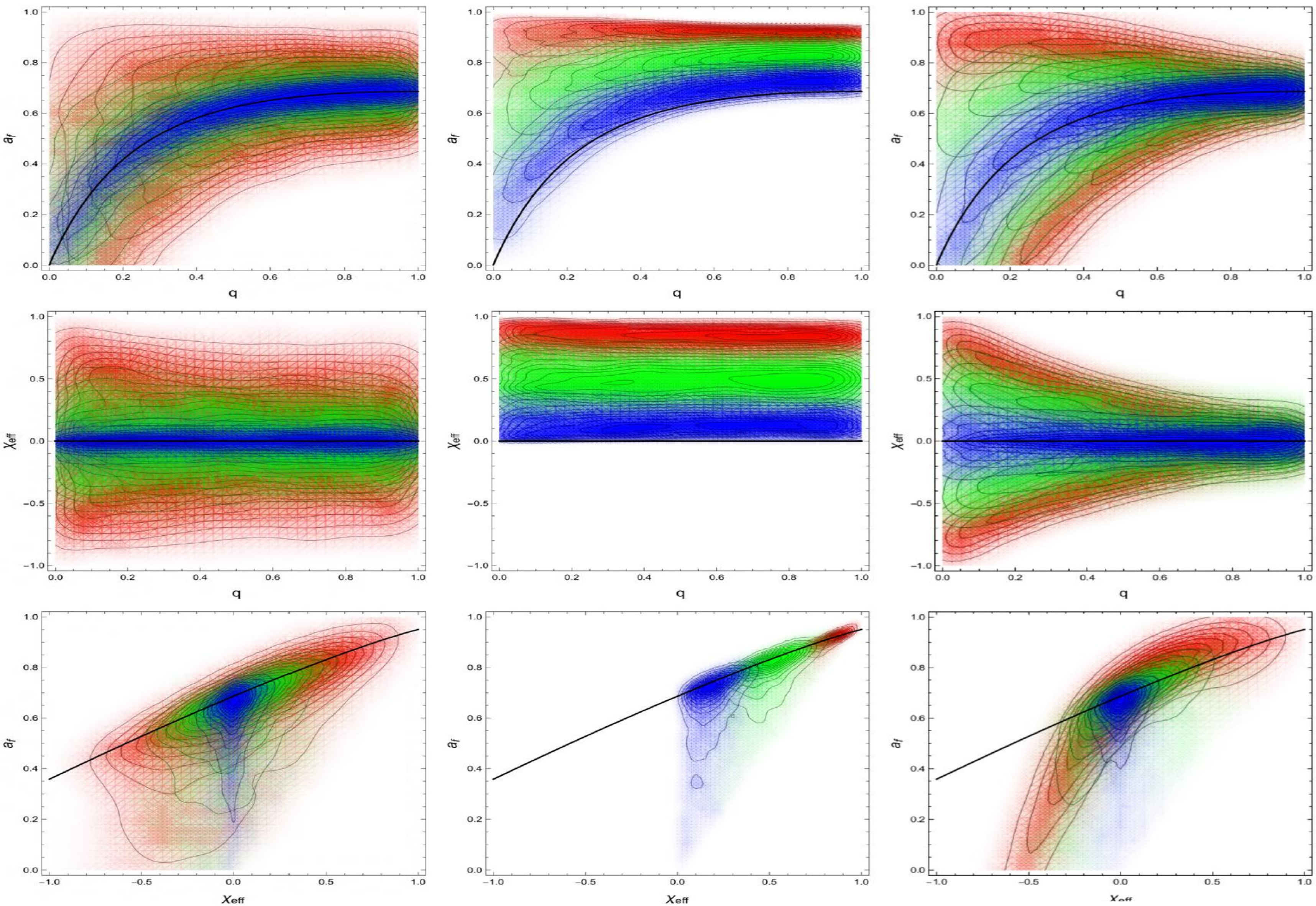
$$\chi_{\rm eff}(S_1 = S_2 = 0) = 0$$

$$a_f(S_1 = S_2 = 0) = 0.686$$



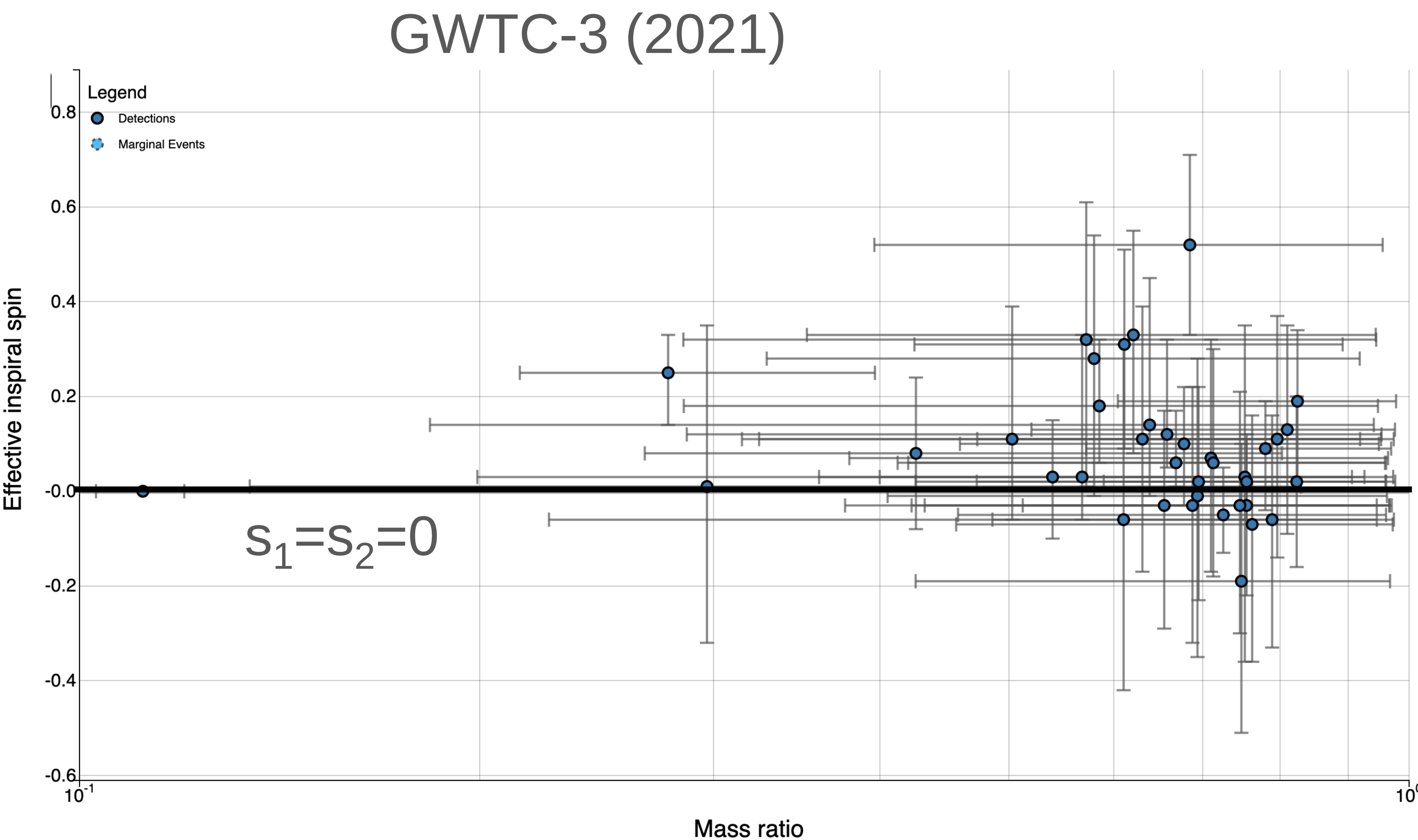
M-ratio, Effective & Final Spin: Priors

isotropic spin | aligned spin | anti-aligned spin

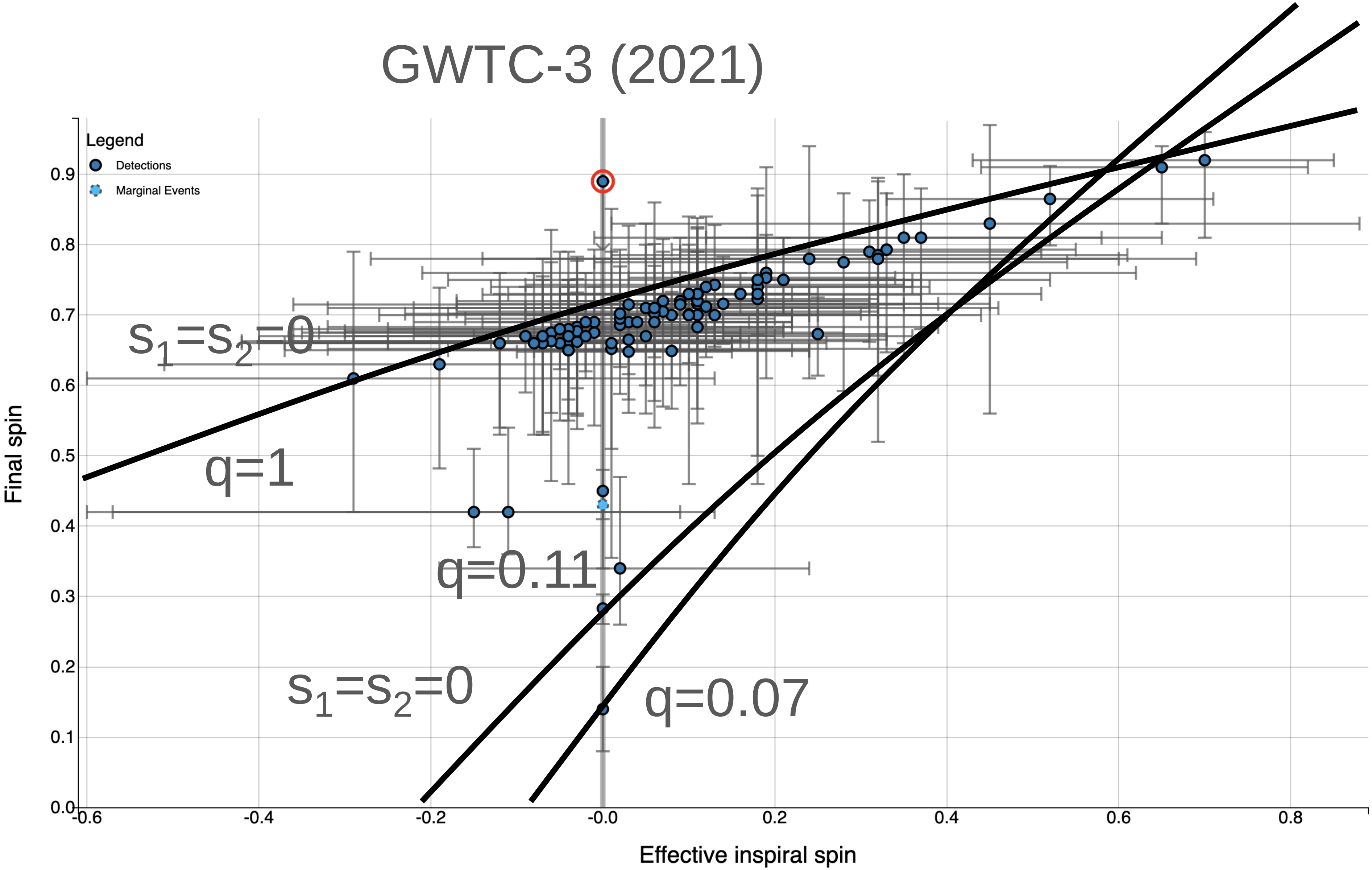


JGB, Nuño Siles, Ruiz Morales (2020)

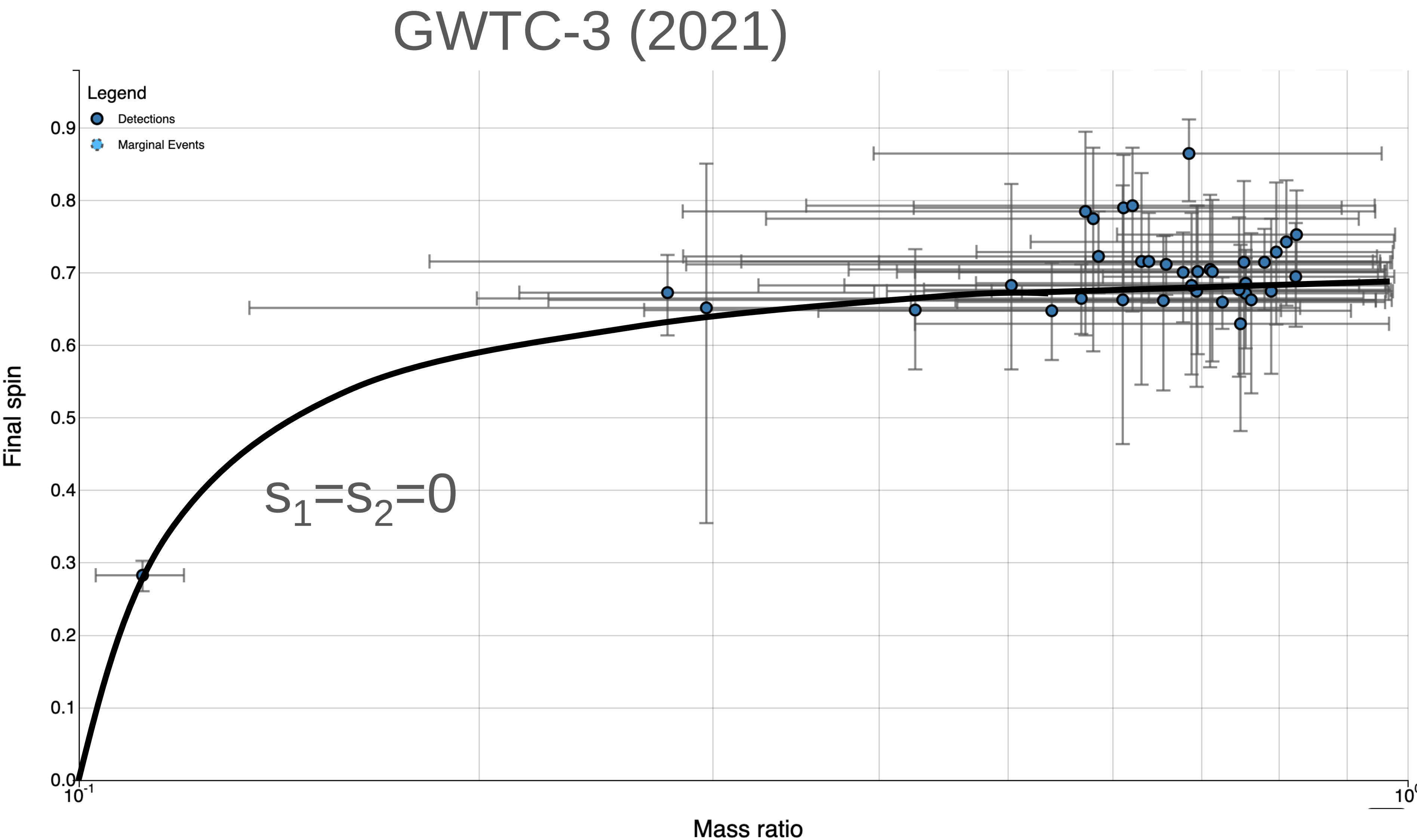
Mass ratio and effective spin



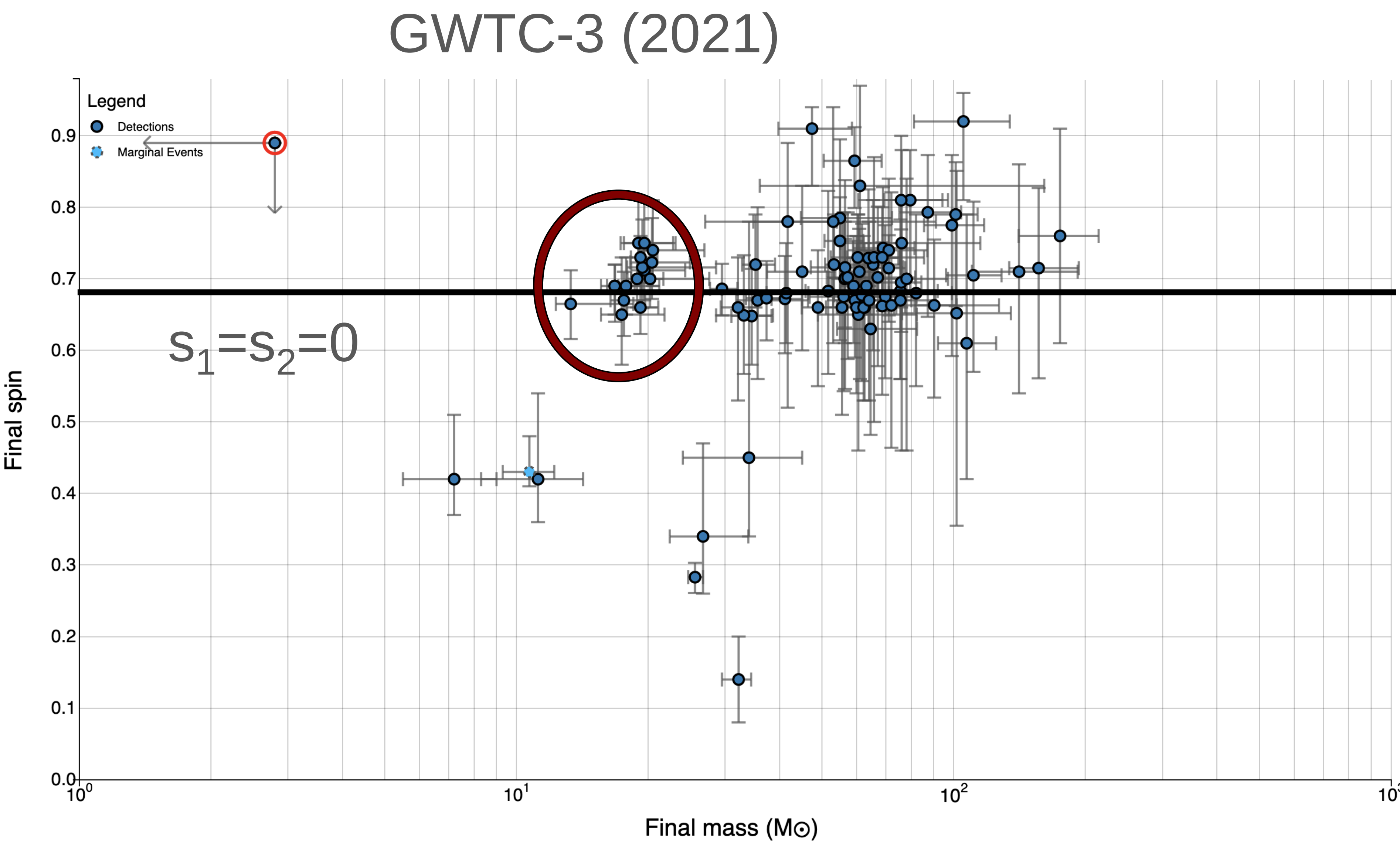
Final spin and effective spin



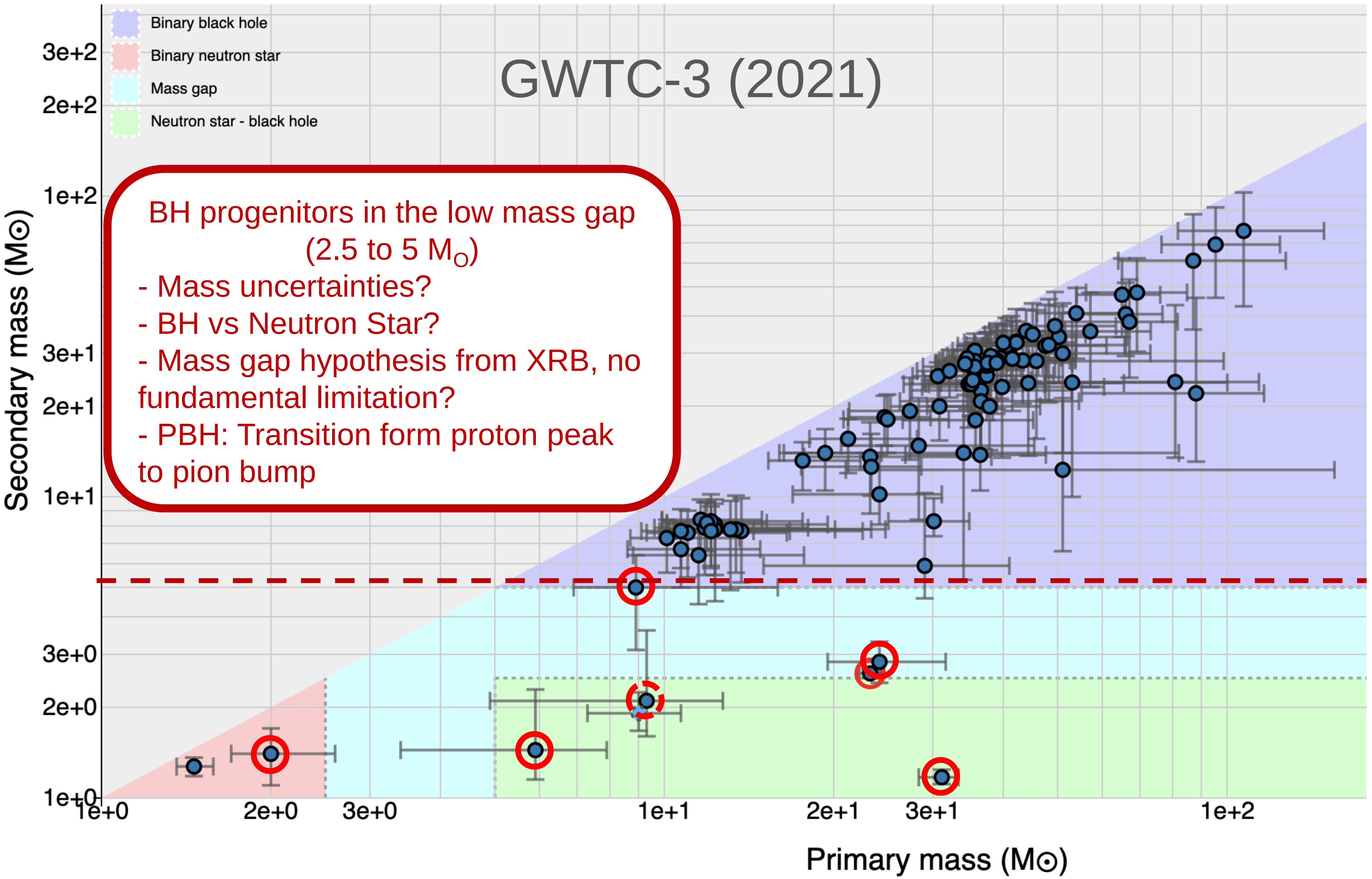
Mass ratio and final spin



Final mass and final spin



Are LIGO/Virgo BH Primordial?



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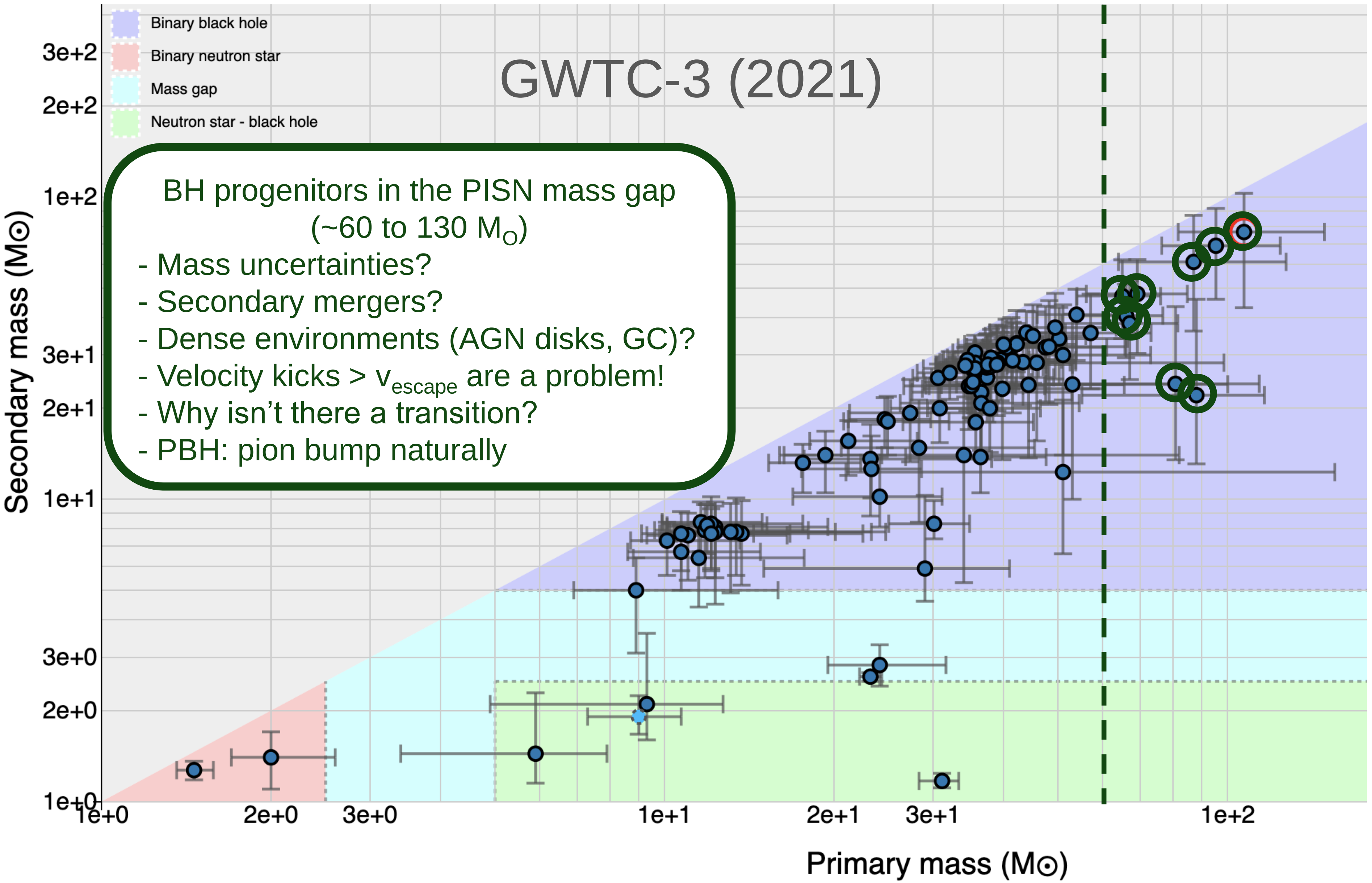

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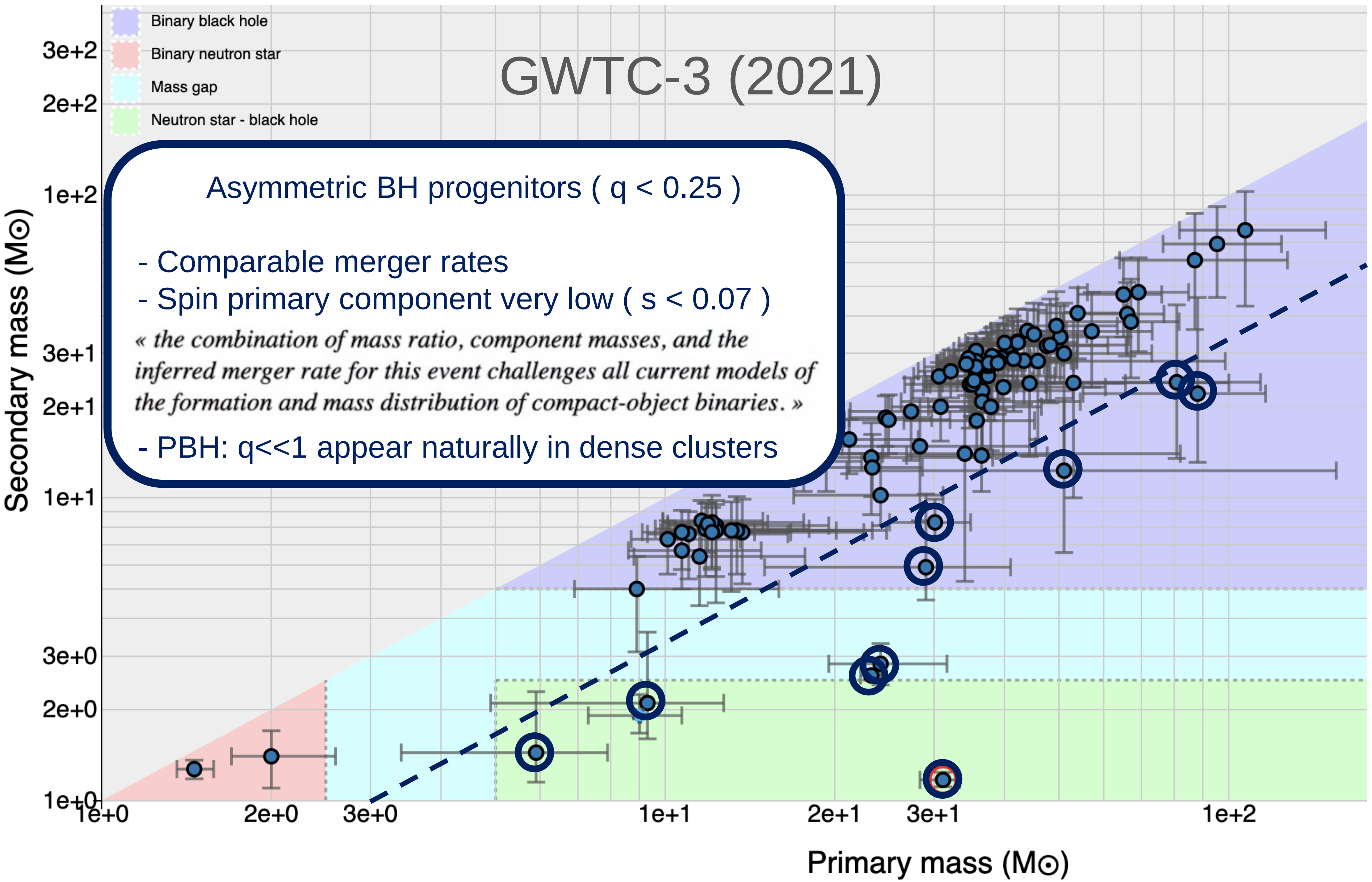

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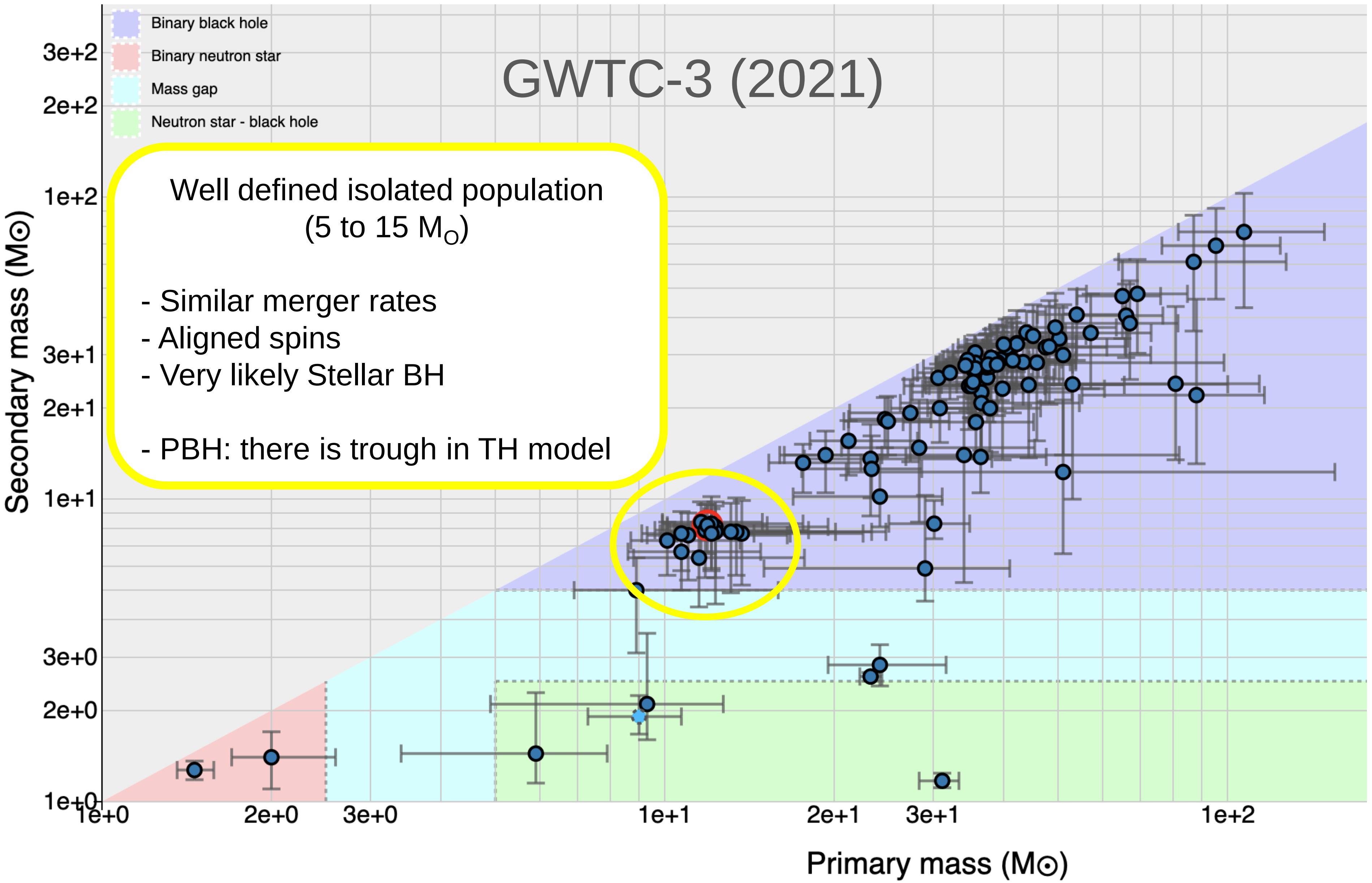
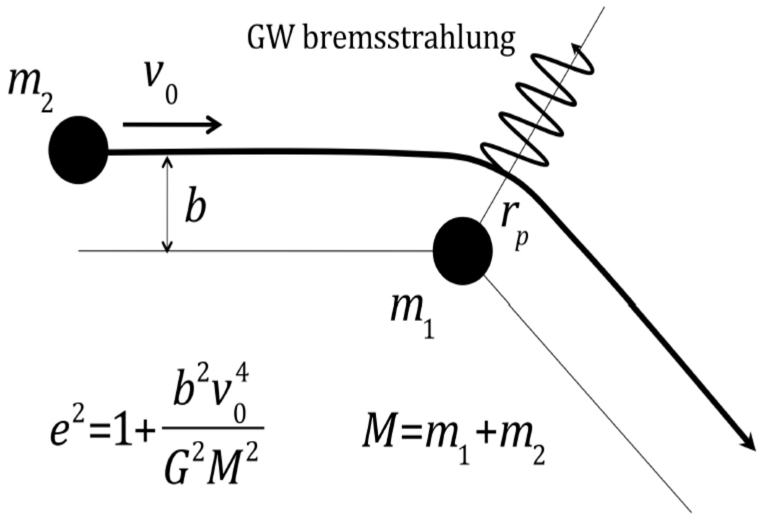


Close Hyperbolic Encounters

Primordial Black Holes in dense clusters scatter off each other



$$e^2 = 1 + \frac{b^2 v_0^4}{G^2 M^2} \qquad M = m_1 + m_2$$

$$\varphi_0 = \arccos\left(-\frac{1}{e}\right)$$

$$r(\varphi) = \frac{b \sin\varphi_0}{\cos(\varphi - \varphi_0) - \cos\varphi_0} = \frac{a\,(e^2 - 1)}{1 + e\cos(\varphi - \varphi_0)}$$

$$r_{\min} = a\,(e - 1) = b\sqrt{\frac{e-1}{e+1}} > R_s \equiv \frac{2GM}{c^2}$$

$$b\,v_0 = r_{\min}\,v_{\max} \qquad v_{\max} < c$$

$$\beta \equiv \frac{v_0}{c} < \sqrt{\frac{e-1}{e+1}} \qquad b > R_s\,\frac{(e+1)^{3/2}}{2(e-1)^{1/2}}$$

JGB, Nesseris (2018)

Close Hyperbolic Encounters

Amplitude and Power emitted in GW

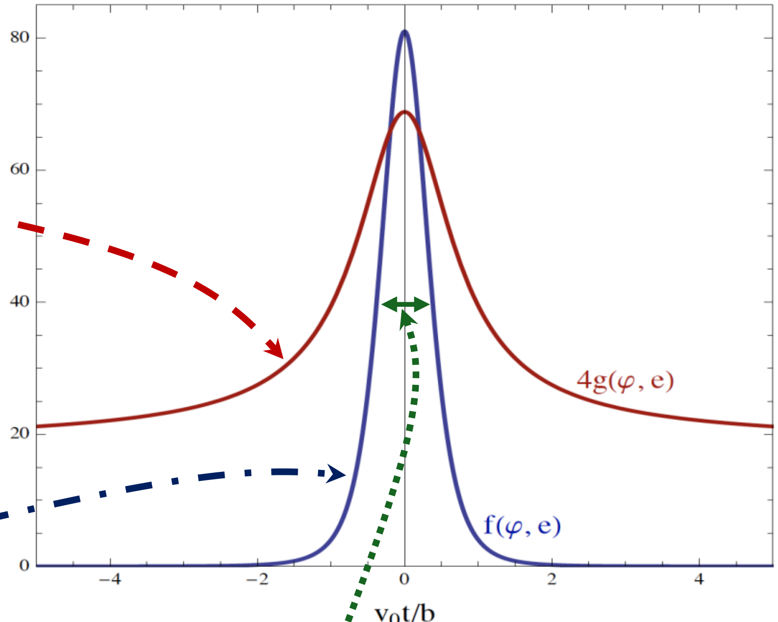
$$Q_{ij} = \mu\, r^2(\varphi) \begin{pmatrix} 3\cos^2\varphi - 1 & 3\cos\varphi\sin\varphi & 0 \\ 3\cos\varphi\sin\varphi & 3\sin^2\varphi - 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$h_c = \frac{2G}{R\,c^4}\langle \ddot{Q}_{ij}\ddot{Q}^{ij}\rangle^{1/2}_{i,j=1,2} = \frac{2G\mu\, v_0^2}{R\,c^4}\, g(\varphi,\, e)$$

$$g(\varphi,\, e) \;=\; \frac{\sqrt{2}}{e^2-1}\Big[36 + 59\,e^2 + 10\,e^4 + (108 + 47\,e^2)\,e\,\cos(\varphi-\varphi_0) + 59\,e^2\,\cos 2(\varphi-\varphi_0) + 9\,e^3\cos 3(\varphi-\varphi_0)\Big]^{1/2}$$

$$P = \frac{dE}{dt} = -\frac{G}{45c^5}\langle \dddot{Q}_{ij}\dddot{Q}^{ij}\rangle = \frac{32G\mu^2 v_0^6}{45c^5\, b^2}\, f(\varphi,\, e)$$

$$f(\varphi,\, e) \;=\; \frac{3\,(1+e\,\cos(\varphi-\varphi_0))^4}{8(e^2-1)^4}\Big[24 + 13\,e^2 + 48\,e\,\cos(\varphi-\varphi_0) + 11\,e^2\cos 2(\varphi-\varphi_0)\Big]$$



Time duration of Burst:

$$t_{1/2} \simeq 1ms\left(\frac{b}{10^{-8}\mathrm{AU}}\right)\left(\frac{0.01}{\beta}\right)(e-1)\sqrt{\frac{3\ln 2}{e + 35(1+e)e}}$$

JGB, Nesseris (2018)

Close Hyperbolic Encounters

Power spectrum (frequency domain)

$$\Delta E = \int_{-\infty}^{\infty} P(t)\,dt = \frac{1}{\pi}\int_{0}^{\infty} P(\omega)\,d\omega = -\frac{8}{15}\frac{G^{7/2}}{c^5}\frac{M^{1/2}m_1^2 m_2^2}{r_{min}^{7/2}} f(e)$$

$$f(e) = \frac{1}{(1+e)^{7/2}}\left[24\arccos\left(-\frac{1}{e}\right)\left(1+\frac{73}{24}e^2+\frac{37}{96}\right) + \sqrt{e^2-1}\left(\frac{301}{6}+\frac{673}{12}e^2\right)\right]$$

Quadrupole tensor

$$Q_{ij} = \frac{1}{2}a^2\mu\begin{pmatrix} (3-e^2)\cosh 2\xi - 8e\cosh\xi & 3\sqrt{e^2-1}(2e\sinh\xi - \sinh 2\xi) & 0 \\ 3\sqrt{e^2-1}(2e\sinh\xi - \sinh 2\xi) & (2e^2-3)\cosh 2\xi + 4e\cosh\xi & 0 \\ 0 & 0 & 4e\cosh\xi - e^2\cosh 2\xi \end{pmatrix}$$

$$r(\xi) = a(e\cosh\xi - 1) \qquad t(\xi) = \nu_0(e\sinh\xi - \xi) \qquad \nu_0 = \sqrt{a^3/GM}$$

Close Hyperbolic Encounters

Power spectrum (frequency domain)

$$
\begin{aligned}
P(\omega) &= \frac{G}{45c^5} \sum_{i,j} |\widehat{\dddot{Q}_{ij}}|^2 \\
&= \frac{G^3\mu^2 M^2}{a^2 c^5} \left(\frac{\pi^2}{180} \, \nu^4 \sum_{i,j} |\widehat{C_{ij}}|^2 \right) \\
&= \frac{G^3\mu^2 M^2}{a^2 c^5} \, \frac{16\pi^2}{180} \, \nu^4 F_e(\nu),
\end{aligned}
$$

$$
\begin{aligned}
F_e(\nu) &= \left| \frac{3(e^2-1)}{e} H^{(1)\prime}_{i\nu}(i\nu e) + \frac{e^2-3}{e^2} \frac{i}{\nu} H^{(1)}_{i\nu}(i\nu e) \right|^2 \\
&+ \left| \frac{3(e^2-1)}{e} H^{(1)\prime}_{i\nu}(i\nu e) + \frac{2e^2-3}{e^2} \frac{i}{\nu} H^{(1)}_{i\nu}(i\nu e) \right|^2 \\
&+ \left| \frac{i}{\nu} H^{(1)}_{i\nu}(i\nu e) \right|^2 + \frac{18\,(e^2-1)}{e^2} \times \\
&\times \left| \frac{(e^2-1)}{e} \, i \, H^{(1)}_{i\nu}(i\nu e) + \frac{1}{\nu} H^{(1)\prime}_{i\nu}(i\nu e) \right|^2
\end{aligned}
$$

Total energy emitted:

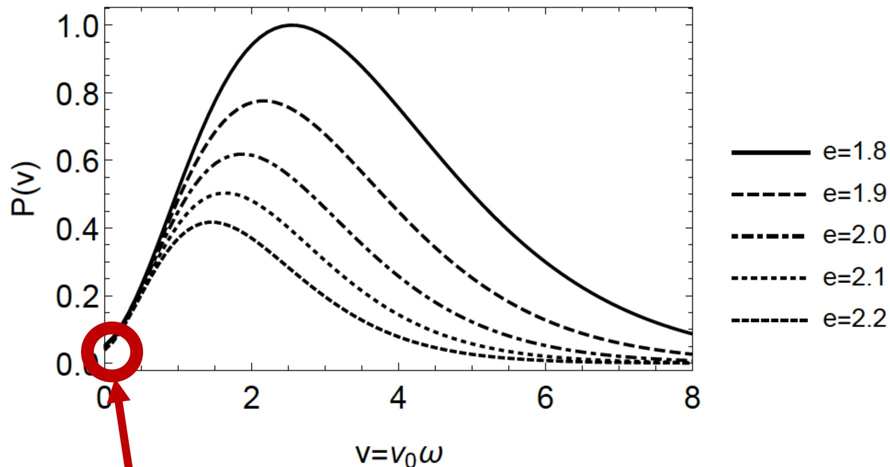
$$
\begin{aligned}
\Delta E &= \int_{-\infty}^{+\infty} P(t) dt = \int_0^{+\infty} \frac{P(\omega)}{\pi} d\omega \\
&= \left(\frac{G^{7/2}\mu^2 M^{5/2}}{c^5 a^{7/2}} \right) \frac{16\,\pi}{180} \int_0^{+\infty} \nu^4 F_e(\nu) d\nu \,.
\end{aligned}
$$

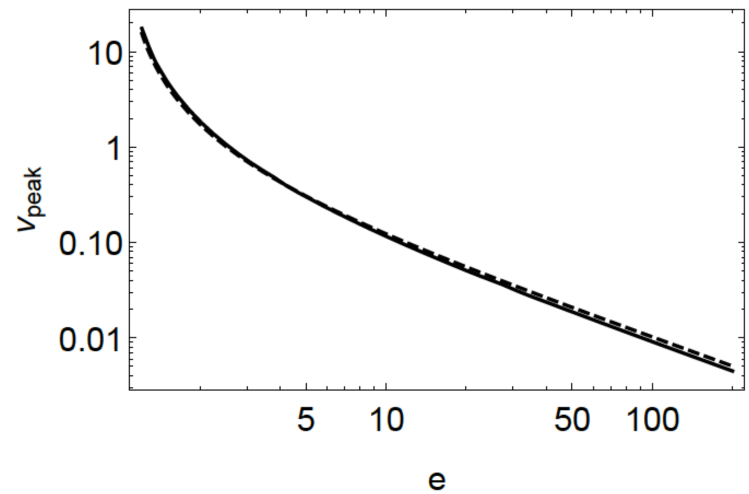
$$
\begin{aligned}
\nu^4 F_e(\nu) &\simeq \frac{12\, F_y(\nu)}{\pi\, y\, (y^2+1)^2} \, e^{-2\nu z(y)} \\
F_y(\nu) &= \nu \left(1 - y^2 - 3\nu y^3 + 4y^4 + 9\nu y^5 + 6\nu^2 y^6\right) \\
z(y) &= y - \arctan y \,, \qquad y \equiv \sqrt{e^2-1}
\end{aligned}
$$

Close Hyperbolic Encounters

Peak frequency: $P_{\max} = \frac{32}{45} \frac{q^2 \beta^{10}}{(1+q)^4} \frac{9(e+1)}{(e-1)^5} \frac{c^5}{G}$

$$c^5/G = M_P/t_P = 3.6295 \times 10^{59} \text{ erg/s} = 9.3064 \times 10^{25} \mathcal{L}_\odot,$$





GW memory effect (after scattering, s.t. remembers the event)

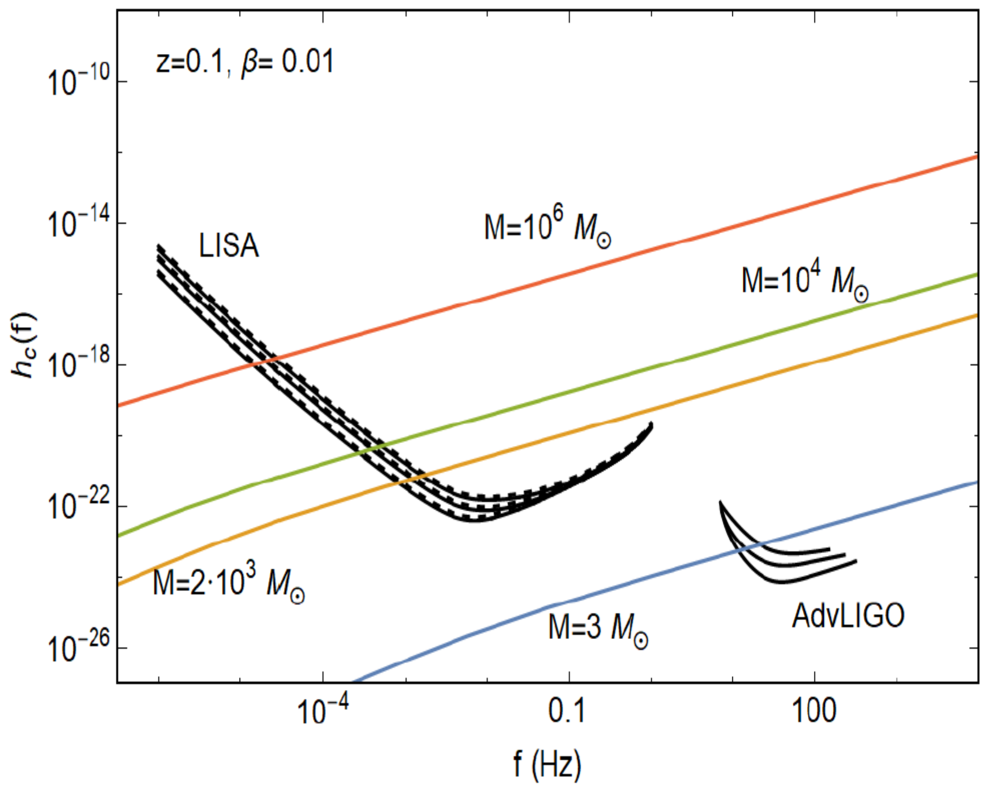
$$P(\omega=0) = \frac{G^3 \mu^2 M^2}{a^2 c^5} \frac{32\,(e^2-1)}{5e^4}.$$

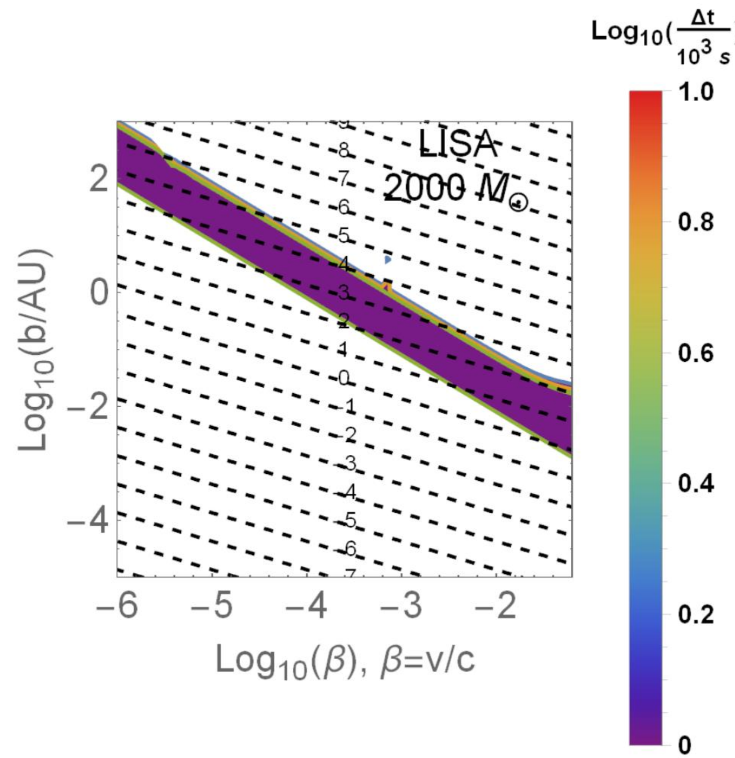
except for $e = 1$ and $e \to \infty$.

JGB, Nesseris (2018)

Close Hyperbolic Encounters

Detection at LIGO/Virgo/KAGRA and LISA

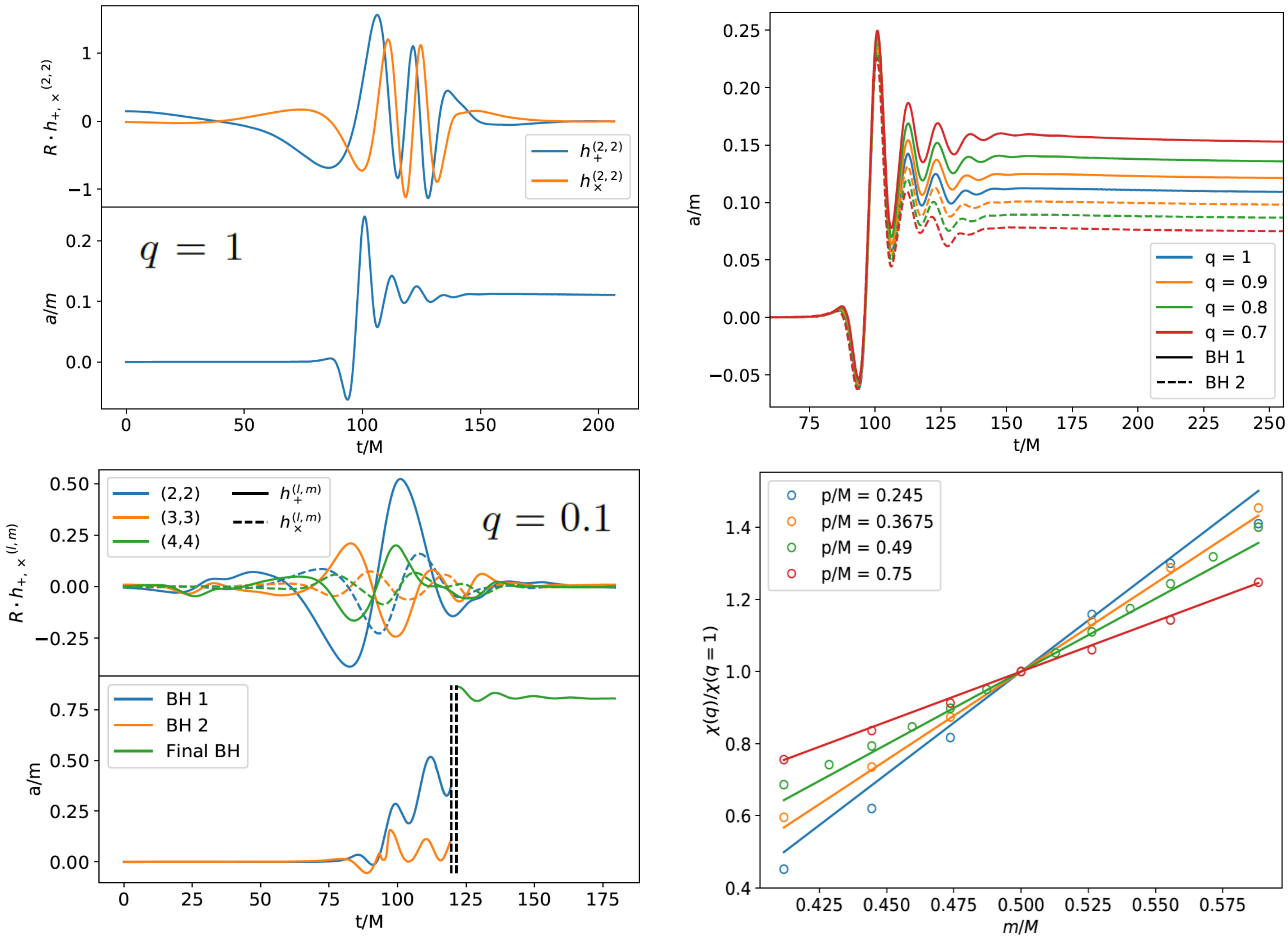




JGB, Nesseris (2018)

PBH spin-up by CHE

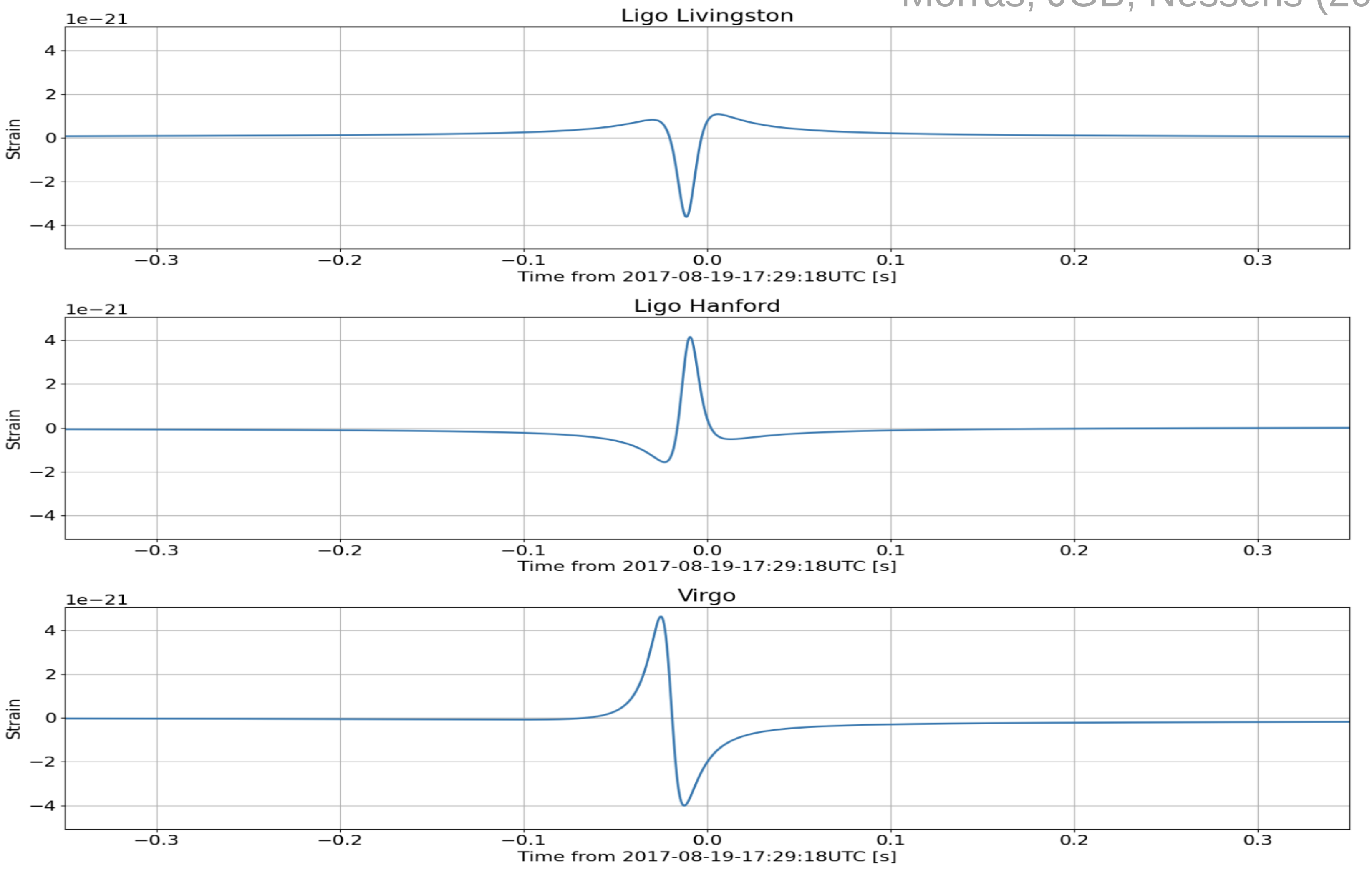
Jaraba, JGB (2021)



Close Hyperbolic Encounters

How do they look like?   Simulated injections

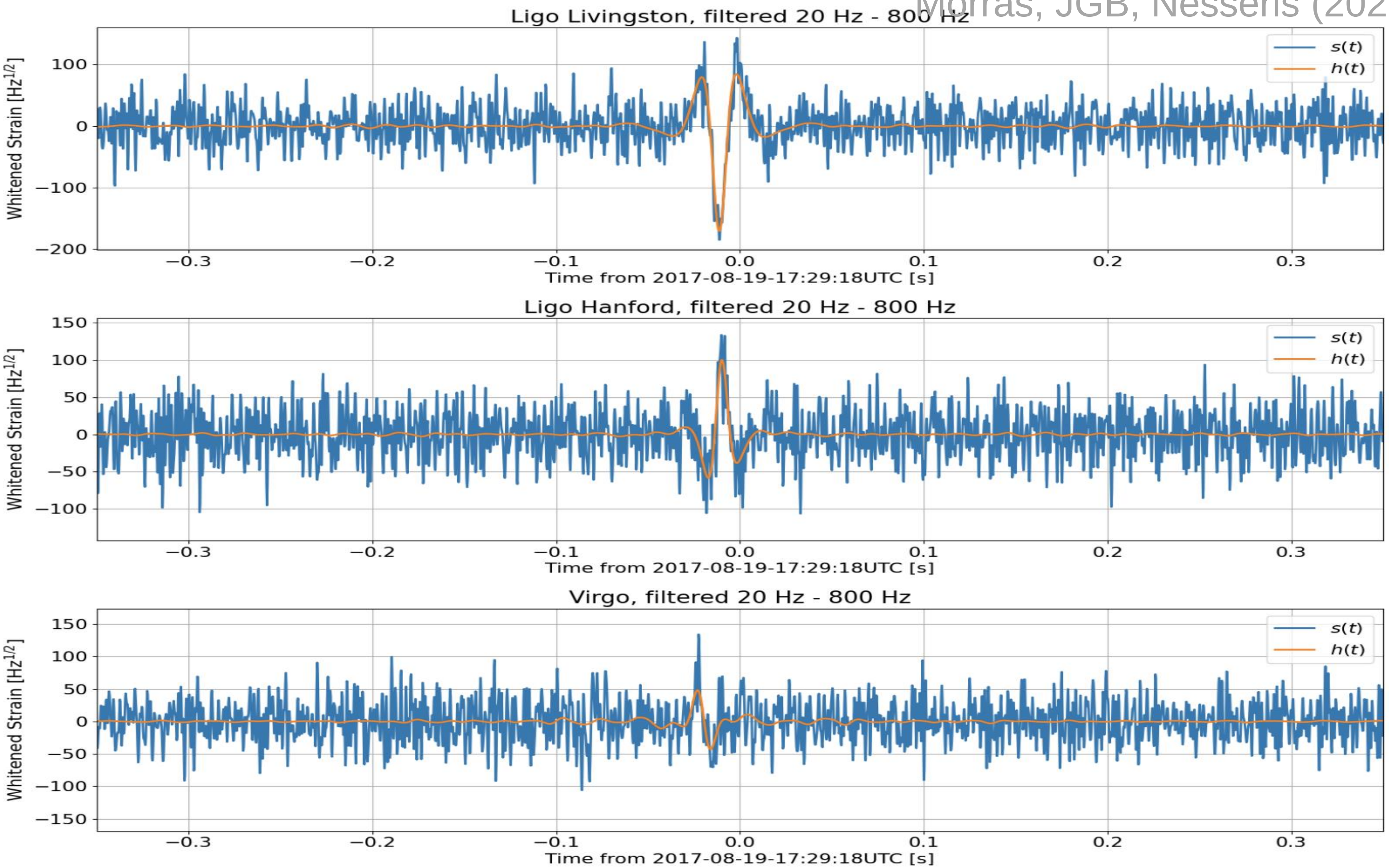
Morras, JGB, Nesseris (2021)



Close Hyperbolic Encounters

How do they look like? Strain amplitude h(t)

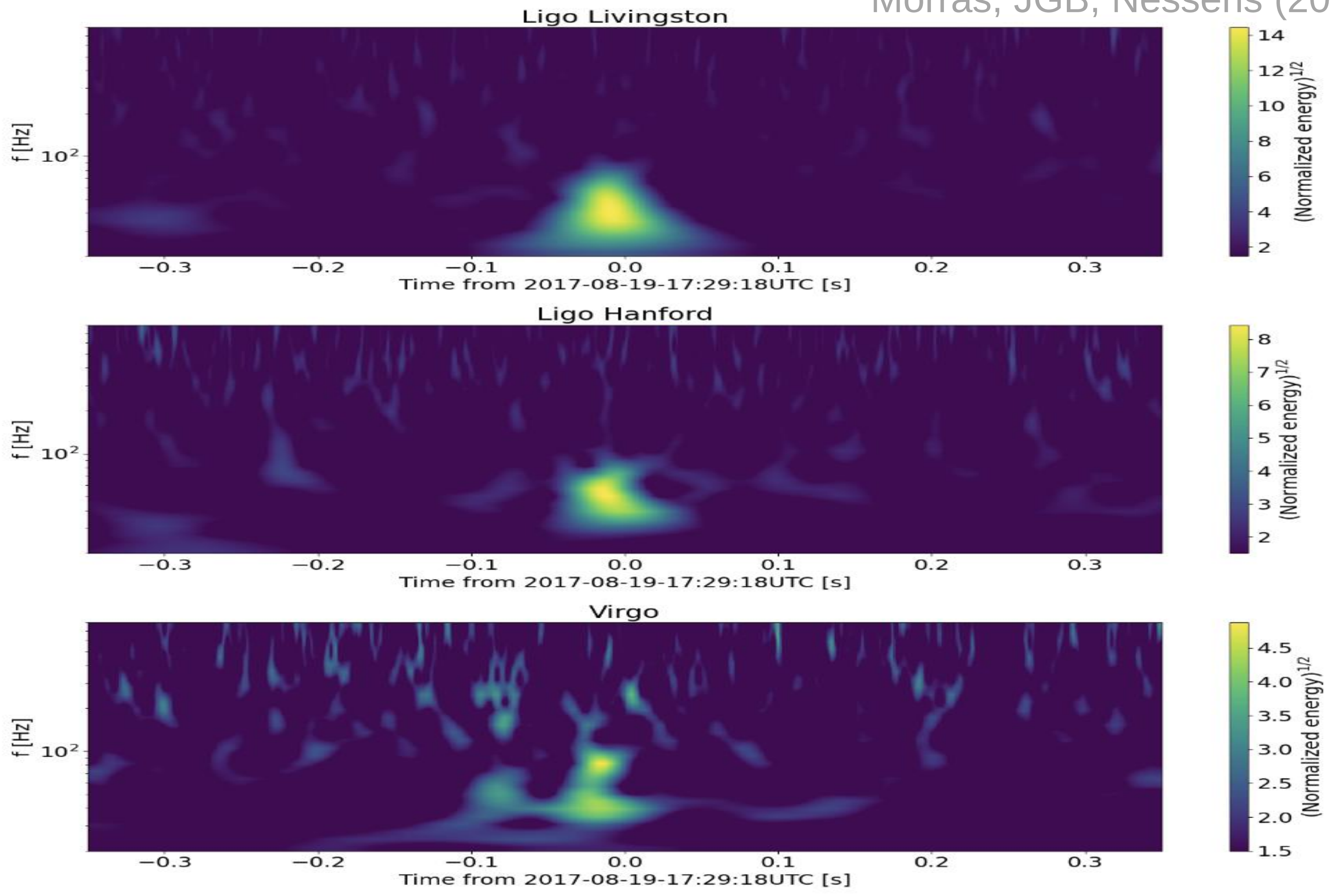
Morras, JGB, Nesseris (2021)



Close Hyperbolic Encounters

How do they look like? Spectrogram f(t)

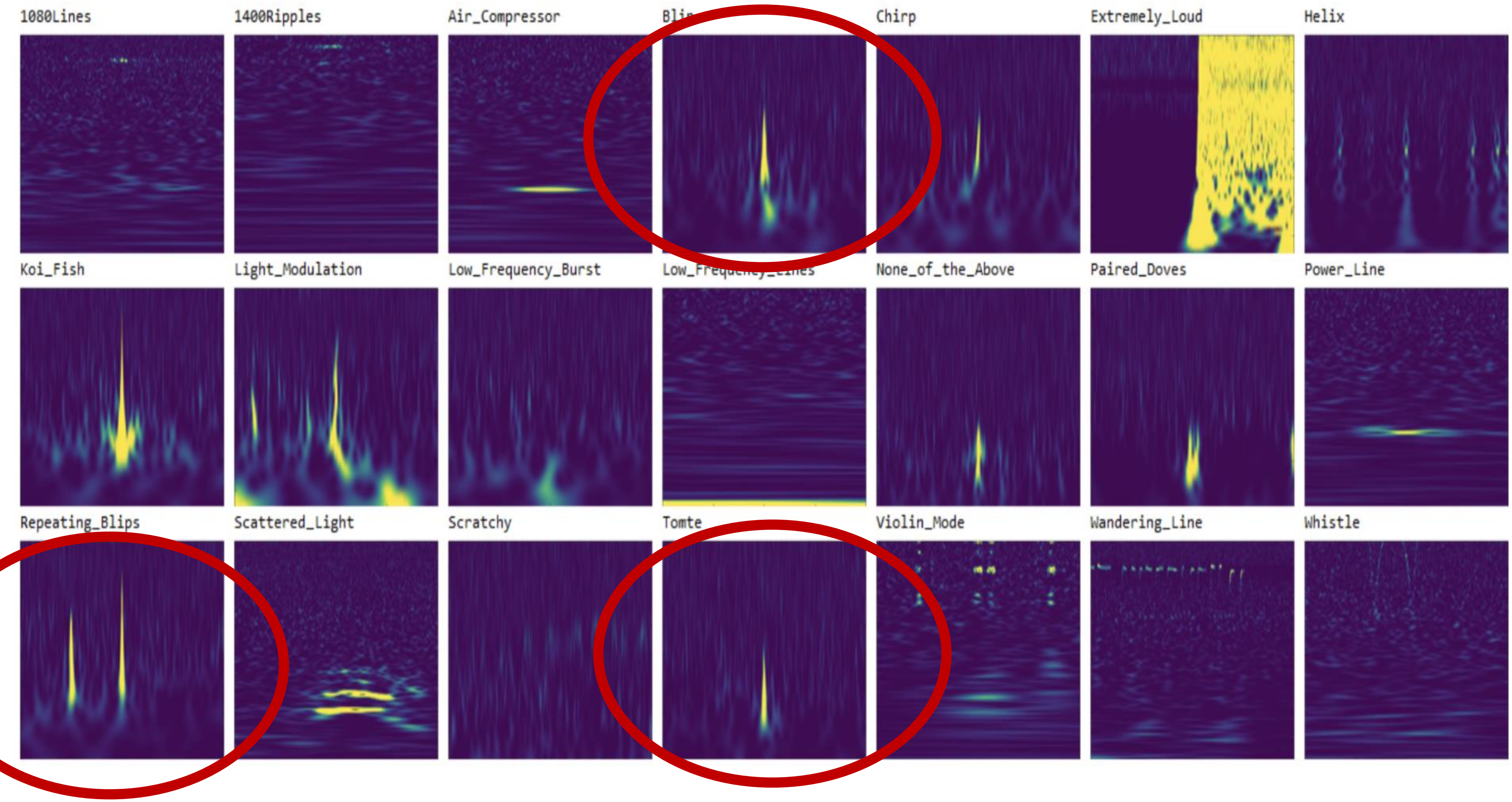
Morras, JGB, Nesseris (2021)



Close Hyperbolic Encounters

How do they look like?

Can they be confused with glitches?



Morras, JGB, Nesseris (2021)

SGWB from BBH & CHE

JGB, Jaraba, Kuroyanagi (2022)

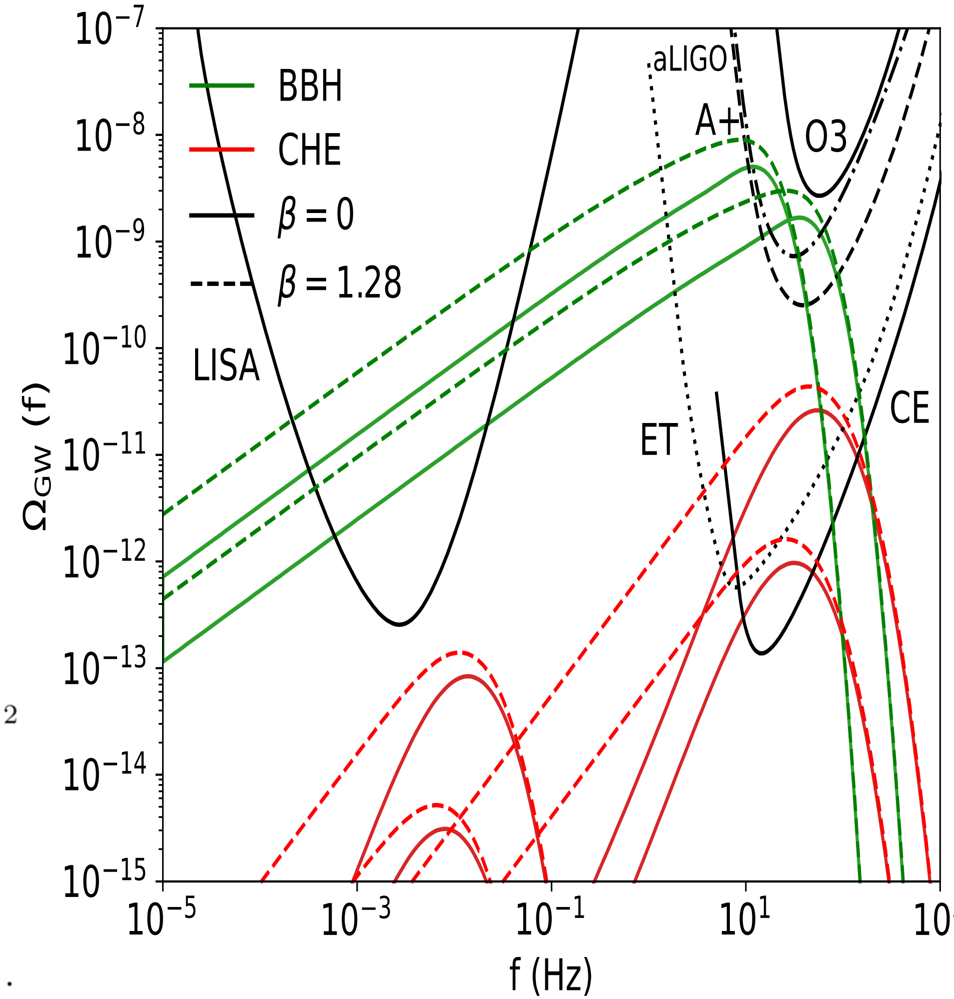
SGWB form Black Hole Binaries

$$\Omega_{\rm GW}^{\rm BBH}(f) \approx 2.39 \times 10^{-13}\, h_{70} \times \left(\frac{\Omega_{\rm DM}}{0.25}\right)^2 \left(\frac{\delta_{\rm loc}}{10^8}\right) \left(\frac{v_0}{10\ {\rm km/s}}\right)^{-11/7} \left(\frac{f}{\rm Hz}\right)^{2/3} \times \int dm_1\, dm_2 \frac{f(m_1)\, f(m_2)\, (m_1+m_2)^{23/21}}{(m_1\, m_2)^{5/7}}\,,$$

$$\tau(z) \propto (1+z)^\beta$$

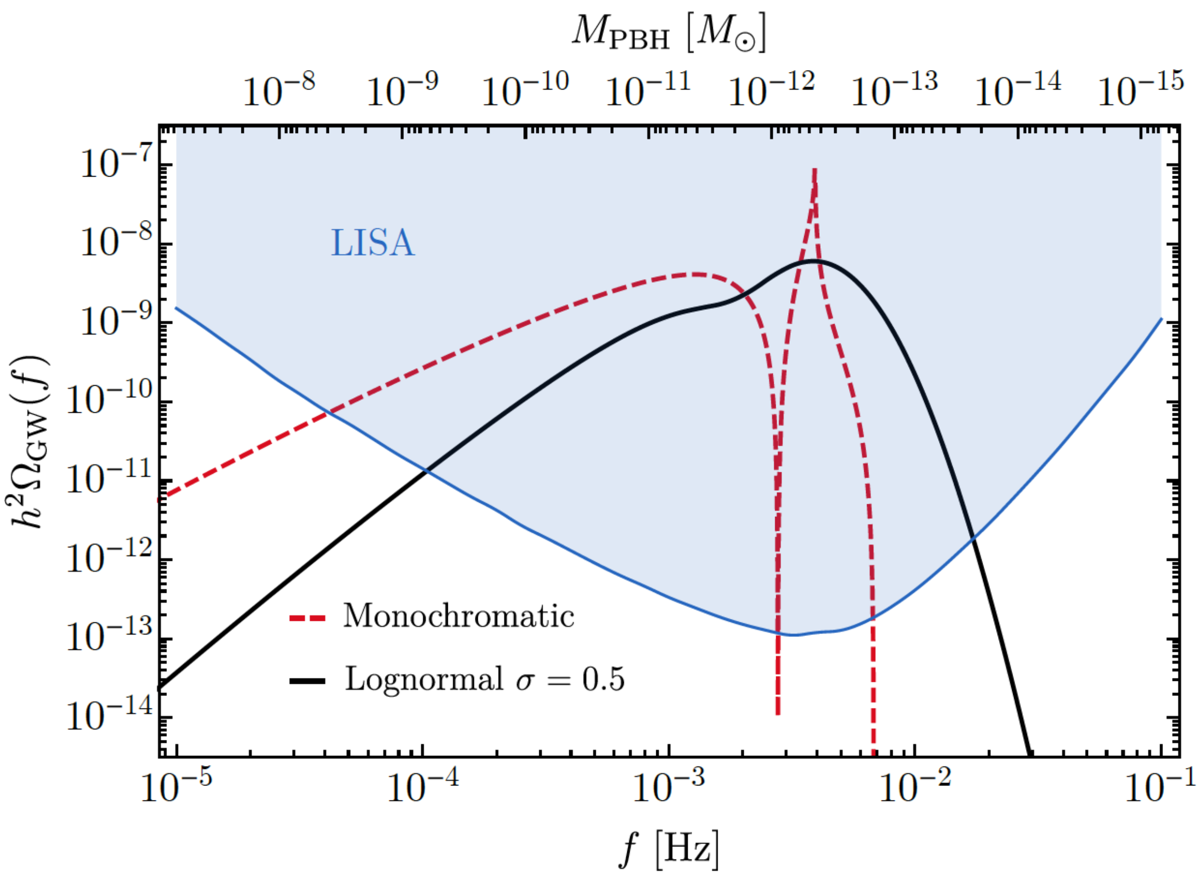
Close Hyperbolic Encounters

$$\Omega_{\rm GW}^{\rm CHE}(f) \approx 9.81 \times 10^{-13}\, h_{70} \left(\frac{\Omega_{\rm M}}{0.3}\right)^{-1/2} \left(\frac{\Omega_{\rm DM}}{0.25}\right)^2 \times \left(\frac{\delta_{\rm loc}}{10^8}\right) \left(\frac{a}{0.1\ {\rm AU}}\right) \left(\frac{f}{10{\rm Hz}}\right)^2 \left(\frac{y}{0.01}\right) \times \int \frac{dm_1}{100 M_\odot} \frac{dm_2}{100 M_\odot} f(m_1)\, f(m_2)\, e^{-2x_0 \xi(y)}\, \tilde{I}[y, x_0]\,.$$



SGWB: second order perturb.

JGB, Peloso, Unal (2018)
Bartolo et al. (2019)



Gaussian P(k)

Lognormal

$$\mathcal{P}_\zeta(k) = A_\zeta \exp\left(-\frac{\ln^2(k/k_\star)}{2\sigma^2}\right)$$

Monochromatic

$$\mathcal{P}_\zeta(k) = A_s\, k_\star \delta\left(k - k_\star\right)$$

$$\Omega_{\rm GW}(\eta_0, k) = \frac{\Omega_{r,0} A_s^2}{15552}\frac{g_*(\eta_f)}{g_*(\eta_0)}\left(\frac{g_{*S}(\eta_0)}{g_{*S}(\eta_f)}\right)^{4/3}\left(\frac{4k_\star}{k} - \frac{k}{k_\star}\right)^2 \theta\left(2k_\star - k\right)\left[\mathcal{I}_c^2\left(\frac{k_\star}{k}, \frac{k_\star}{k}\right) + \mathcal{I}_s^2\left(\frac{k_\star}{k}, \frac{k_\star}{k}\right)\right]$$

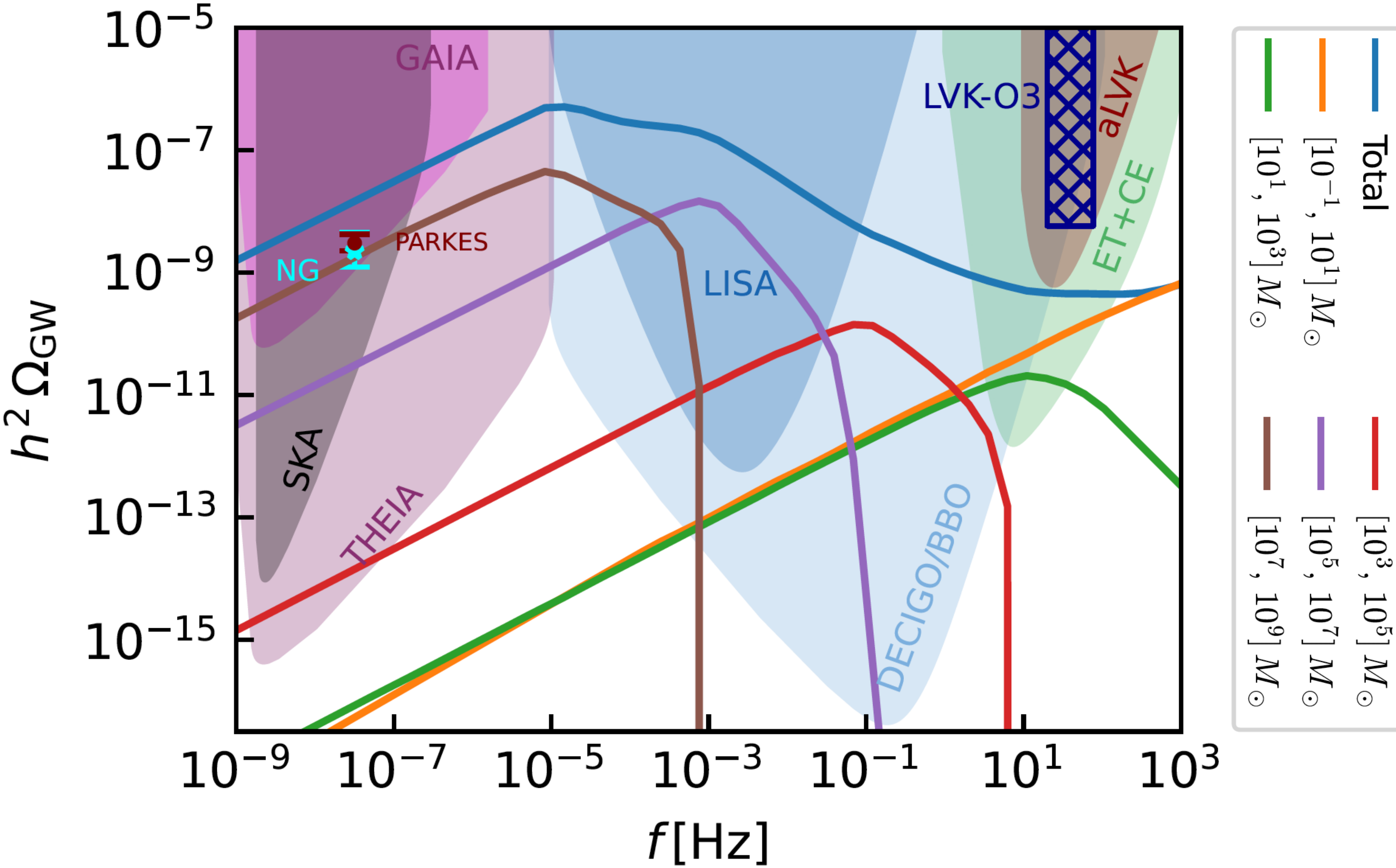
$$\mathcal{I}_c(x,y) = -36\pi\frac{(s^2+d^2-2)^2}{(s^2-d^2)^3}\theta(s-1)\ ,$$

$$\mathcal{I}_s(x,y) = -36\frac{(s^2+d^2-2)}{(s^2-d^2)^2}\left[\frac{(s^2+d^2-2)}{(s^2-d^2)}\log\frac{(1-d^2)}{|s^2-1|} + 2\right]$$

$$d \equiv \frac{1}{\sqrt{3}}|x-y|, \qquad s \equiv \frac{1}{\sqrt{3}}(x+y), \qquad (d,s) \in [0, 1/\sqrt{3}] \times [1/\sqrt{3}, +\infty).$$

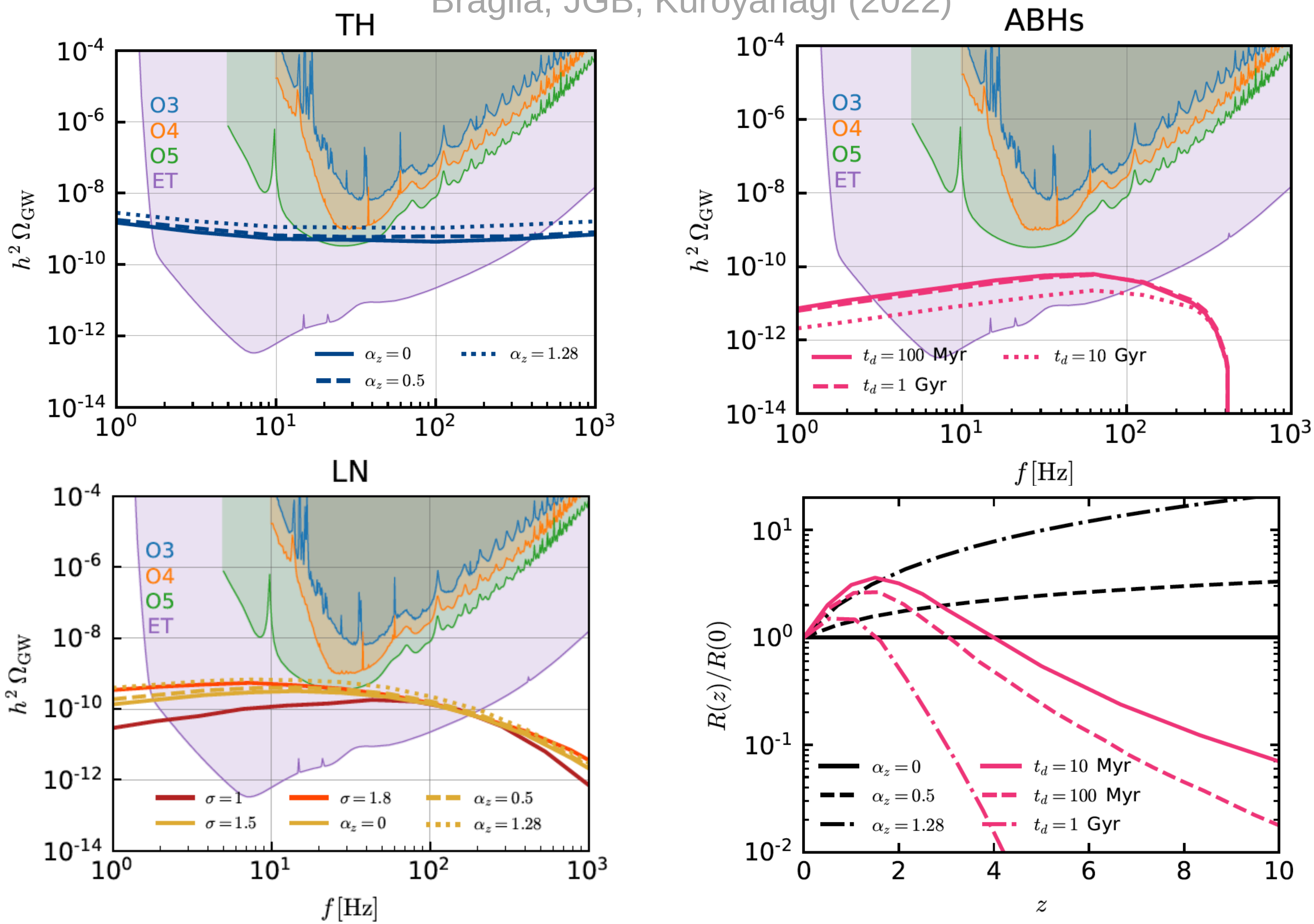
SGWB: Thermal History Model

Braglia, JGB, Kuroyanagi (2022)

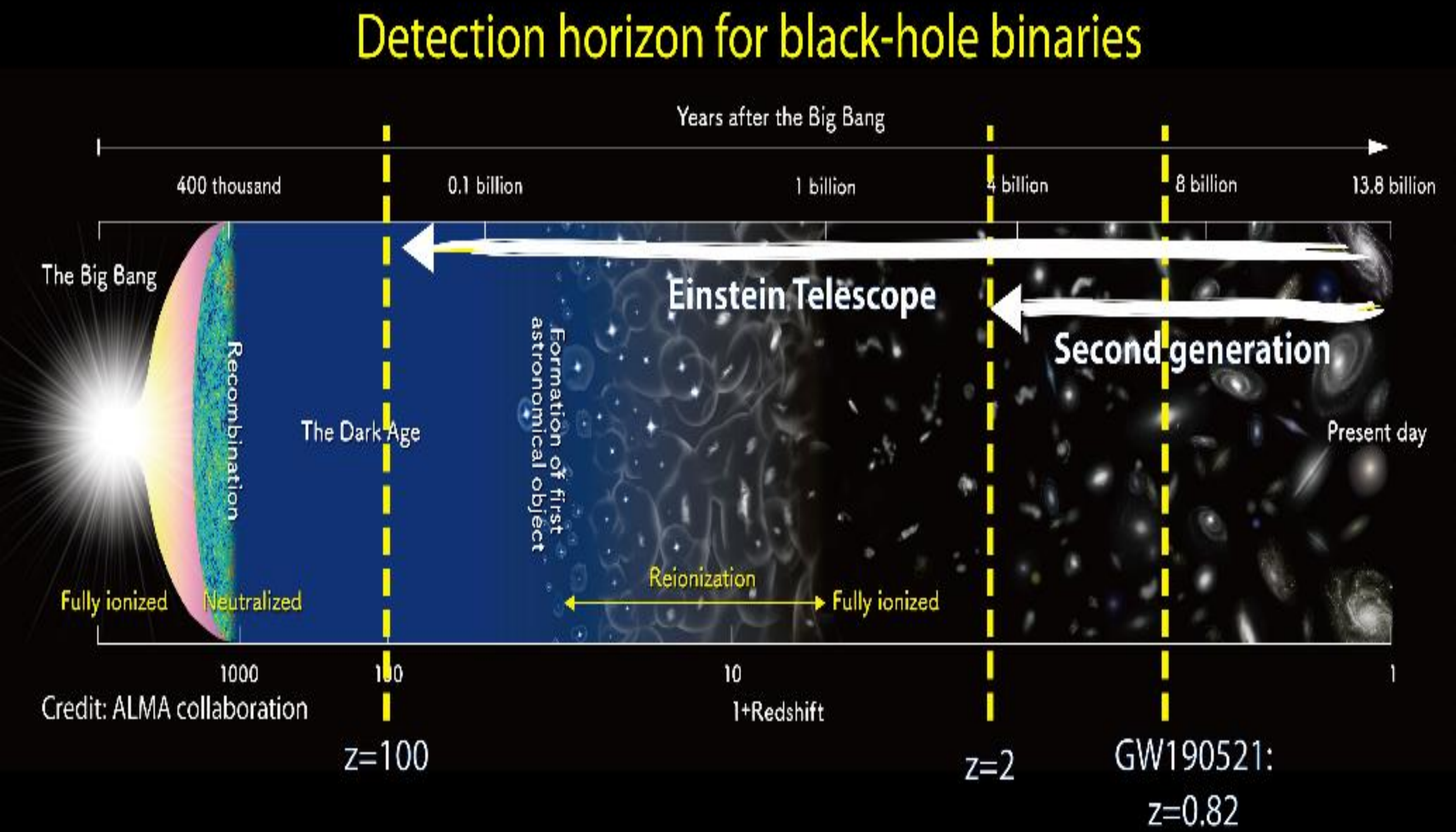


SGWB: TH vs LN vs ABH

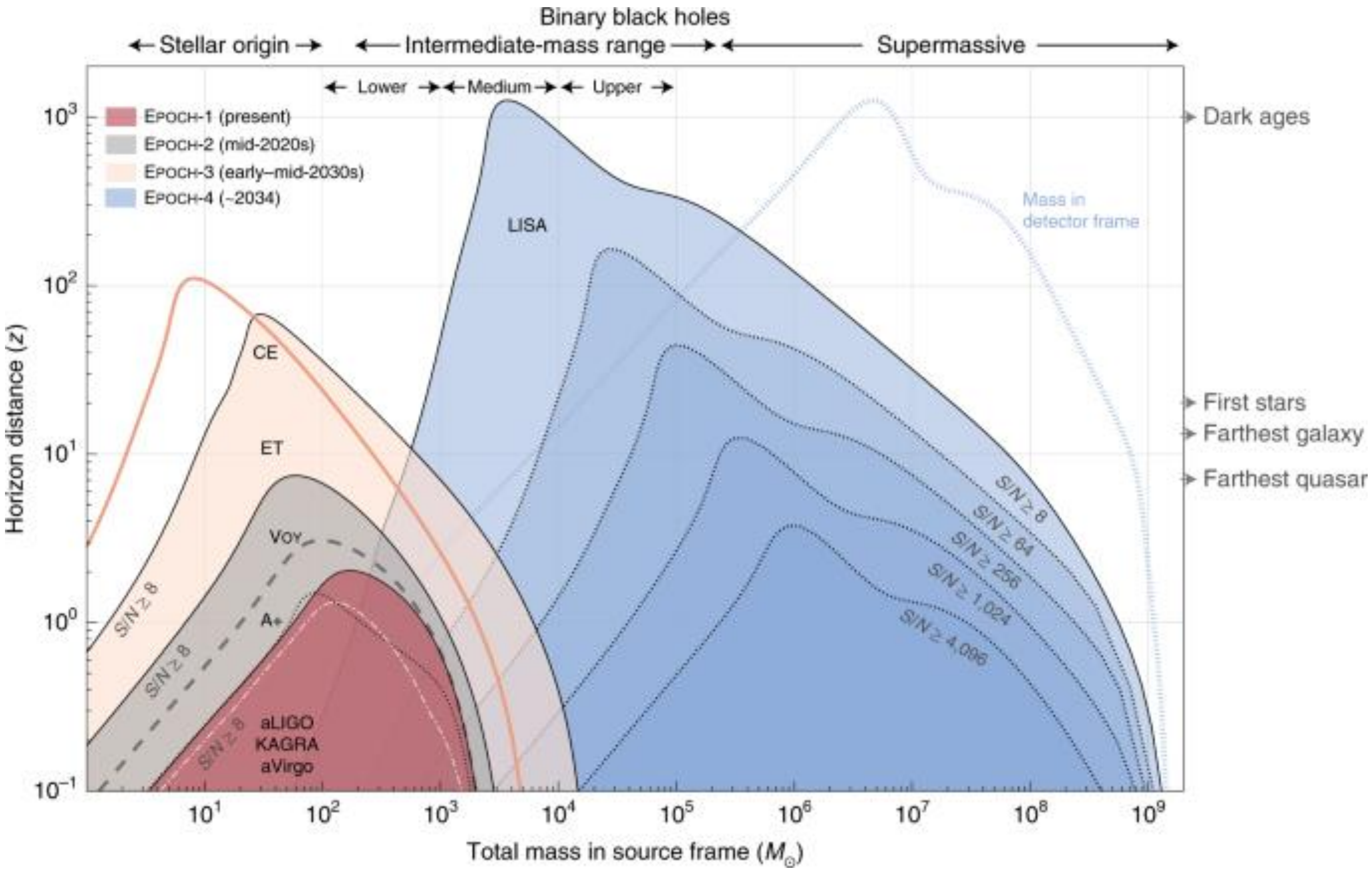
Braglia, JGB, Kuroyanagi (2022)



The future of GW (G3)



BBH sensitivity in future G3 GW



Conclusions

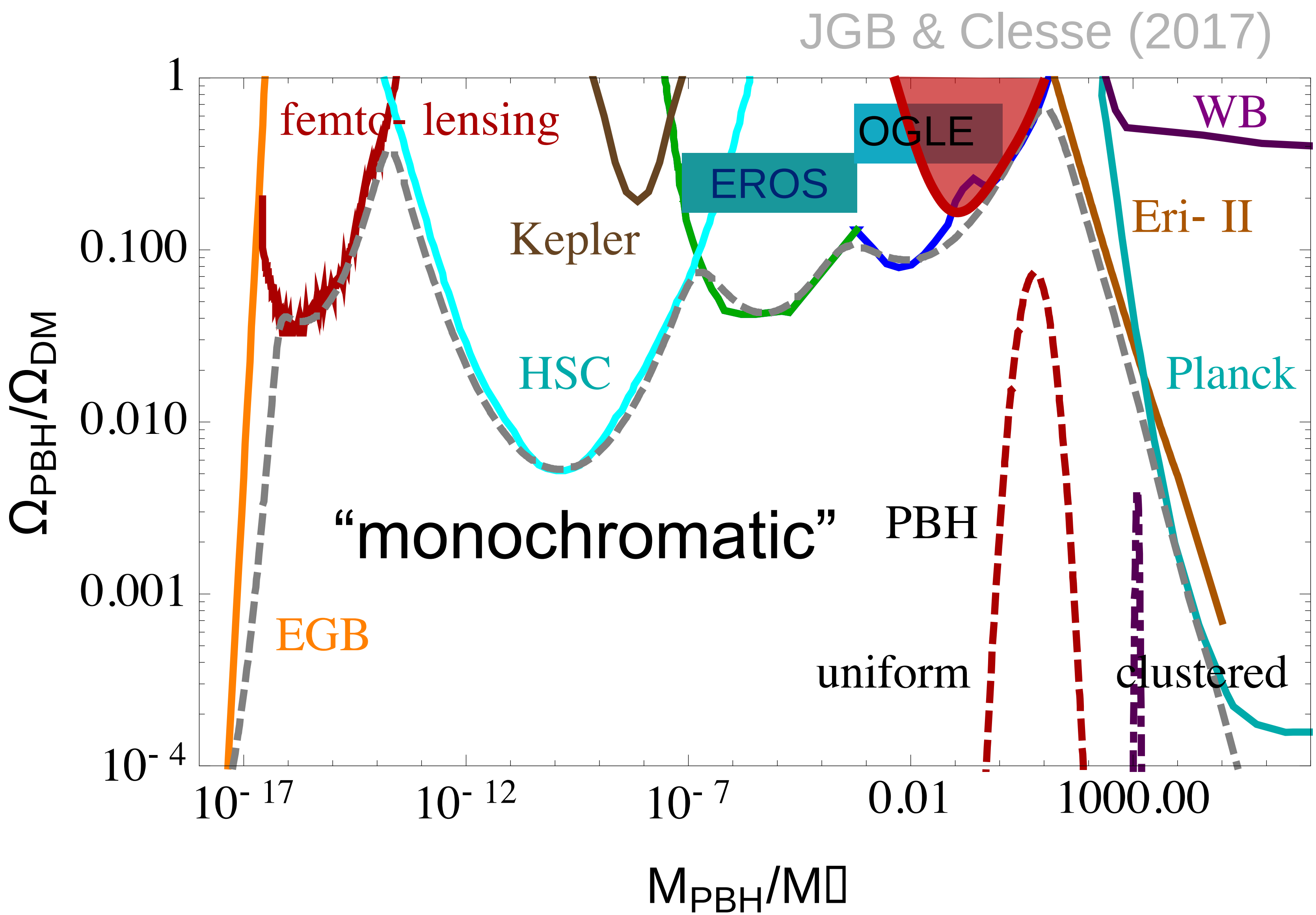
- Quantum diffusion inevitably generates PBH
- Thermal history predicts PBH have multimodal mass distribution ~ 1E-5, 1, 100, 1E5 Msun (1E-10 also?)
- The predicted PBH spin and mass distribution has been measured by LIGO/Virgo + OGLE around 1-100 Msun (features: peak+plateau)
- Other peaks could be explored with microlensing
- PBH scenario can explain various cosmic conundra
- Paradigm shift in Structure Formation of Universe
- Very rich phenomenology: multiscale, multiepoch, multiprobe => Future G3 detectors (ET, LISA, GAIA)

Backup slides

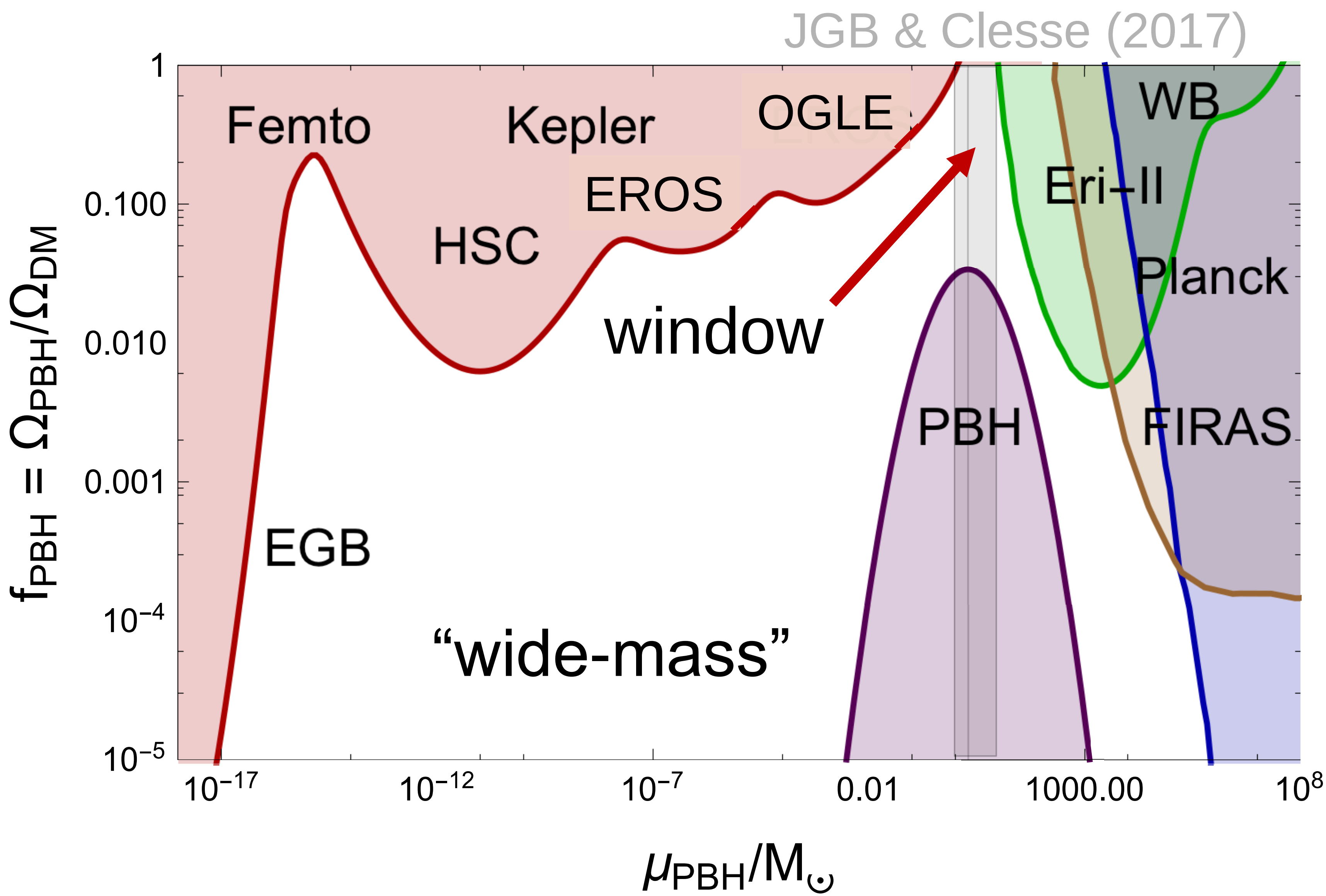
PBH scenario (1996-2022)

- From Quantum Fluctuations during inflation to PBH as all of DM
- Quantum diffusion → NG tails → PBH inevitable @ small scales
- Gravitational collapse during radiation era: Thermal History
- Origin of matter (baryons) and DM at QCD transition: $\Omega_{\rm DM} \sim 5\Omega_{\rm B}$
- Multimodal mass distribution PBH: 10^{-5}, 1, 50, 10^5 Msun
- PNG → Clustered PBH: 10^6 Msun evades all "monochromatic"
- Seeds for Large Scale Structure: IMBH and SMBH
- Resolve Small Scale Structure CDM crisis: UFDG, core-cusp…
- Very rich phenomenology: wealth of observational signatures
- Gravitational Lensing probes: strong, weak, micro, etc.
- Gravitational Waves probe: mass, spin, merger rate, clustering
- CMB spectral distortions: mass range, clustering prop. PBH
- Galactic structures: UFDG, rot. curves, MBH(Mhalo), HVS-GAIA
- Bright future: G3 GWO ET & LISA, LSST, Pixie, Theia,

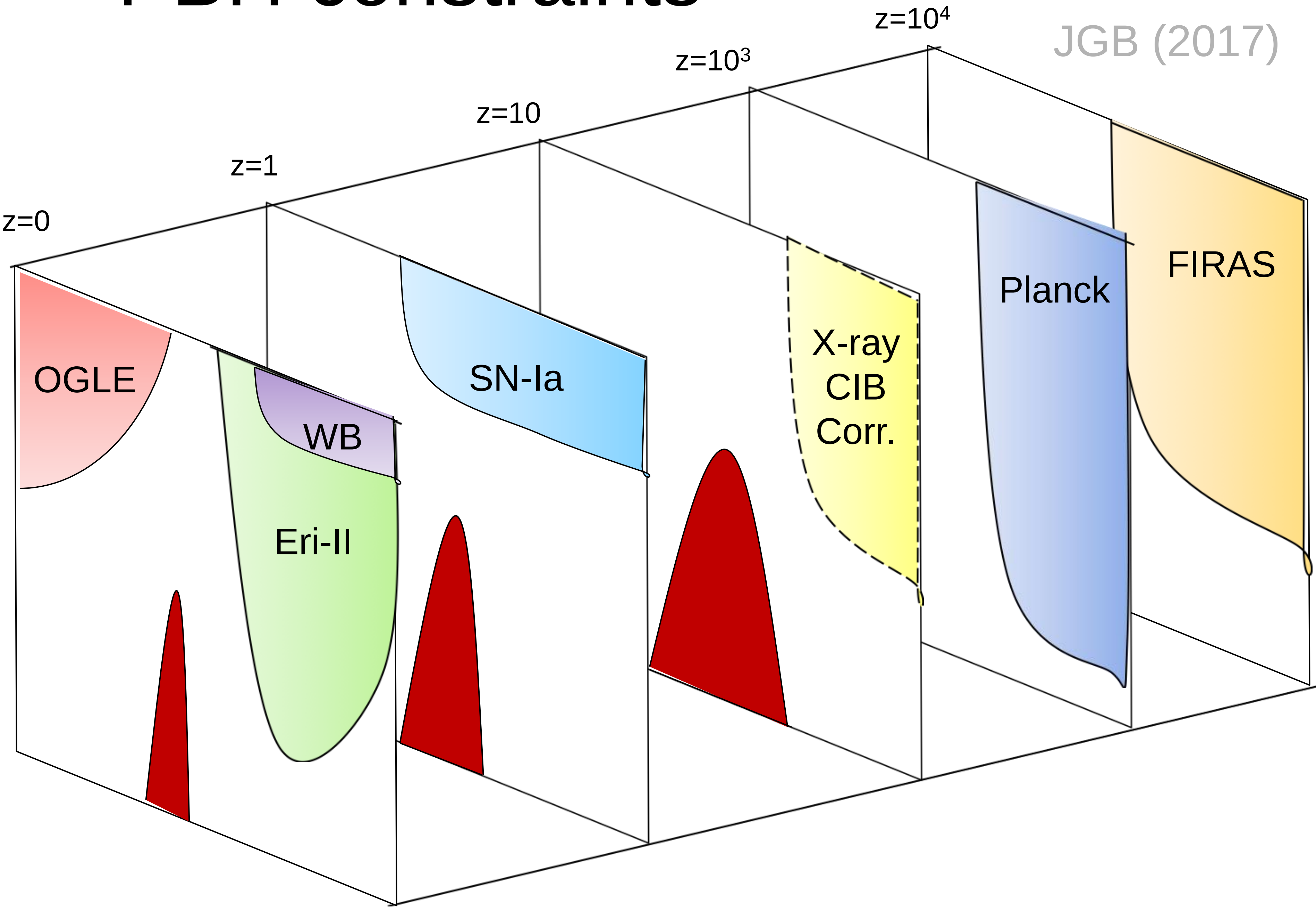
PBH constraints



PBH constraints



PBH constraints

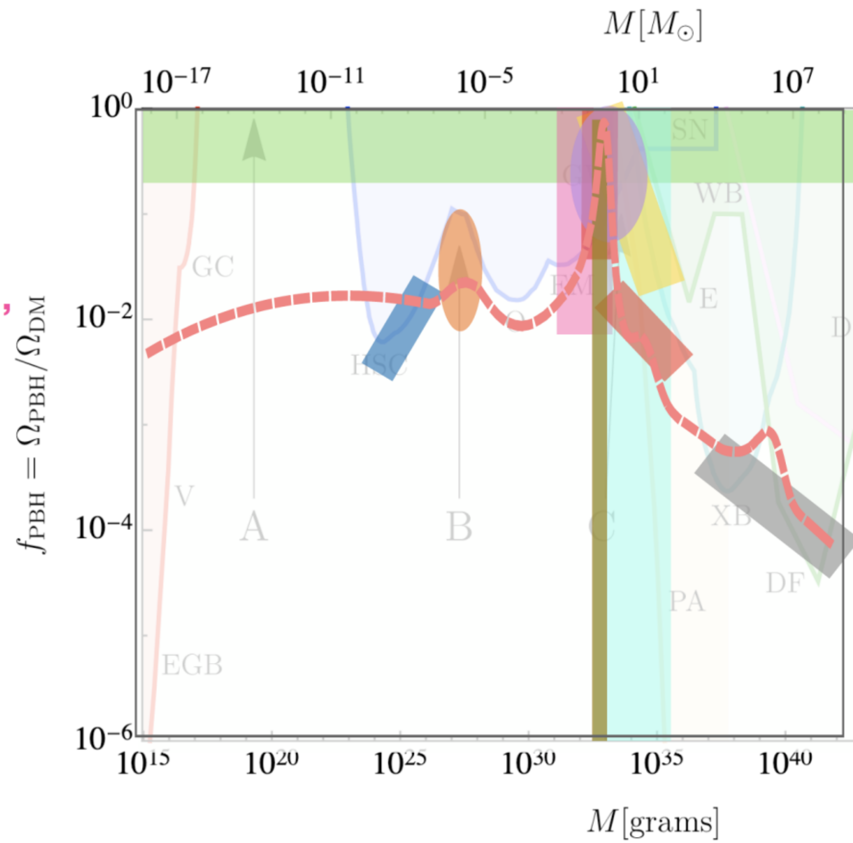


PBH constraints

Clesse (2021)

Limits vs clues: a question of point of view

- Dark Matter [Chapline 75, Carr+Hawking 75]
- HSC: short microlensing event [Niikura+17]
- OGLE: microlensing in galactic center [Mros+17]
- Quasar micrrolensing in non-aligned galaxies [Hawkins], (+microlensing in M31 and SMC/LMC)
- OGLE+Gaia: BHs in the low mass gap, towards the galactic center) [Wyrzykowski+19]
- Critical radius of ultra-faint dwarf galaxies [SC+17]
- Core-cusp problem [SC+17, Boldrini+19]
- LIGO/Virgo (solar-mass and 20-100 solar mass)
- GW background from pulsar timing arrays [De Luca+19]
- Intermediate-mass and supermassive black holes (one per halo and BH-halo mass relation) [Carr+19]



Carr & Kuhnel, 2006.02838

Cosmic Conundra explained

Clesse, JGB (2017)

Carr, Clesse, JGB, Kühnel (2019)

- Planetary-mass microlensing
- Quasar microlensing
- OGLE/GAIA microlensing Gal.Bulge
- CIB/X-ray background
- UFDG substructure large M/L
- IMHB & SMBH seeds for LSS
- Mass, spin & merger rate LVC BBH

Massive PBH = seeds of structure

- Massive primordial black holes with $10^{-5}\ M_\odot < M_{PBH} < 10^6\ M_\odot$, which cluster and merge and could resolve some of the most acute problems of ΛCDM paradigm.
- ΛCDM N-body simulations never reach the $10^3\ M_\odot$ particle resolution, so for them PBH DM is as good as Particle DM.
- PBH DM paradigm naturally incorporates all properties of collisionless CDM scenario on large scales but differs on small scales.

CIB x CXB fluctuations indicate high-z BH population

SIGNIFICANT COSMIC BACKGROUND FLUCTUATIONS HAVE BEEN FOUND BOTH IN THE NIR AND IN X-RAYS.

THE STRONG CIB/CXB CROSS-CORRELATION SIGNAL INDICATES A SUBSTANTIAL CONTRIBUTION OF BLACK HOLES TO THE SIGNAL.

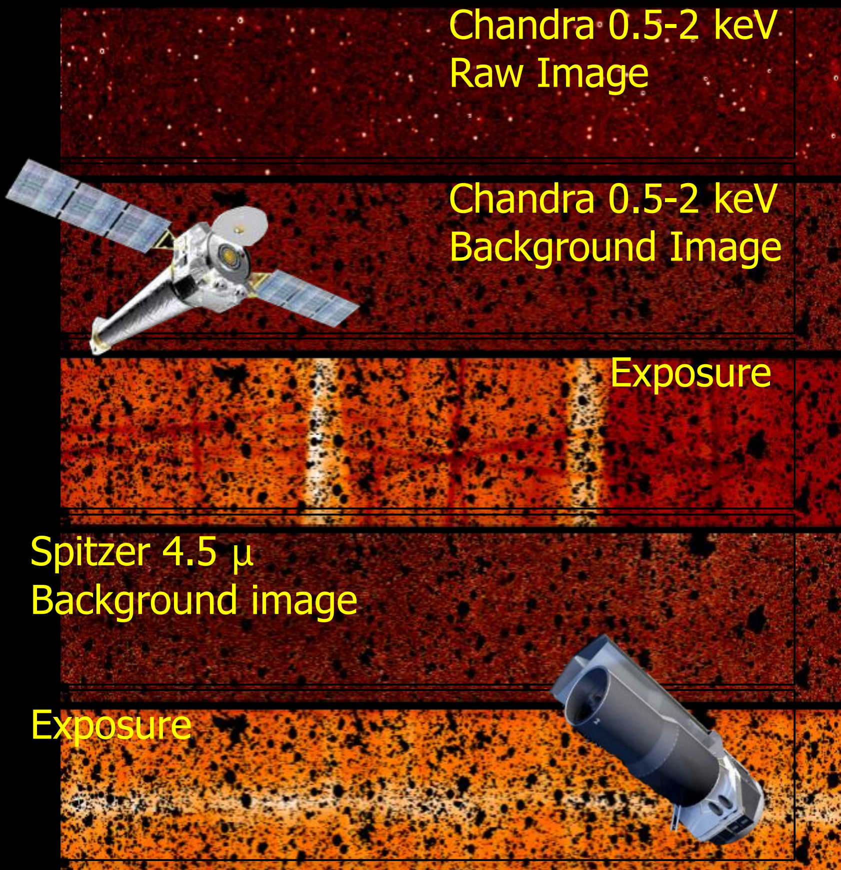
THERE IS NO CORRELATION WITH FLUCTUATIONS IN THE DEEPEST HST IMAGES, THEREFORE THE SIGNAL LIKELY COMES FROM REDSHIFTS Z>13.

LARGE ANGULAR SCALE ALSO POINTS TO HIGH-Z ORIGIN.

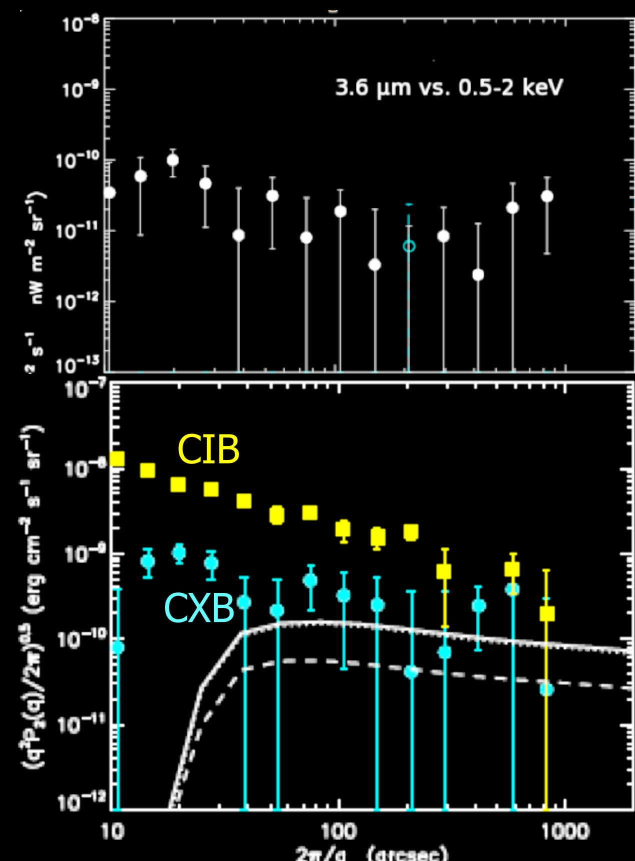
Hasinger (2021)

Fingerprint of the first Black Holes?

Hasinger (2021)



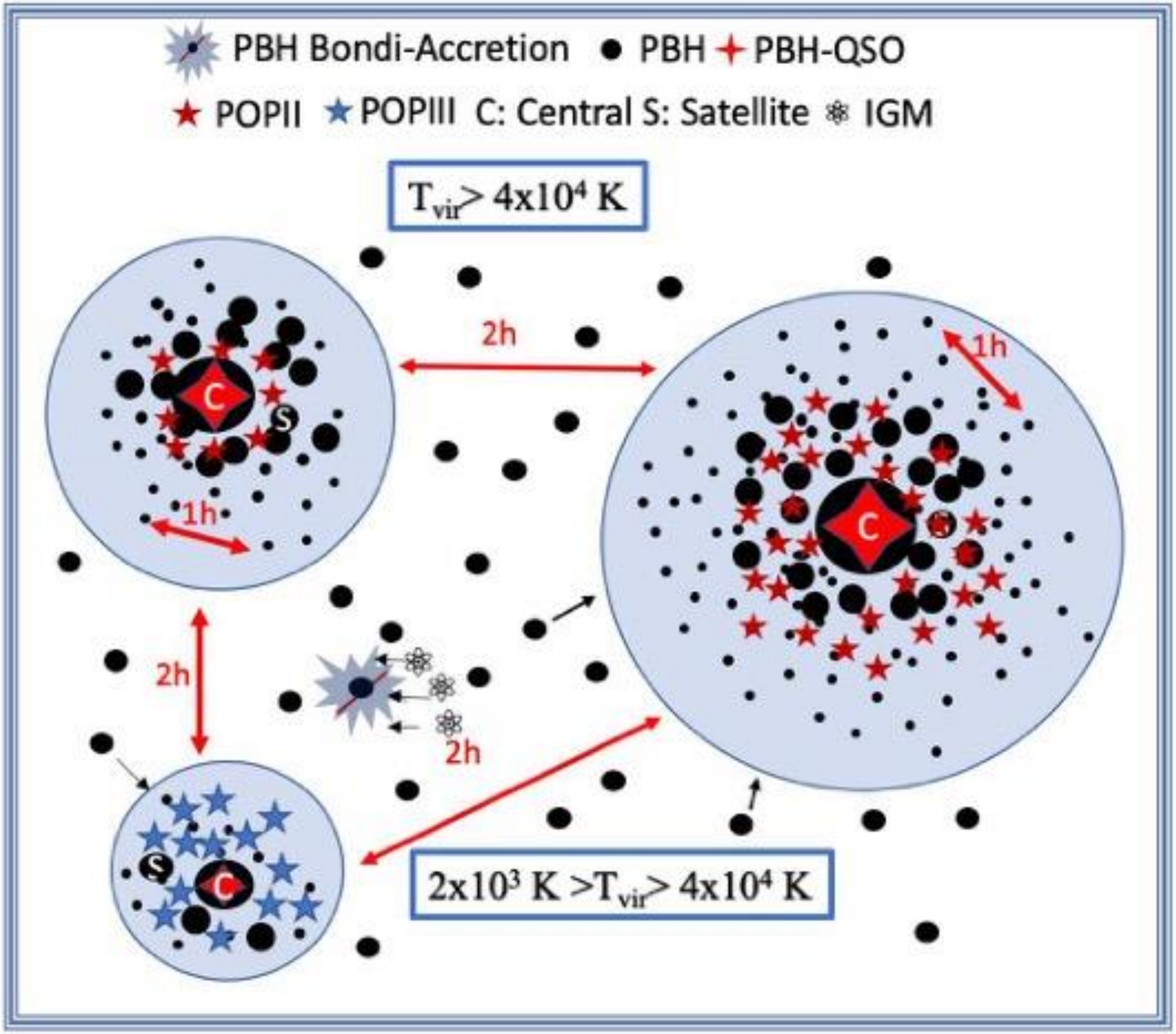
CIB x CXB Cross-Power



CAPPELLUTI+13, MITCHELL-WYNNE+16, YUE+13, PACUCCI+15, HELGASON+14

Early Star Formation

Hasinger (2021)



Hasinger (2021)