10th LISA Cosmology WG workshop

Gravitational Wave Probes of Primordial Black Holes

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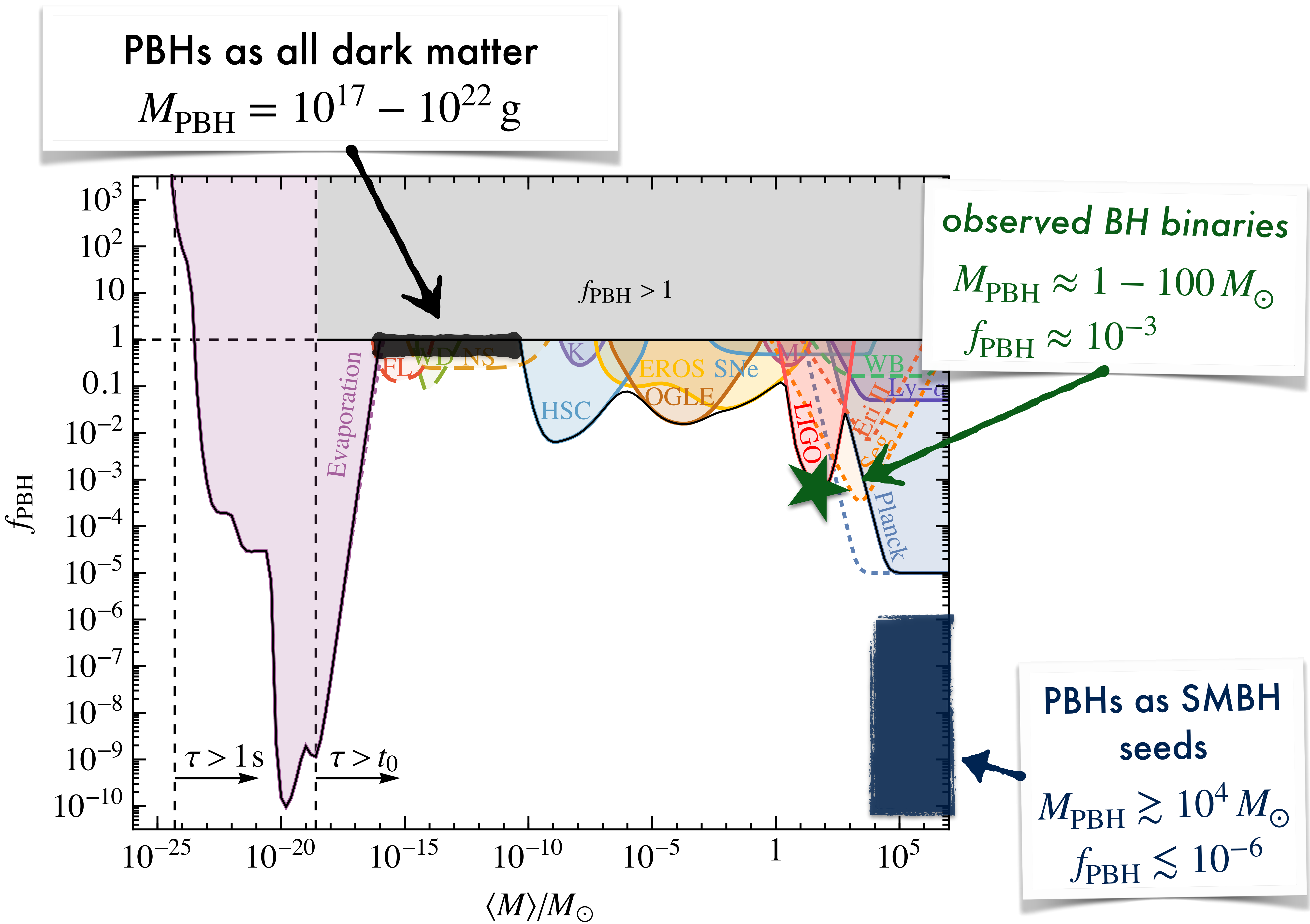
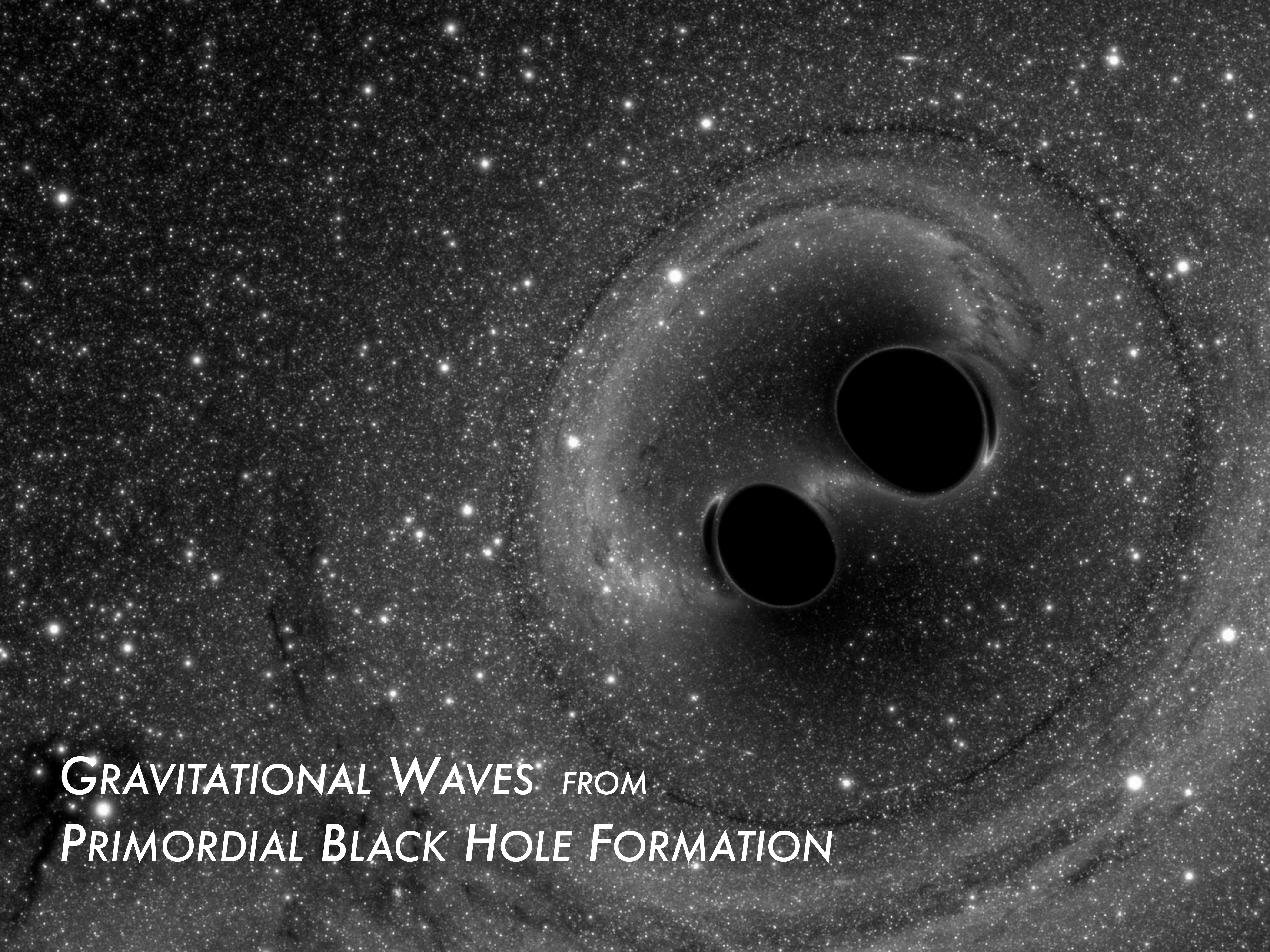
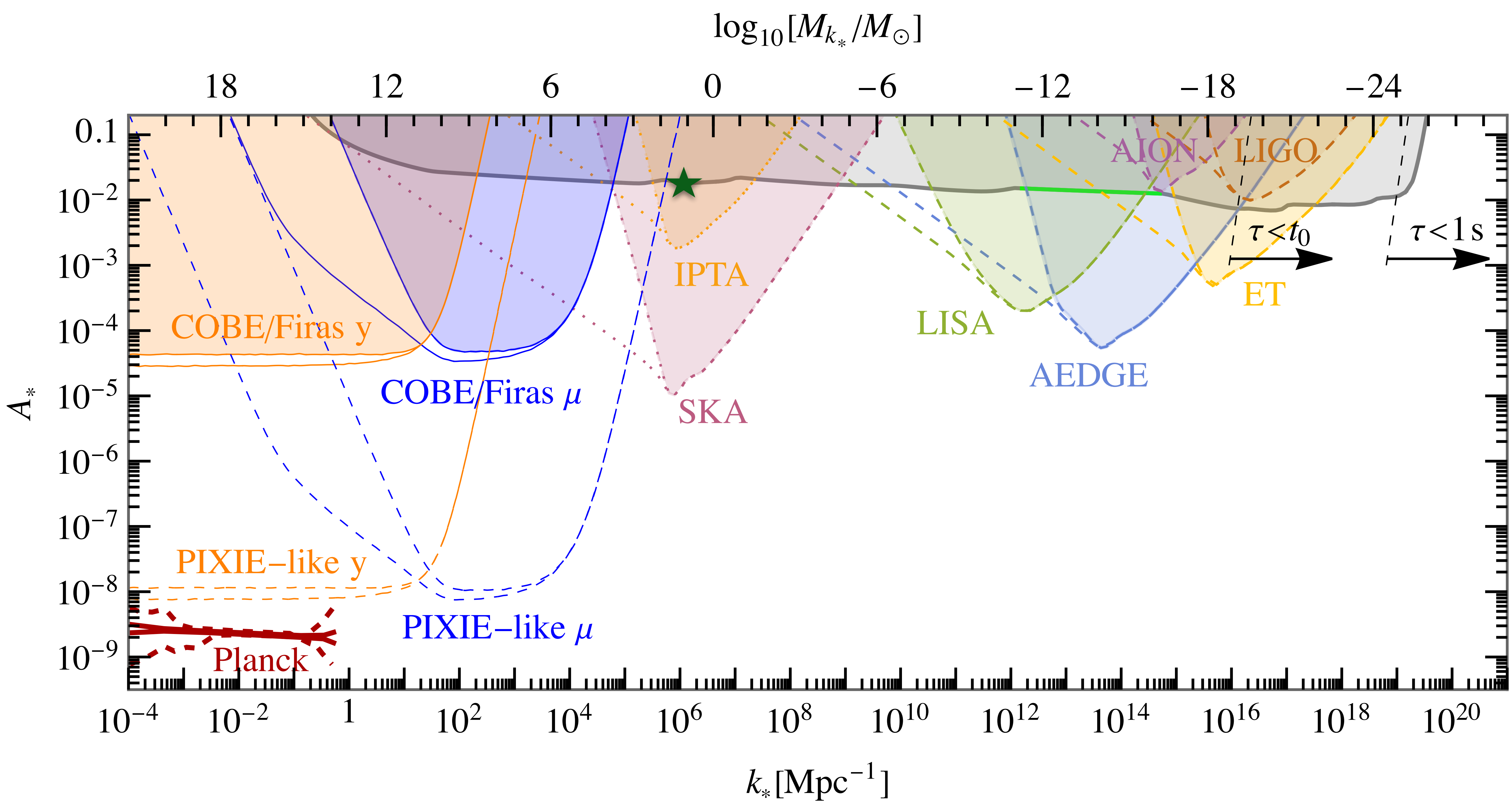
Keemilise ja Bioloogilise Füüsika Instituut
National Institute of Chemical Physics and Biophysics


PBHs as all dark matter
$M_{\rm PBH} = 10^{17} - 10^{22}\,{\rm g}$
observed BH binaries
$M_{\rm PBH} \approx 1 - 100\,M_\odot$
$f_{\rm PBH} \approx 10^{-3}$
PBHs as SMBH seeds
$M_{\rm PBH} \gtrsim 10^4\,M_\odot$
$f_{\rm PBH} \lesssim 10^{-6}$
$f_{\rm PBH} > 1$
Evaporation
FL
WD
NS
K
HSC
EROS
SNe
OGLE
LIGO
WB
Ly-α
Planck
Eri II
$\tau > 1\,{\rm s}$
$\tau > t_0$
$f_{\rm PBH}$
$\langle M\rangle/M_\odot$


GRAVITATIONAL WAVES FROM
PRIMORDIAL BLACK HOLE FORMATION

Scalar induced GWs



[2205.13540 Karam et al]

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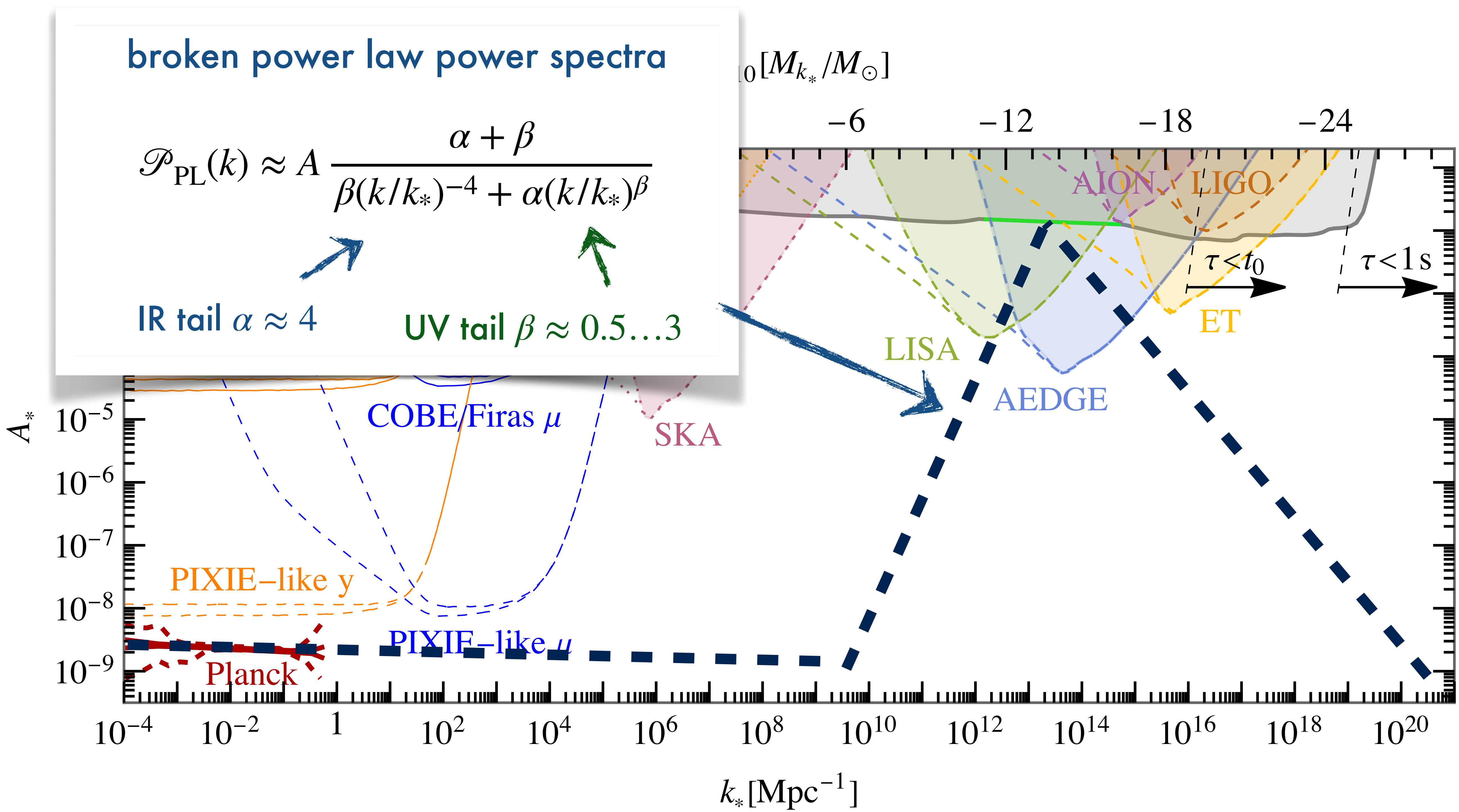

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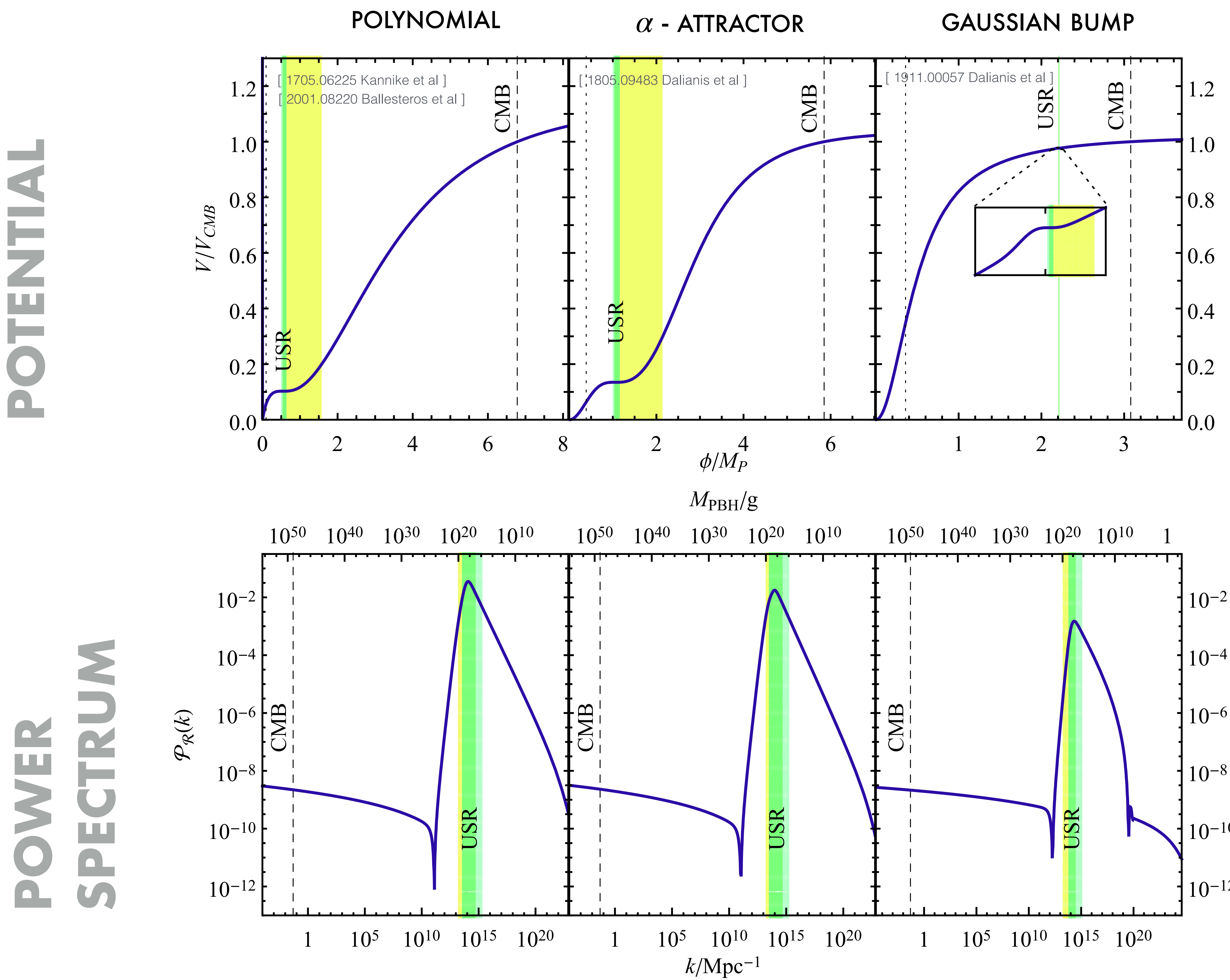
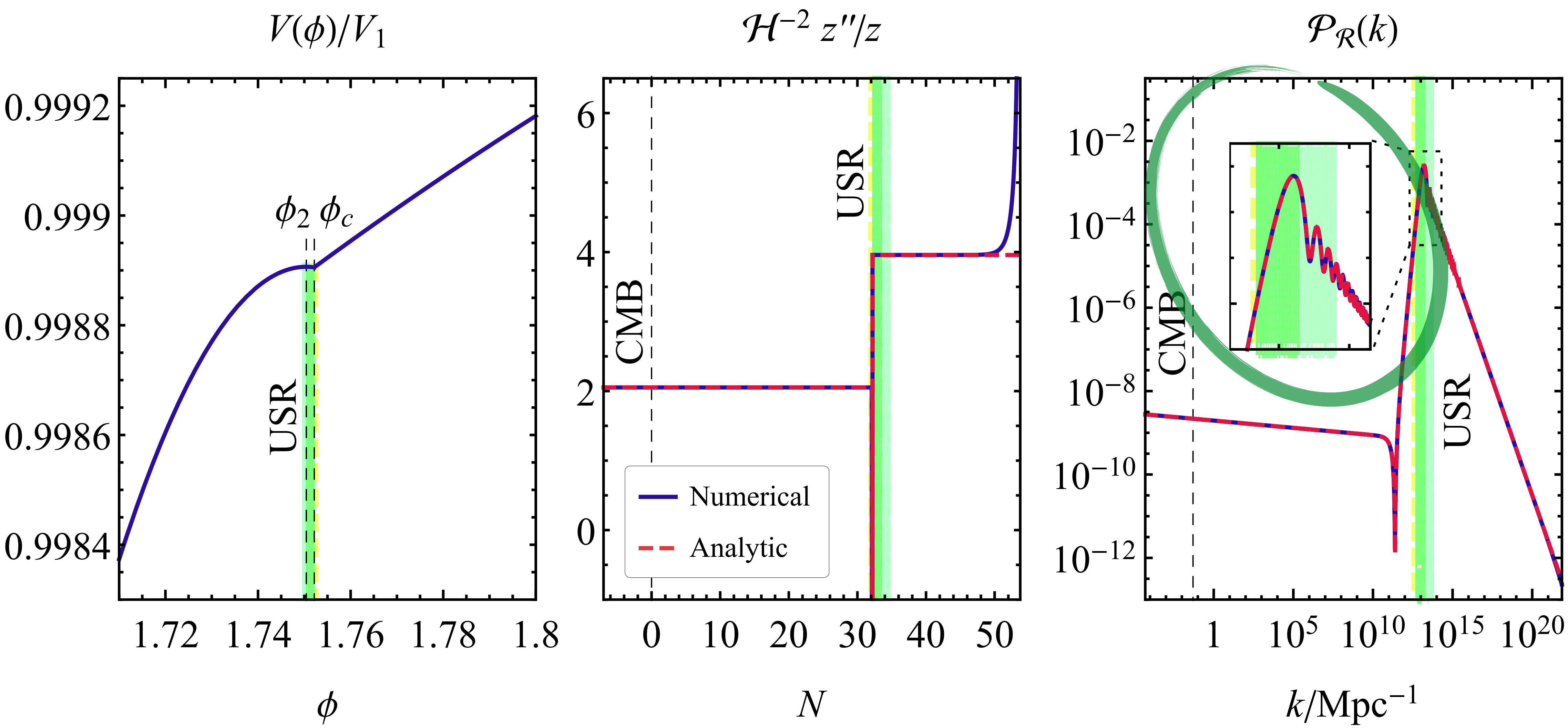


POLYNOMIAL
α - ATTRACTOR
GAUSSIAN BUMP
POTENTIAL
POWER SPECTRUM
[1705.06225 Kannike et al]
[2001.08220 Ballesteros et al]
[1805.09483 Dalianis et al]
[1911.00057 Dalianis et al]
USR
CMB
V/V_{CMB}
ϕ/M_P
$M_{\rm PBH}$/g
$\mathcal{P}_{\mathcal{R}}(k)$
k/Mpc^{-1}

Instantaneous SR to USR transitions

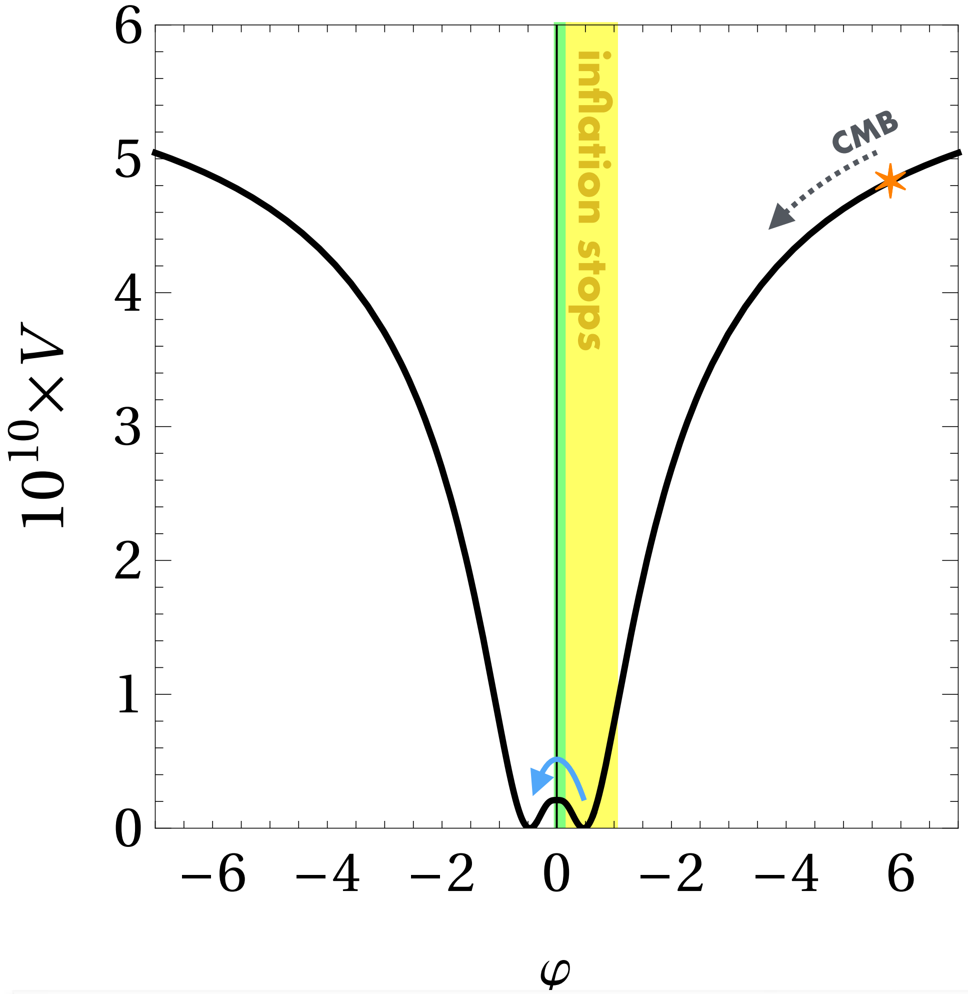


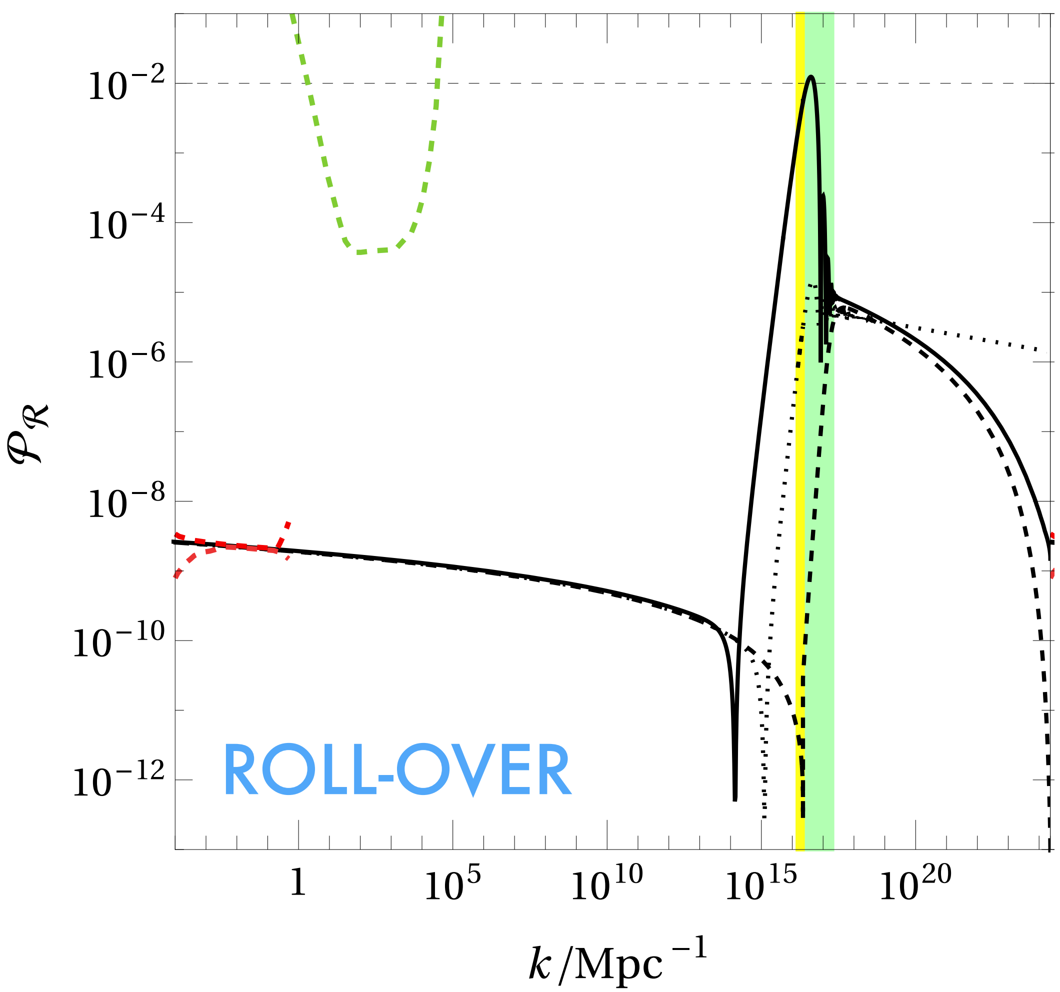
- *analytically solvable*
- *contains power spectra viable for both PBHs and CMB*
- *approximates quasi-inflection point models quite well*
- *oscillatory features*

[2205.13540 Karam et al]

Double-well potentials

(temporary end of inflation)





- *modes enhanced due to non-adiabaticities*
- **no dip** *in the power spectrum if the field* **rolls back** *from the peak*
- *less tuning required*
- *non-gaussianities?*

[2305.09630 Karam et al]

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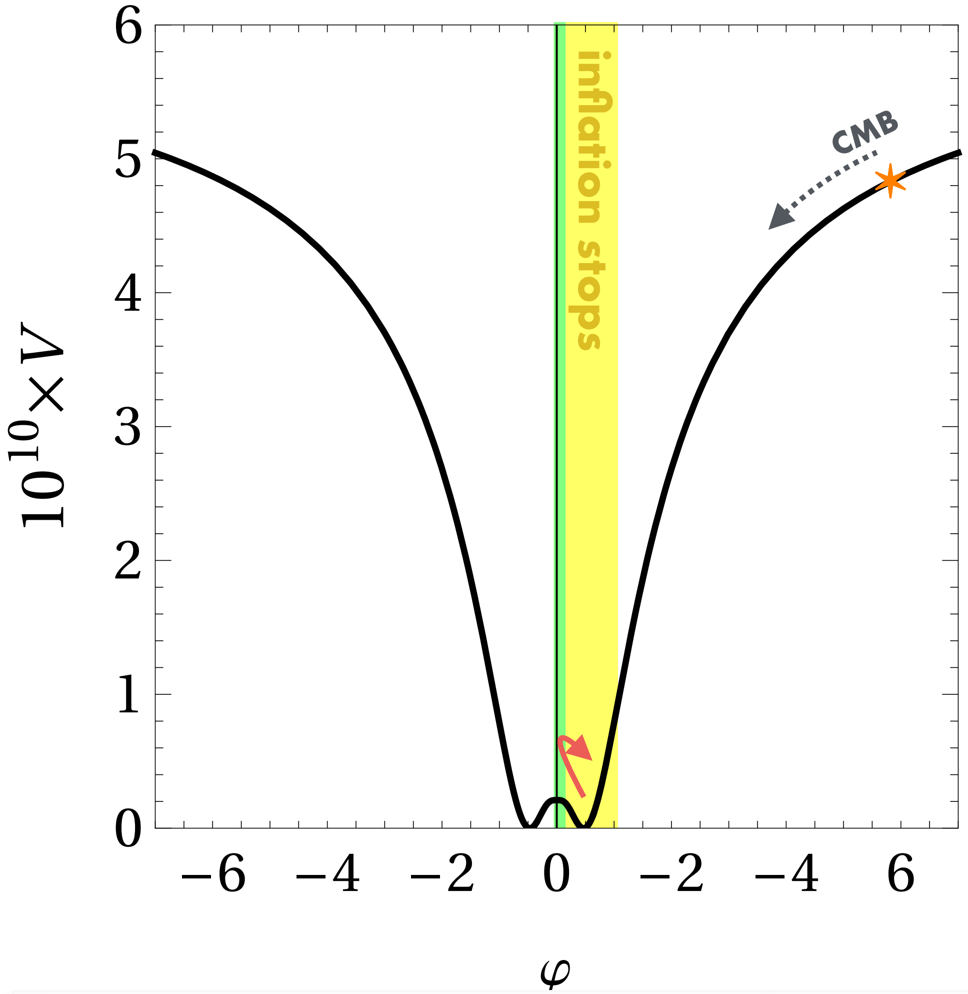

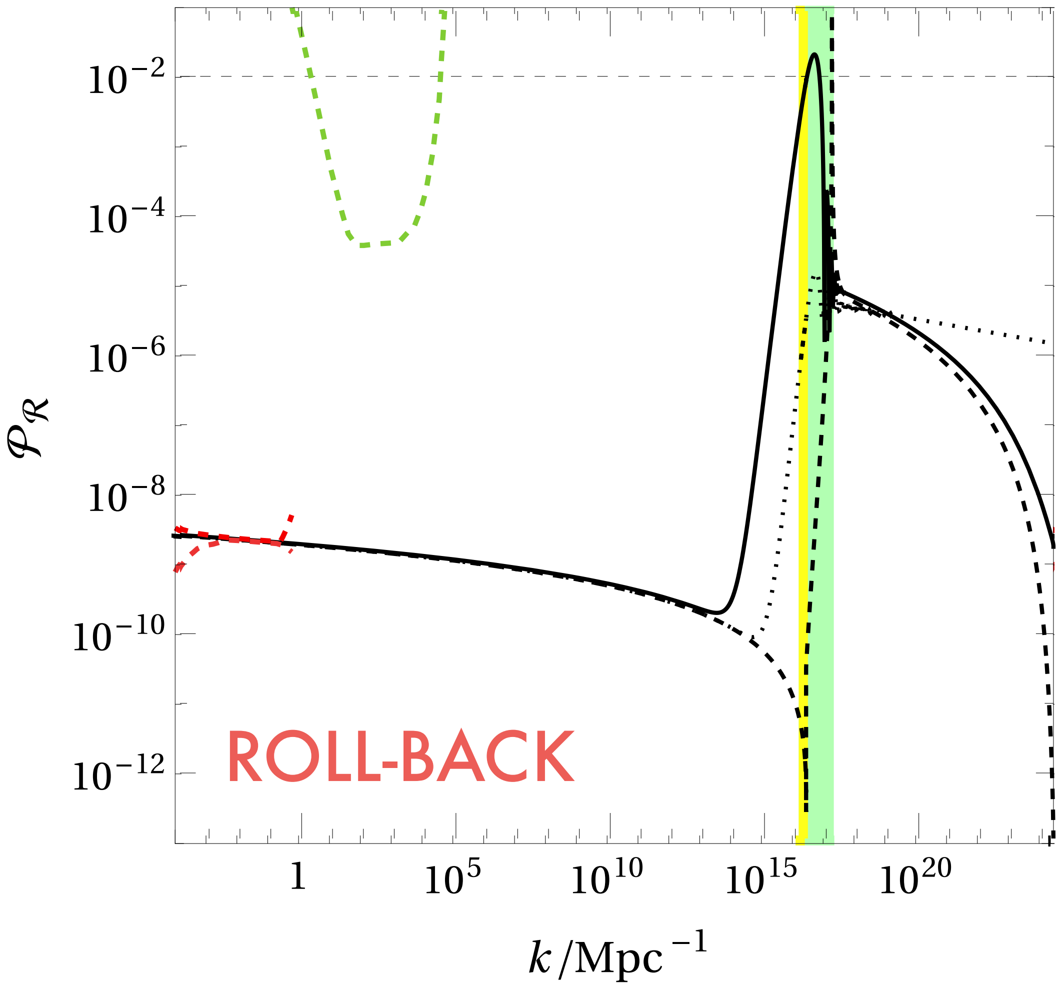

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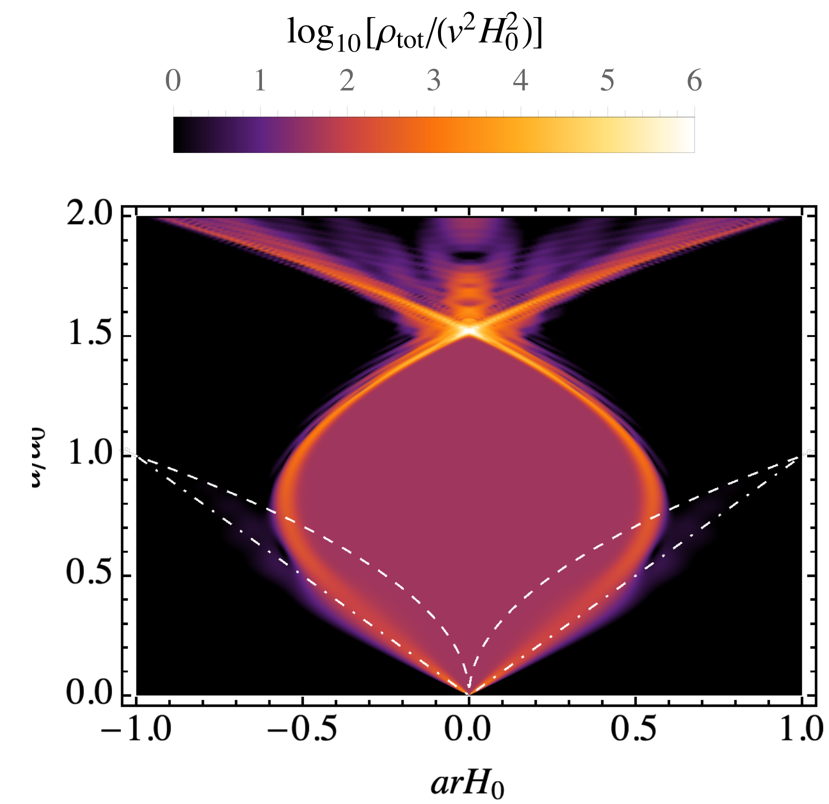
[2305.09630 Karam et al]

PBH formation

mechanisms:

current focus

- inflationary perturbations [Hawking, Carr 1974, Carr 1975]
- collapse of cosmic strings [Hawking 1989]
- vacuum bubbles
  - bubble collisions in first order phase transitions [Hawking 1982]
  - collapse of false vacuum bubbles [1512.01819,1710.02865,2001.09160]
- collapse of compact objects
  - *oscillons* [1801.03321]
  - *Q-balls* [1612.02529,1706.09003,1907.10613]
  - *Fermi balls* [2106.00111]
- Yukawa "fifth force" [2008.12456]
- ...



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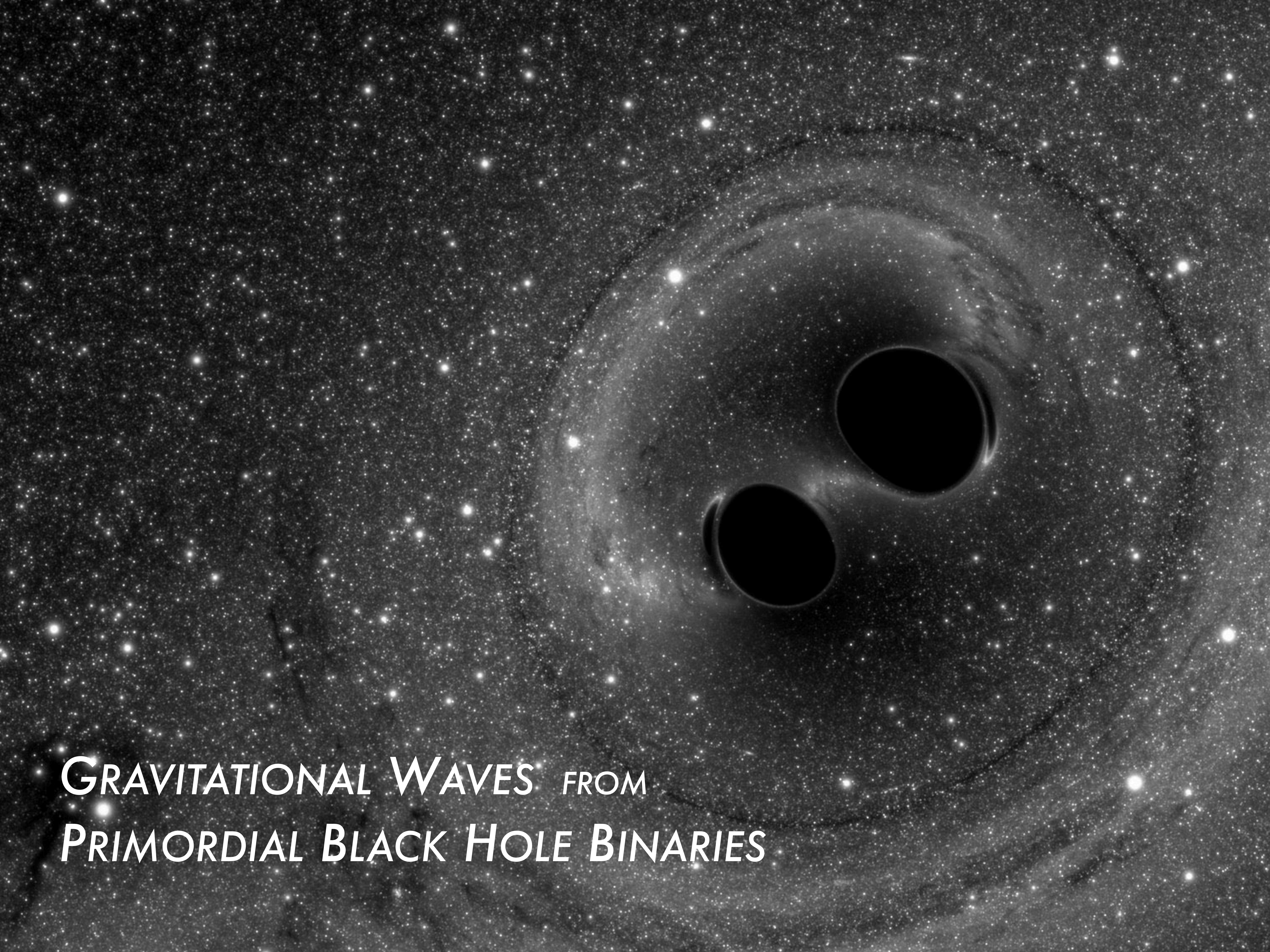
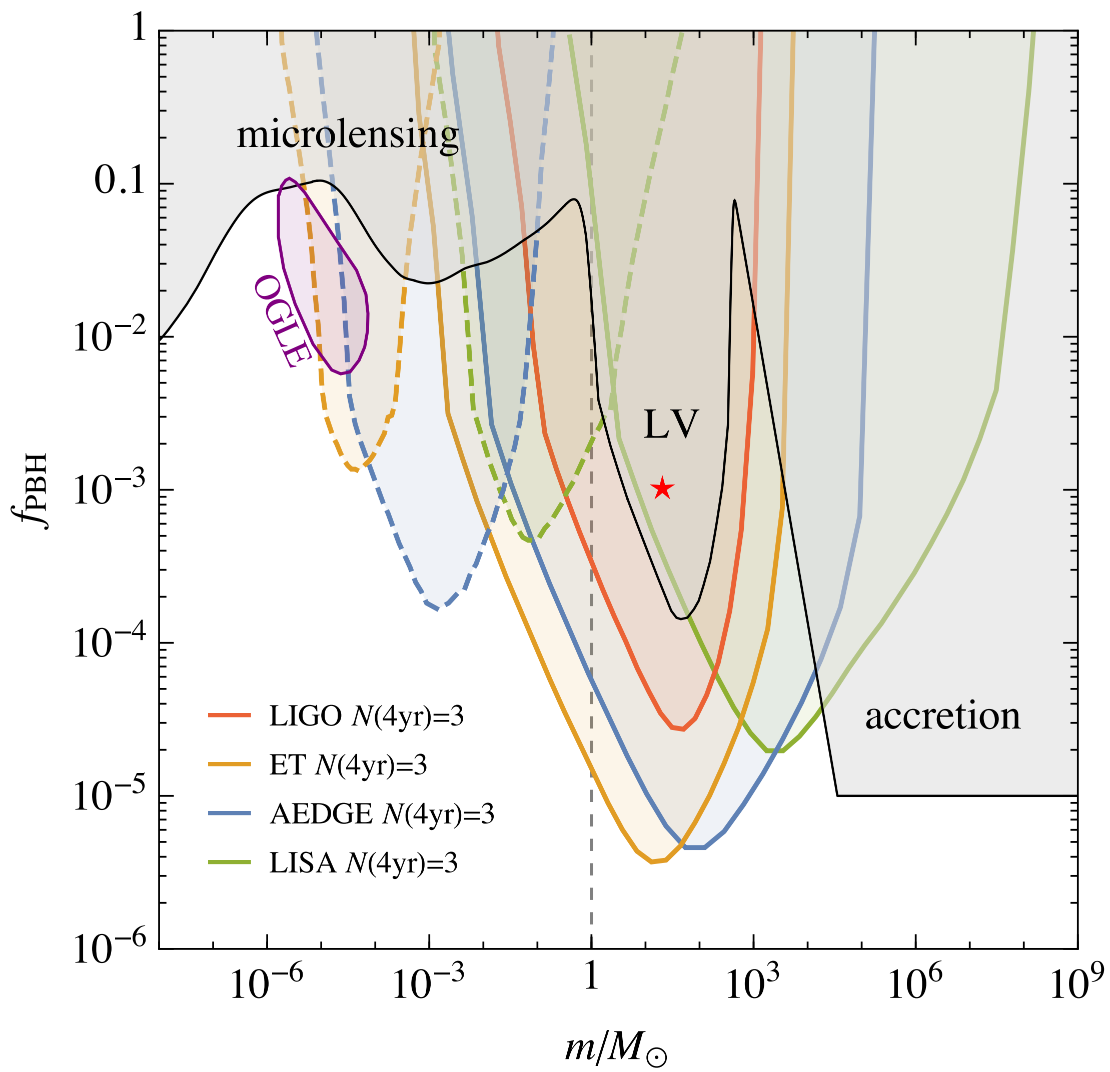
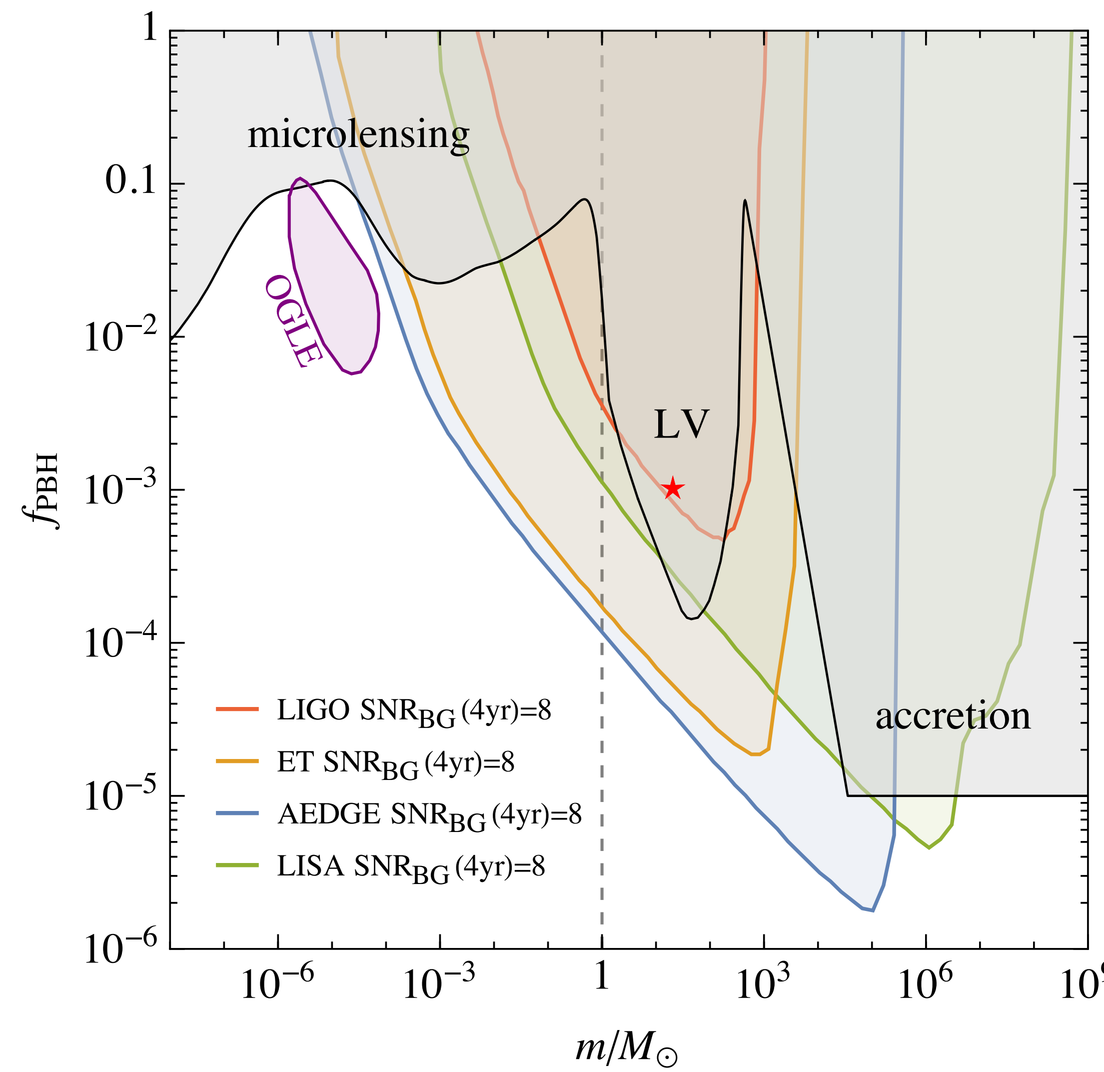

GRAVITATIONAL WAVES FROM
PRIMORDIAL BLACK HOLE BINARIES

Prospects for PBH binaries





Individual Binaries

SGWB

[2107.03379 Pujolas et al]

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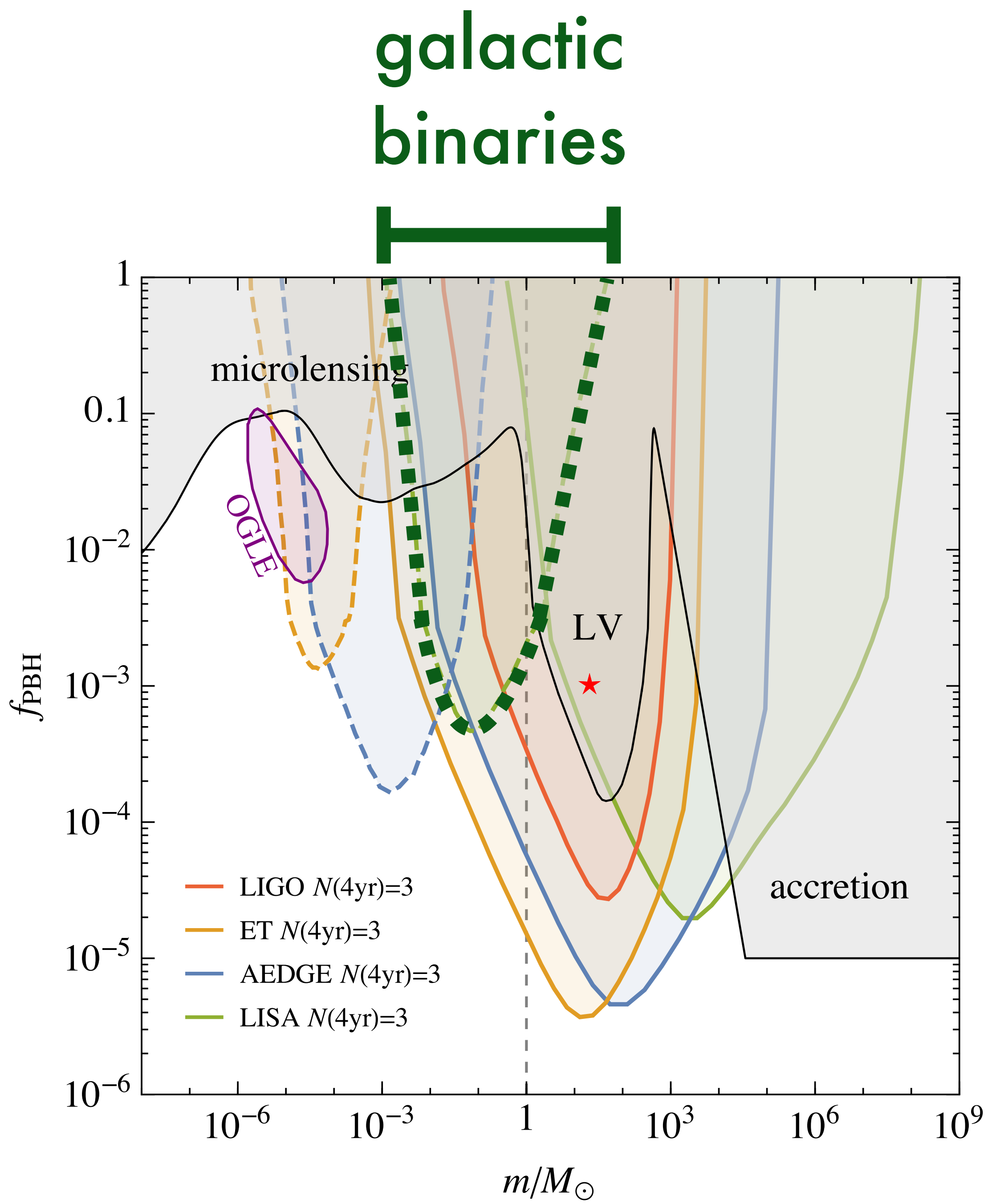
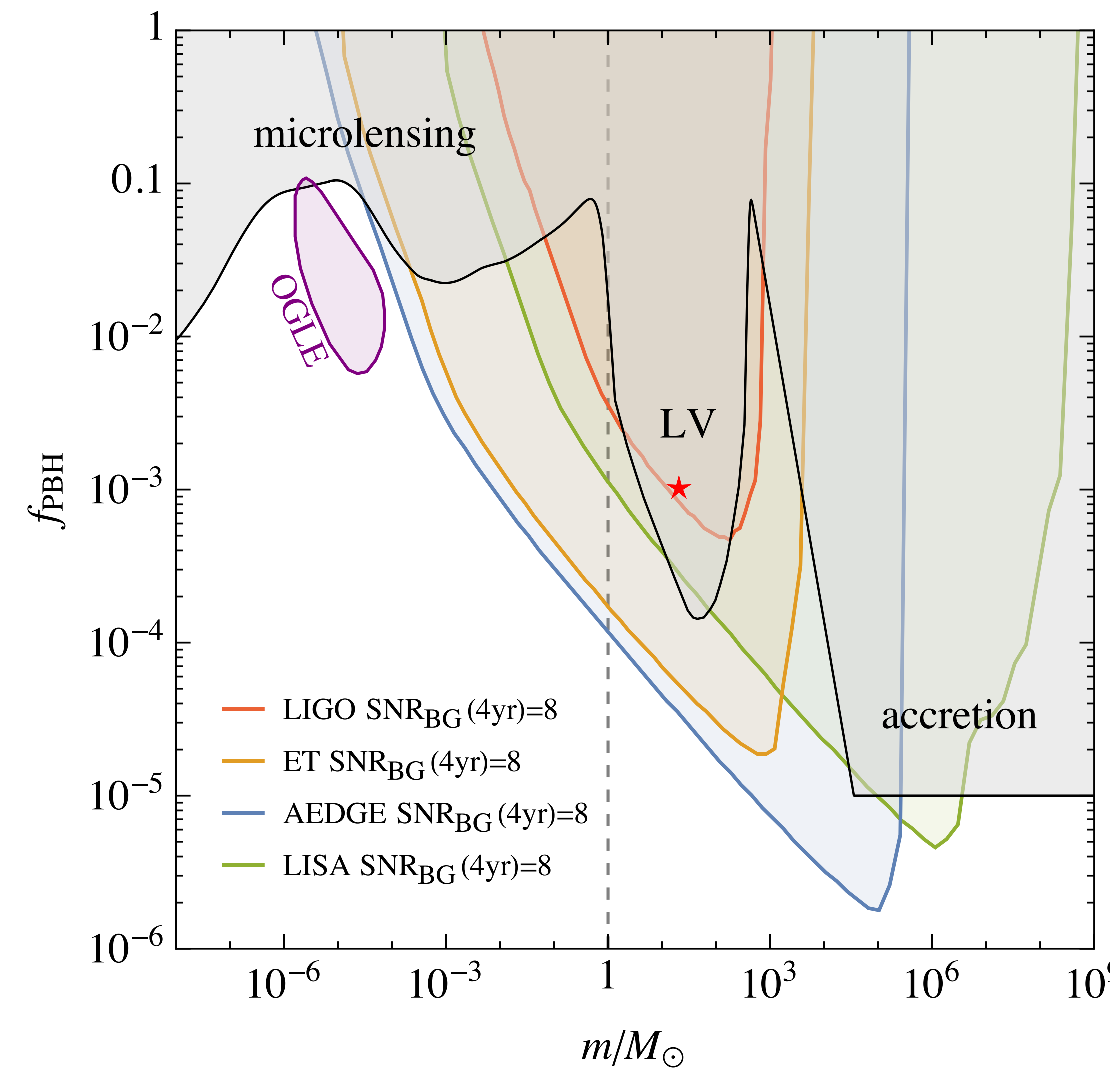


INDIVIDUAL BINARIES



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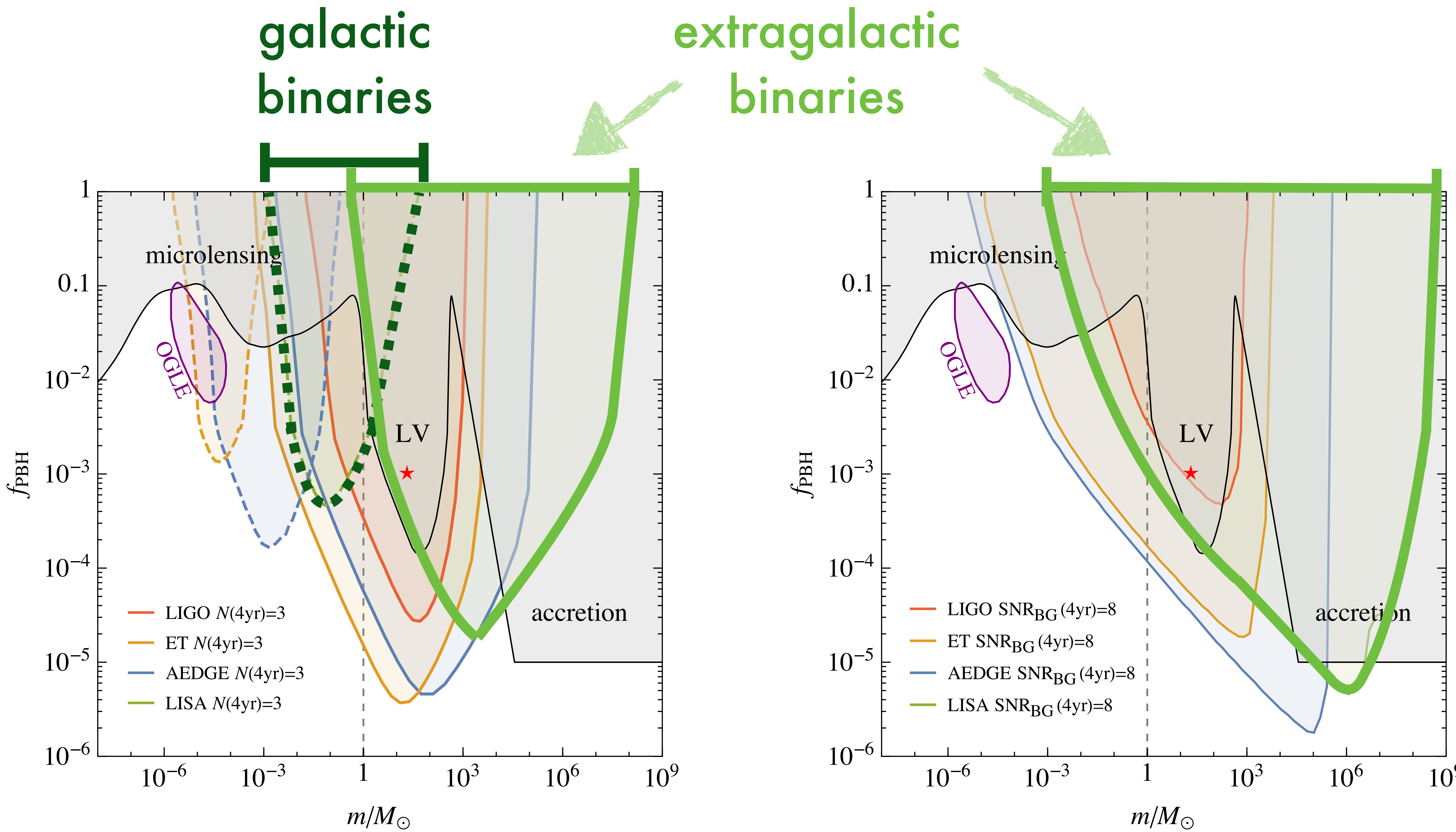

Individual Binaries

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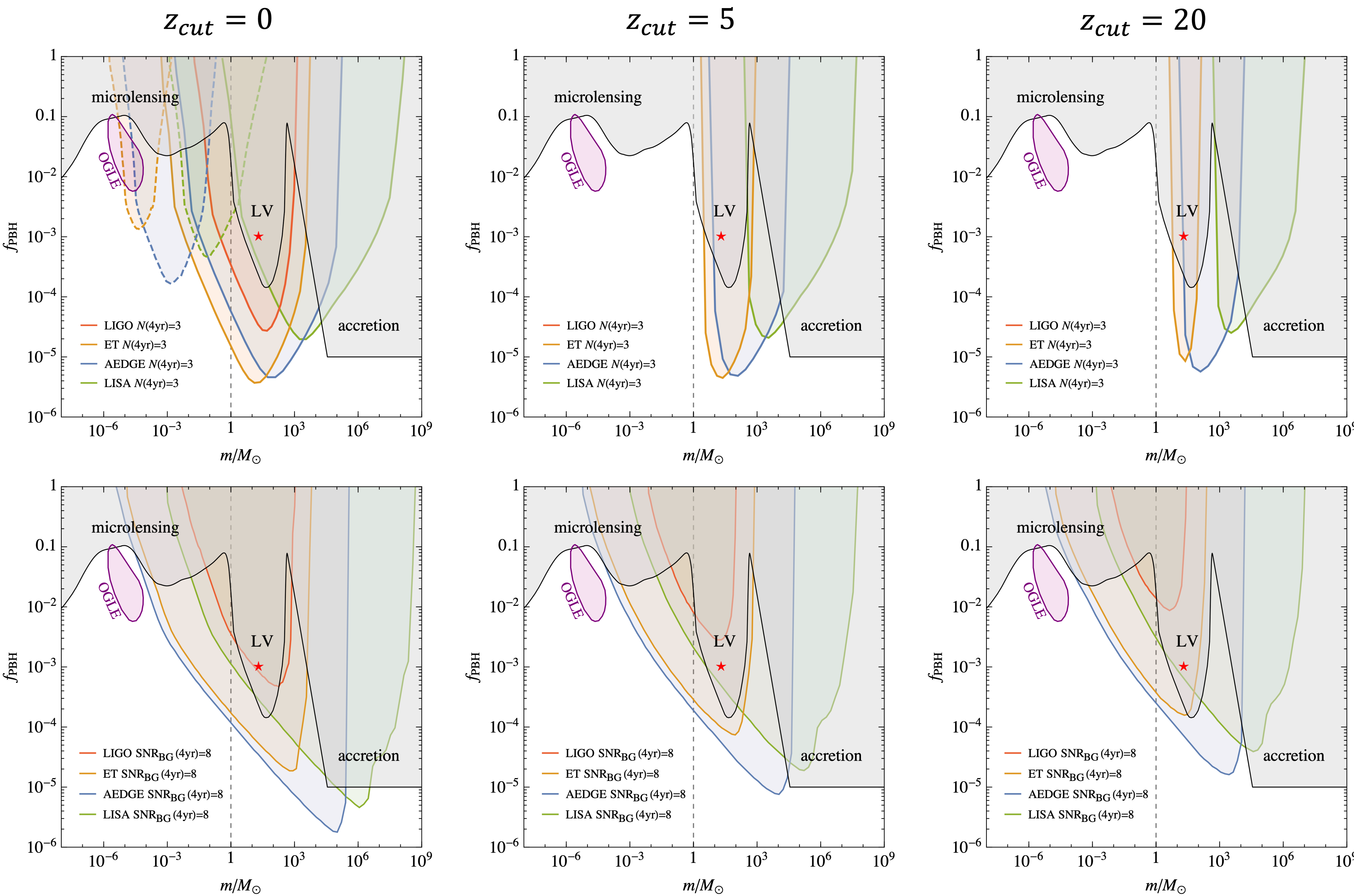
Individual Mergers



SGWB

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PBH BINARIES

dominates if

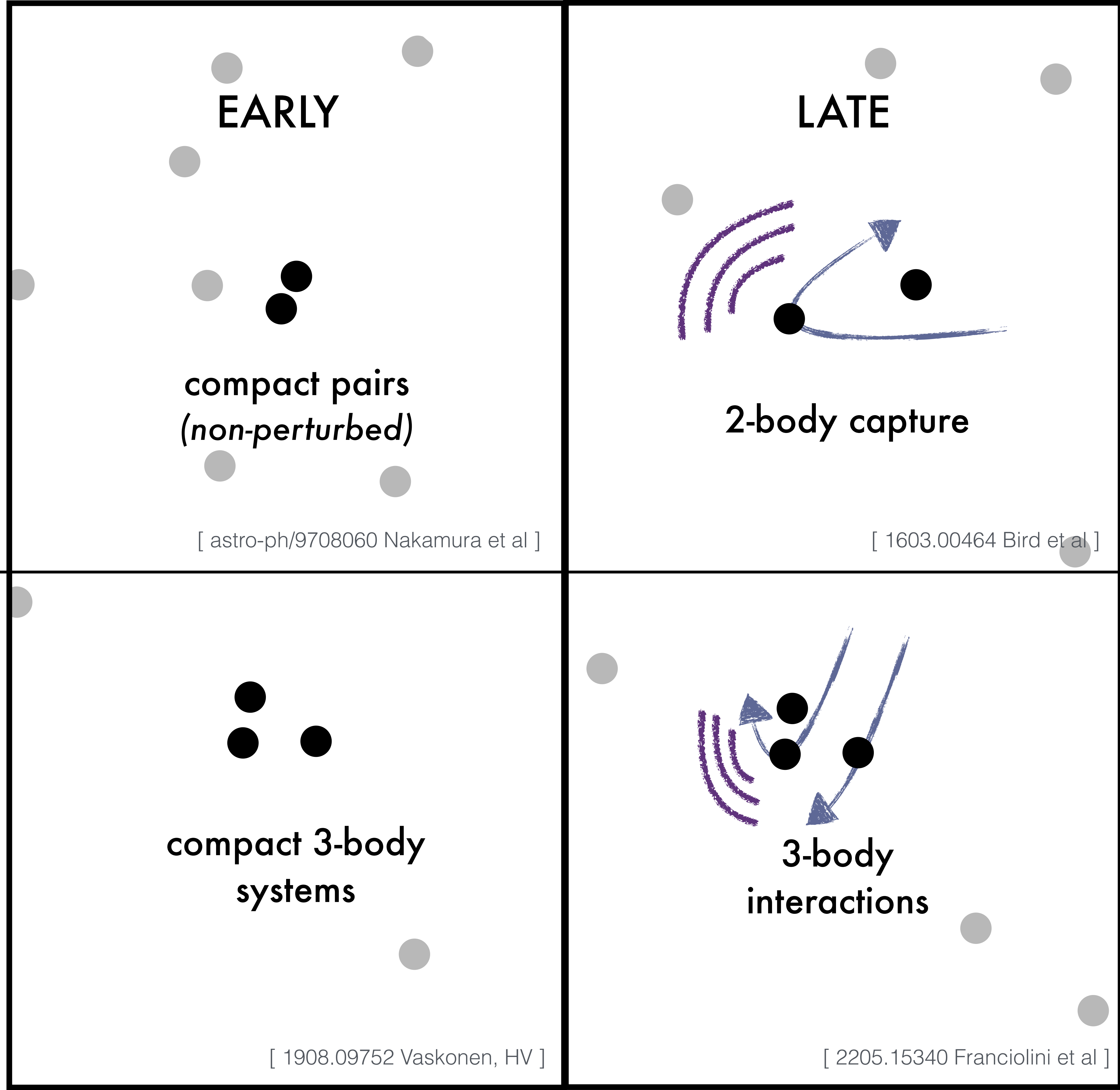
$f_{\rm PBH} \ll 1$

highly eccentric

dominates if

$f_{\rm PBH} \sim 1$

some evolution via BH-BBH collisions



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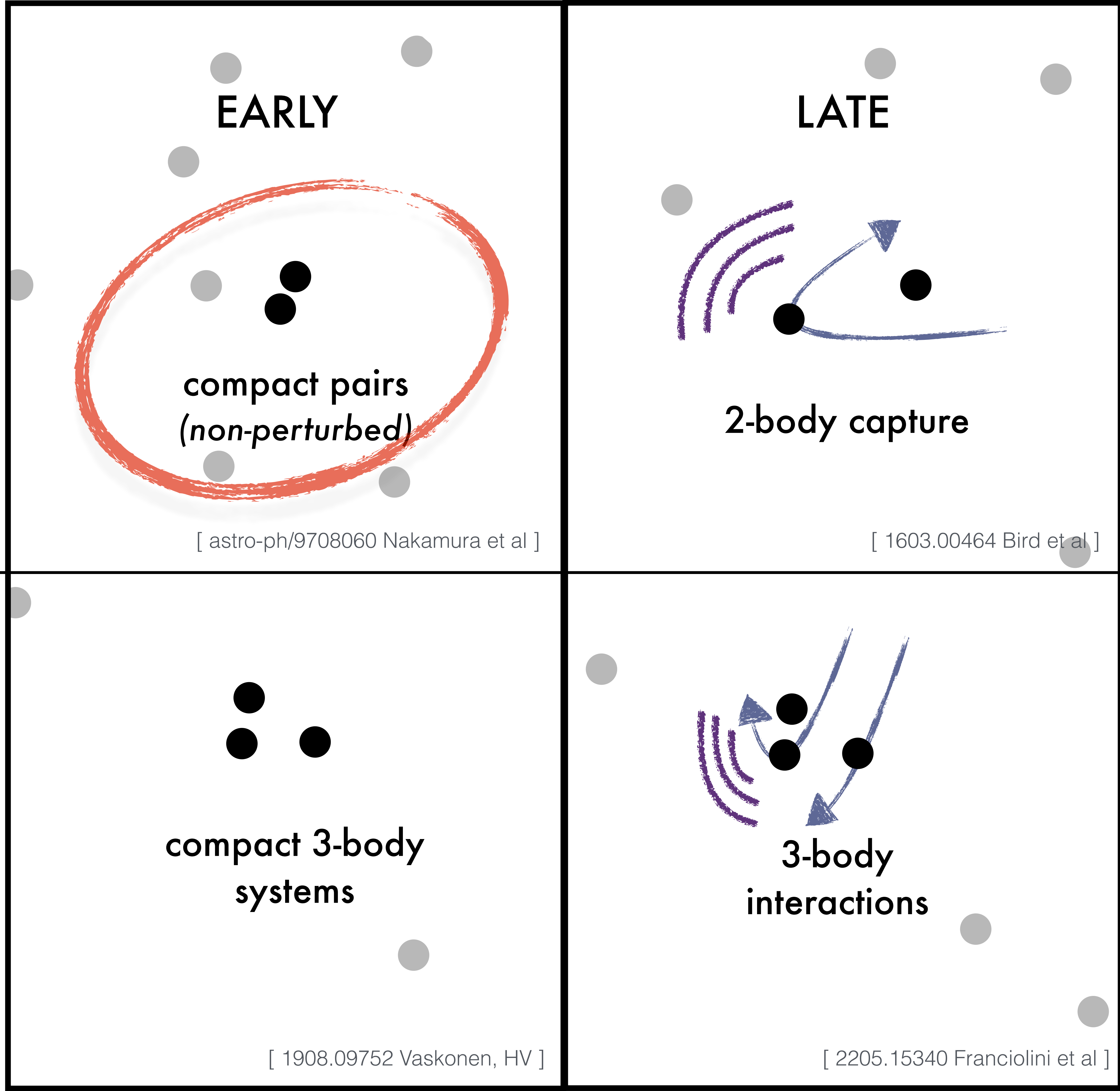

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MERGER RATE

$$\frac{\mathrm{d}R_{\mathrm{np}}}{\mathrm{d}m_1\mathrm{d}m_2} \approx \frac{1.6\times 10^6}{\mathrm{Gpc}^3\mathrm{yr}}\, f_{\mathrm{PBH}}^{\frac{53}{37}} \left[\frac{t}{t_0}\right]^{-\frac{34}{37}} \left[\frac{M}{M_\odot}\right]^{-\frac{32}{37}} \eta^{-\frac{34}{37}} S[\psi, f_{\mathrm{PBH}}, M] \frac{\psi(m_1)\psi(m_2)}{\langle m\rangle^2}$$

**DOES NOT CONTAIN PBH BINARY SUBPOPULATIONS: perturbed initial binaries, binaries formed in present DM haloes, ...*

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Observations give
$R_{\mathrm{observed}} \approx \mathcal{O}(10)\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Universal time dependence

Most binaries can be disrupted:
$S_{\mathrm{sup}} \approx \mathcal{O}(10^{-3})$ for $f_{\mathrm{PBH}} \approx 1$

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TYPICAL CHARACTERISTICS

These PBH binaries are…

- Hard => collisions tend to harden them further
- Extremely eccentric => collisions tend to reduce eccentricity, increase coalescence time by several ordres of magnitude
- large mass ratios suppressed

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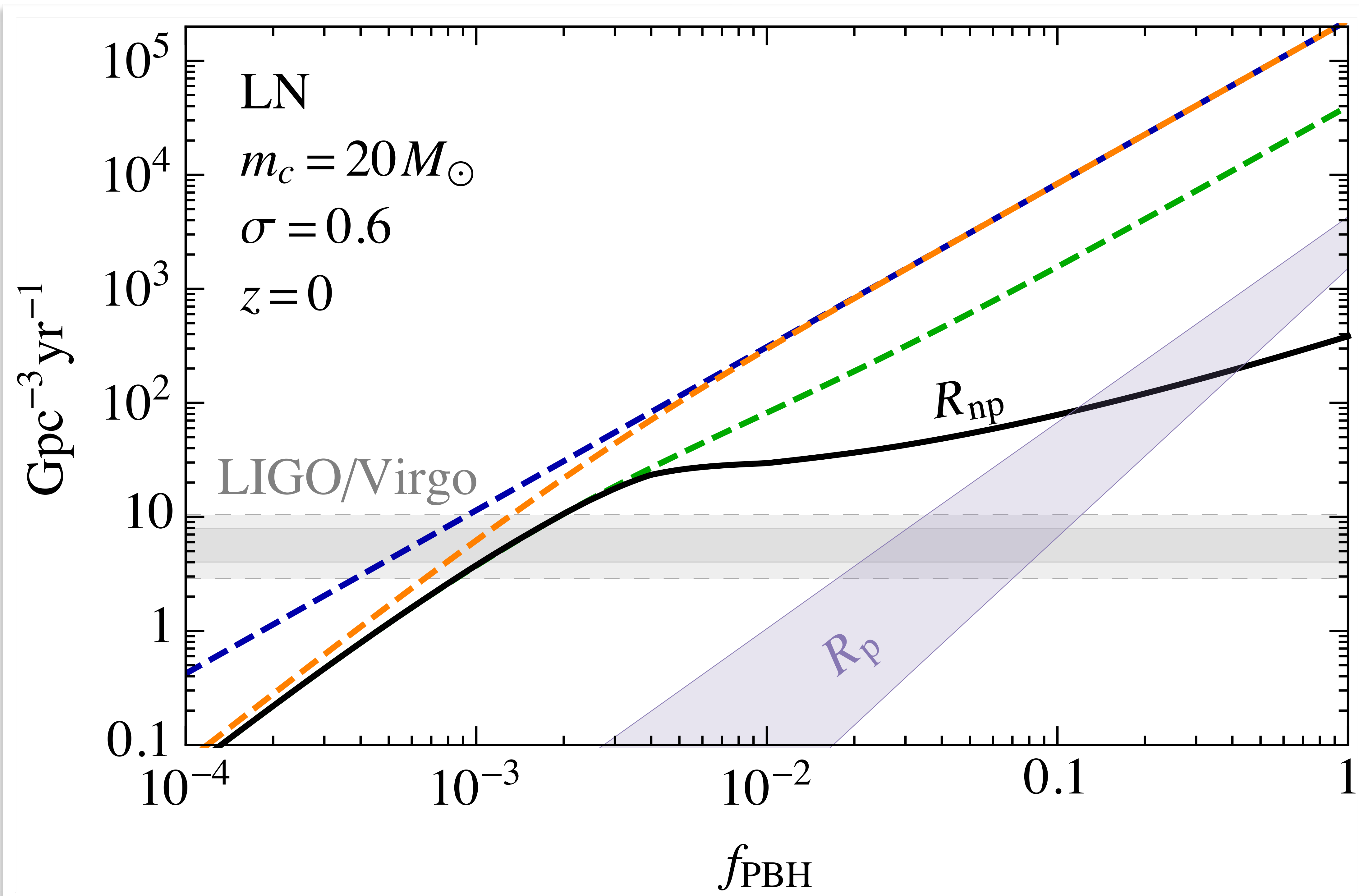
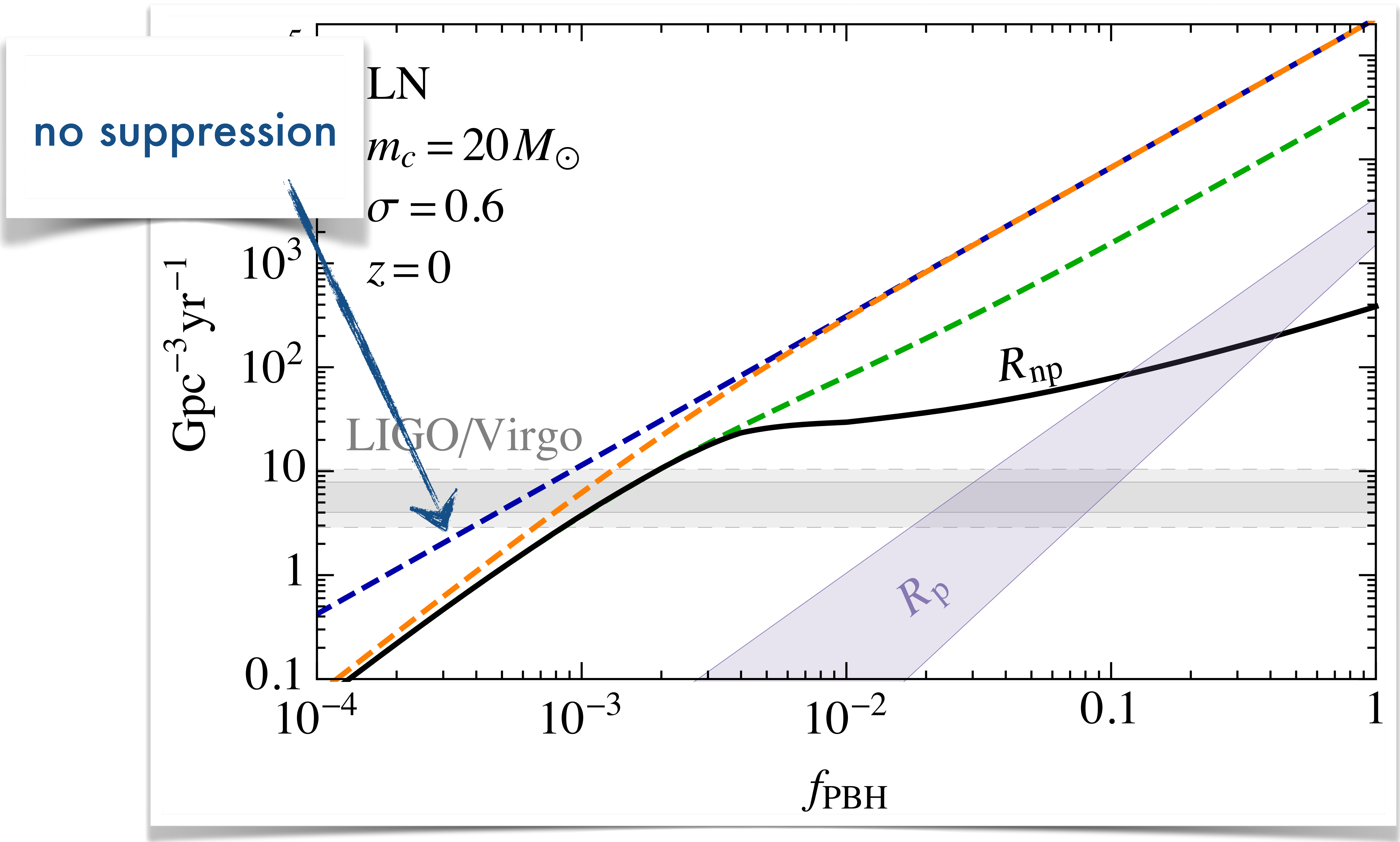
MERGER RATE



**assuming a log-normal mass function* $\psi(m) \propto \exp\left[-\ln^2(m/m_c)/(2\sigma^2)\right]$

[2012.02786 Vaskonen et al]

MERGER RATE



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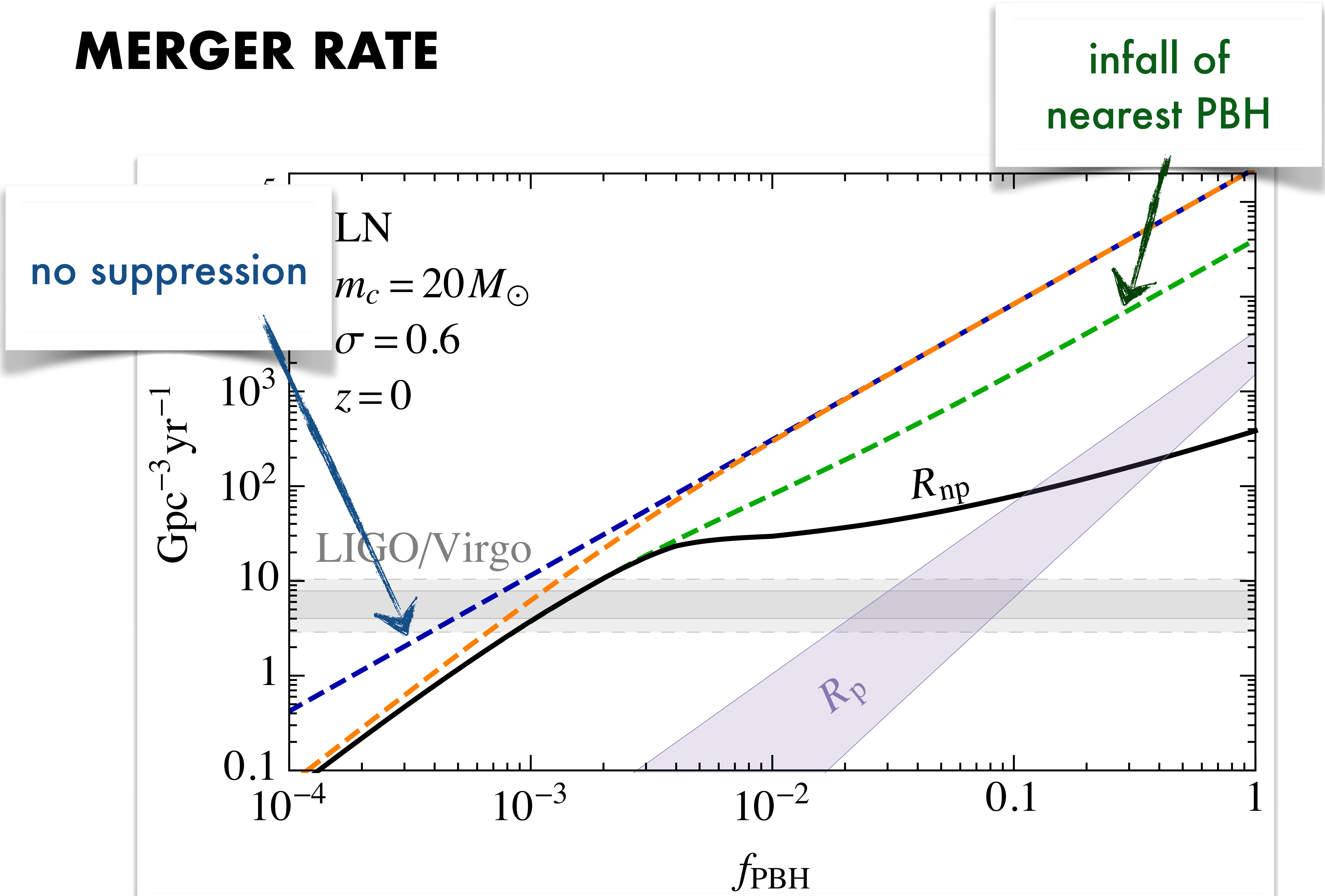

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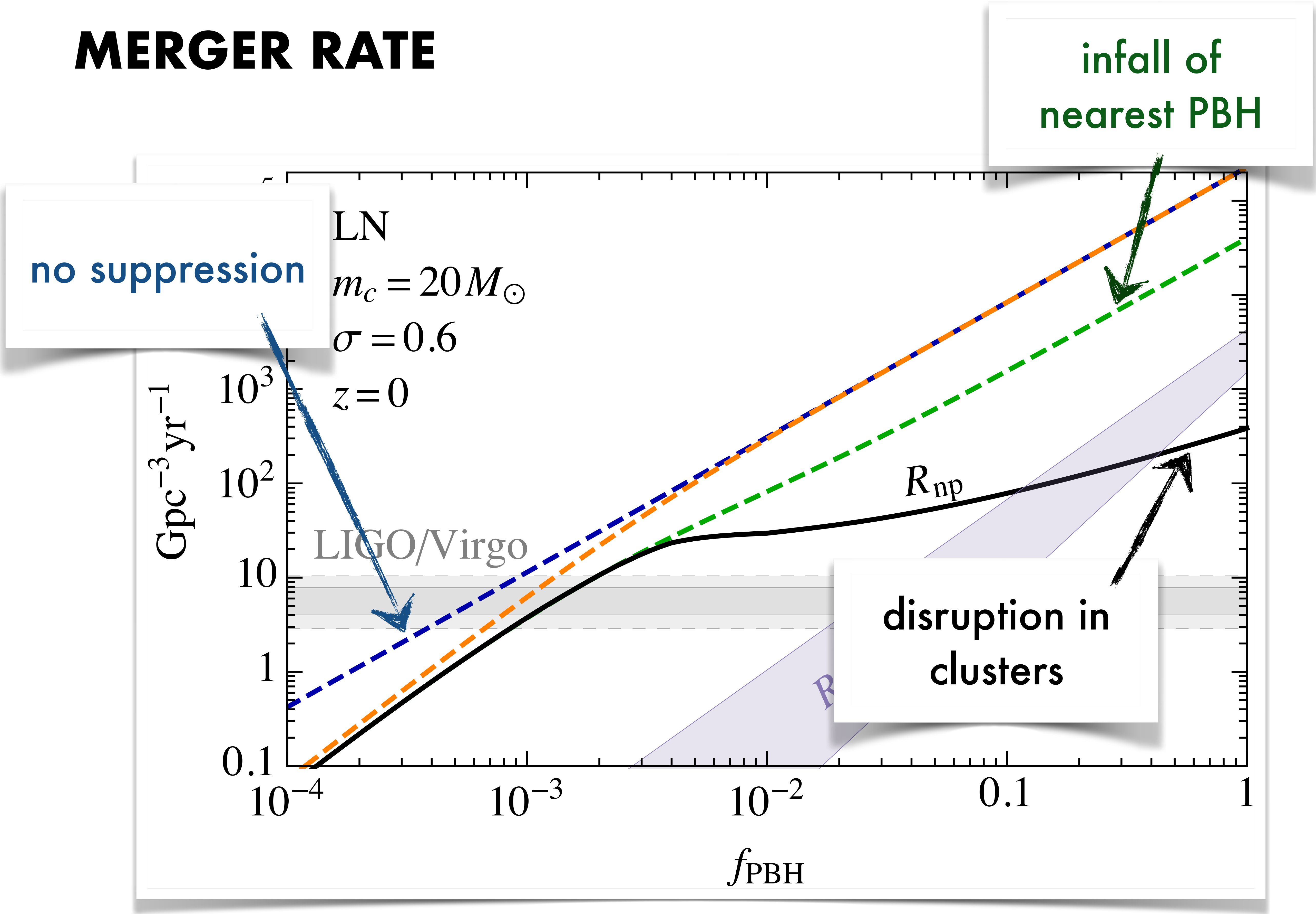

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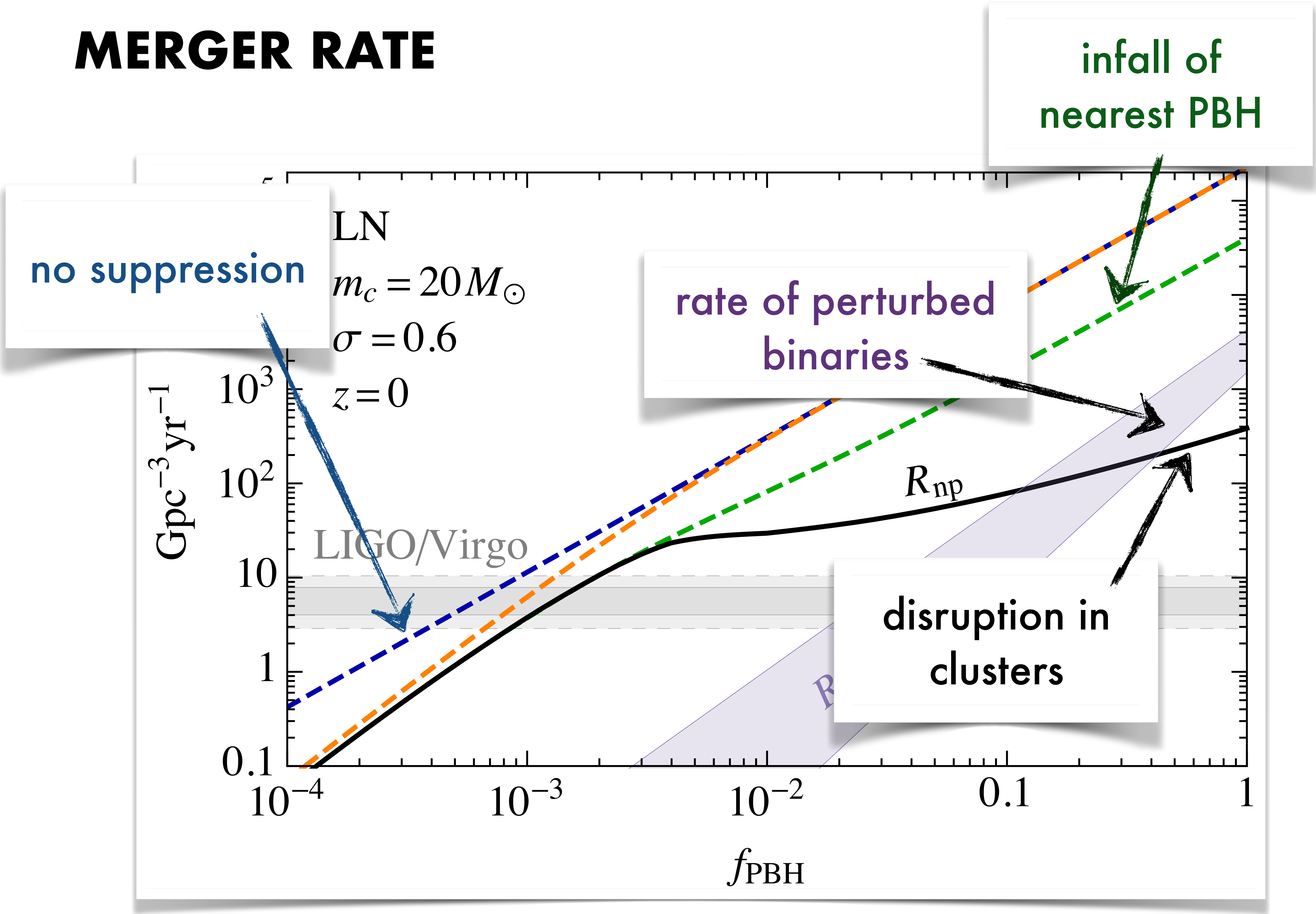

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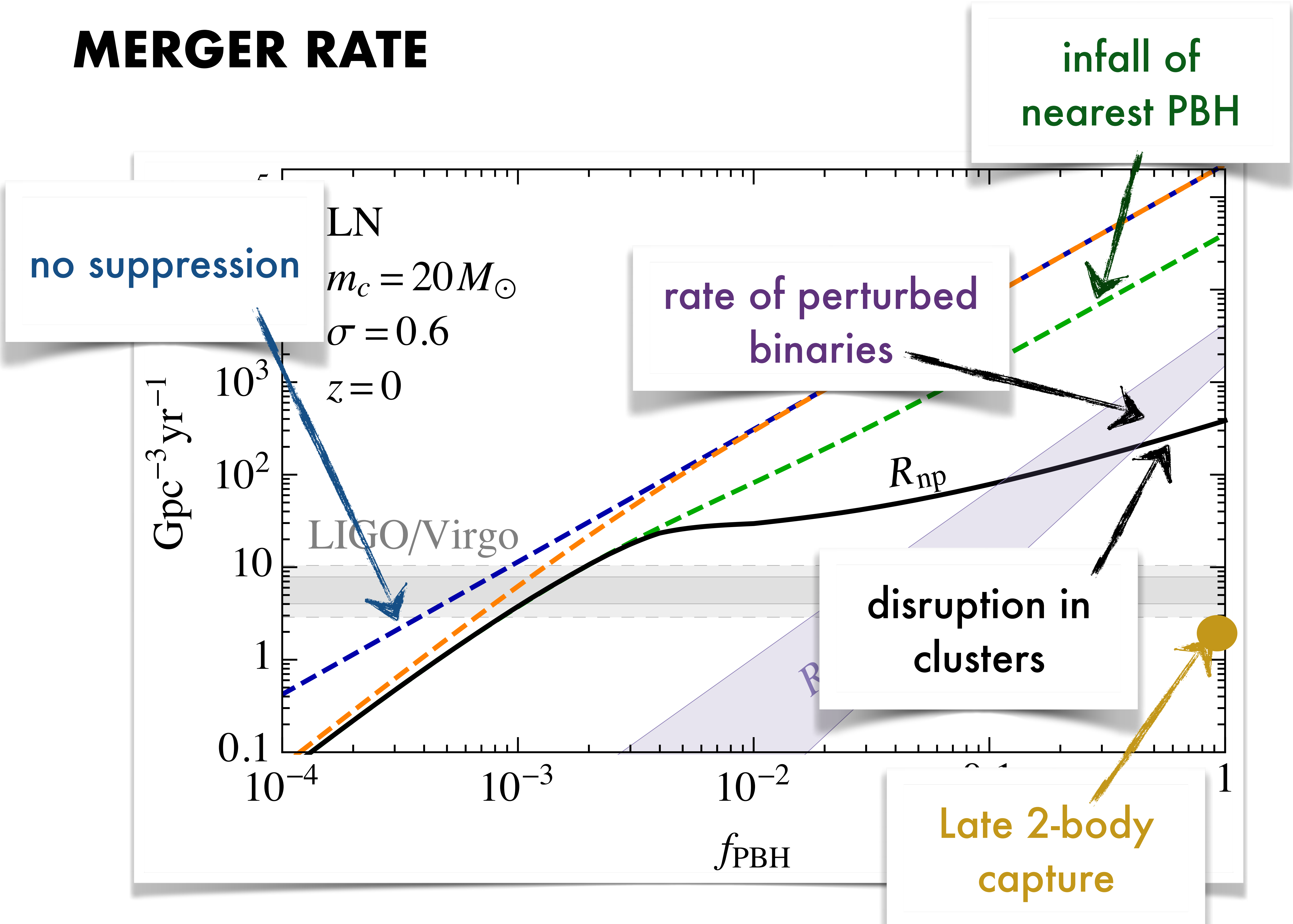

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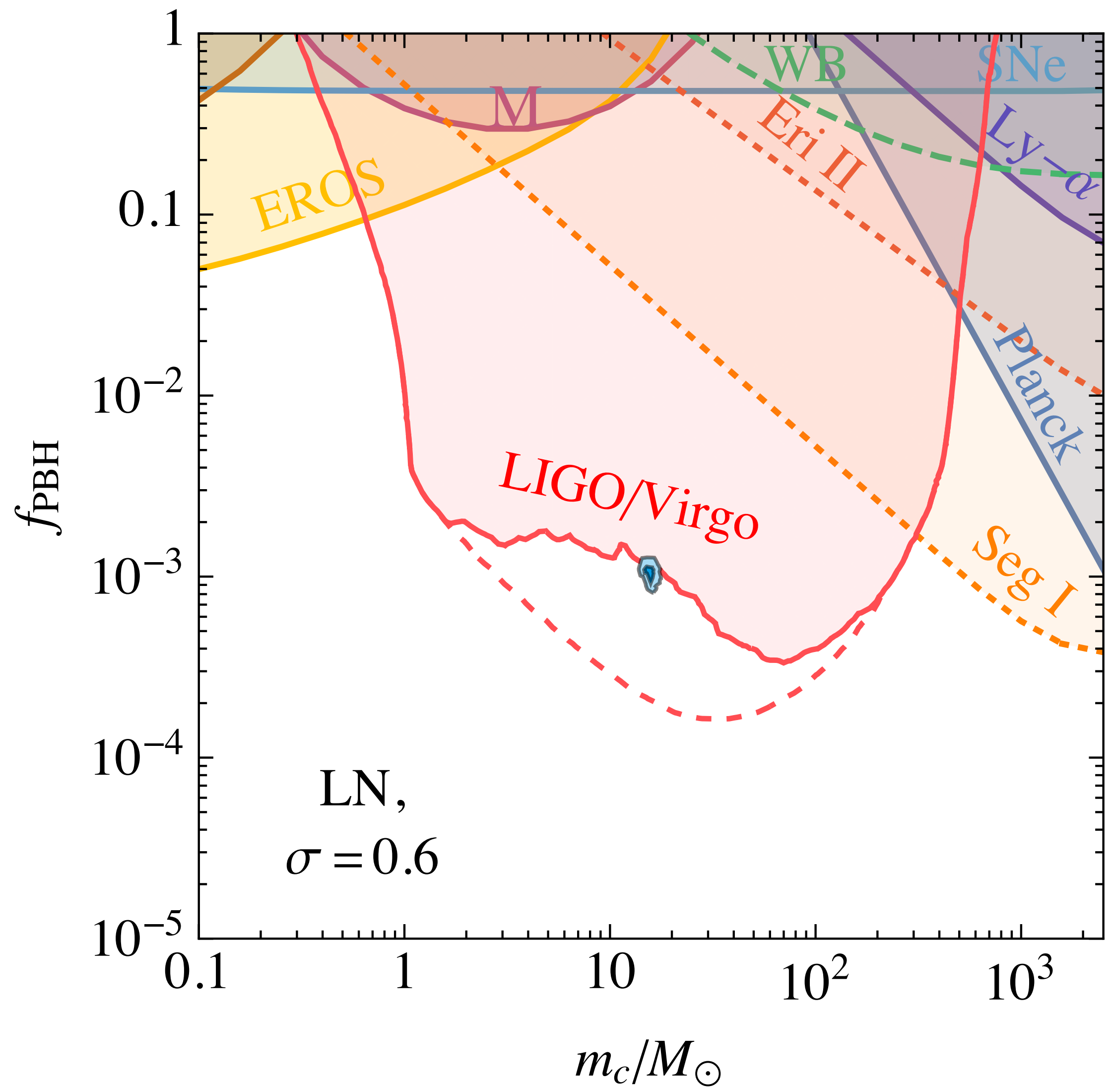
PBHs with LVK

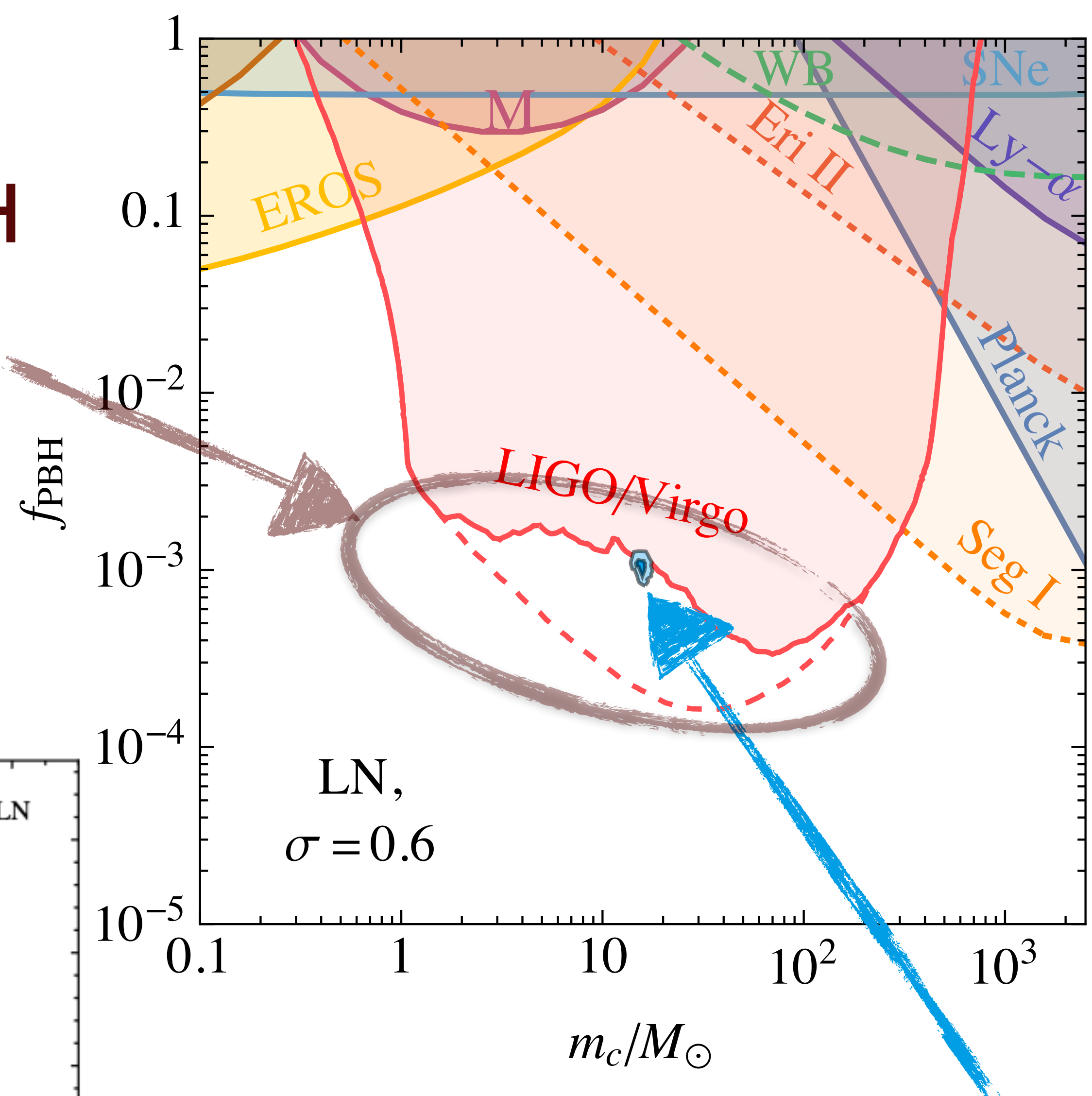


** non-perturbed binary formation channel only*

[2012.02786 Vaskonen et al]

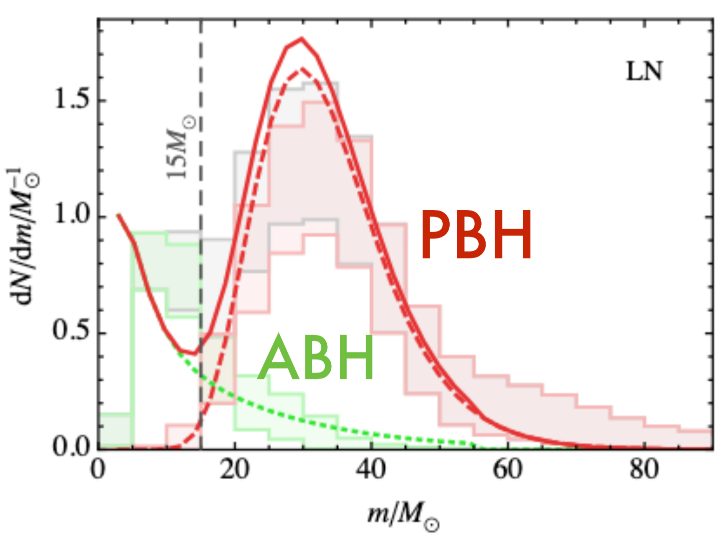
PBHs with LVK

scenarios with PBH subpopulations



best-fit PBH only scenario

for example:



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Open problems

OPEN PROBLEMS

- **WIDE MASS DISTRIBUTIONS** *SPANNING SEVERAL ORDERS OF MAGNITUDE*
  - *binary evolution with wide mass functions*

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  - *large uncertainties in accretion physics, incl. accretion into binaries*
  - *relevant for the evolution of spin and eccentricities*

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- **Accretion**
  - *large uncertainties in accretion physics, incl. accretion into binaries*
  - *relevant for the evolution of spin and eccentricities*
- **Impact of eccentricity in GW analyses**
  - *relevant for long-lived inspiralling binaries*

SUMMARY

LISA is expected to cover the asteroid mass window using the scalar induced SGWB *(assuming PBHs from inflation)*

LISA could observe PBH binaries in the solar mass range over 12 orders of magnitude ($M_{\rm PBH} = 10^{-3} - 10^9 M_{\rm odot}$) and PBH abundances as low as $f_{\rm PBH} = 10^{-5}$. Expeted to probe subsolar mass galactic PBH binaries.

To cover the full range of PBH models, improvements needed in PBH binary population *(and SWGB)* modelling *(wide mass functions, PBH structure formation and binary evolution, eccentricities, accretion and spin, 3-body channels, GWs signals alternative PBH formation scenarios...)*