Origin, evolution and signatures of Primordial Black Holes as Dark Matter

JGB & S. Clesse, Sci. Am. July 2017, 39 (review)
JGB & Ruiz Morales, Phys. Dark Univ. 18 (2017) 47
Ezquiaga, JGB & Ruiz Morales, arXiv:1705.04861, PLB
JGB, J.Phys.Conf 840 (2017) 012032 (scenario)
JGB & S. Nesseris, Phys. Dark Univ. 18 (2016) 123
S. Clesse & JGB, arXiv:1610.08479, PDU accepted
JGB, M. Peloso & C. Unal, JCAP 1709 (2017) 013
JGB, M. Peloso & C. Unal, JCAP 1612 (2016) 031
S. Clesse & JGB, Phys Dark Univ 10 (2016) 002
S. Clesse & JGB, Phys Rev D92 (2015) 023524
JGB, Linde & Wands, Phys Rev D54 (1996) 6040

Juan García-Bellido
13th November 2017
IPMU Tokyo

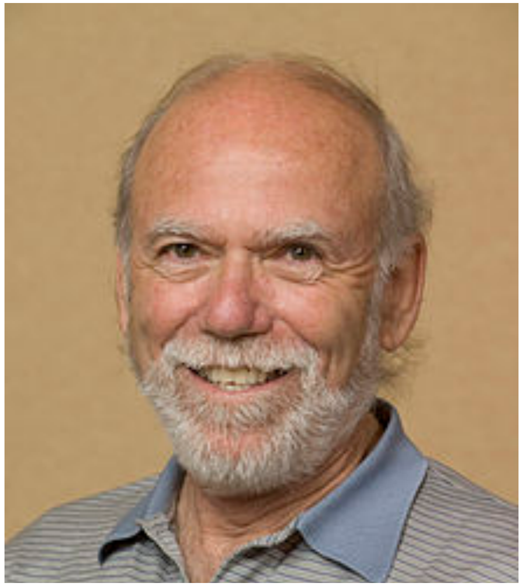
Outline

- The discovery of 5 BHB by AdvLIGO has opened a new Era of Astronomy
- Is Cold Dark Matter made of PBH ?
- Quantum origin => Peaks in curvature
- Astrophysical signatures
- Cosmological signatures
- Test PBH scenario with GW emission
- Conclusions

The Nobel Prize in Physics 2017

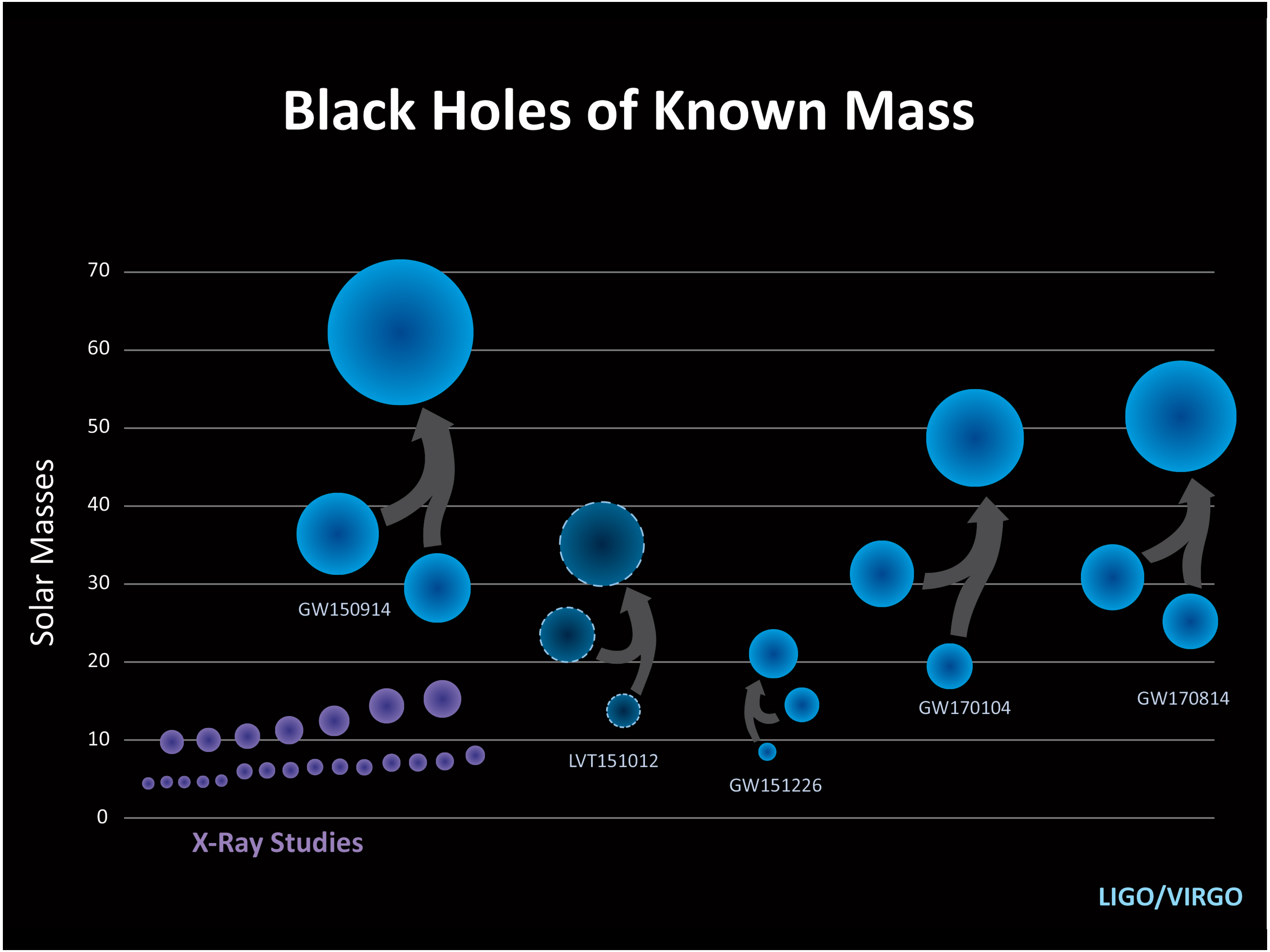
“for decisive contributions to the LIGO detector and the observation of gravitational waves”

Reiner Weiss

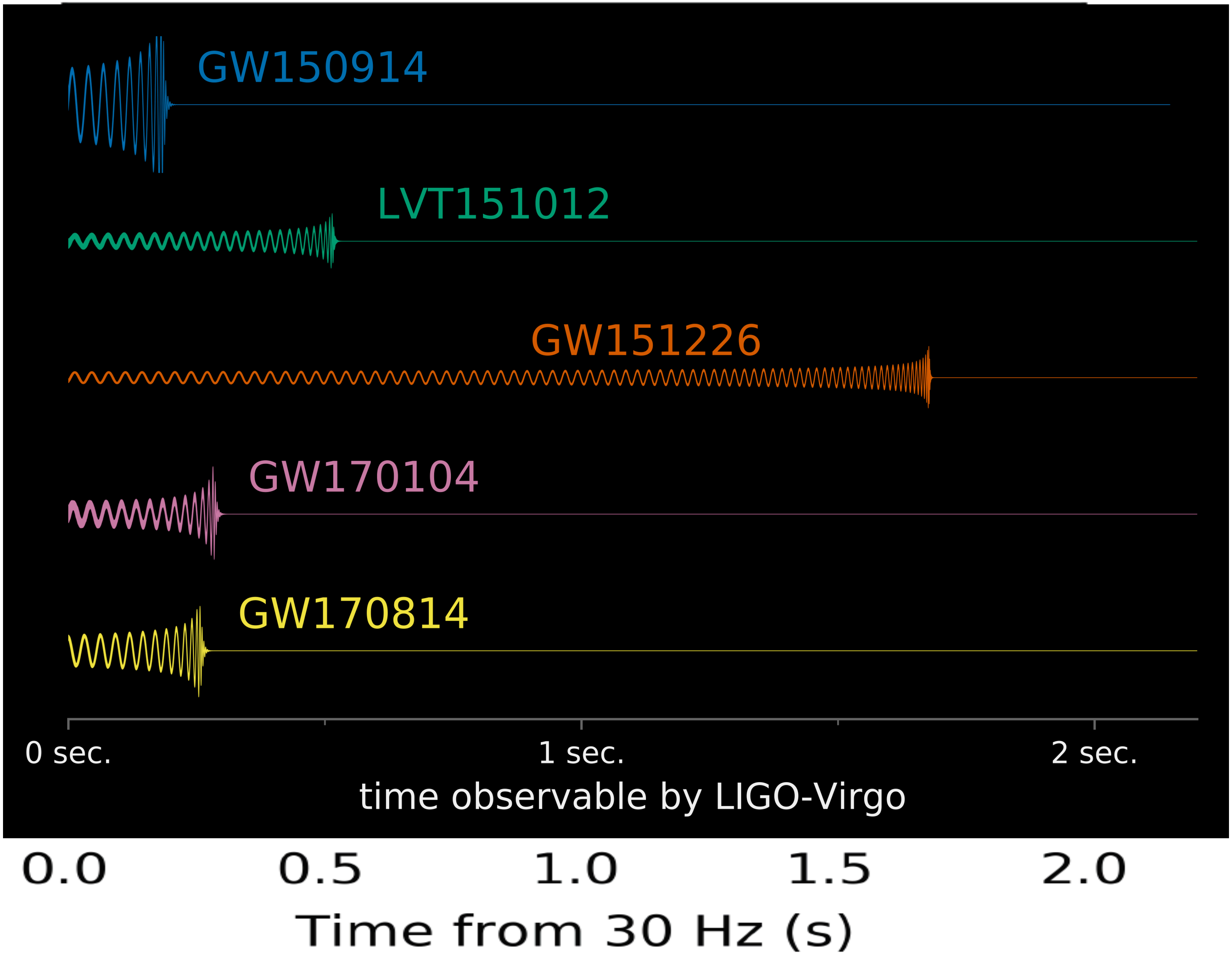


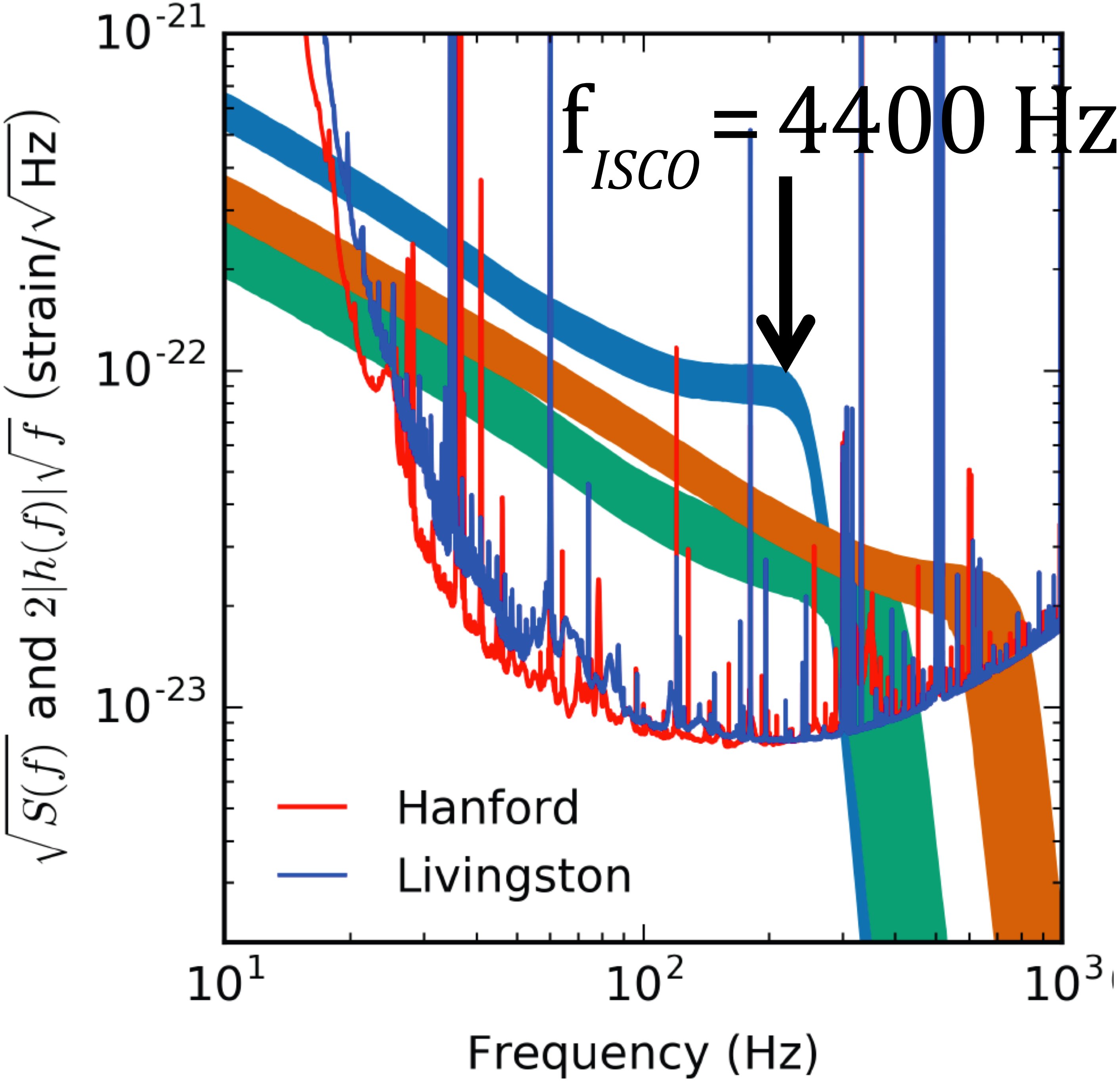
Barry C. Barish

Kip S. Thorne



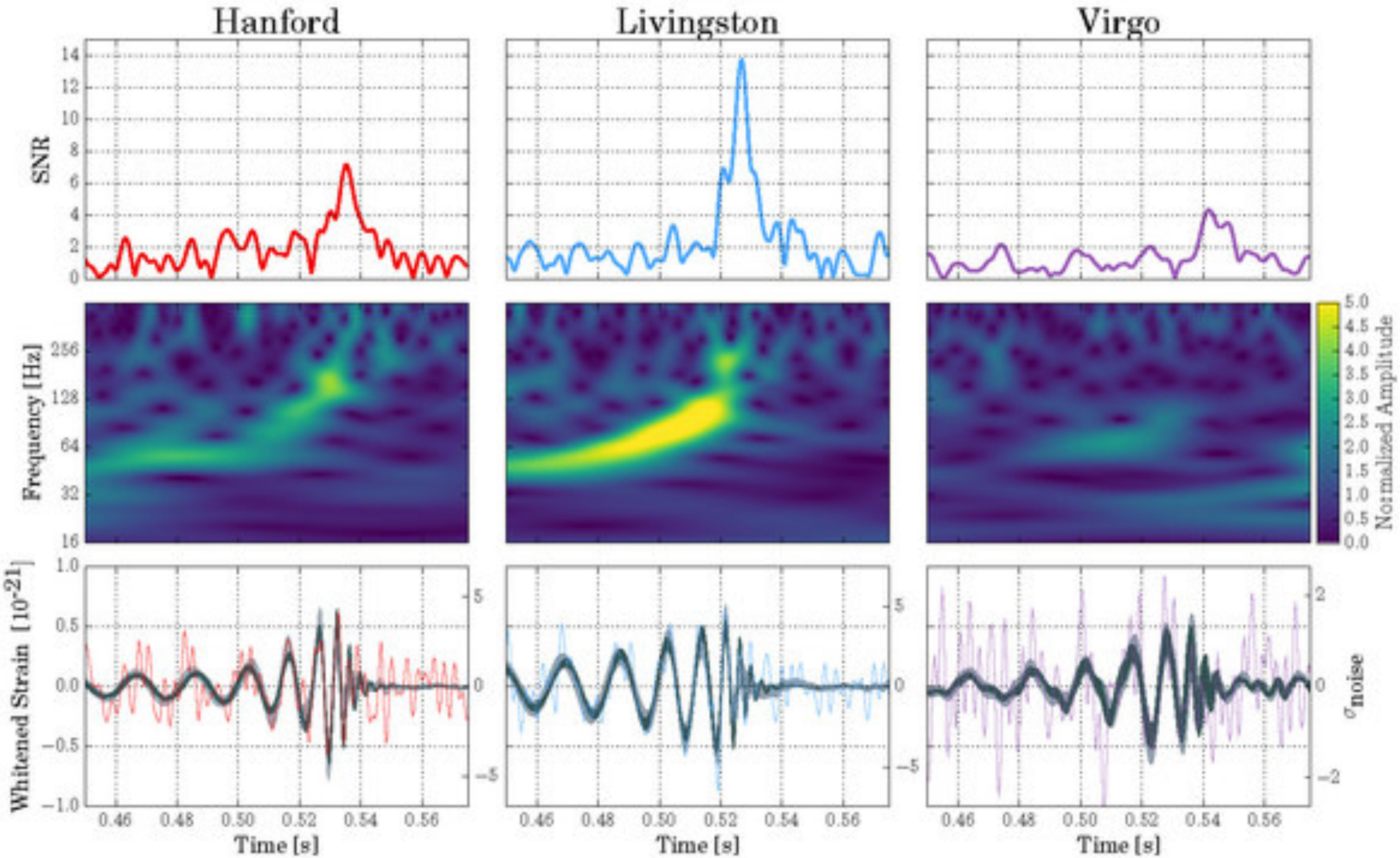
Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
GW150914
LVT151012
GW151226
GW170104
GW170814
X-Ray Studies
LIGO/VIRGO

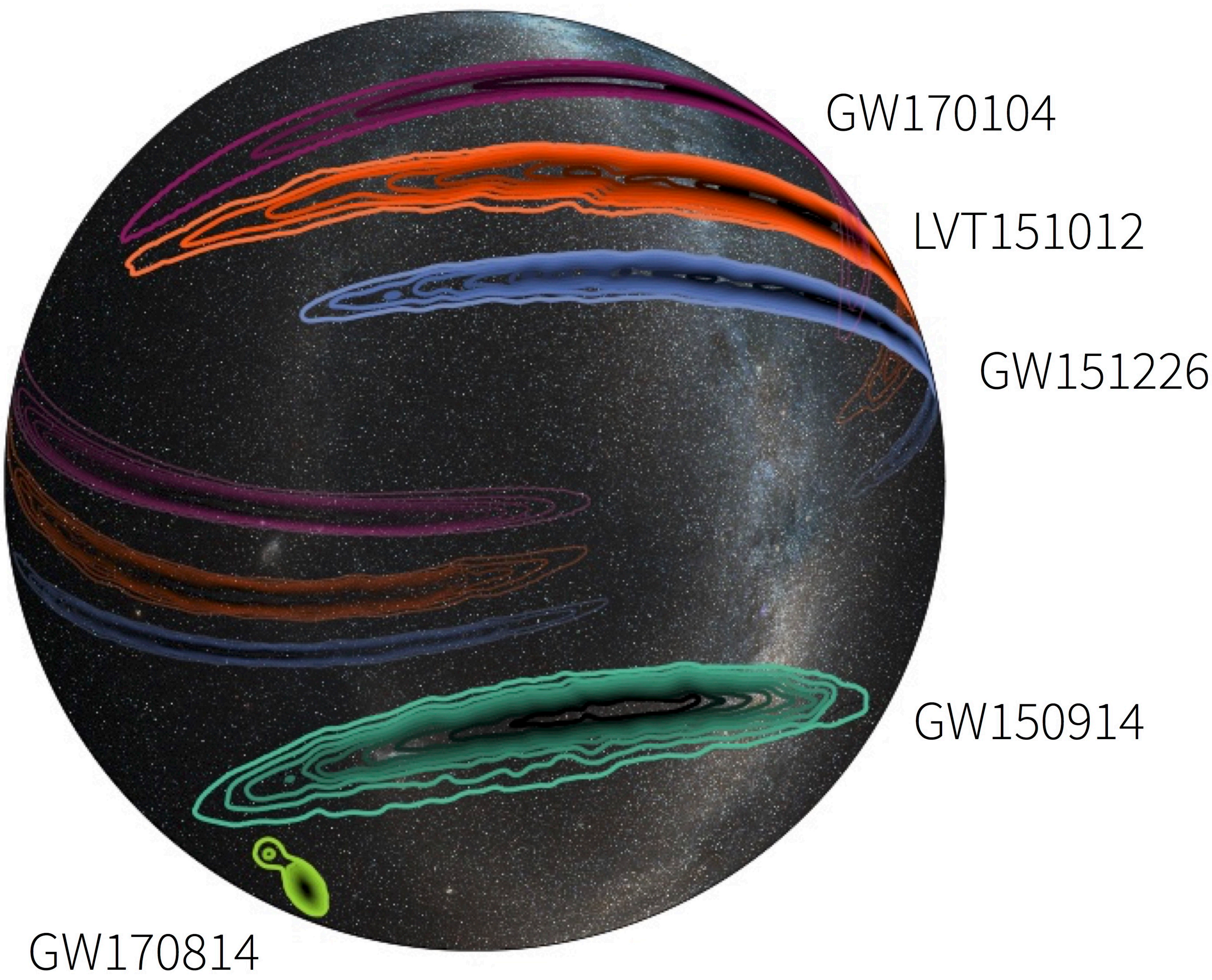

GW150914
LVT151012
GW151226
GW170104
GW170814
0 sec.
1 sec.
2 sec.
time observable by LIGO-Virgo
0.0
0.5
1.0
1.5
2.0
Time from 30 Hz (s)



$$f_{ISCO} = 4400\ \text{Hz}\ \frac{M_\odot}{M}$$

GW170814 detected by LVC



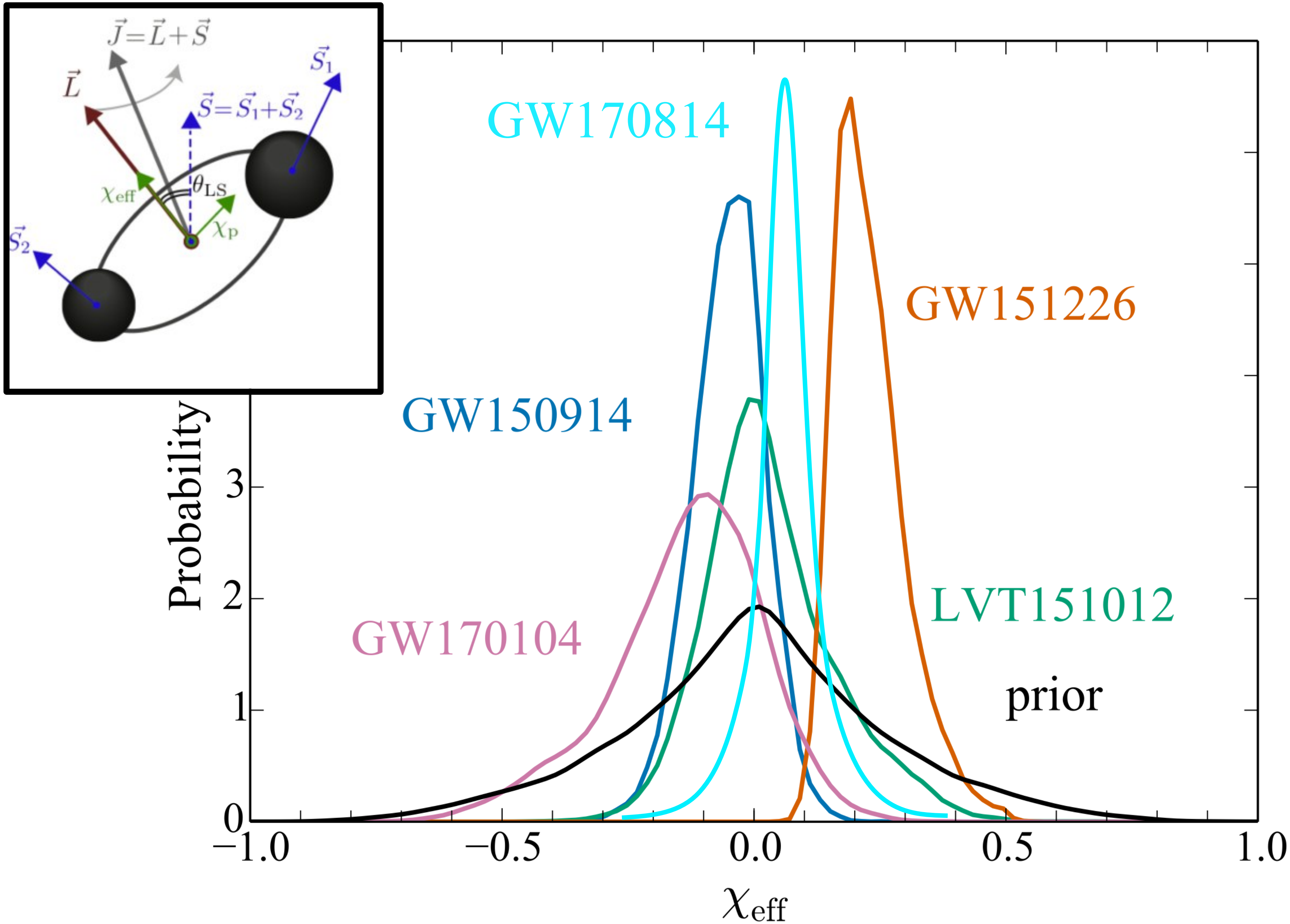

GW170104
LVT151012
GW151226
GW150914
GW170814

Gravitational Wave Astronomy

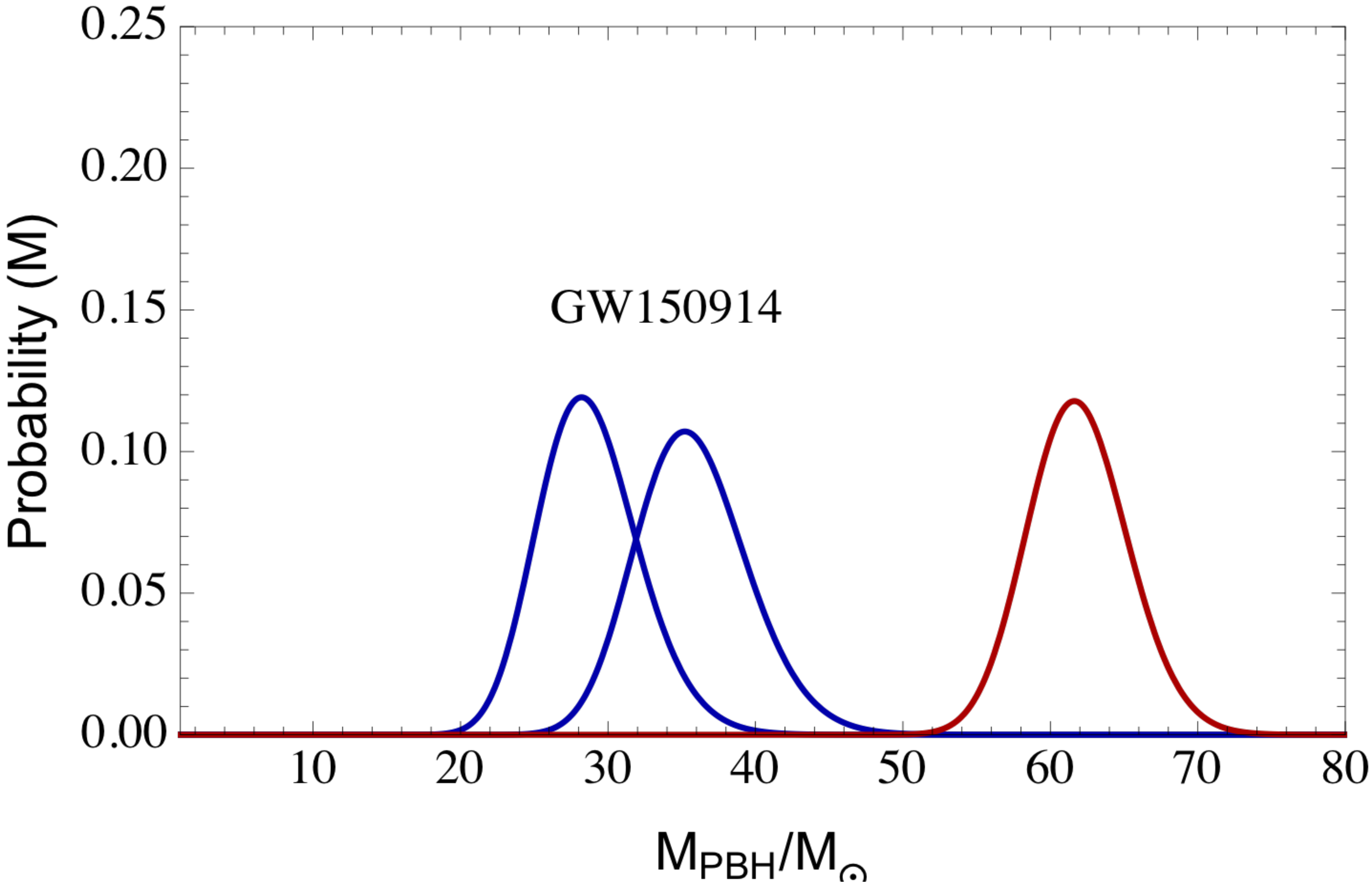
- AdvLIGO + VIRGO (+KAGRA, +INDIGO)
- GW150914 = 36 + 29 $M_{\odot}$ BH binary
- LVT151012 = 23 + 13 $M_{\odot}$ "candidate"
- GW151226 = 14 + 8 $M_{\odot}$ BH binary
- GW170401 = 32 + 20 $M_{\odot}$ BH binary
- GW170814 = 31 + 25 $M_{\odot}$ BH binary
- Expected 10-150 events/yr/Gpc^3
- AdvLIGO+ can map the mass and spin

Massive BH (0.1 $M_{\odot}$ < M_{BH} < 150 M_{sun})

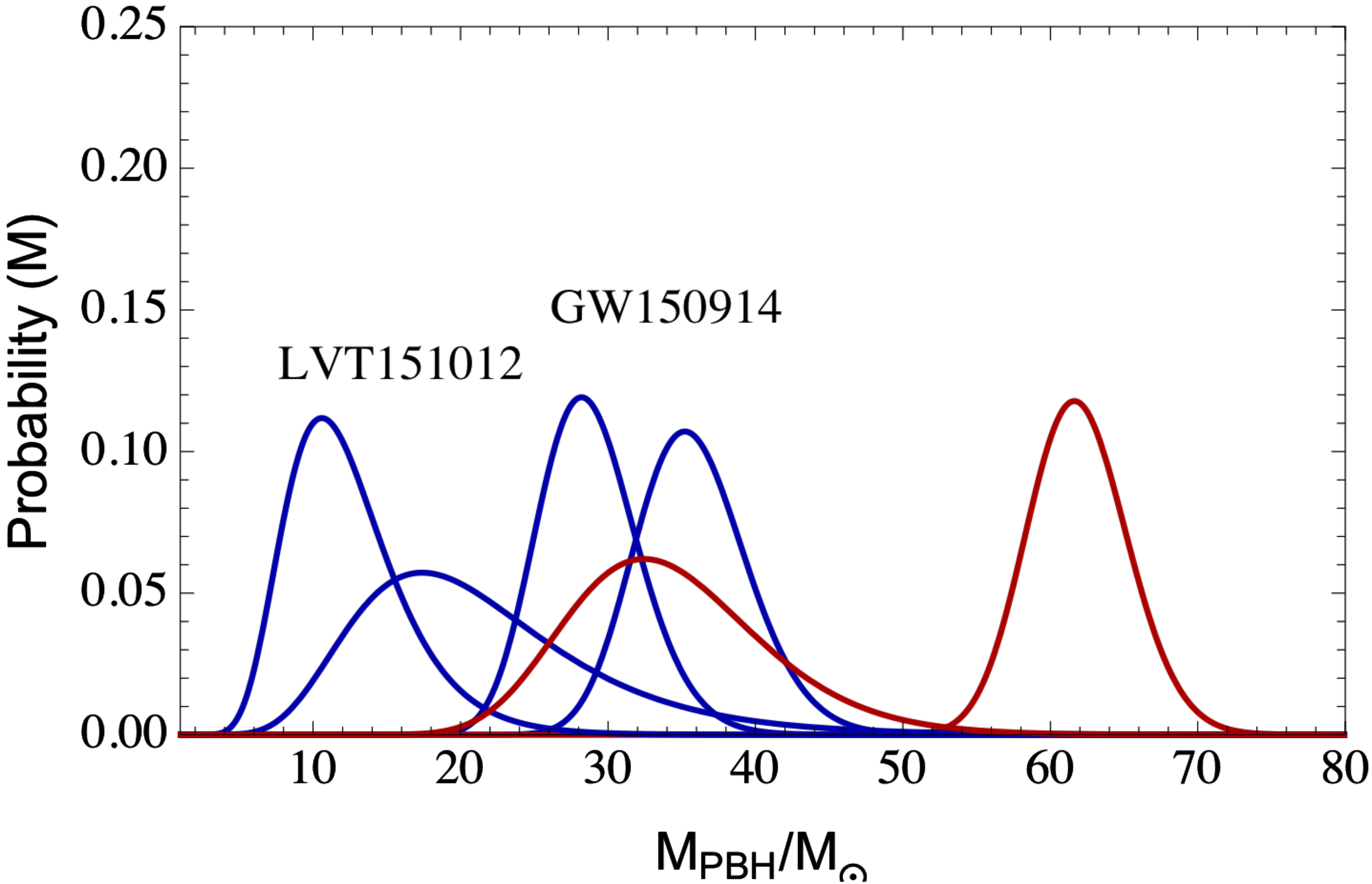
Spin distribution of LIGO BHB



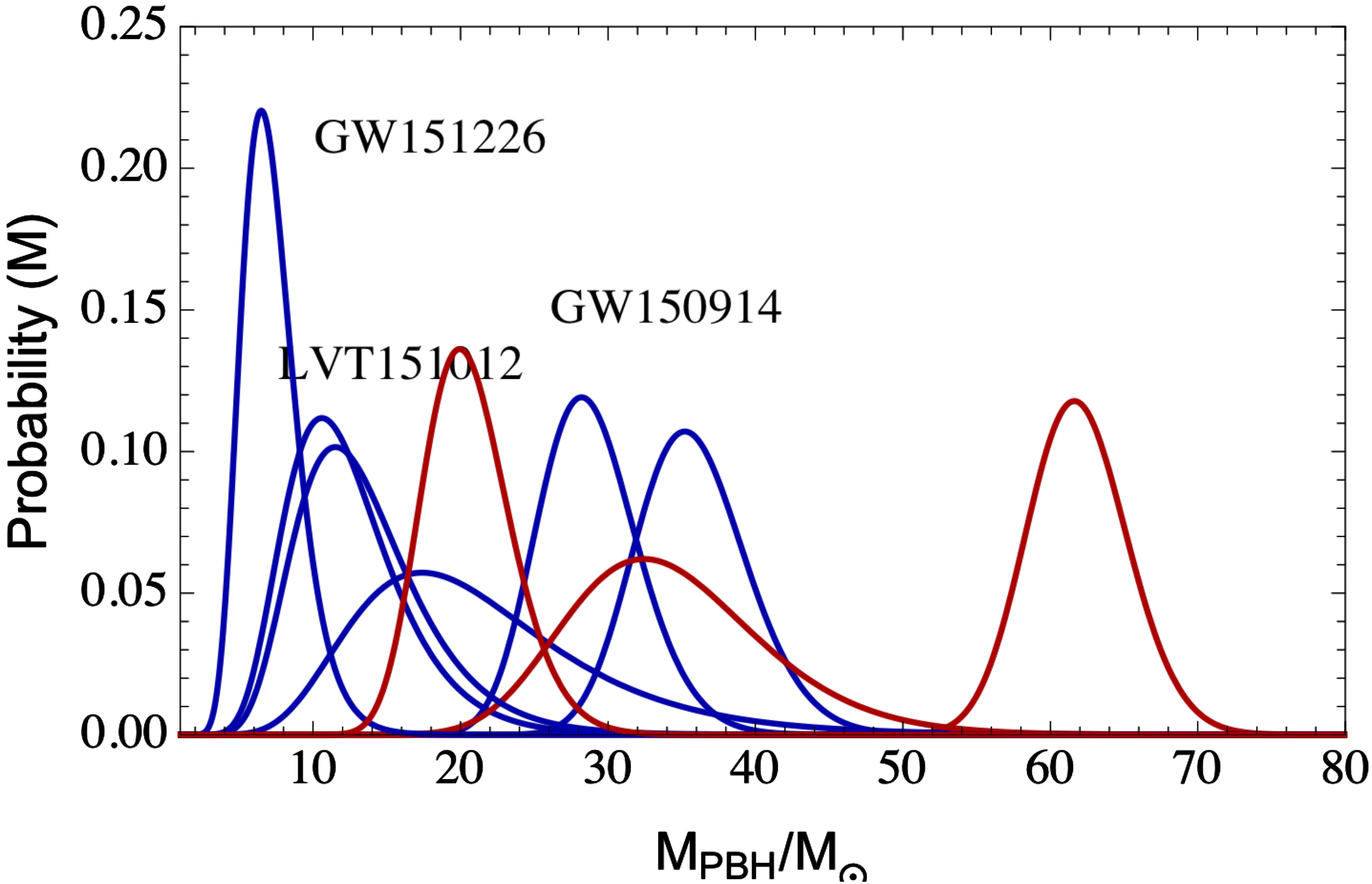
Mass distribution of LIGO BHB



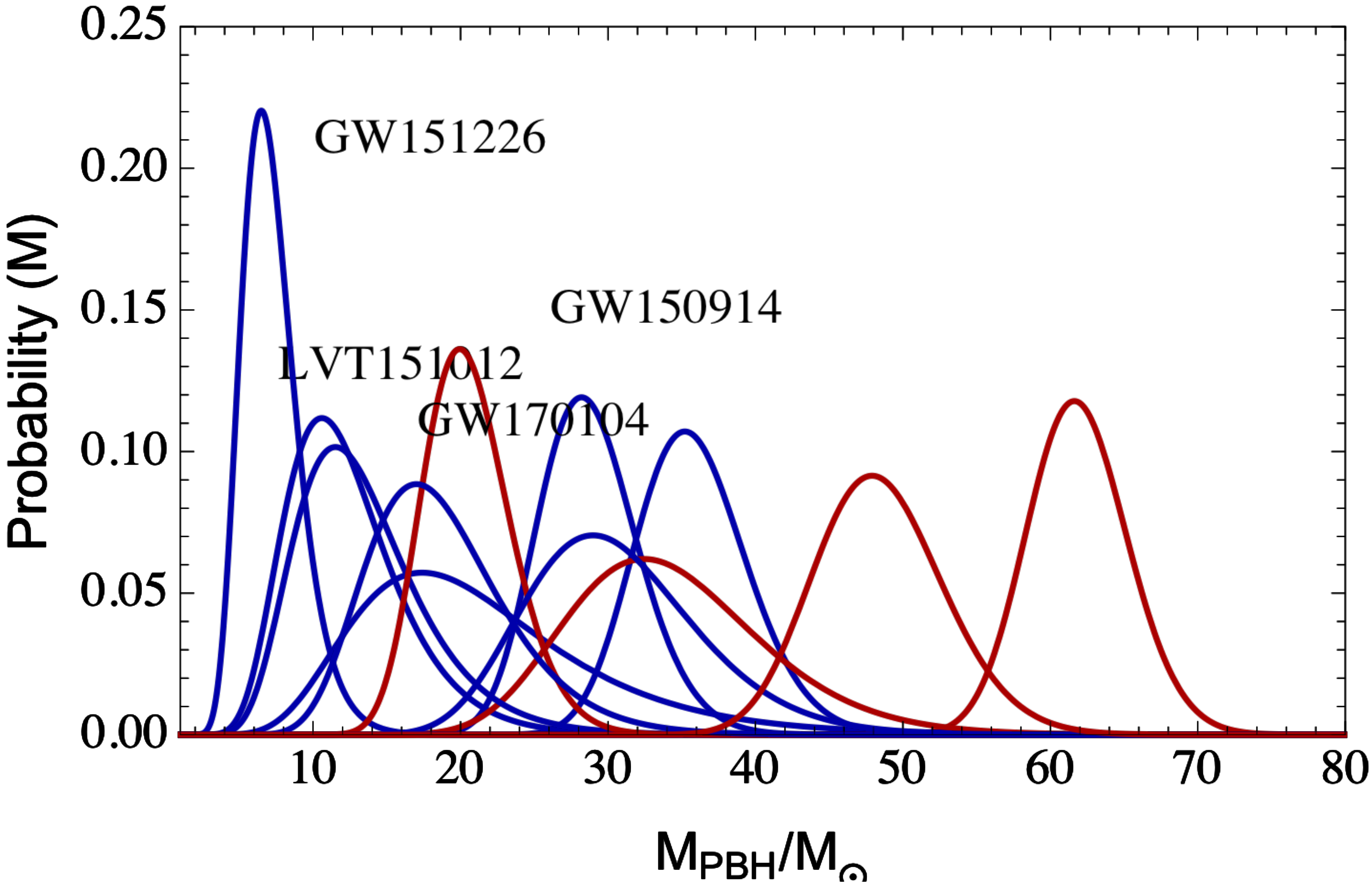
Mass distribution of LIGO BHB



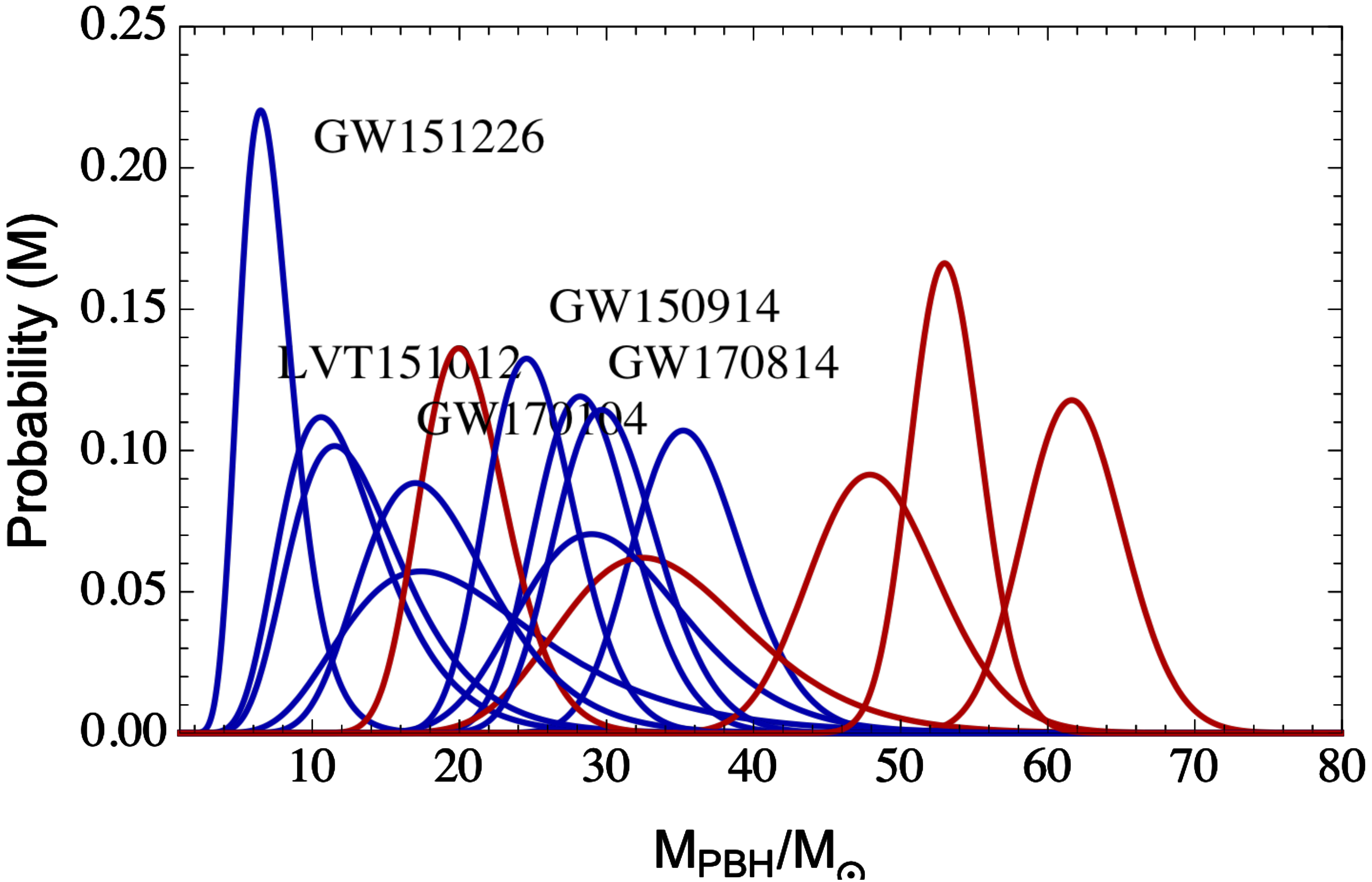
Mass distribution of LIGO BHB



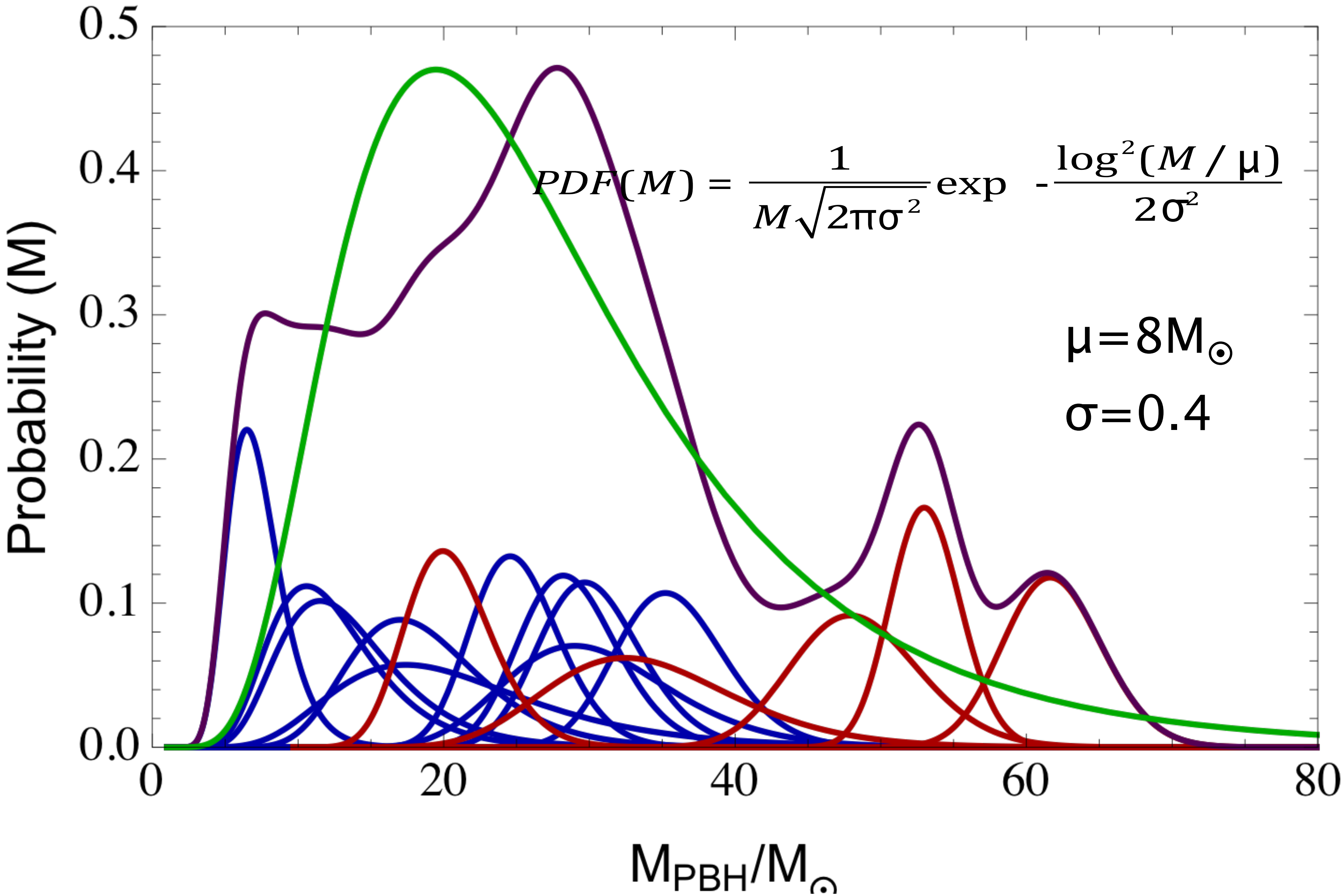
Mass distribution of LIGO BHB



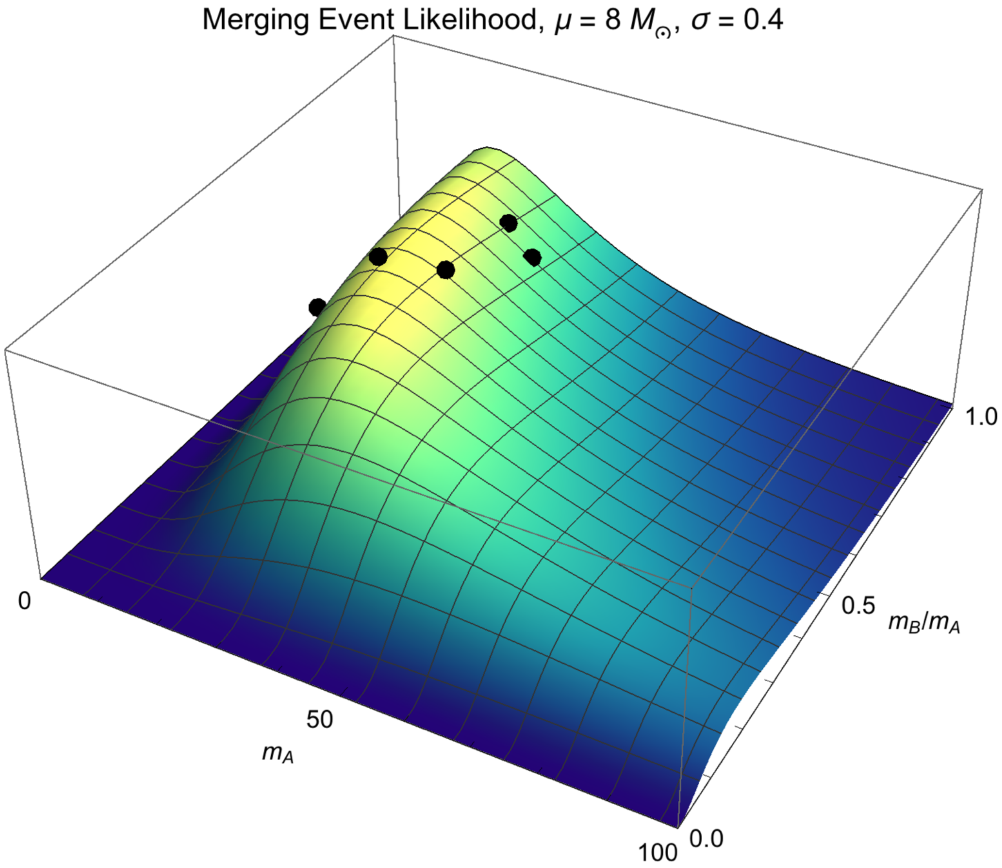
Mass distribution of LIGO BHB



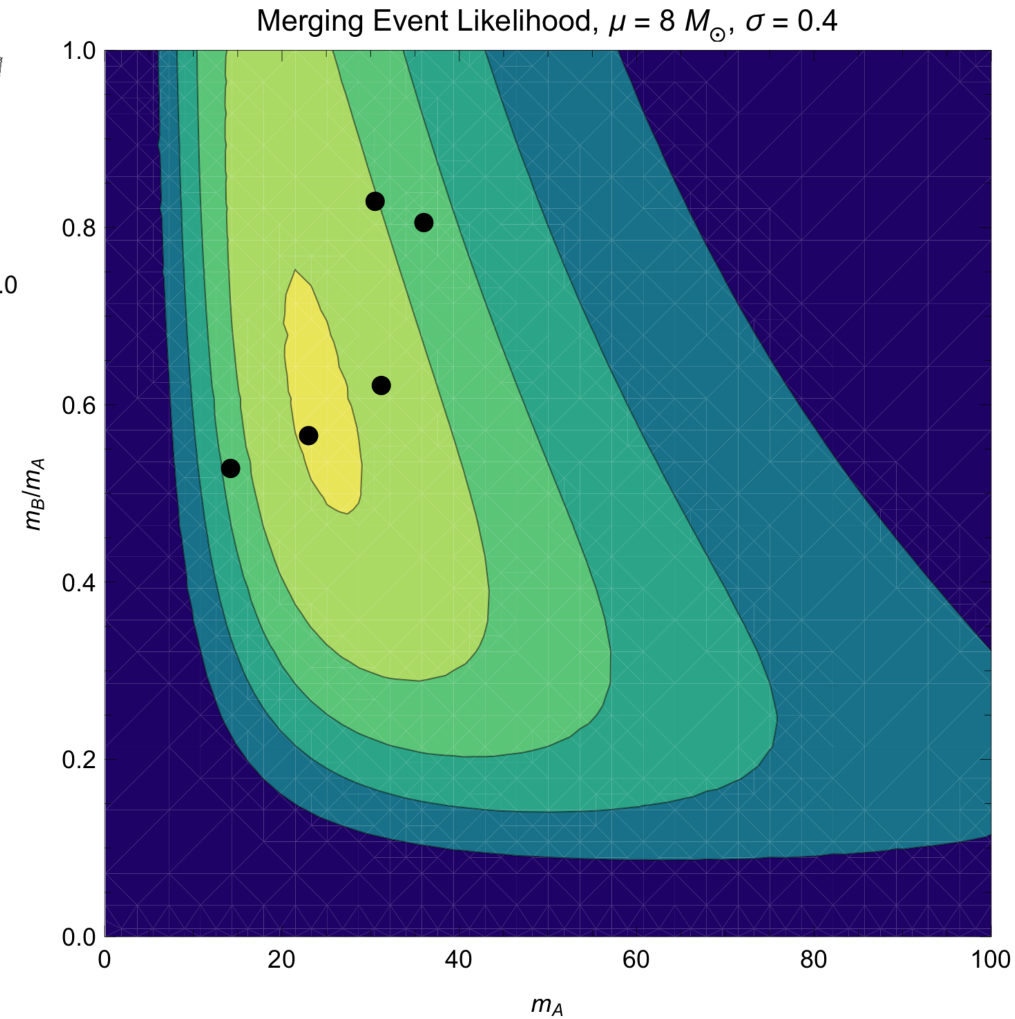
Mass distribution of LIGO BHB



AdvLIGO BHB event rate

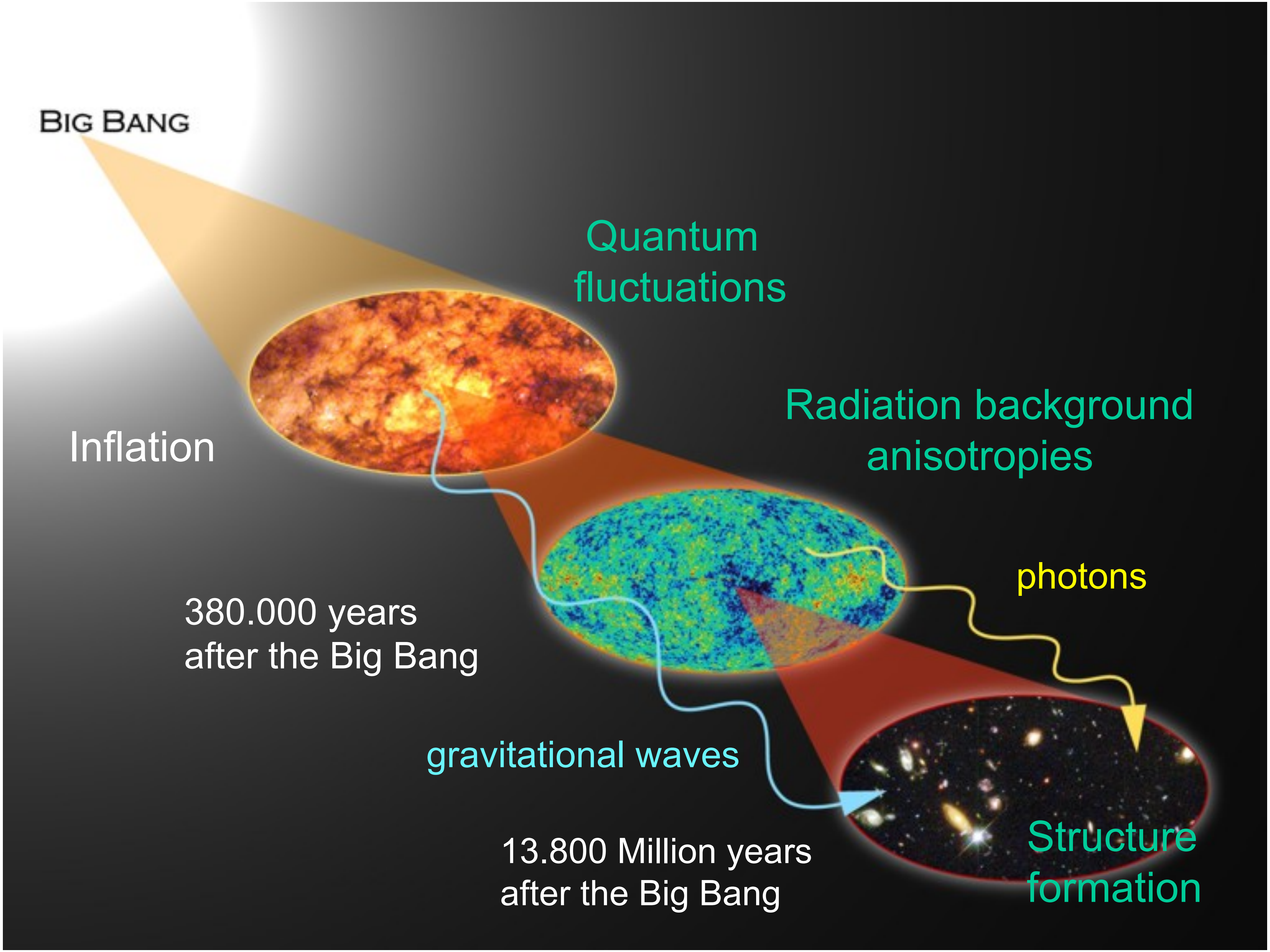


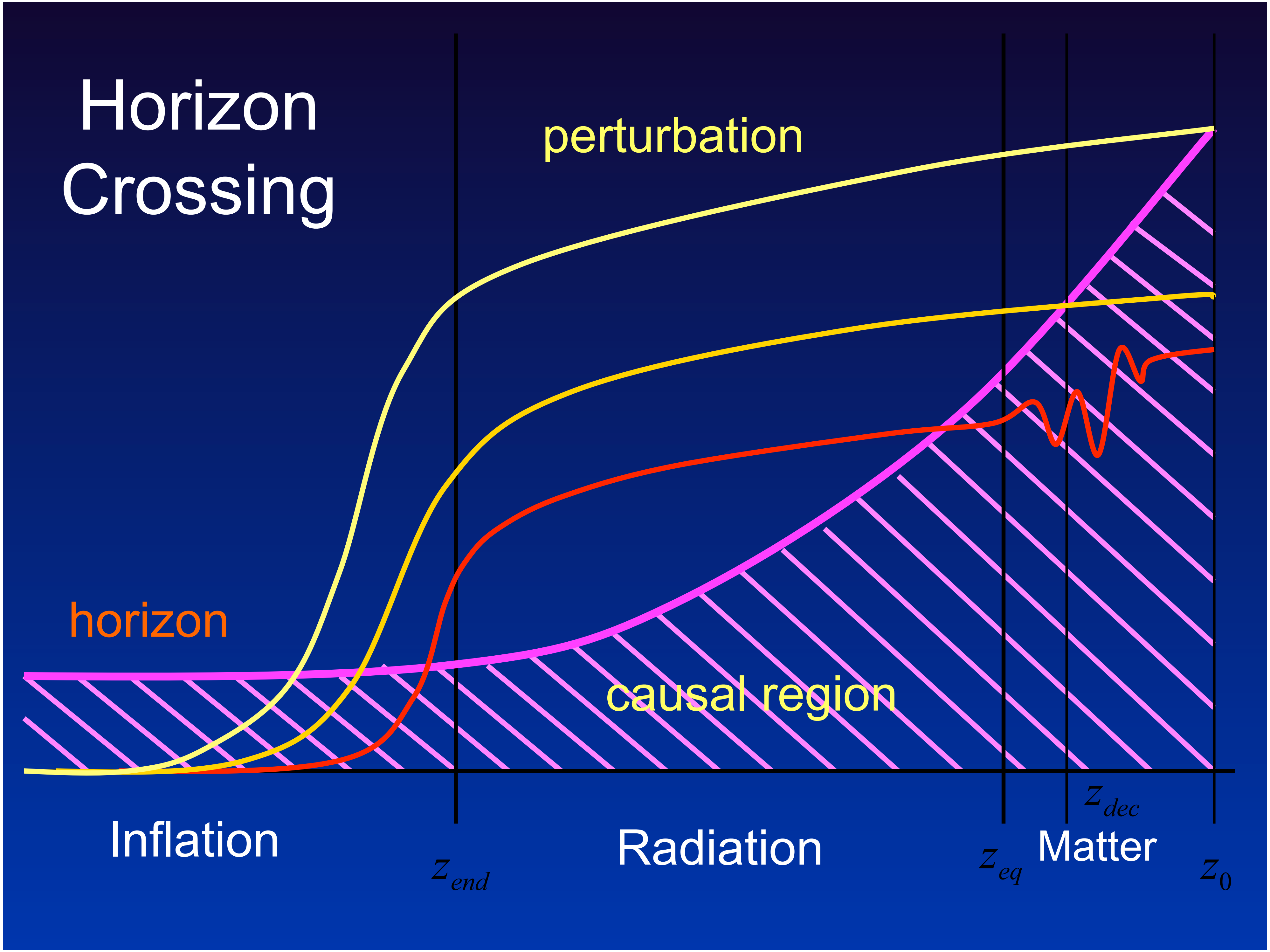
Clesse, JGB (2016)



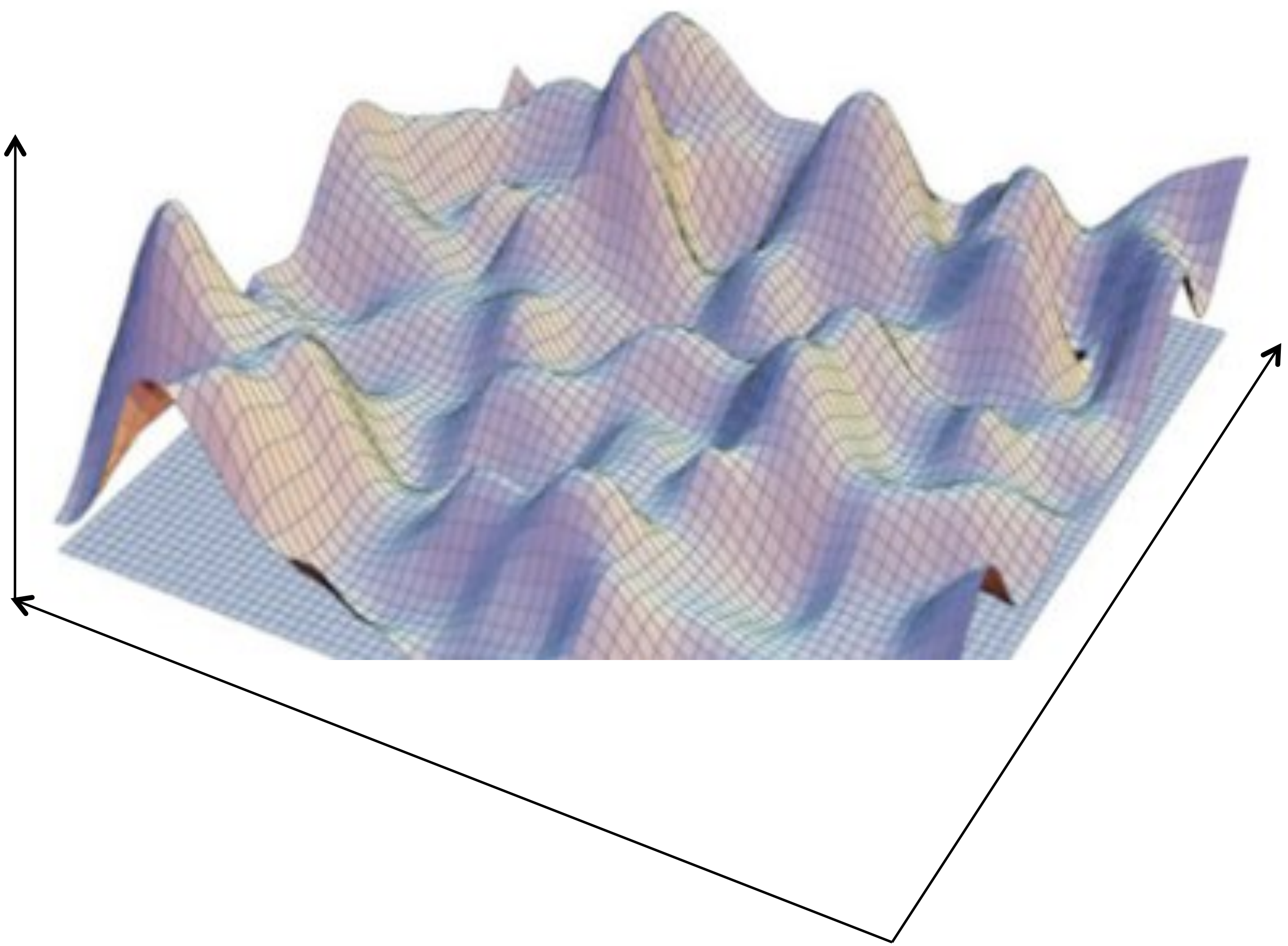
CGB model

Massive PBH from Inflation as DM


BIG BANG
Quantum
fluctuations
Inflation
Radiation background
anisotropies
photons
380.000 years
after the Big Bang
gravitational waves
13.800 Million years
after the Big Bang
Structure
formation


Horizon
Crossing
perturbation
horizon
causal region
Inflation
Radiation
Matter
z_{end}
z_{eq}
z_{dec}
z_0

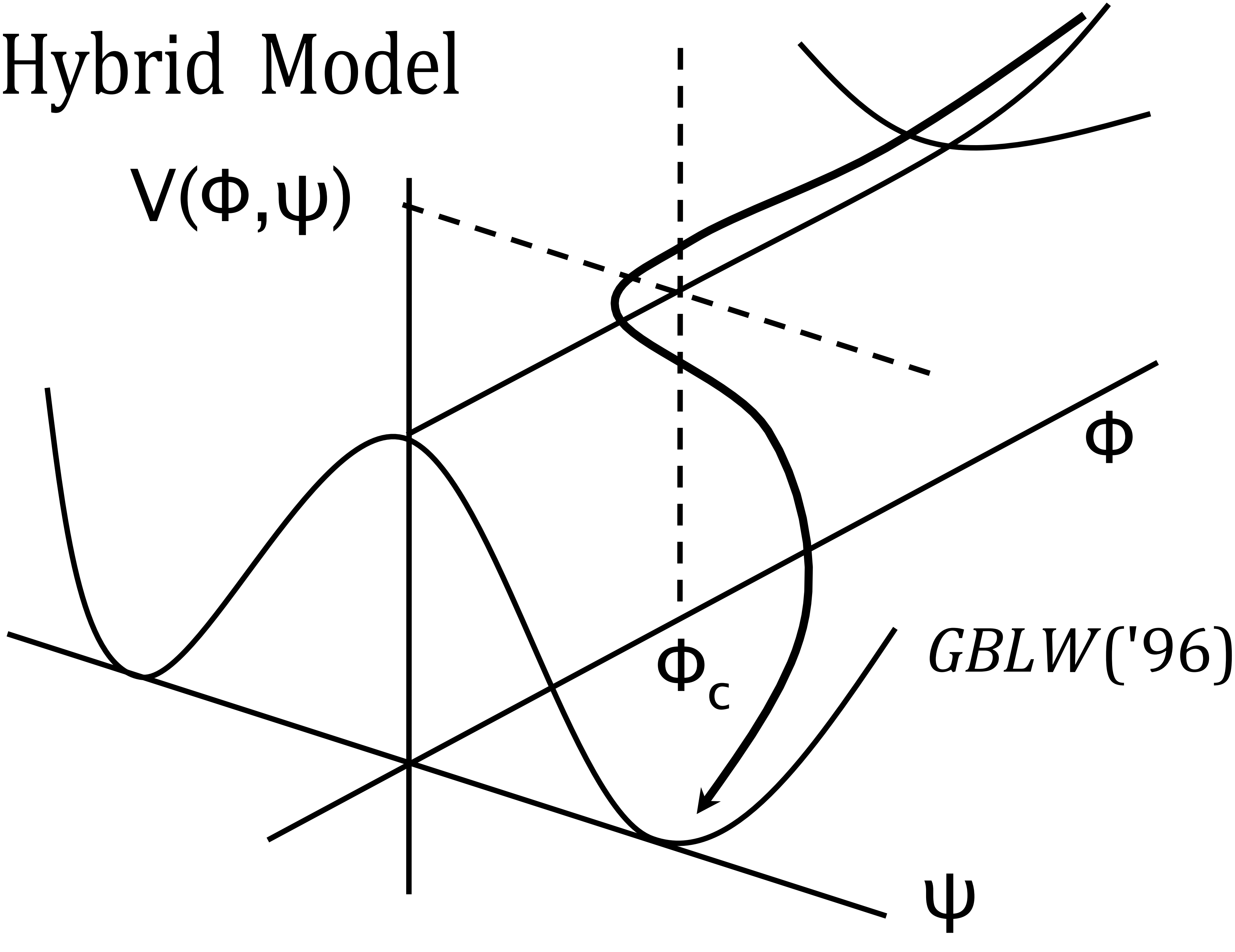
Space-time ripples



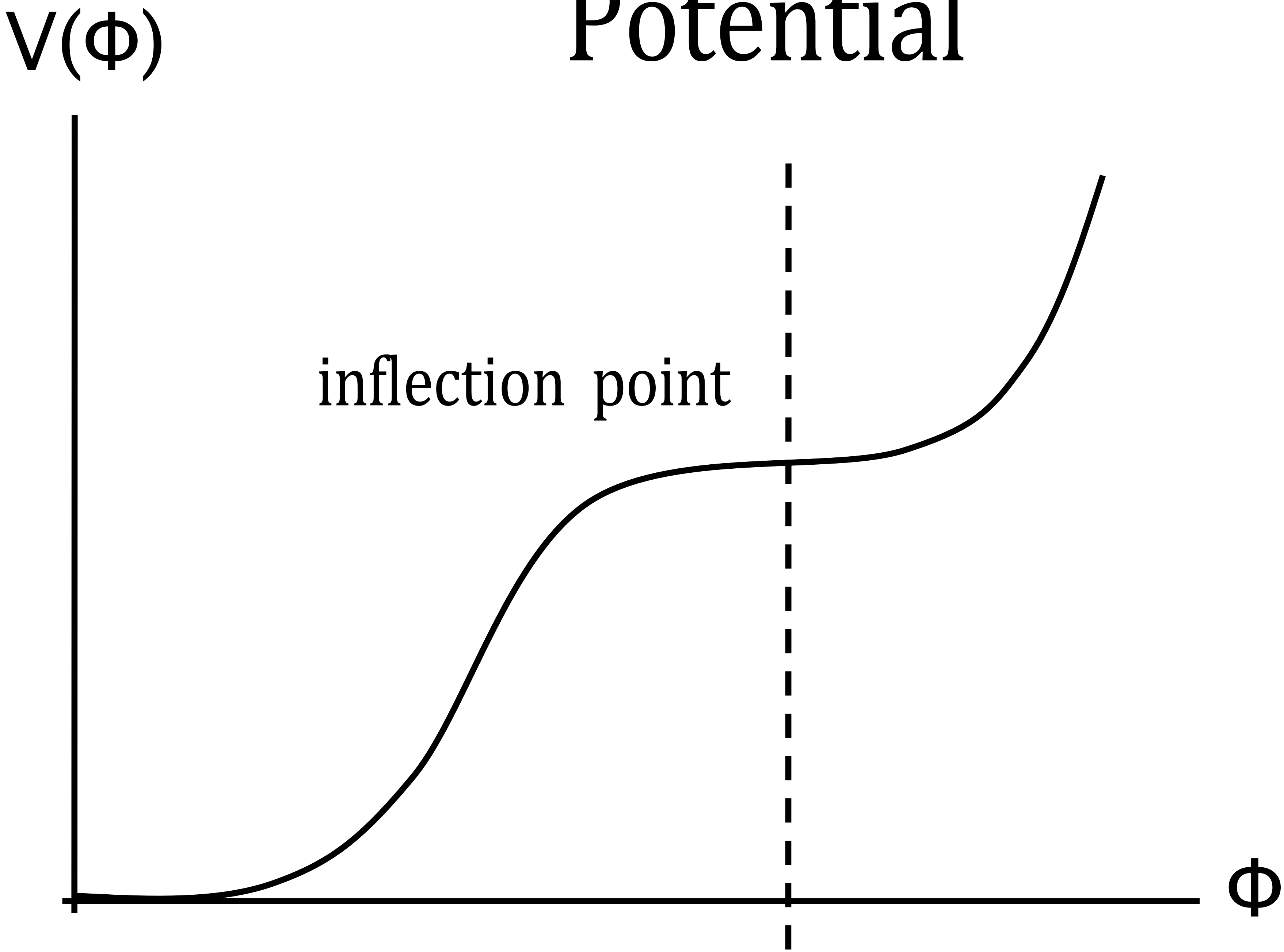
Stretched to cosmological scales

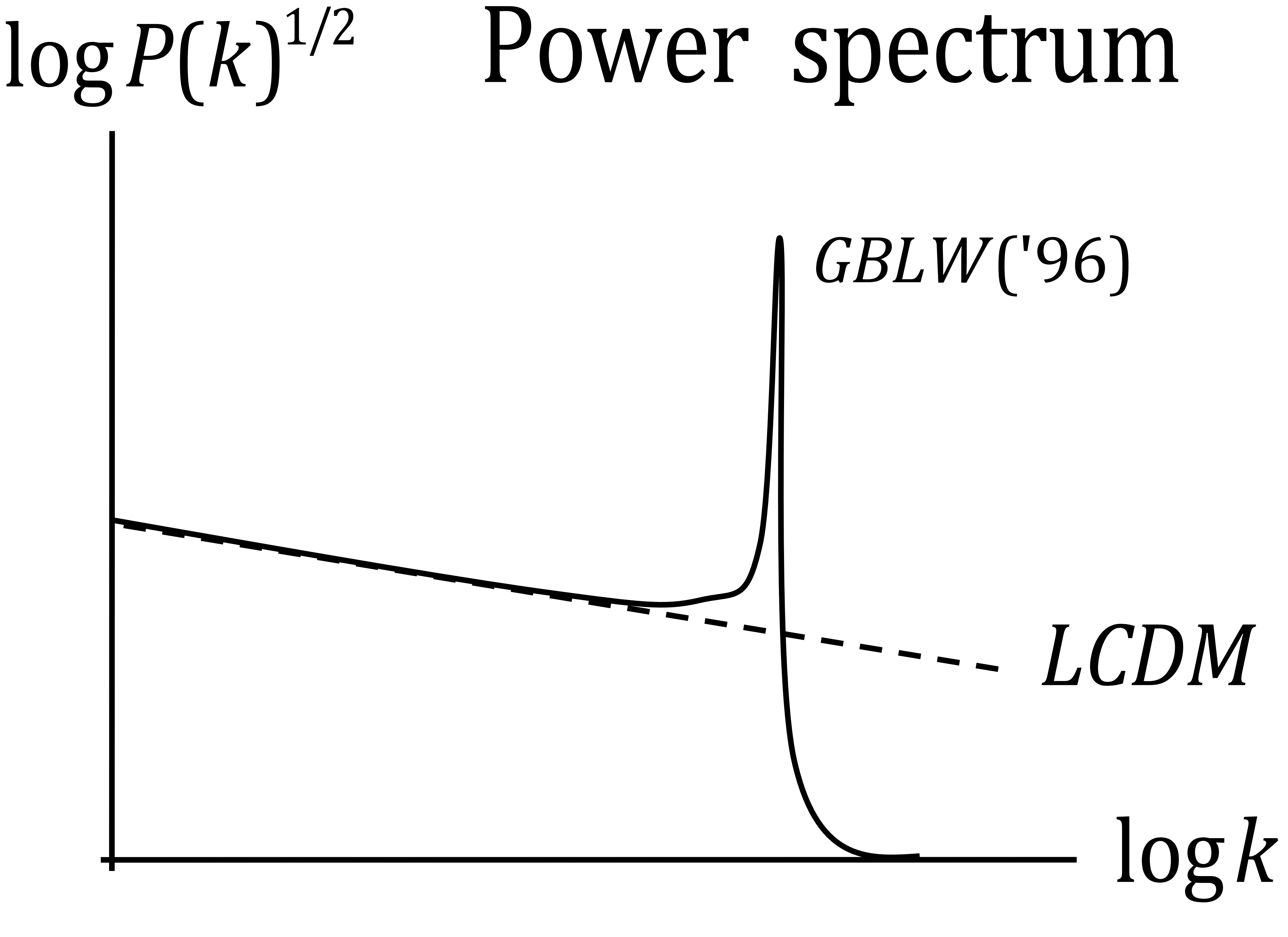
What models of Inflation produce PBH?

Hybrid Model

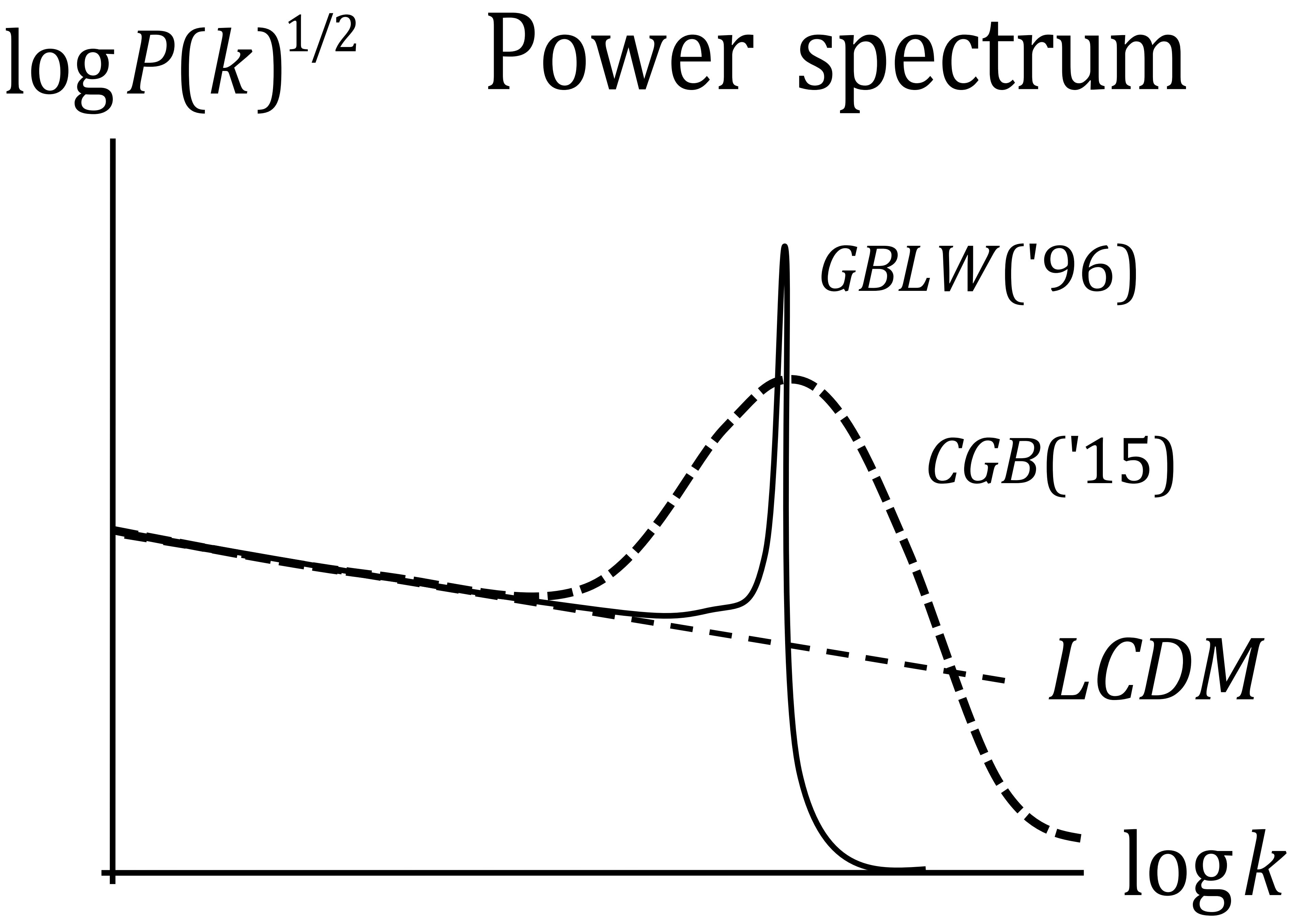


Potential

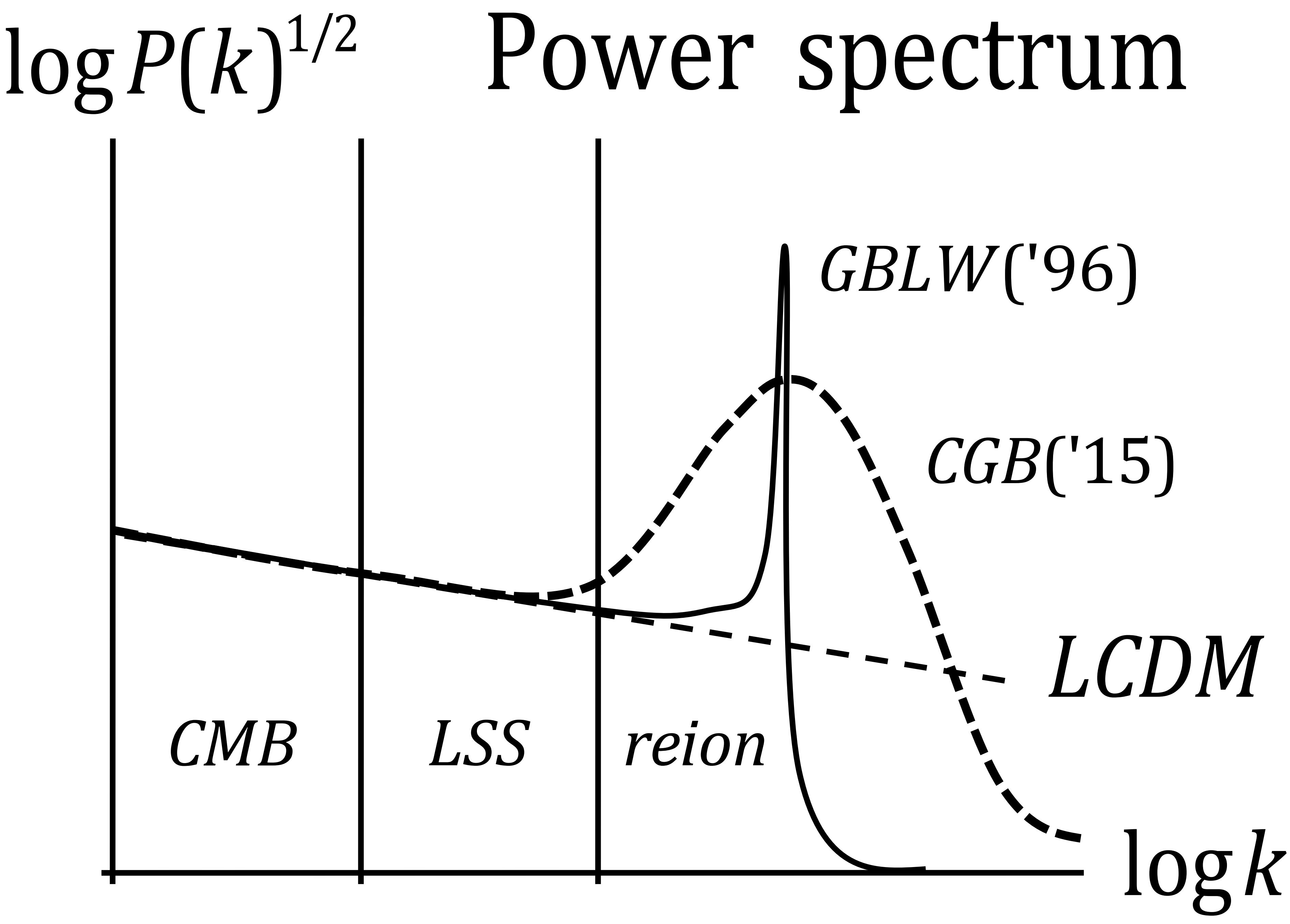




$\log P(k)^{1/2}$
Power spectrum
$GBLW$('96)
$LCDM$
$\log k$

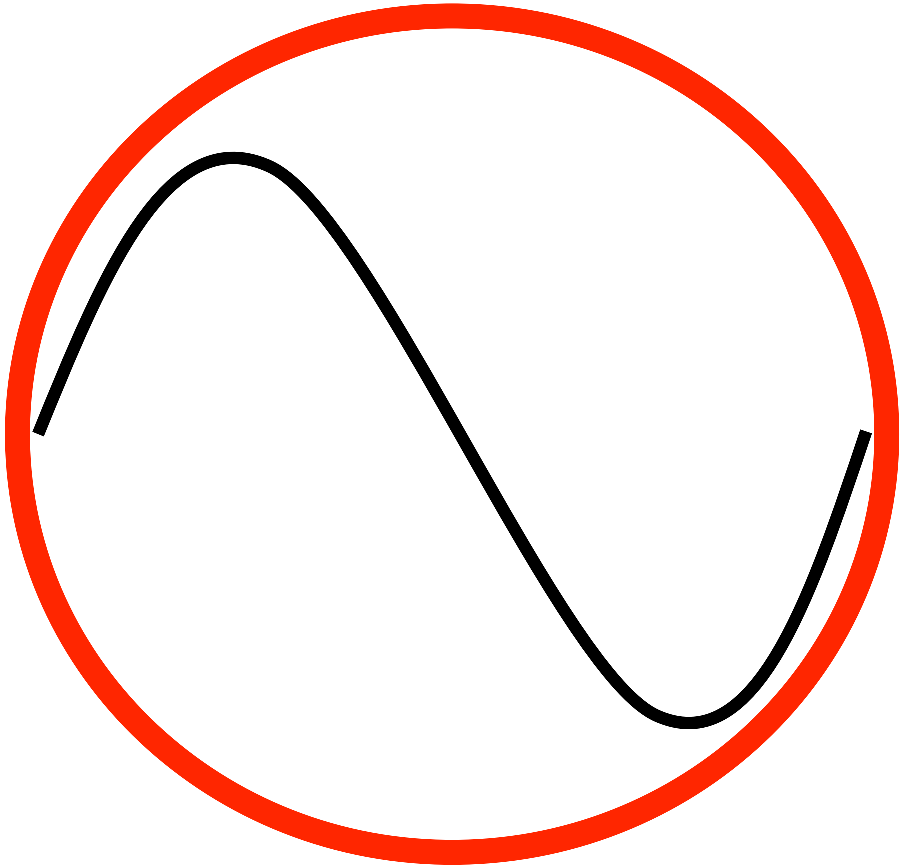


$\log P(k)^{1/2}$
Power spectrum
$GBLW$('96)
CGB('15)
$LCDM$
$\log k$

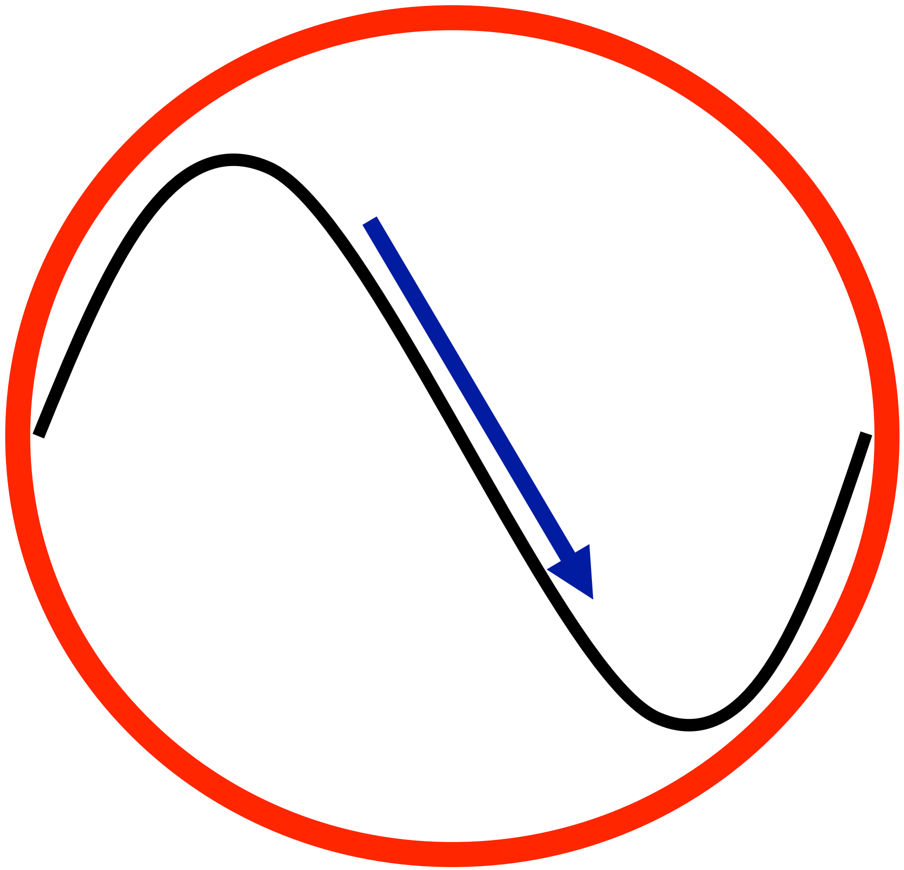


$\log P(k)^{1/2}$
Power spectrum
GBLW('96)
CGB('15)
LCDM
CMB
LSS
reion
$\log k$

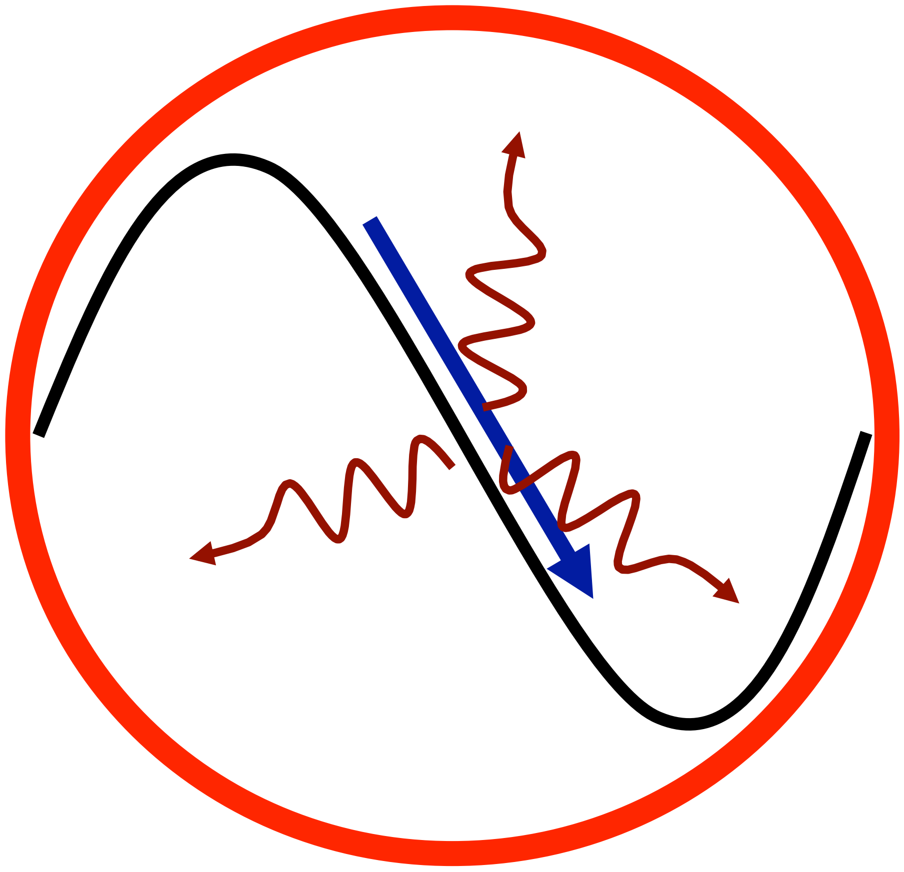
Gravitational Collapse of PBH



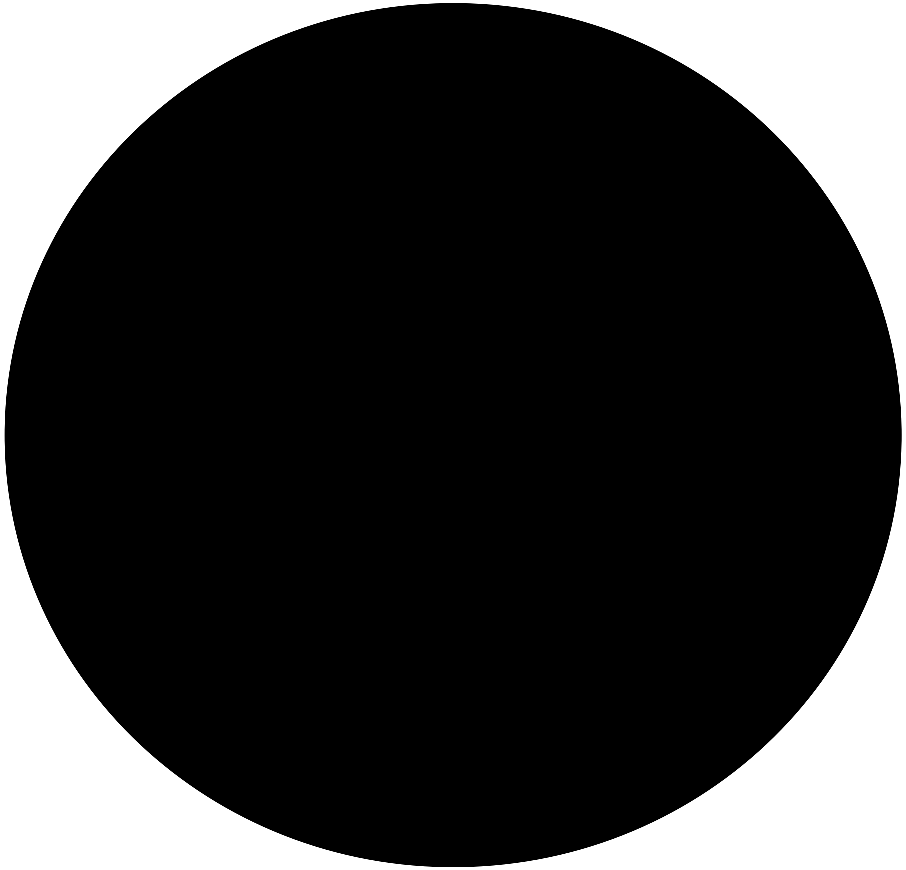
Gravitational Collapse of PBH



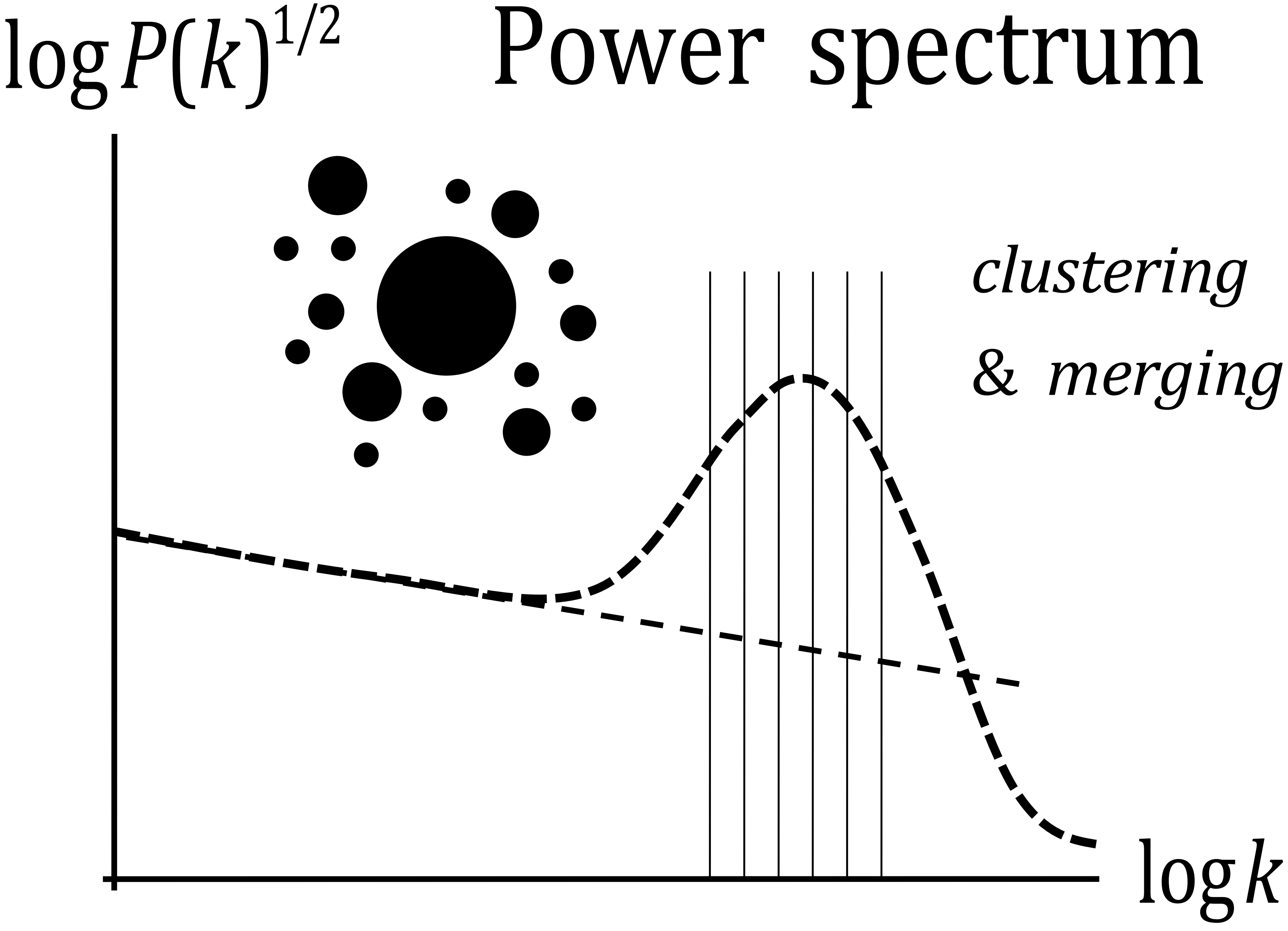
Gravitational Collapse of PBH



Gravitational Collapse of PBH



$$M_{PBH} \simeq M_{Hor}$$



log P(k)^1/2
Power spectrum
clustering
& merging
log k

Critical Higgs Inflation

Concrete realization: PBH in Critical Higgs Inflation

Ezquiaga, JGB, Ruiz Morales (2017)

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

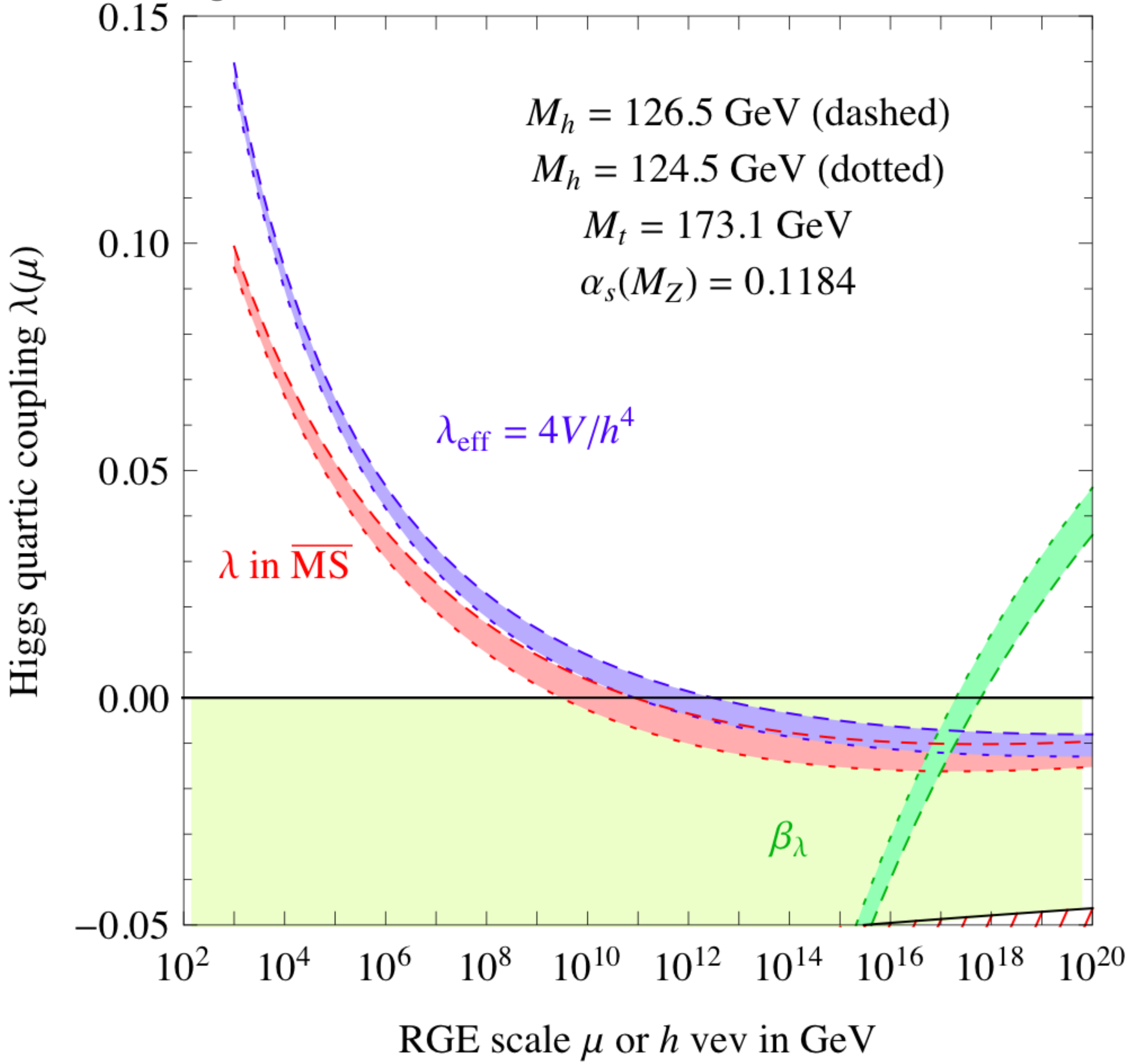
$$\lambda(\phi) \;=\; \lambda_0 + b_\lambda \ln^2(\phi/\mu) \; ,$$

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

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

RGE running of Higgs quartic coupling

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (2014)



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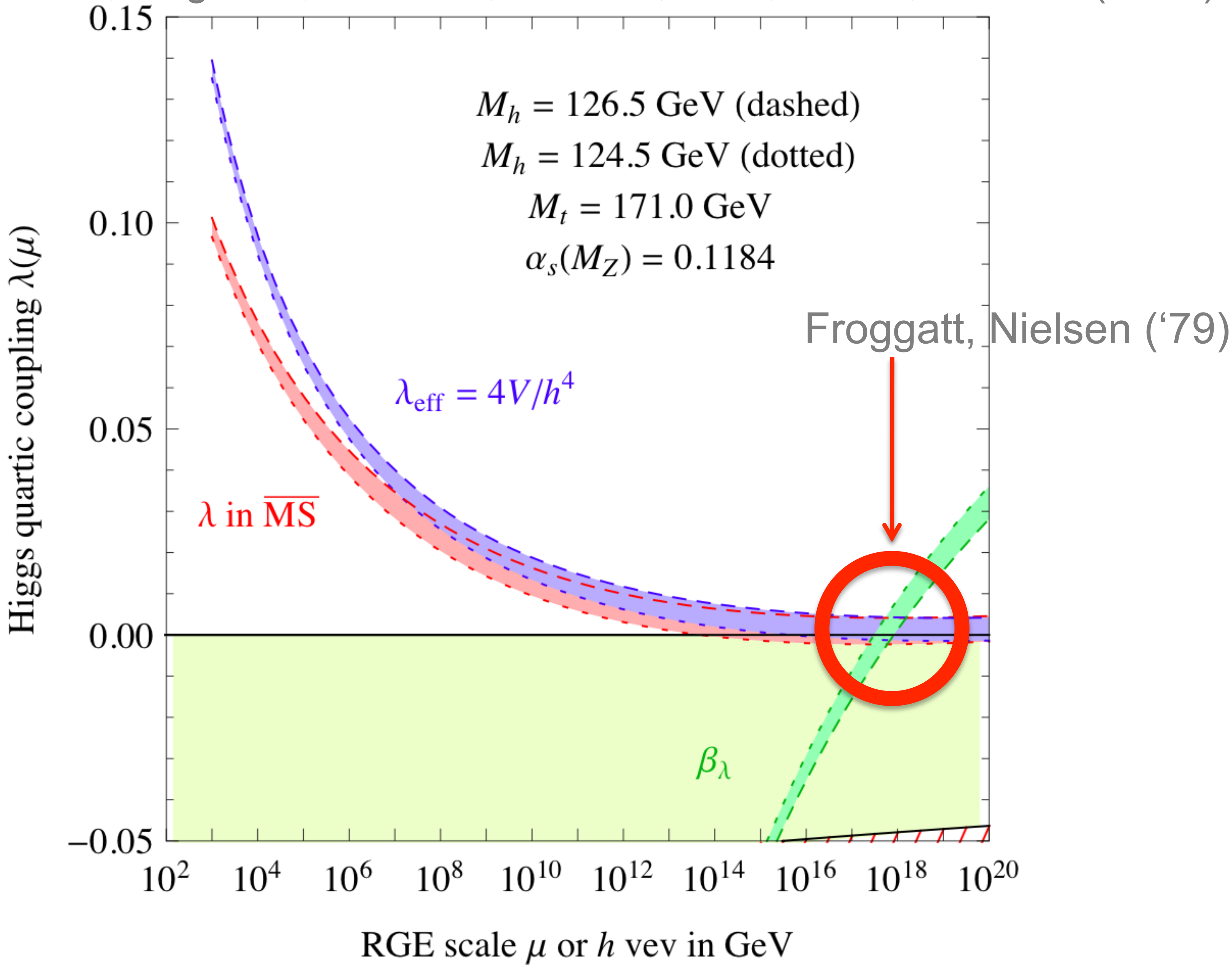


Concrete realization: CHI model

Ezquiaga, JGB, Ruiz Morales (2017)

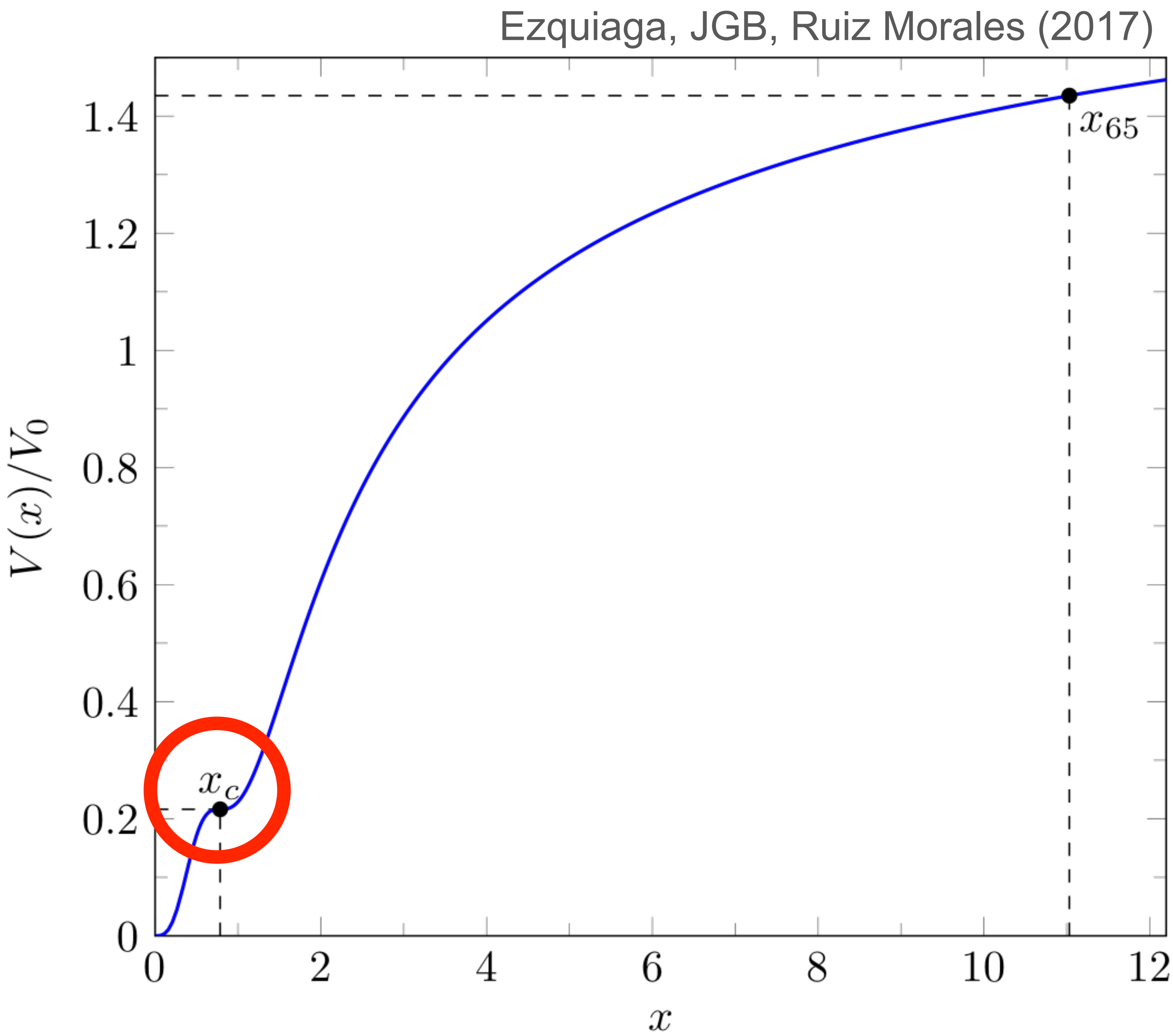
$$S = \int d^4x\sqrt{g}\left[\left(\frac{1}{2\kappa^2} + \frac{\xi(\phi)}{2}\phi^2\right)R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{4}\lambda(\phi)\phi^4\right]$$

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

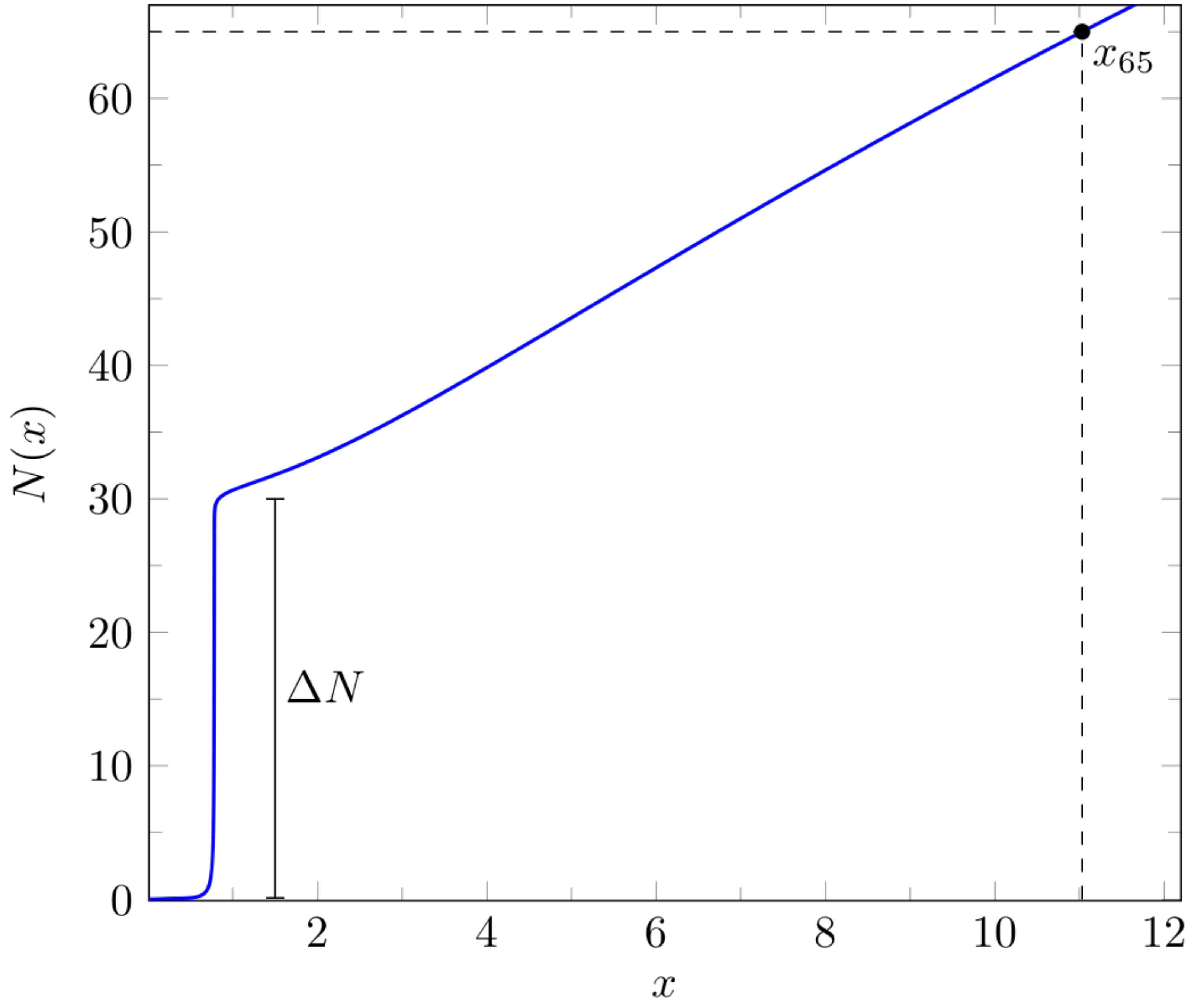
$$\xi(\phi) = \xi_0 + b_\xi \ln(\phi/\mu) ,$$

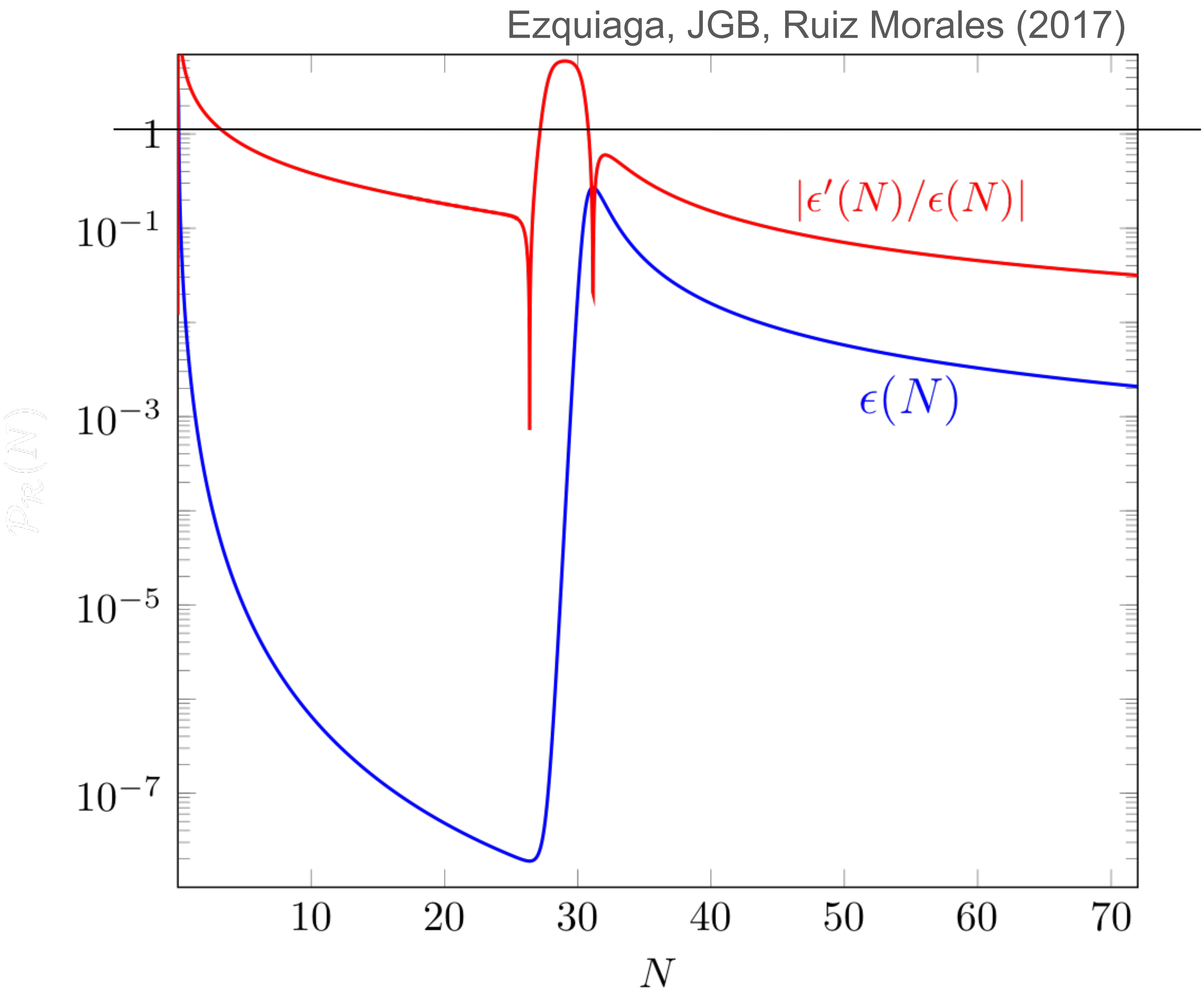
$$V(x) = \frac{V_0\,(1 + a\,\ln^2 x)\,x^4}{(1 + c\,(1 + b\,\ln x)\,x^2)^2} \qquad x = \phi/\mu$$

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

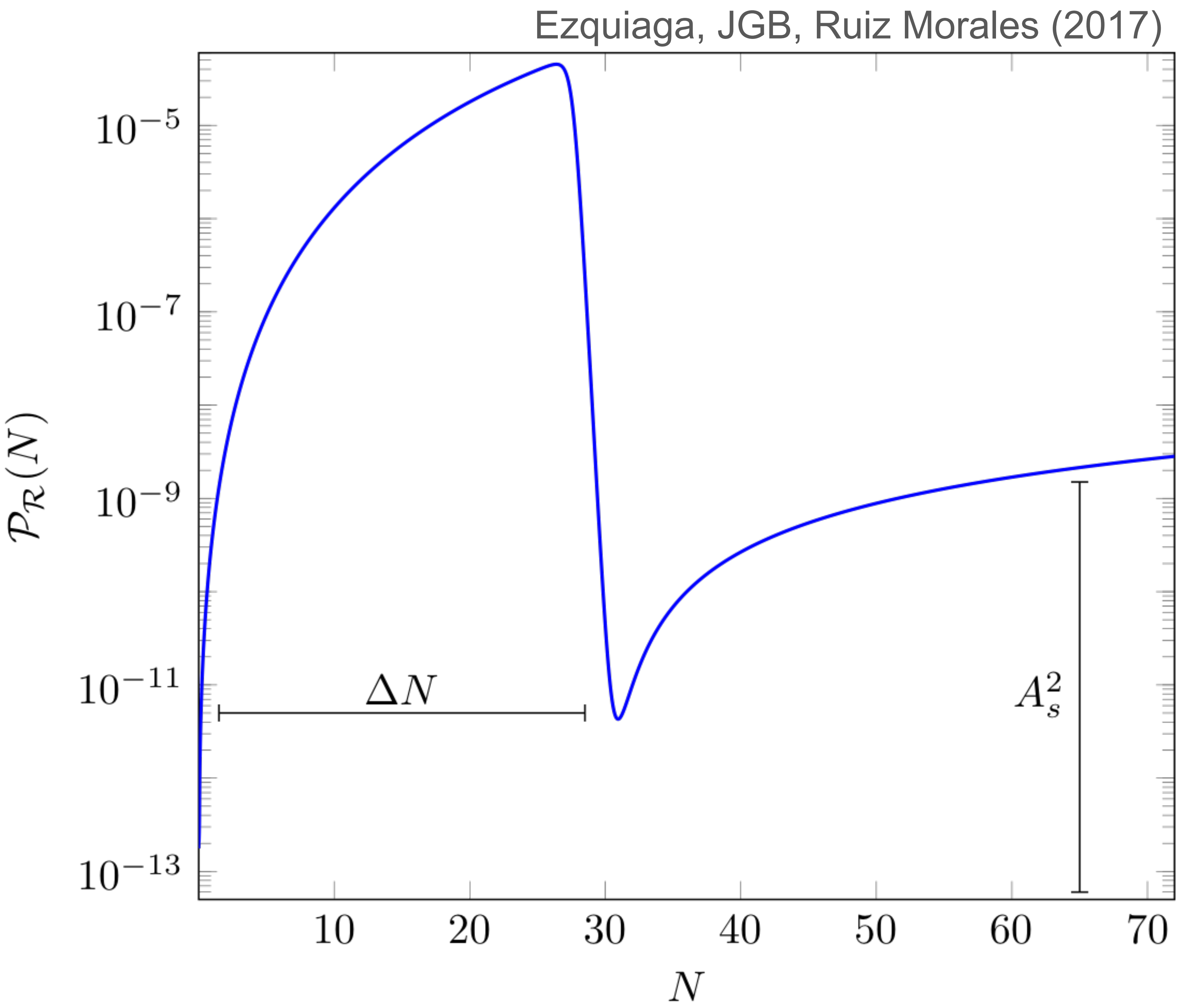

Ezquiaga, JGB, Ruiz Morales (2017)
x_{65}
x_c
$V(x)/V_0$
x
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
2
4
6
8
10
12

Ezquiaga, JGB, Ruiz Morales (2017)





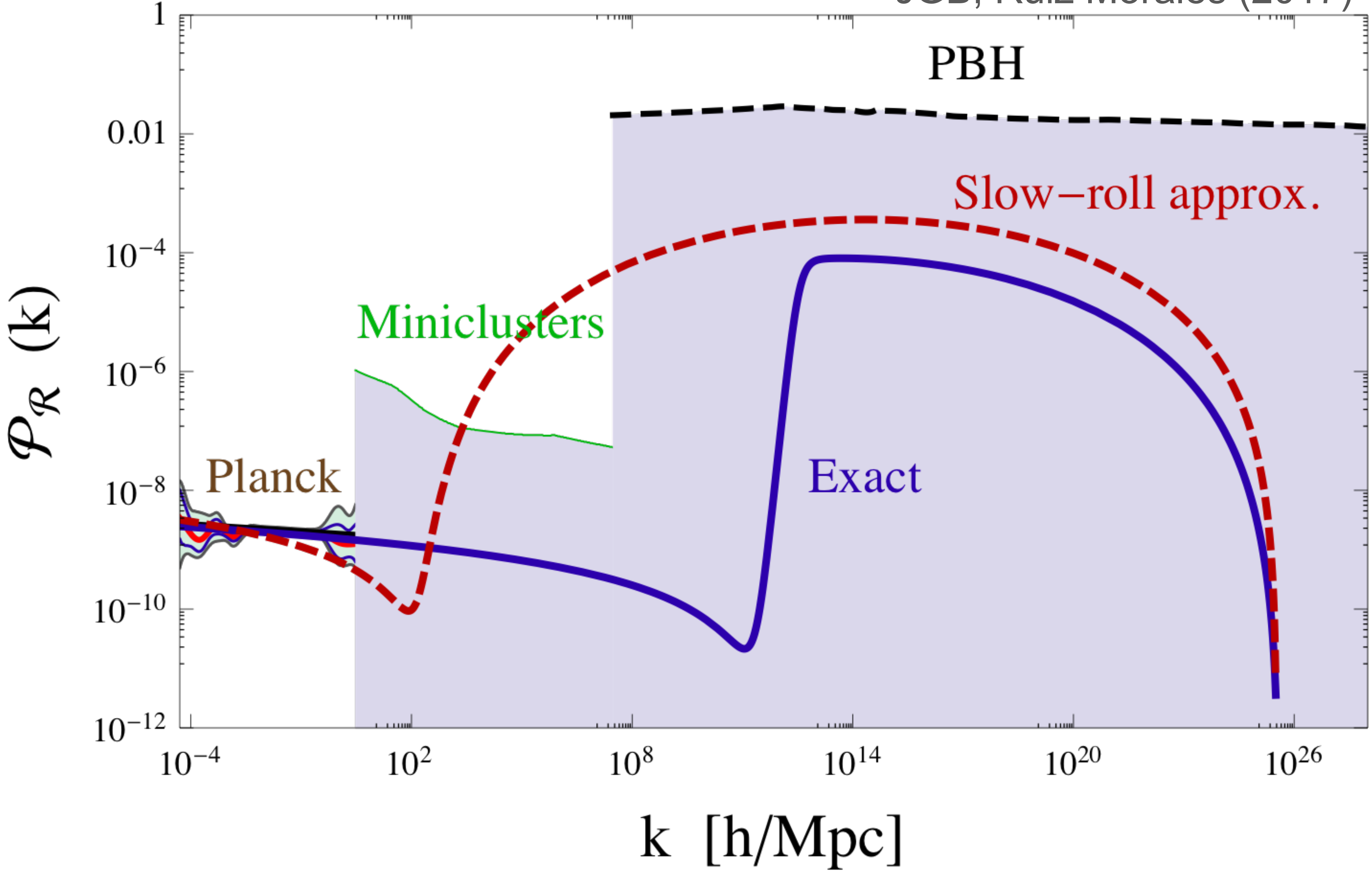
Ezquiaga, JGB, Ruiz Morales (2017)
1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
$\mathcal{P}_{\mathcal{R}}(N)$
$|\epsilon'(N)/\epsilon(N)|$
$\epsilon(N)$
10
20
30
40
50
60
70
N



Ezquiaga, JGB, Ruiz Morales (2017)
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
$\mathcal{P}_{\mathcal{R}}(N)$
ΔN
A_s^2
10
20
30
40
50
60
70
N

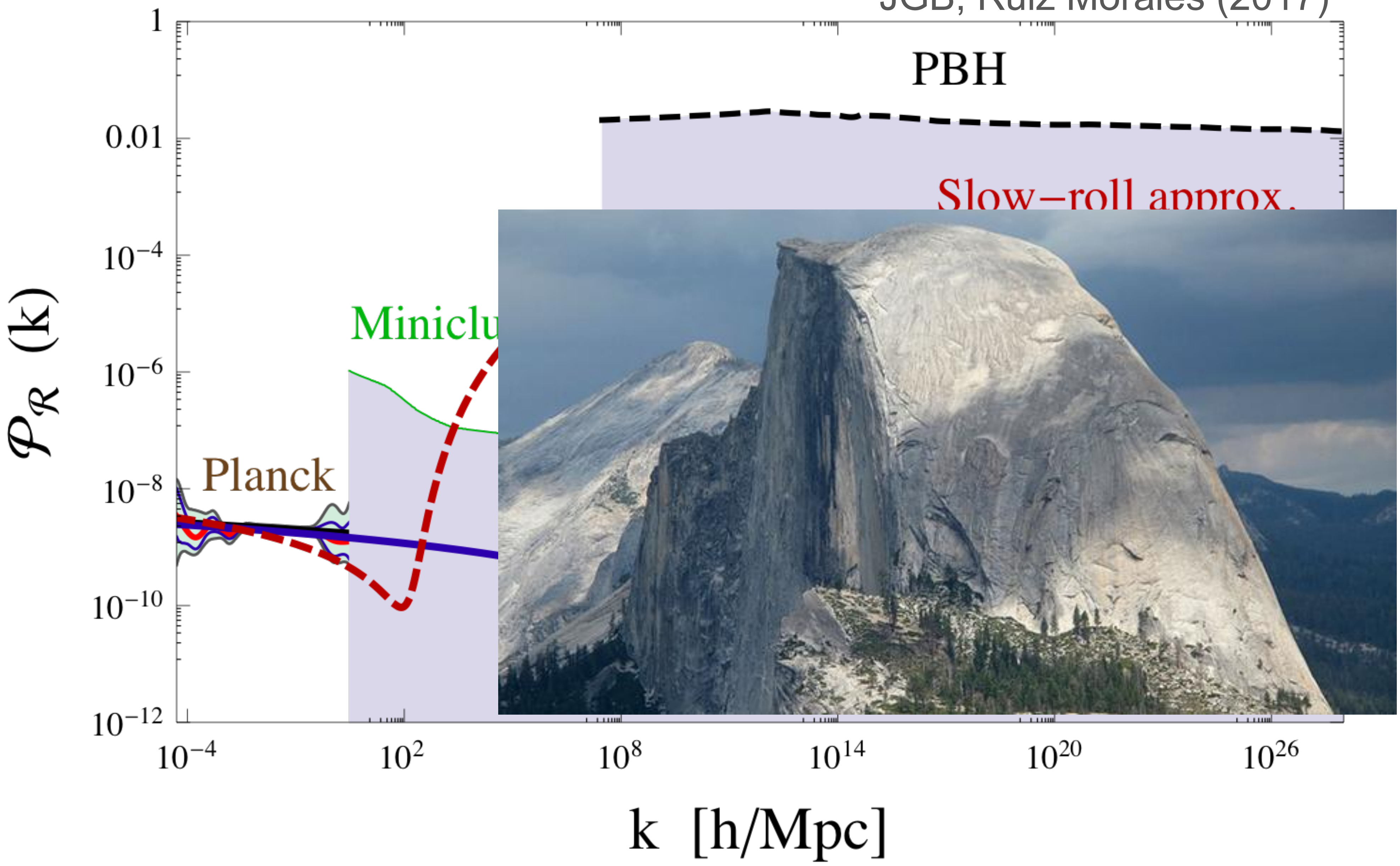
Primordial Spectrum for PBH

JGB, Ruiz Morales (2017)



Primordial Spectrum for PBH

JGB, Ruiz Morales (2017)



CMB & LSS Constraints

CMB Constraints on CHI

Ezquiaga, JGB, Ruiz Morales (2017)

$$
\begin{aligned}
A_s^2 &= 2.14 \times 10^{-9} \\
n_s &= 0.952 \\
r &= 0.043 \\
d\,n_s/d\ln k &= -0.0017
\end{aligned}
$$

$$
\begin{aligned}
\lambda_0 &= 2.3 \times 10^{-7} \\
b_\lambda &= 1.2 \times 10^{-6}
\end{aligned}
\qquad
\begin{aligned}
\xi_0 &= 7.55 \\
b_\xi &= 11.5
\end{aligned}
$$

$$\kappa^2\mu^2 = 0.102$$

CMB Constraints on CHI

Ezquiaga, JGB, Ruiz Morales (2017)

$$V(x \gg x_c) \simeq V_0 \frac{a}{(b\, c)^2} = \frac{1}{4\kappa^4} \frac{b_\lambda}{b_\xi^2} \ll M_{\rm P}^4$$

$$\text{(RGE)} \quad b_\lambda = 1.2 \times 10^{-6} \qquad b_\xi = 11.5$$

Reheating after CHI

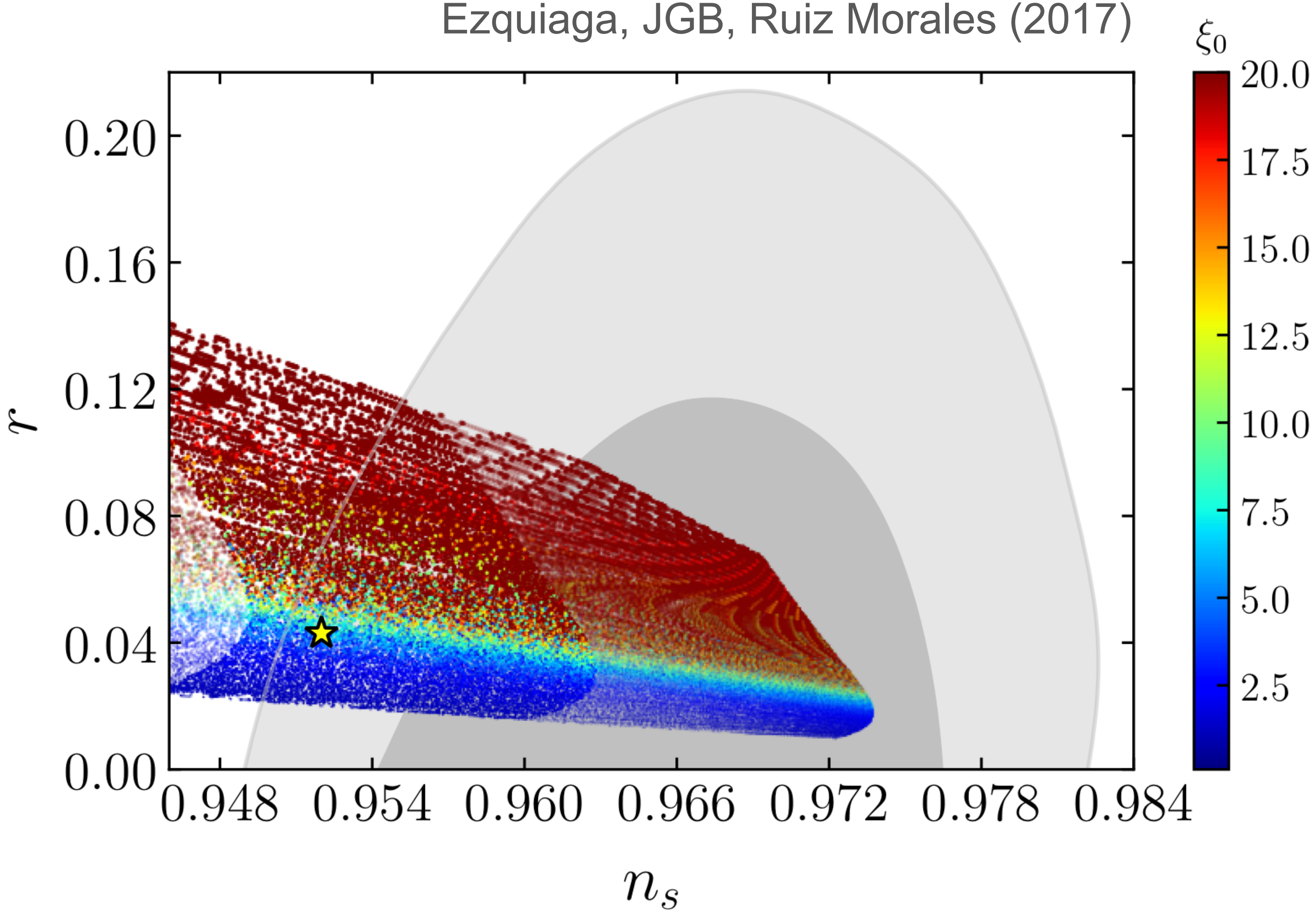
$$\rho_{\rm end} = 2.8 \times 10^{63} \ \text{GeV}$$

$$T_{\rm rh} = 3 \times 10^{15} \ \text{GeV}$$

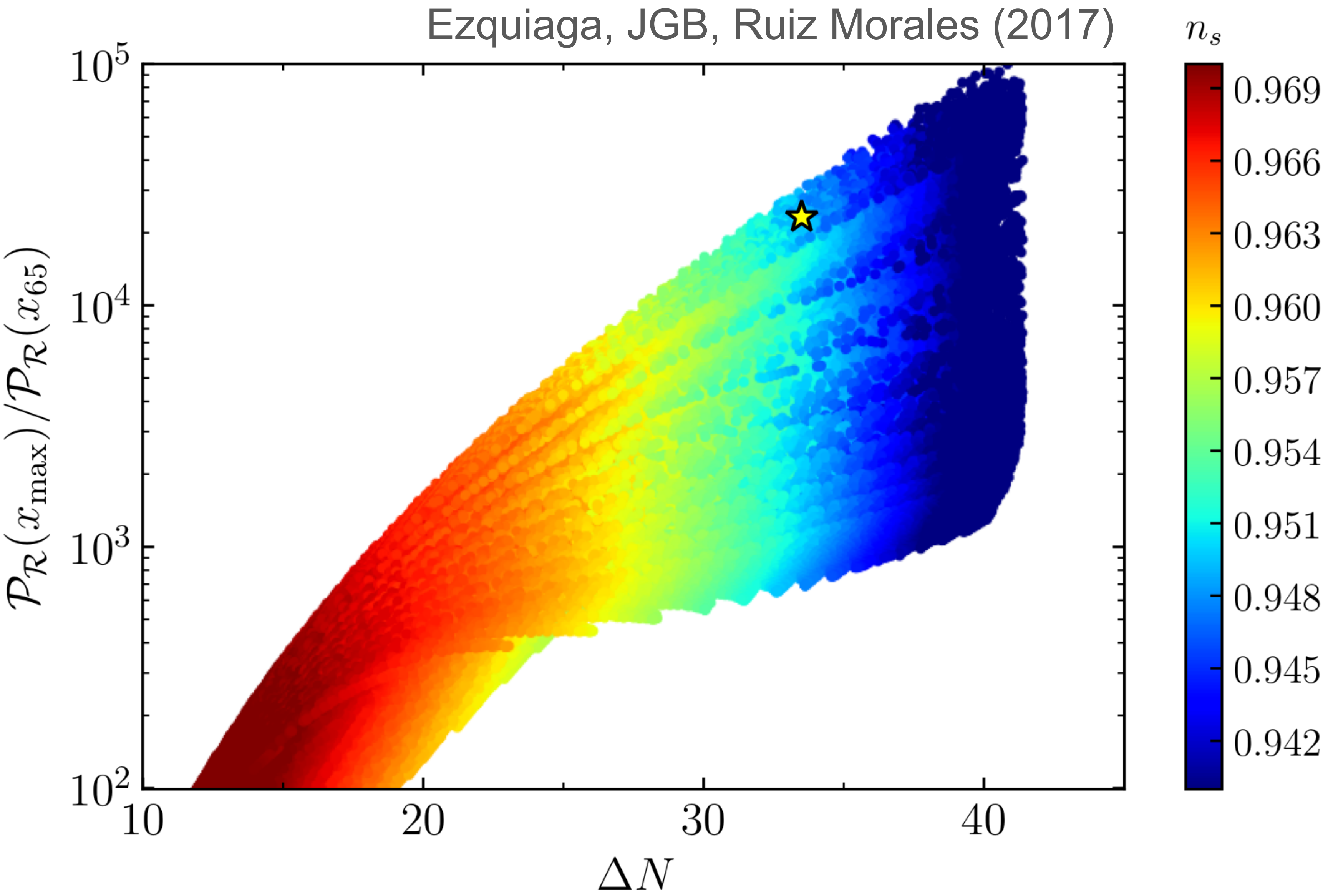
$$(\text{for } g_* = 106.75)$$

CMB Constraints on CHI

Ezquiaga, JGB, Ruiz Morales (2017)



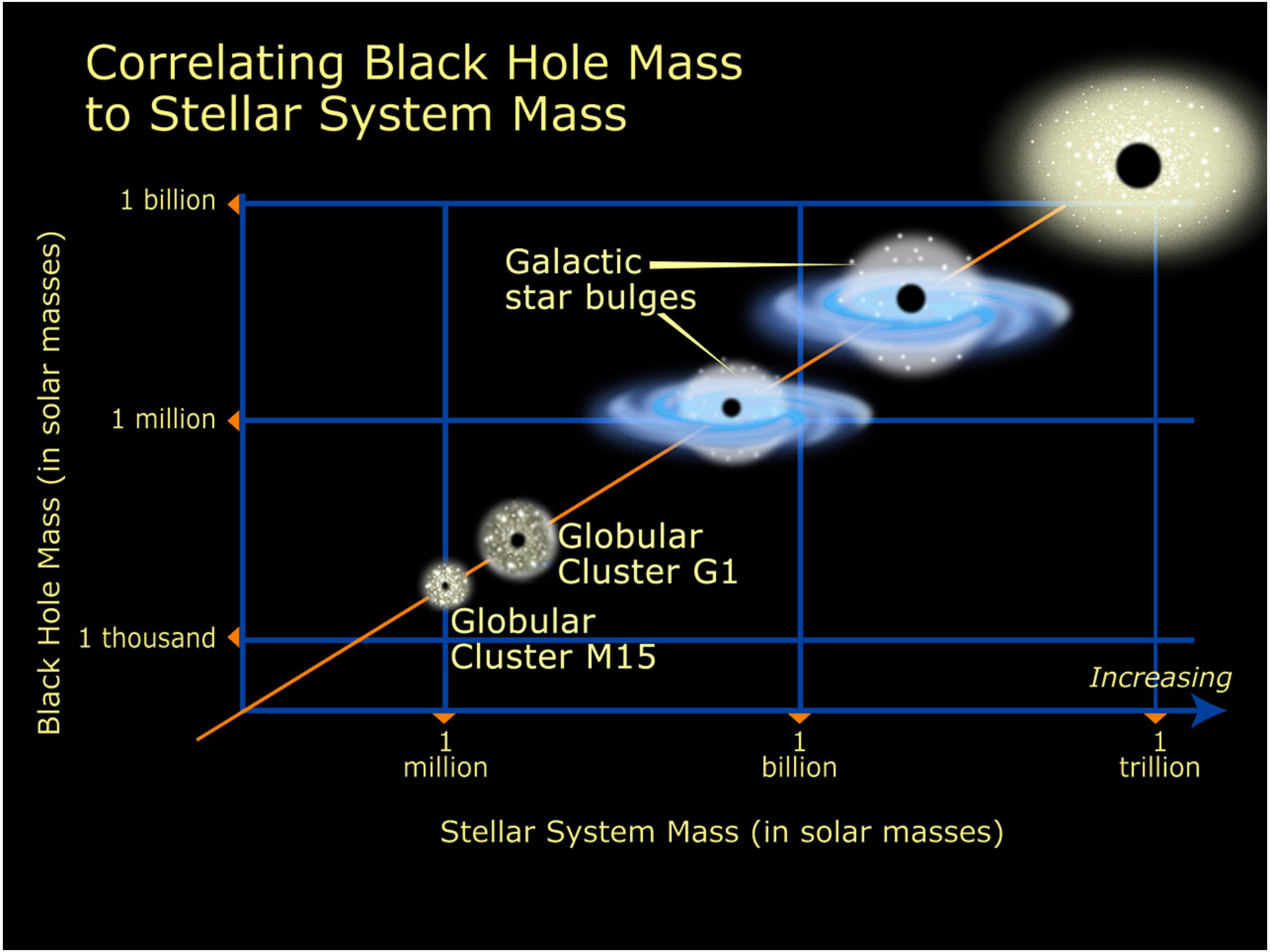
CMB Constraints on CHI



Constraints on Primordial Black Holes

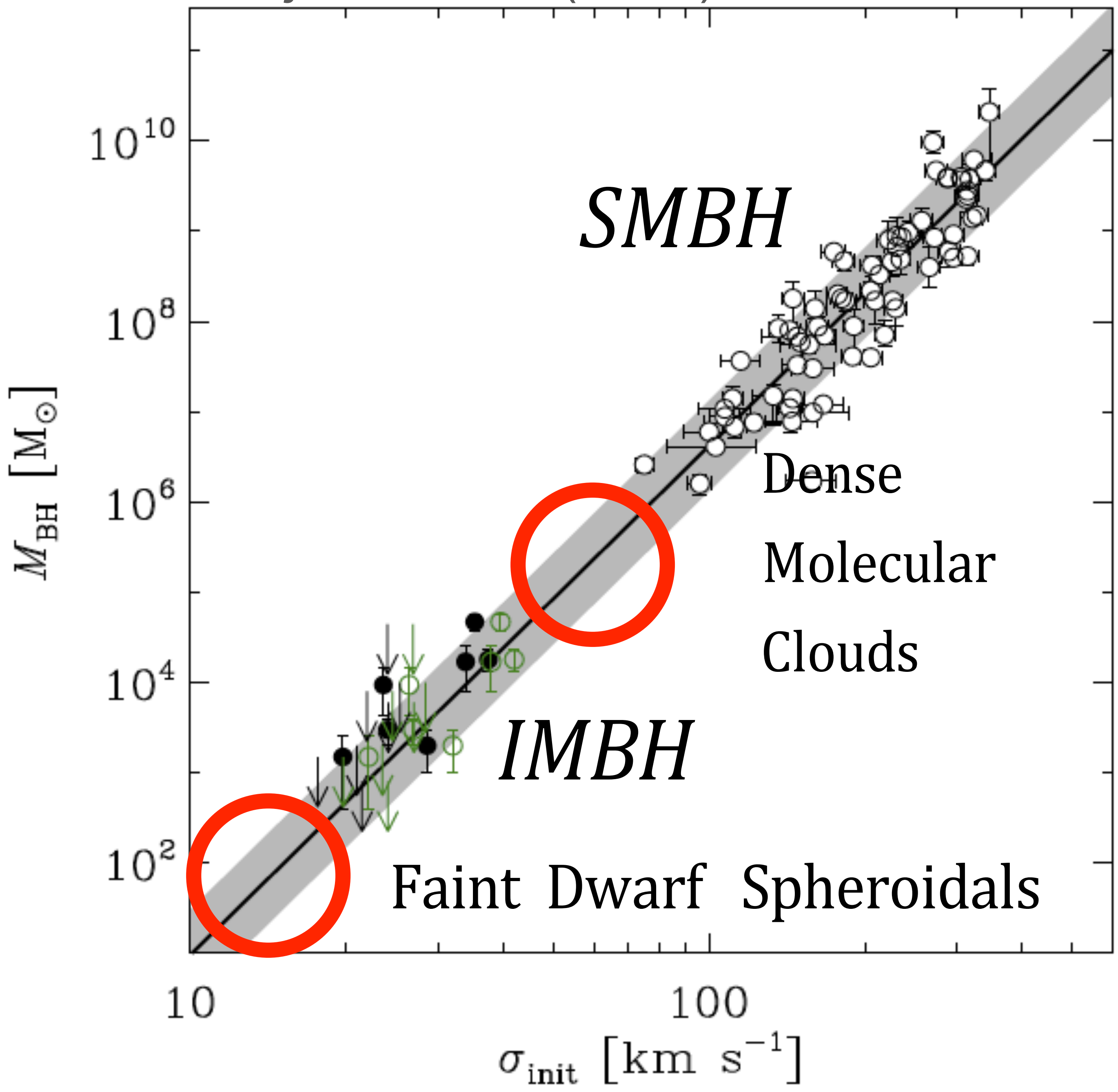
Massive Primordial Black Holes

- These are massive 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.

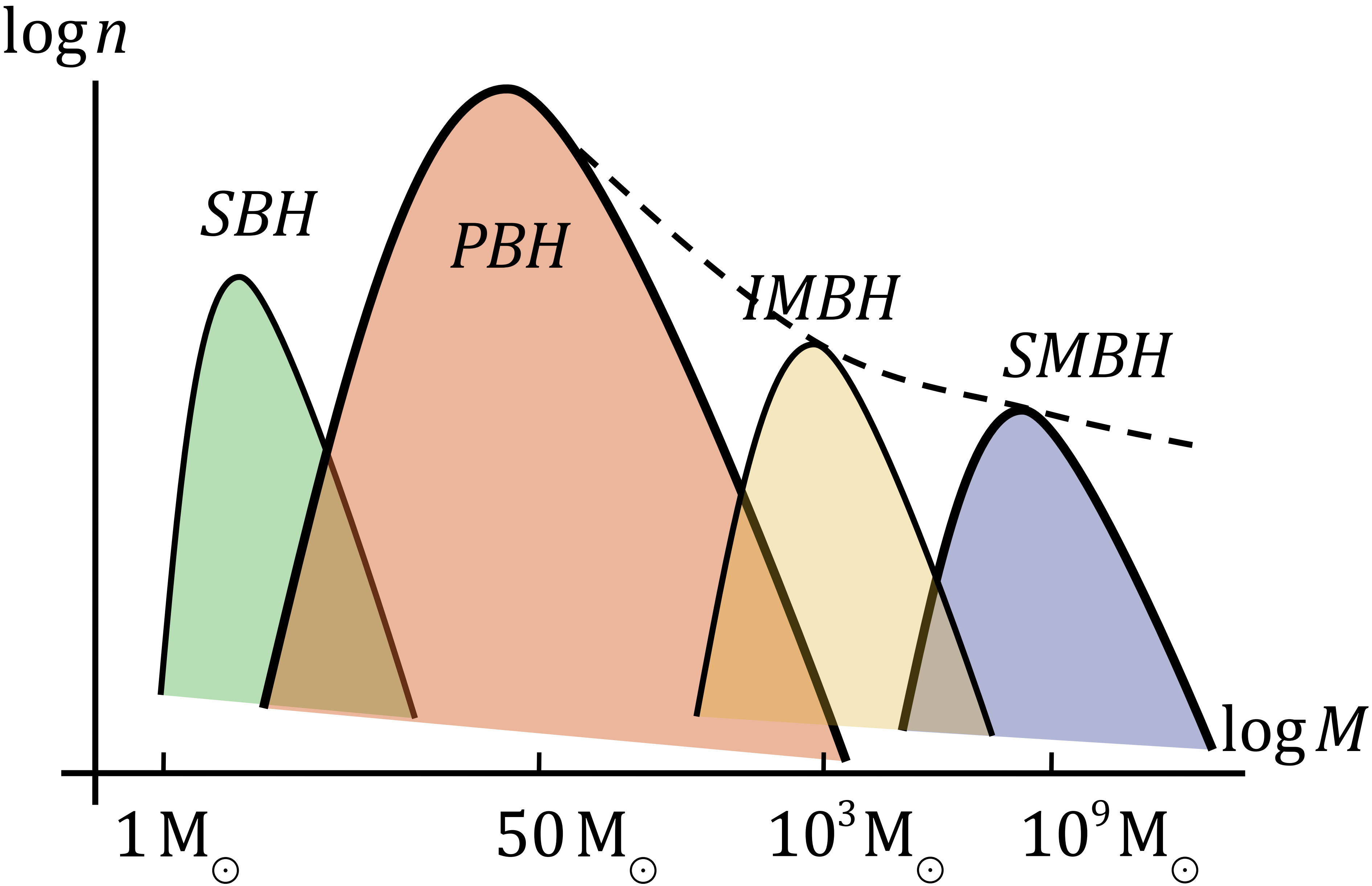


Correlating Black Hole Mass to Stellar System Mass
1 billion
1 million
1 thousand
Black Hole Mass (in solar masses)
Galactic star bulges
Globular Cluster G1
Globular Cluster M15
Increasing
1 million
1 billion
1 trillion
Stellar System Mass (in solar masses)

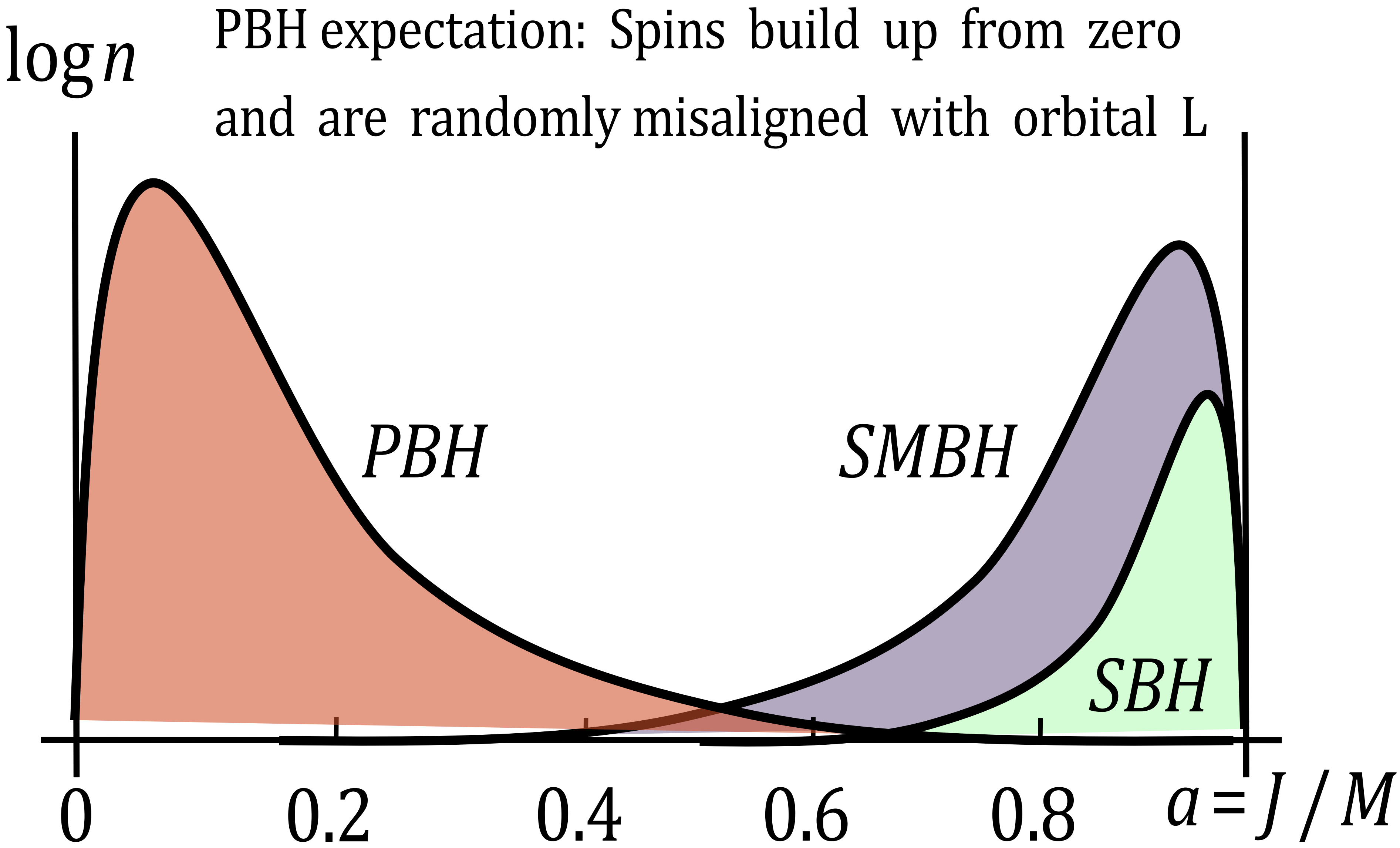
Kruijssen et al. (2013)



Mass distribution of BH



Spin distribution of BH

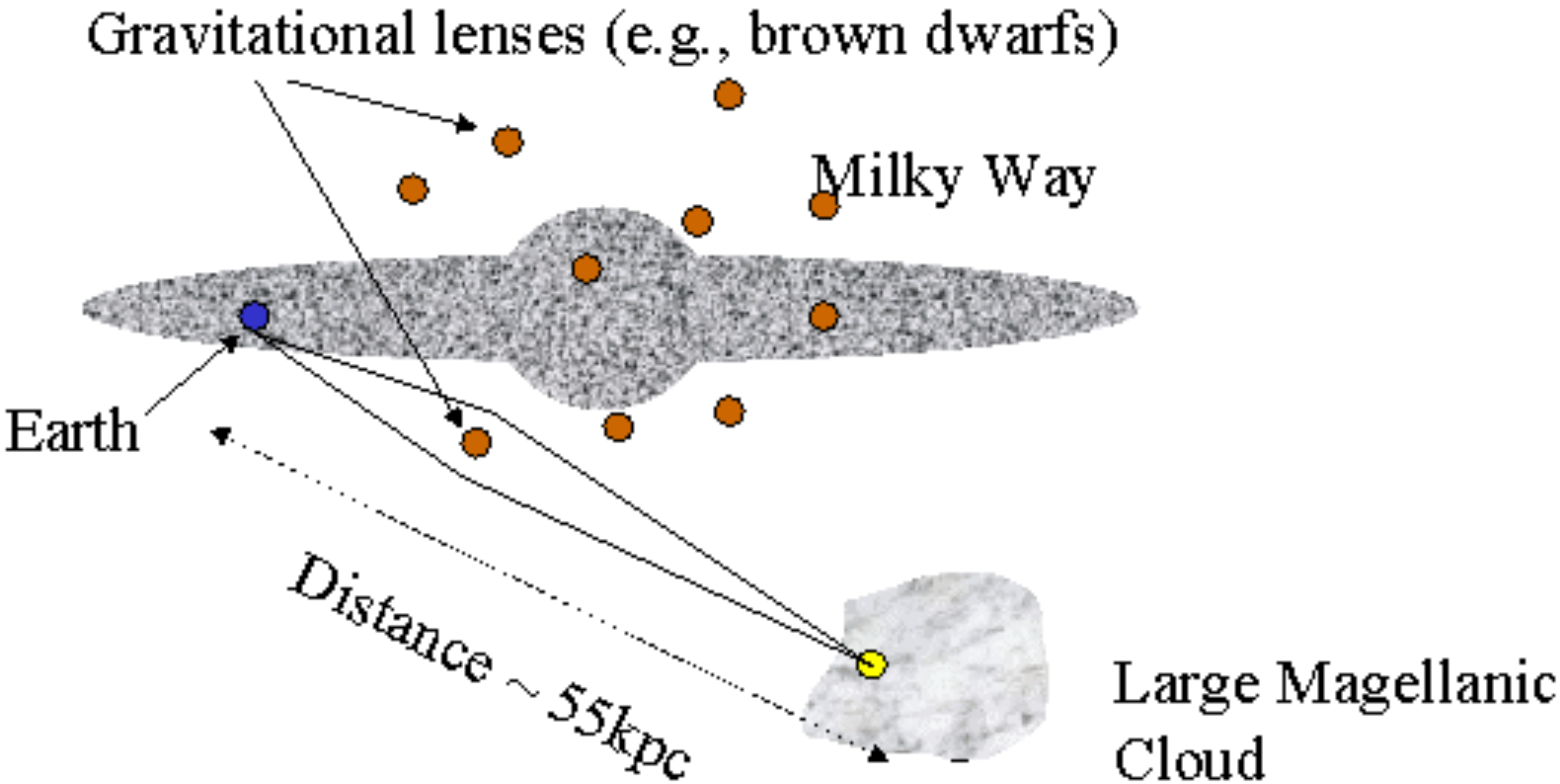


Distinguish MPBH from Stellar BH

- Accretion disks around SBH
- Distribution of spins misaligned
- Mass distribution ≠ IMF
- SBH kicks at formation vs static PBH
- Galaxy formation rate ➔ gal. seeds
- Microlensing events of long duration
- GAIA anomalous astrometry
- CMB distortions with PIXIE/PRISM
- Reionization faster in the past
- N-body simulations below $10^2\ M_\odot$

Signatures of Primordial Black Holes

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

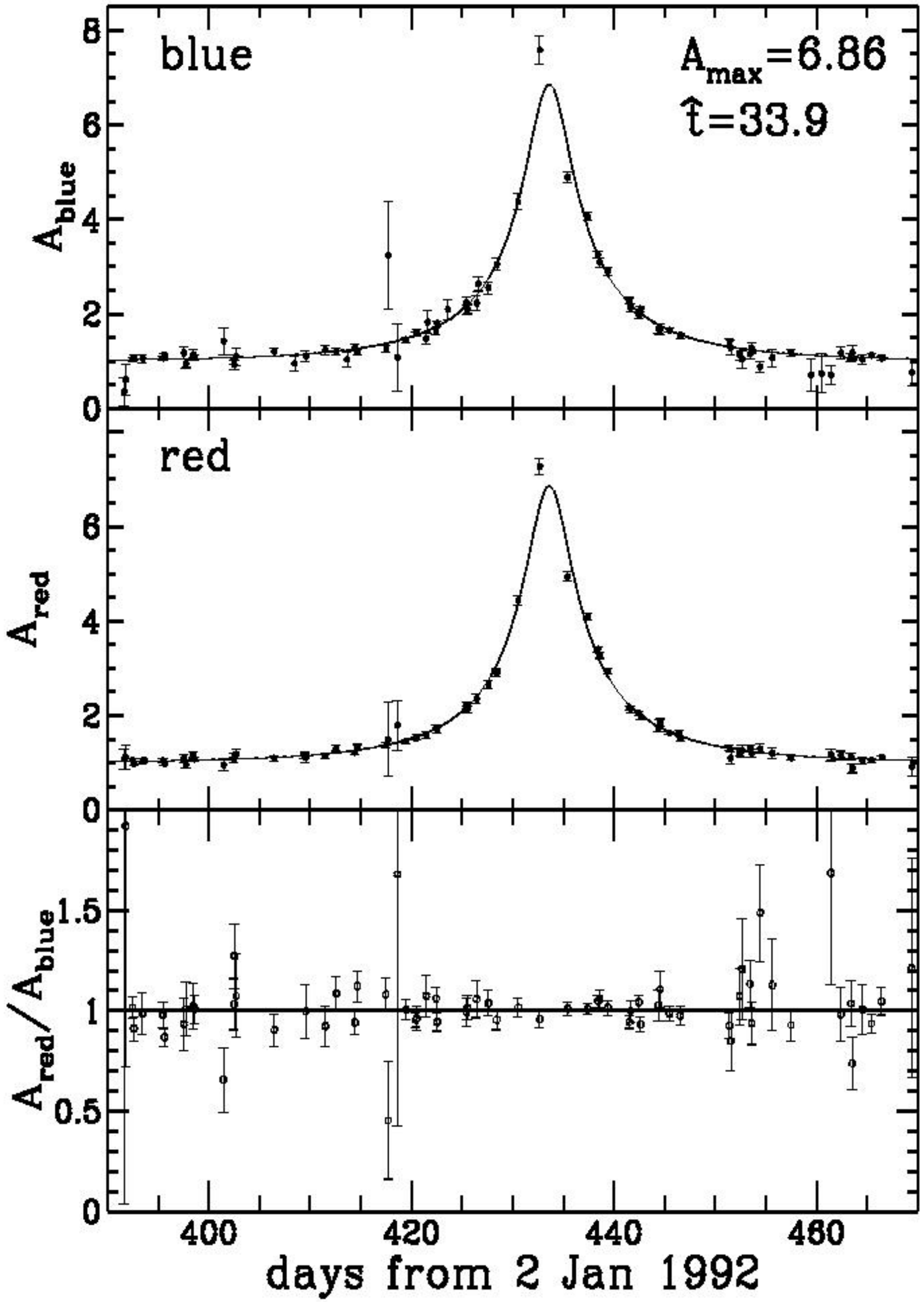
$M_D = 100\,\mathrm{M}_\odot$ => $\overline{Dt} = 4$ years

$M_D = 10\,\mathrm{M}_\odot$ => $\overline{Dt} = 1.23$ years

$M_D = 1\,\mathrm{M}_\odot$ => $\overline{Dt} = 5$ months

$M_D = 0.1\,\mathrm{M}_\odot$ => $\overline{Dt} = 1.5$ months

$M_D = 0.01\,\mathrm{M}_\odot$ => $\overline{Dt} = 2$ weeks



symmetric

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

achromatic

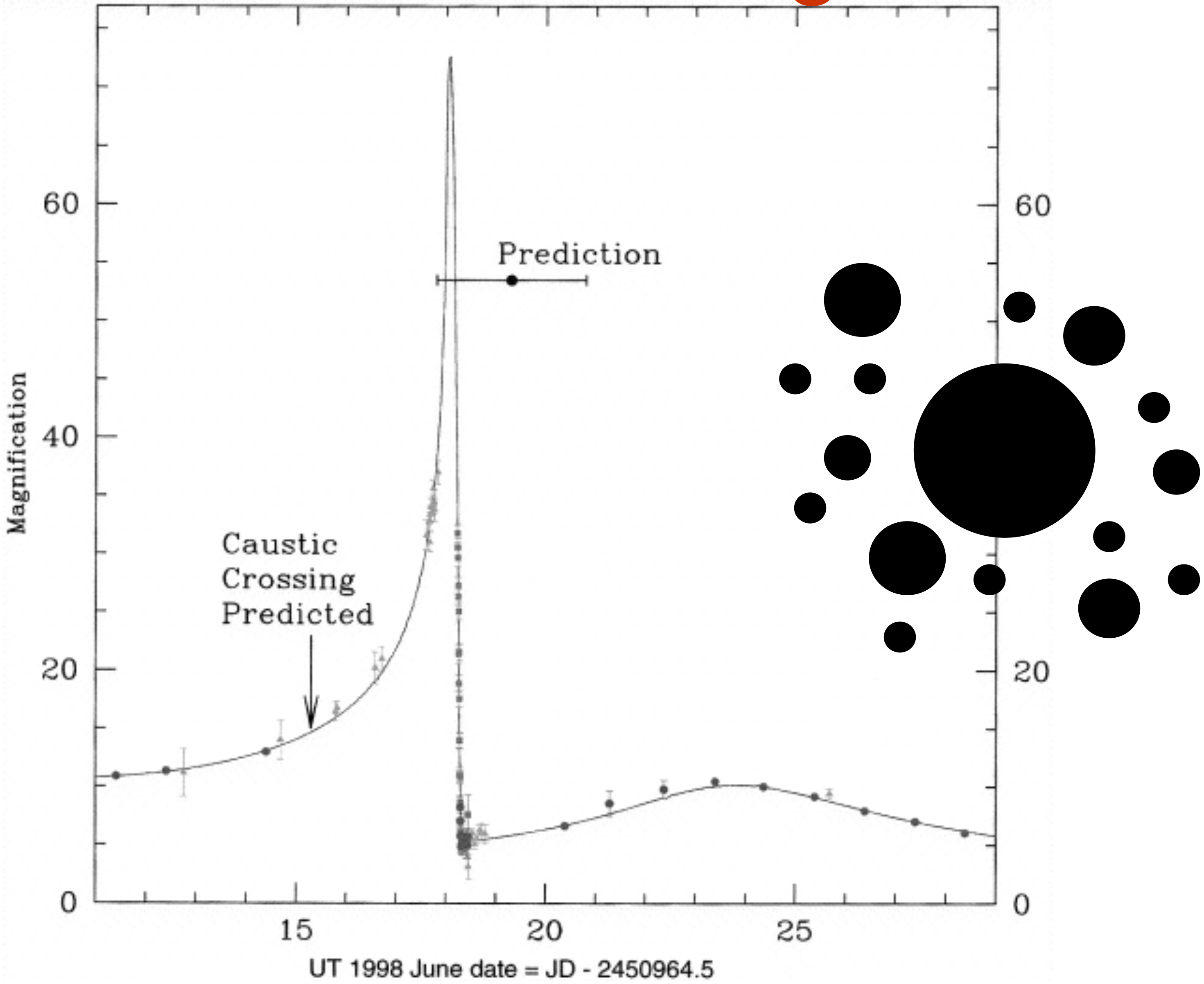
$$\frac{A_{red}}{A_{blue}} = 1.00 \pm 0.05$$

unique

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

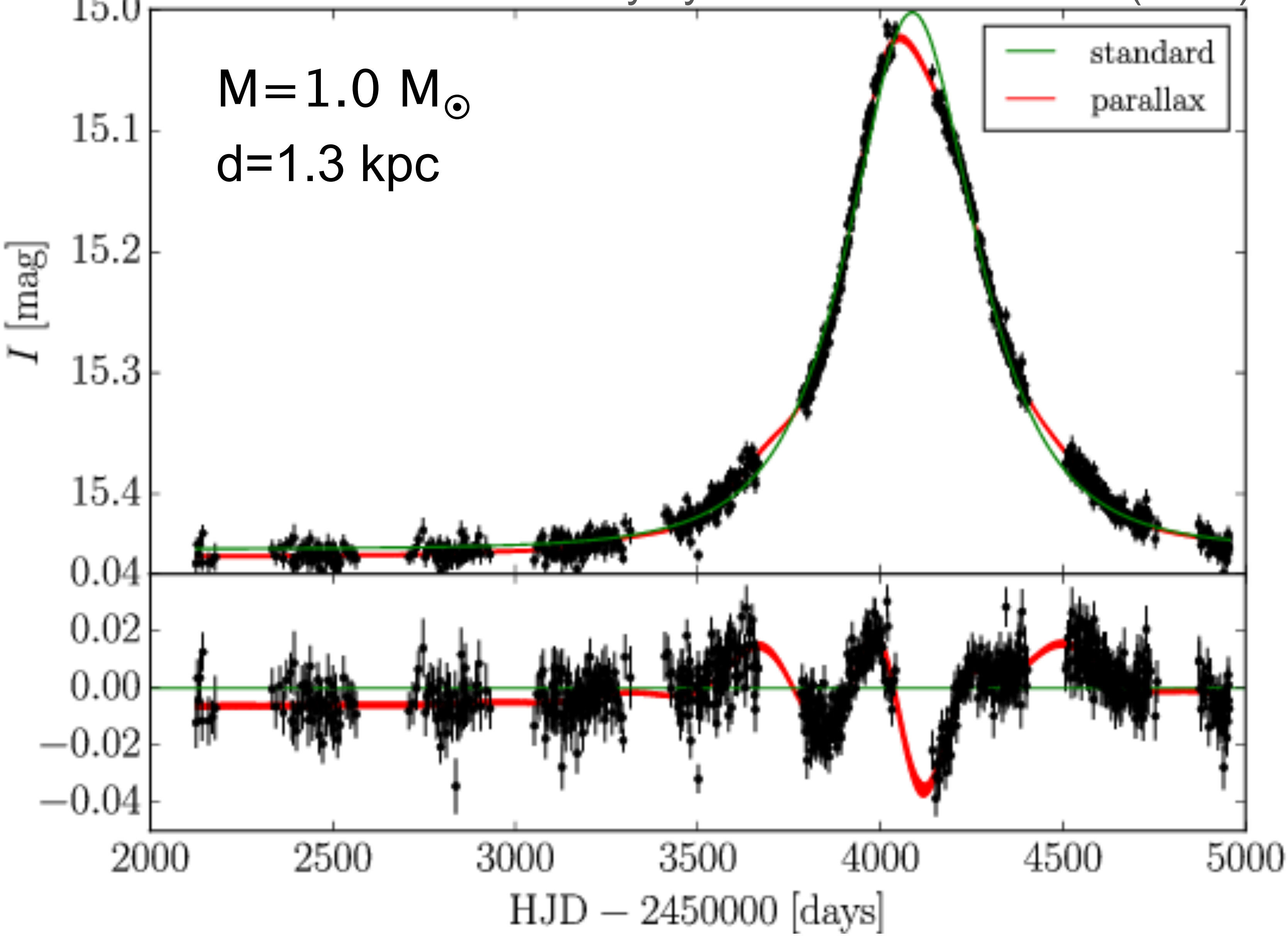
$$M_D = 0.1\, M_\odot$$

Signatures: Clustering of PBH



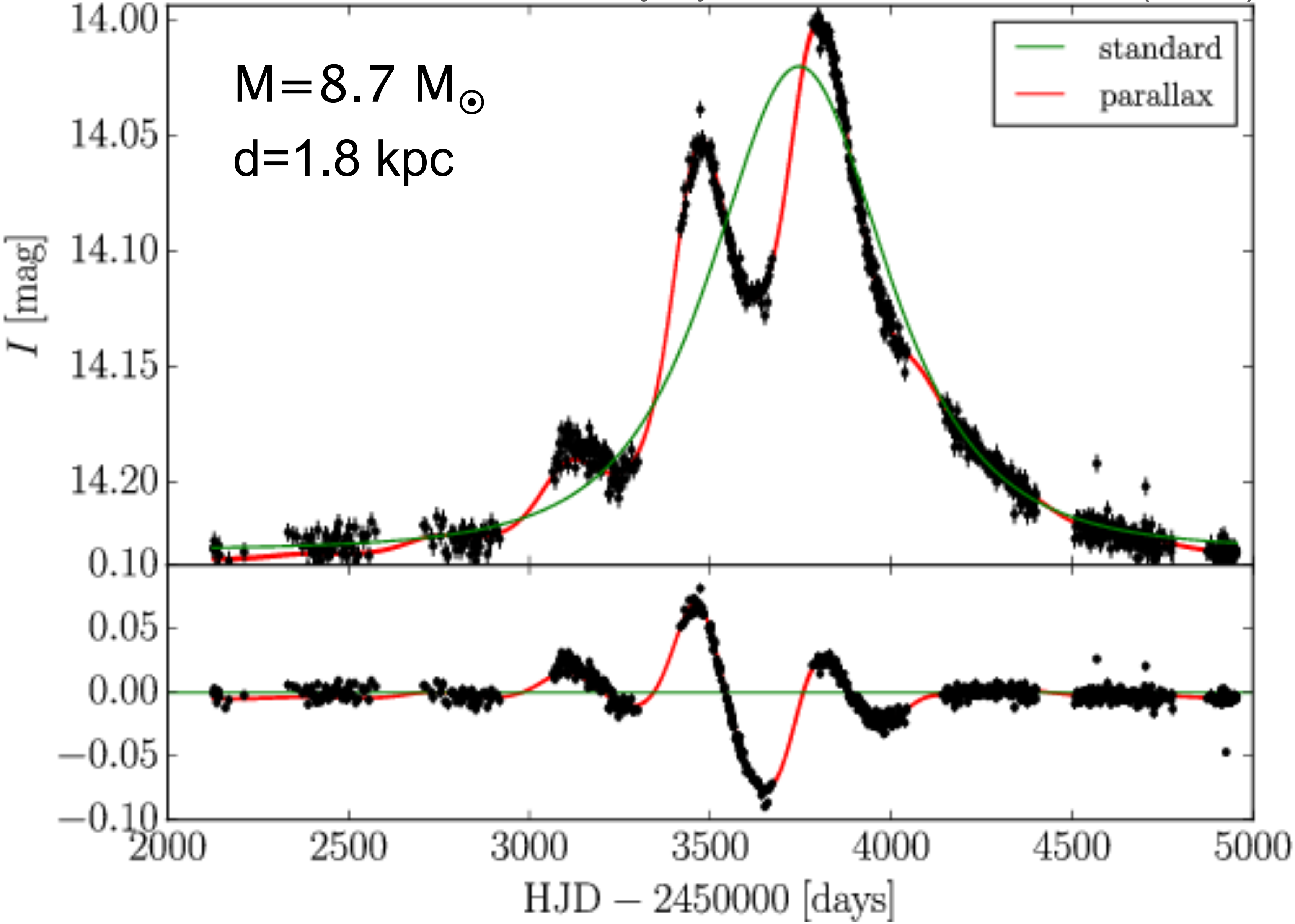
Signatures: Parallax of PBH

Wyrzykowski et al. OGLE-III (2016)



Signatures: Parallax of PBH

Wyrzykowski et al. OGLE-III (2016)



Constraints on clustered PBH

JGB, Clesse (2017)

Uniform (f_{PBH}=1)

$$PDF(M) = \frac{1}{M\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\log^2(M/\mu)}{2\sigma^2}\right)$$

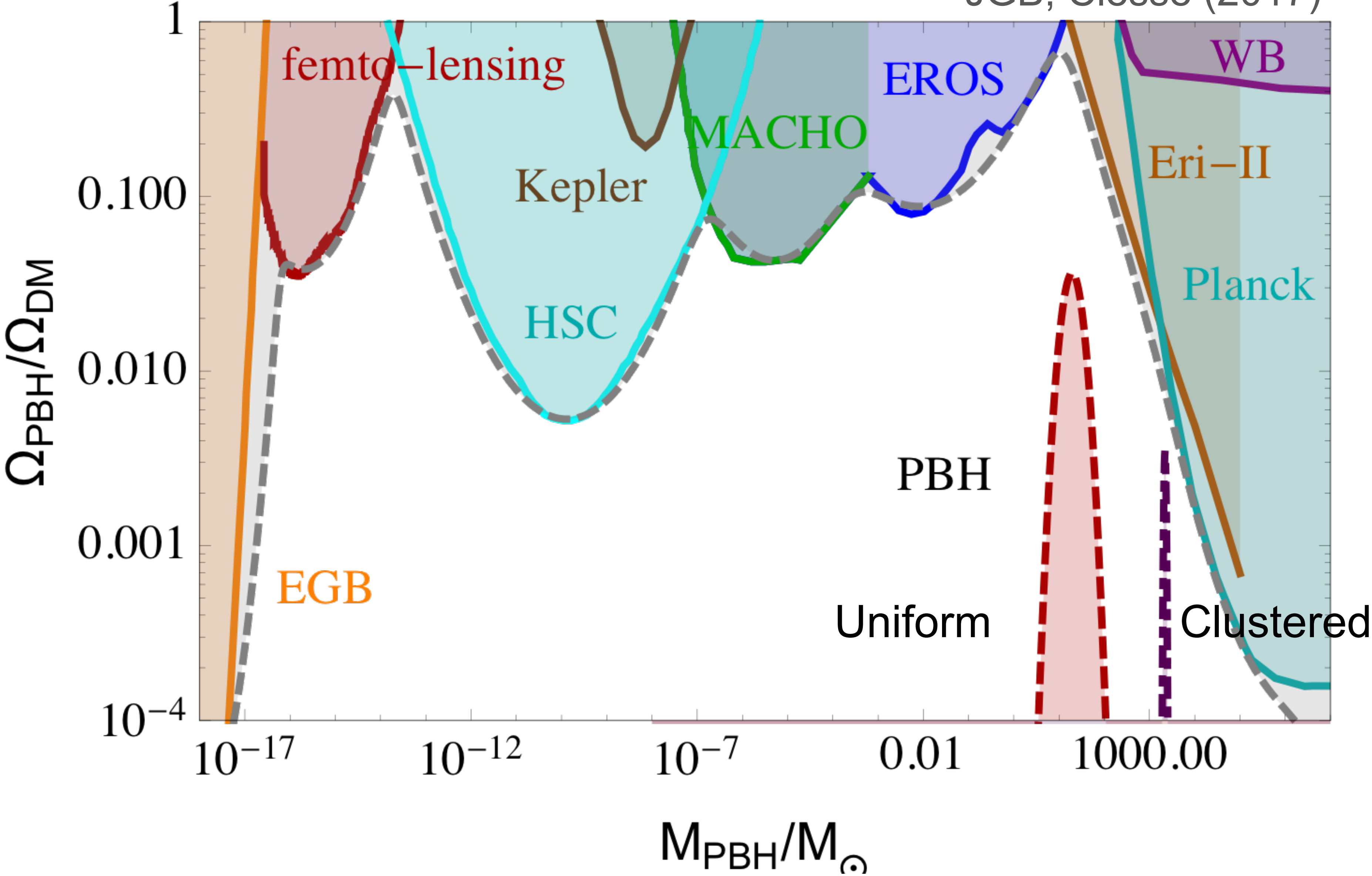
$$\bar{M} = \mu \exp(\frac{1}{2}\sigma^2)$$

Clustered (N_{cl} = 100-1000) new distribution:

$$\mu_{cl} = N_{cl}\,\bar{M} \qquad\qquad \sigma_{cl}{}^2 = (e^{\sigma^2} - 1)/N_{cl}$$

Present Constraints on PBH

JGB, Clesse (2017)



Missing satellite

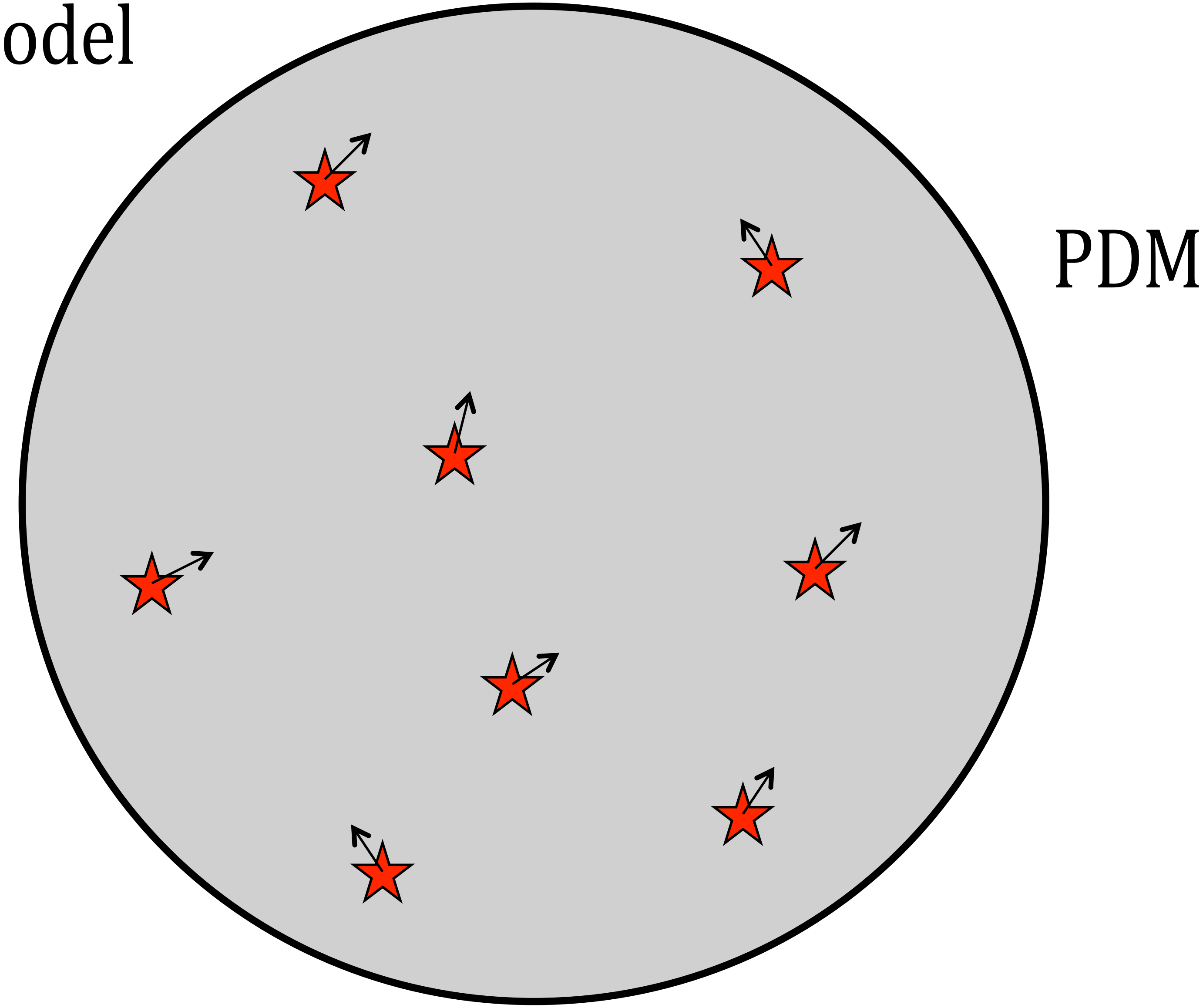
&

Too-big-to-fail

Problems ΛCDM

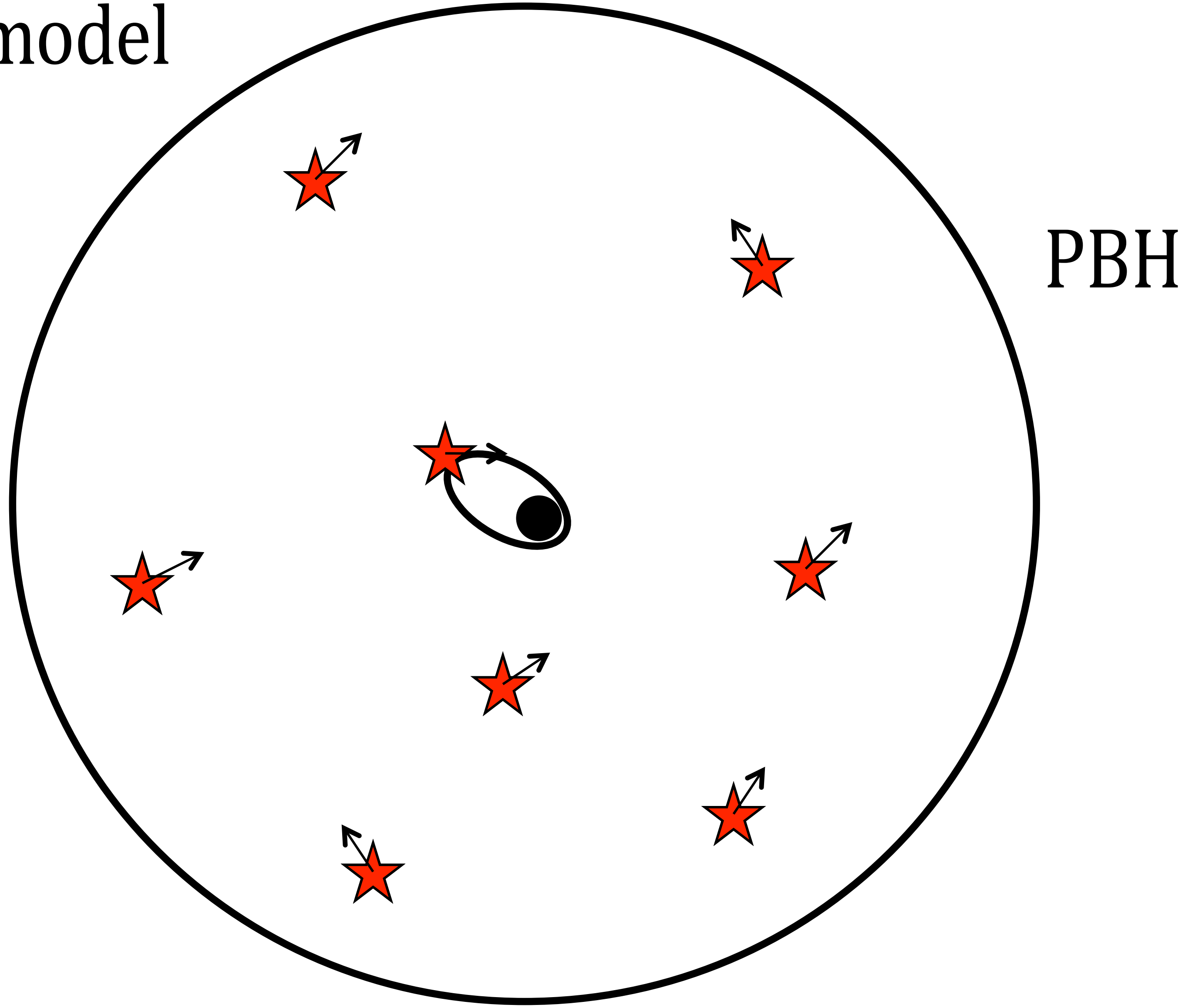
Spatial distribution of DM

Thomson model



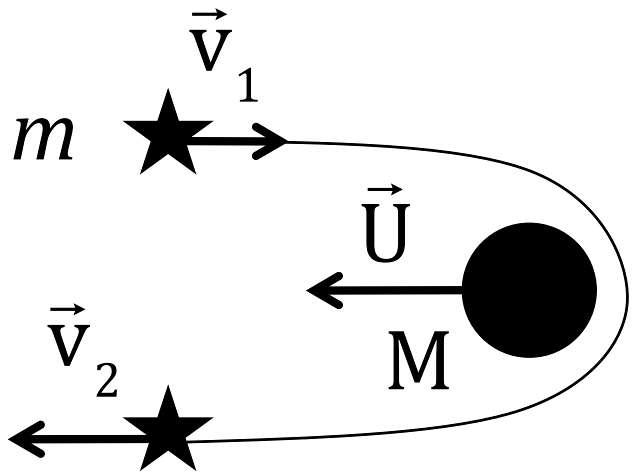
Spatial distribution of DM

Rutherford model



Gravitational slingshot effect

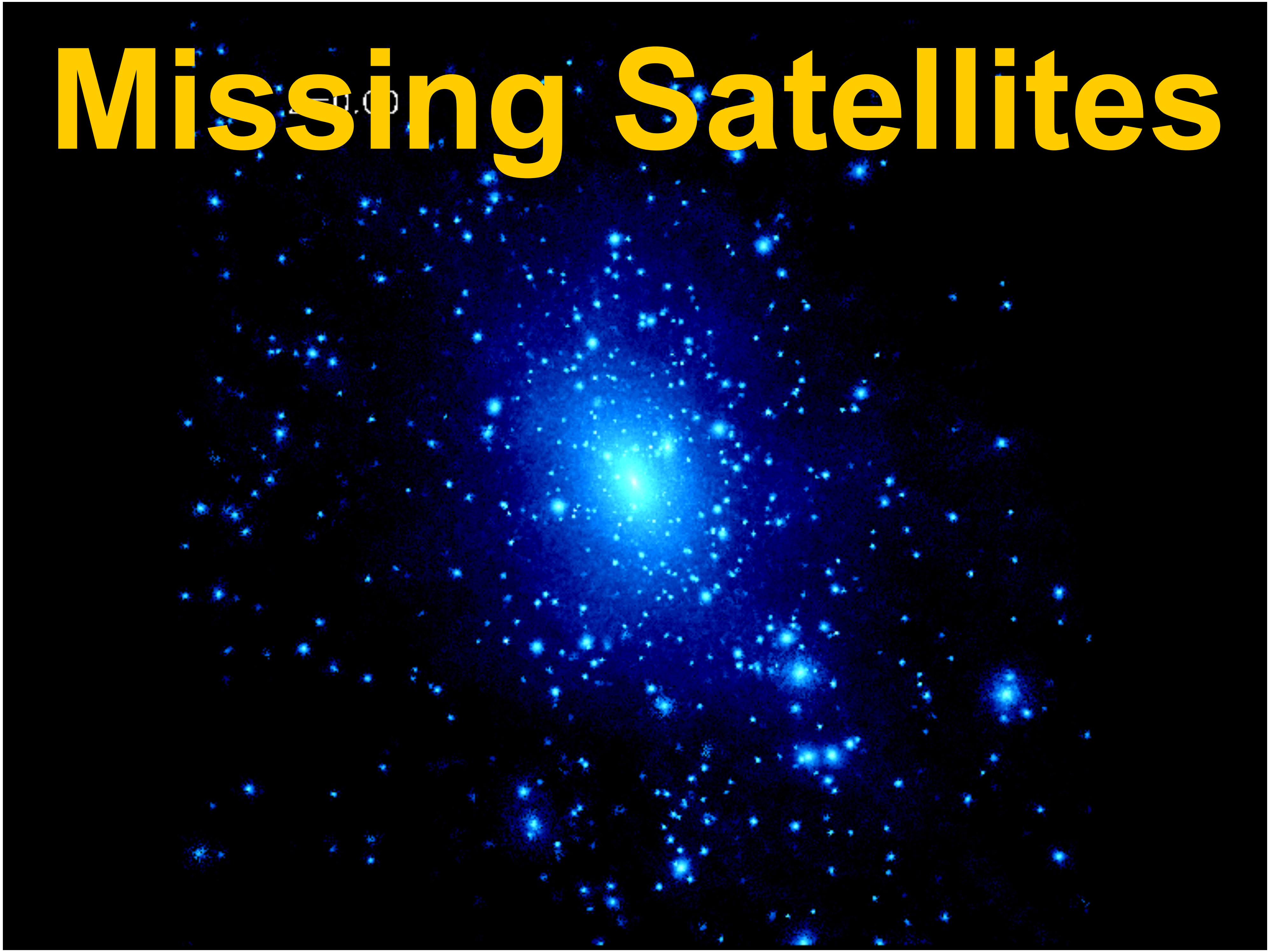
Close encounters of a star with MPBH @ 100 km/s relative motion is enough to expel the star from the stellar cluster.



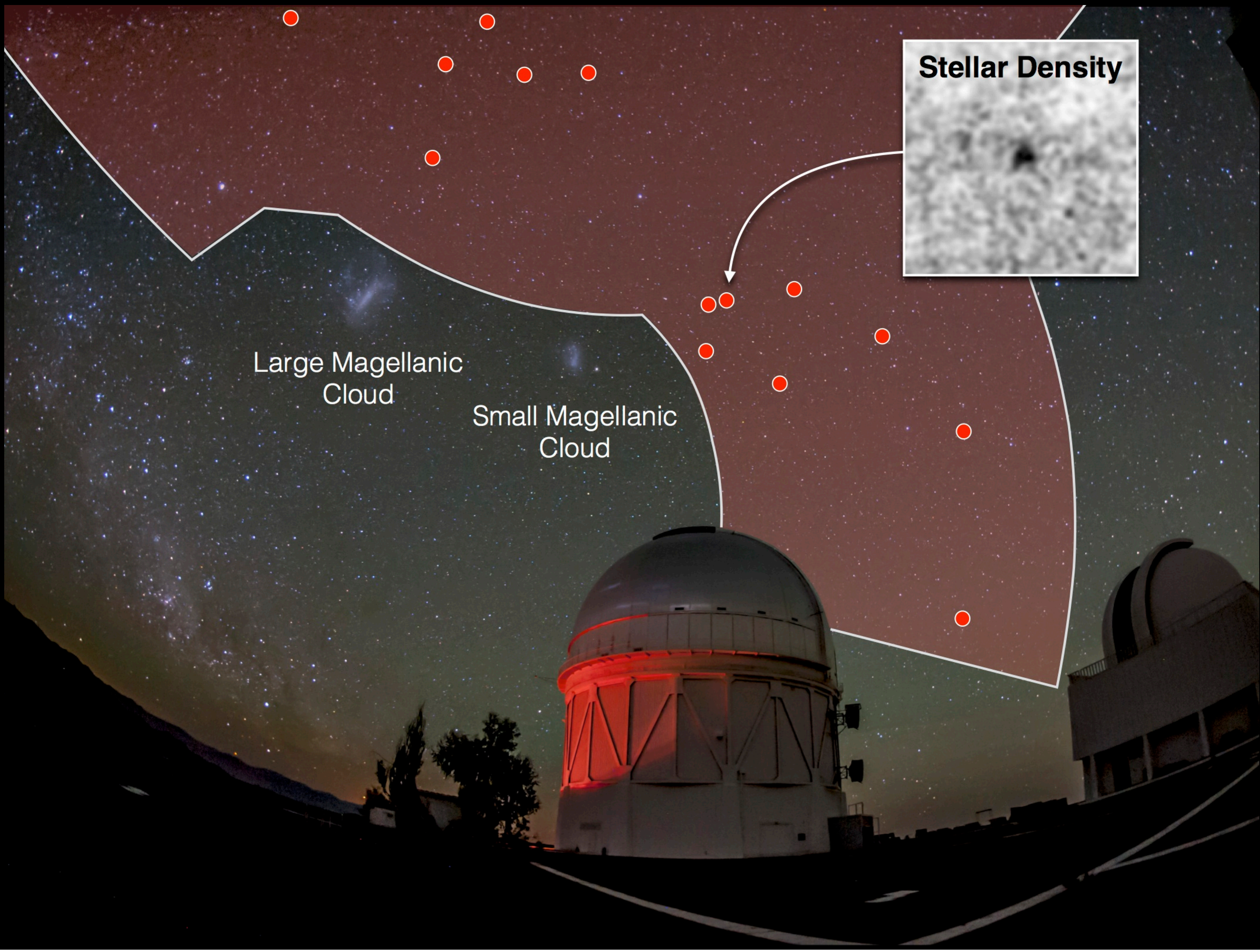
$$\vec{v}_2 = \frac{2\vec{U} + (1 - m/M)\vec{v}_1}{(1 + m/M)}$$

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

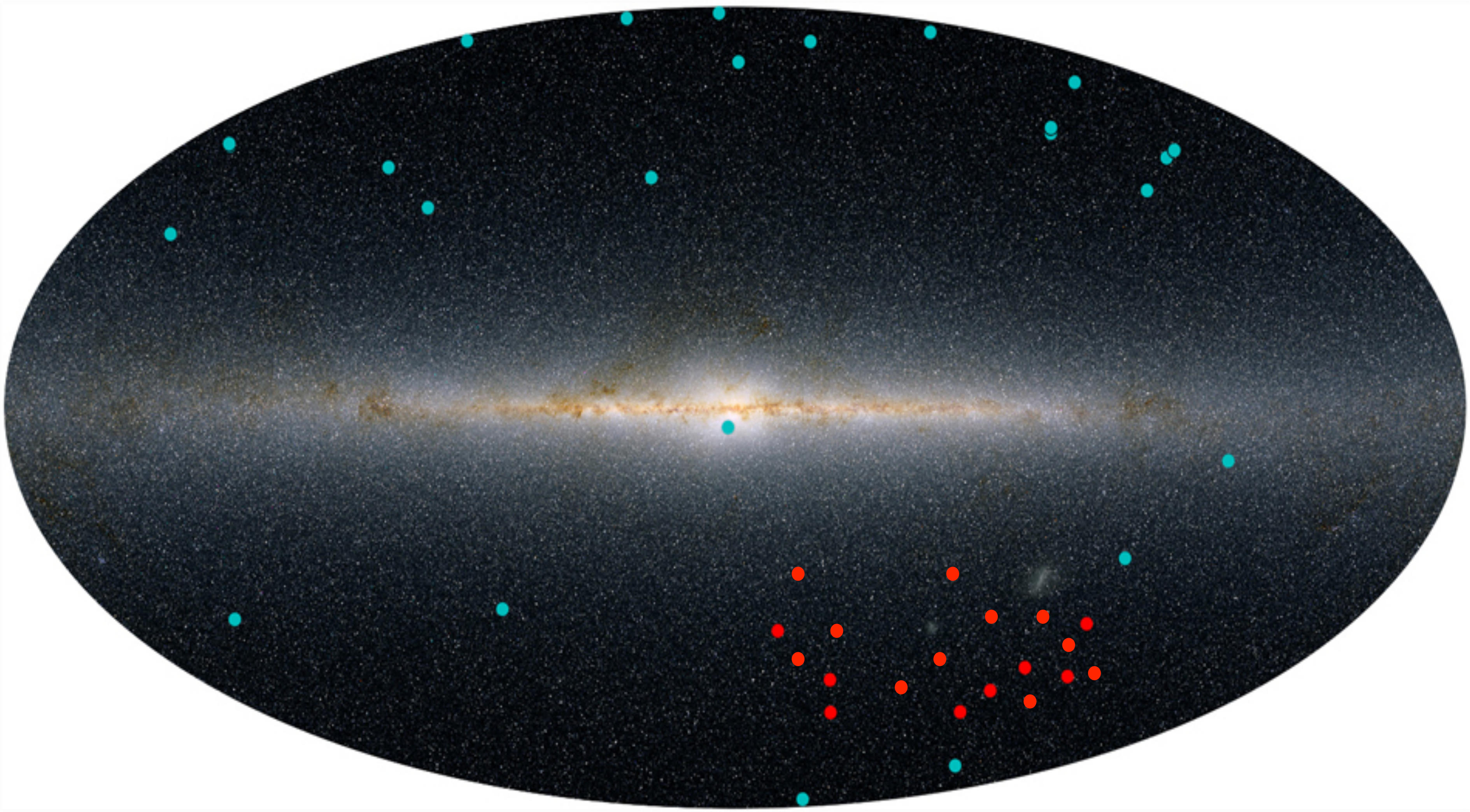
Missing Satellites



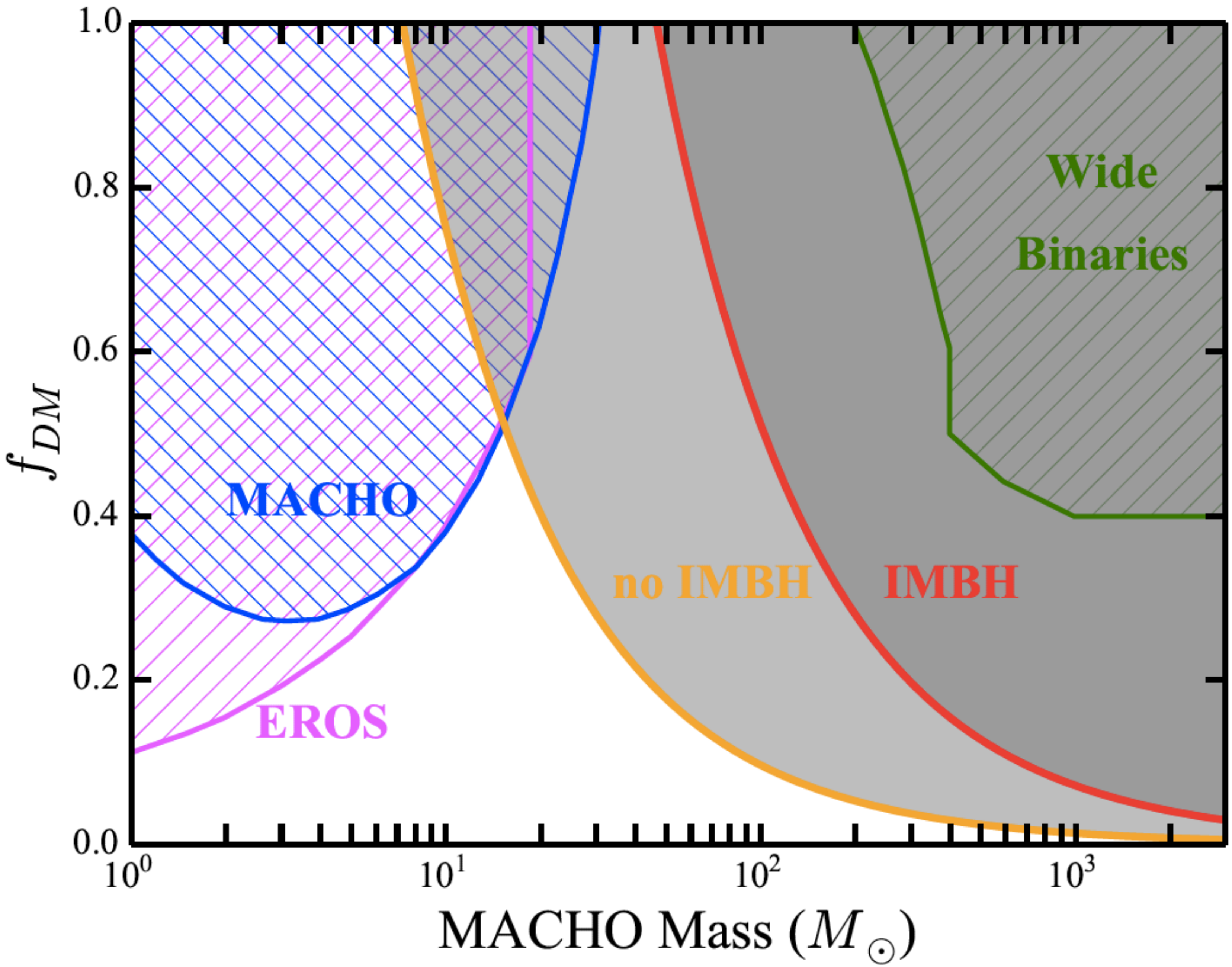
DES Dwarf spheroidals



DES Dwarf spheroidals



Eridanus II dwarf spheroidal



Discussion

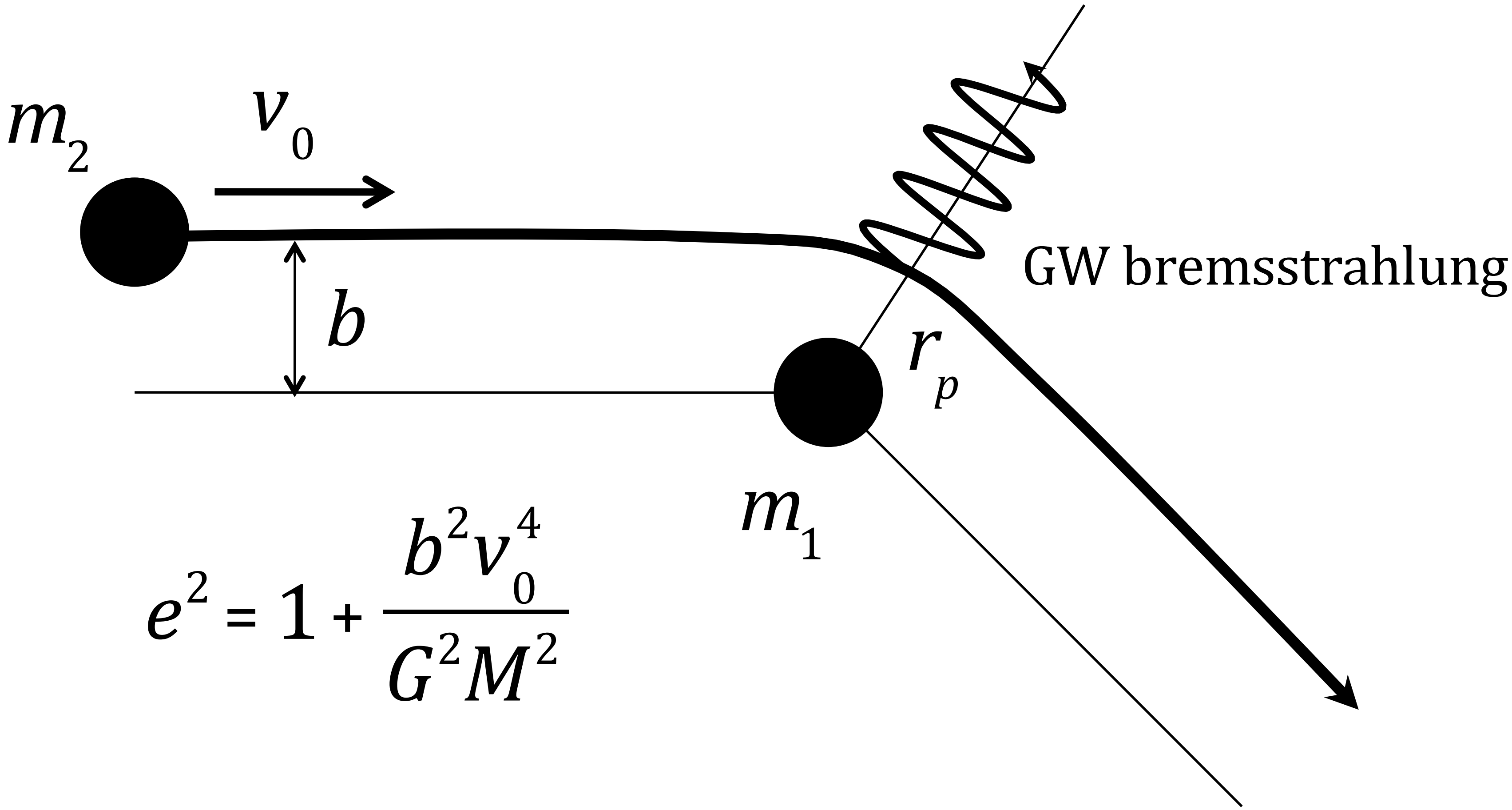
Signatures of PBH as DM

- Seeds of galaxies at high-z
- Reionization starts early (Kashlinsky)
- Larger galaxies form earlier than ΛCDM
- Massive BH at centers QSO @ z>6
- Growth of structure on small scales
- Ultra Luminous X-ray Transients
- MPBH in Andromeda (Chandra)
- GW from inspiraling $M < M_{\odot}$ BH (LIGO)
- Substructure and too-big-to-fail probl.
- Total integrated mass = Ω_M

GW bursts from close encounters

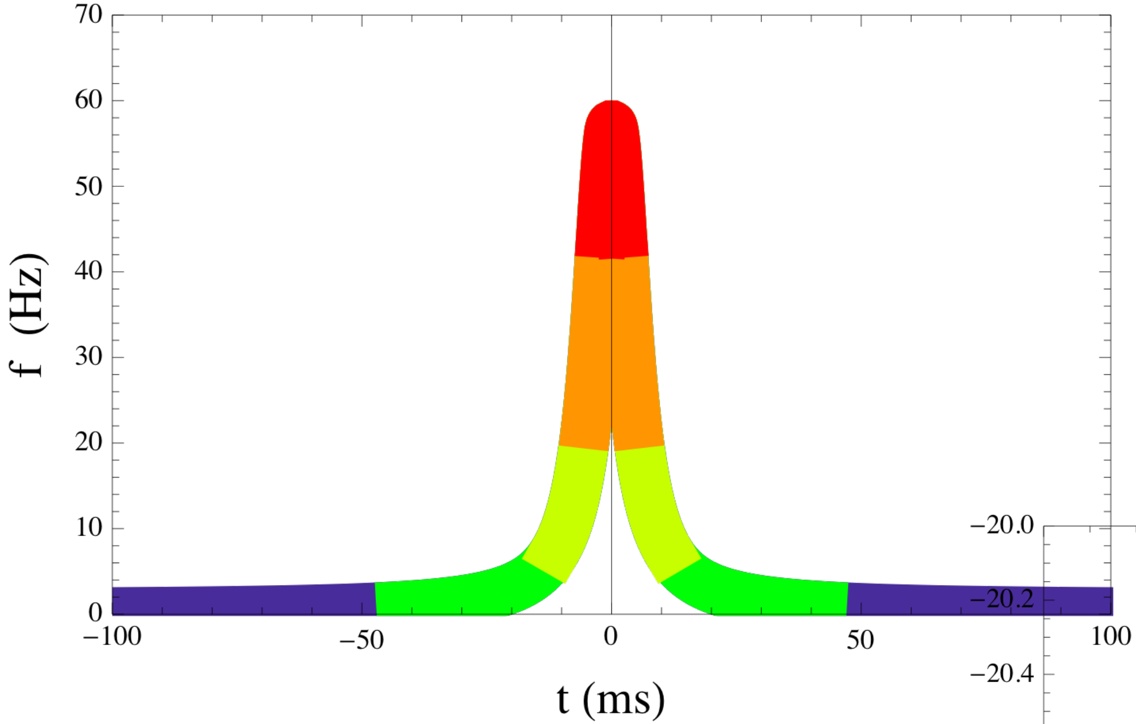
GW bursts

JGB, Nesseris (2017)

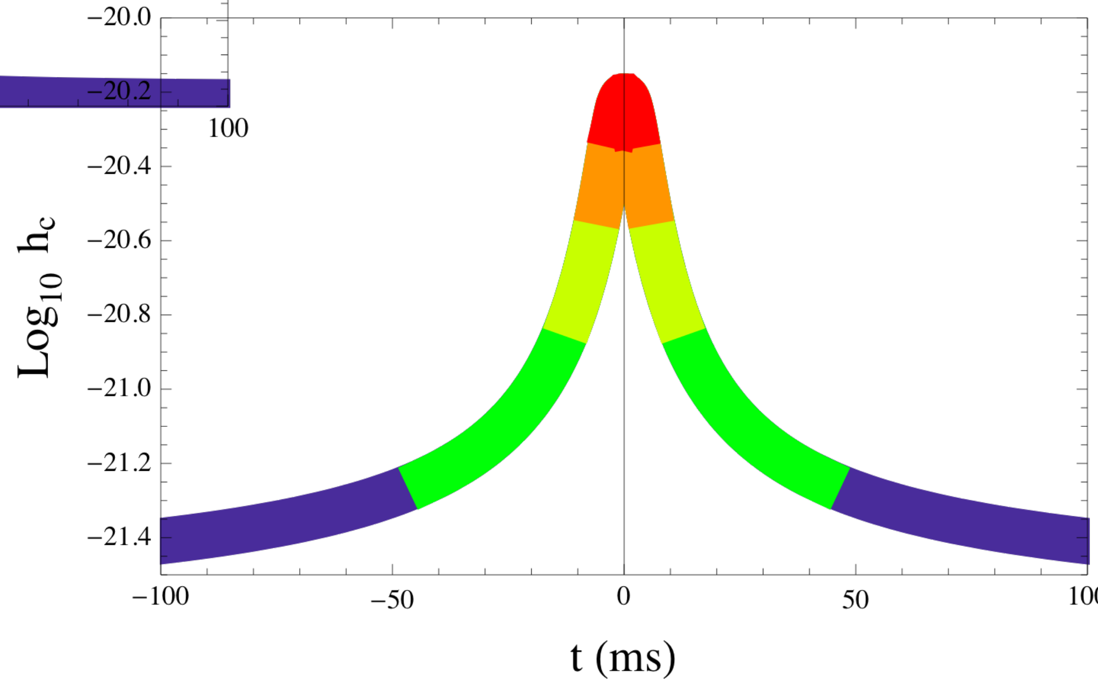


$$e^2 = 1 + \frac{b^2 v_0^4}{G^2 M^2}$$

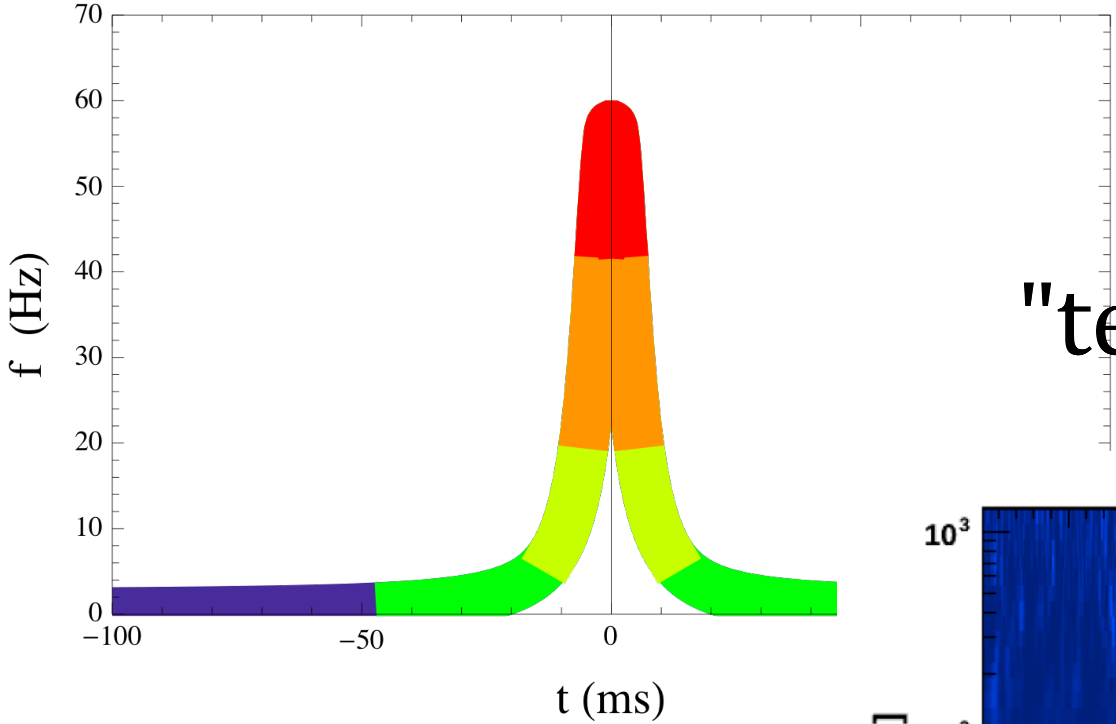
GW bursts



JGB, Nesseris (2017)

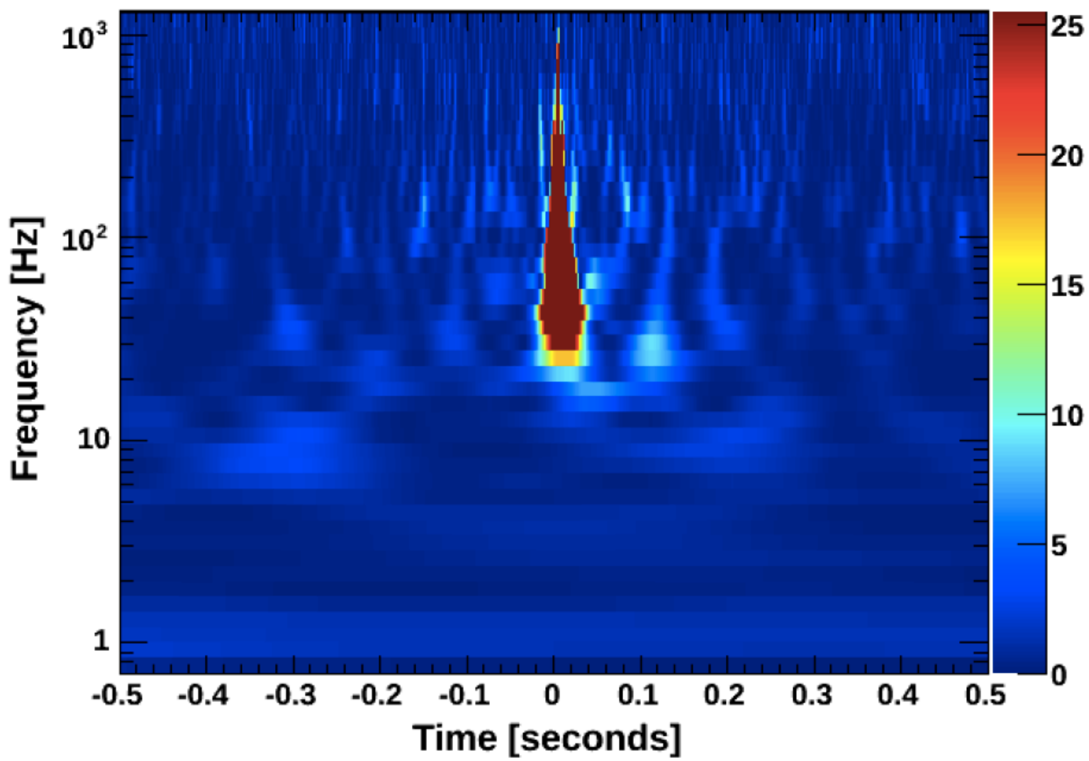


GW bursts

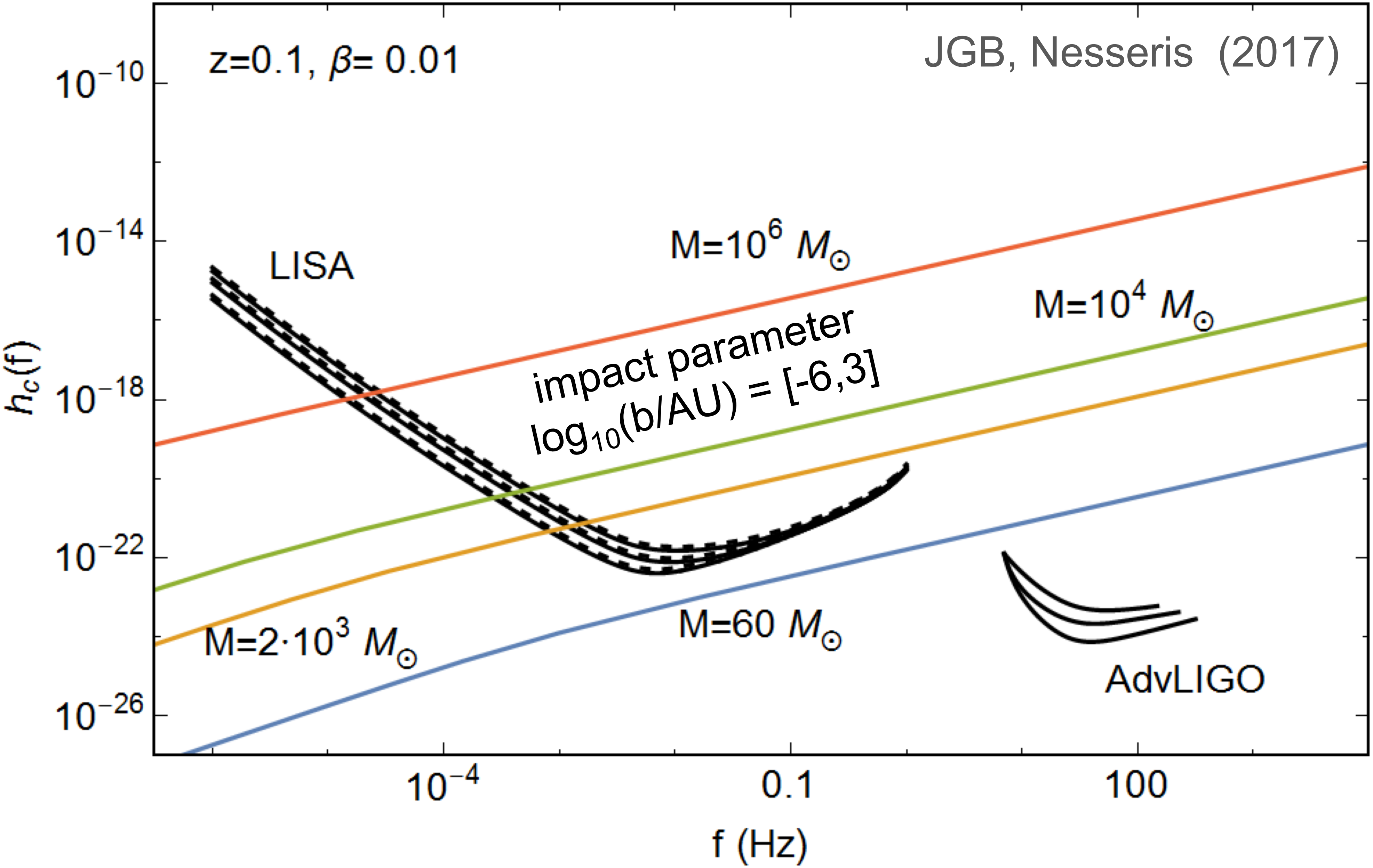


JGB, Nesseris (2017)

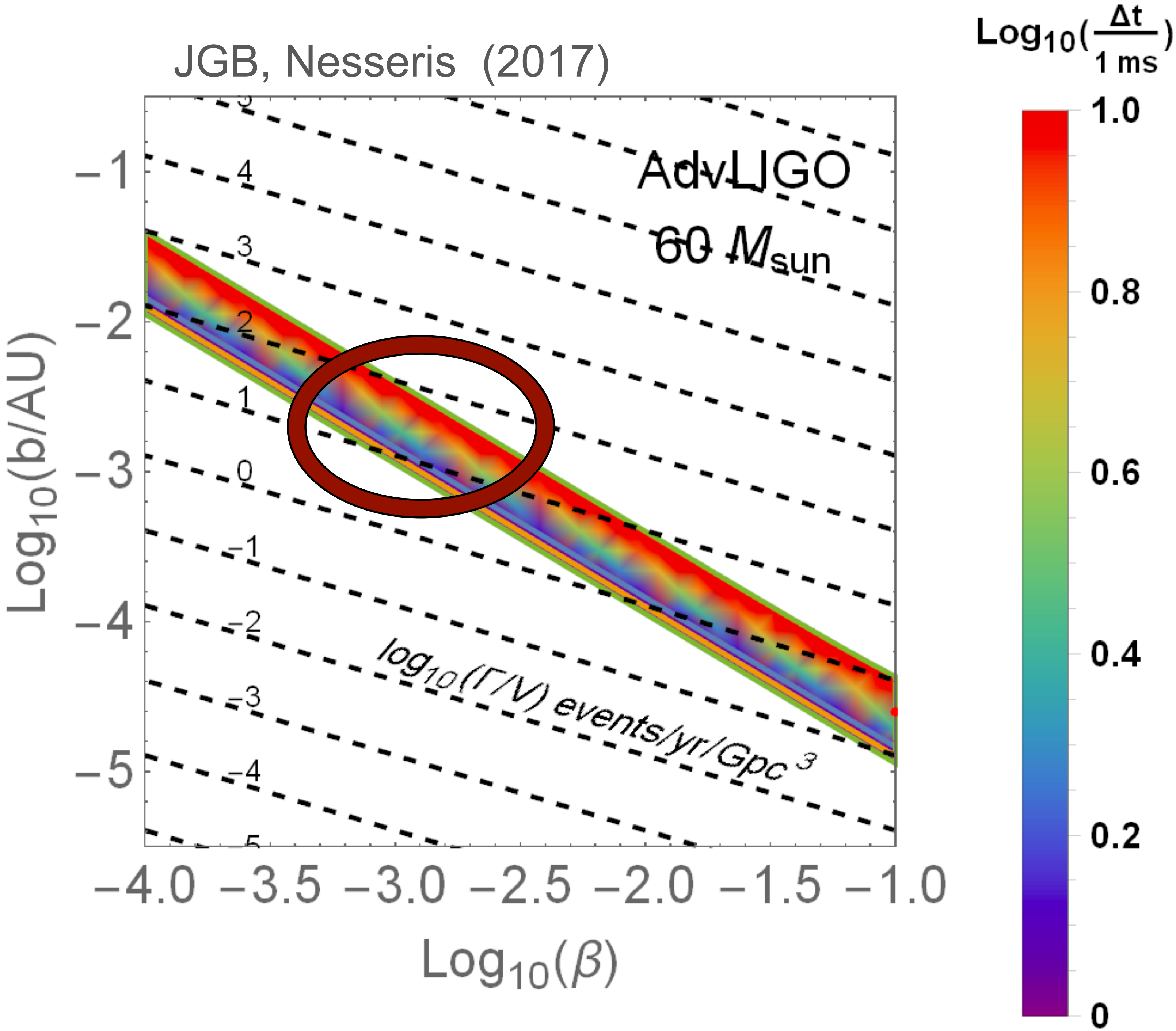
"tear drop glitches"?



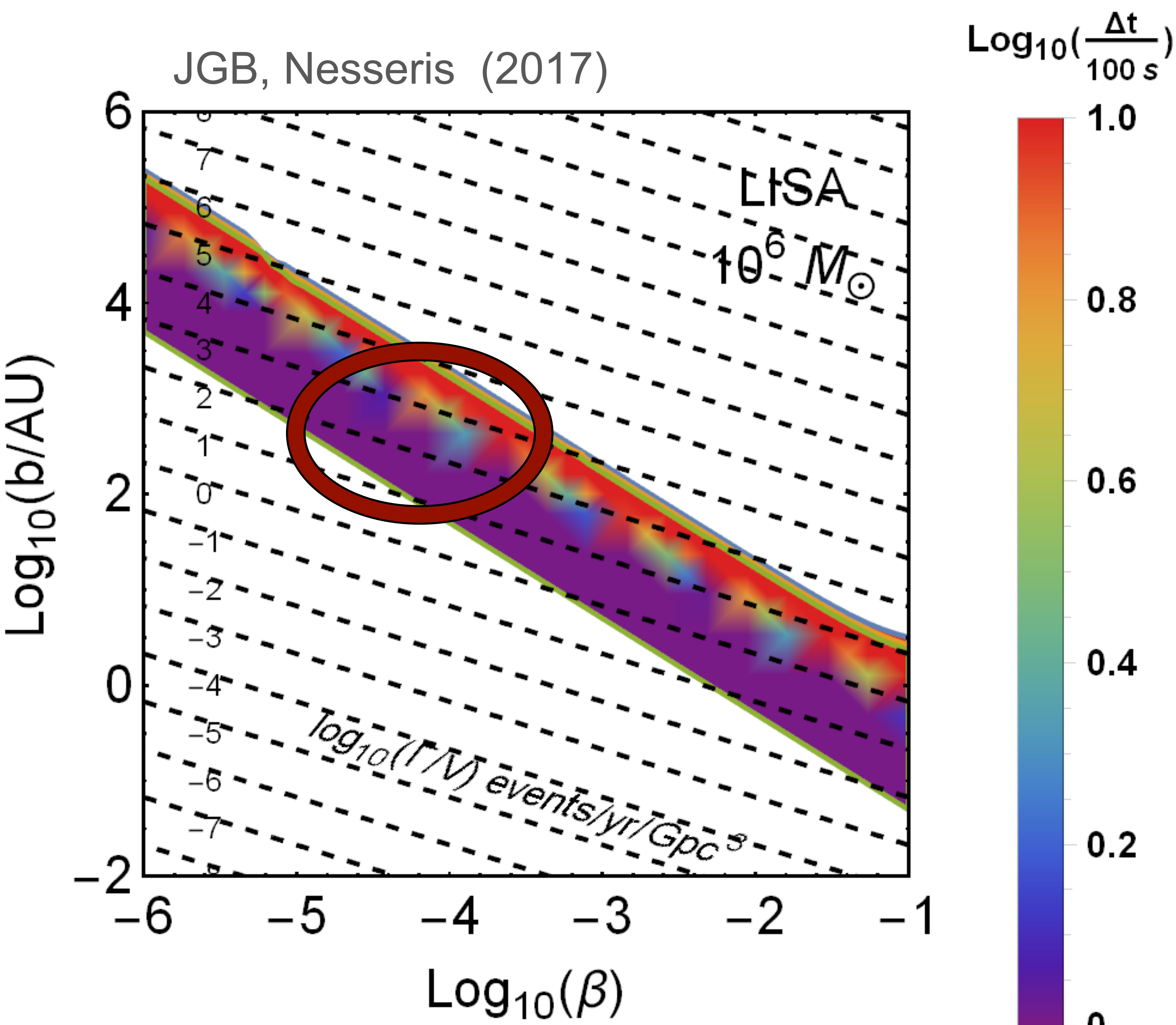
GW bursts



z=0.1, β= 0.01
JGB, Nesseris (2017)
LISA
M=10^6 M⊙
M=10^4 M⊙
impact parameter
log10(b/AU) = [-6,3]
M=2·10^3 M⊙
M=60 M⊙
AdvLIGO
h_c(f)
f (Hz)
10^-10
10^-14
10^-18
10^-22
10^-26
10^-4
0.1
100



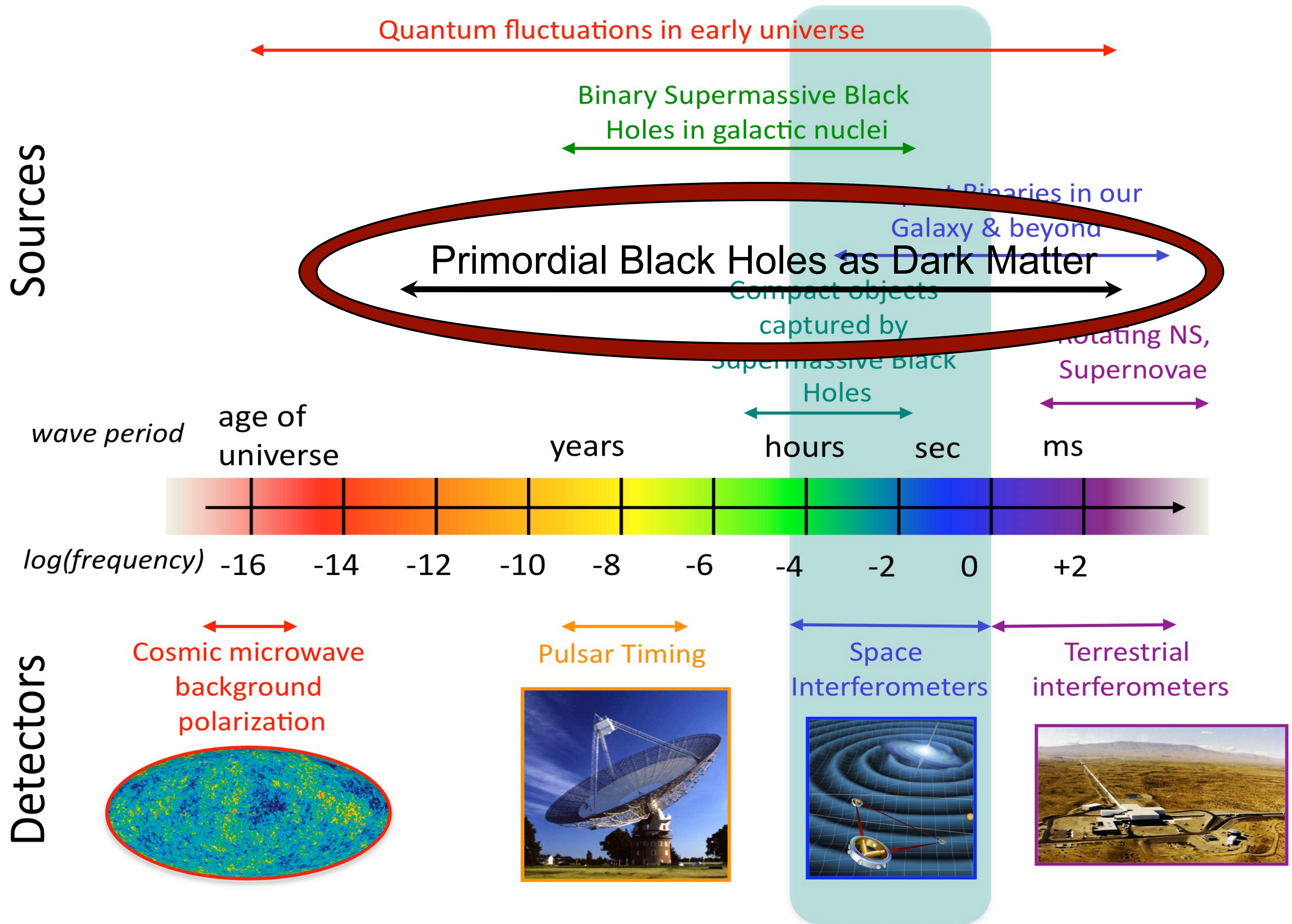
JGB, Nesseris (2017)
AdvLIGO
60 M_{sun}
$log_{10}(\Gamma/V)$ events/yr/Gpc^3
$Log_{10}(b/AU)$
$Log_{10}(\beta)$
$Log_{10}(\frac{\Delta t}{1\ ms})$
-1
-2
-3
-4
-5
-4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0
5
4
3
2
1
0
-1
-2
-3
-4
-5
1.0
0.8
0.6
0.4
0.2
0



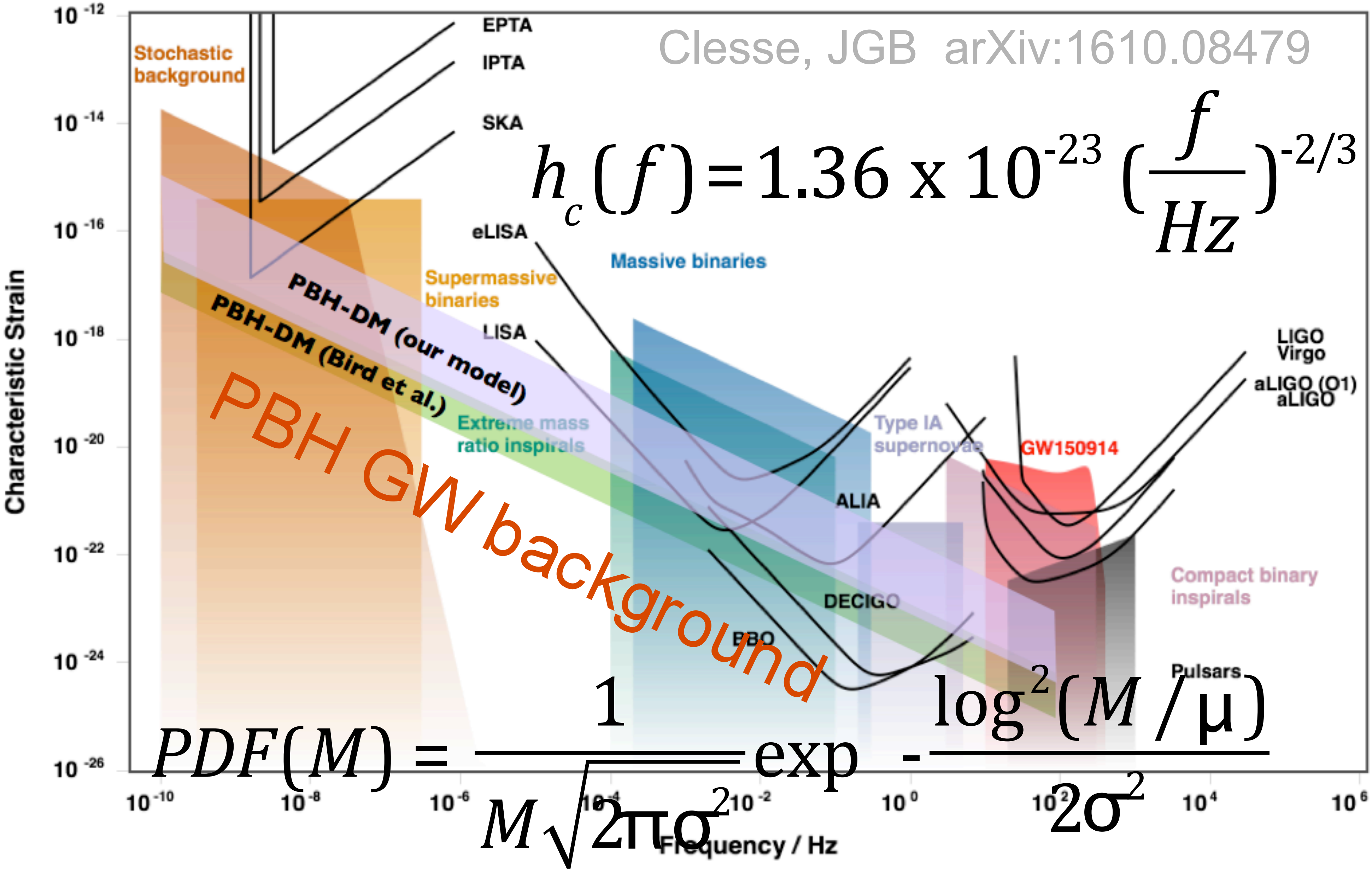
JGB, Nesseris (2017)
LISA
$10^6\ M_\odot$
$log_{10}(\Gamma/V)$ events/yr/Gpc^3
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
$Log_{10}(b/AU)$
$Log_{10}(\beta)$
6
4
2
0
−2
−6
−5
−4
−3
−2
−1
$Log_{10}(\frac{\Delta t}{100\ s})$
1.0
0.8
0.6
0.4
0.2
0

Stochastic Background Grav. Waves

The Gravitational Wave Spectrum



Sensitivity of future GW antenas

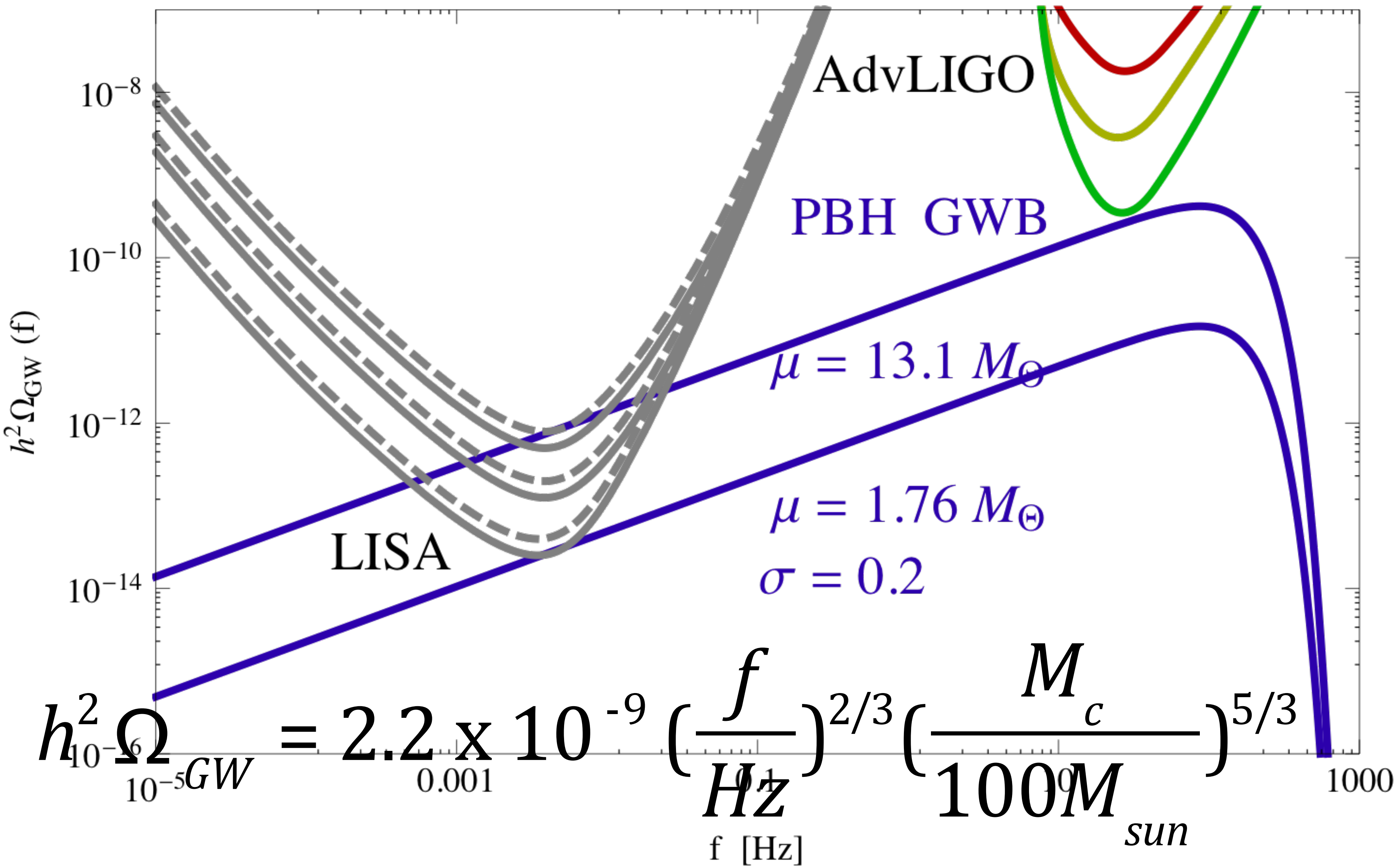


$$h_c(f) = 1.36 \times 10^{-23} \left(\frac{f}{Hz}\right)^{-2/3}$$

$$PDF(M) = \frac{1}{M\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\log^2(M/\mu)}{2\sigma^2}\right)$$

Stochastic Background from MPBH

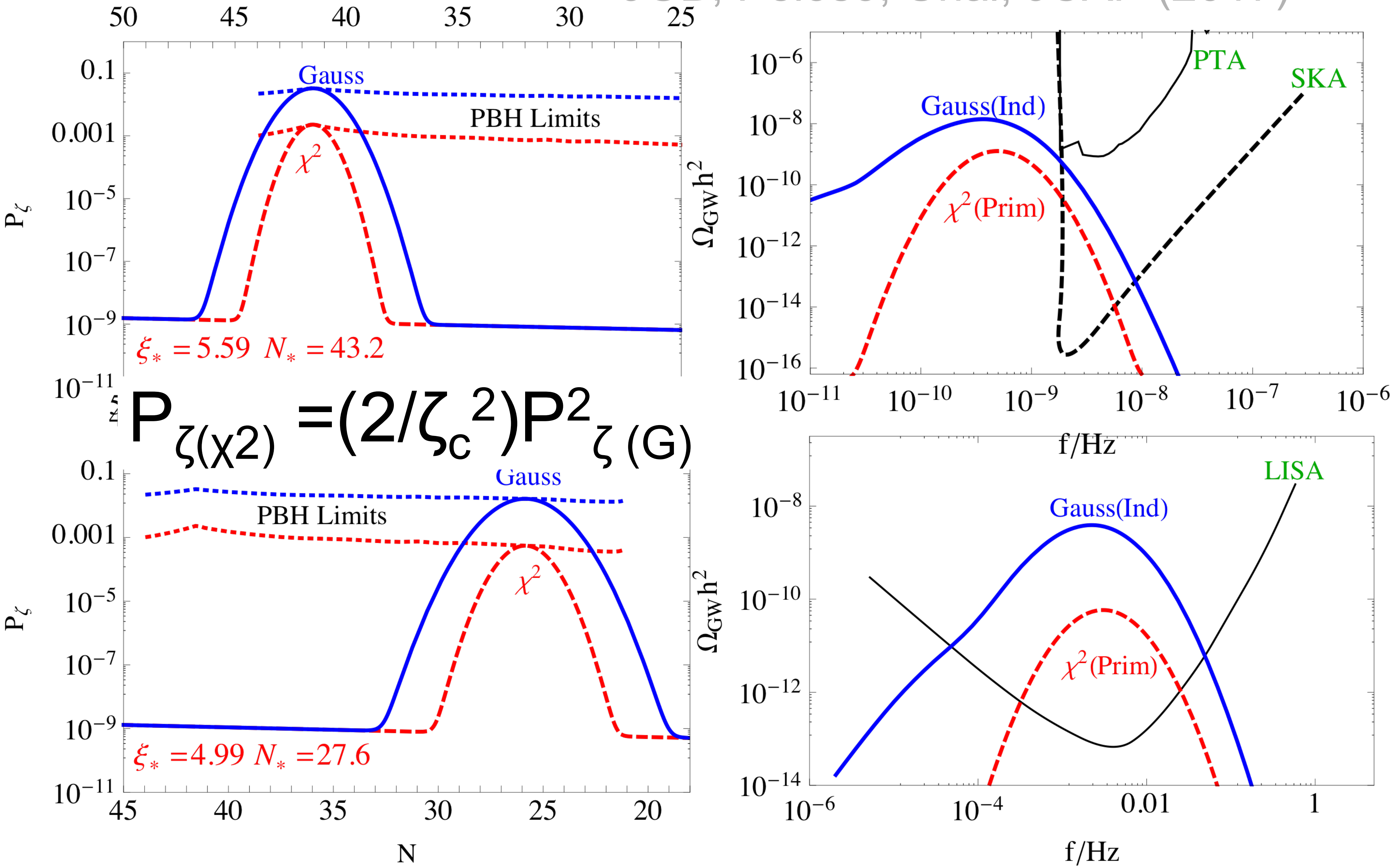
Clesse, JGB arXiv:1610.08479



$$h^2\Omega_{GW} = 2.2 \times 10^{-9} \left(\frac{f}{Hz}\right)^{2/3} \left(\frac{M_c}{100 M_{sun}}\right)^{5/3}$$

Second order background GW

JGB, Peloso, Unal, JCAP (2017)



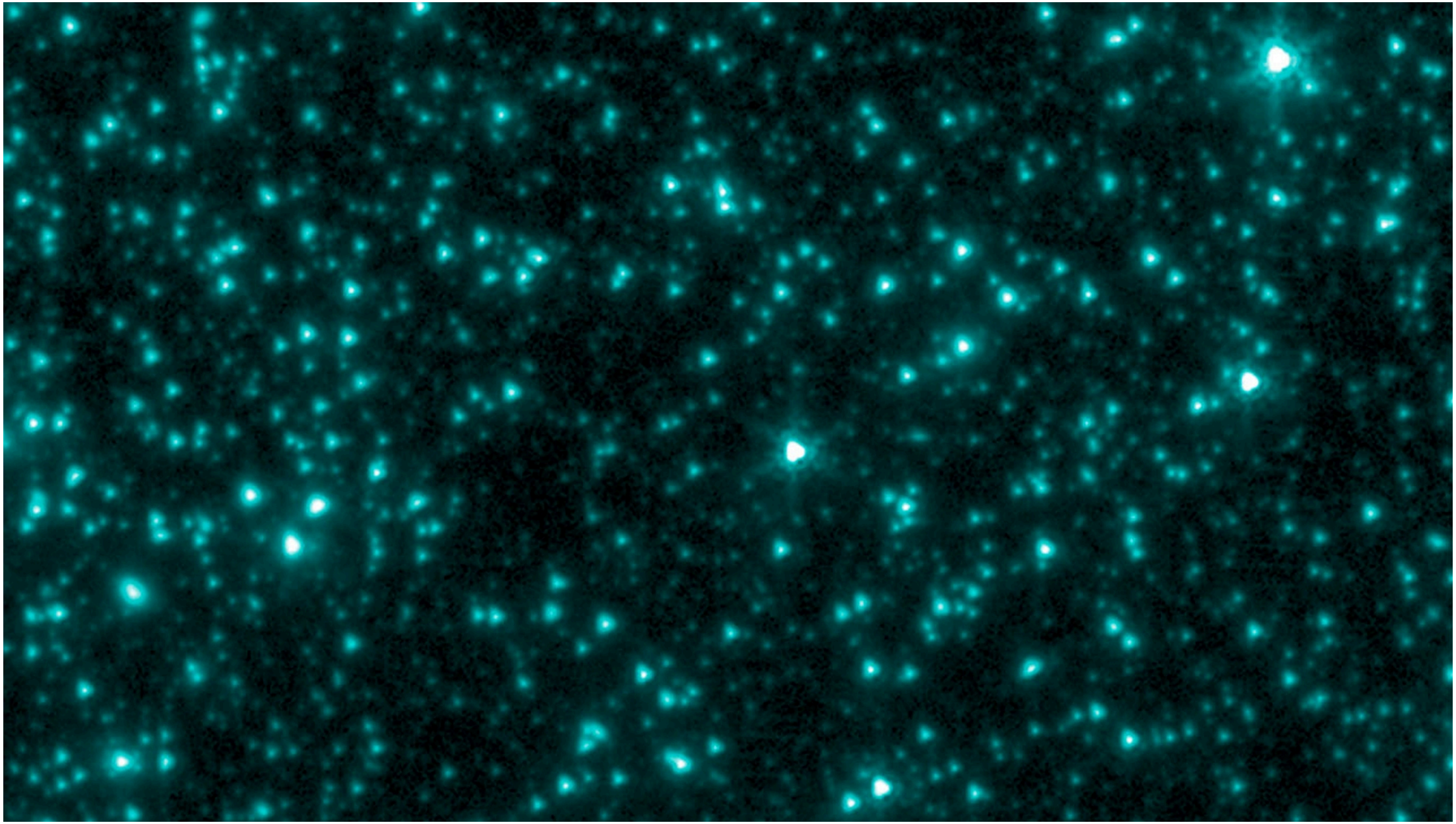
$$P_{\zeta(\chi 2)} = (2/\zeta_c^{\,2}) P^2_{\zeta\,(G)}$$

Conclusions

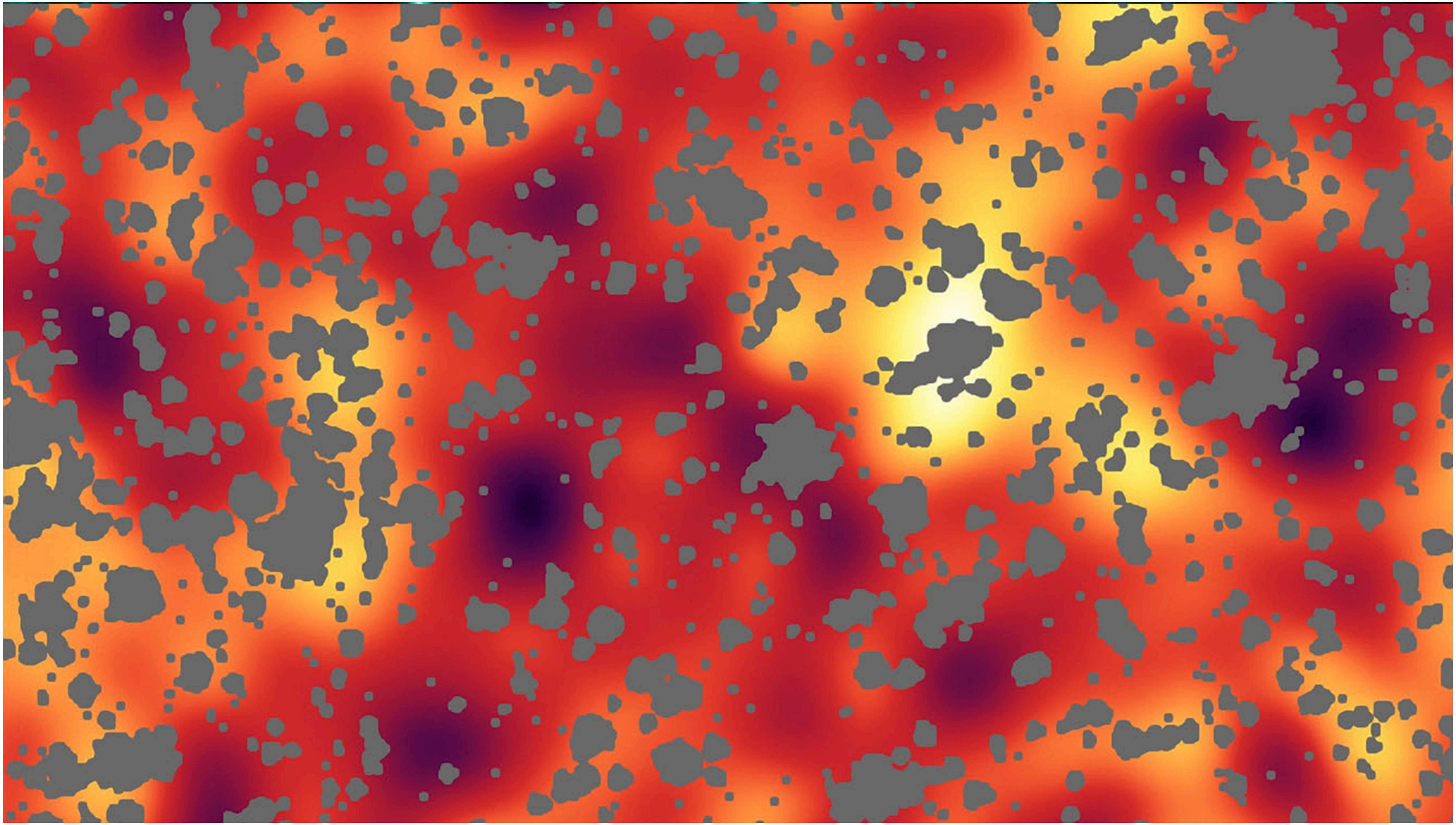
- Massive Primordial Black Holes are the perfect candidates for collisionless CDM, in excellent agreement with CMB and LSS observations.
- MPBHs could also resolve some of the most acute problems of ΛCDM paradigm, like early structure formation and substructure problems.
- MPBHs open a new window into the Early Universe, ~ 20-40 efolds before end inflation.
- There are many ways to test this idea in the near future from CMB, LSS, X-rays and GW.
- LISA/PTA could detect the stoch. background from MPBH merging since recombination.

Fluctuations CIB & X-ray Background

Kashlinsky (2016)

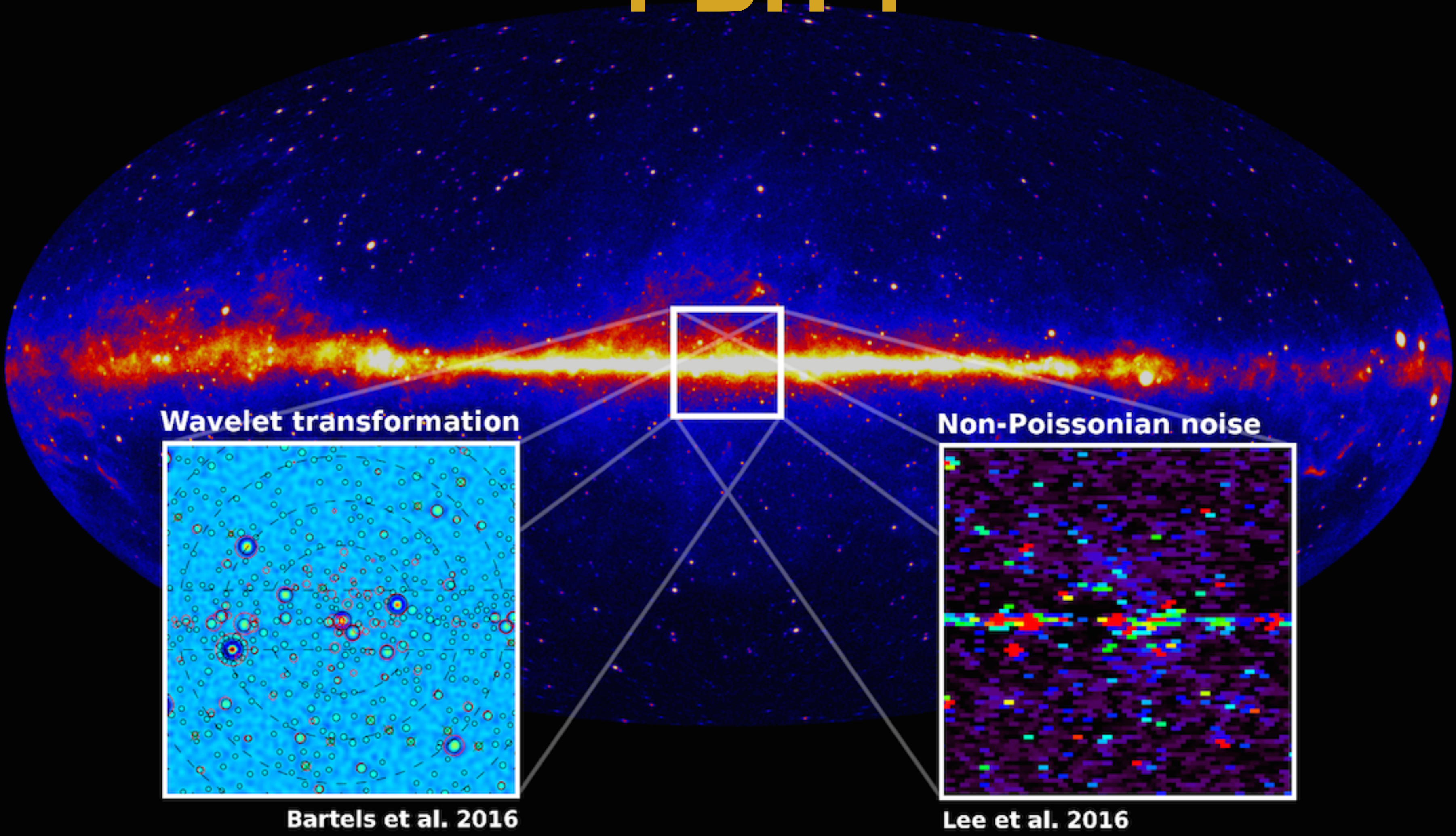


Kashlinsky (2016)



Diffuse Gamma-ray Background

Fermi-LAT Point Sources = PBH ?



Chandra Deep Field South

Chandra Deep Field South (2017)