Correlating Gravitational Waves and Gamma-ray Signals from Primordial Black Holes

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Based on 2202.04653 with

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Mitchell Conference 05/26/2022

There are four key words in the story

Large Primordial Curvature Perturbation

Primordial Blackholes

Gravitational Waves

Gamma-ray signal

Let's first organize the keywords by the cosmological history

Large Primordial Curvature Perturbation

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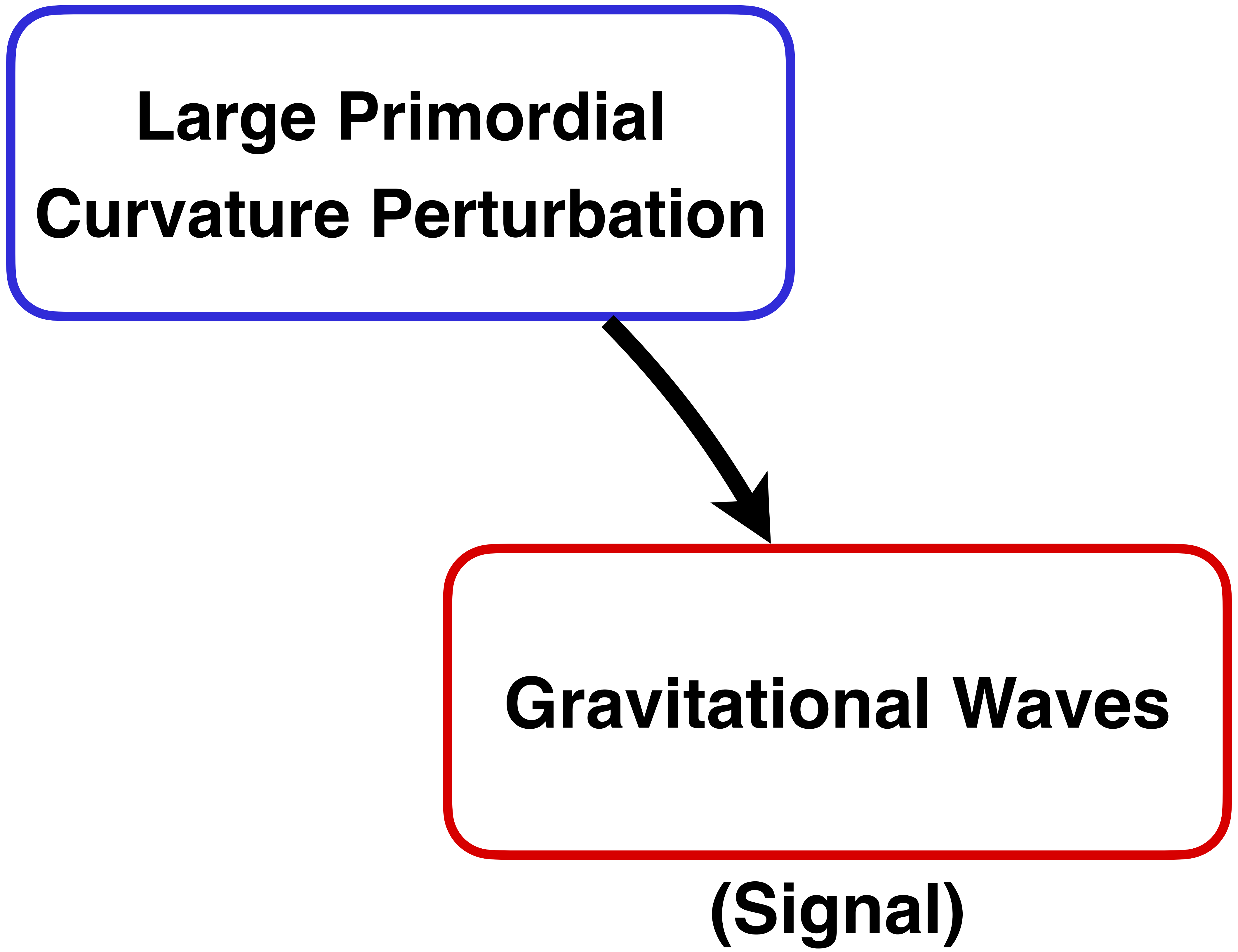

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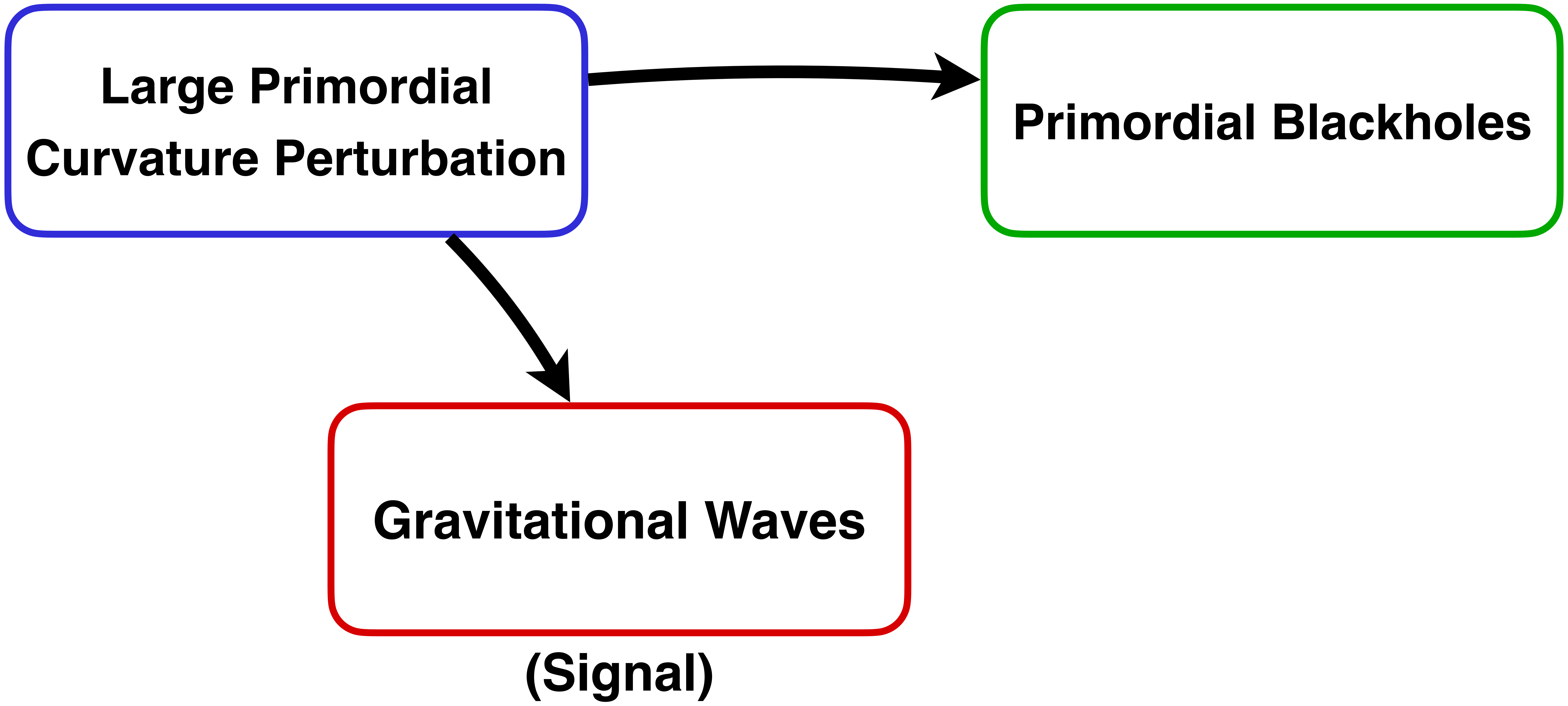

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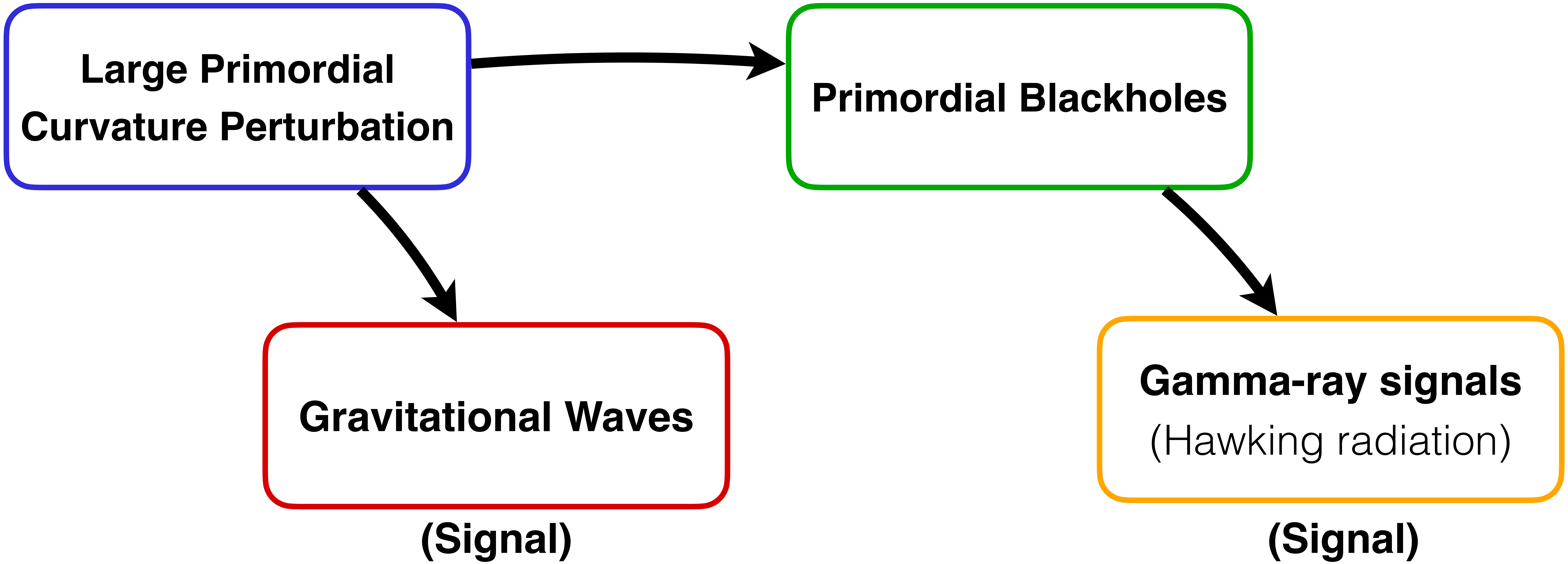
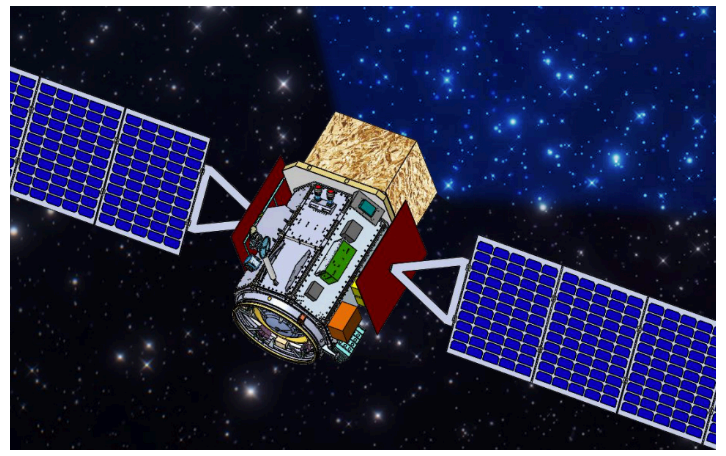


Proposed gamma-ray detectors open up new territory for observing PBH with mass $\sim 10^{14} - 10^{17}\,\mathrm{g}$

If seeing new gamma-ray signals

such as from the e-ASTROGAM

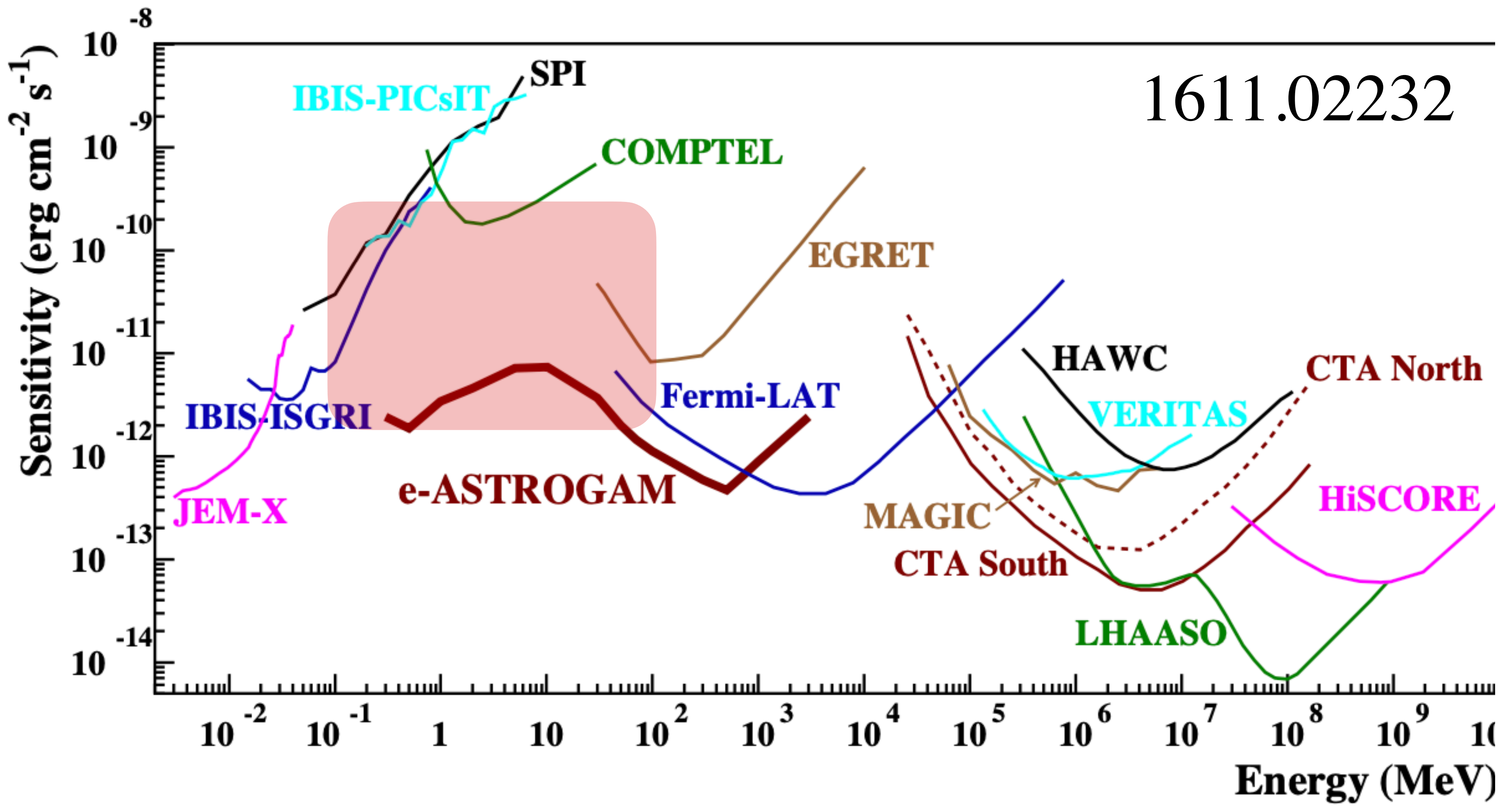
or the AMEGO

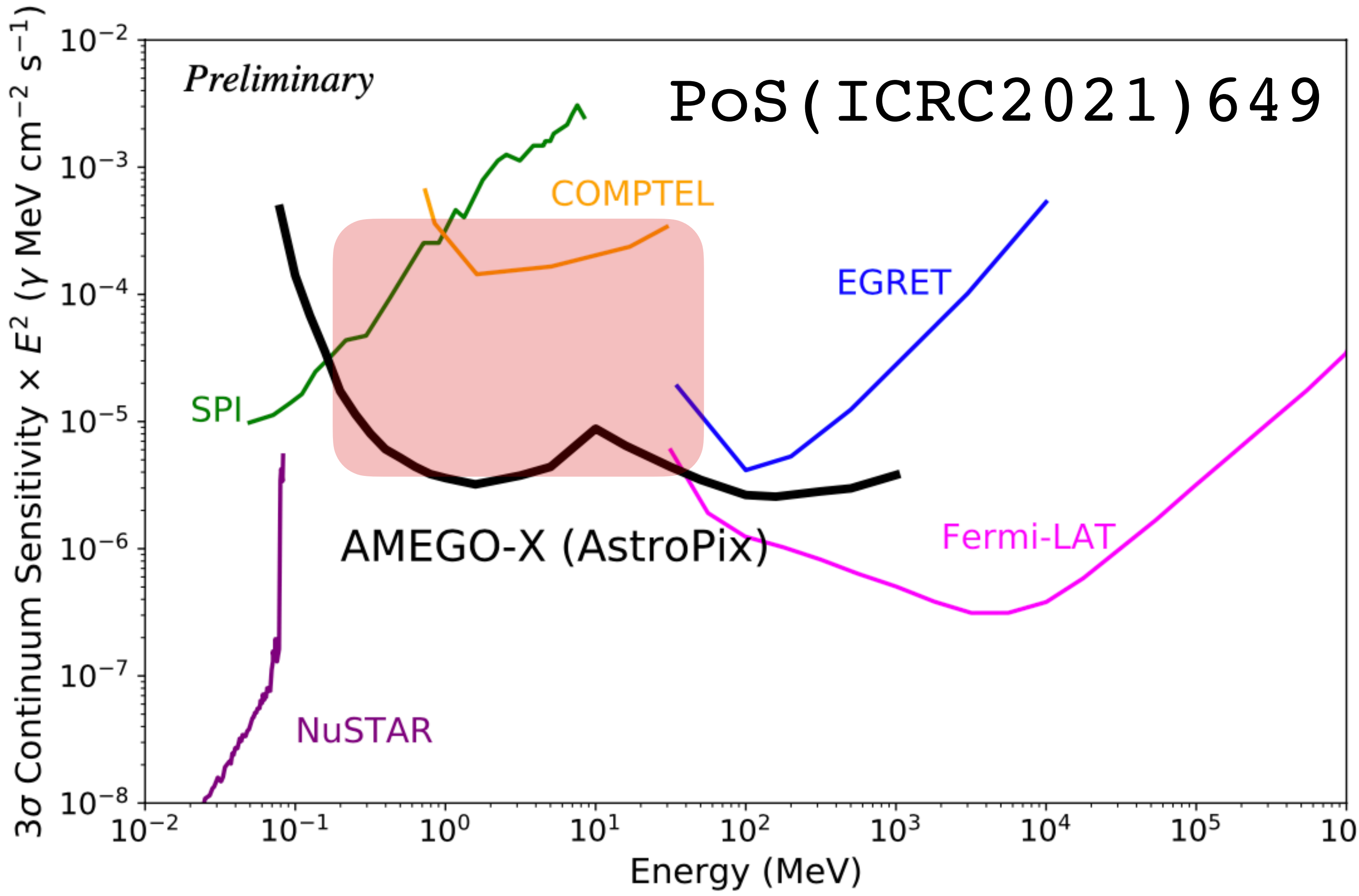


cover the energy gap

$$E_\gamma \sim 0.1 - 100\,\mathrm{MeV}$$

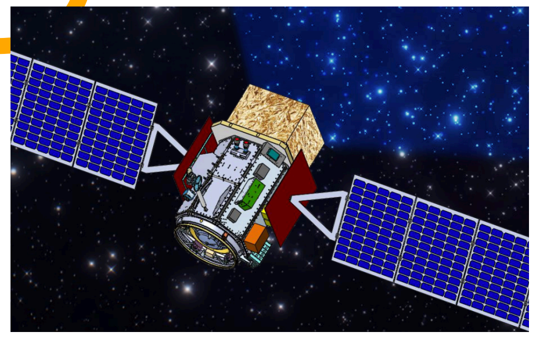
The "asteroid mass" black holes
Coogan, Morrison, Profumo (2020)





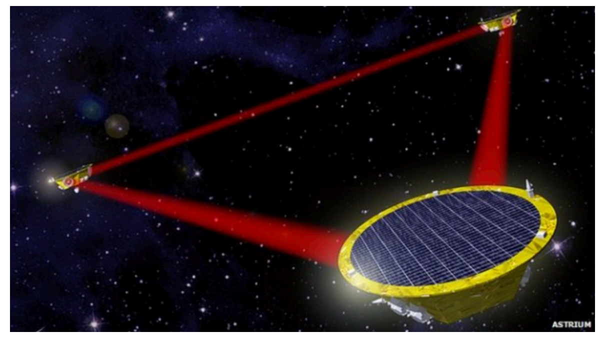
Let's re-organize these key words

If seeing new gamma-ray signals —fit→ **PBH mass function**



PBH mass function —determines→ **Primordial curvature power spectrum**

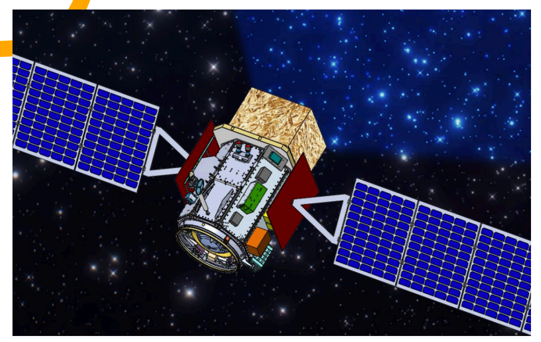
Primordial curvature power spectrum —predicts→ **Visible GW signals at future experiments**

LISA  BBO, DECIGO, ET, …

We show: seeing the gamma-ray signal + PBH from primordial curvature fluctuations => guaranteed visible GW signals at future experiments!

Theory prior

If seeing new gamma-ray signals —fit→ **PBH mass function**



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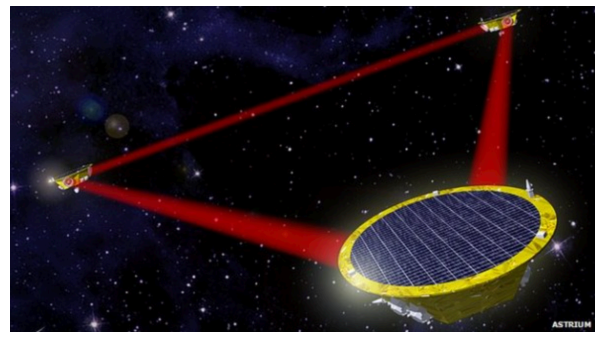
LISA  BBO, DECIGO, ET, …

Consider two types of curvature perturbations

δ - function $$P_{\zeta,\delta}(k) = A_\delta\, \delta\left(\log\left(\frac{k}{k_{p,\delta}}\right)\right)$$

Log-normal distribution $$P_\zeta(k) = \frac{A}{\sqrt{2\pi\sigma^2}}\,\exp\left(-\frac{(\log k - \log k_p)^2}{2\sigma^2}\right)$$

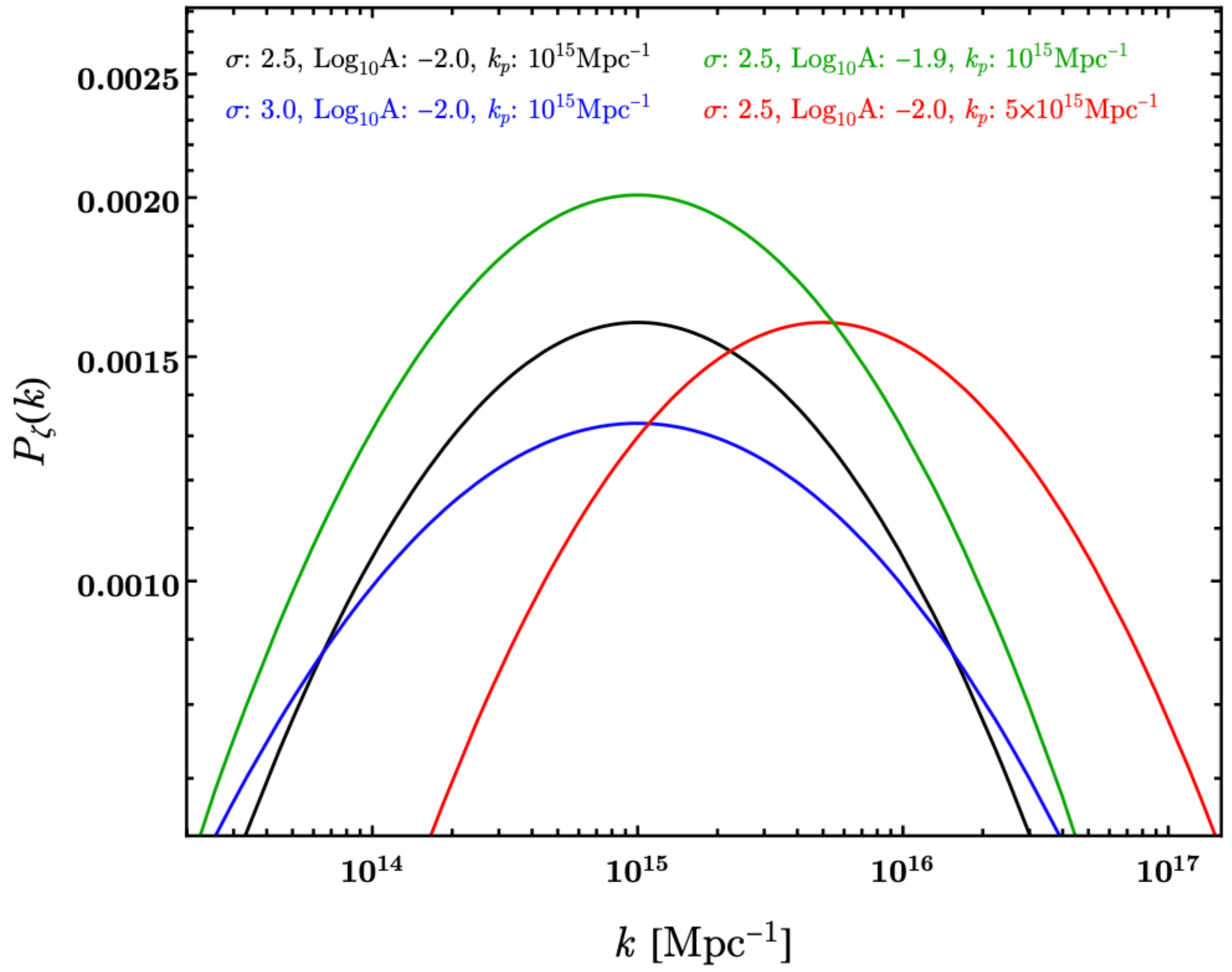
Press-Schechter formalism

+ Gaussian window function

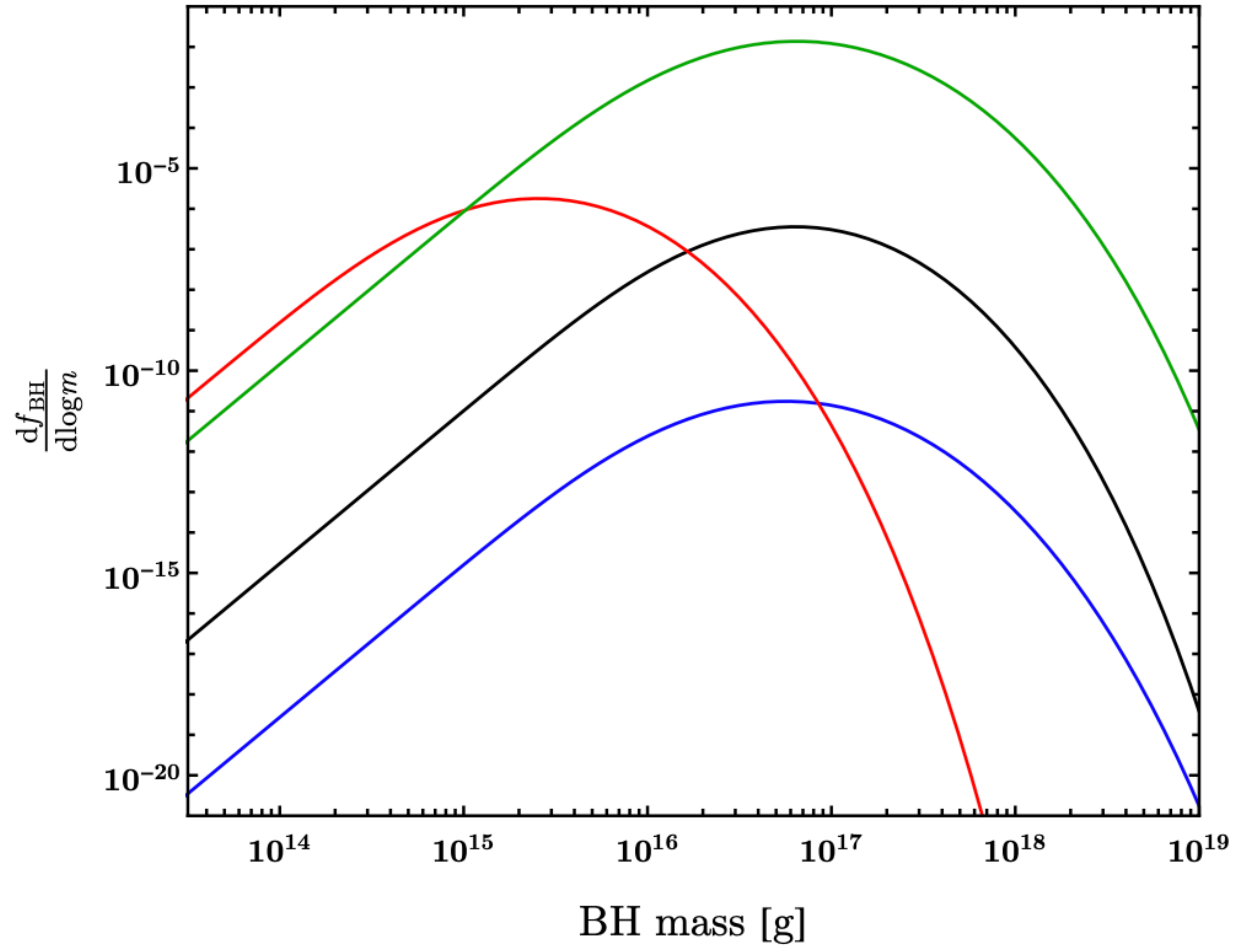
+ $m(R,\delta) = M_H(R)K(\delta-\delta_c)^\gamma$

with $(K,\delta_c,\gamma) = (10, 0.25, 0.36)$

[Young & Musso (2020)]

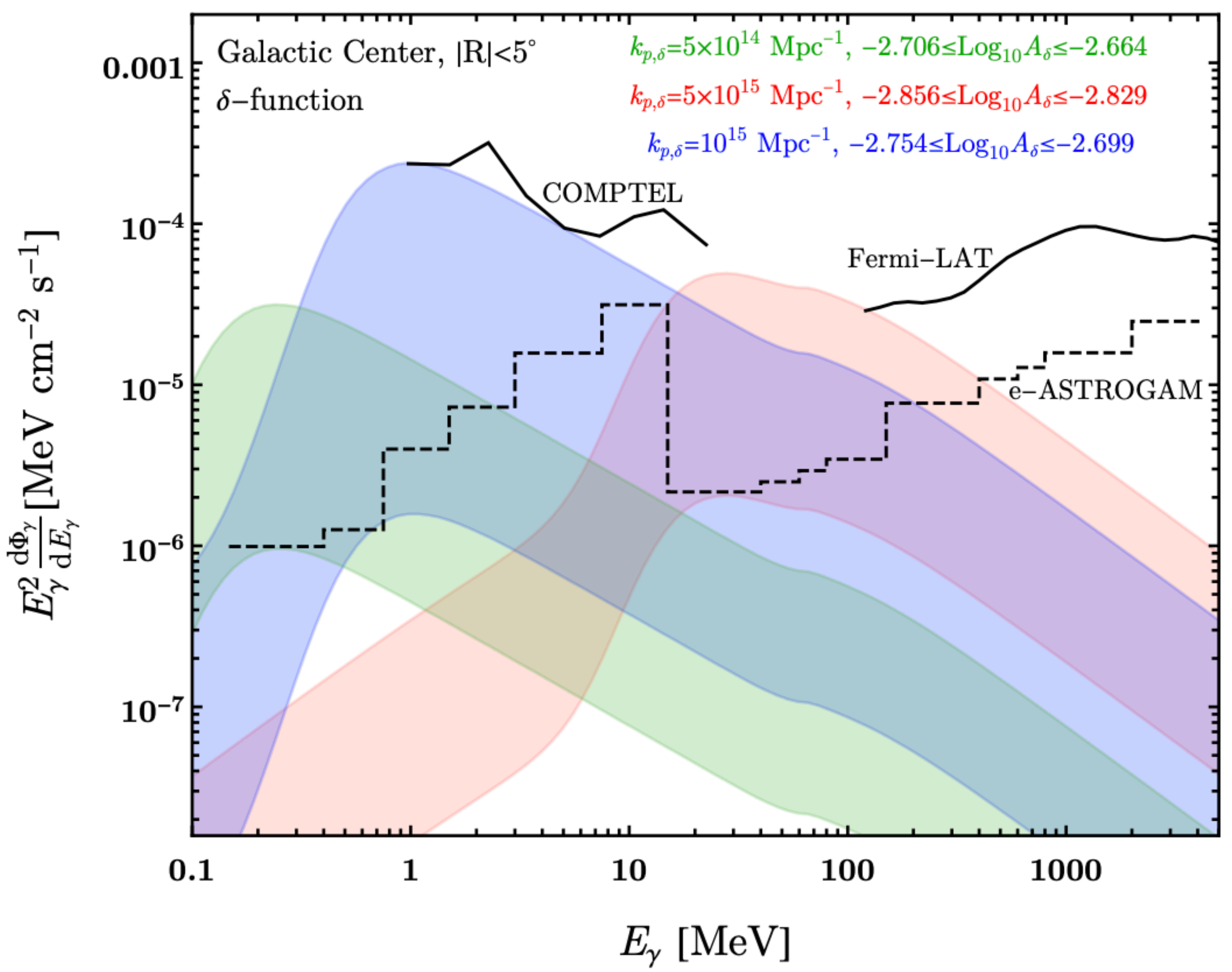


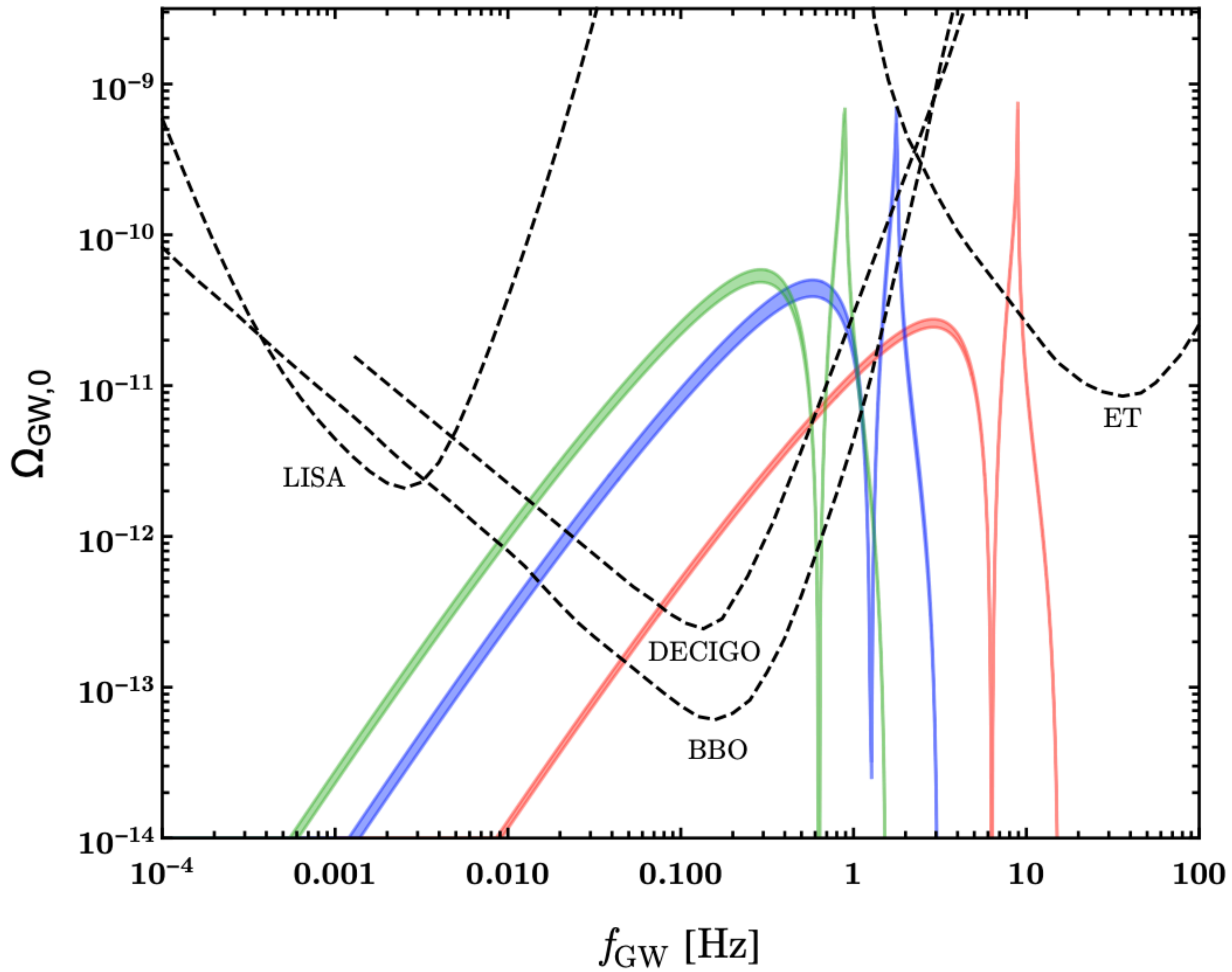
Can estimate $\dfrac{\mathrm{d}f_{\mathrm{BH}}}{\mathrm{d}\,m}$, $f_{\mathrm{BH}} \equiv \dfrac{\Omega_{\mathrm{BH}}}{\Omega_{\mathrm{CDM}}}$



For the $P_\zeta(k)$ that gives visible gamma-ray signal, we can calculate the companion GW signals

δ - function $\quad P_{\zeta,\delta}(k) = A_\delta\, \delta\left(\log\left(\frac{k}{k_{p,\delta}}\right)\right)$





For the $P_\zeta(k)$ that gives visible gamma-ray signal, we can calculate the companion GW signals

Upper boundary: existing bounds or $f_{\mathrm{BH}} \leq 1$

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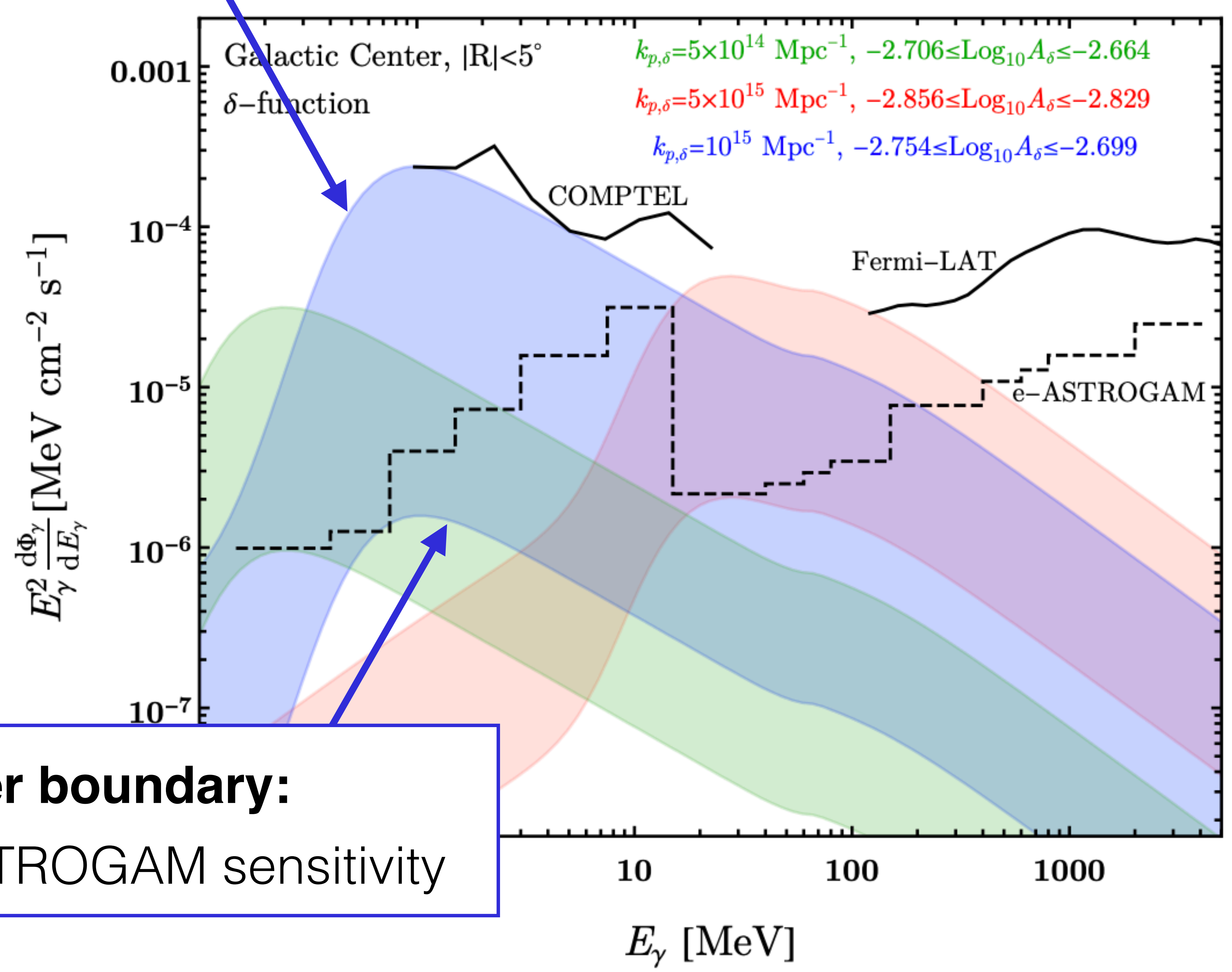
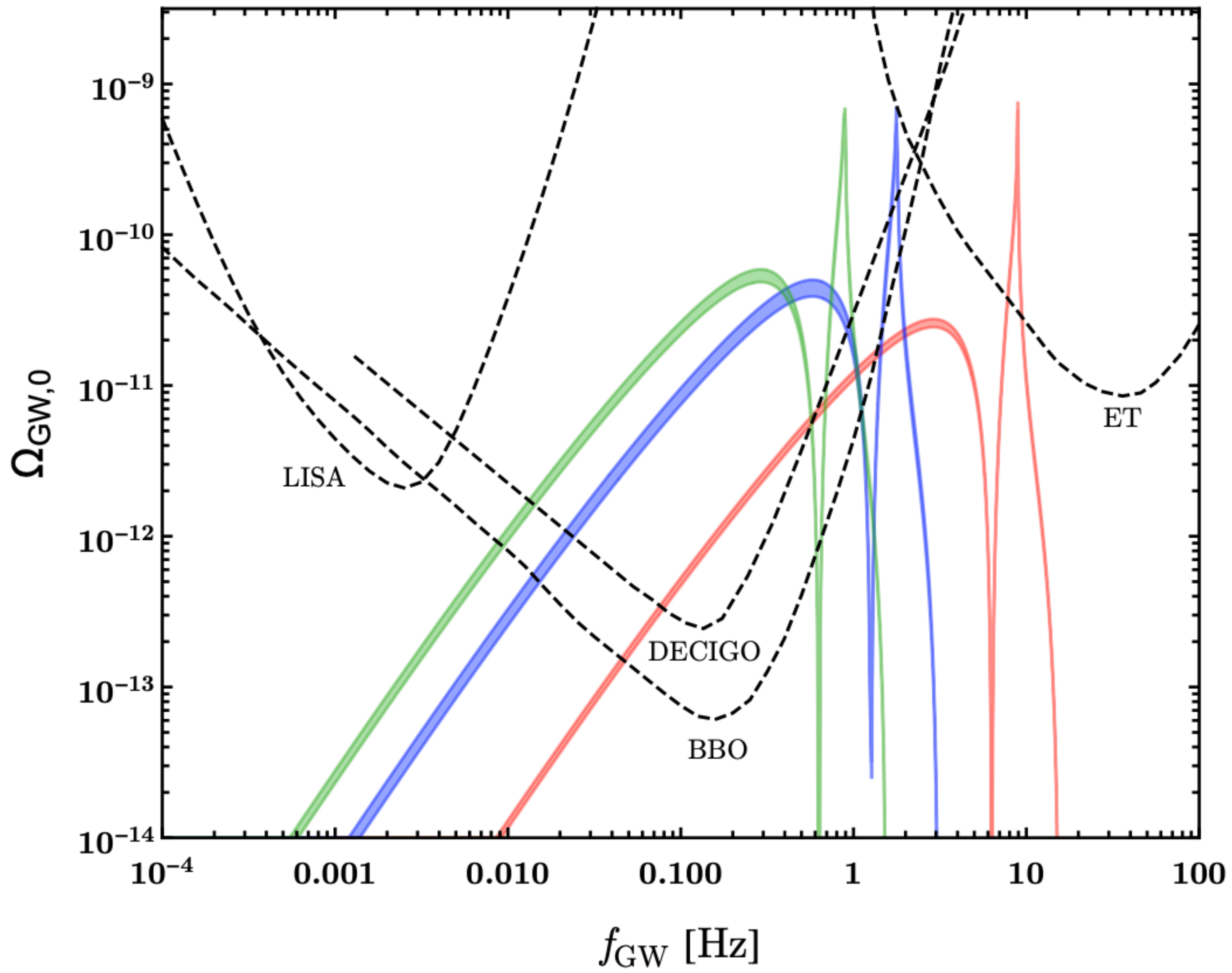
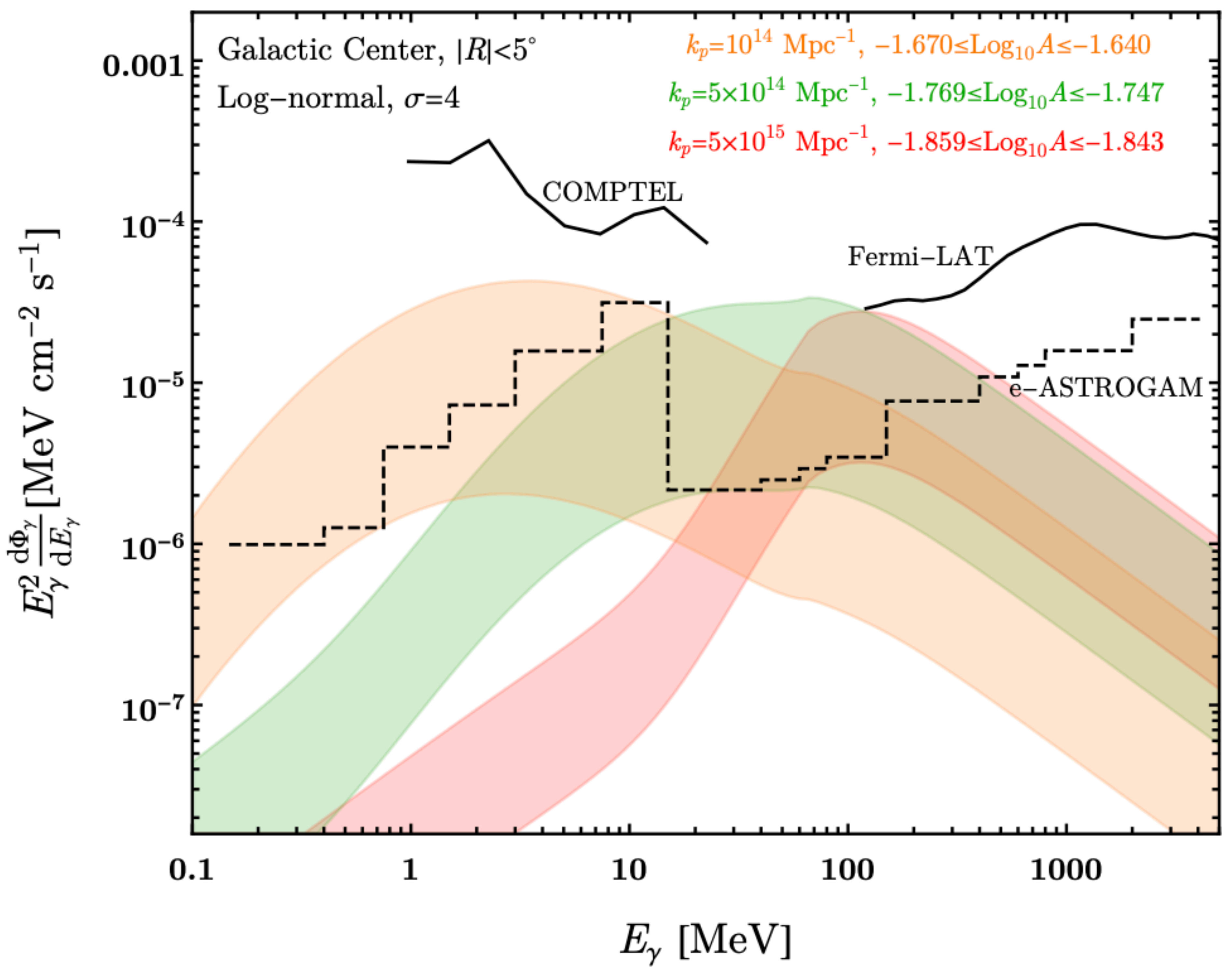


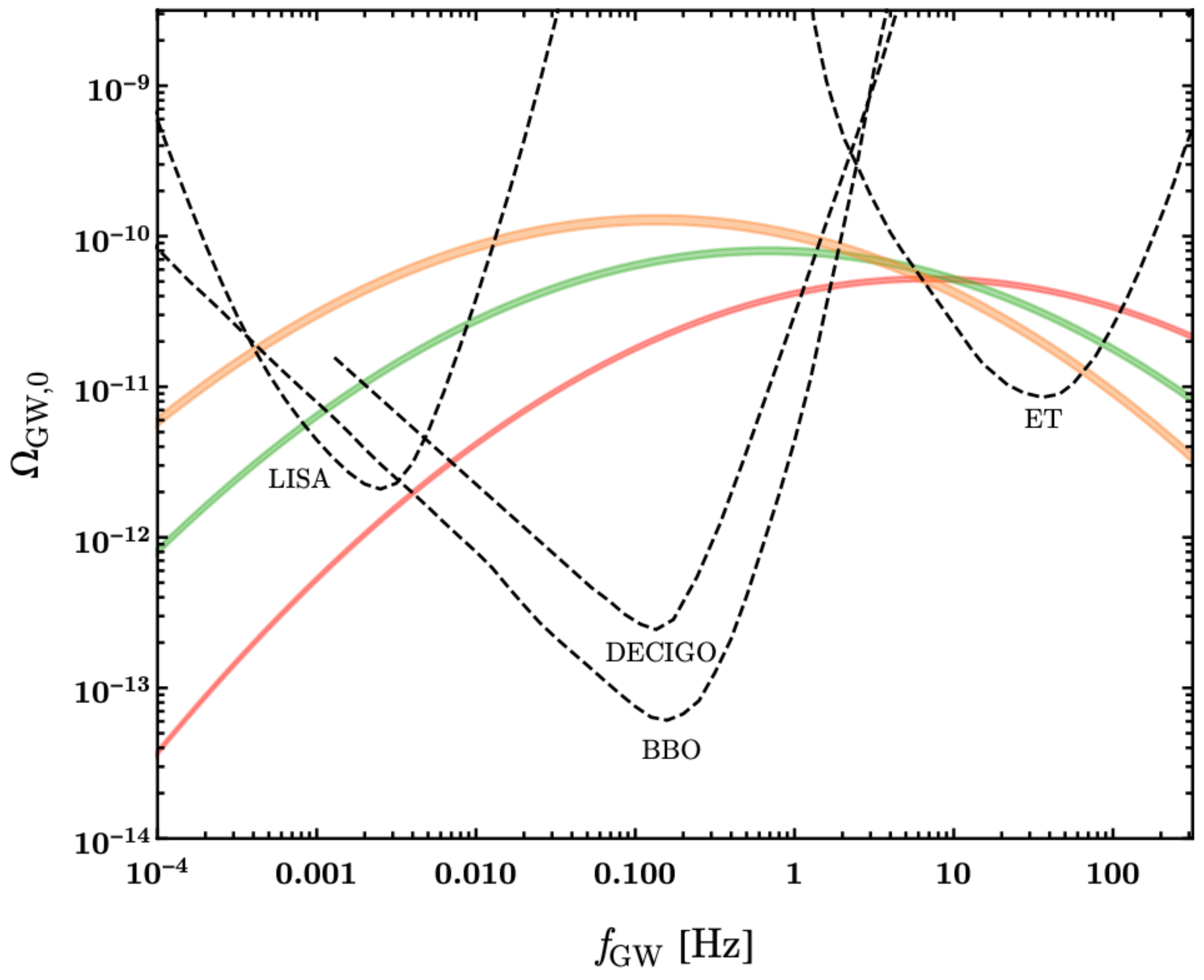
Lower boundary:
above e-ASTROGAM sensitivity



For the $P_\zeta(k)$ that gives visible gamma-ray signal, we can calculate the companion GW signals

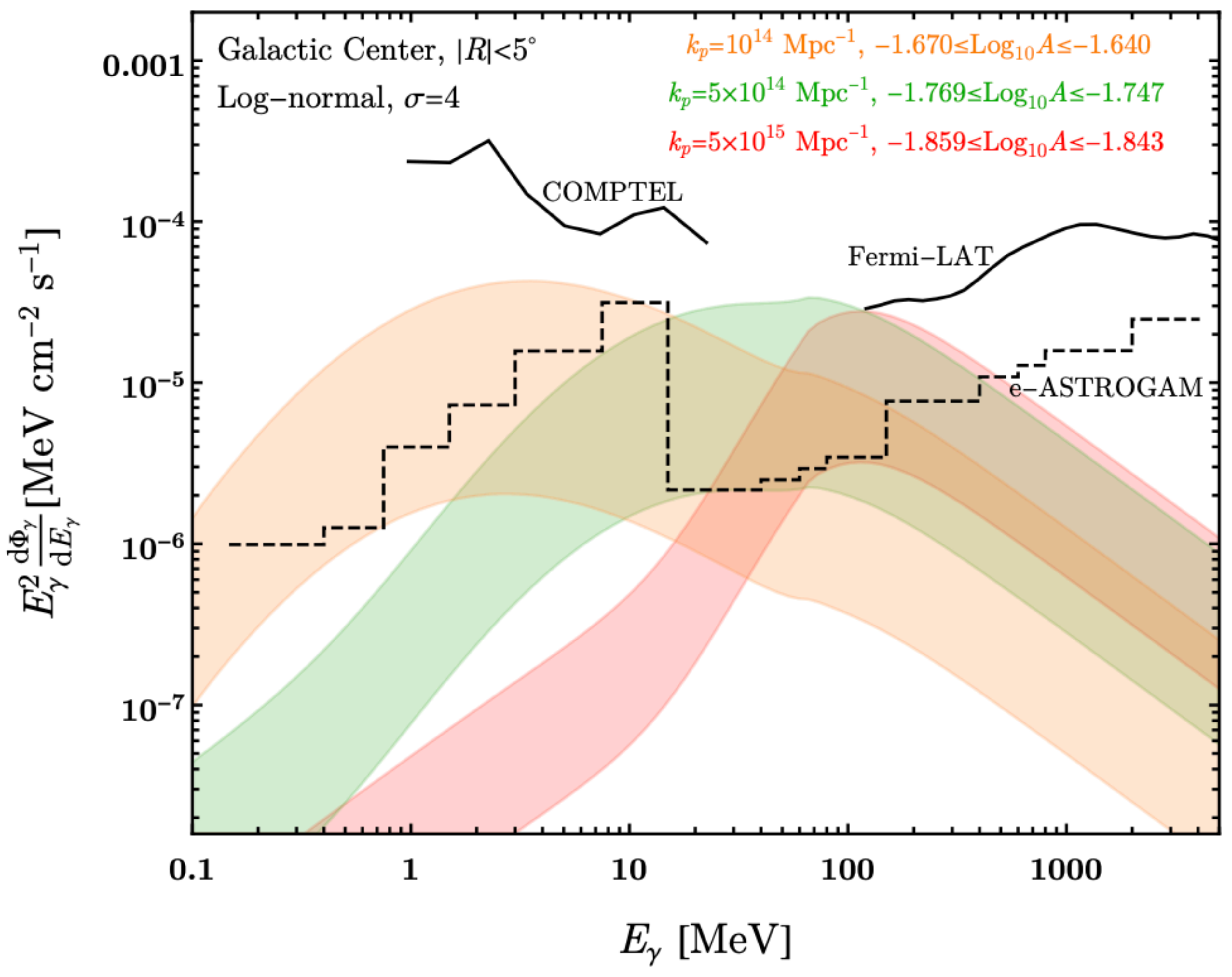
Log-normal $\sigma = 4$ $$P_\zeta(k) = \frac{A}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\log k - \log k_p)^2}{2\sigma^2}\right)$$

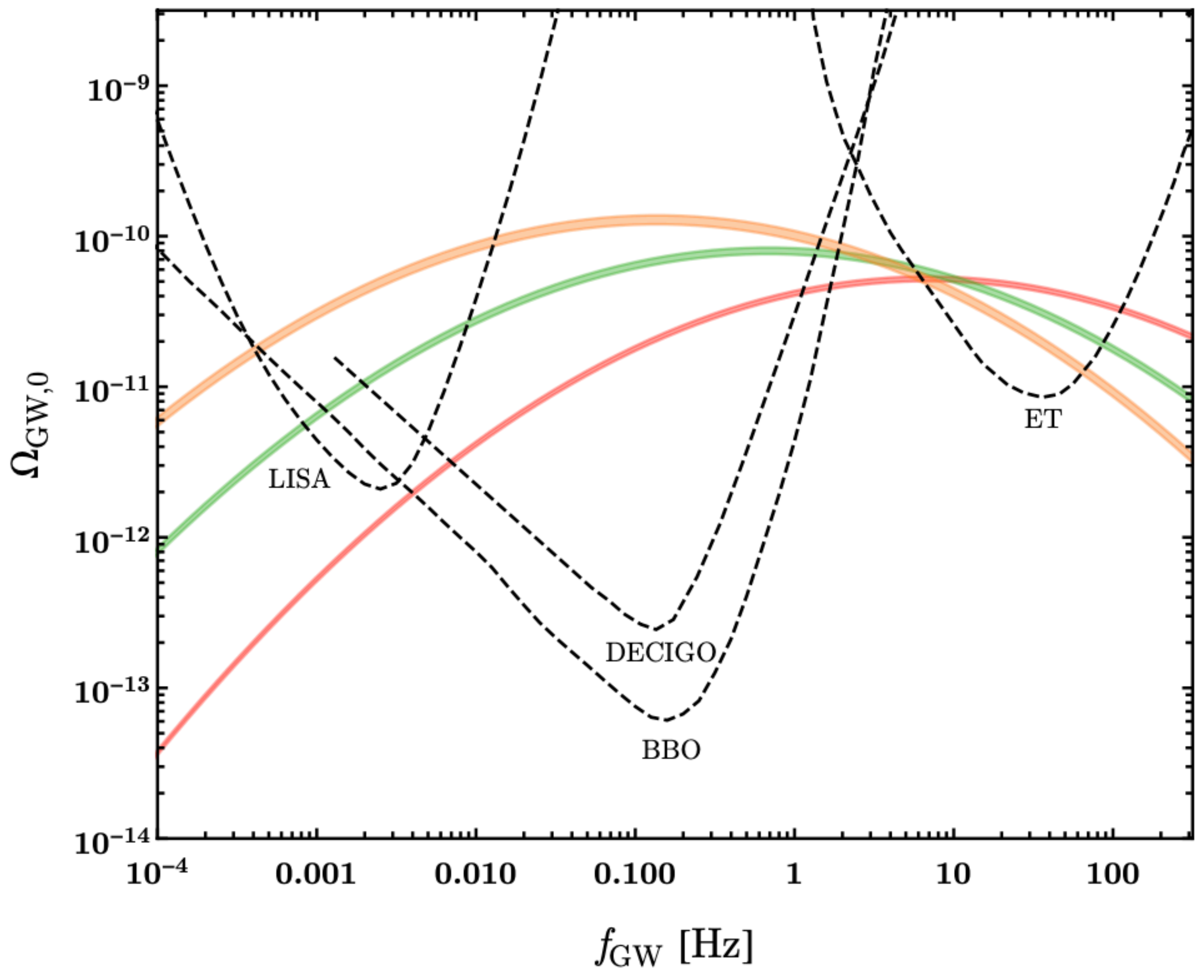




For the $P_\zeta(k)$ that gives visible gamma-ray signal, we can calculate the companion GW signals

Smaller variations in the GW signal!

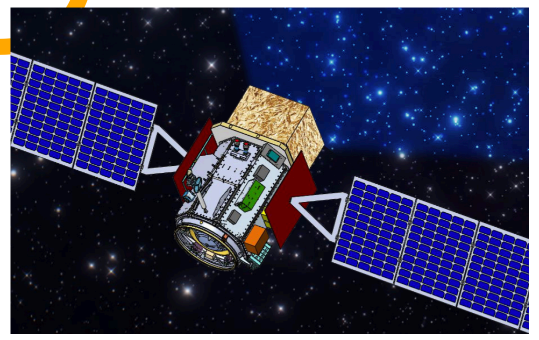




If seeing both types of the signals:

measure curvature power spectrum, check if the theory prior is plausible

If seeing new gamma-ray signals



fit →

Theory prior

PBH mass function

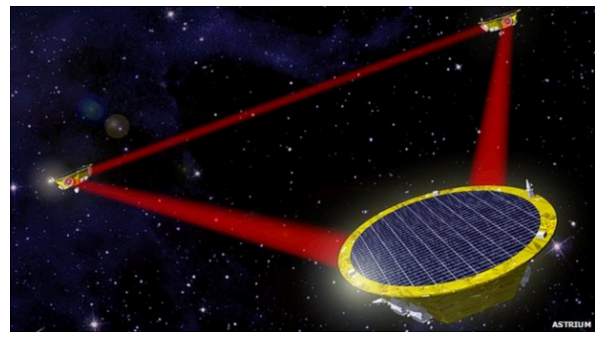
↓ **determines**

Primordial curvature power spectrum

← **predicts**

Visible GW signals at future experiments

LISA

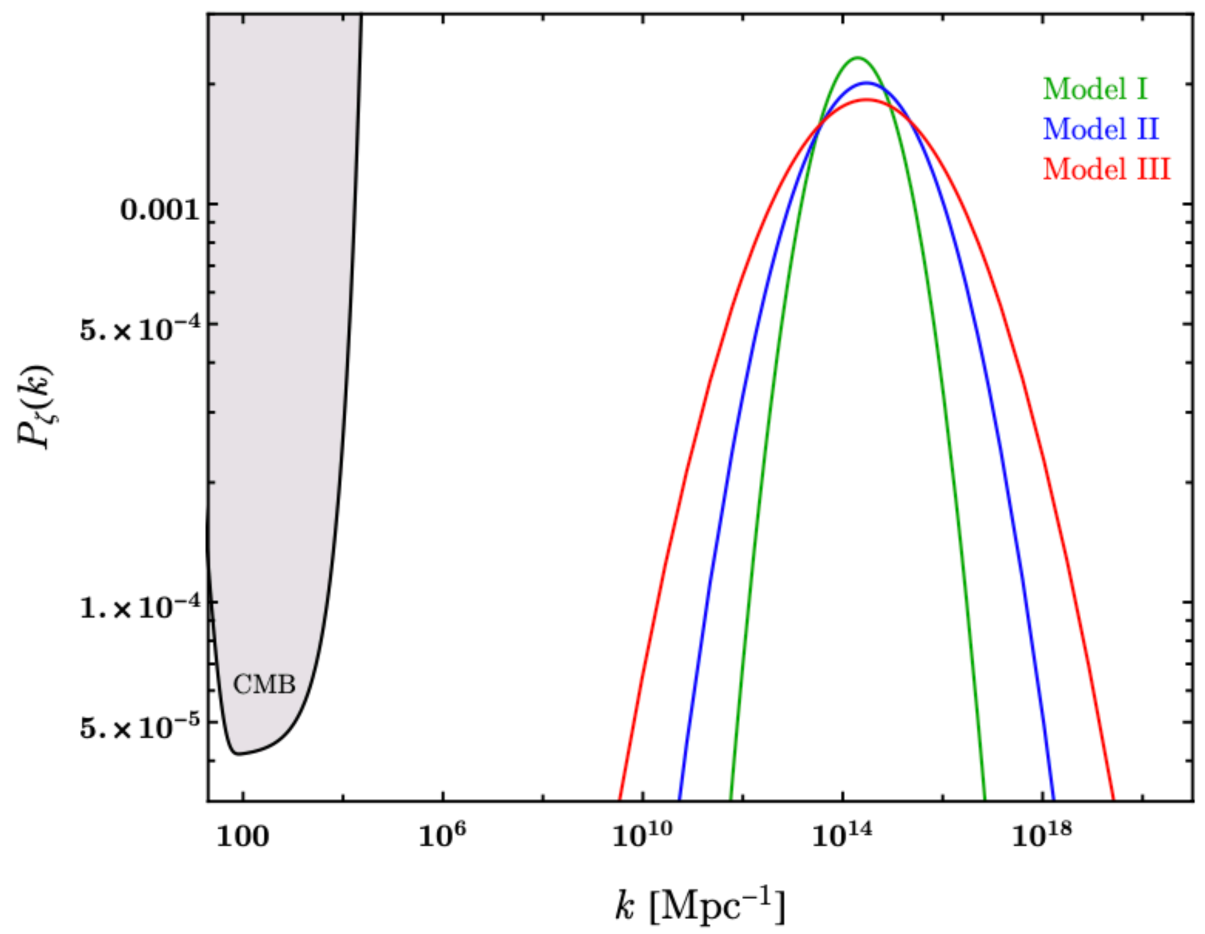


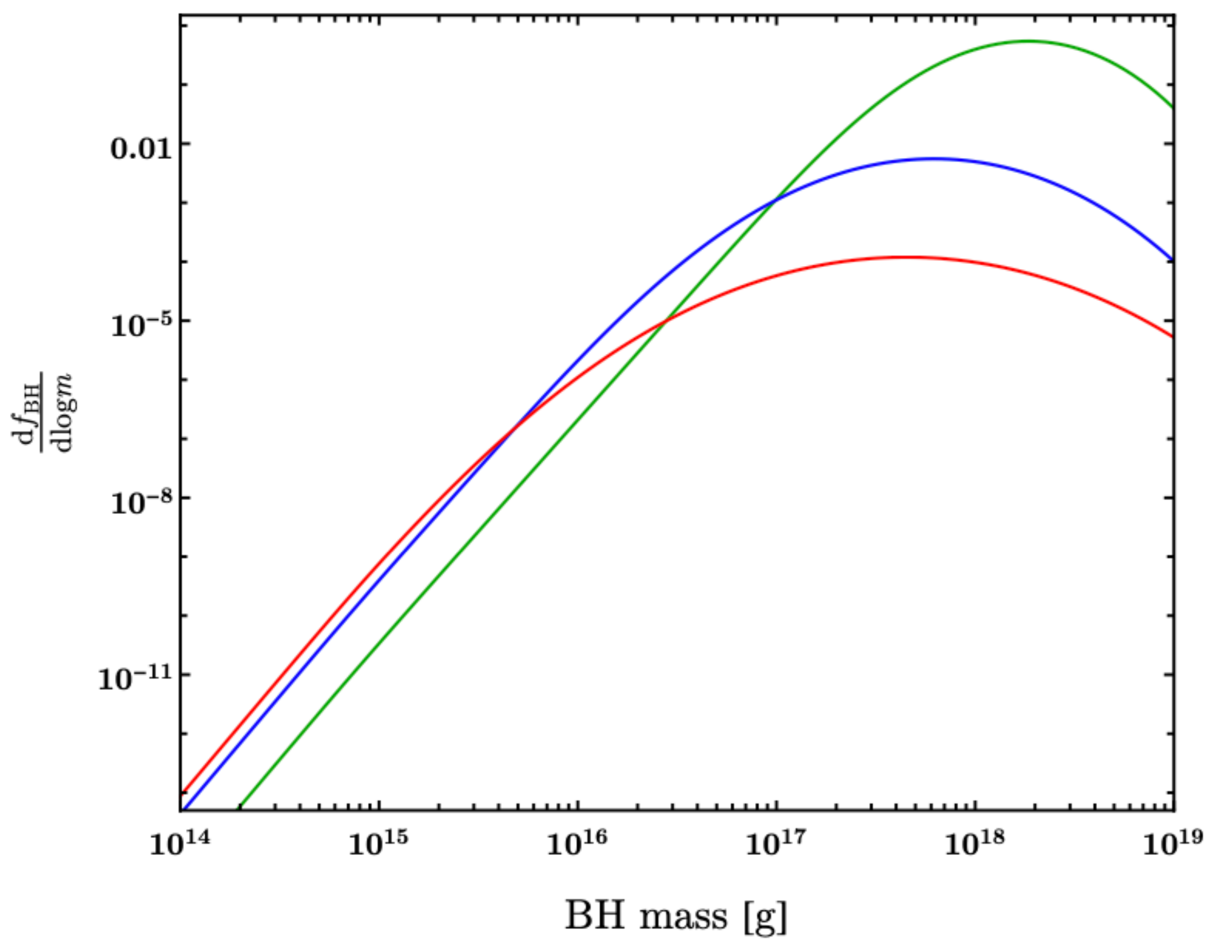
BBO, DECIGO, ET, …

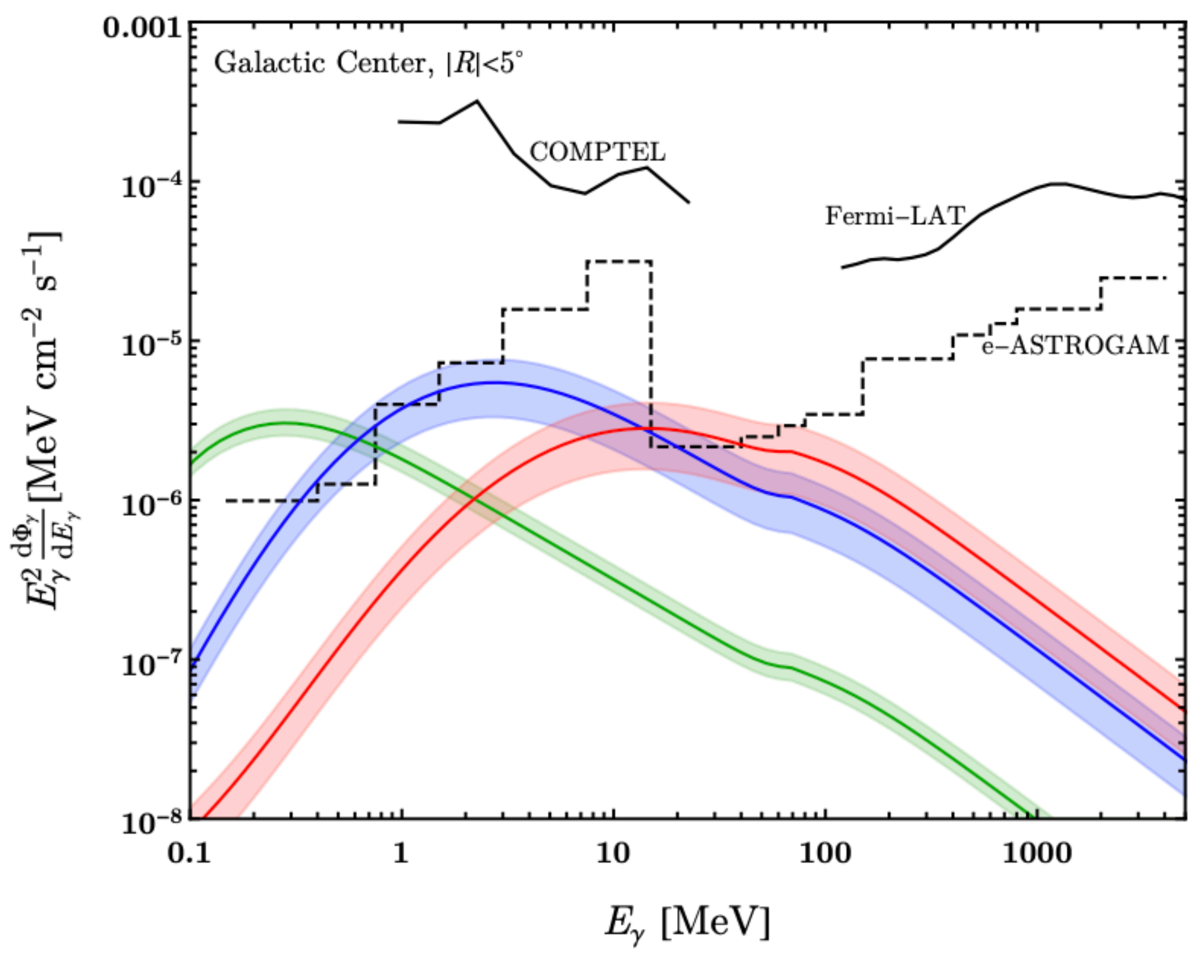
Assuming one of the log-normal $P_\zeta(k)$ example is real

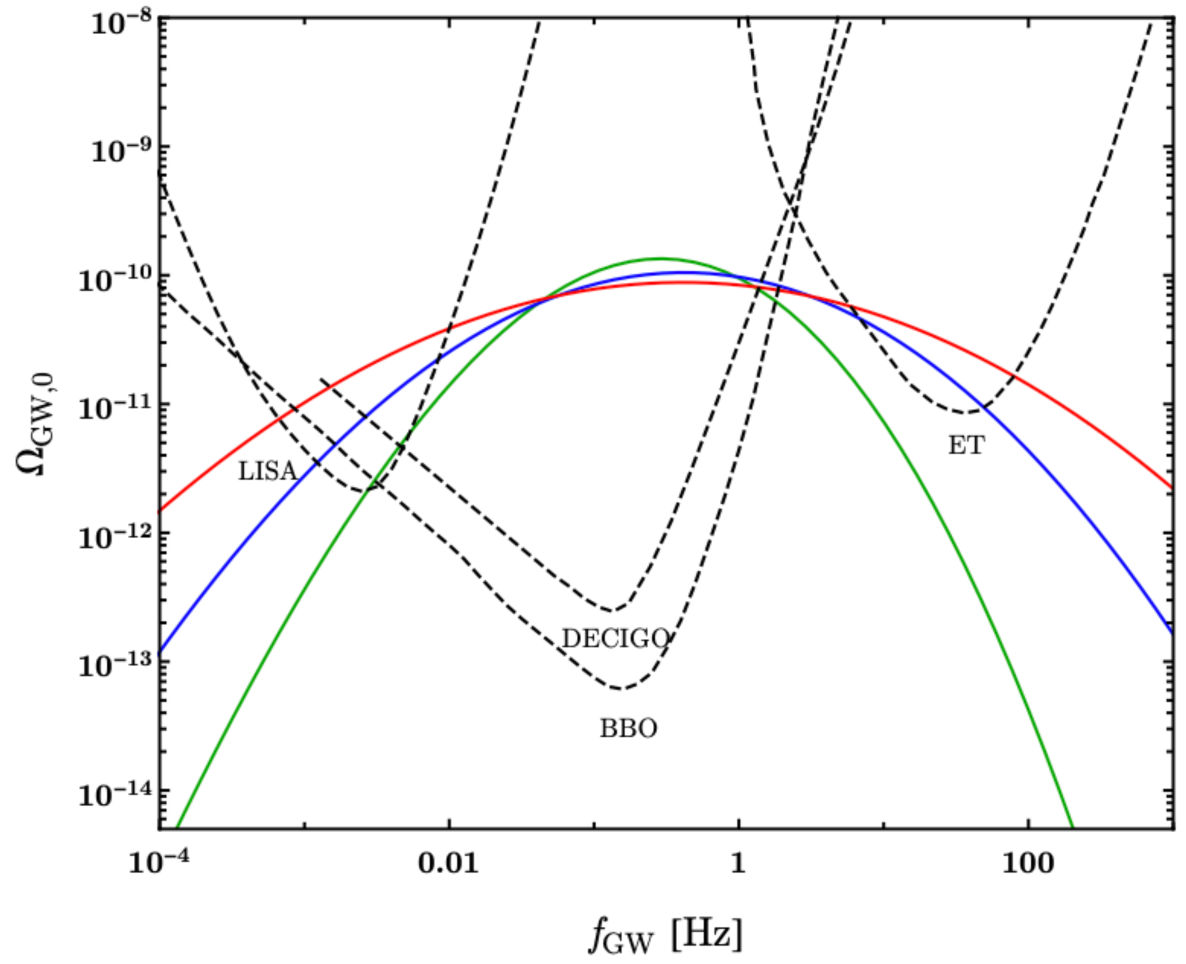
Model	σ	k_p [Mpc^{-1}]	$\log_{10} A$	$A(2\pi\sigma^2)^{-\frac{1}{2}}$	$f_{\mathrm{BH,total}}$	m^{peak} [g]	σ_m	γ_{eff}
I	2	2×10^{14}	-1.933	2.327×10^{-3}	1.0	1.8×10^{18}	0.76	3.6
II	3	3×10^{14}	-1.820	2.013×10^{-3}	1.4×10^{-2}	6.1×10^{17}	1.0	2.8
III	4	3×10^{14}	-1.737	1.827×10^{-3}	3.7×10^{-4}	4.5×10^{17}	1.2	2.0

Each give a “ true ” gamma-ray and GW spectrum



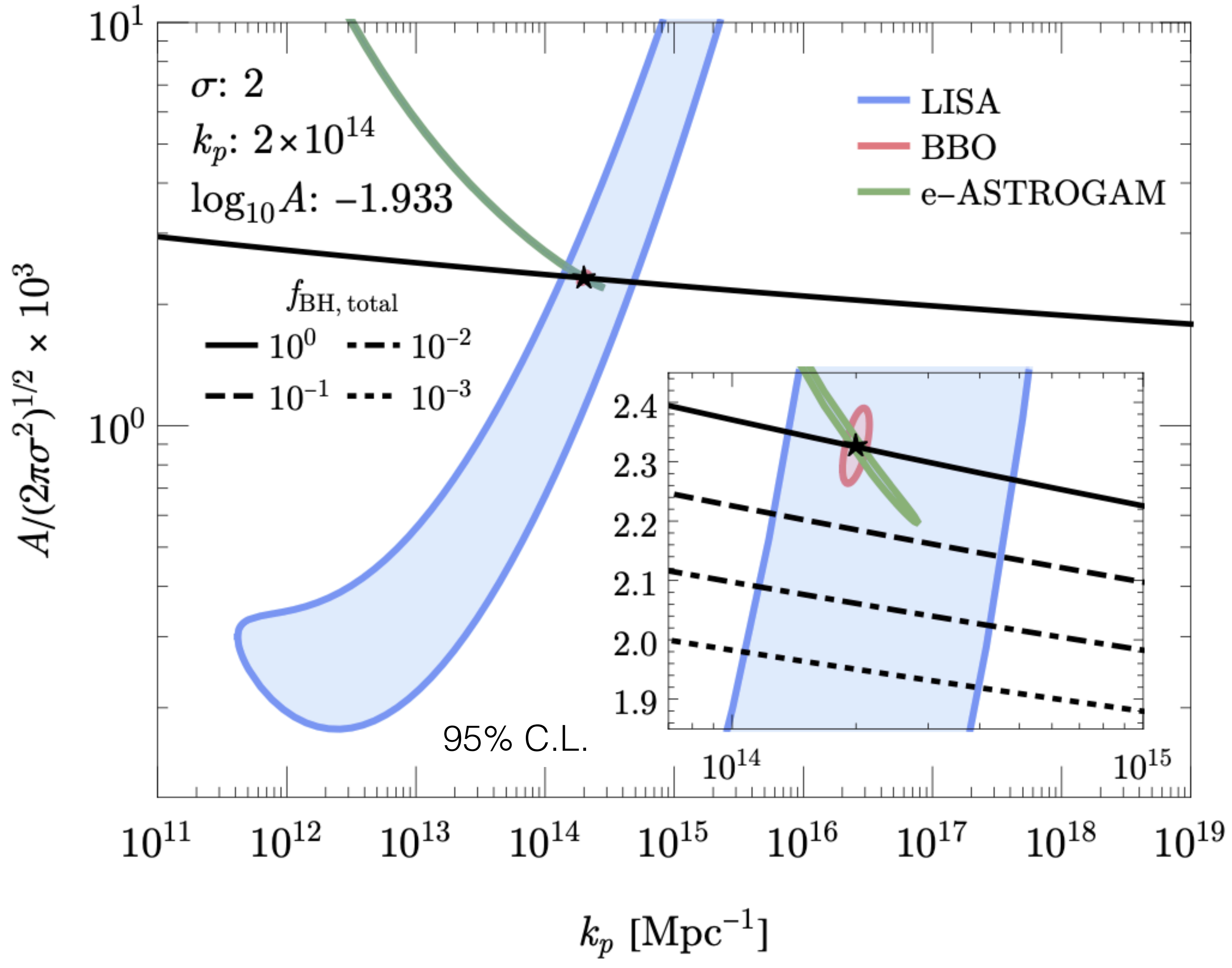


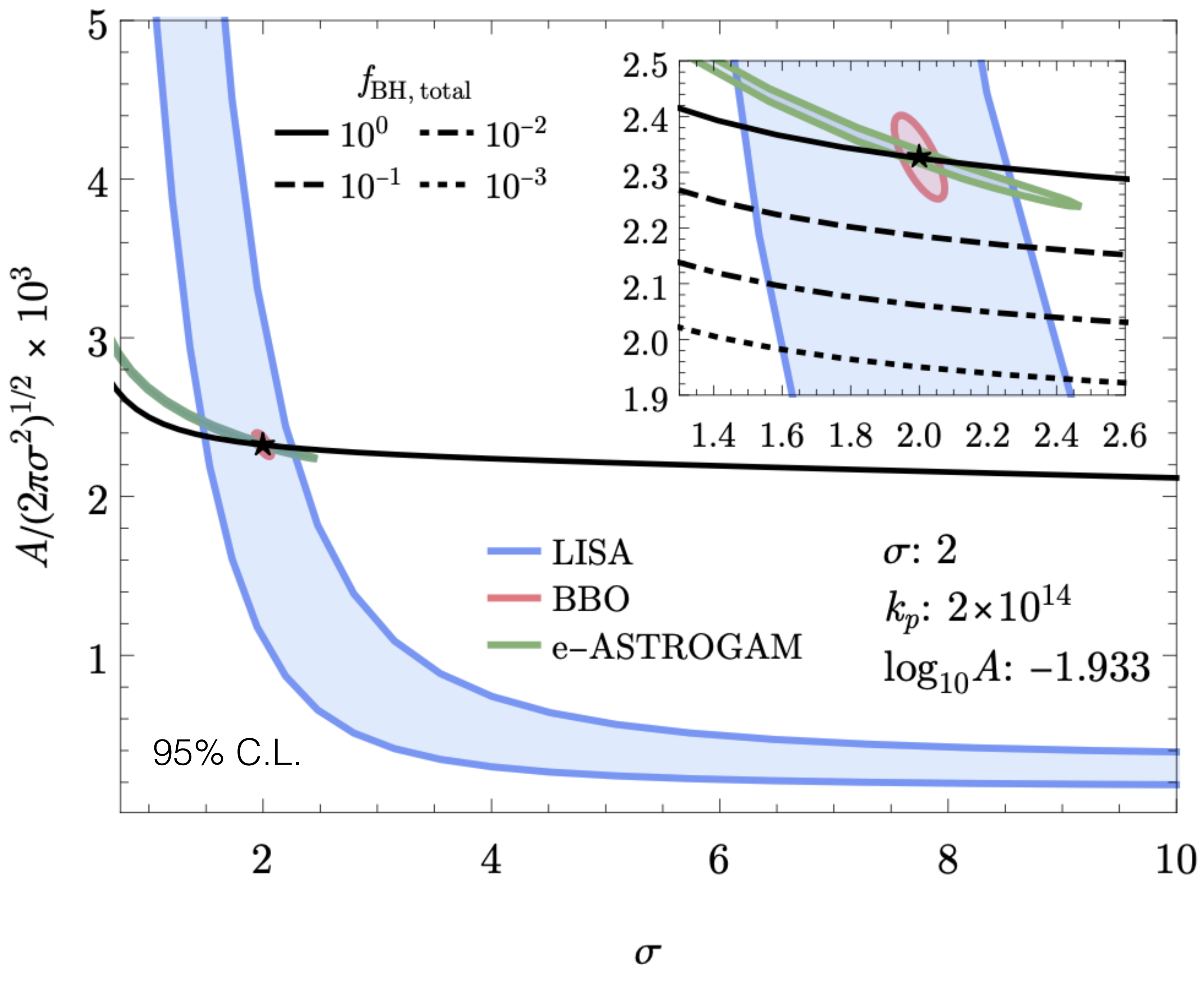




Question: how well can we measure the three $P_\zeta(k)$ parameters?

Model I (with a narrower $P_\zeta(k)$ $\sigma = 2$), capable of obtaining $f_{\rm BH} = 1$





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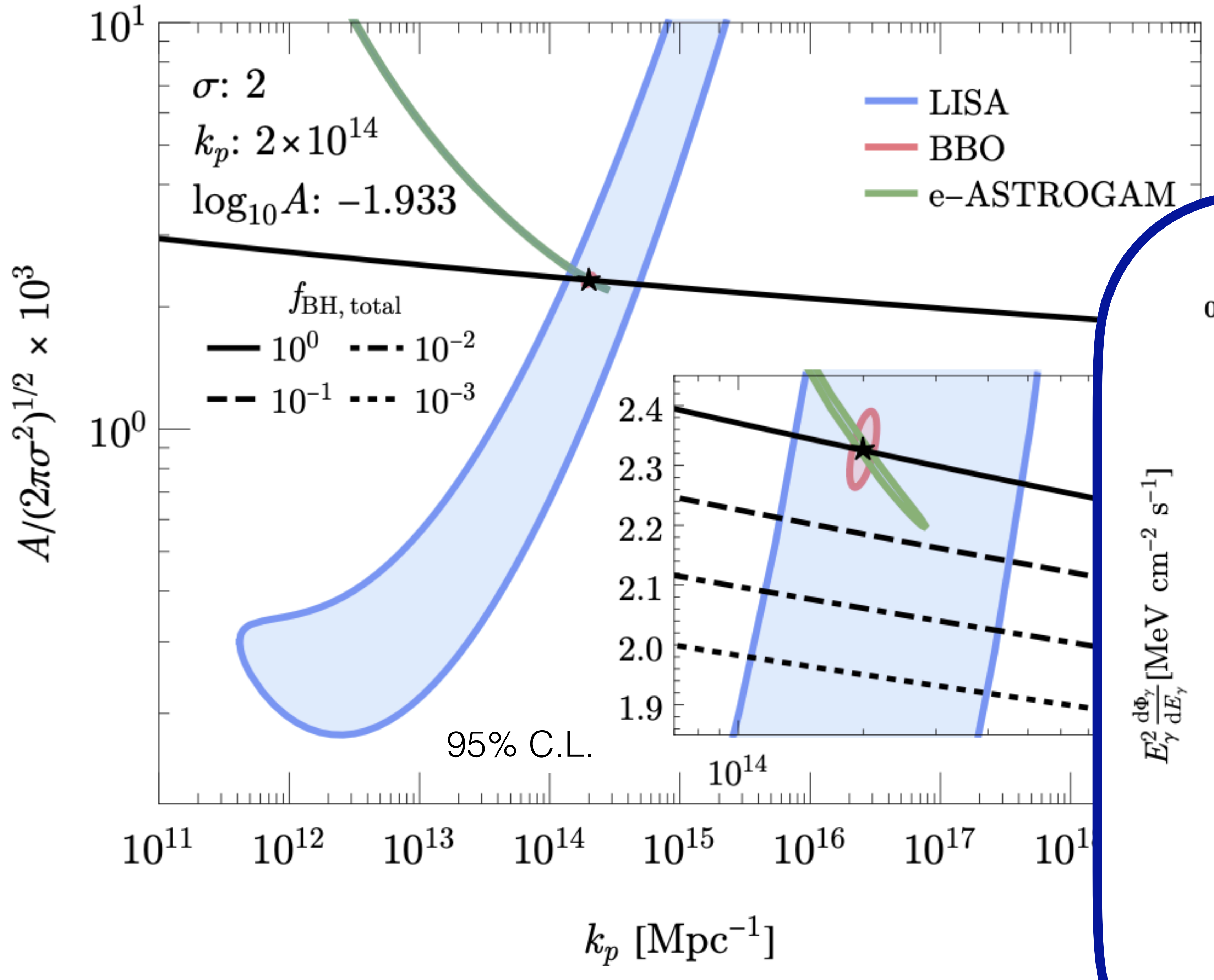
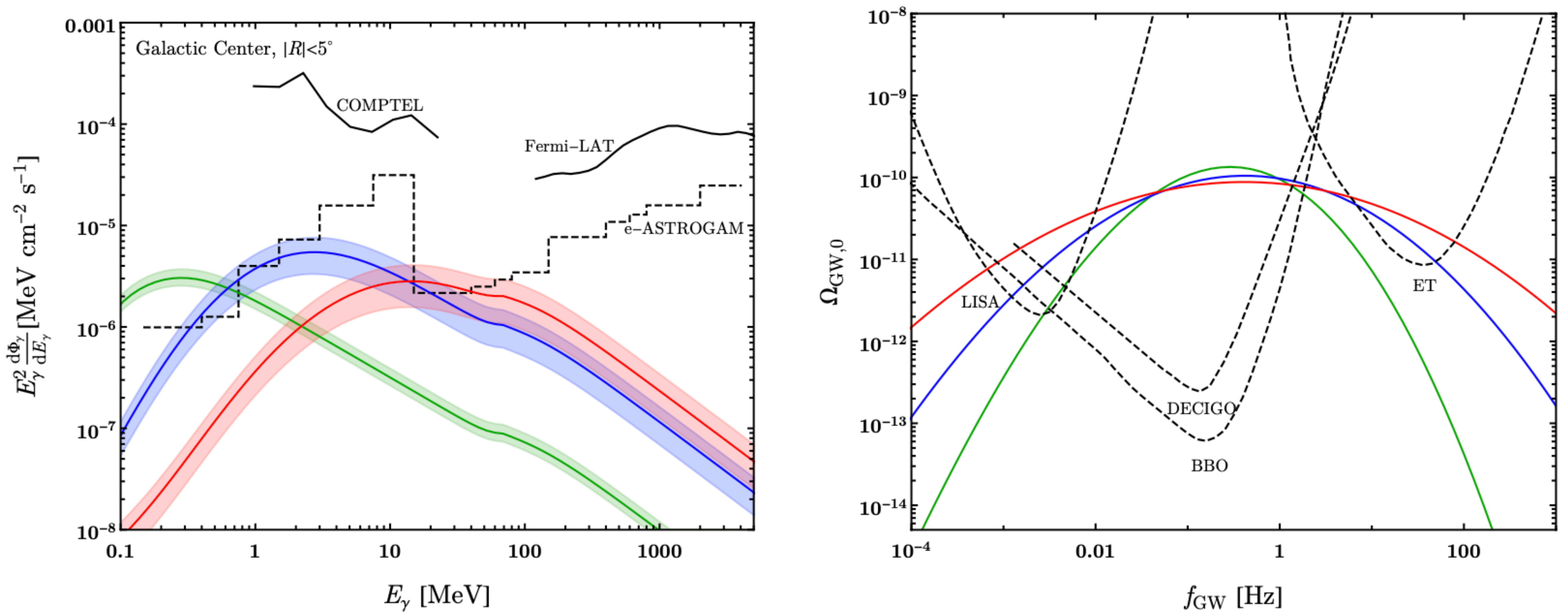
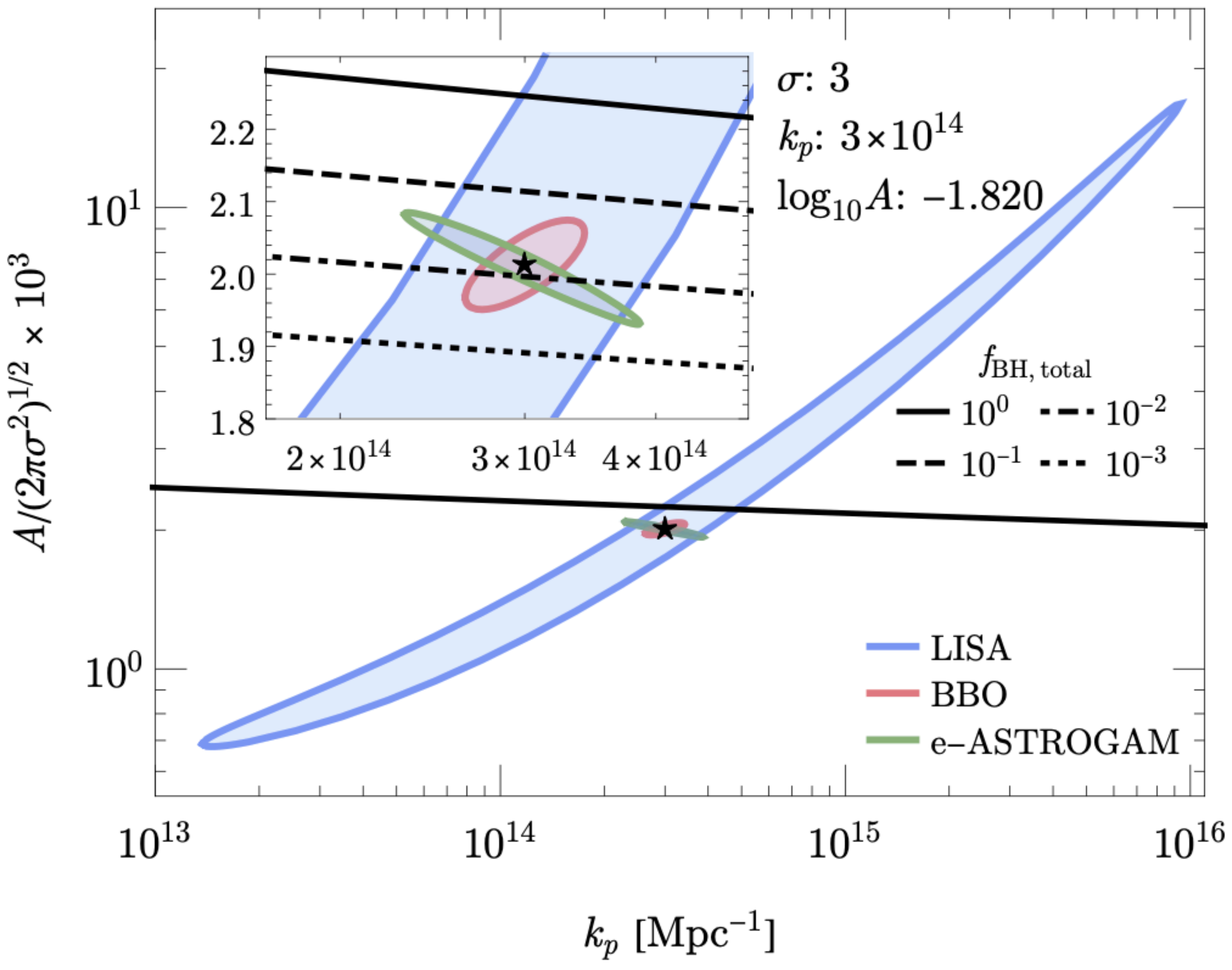


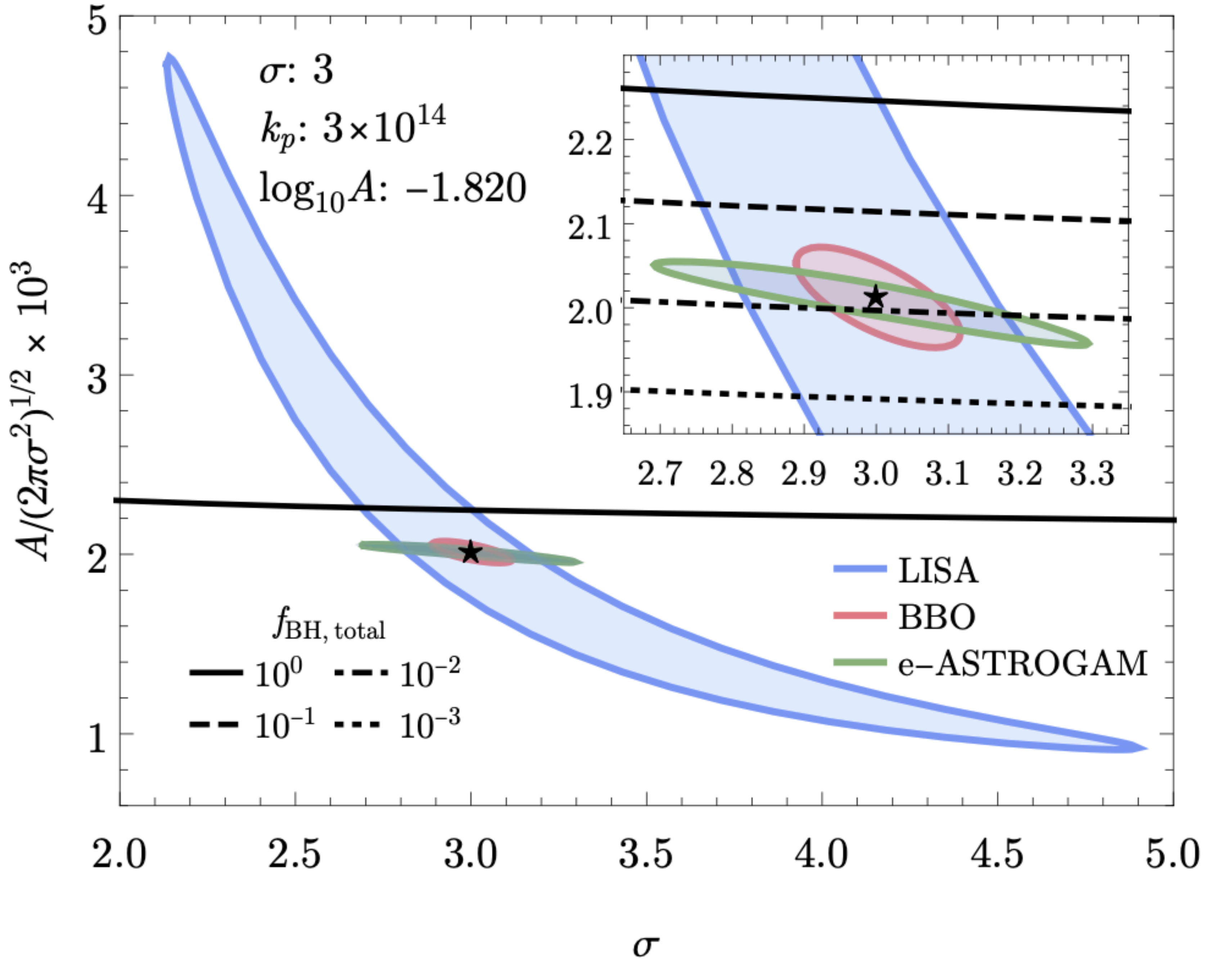
e-ASTROGAM & LISA has opposite directions for the $A - k_p$ degeneracy



Question: how well can we measure the three $P_\zeta(k)$ parameters?

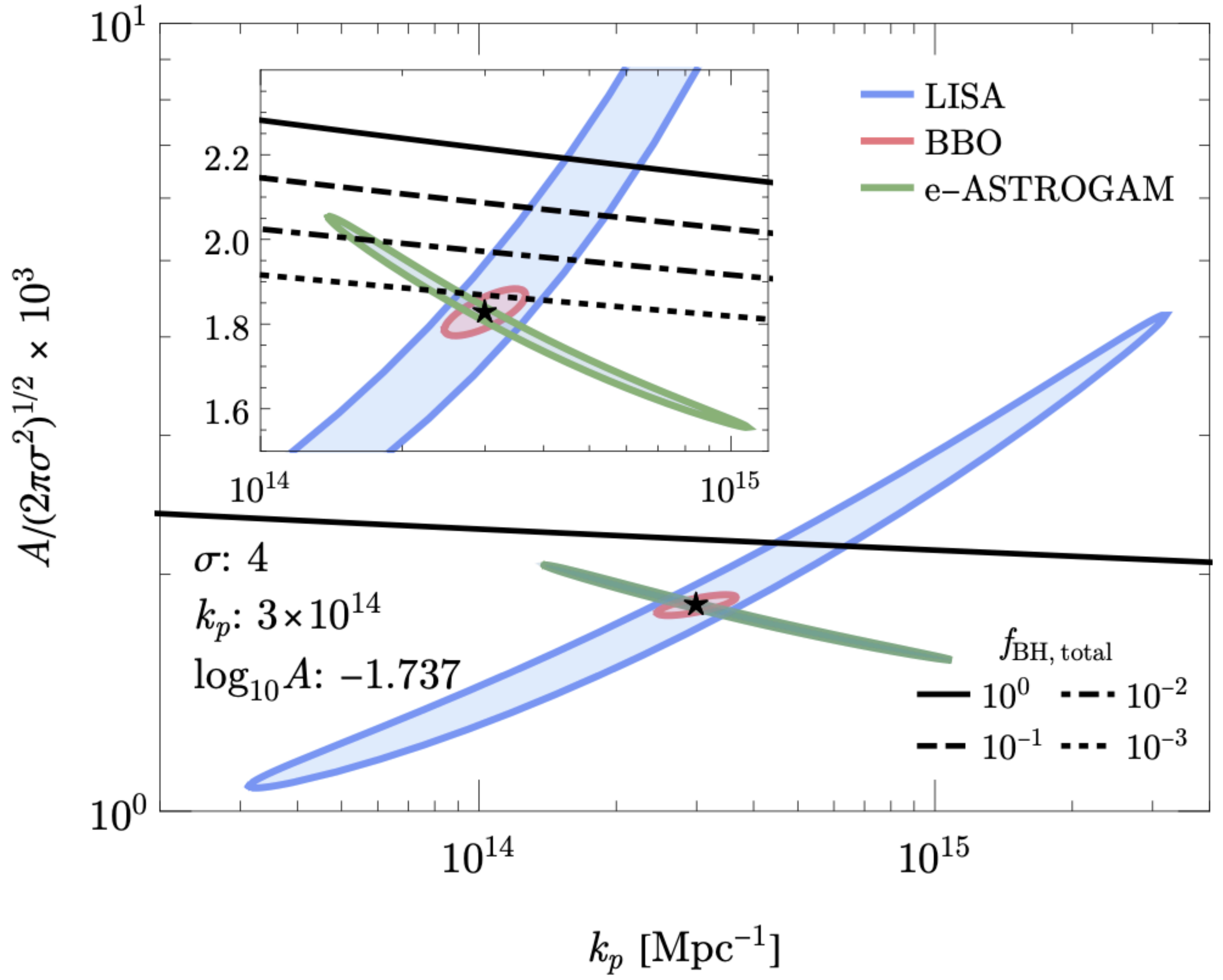
Model II (with $\sigma = 3$)

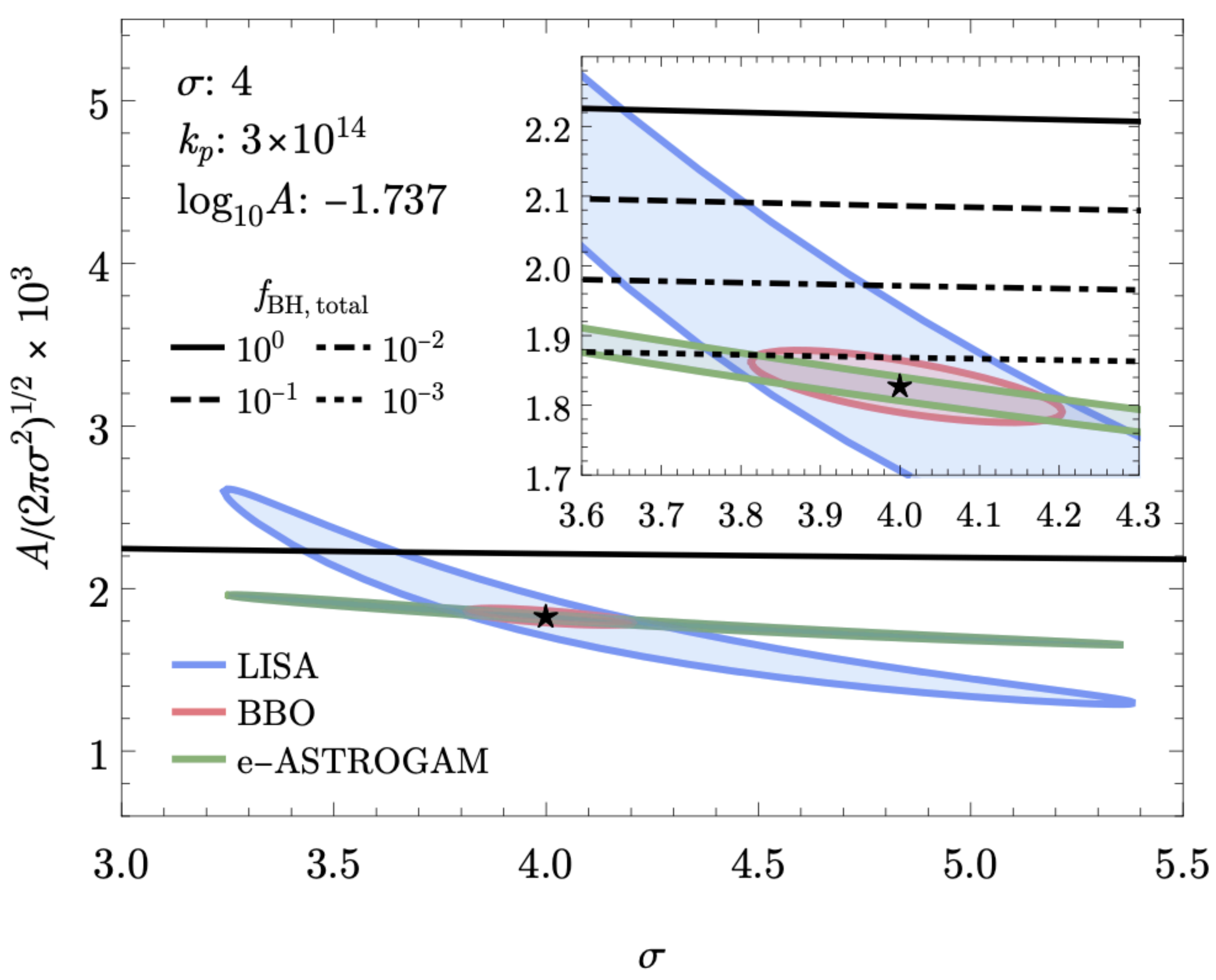




Question: how well can we measure the three $P_\zeta(k)$ parameters?

Model III (with $\sigma = 4$)





Conclusion

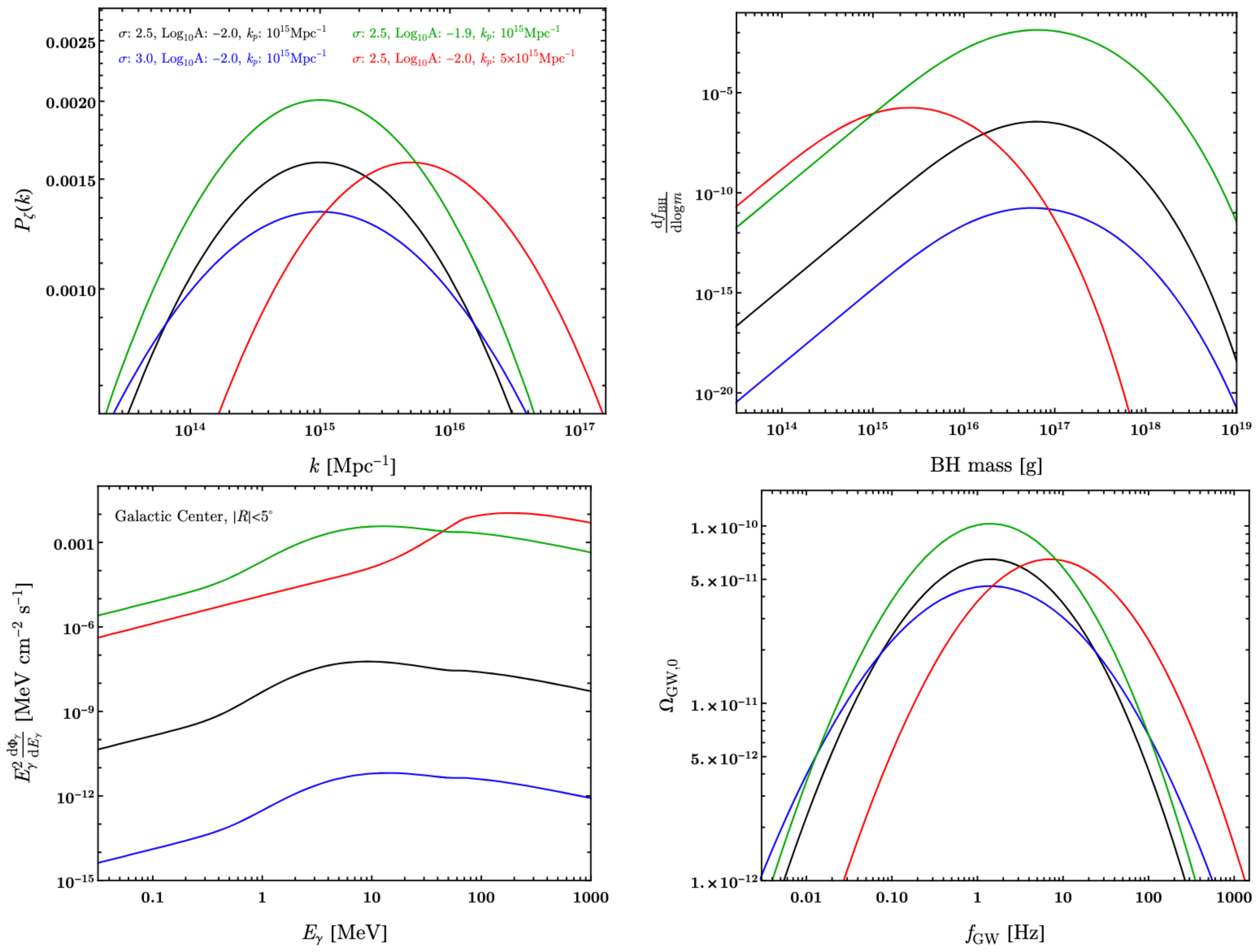
If we get to see the Hawking radiation at e-ASTROGAM from primordial black holes produced by density perturbations, we will see the GW signal produced by the same density perturbations at future detectors (BBO, DECIGO, LISA, ET)

Correlating the gamma-ray and GW signals allows a precise measurement of the primordial curvature power spectrum. This also leads to a smoking gun signal for distinguishing the PBH from other other gamma-ray sources

Different PBH production mechanisms, such as from the first order phase transition, predict different relations between gamma-ray & GW signals

Backup Slides

From $P_\zeta(k)$ to gamma-ray & GW spectra



$$m^{\rm peak} = \gamma_{\rm eff} M_H(R = k_p^{-1})$$

$$\simeq 2 \times 10^{16}\ {\rm g} \times \gamma_{\rm eff} \left(\frac{k_p}{10^{15}\ {\rm Mpc}^{-1}}\right)^{-2}$$

$$T_{\rm BH} = \frac{1}{8\pi G_N m} = 1.05 \left(\frac{10^{16}\,{\rm g}}{m}\right)\ {\rm MeV}$$

$$E_\gamma^{\rm peak} \approx 10\, T_{\rm BH}(m^{\rm peak})$$

$$\approx 1\,{\rm MeV} \left(\frac{5}{\gamma_{\rm eff}}\right) \left(\frac{k_p}{10^{15}\ {\rm Mpc}^{-1}}\right)^{2}$$

GW signals assuming different threshold δ_c