THE GRAVITATIONAL SUNYAEV-ZELDOVICH EFFECT AS A PROBE OF PRIMORDIAL BLACK HOLES AS DARK MATTER CANDIDATES

Marcell Howard

University of Pittsburgh

5th Year PhD Candidate

Pitt Pheno

JCAP01(2024)045/arXiv:2309.15925

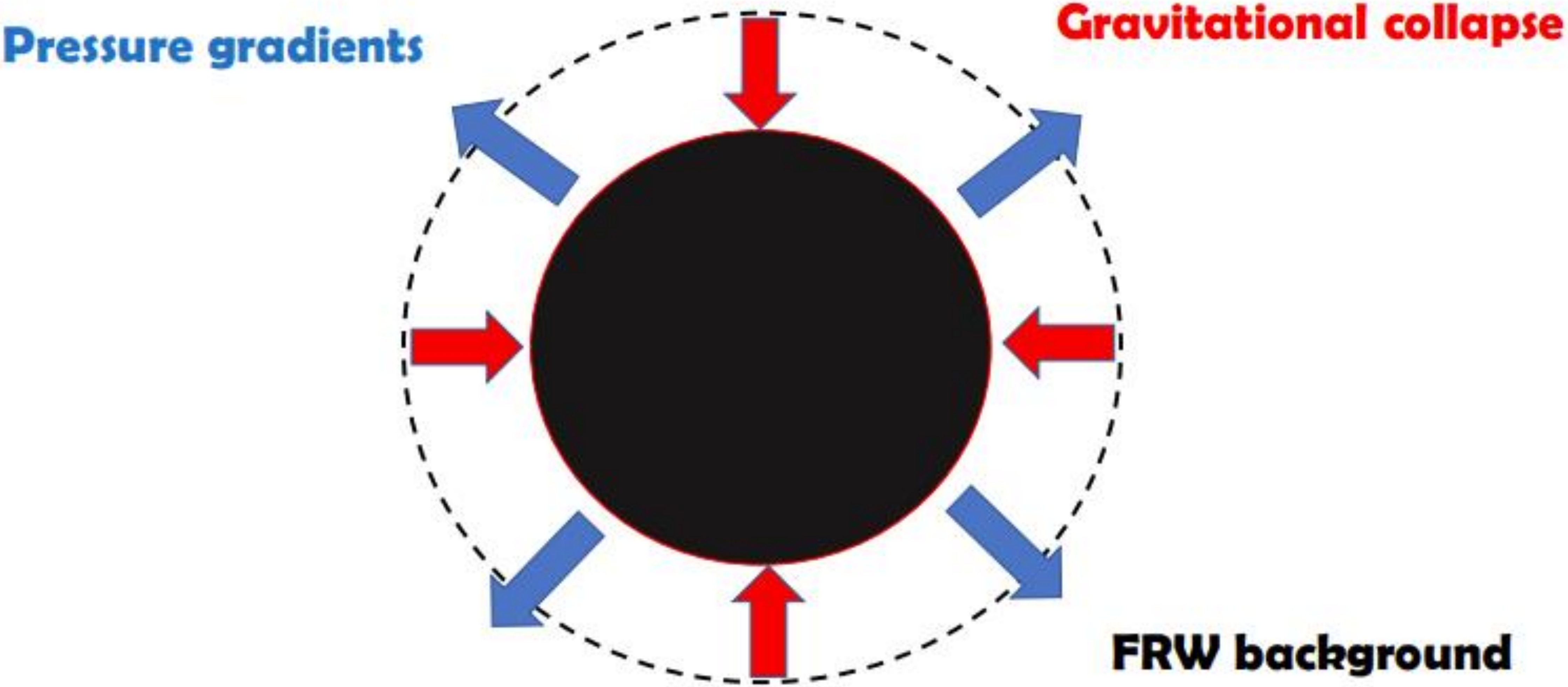
CO-AUTHOR

PRIMORDIAL BLACK HOLES

WHAT EVEN ARE PRIMORDIAL BLACK HOLES?

- Primordial black holes (PBHs) are black holes that formed before the first stars

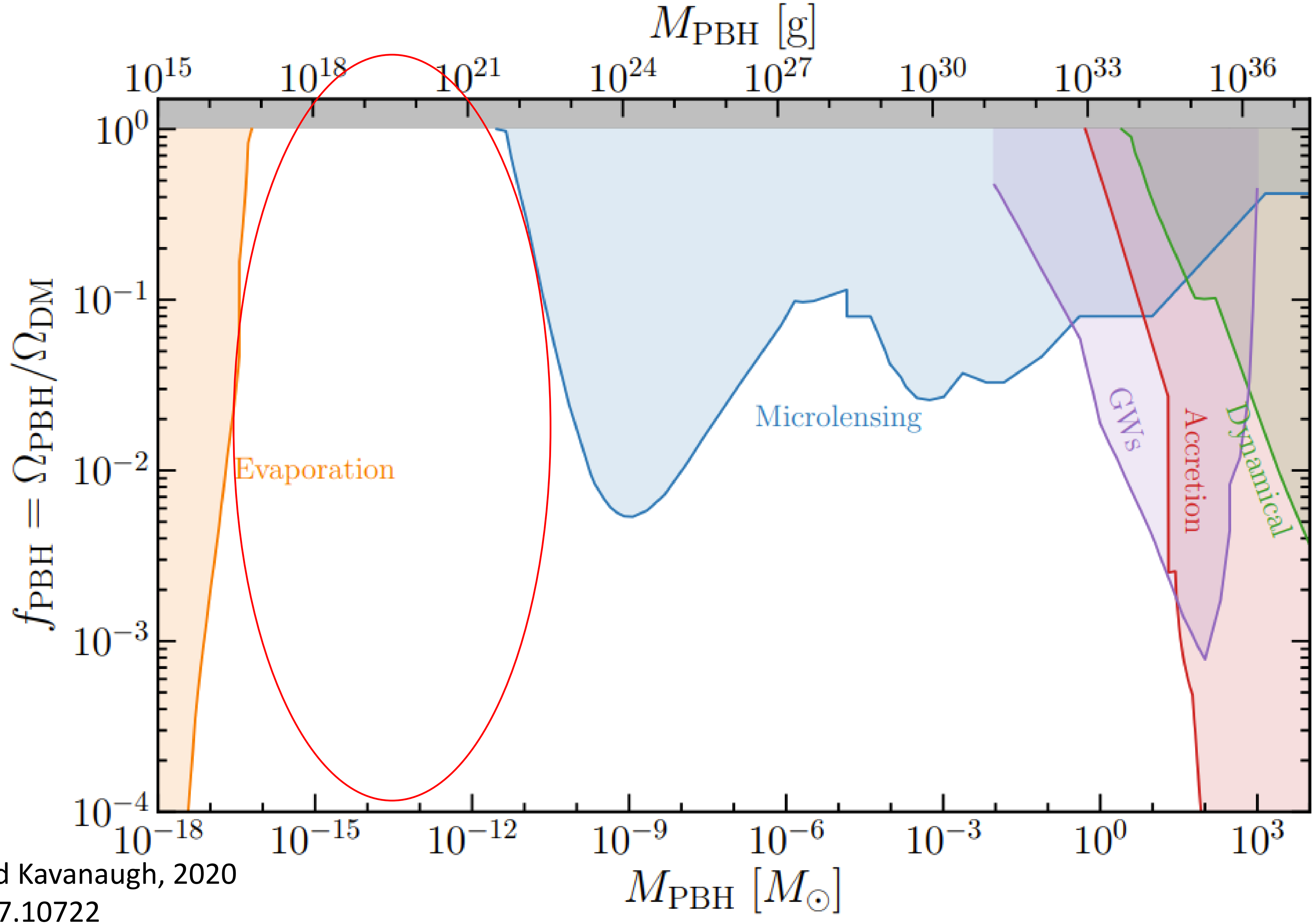
- PBHs can form with a wide range of masses
  - Conventional BHs can never be smaller than a solar mass



Escrivà, 2022, arXiv: 2111.12693

PBHS ARE INTERESTING FOR ALL SORTS OF REASONS!

- Probe of early universe homogeneity
- Potential seeds of current supermassive black holes
- Dark matter



Green and Kavanaugh, 2020
arXiv:2007.10722

STOCHASTIC GRAVITATIONAL WAVE BACKGROUNDS

STOCHASTIC GRAVITATIONAL WAVE BACKGROUNDS

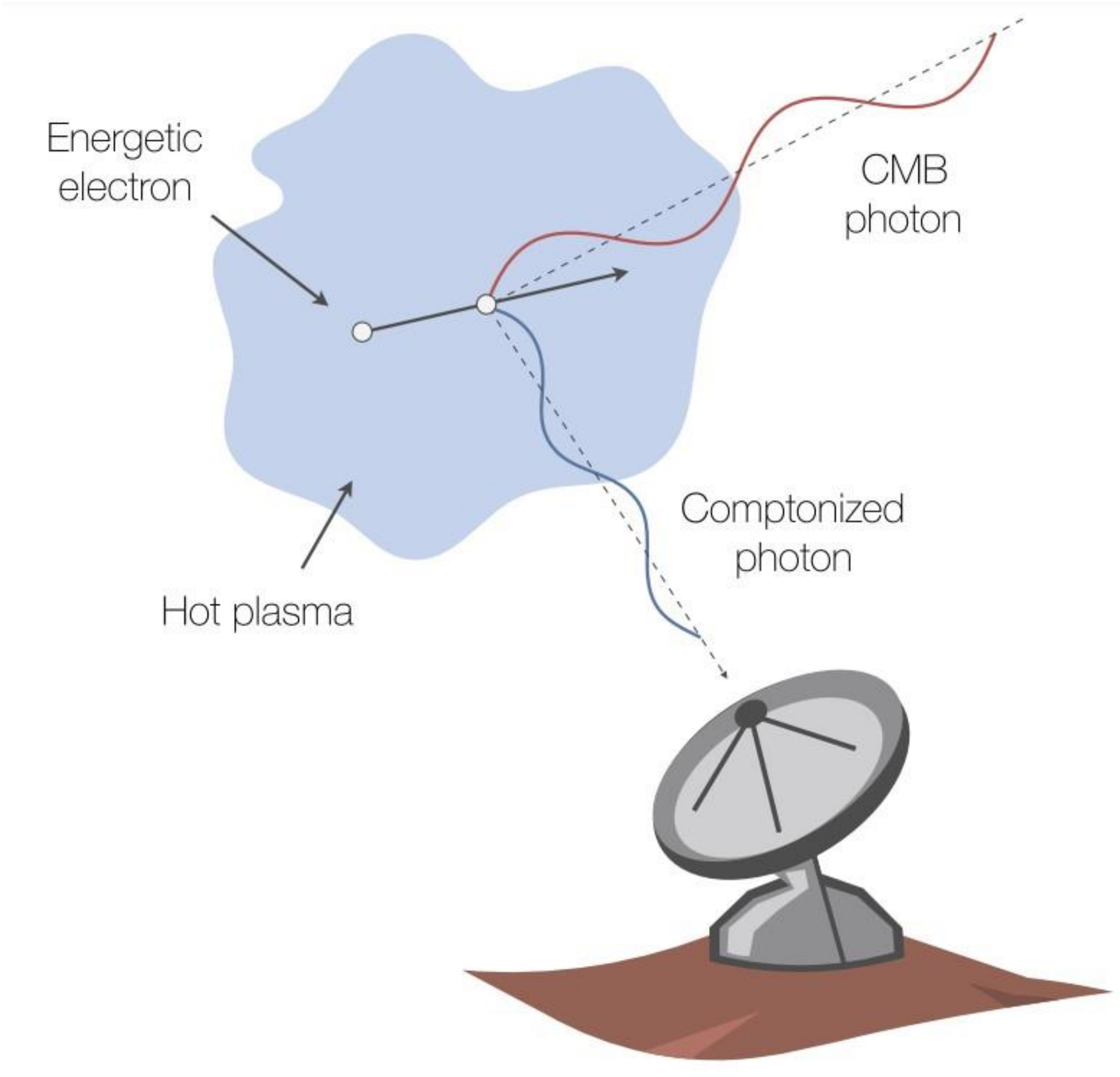
- Gravitational wave signals from unresolvable sources
- Astrophysical and Cosmological
- Many different potential sources for both:
  - Inflation, phase transitions, binary black hole mergers, and many more

WHY PRIMORDIAL GRAVITATIONAL WAVES ARE INTERESTING

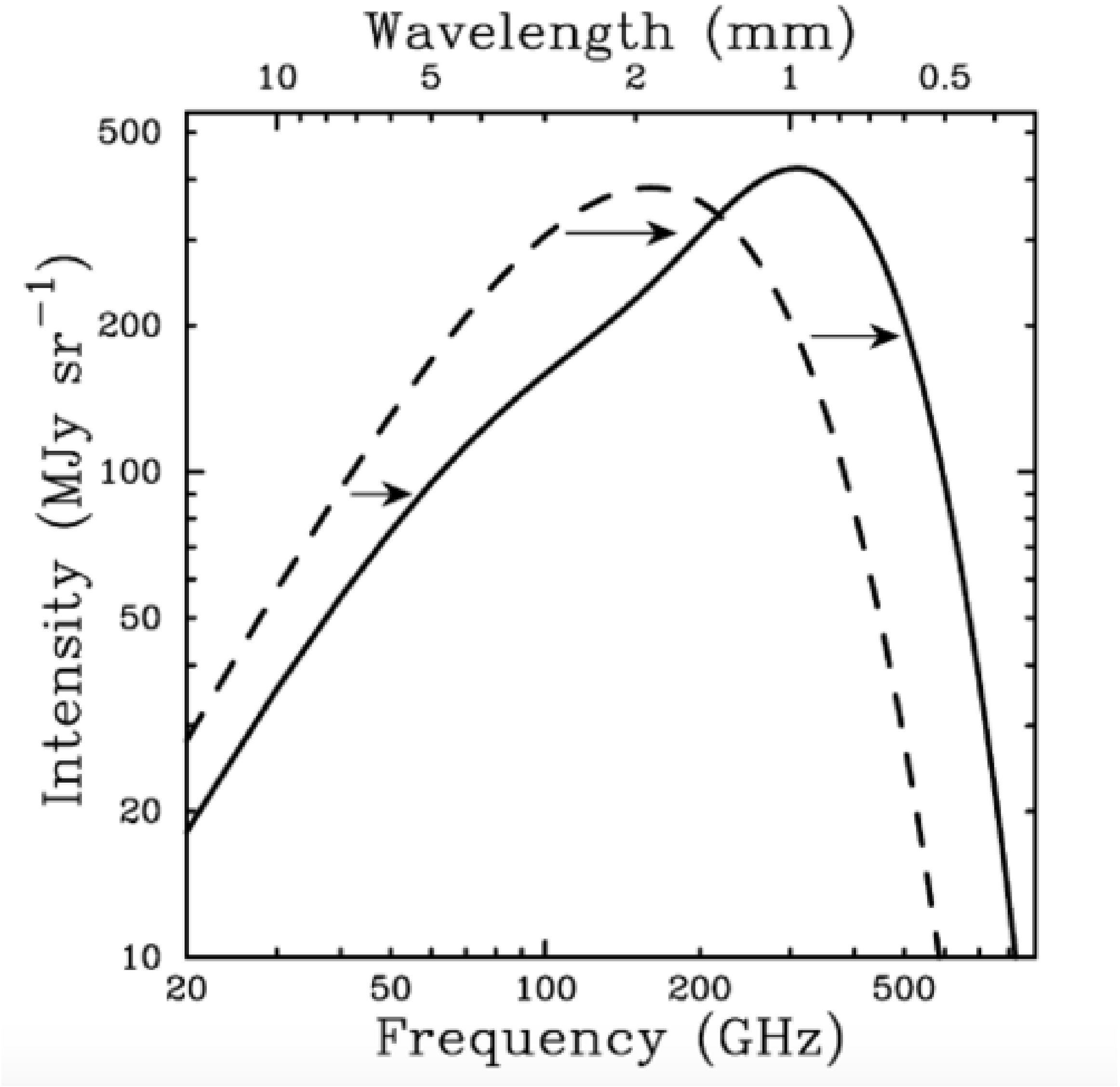
- Provides a direct signal of the very early universe

- Explore energy scales far beyond those accessible by other means

The Sunyaev-Zeldovich effect

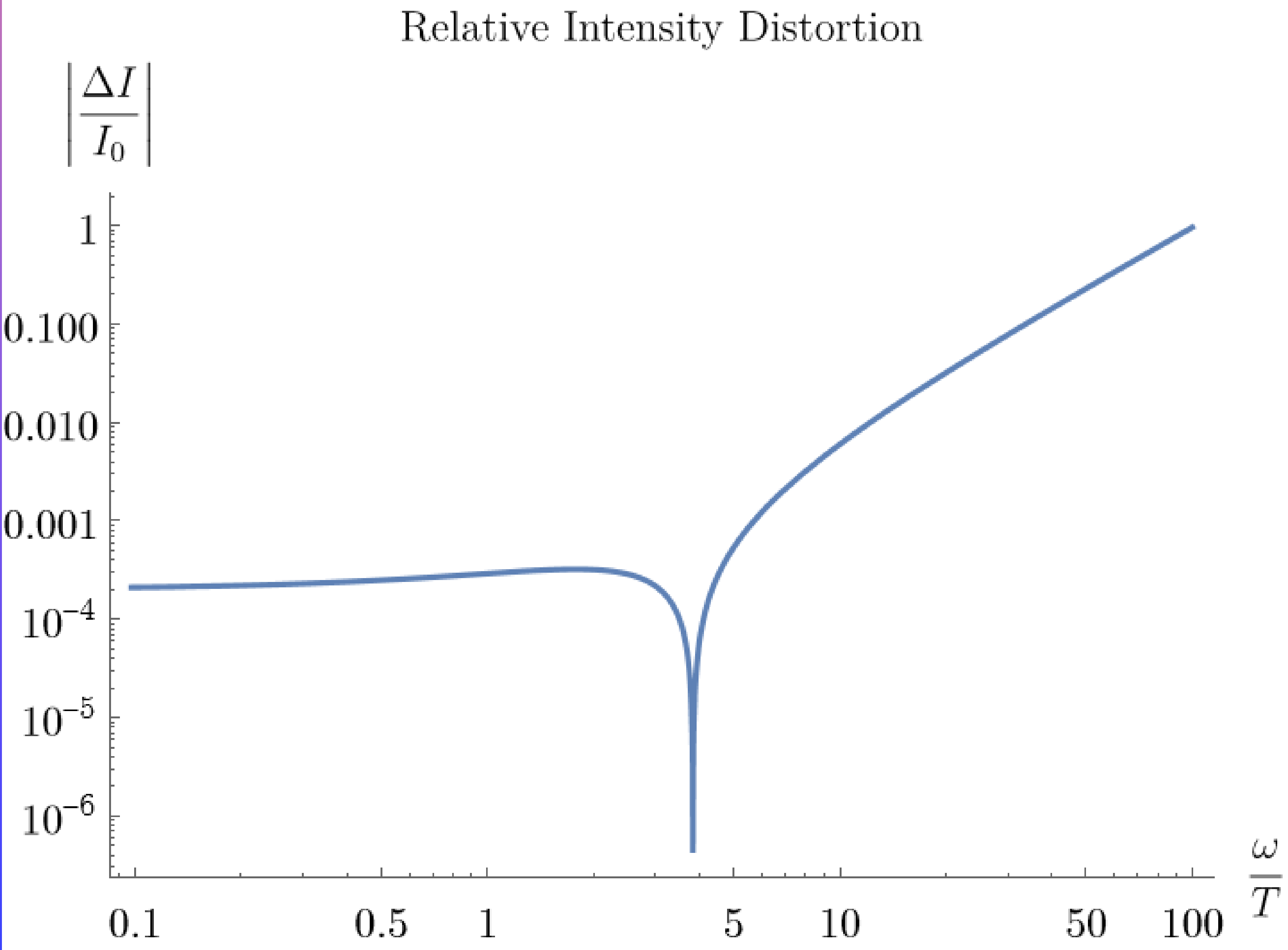


Mroczkowski et al. 2019



Carlstrom et al. 2002

KOMPANEETS EQUATION

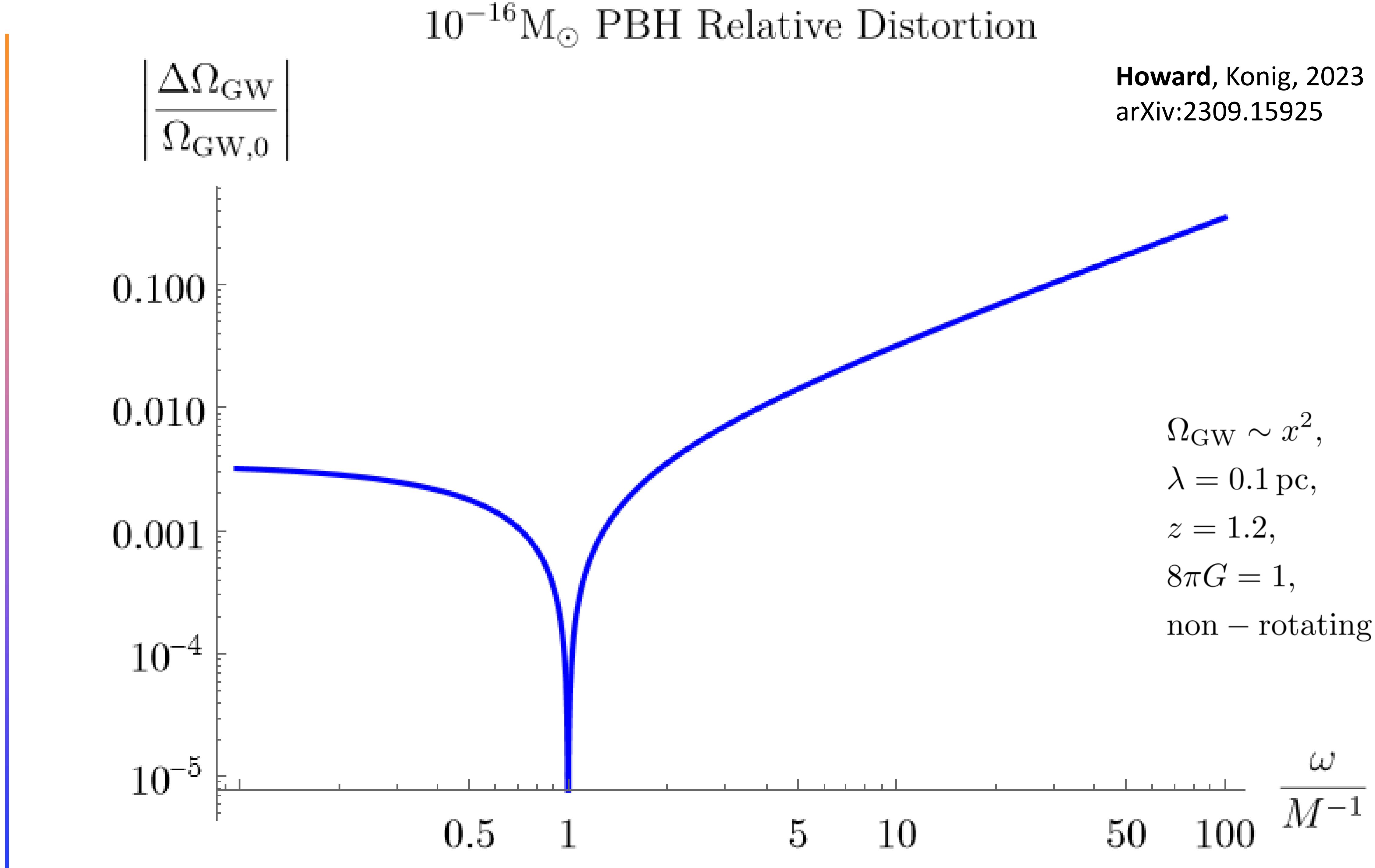


PBH AS DARK MATTER ASSUMPTIONS

- Non-relativistic $|\vec{p}| \ll M$
- Soft gravitons $\omega \ll M$
- Small energy shift $\frac{\omega' - \omega}{T_H} = x' - x \equiv \Delta \ll 1$
- Monochromatic mass function

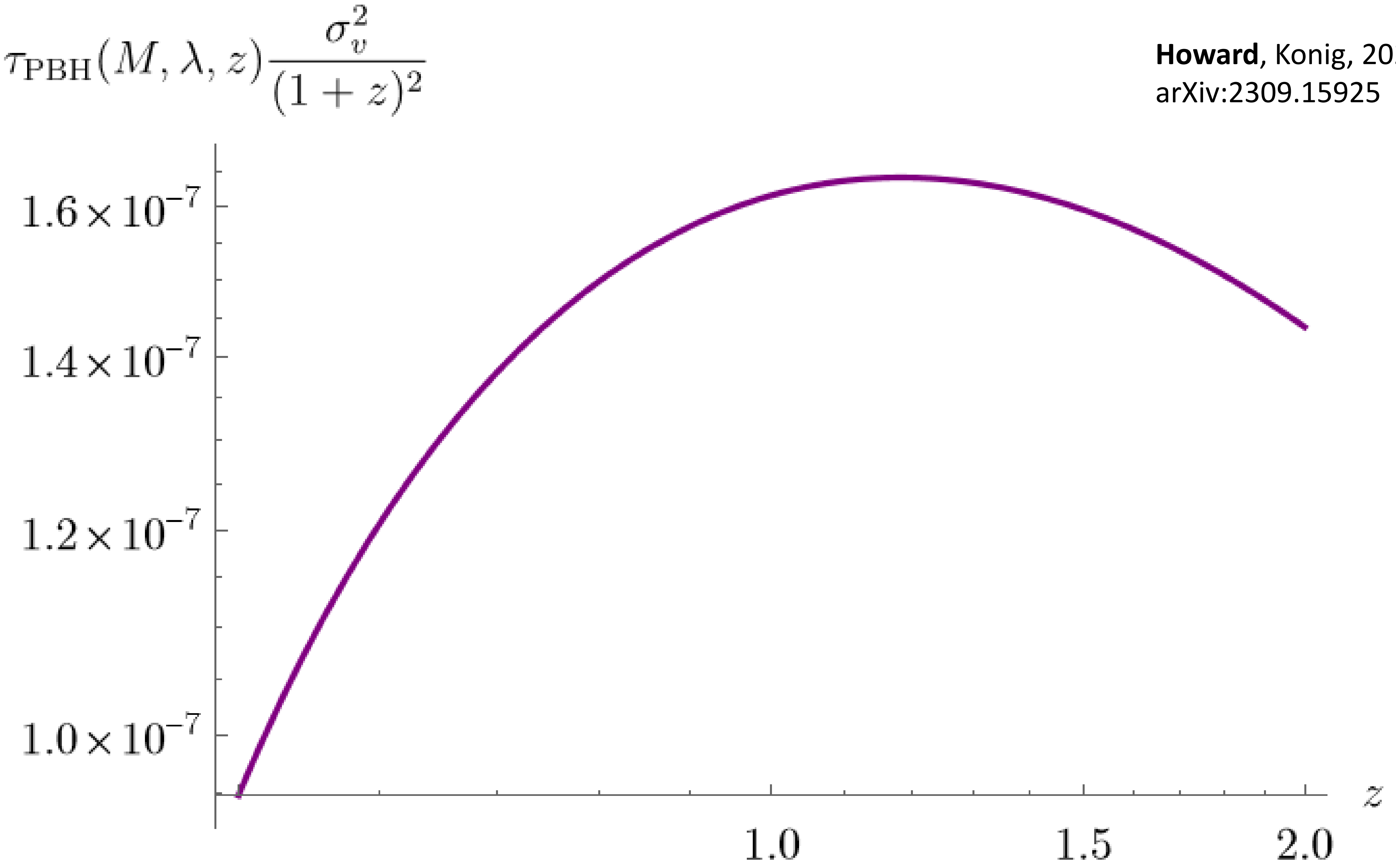
$$\mathcal{N}(\vec{p})\,\mathrm{d}^3\vec{p} = \frac{n_{\mathrm{PBH}}}{(\sqrt{2\pi}M\sigma_v)^3}\exp\left(-\frac{\vec{p}^2}{2M^2\sigma_v^2}\right)\mathrm{d}^3\vec{p}, \qquad \sigma_v = 200\,\mathrm{km/s}, \qquad n_{\mathrm{PBH}}(z) = \frac{\Omega_{\mathrm{CDM}}\rho_c(1+z)^3}{M}$$


200km/s


$10^{-16}M_\odot$ PBH Relative Distortion
$\left|\frac{\Delta\Omega_{GW}}{\Omega_{GW,0}}\right|$
0.100
0.010
0.001
10^{-4}
10^{-5}
0.5
1
5
10
50
100
$\frac{\omega}{M^{-1}}$
Howard, Konig, 2023
arXiv:2309.15925
$\Omega_{GW} \sim x^2$,
$\lambda = 0.1\,\mathrm{pc}$,
$z = 1.2$,
$8\pi G = 1$,
non − rotating

$10^{-16} M_\odot$ PBH Compton $- y$ parameter

Howard, Konig, 2023
arXiv:2309.15925



CHALLENGES FOR MEASUREMENT

- (Single-field) Inflation
  - Need to know the initial amplitude to better than 0.1%
  - Ceases to be a simple power-law after 25 e-folds (Caligiuri et al., 2015)

- Early universe phase transitions
  - Break in power law at high frequencies hard to disentangle early universe turbulence from late universe elastic scattering

Summary

- PBHs are black holes that formed before the first stars that are primarily thought to form from the collapse of primordial inhomogeneities
- The literature on the constraints of PBHs as dark matter candidates is vast and varied
- Cosmic gravitational wave backgrounds (if they can be measured) can provide another probe from scattering considerations

THANK YOU

Marcell Howard

mah455@pitt.edu

REFERENCES

- A. Escriv`a, PBH Formation from Spherically Symmetric Hydrodynamical Perturbations: A Review, Universe 8 (2022) 66.
- A.M. Green and B.J. Kavanagh, Primordial black holes as a dark matter candidate, Journal of Physics G Nuclear Physics 48 (2021) 043001.
- Review, Universe 8 (2022) 66J.E. Carlstrom, G.P. Holder and E.D. Reese, Cosmology with the Sunyaev-Zel’dovich effect, Annual Review of Astronomy and Astrophysics 40 (2002) 643.
- T Mrockowski et al., Astrophysics with the Spatially and Spectrally Resolved Sunyaev-Zeldovich Effects: A Millimetre/Submillimetre Probe of the Warm and Hot Universe, Space Science Reviews 215 (2018) 1.

GRAVITATIONAL KOMPANEETS EQUATION

$$\Delta n(x, z; 0) = yA_T \left[\tilde{J}_1(x, \lambda; 0) + \frac{1}{2}\tilde{J}_2(x, \lambda; 0) + \frac{\alpha(\tilde{J}_1(x, \lambda; 0) + \tilde{J}_2(x, \lambda; 0))}{x} + \frac{\alpha(\alpha - 1)\tilde{J}_2(x, \lambda; 0)}{2x^2} \right] x^\alpha$$

$$J_\ell(x, \lambda; s) = 2\pi \int_{\theta_{\min}(\lambda)}^{\theta_{\max}} \sin\theta \, \mathrm{d}\theta \int \mathrm{d}^3\mathbf{p} \left(1 - \frac{\mathbf{p}}{m} \cdot \hat{\mathbf{n}}\right) \frac{\mathrm{d}\sigma_s(\mathbf{p}, x, \theta)}{\mathrm{d}\theta} \mathcal{N}(\mathbf{p}) \Delta^\ell(x, \theta)$$

$$\mathcal{N}(\mathbf{p}) \, \mathrm{d}^3\mathbf{p} = \frac{n_{\mathrm{PBH}}}{(\sqrt{2\pi} M \sigma_v)^3} \exp\left(-\frac{\mathbf{p}^2}{2M^2\sigma_v^2}\right) \mathrm{d}^3\mathbf{p}$$

GRAVITATIONAL COMPTON CROSS SECTION

$$\sigma_{\mathrm{GC}}(M,\lambda) = 2\pi(GM)^2 \int_{\theta_{\min}(\lambda)}^{\theta_{\max}} \mathrm{d}\theta \left[\cot^4\left(\frac{\theta}{2}\right)\cos^4\left(\frac{\theta}{2}\right) + \sin^4\left(\frac{\theta}{2}\right)\right] \simeq \frac{4\pi(GM)^2}{b^2}$$

$$b = \sin\left((2GM/\lambda)^{2/3}/2\right) \approx (2GM/\lambda)^{2/3}/2$$

INFRARED DIVERGENCE OF LOW ENERGY COULOMB SCATTERING

- The cross section has an infrared divergence due to Coulomb scattering:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto \frac{1}{\theta^4}, \quad \text{for} \quad \theta \to 0$$

- Introduce a cutoff at Geometric Optics limit:

$$\theta_{\mathrm{min}} = \frac{2r_s}{b_{\mathrm{max}}}, \qquad b_{\mathrm{max}} = (2\sqrt{3}\lambda^2 r_s)^{\frac{1}{3}}, \qquad r_s = 2GM$$