Primordial Black Holes as Dark Matter and Models of Inflation

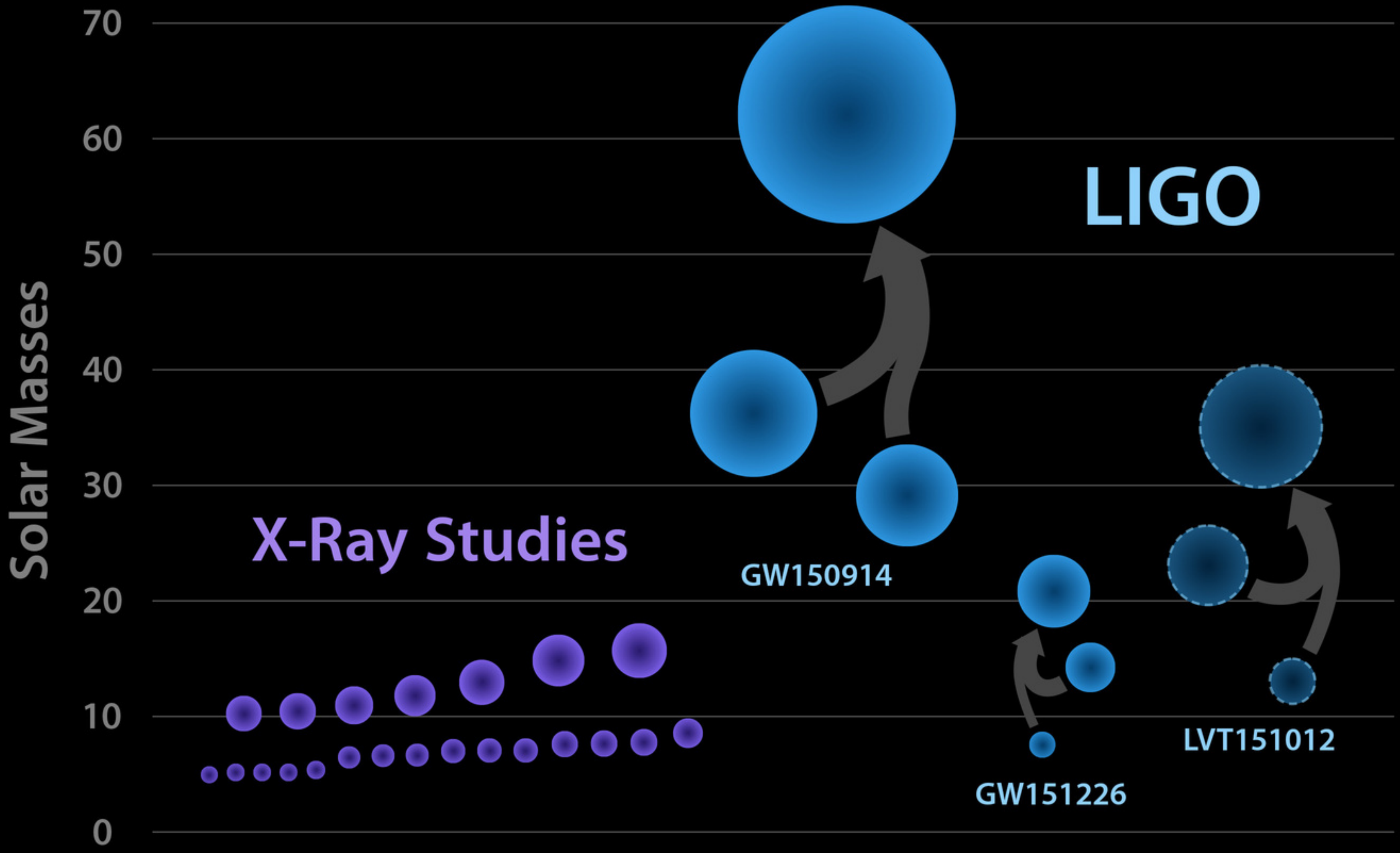
based on JGB & Ruiz Morales, arXiv:1702.03901
Ezquiaga, JGB & Ruiz Morales, arXiv:1705.04861
arXiv:1702.08275, S. Clesse & JGB, arXiv:1610.08479
JGB, M. Peloso & C. Unal, JCAP 12 (2016) 031
S. Clesse & JGB, Phys Dark Univ 10 (2016) 002
S. Clesse & JGB, Phys Rev D92 (2015) 023524
JGB, Linde & Wands, Phys Rev D54 (1996) 6040

Juan García-Bellido
16th May 2017

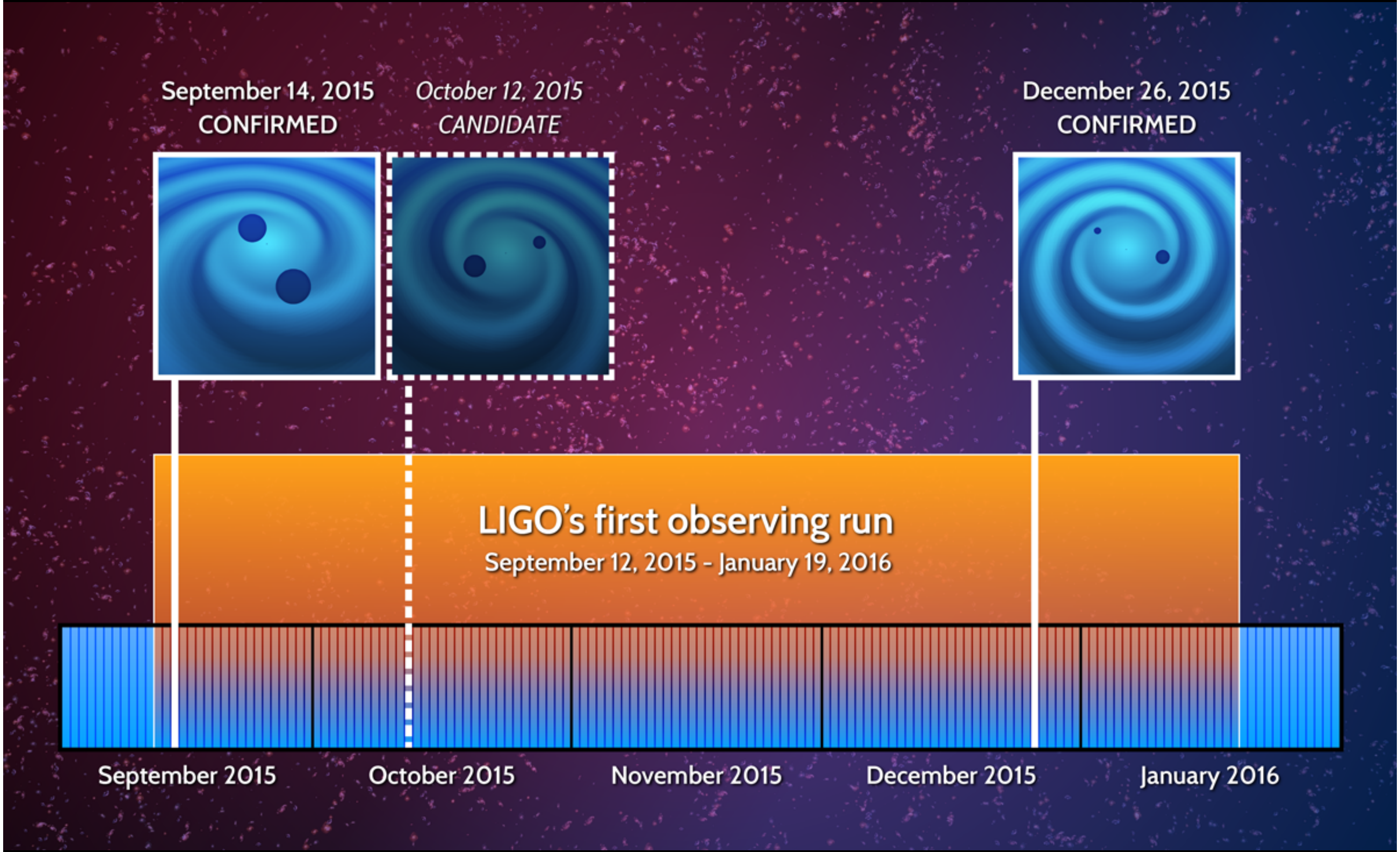
Outline

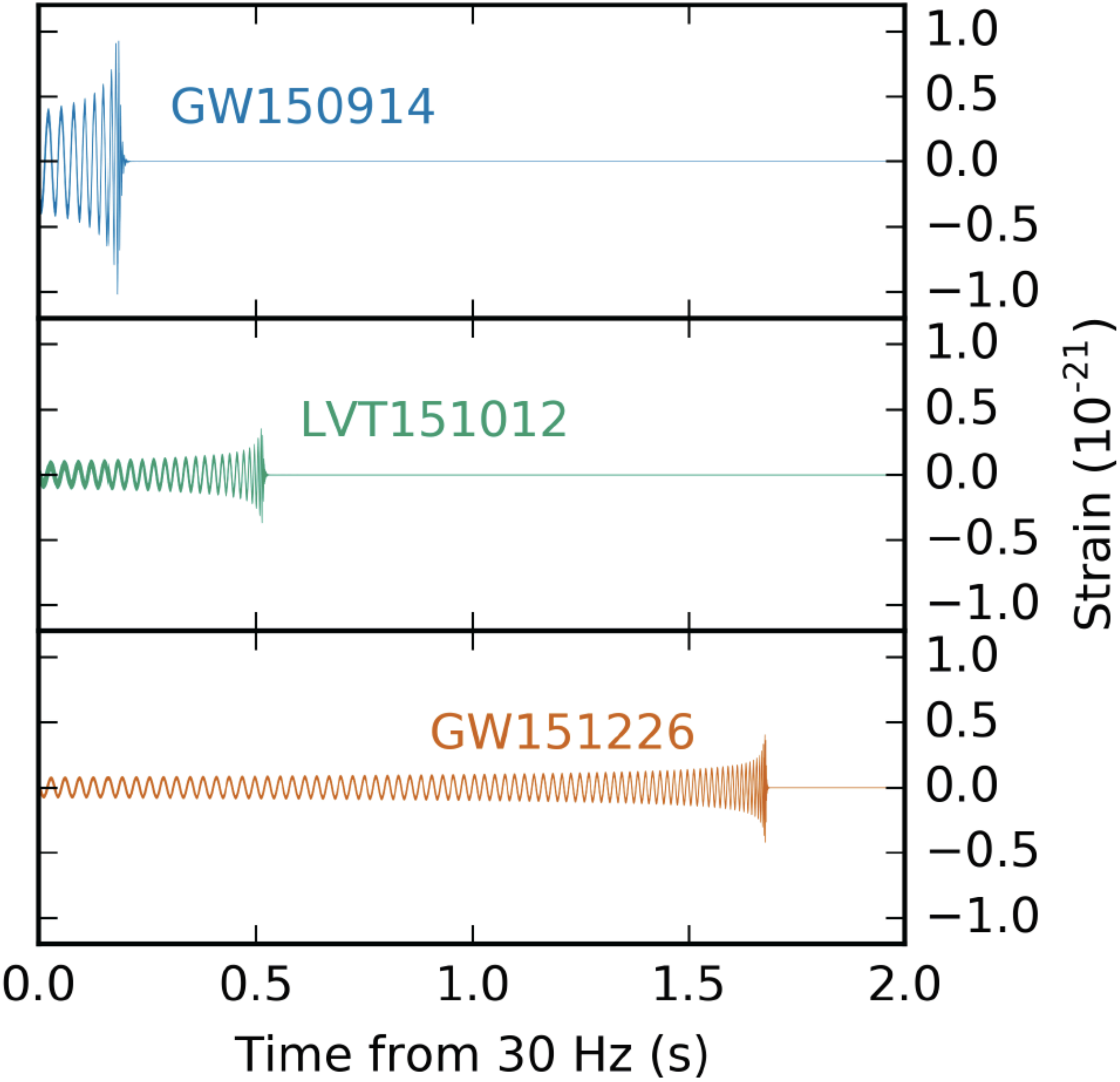
- Discovery of 3 BHB by aLIGO-O1 started a new era of GW Astronomy
- PBH = Dark Matter
- Peaks in Curvature (Quantum orig.)
- Higgs = Inflaton (Critical Higgs Inf.)
- Particle Physics Beyond SM
- Test PBH with GW interferometers
- Conclusions

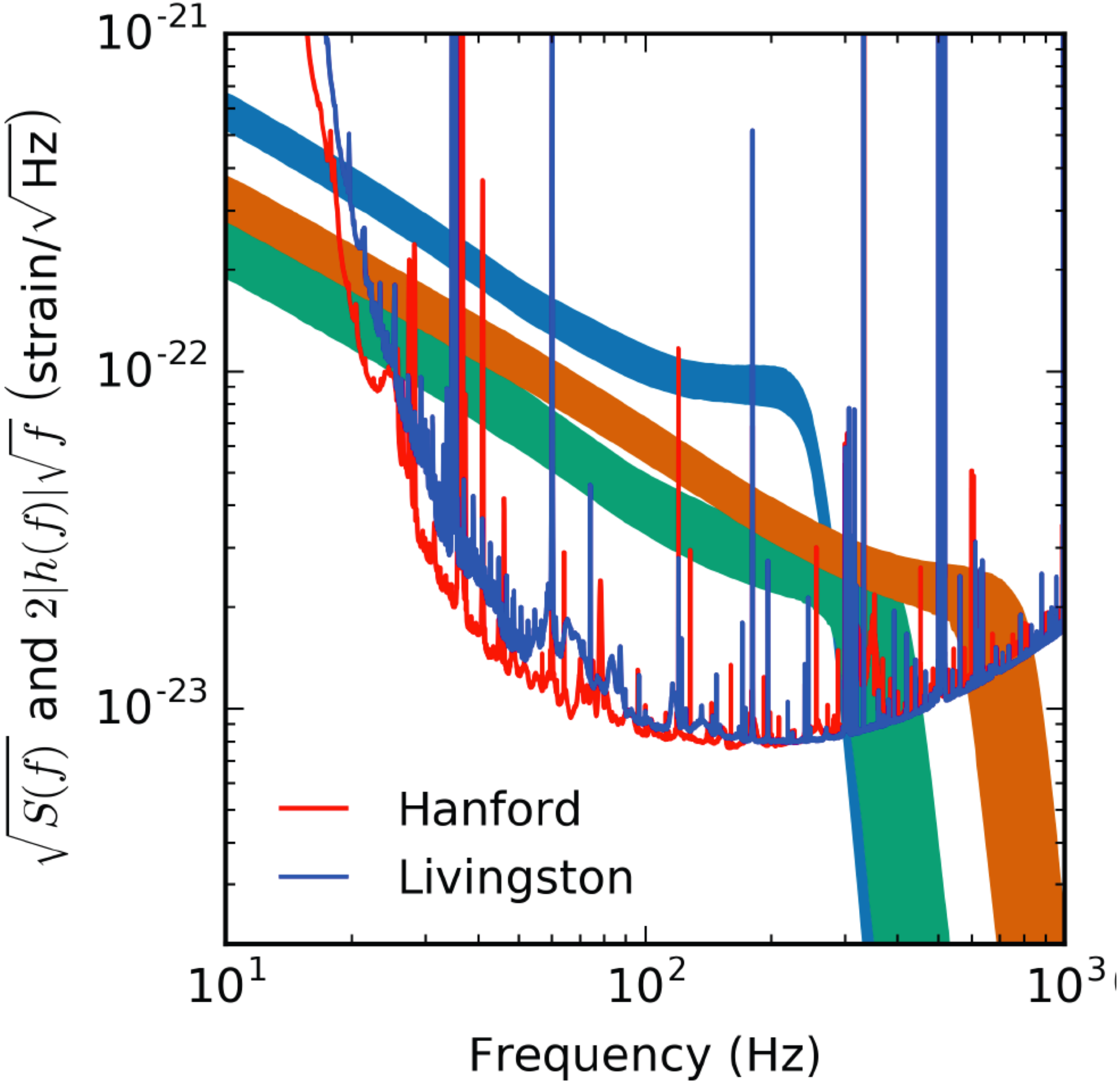
Black Holes of Known Mass



Merging Binary BHs @ LIGO



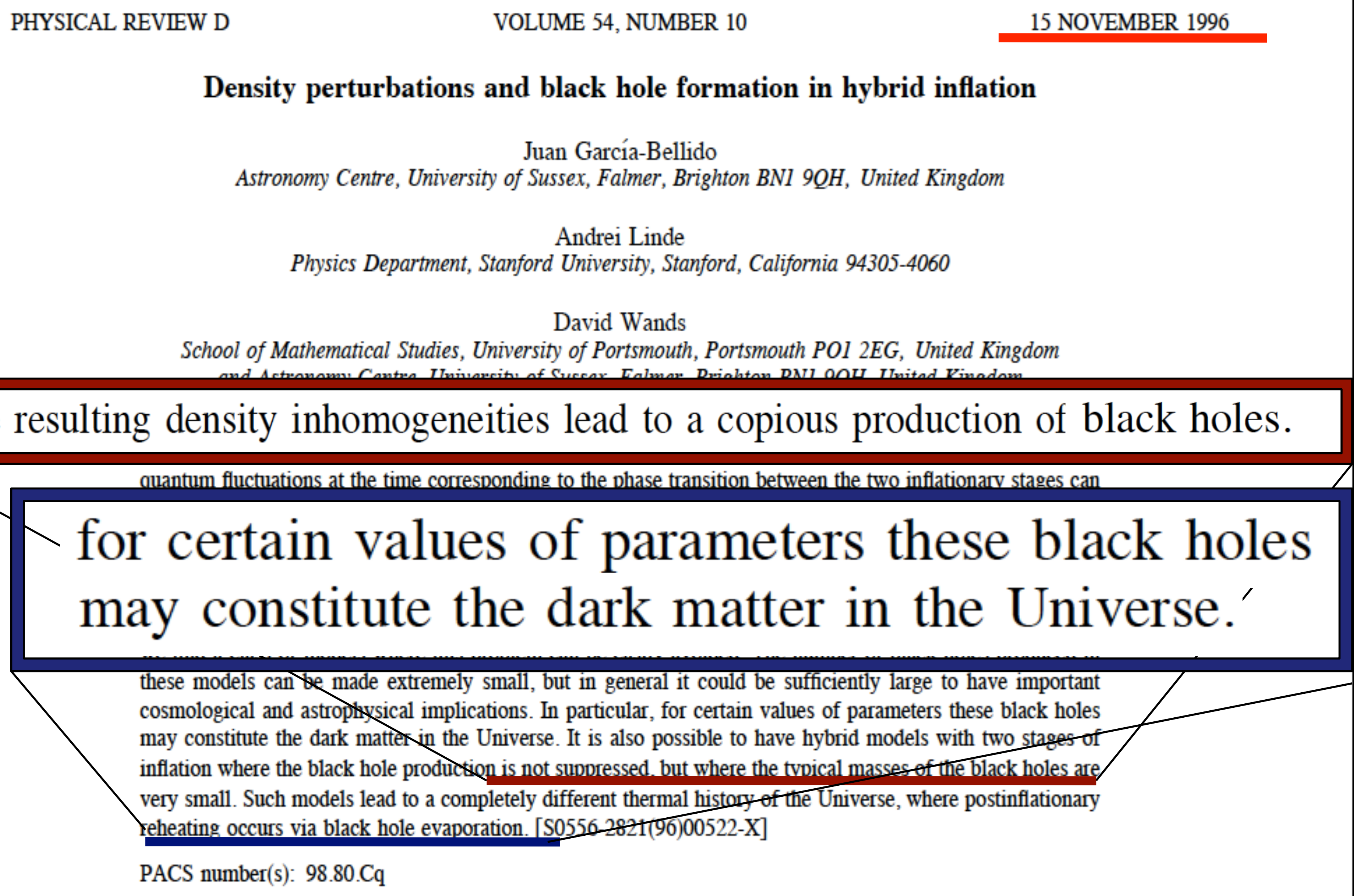

GW150914
LVT151012
GW151226
1.0
0.5
0.0
−0.5
−1.0
Strain (10^{-21})
0.0
0.5
1.0
1.5
2.0
Time from 30 Hz (s)


10^{-21}
10^{-22}
10^{-23}
10^{1}
10^{2}
10^{3}
Frequency (Hz)
$\sqrt{S(f)}$ and $2|h(f)|\sqrt{f}$ (strain/$\sqrt{\text{Hz}}$)
Hanford
Livingston

Gravitational Wave Astronomy

- Discovery of binary BHs by AdvLIGO
- VIRGO, KAGRA, INDIGO = GW Astron
- GW150914 = 36 + 29 M_{sun} BH binary
- GW151226 = 14 + 8 M_{sun} BH binary
- LVT151012 = 23 + 13 M_{sun} “candidate”
- Expected 50-100 events/yr/Gpc^3
- AdvLIGO+ can map the mass and spin Massive BH ($0.1\ M_{sun} < M_{BH} < 150\ M_{sun}$) n.b. $f_{ISCO} = 4400\ Hz\ (M_{sun}/M_{BH})$

Massive Primordial Black Holes as DM



PHYSICAL REVIEW D VOLUME 54, NUMBER 10 15 NOVEMBER 1996

Density perturbations and black hole formation in hybrid inflation

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and Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom

. The resulting density inhomogeneities lead to a copious production of black holes.

quantum fluctuations at the time corresponding to the phase transition between the two inflationary stages can

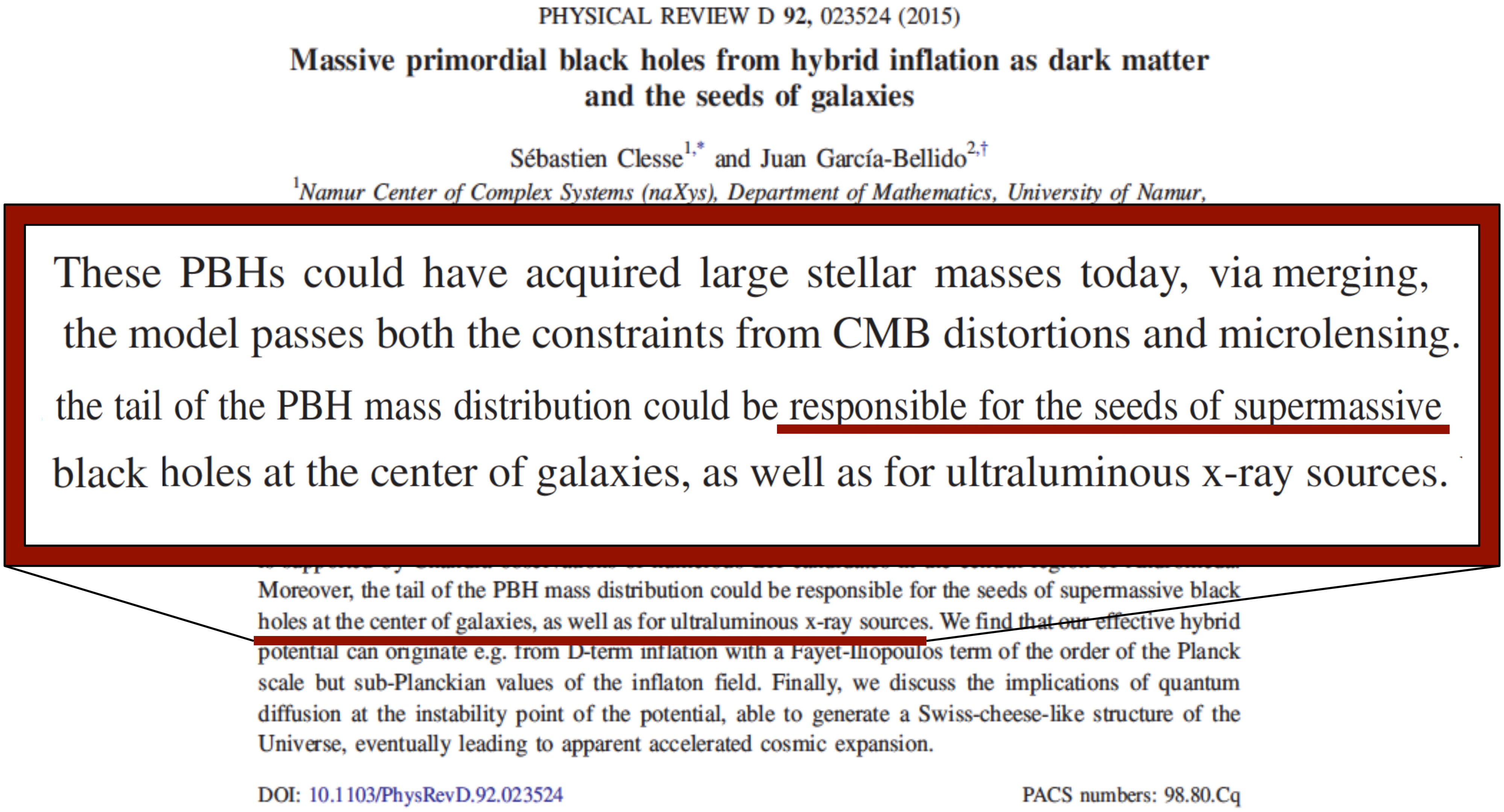
for certain values of parameters these black holes may constitute the dark matter in the Universe.

these models can be made extremely small, but in general it could be sufficiently large to have important cosmological and astrophysical implications. In particular, for certain values of parameters these black holes may constitute the dark matter in the Universe. It is also possible to have hybrid models with two stages of inflation where the black hole production is not suppressed, but where the typical masses of the black holes are very small. Such models lead to a completely different thermal history of the Universe, where postinflationary reheating occurs via black hole evaporation. [S0556-2821(96)00522-X]

PACS number(s): 98.80.Cq

Steven Weinberg

“our problem is not that we
take our theories too seriously,
but that we
don't take them seriously enough”



PHYSICAL REVIEW D **92**, 023524 (2015)

Massive primordial black holes from hybrid inflation as dark matter and the seeds of galaxies

Sébastien Clesse[1,*] and Juan García-Bellido[2,†]
[1]*Namur Center of Complex Systems (naXys), Department of Mathematics, University of Namur,*

These PBHs could have acquired large stellar masses today, via merging, the model passes both the constraints from CMB distortions and microlensing.

the tail of the PBH mass distribution could be responsible for the seeds of supermassive black holes at the center of galaxies, as well as for ultraluminous x-ray sources.

Moreover, the tail of the PBH mass distribution could be responsible for the seeds of supermassive black holes at the center of galaxies, as well as for ultraluminous x-ray sources. We find that our effective hybrid potential can originate e.g. from D-term inflation with a Fayet-Iliopoulos term of the order of the Planck scale but sub-Planckian values of the inflaton field. Finally, we discuss the implications of quantum diffusion at the instability point of the potential, able to generate a Swiss-cheese-like structure of the Universe, eventually leading to apparent accelerated cosmic expansion.

DOI: 10.1103/PhysRevD.92.023524 PACS numbers: 98.80.Cq

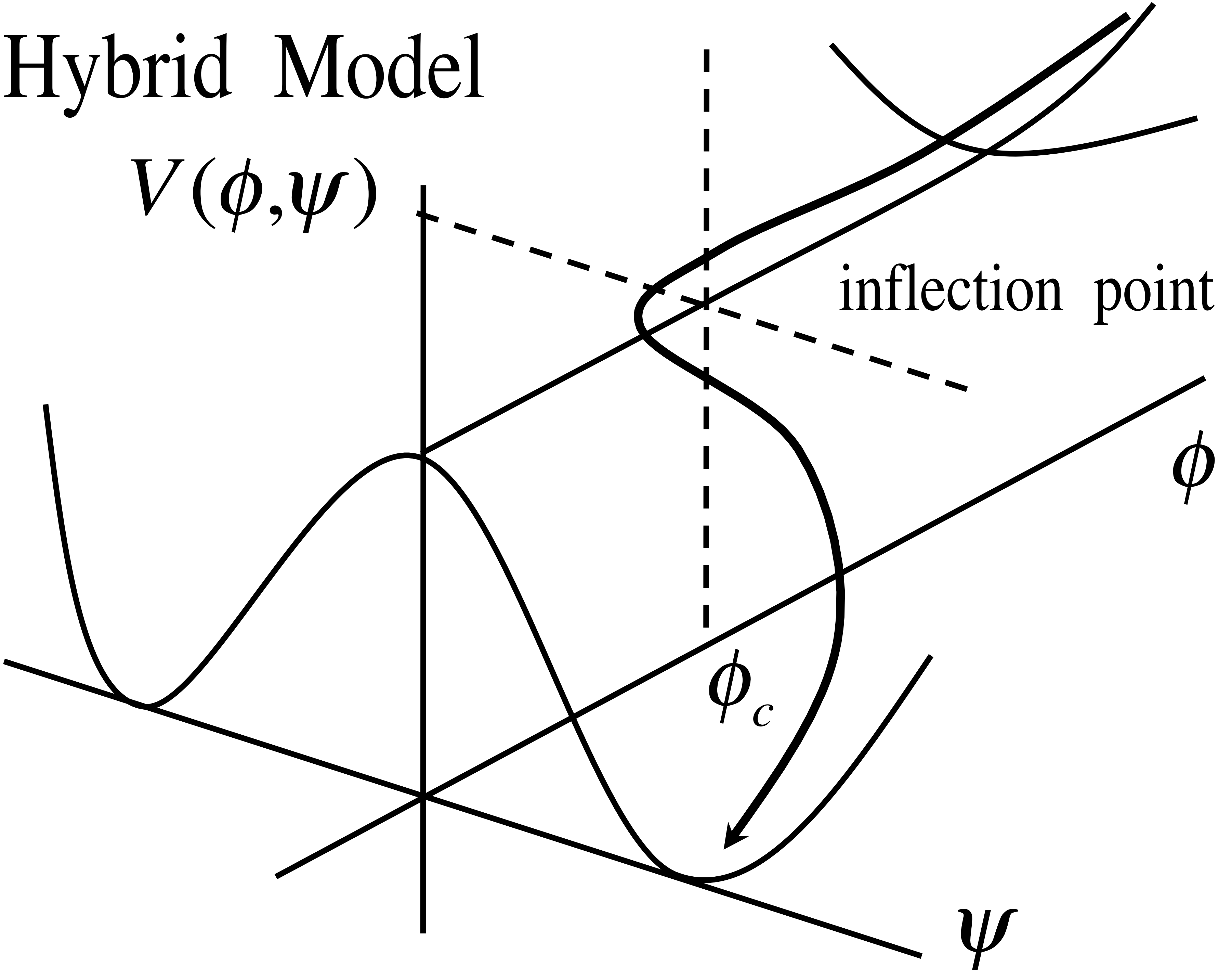
PHYSICAL REVIEW D **92,** 023524 (2015)

Moreover, PBH binaries should emit gravitational waves that could be detected by future gravitational wave experiments such as LIGO, DECIGO and eLISA [70,71].

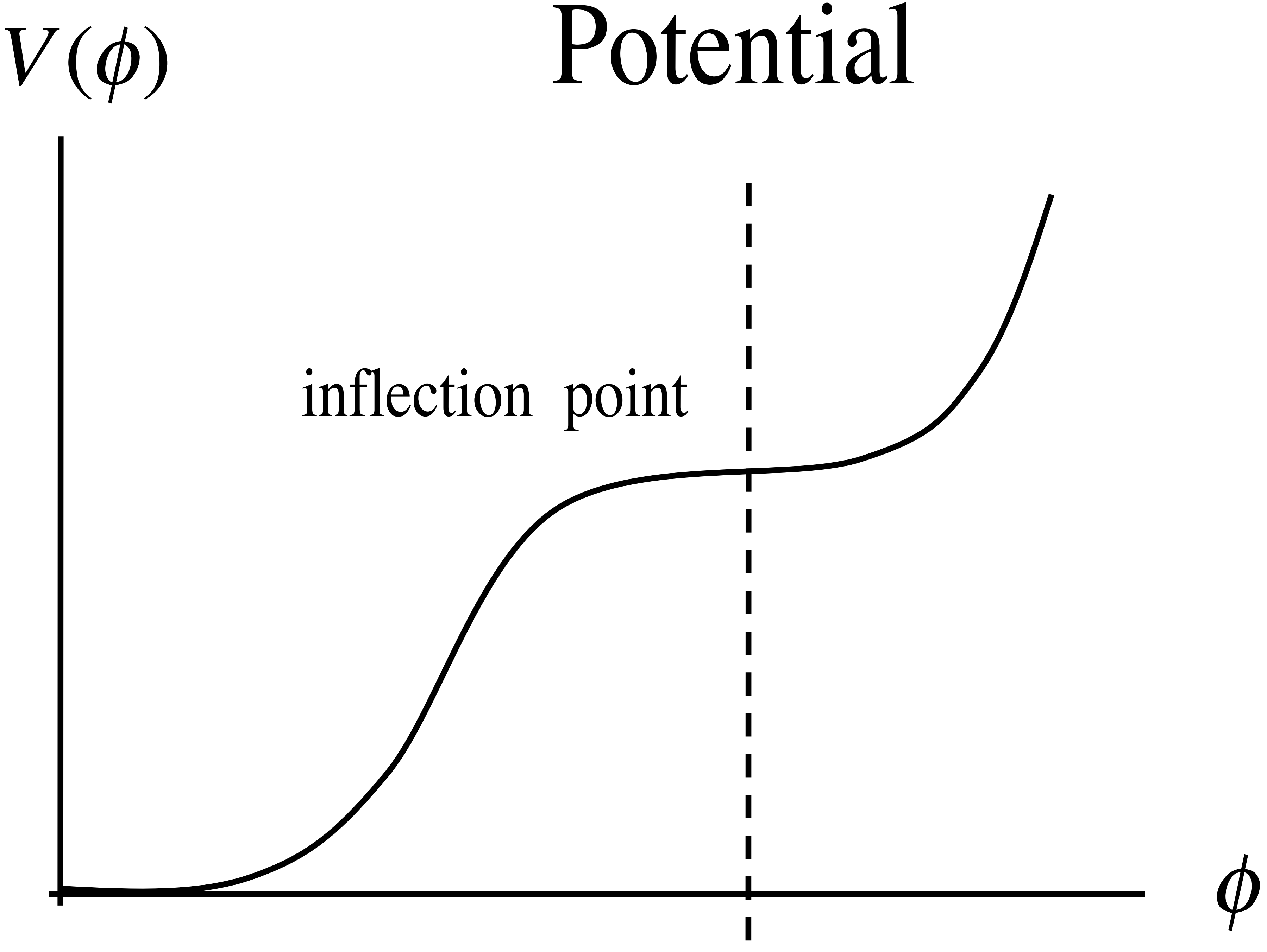
Binaries of PBHs forming a fraction of dark matter should emit gravitational waves; this results in a background of gravitational waves that could be observed by LIGO, DECIGO and eLISA [70–72].

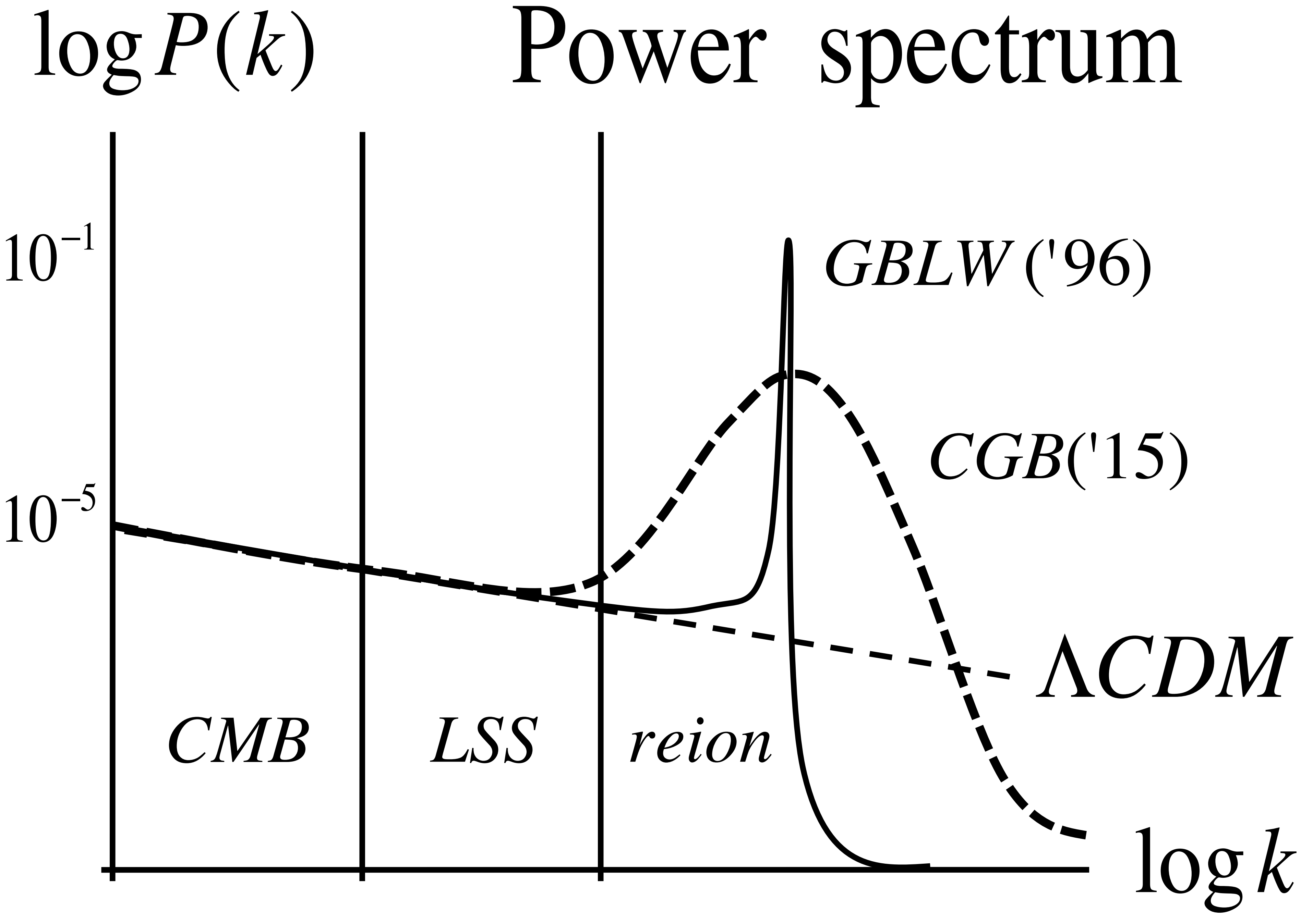
What models of Inflation produce PBH

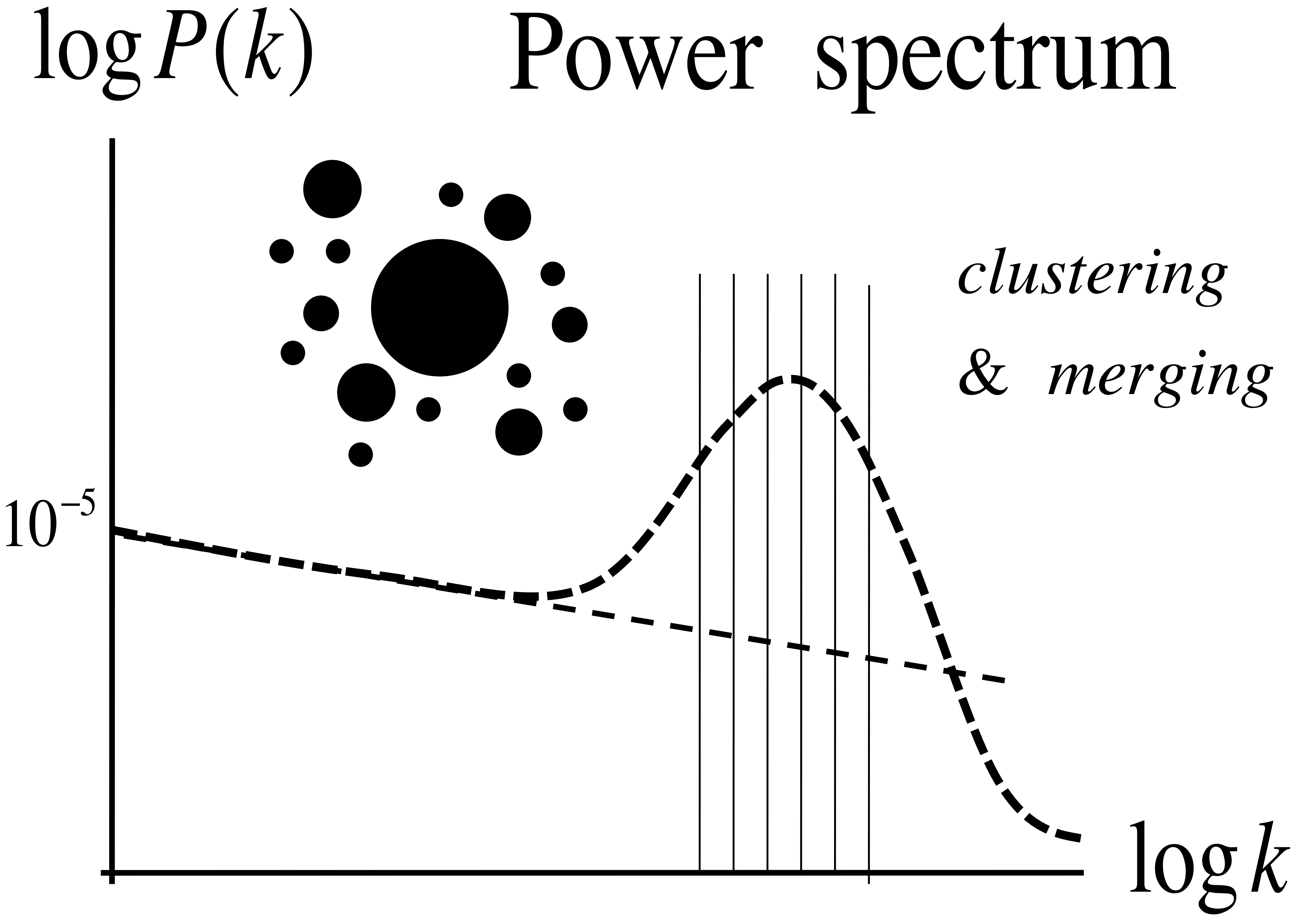
Hybrid Model



Potential

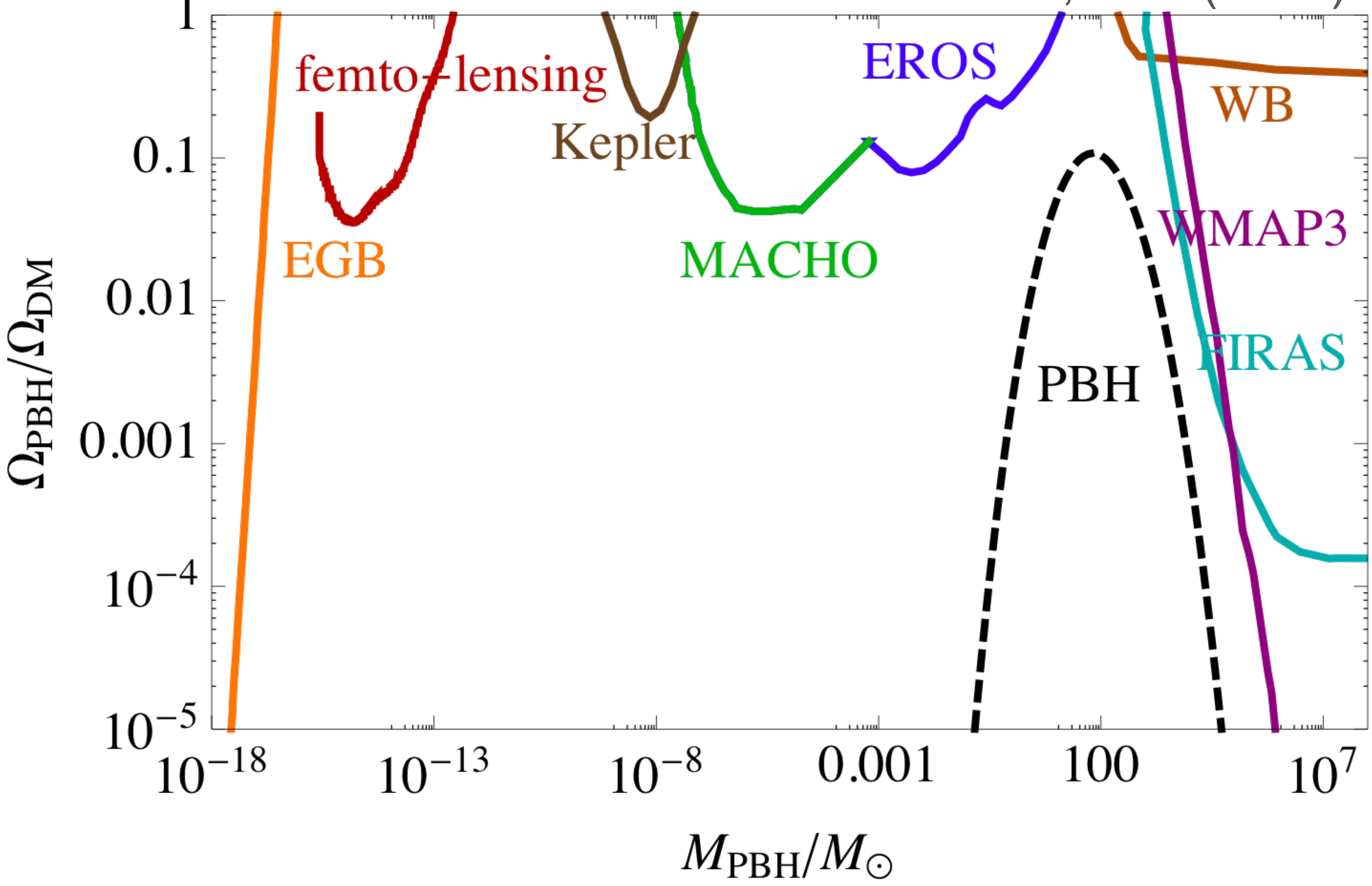



$\log P(k)$
Power spectrum
10^{-1}
10^{-5}
GBLW ('96)
CGB ('15)
ΛCDM
CMB
LSS
reion
$\log k$


$\log P(k)$
Power spectrum
clustering
& merging
10^{-5}
$\log k$

Present Constraints on PBH

Clesse, JGB (2015)



Critical Higgs Inflation

Concrete realization: PBH in Critical Higgs Inflation

Ezquiaga, JGB, Ruiz Morales (2017)

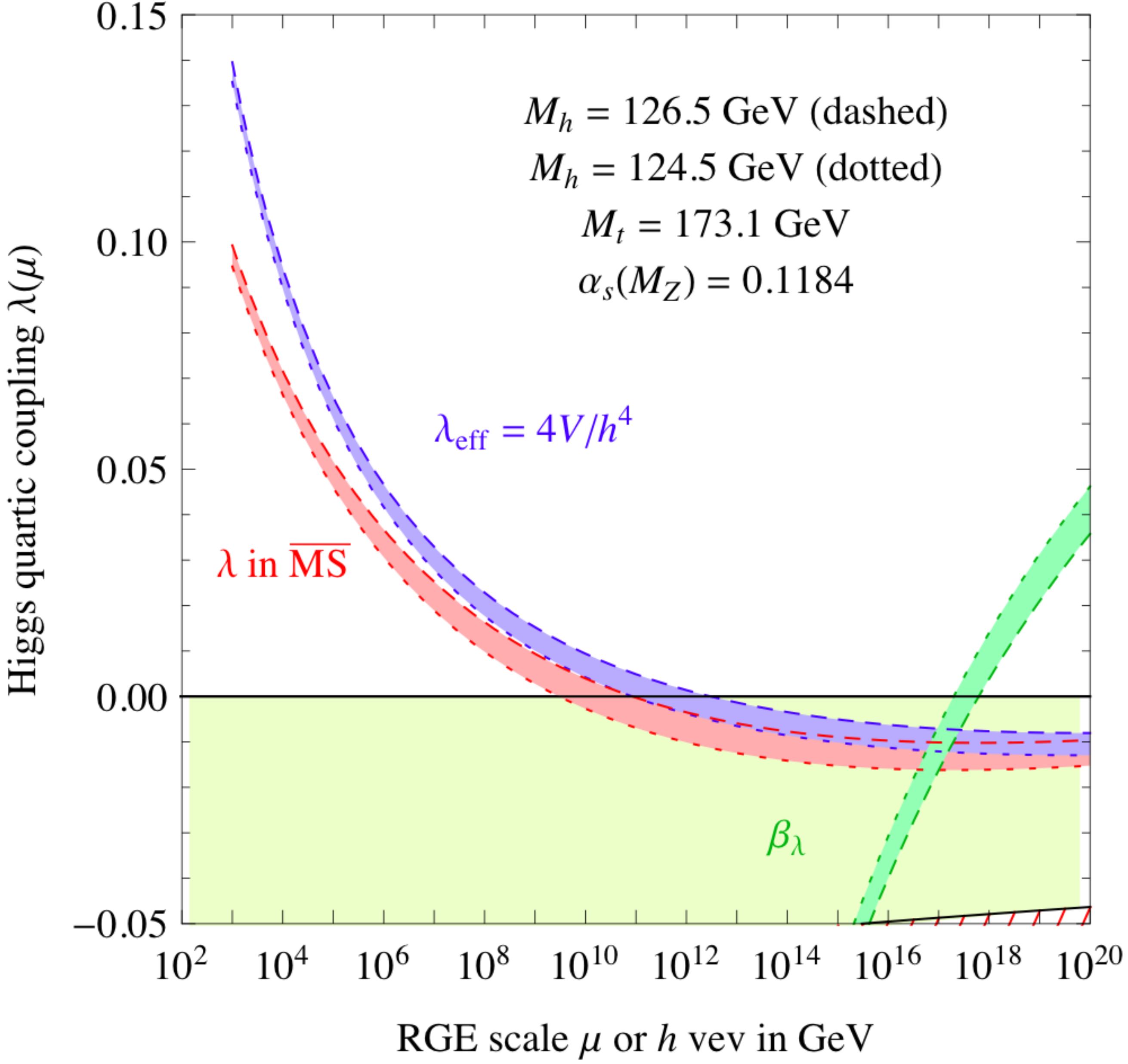
$$S=\int d^4x\sqrt{g}\left[\left(\frac{1}{2\kappa^2}+\frac{\xi(\phi)}{2}\phi^2\right)R-\frac{1}{2}(\partial\phi)^2-\frac{1}{4}\lambda(\phi)\phi^4\right]$$

$$\begin{aligned}\lambda(\phi) &= \lambda_0+b_\lambda\ln^2\left(\phi/\mu\right)\ ,\\ \xi(\phi) &= \xi_0+b_\xi\ln\left(\phi/\mu\right)\ ,\end{aligned}$$

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

Non-minimal coupling of Higgs to gravity

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



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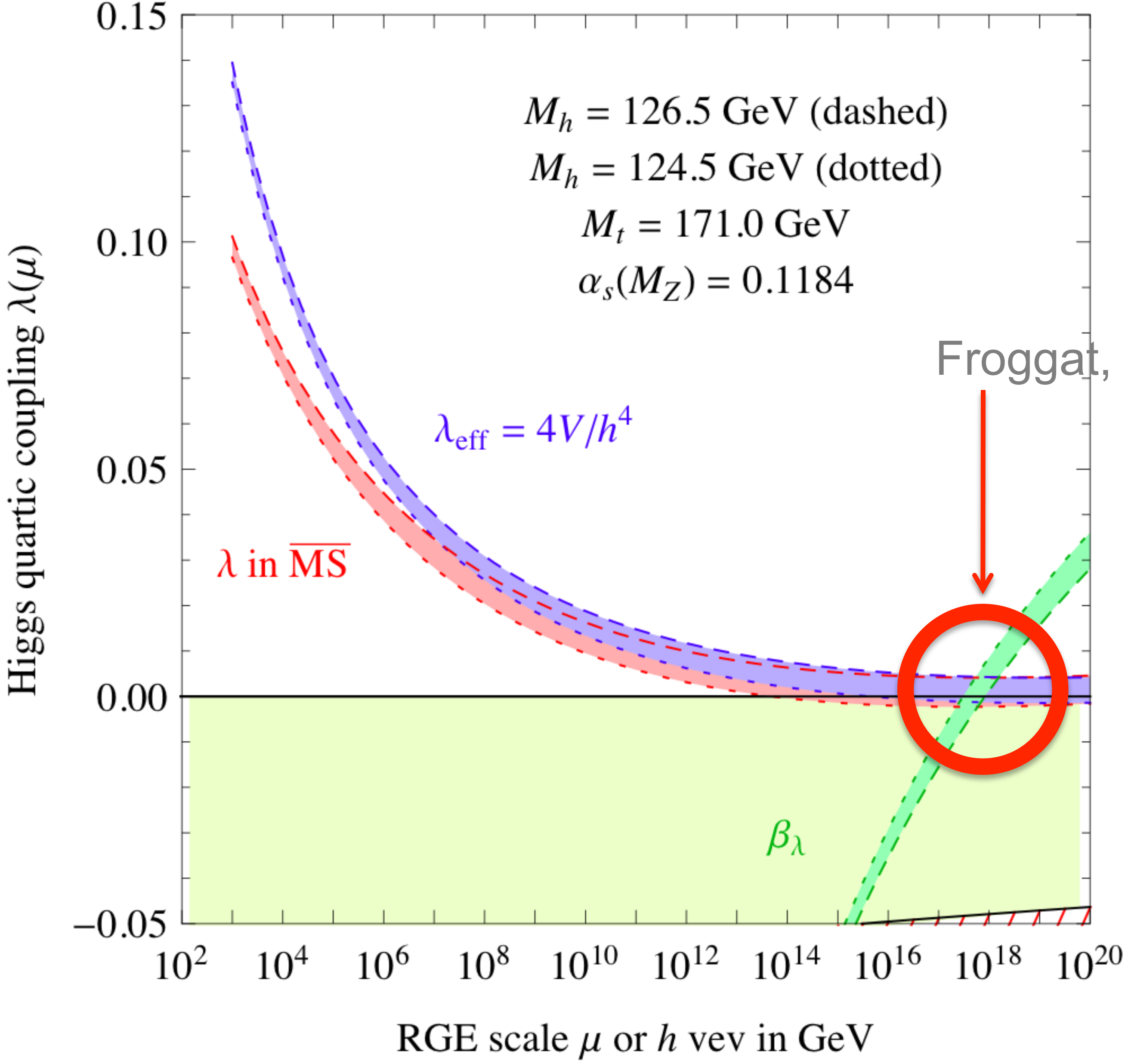
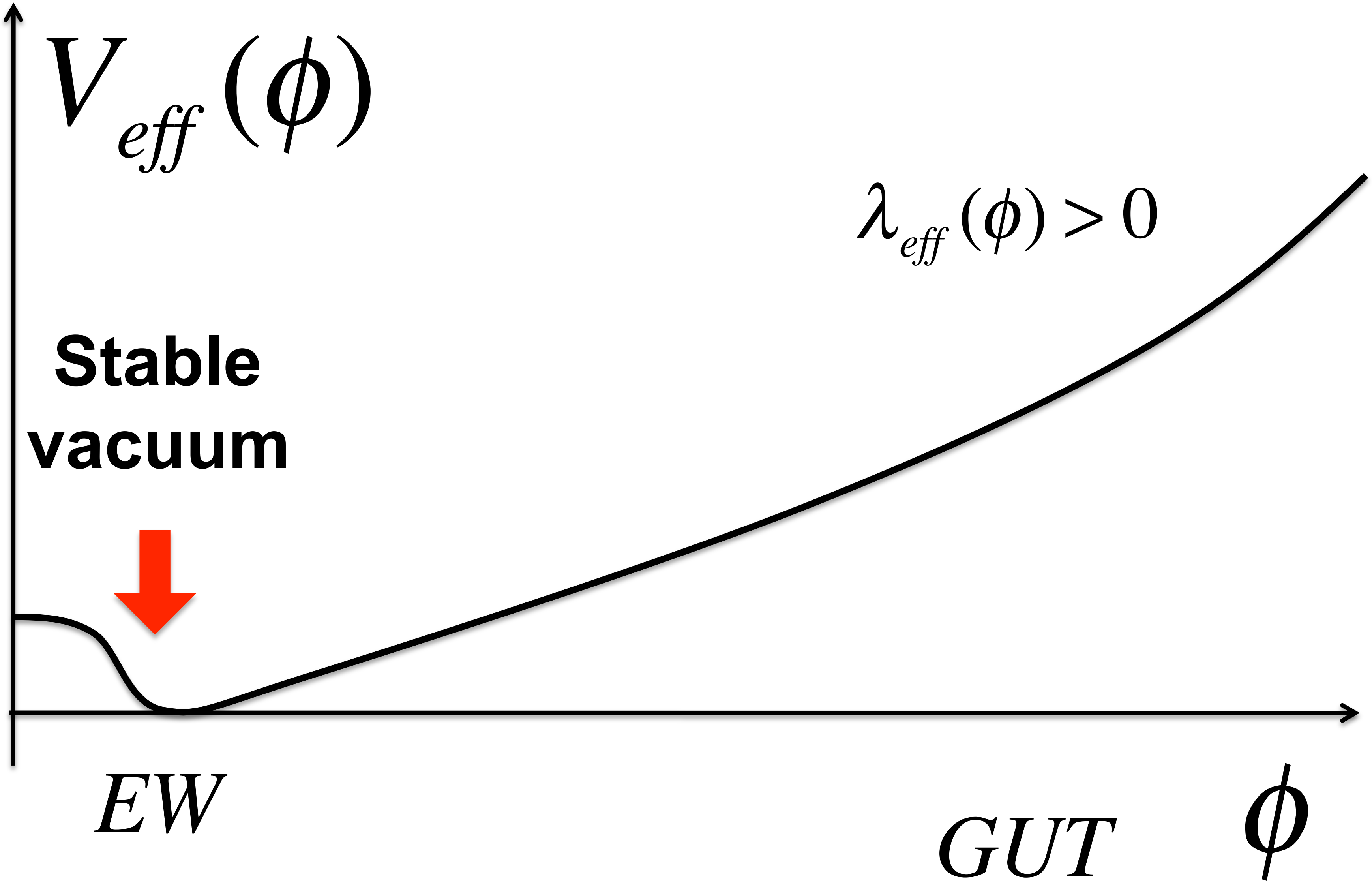
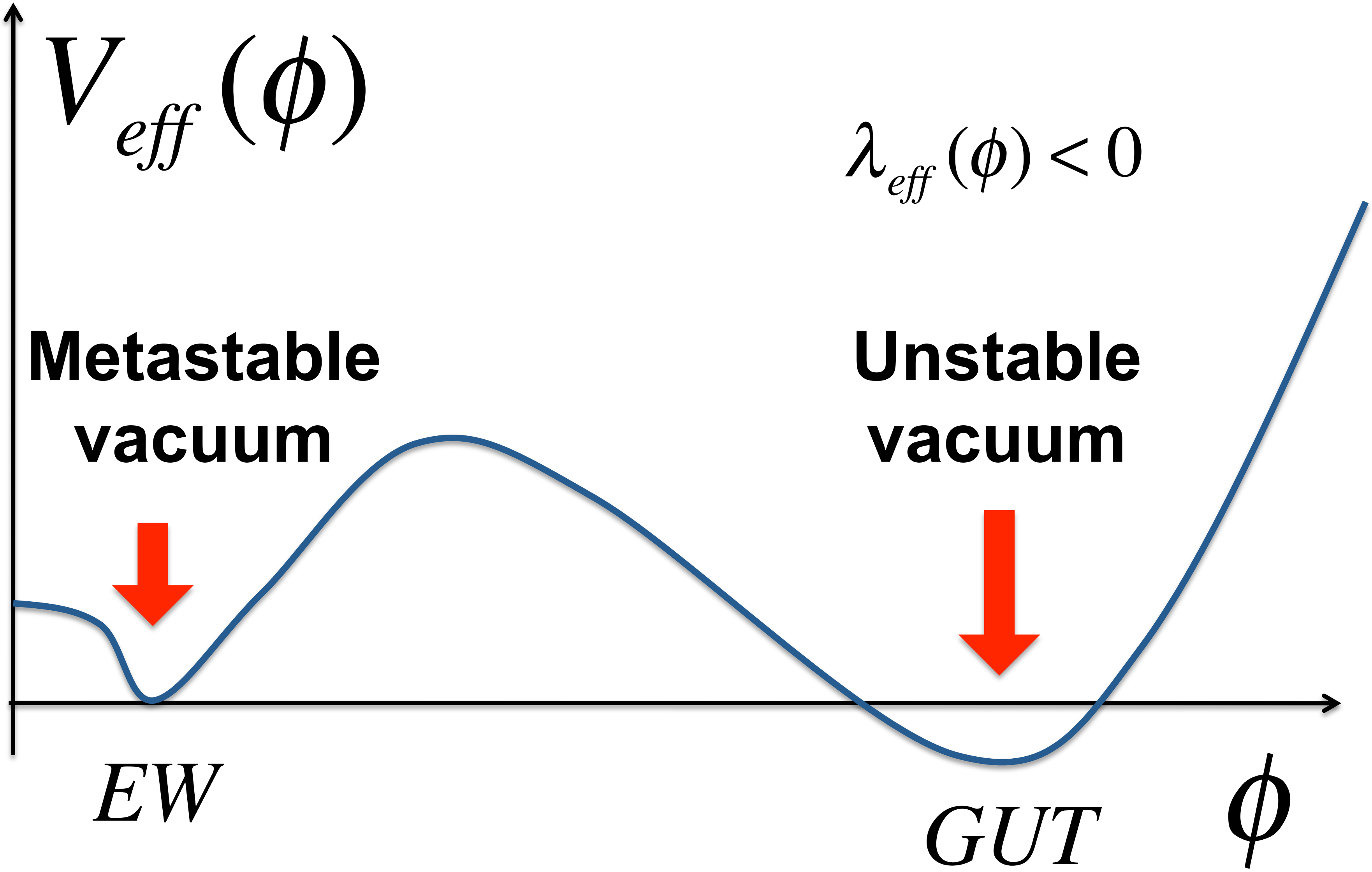


Froggat, Nielsen ('70)

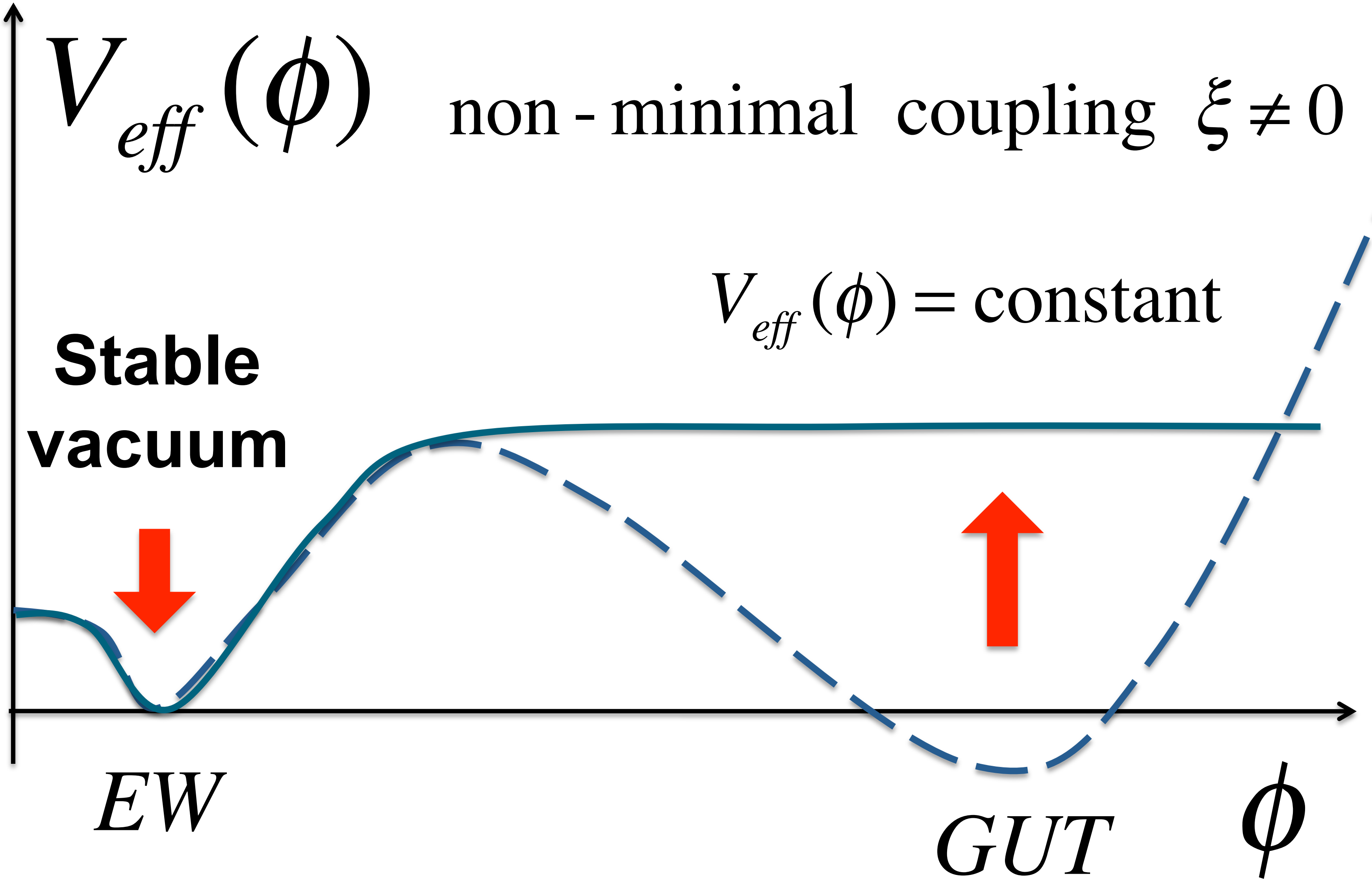
Higgs effective potential



Higgs effective potential



Higgs effective potential



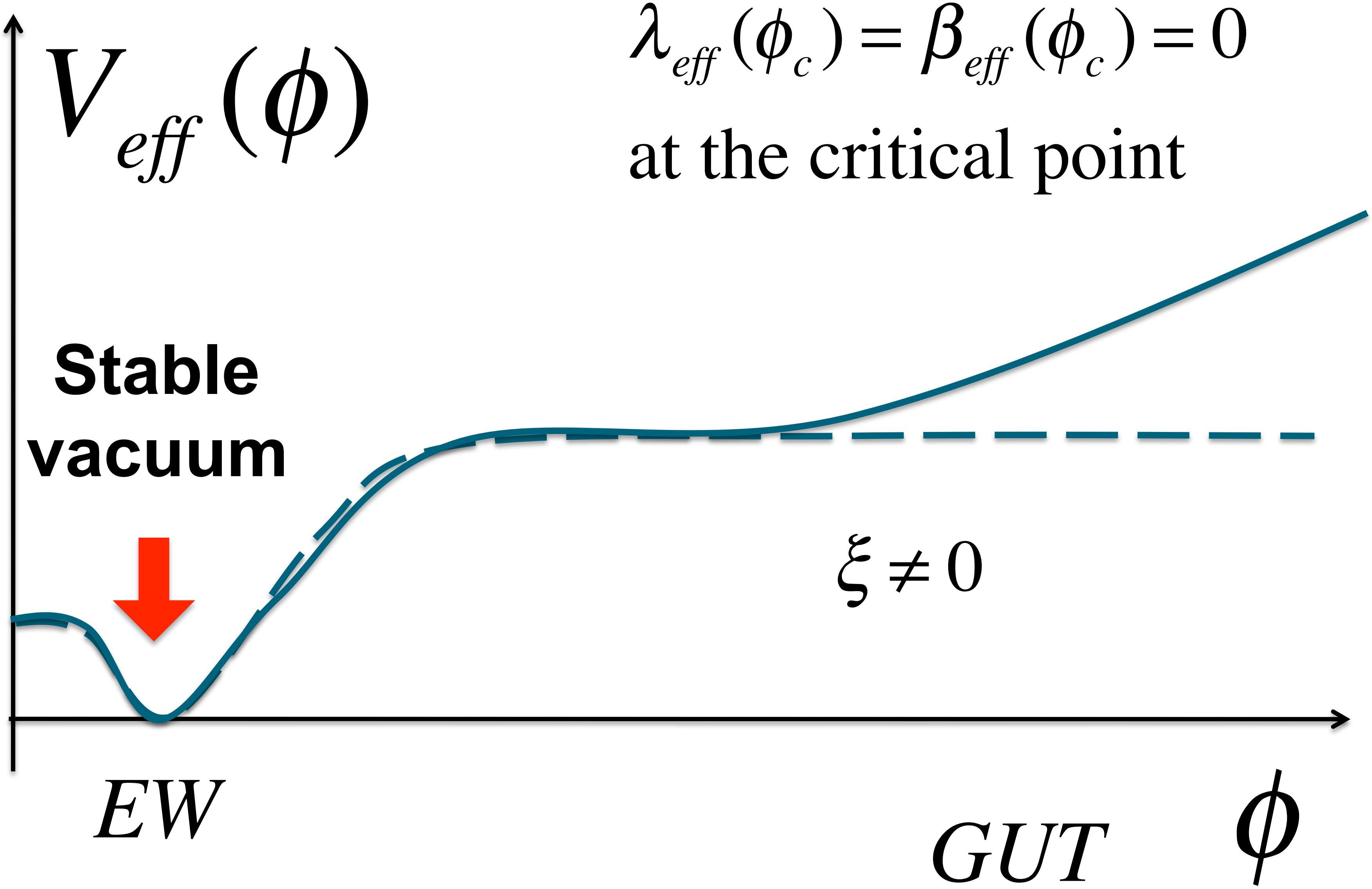
non - minimal coupling $\xi \neq 0$

$V_{eff}(\phi) = \text{constant}$

Higgs effective potential

$$\lambda_{eff}(\phi_c) = \beta_{eff}(\phi_c) = 0$$

at the critical point



Concrete realization: CHI model

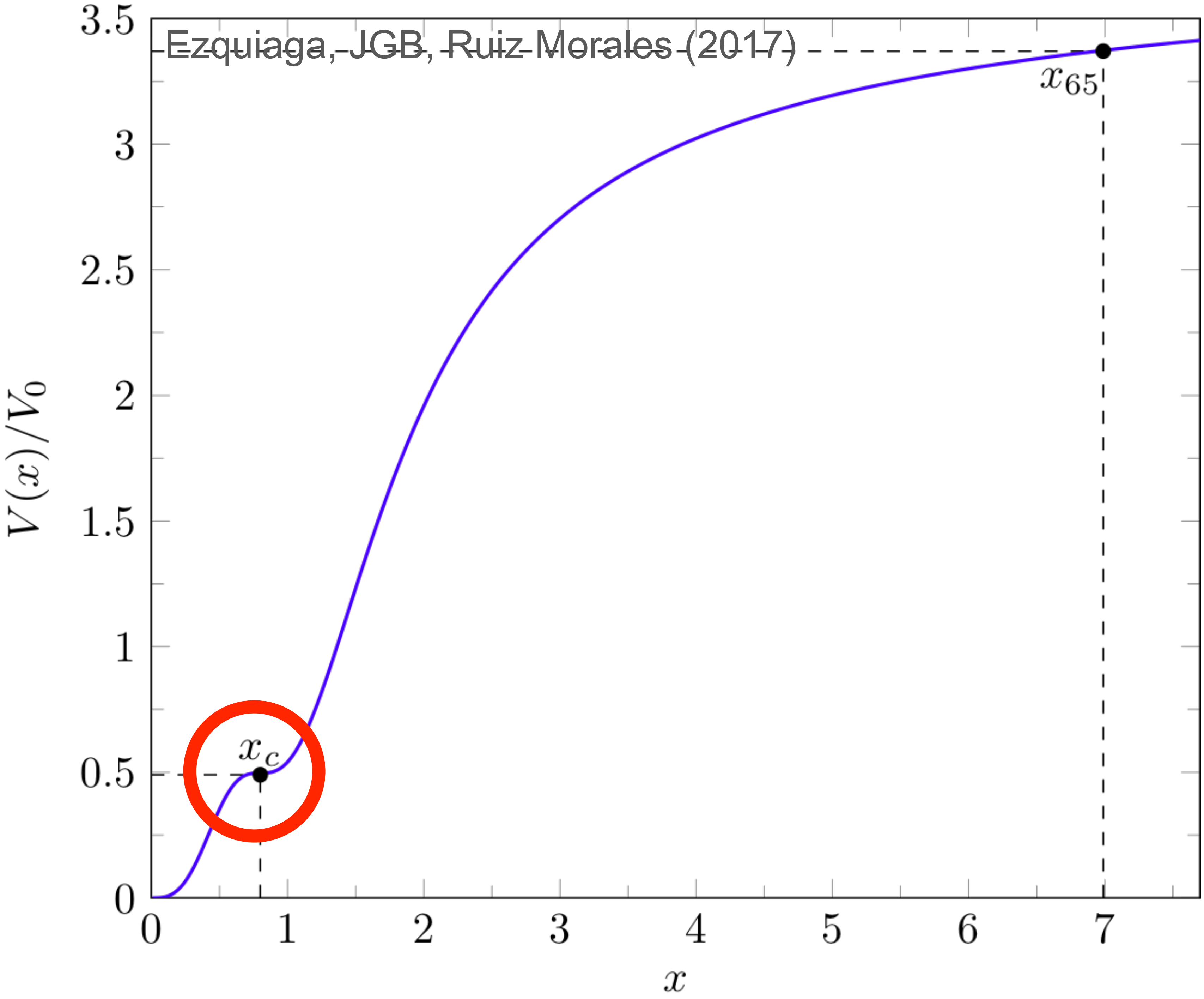
Ezquiaga, JGB, Ruiz Morales (2017)

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

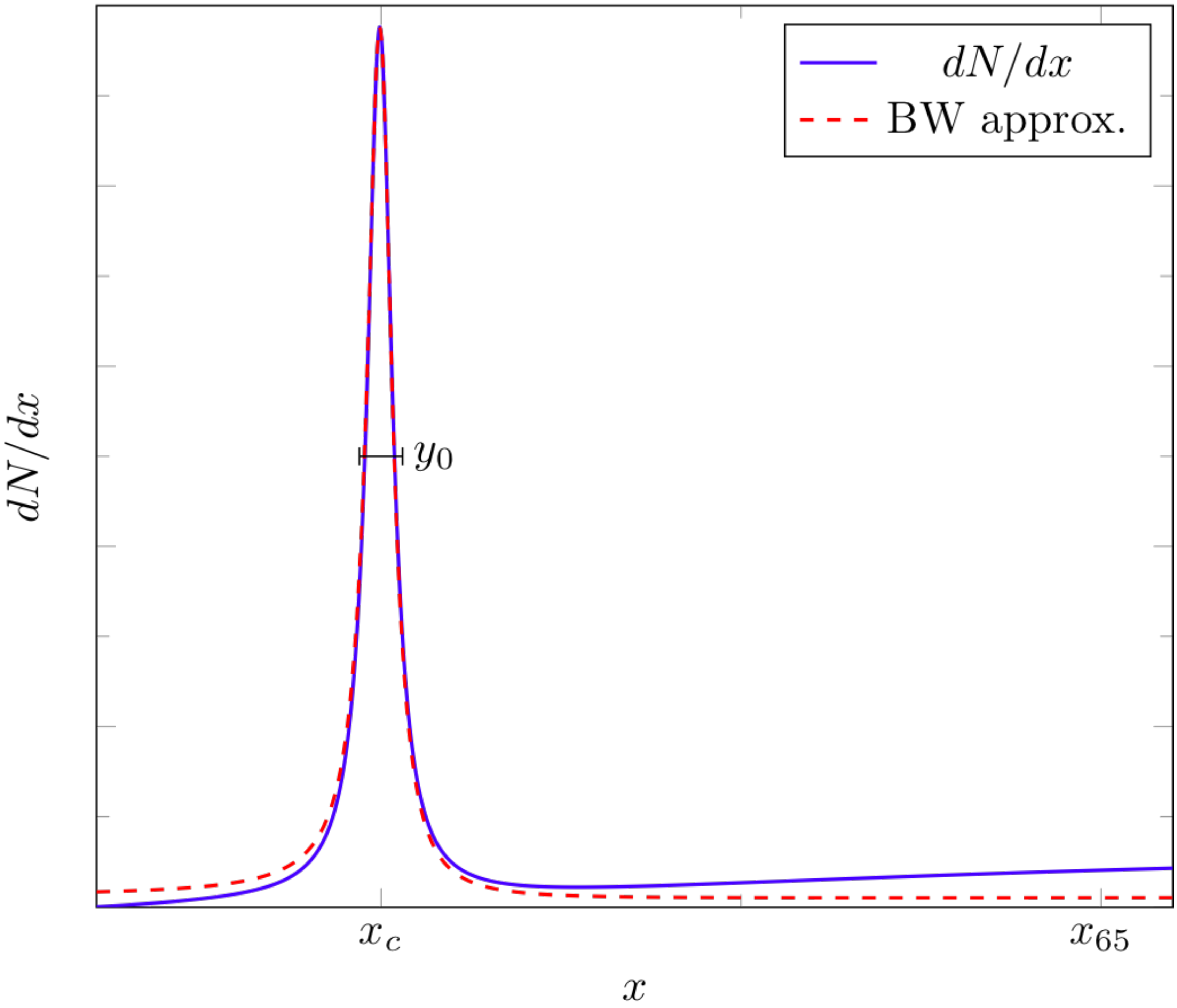
$$\begin{aligned}\lambda(\phi) &= \lambda_0+b_\lambda \ln^2\left(\phi/\mu\right) ,\\ \xi(\phi) &= \xi_0+b_\xi \ln\left(\phi/\mu\right) ,\end{aligned}$$

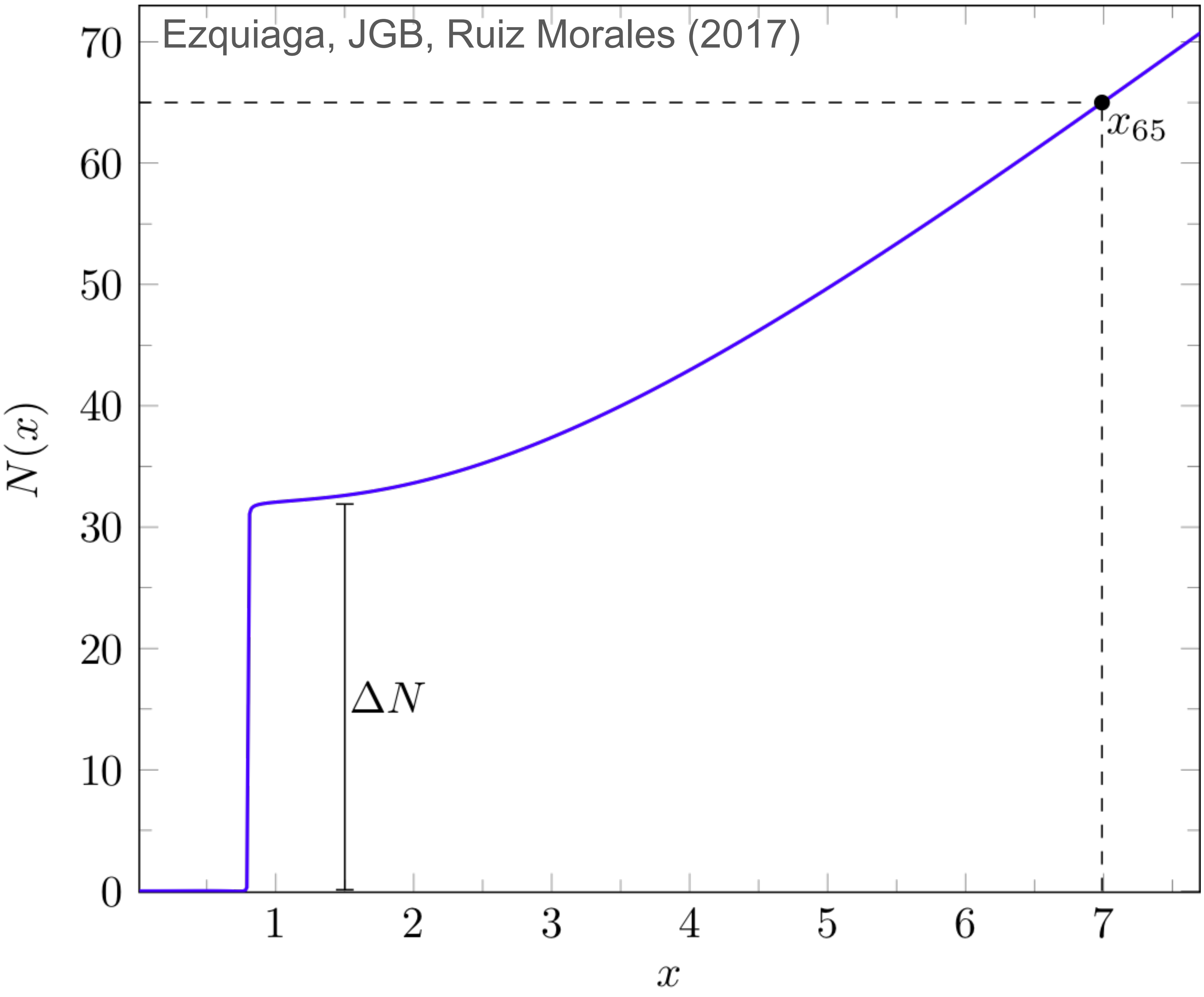
$$V(x)=\frac{V_0\,(1+a\,\ln^2 x)\,x^4}{(1+c\,(1+b\,\ln x)\,x^2)^2} \qquad x = \phi/\mu$$

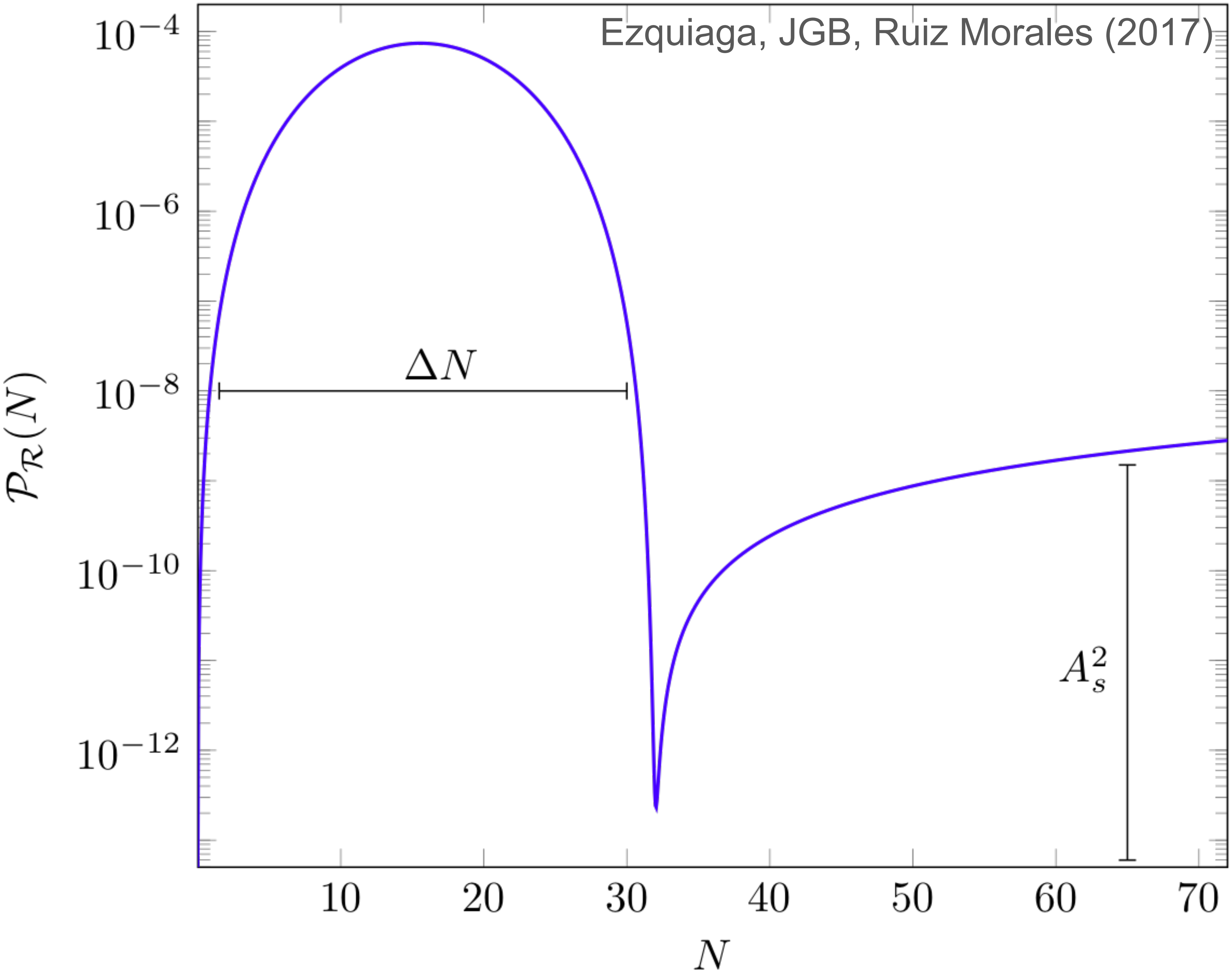
$$V_0=\lambda_0\mu^4/4,\ a=b_\lambda/\lambda_0,\ b=b_\xi/\xi_0 \text{ and } c=\xi_0\,\kappa^2\mu^2$$



Ezquiaga, JGB, Ruiz Morales (2017)


dN/dx
BW approx.
y_0
dN/dx
x_c
x_{65}
x

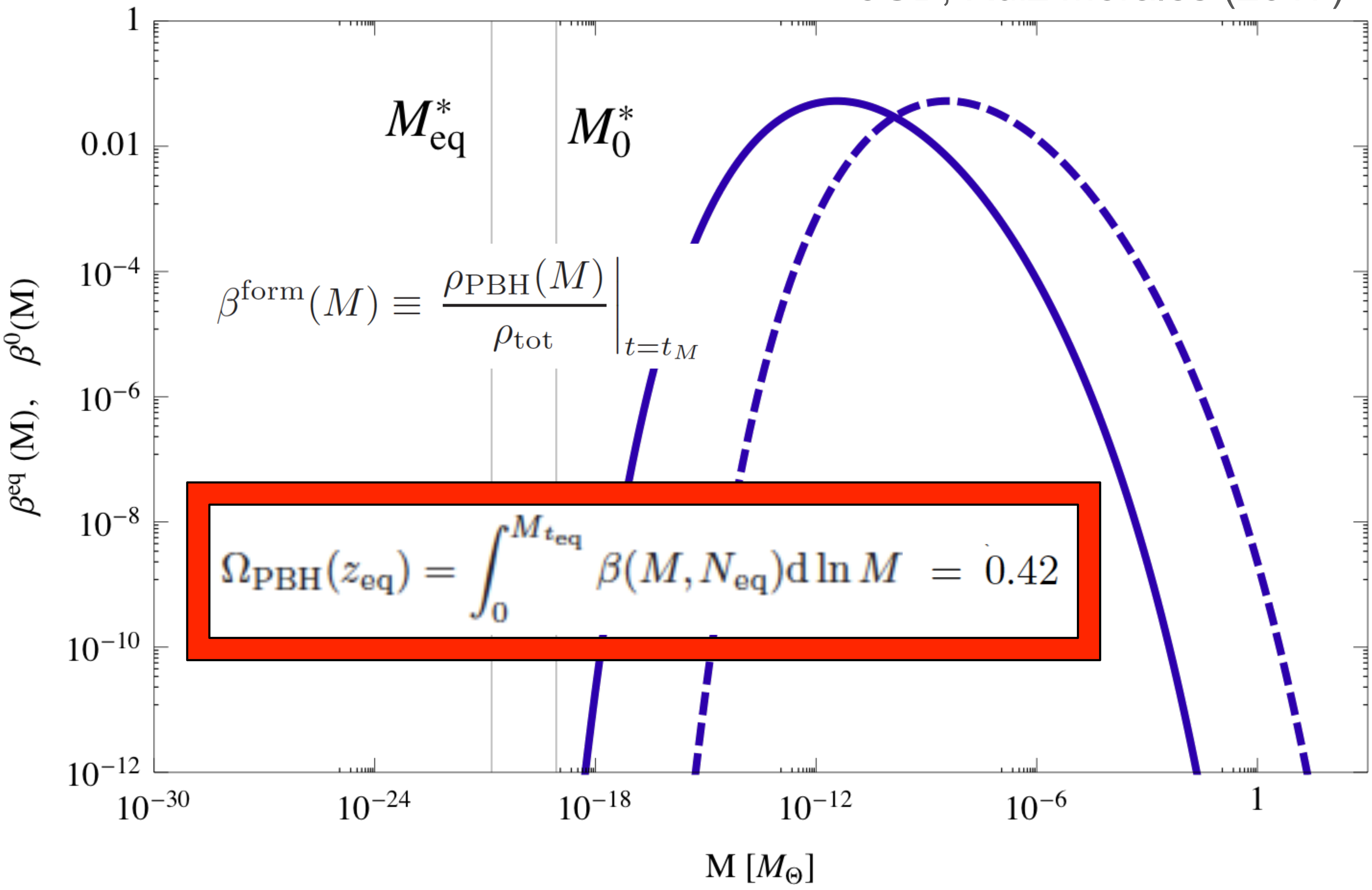

Ezquiaga, JGB, Ruiz Morales (2017)
$N(x)$
x
ΔN
x_{65}
0
10
20
30
40
50
60
70
1
2
3
4
5
6
7


Ezquiaga, JGB, Ruiz Morales (2017)
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$\mathcal{P}_{\mathcal{R}}(N)$
ΔN
A_s^2
10
20
30
40
50
60
70
N

CMB & LSS Constraints

Mass Spectrum @ MR equality

JGB, Ruiz Morales (2017)

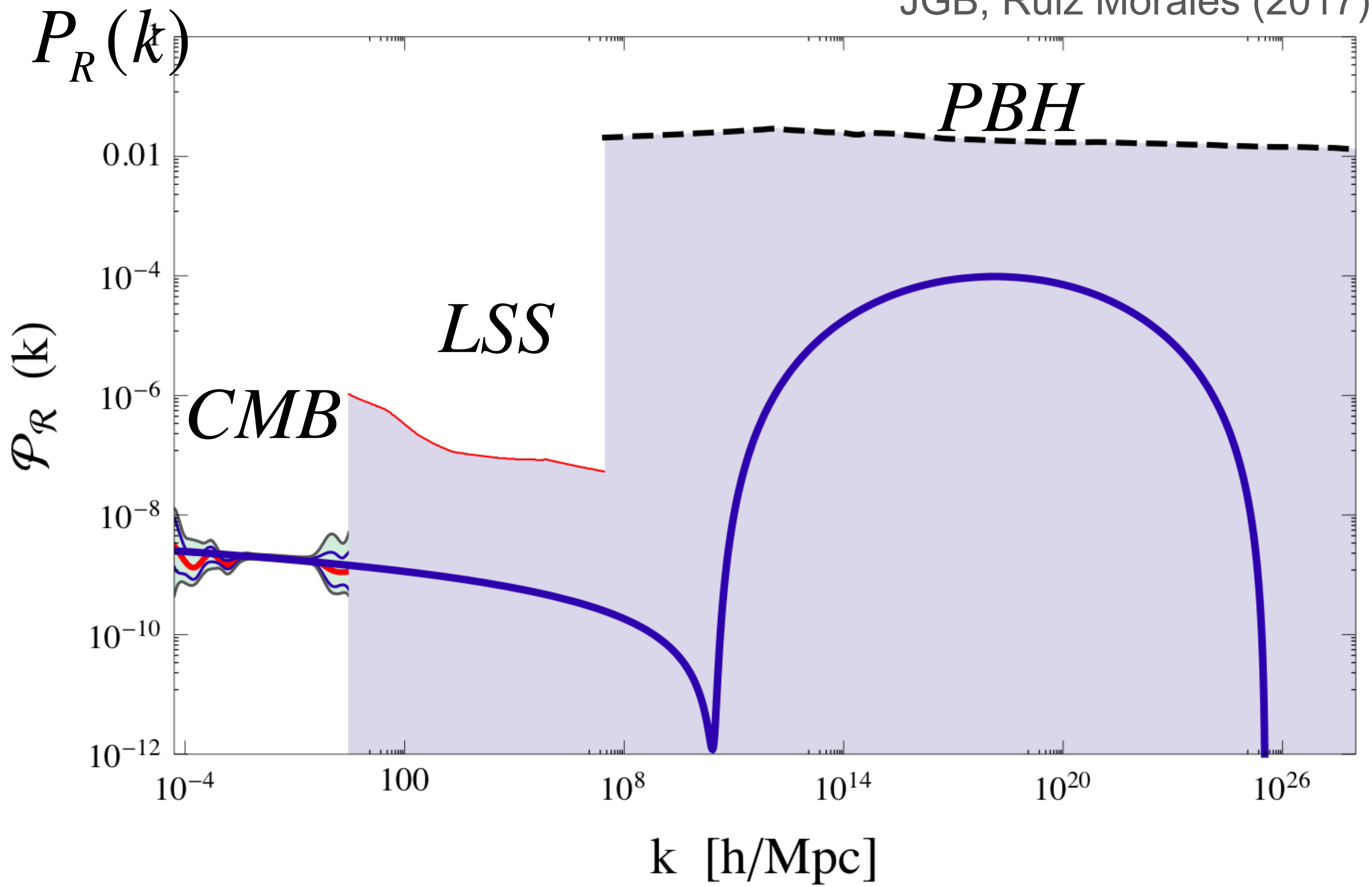


$$\beta^{\rm form}(M) \equiv \left.\frac{\rho_{\rm PBH}(M)}{\rho_{\rm tot}}\right|_{t=t_M}$$

$$\Omega_{\rm PBH}(z_{\rm eq}) = \int_0^{M_{t_{\rm eq}}} \beta(M, N_{\rm eq}) {\rm d}\ln M \;=\; 0.42$$

Primordial Spectrum for PBH

JGB, Ruiz Morales (2017)



CMB Constraints on CHI

Ezquiaga, JGB, Ruiz Morales (2017)

$$A_s^2 = 2.1 \times 10^{-9}$$

$$n_s = 0.9566$$

$$r = 0.028$$

$$dn_s/d\ln k = -0.00144$$

$$\lambda_0 = 1.2 \times 10^{-6} \qquad \xi_0 = 21$$

$$b_\lambda = 0.9 \times 10^{-5} \qquad b_\xi = 40.6$$

$$\kappa^2 \mu^2 = 0.0226$$

CMB Constraints on CHI

Ezquiaga, JGB, Ruiz Morales (2017)

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

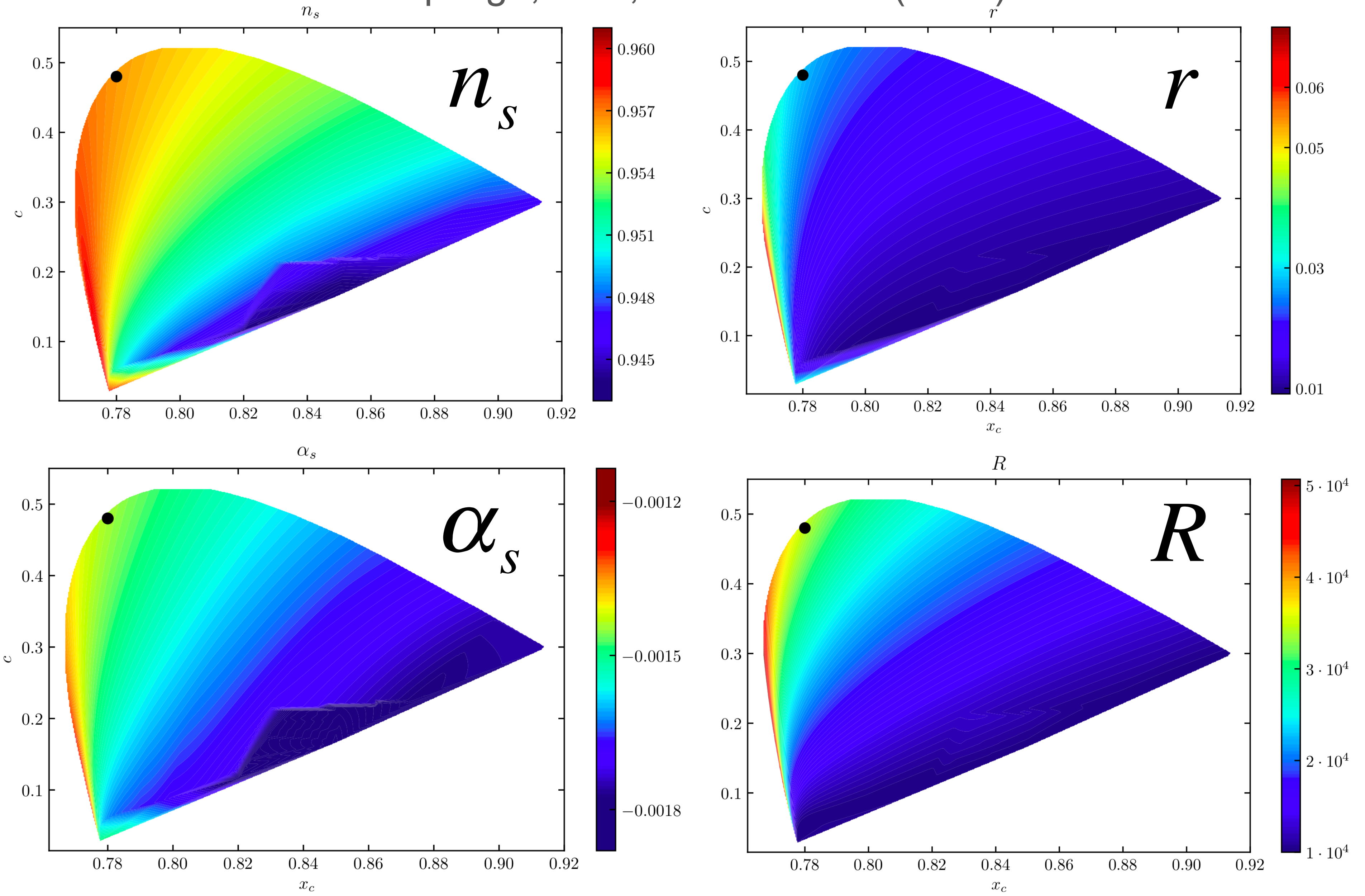
$$({\rm RGE}) \quad b_\lambda = 0.9 \times 10^{-5} \qquad b_\xi = 40.6$$

Reheating after CHI

$$\begin{aligned} \rho_{\rm end} &= 2.8 \times 10^{63}\ {\rm GeV} \\ T_{\rm rh} &= 3 \times 10^{15}\ {\rm GeV} \end{aligned} \qquad (\text{for } g_* = 106.75)$$

CMB Constraints on CHI

Ezquiaga, JGB, Ruiz Morales (2017)



CMB Constraints on CHI

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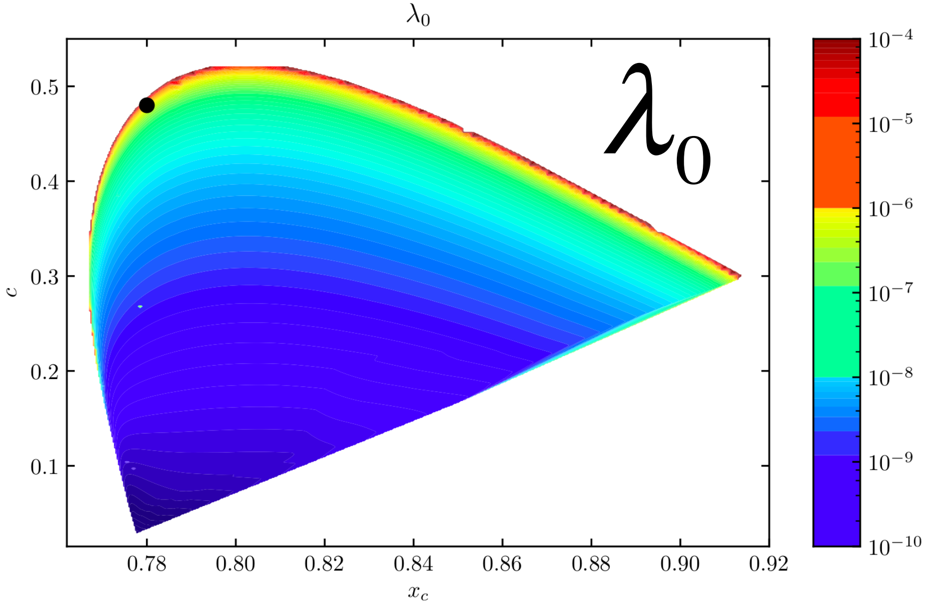
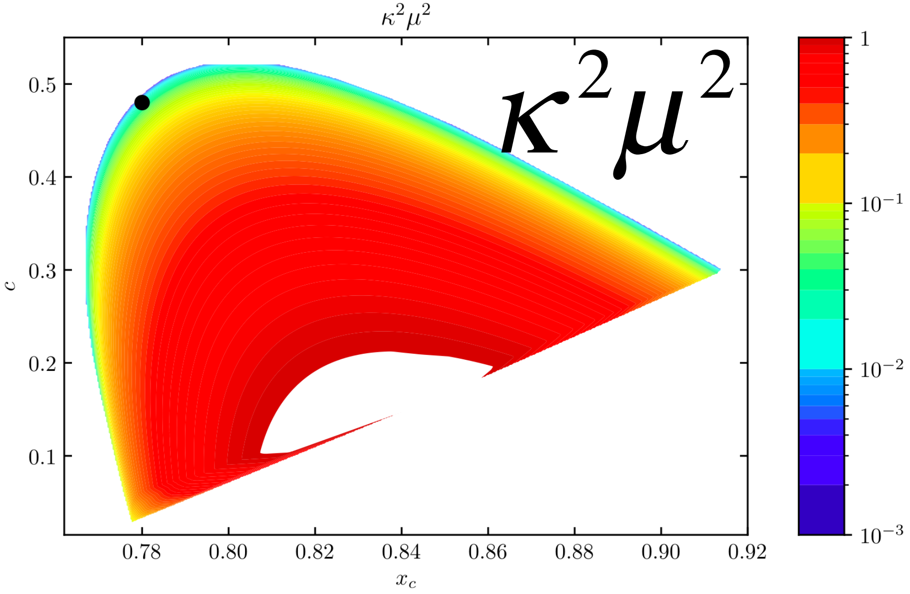
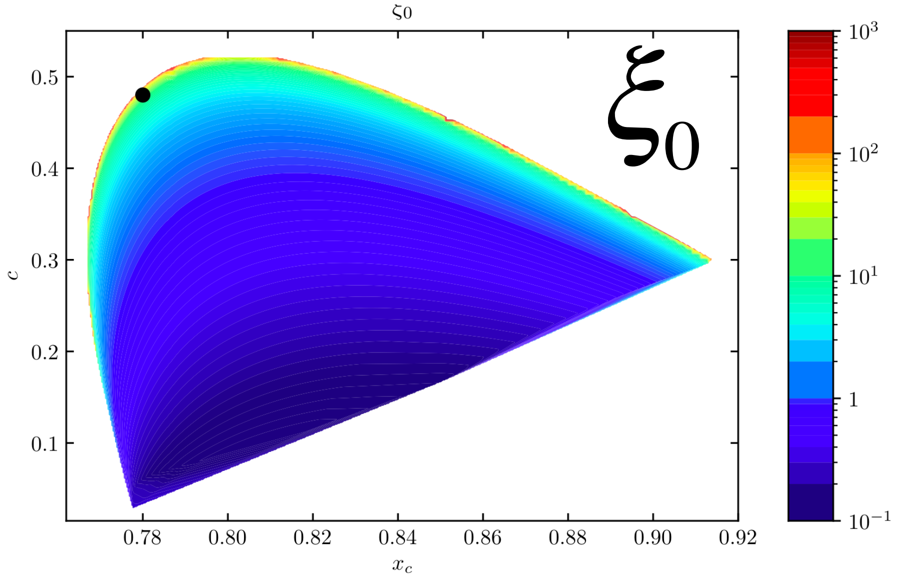
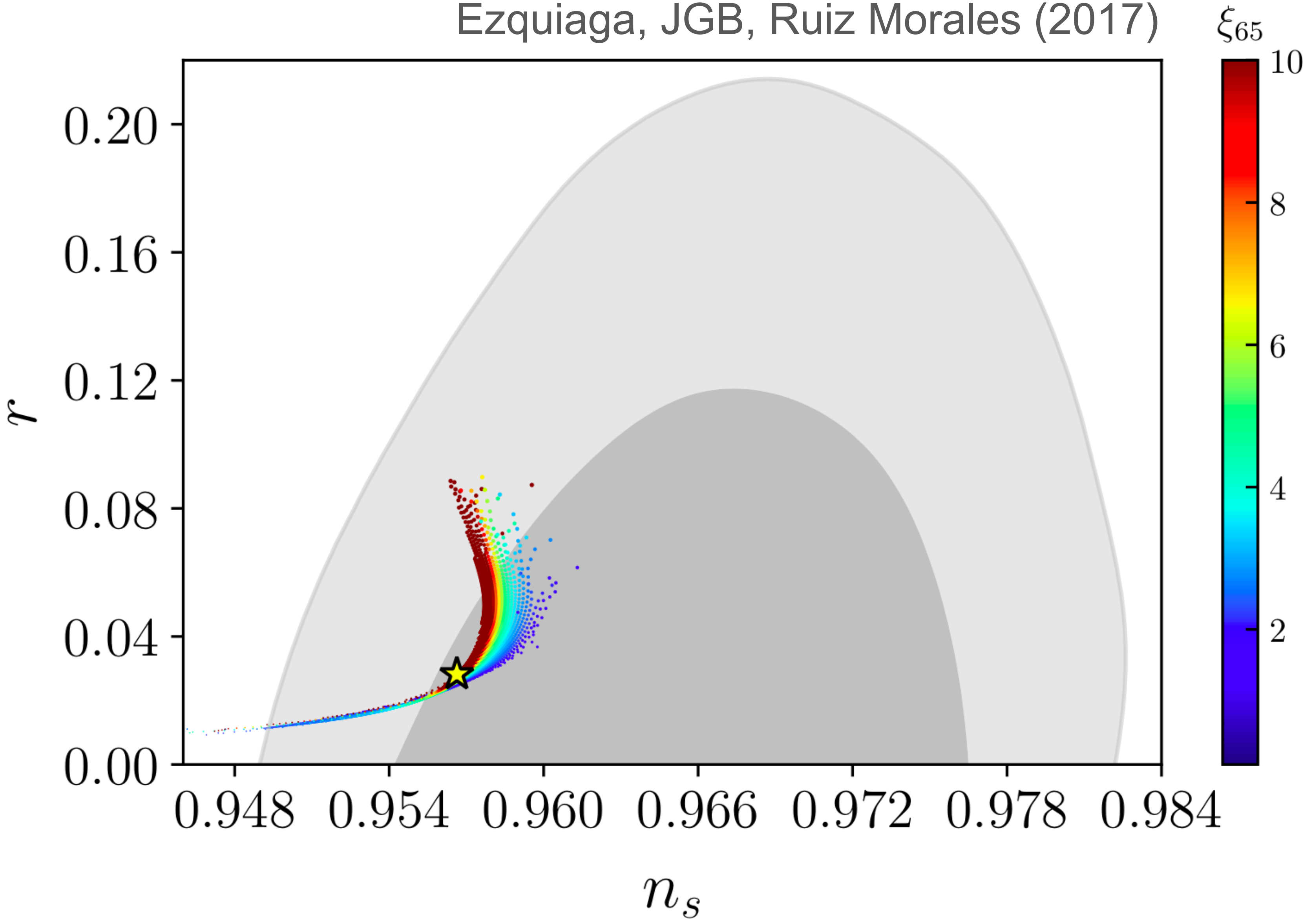






CMB Constraints on CHI

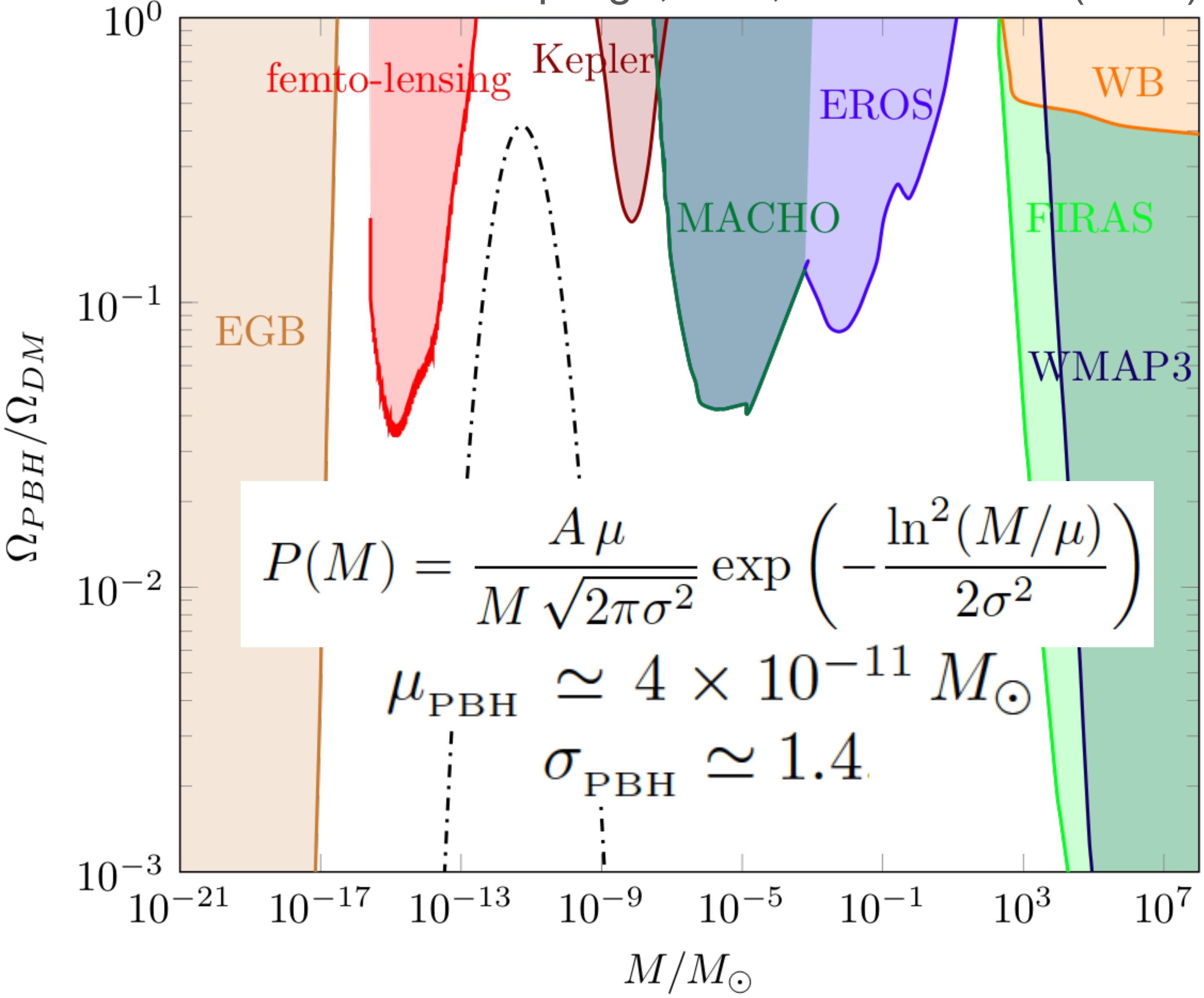
Ezquiaga, JGB, Ruiz Morales (2017)



Constraints on Primordial Black Holes

Present Constraints on PBH

Ezquiaga, JGB, Ruiz Morales (2017)



$$P(M) = \frac{A\,\mu}{M\,\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\ln^2(M/\mu)}{2\sigma^2}\right)$$

$$\mu_{\rm PBH} \simeq 4 \times 10^{-11}\, M_\odot$$

$$\sigma_{\rm PBH} \simeq 1.4$$

Massive Primordial Black Holes

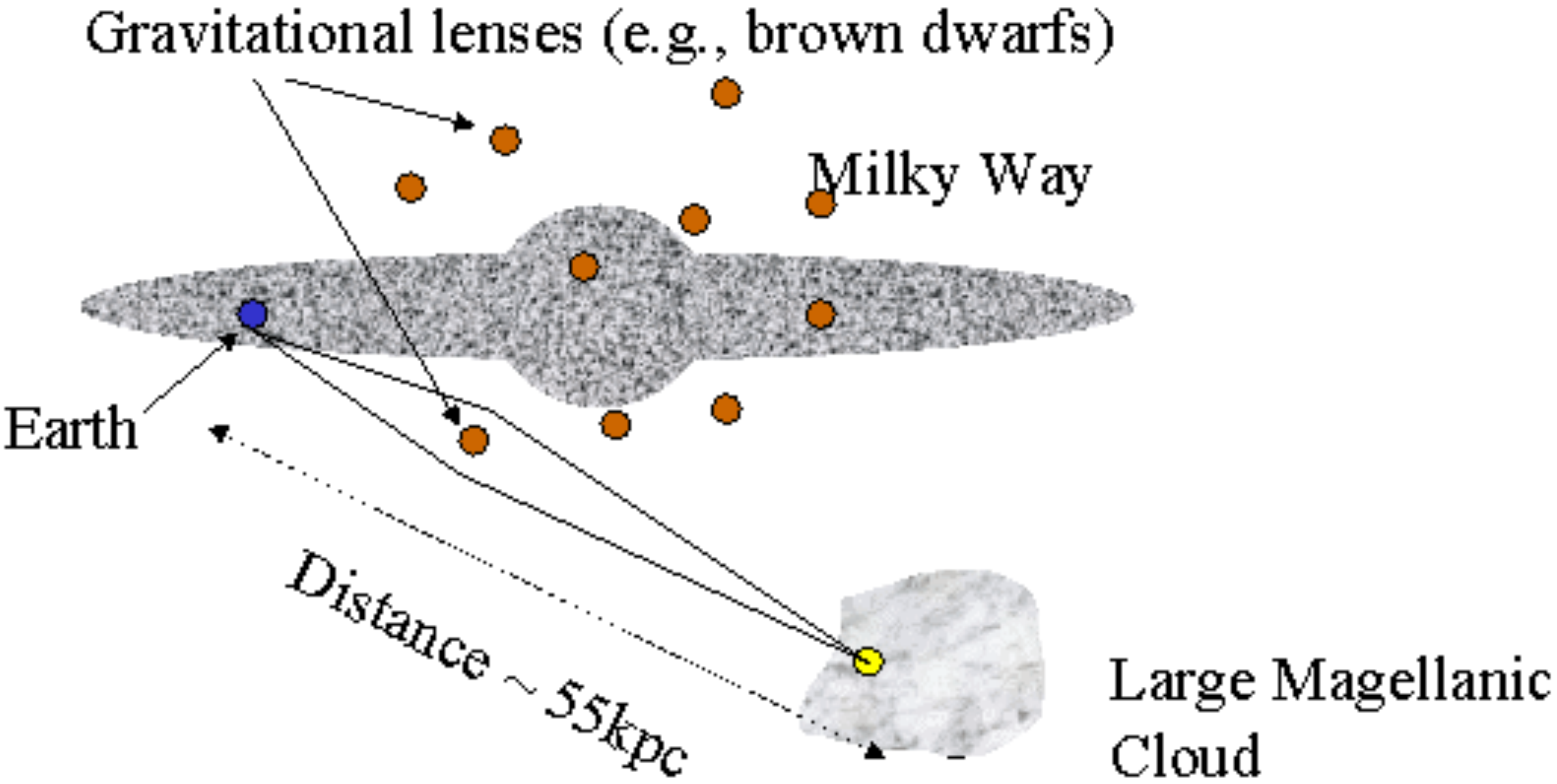
- These are NOT the (small) PBH with $10^{-24}\,M_\odot < M_{PBH} < 10^{-13}\,M_\odot$ of Carr et al.
- These are black holes with $10^{-12}\,M_\odot < M_{PBH} < 10^{-8}\,M_\odot$ which cluster and merge and could resolve some of the most acute problems of ΛCDM paradigm.
- ΛCDM N-body simulations never reach the $100\,M_\odot$ particle resolution, so for them PBH is as good as PDM.

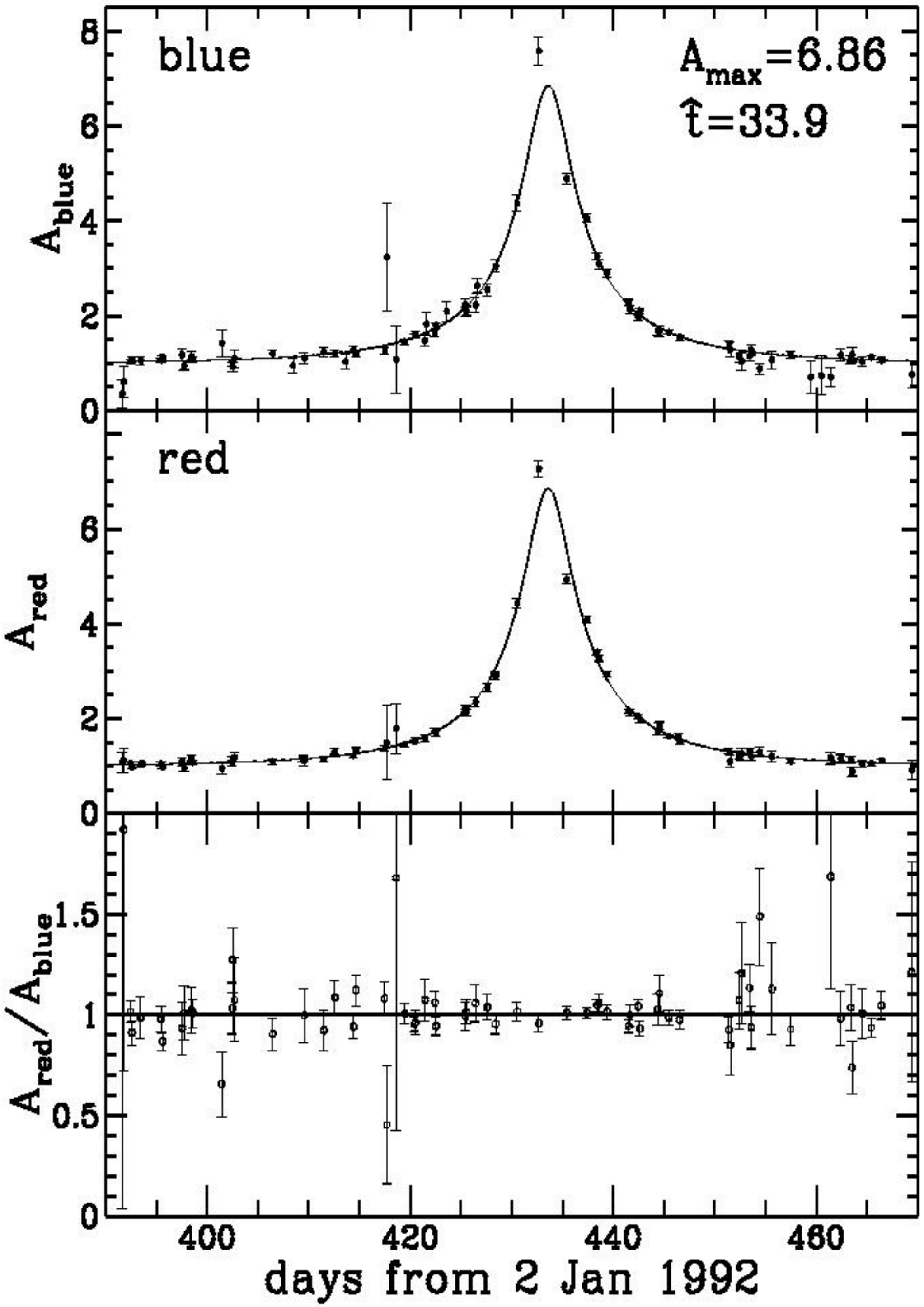
Distinguish MPBH from Stellar BH

- Accretion disks
- Distribution of spins
- 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_{sun}

Signatures of Primordial Black Holes

Microlensing





symmetric

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

achromatic

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

unique

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

$$\Rightarrow \quad M_D \approx 0.1 M_\Theta$$

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

$$\overline{\Delta t} = \frac{r_E}{\upsilon} = \frac{\sqrt{4GM_D d}}{\upsilon}$$ average $\frac{1}{2}$ crossing

$M_D = 100\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 4$ years

$M_D = 10\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 1.23$ years

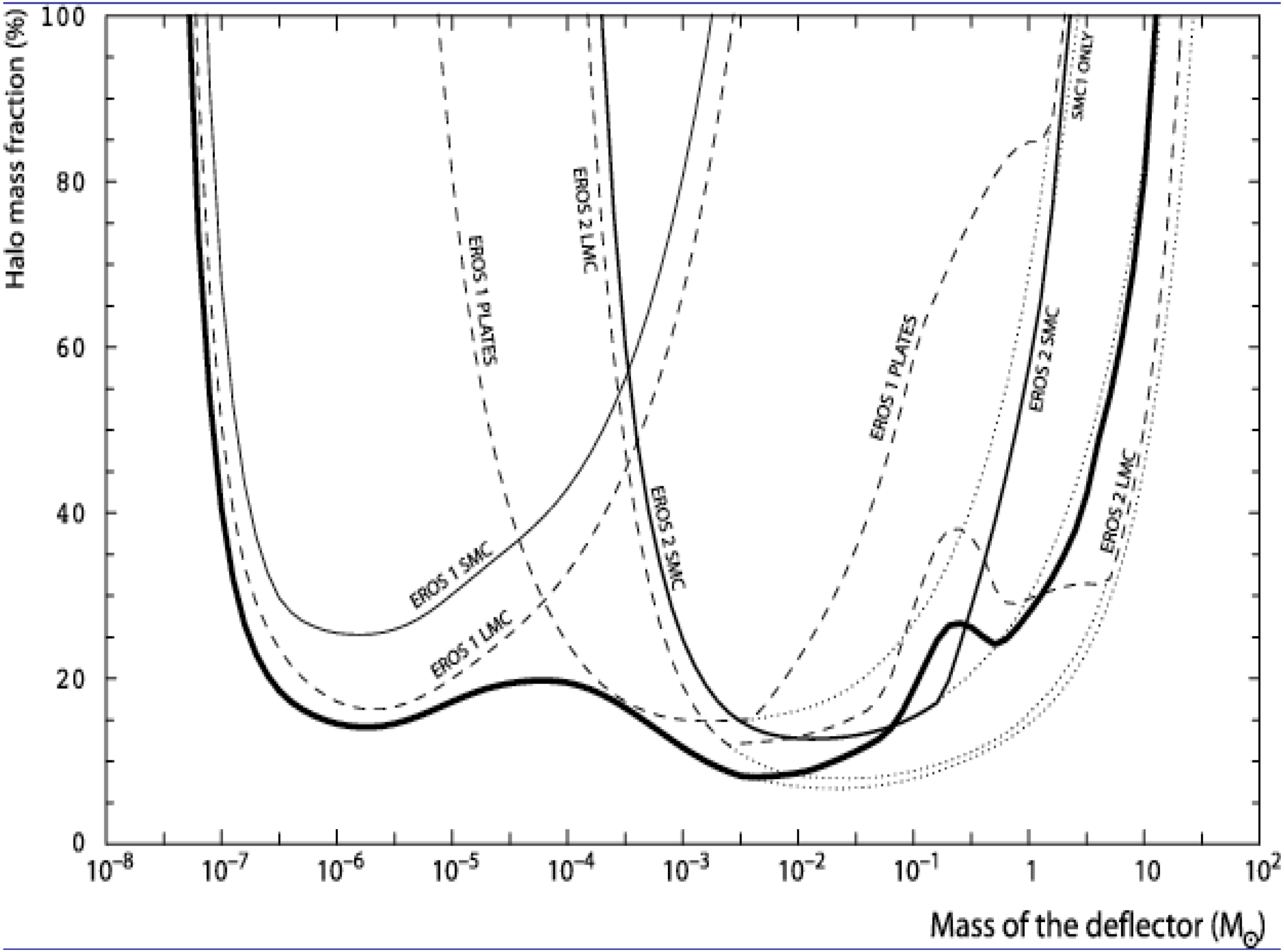
$M_D = 1\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 5$ months

$M_D = 0.1\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 1.5$ months

$M_D = 10^{-2}\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 2$ weeks

$M_D = 10^{-4}\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 1.5$ day

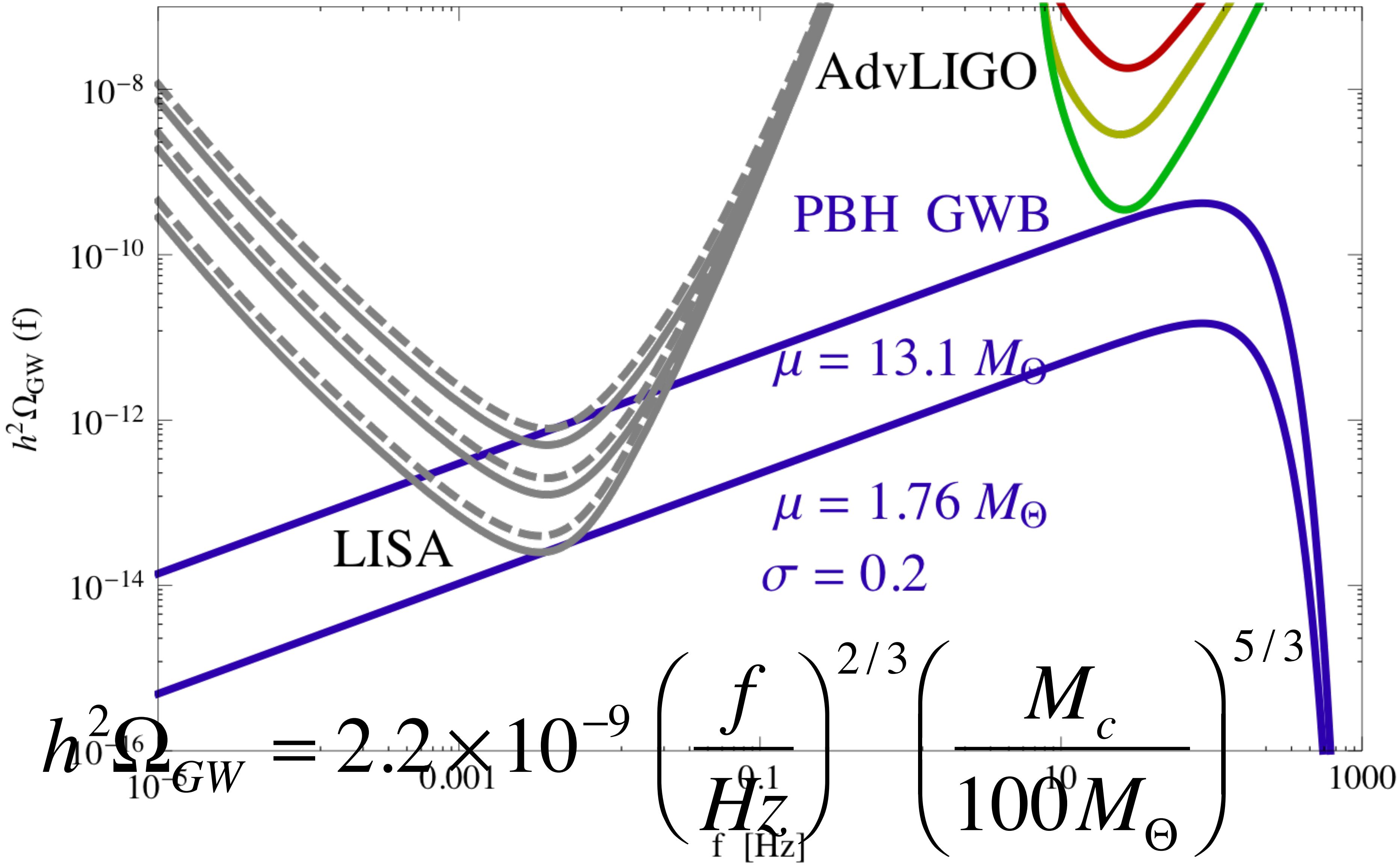
P. Tisserand (2007)



Stochastic Background Grav. Waves

Stochastic Background from MPBH

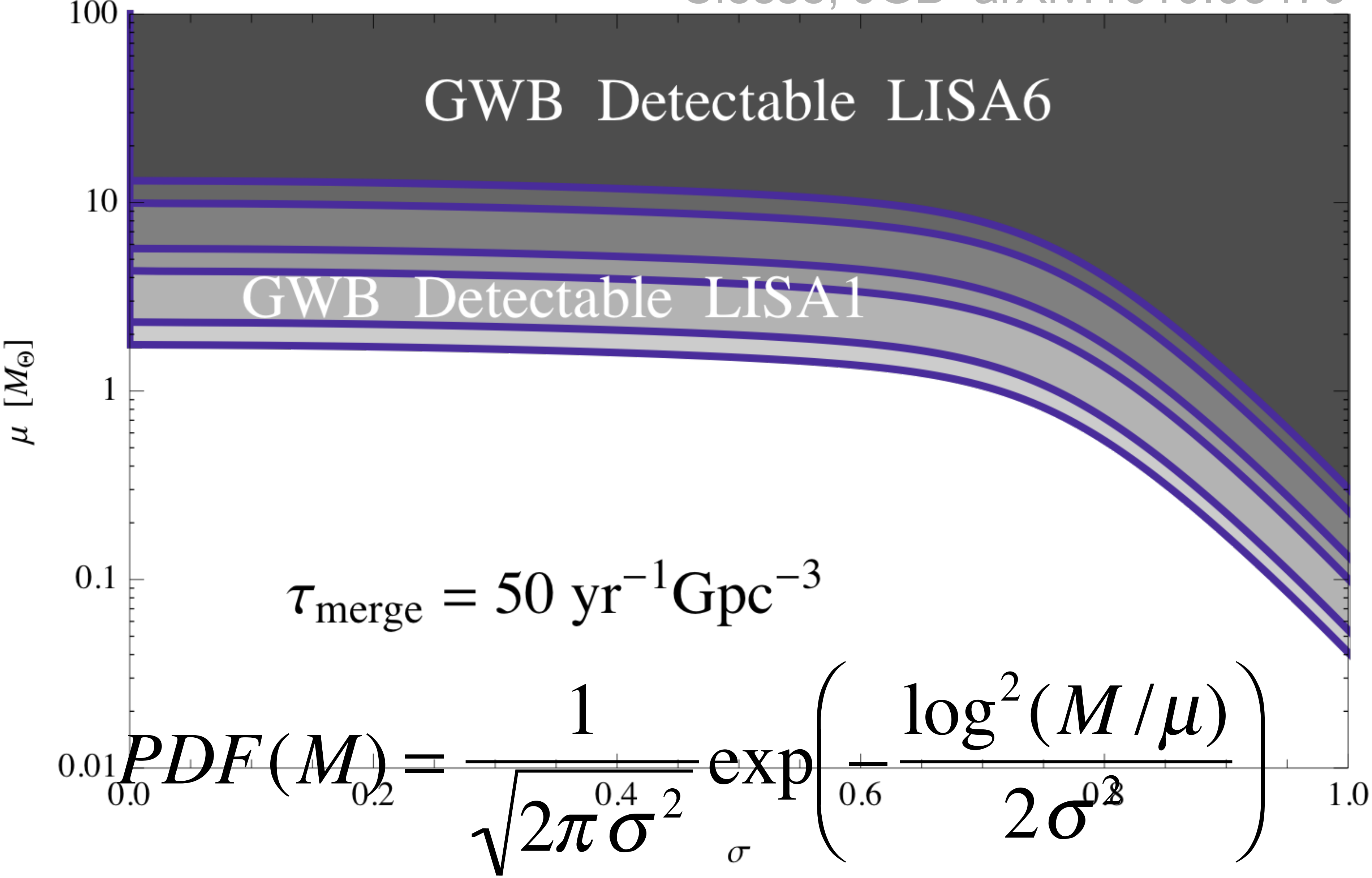
Clesse, JGB arXiv:1610.08479



$$h^2\Omega_{GW} = 2.2\times10^{-9}\left(\frac{f}{Hz}\right)^{2/3}\left(\frac{M_c}{100M_\Theta}\right)^{5/3}$$

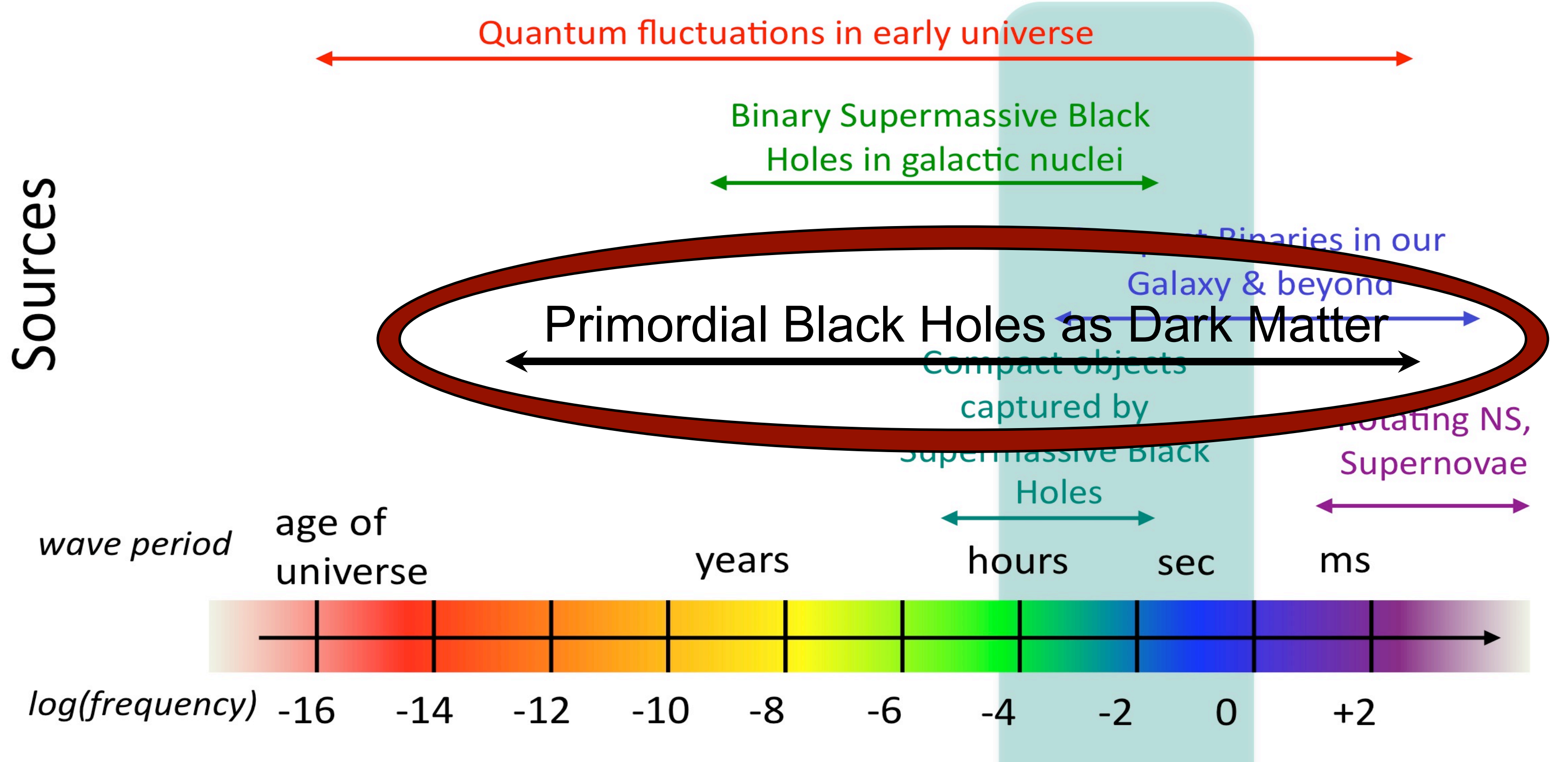
Stochastic Background from MPBH

Clesse, JGB arXiv:1610.08479



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

The Gravitational Wave Spectrum



Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Binaries in our Galaxy & beyond

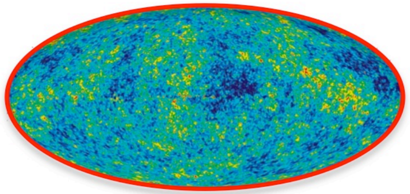
Primordial Black Holes as Dark Matter

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

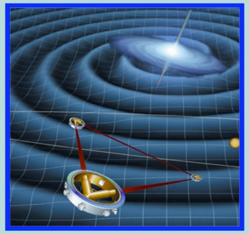
Detectors

Cosmic microwave background polarization



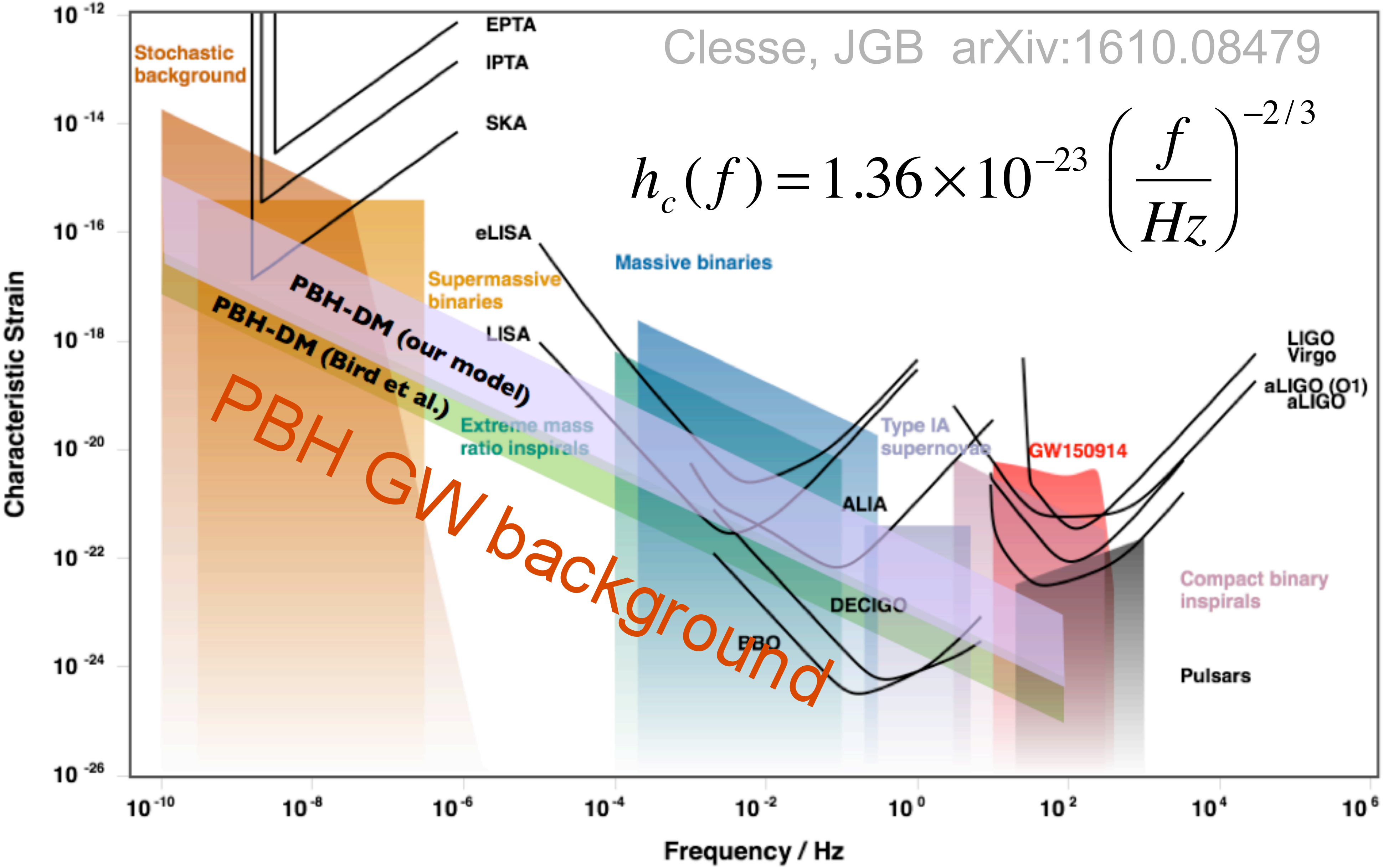
Pulsar Timing

Space Interferometers



Terrestrial interferometers

Sensitivity of future GW antenas



Clesse, JGB arXiv:1610.08479

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

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 BH (LIGO)
- Substructure and too-big-to-fail probl.
- Total integrated mass = Ω_M

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.