Primordial Black Holes as Dark Matter

JGB & S. Clesse, Sci. Am. July 2017, 39 - 43
JGB & Ruiz Morales, arXiv:1702.03901, PDU
Ezquiaga, JGB & Ruiz Morales, arXiv:1705.04861, PLB
JGB, J.Phys.Conf 840 (2017) 012032
JGB & S. Nesseris, arXiv:1706.02111, PDU
S. Clesse & JGB, arXiv:1610.08479, PDU
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

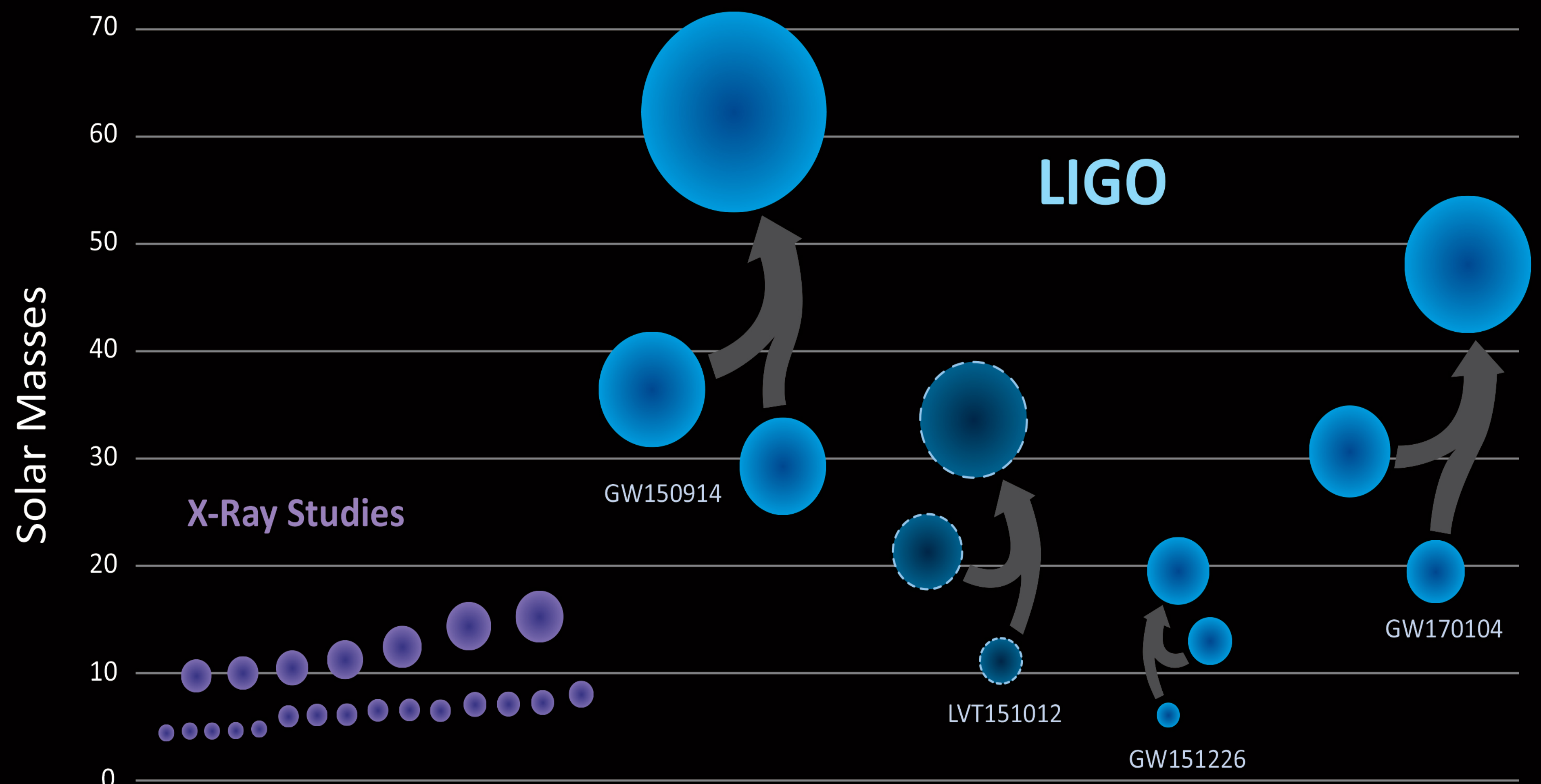
UAM ift

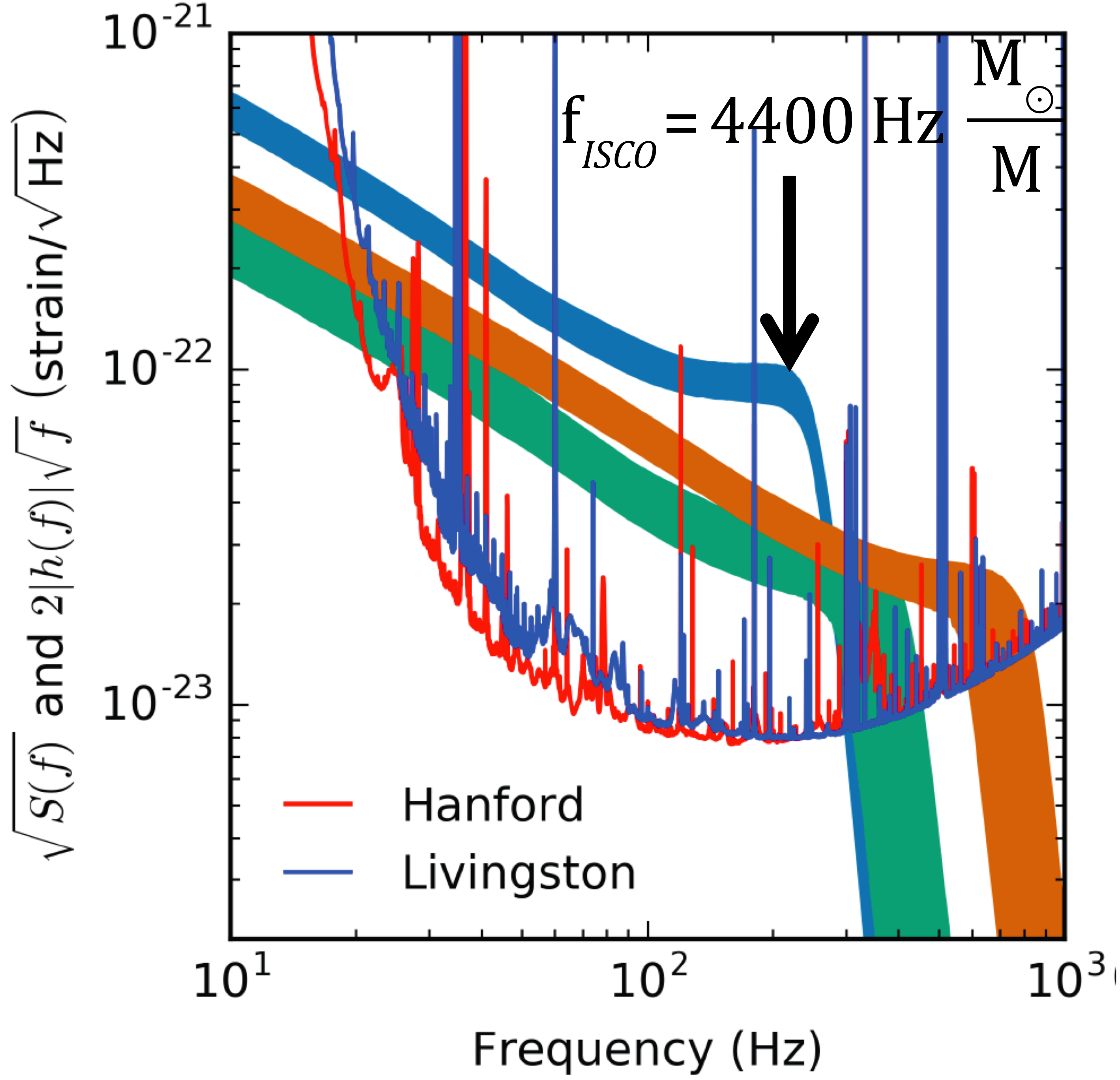
Juan García-Bellido
26th September 2017

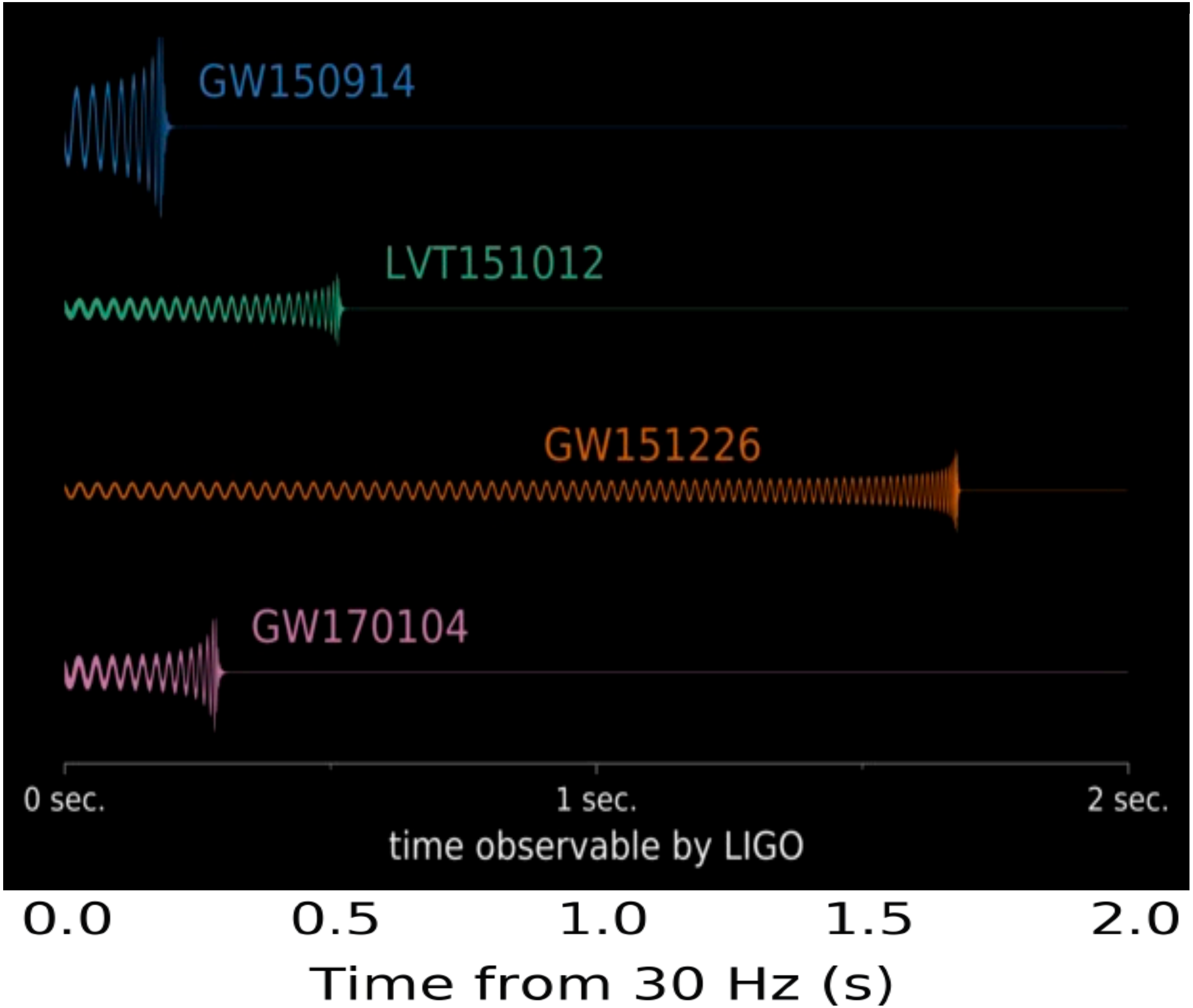
Outline

- The discovery of 4 BHB by AdvLIGO has opened a new Era of Astronomy
- Dark Matter = PBH
- Quantum origin => Peaks in curvature
- Inflaton = Higgs (Critical Higgs Infl)
- Particle Physics beyond SM (?)
- Test PBH scenario with GW interferom
- Conclusions

Black Holes of Known Mass




$f_{ISCO} = 4400\ \mathrm{Hz}\ \frac{M_\odot}{M}$
$\sqrt{S(f)}$ and $2|h(f)|\sqrt{f}$ (strain/$\sqrt{\mathrm{Hz}}$)
Frequency (Hz)
Hanford
Livingston
10^{-21}
10^{-22}
10^{-23}
10^{1}
10^{2}
10^{3}


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

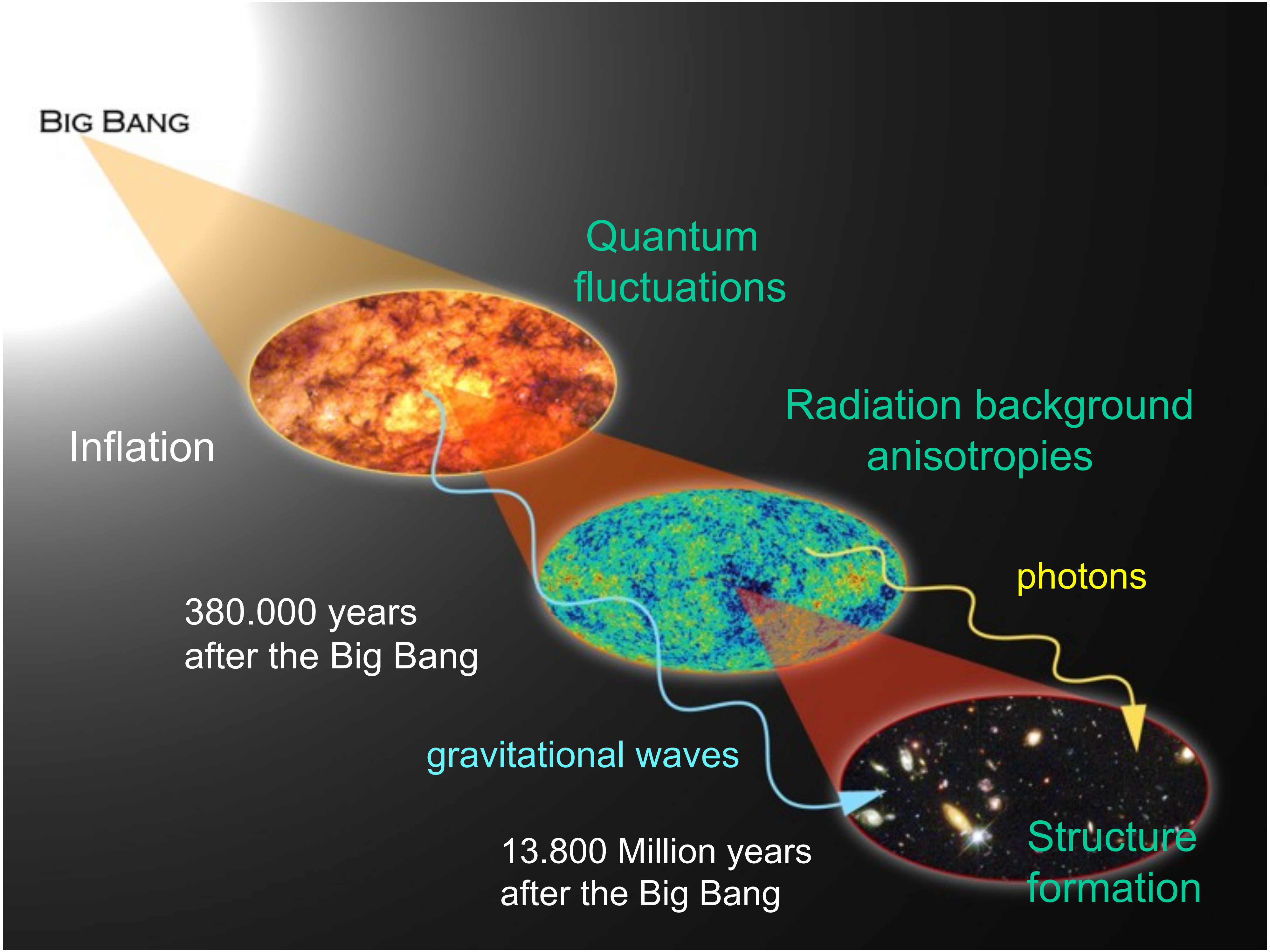
Gravitational Wave Astronomy

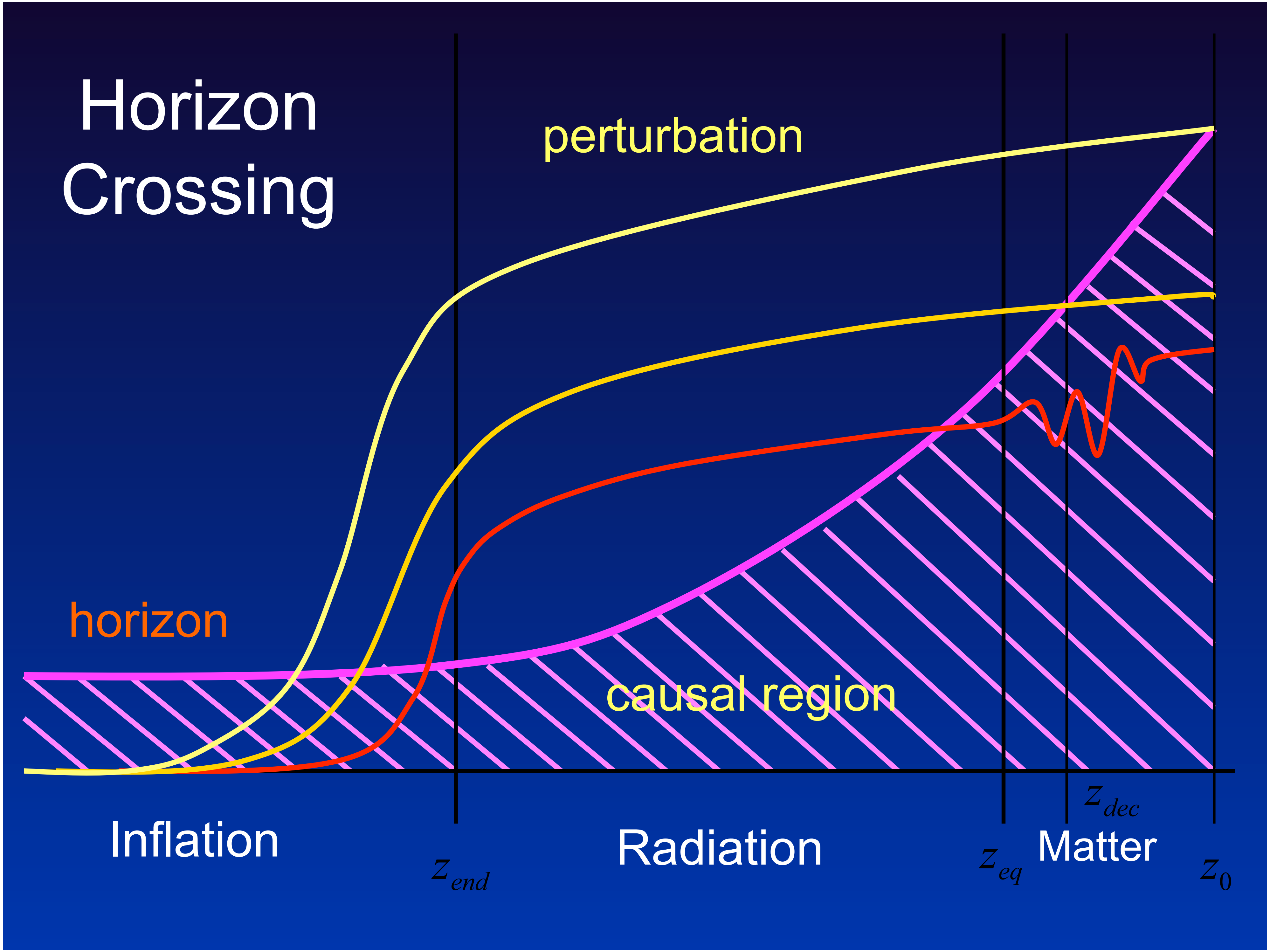
- AdvLIGO + VIRGO, KAGRA, INDIGO
- GW150914 = 36 + 29 M_{sun} BH binary
- GW151226 = 14 + 8 M_{sun} BH binary
- LVT151012 = 23 + 13 M_{sun} "candidate"
- GW170401 = 32 + 20 M_{sun} BH binary
- Expected 50-100 events/yr/Gpc^3
- AdvLIGO+ can map the mass and spin

  Massive BH (0.1 M_{sun} < M_{BH} < 150 M_{sun})

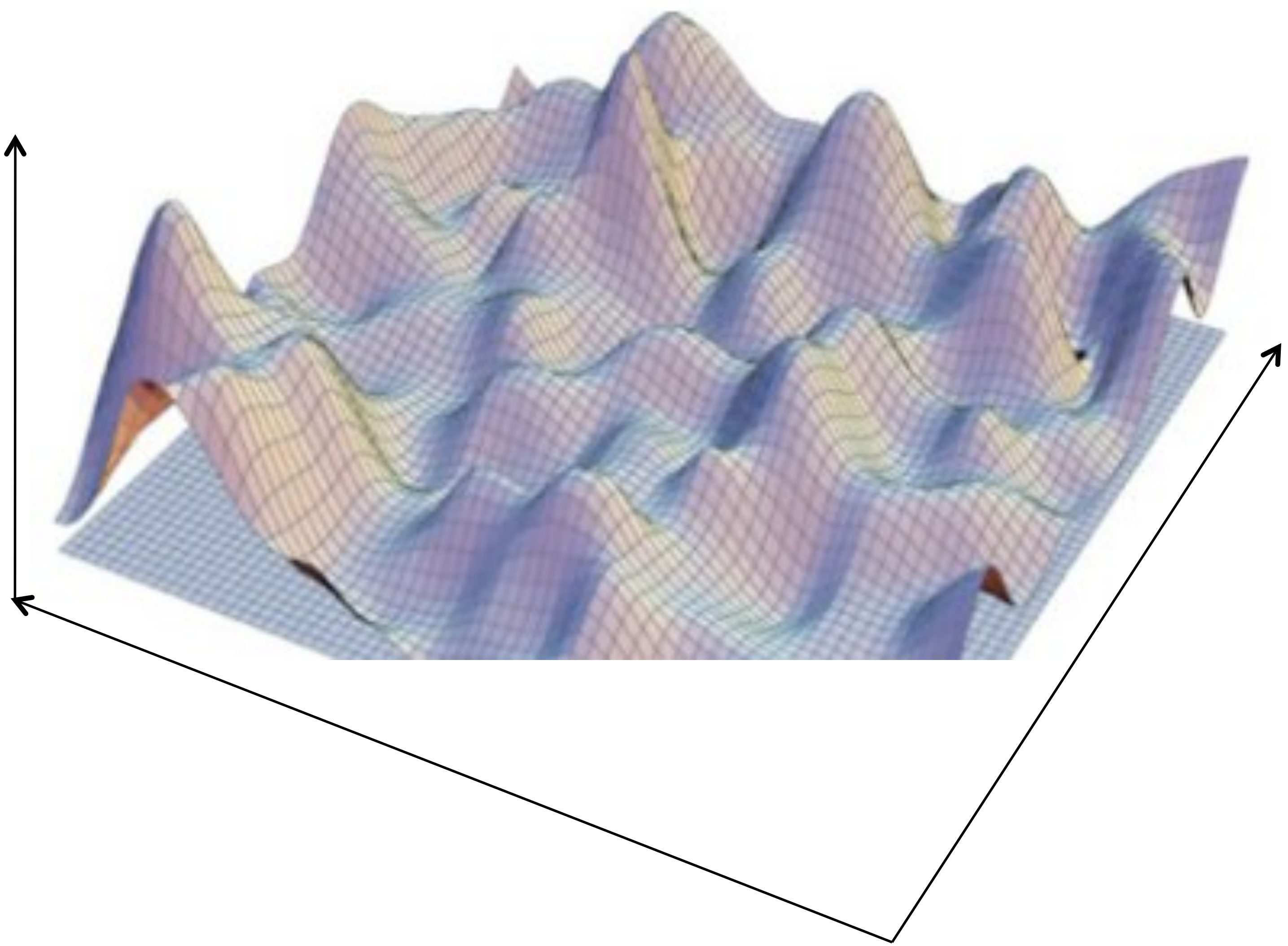
  n.b. $f_{ISCO} = 4400$ Hz (M_{sun}/M_{BH})

Massive 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

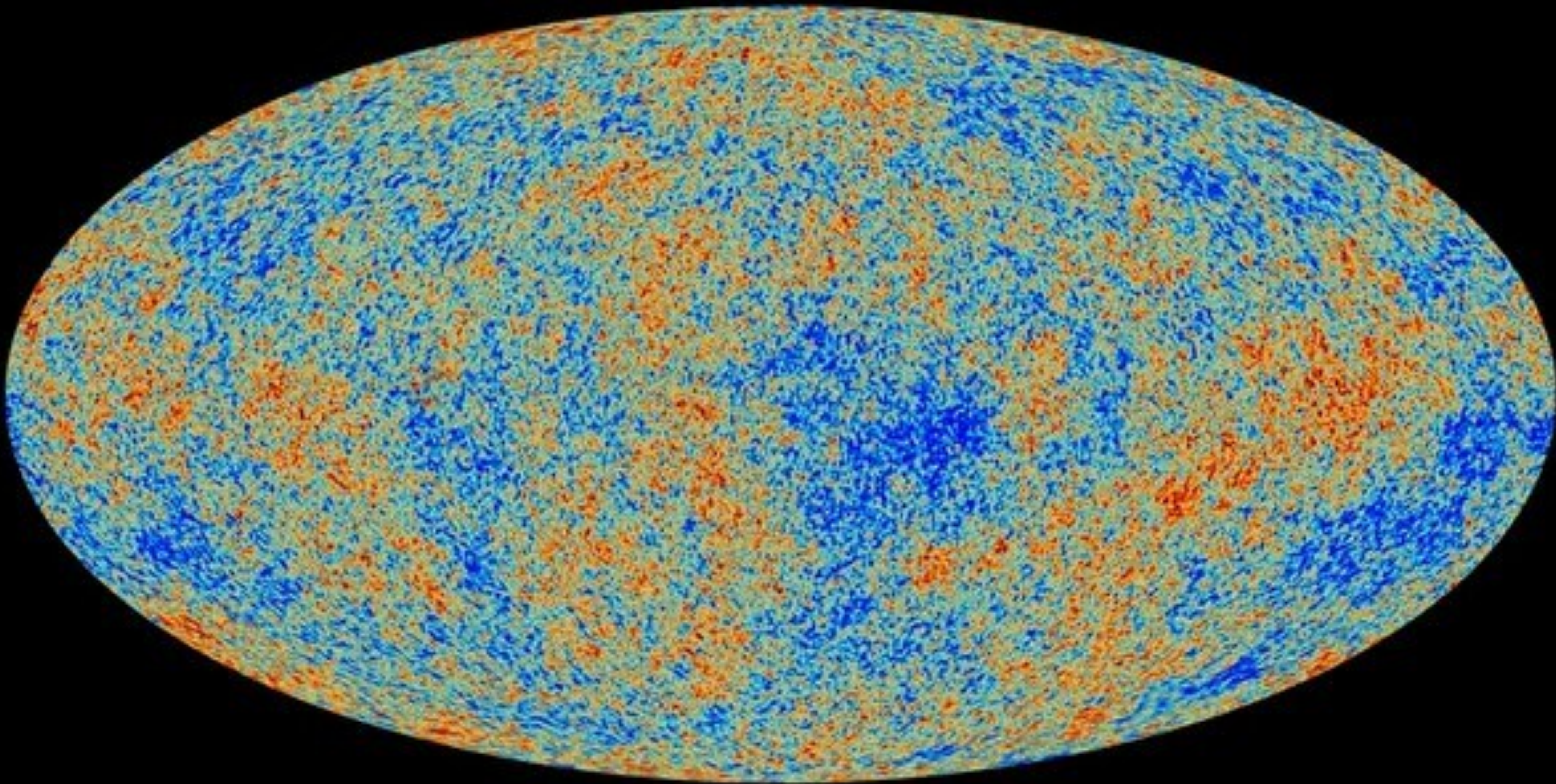

Horizon
Crossing
perturbation
horizon
causal region
Inflation
Radiation
Matter
z_{end}
z_{eq}
z_{dec}
z_0

Space-time ripples

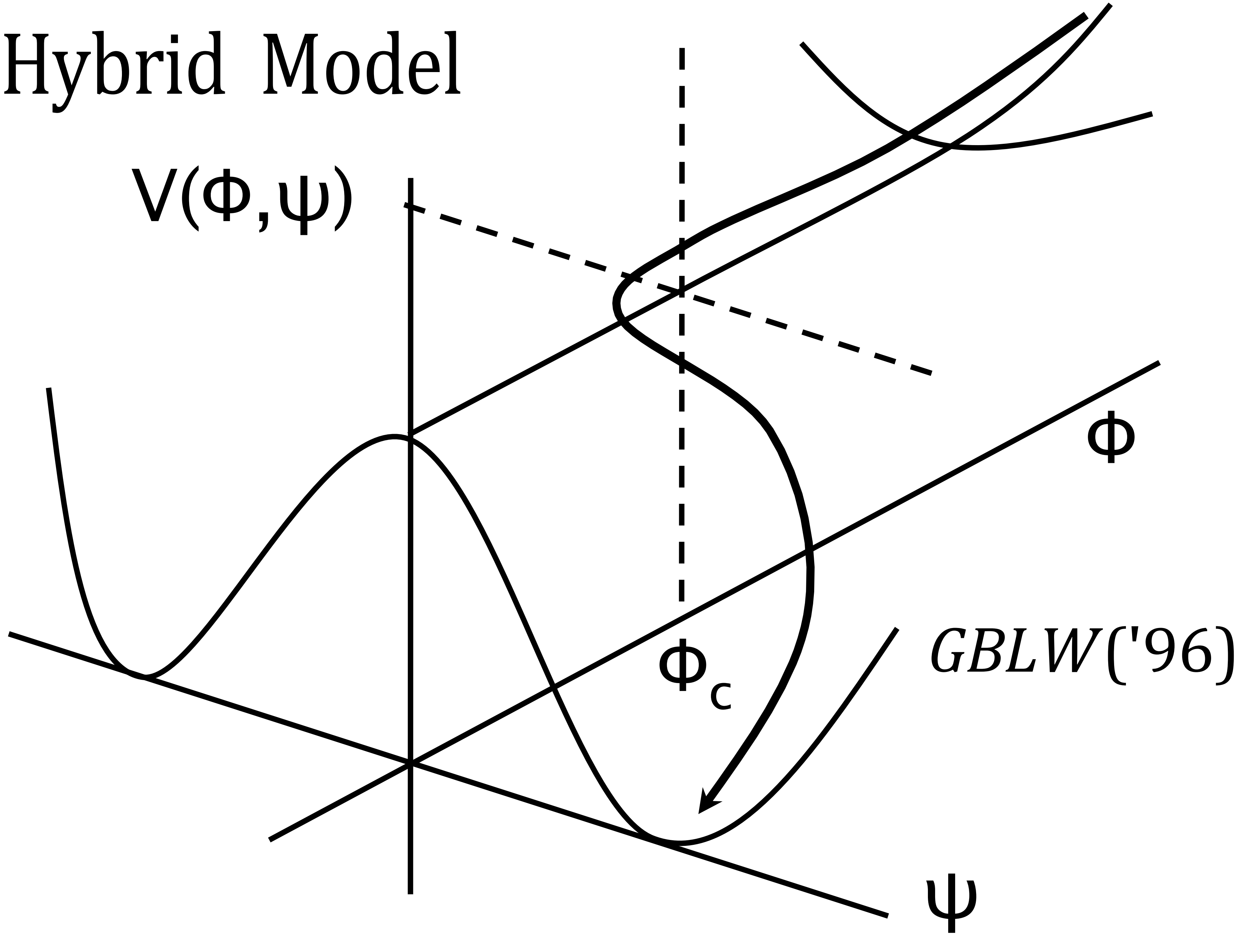


Stretched to cosmological scales

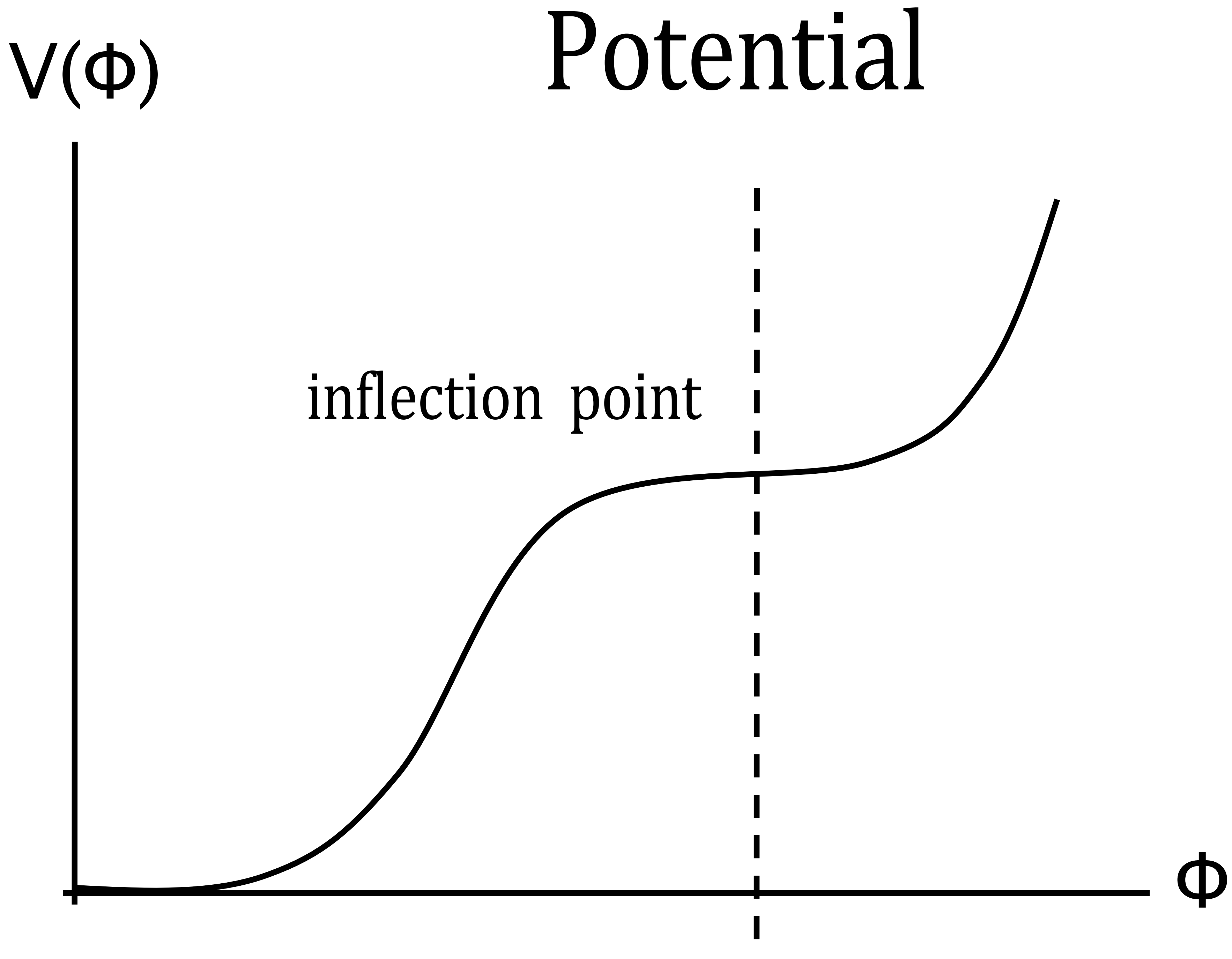
Planck (2015)

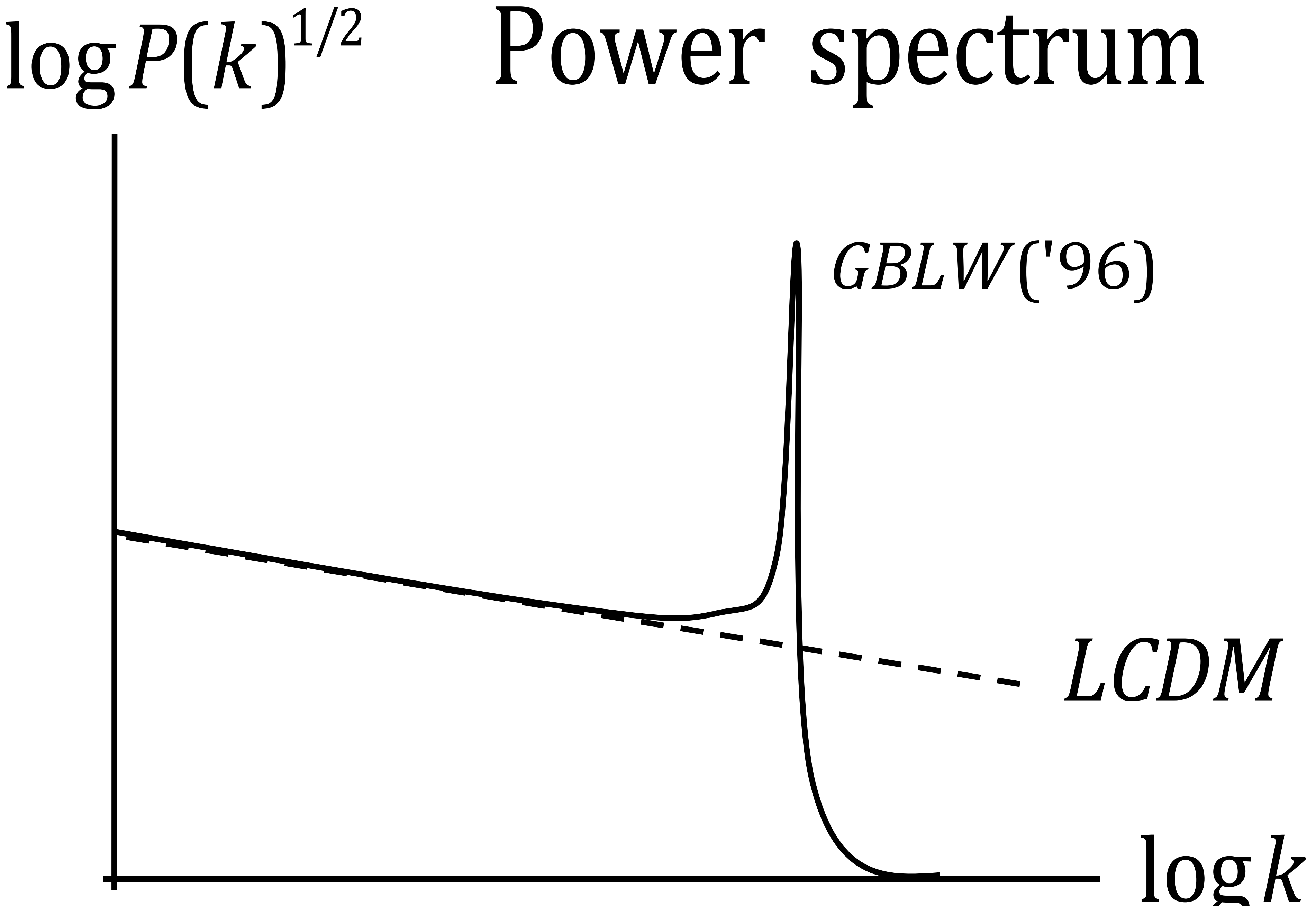


What models of Inflation produce PBH?

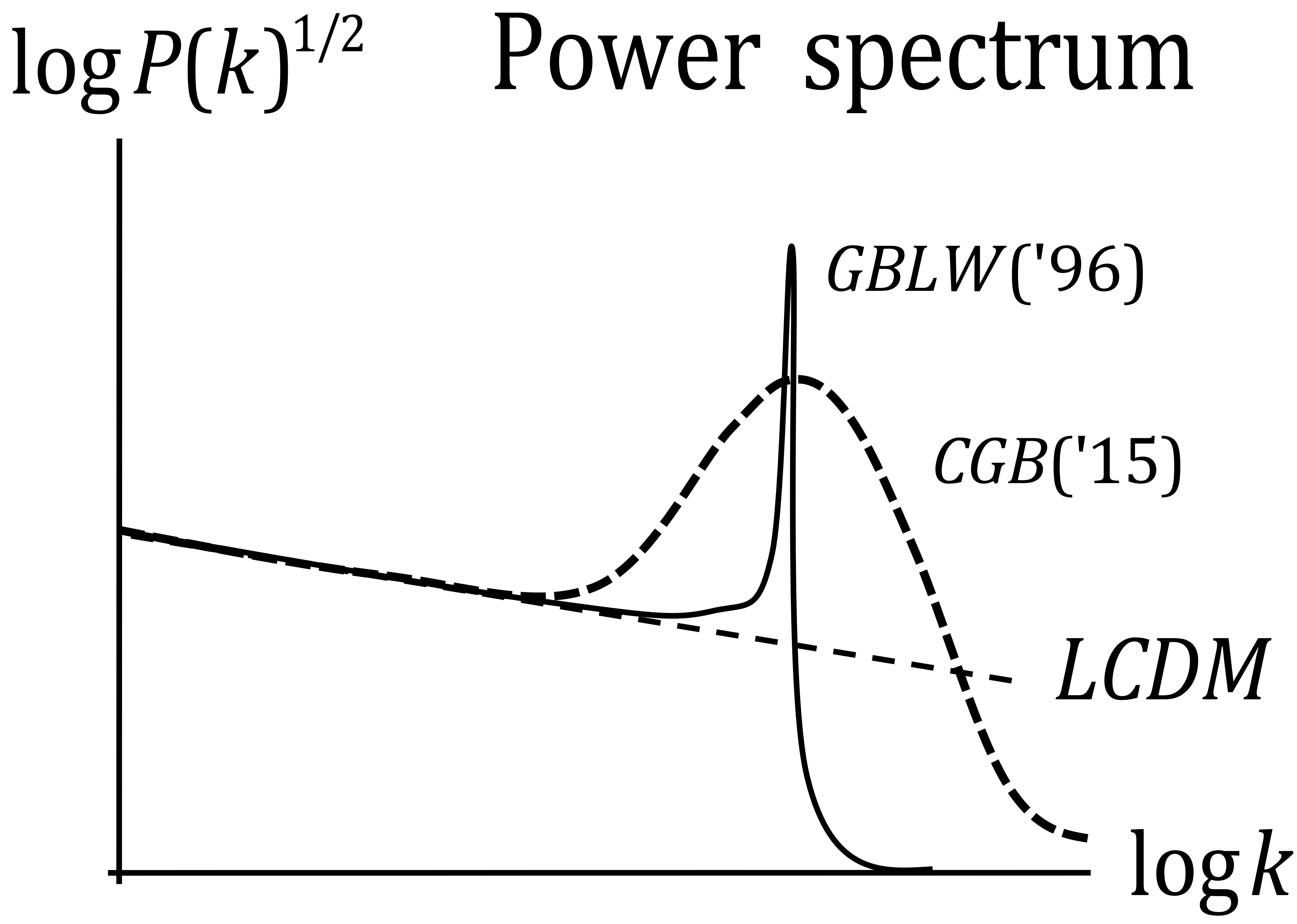


Hybrid Model
V(Φ,ψ)
Φ
Φc
GBLW('96)
ψ

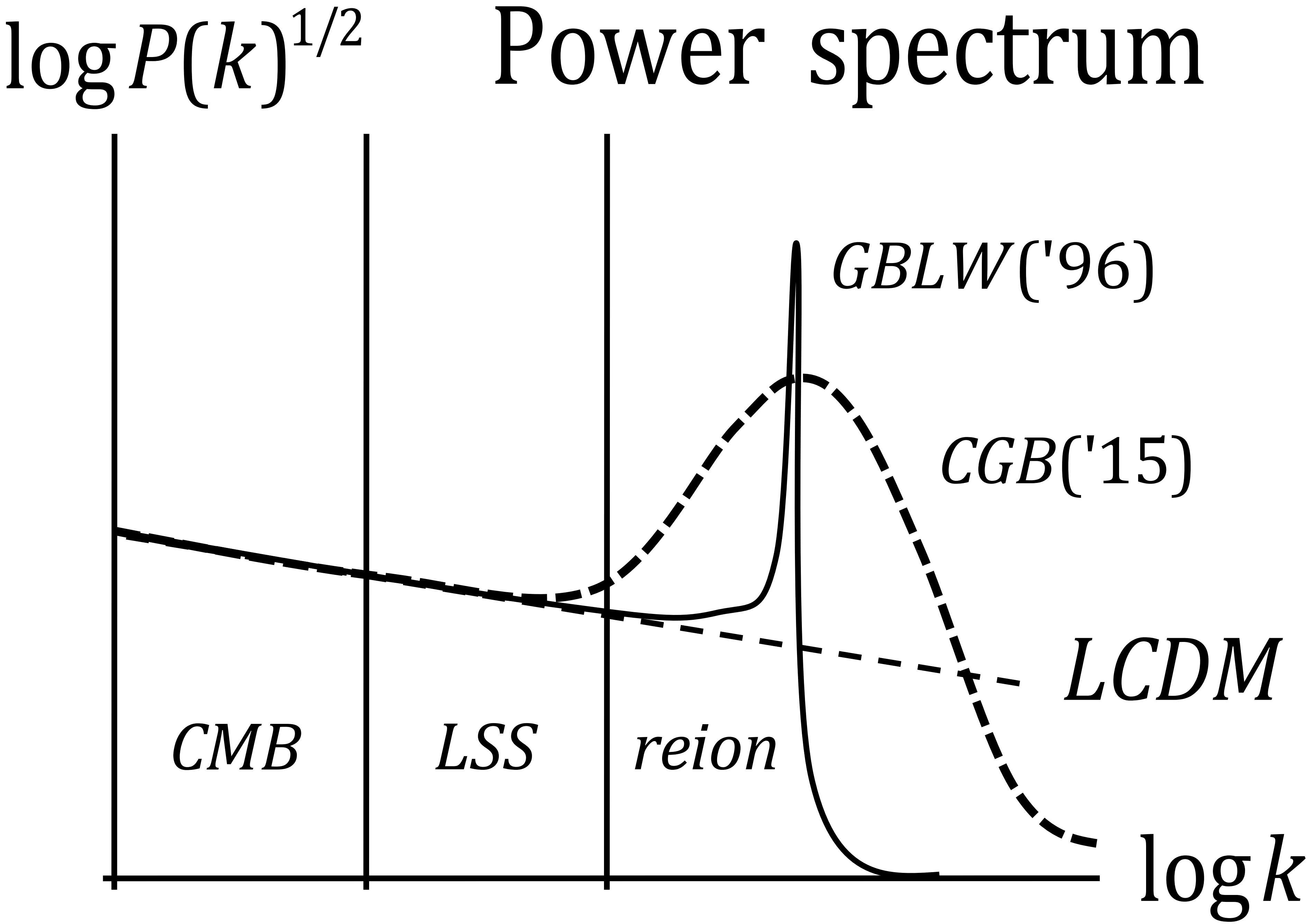

Potential
V(Φ)
inflection point
Φ



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

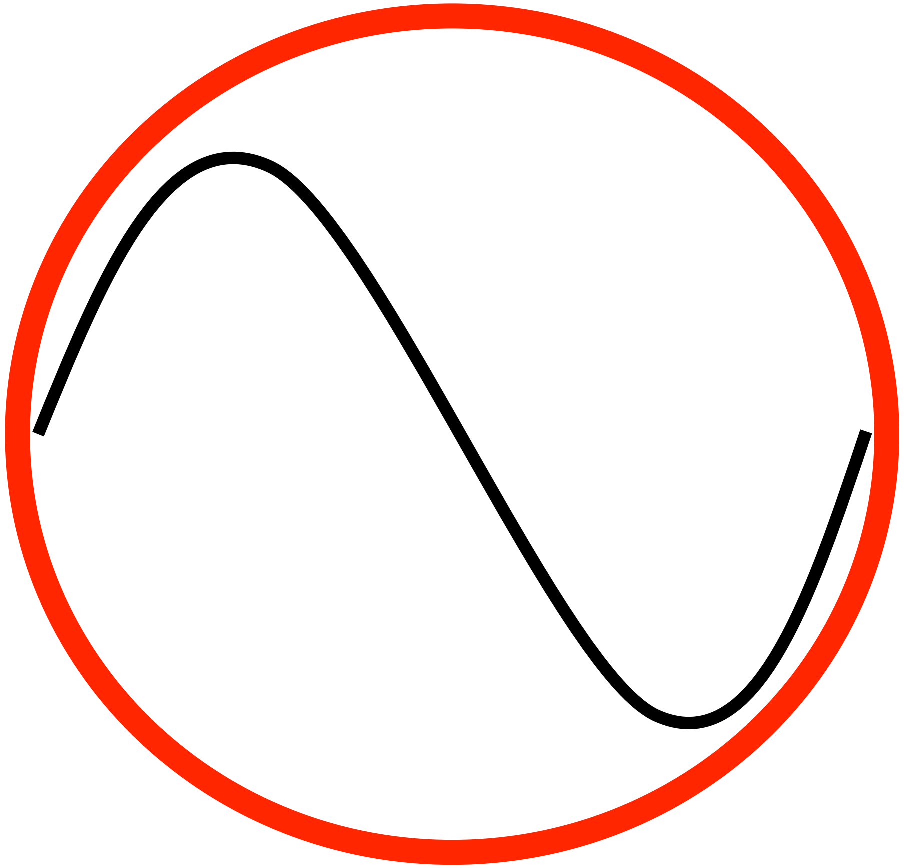


$\log P(k)^{1/2}$
Power spectrum
$GBLW('96)$
$CGB('15)$
$LCDM$
$\log k$

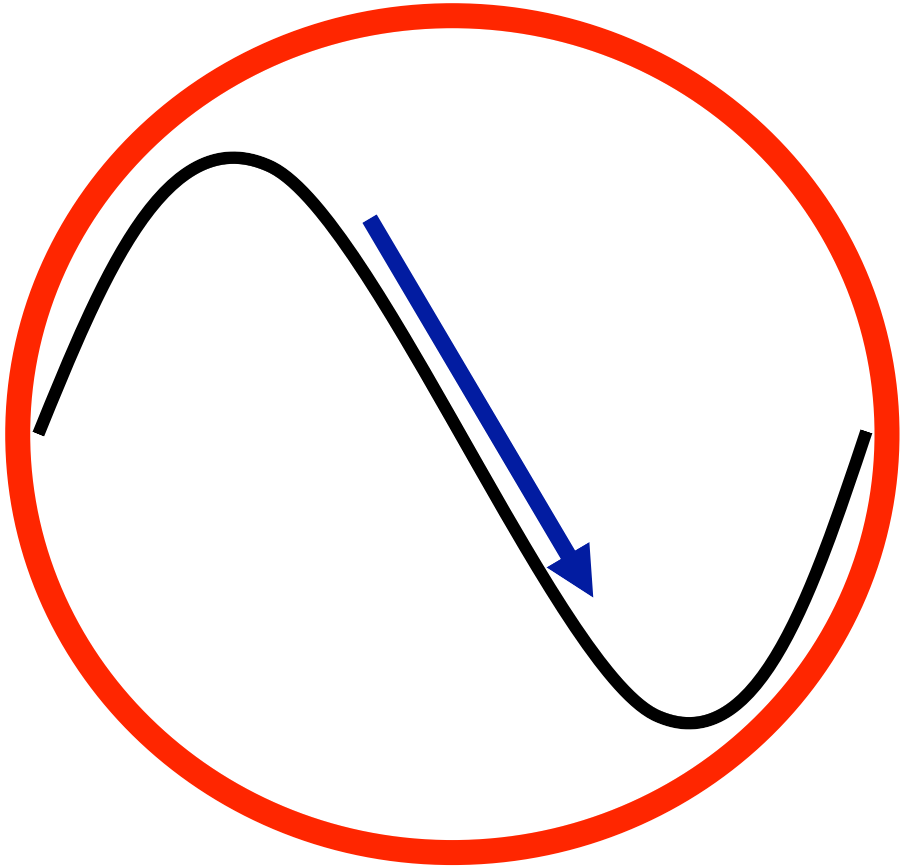


$\log P(k)^{1/2}$
Power spectrum
GBLW('96)
CGB('15)
LCDM
CMB
LSS
reion
$\log k$

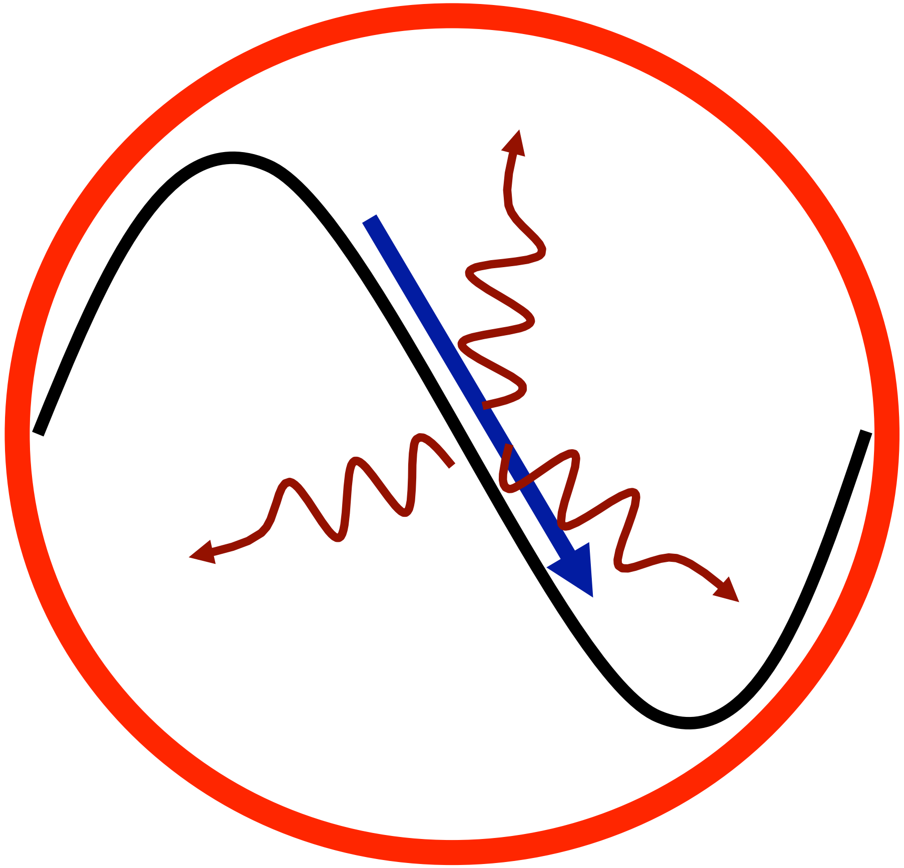
Gravitational Collapse of PBH



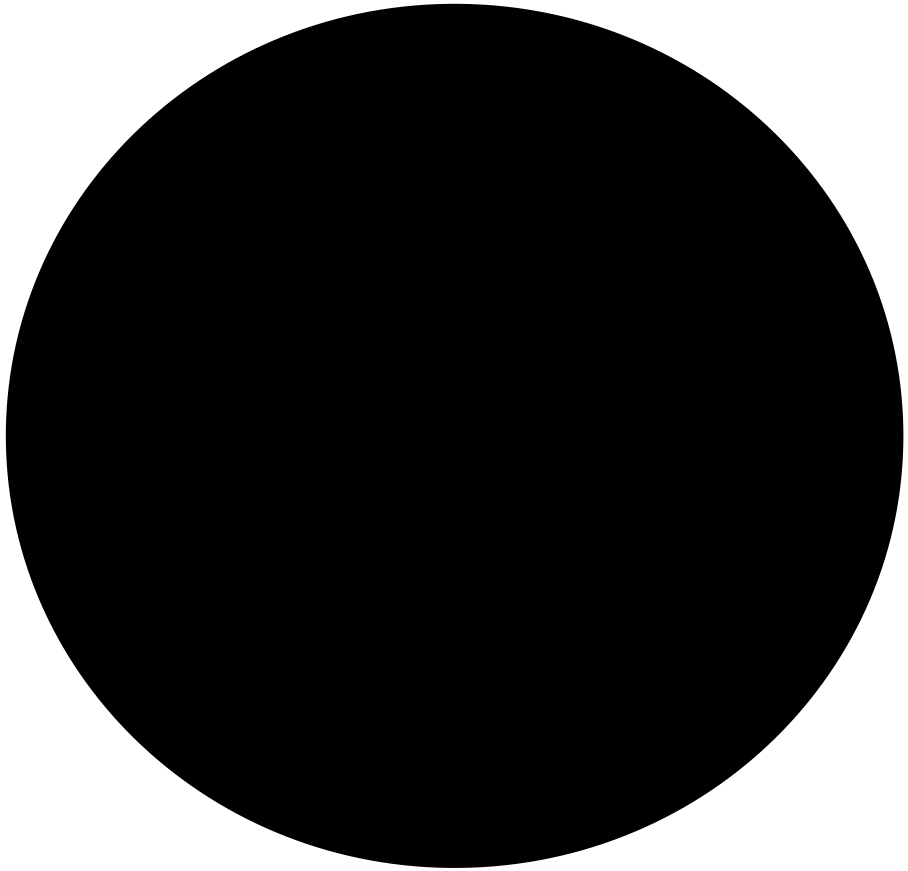
Gravitational Collapse of PBH



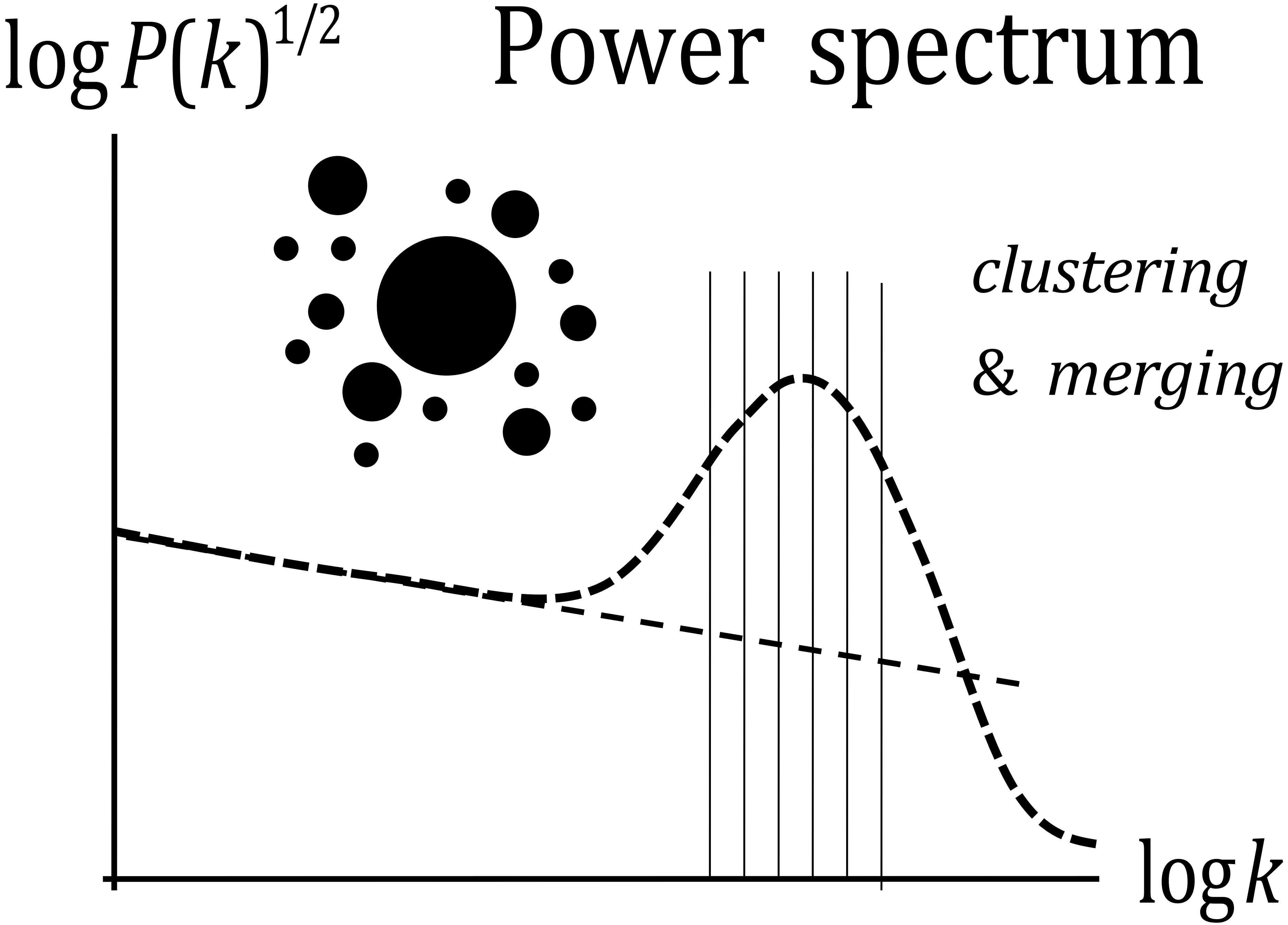
Gravitational Collapse of PBH



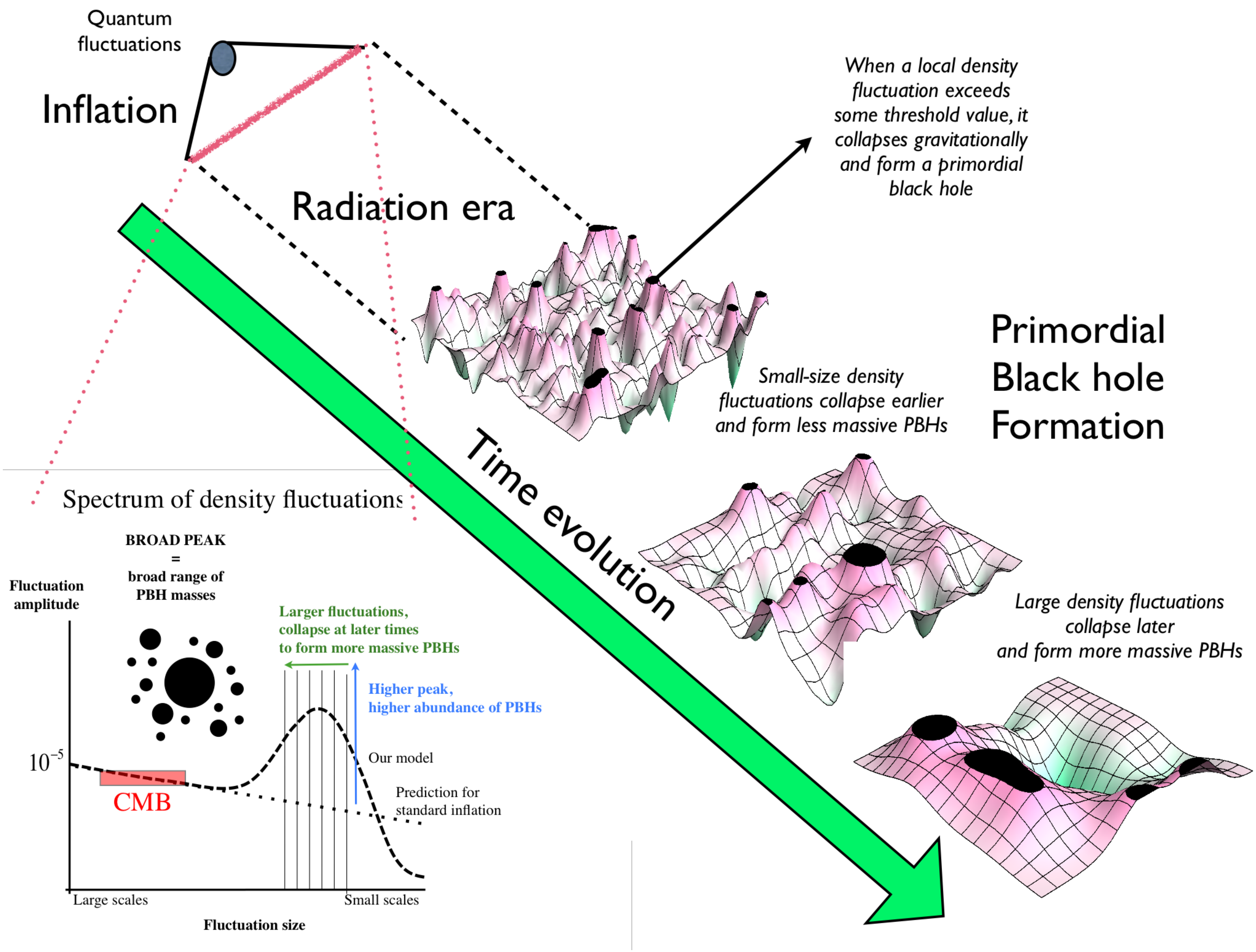
Gravitational Collapse of PBH



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



$\log P(k)^{1/2}$
Power spectrum
clustering
& merging
$\log k$



Quantum fluctuations
Inflation
Radiation era
When a local density fluctuation exceeds some threshold value, it collapses gravitationally and form a primordial black hole
Primordial Black hole Formation
Small-size density fluctuations collapse earlier and form less massive PBHs
Time evolution
Large density fluctuations collapse later and form more massive PBHs
Spectrum of density fluctuations
BROAD PEAK = broad range of PBH masses
Fluctuation amplitude
Larger fluctuations, collapse at later times to form more massive PBHs
Higher peak, higher abundance of PBHs
Our model
Prediction for standard inflation
10^{-5}
CMB
Large scales
Small scales
Fluctuation size

Critical Higgs Inflation

Concrete realization: PBH in Critical Higgs Inflation

Ezquiaga, JGB, Ruiz Morales (2017)

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

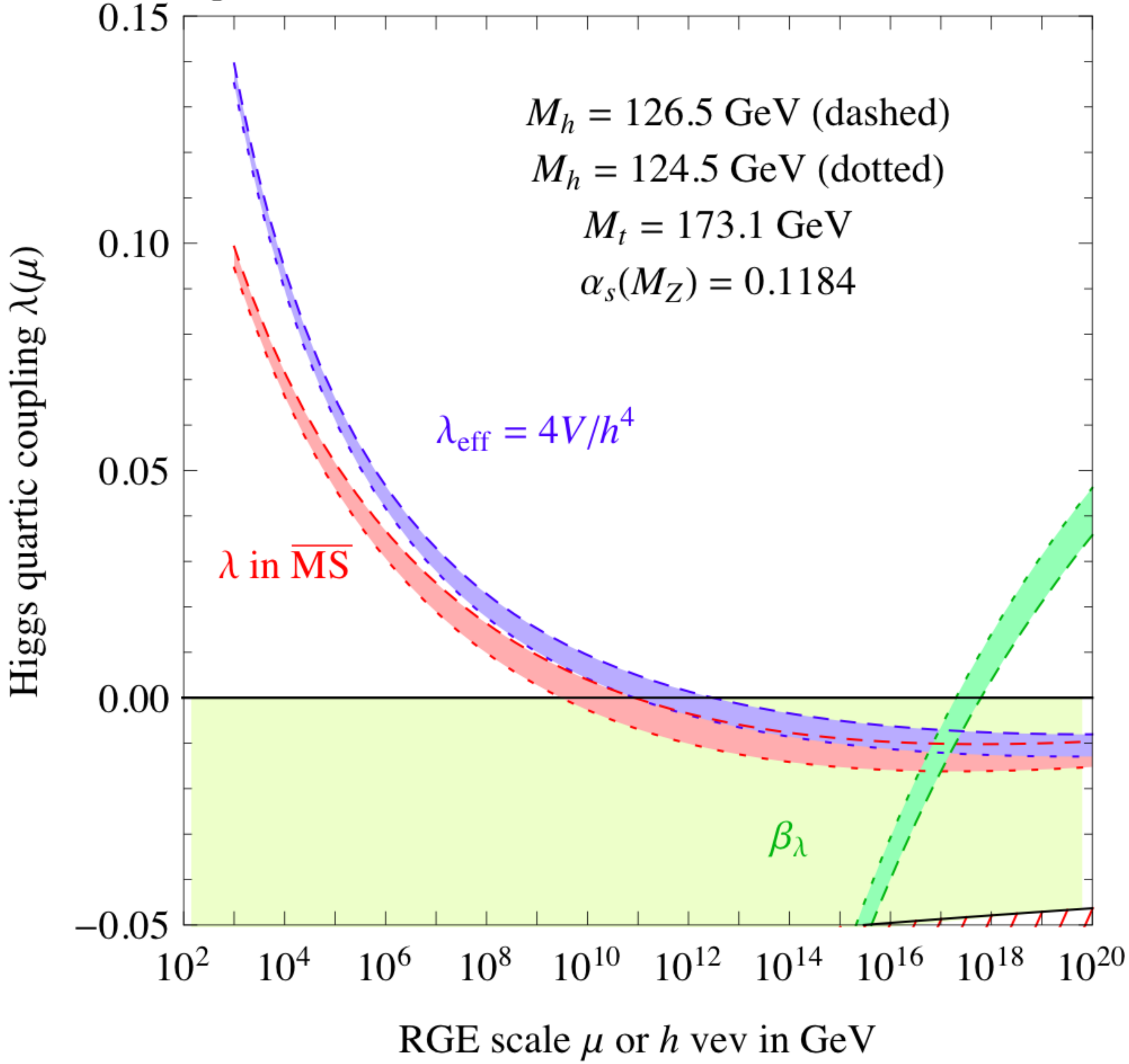
$$\lambda(\phi) \;=\; \lambda_0 + b_\lambda \ln^2(\phi/\mu) \;,$$

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

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

RGE running of Higgs quartic coupling

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



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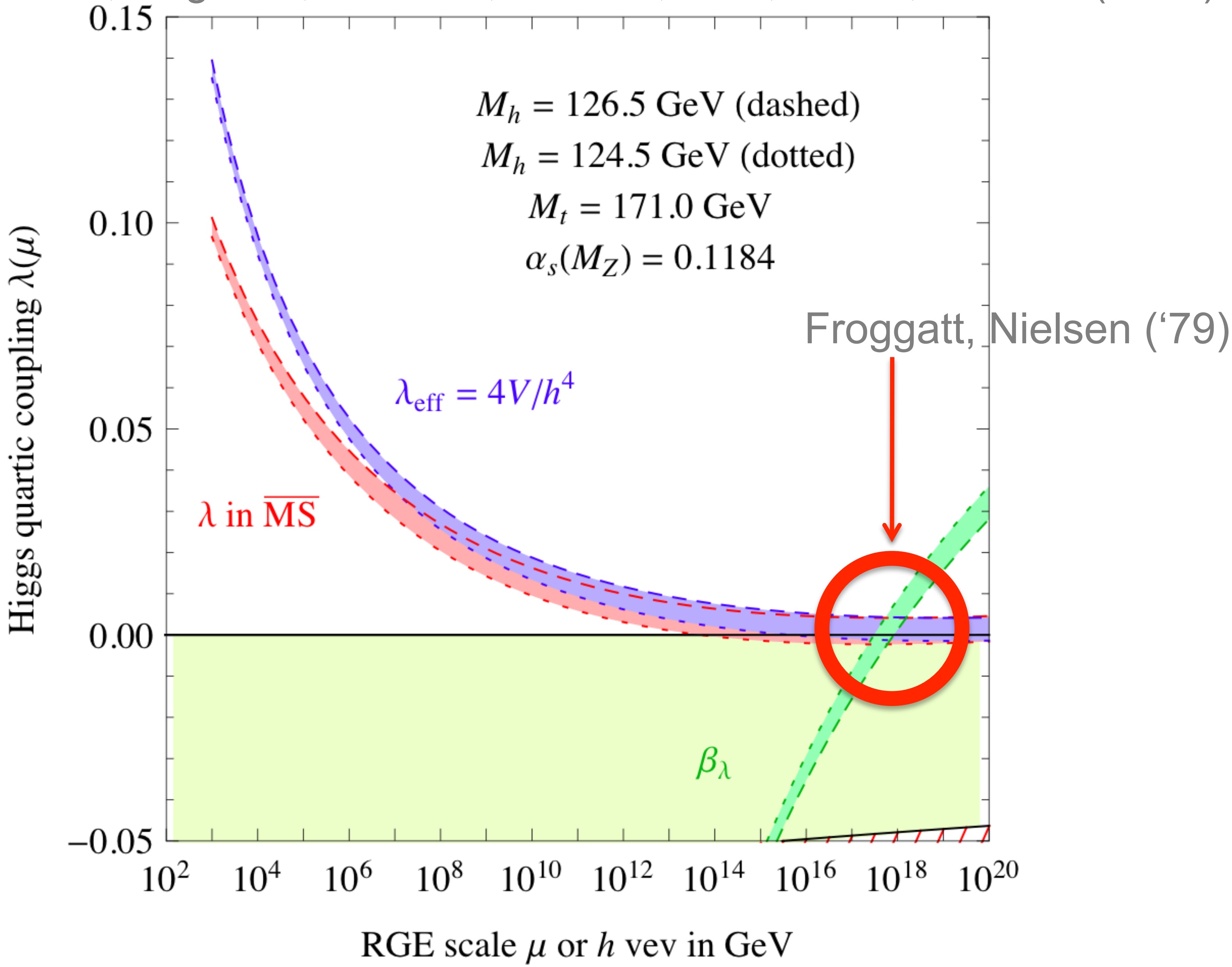


Concrete realization: CHI model

Ezquiaga, JGB, Ruiz Morales (2017)

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

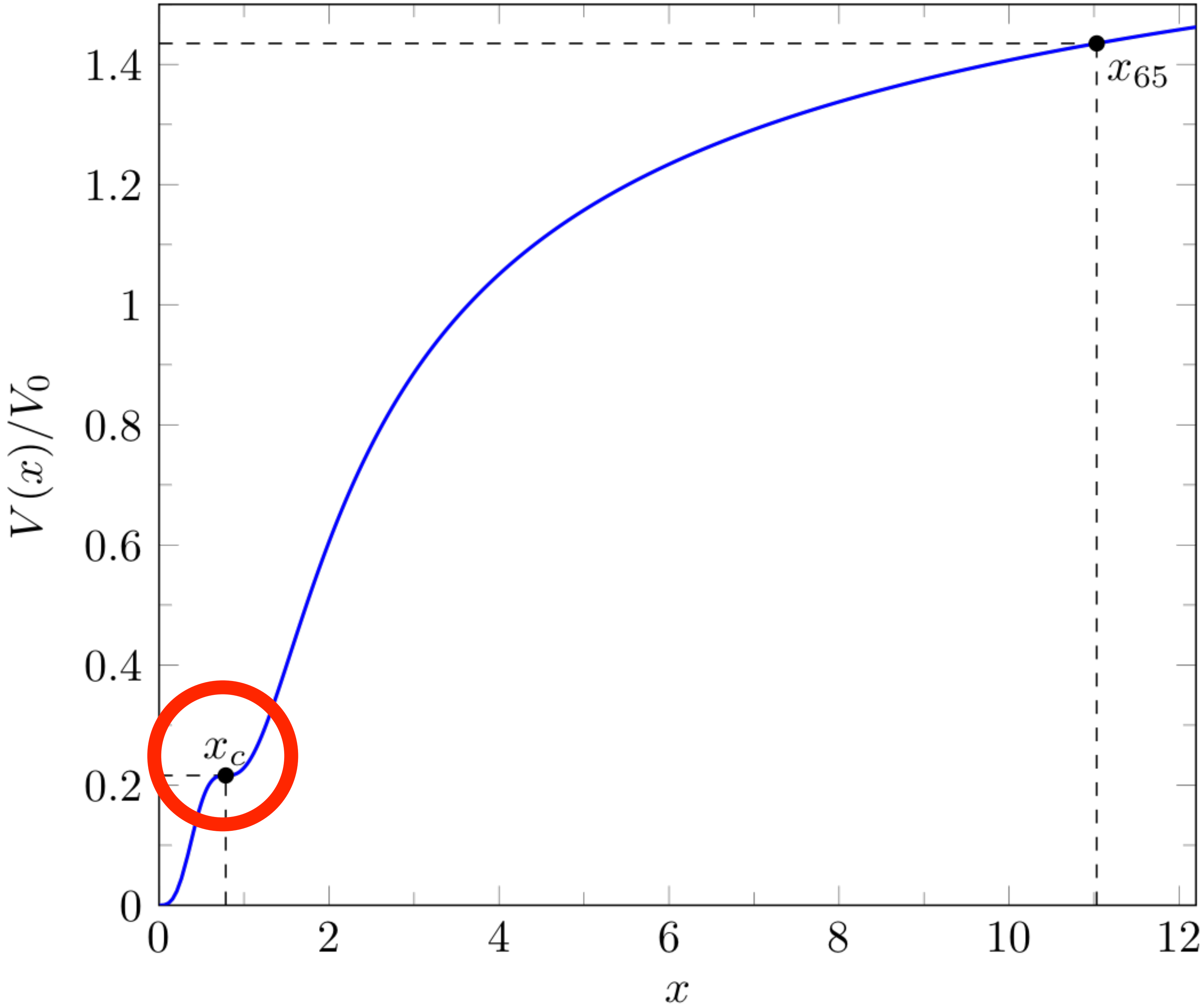
$$\lambda(\phi) = \lambda_0 + b_\lambda \ln^2 (\phi/\mu) \; ,$$

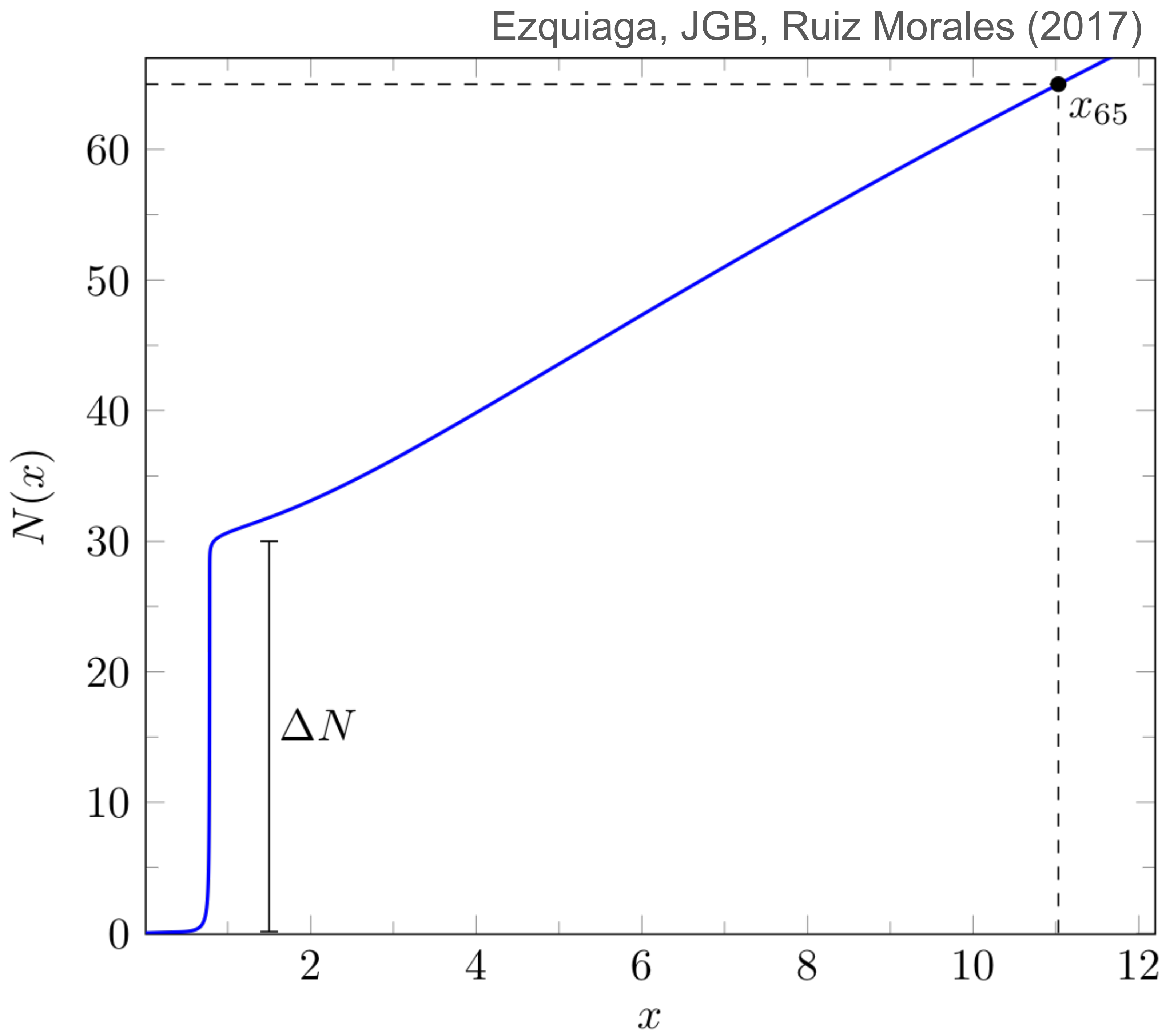
$$\xi(\phi) = \xi_0 + b_\xi \ln (\phi/\mu) \; ,$$

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

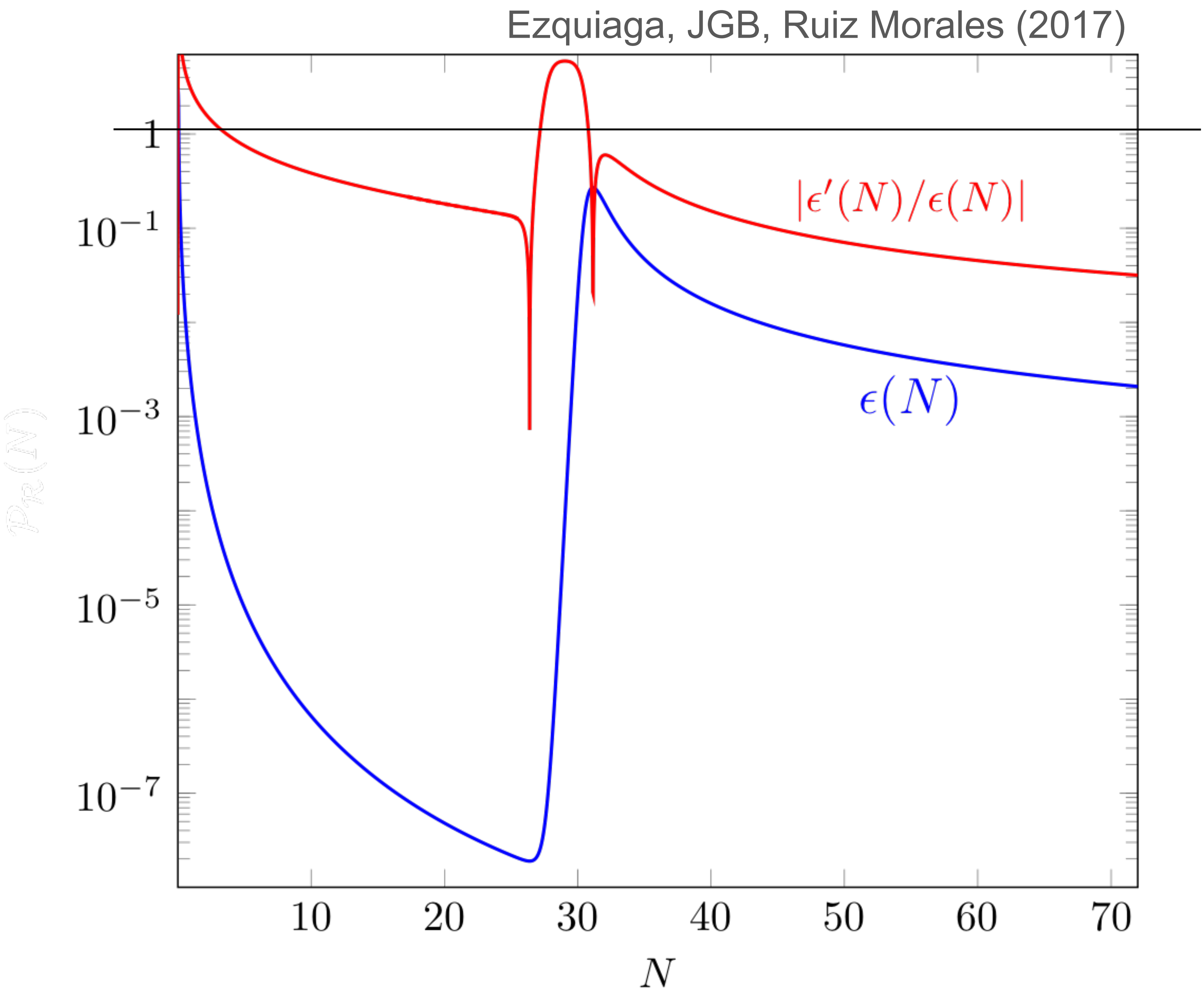
$$V_0 = \lambda_0 \mu^4/4, \; a = b_\lambda/\lambda_0, \; b = b_\xi/\xi_0 \text{ and } c = \xi_0 \, \kappa^2 \mu^2$$

Ezquiaga, JGB, Ruiz Morales (2017)

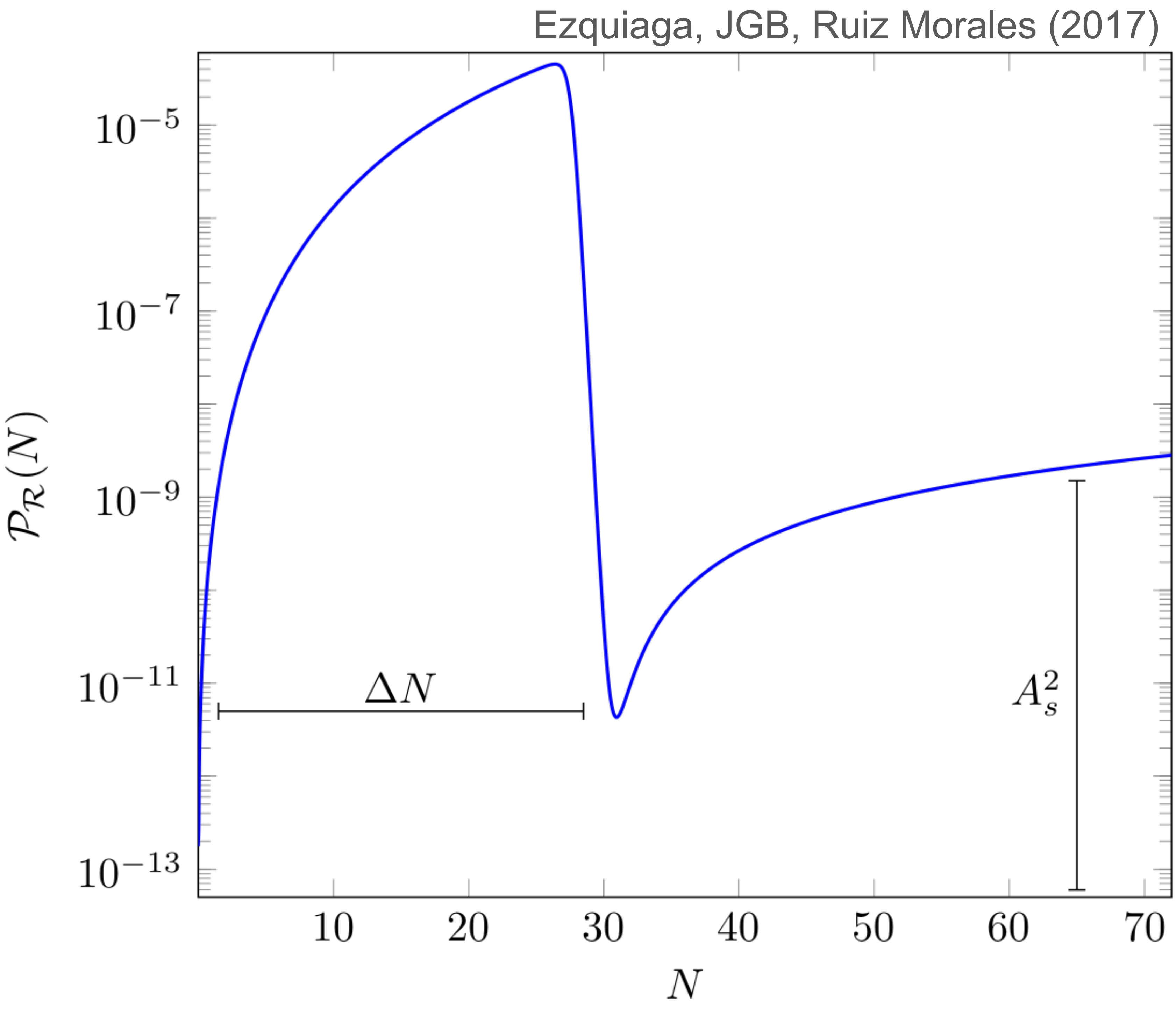




Ezquiaga, JGB, Ruiz Morales (2017)
x_{65}
ΔN
$N(x)$
x
0
10
20
30
40
50
60
2
4
6
8
10
12

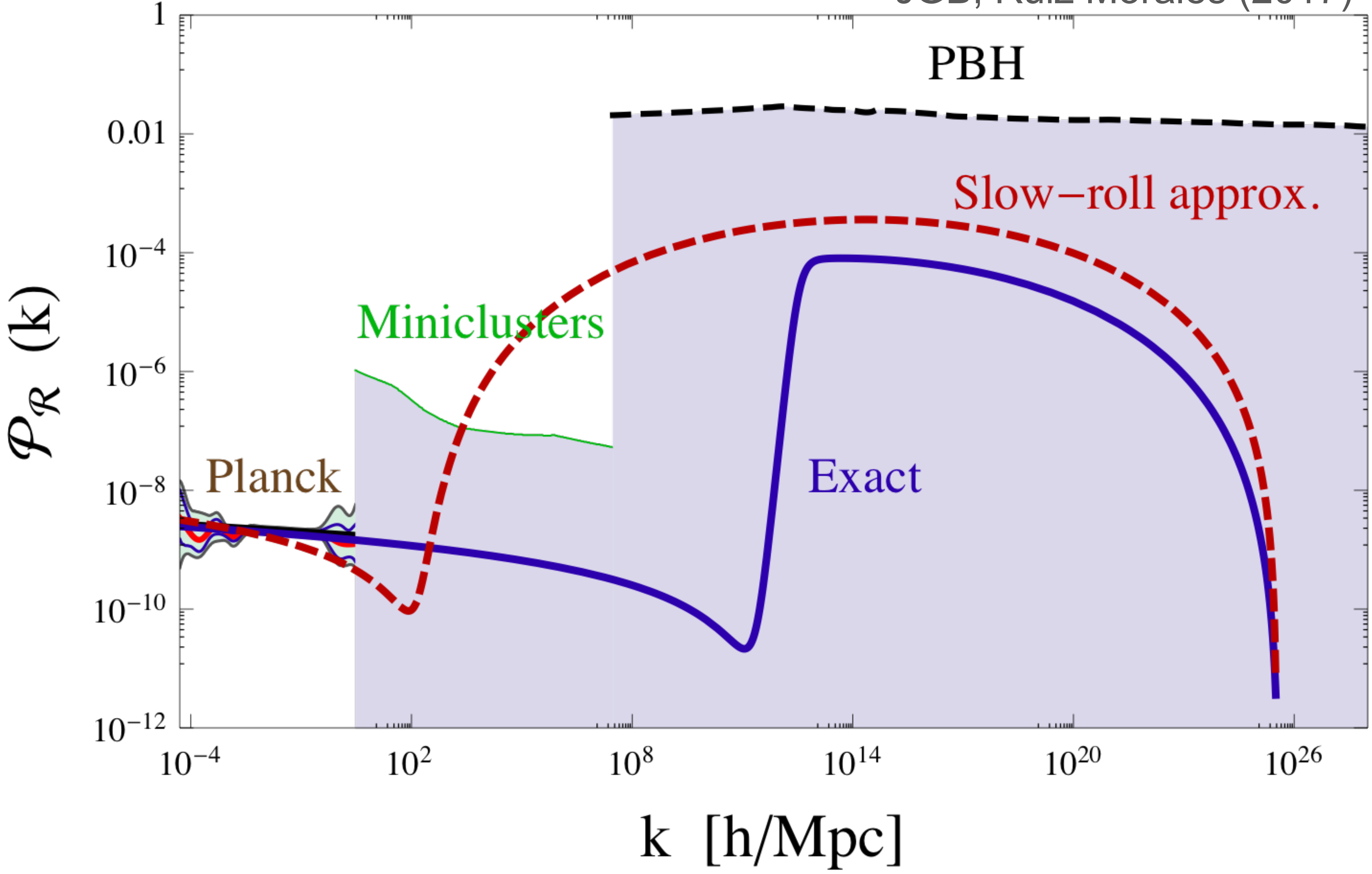


Ezquiaga, JGB, Ruiz Morales (2017)
1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
$|\epsilon'(N)/\epsilon(N)|$
$\epsilon(N)$
10
20
30
40
50
60
70
N


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)



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)

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

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

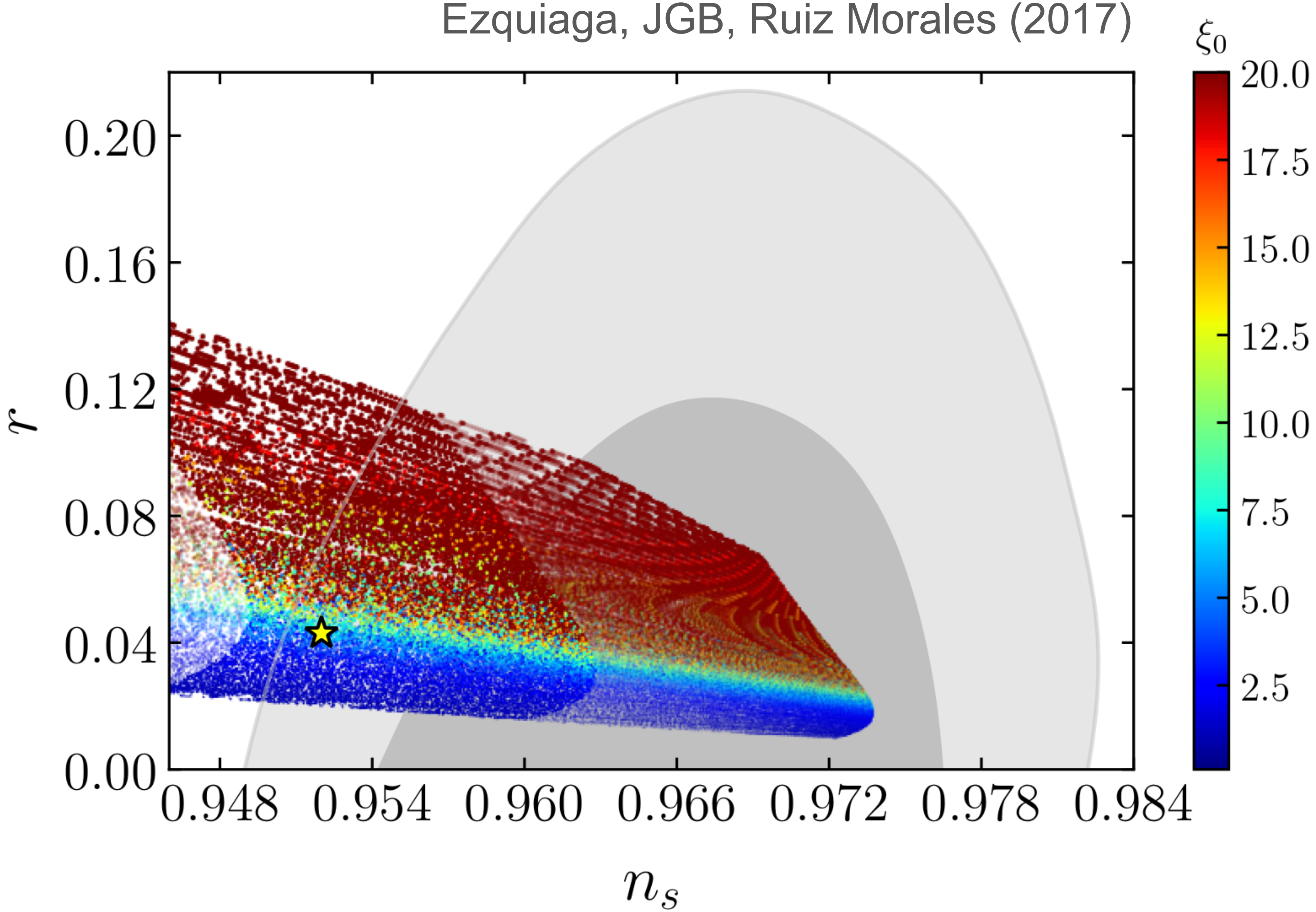
Reheating after CHI

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

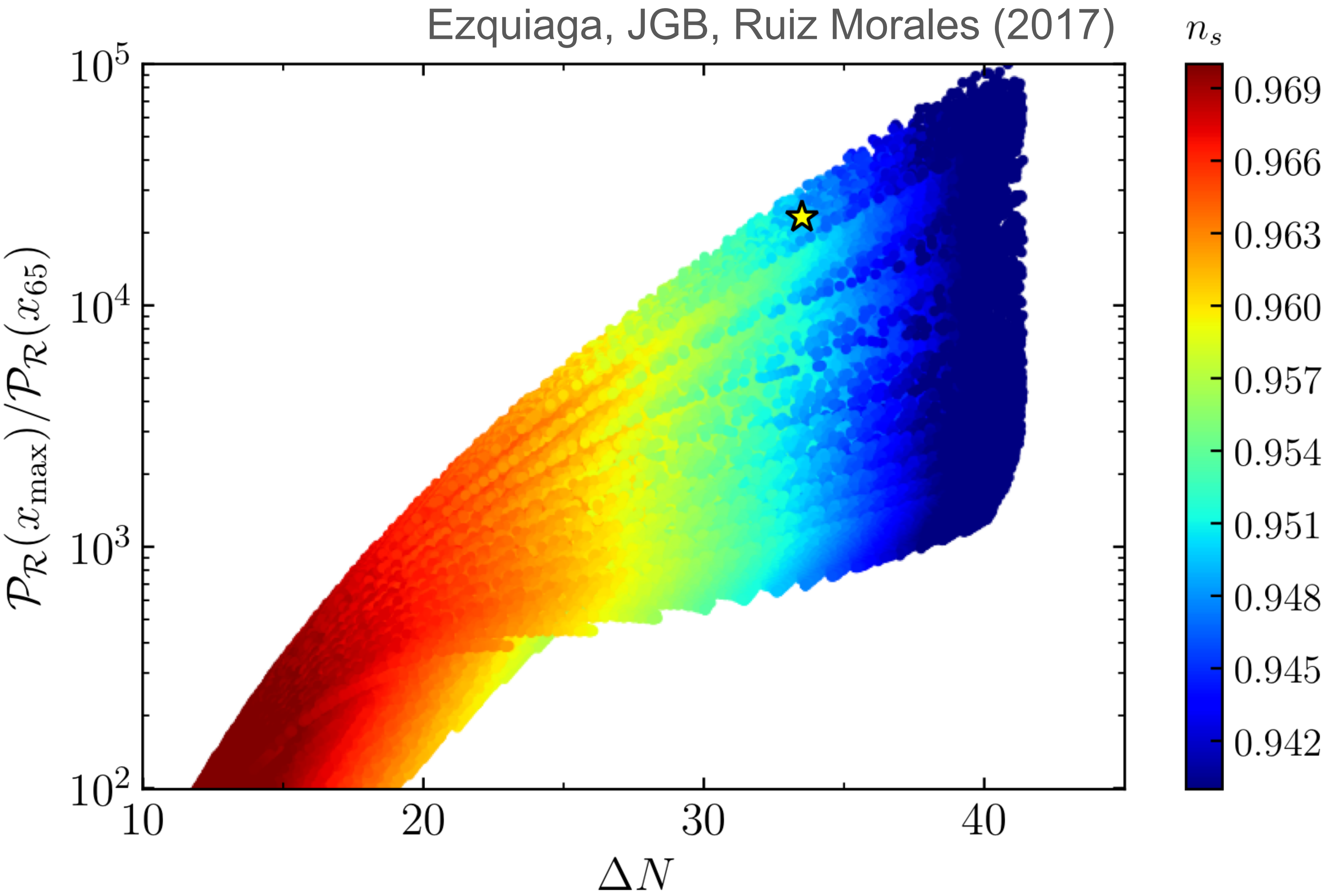
$$T_\mathrm{rh} = 3 \times 10^{15}\ \mathrm{GeV} \qquad (\text{for } g_* = 106.75)$$

CMB Constraints on CHI

Ezquiaga, JGB, Ruiz Morales (2017)



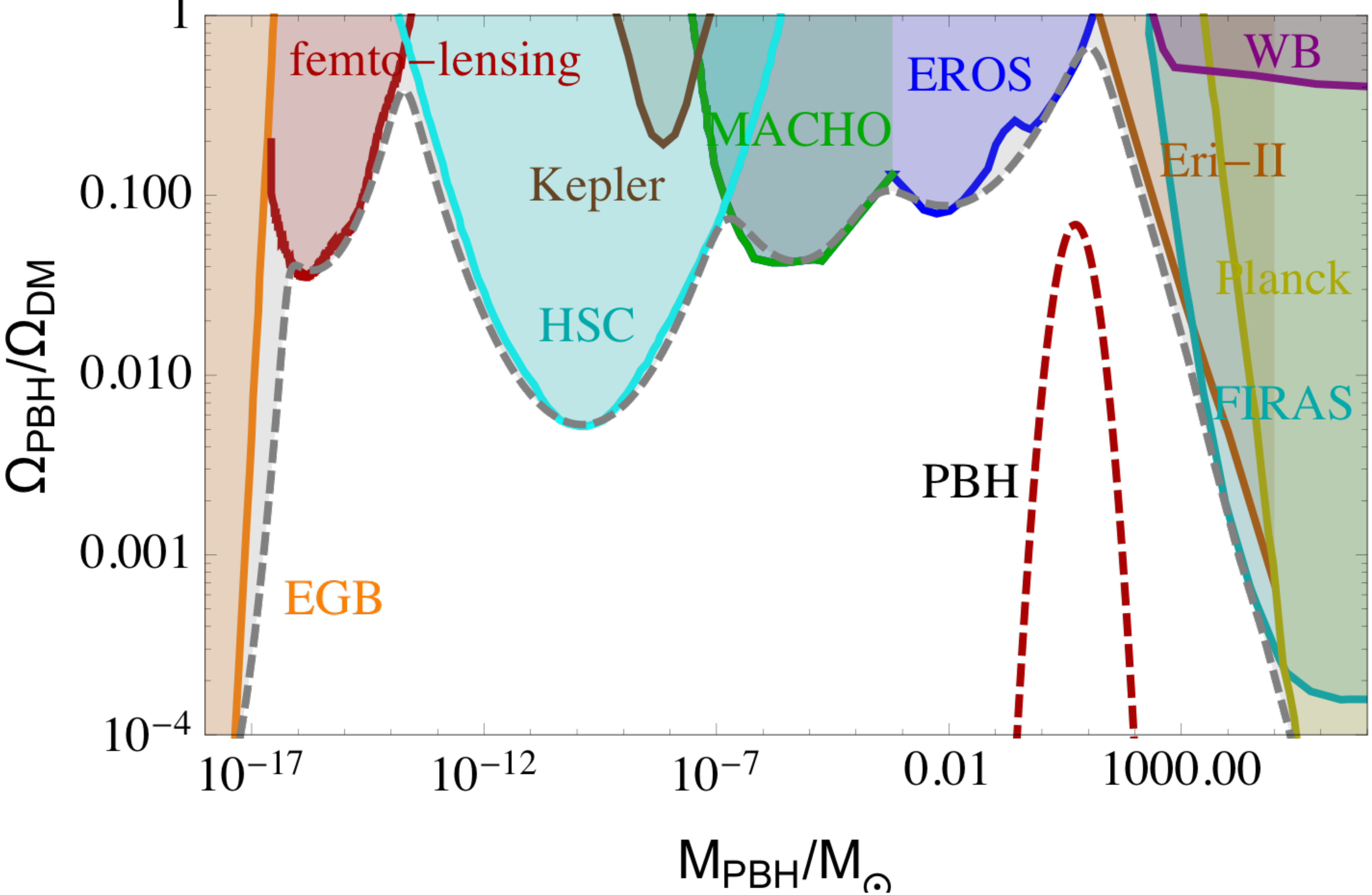
CMB Constraints on CHI



Constraints on Primordial Black Holes

Present Constraints on PBH

Ezquiaga, JGB, Ruiz Morales (2017)

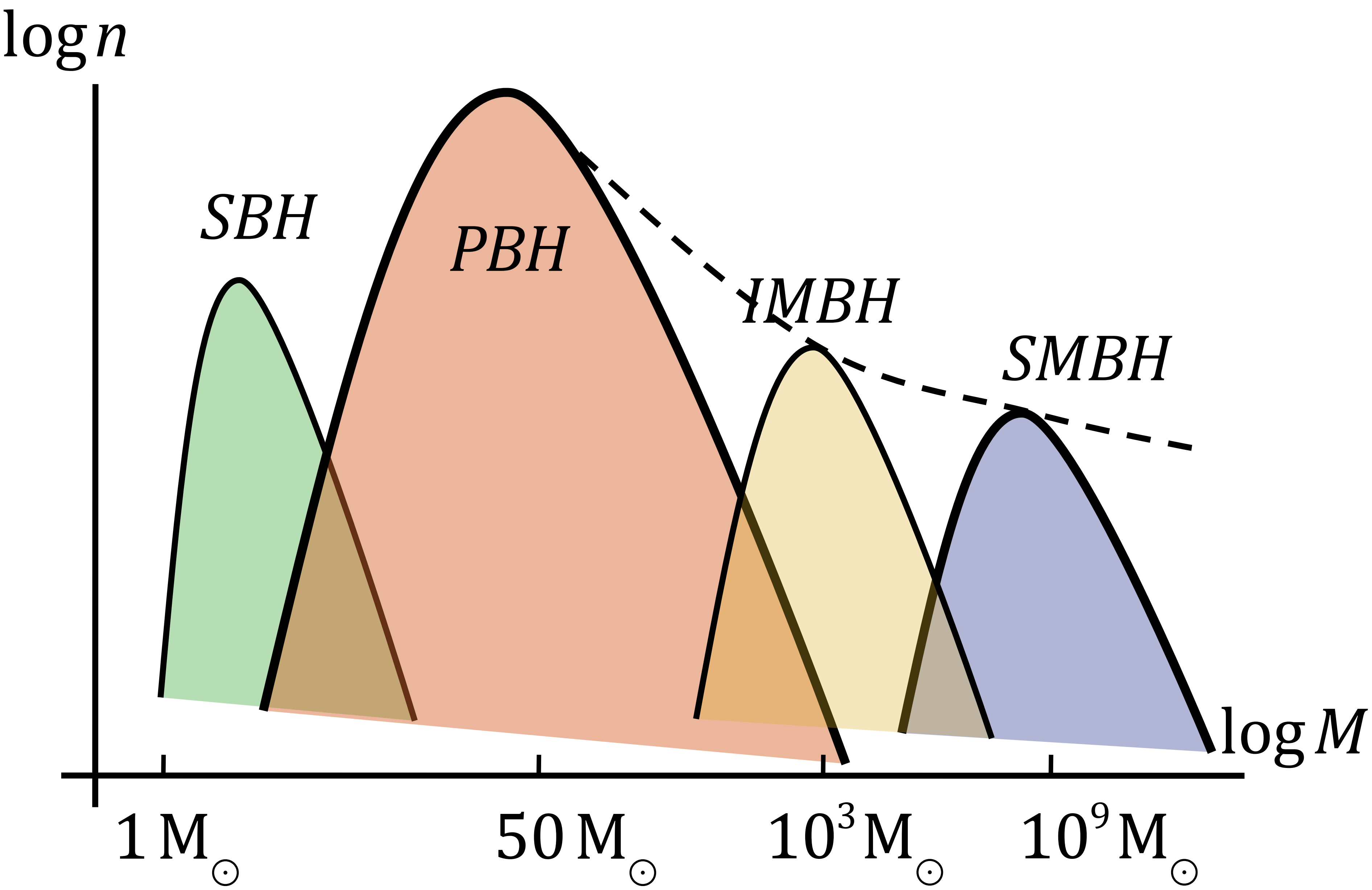


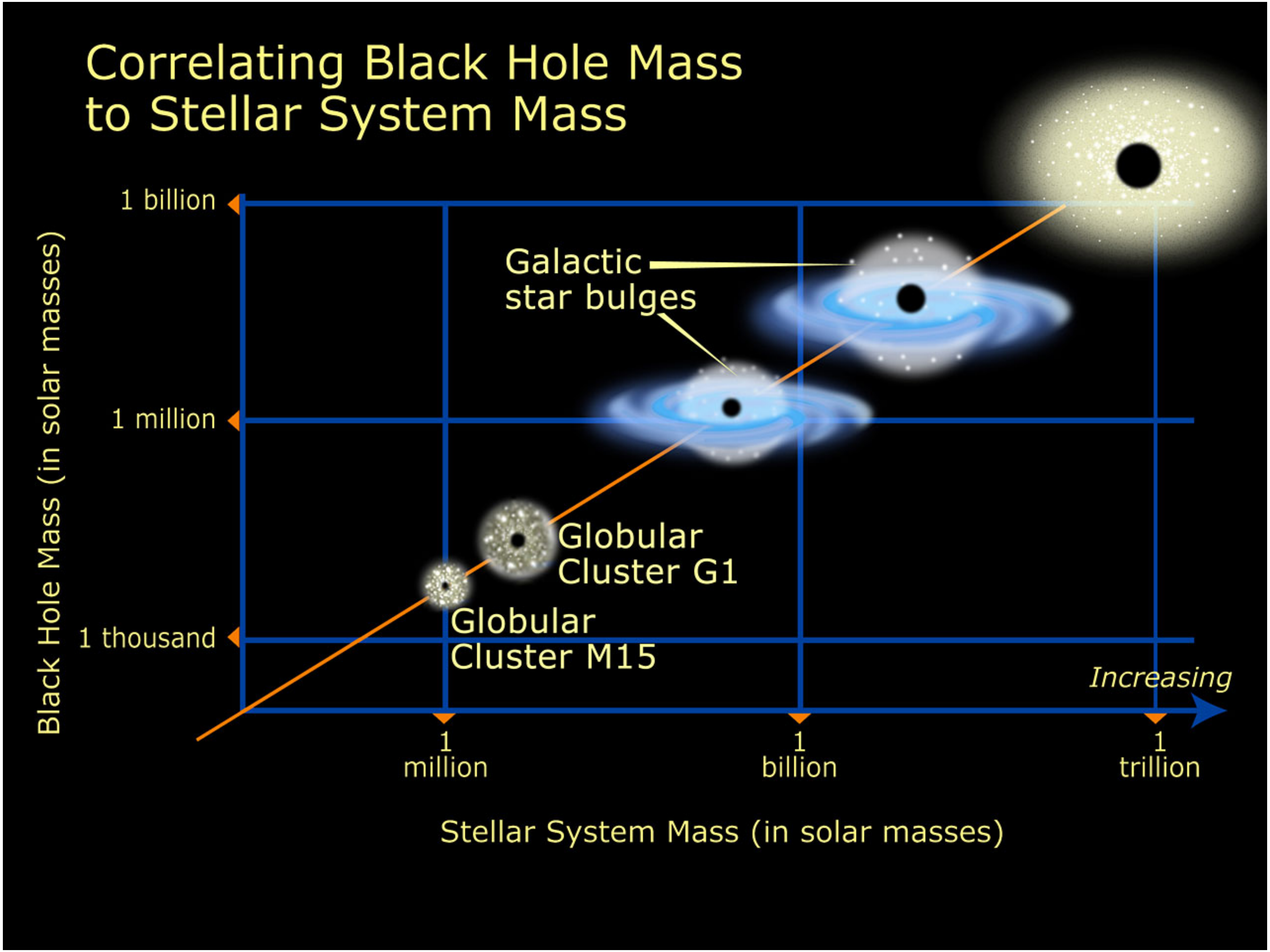
Massive Primordial Black Holes

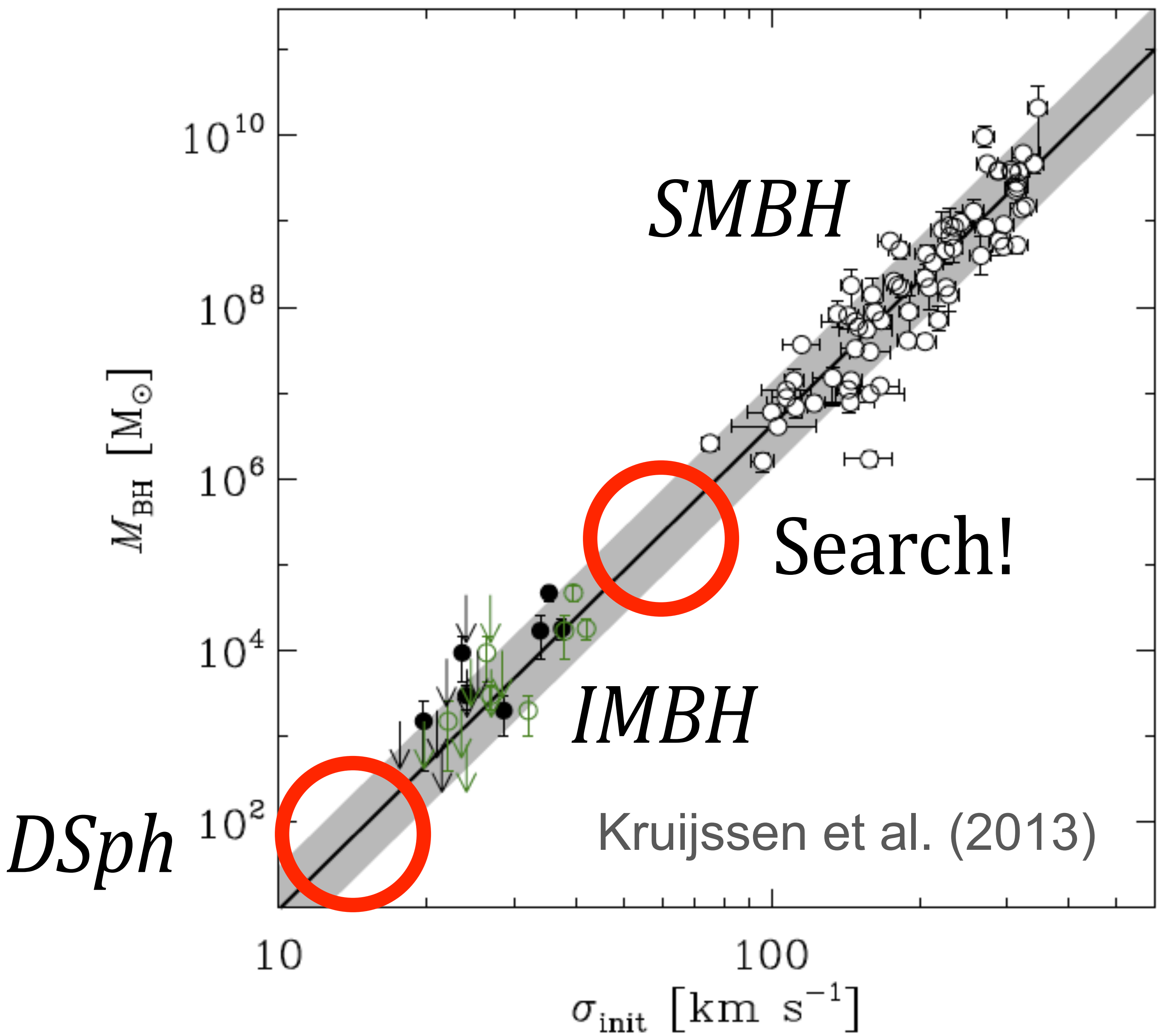
- These are massive black holes with $10^{-2}\ M_{\odot} < M_{PBH} < 10^{2}\ M_{\odot}$, which cluster and merge and could resolve some of the most acute problems of ΛCDM paradigm.

- ΛCDM N-body simulations never reach the $100\ M_{\odot}$ particle resolution, so for them PBH is as good as PDM.

Mass distribution of BH

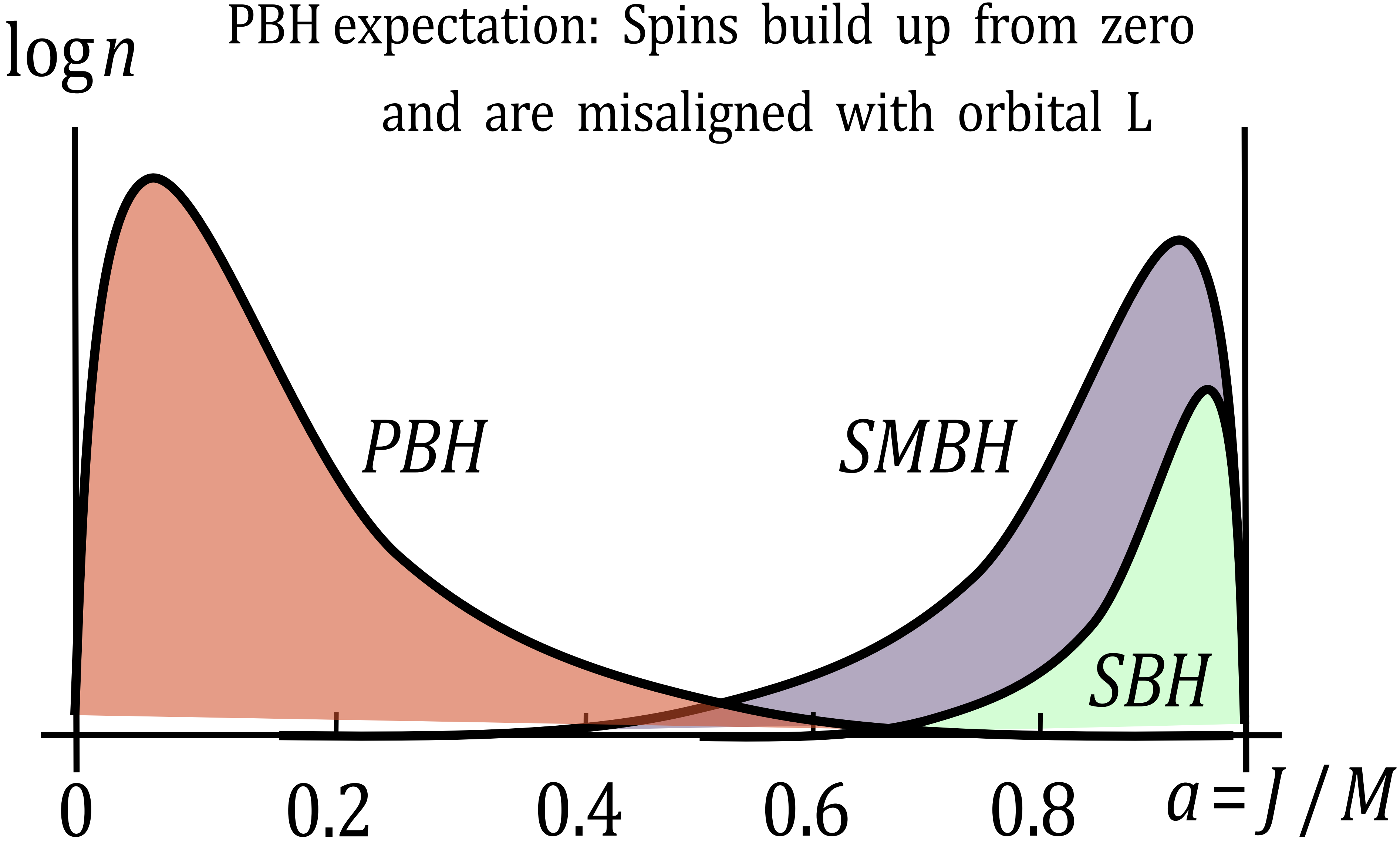



Correlating Black Hole Mass
to Stellar System Mass
Black Hole Mass (in solar masses)
1 billion
1 million
1 thousand
Galactic
star bulges
Globular
Cluster G1
Globular
Cluster M15
Increasing
1
million
1
billion
1
trillion
Stellar System Mass (in solar masses)


SMBH
Search!
IMBH
DSph
Kruijssen et al. (2013)
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
M_{BH} [$M_\odot$]
10
100
σ_{init} [km s^{-1}]

Spin distribution of BH

PBH expectation: Spins build up from zero and are misaligned with orbital L

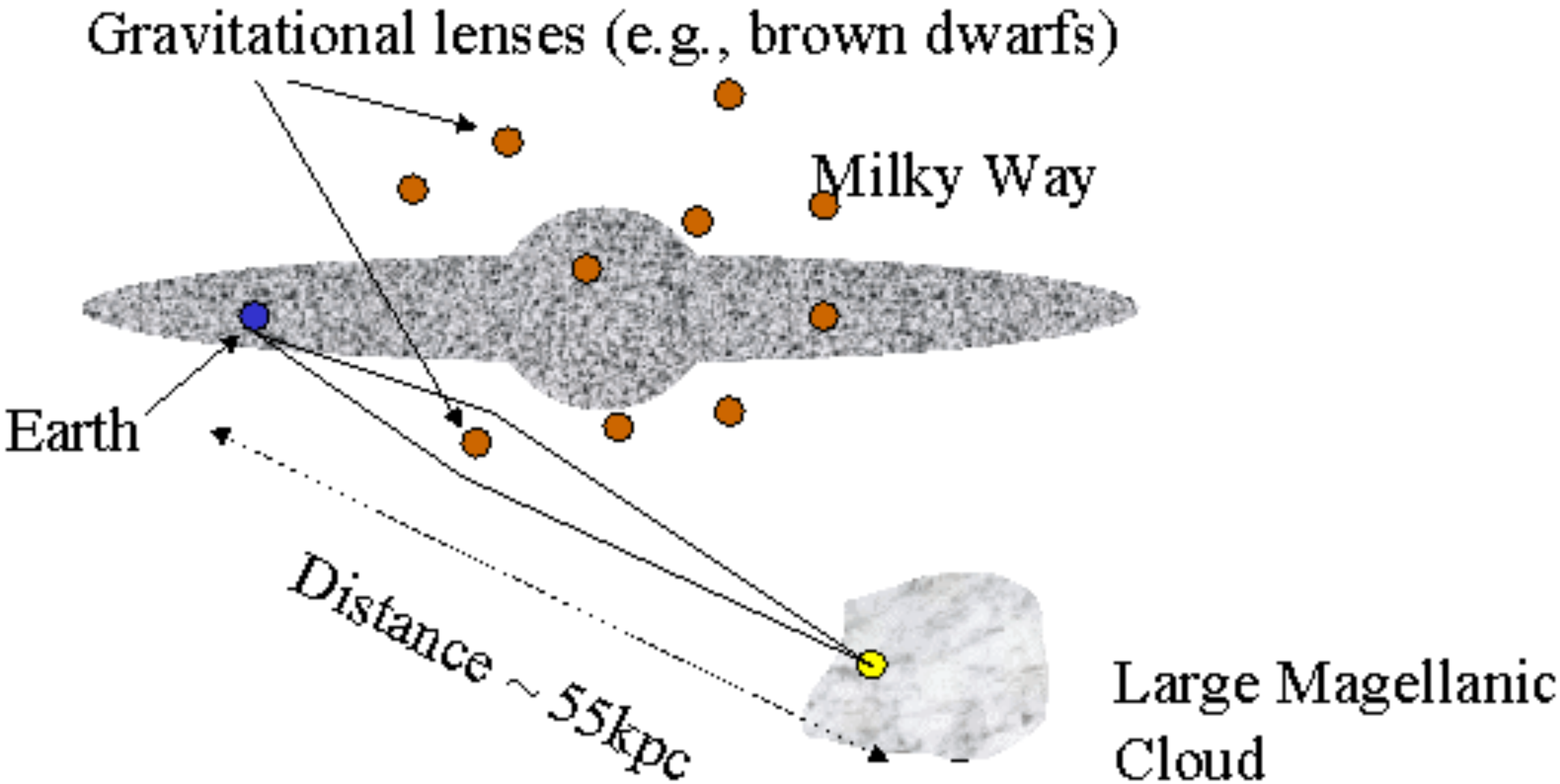


Distinguish MPBH from Stellar BH

- 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_{sun}

Signatures of Primordial Black Holes

Microlensing



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

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

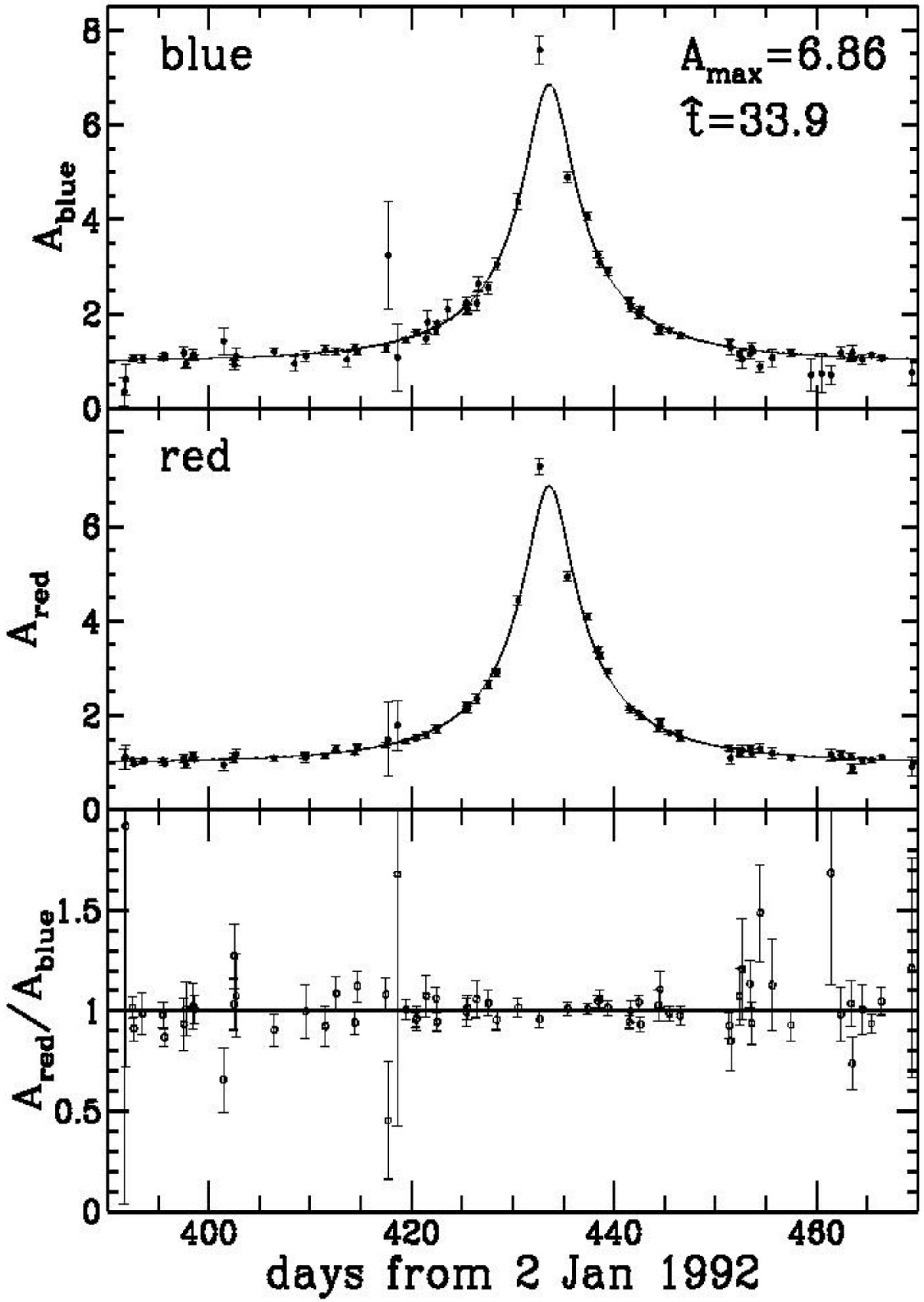
$M_D = 100\,\mathrm{M}_\odot$ => $\overline{Dt} = 4$ years

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

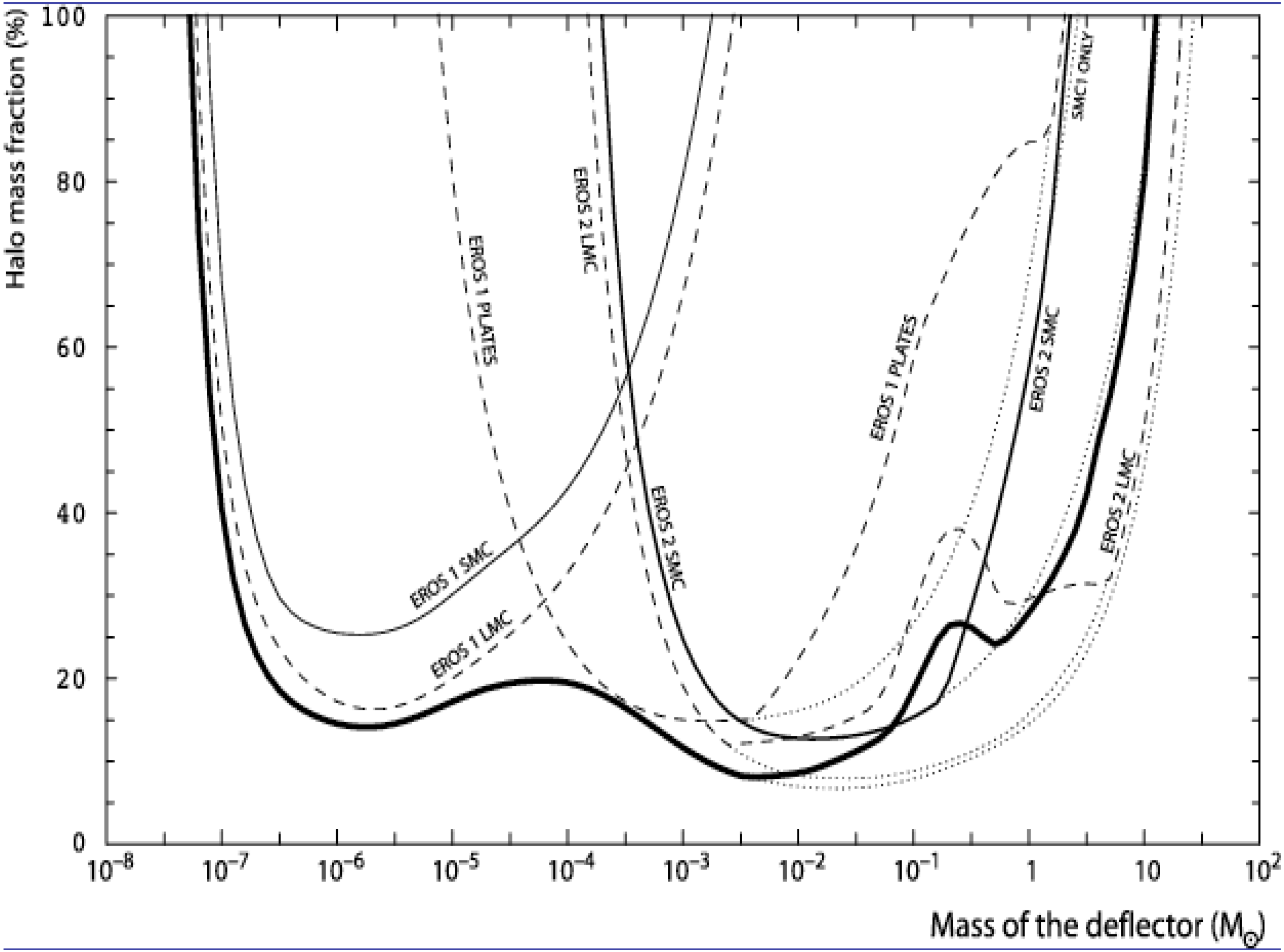
$$\frac{A_{red}}{A_{blue}} = 1.00 \pm 0.05$$

unique

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

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

P. Tisserand (2007)



Missing satellite

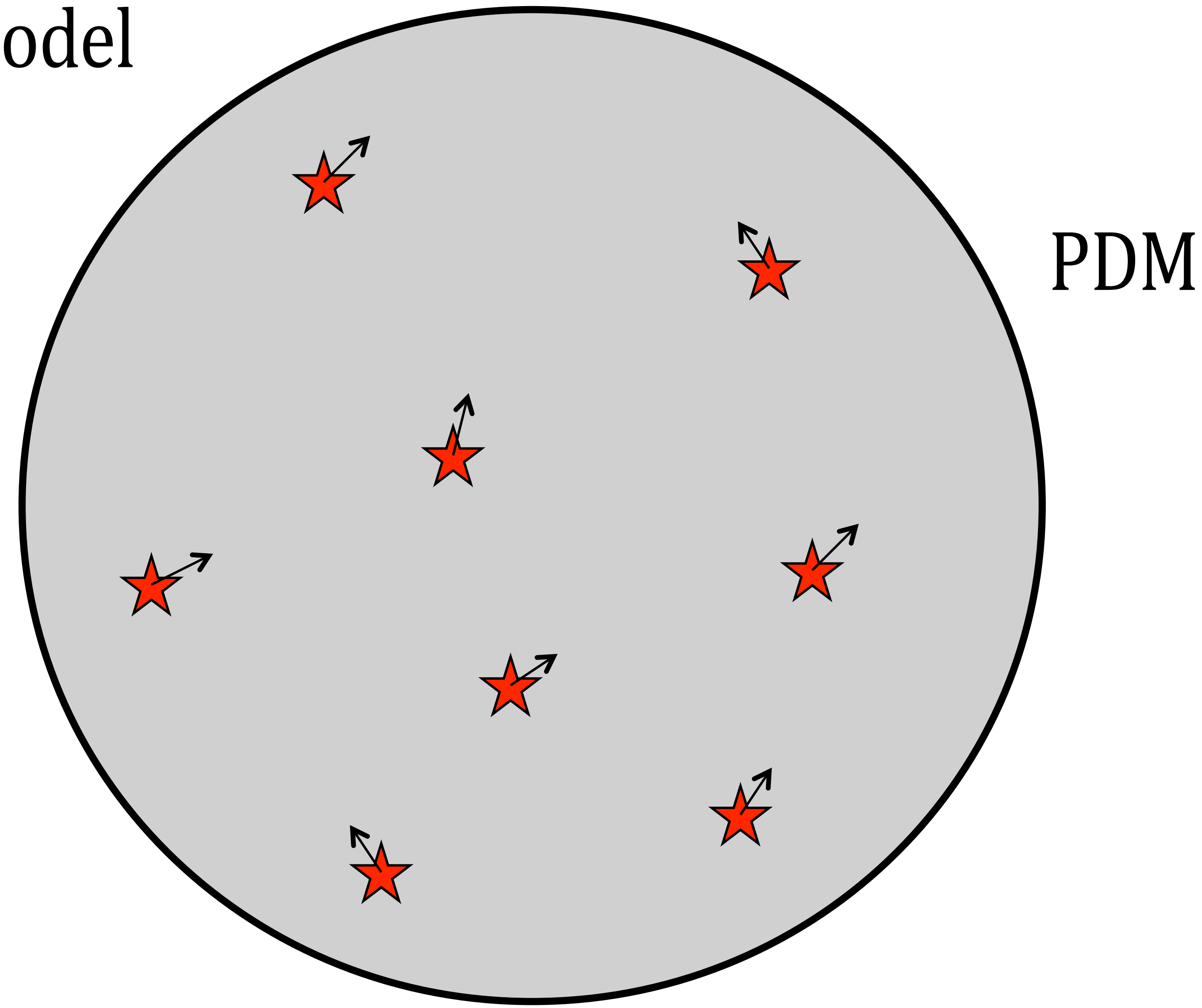
&

Too-big-to-fail

Problems ΛCDM

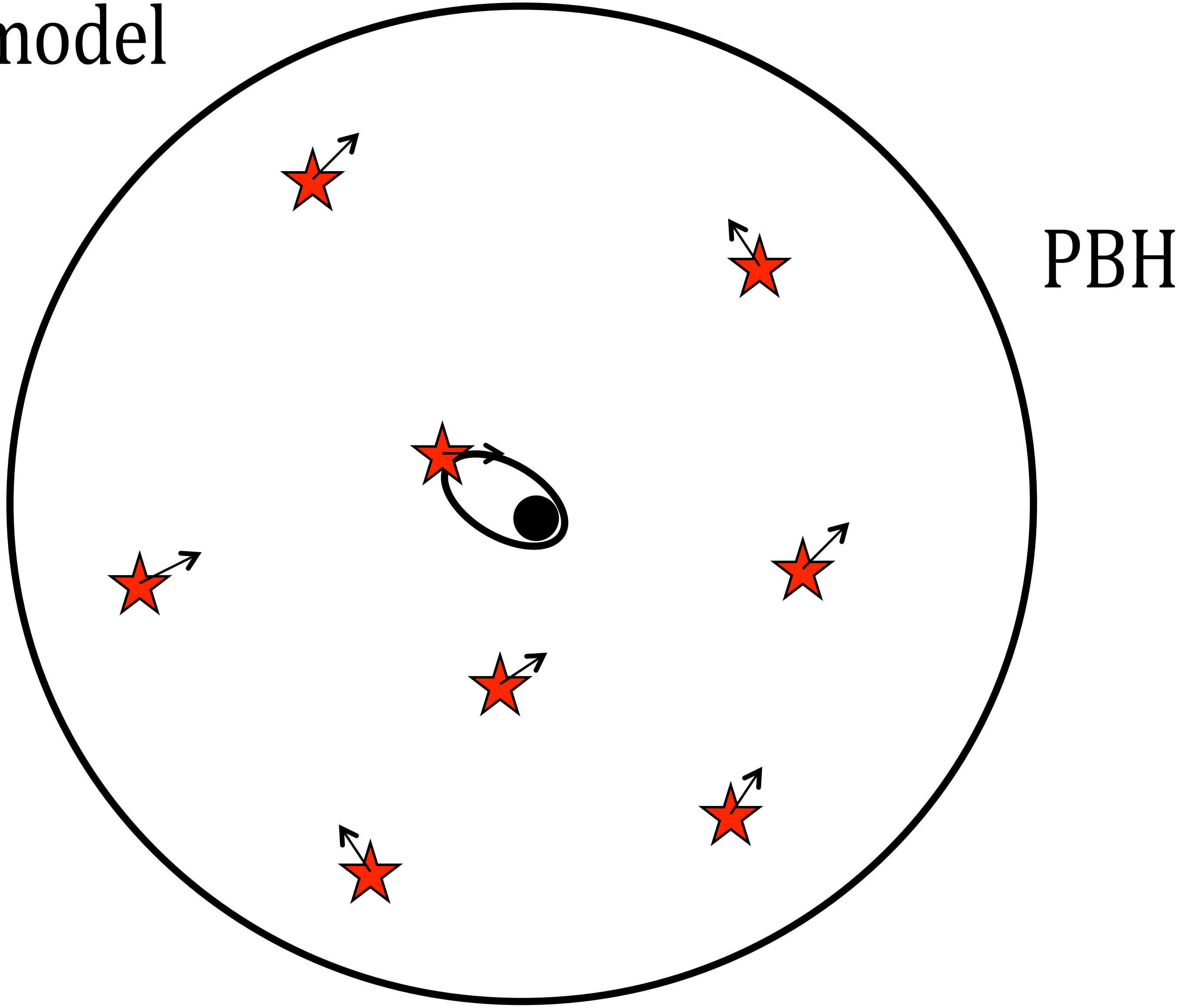
Spatial distribution of DM

Thomson model



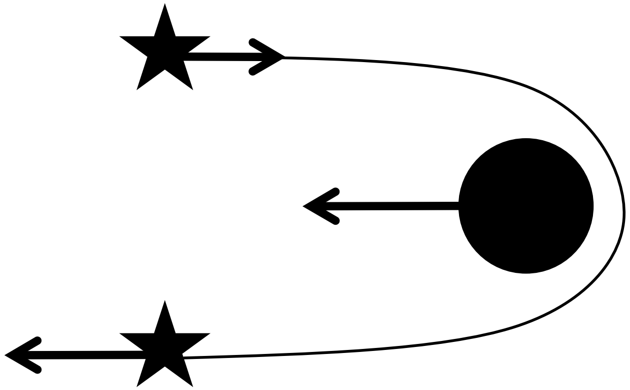
Spatial distribution of DM

Rutherford model



Gravitational slingshot effect

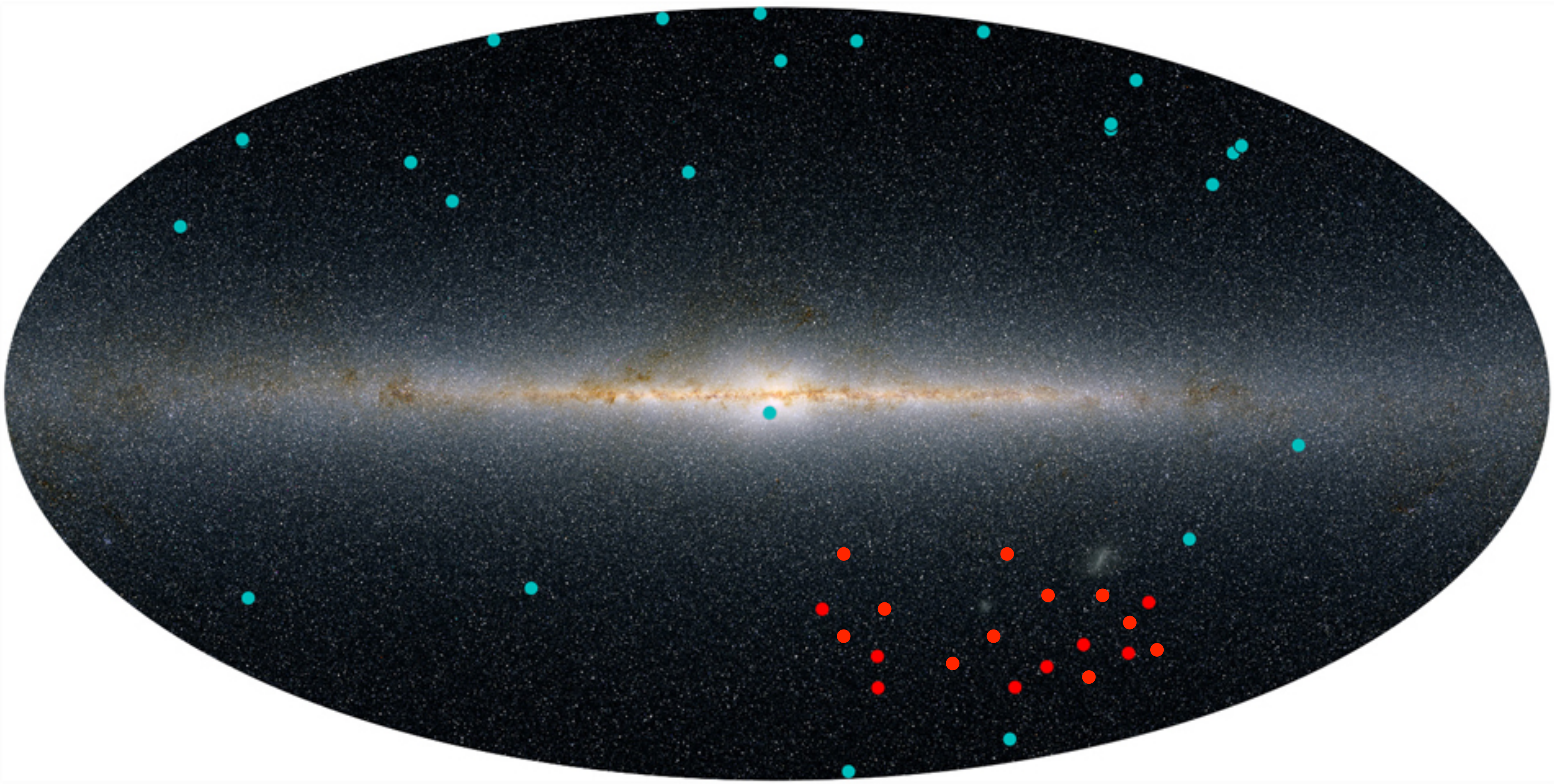
Close encounters of a star with MPBH @ 100 km/s relative motion is enough to expel the star from the stellar cluster.

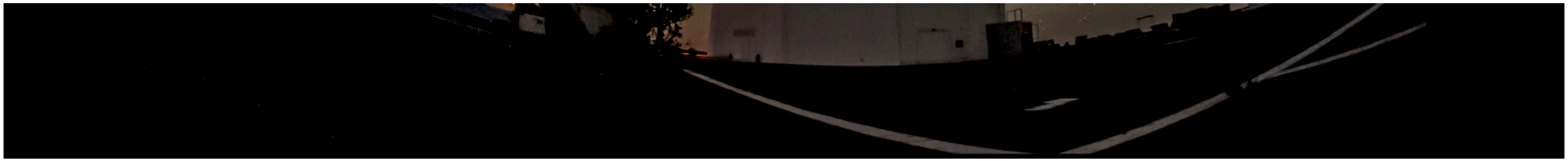


$$\vec{v}_2 = \frac{2\vec{U} + (1 - m/M)\vec{v}_1}{(1 + m/M)}$$

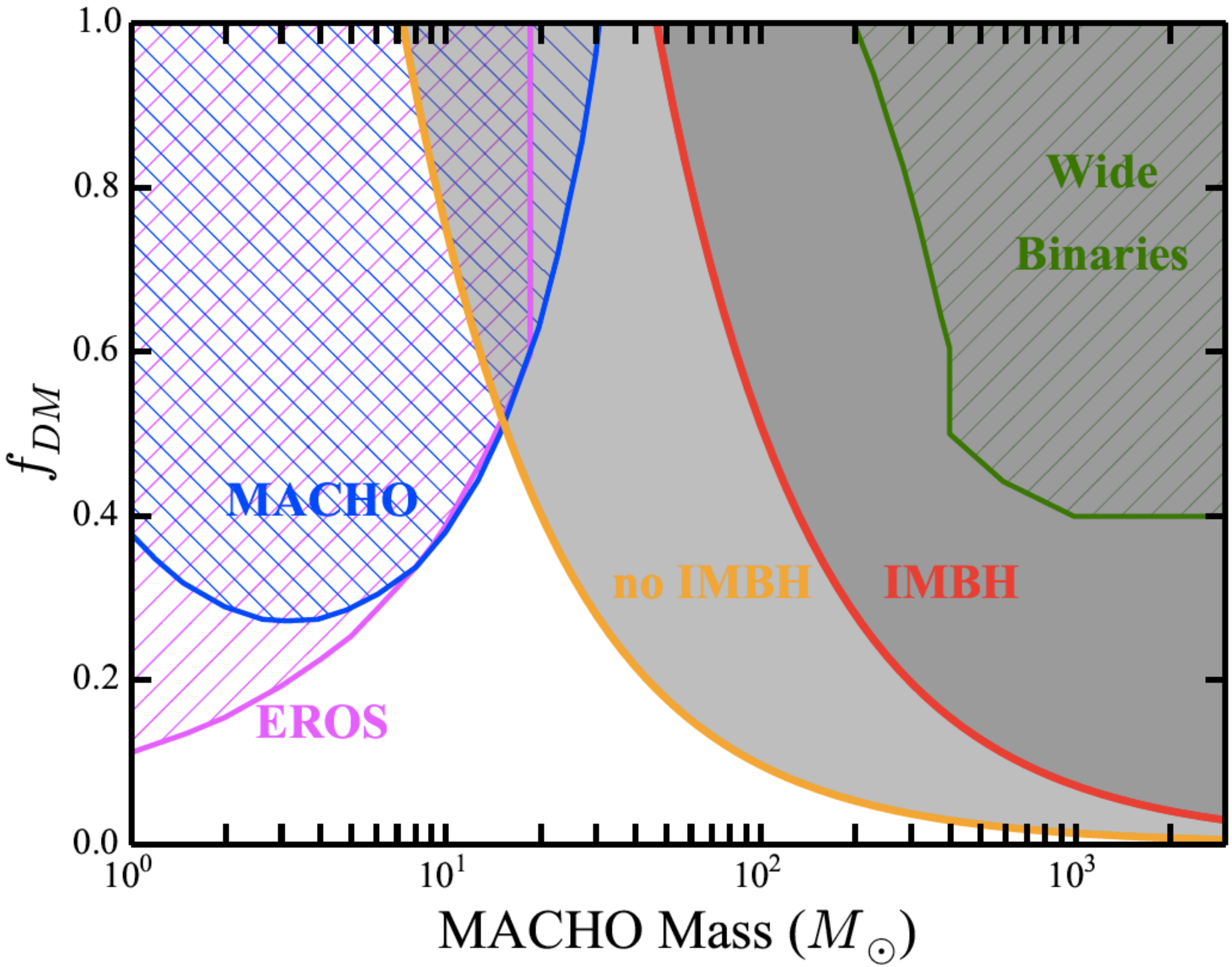
It may explain large M/L ratios of dSph by ejection of stars in the cluster, $v > v_{esc}$.

DES Dwarf spheroidals





Eridanus II dwarf spheroidal



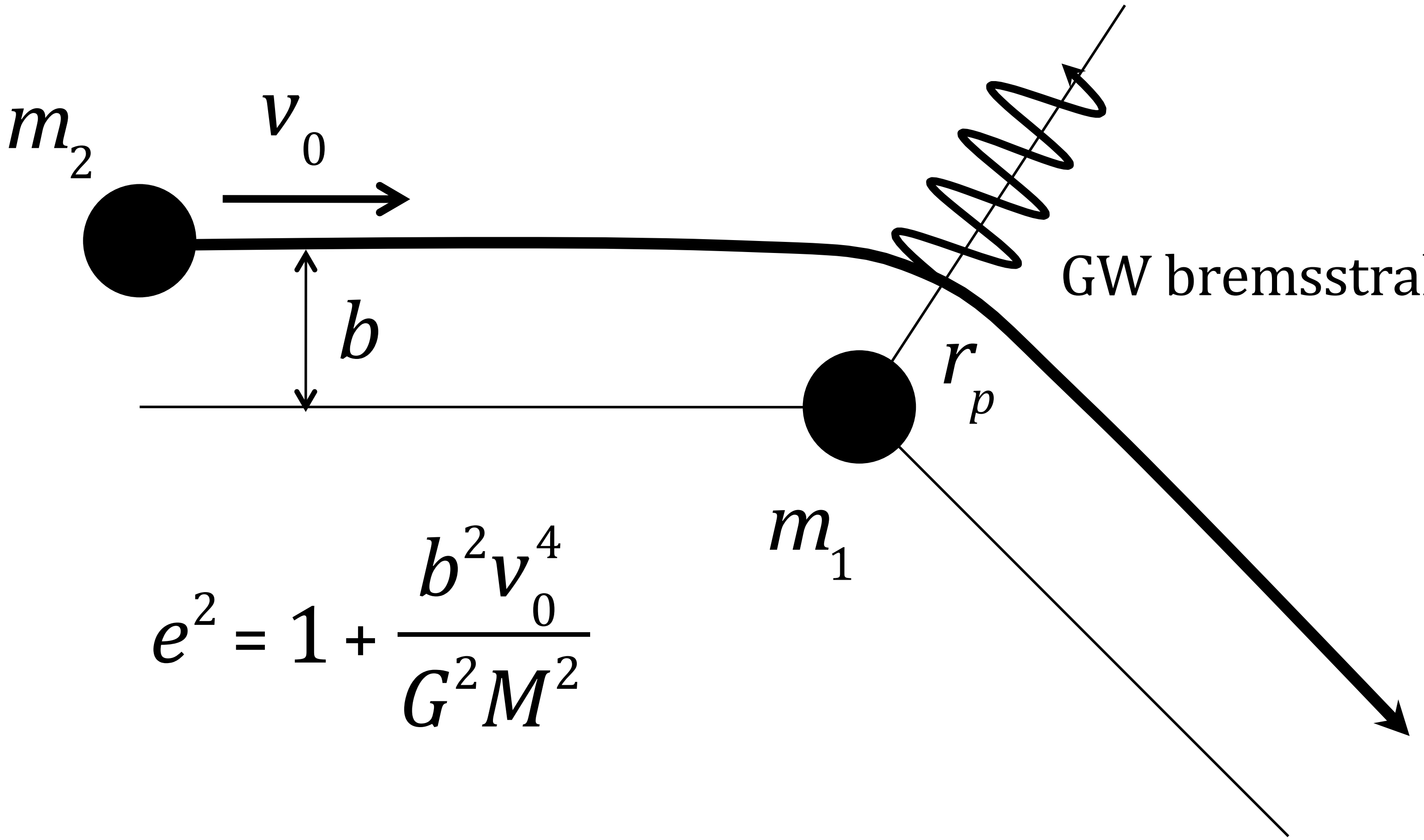
Signatures of PBH as DM

- 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

GW bursts from close encounters

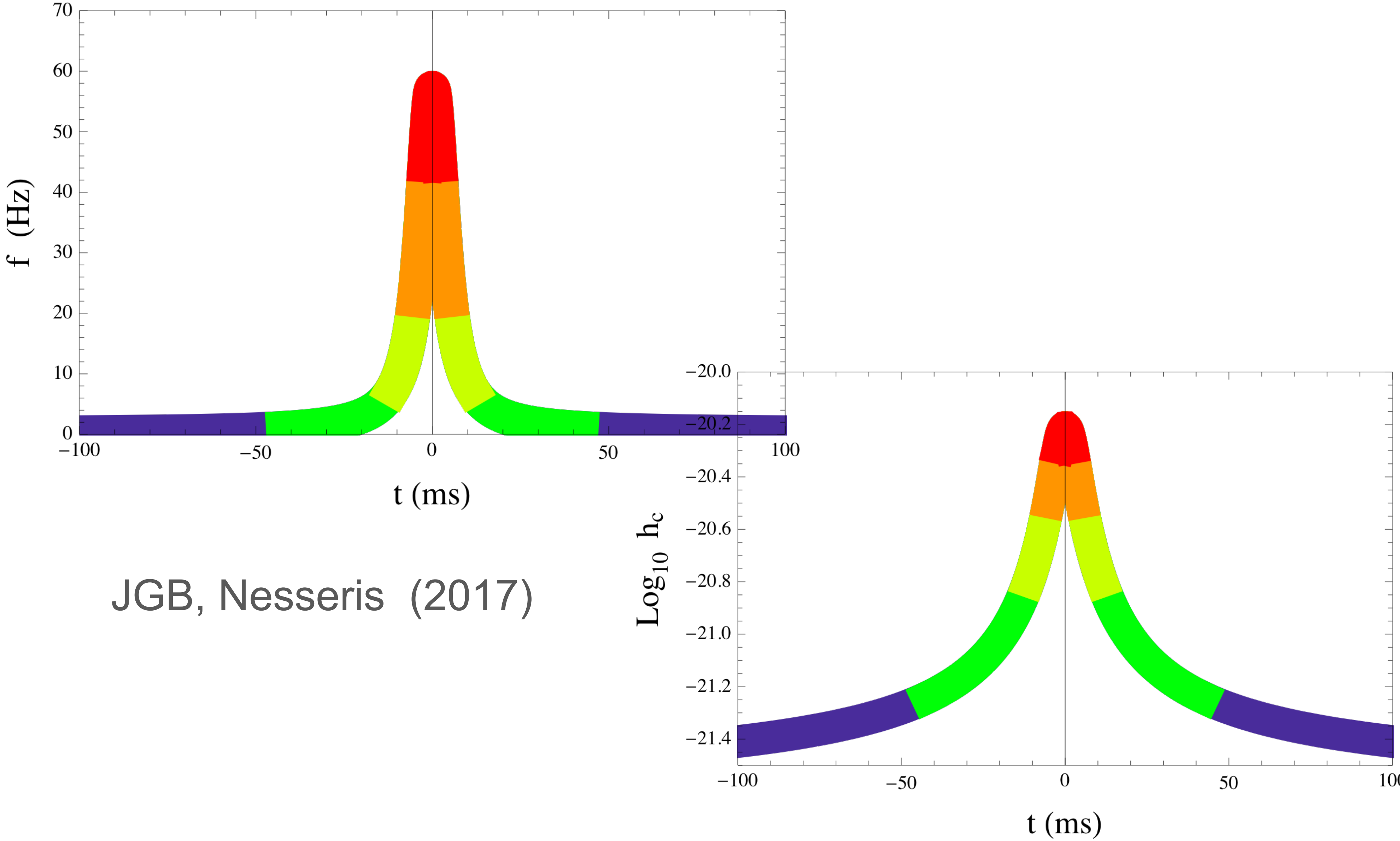
GW bursts

JGB, Nesseris (2017)



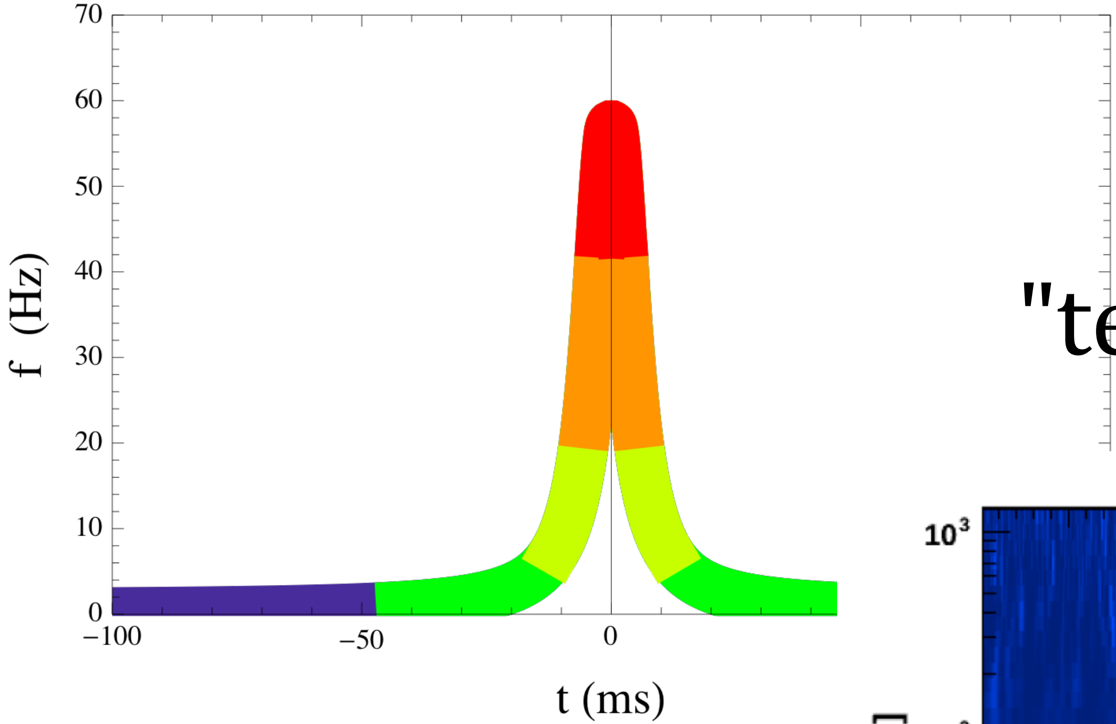
$$e^2 = 1 + \frac{b^2 v_0^4}{G^2 M^2}$$

GW bursts



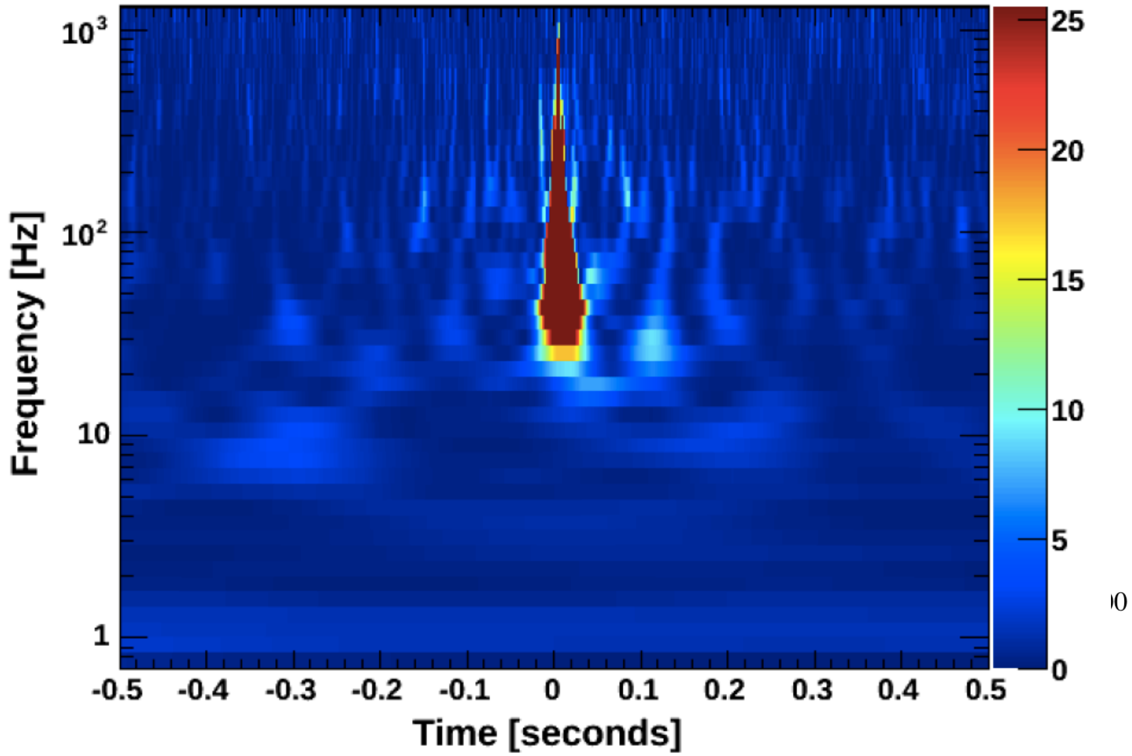
JGB, Nesseris (2017)

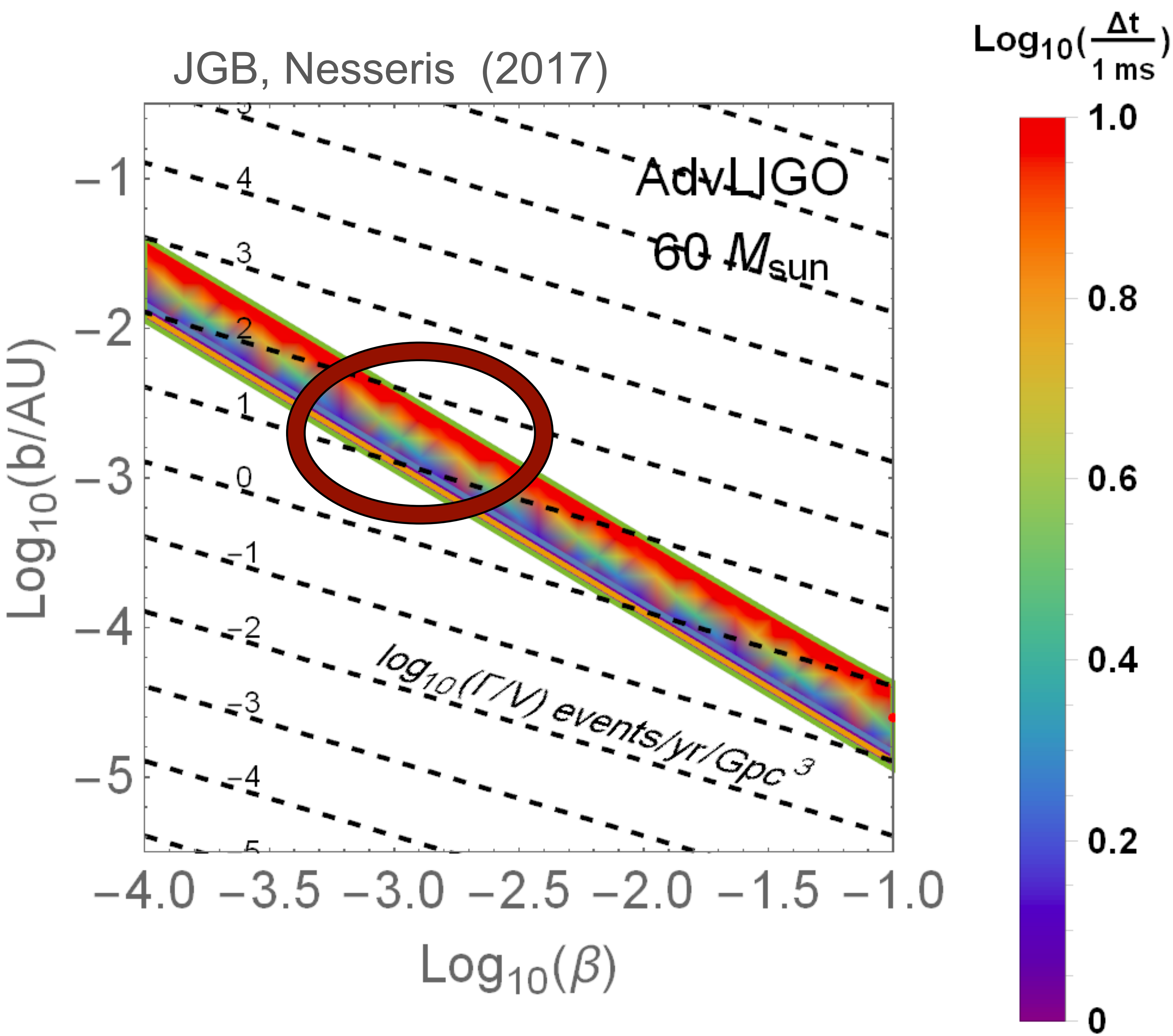
GW bursts



JGB, Nesseris (2017)

"tear drop glitches"?

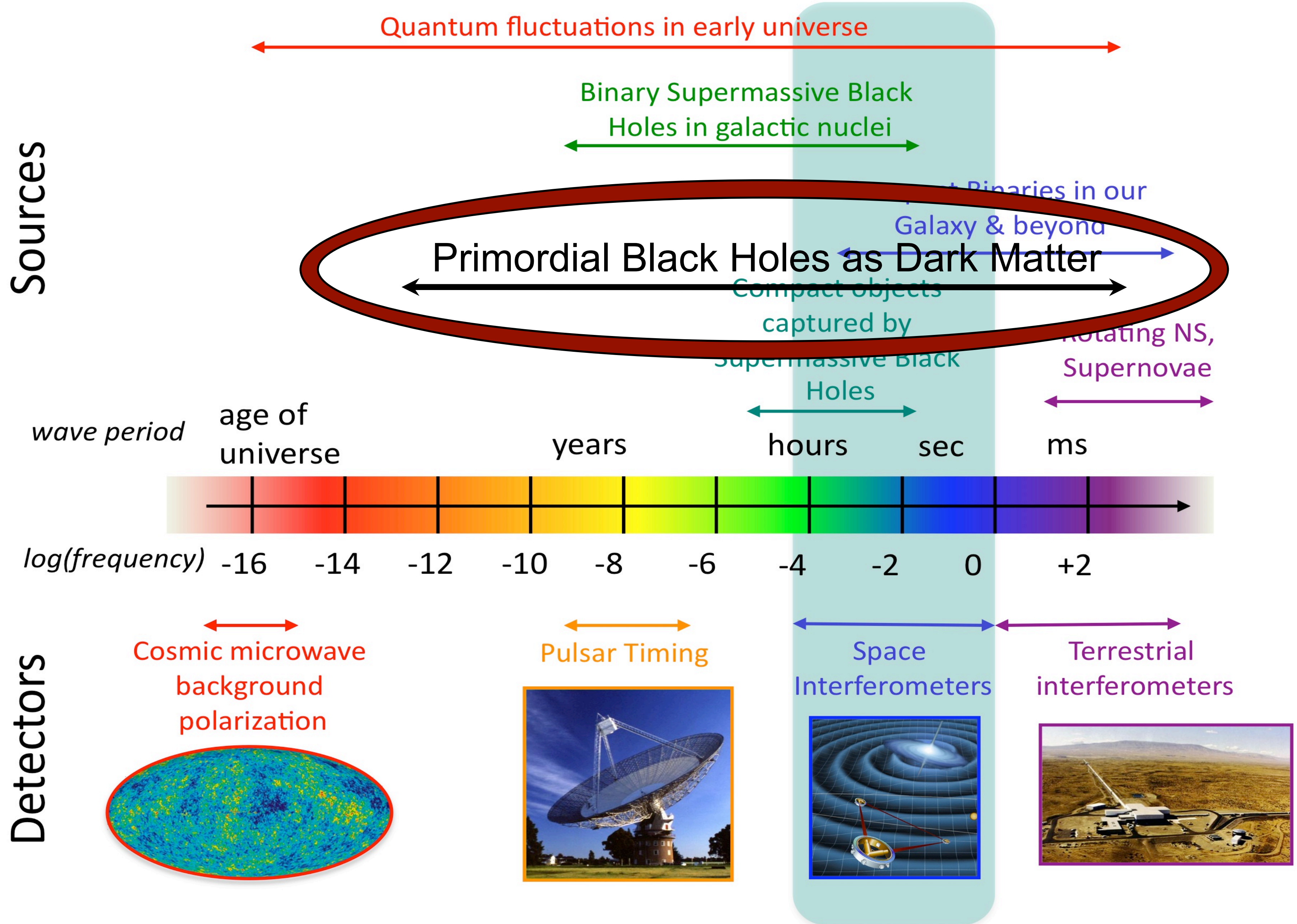




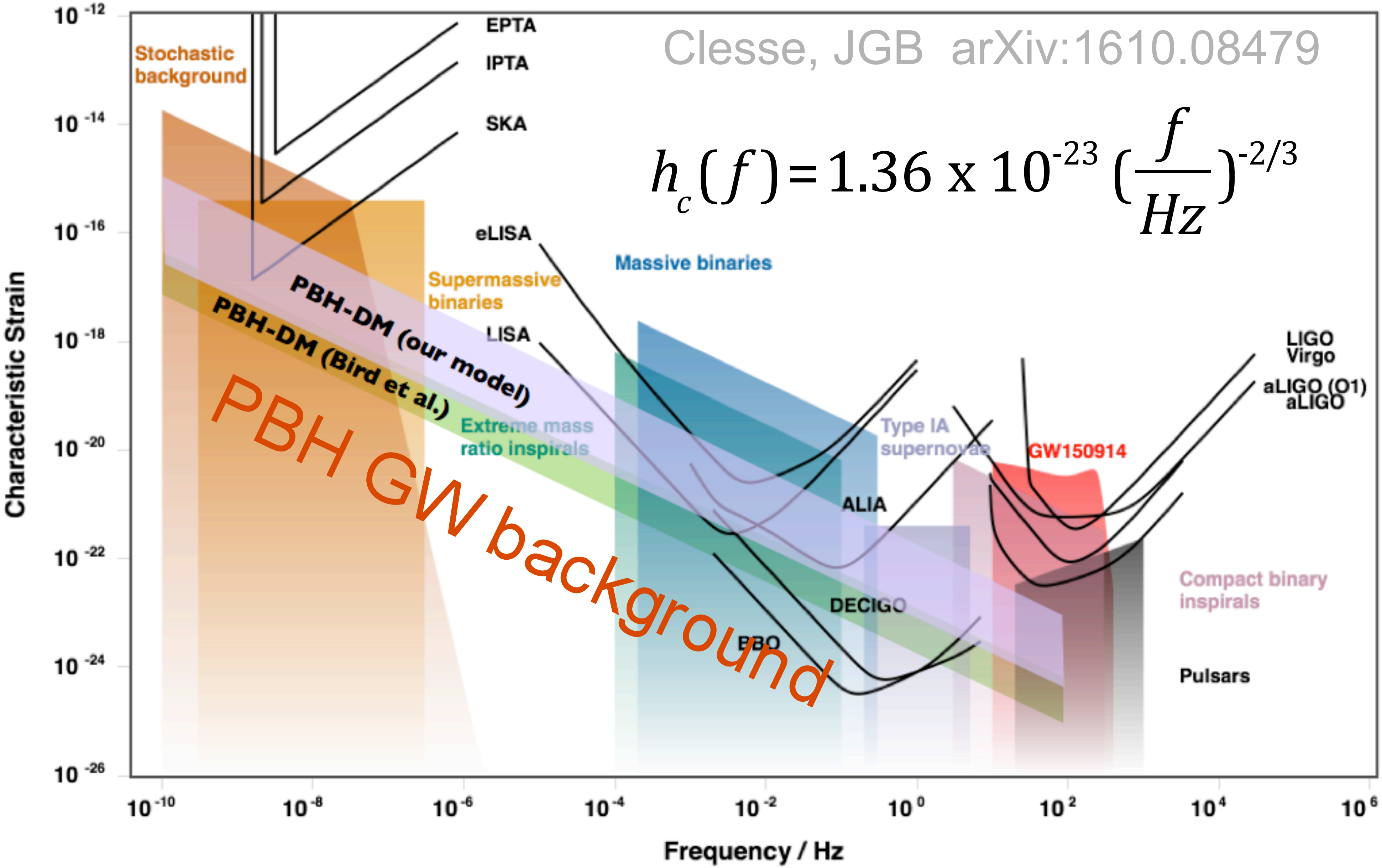
JGB, Nesseris (2017)
AdvLIGO
60 M_{sun}
$log_{10}(\Gamma/V)$ events/yr/Gpc^3
5
4
3
2
1
0
−1
−2
−3
−4
−5
Log_{10}(b/AU)
−1
−2
−3
−4
−5
−4.0
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
$Log_{10}(\beta)$
$Log_{10}(\frac{\Delta t}{1\ ms})$
1.0
0.8
0.6
0.4
0.2
0

Stochastic Background Grav. Waves

The Gravitational Wave Spectrum



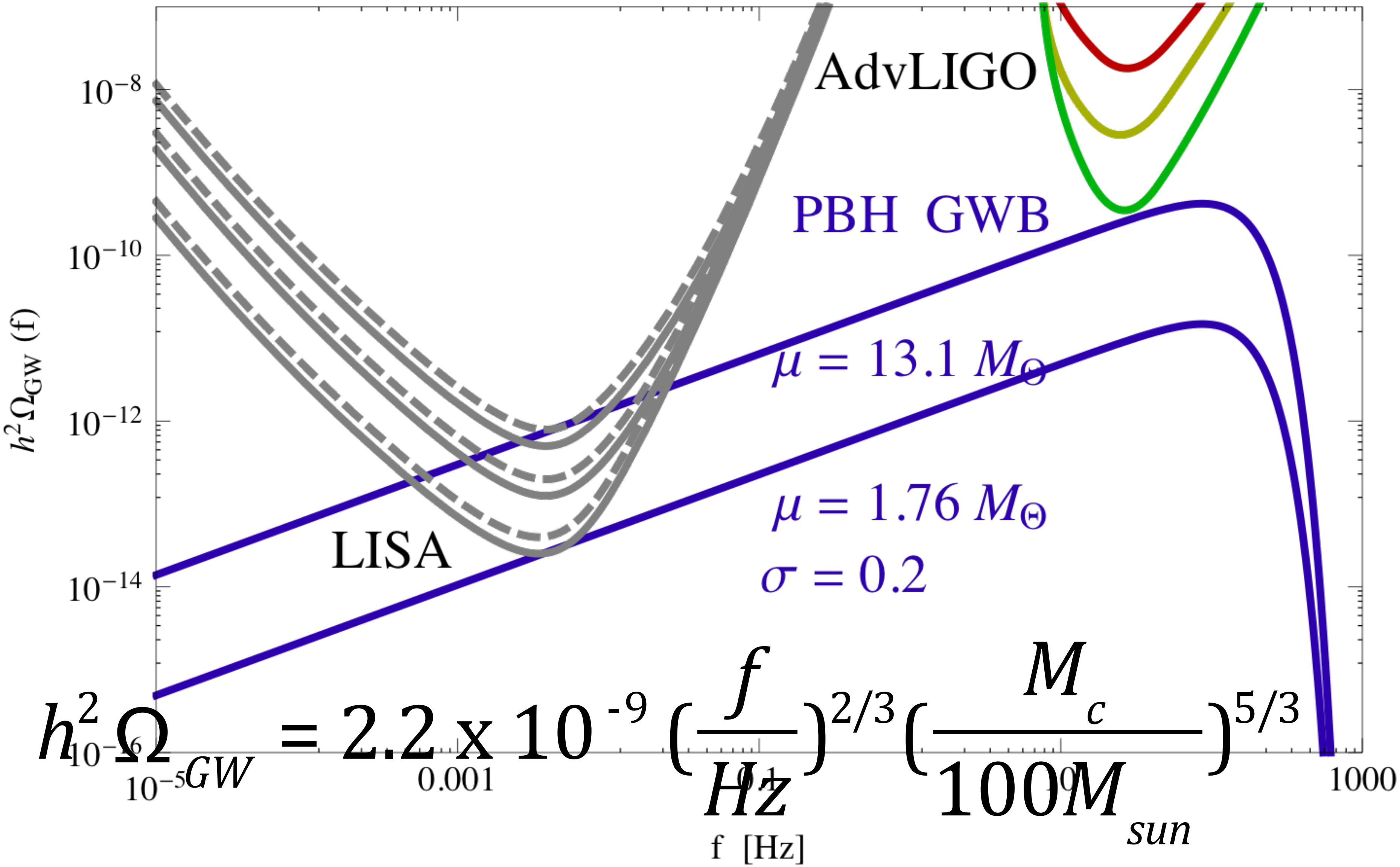
Sensitivity of future GW antenas



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

Stochastic Background from MPBH

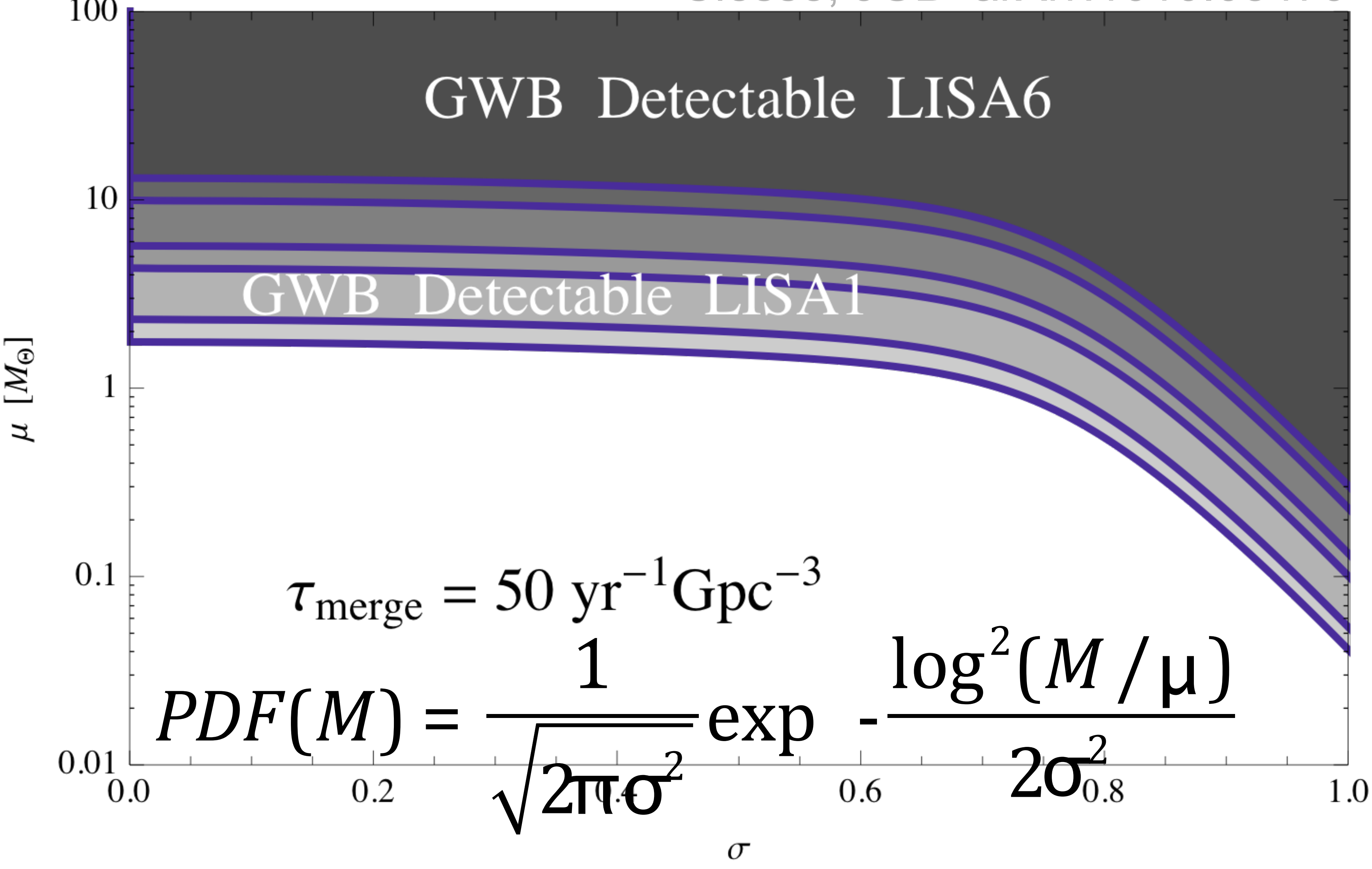
Clesse, JGB arXiv:1610.08479



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

Stochastic Background from MPBH

Clesse, JGB arXiv:1610.08479



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

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.