Primordial Black Holes as Dark Matter

JGB & S. Clesse, Sci. Am. July 2017, 39 (review)
JGB & S. Clesse, arXiv:1710.0XXXX,
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, arXiv:1706.02111, PDU accepted
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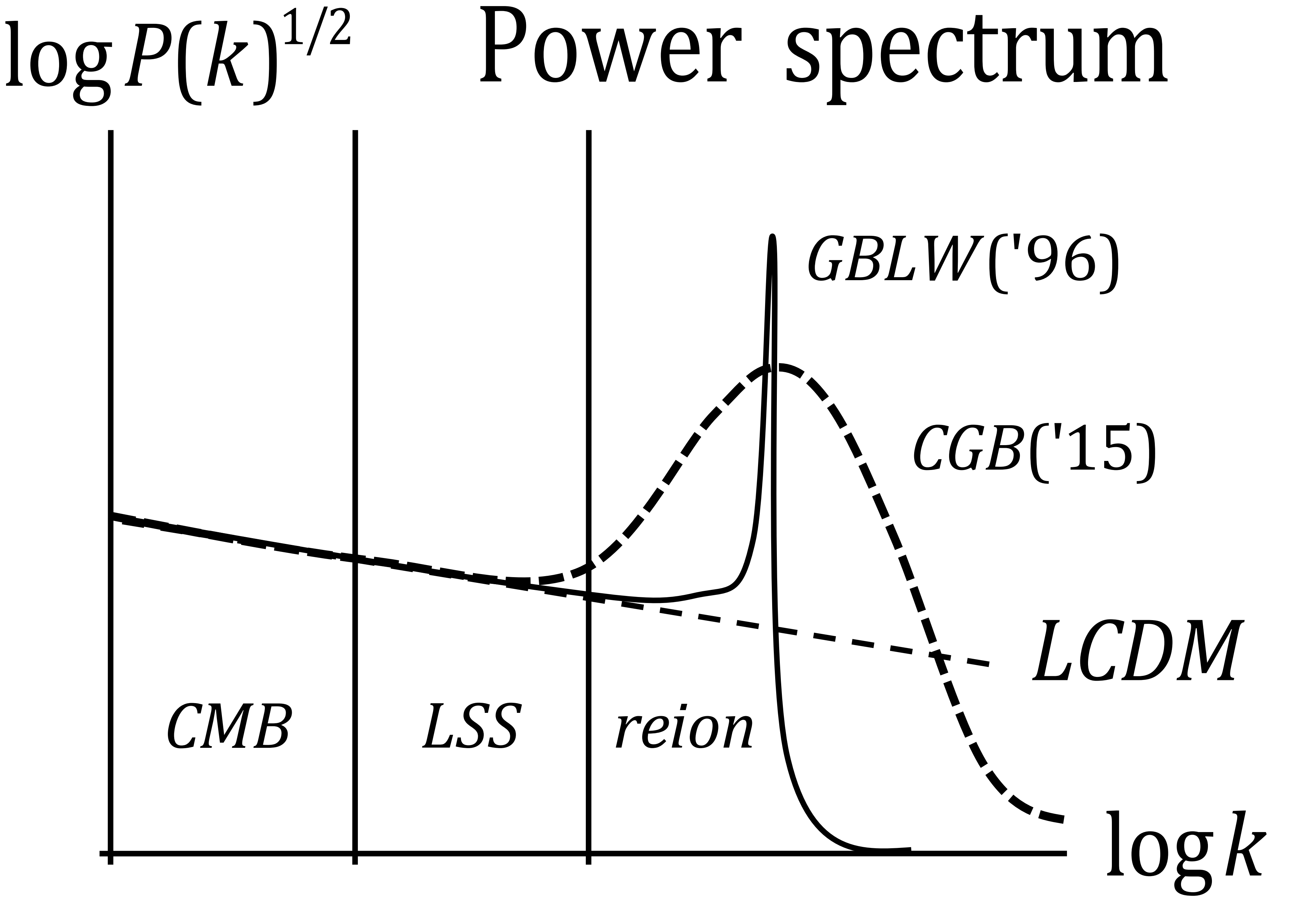
JGB, M. Peloso & C. Unal, JCAP 1709 (2017) 013
JGB, M. Peloso & C. Unal, JCAP 1612 (2016) 031
S. Clesse & JGB, Phys Dark Univ 10 (2016) 002
S. Clesse & JGB, Phys Rev D92 (2015) 023524
JGB, Linde & Wands, Phys Rev D54 (1996) 6040

Juan García-Bellido

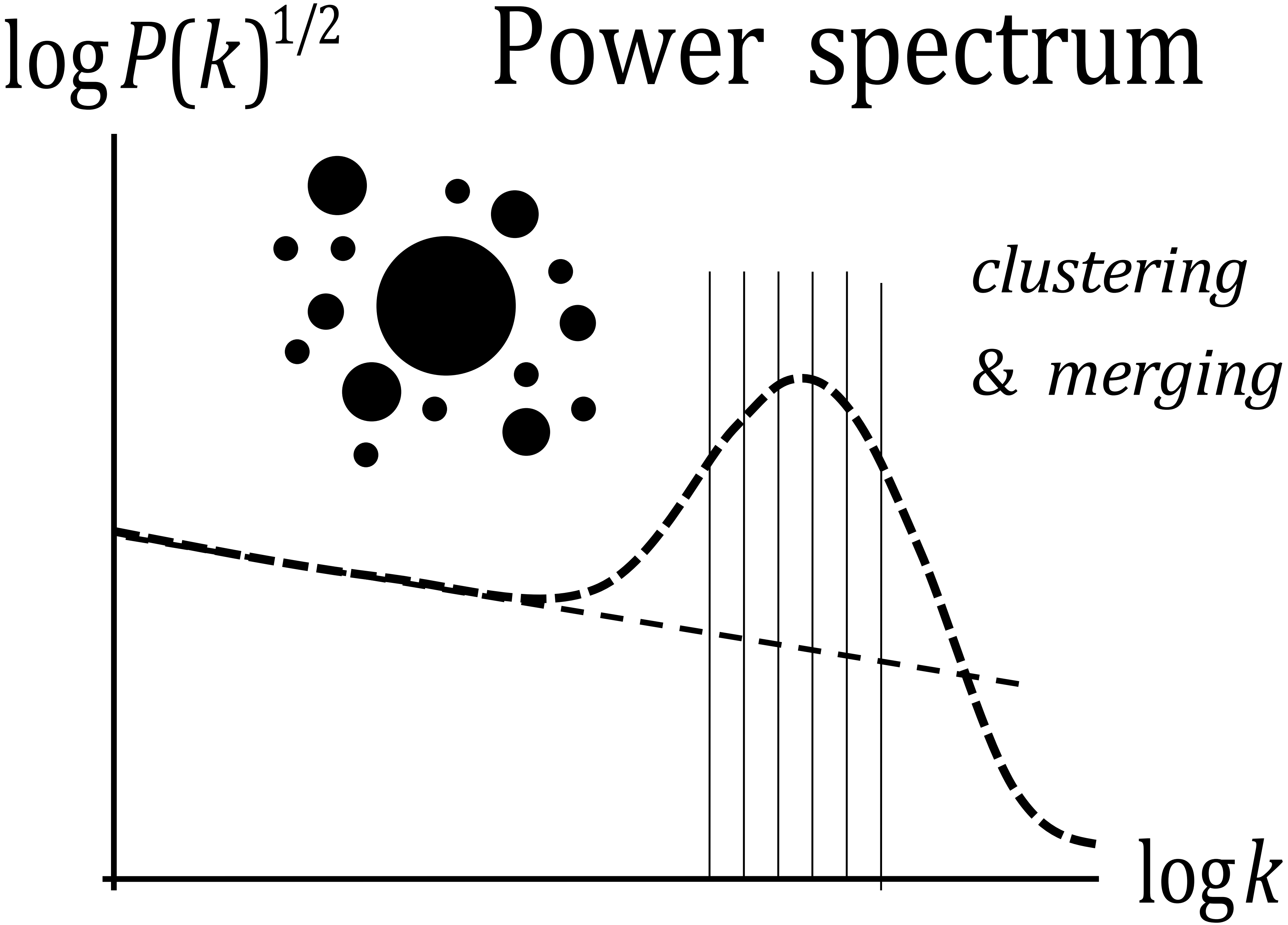
19th October 2017

LISA Cos WG Meeting

Massive PBH from Inflation as DM



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

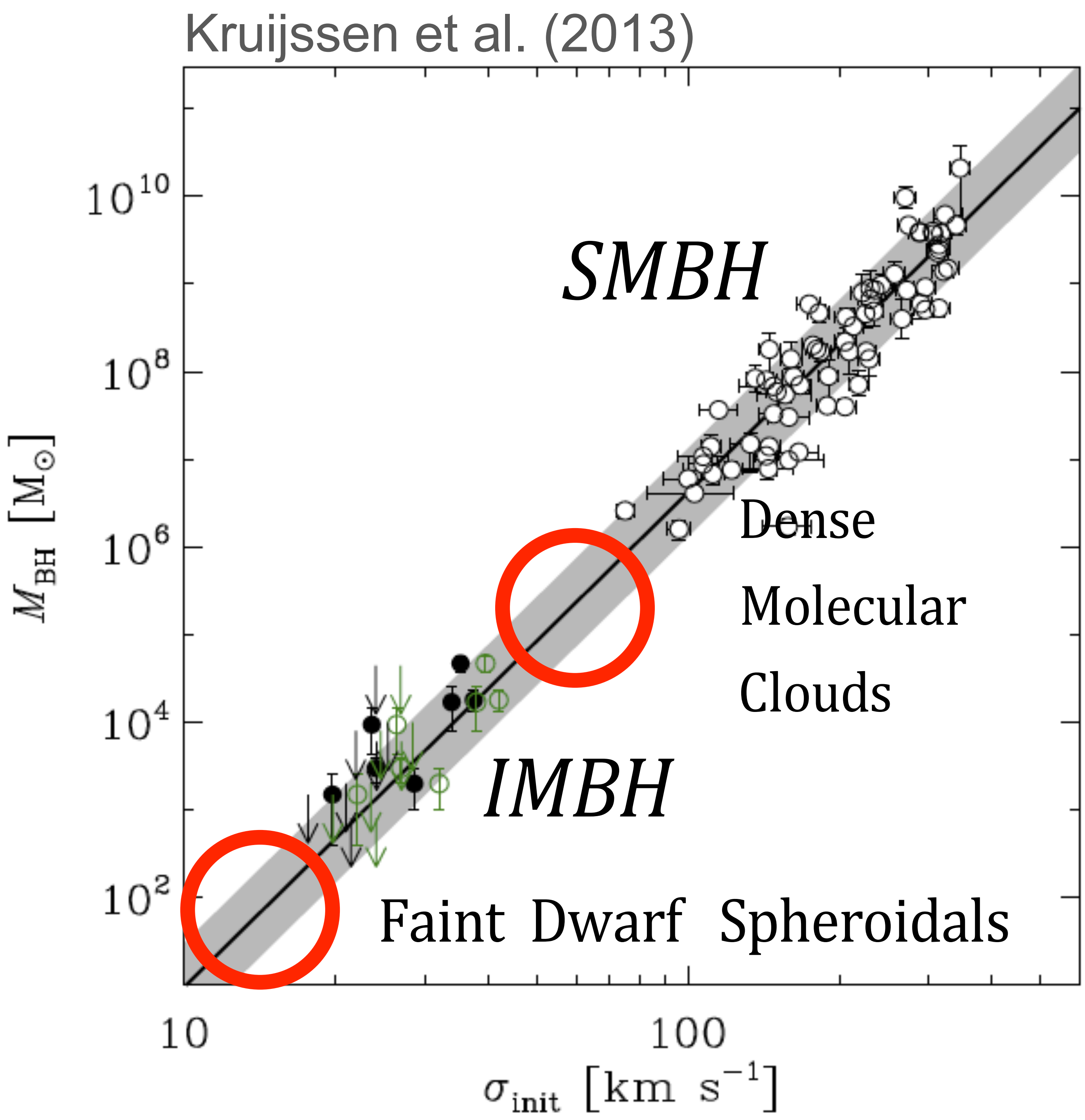


Power spectrum
log P(k)^1/2
clustering
& merging
log k

Constraints on Primordial Black Holes

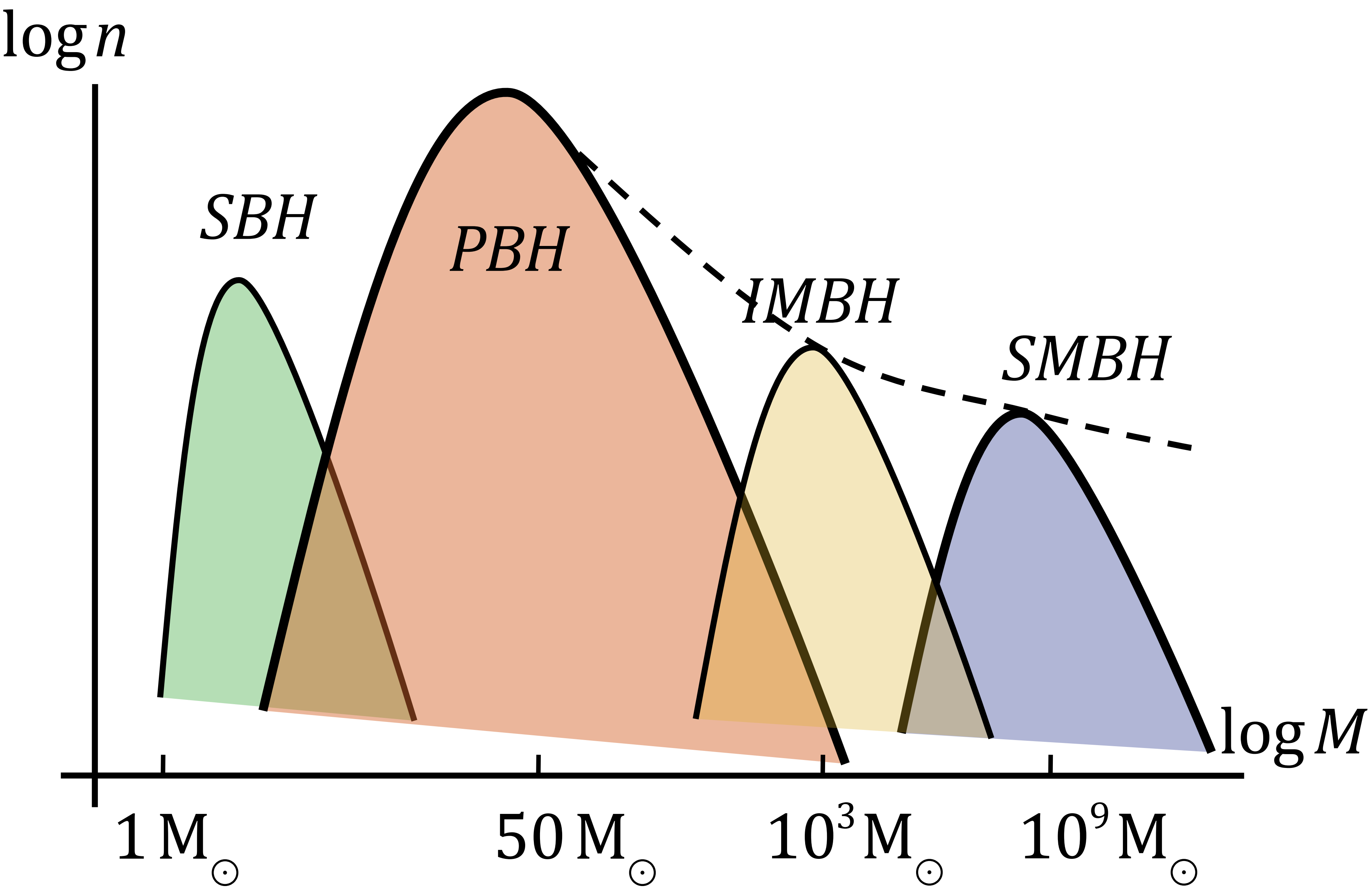
Massive Primordial Black Holes

- 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.

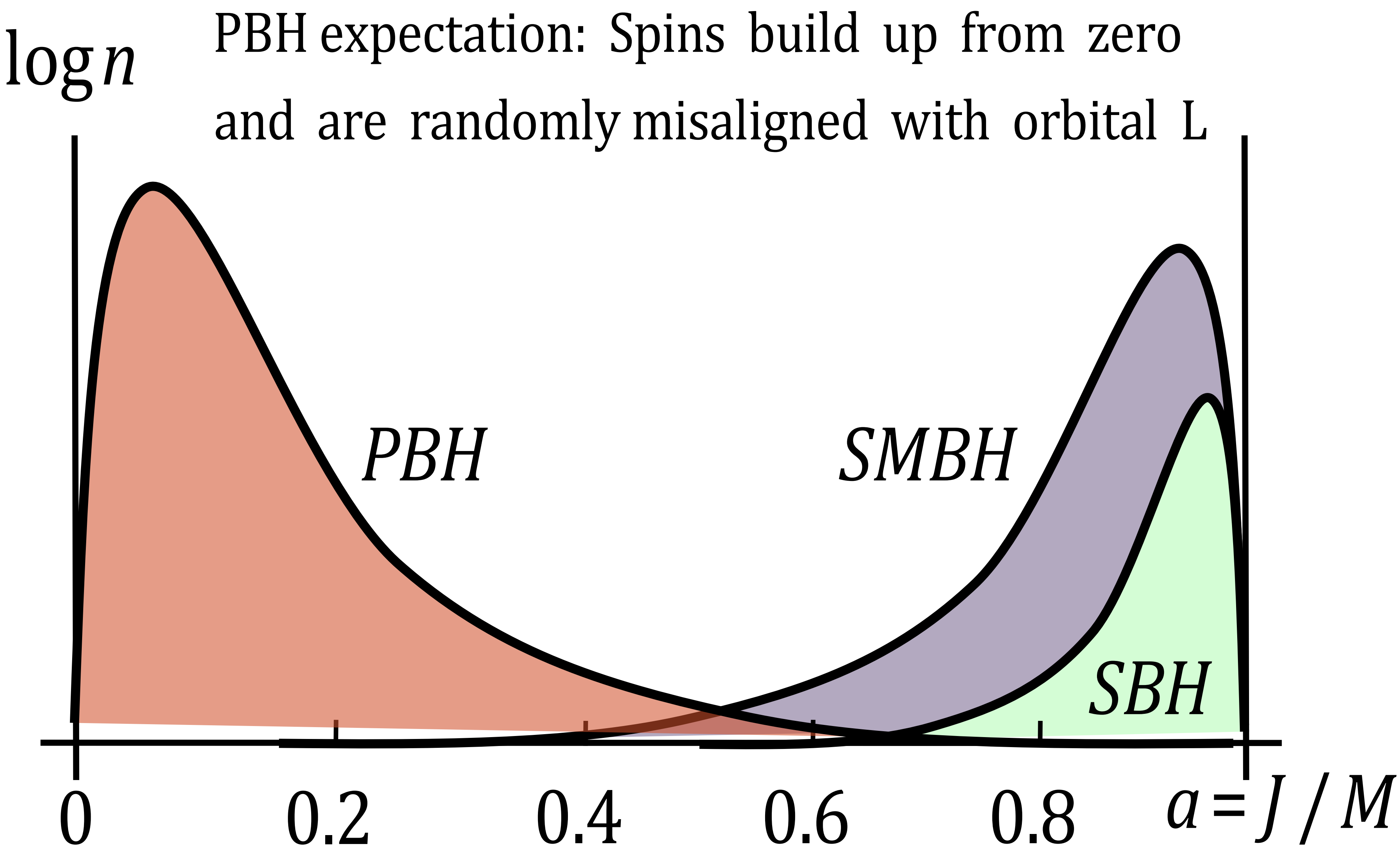


Kruijssen et al. (2013)
SMBH
Dense
Molecular
Clouds
IMBH
Faint Dwarf Spheroidals
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
M_{BH} [$M_\odot$]
10
100
σ_{init} [km s^{-1}]

Mass distribution of BH



Spin distribution of BH

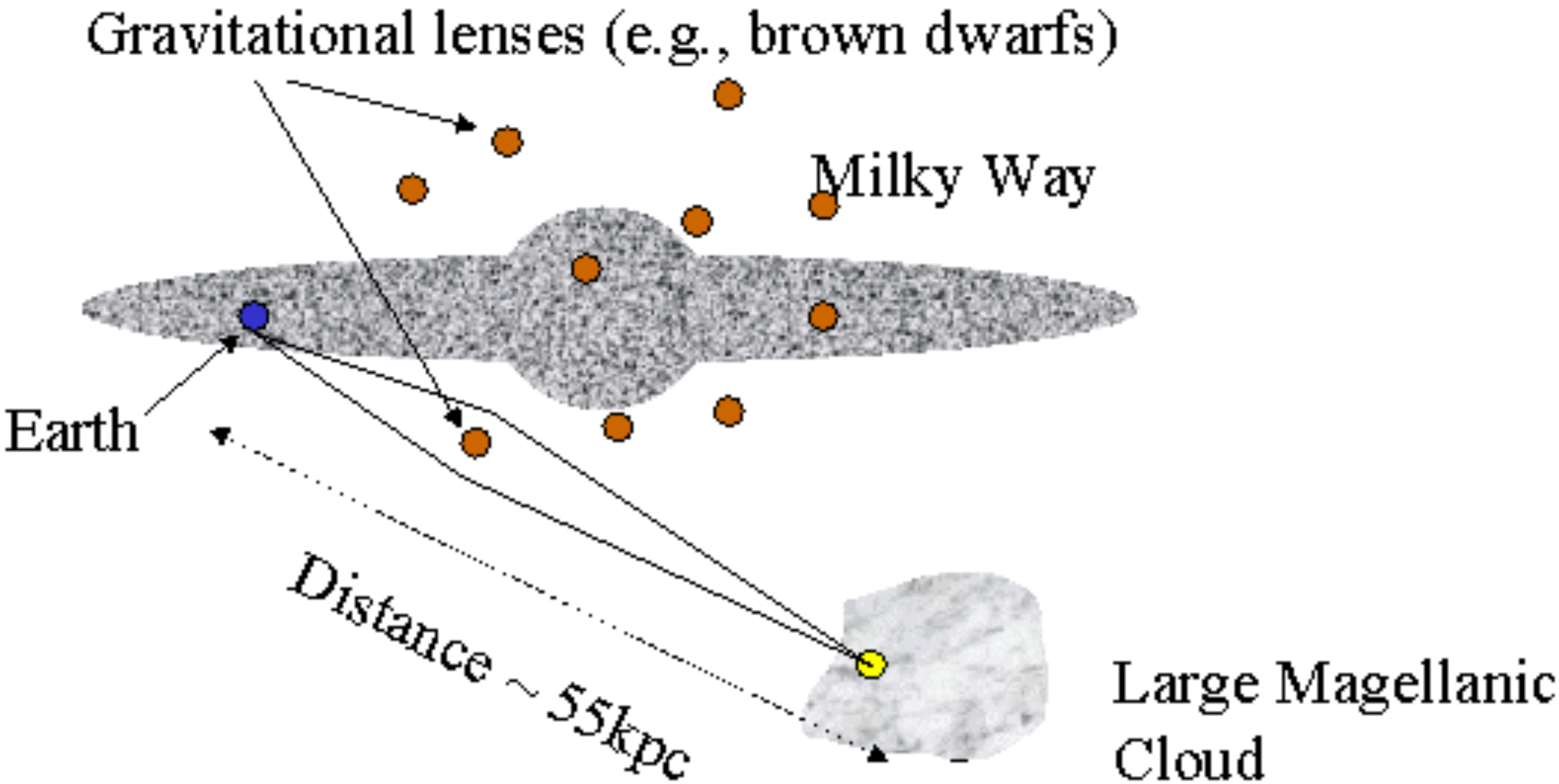


Distinguish MPBH from Stellar BH

- 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

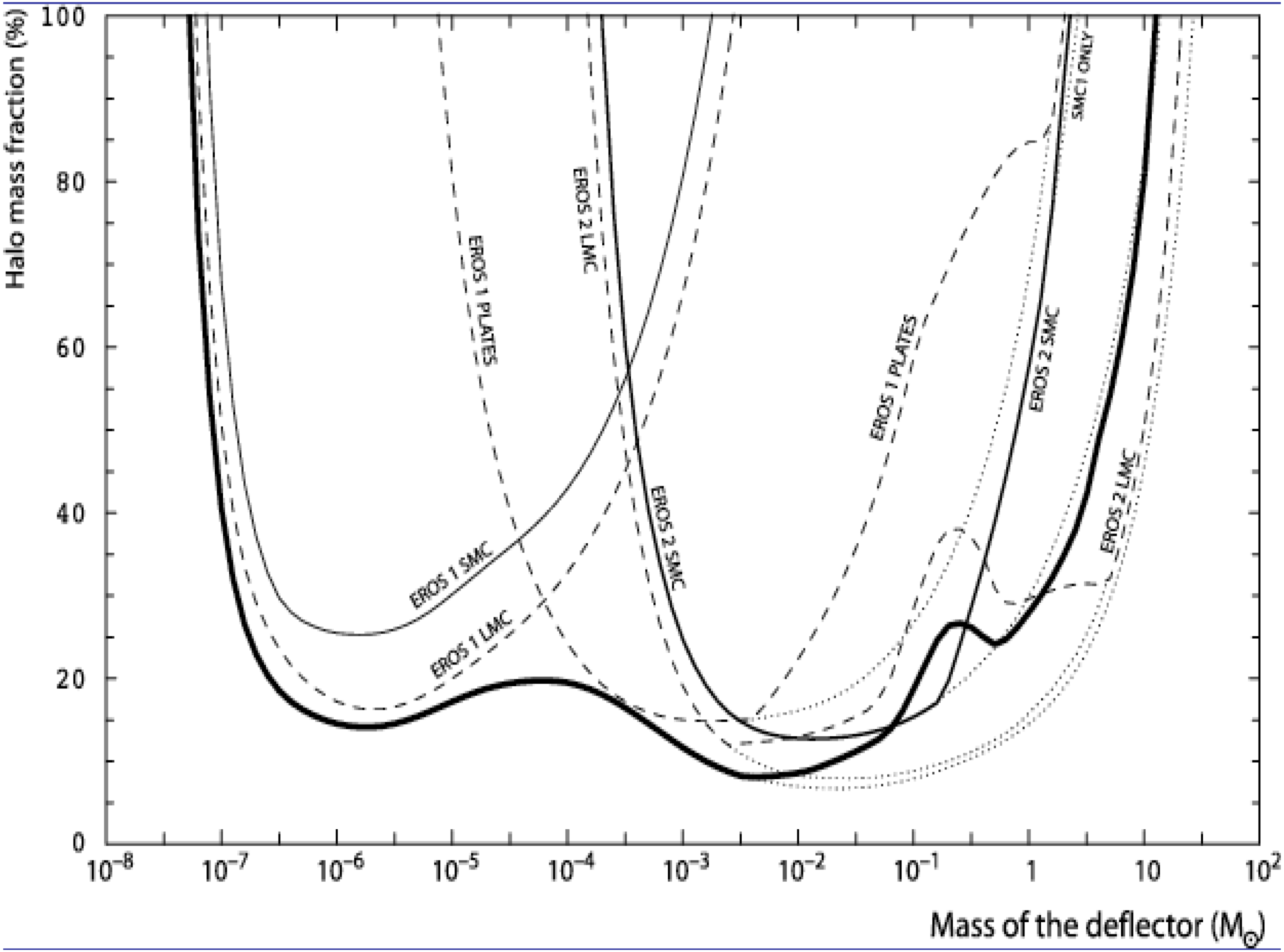
$M_D = 10\,\mathrm{M}_\odot$ => $\overline{Dt} = 1.23$ years

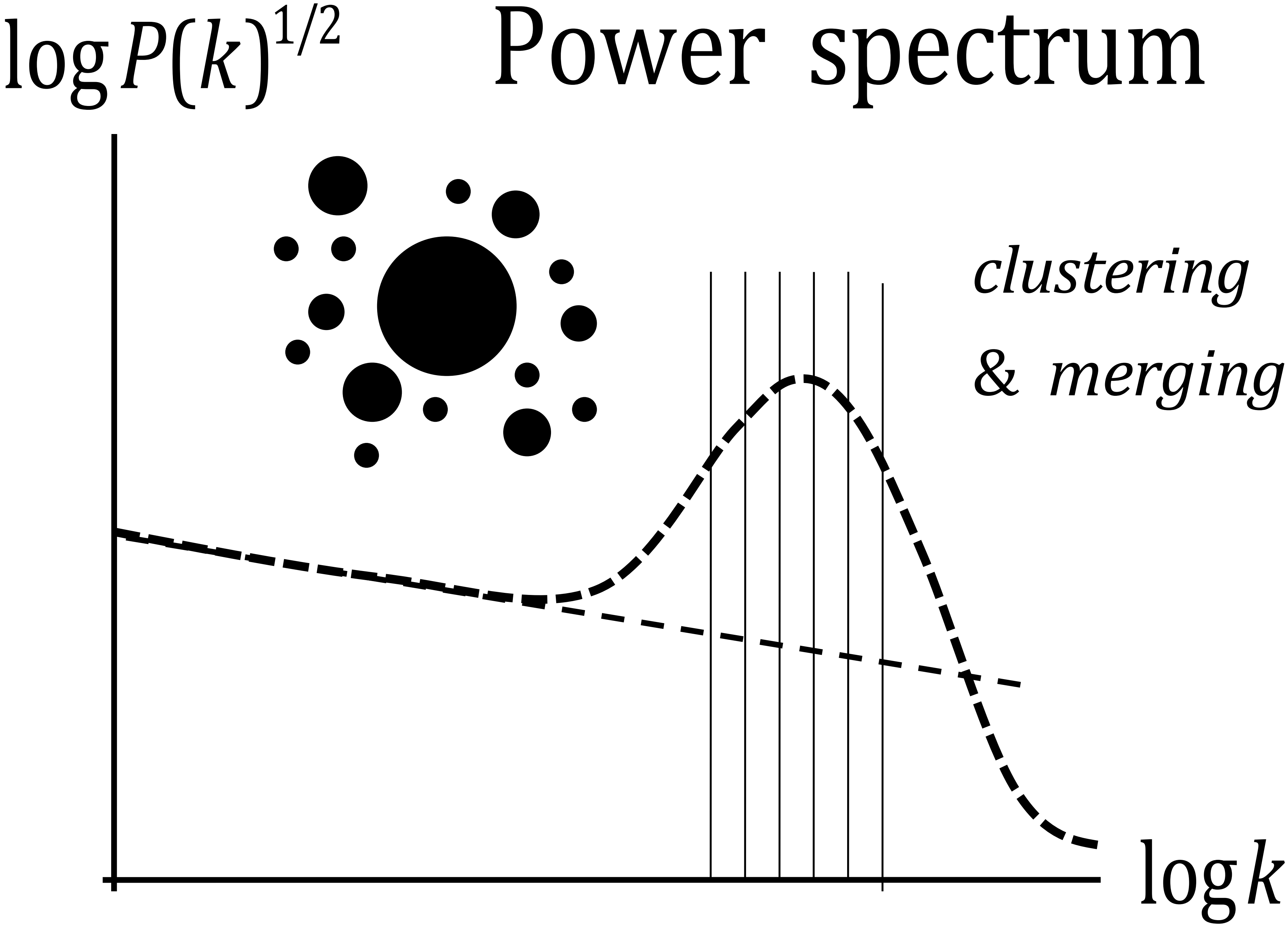
$M_D = 1\,\mathrm{M}_\odot$ => $\overline{Dt} = 5$ months

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

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

P. Tisserand (2007)




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

Constraints on clustered PBH

$$P(M) = \frac{\mathrm{d}\, n_{\rm PBH}}{\mathrm{d}\ln M} = \frac{f_{\rm PBH}}{\sqrt{2\pi}\,\sigma}\,\exp\left[-\frac{\ln^2(M/\mu)}{2\sigma^2}\right],$$

$$C_i(M) = A_i\,\exp\left(\frac{\ln^2(M/m_i)}{2s_i^2}\right),$$

$$\int_0^\infty \frac{dM}{M}\,\frac{P(M)}{C(M)} \leq 1\,.$$

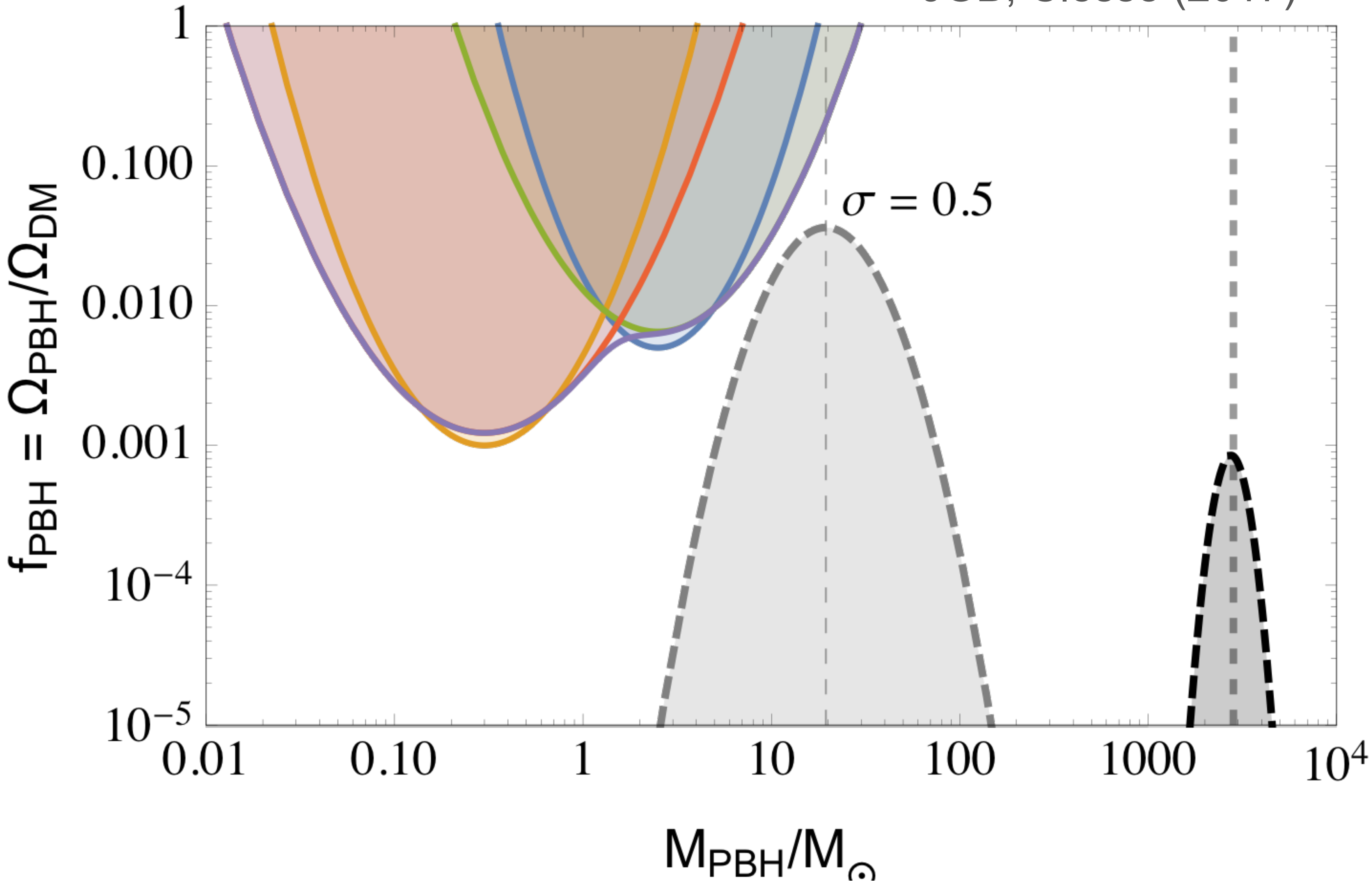
JGB, Clesse (2017)

$$\frac{f_{\rm PBH}\, s_i}{A_i\sqrt{s_i^2+\sigma^2}}\,\exp\left(-\frac{\ln^2(\mu/m_i)}{2(s_i^2+\sigma^2)}\right) \leq 1$$

$$f_{\rm PBH}(M) \leq \left[\sum_{i=1}^{N} \frac{s_i^2}{A_i^2(s_i^2+\sigma^2)}\,\exp\left(-\frac{\ln^2(M/m_i)}{(s_i^2+\sigma^2)}\right)\right]^{-1/2}$$

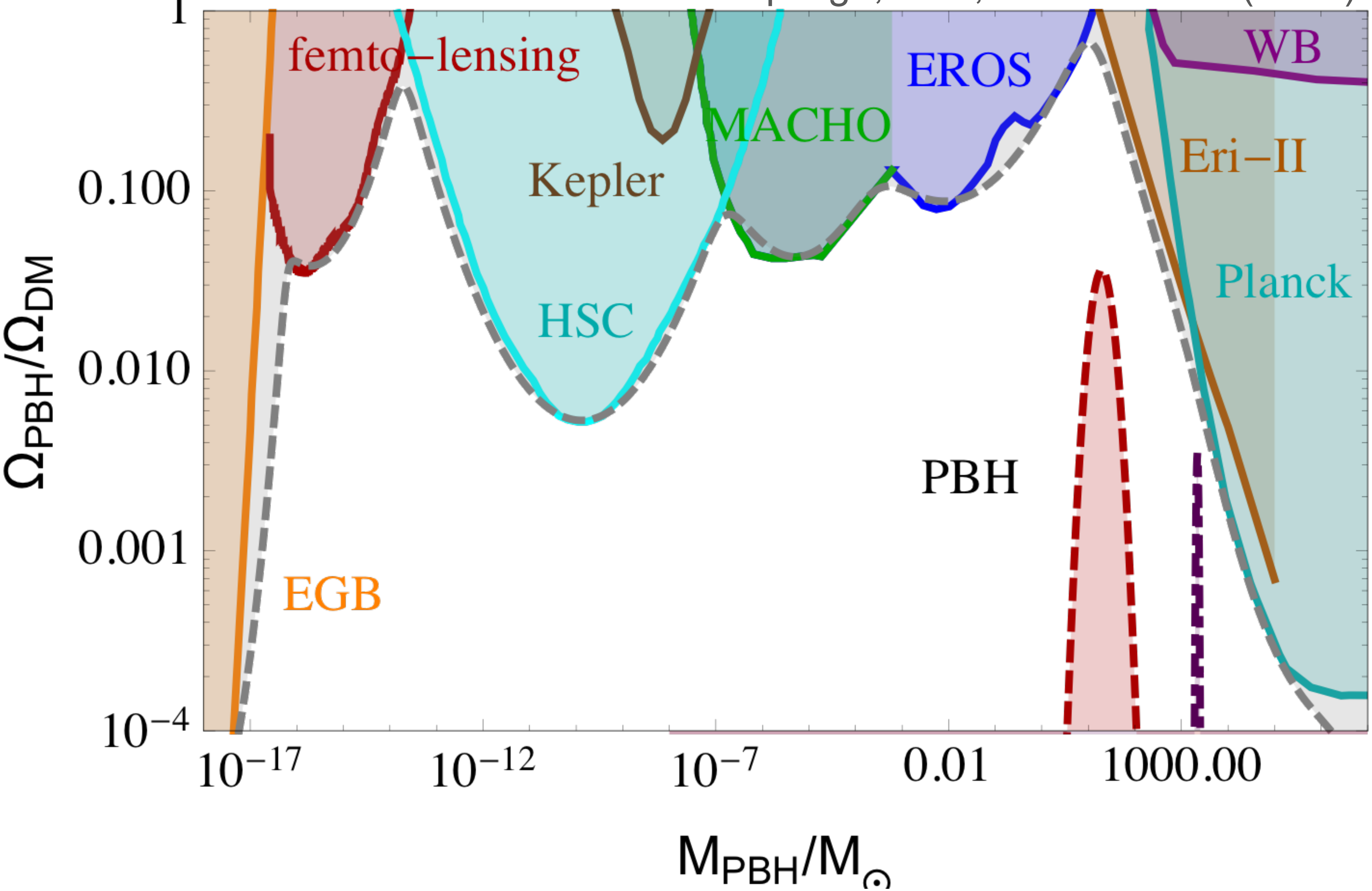
Constraints on clustered PBH

JGB, Clesse (2017)



Present Constraints on PBH

Ezquiaga, JGB, Ruiz Morales (2017)



Missing satellite

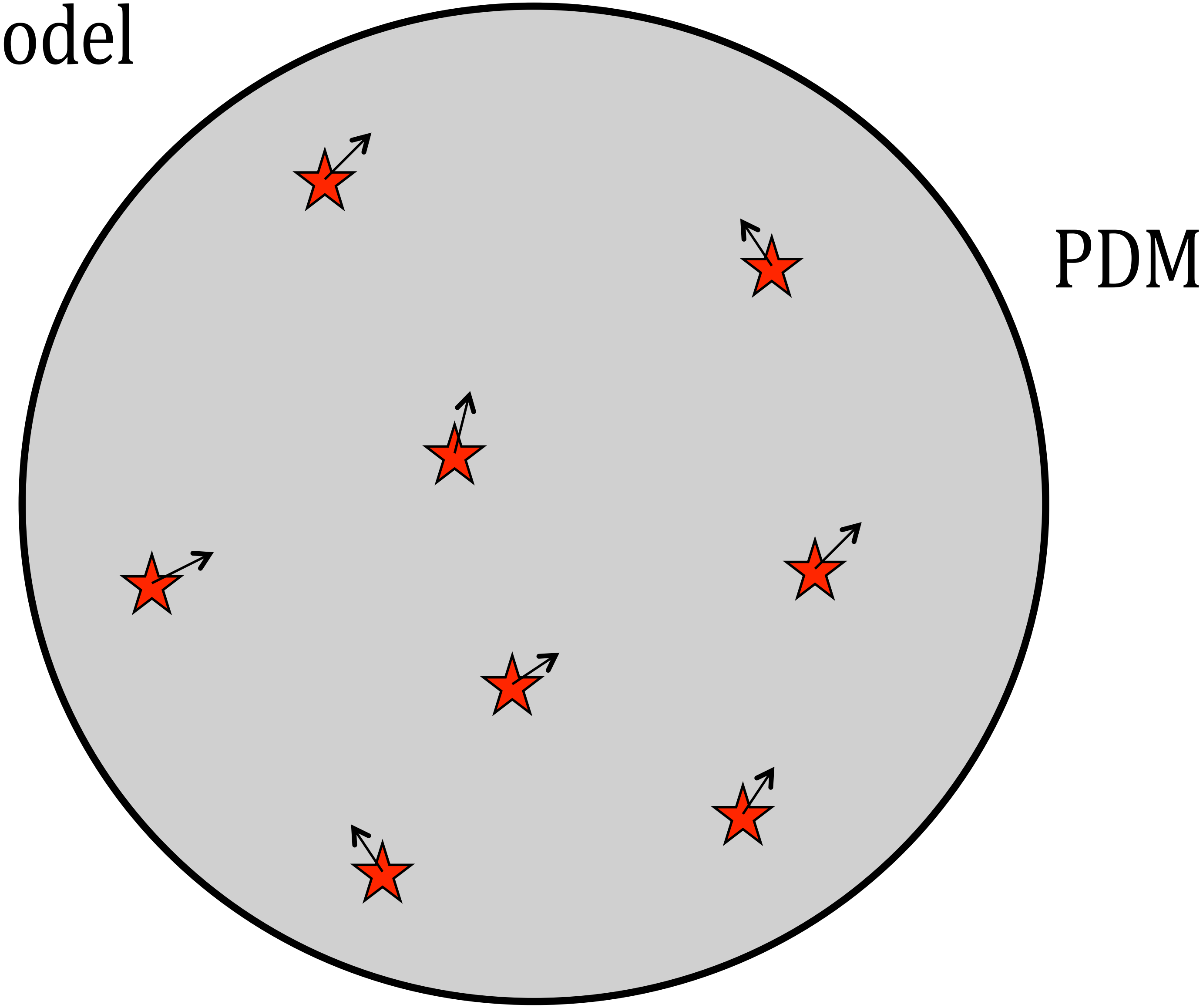
&

Too-big-to-fail

Problems ΛCDM

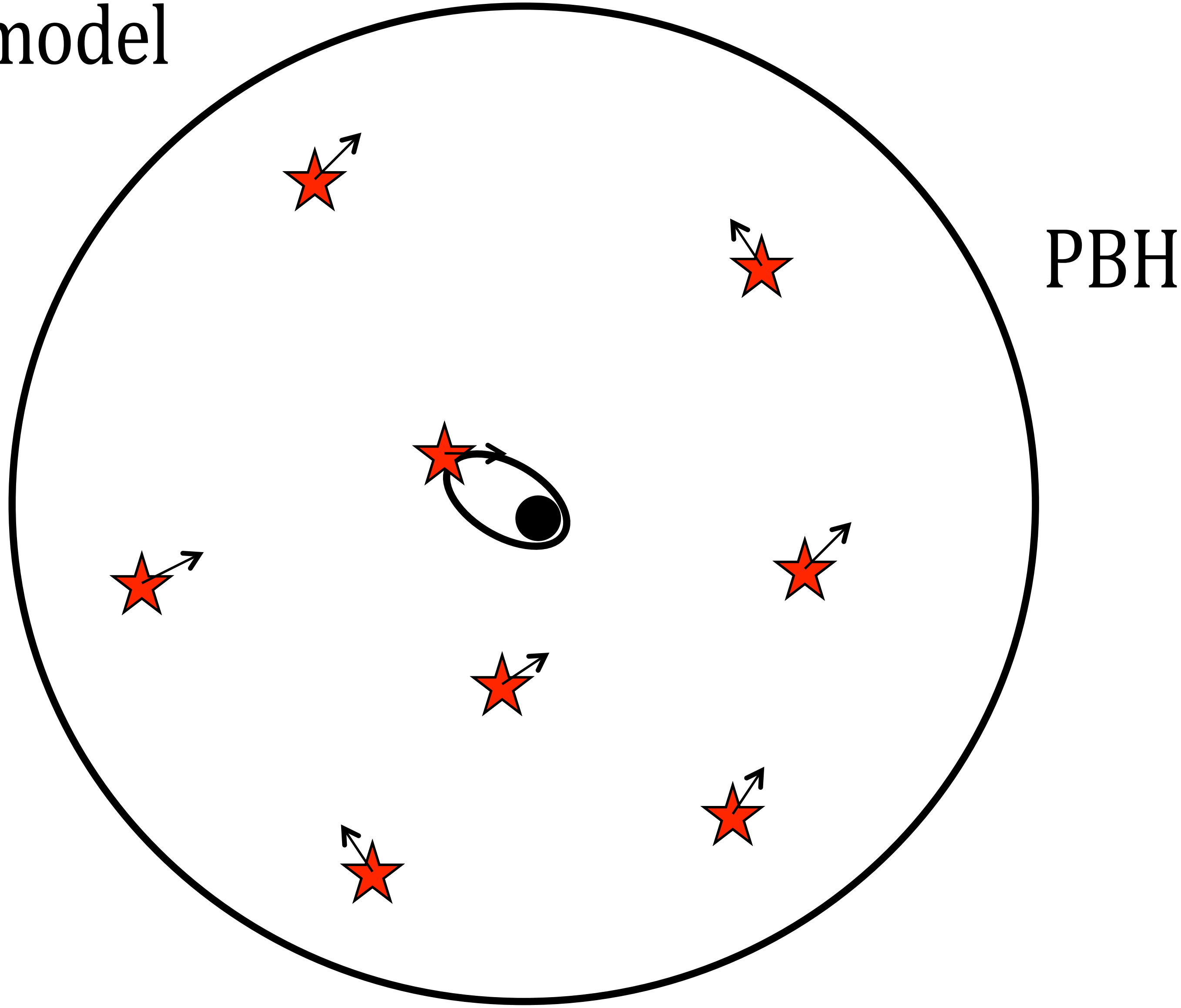
Spatial distribution of DM

Thomson model



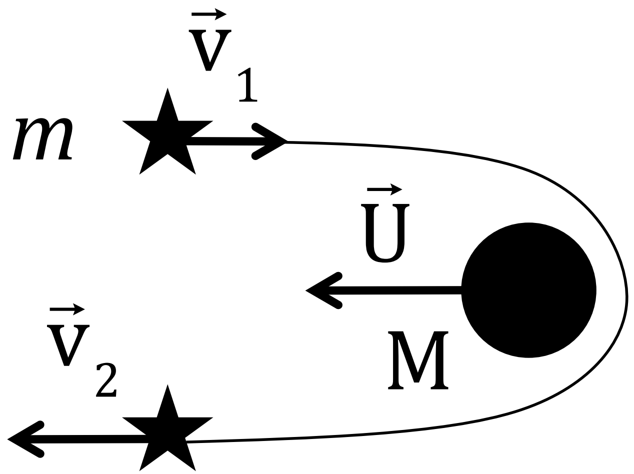
Spatial distribution of DM

Rutherford model



Gravitational slingshot effect

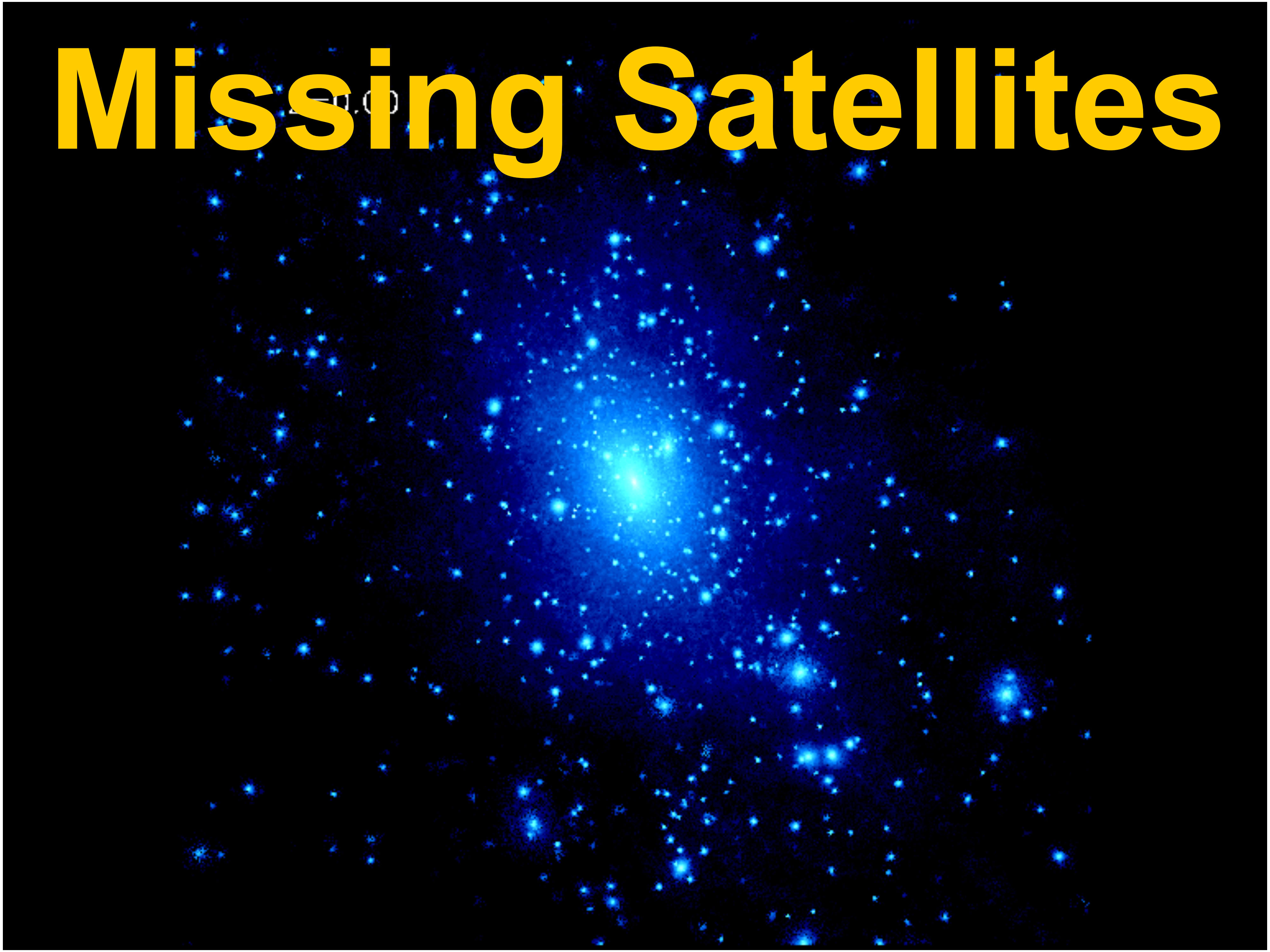
Close encounters of a star with MPBH @ 100 km/s relative motion is enough to expel the star from the stellar cluster.



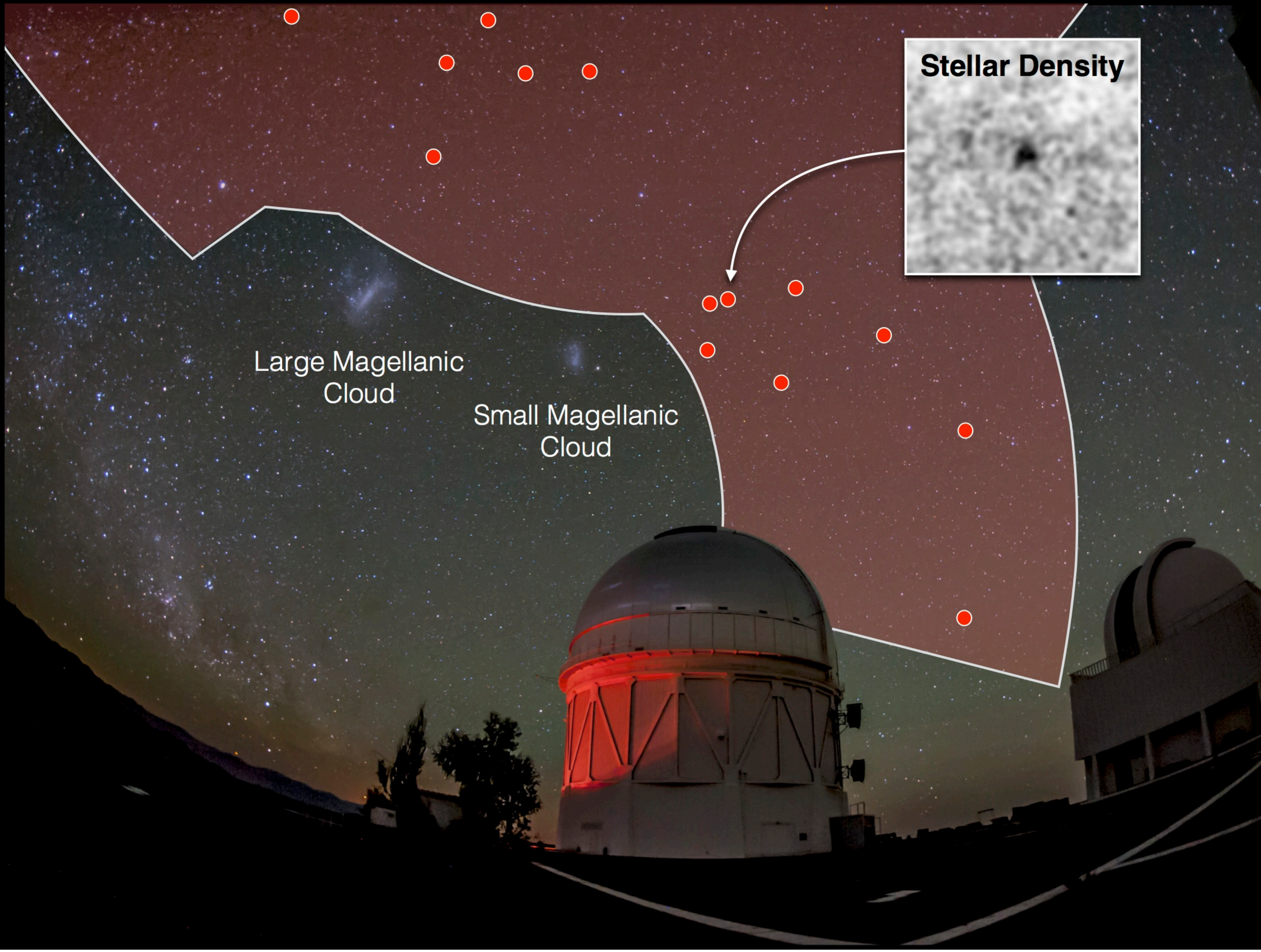
$$\vec{v}_2 = \frac{2\vec{U} + (1 - m/M)\vec{v}_1}{(1 + m/M)}$$

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

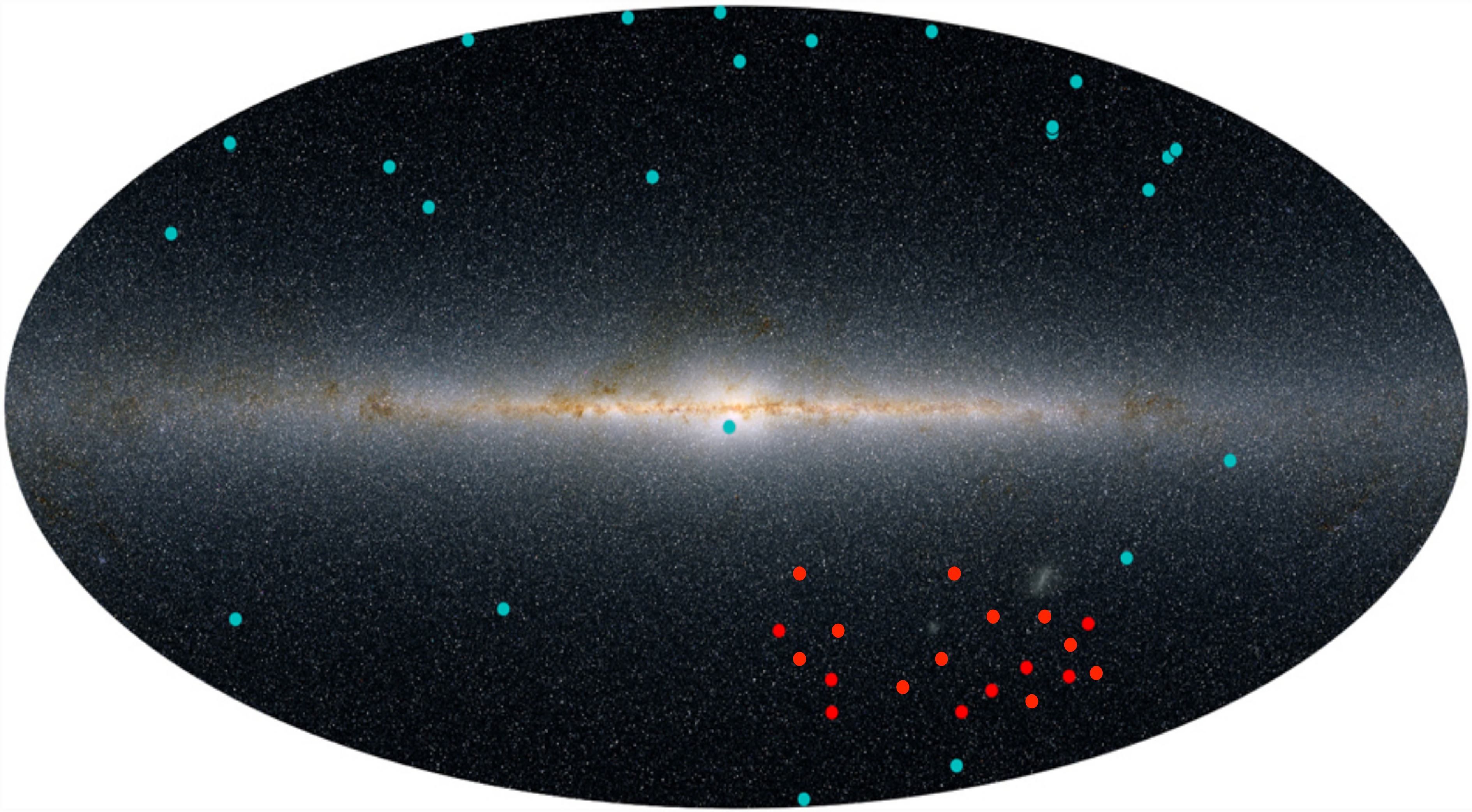
Missing Satellites



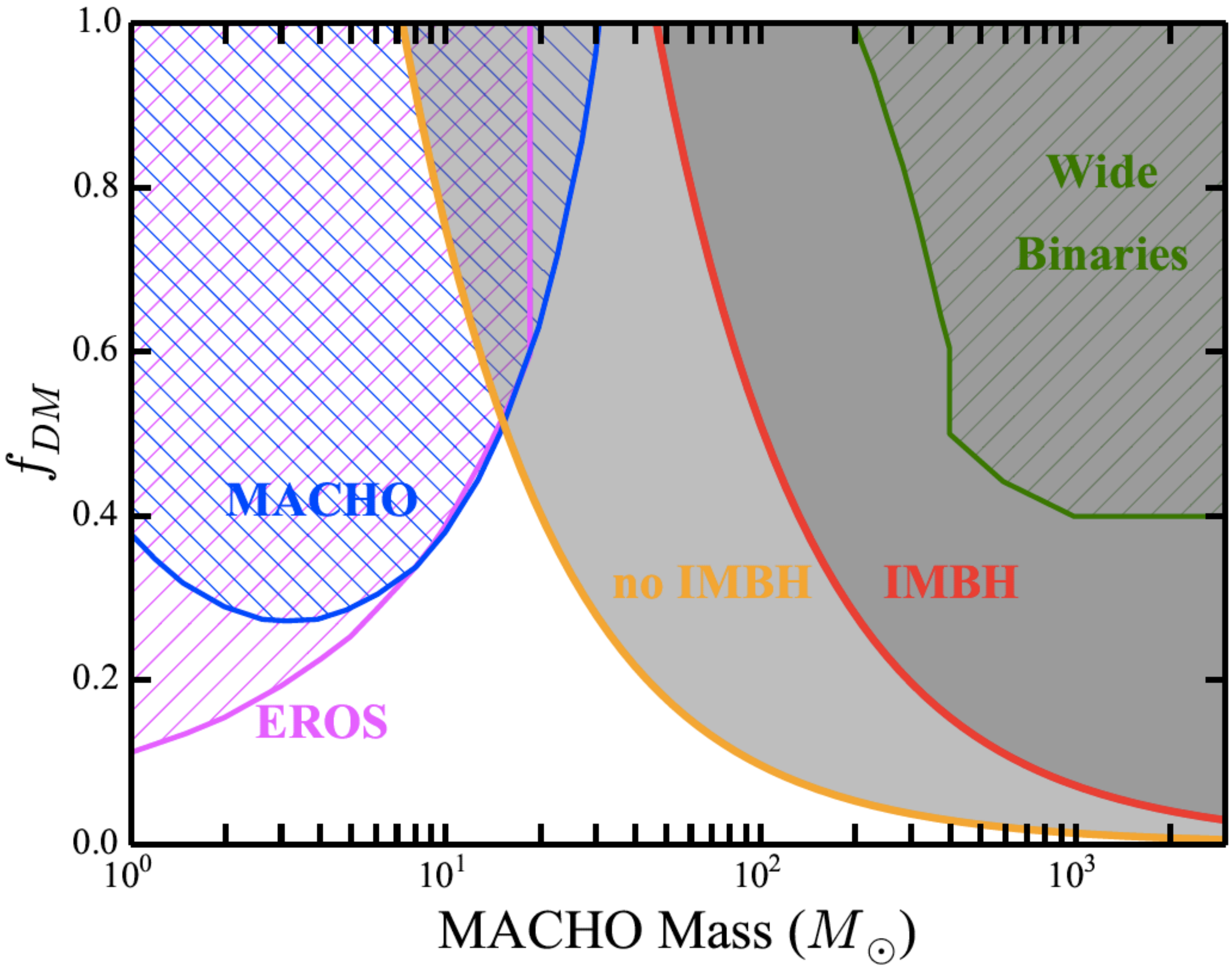
DES Dwarf spheroidals



DES Dwarf spheroidals



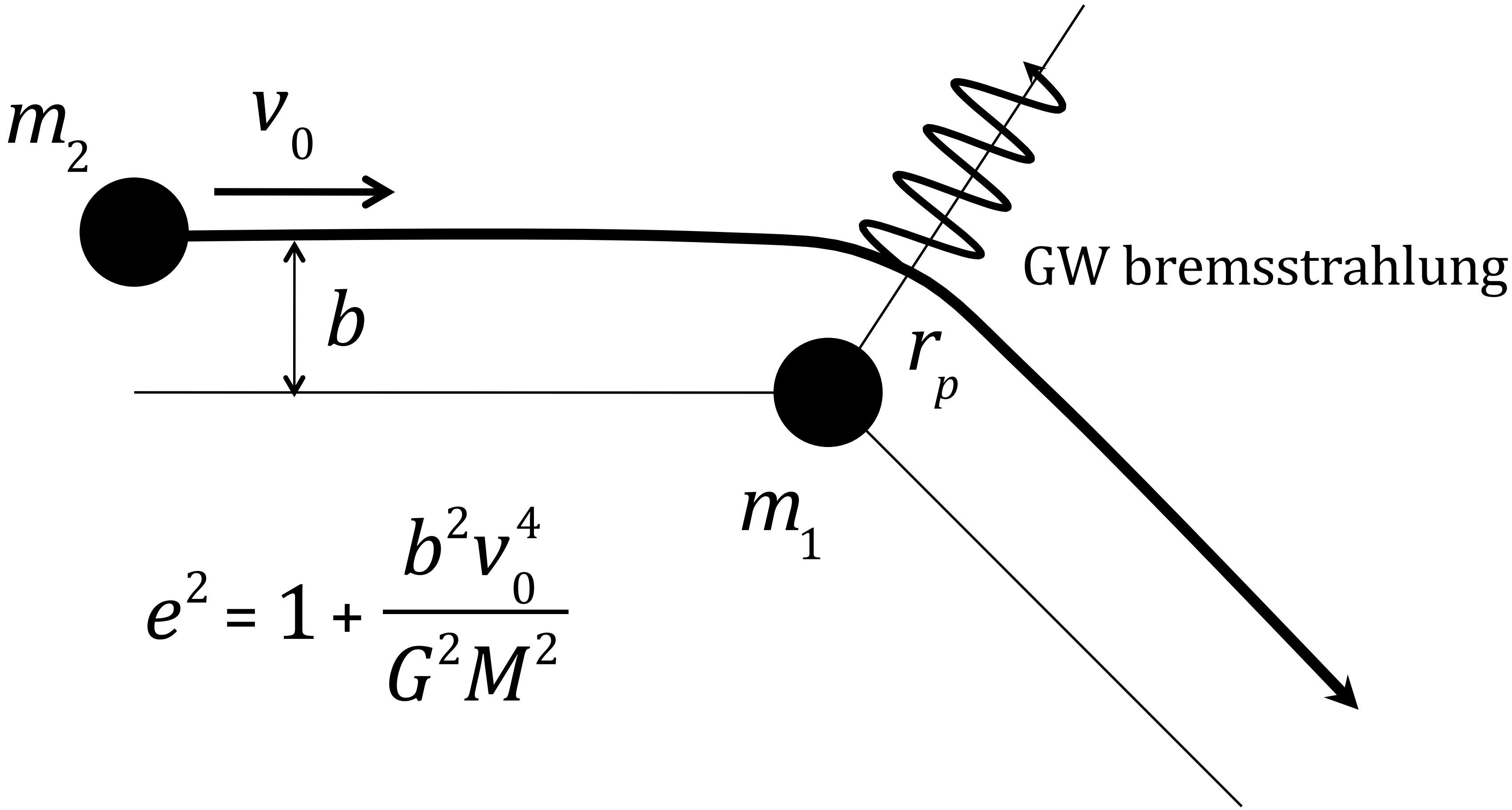
Eridanus II dwarf spheroidal



GW bursts from close encounters

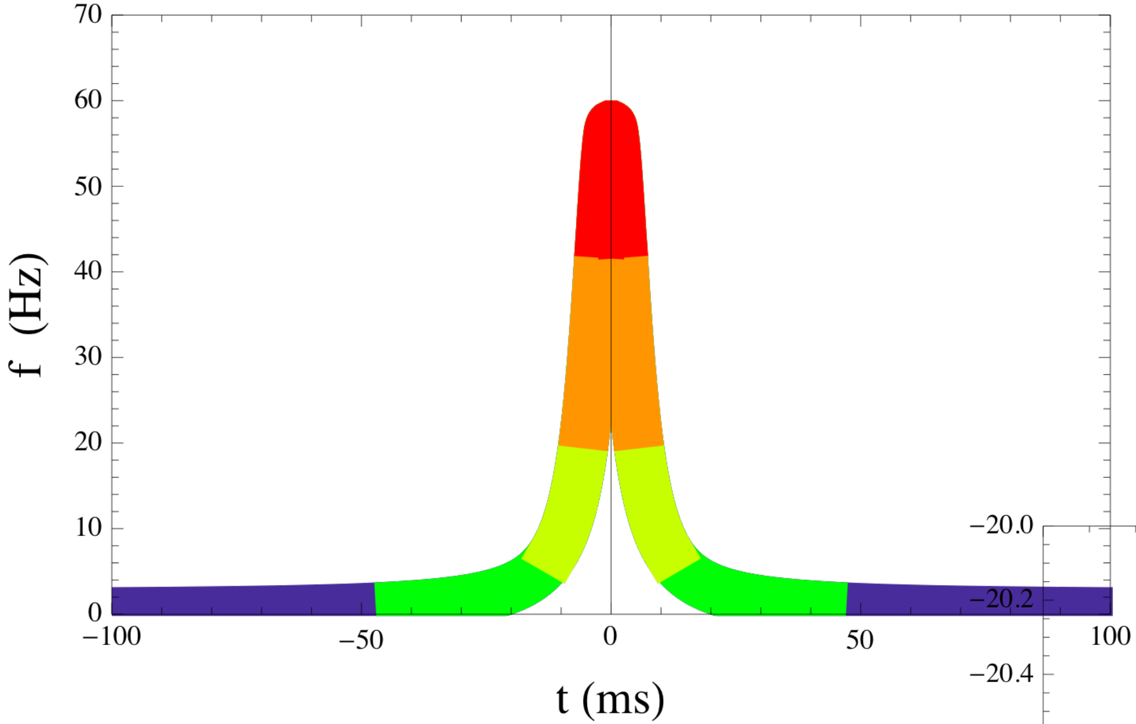
GW bursts

JGB, Nesseris (2017)

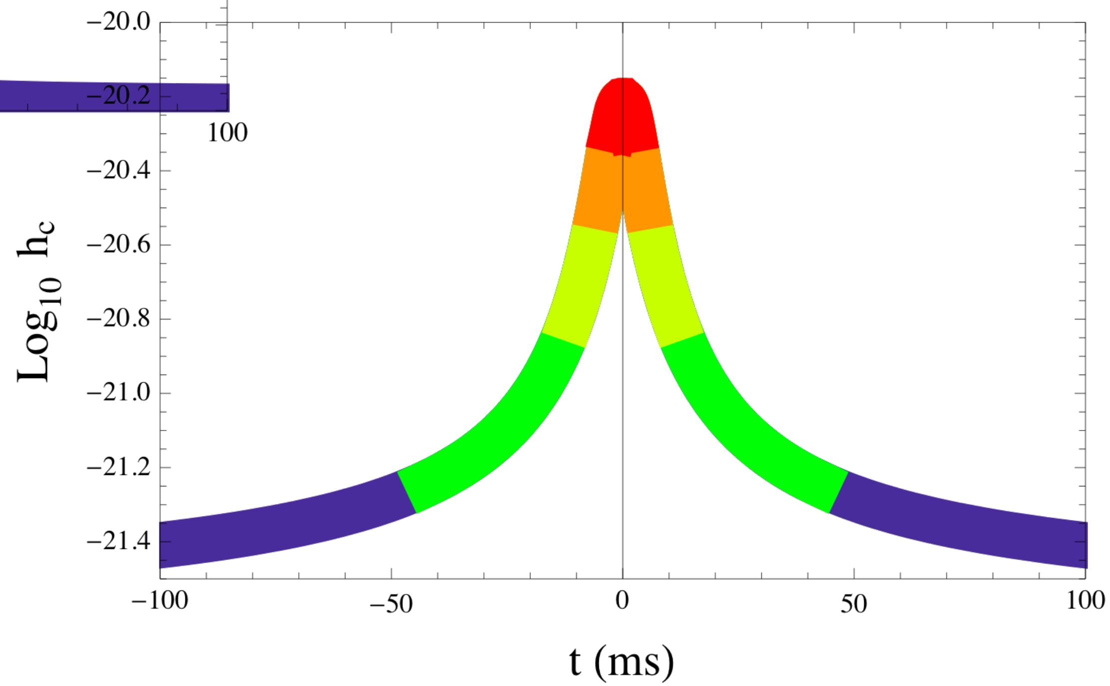


$$e^2 = 1 + \frac{b^2 v_0^4}{G^2 M^2}$$

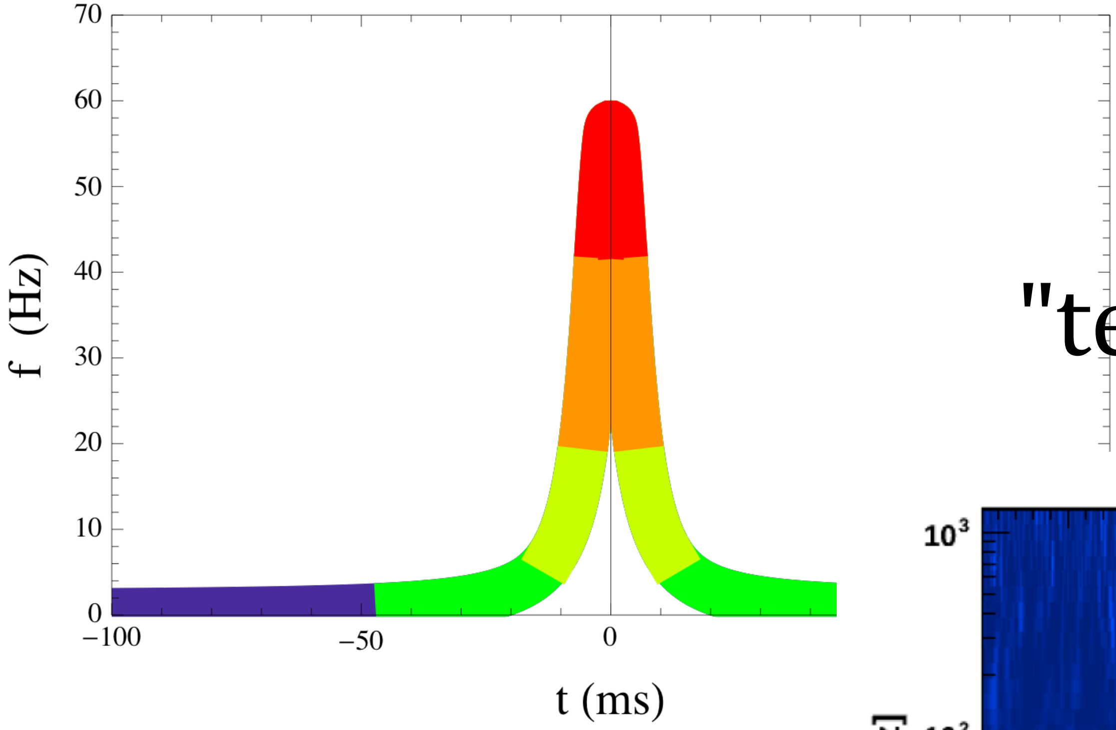
GW bursts



JGB, Nesseris (2017)

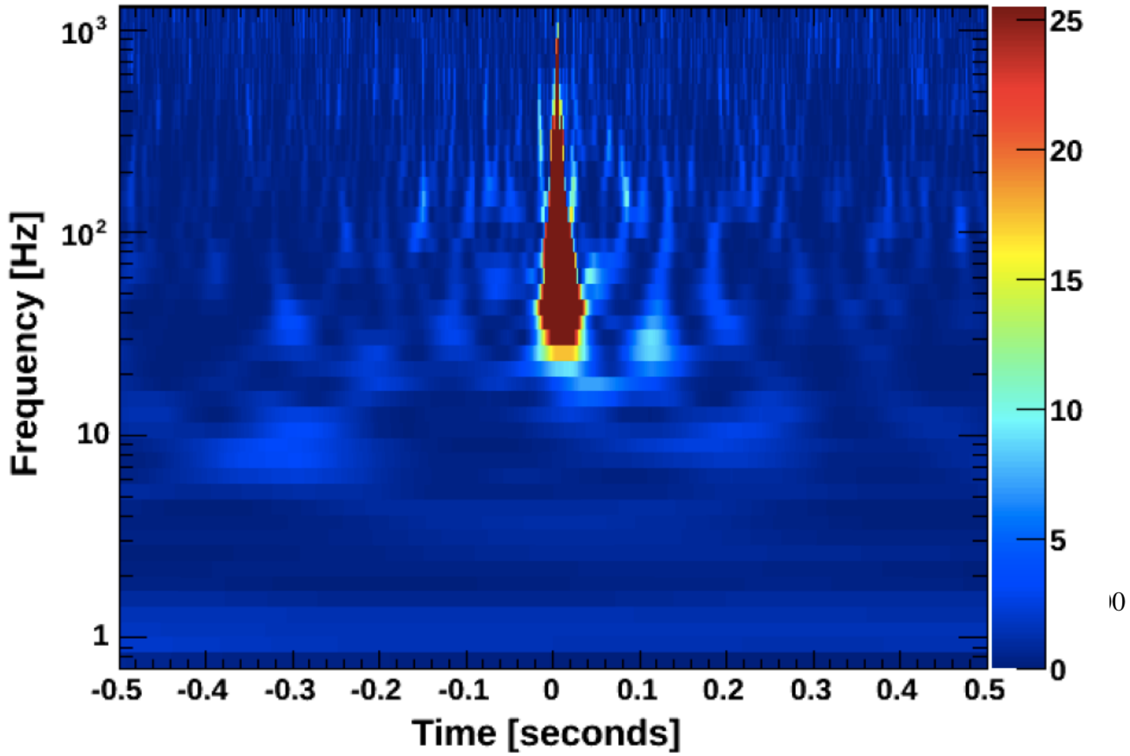


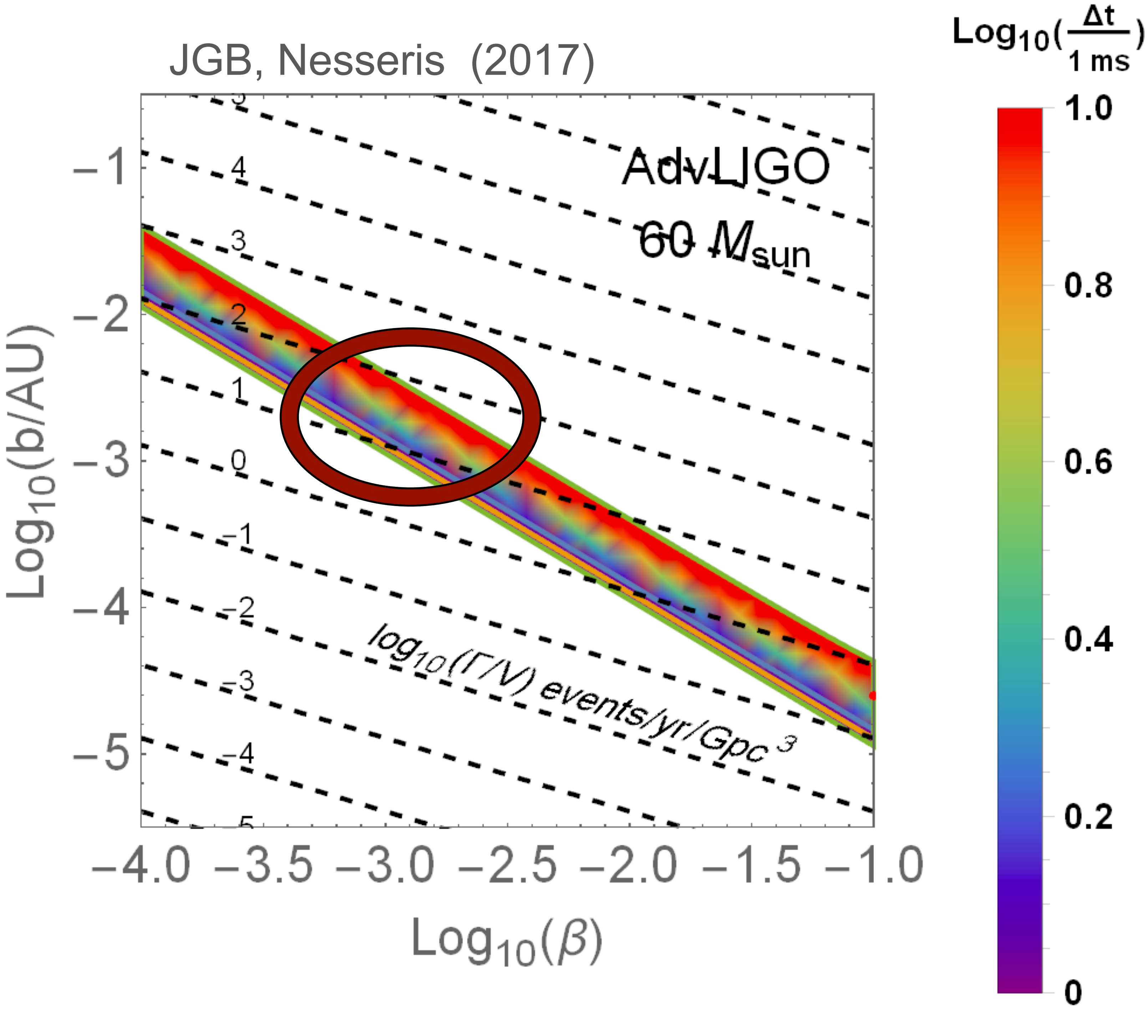
GW bursts



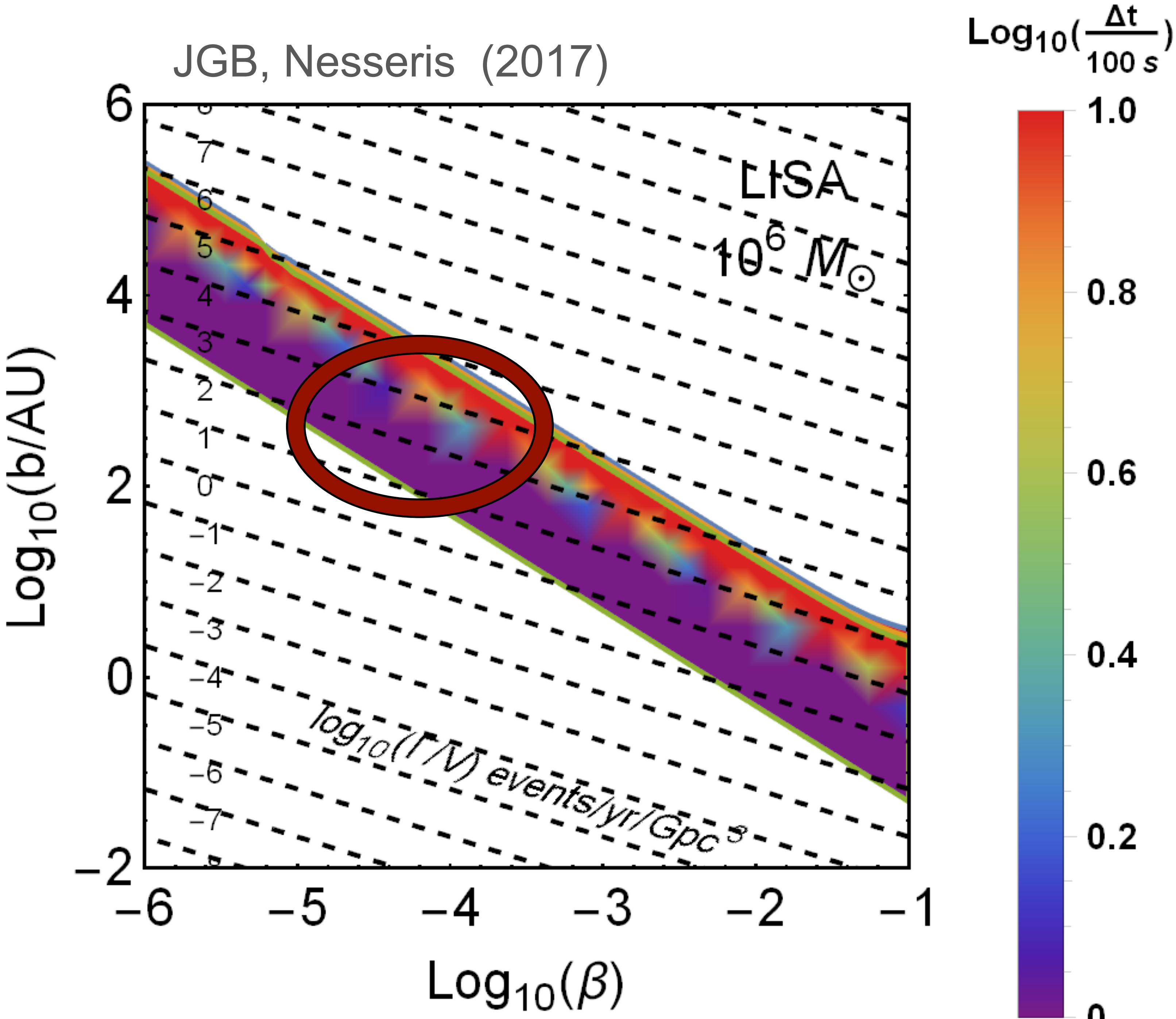
JGB, Nesseris (2017)

"tear drop glitches"?



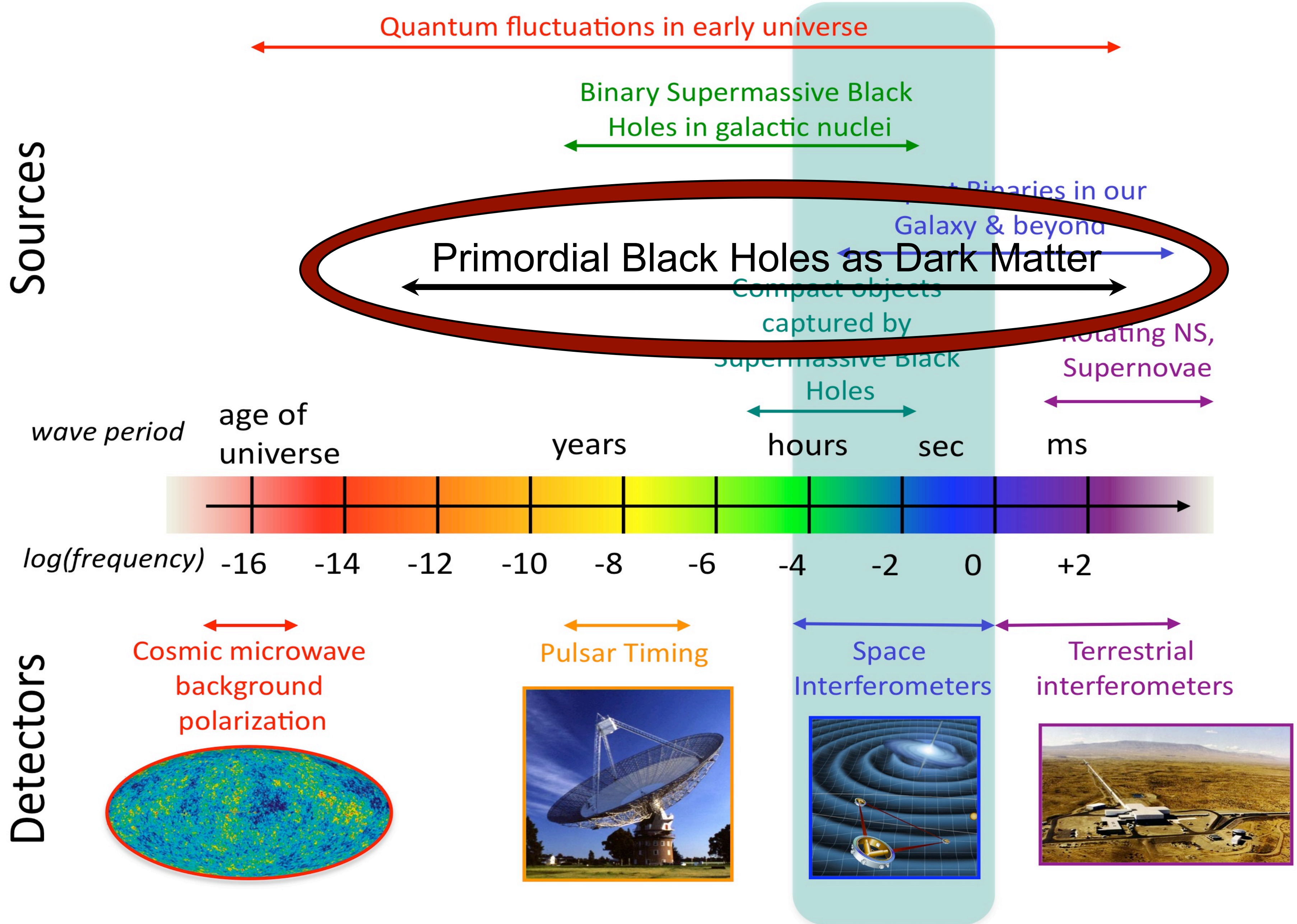


JGB, Nesseris (2017)
AdvLIGO
60 M_{sun}
$log_{10}(\Gamma/V)$ events/yr/Gpc^3
Log$_{10}$(b/AU)
Log$_{10}$(β)
Log$_{10}$($\frac{\Delta t}{1\ ms}$)


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

Stochastic Background Grav. Waves

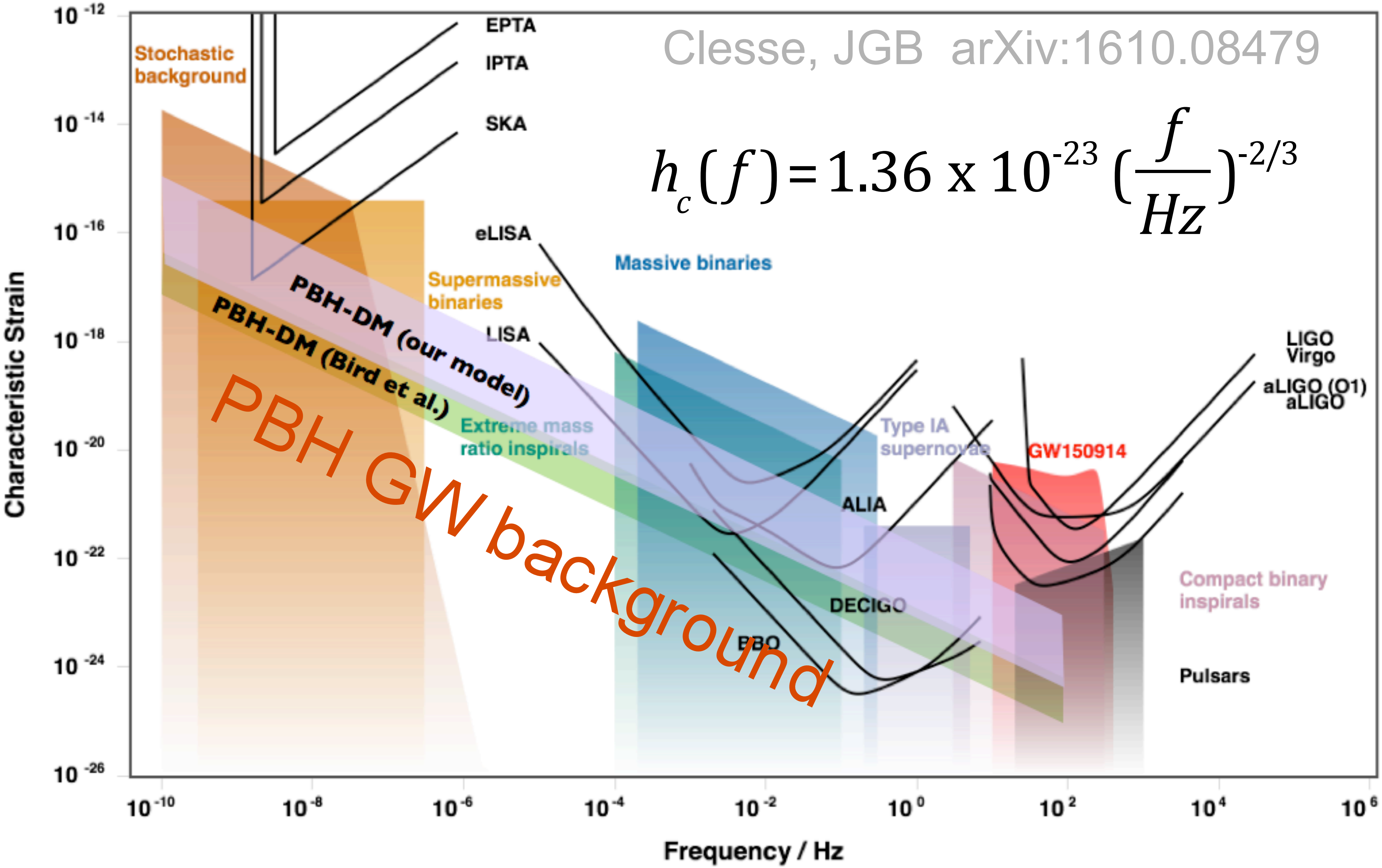
The Gravitational Wave Spectrum



Sensitivity of future GW antenas

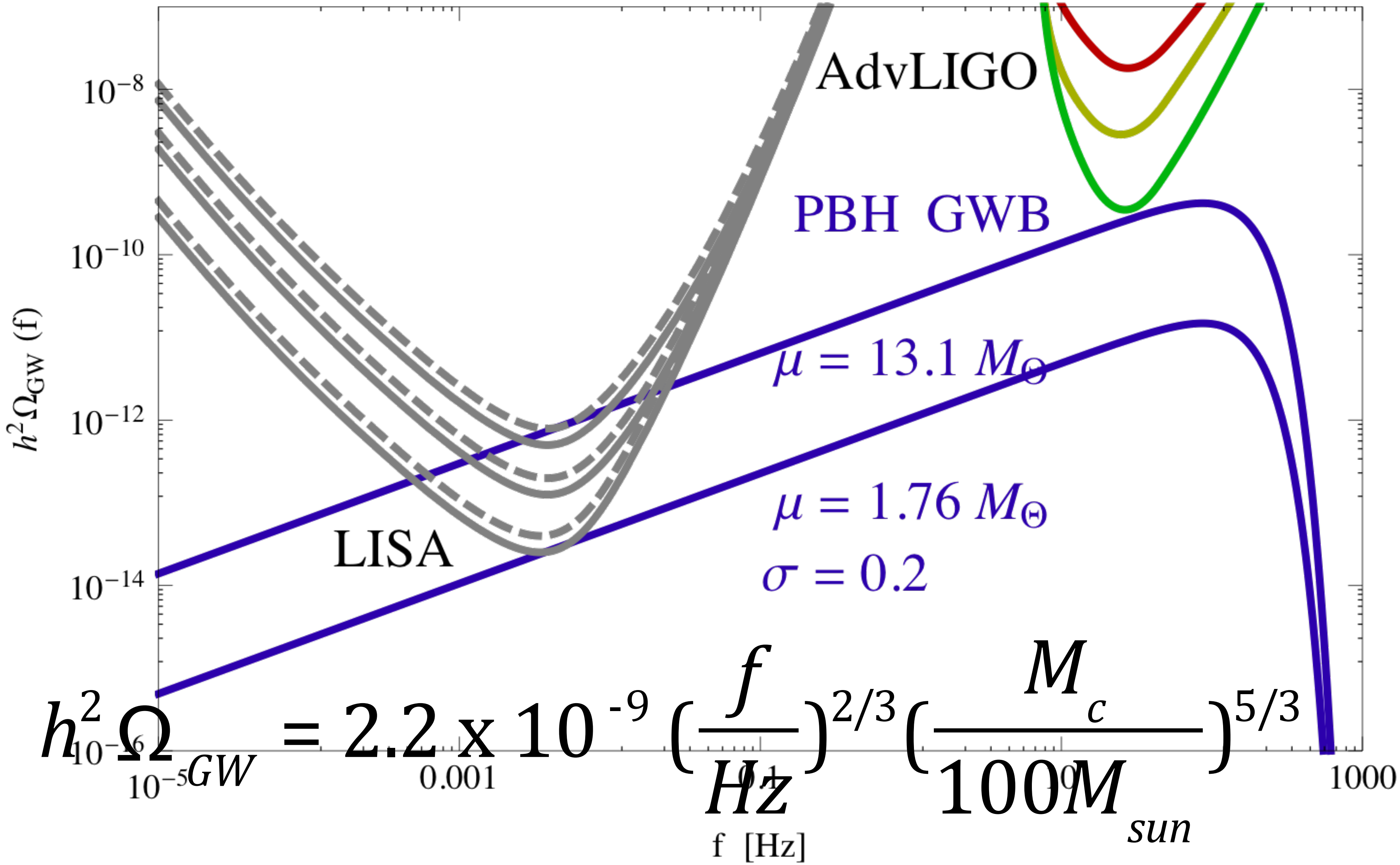
Clesse, JGB arXiv:1610.08479

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



Stochastic Background from MPBH

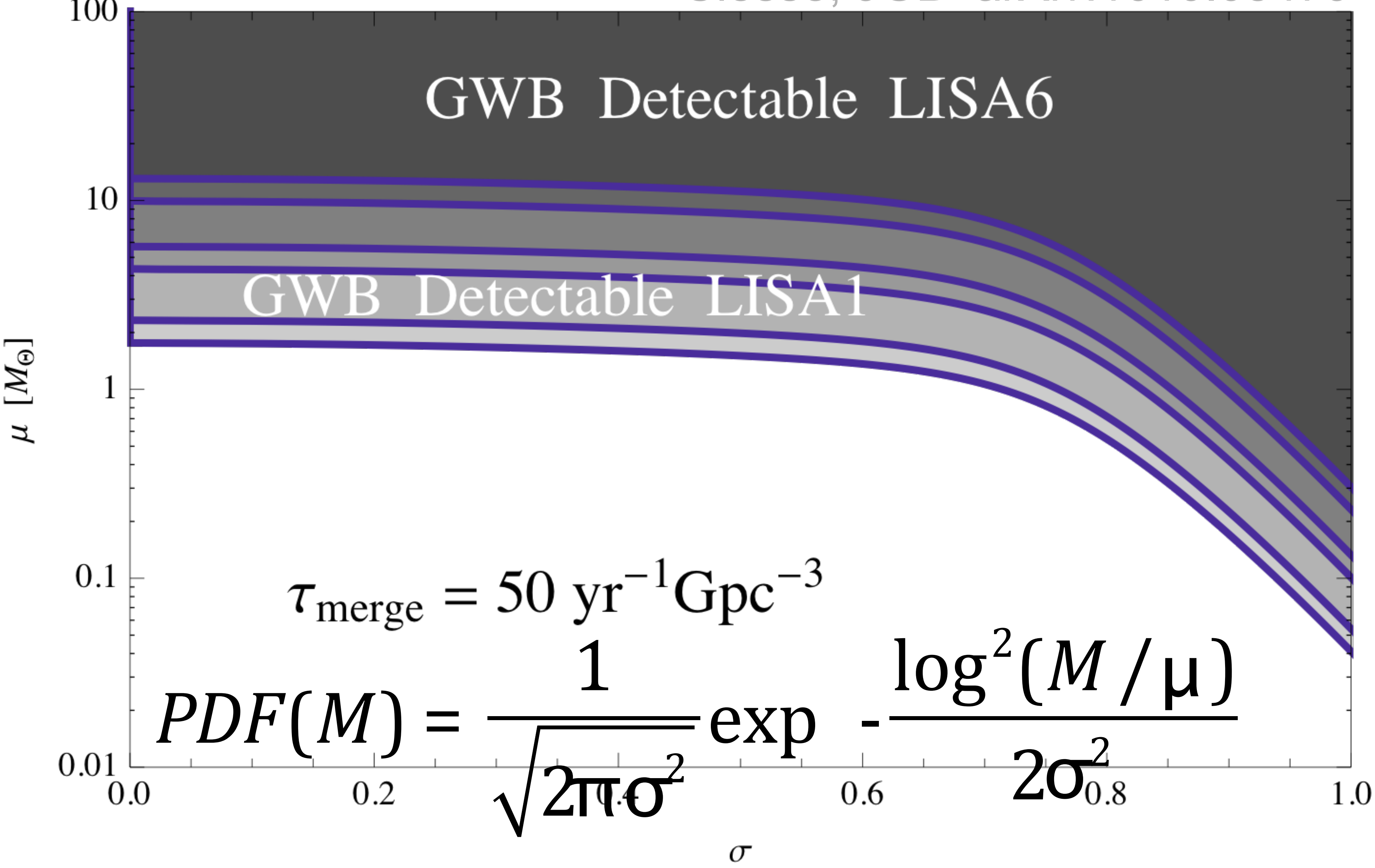
Clesse, JGB arXiv:1610.08479



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

Stochastic Background from MPBH

Clesse, JGB arXiv:1610.08479



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

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

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.