Precision Cosmology

IMFP Winter Meeting 2022

Benasque, 6th September 2022

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IFT-UAM/CSIC

Overview

From Fundamental Physics to Precision Cosmology

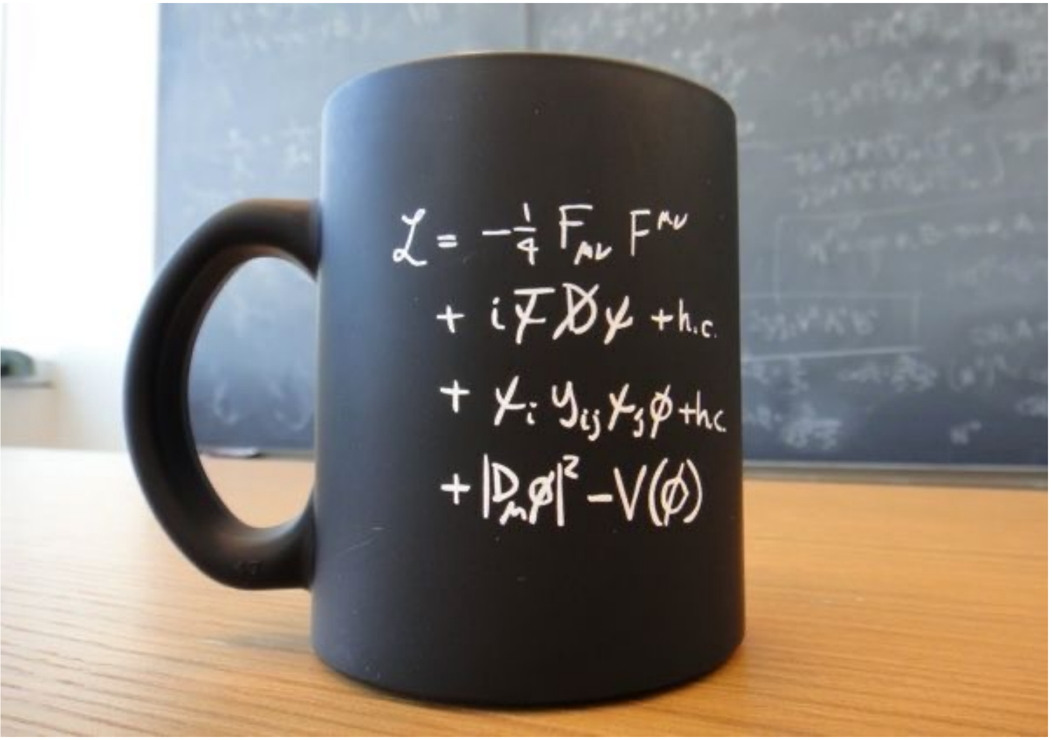
- From non-minimal coupling ξ to Higgs Inflation
- Renormalization Group Equations ($\lambda(\mu)$, $\xi(\mu)$)
- Critical Higgs Inflation and PBH = DM
- Inevitable Quantum Diffusion = PNG
- Signatures of QDiff in CMB and LSS
- Signatures of PBH in microlensing & GW
- Hubble tension and future surveys.
- Entropic Forces and Structure Formation
- Cosmic Acceleration from First Principles

CERN

10 years HIGGS boson discovery

4th July 2012 – Higgs boson discovery

Standard Model Lagrangian



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

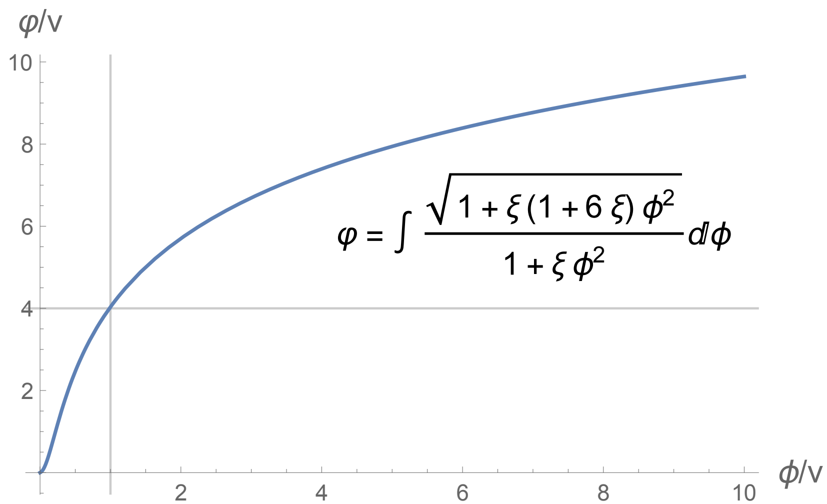
$$R = 12H^2 + 6\dot{H} \rightarrow R_0 = 9.2\, H_0^2 \rightarrow m_H = \sqrt{\xi R_0} = 2\times 10^{-32}\ \mathrm{eV}$$

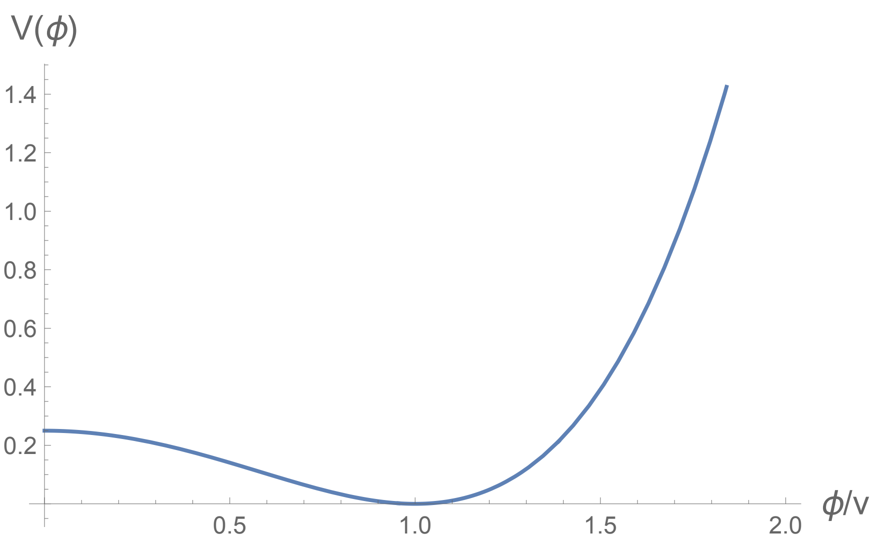
Conformal redefinition of metric and Higgs

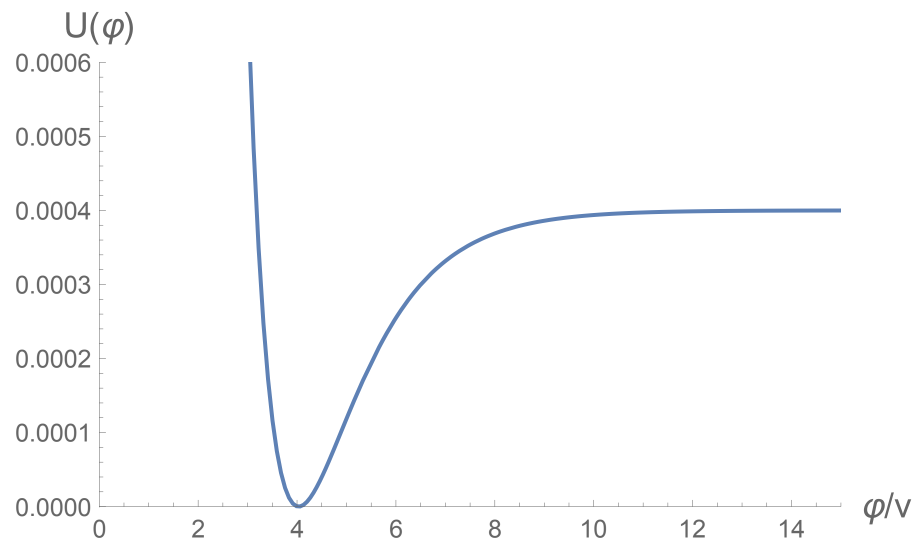
$$g_{\mu\nu} \to (1+\xi\phi^2)\, g_{\mu\nu}$$

$$\phi \to \varphi$$

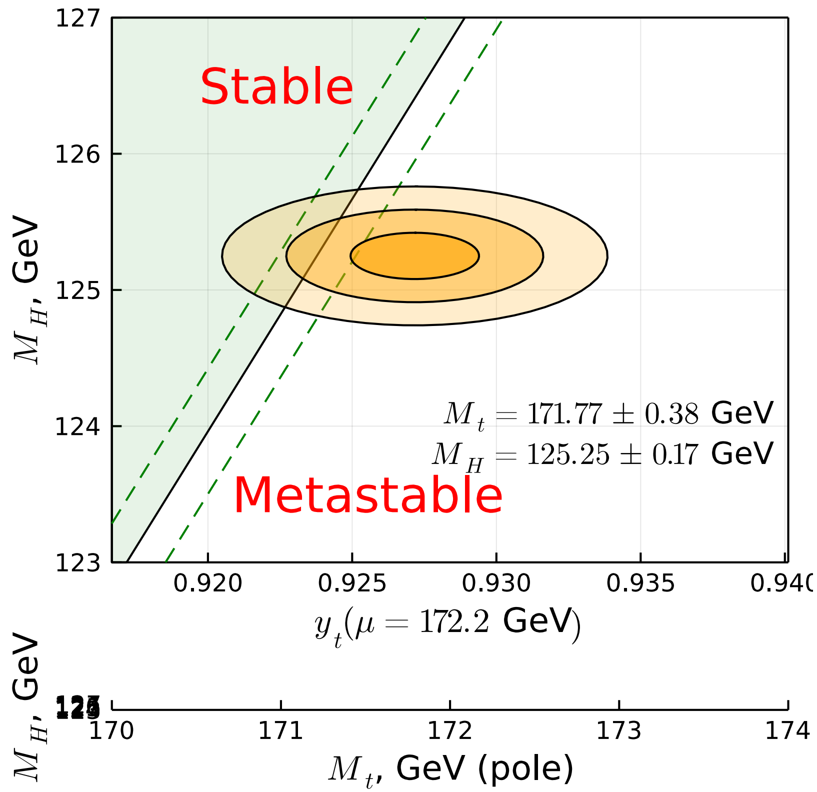
$$V(\phi) \to \frac{V(\phi)}{(1+\xi\phi^2)^2}$$







EW vacuum metastability

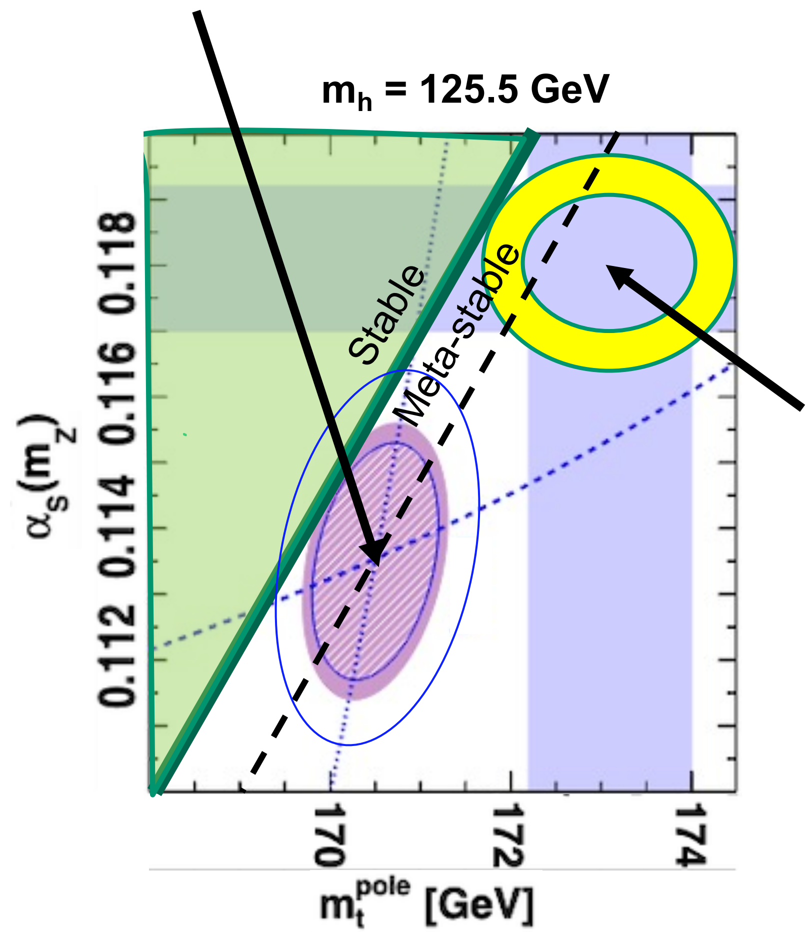


$$m_t^{\text{pole}} = 170.5 \pm 0.8\,\text{GeV}$$

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

LHC-CMS Collab. (2020)

https://arxiv.org/abs/1904.05237

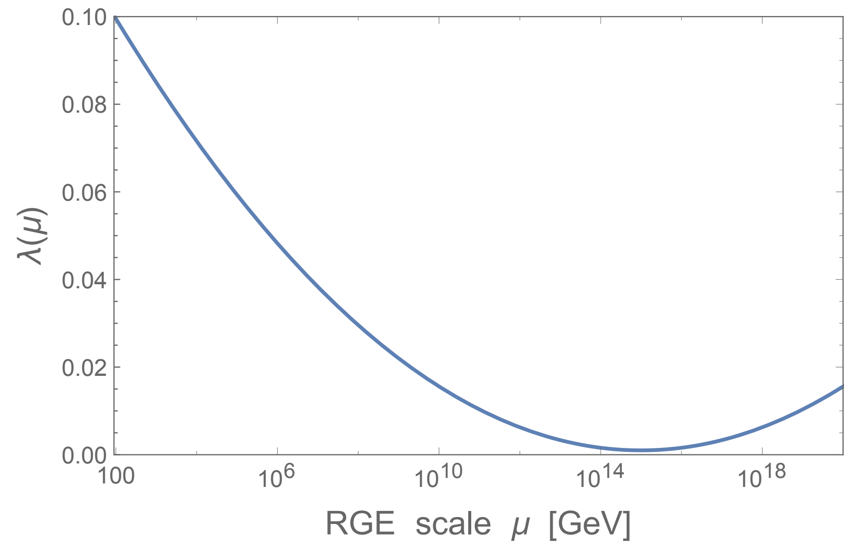


Buttazzo et al. (2012)

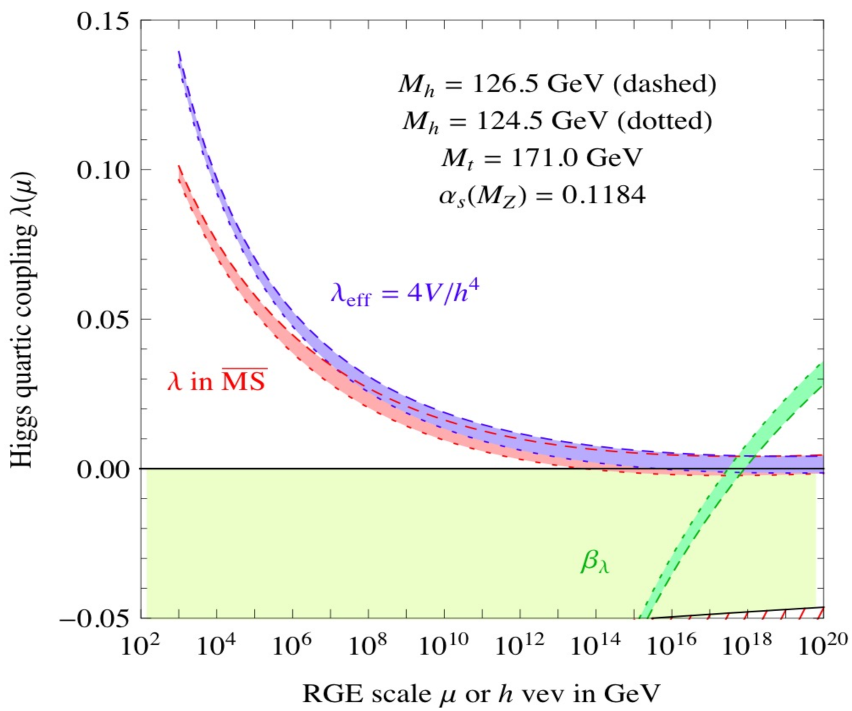
https://arxiv.org/pdf/1112.3022.pdf

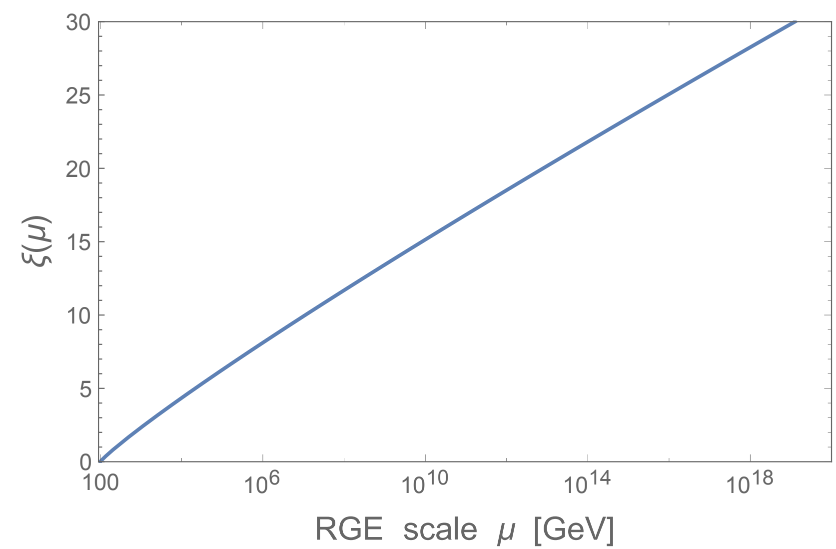
Renormalization of Higgs couplings

$$\lambda(\phi) \;=\; \lambda_0 + b_\lambda \ln^2(\phi/\mu) \;,$$
$$\xi(\phi) \;=\; \xi_0 + b_\xi \ln(\phi/\mu) \;,$$



Buttazzo et al (2014)





Critical Higgs Inflation

Ezquiaga, JGB, Ruiz Morales (2017)

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

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

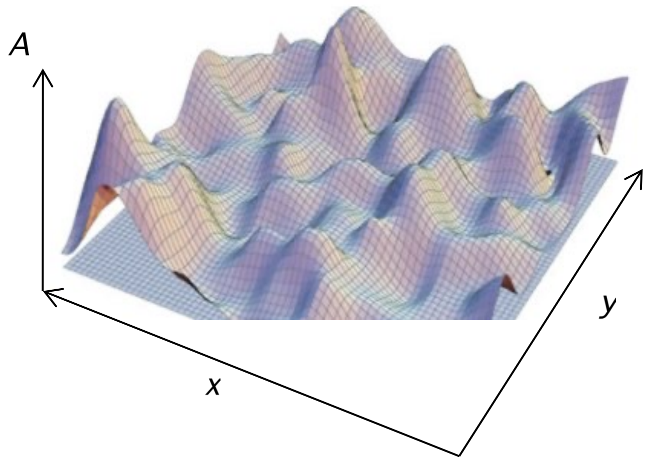
$$\xi(\phi) = \xi_0 + b_\xi \ln (\phi/\mu) ,$$

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

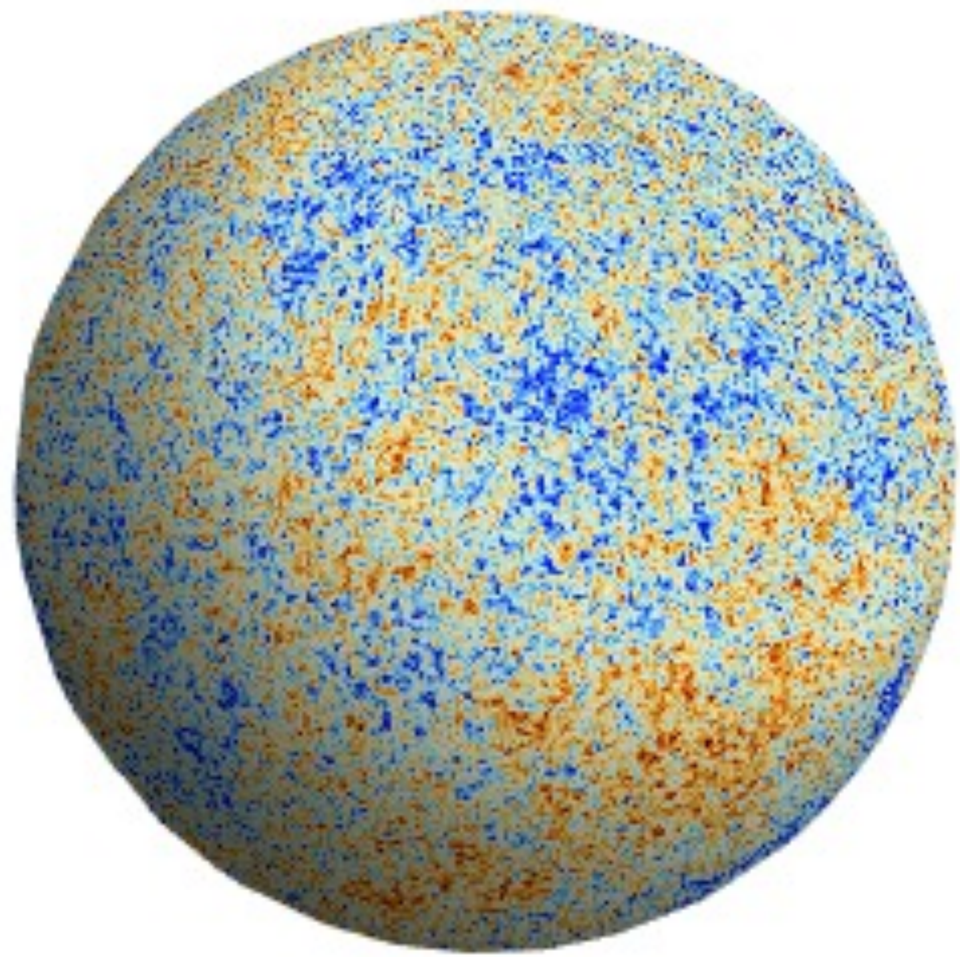
$$V(x) = \frac{V_0\,(1 + a\,\ln^2 x)\,x^4}{(1 + c\,(1 + b\,\ln x)\,x^2)^2} \qquad x = \phi/\mu$$

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

Inflation

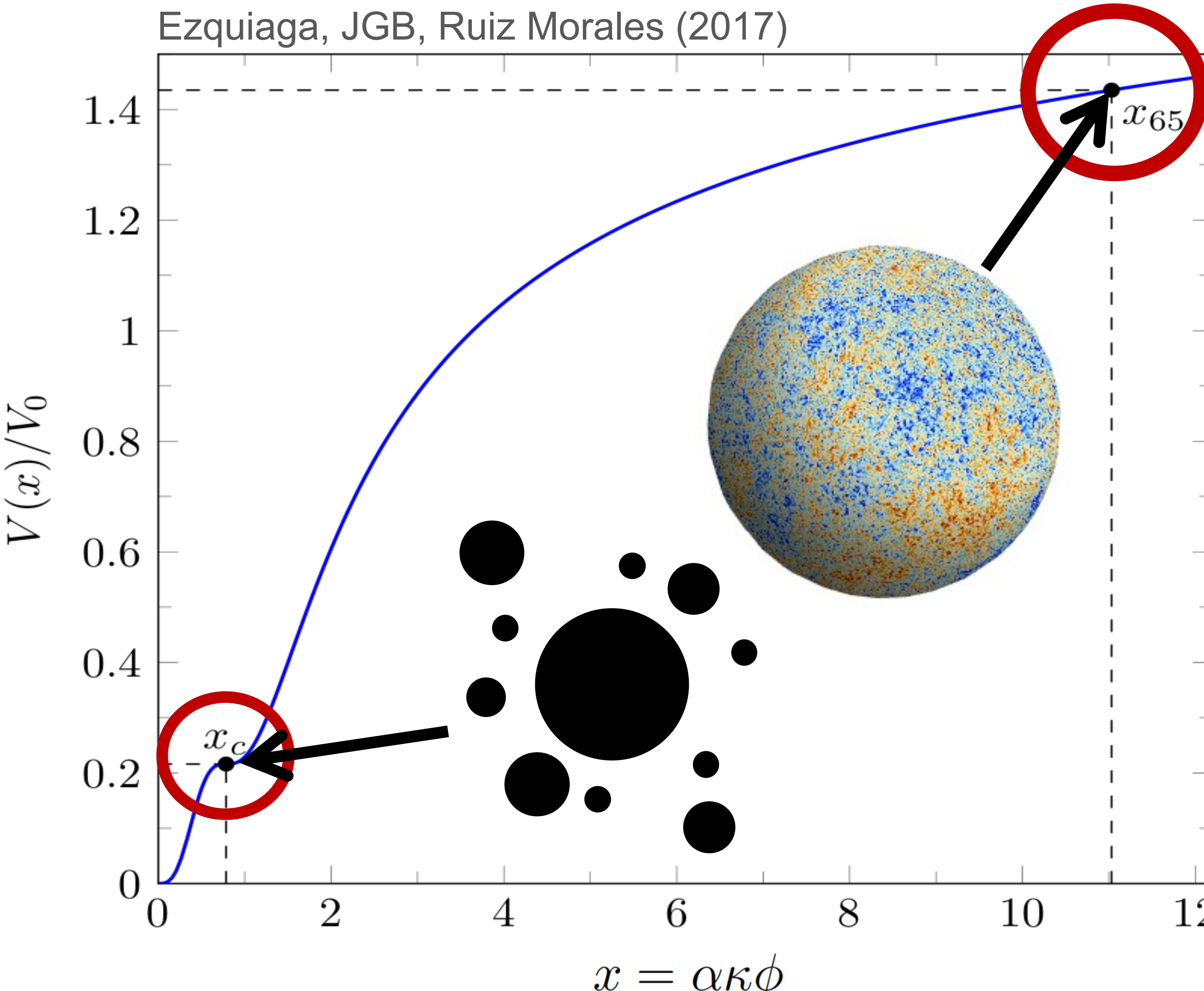


Quantum Fluctuations=
Ripples in Space-Time

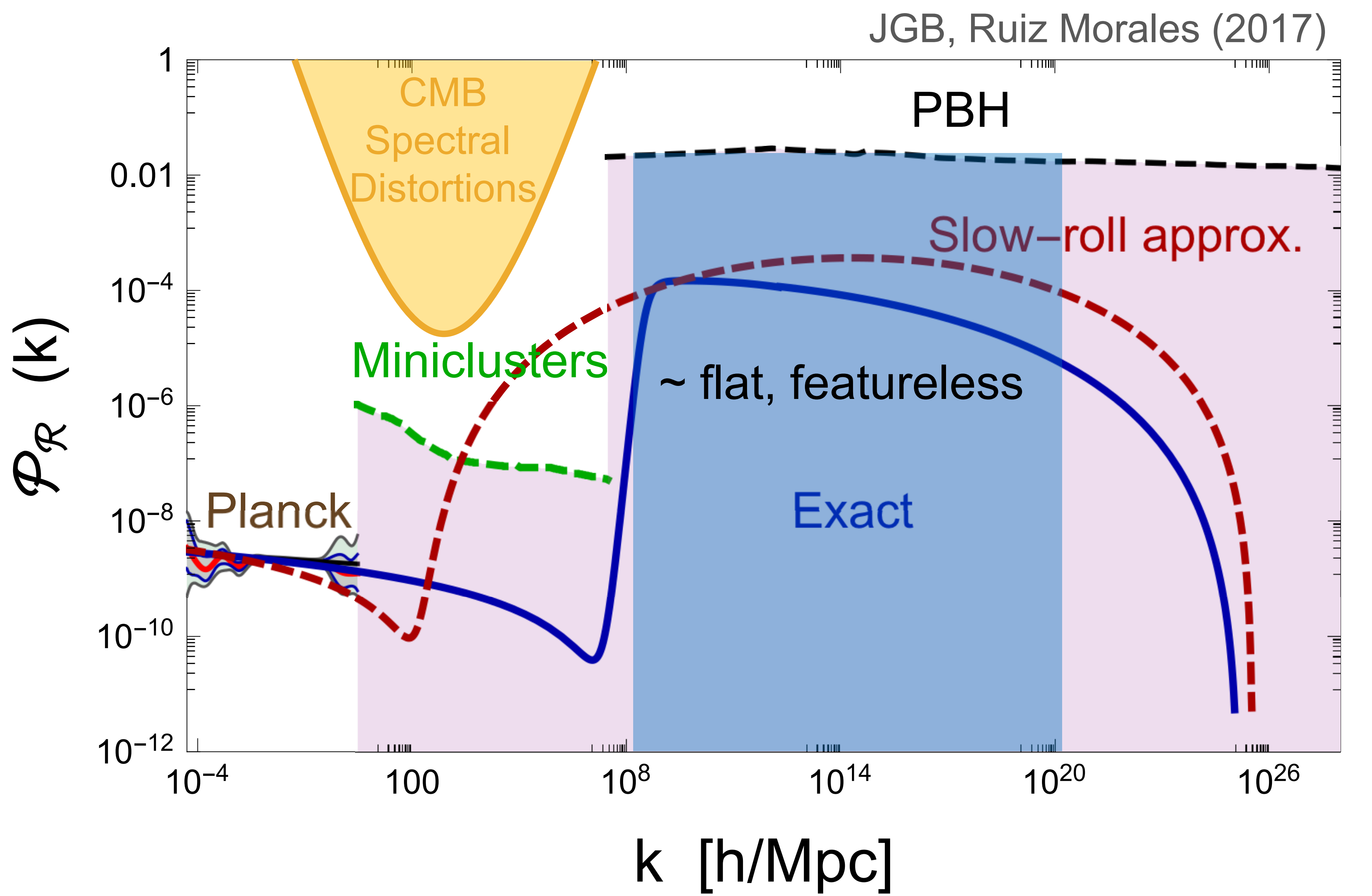


Stretched to cosmological distances

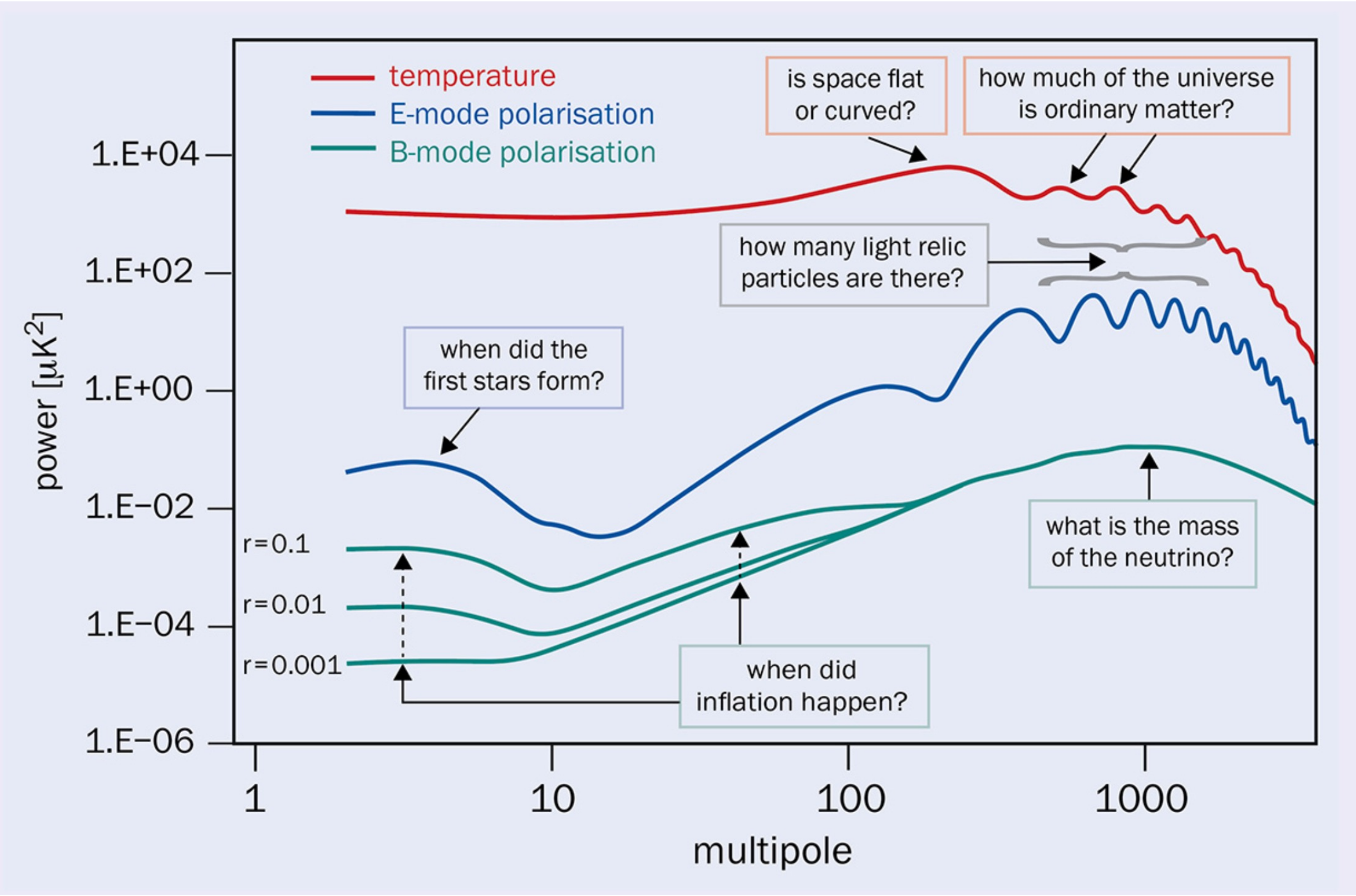
Ezquiaga, JGB, Ruiz Morales (2017)



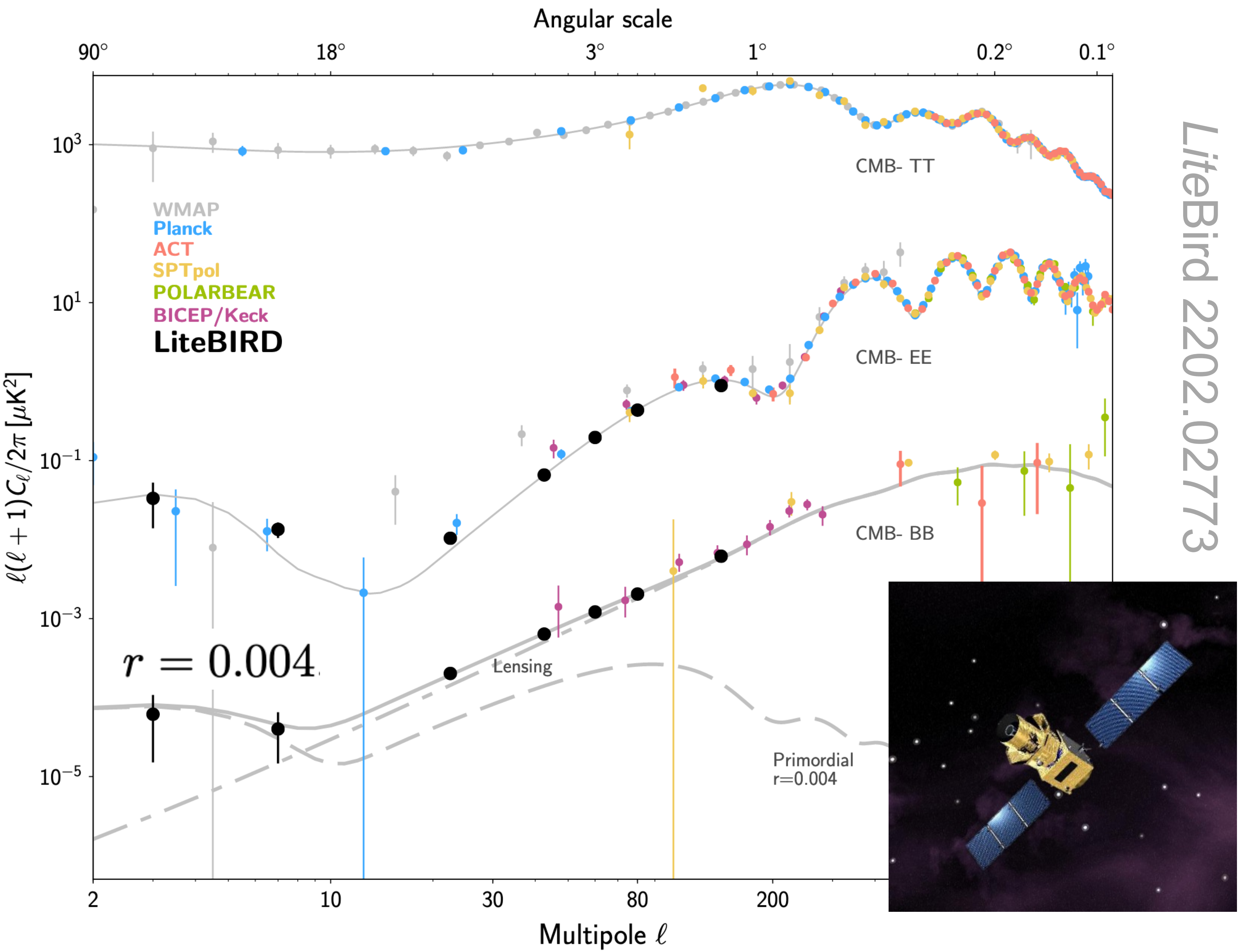
Primordial Power Spectrum



Future experiments will search for B modes



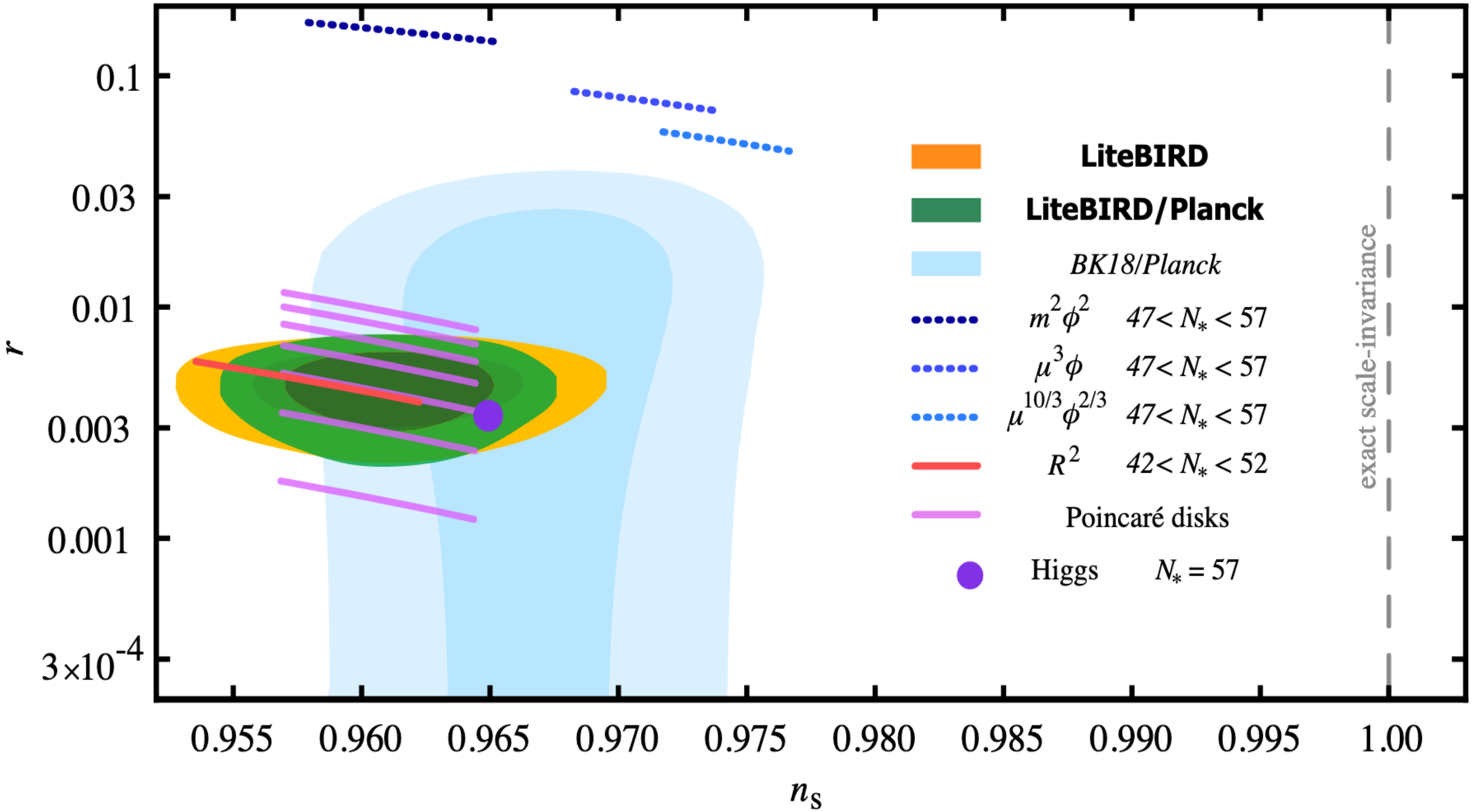
Future experiments will search for B modes



LiteBird 2202.02773

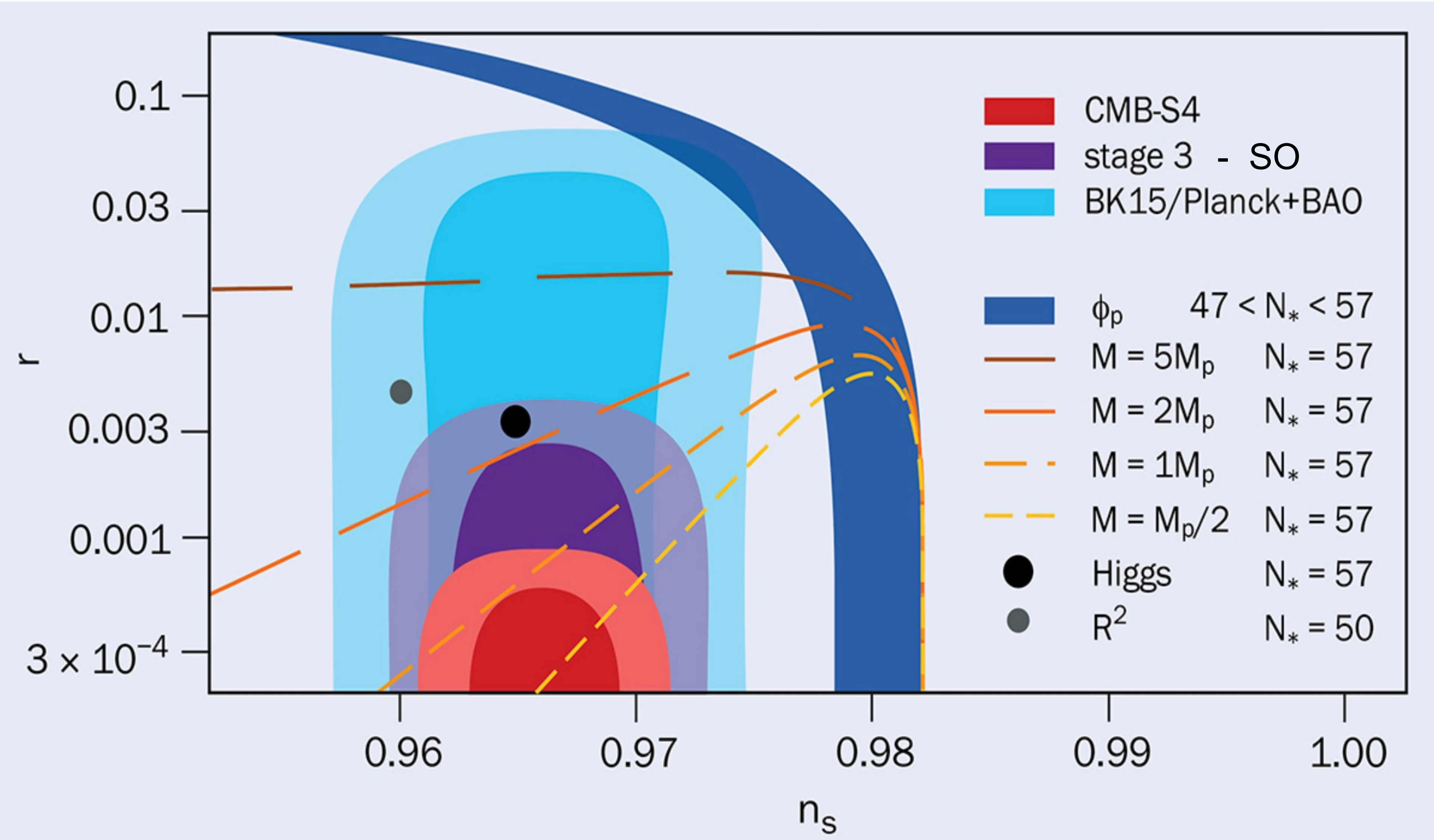
Future experiments will search for B modes

*Lite*Bird 2202.02773

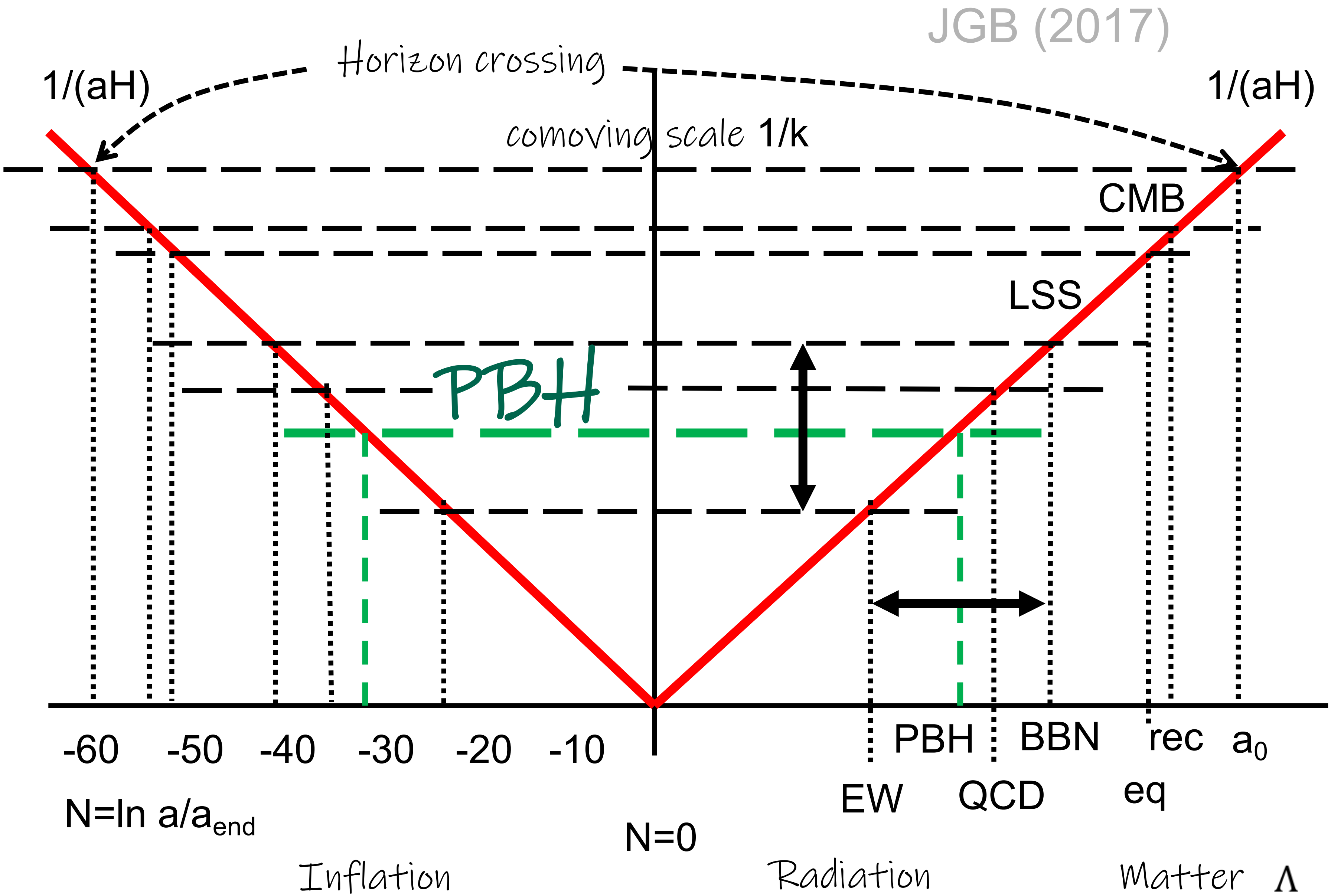


Future experiments will search for B modes

CMB-S4 (2022)

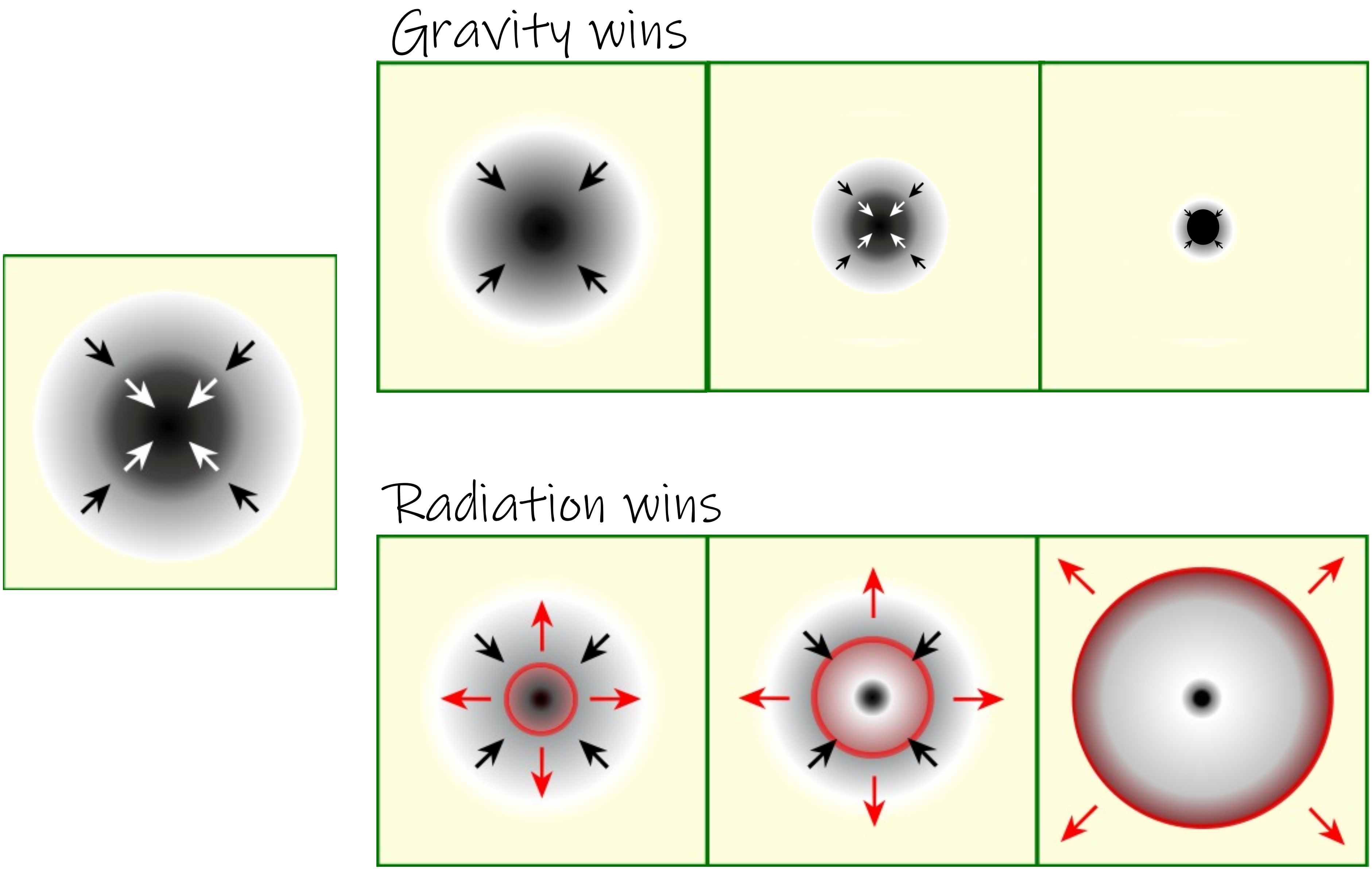


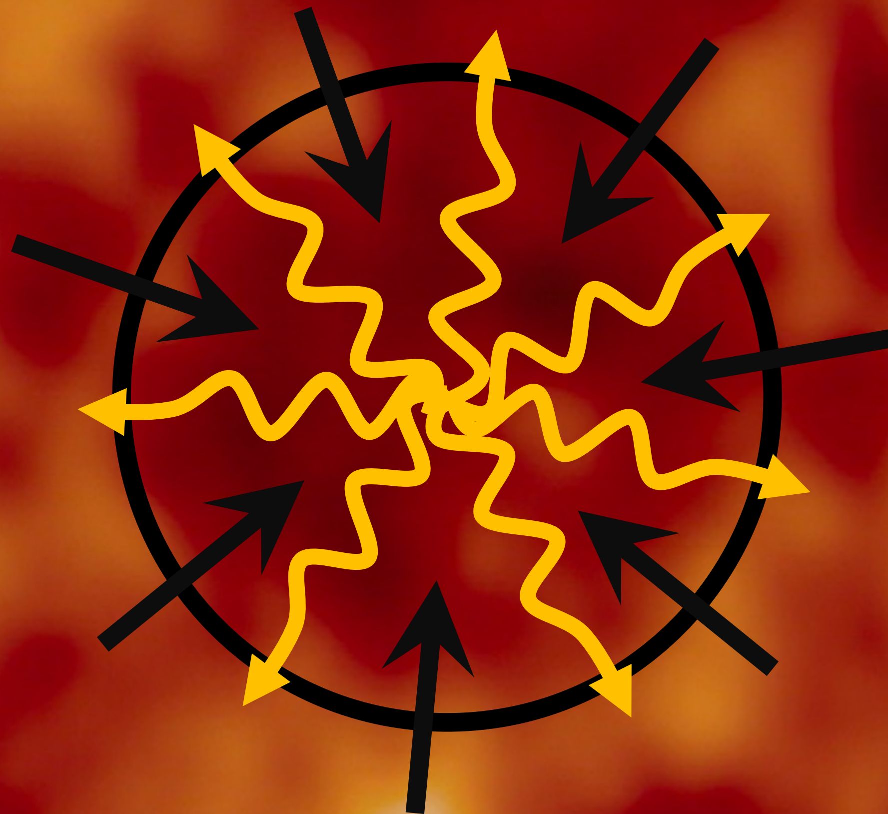
Inflation



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
PBH
BBN
rec
a$_0$
EW
QCD
eq
Inflation
Radiation
Matter
Λ

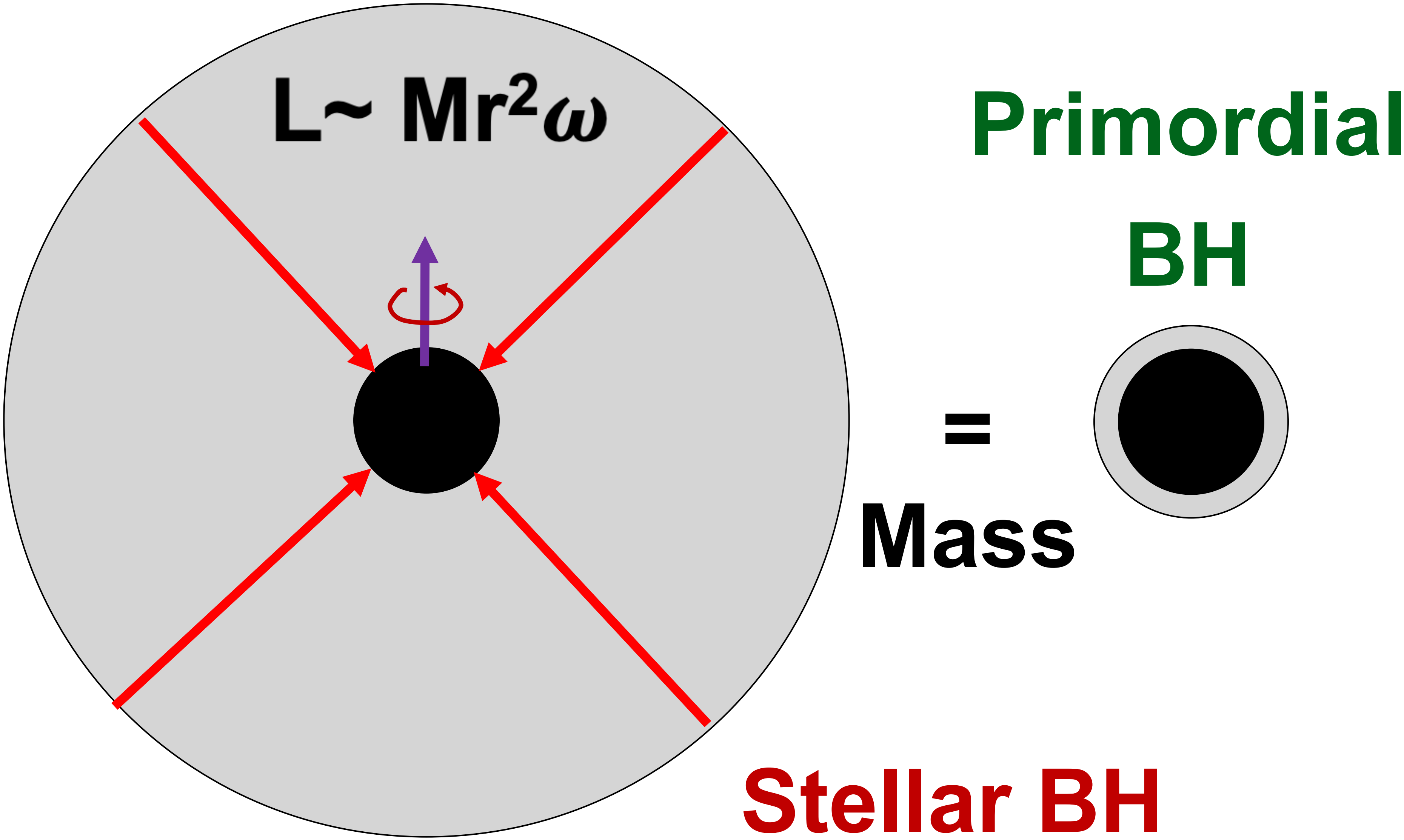
Gravitational Collapse



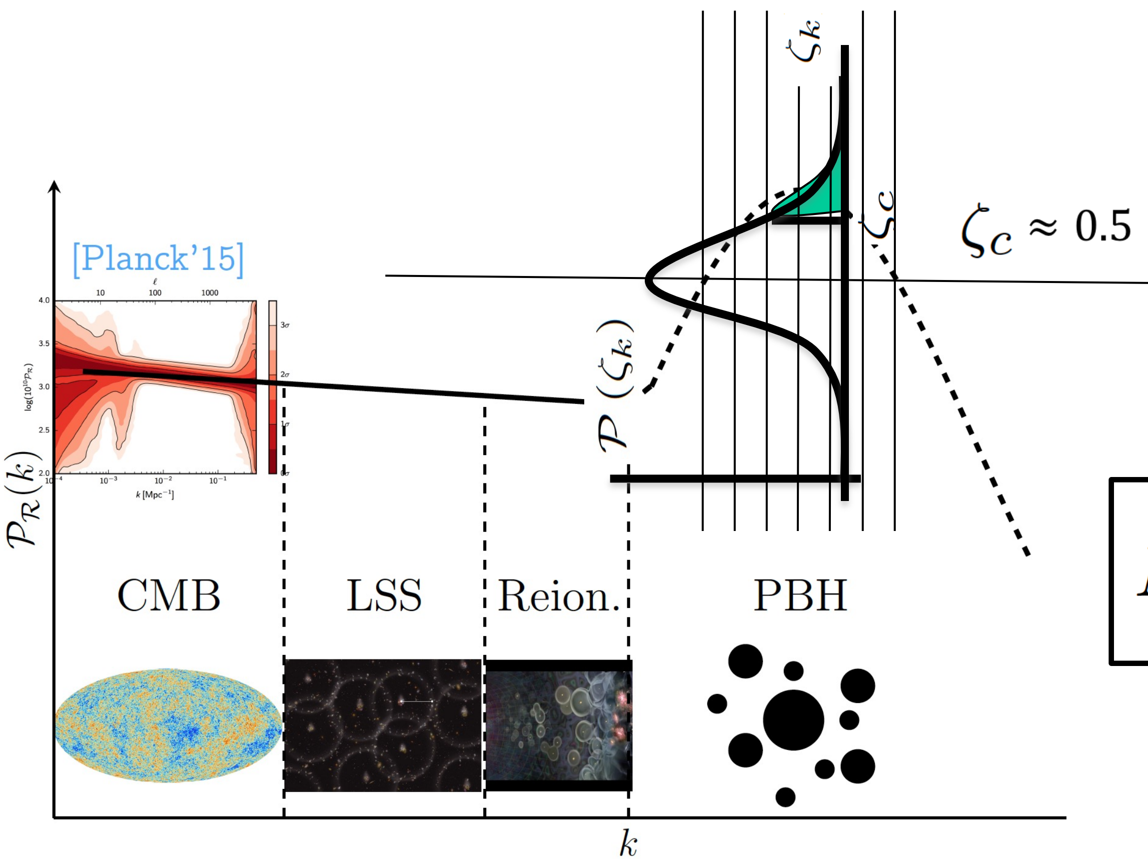


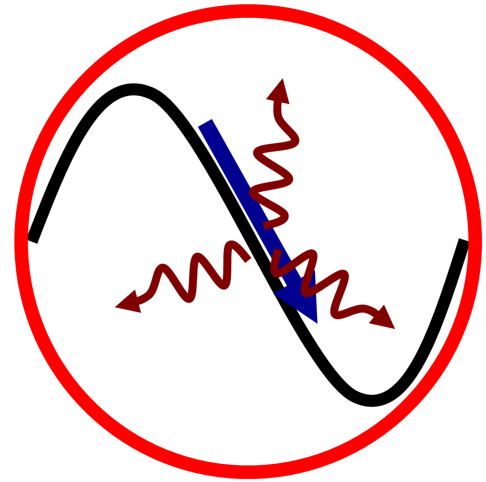
Primordial plasma

PBH are ~ spinless



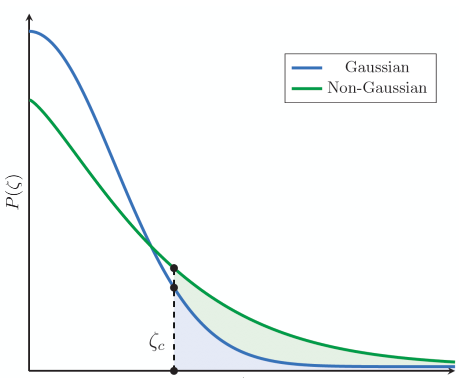
Gravitational Collapse of PBH





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

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



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

Stochastic δN - formalism

Coarse-grained curvature perturbation

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

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

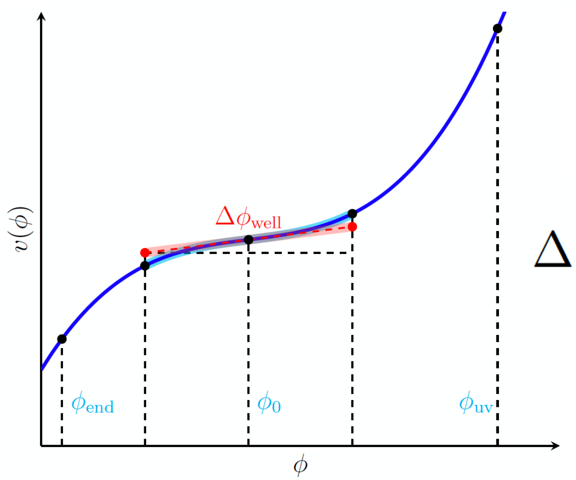
Fokker-Planck Diffusion Eq.

Determined by the poles of the characteristic function

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

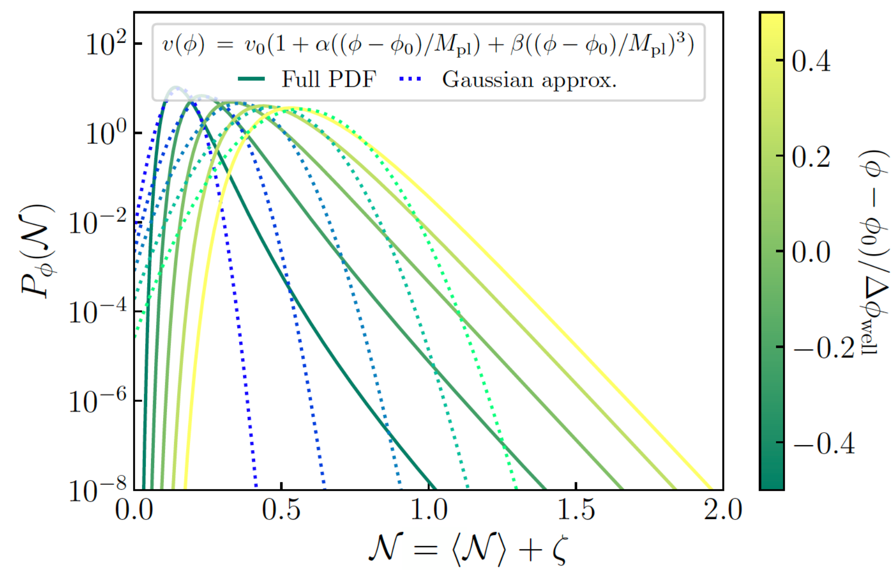
Ezquiaga, JGB, Vennin (2019)

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



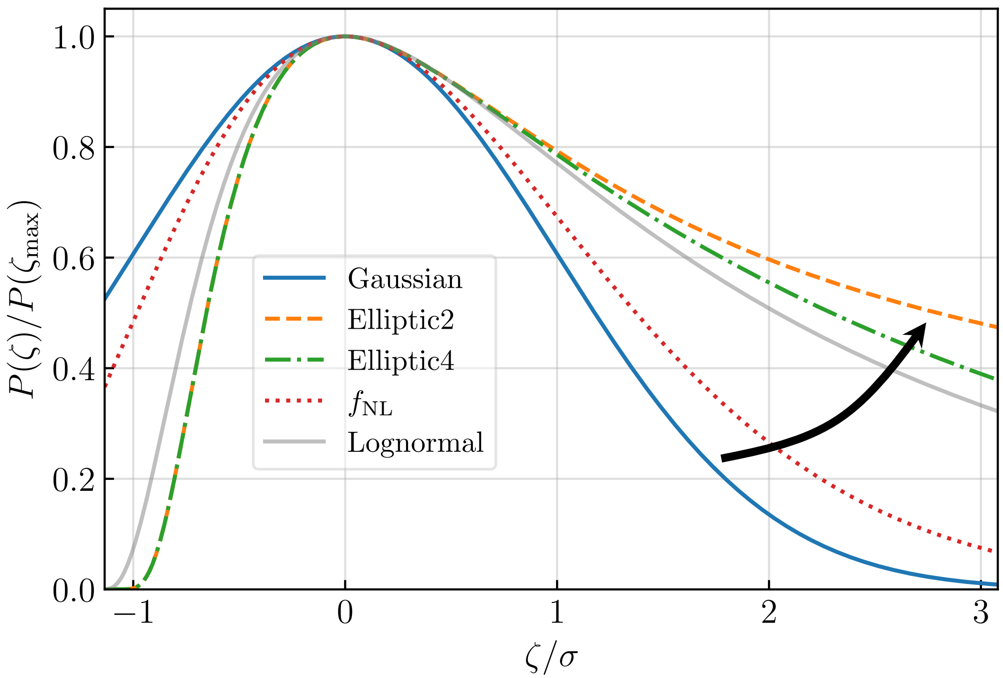
$$\alpha \gg (v_0^2\beta)^{1/3}$$

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



Quantum Diffusion @ CMB & LSS

Ezquiaga, JGB, Vennin (2022)



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

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

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

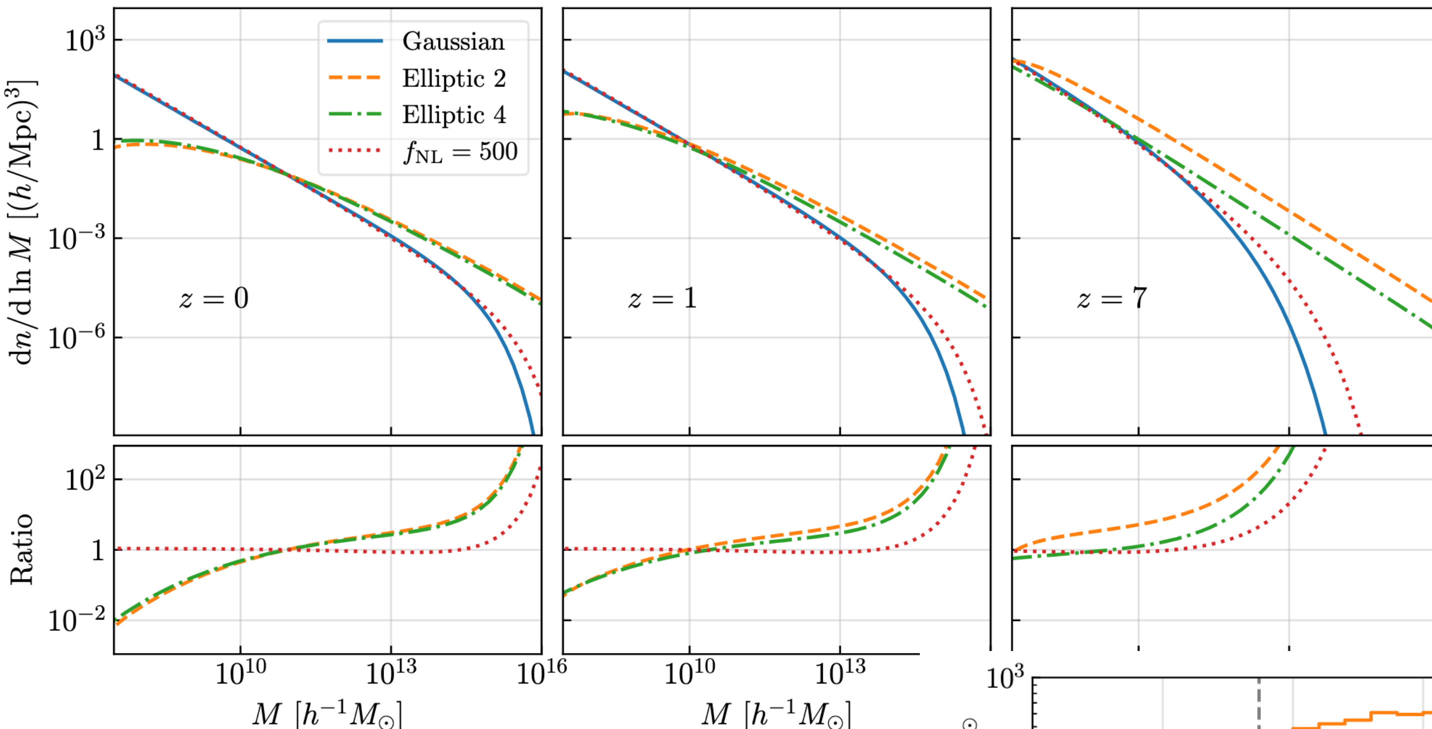
$$\mathrm{LN}(x, \rho, \sigma) = \frac{1}{\rho\,\sigma\sqrt{2\pi}}\exp\left[-\frac{\ln(x/\rho)^2}{2\sigma^2} - \frac{\sigma^2}{2}\right]$$

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

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

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

Quantum Diffusion @ CMB & LSS

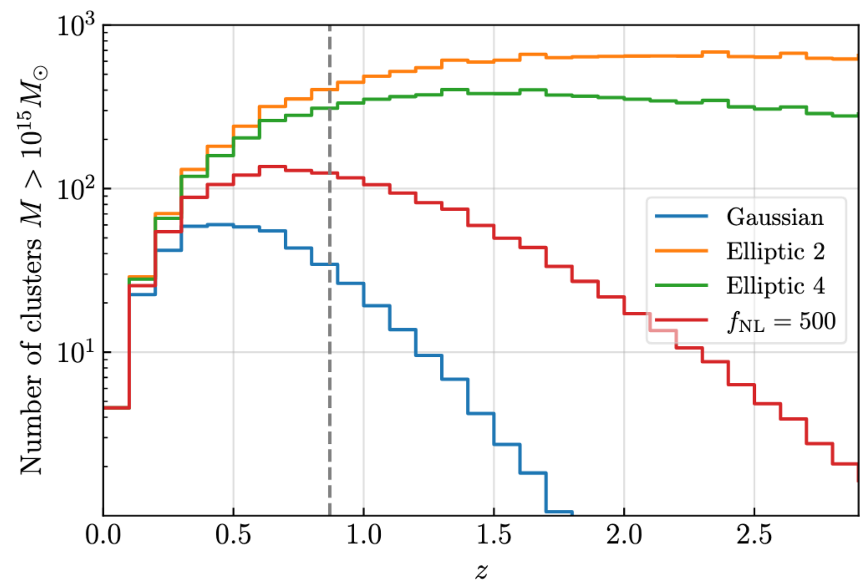


Halo Mass Function

Ezquiaga, JGB, Vennin (2022)

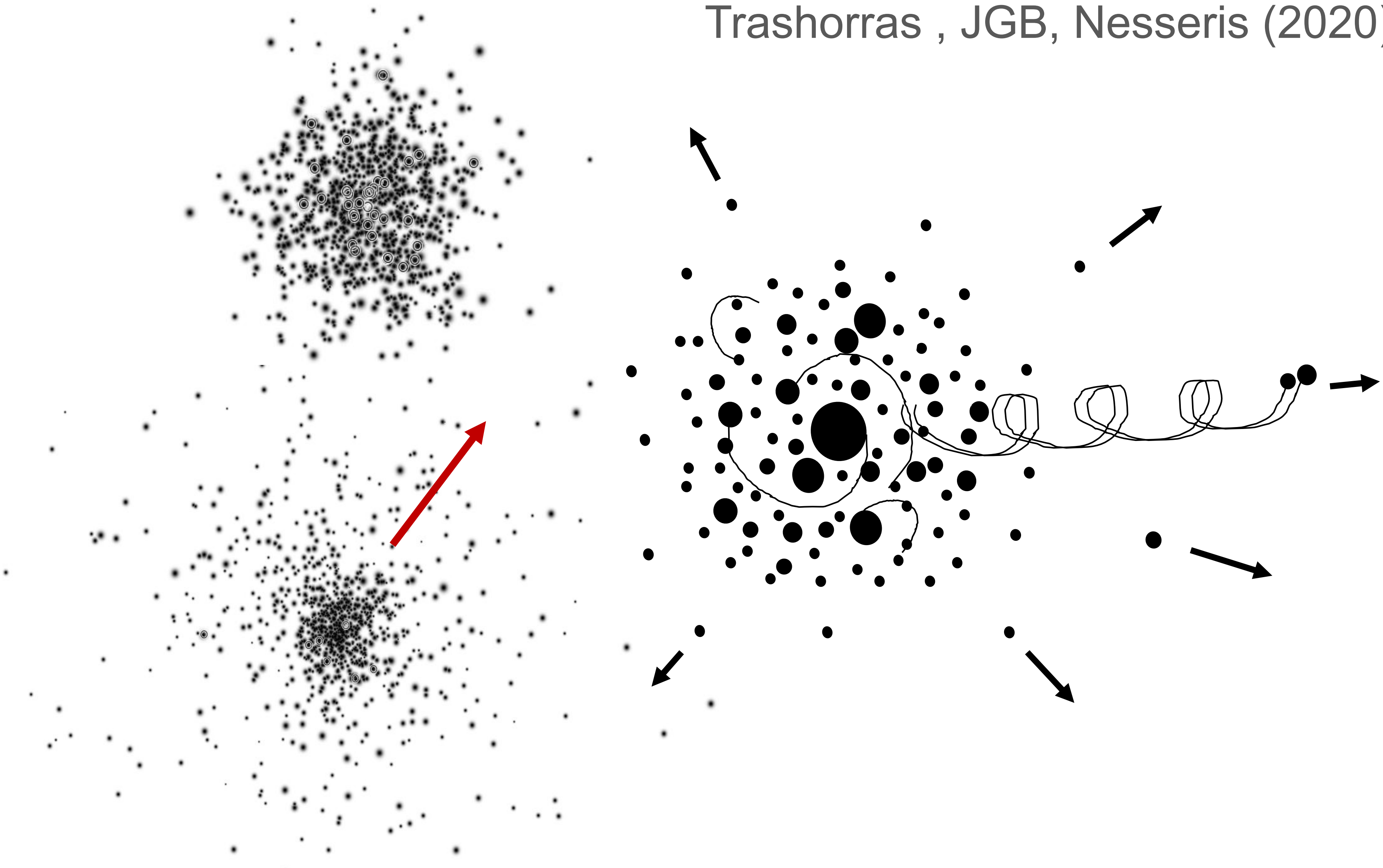
El Gordo

$$M \sim 3 \cdot 10^{15} M_\odot \text{ at } z = 0.87$$

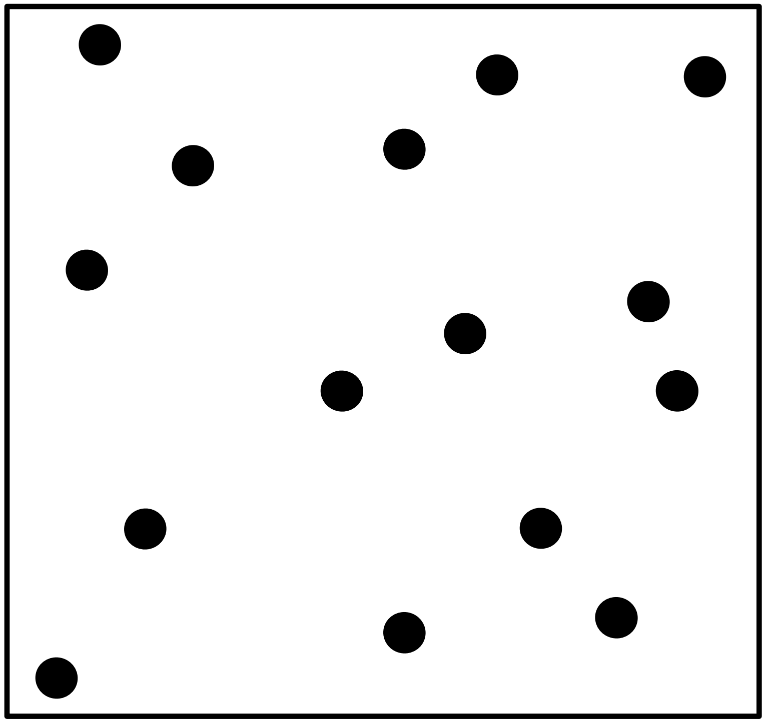


PBH clusters

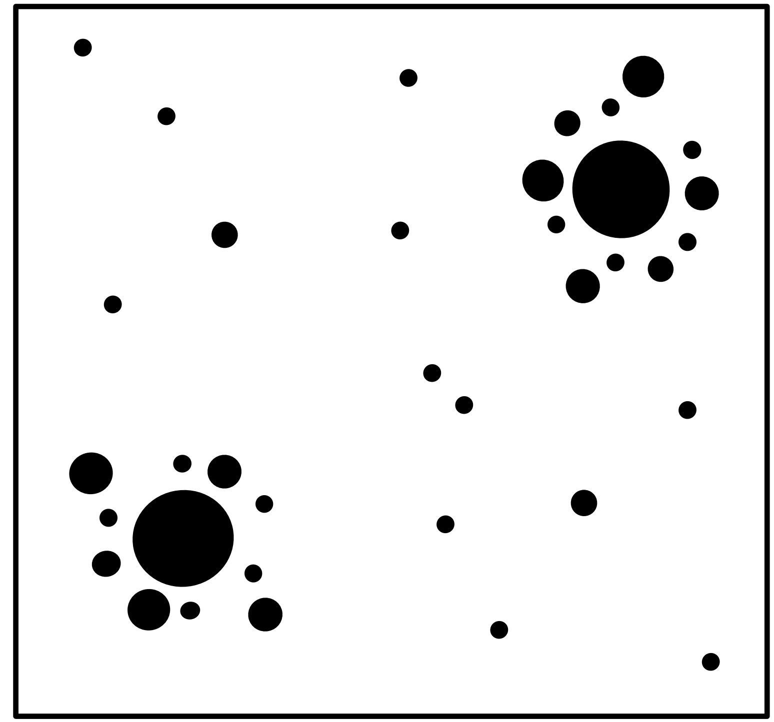
Trashorras , JGB, Nesseris (2020)



Spatial Distribution PBH



- Monochromatic
- Uniformly distributed

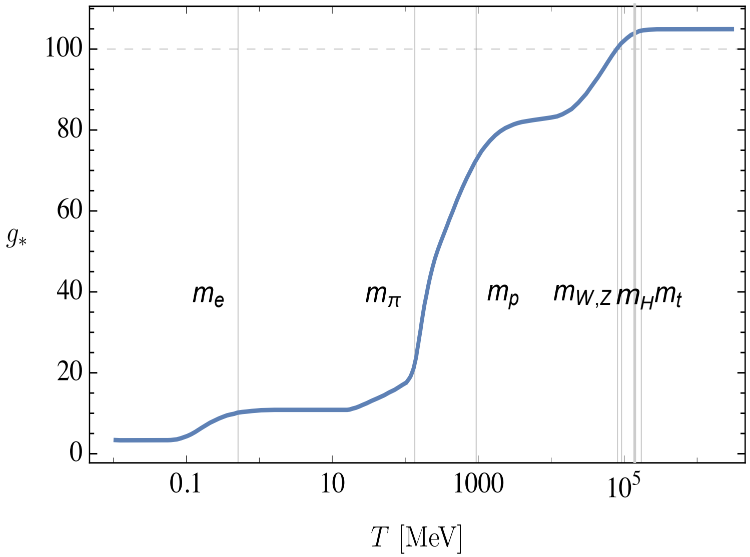


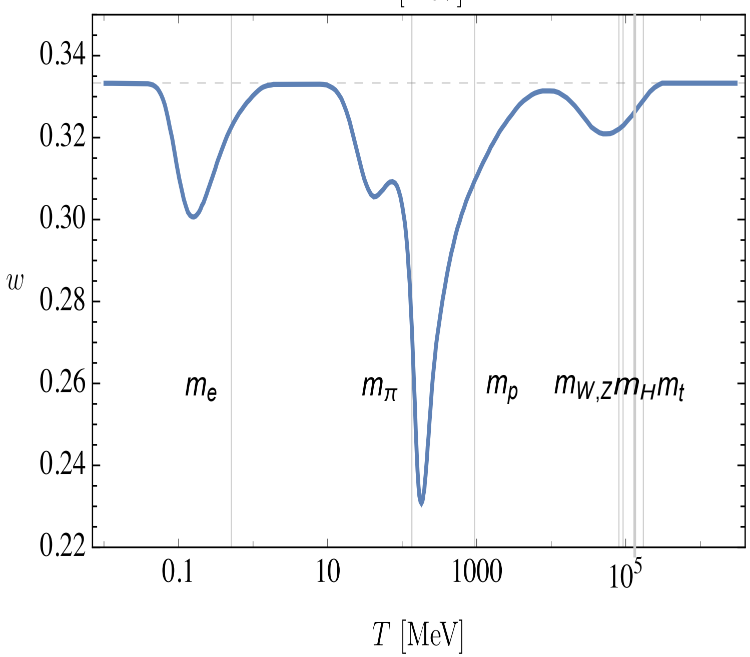
- Broad range of masses
- PBH in clusters

JGB (2017)

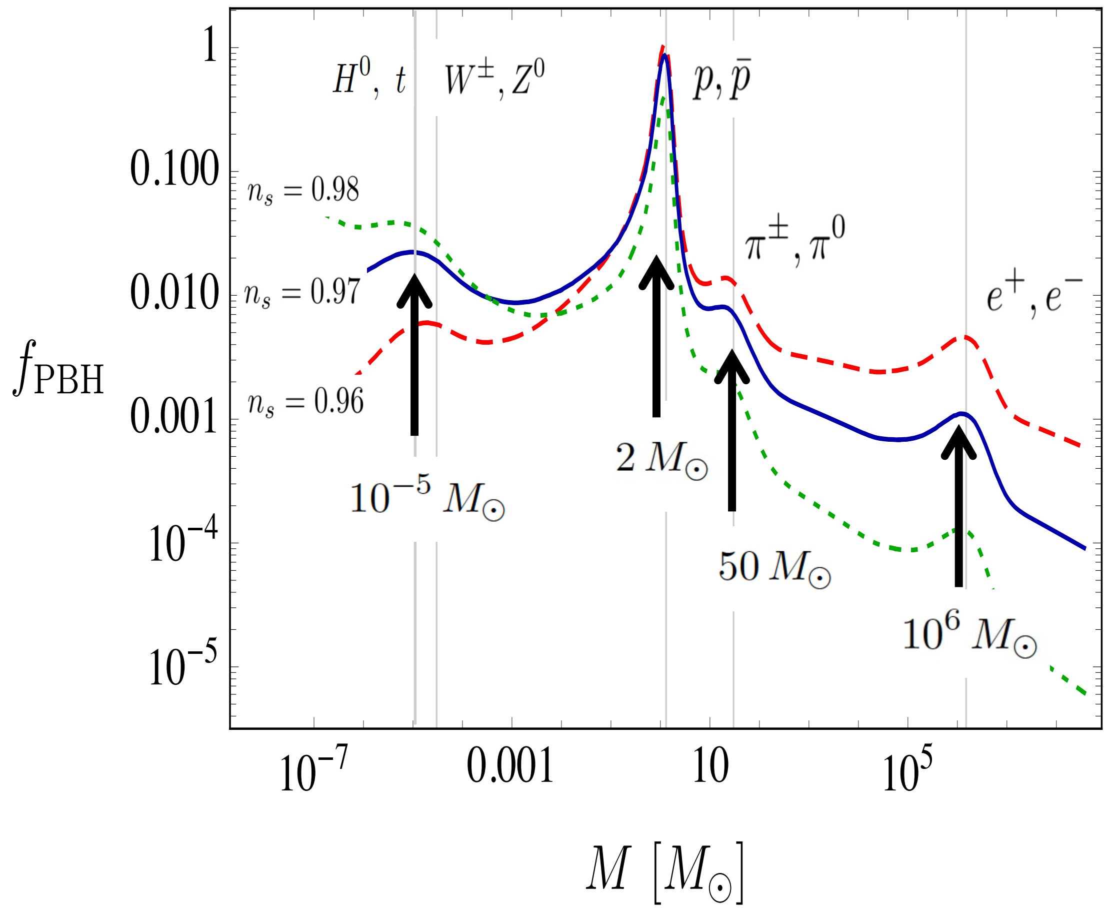
Thermal history of the universe

Carr, Clesse, JGB, Kühnel (2019)





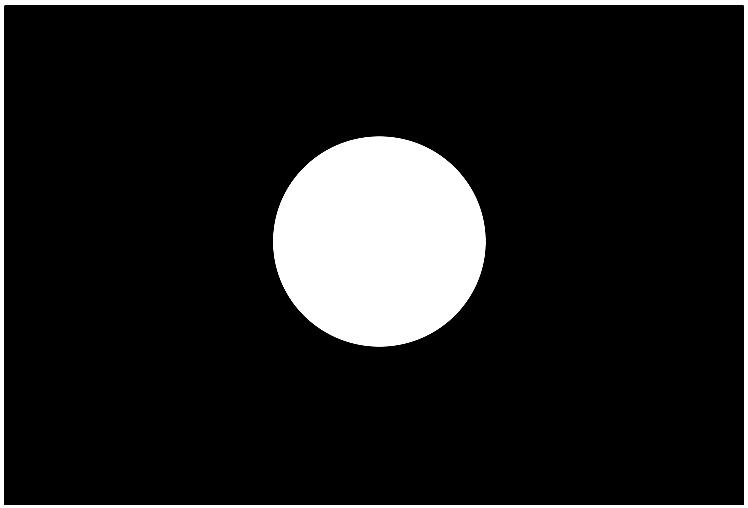
PBH mass spectrum

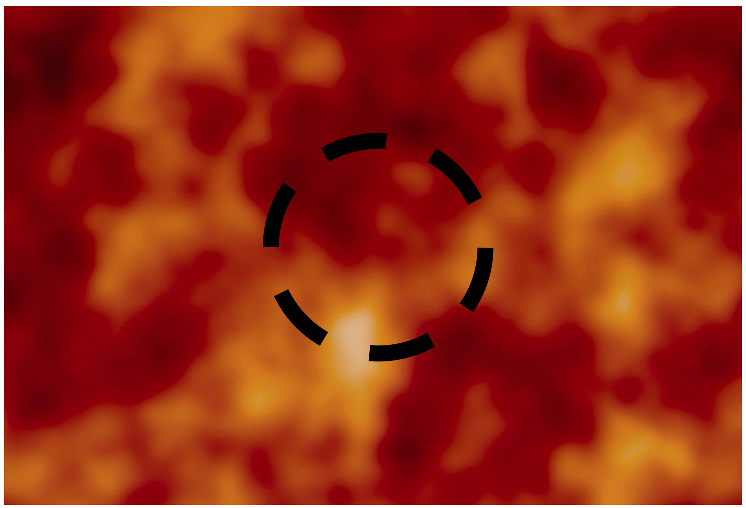


Origin of stellar & PBH masses

Chandrasekhar mass
(Pauli Excl.)

Mass within horizon
@ QCD (Causality)





$$M_{\rm Chandra} \simeq \frac{2}{\mu^2}\sqrt{\frac{3\pi}{4}}\,\frac{M_{\rm P}^3}{m_{\rm p}^2} \simeq 1.4\,M_\odot$$

$$M_{\rm PBH} \simeq \frac{4\pi}{3}\,\rho_{\rm rad}\,d_{\rm H}^3 \simeq \frac{3\sqrt{5}}{4\pi^{3/2}\sqrt{g_*}}\,\frac{M_{\rm P}^3}{\Lambda_{\rm QCD}^2} \simeq 2\,M_\odot$$

Electroweak baryogenesis @ QCD

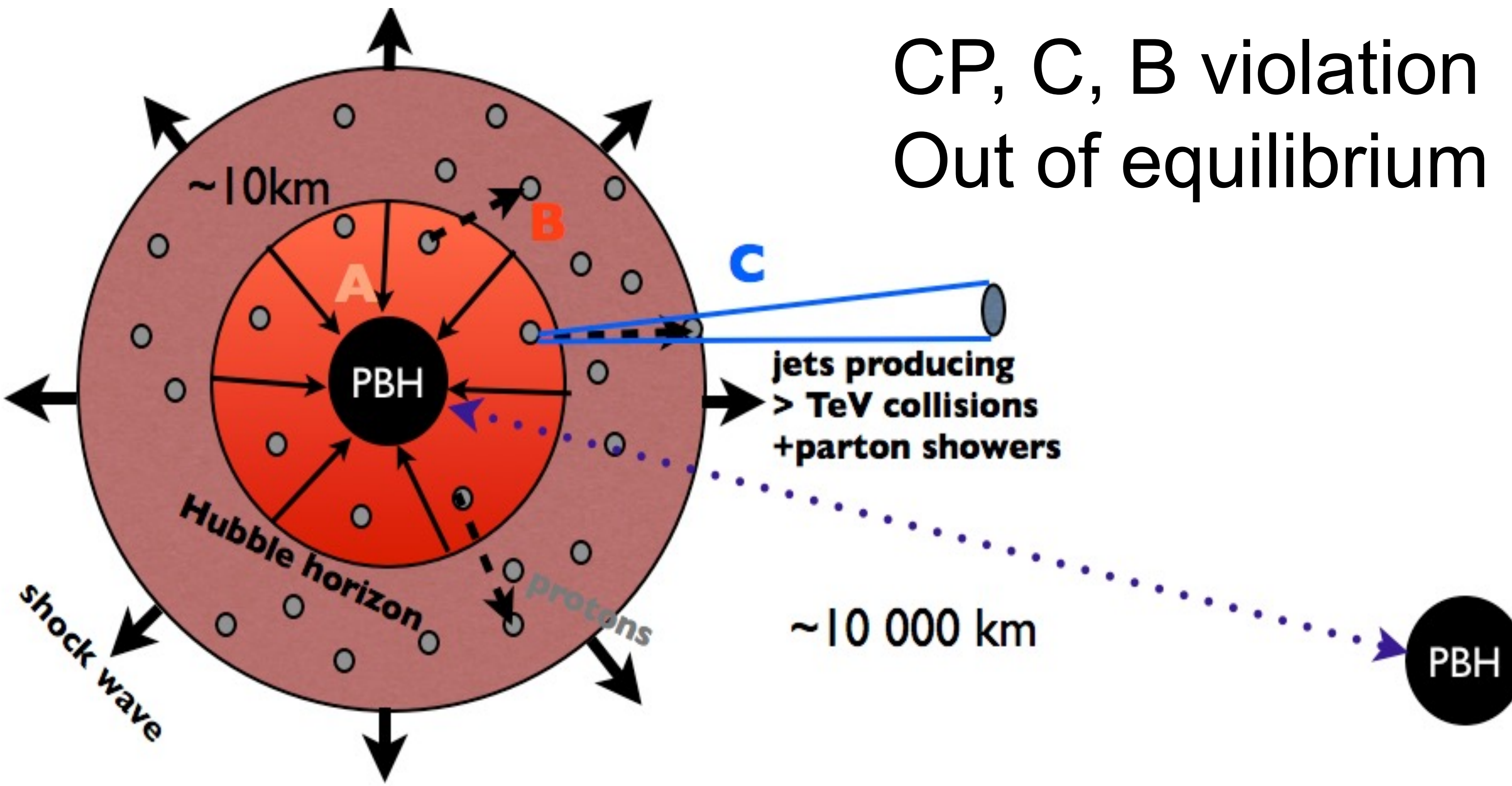
"Primordial supernova"

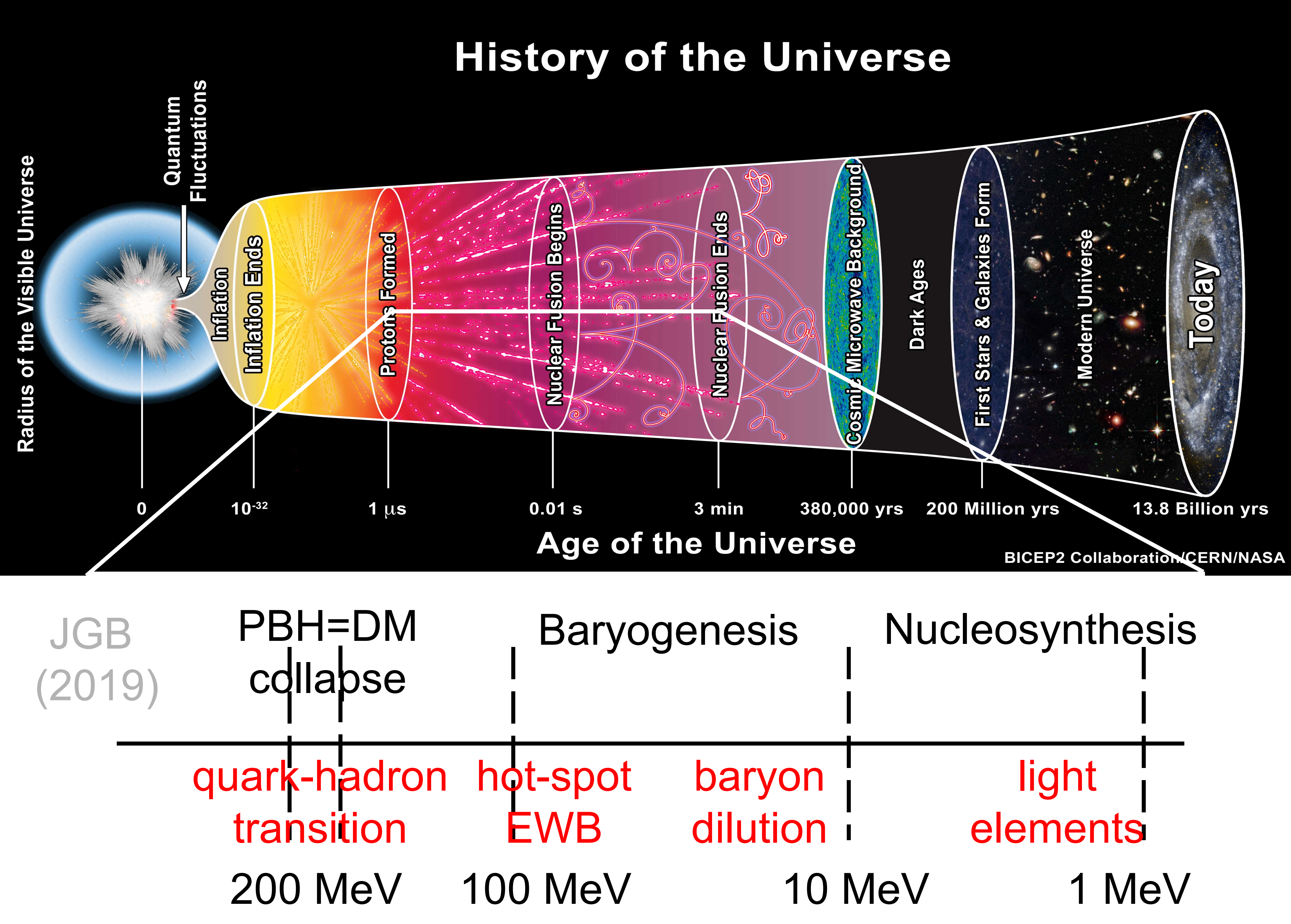
JGB, Carr, Clesse (2019)

Sakharov conditions:

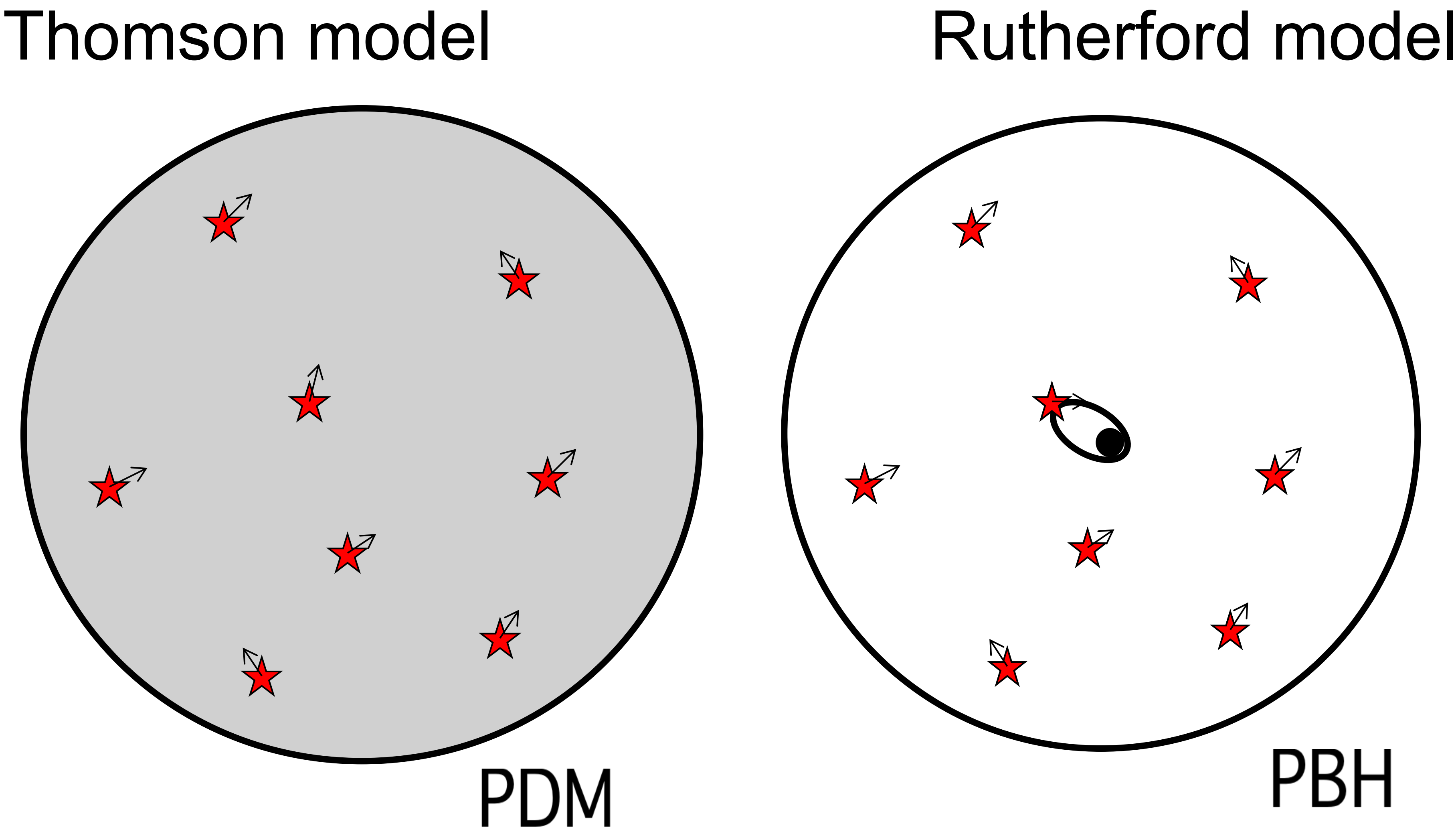
CP, C, B violation

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

Spatial distribution of DM

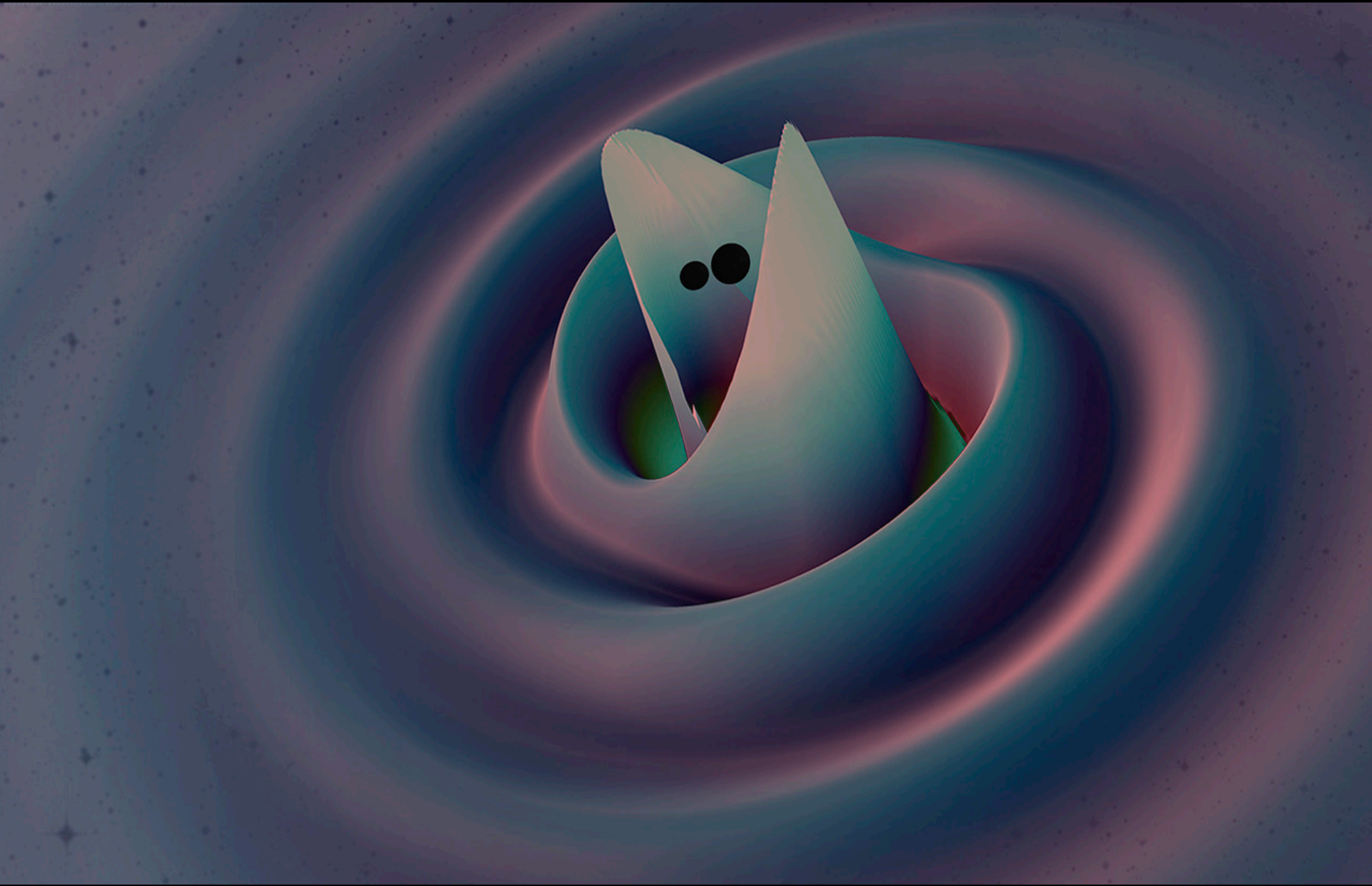


JGB (2017)

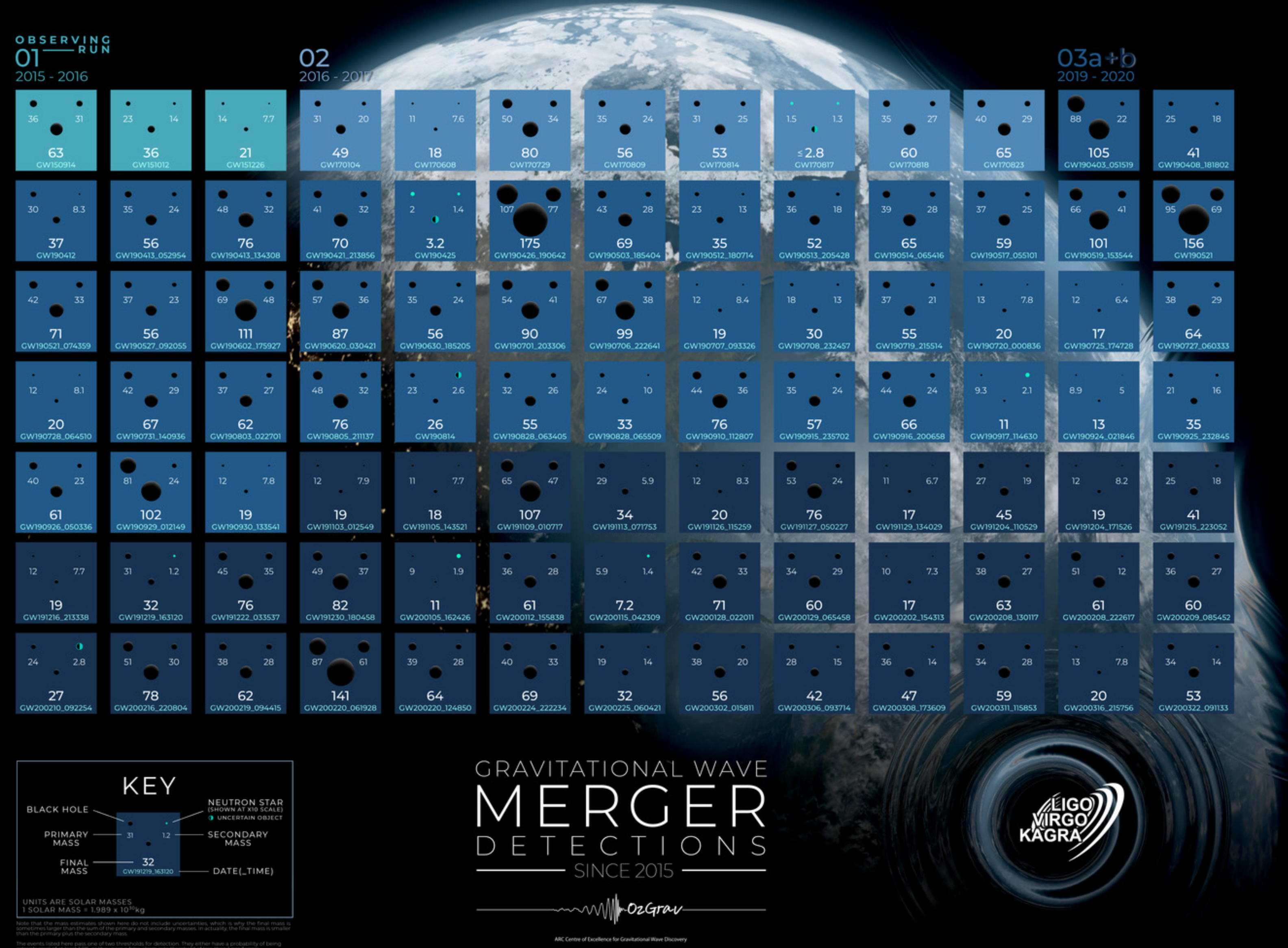
Massive PBH = seeds of structure

- 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.

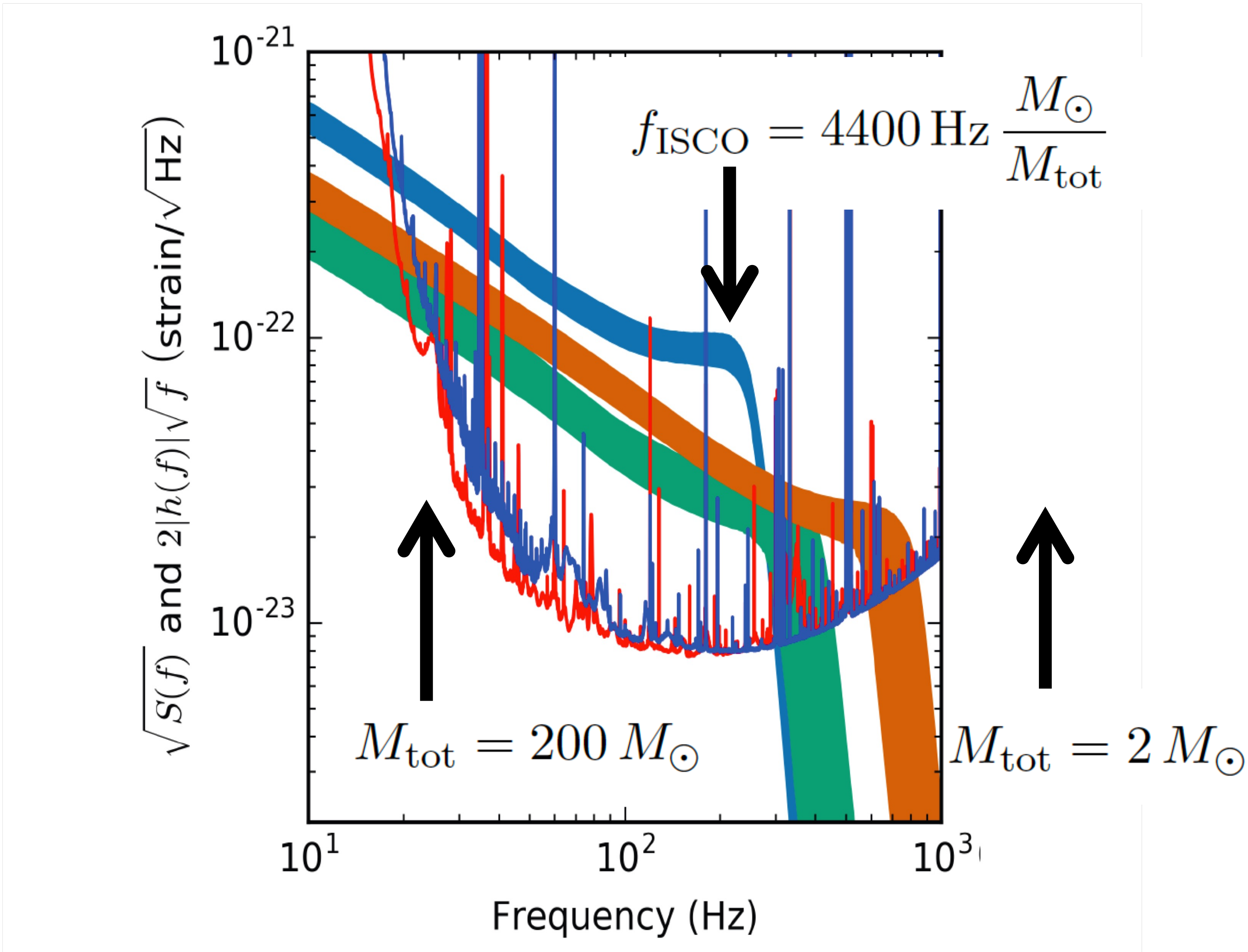
GW emission



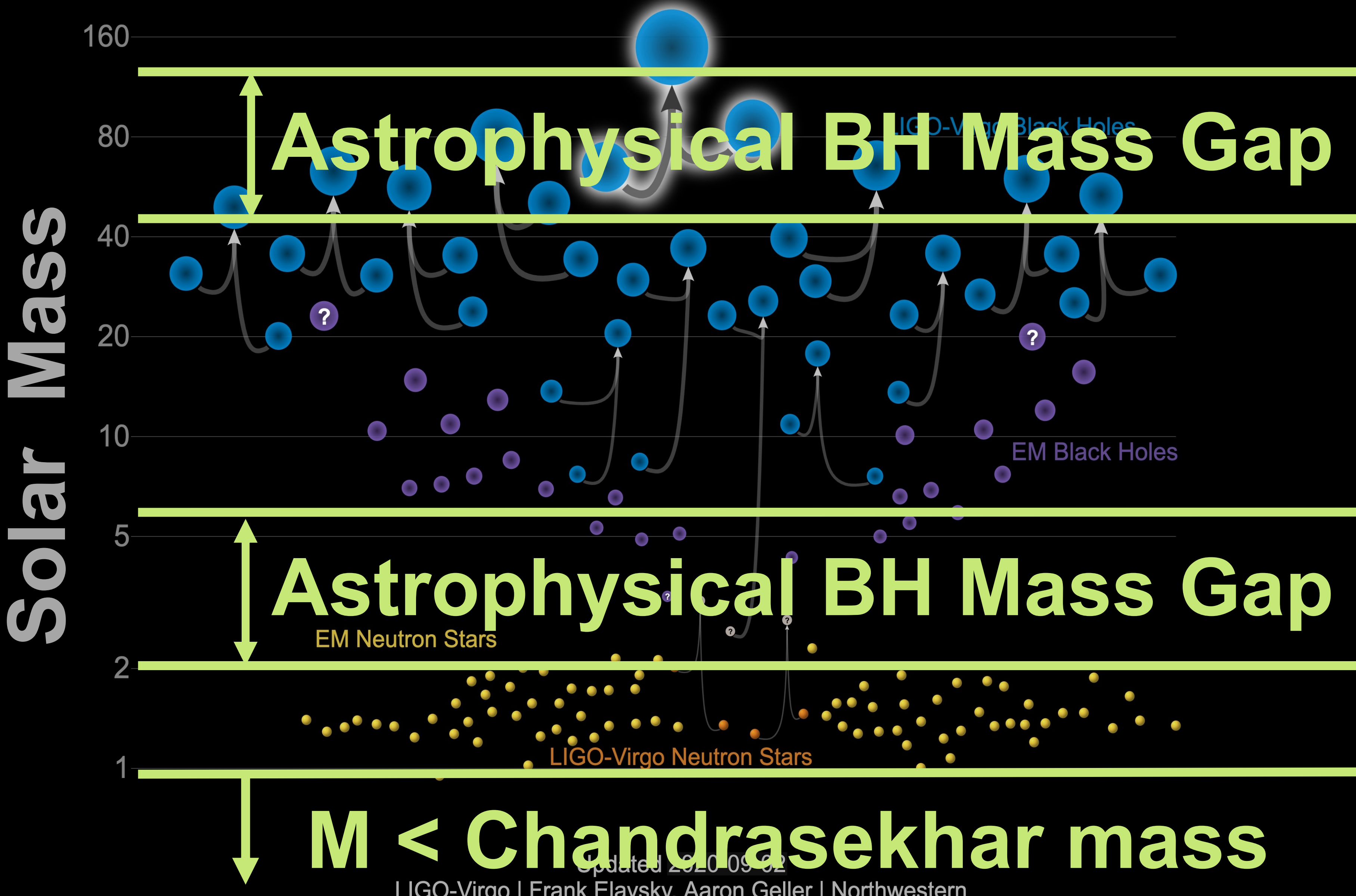
GWTC-3


OBSERVING RUN
01
2015 - 2016
02
2016 - 2017
O3a+b
2019 - 2020
36 31 63 GW150914
23 14 36 GW151012
14 7.7 21 GW151226
31 20 49 GW170104
11 7.6 18 GW170608
50 34 80 GW170729
35 24 56 GW170809
31 25 53 GW170814
1.5 1.3 ≤2.8 GW170817
35 27 60 GW170818
40 29 65 GW170823
88 22 105 GW190403_051519
25 18 41 GW190408_181802
30 8.3 37 GW190412
35 24 56 GW190413_052954
48 32 76 GW190413_134308
41 32 70 GW190421_213856
2 1.4 3.2 GW190425
107 77 175 GW190426_190642
43 28 69 GW190503_185404
23 13 35 GW190512_180714
36 18 52 GW190513_205428
39 28 65 GW190514_065416
37 25 59 GW190517_055101
66 41 101 GW190519_153544
95 69 156 GW190521
42 33 71 GW190521_074359
37 23 56 GW190527_092055
69 48 111 GW190602_175927
57 36 87 GW190620_030421
35 24 56 GW190630_185205
54 41 90 GW190701_203306
67 38 99 GW190706_222641
12 8.4 19 GW190707_093326
18 13 30 GW190708_232457
37 21 55 GW190719_215514
13 7.8 20 GW190720_000836
12 6.4 17 GW190725_174728
38 29 64 GW190727_060333
12 8.1 20 GW190728_064510
42 29 67 GW190731_140936
37 27 62 GW190803_022701
48 32 76 GW190805_211137
23 2.6 26 GW190814
32 26 55 GW190828_063405
24 10 33 GW190828_065509
44 36 76 GW190910_112807
35 24 57 GW190915_235702
44 24 66 GW190916_200658
9.3 2.1 11 GW190917_114630
8.9 5 13 GW190924_021846
21 16 35 GW190925_232845
40 23 61 GW190926_050336
81 24 102 GW190929_012149
12 7.8 19 GW190930_133541
12 7.9 19 GW191103_012549
11 7.7 18 GW191105_143521
65 47 107 GW191109_010717
29 5.9 34 GW191113_071753
12 8.3 20 GW191126_115259
53 24 76 GW191127_050227
11 6.7 17 GW191129_134029
27 19 45 GW191204_110529
12 8.2 19 GW191204_171526
25 18 41 GW191215_223052
12 7.7 19 GW191216_213338
31 1.2 32 GW191219_163120
45 35 76 GW191222_033537
49 37 82 GW191230_180458
9 1.9 11 GW200105_162426
36 28 61 GW200112_155838
5.9 1.4 7.2 GW200115_042309
42 33 71 GW200128_022011
34 29 60 GW200129_065458
10 7.3 17 GW200202_154313
38 27 63 GW200208_130117
51 12 61 GW200208_222617
36 27 60 GW200209_085452
24 2.8 27 GW200210_092254
51 30 78 GW200216_220804
38 28 62 GW200219_094415
87 61 141 GW200220_061928
39 28 64 GW200220_124850
40 33 69 GW200224_222234
19 14 32 GW200225_060421
38 20 56 GW200302_015811
28 15 42 GW200306_093714
36 14 47 GW200308_173609
34 28 59 GW200311_115853
13 7.8 20 GW200316_215756
34 14 53 GW200322_091133
KEY
BLACK HOLE
NEUTRON STAR (SHOWN AT X10 SCALE)
UNCERTAIN OBJECT
PRIMARY MASS
SECONDARY MASS
FINAL MASS
DATE(_TIME)
31 1.2 32 GW191219_163120
UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10³⁰kg
Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.
The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015
OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery
LIGO
VIRGO
KAGRA

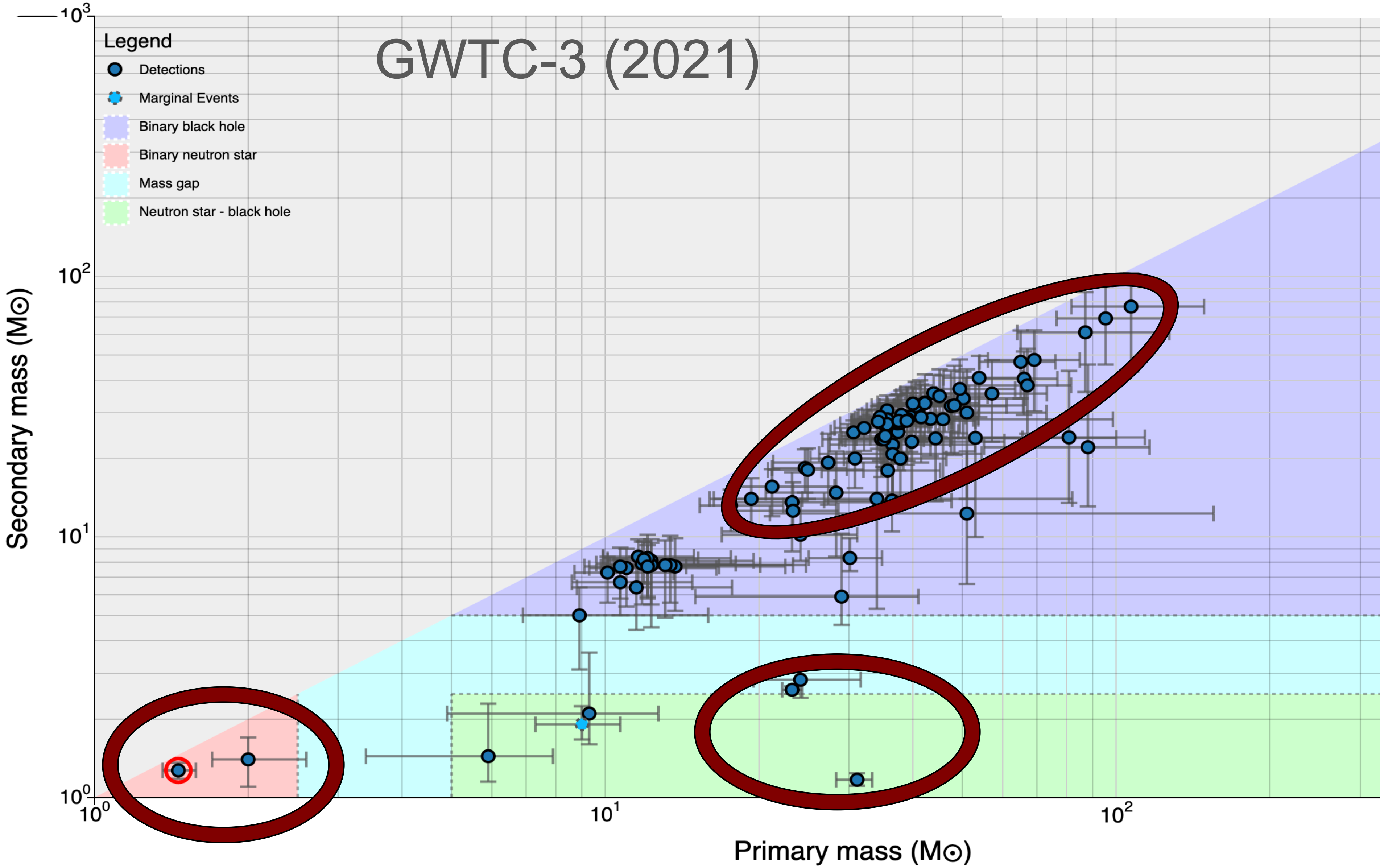
LVC BBH events



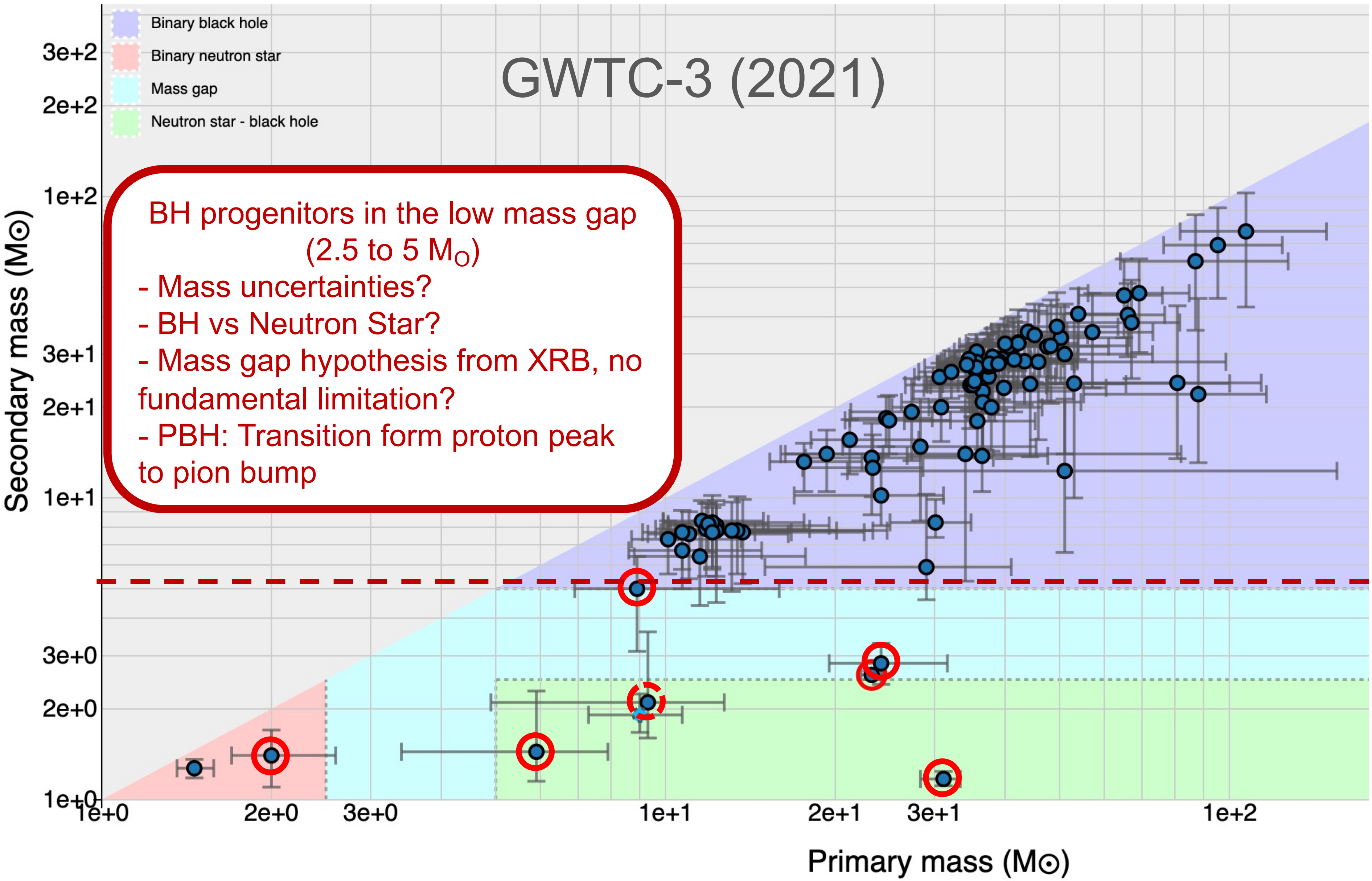
Black Holes and Neutron Stars



Primary and secondary masses



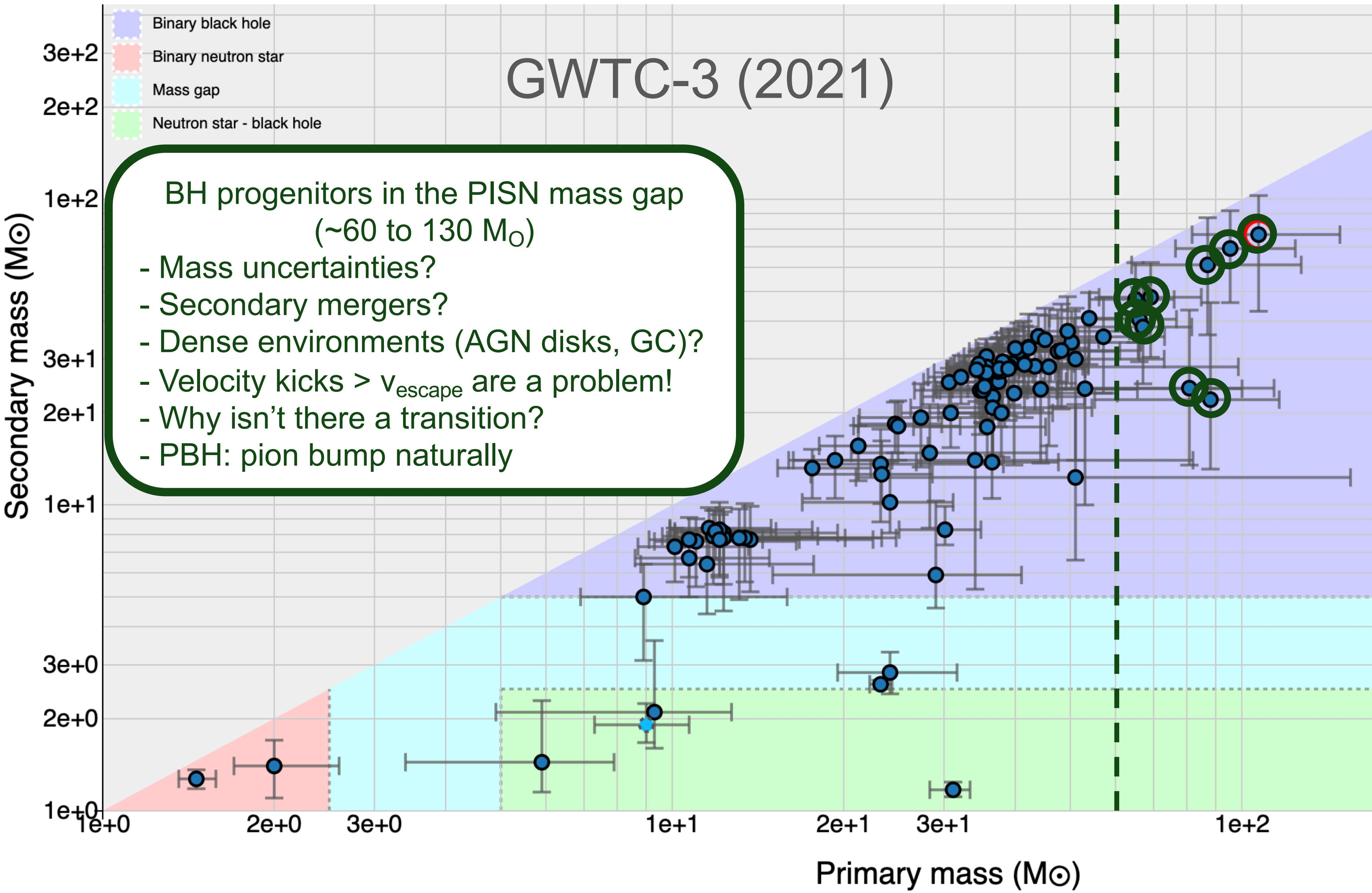
Are LIGO/Virgo BH Primordial?



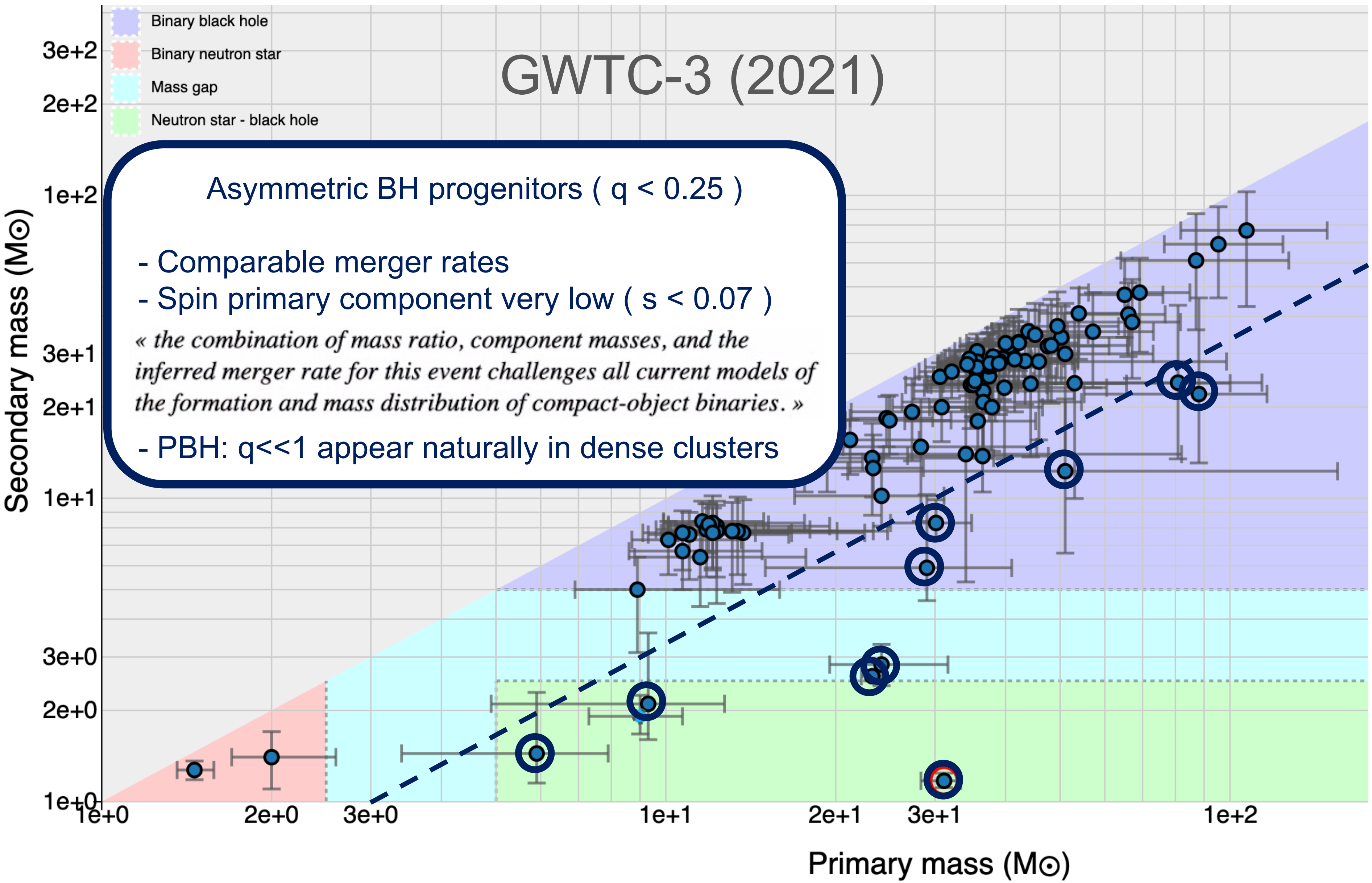
BH progenitors in the low mass gap (2.5 to 5 $M_{\odot}$)

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

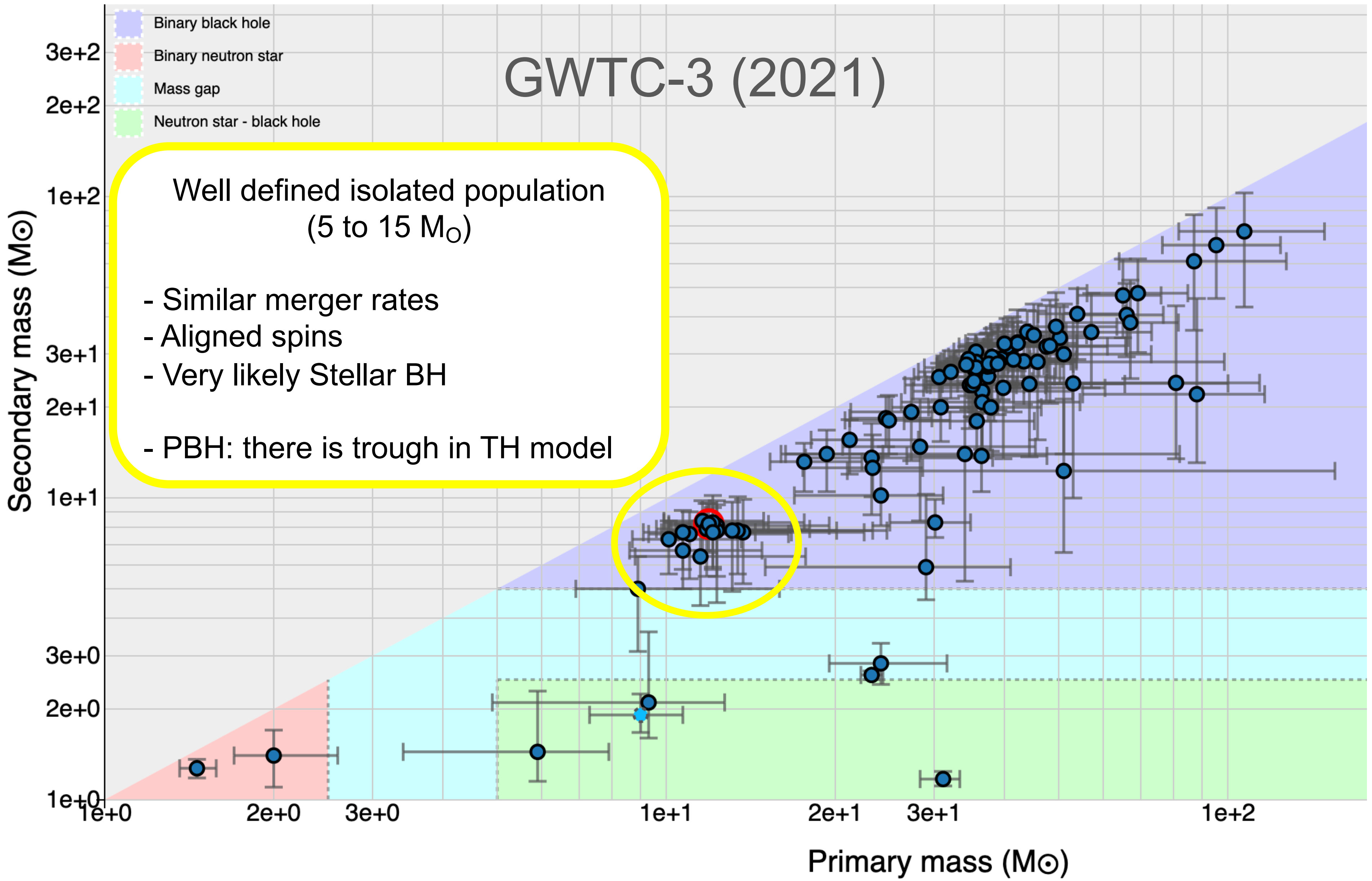
Are LIGO/Virgo BH Primordial?



Are LIGO/Virgo BH Primordial?

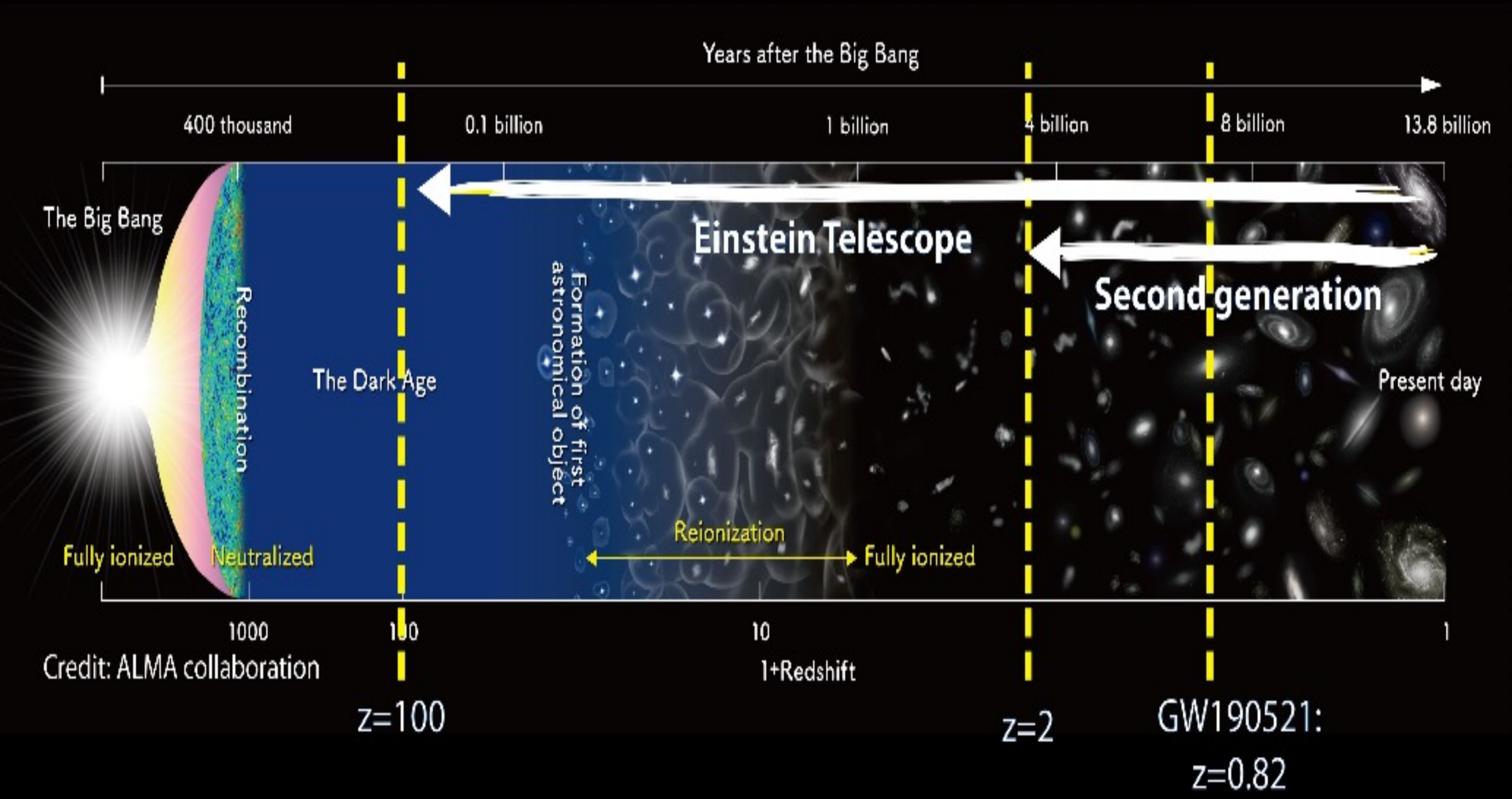


Are LIGO/Virgo BH Primordial?

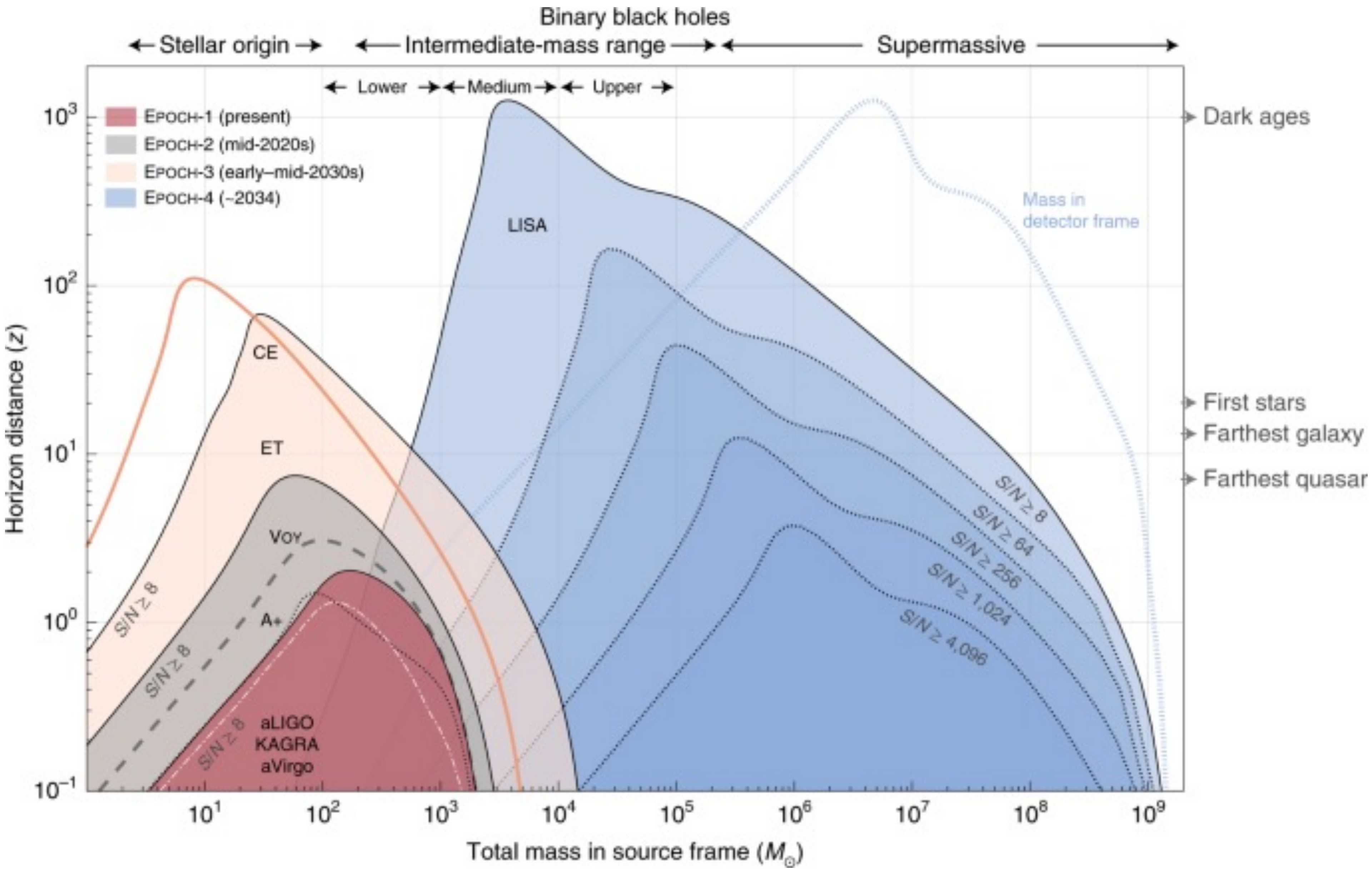


The future of GW (G3)

Detection horizon for black-hole binaries



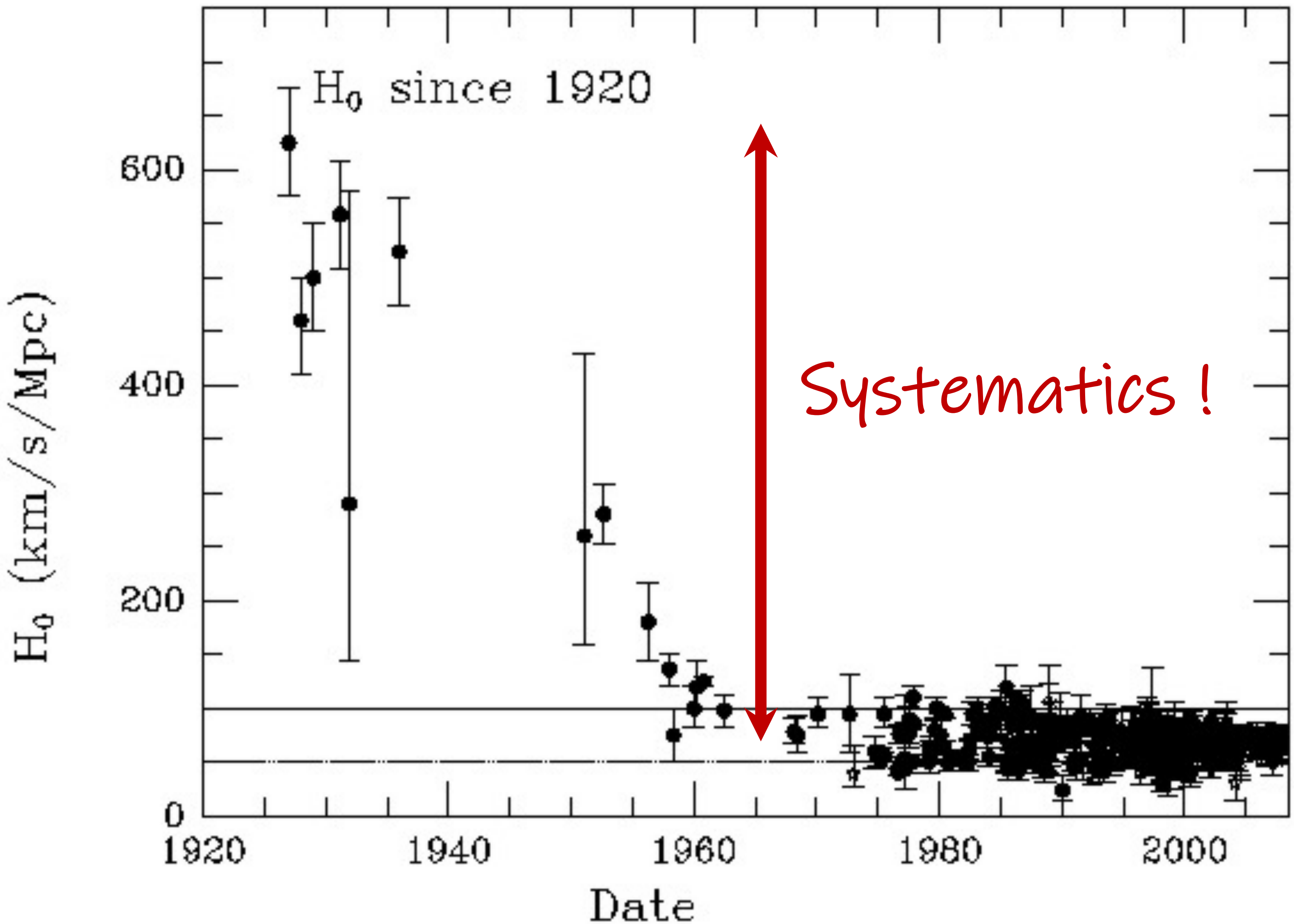
BBH sensitivity in future G3 GW



Partial Summary

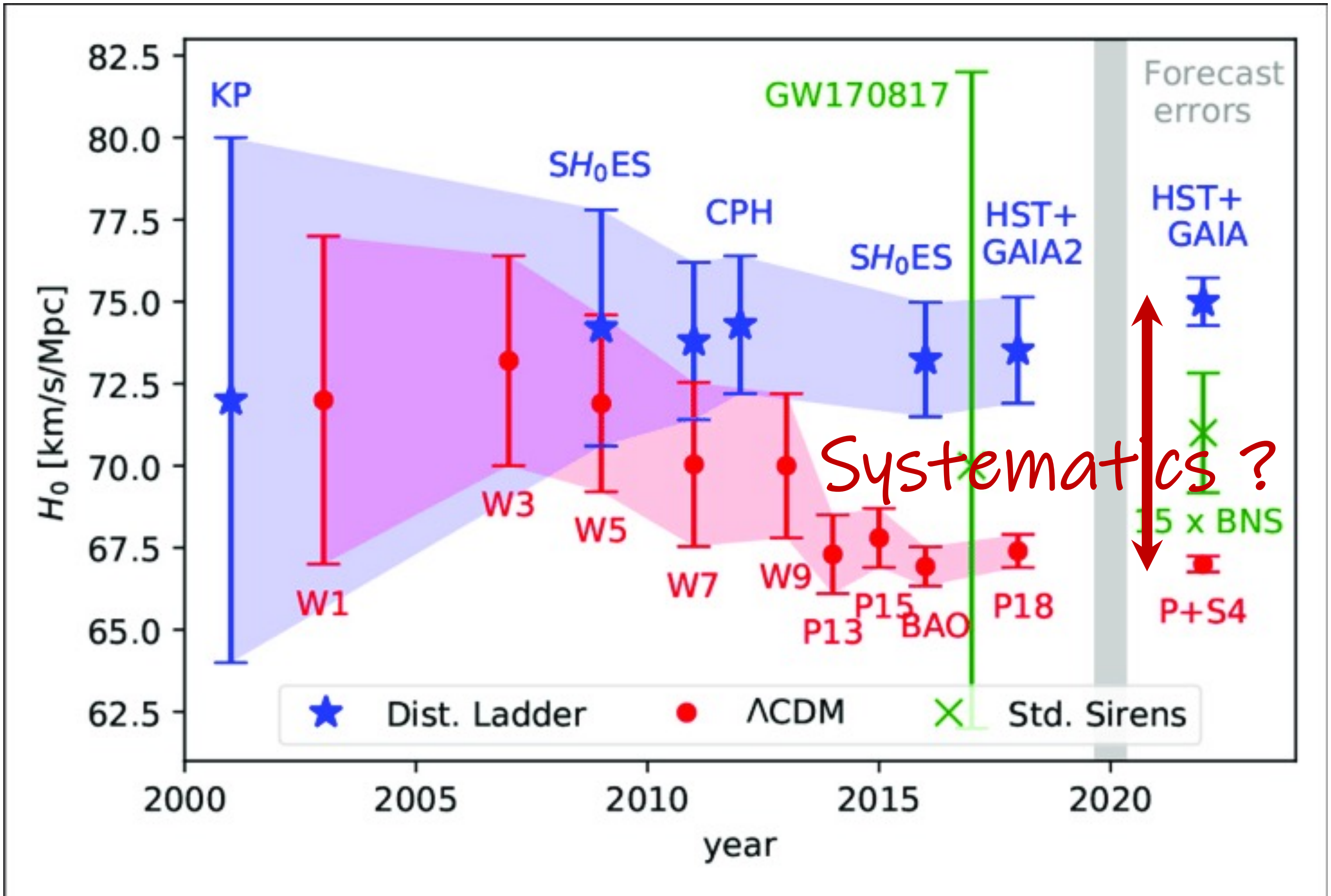
- Quantum diffusion inevitably generates PBH
- Thermal history predicts PBH have multimodal mass distribution $\sim 10^{-5}, 1, 100, 10^{5}\ M_\odot$ ($10^{-10}\ M_\odot$ also?)
- The predicted PBH spin and mass distribution has been measured by LIGO/Virgo + OGLE around 1-100 $M_\odot$ (features: peak & 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)

Hubble Tension ca. 2000



CfA Harvard webpage

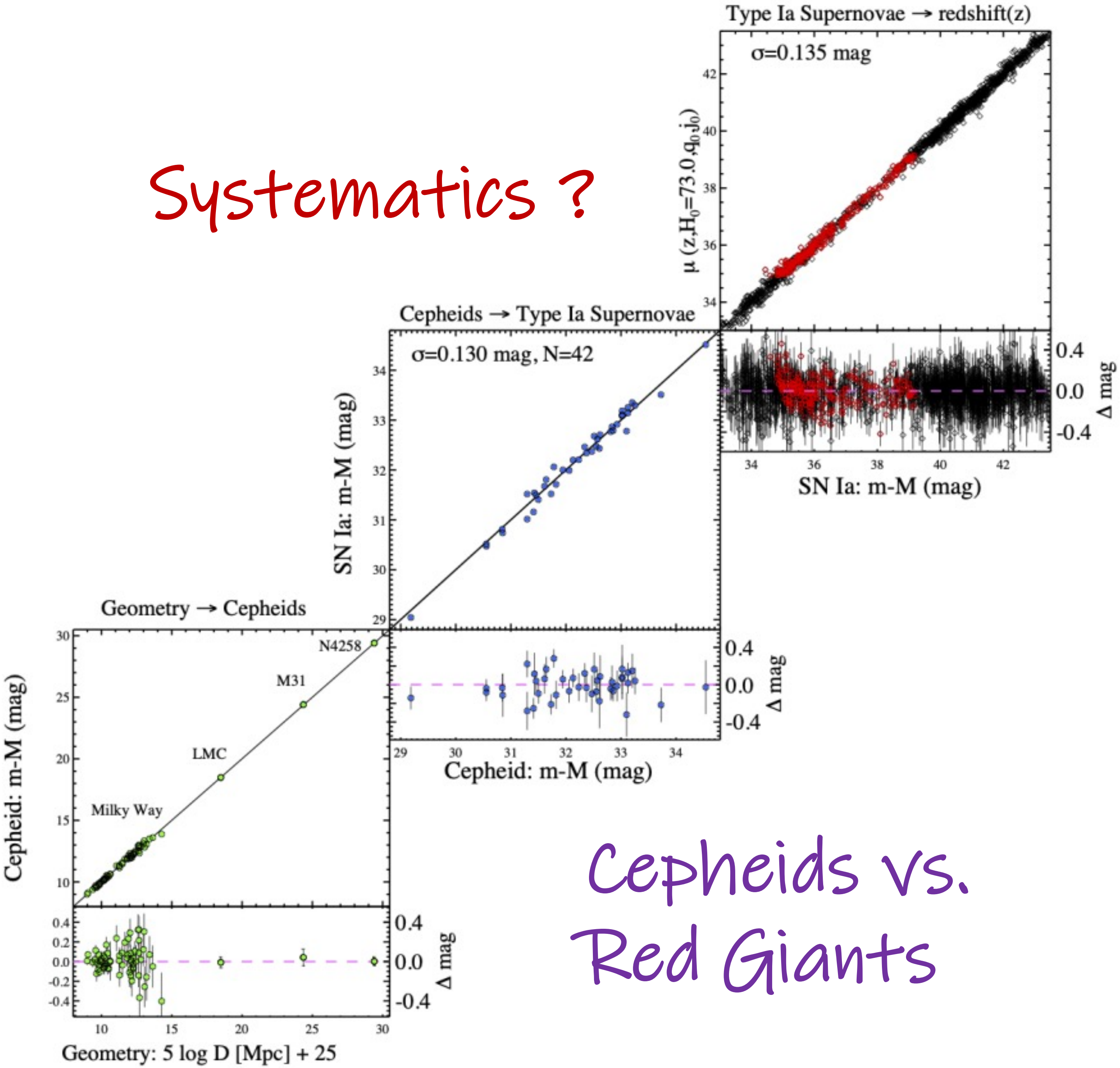
Hubble Tension ca. 2020



Benson et al. (2017)

Hubble Tension ca. 2021

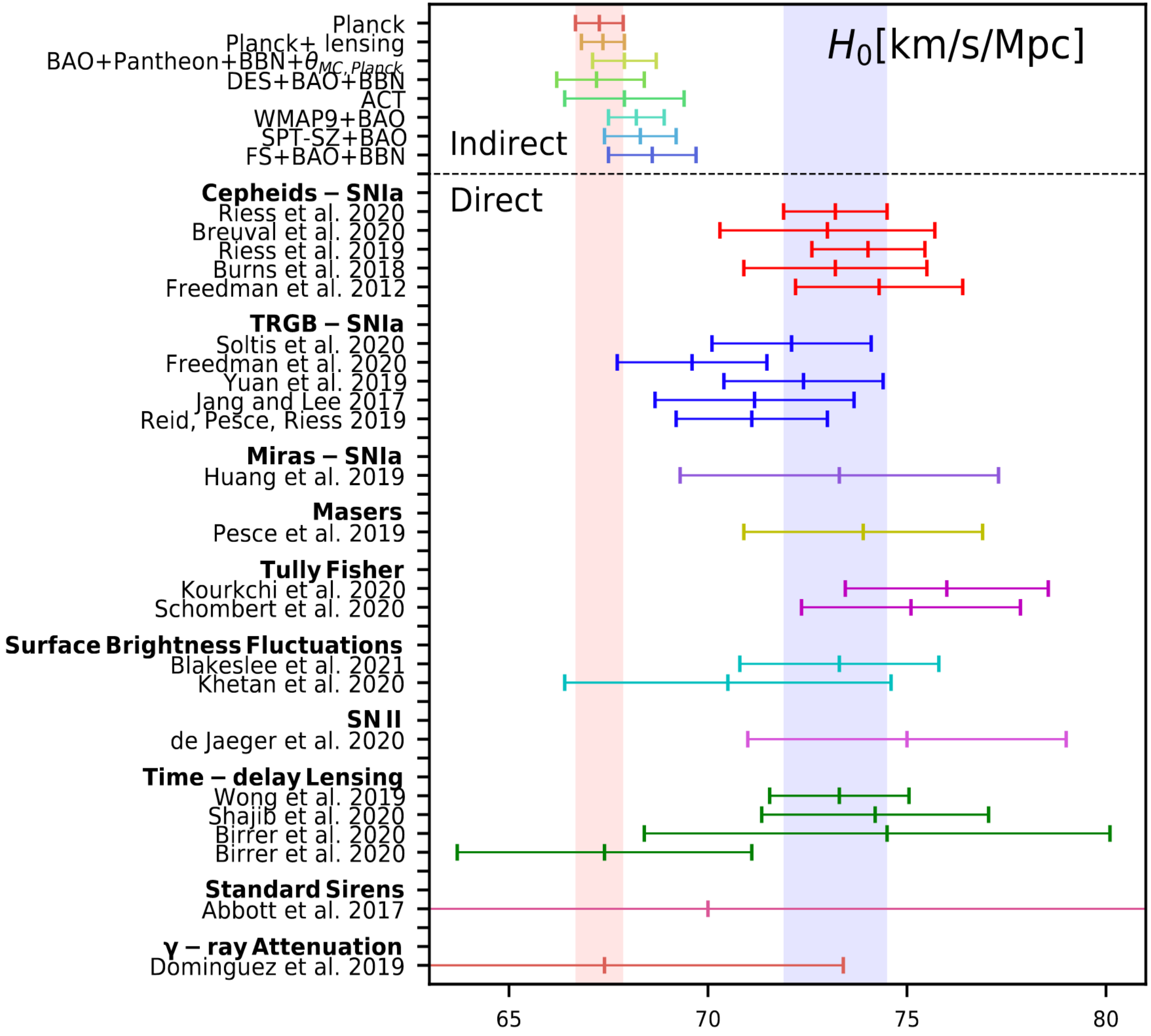
Systematics ?



Cepheids vs.
Red Giants

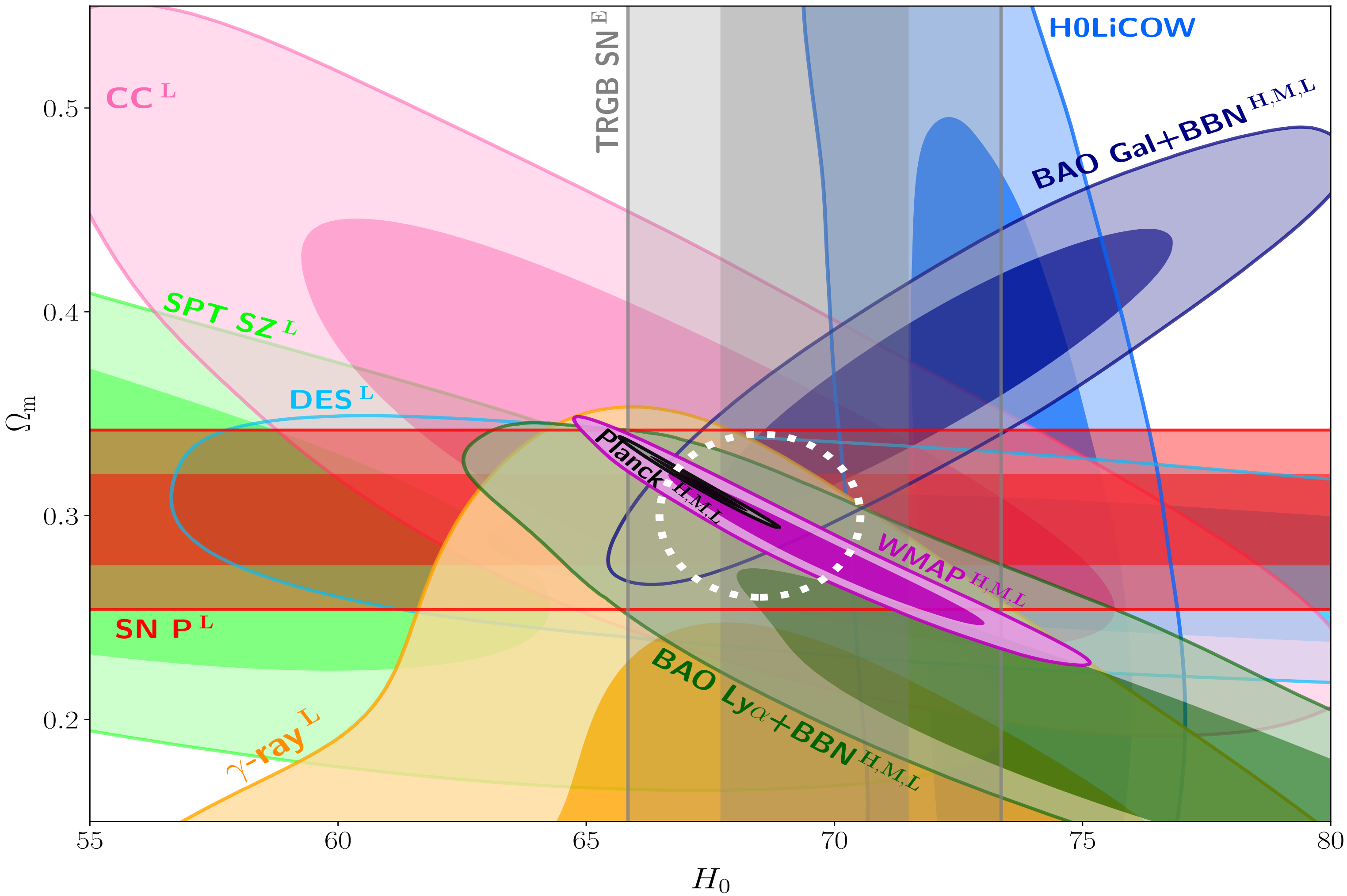
Di Valentino et al. (2021)

Hubble Tension ca. 2021



Di Valentino (2021)

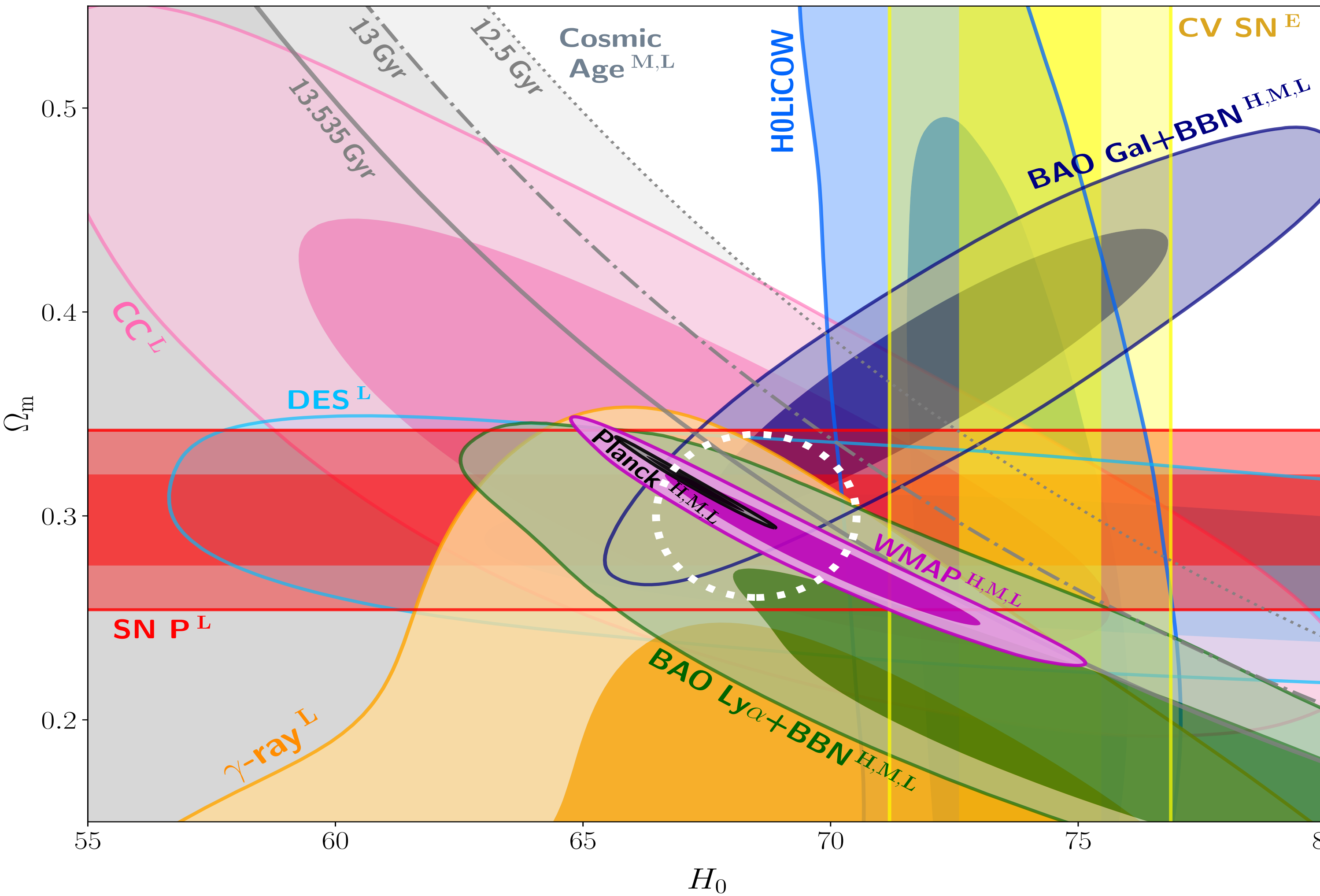
Hubble Tension ca. 2022



Mack et al. (2022)

Contours correspond to SN P (red), DES (light blue), CC (pink), H0LiCOW (blue), BAO Gal (navy), BAO Lyα (green), γ-ray (orange), WMAP (magenta), Planck (black), CV SN (yellow) and some guiding cosmic-age constraints ($t_* = 13.535$, 13 and 12.5 Gyr; orange). See the text for descriptions and sources of those constraints. Each constraint in the figure is labeled according to whether it can be changed by nonstandard high-z models (H), mid-z models (M), low-z models (L), or local environmental factors (E). See the text for the definition of those model categories. We leave the H0LiCOW technique without a label because it is relatively insensitive to the underlying cosmological model.

Hubble Tension ca. 2022



Mack et al. (2022)

Contours correspond to SN P (red), DES (light blue), CC (pink), H0LiCOW (blue), BAO Gal (navy), BAO Lyα (green), γ-ray (orange), WMAP (magenta), Planck (black), CV SN (yellow) and some guiding cosmic-age constraints ($t_* = 13.535$, 13 and 12.5 Gyr; orange). See the text for descriptions and sources of those constraints. Each constraint in the figure is labeled according to whether it can be changed by nonstandard high-z models (H), mid-z models (M), low-z models (L), or local environmental factors (E). See the text for the definition of those model categories. We leave the H0LiCOW technique without a label because it is relatively insensitive to the underlying cosmological model.

Forces in Physics

- **Fundamental Forces**

  Gravitation, Strong, Weak, E.M.

- **Residual Forces**

  Molecular, Nuclear, Surface Tension

- **Collective Forces**

  Brownian motion, Entropic Forces

$$F dx = dW = -dU + T dS \;\Rightarrow\; F = -\frac{dU}{dx} + T\frac{dS}{dx}$$

Entropic forces in GR

$$\mathcal{S} = \frac{1}{2\kappa}\int d^4x\sqrt{-g}R + \int d^4x\mathcal{L}_m(g_{\mu\nu}, S)$$

Thermodynamical constraint

$$\delta\mathcal{S} = \int d^4x\left(\frac{1}{2\kappa}\frac{\delta(\sqrt{-g}R)}{\delta g^{\mu\nu}} + \frac{\delta\mathcal{L}_m}{\delta g^{\mu\nu}}\right)\delta g^{\mu\nu} + \int d^4x\frac{\partial\mathcal{L}_m}{\partial S}\delta S = 0$$

Variational constraint: 2nd law thermodynamics

$$\frac{\partial\mathcal{L}_m}{\partial s}\delta s = \frac{1}{2}\sqrt{-g}f_{\mu\nu}\delta g^{\mu\nu}$$

Non-equilibrium Einstein field equations

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \kappa\left(T_{\mu\nu} - f_{\mu\nu}\right) \quad \Rightarrow \quad D^\mu T_{\mu\nu} = D^\mu f_{\mu\nu}$$

entropic force

Bianchi identities

Entropic forces in GR

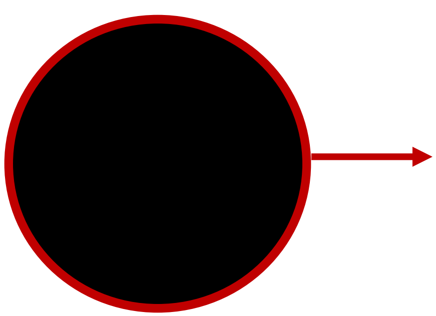
Temperature and Entropy from the gravity sector

- Horizon $\mathcal{H}$ with induced metric h

$$\mathcal{S}_{\text{GHY}} = \frac{1}{8\pi G}\int_H d^3y\,\sqrt{h}\,K = \frac{1}{8\pi G}\int_H dt\,\sin\theta d\theta\,d\phi\,\sqrt{h}\,K$$

- Schwarzschild black hole

$$ds^2 = -\left(1-\frac{2GM}{r}\right)dt^2 + \left(1-\frac{2GM}{r}\right)^{-1}dr^2 + r^2 d\Omega_2^2 \,.$$



$$n = -\sqrt{1-\frac{2GM}{r}}\,\partial_r$$

normal vector to S_2 of radius r

Entropic forces in GR

$$\mathcal{S}_{\rm GHY} = \frac{1}{8\pi G}\int_H d^3y\,\sqrt{h}\,K = \frac{1}{8\pi G}\int_H dt\,\sin\theta d\theta\,d\phi\,\sqrt{h}\,K$$

$\sqrt{h}K = (3GM - 2r)\sin\theta$ at event horizon $r = 2GM$

$$\mathcal{S}_{\rm GHY} = -\frac{1}{2}\int dt\,Mc^2 = -\int dt\,T_{\rm BH}S_{\rm BH}$$

Classical (emergent)

$$T_{\rm BH} = \frac{\hbar c^3}{8\pi GM}$$

quantum origin

$$S_{\rm BH} = \frac{A\,c^3}{4G\hbar} = \frac{4\pi GM^2}{\hbar c}$$

Entropic forces in GR

- Contribution to bulk entropy of the **inevitable** Schwarzschild black hole component of Dark Matter

Assuming BH total comoving number is conserved, their Total energy density and entropy density $(\hbar = c = 1)$ is

$$\rho_{BH} = n_{BH}\, M\,, \qquad s_{BH} = n_{BH}\, 4\pi G M^2$$

Therefore $$a^3 \frac{d}{dt}(\rho_{BH} a^3) = T_{BH} \frac{d}{dt}(s_{BH} a^3) = 0$$

No contribution to entropic force of the universe unless multiple **black hole mergers** or significant **mass accretion,** Which may change **mass or number density** of black holes.

Entropic forces in FLRW

Non-equilibrium thermodynamics in expanding universe

$$ds^2 = -N(t)^2 dt^2 + a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega_2^2\right)$$

$$T^{\mu\nu} = (\rho + p)u^\mu u^\nu + p g^{\mu\nu}$$

$$D^\mu T_{\mu\nu} = D^\mu f_{\mu\nu}$$

2nd law thermodynamics

$$T dS = d(\rho a^3) + p\, d(a^3)$$

$$\dot\rho + 3H(\rho + p) = \frac{T\dot S}{a^3}$$

Hamiltonian constraint

$$\dot a^2 + k = \frac{8\pi G}{3}\rho\, a^2$$

Friedmann/Raychaudhuri equation

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{4\pi G}{3}\frac{T\dot S}{a^3 H}$$

Entropic forces in FLRW

- Causal Cosmological Horizon $\mathcal{H}$

$$\sqrt{h}K = 2N(t)\, r\, a\sqrt{1-kr^2}\,\sin\theta$$ Trace extrinsic curvature

$$d_H \;=\; a\,\eta$$ Causal horizon distance

$$r_H = \sinh(\eta\sqrt{-k})/\sqrt{-k}$$ Conformal time η

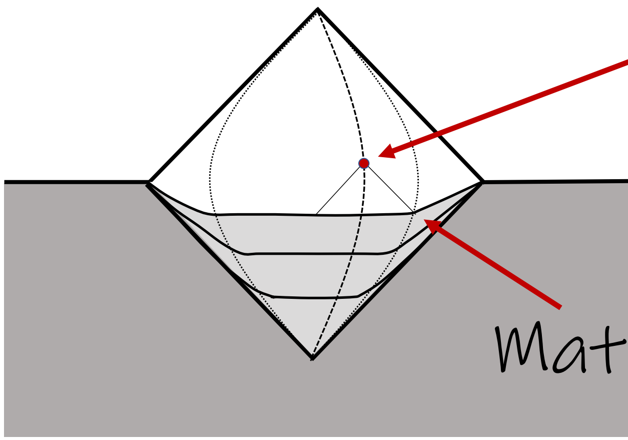
$$S_{GHY} \;=\; -\frac{1}{2G}\int dt\, N(t)\,\frac{a}{\sqrt{-k}}\sinh(2\eta\sqrt{-k})$$

$$= \;-\int dt\, N(t)\, T_H S_H = -\int dt\, N\, a^3 \rho_H$$

$$T_H = \frac{\hbar c}{2\pi}\frac{\sinh(2\eta\sqrt{-k})}{a\, r_H^2\sqrt{-k}}\,, \qquad S_H = \frac{c^3}{\hbar}\frac{\pi a^2 r_H^2}{G}$$

Emergent

Cosmic Acceleration



Observer's causal horizon

$$\rho_H\, a^2 = \frac{T_H S_H}{a} = \frac{1}{2G}\,\frac{\sinh(2a_0 H_0 \eta)}{a_0 H_0}$$

Matching: $H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \quad \Longrightarrow \quad \sqrt{-k} = a_0 H_0$

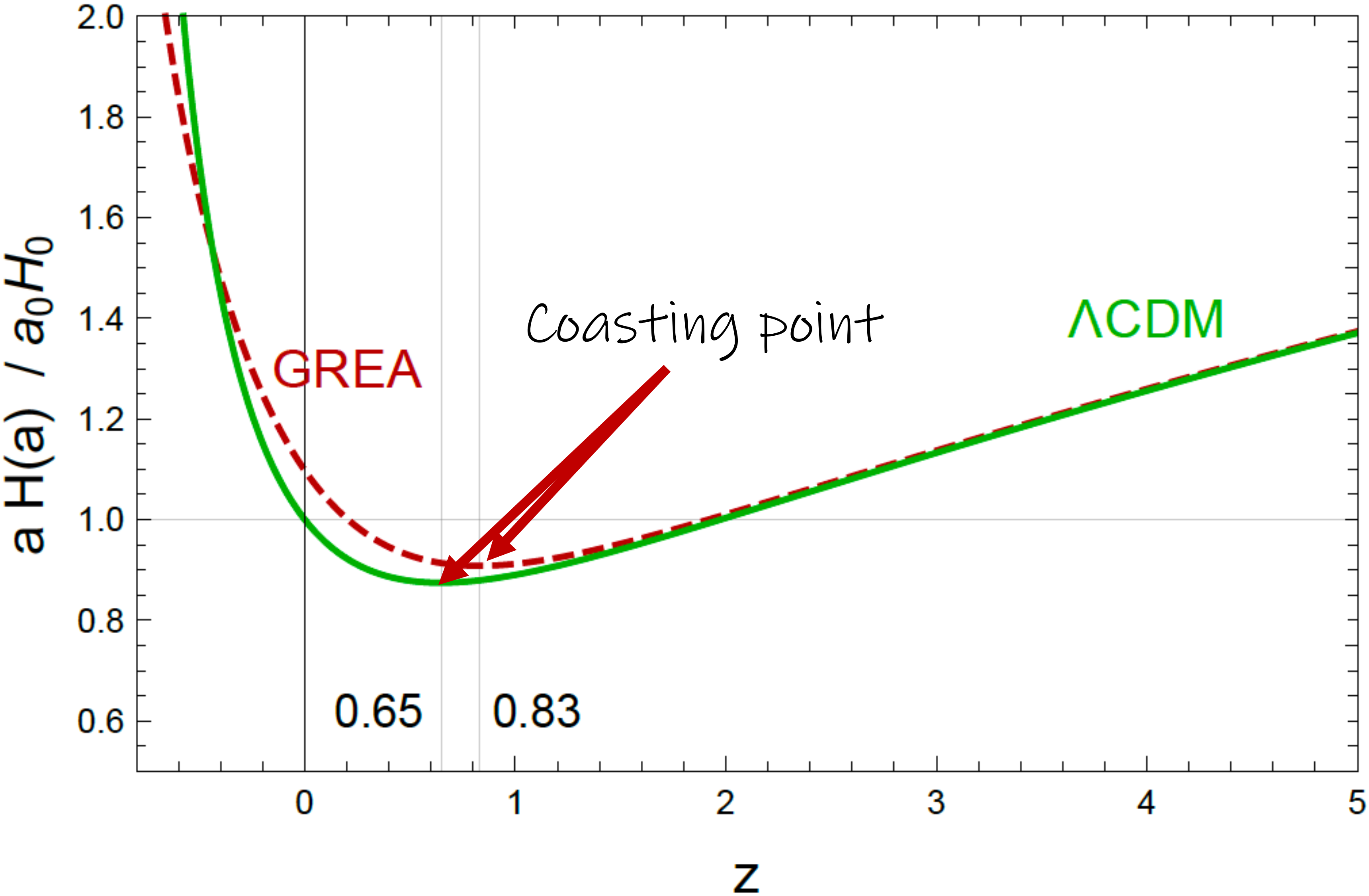
Hamiltonian constraint in conformal time
(primes denote derivatives w.r.t. $\tau = a_0 H_0 \eta$)

$$\left(\frac{a'}{a}\right)^2 = \Omega_{\rm M}\left(\frac{a_0}{a}\right) + \Omega_{\rm K} + \frac{4\pi}{3}\Omega_{\rm K}^{3/2}\sinh(2\tau)$$

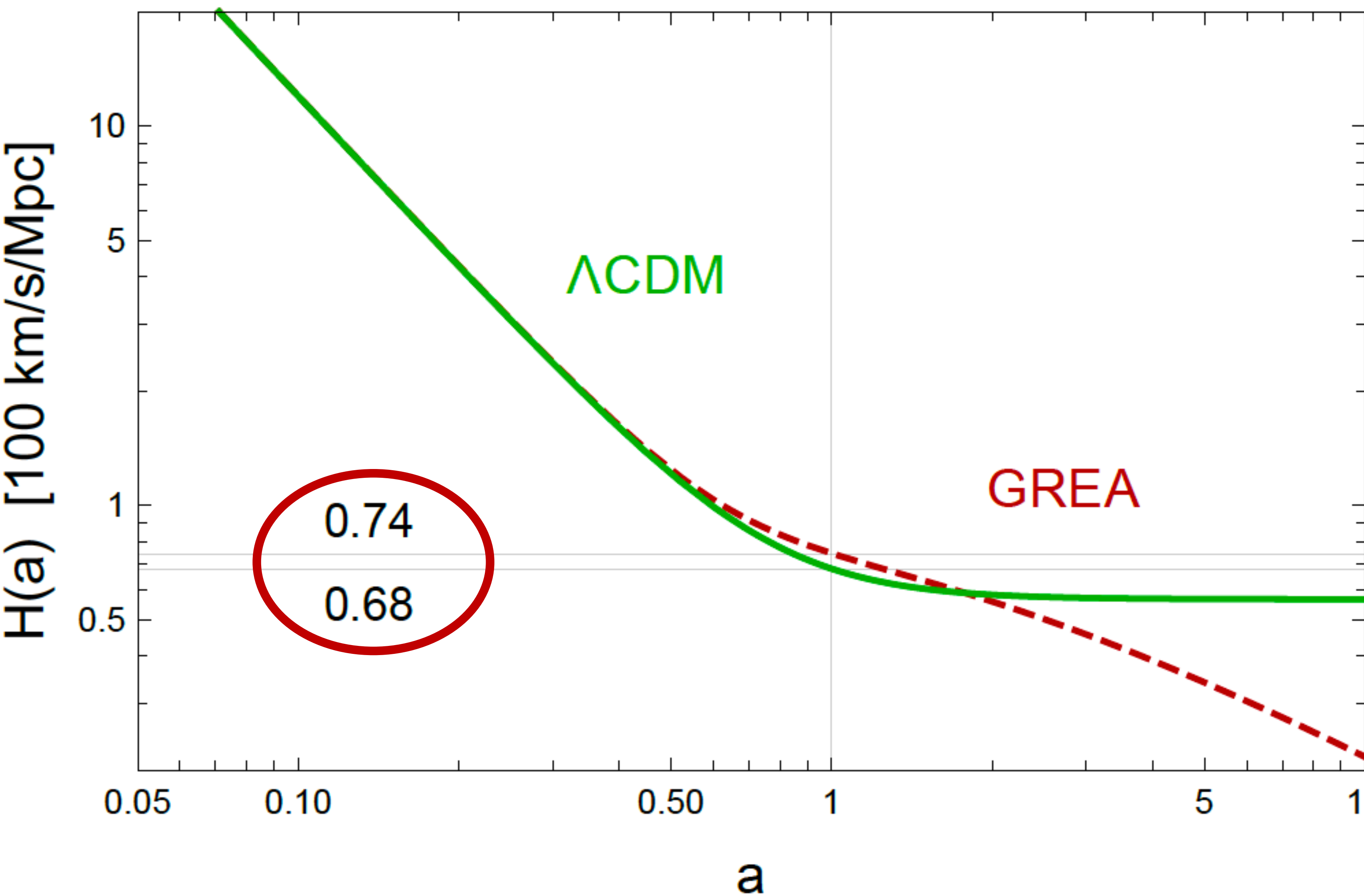
Entropic force term

Note: $\Lambda = 0$

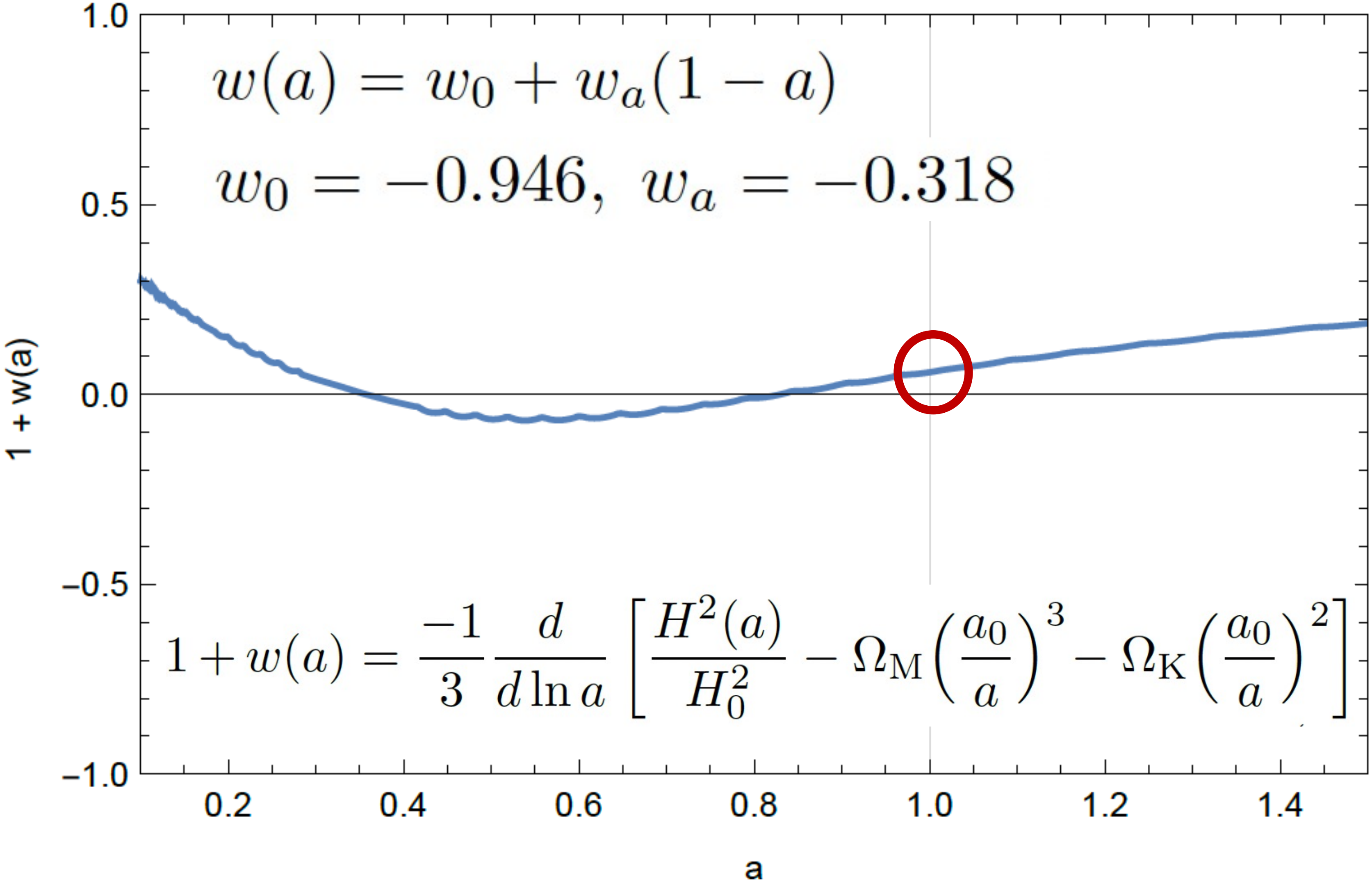
Cosmic Acceleration



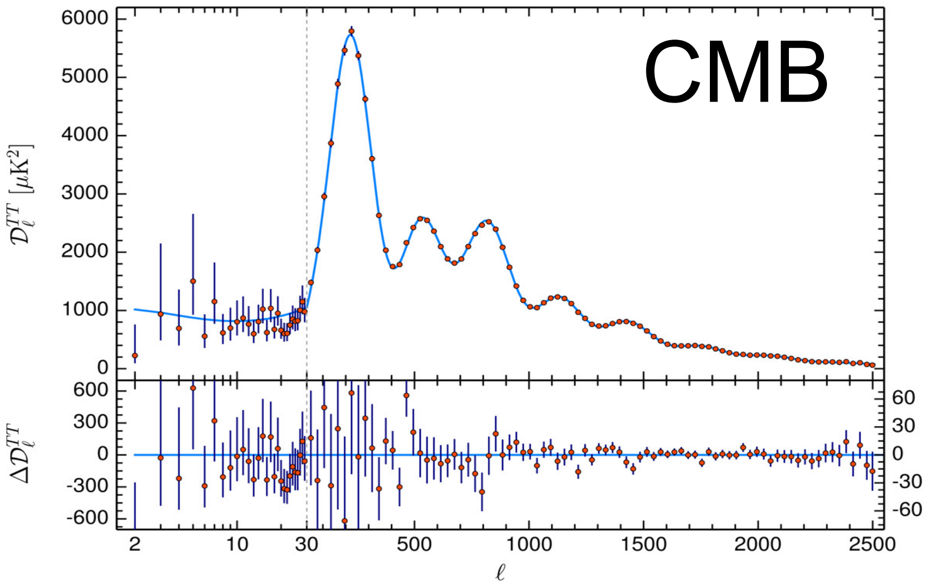
Cosmic Acceleration

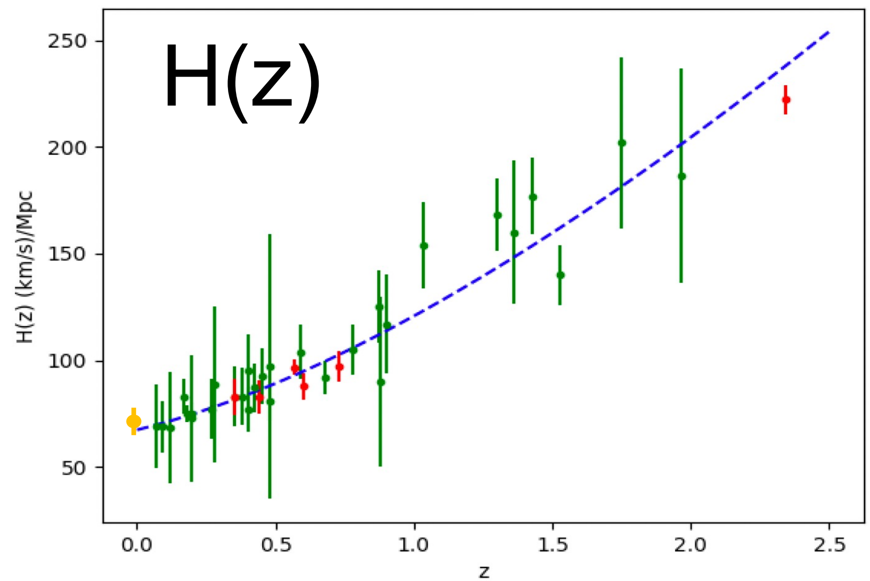


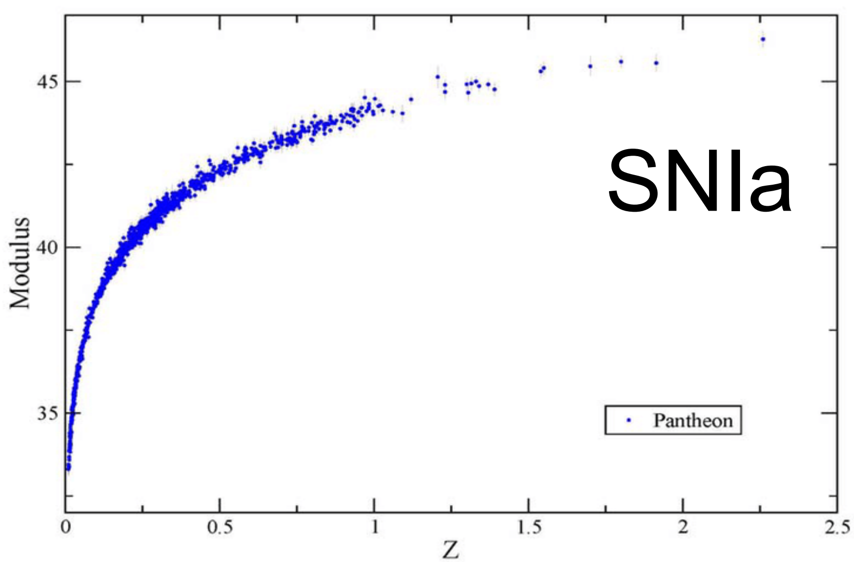
Cosmic Acceleration

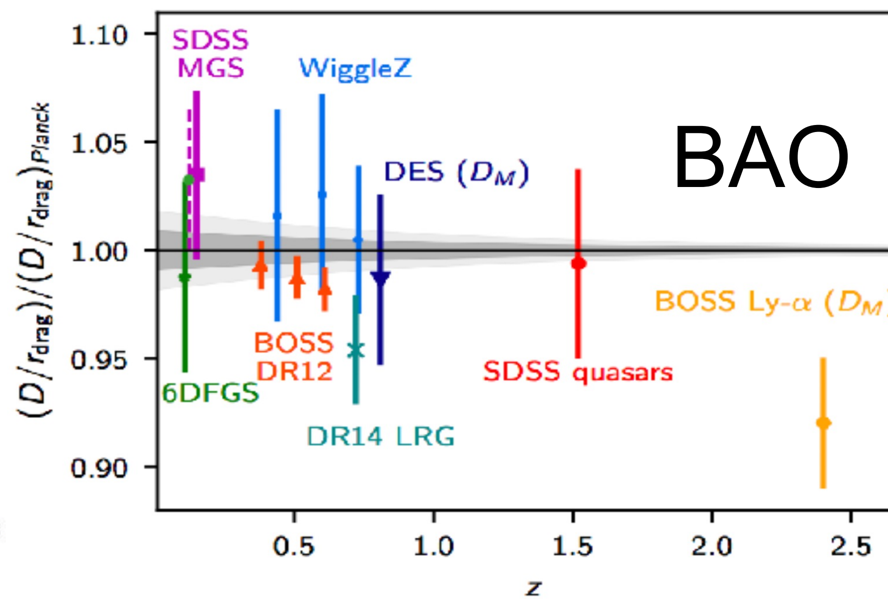


Cosmo Observations



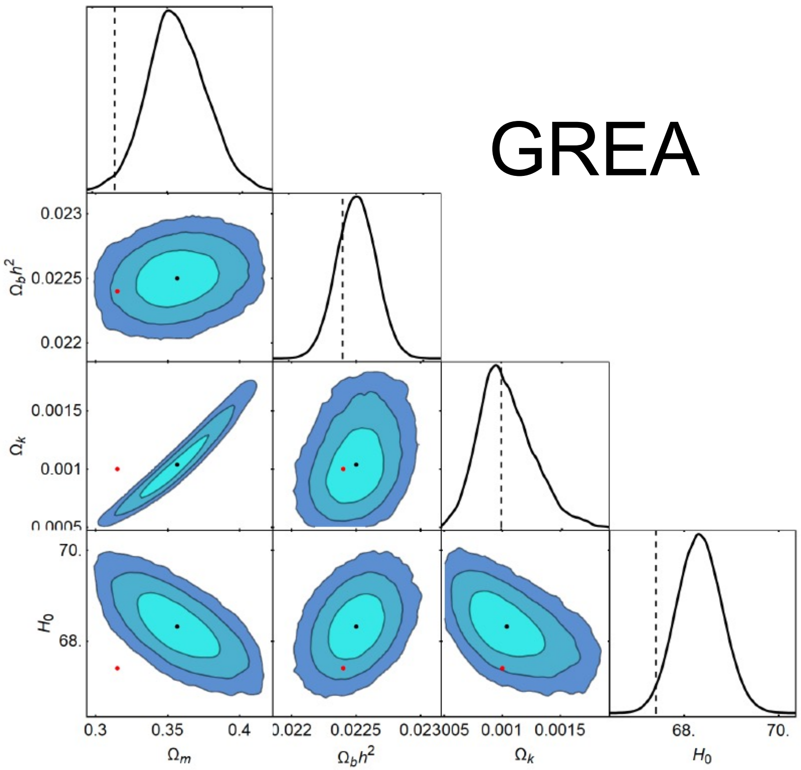


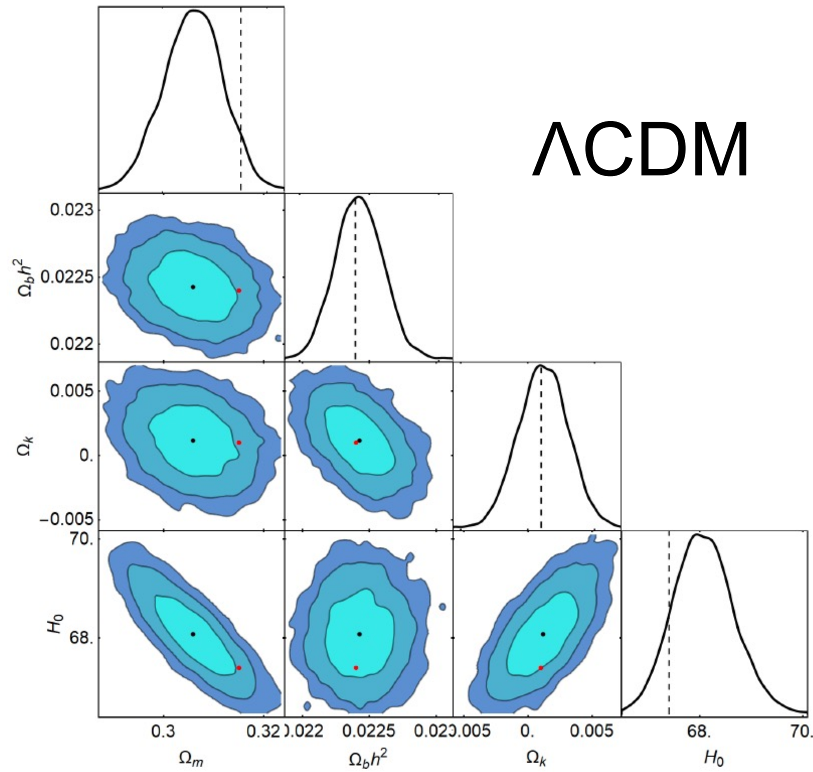




Cosmic Constraints

Arjona, Espinosa, JGB & Nesseris (2021)





Model	$\Omega_{m,0}$	$\Omega_{b,0}h^2$	$\Omega_{k,0}$	H_0	χ^2_{min}	$\log Z(1)$
ΛCDM	0.3057 ± 0.0056	0.0224 ± 0.0002	0.0012 ± 0.0018	68.08 ± 0.58	1075.63	-557.515
GREAT	0.3522 ± 0.0190	0.0225 ± 0.0001	0.0010 ± 0.0002	68.38 ± 0.48	1071.35	-548.509

Cosmic Constraints

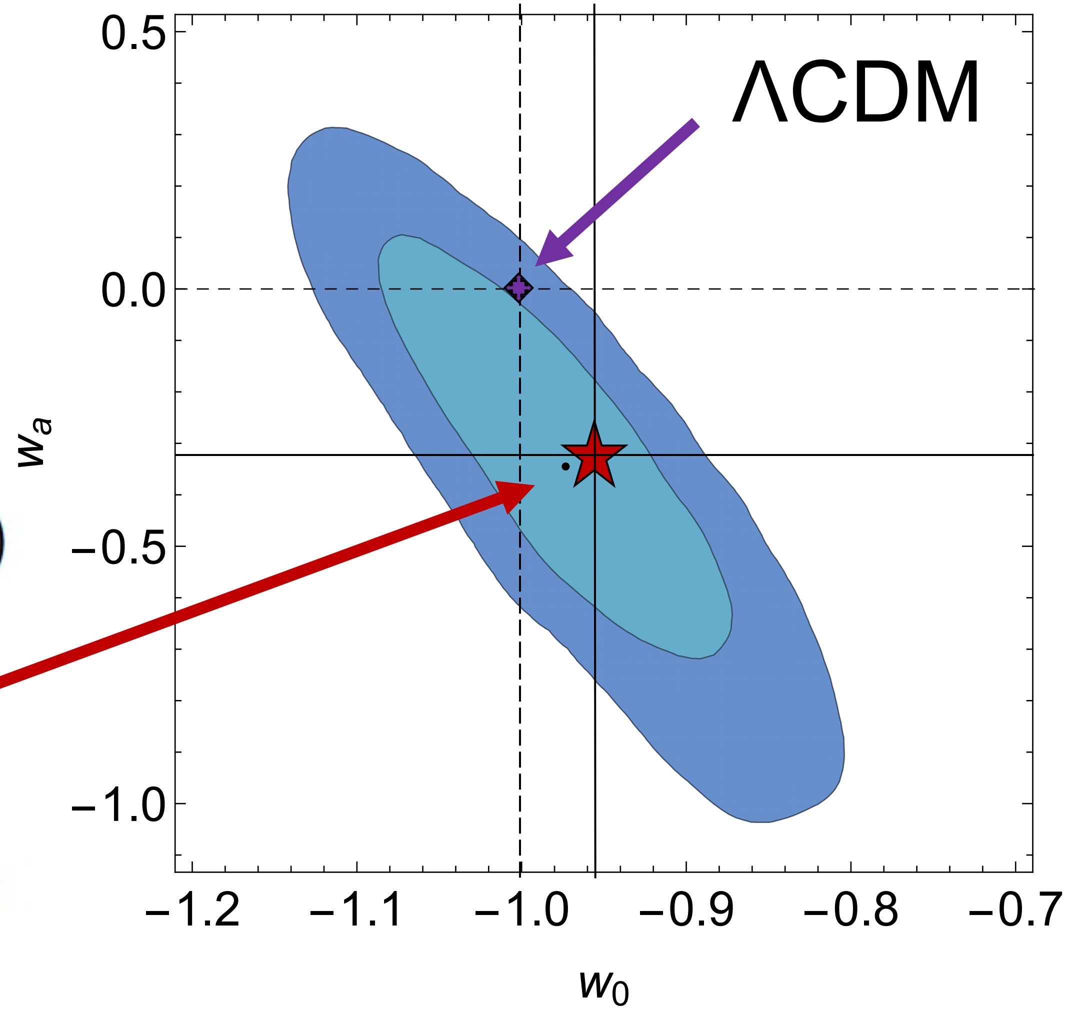
Arjona, Espinosa, JGB & Nesseris (2021)

Same data but with (w_0, w_a) free:

$$w(a) = w_0 + w_a(1 - a)$$

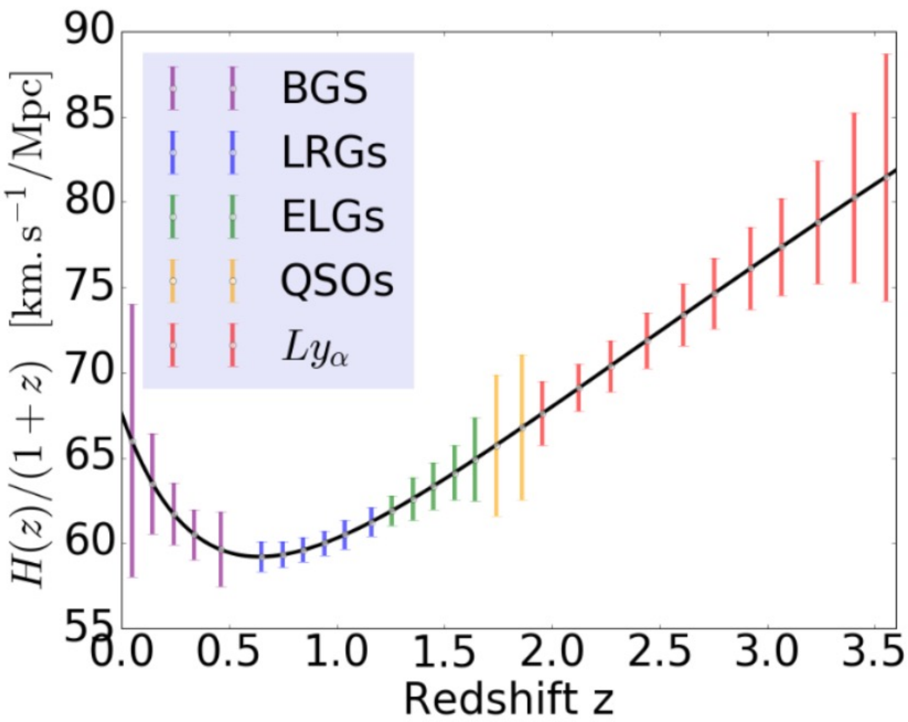
GREA

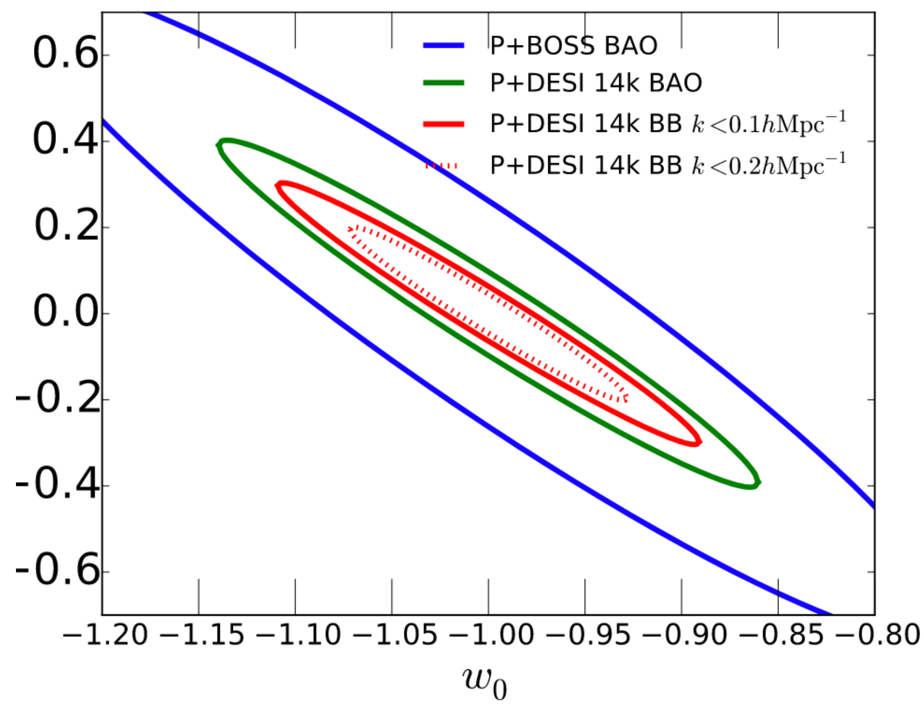
$$w_0 = -0.946,\ w_a = -0.318$$



Future Constraints

DESI Coll. (2016)



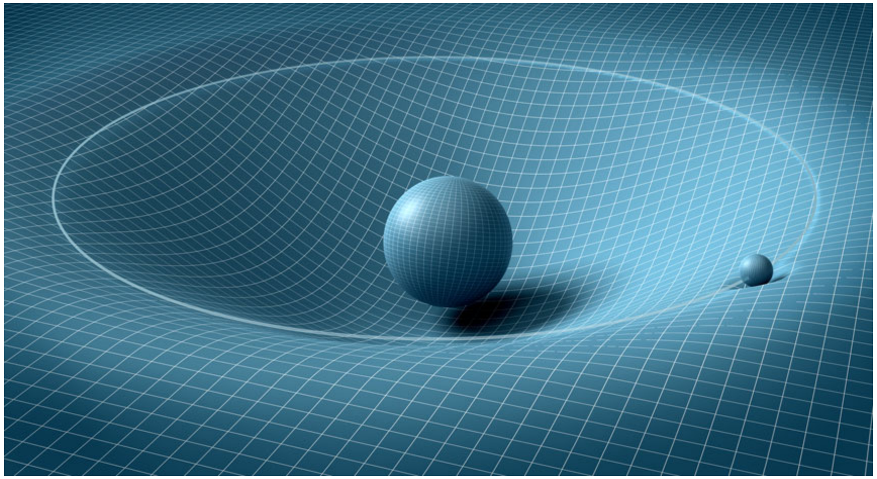


Conclusions

- Non-equilibrium phenomena in GR: entropic forces
- ADM (3+1) slicing: Raychaudhuri eq. grav. collapse
- Cosmic acceleration from first principles
- No need for a Cosmological Constant
- Future Infinity is Flat Space Minkowsky
- Just QFT, GR and Non eq. Thermodynamics
- Multiple consequences for Large Scale Structure
- Possible solution to the H_0 tension
- Future: Preheating after inflation (Big Bang)
- Future: Cosmic Web Entropy: Cosmic Voids

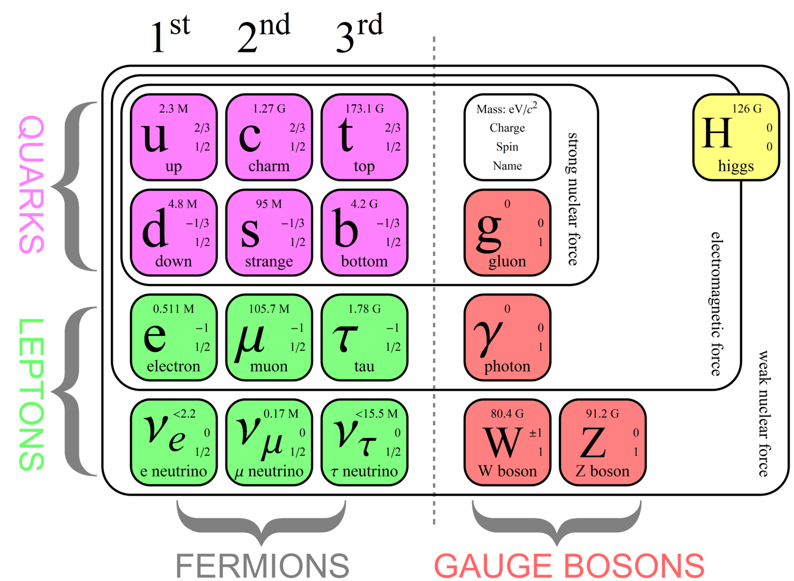
On the shoulders of giants

General Relativity



Thermodynamics

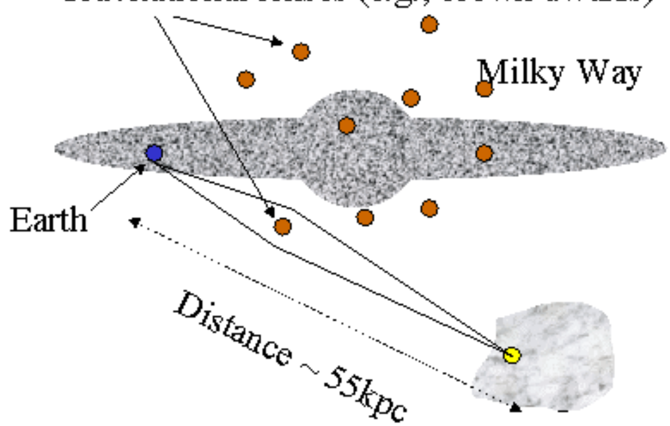
Quantum Mechanics



Backup slides

Long duration microlensing events OGLE-GAIA

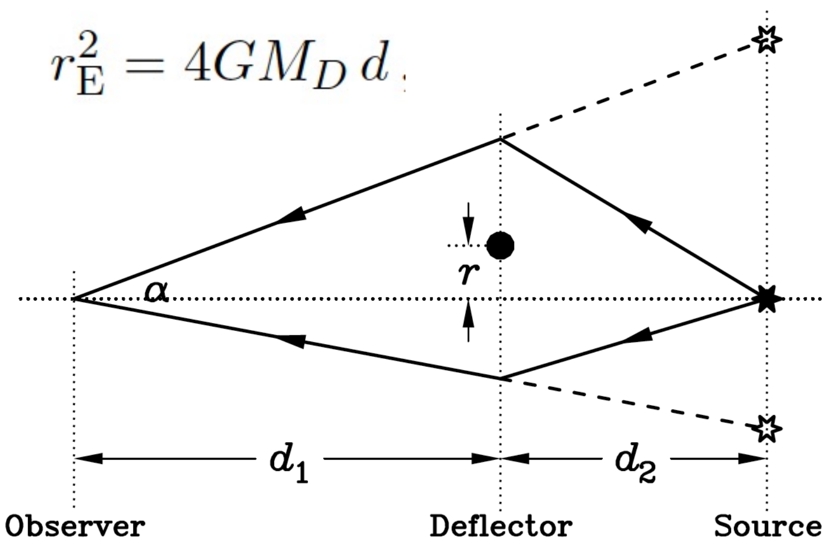
Microlensing



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

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

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



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

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

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

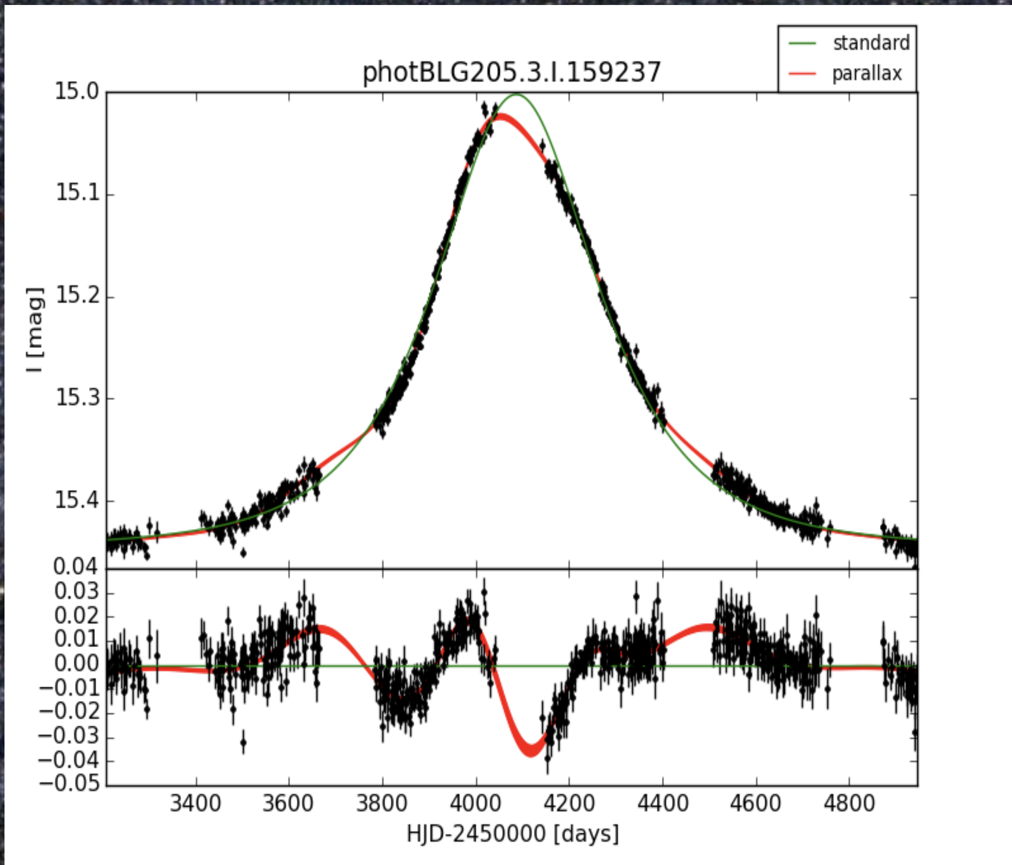
$M_D = 1\,M_\odot$ => $\overline{Dt} = 5$ months

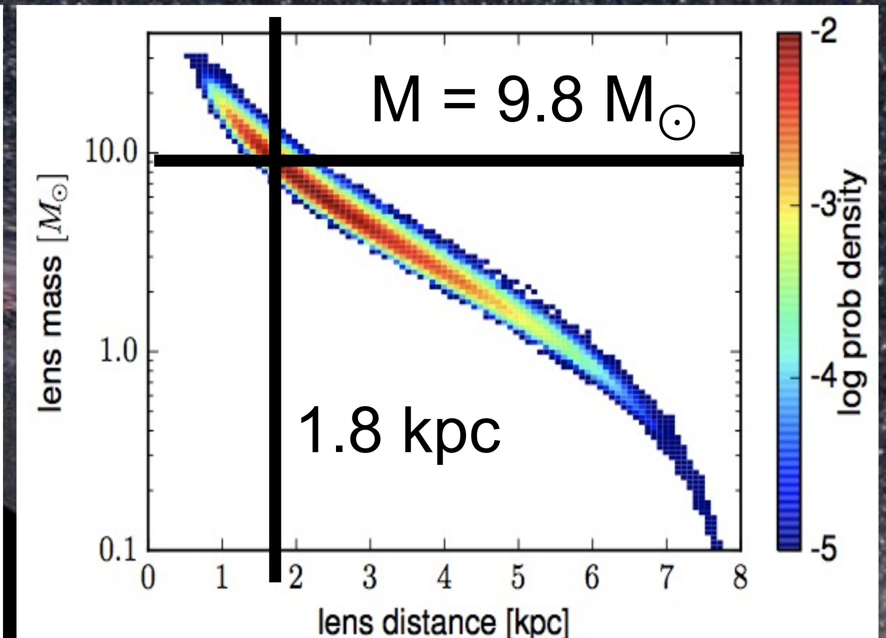
$M_D = 0.1\,M_\odot$ => $\overline{Dt} = 1.5$ months

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

OGLE3-UL-PAR-02 - candidate BH

Wyrzykowski (2016)



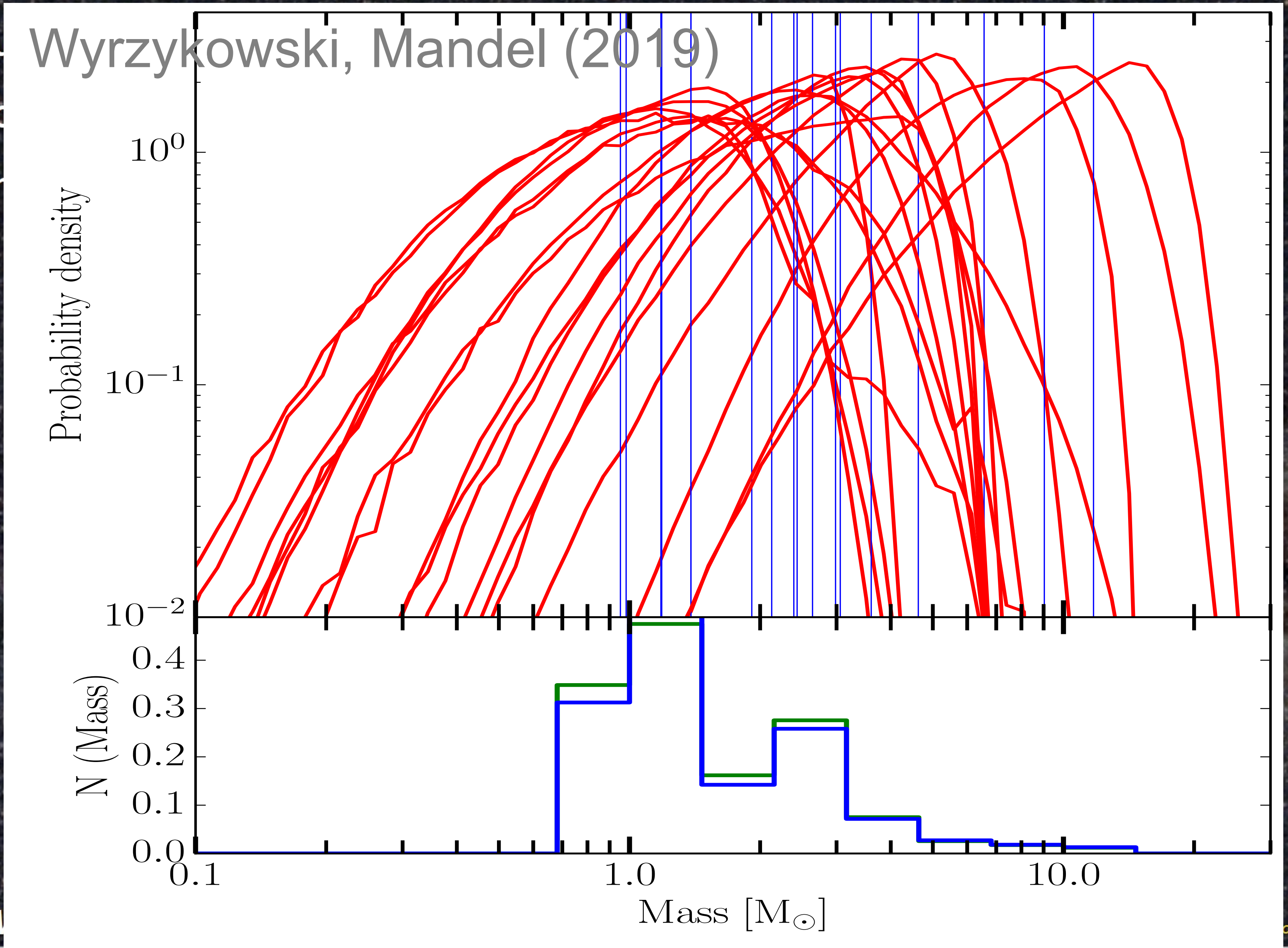


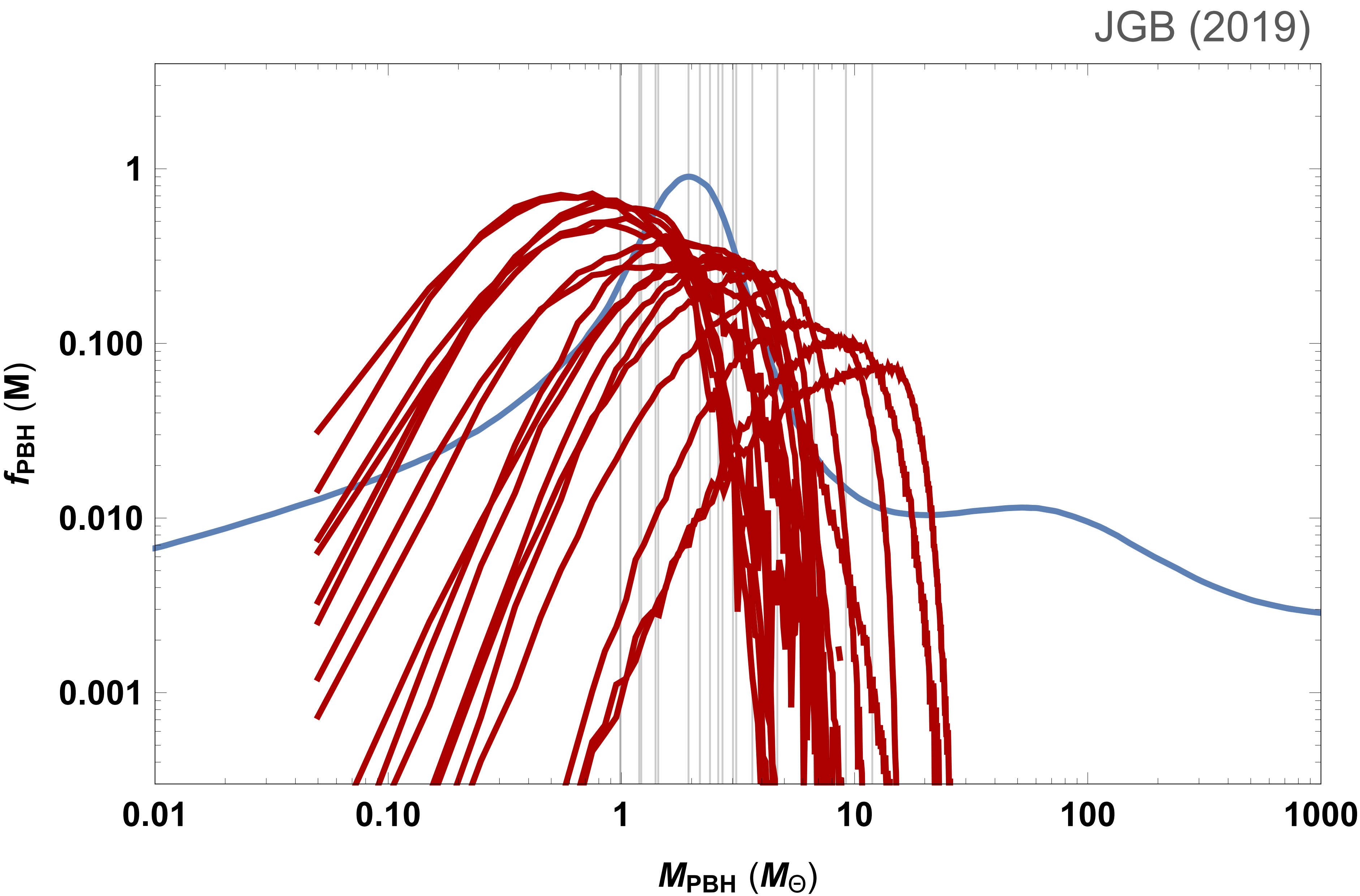
$$\overline{D}t = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v}$$

OGLE photometry
from 2001-2008
and microlensing model

Mass, Distance (degenerated estimate)

MASS FUNCTION




JGB (2019)
1
0.100
0.010
0.001
f_{PBH} (M)
0.01
0.10
1
10
100
1000
M_{PBH} ($M_{\odot}$)

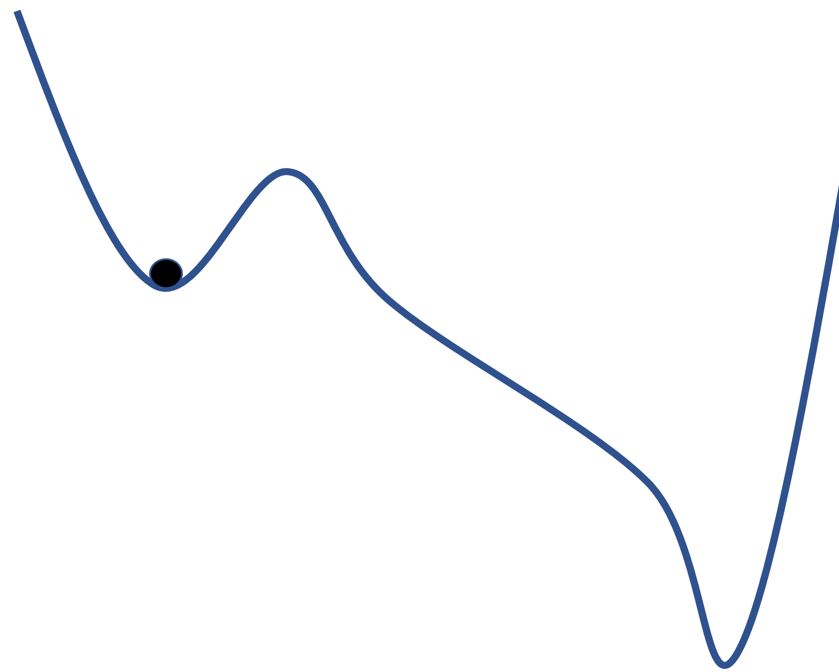
Open Universe model for GREA

Cosmic Acceleration

Penrose diagram

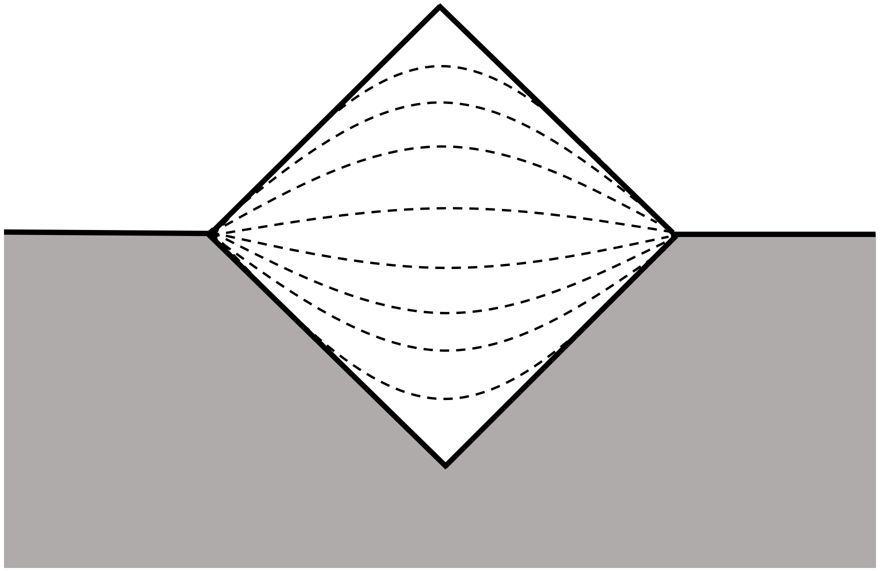
de Sitter

Potential



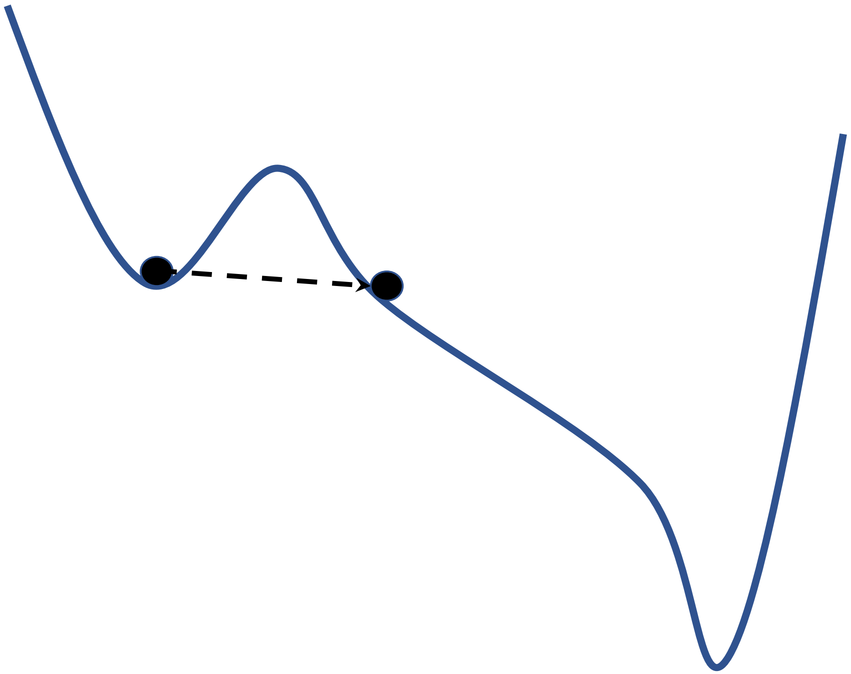
Cosmic Acceleration

Penrose diagram



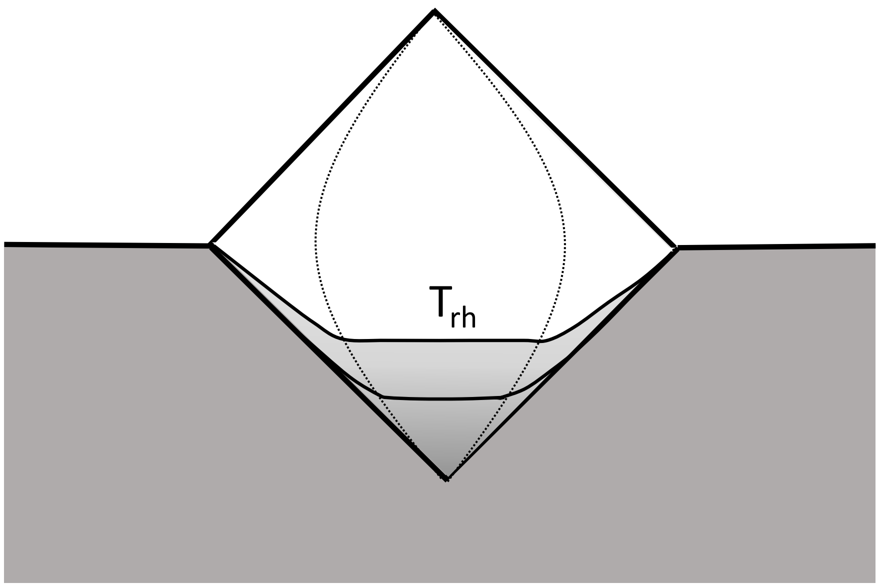
Open **empty** universe

Potential



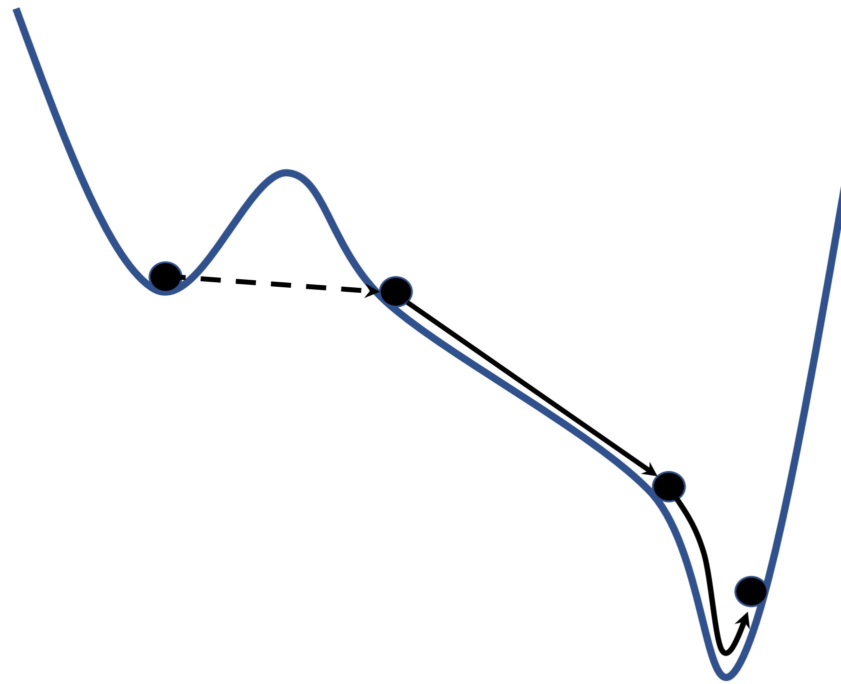
Cosmic Acceleration

Penrose diagram



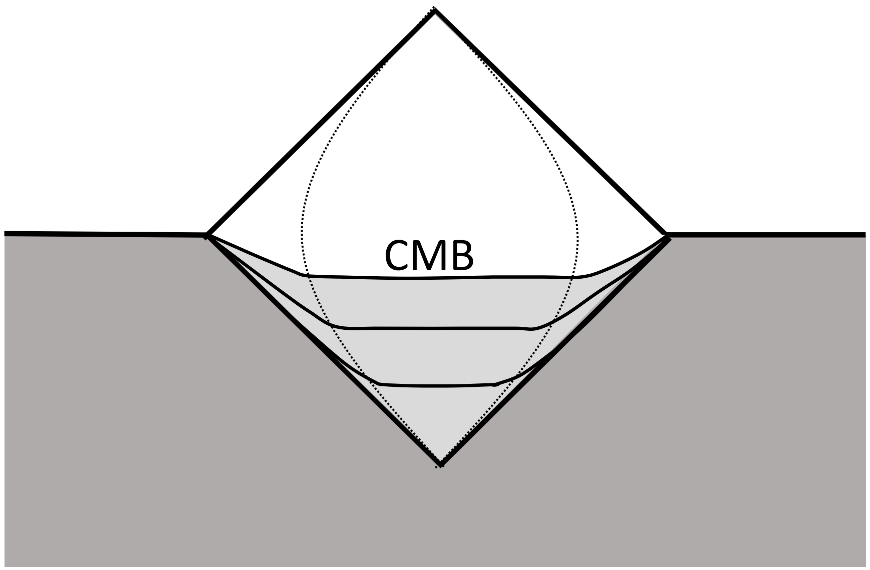
Flat **reheated** universe

Potential



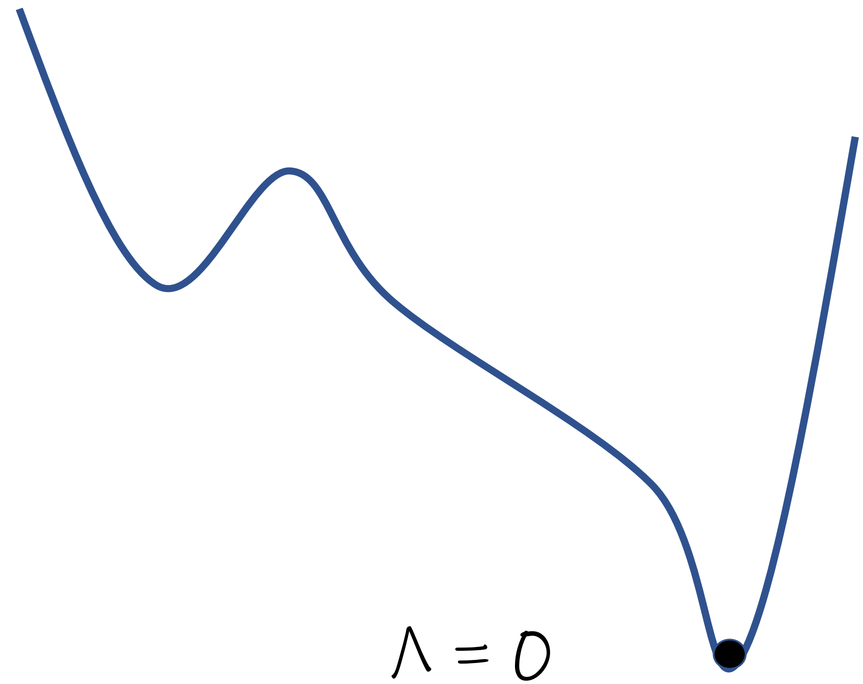
Cosmic Acceleration

Penrose diagram



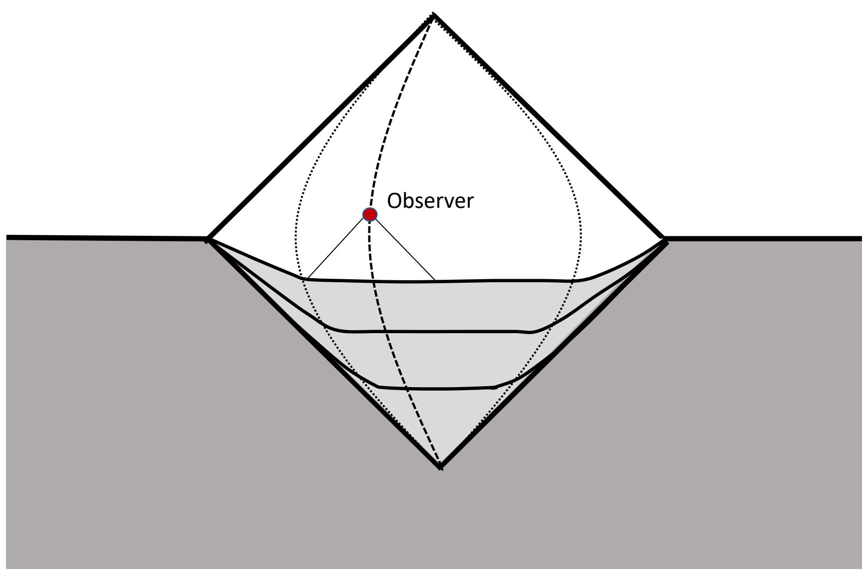
Flat **late** universe

Potential



Cosmic Acceleration

Penrose diagram



Flat **late** universe

Potential