Primordial Black Holes

Rencontres de Blois, Blois, 26th May 2022

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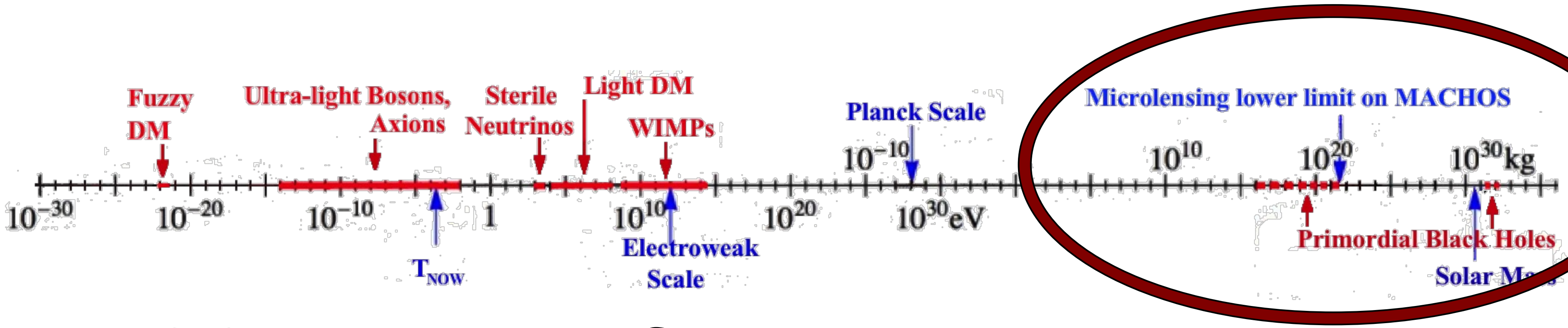
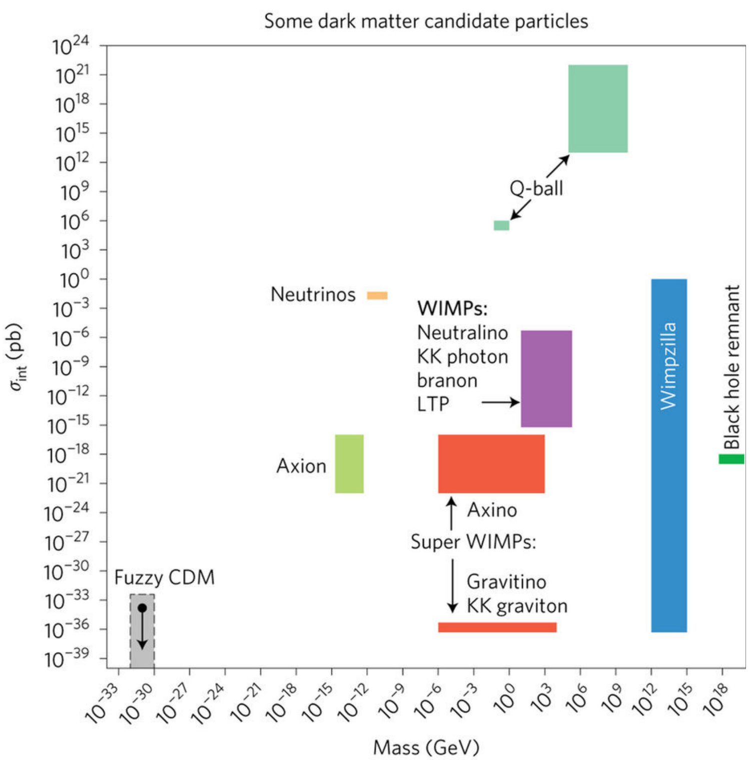
PBH scenario (1996-2022)

- 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,

What is Dark Matter?

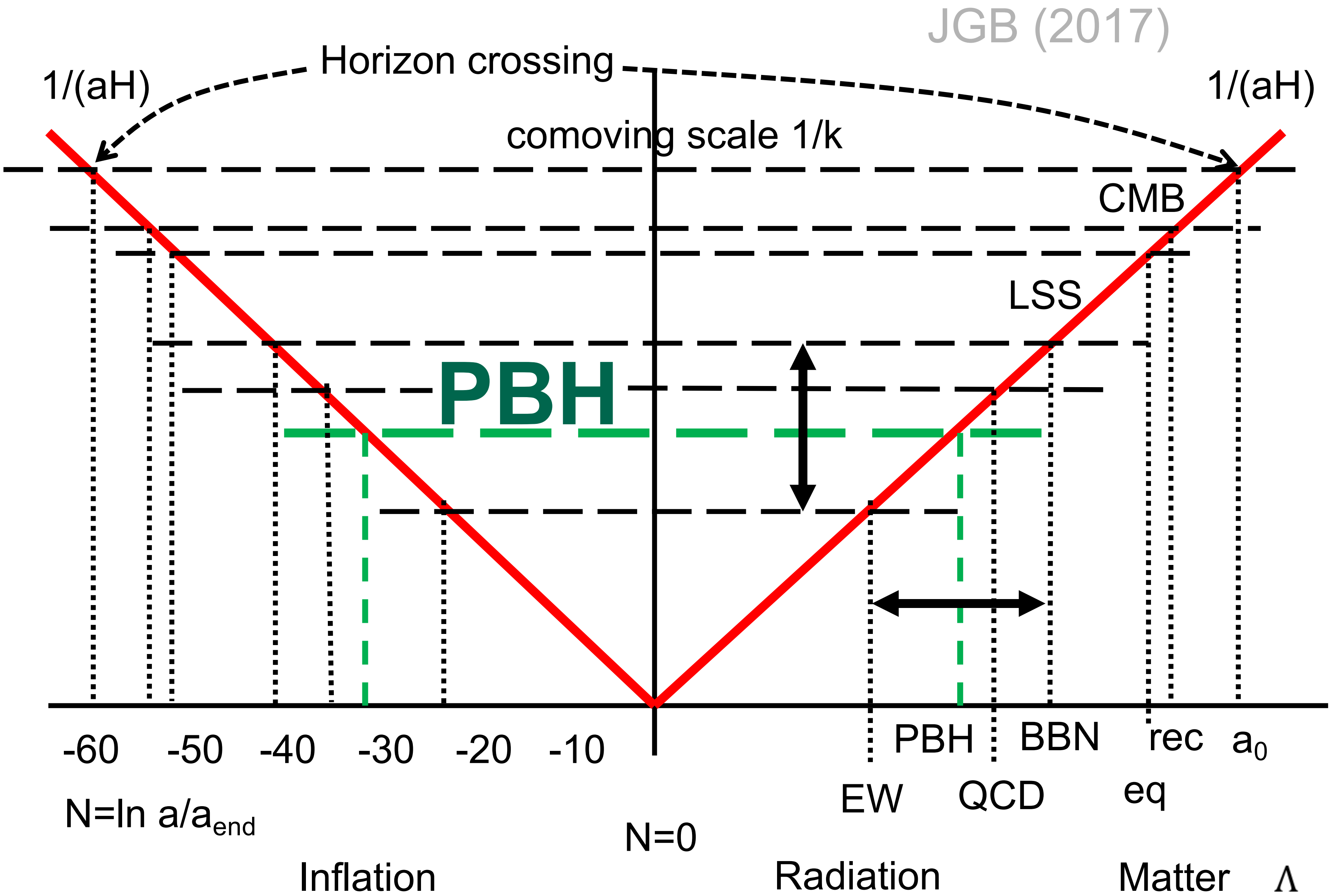


90 orders of magnitud in mass



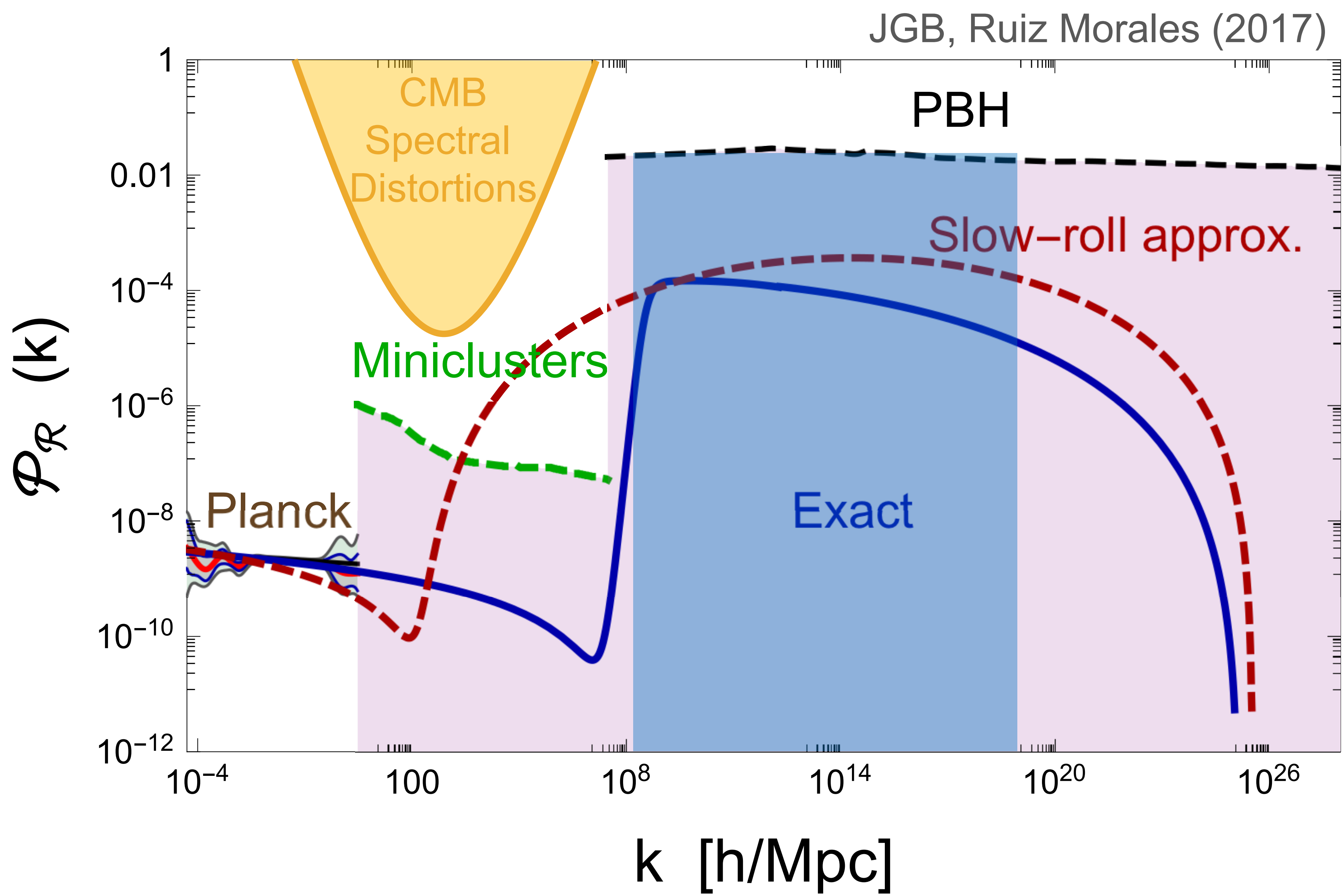
80 orders of magnitud in strength

Inflation

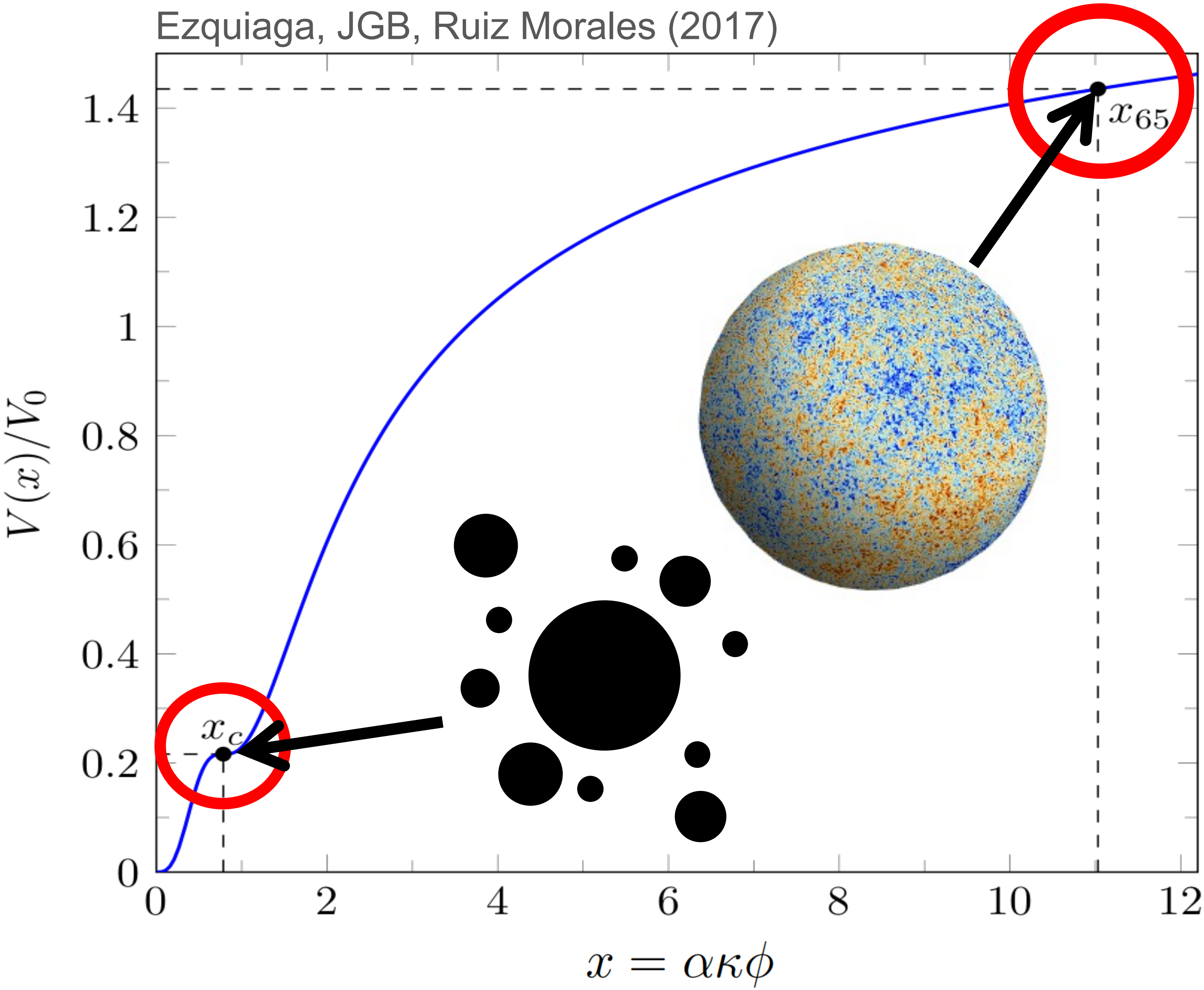


JGB (2017)
Horizon crossing
1/(aH)
1/(aH)
comoving scale 1/k
CMB
LSS
PBH
-60
-50
-40
-30
-20
-10
N=ln a/a_end
N=0
EW
PBH
QCD
BBN
rec
eq
a_0
Inflation
Radiation
Matter
Λ

Primordial Spectrum PBH

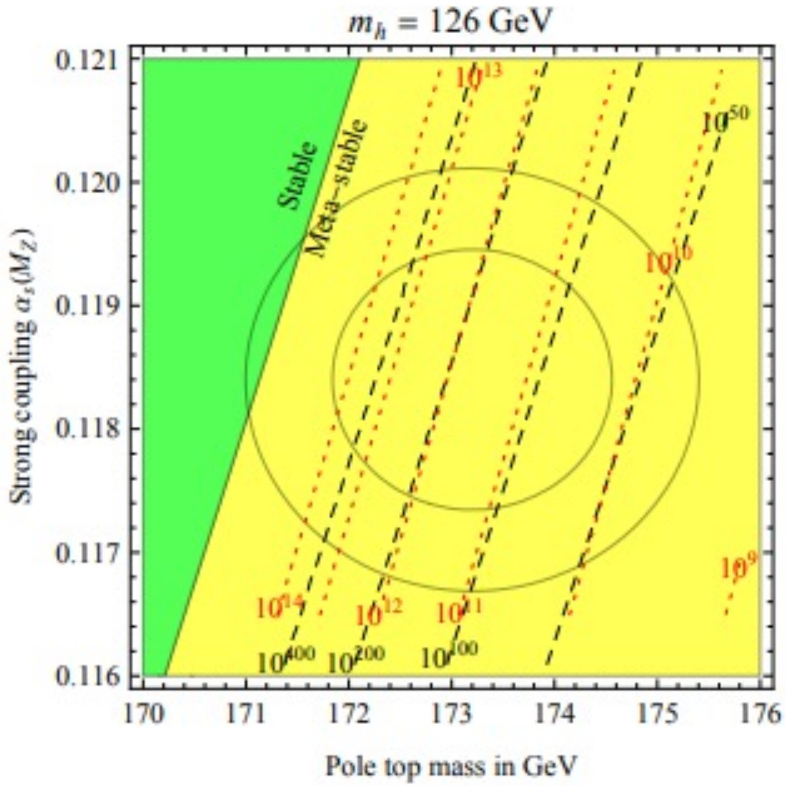


Ezquiaga, JGB, Ruiz Morales (2017)



EW vacuum meta-stability

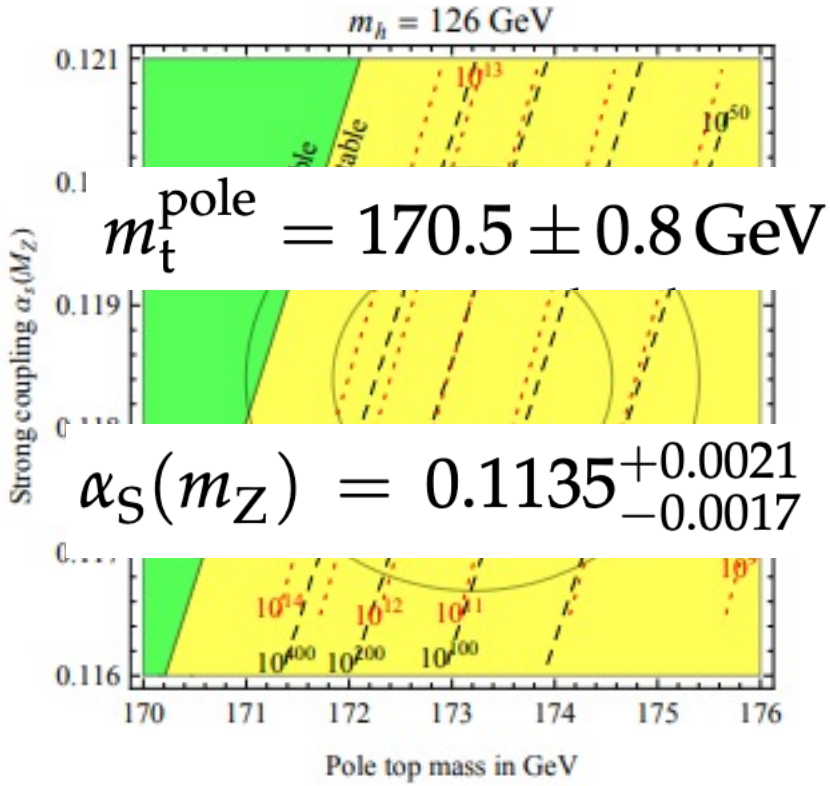
Buttazzo et al. (2012)



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

EW vacuum meta-stability

Buttazzo et al. (2012)

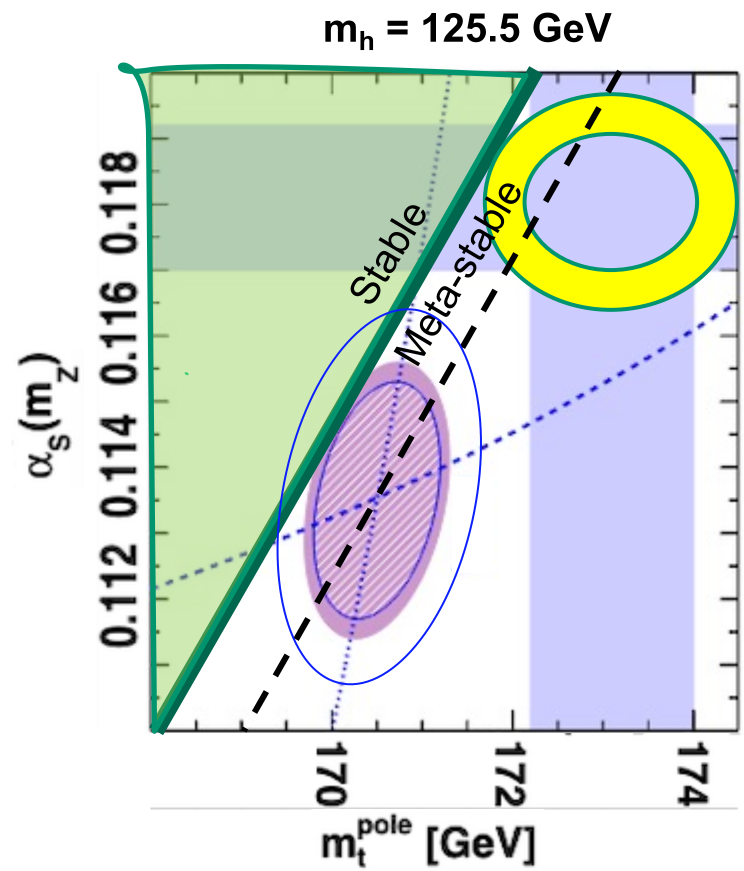


$$m_t^{\rm pole} = 170.5 \pm 0.8\,{\rm GeV}$$

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

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

CMS Collab. (2020)



https://arxiv.org/abs/1904.05237

Critical Higgs Inflation

Standard Model Lagrangian

Ezquiaga, JGB, Ruiz Morales (2017)

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

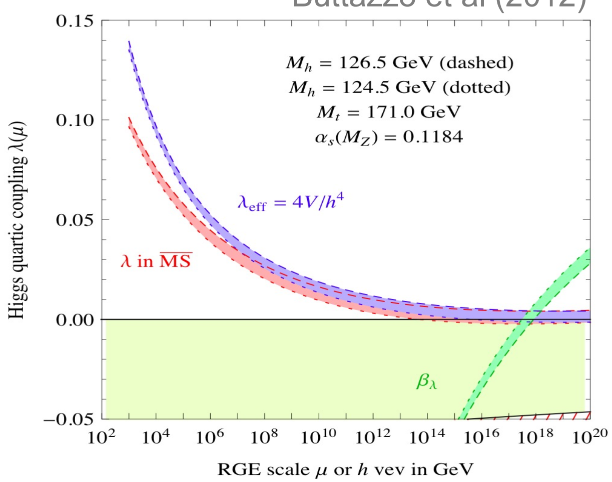
$$S = \int d^4x \sqrt{g} \left[\left(\frac{1}{2\kappa^2} + \frac{\xi(\phi)}{2} \phi^2 \right) R - \frac{1}{2} (\partial\phi)^2 - \frac{1}{4} \lambda(\phi) \phi^4 \right]$$

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

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

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

Buttazzo et al (2012)

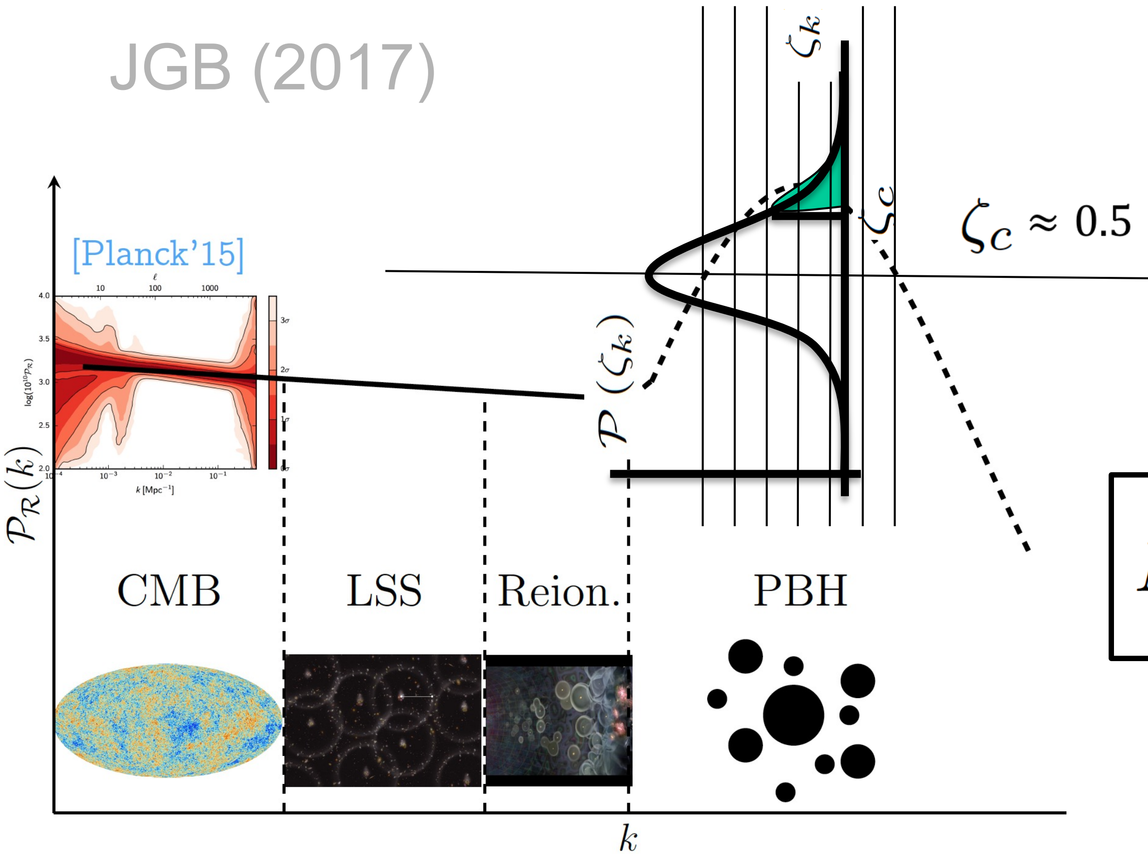


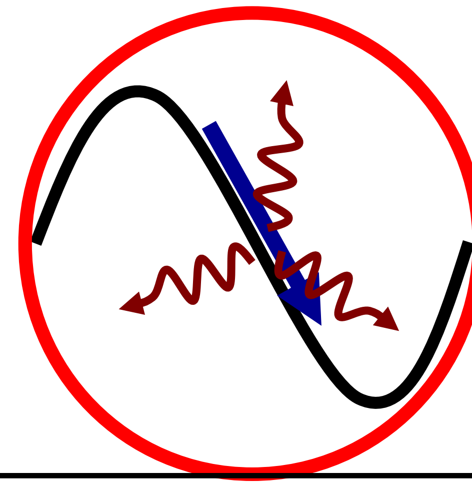
$$V(x) = \frac{V_0 \left(1 + a \ln^2 x\right) x^4}{\left(1 + c\left(1 + b \ln x\right) x^2\right)^2} \qquad x = \phi/\mu$$

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

Gravitational Collapse of PBH

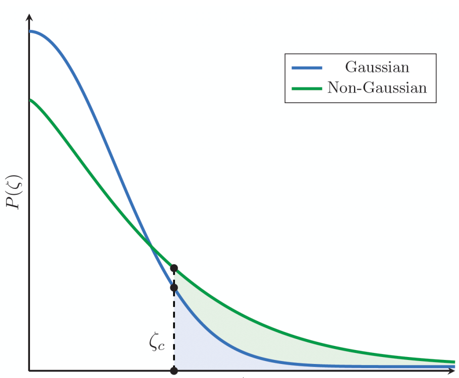
JGB (2017)





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

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



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

Stochastic δN - formalism

Coarse-grained curvature perturbation

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

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

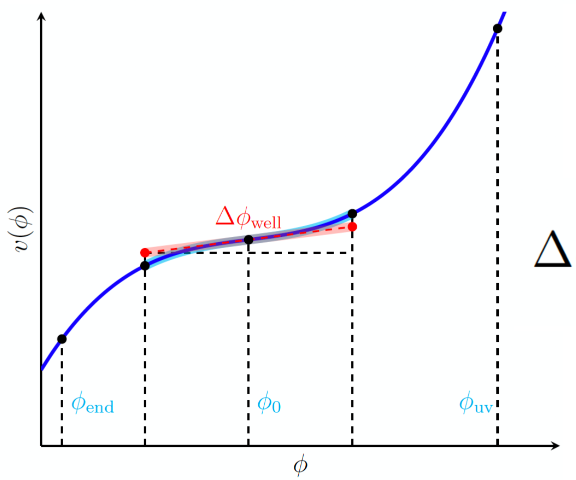
Fokker-Planck Diffusion Eq.

Determined by the poles of the characteristic function

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

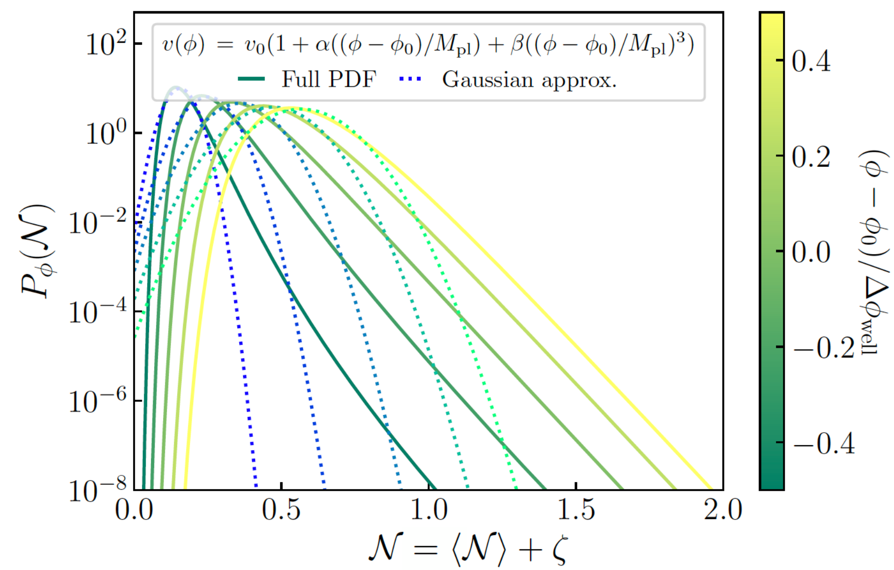
Ezquiaga, JGB, Vennin (2019)

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



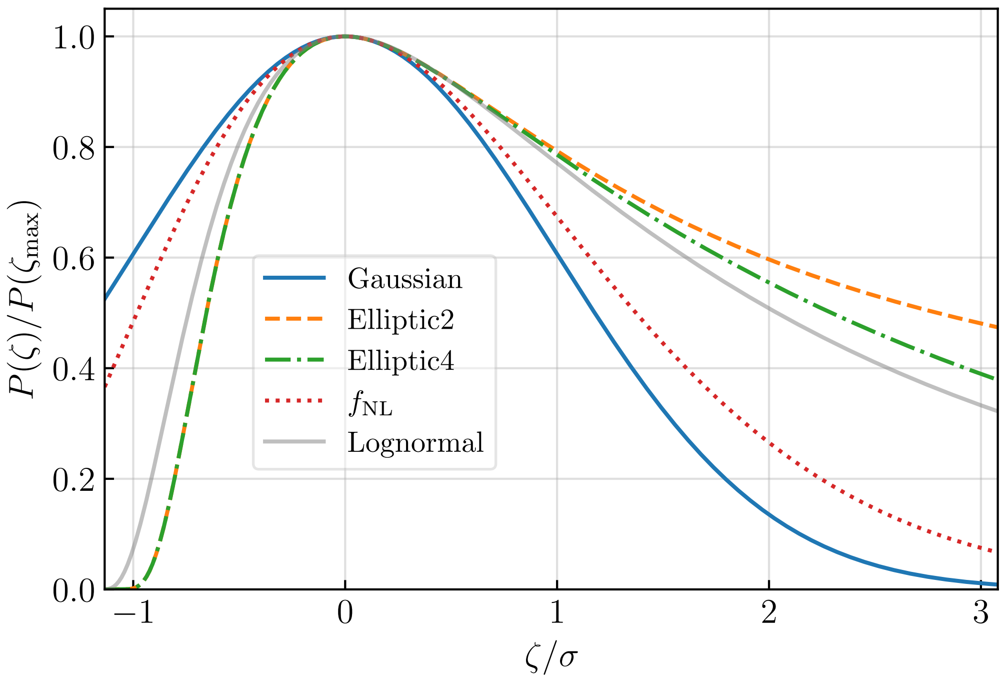
$$\alpha \gg (v_0^2 \beta)^{1/3}$$

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



Quantum Diffusion @ CMB & LSS

Ezquiaga, JGB, Vennin (2022)



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

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

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

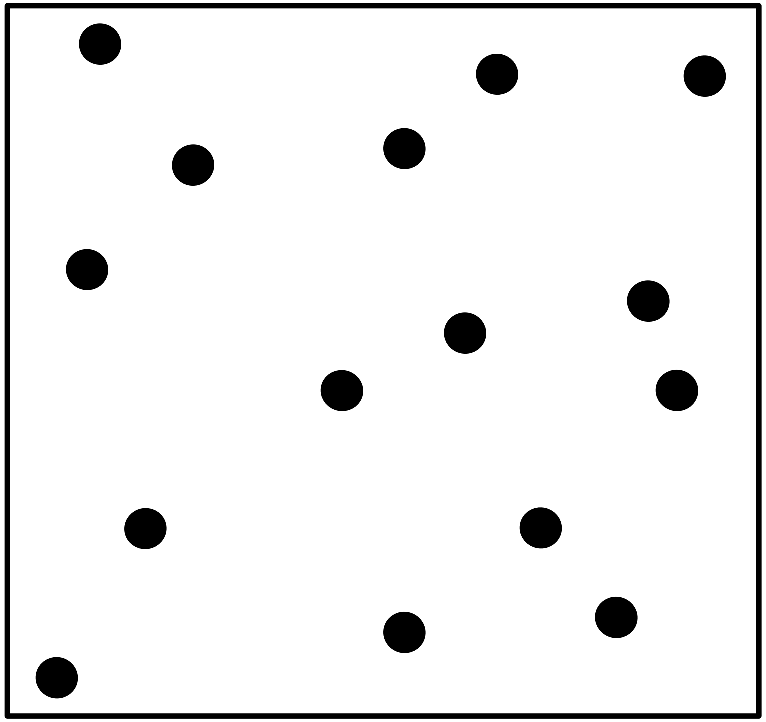
$$\mathrm{LN}(x,\rho,\sigma) = \frac{1}{\rho\,\sigma\sqrt{2\pi}}\exp\left[-\frac{\ln(x/\rho)^2}{2\sigma^2} - \frac{\sigma^2}{2}\right]$$

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

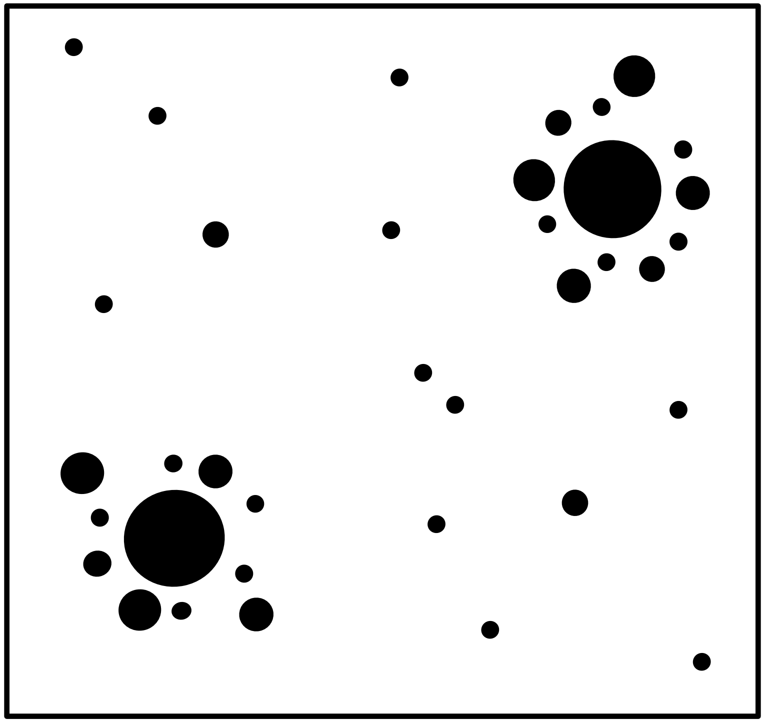
$$P_{\rm NL}(\zeta) = \frac{1}{\sqrt{2\pi\sigma_{\rm G}^2\Delta}}\left[e^{-\frac{25(\sqrt{\Delta}-1)^2}{72 f_{\rm NL}^2\sigma_{\rm G}^2}} + e^{-\frac{25(\sqrt{\Delta}+1)^2}{72 f_{\rm NL}^2\sigma_{\rm G}^2}}\right]$$

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

Spatial Distribution PBH



- Monochromatic
- Uniformly distributed

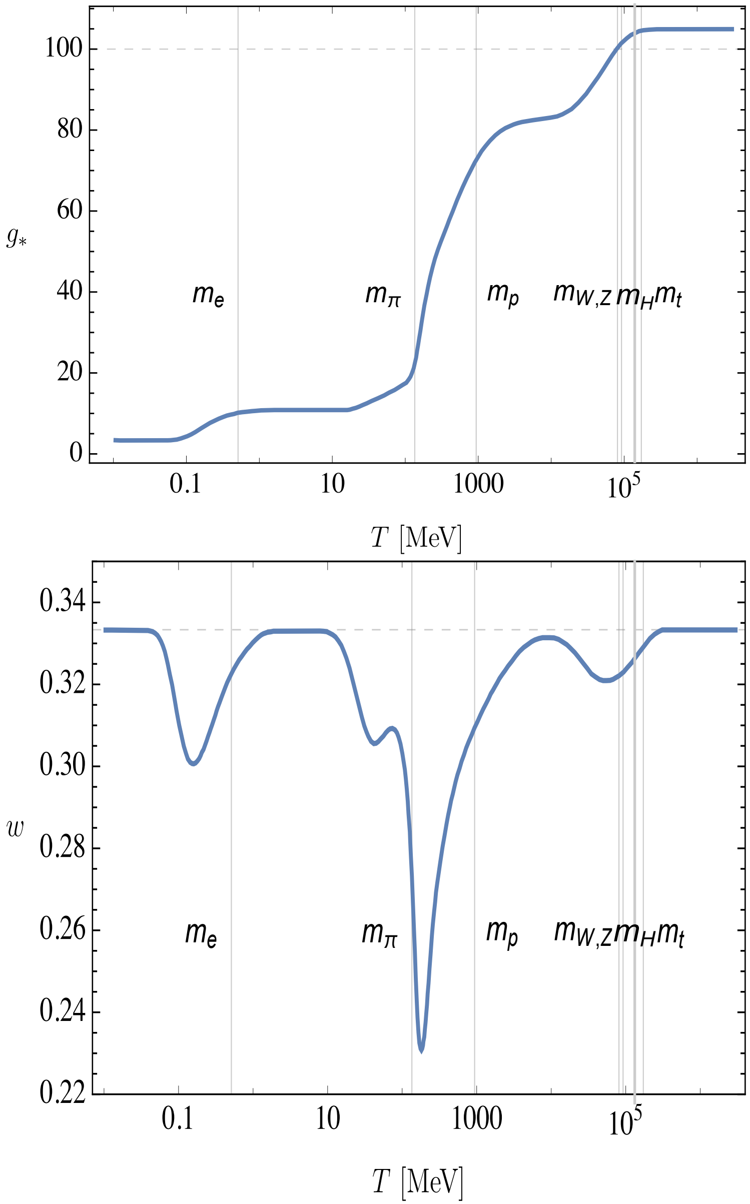


- Broad range masses
- PBH clusters

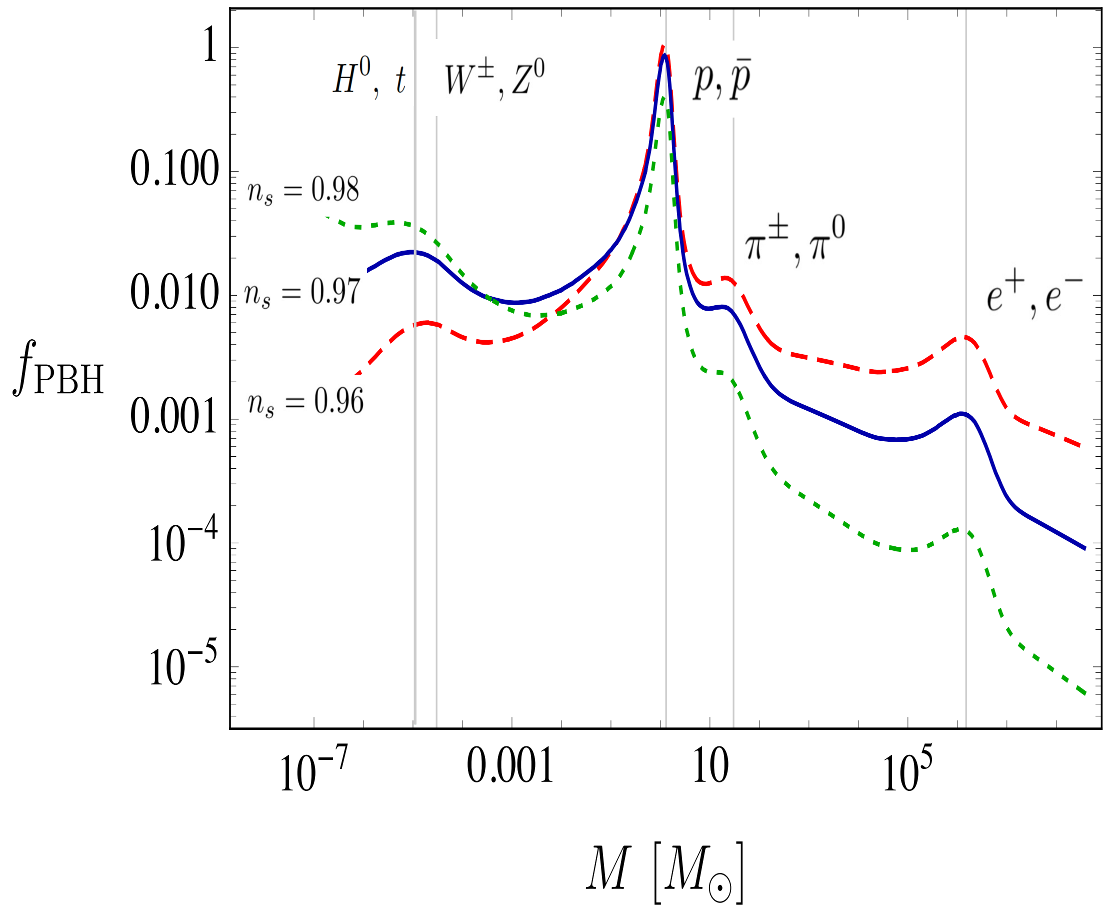
JGB (2017)

Thermal history of the universe

Carr, Clesse, JGB, Kühnel (2019)



PBH mass spectrum



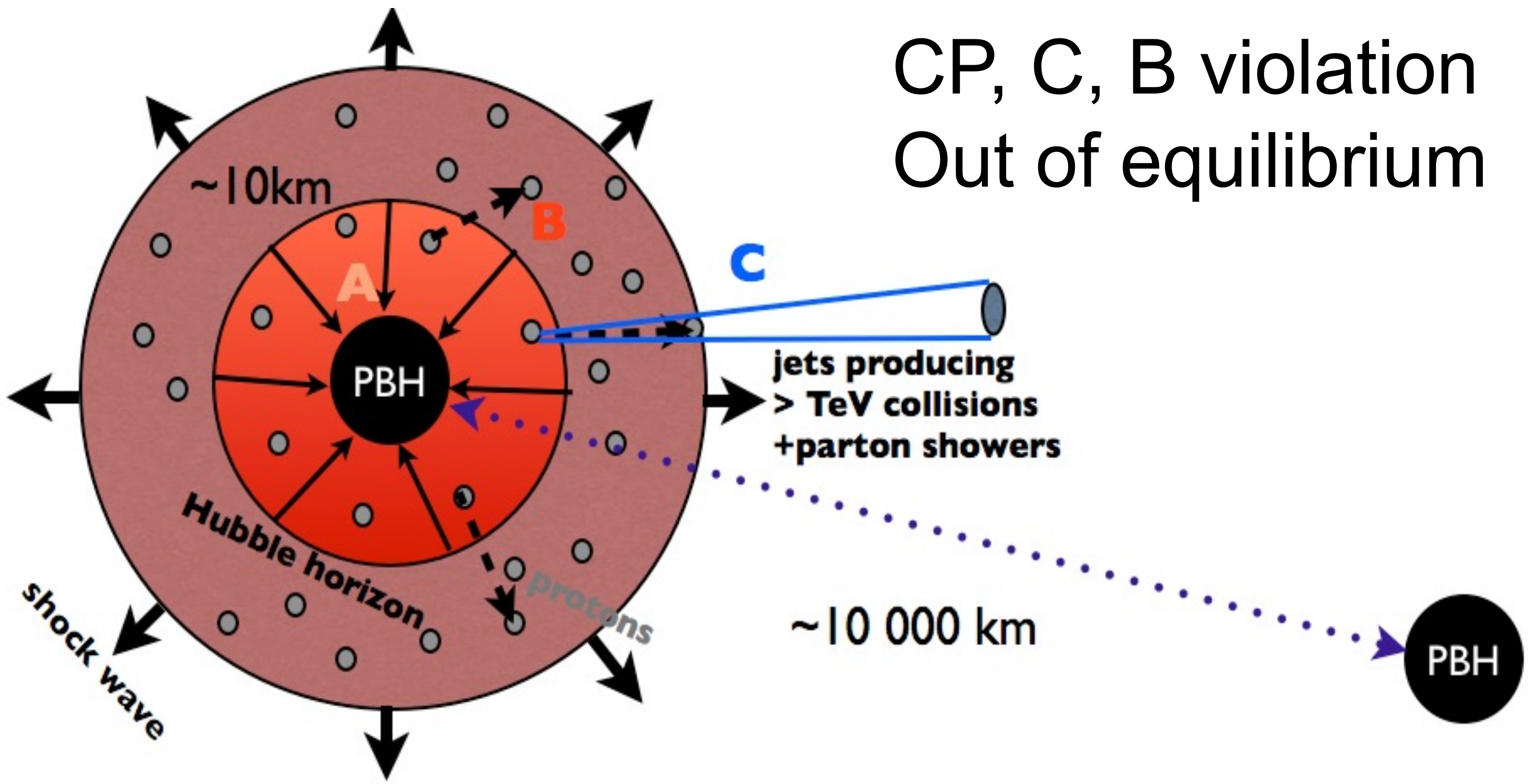
Electroweak baryogenesis @ QCD

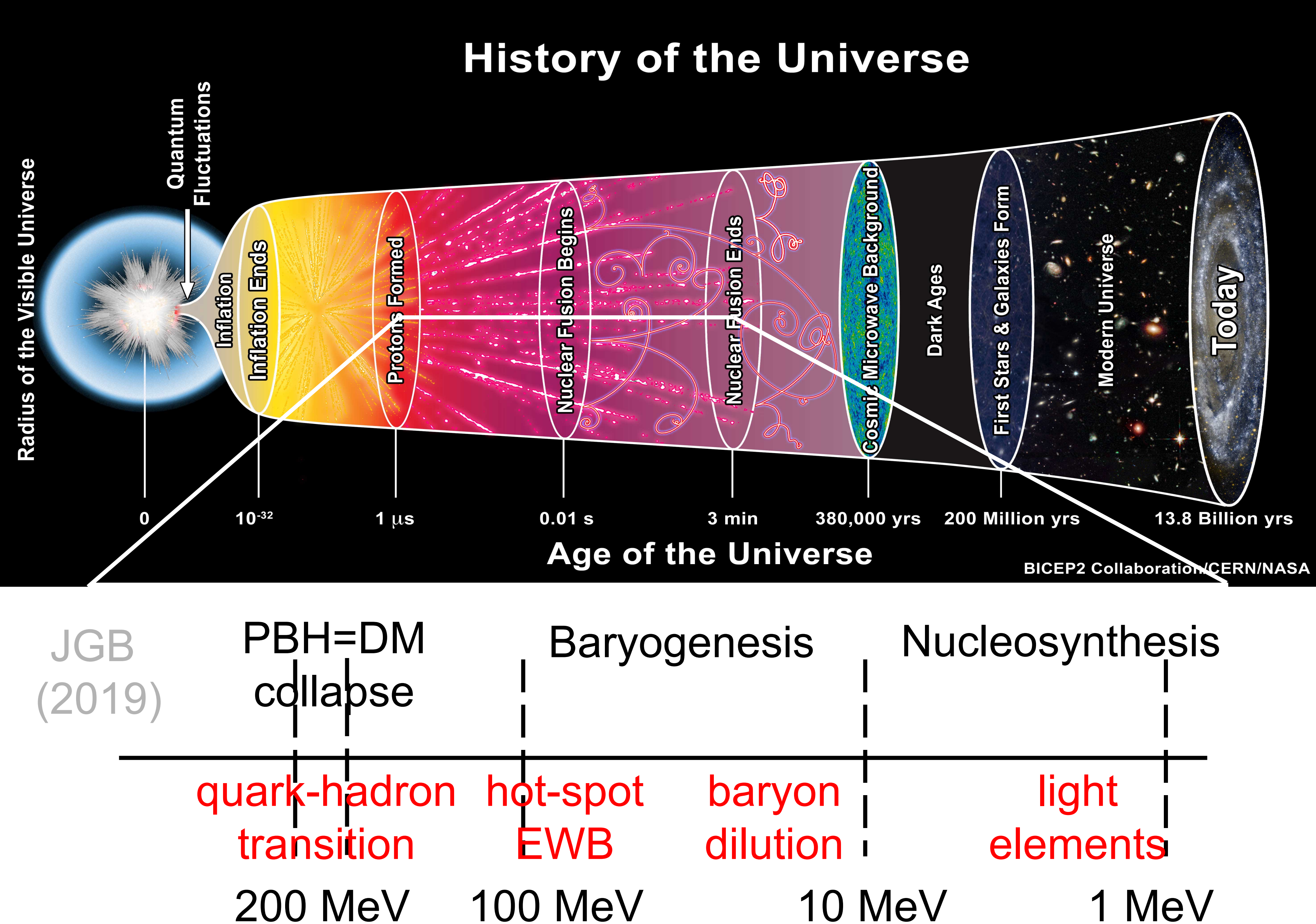
"Primordial supernova"

JGB, Carr, Clesse (2019)

Sakharov conditions:

CP, C, B violation
Out of equilibrium



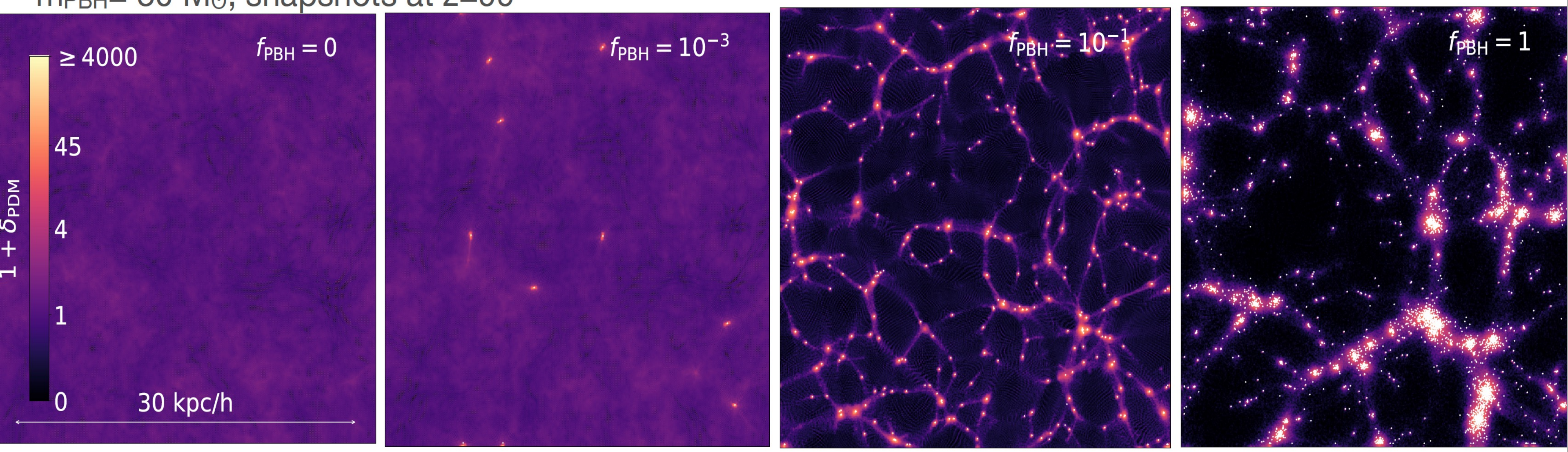

History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10-32
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 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

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



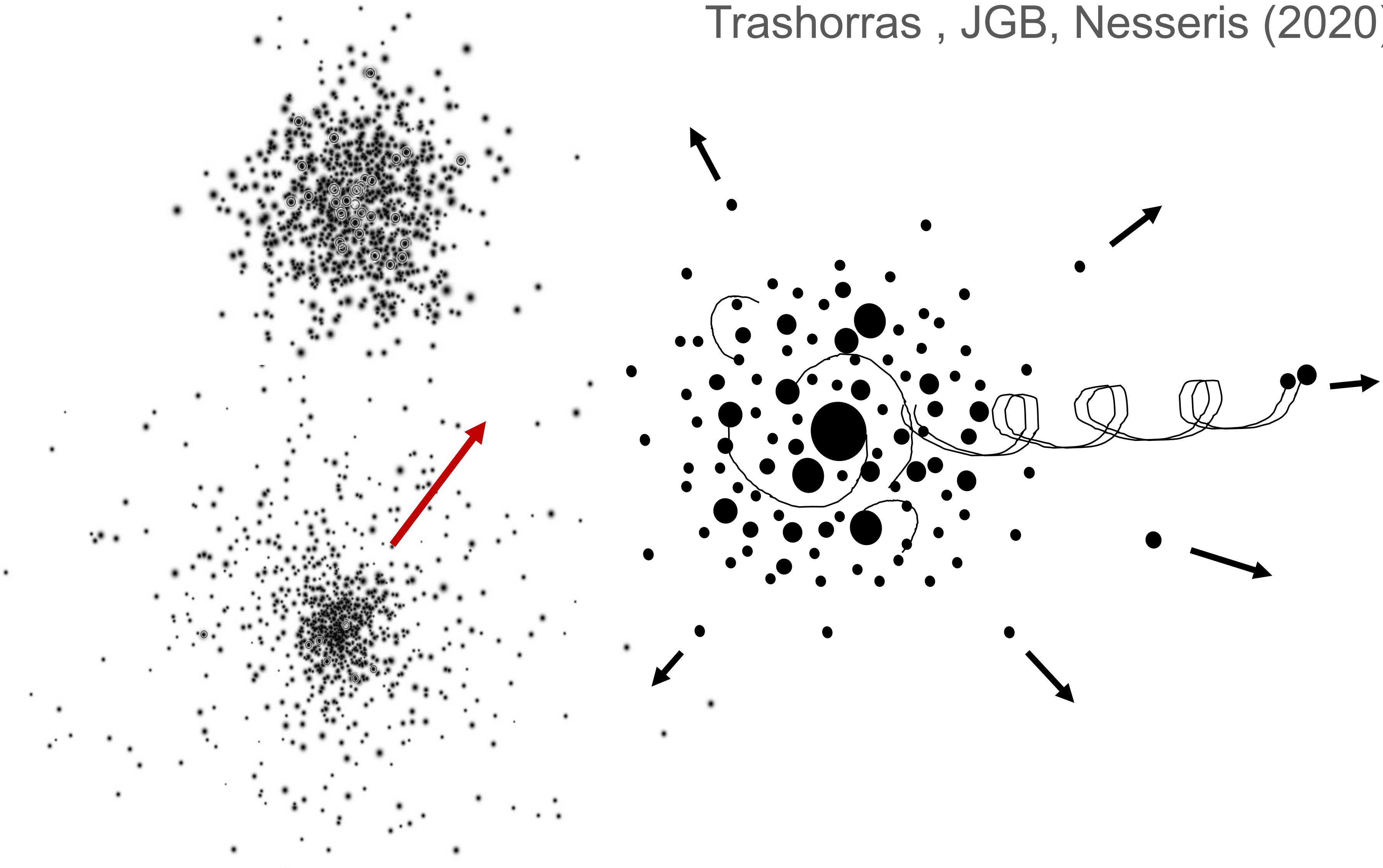
Halos of 10^6 - 10^7 $M_\odot$

On small scales, completely different than particle-CDM !

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

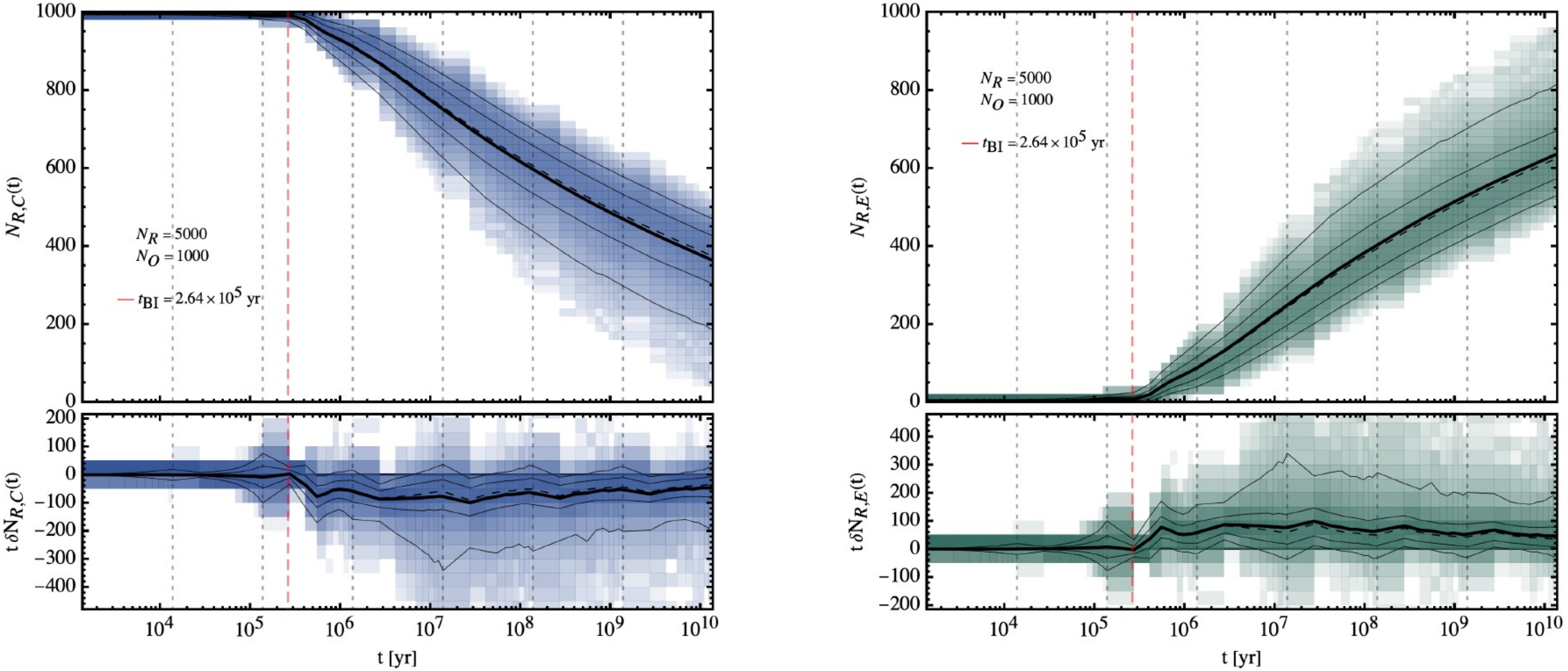
PBH clusters

Trashorras , JGB, Nesseris (2020)



Primordial Black Holes Clusters

Trashorras, JGB, Nesseris (2020)

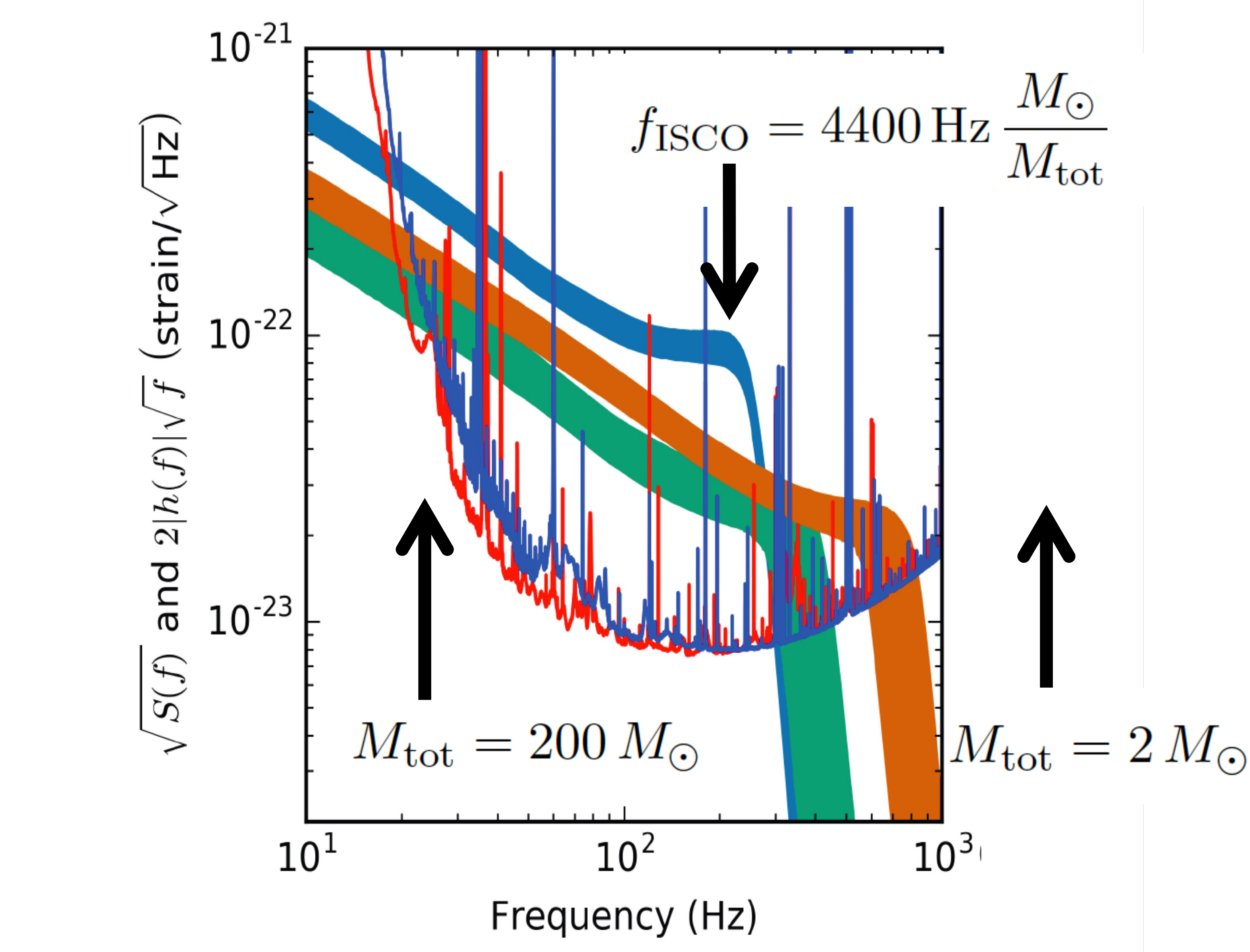


(a) Remaining cluster population of objects, $N_{\mathrm{R,C}}(t)$.

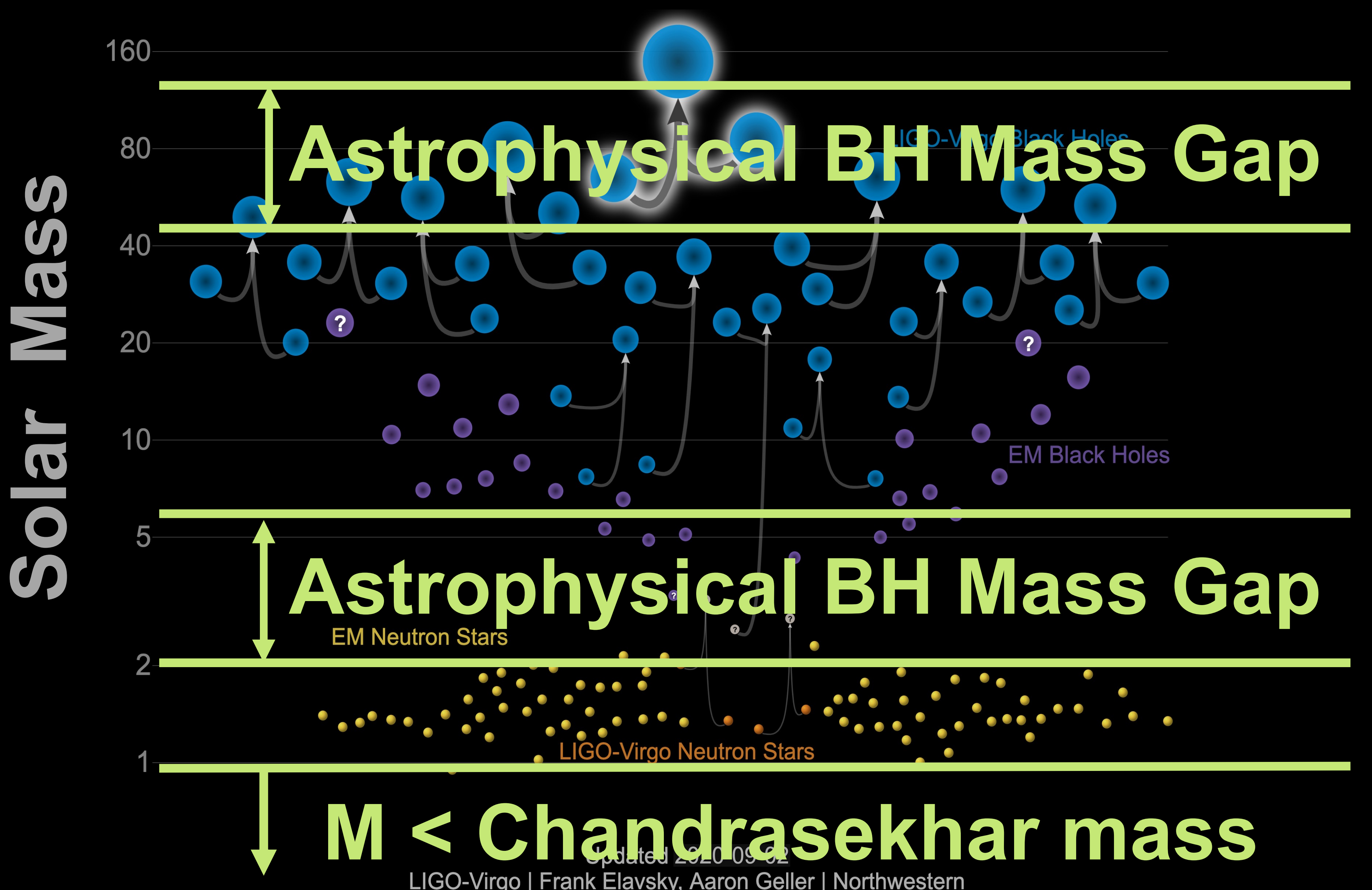
(b) Remaining ejecta population of objects, $N_{\mathrm{R,E}}(t)$.

Clusters slingshot light components

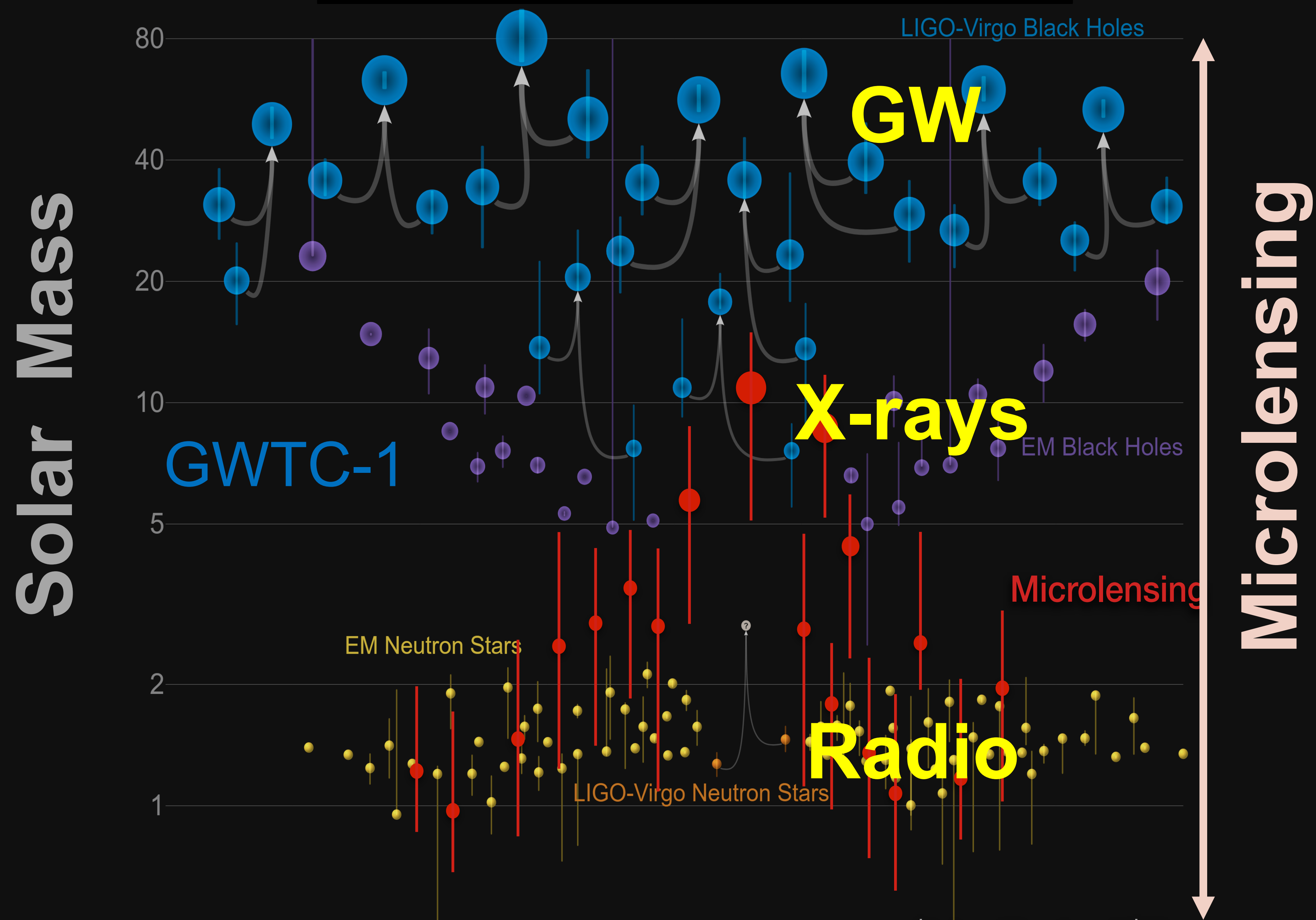
LVC BBH events



Black Holes and Neutron Stars

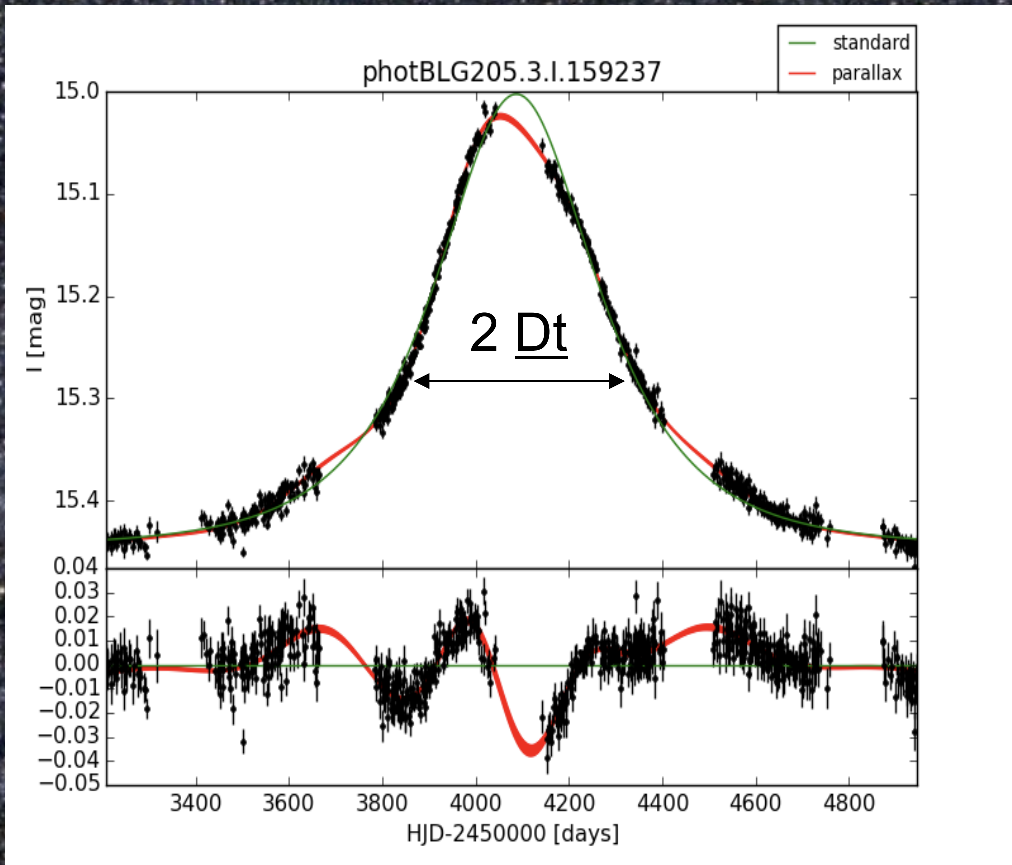


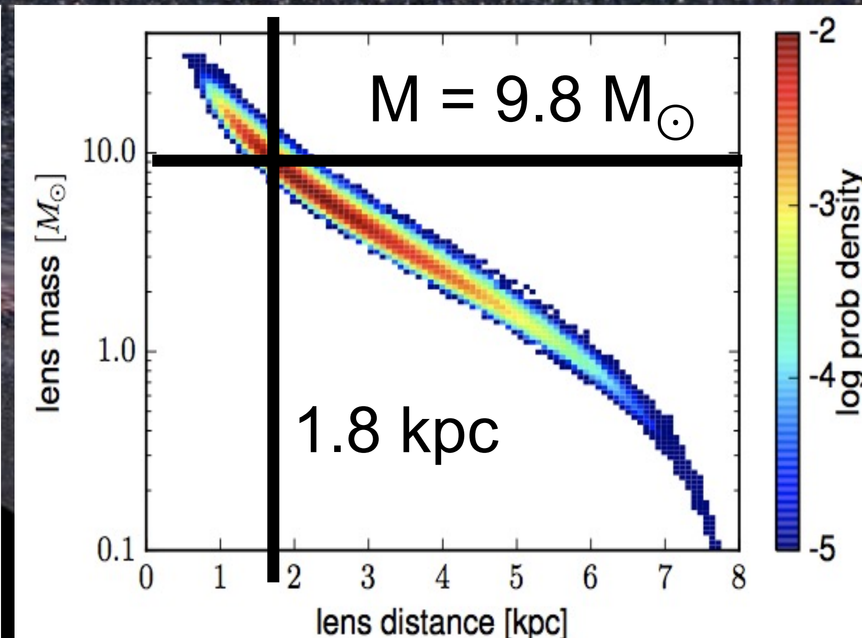
Black Holes and Neutron Stars



OGLE3-UL-PAR-02 - candidate BH

Wyrzykowski (2016)



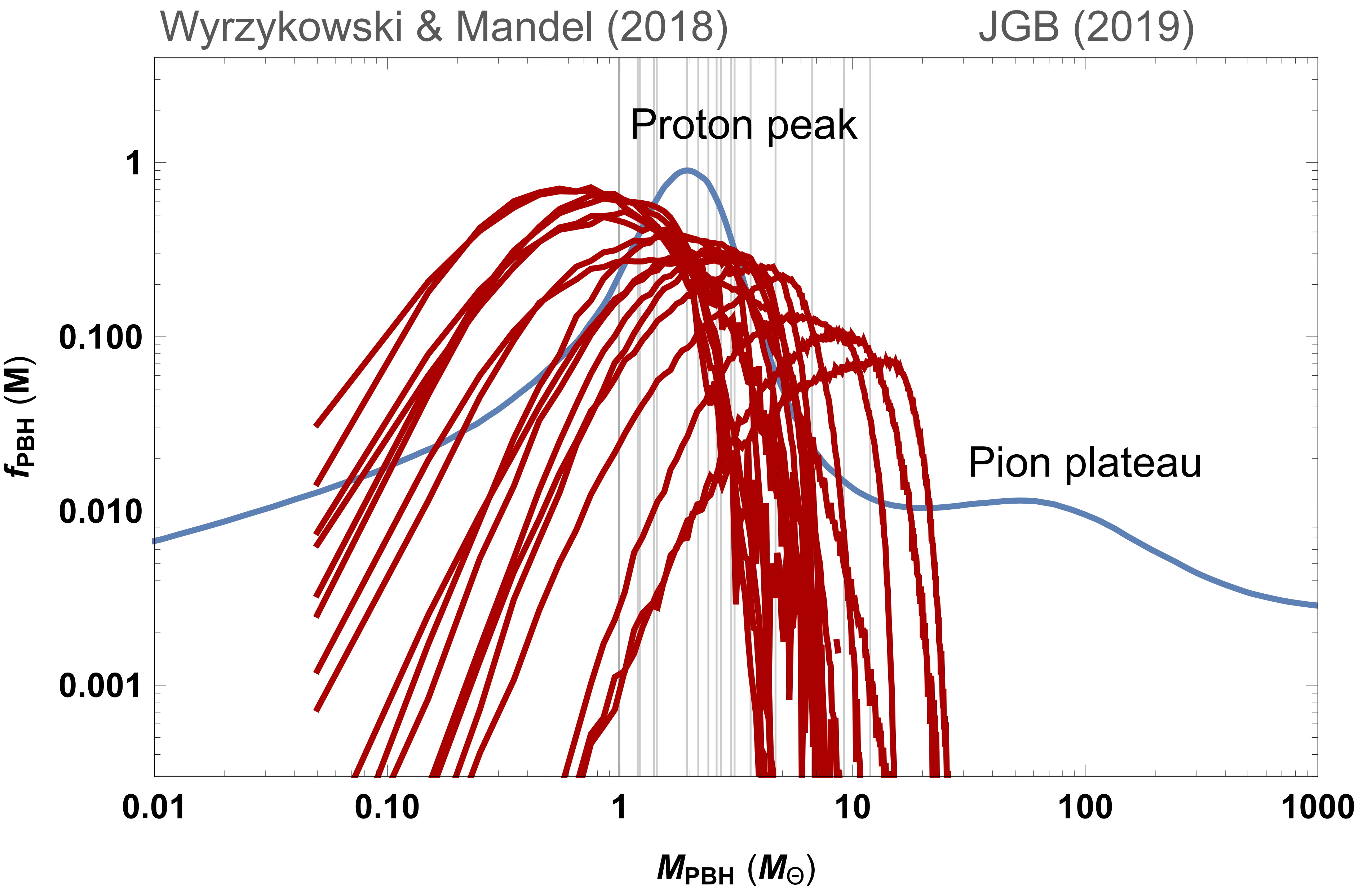


$$\overline{Dt} = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v}$$

OGLE photometry from 2001-2008 and microlensing model

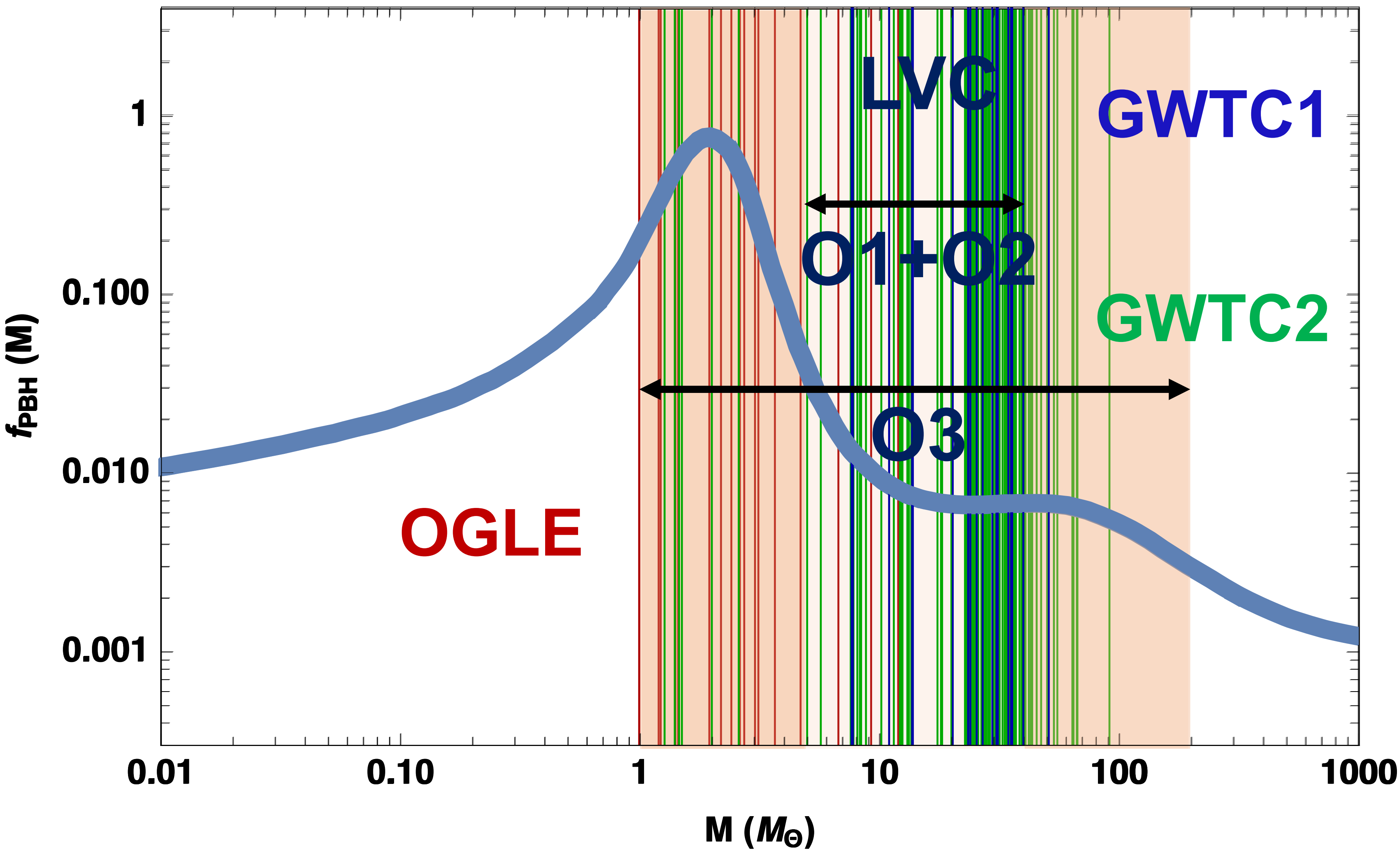
Mass, Distance (degenerated estimate)

Primordial Black Holes & OGLE

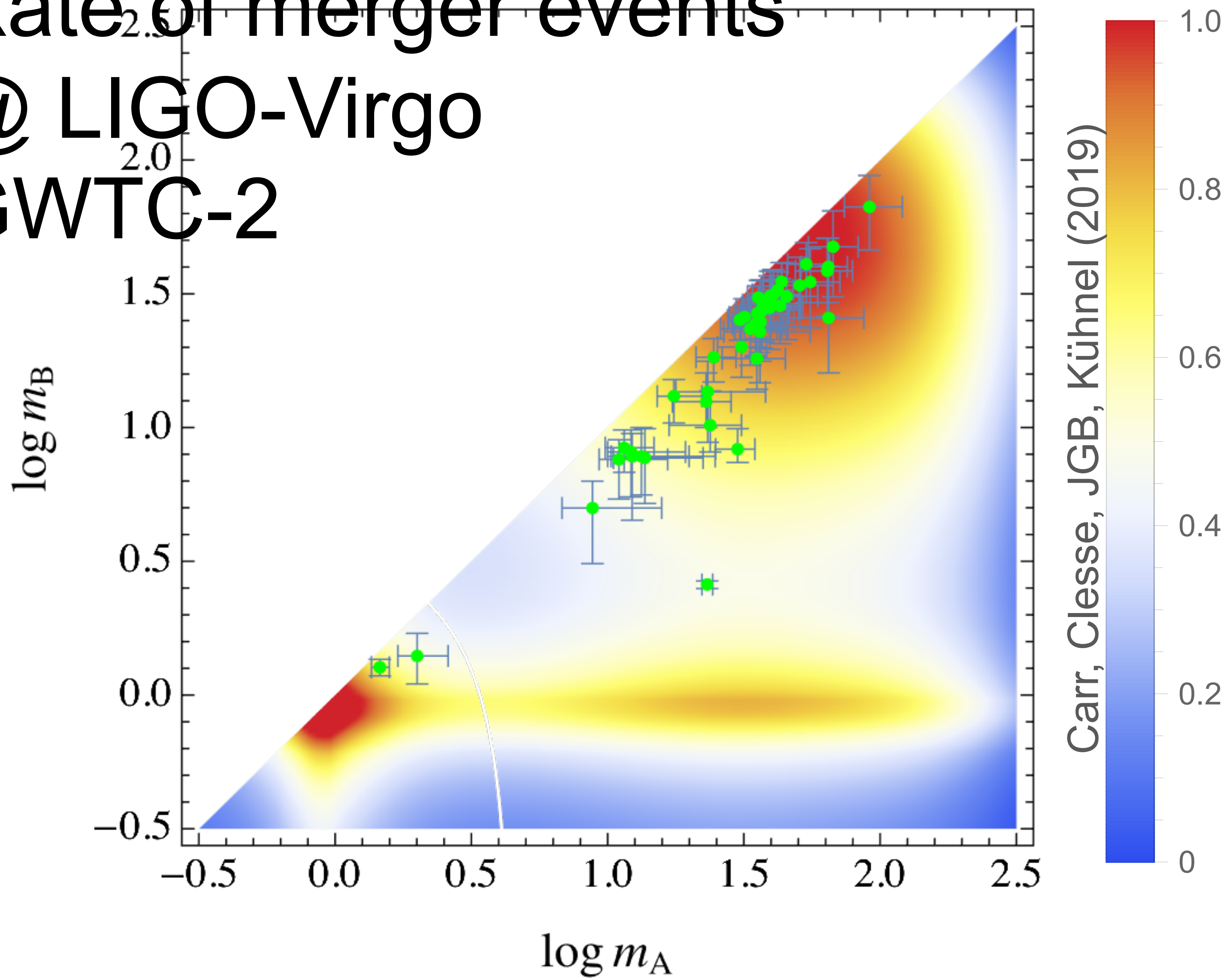


Model prediction: mass spectrum

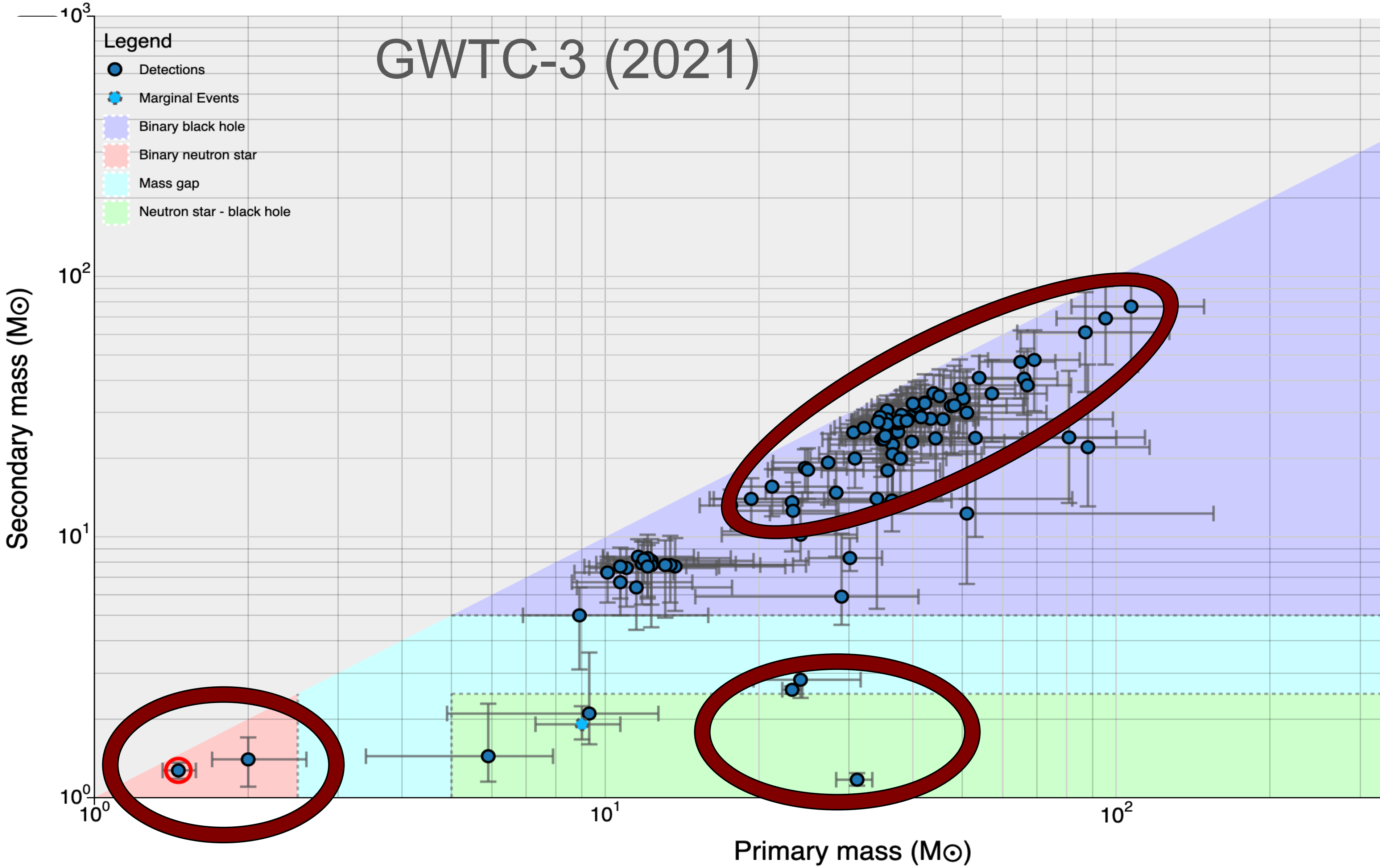
JGB, Clesse (2020)



Rate of merger events @ LIGO-Virgo GWTC-2

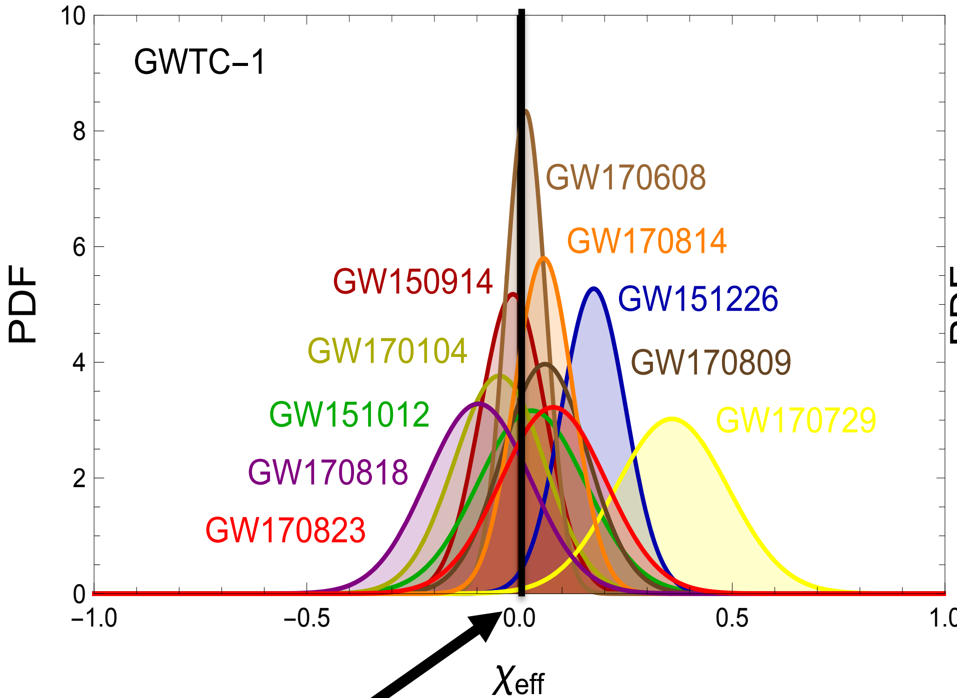


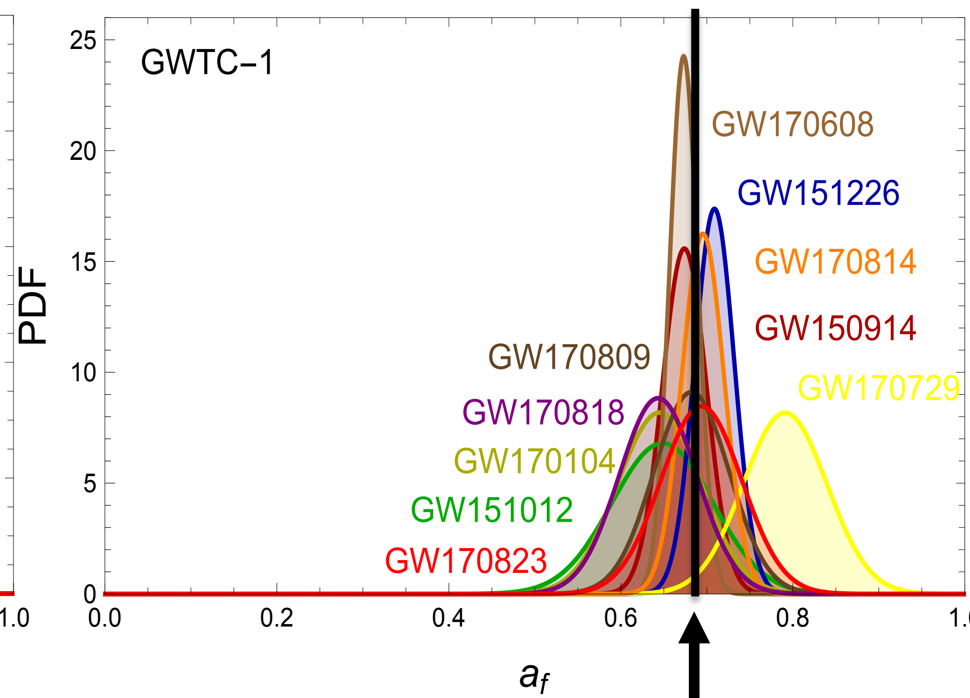
Primary and secondary masses



Effective & Final Spin

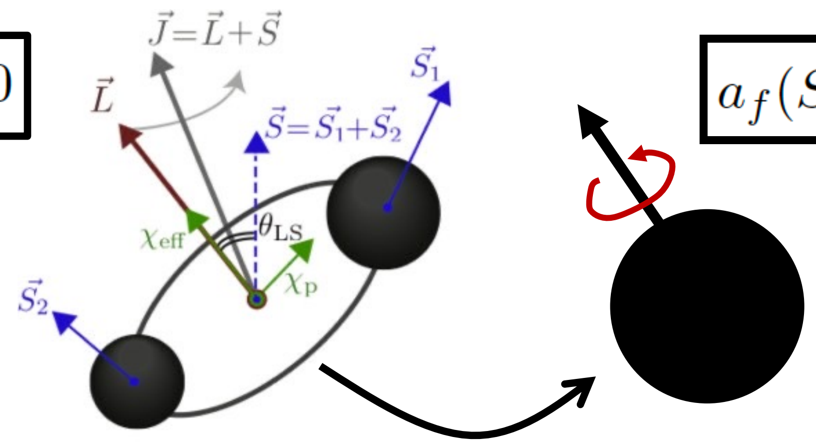
JGB (2019)



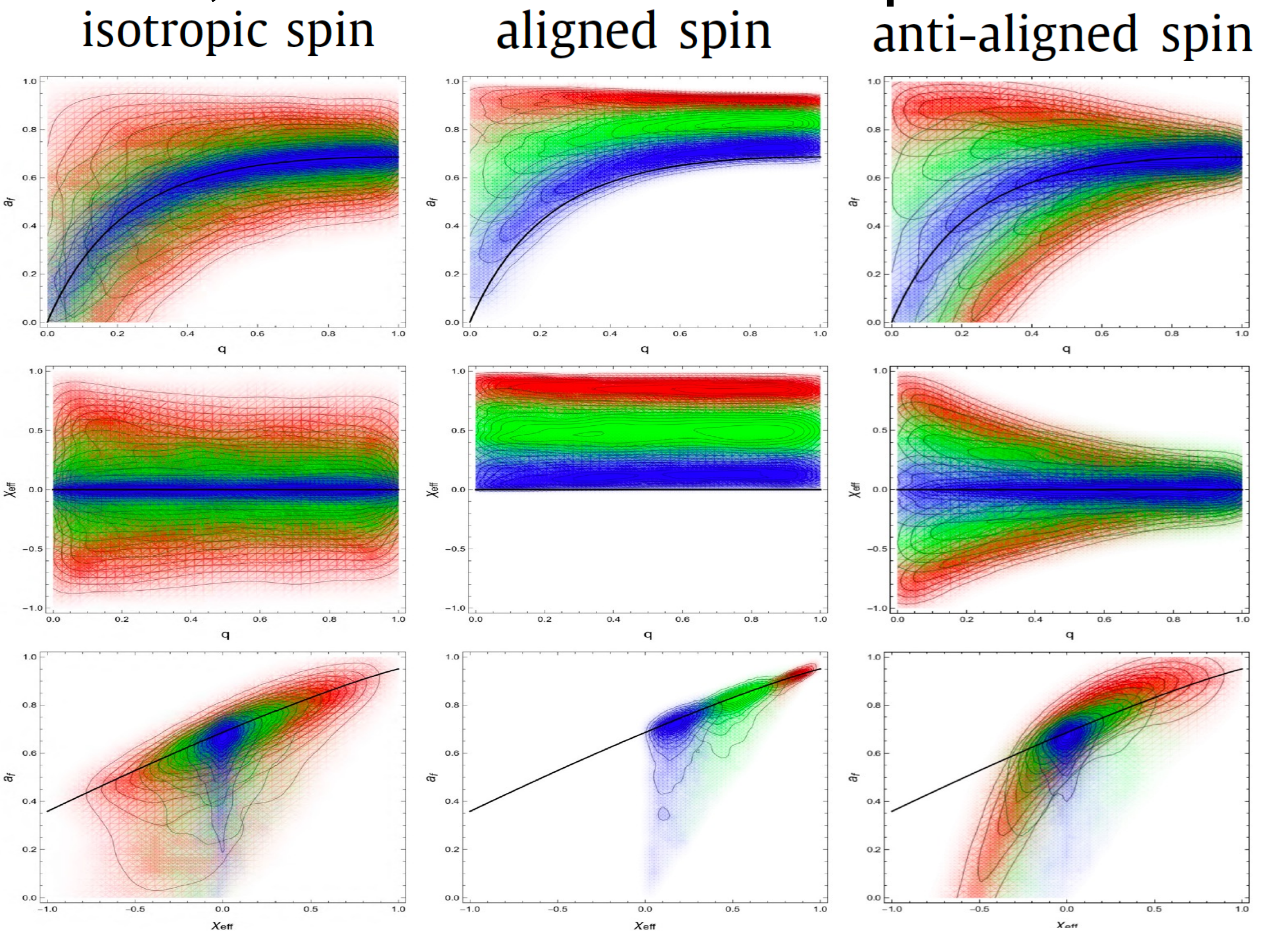


$$\chi_{\rm eff}(S_1 = S_2 = 0) = 0$$

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

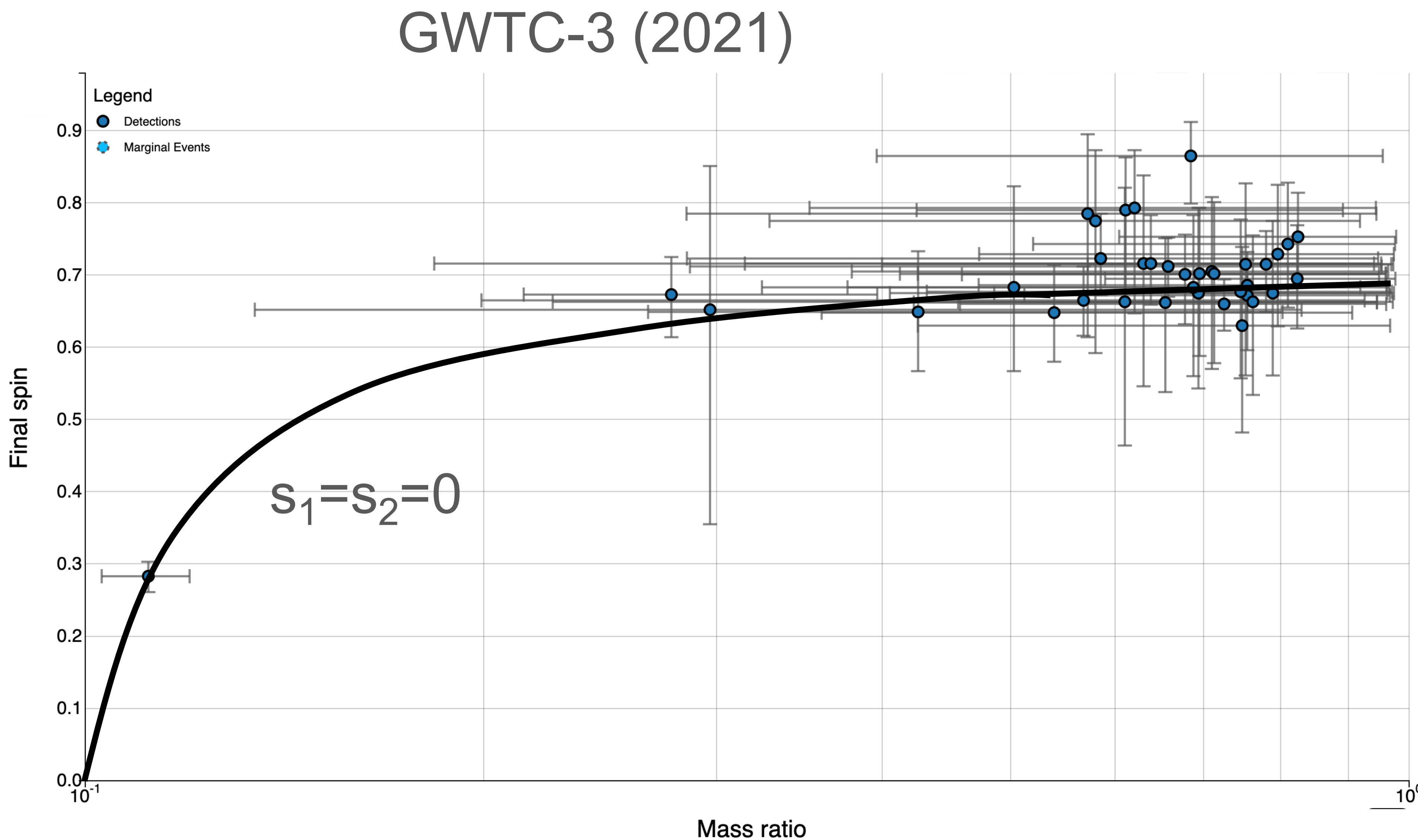


M-ratio, Effective & Final Spin: Priors

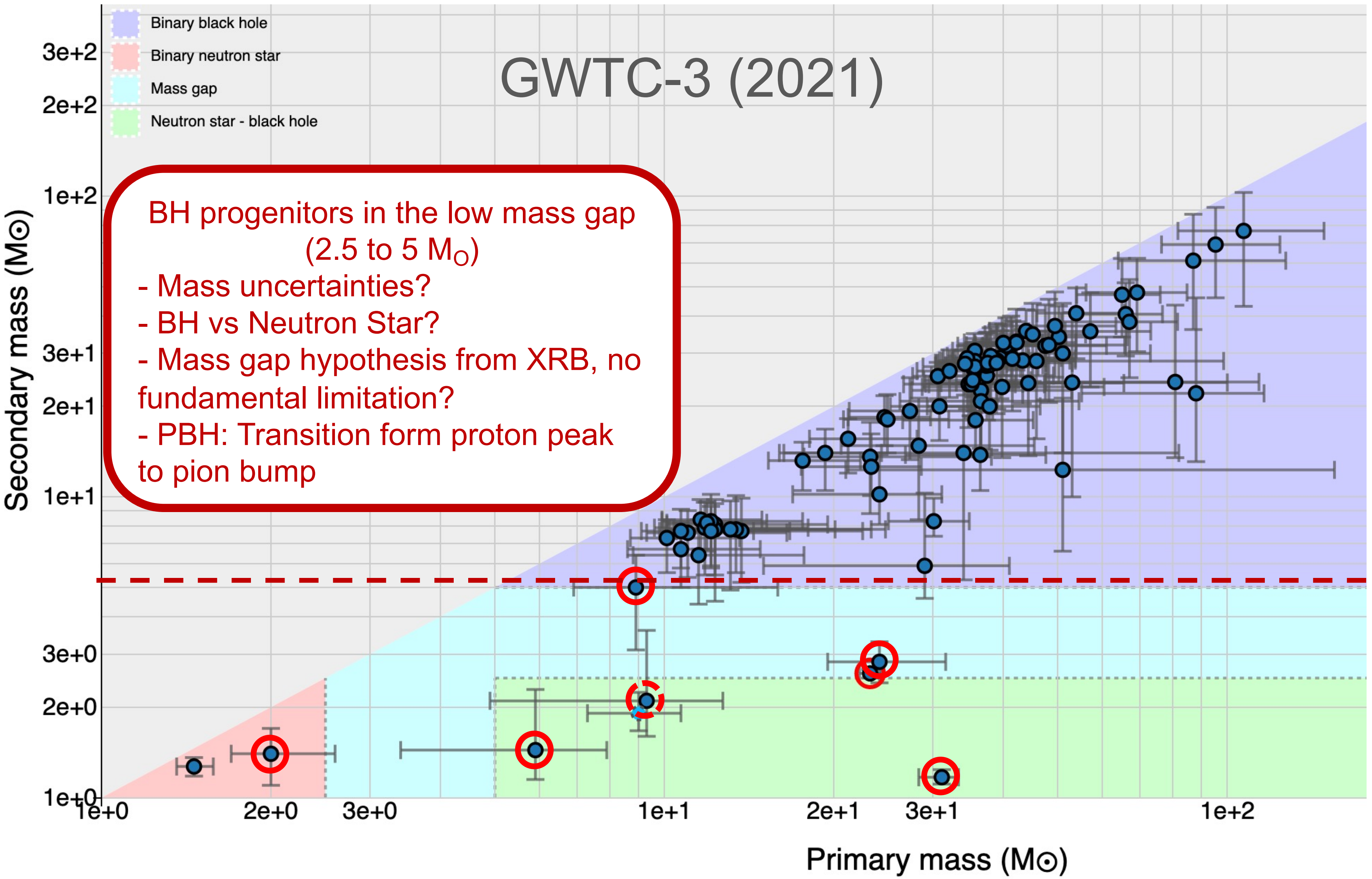


JGB, Nuño Siles, Ruiz Morales (2020)

Mass ratio and final spin



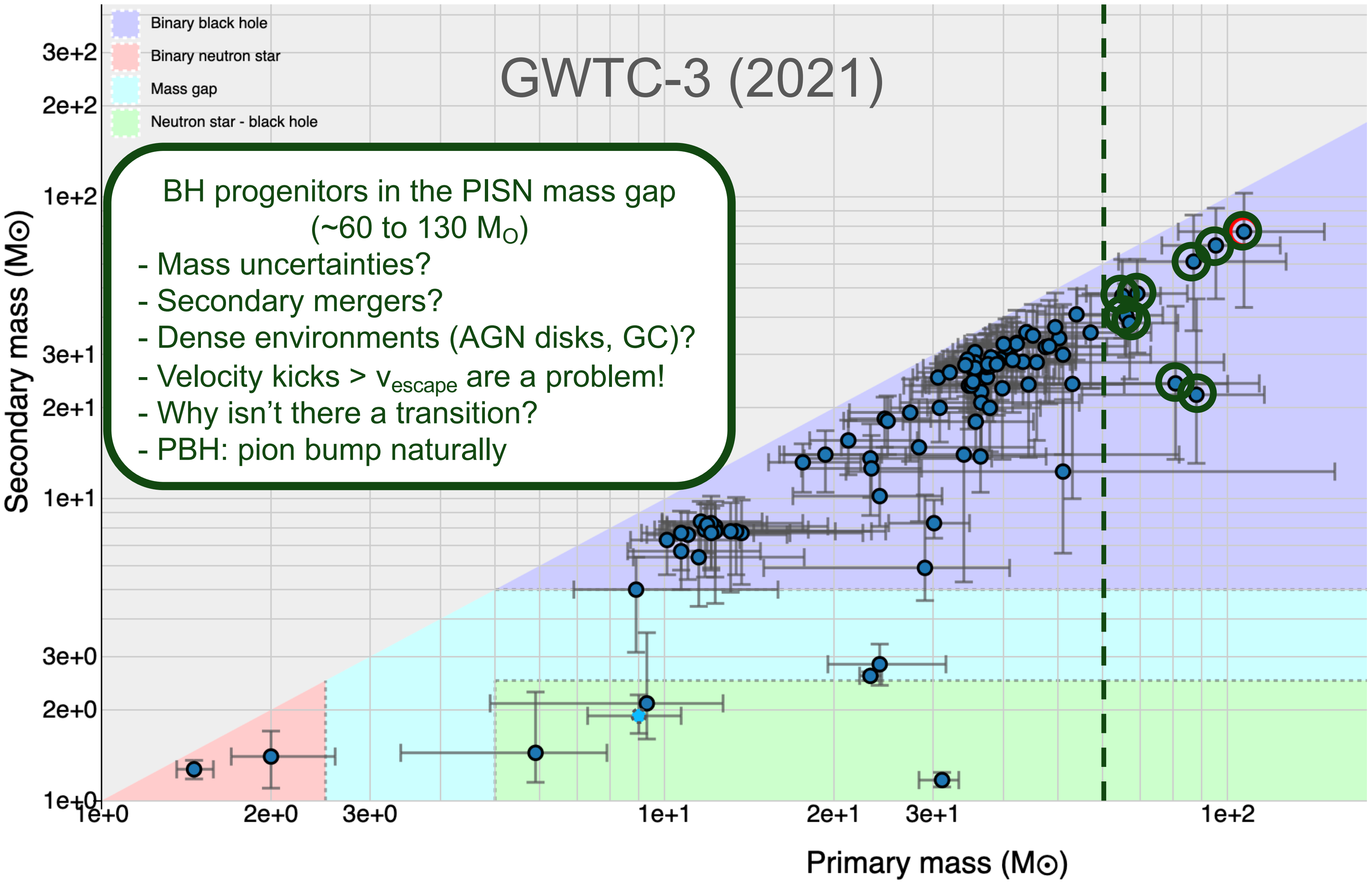
Are LIGO/Virgo BH Primordial?



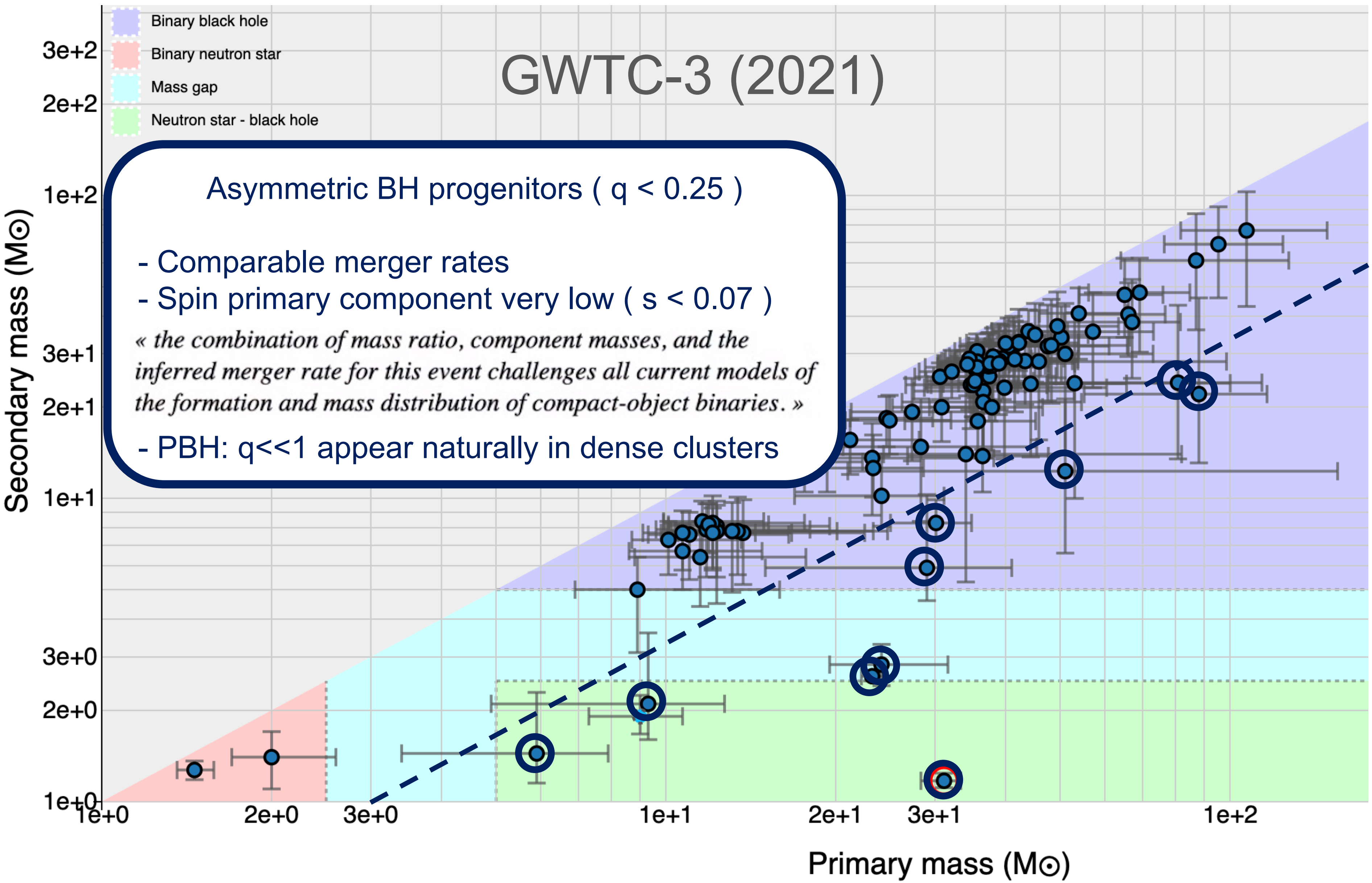
BH progenitors in the low mass gap (2.5 to 5 M_O)

- Mass uncertainties?
- BH vs Neutron Star?
- Mass gap hypothesis from XRB, no fundamental limitation?
- PBH: Transition form proton peak to pion bump

Are LIGO/Virgo BH Primordial?



Are LIGO/Virgo BH Primordial?



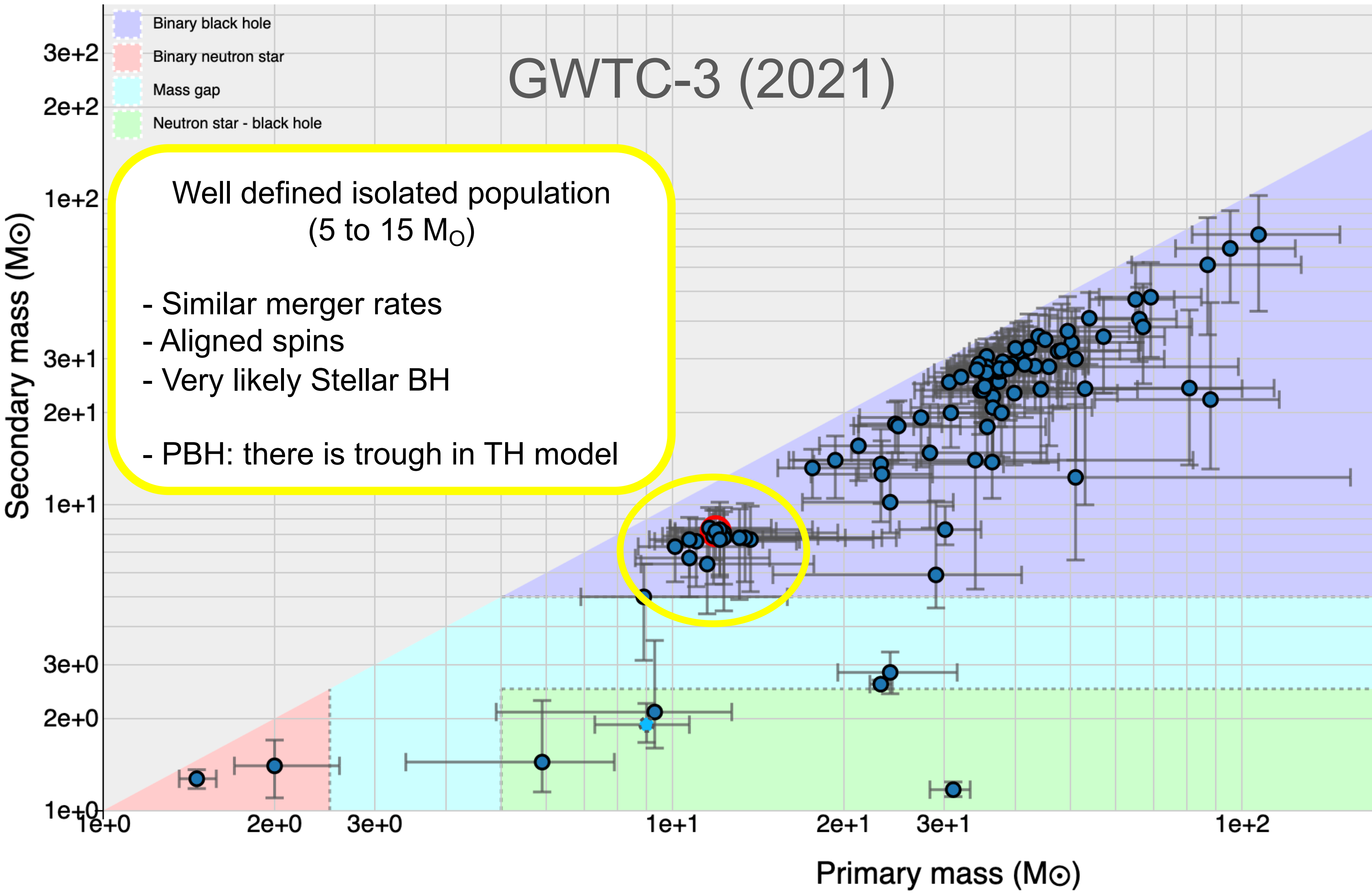
Asymmetric BH progenitors (q < 0.25)

- Comparable merger rates
- Spin primary component very low (s < 0.07)

« the combination of mass ratio, component masses, and the inferred merger rate for this event challenges all current models of the formation and mass distribution of compact-object binaries. »

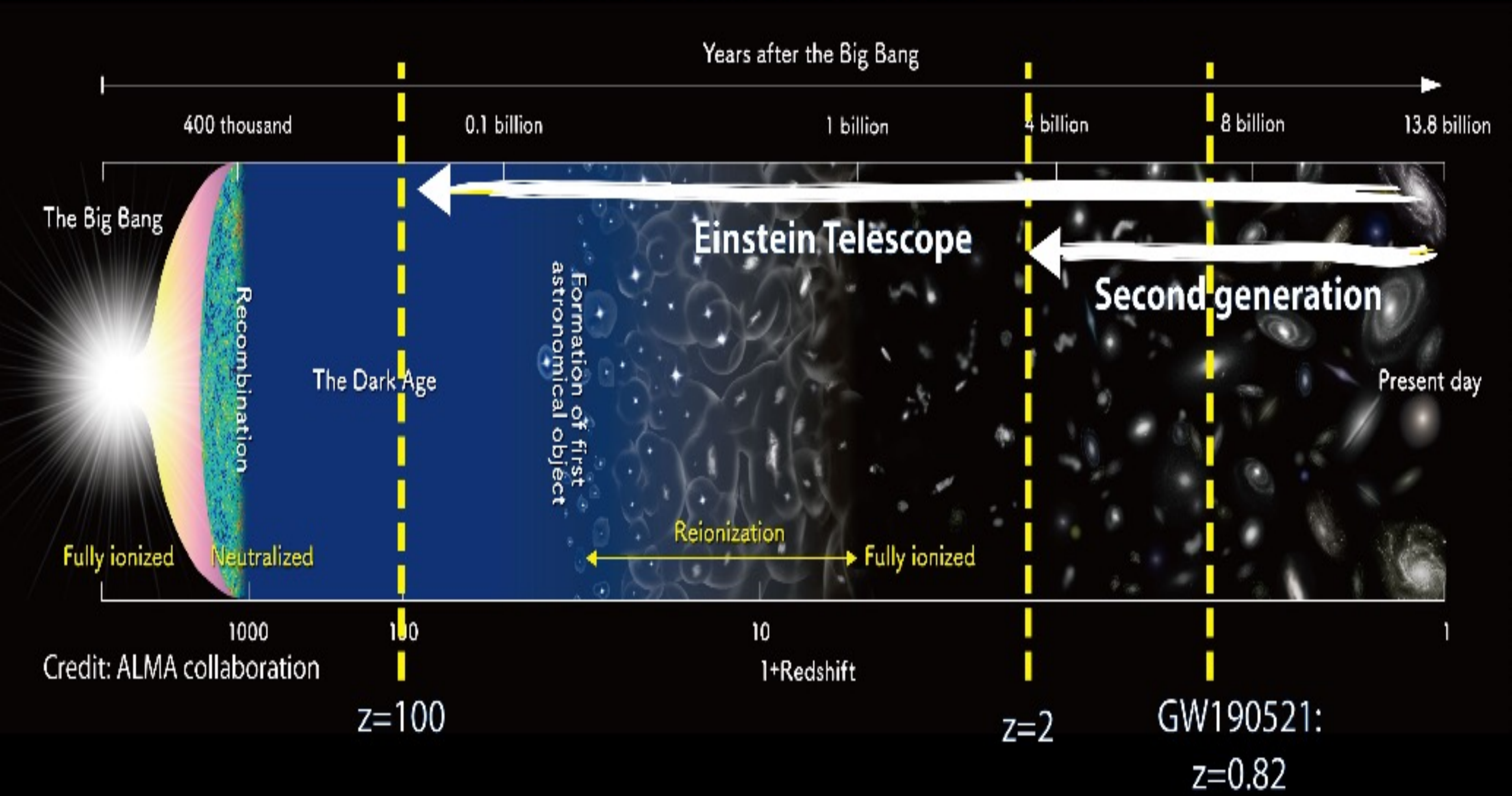
- PBH: q<<1 appear naturally in dense clusters

Are LIGO/Virgo BH Primordial?

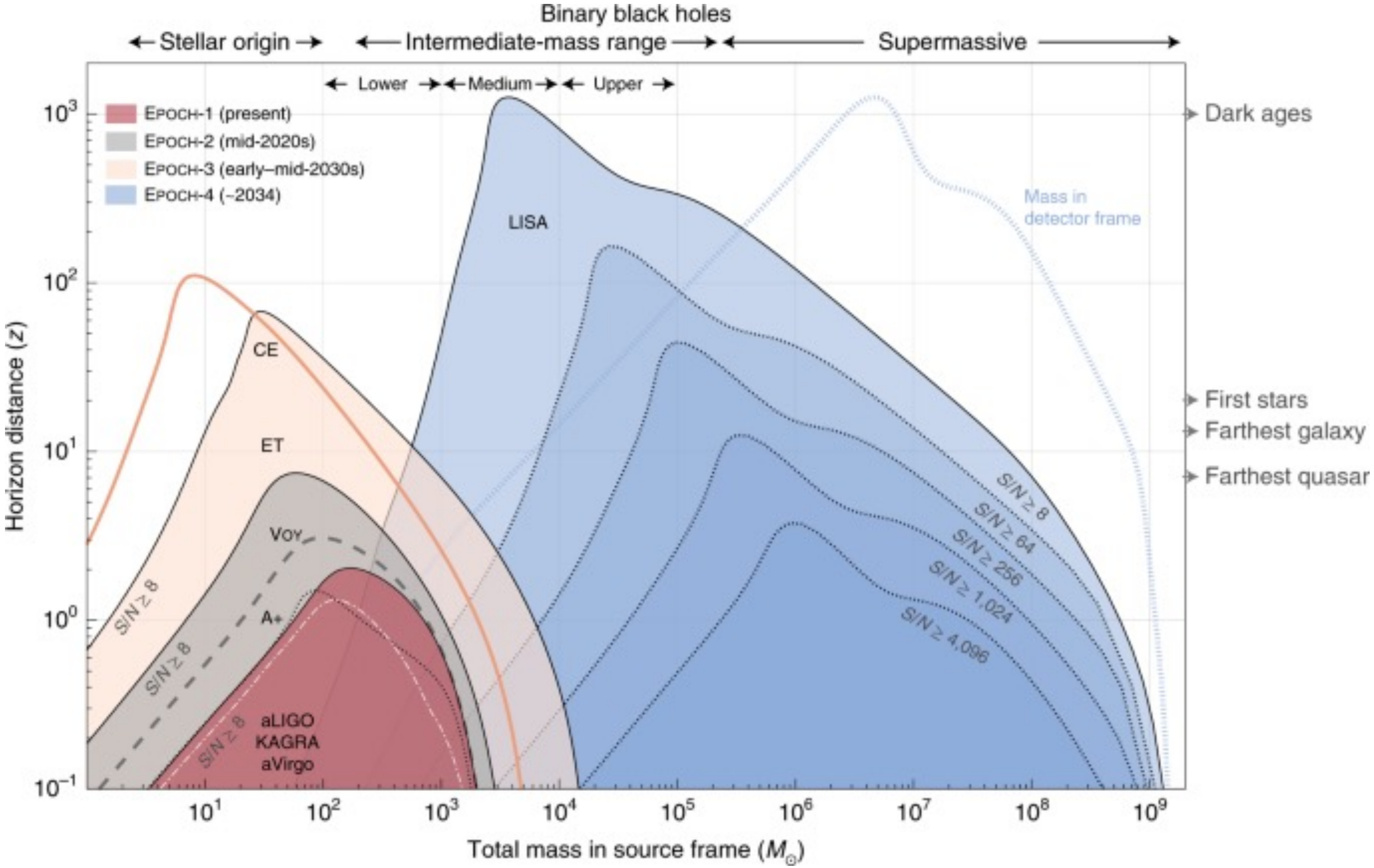


The future of GW (G3)

Detection horizon for black-hole binaries



BBH sensitivity in future G3 GW



SGWB from BBH & CHE

JGB, Jaraba, Kuroyanagi (2022)

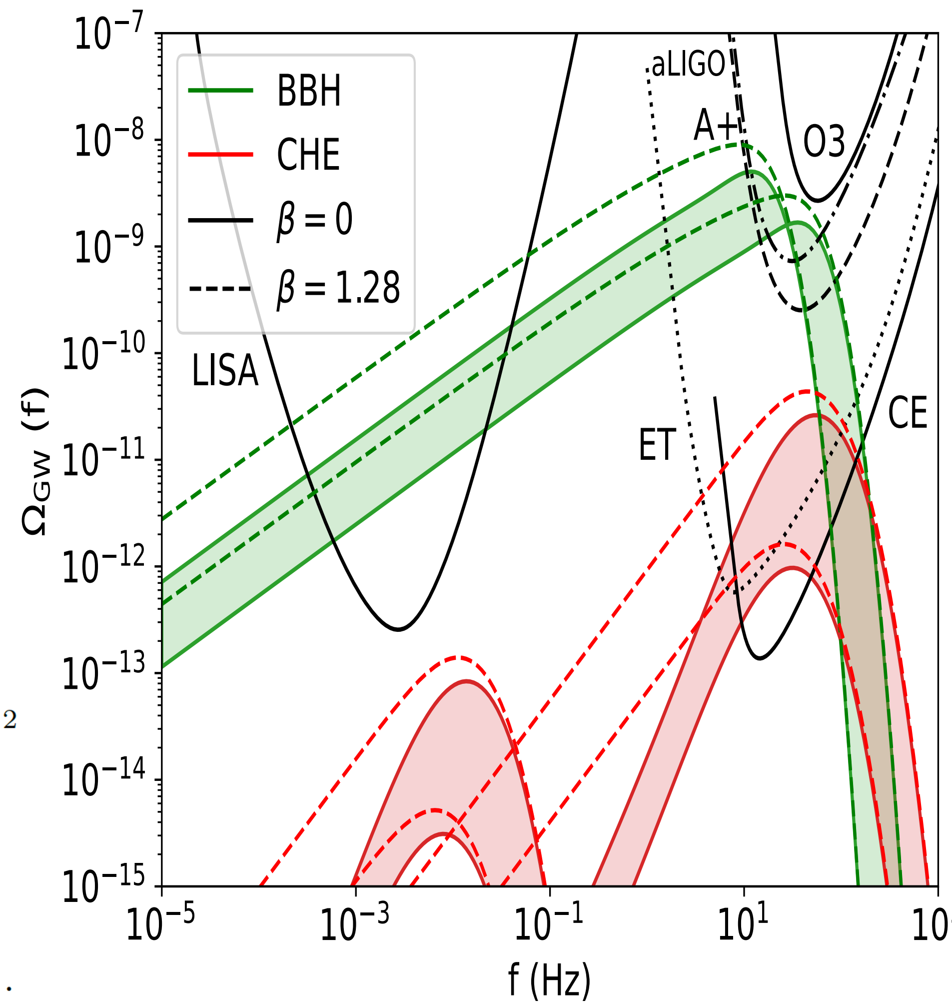
SGWB form Black Hole Binaries

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

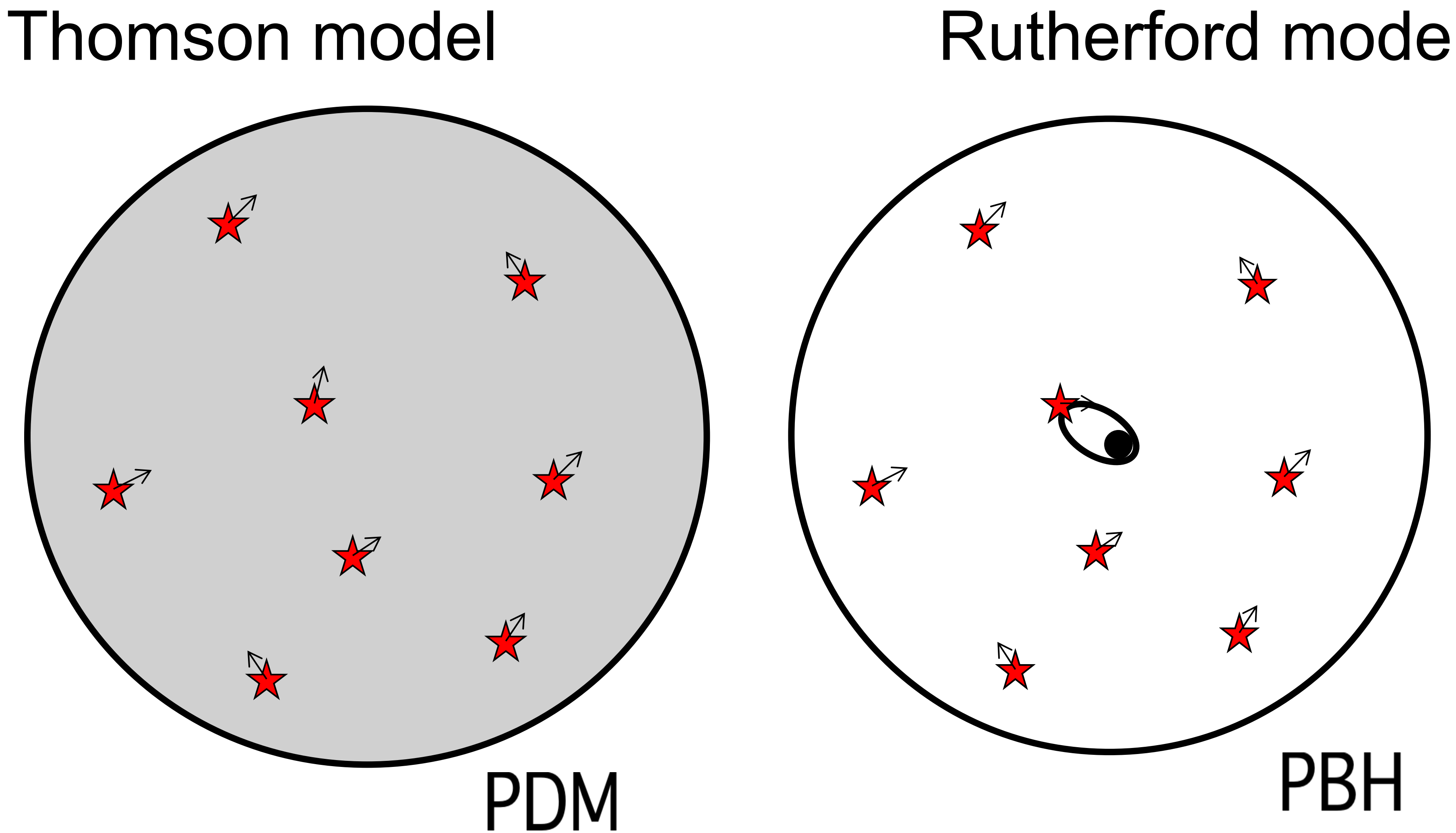
$$\tau(z) \propto (1+z)^\beta$$

Close Hyperbolic Encounters

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



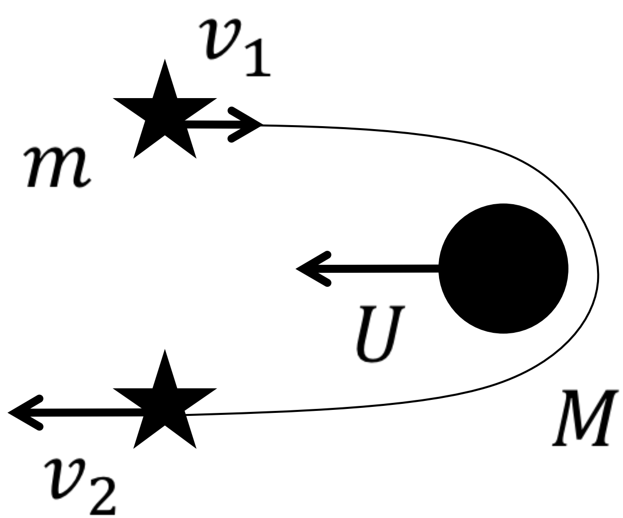
Spatial distribution of DM



JGB (2017)

Gravitational slingshot effect

Close encounters of a star with MPBH @ 100 km/s relative motion is enough to expel the star from the stellar cluster.



$$v_2 = \frac{2U + (1 - \frac{m}{M})v_1}{(1 - \frac{m}{M})}$$

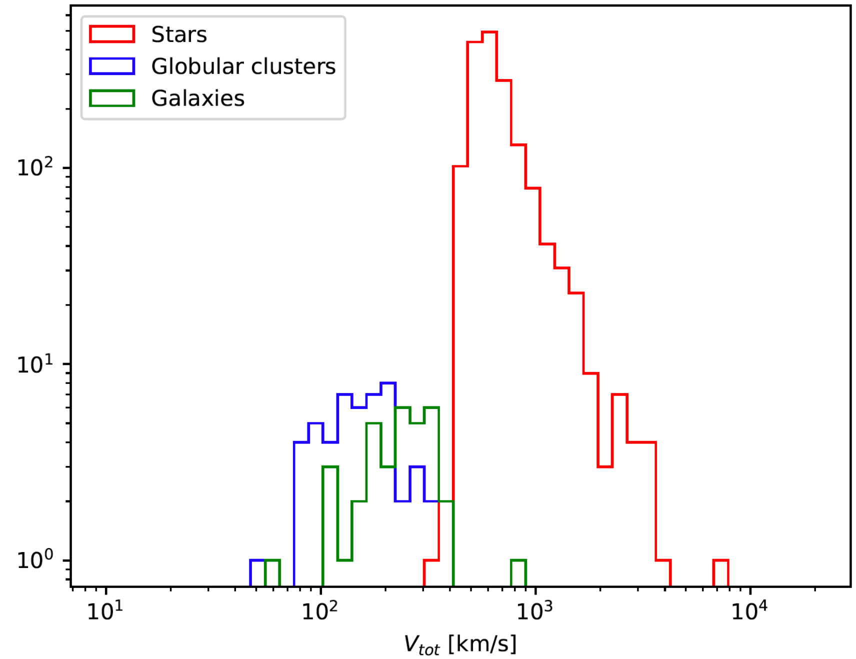
It may explain large M/L ratios of dSph by ejection of stars in the cluster, $v > v_{esc}$.

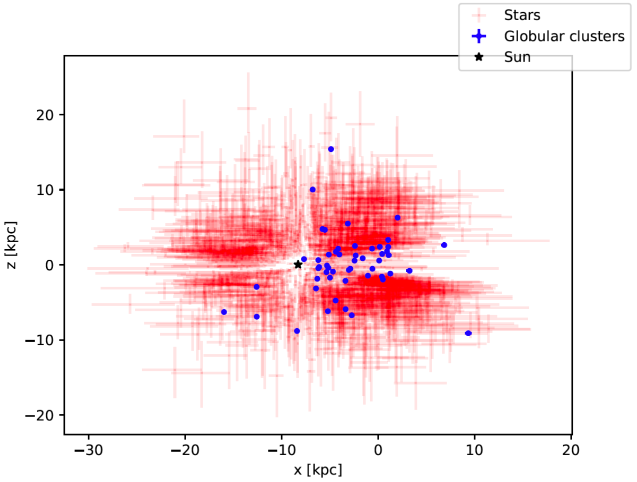
Hipervelocity Stars in GAIA DR2

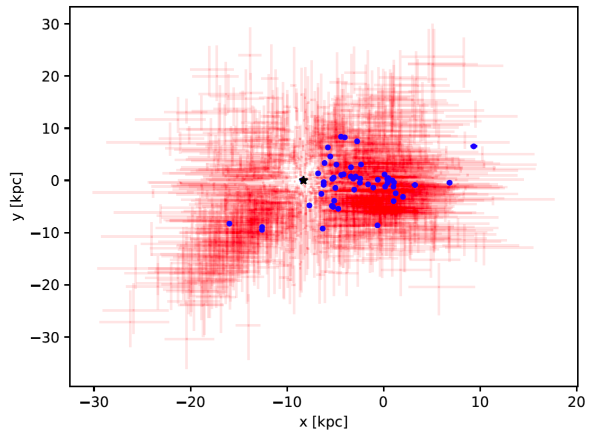
Montanari, JGB (2019)

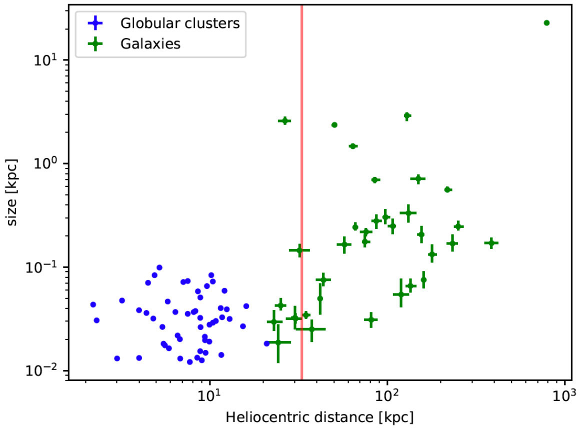
6D phase-space (+ size for globular clusters

- 1642 HVS stars (Gaia DR2).
- 52 globular clusters (Gaia DR2).
- 35 galaxies (DES + Gaia DR2).



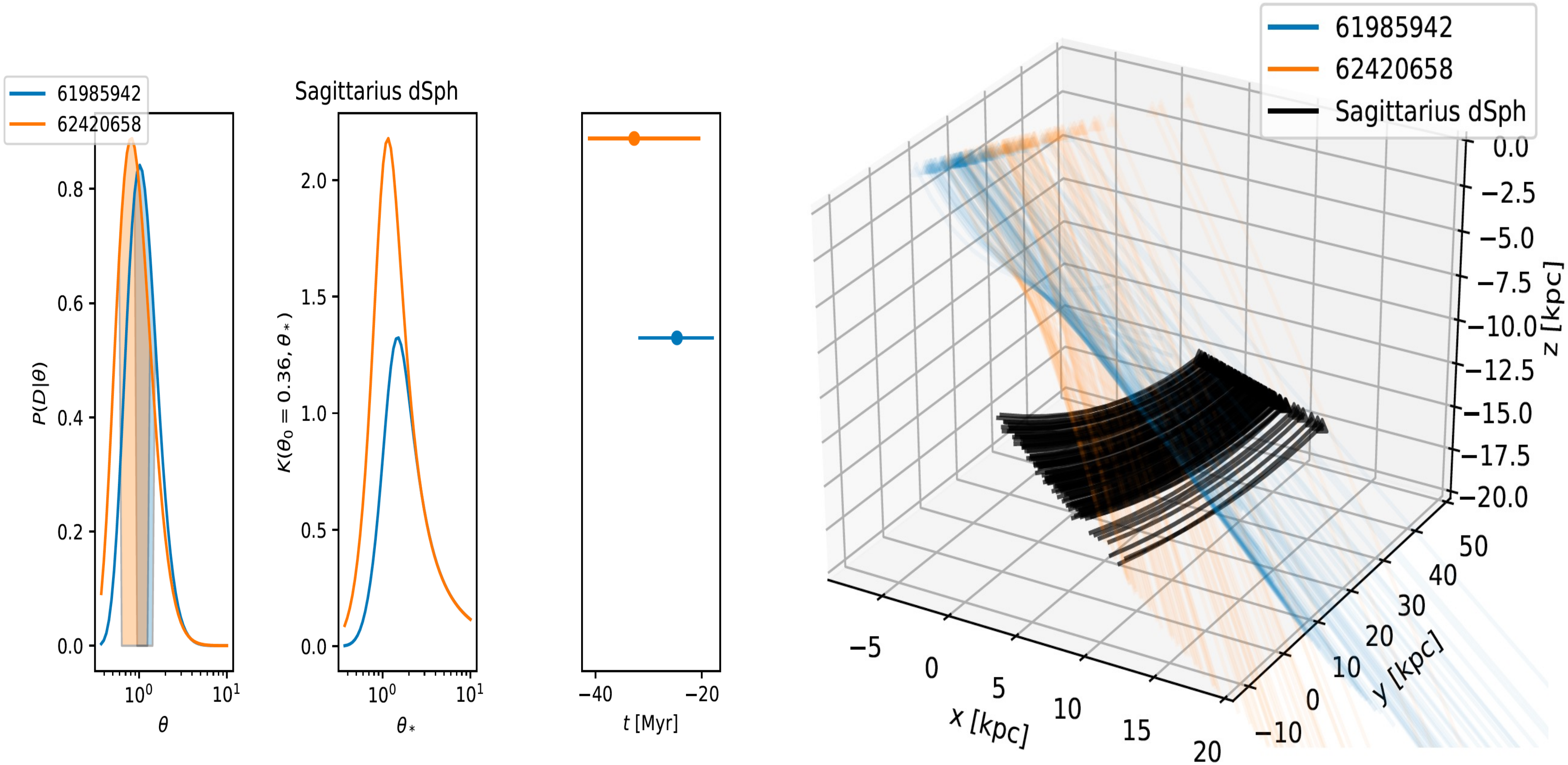






Hipervelocity Stars in GAIA DR2

Montanari, JGB (2019)



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.

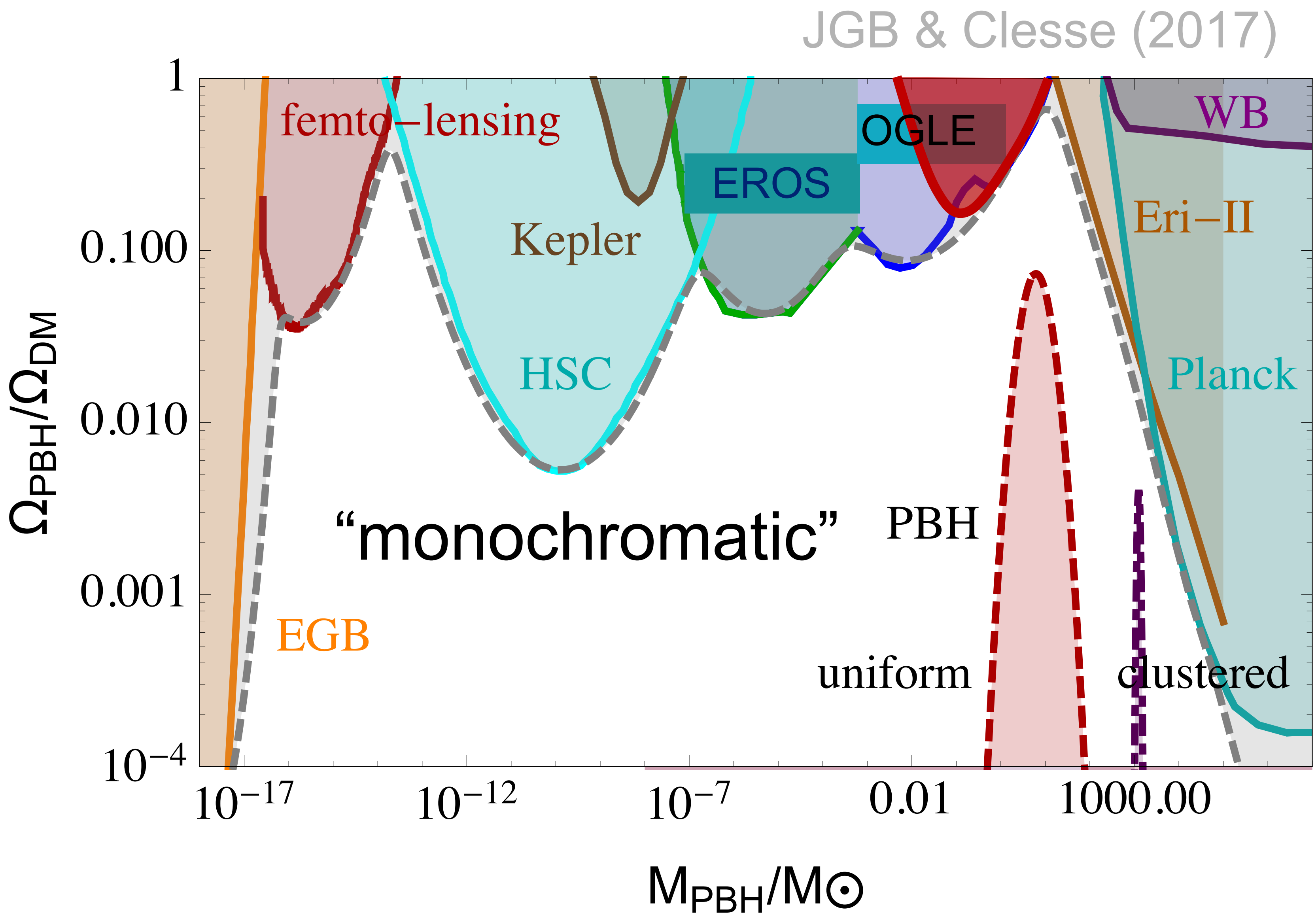
Cosmic Conundra explained

Clesse, JGB (2017)

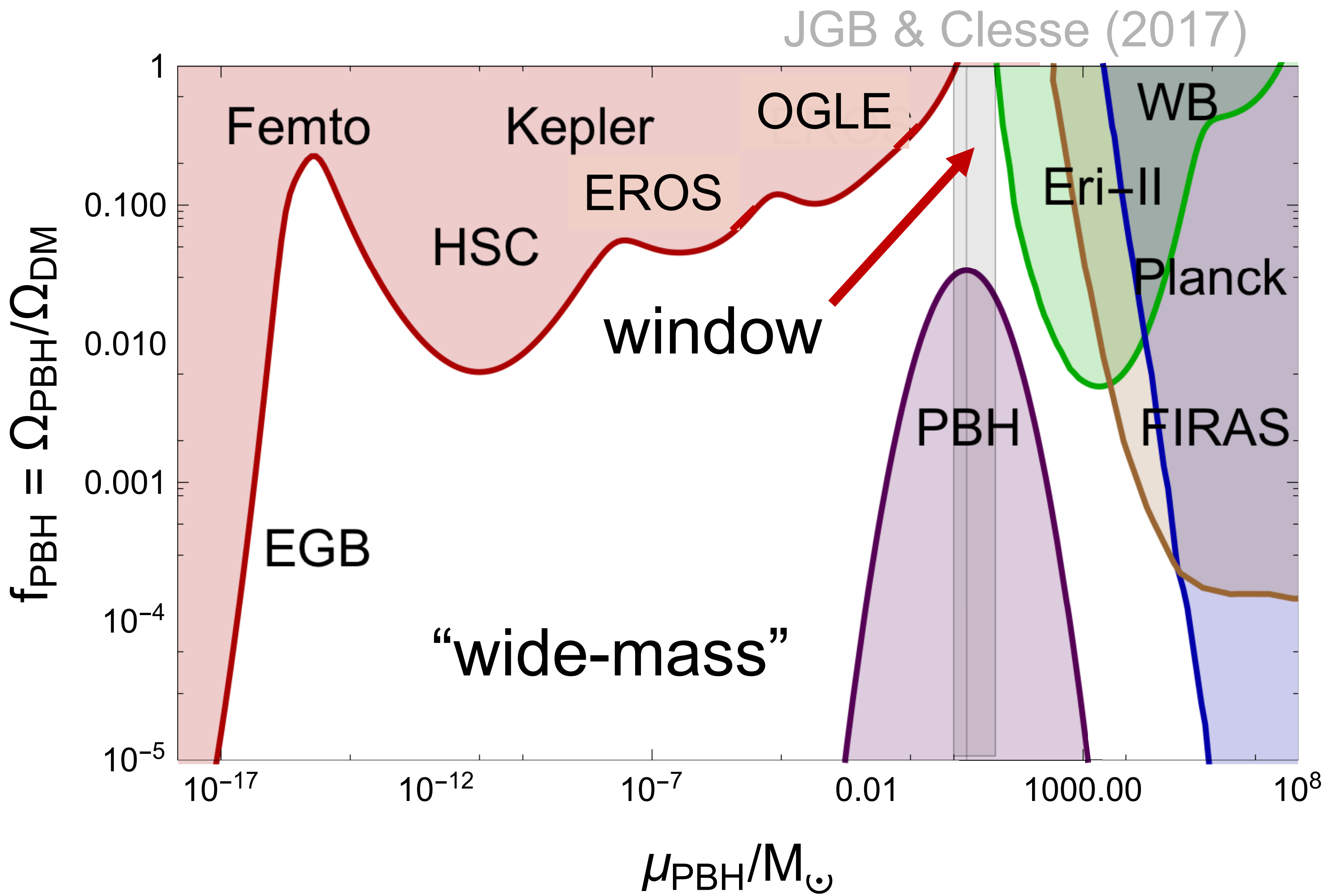
Carr, Clesse, JGB, Kühnel (2019)

- 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

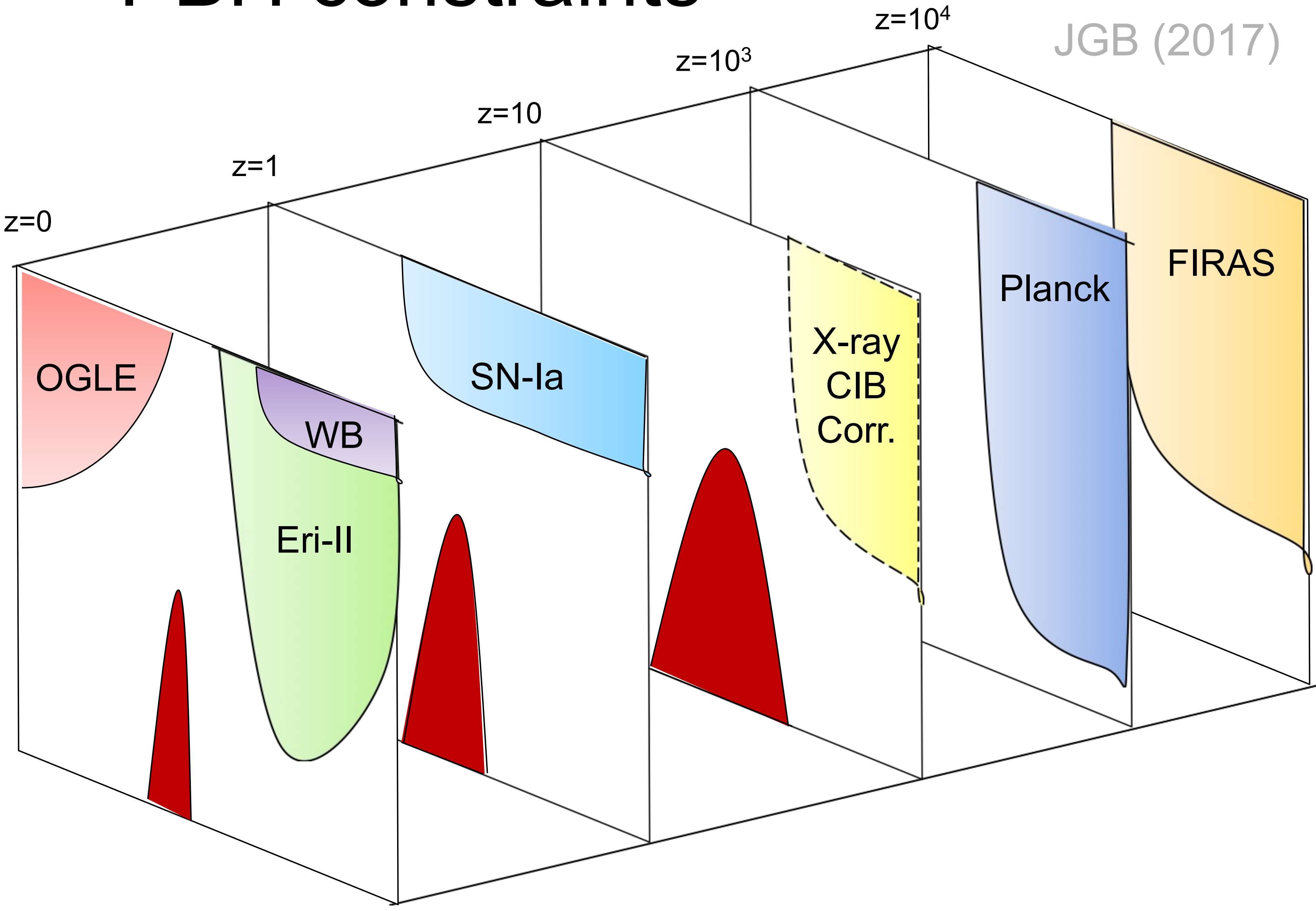
PBH constraints



PBH constraints



PBH constraints



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)