Primordial black hole dark matter

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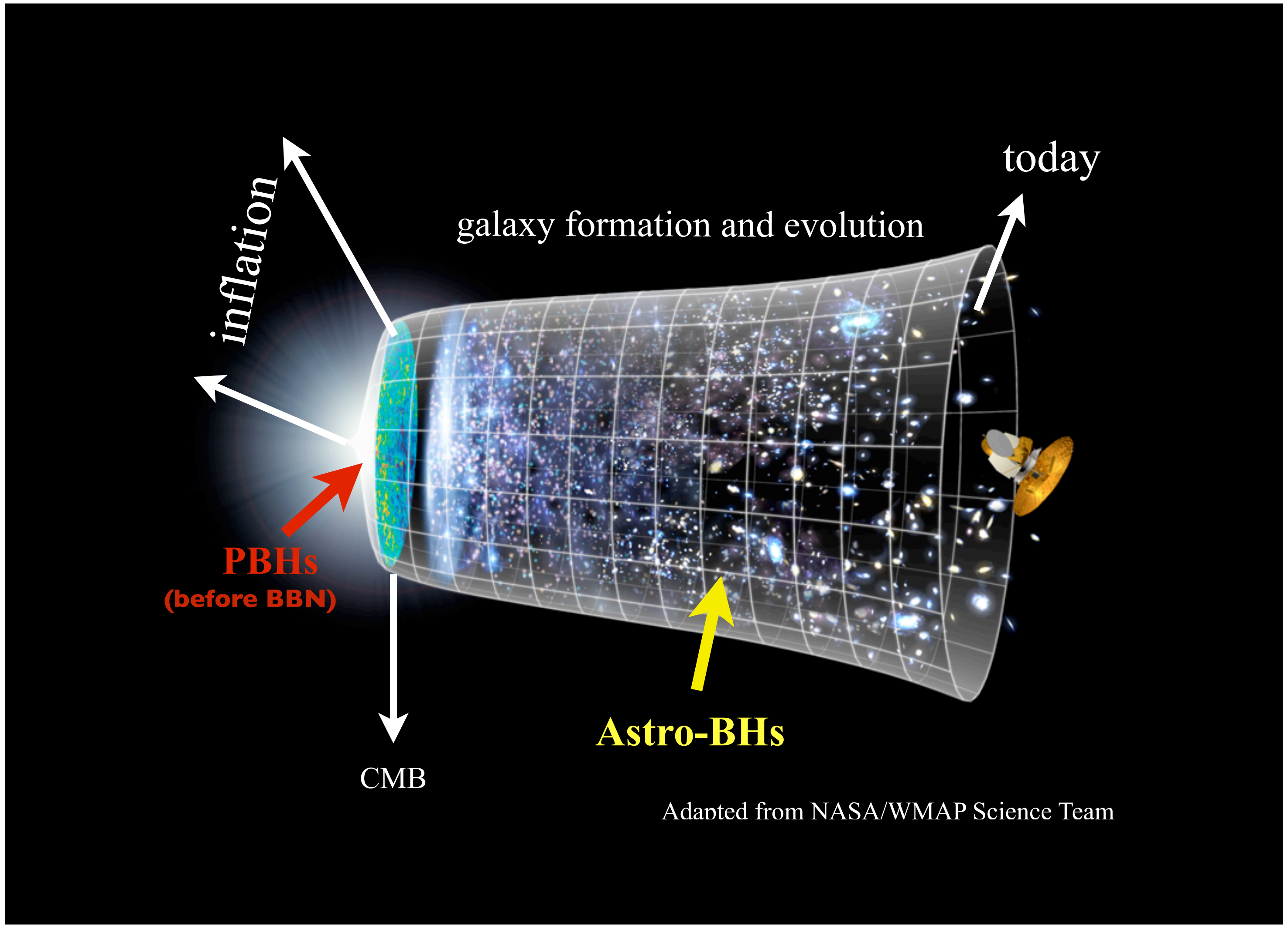
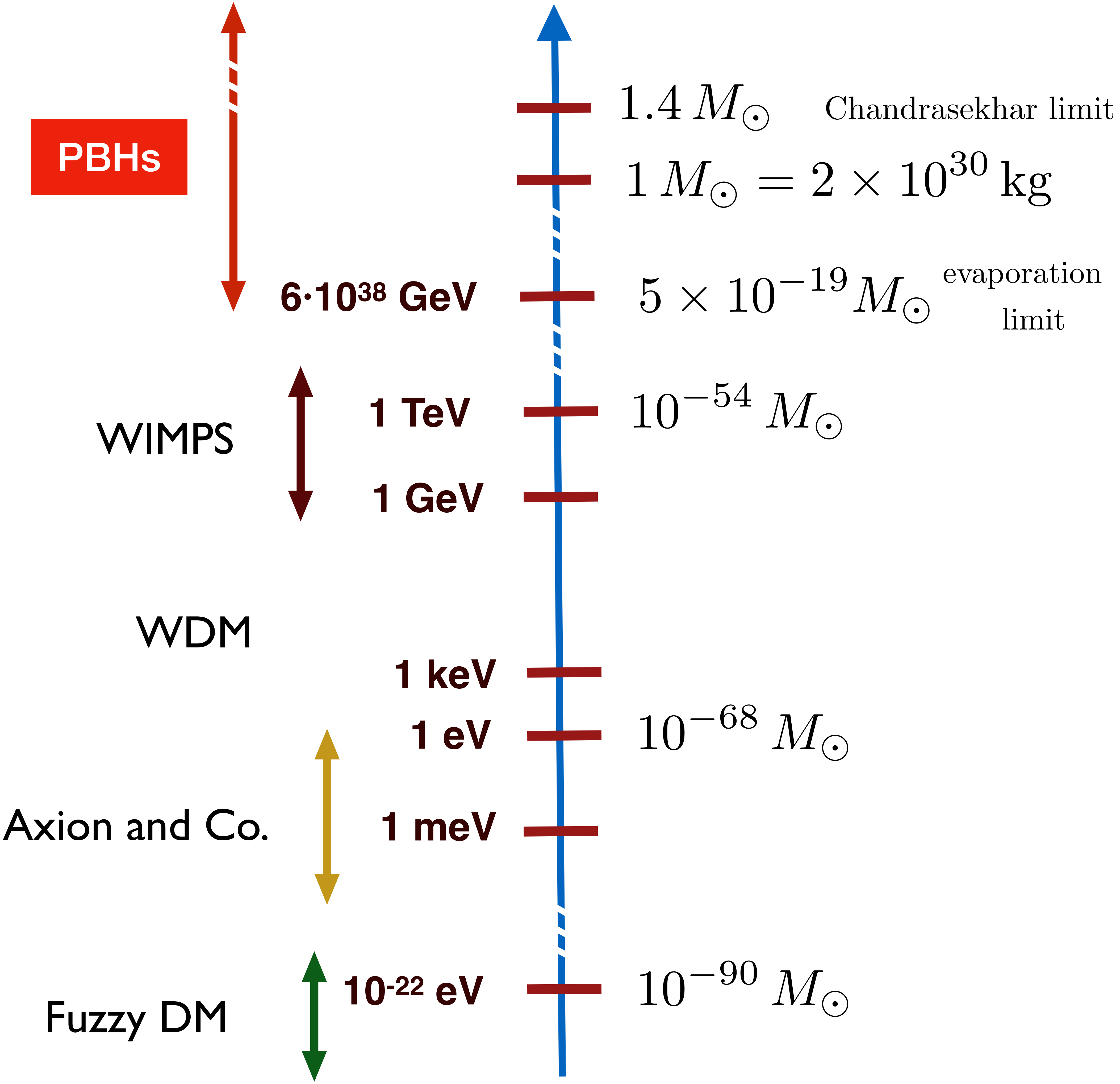
Primordial black holes

Zeldovich and Novikov 1967, Hawking1971, Hawking & Carr 1974, etc…

1. Bounds on their abundance. DM?
2. Formation. How and when?



Adapted from NASA/WMAP Science Team



PBHs

$1.4\,M_\odot$ Chandrasekhar limit

$1\,M_\odot = 2 \times 10^{30}$ kg

$6{\cdot}10^{38}$ GeV

$5 \times 10^{-19} M_\odot$ evaporation limit

WIMPS

1 TeV

$10^{-54}\,M_\odot$

1 GeV

WDM

1 keV

1 eV

$10^{-68}\,M_\odot$

Axion and Co.

1 meV

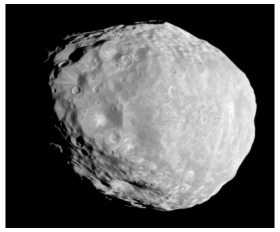
Fuzzy DM

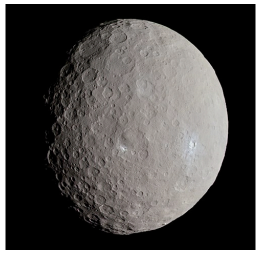
10^{-22} eV

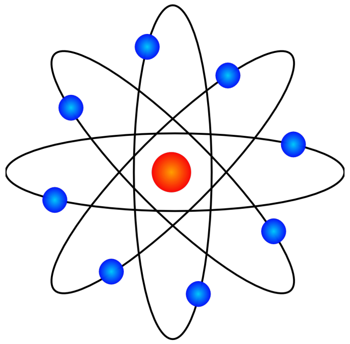
$10^{-90}\,M_\odot$

PBHs

M	$r_s = \frac{2GM}{c^2}$
$100\,M_\odot$	$300\,\mathrm{km}$
$M_\odot$	$3\,\mathrm{km}$
$10^{-12}\,M_\odot$	$3\,\mathrm{nm}$
$10^{-16}\,M_\odot$	$3\times10^{-4}\,\mathrm{nm}$







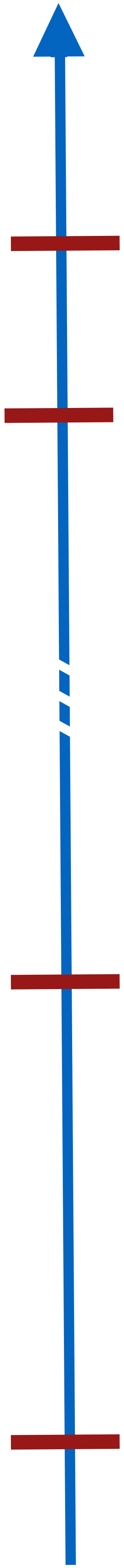
$\sim 0.1\,\mathrm{nm}$

PBHs

binary BH mergers

100 Hz

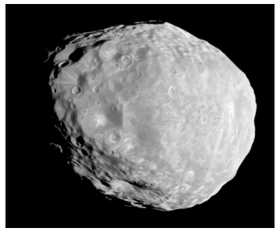
Courtesy
Caltech/MIT/LIGO Laboratory



M

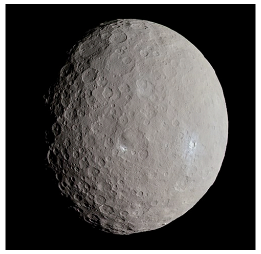
$$r_s = \frac{2GM}{c^2}$$

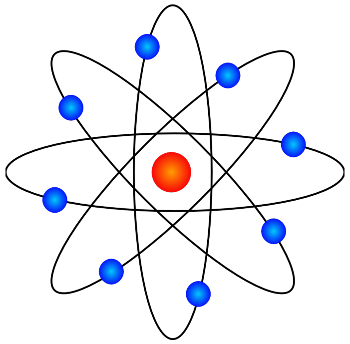
$100\,M_\odot$ — 300 km



$M_\odot$ — 3 km

$10^{-12}\,M_\odot$ — 3 nm





$\sim 0.1\,\mathrm{nm}$

$10^{-16}\,M_\odot$ — $3 \times 10^{-4}\,\mathrm{nm}$

PBHs

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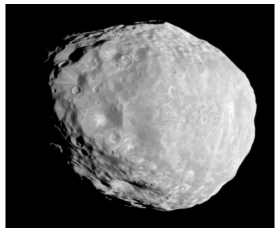
Caltech/MIT/LIGO Laboratory

M

$$r_s = \frac{2GM}{c^2}$$

$100\, M_\odot$ 300 km

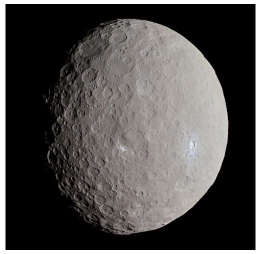


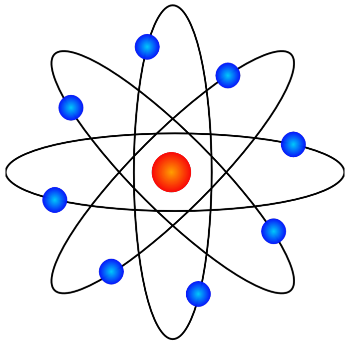
$M_\odot$ 3 km

$10^{-12}\, M_\odot$ 3 nm

100% DM

asteroid
mass
window





$\sim 0.1\,\mathrm{nm}$

$10^{-16}\, M_\odot$ $3 \times 10^{-4}\,\mathrm{nm}$

PBHs

binary BH mergers

$100\,\mathrm{Hz}$

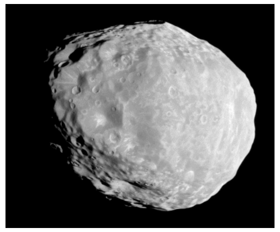
Courtesy
Caltech/MIT/LIGO Laboratory

M

$$r_s = \frac{2GM}{c^2}$$

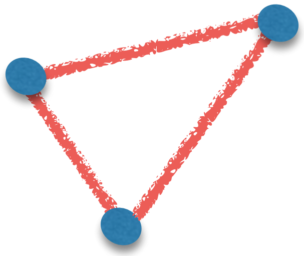
$100\,M_\odot$ — $300\,\mathrm{km}$

$M_\odot$ — $3\,\mathrm{km}$



$0.03\,\mathrm{Hz} - 3\,\mathrm{Hz}$

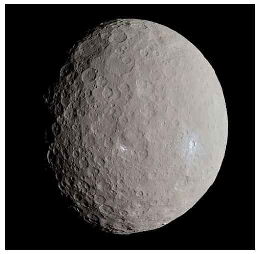
e.g. LISA



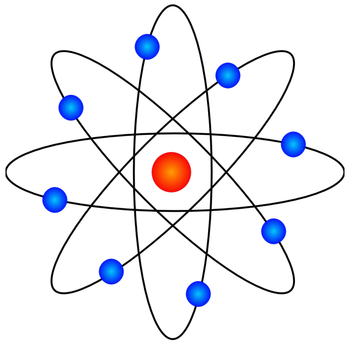
stochastic
background
of GWs

100% DM

asteroid
mass
window

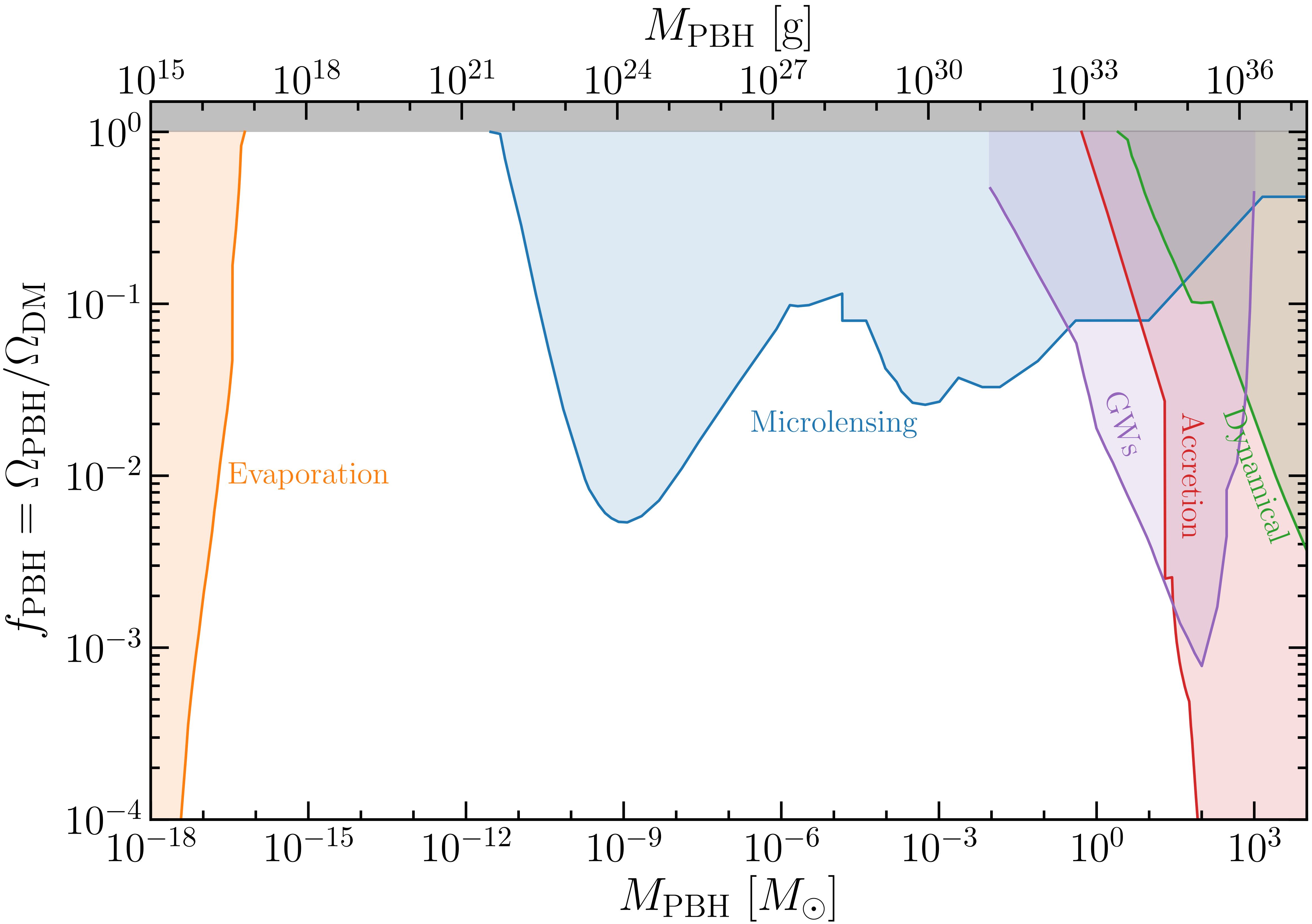


$10^{-12}\,M_\odot$ — $3\,\mathrm{nm}$



$\sim 0.1\,\mathrm{nm}$

$10^{-16}\,M_\odot$ — $3\times10^{-4}\,\mathrm{nm}$

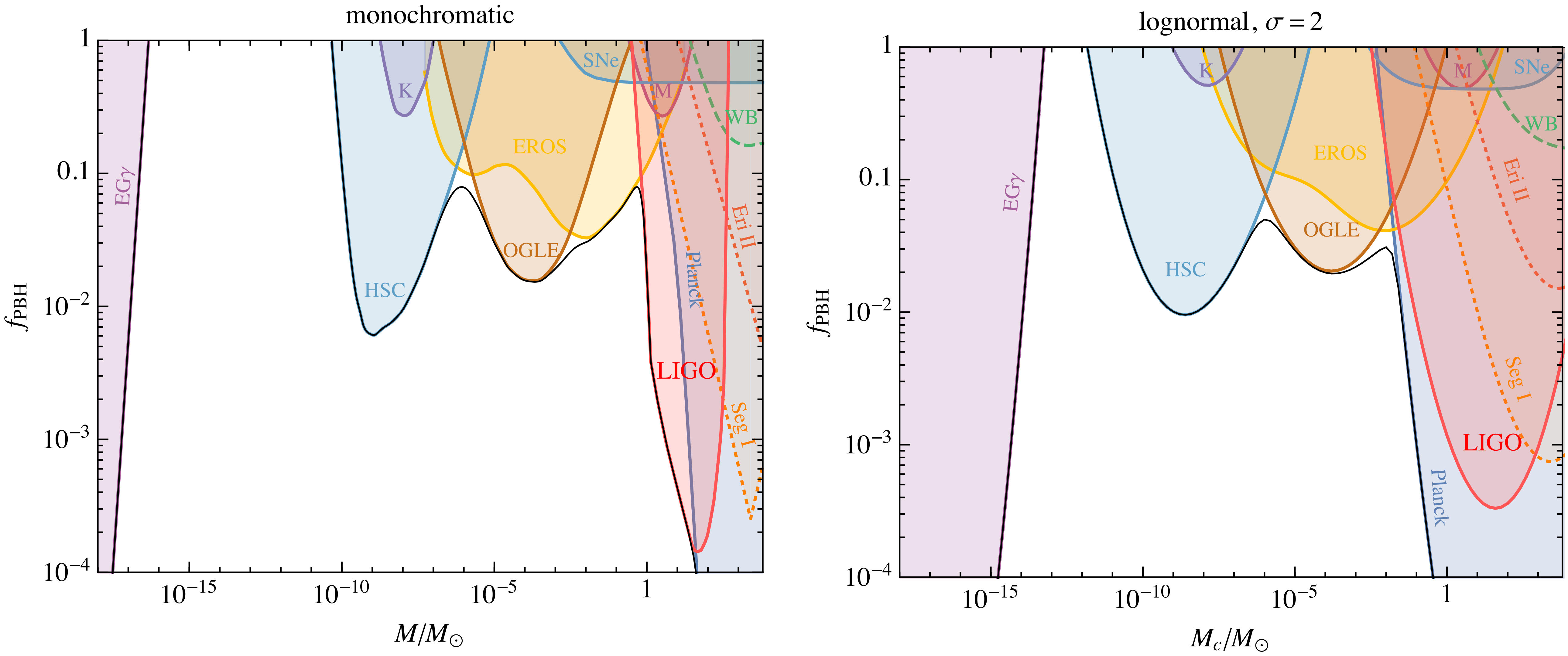


https://github.com/bradkav/PBHbounds

Green, Kavanagh 2007.10722 (v3 December 2020)

$$f(M) = \delta(M - M_{\mathrm{PBH}})$$

$$M f(M) = \frac{f_{\mathrm{PBH}}}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{\log^2\left(\frac{M}{M_c}\right)}{2\sigma^2} \right]$$

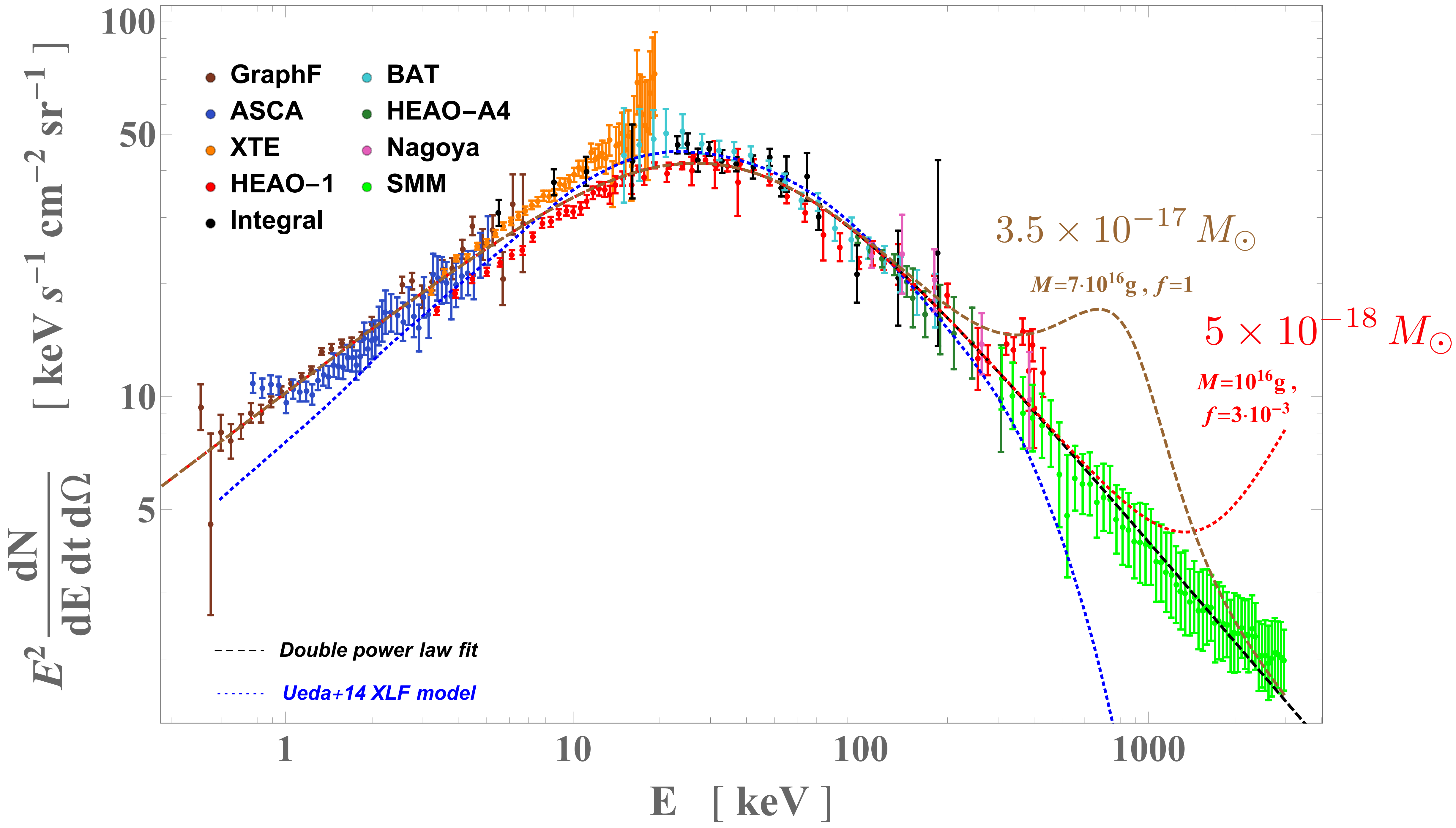


Carr, Kohri, Sendouda, Yokoyama 2002.12778 (v2 May 2021)
(by Raidal, Vaskonen, Veermäe. See also 1705.05567)

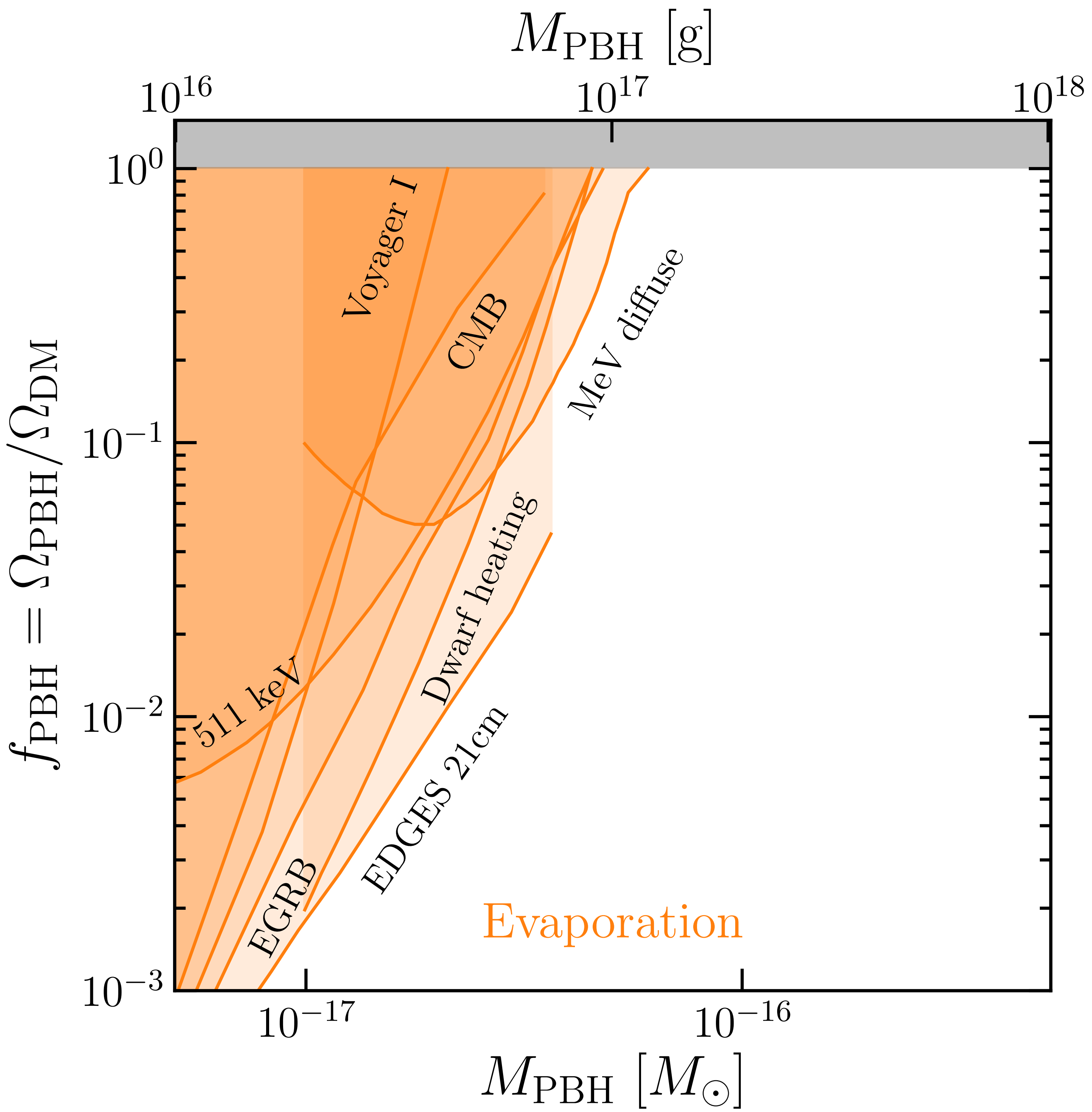
Evaporation

$$T = \frac{\hbar c^2}{8\pi G\, k_B M} = 6\times 10^{-8}\frac{M_\odot}{M} K$$

Bound for $M \lesssim 10^{17}\, g \simeq 5\times 10^{-17} M_\odot$

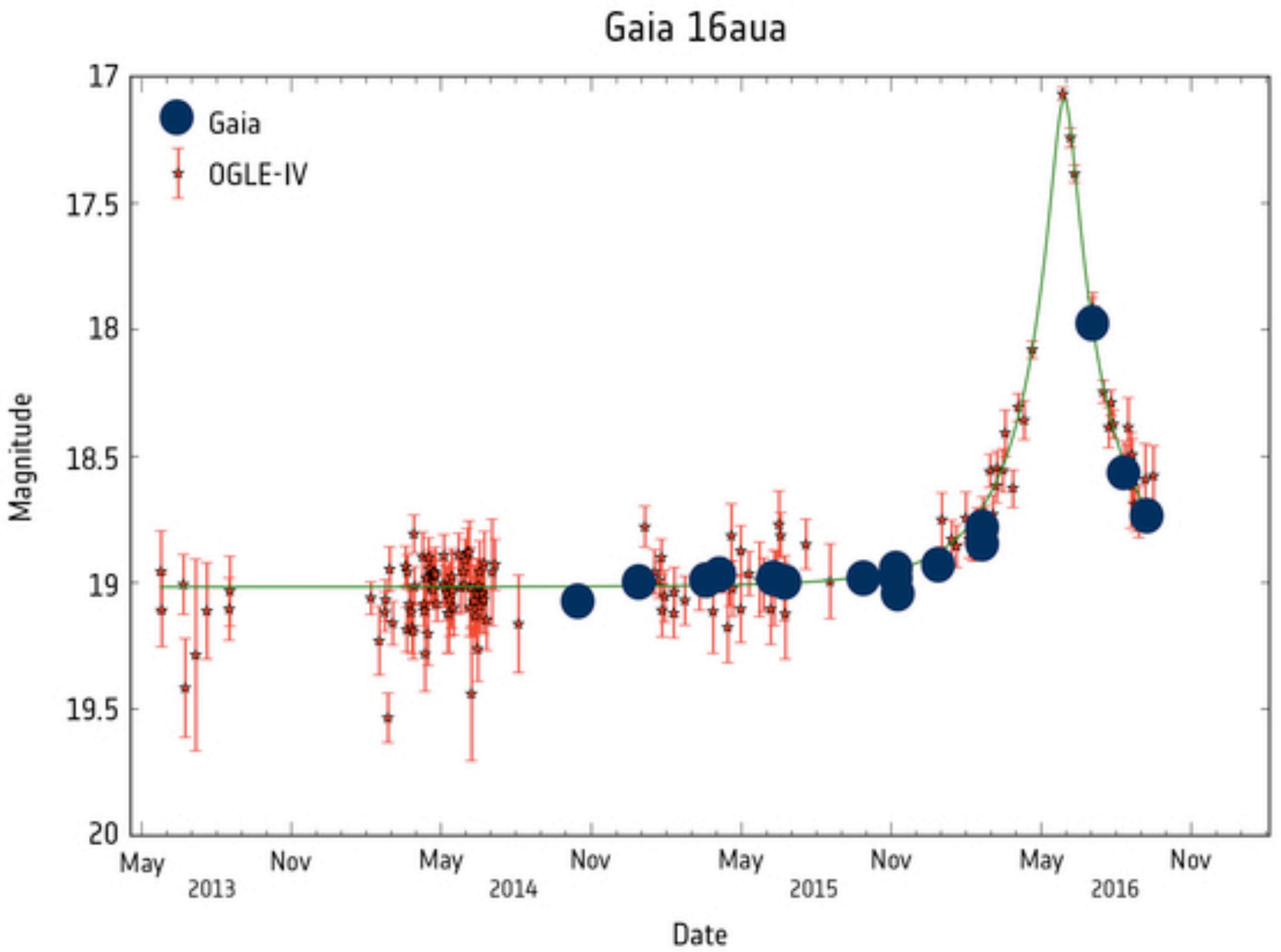


Ballesteros, Coronado-Blázquez, Gaggero. 1906.10113



Green, Kavanagh 2007.10722 (December 2020)

Microlensing



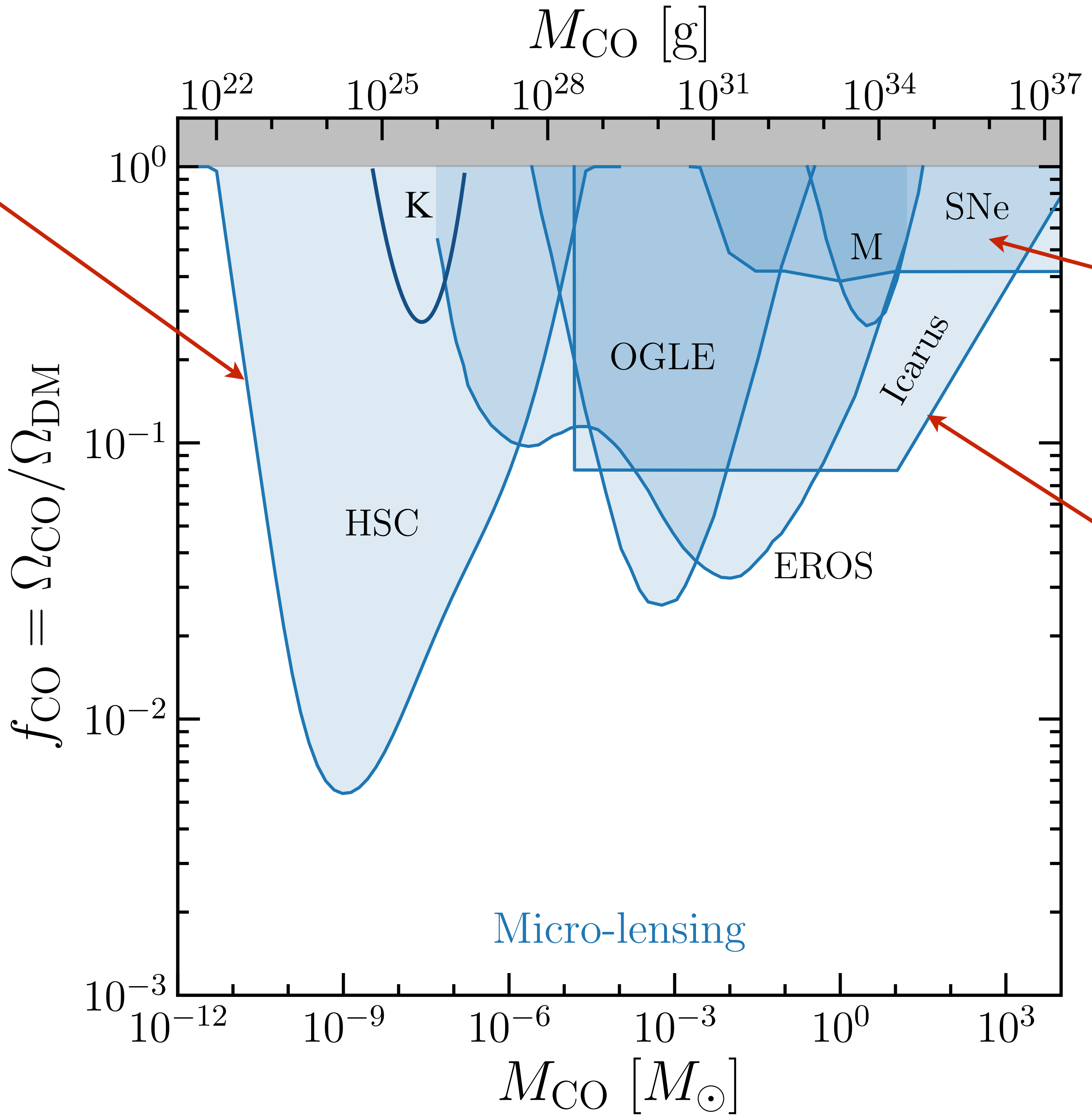
Copyright: ESA/Gaia/DPAC, L. Wyrzykowski, OGLE team (Warsaw), Z. Kostrzewa-Rutkowska (SRON/RU)

Eros, OGLE: Galactic Bulge and Magellanic Clouds.

Subaru HSC: M31 (finite source and wave optics effects)

For $M \sim 10^{-10} M_\odot$, $r_s \sim \lambda$

Smyth et al.
1910.01285

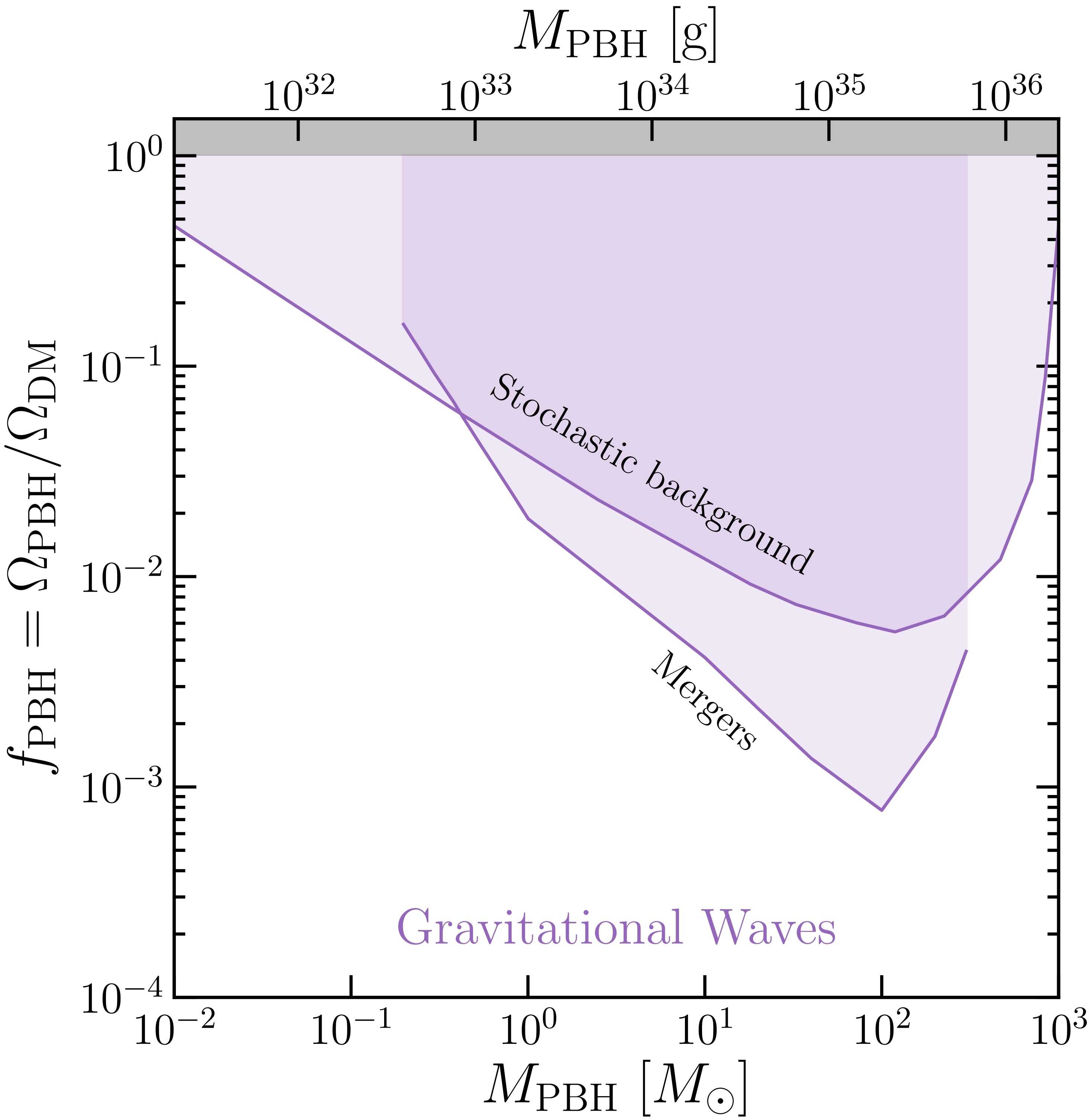


Zumalacarregui and
Seljak 1712.02240

Oguri et al.
1710.00148

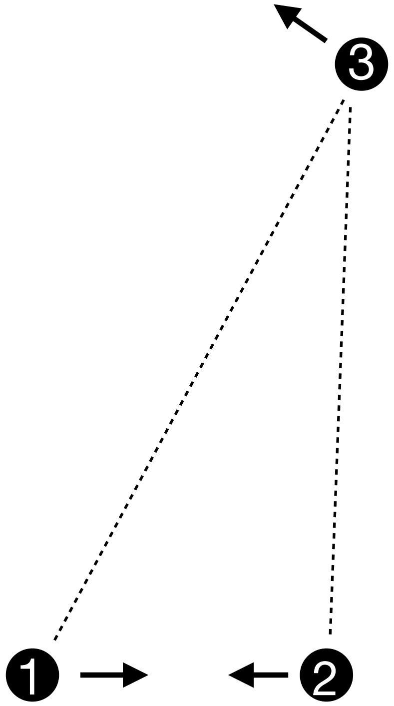
Green, Kavanagh 2007.10722 (December 2020), edited.

GWs

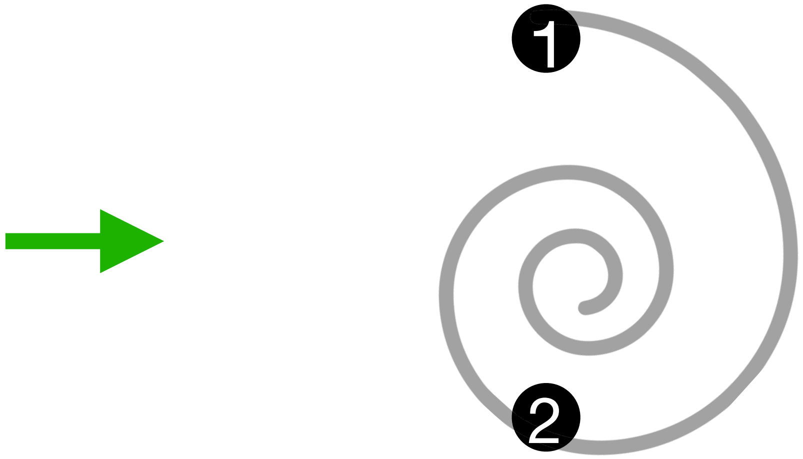


Green, Kavanagh 2007.10722 (December 2020)

- February 2016. LIGO announces GW150914. BHs of ~**30 Solar masses**
- Did **LIGO** detect (**THE**) dark matter? (Bird et al 2016. Clesse and García-Bellido 2016)
- Most likely **NO**
- Two mechanisms to form PBHs binaries:
    - Late Universe (in halos)
    - ★ Early Universe (before matter radiation equality). Nakamura et al 1997
- **MAX 0.1% — 1%** of the DM in the range **1-100 Solar Masses**

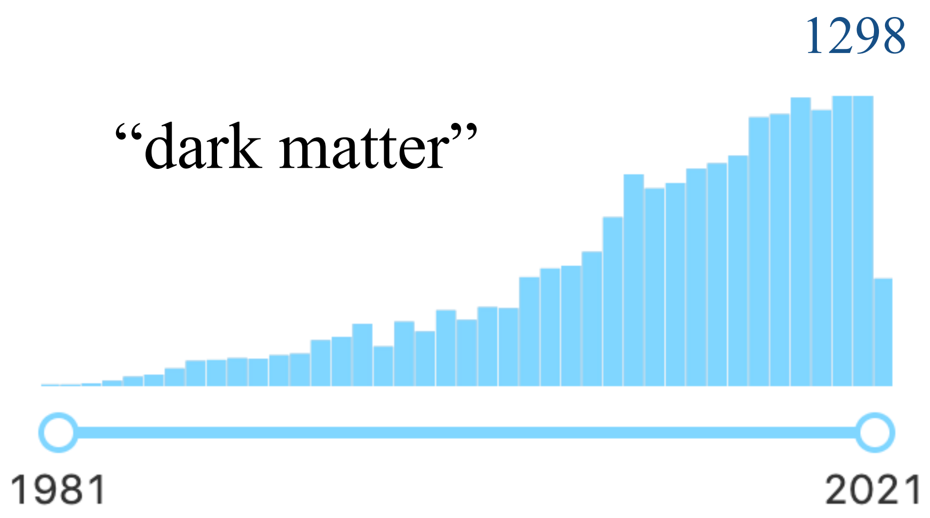


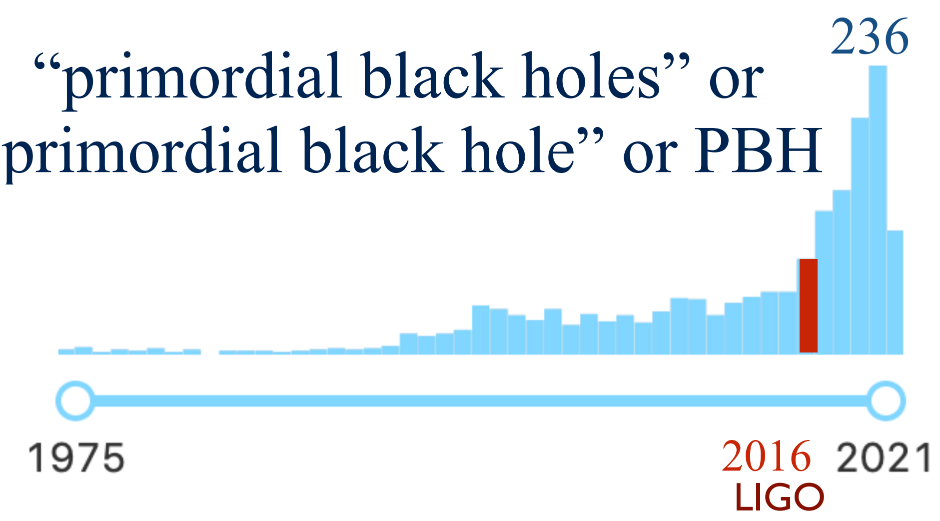
Form during radiation domination

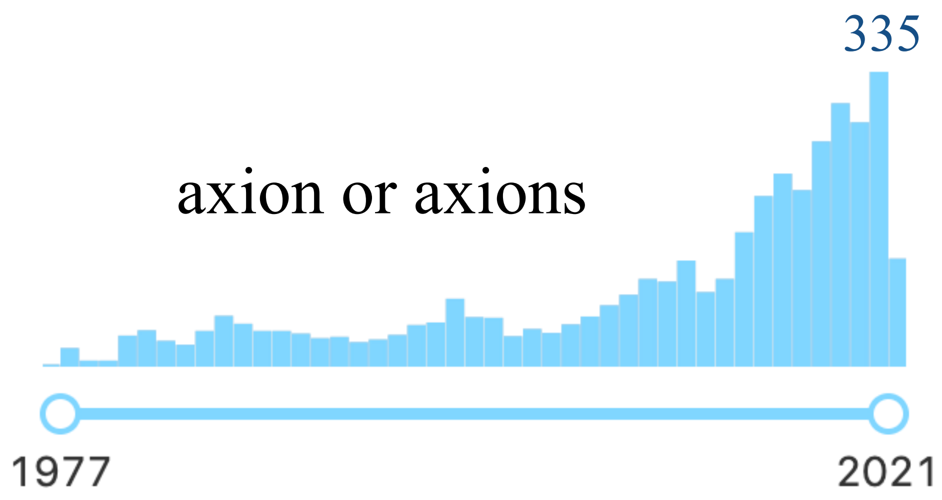


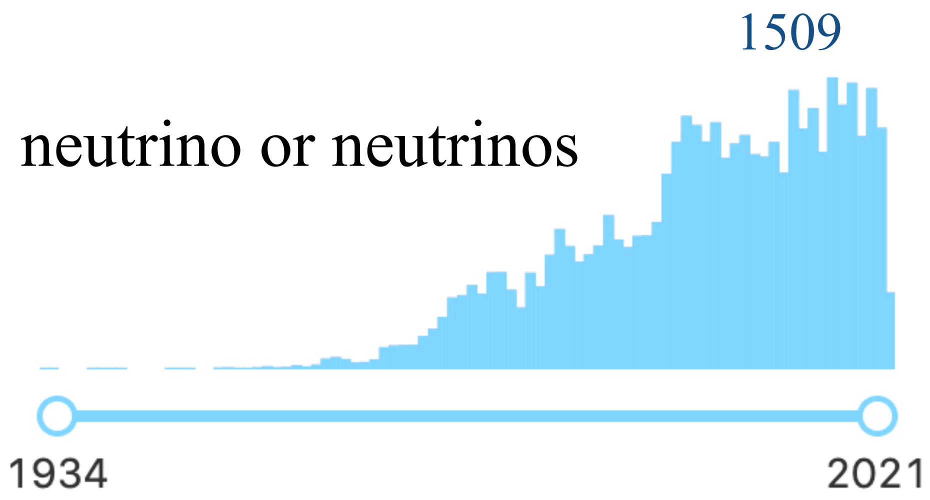
Merge today. Observable by LIGO-Virgo if $M \sim 10\, M_\odot$

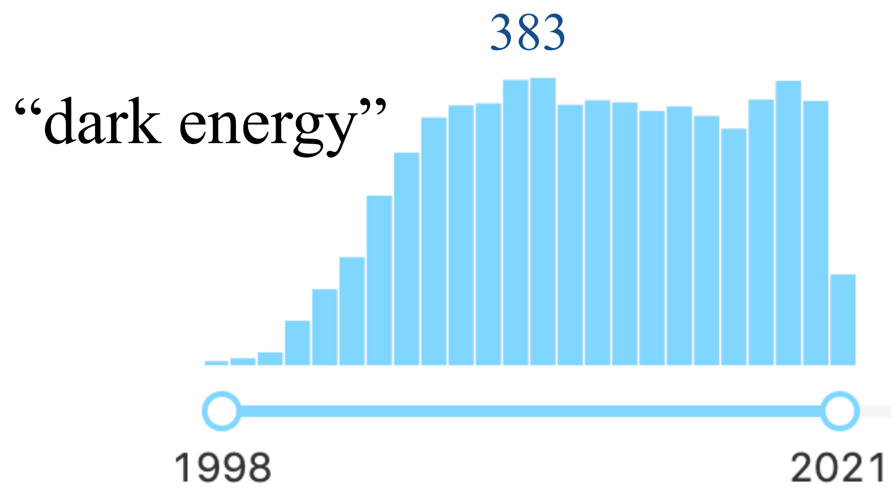
The popularity of inVisibles according to iNSPIRE HEP

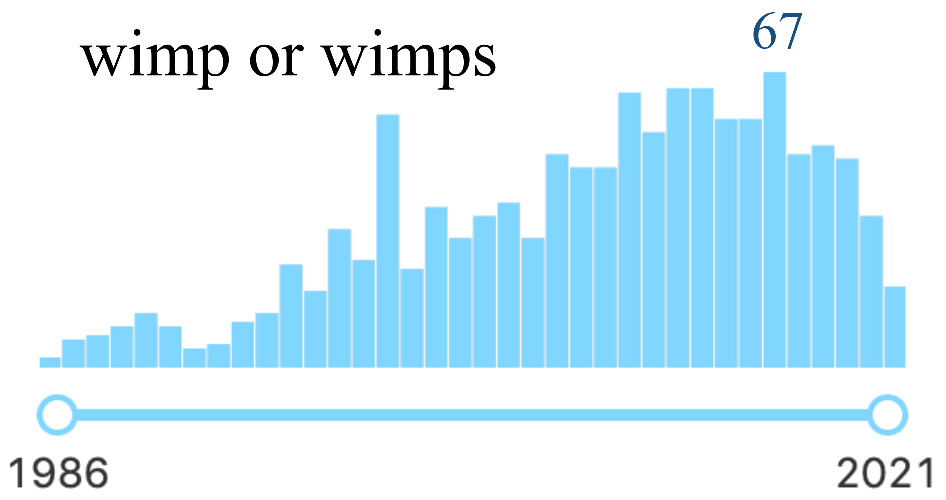

“dark matter”


“primordial black holes” or “primordial black hole” or PBH

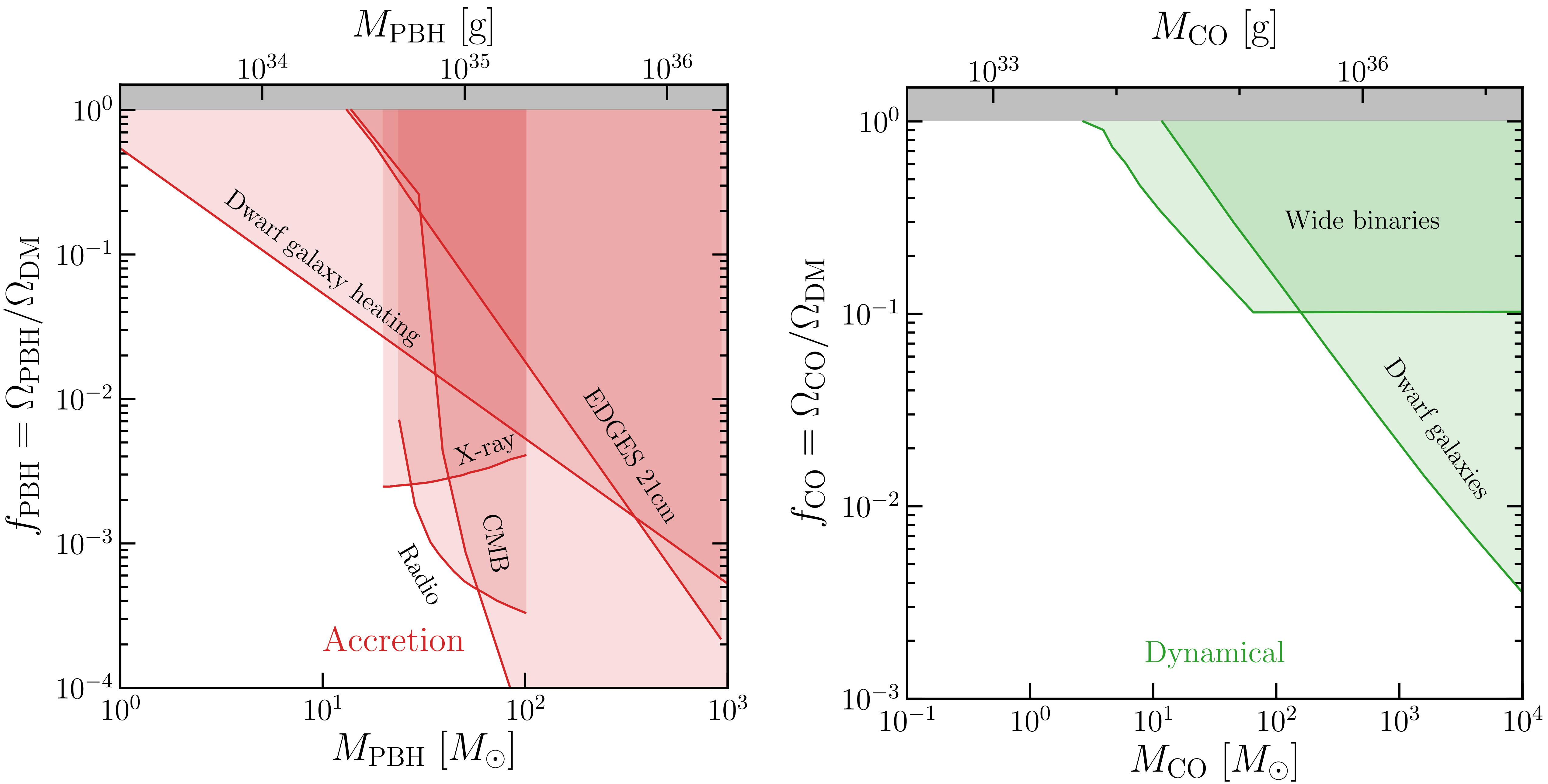

axion or axions


neutrino or neutrinos


“dark energy”

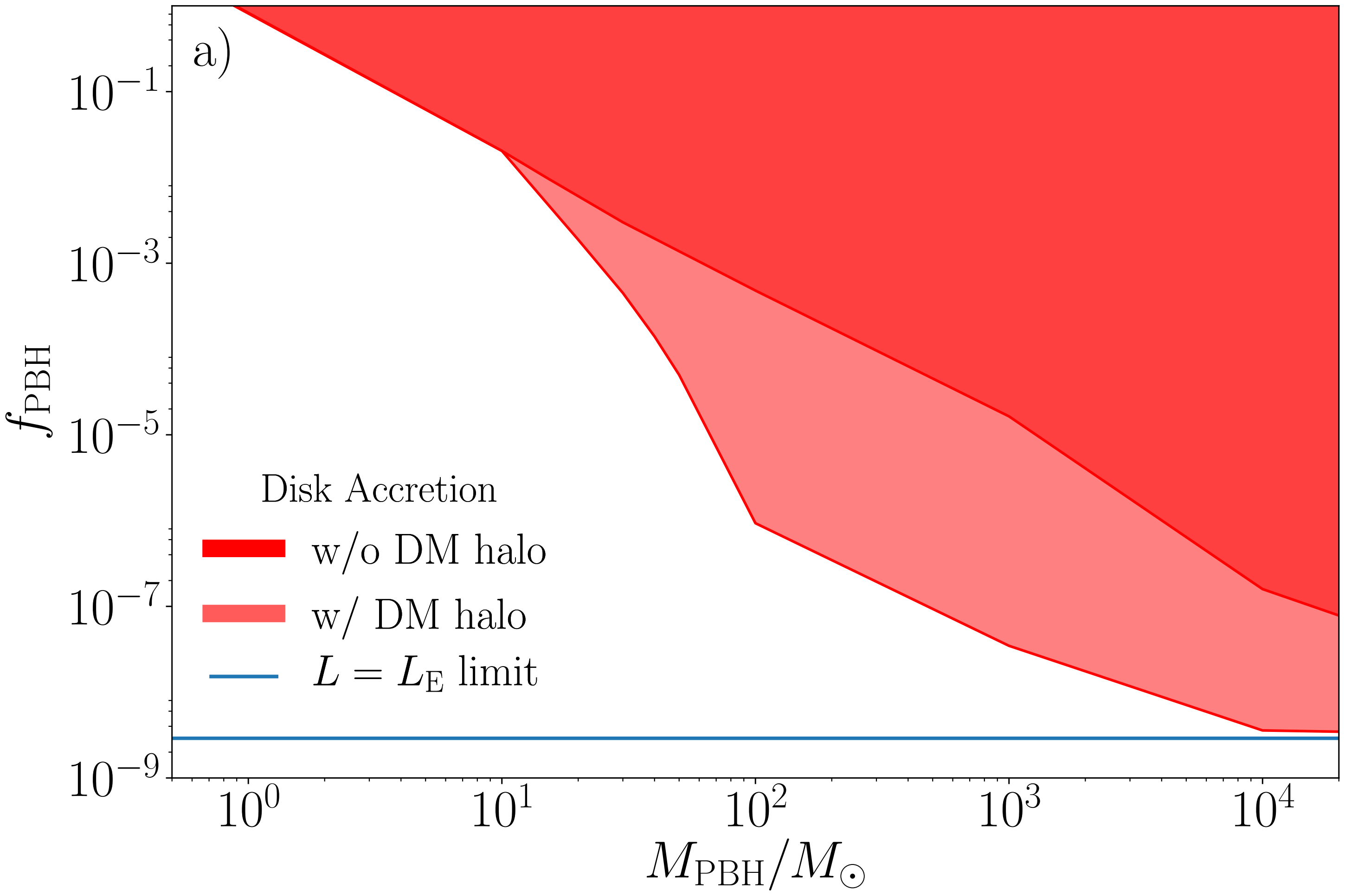

wimp or wimps

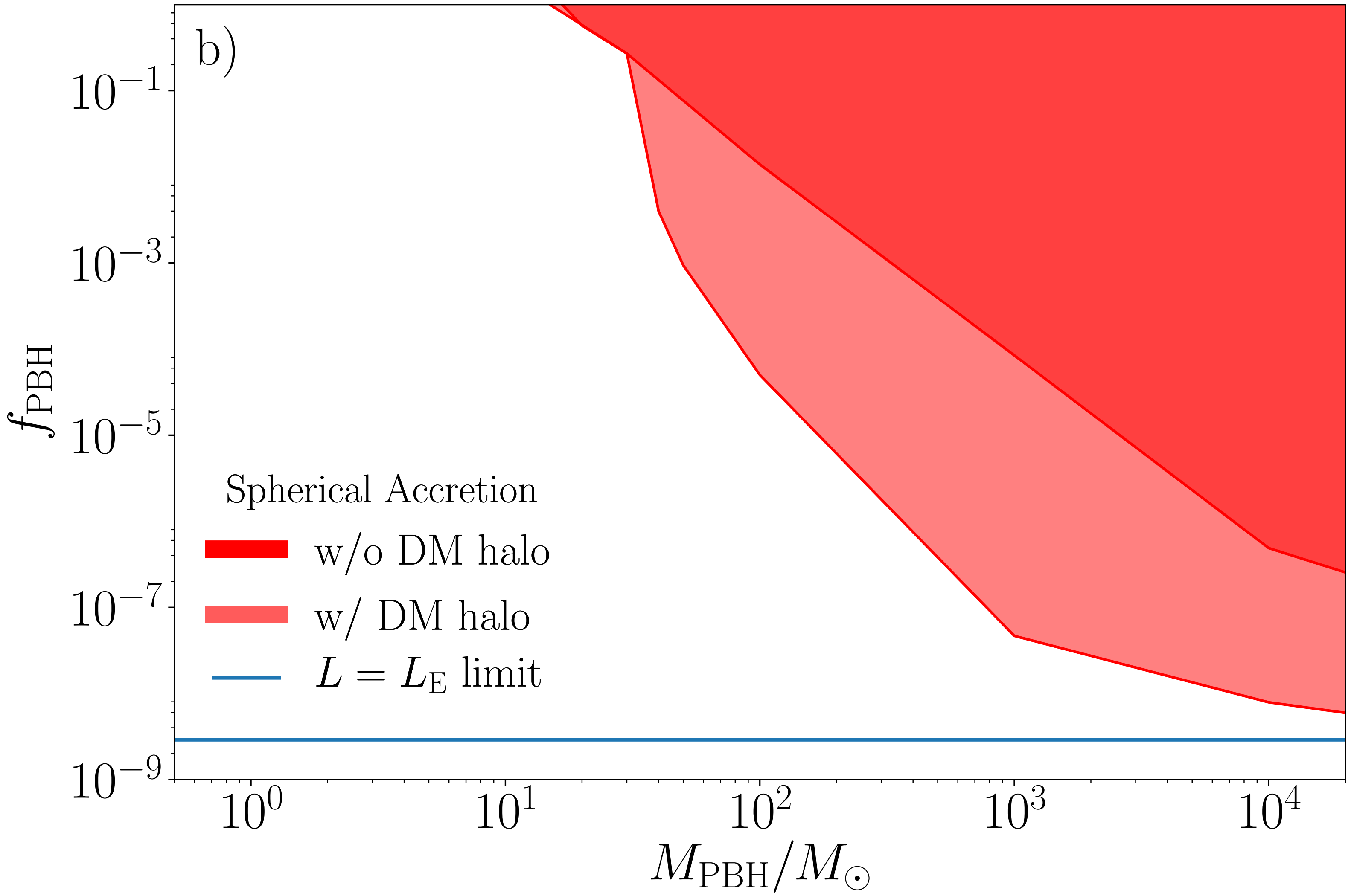
Accretion & Dynamical bounds



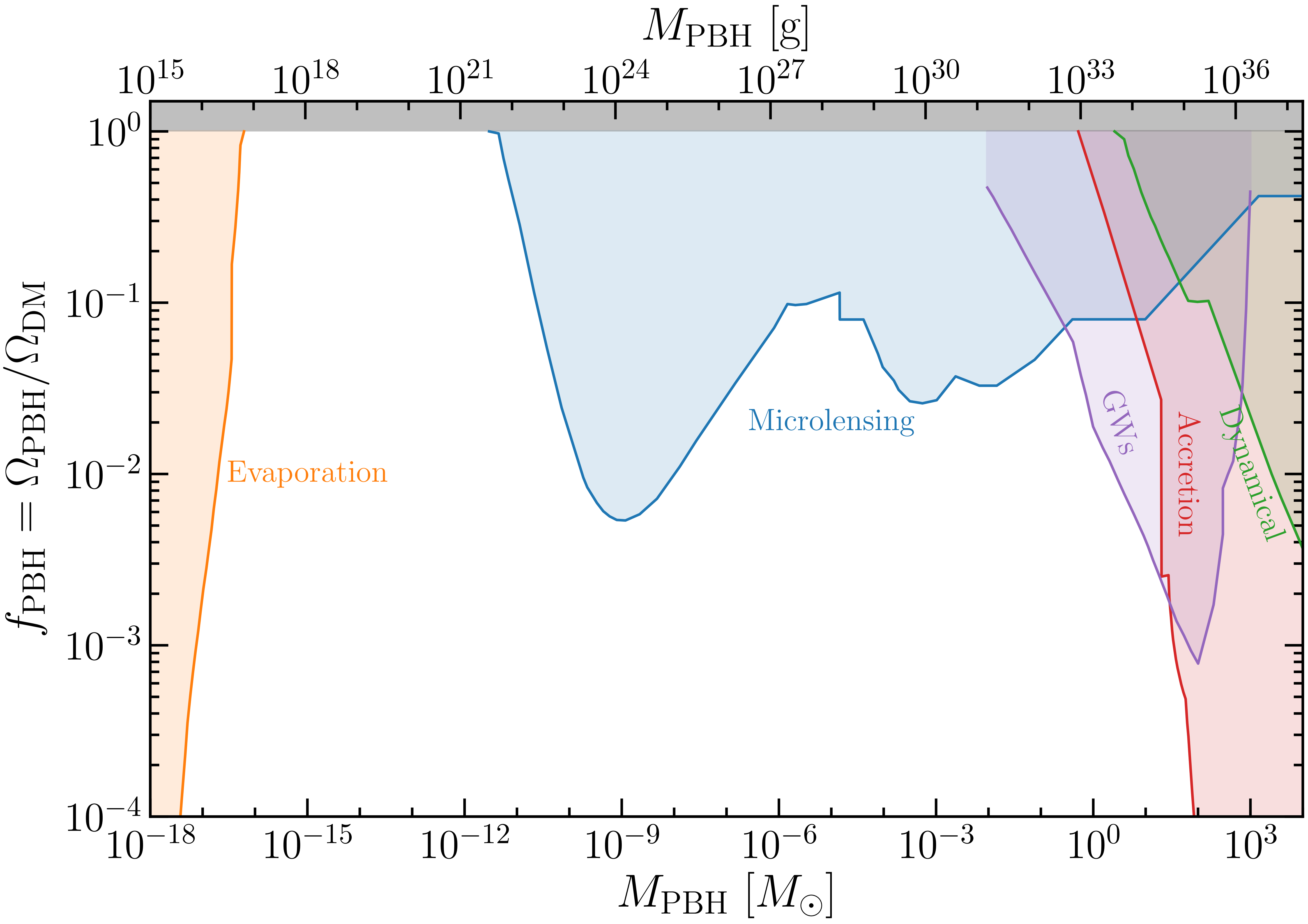
Green, Kavanagh 2007.10722 (December 2020)

CMB bounds on primordial black holes including dark matter halo accretion





Figures from
Serpico, Poulin, Inman, Kohri,
2002.10771



https://github.com/bradkav/PBHbounds

Green, Kavanagh 2007.10722 (v3 December 2020)

Situation before ~2019

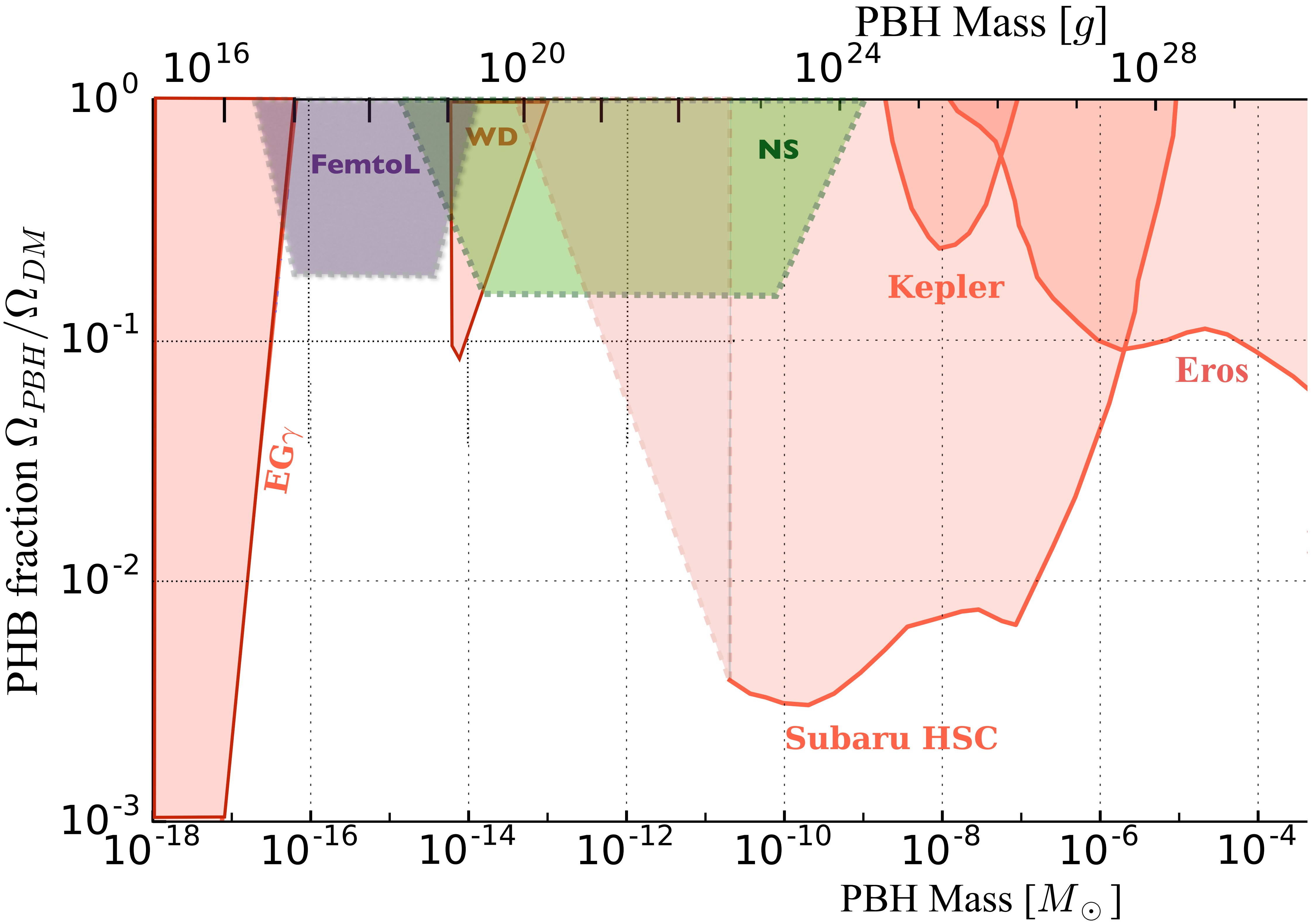


Figure from Katz et al.
1807.11495 (modified)

See also Montero-Camacho et al.
1906.05950

Smyth et al.
1910.01285

Primordial black hole formation

Inflation:

— Origin of CMB temperature fluctuations
— Seeds of large scale structure
} small primordial fluctuations

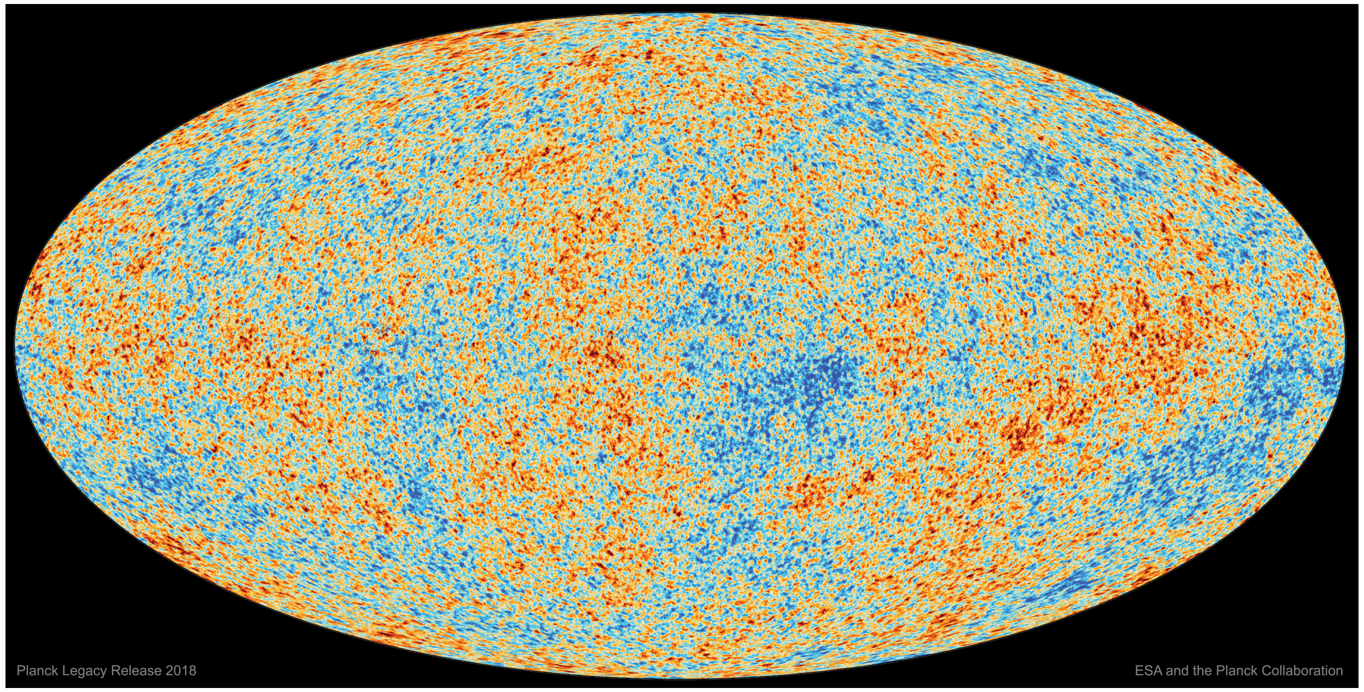


Image Credit: European Space Agency, Planck Collaboration

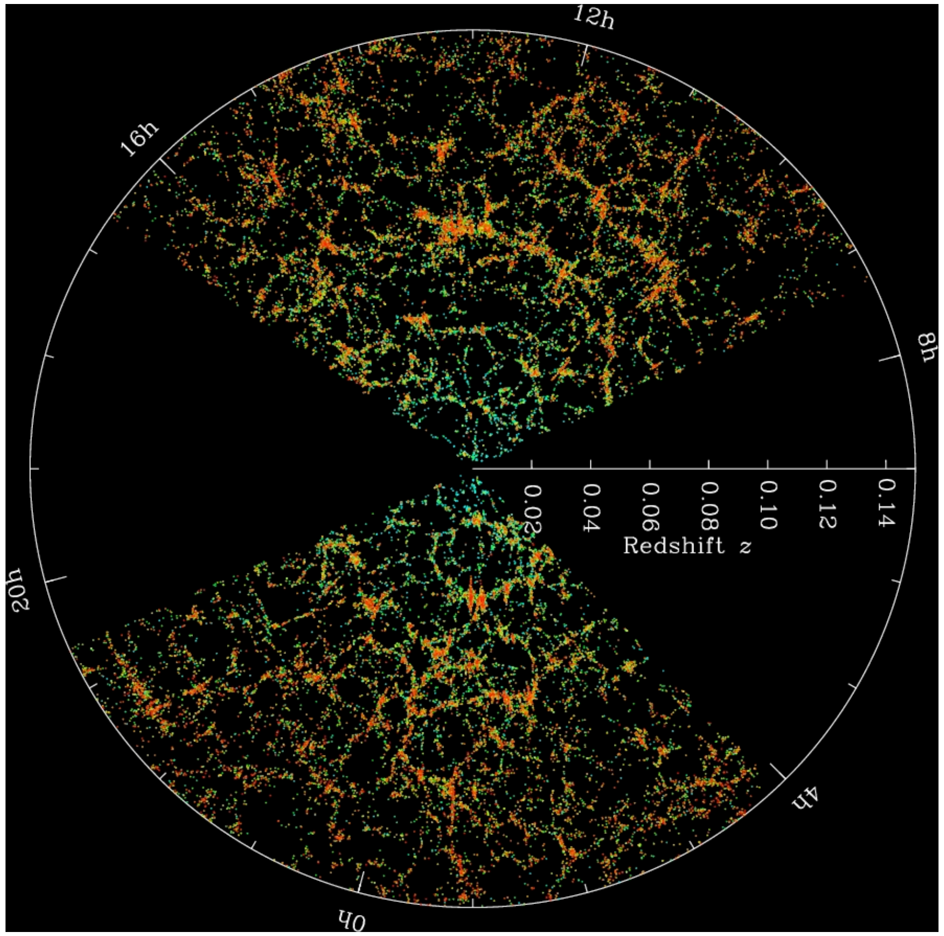
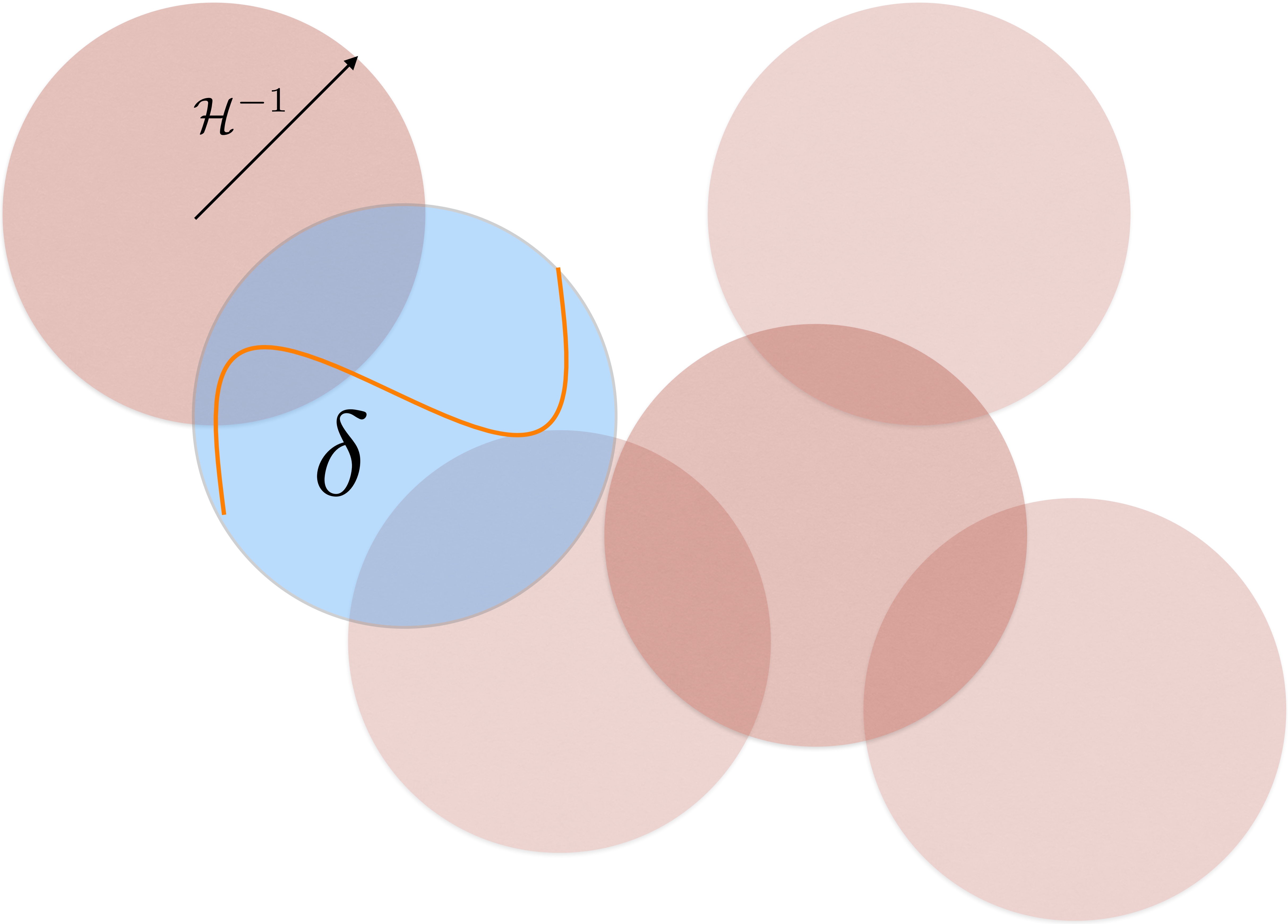
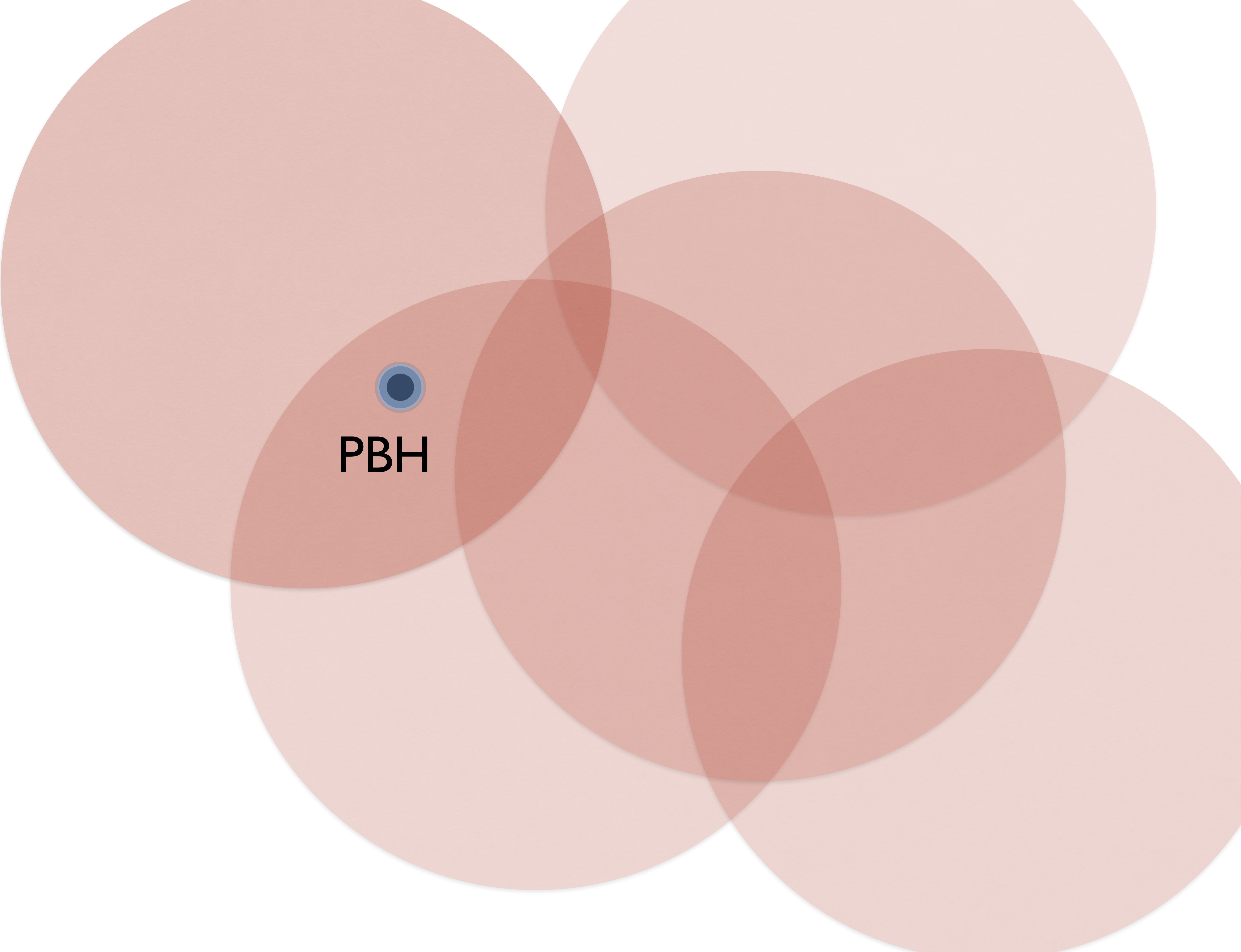
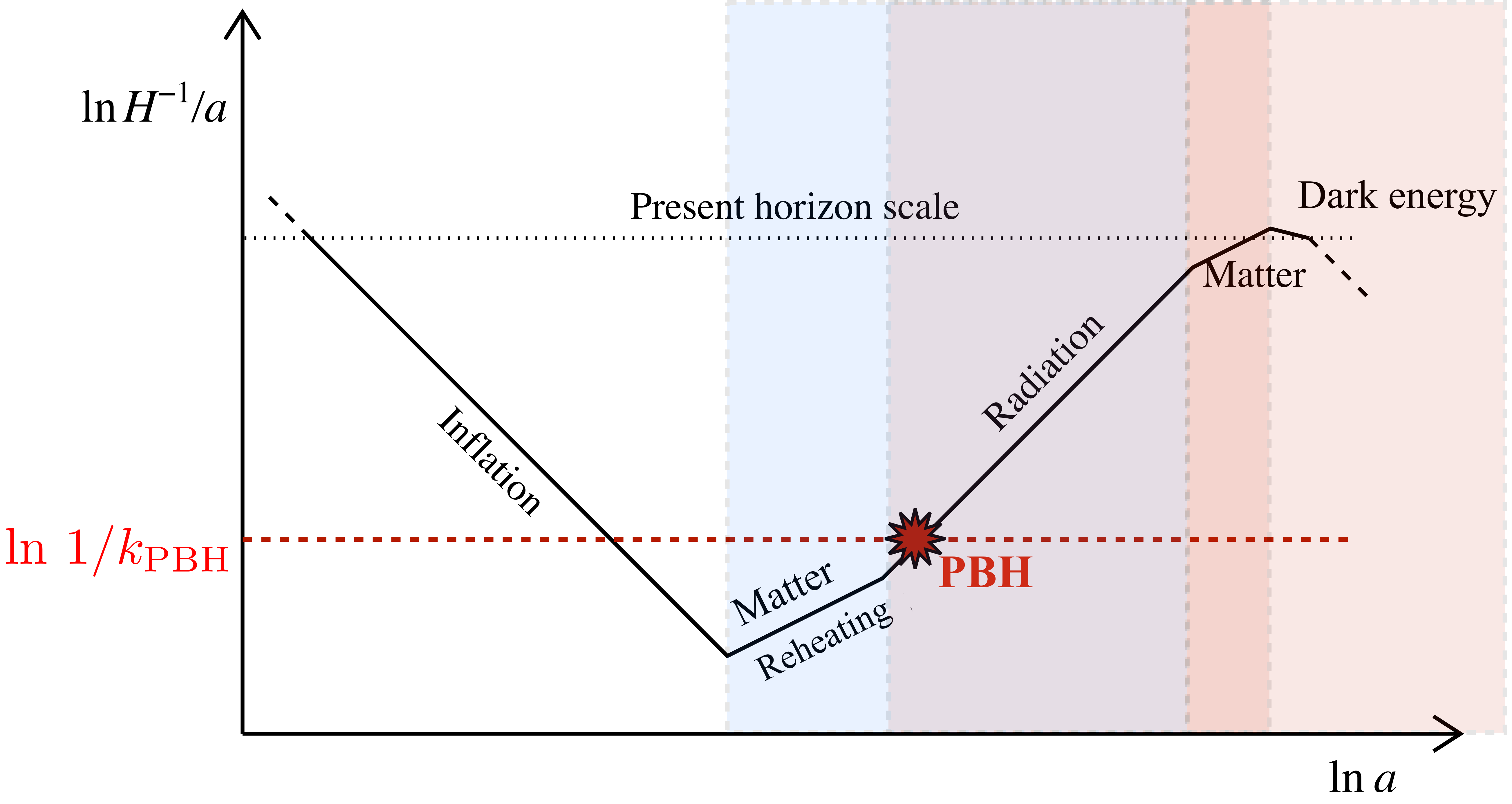


Image Credit: M Blanton and SDSS

— Seeds of DM? : large primordial fluctuations → PBH DM


$\mathcal{H}^{-1}$
δ


PBH



Adapted from Liddle and Leach, 2003

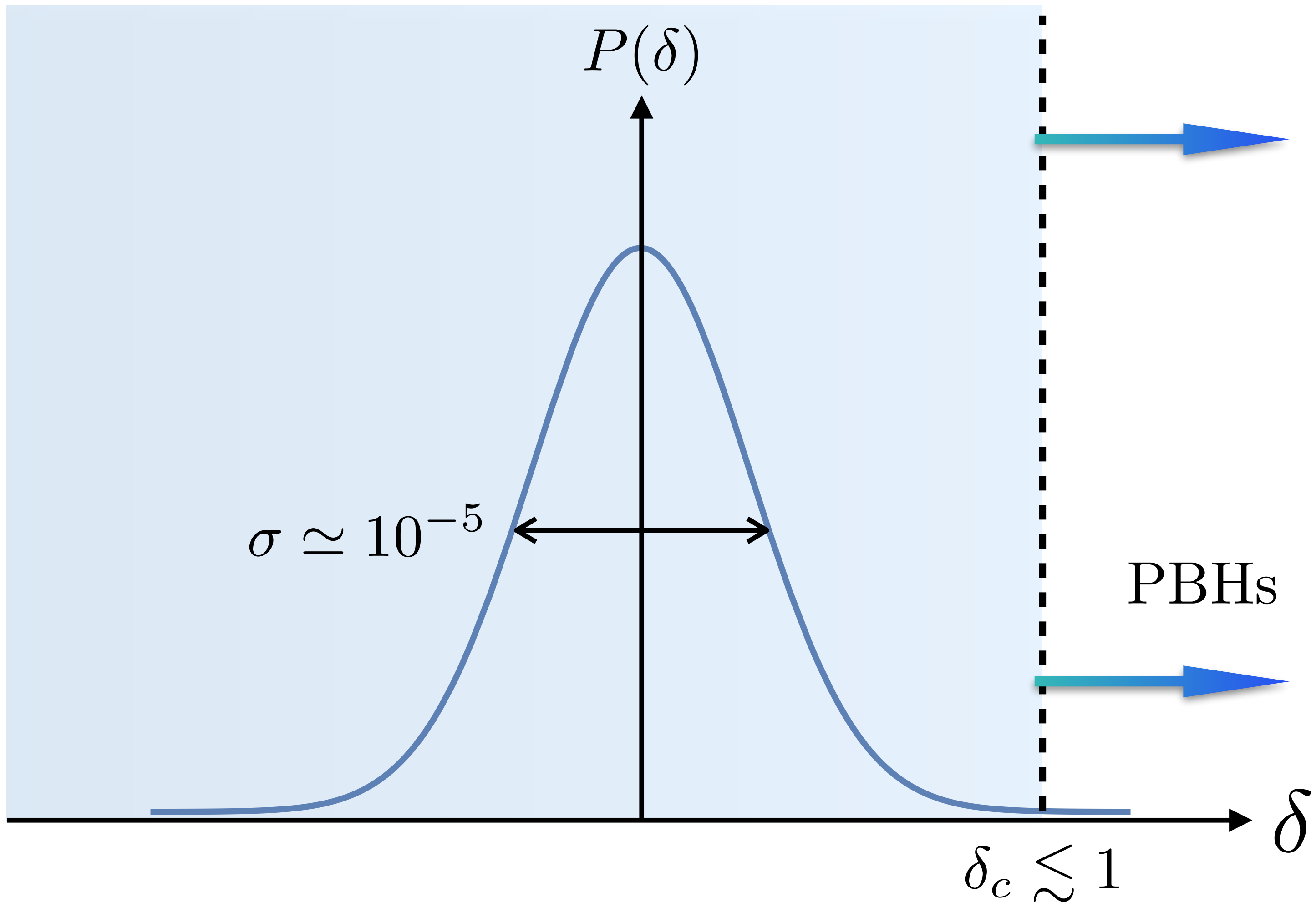
Individual masses

$$M \sim \frac{4}{3}\pi\,\rho\,H^{-3}$$

$$M \sim 10^{-14}\left(\frac{10^{13}\,\mathrm{Mpc}^{-1}}{k}\right)^{2} M_{\odot}$$

$$N_e \simeq 18 - \frac{1}{2}\log\frac{M}{M_{\odot}}$$

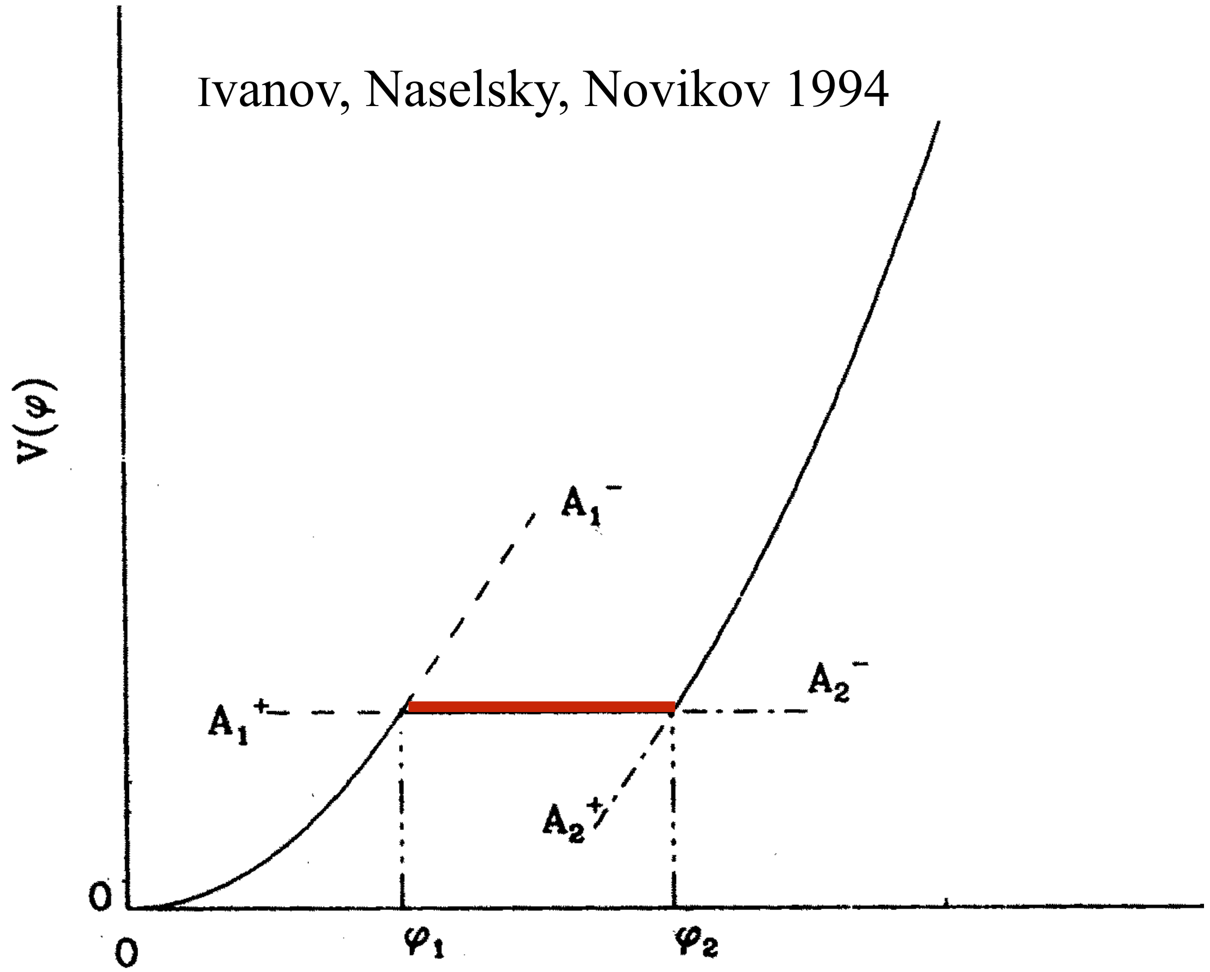
PBH abundance (assuming Gaussianity)

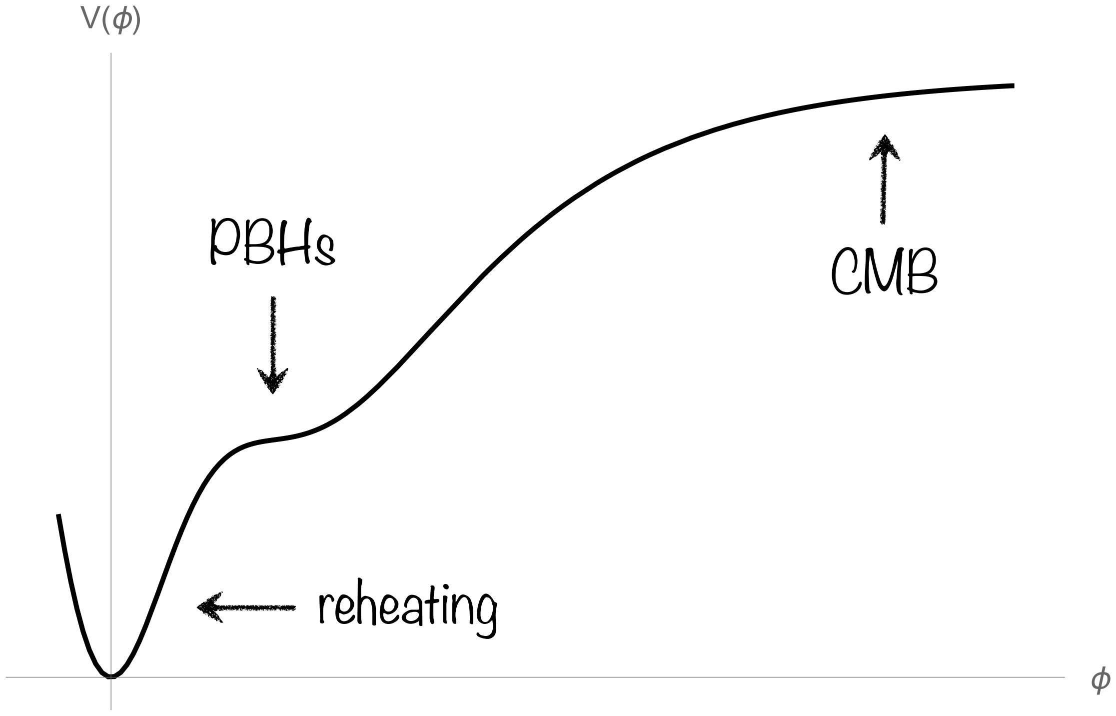


$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \propto \int_{\delta_c}^{\infty} \exp\left(-\frac{\delta^2}{2\sigma^2}\right) d\delta$$

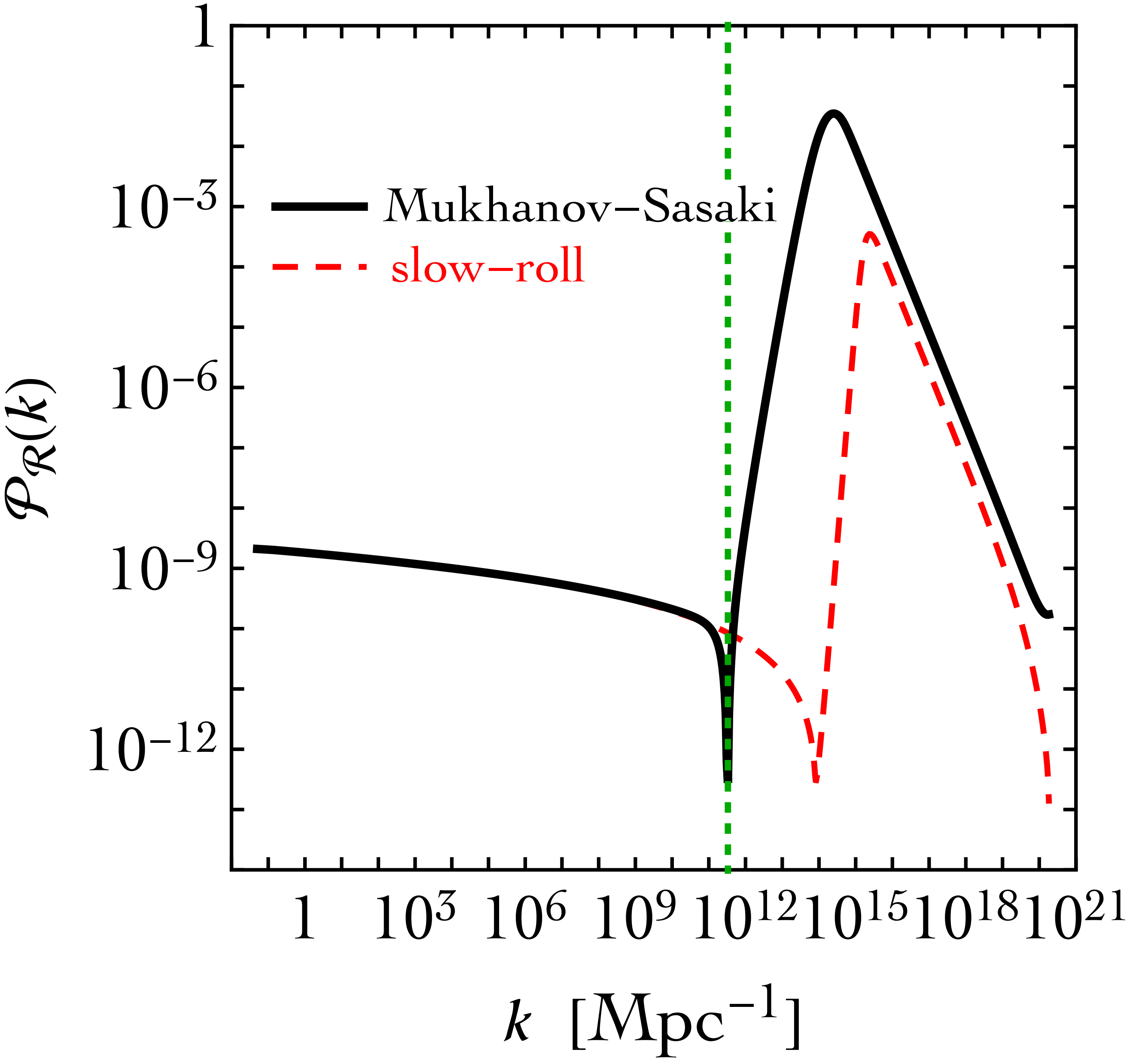
$$\sigma \sim \mathcal{P}_{\mathcal{R}} \sim 10^{-2} \implies \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \sim 1$$

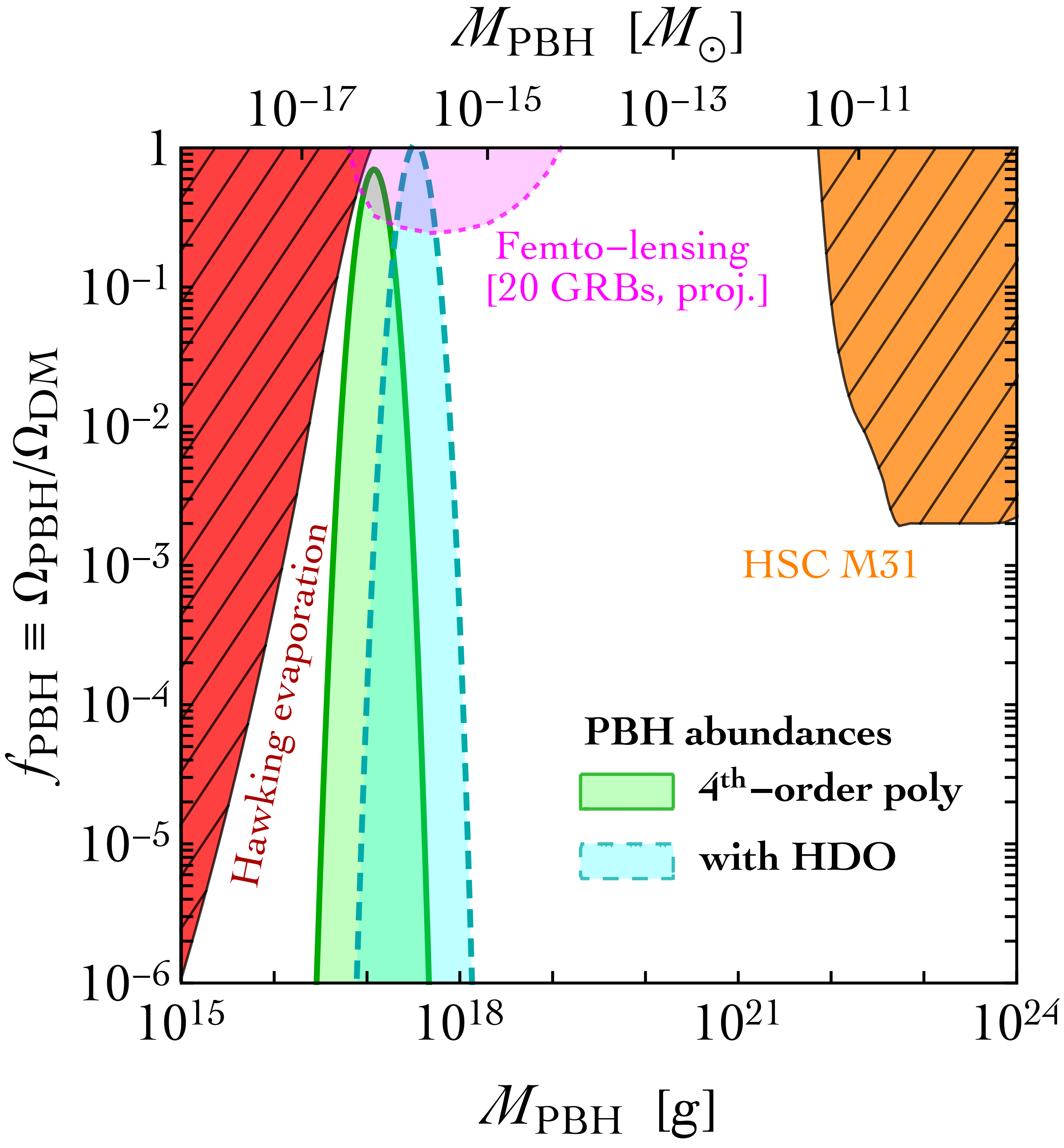
Inflation and primordial black holes as dark matter


Ivanov, Naselsky, Novikov 1994



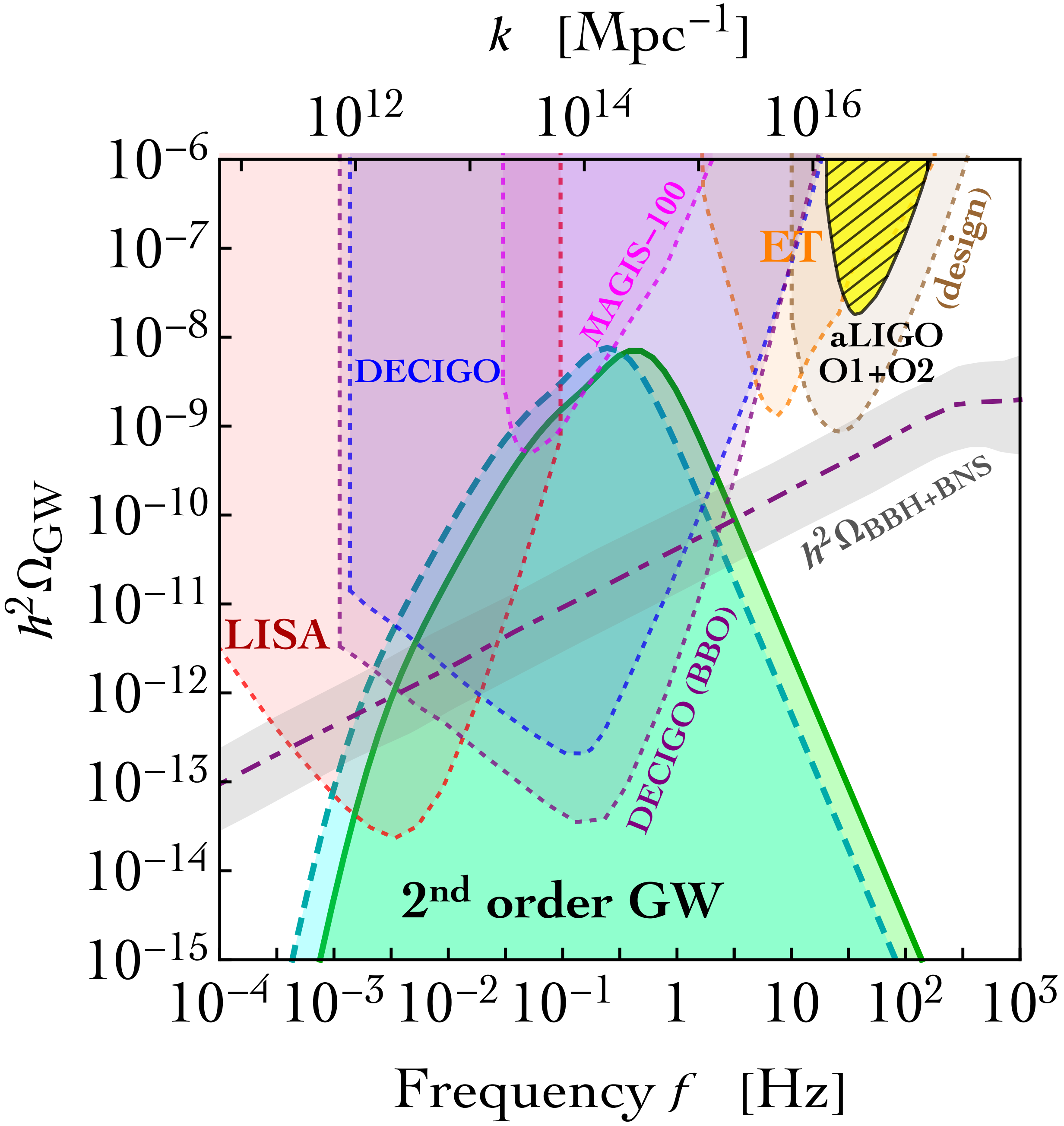
$$\mathcal{P}_{\mathcal{R}} \sim \left(\frac{H}{m_P}\right)^2 \left(\frac{H}{\dot{\phi}}\right)^2 \sim \left(\frac{V}{m_P^2 V'}\right)^2 \frac{V}{m_P^4}$$





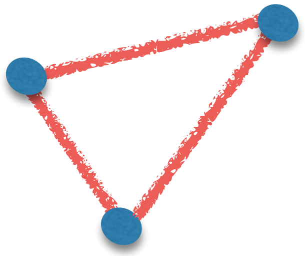
GB, Rey, Taoso, Urbano, 2020

GWs: $$\left(\frac{M_{\rm PBH}}{10^{17}\,{\rm g}}\right)^{-1/2} \simeq \frac{k}{2\cdot 10^{14}\,{\rm Mpc}^{-1}} \simeq \frac{f}{0.3\,{\rm Hz}}$$



$$\Omega_{\rm GW} \sim \mathcal{P}_h \sim (\mathcal{P}_{\mathcal{R}})^2$$

e.g. LISA



(NANOGRAV Sept 2020: 10^{-8}Hz)

GB, Rey, Taoso, Urbano, 2020

$\mathcal{R}$: Comoving curvature perturbation from an EFT perspective

$$\mathcal{S} = \int \mathrm{d}t\, \mathrm{d}^3x\, M^2 \frac{a^3\epsilon}{c_\mathrm{s}^2}\left[\dot{\mathcal{R}}^2 - \frac{c_\mathrm{s}^2}{a^2}|\vec{\nabla}\mathcal{R}|^2 - m^2\mathcal{R}^2\right]$$

functions of time

PBH DM

$$10^{-12}\, M_\odot \quad — \quad 10^{-16} M_\odot$$

Interesting directions:

1. How to test the above window?
2. Phenomenology of PBH formation
3. Implications for other BSM problems