Title: Using LISA-like Gravitational Wave Detectors to Search for Primordial Black Holes

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Abstract: <p>Primordial black hole (PBH), which can be naturally produced in the early universe, remains a promising dark matter candidate . It can merge with a supermassive black hole (SMBH) in the center of a galaxy and generate gravitational wave (GW) signals in the favored frequency region of LISA-like experiments. In this work, we initiate the study on the event rate calculation for such extreme mass ratio inspirals (EMRI). Including the sensitivities of various proposed GW detectors, we find that such experiments offer a novel and outstanding tool to test the scenario where PBH constitutes (fraction of) dark matter. The PBH energy density fraction of DM (fPBH) could potentially be explored as small as 10^âˆ'3âˆ¼10^âˆ'4. Further, LISA has the capability to search for PBH mass upto 10^âˆ'2âˆ¼10^âˆ'1 solar mass. Other proposed GW experiments can probe lower PBH mass regime.</p>

# Using LISA-like Gravitational Wave Detectors to Search for Primordial Black Holes

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arXiv:1709.03500 [astro-ph.CO]
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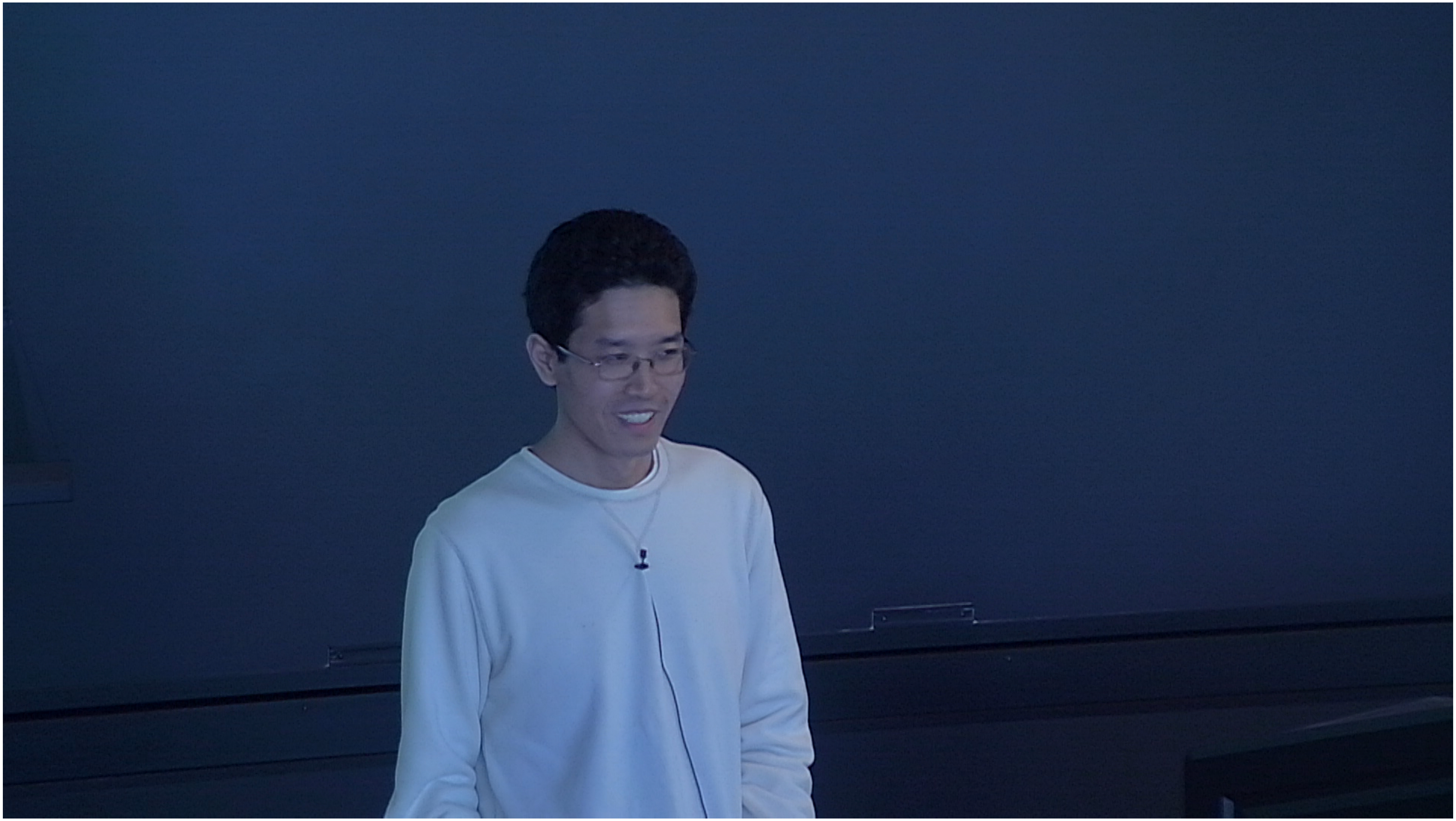


# ~~Searching for Confining Hidden Valleys at the LHC(b)~~

"Nobody here cares about this topic!!!"

------ a postdoc at PI

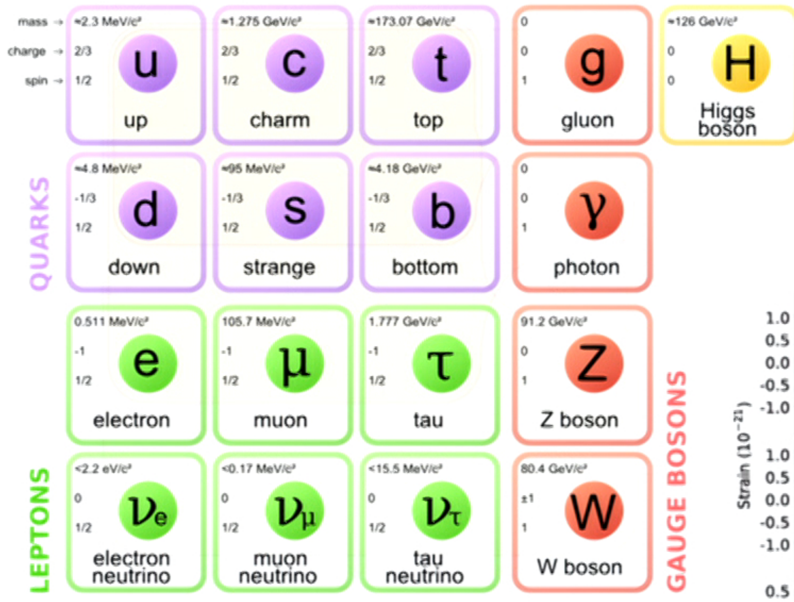
Yue Zhao

MCTP, University of Michigan

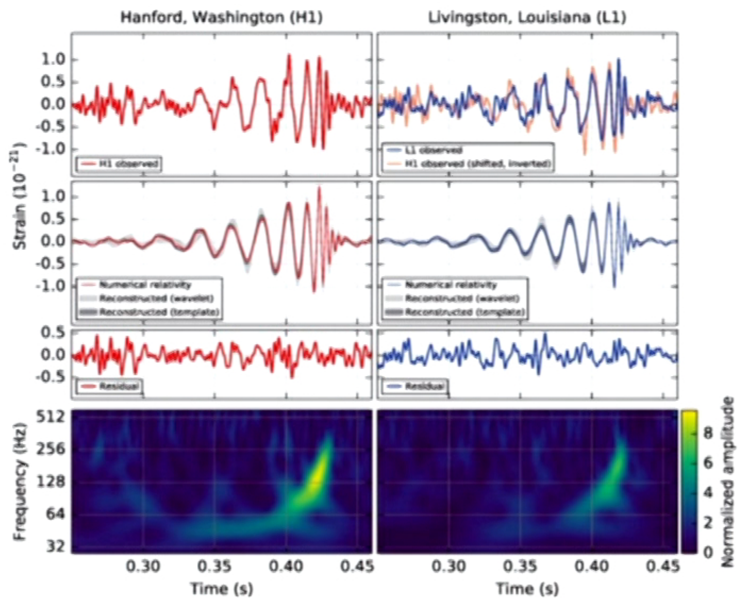
Perimeter Institute

with Aaron Pierce, Bibhushan Shakya, Yuhsin Tsai
arXiv:1708.05389 [hep-ph]

# Current Status of Particle Physics:



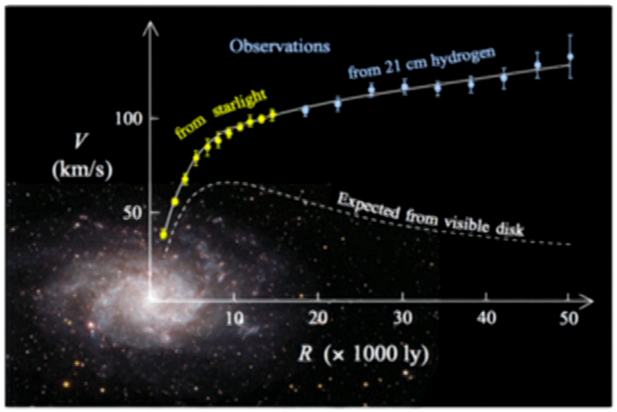

+ Dark Sector?



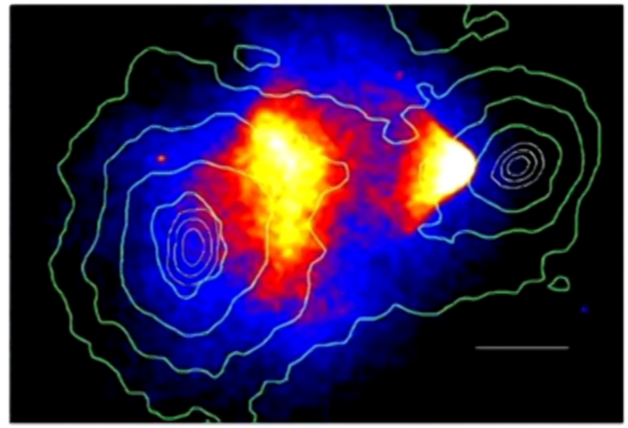
# Dark Matter Overview:

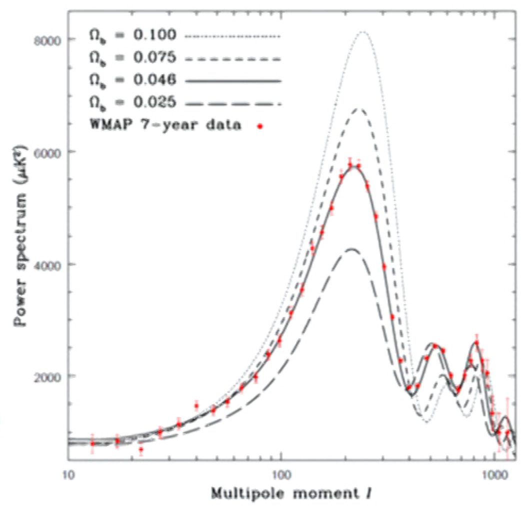
## Why do we need DM?

• Galaxy rotation curve (Wikipedia)




• Bullet Cluster (Deep Chandra)



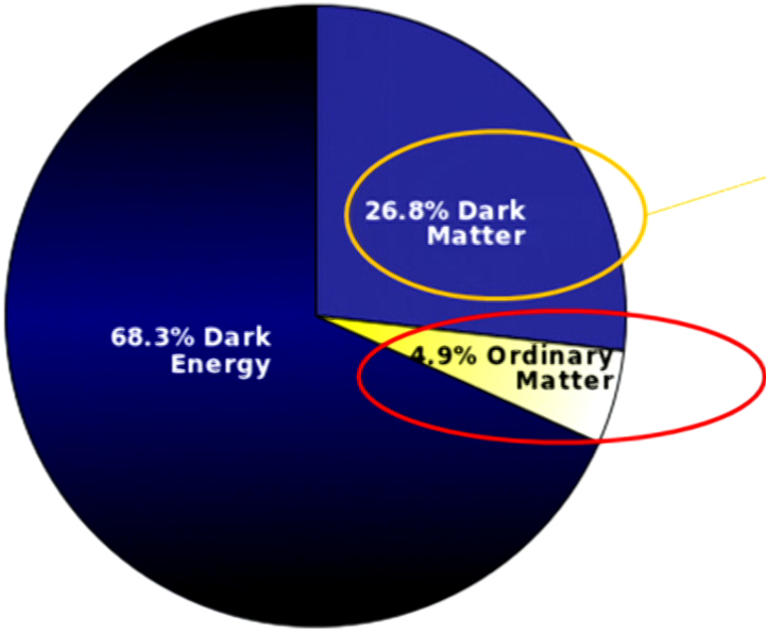



• The CMB Anisotropy Power Spectrum

(WMAP year 5 data)

# Dark Matter Overview:

How much do we have?




(Wikipedia)

We only know DM through its gravitational interaction!

We only understand 5% of the Universe!

# Popular Choices:

- WIMP:

  Possible solutions of Gauge Hierarchy problem.

- Axion:

  Possible solutions to strong CP problem.

Naturalness concerns.

- Primordial Black Holes:

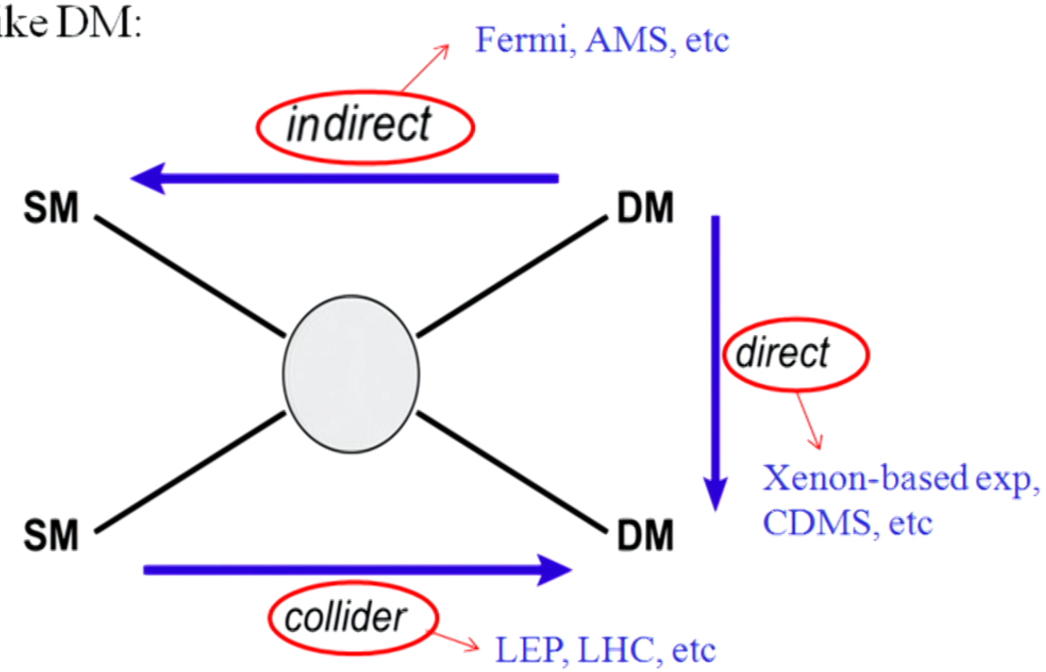
  No needs for additional particles.

  Very interesting possibility from particle physics viewpoint.

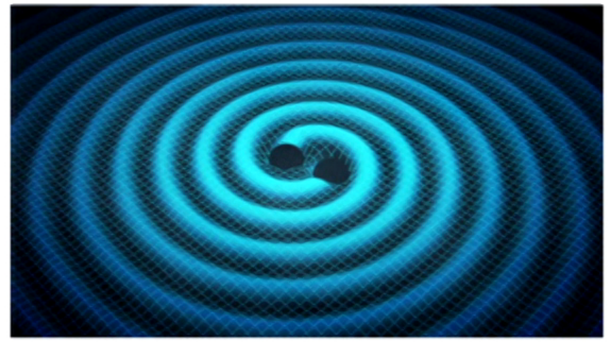
  Can be produced in various ways:
  multi-stage inflation
  matter dominated era before BBN

# Detection Strategies:

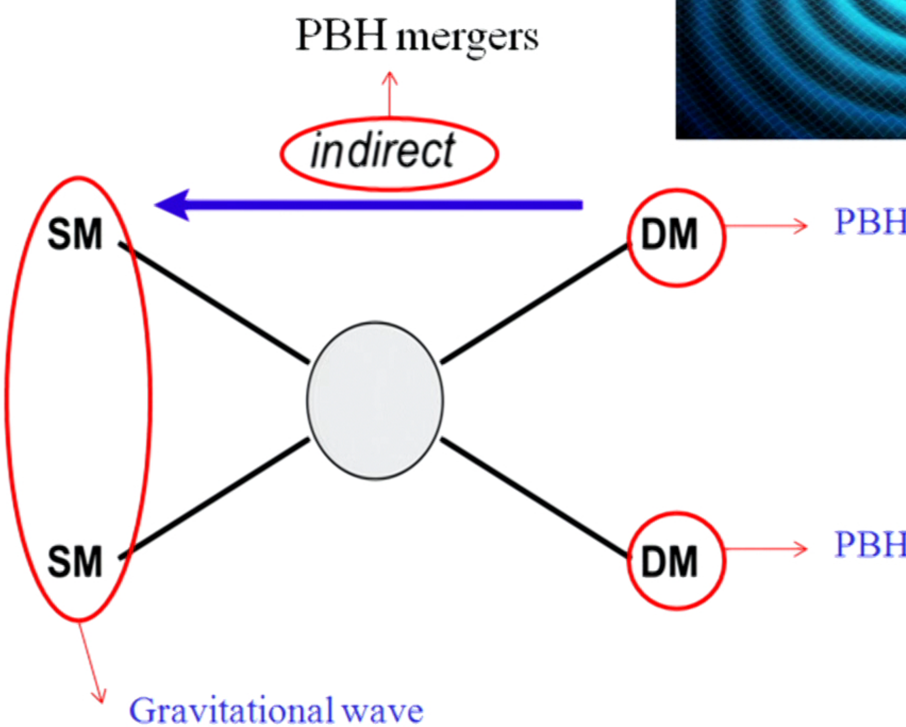
Particle-like DM:



# Detection Strategies:



PBH:

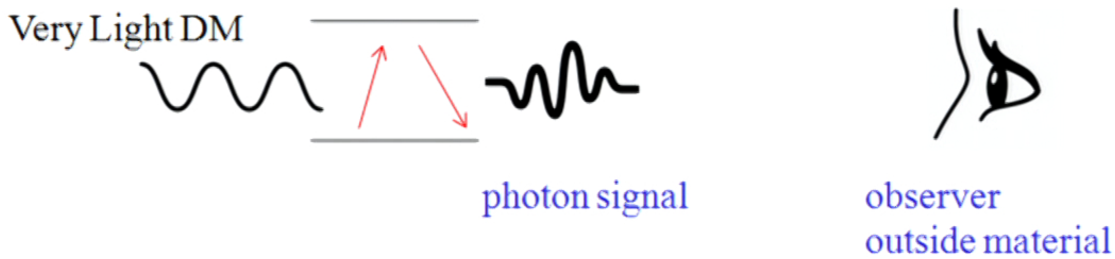



Phys. Rev. Lett. 116, 201301 (2016)
S. Bird, etc

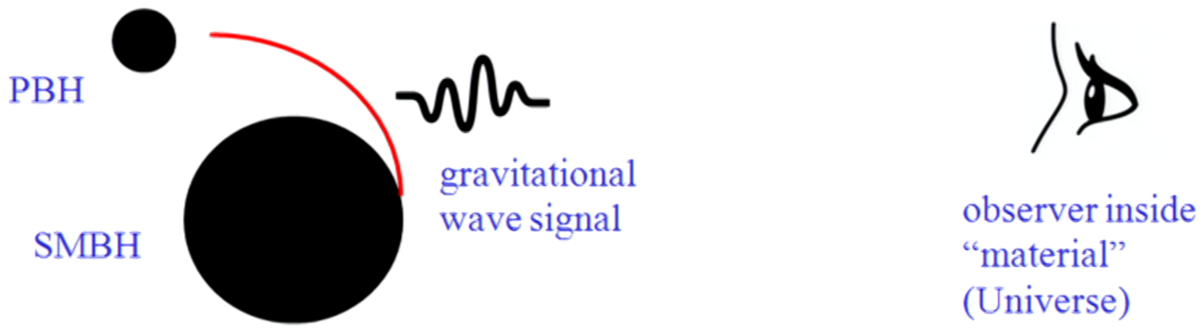
# Detection Strategies:

Very Light (wave-like) DM: great contributions by (semi-) local group

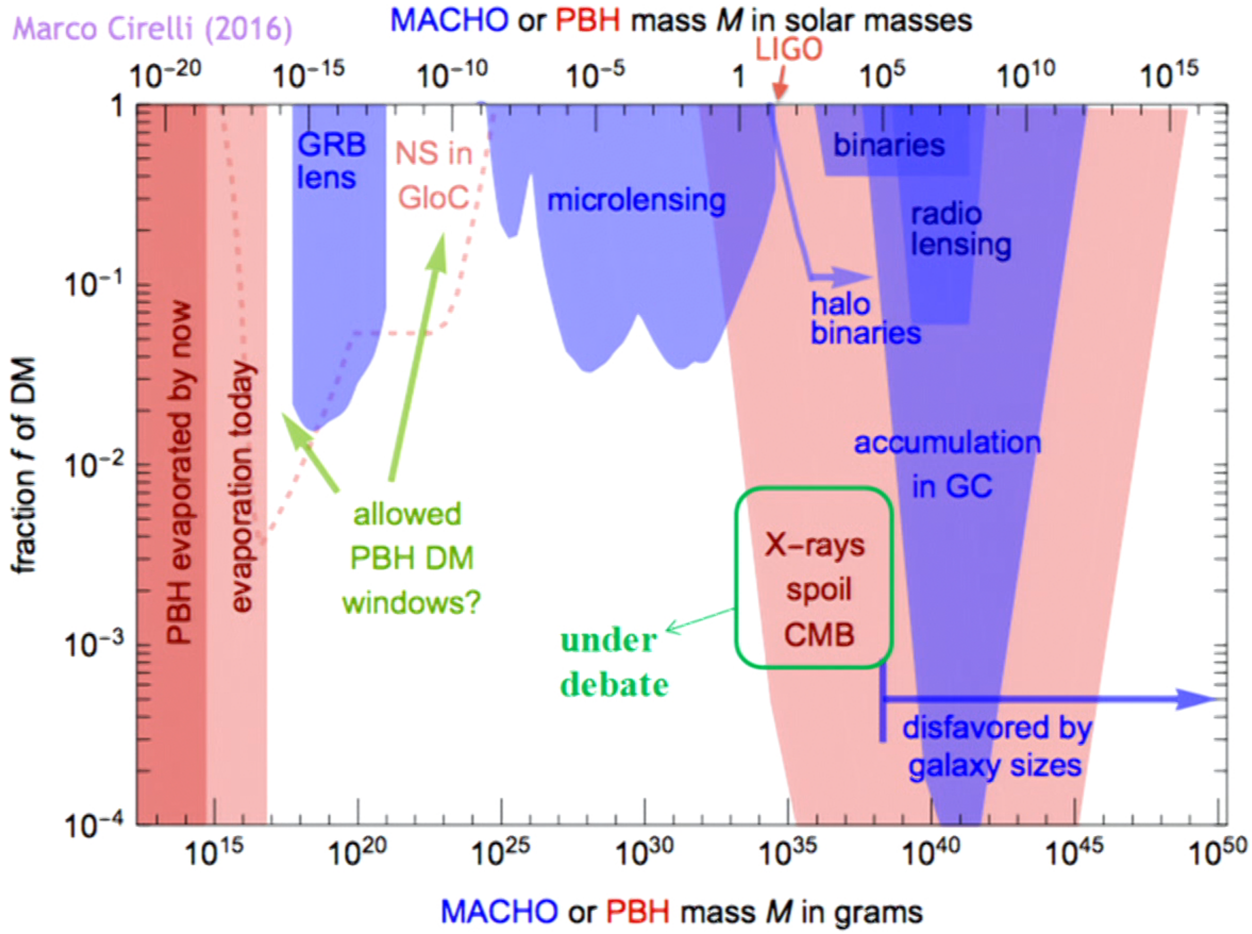
atomic clocks 1405.2925   resonant-mass antennas 1508.01798   molecules 1709.05354   ….




PBH: Extreme Mass Ratio Inspirals

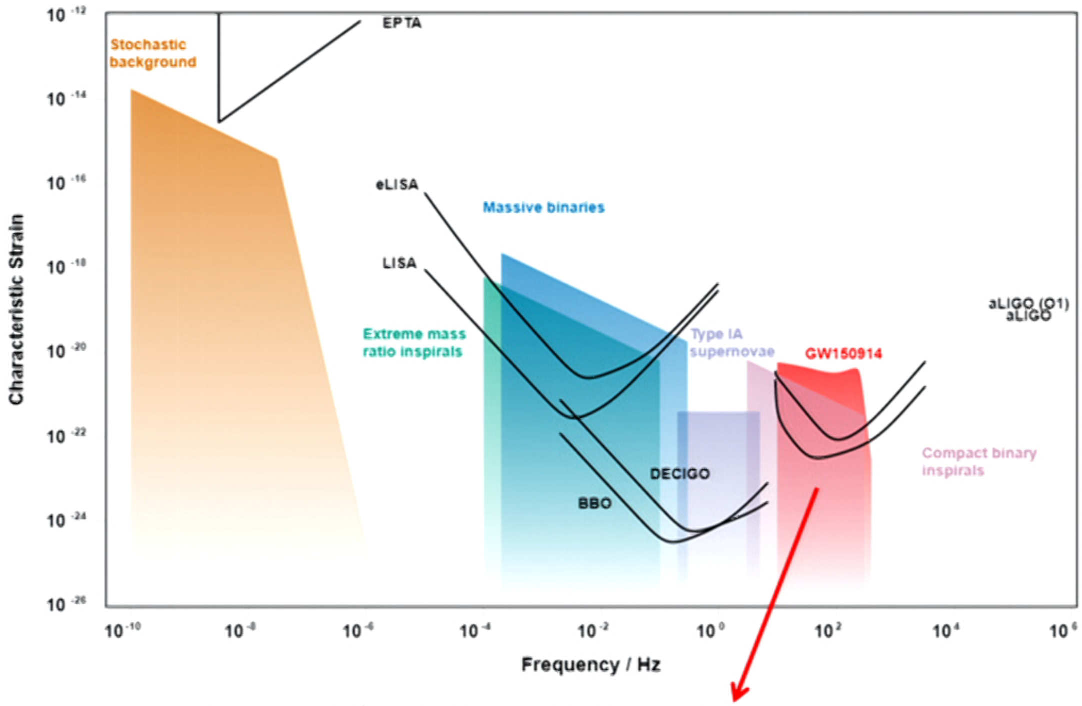


# Existing PBH Constraints:



# Probing PBH by GW detectors:

- LIGO-like GW detectors:

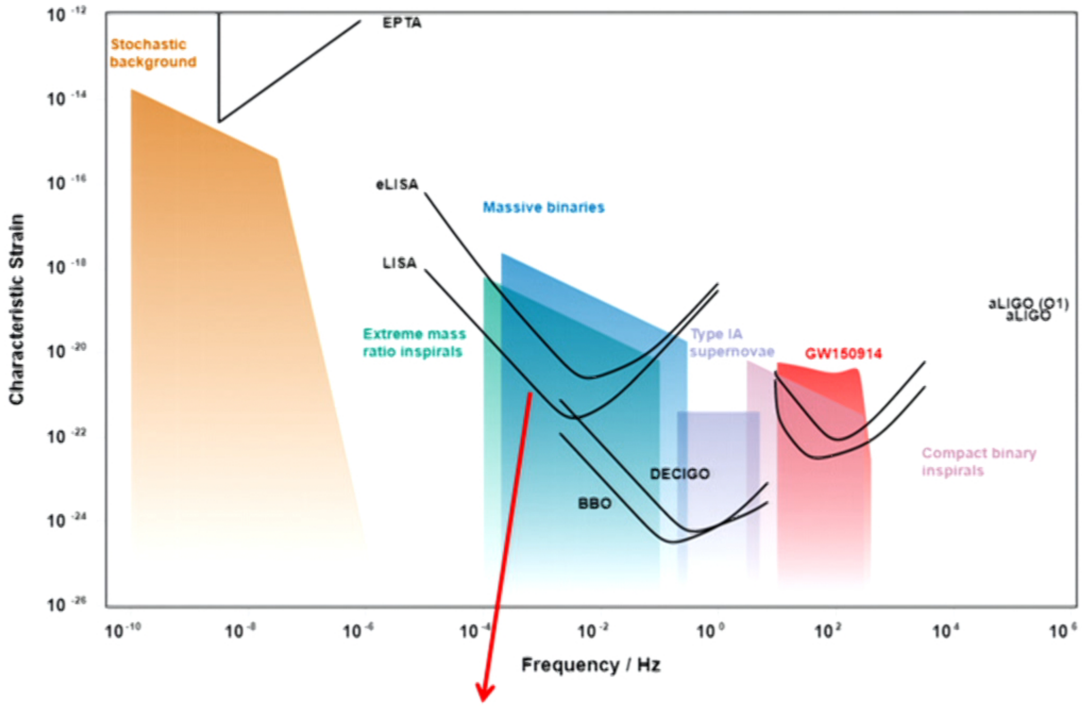



Frequency optimized for BH ~ O(10) $M_\odot$

Not easy to probe PBH with smaller mass.

# Probing PBH by GW detectors:

- LISA-like GW detectors: JUST APPROVED BY ESA!




Frequency optimized for BH $\sim O(10^6)\ M_\odot$

⇨ PBH - SMBH EMRI

# Master Formula:

$$\Gamma = \int \mathcal{R}(M,\mu) \left( \frac{dn(M,z)}{dM} dM \right) (p(s,z)ds) \left( \frac{dV_c}{dz} dz \right)$$

intrinsic EMRI rate
well studied for SMBH-ABH
rescale for PBH mass and density

SMBH mass spectrum
$10^4$ - $10^7$ $M_\odot$
provided in astrophysics

SMBH spin distribution
likely to be almost extremal
little effects to final results

volume integral
truncated by SNR

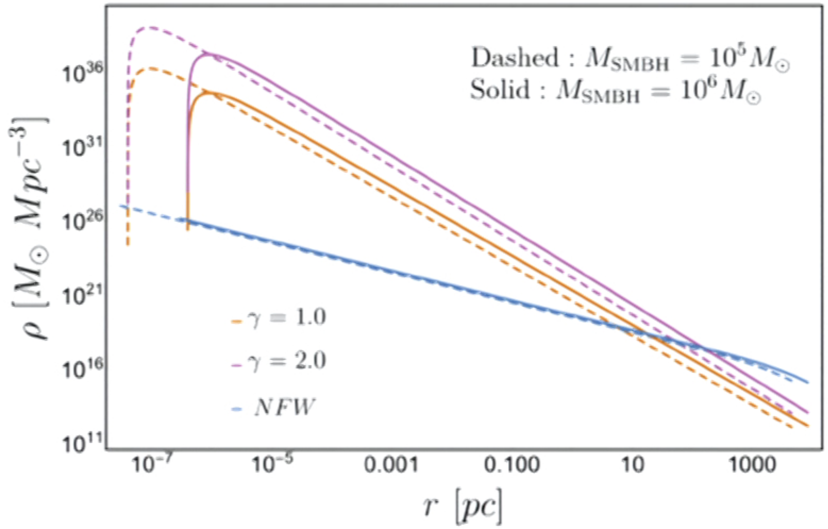
# DM Profile:

Collisionless Cold DM: NFW profile

⇨ other effects (baryonic feedback): cored profile

⇨ adiabatic growth of SMBH: spiky profile

Schw: P. Gondolo and J. Silk (99); L. Sadeghian, F. Ferrer, and C. M. Will (13);
Kerr: F. Ferrer, A. M. da Rosa, and C. M. Will (17)




H. Nishikawa, et. al.
arXiv:1708.08449 [astro-ph.CO]

# DM Profile:

$$\rho(r) = \frac{\rho_s}{\frac{r}{R_s}(1+\frac{r}{R_s})^2}$$ ⇨ a simple function of SMBH mass (M)

$$\rho_s = \frac{200}{3}\frac{c_{200}^3}{g(c_{200})}\rho_c; \quad R_s = \left[\frac{M_{200}}{4\pi\rho_s g(c_{200})}\right]^{1/3}$$ ⇨ $(\rho_s, R_s) \to (c_{200}, M_{200})$

$$c_{200} = 10^{0.905}\left(\frac{M_{200}}{10^{12}h^{-1}M_\odot}\right)^{-0.101}$$ ⇨ $c_{200}(M_{200})$

↘ concentration-mass relation, only valid in low redshift.
Truncate our calculation at z=1.

A. A. Dutton and A. V. Macci (arXiv:1402.7073)

$$\frac{M}{3\times 10^6 M_\odot} \approx 3.3\left(\frac{M_{200}}{10^{12}M_\odot}\right)^{1.65}$$ ⇨ $M_{200}(M_{SMBH})$

L. Ferrarese (Astrophys. J. 578 (2002) 90-97)

# DM Profile:

EMRIs are mainly by COs within SMBH radius of influence.

$$r_h = \frac{GM}{\sigma^2} = 2\text{pc}\left(\frac{M}{3\times 10^6 M_\odot}\right)^{1/2}$$

Comparing PBH number density with that of ABH:

$$\mathcal{G}(M,\mu) = f_{\rm PBH}\frac{\rho_{\rm NFW}(M, r_h(M))/\mu}{n_{\rm BH}(M)}$$

⇩

When $\mu = 10 M_\odot$ and $M = 10^6 M_\odot$, $\mathcal{G}$ is $\mathcal{O}(1)$.

It reasonable to expect a large rate for PBH-SMBH EMRIs.

# GW Strain:

Circular and equatorial EMRIs (Teukolsky; Finn, Thorn):

$$h_{c,1} = \frac{5}{\sqrt{672\pi}} \frac{\eta^{1/2} M}{r_o} \tilde{\Omega}^{1/6} \mathcal{H}_{c,1} \ ,$$

$$h_{c,m} = \sqrt{\frac{5(m+1)(m+2)(2m+1)!m^{2m}}{12\pi(m-1)[2^m m!(2m+1)!!]^2}} \frac{\eta^{1/2} M}{r_o} \times \tilde{\Omega}^{(2m-5)/6} \mathcal{H}_{c,m}, \quad m \geq 2 \ .$$

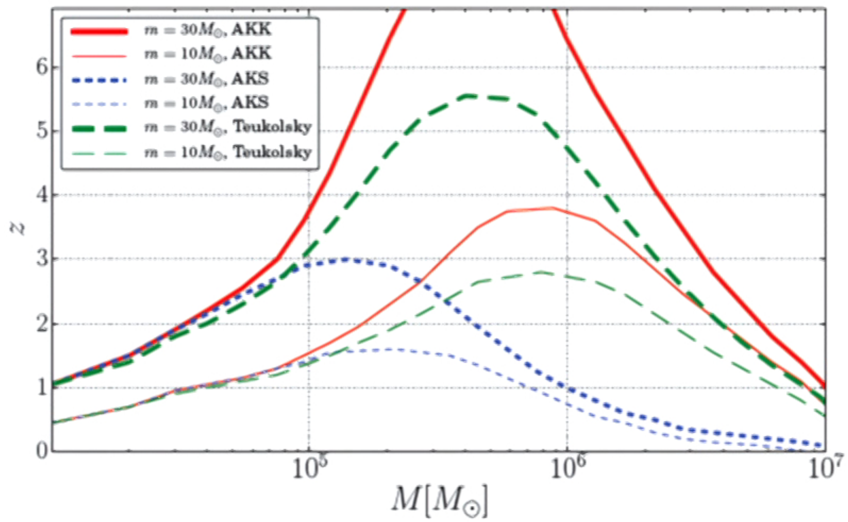
Most EMRI are highly elliptical and not equatorial.

Analytic kludge model (Barack,Cutler) : AKK & AKS

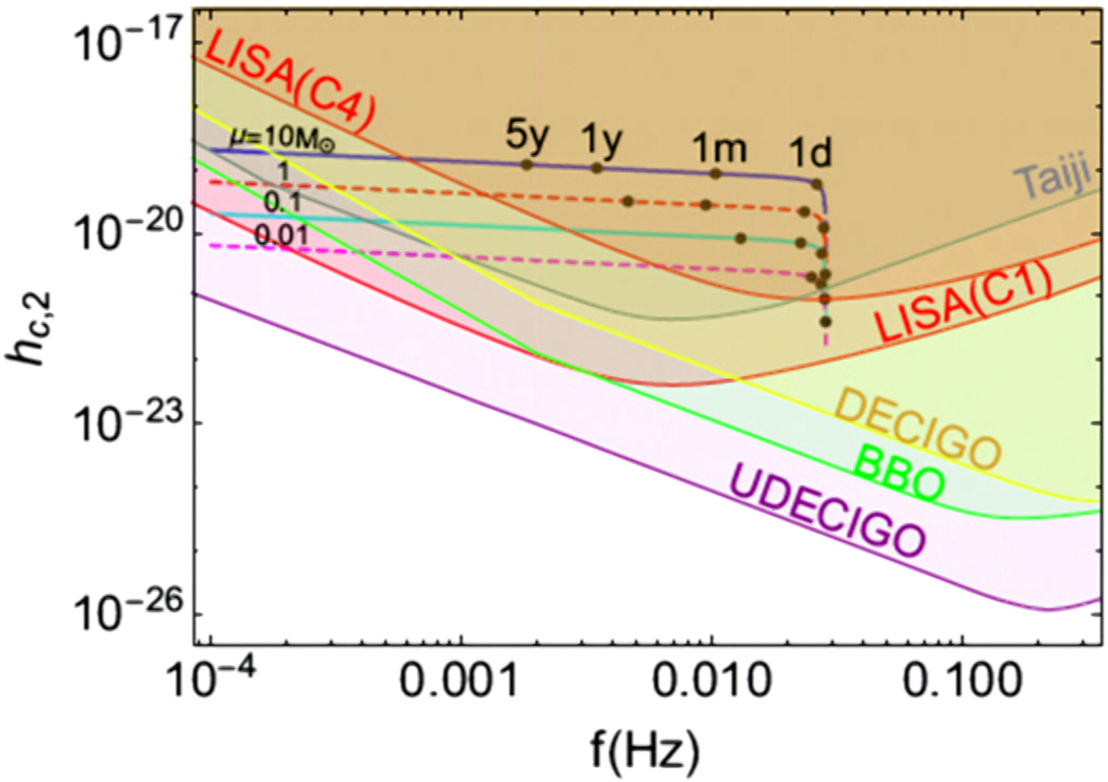
# GW Strain:

AKK and AKS are used to quantify the uncertainty, Teukolsky solution falls in between.

S. Babak et. al. Phys. Rev. D 95, 103012 (2017)



# GW Strain:




$M = 10^6 M_\odot$ ; Spin = 0.999 ; 1 Gpc

# GW Strain:

A very quick back-of-envelop estimation:

$$h_c \sim \sqrt{\mu M}$$

To achieve comparable $h_c$ :

LIGO:

$\mu \sim M \sim 10 M_\odot$

LISA:

$\mu \sim 10^{-4} M_\odot, M \sim 10^6 M_\odot$

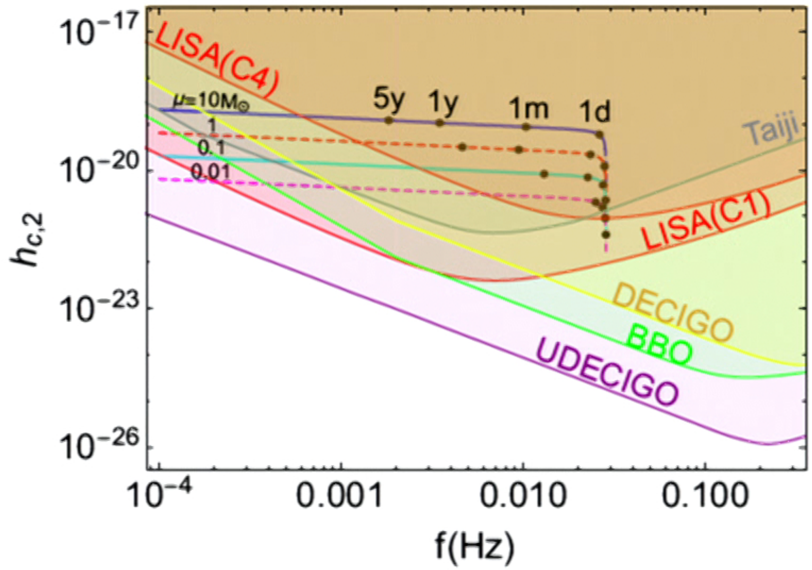
⇨ Not crazy to expect LISA can be sensitive to light PBHs.

# GW Strain:

$$\mathrm{SNR}^2 = \frac{\mathcal{S}^2}{\mathcal{N}^2} = \sum_m \int \left[ \frac{h_{c,m}(f_m)}{h_n(f_m)} \right]^2 d \ln f_m$$

Inspiral lasts much longer than experiment operation time.

⇨ Only a small fraction of one event is recorded.



# GW Strain:

$$\Delta f/f \sim \mu/M^2 \qquad h_c \sim \sqrt{\mu M}$$

Lighter SMBH helps to increase SNR.

For each EMRI,

SNR > 15 ⇨ cut on redshift

$$z_{\max} = min(z|_{\mathrm{SNR}=15}, 1)$$

validity on astrophysical relations

# Rescattering vs Slow-Inspiral:

Changing orbit through two processes:

- Gravity-mediated scattering

$$\Delta v = 2Gm_{|} \quad /(bu)$$

$$\frac{d\langle v^2\rangle}{dt} = \int 2\pi b db \int d^3u \left(\frac{2Gm}{bu}\right)^2 u f_0(u,r)$$

Relaxation time is controlled by the species with largest $m_i^2 n_i$

⇨ main-sequence stars

No dependence on PBH mass.

# Rescattering vs Slow-Inspiral:

Changing orbit through two processes:

- Slow inspiral through GW radiation

$$t_0 = \int_{\epsilon_0}^{\infty} \frac{d\epsilon}{d\epsilon/dt} \approx \frac{2\pi\sqrt{Ma}}{\Delta E} \sim \mu^{-1}$$

non-trivial dependence on PBH mass

EMRIs are slow inspirals not interrupted by gravity-mediated scatterings.

⇨ Competition between $t_0$ and $t_{relax}$

$$\frac{t_0}{t_{relax}}\Big|_{a_c} = 1$$

$a > a_c$, rescatters

$a < a_c$, falls in

# Intrinsic EMRI Rate:

Fokker-Planck Equation:

number density distribution

$$\frac{\partial N(\varepsilon, J; t)}{\partial t} = -\frac{\partial \mathcal{F}(\varepsilon; J)}{\partial J},$$

stellar current into SMBH

Can be solved semi-analytically.

Well studied for ABH-SMBH EMRIs.
Matches well with numerical simulation.

$$\mathcal{R}_{\rm astro}(M) = 400{\rm Gyr}^{-1}\left(\frac{M}{3\times 10^6 M_\odot}\right)^{-0.15}$$

For PBHs, we need to find the proper scaling with PBH mass.

# Intrinsic EMRI Rate:

PBH profile near SMBH.
p~0 after mass segregation.

$$\mathcal{R}_{\rm PBH}(M,\mu) \sim \frac{n_{\rm PBH}(r_h)}{t_h \ln[J_m(a_c)/J_{lc}]}\left(\frac{a_c}{r_h}\right)^{3/2-2p}$$

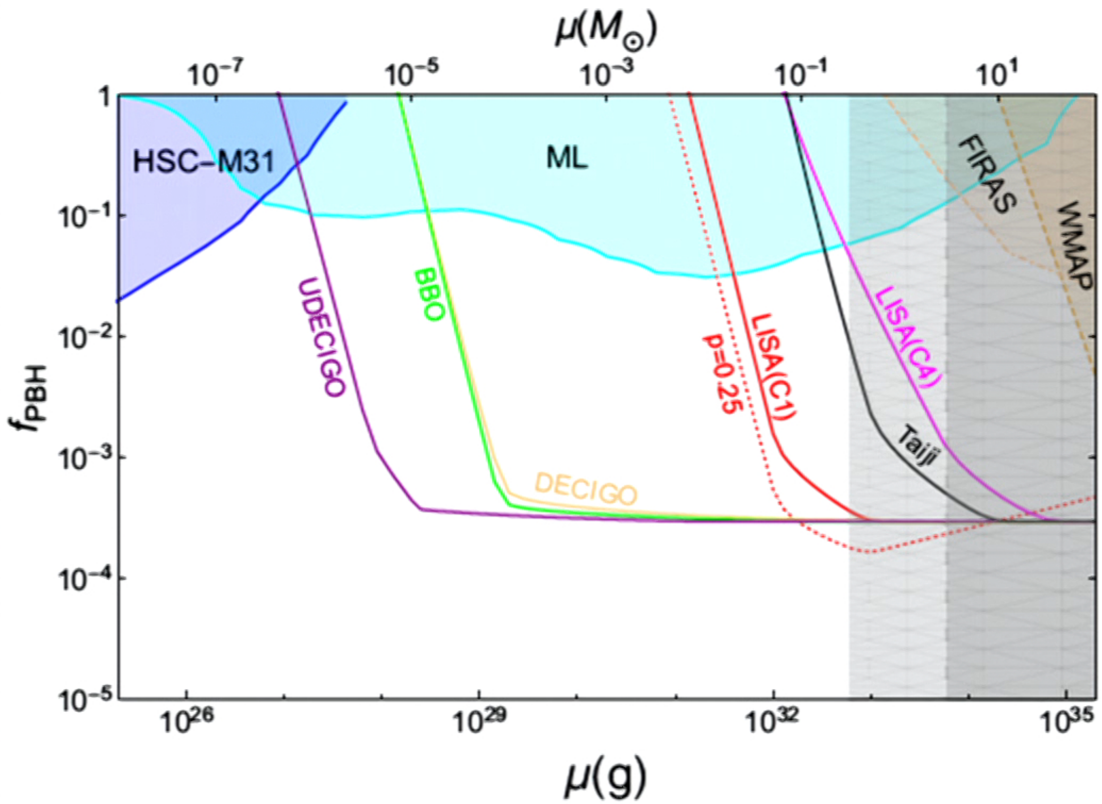
$$\sim \mathcal{G}(M,\mu)\left(\frac{\mu}{10M_\odot}\right)^{\frac{4p-3}{2p-3}} \mathcal{R}_{\rm astro}(M)$$

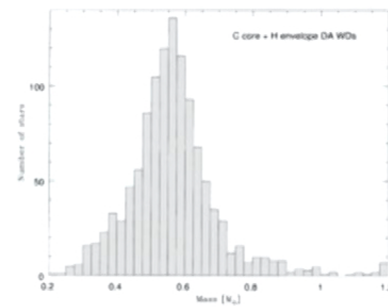
Rescaling of PBH number density.

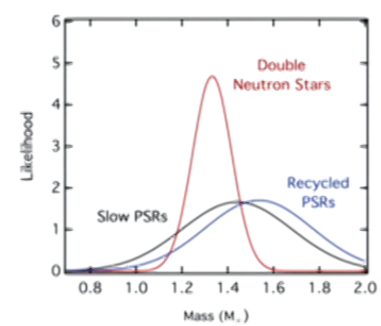
Rescaling of intrinsic EMRI rate for a single PBH.

# Final Results:

One observation may be good enough to claim discovery!





# Conclusion

LISA-like GW detectors is powerful to search for PBHs!

⇨ Large unexplored parameter space can be probed.

PBH mass: $10^{-7} \sim 10\ M_{\odot}$

Fraction can be as small as $10^{-4}$.

⇨ One or few signal events are good enough to declare discovery, if PBH is out of the mass regime of astrophysical COs.

Non-COs (planets) are destroyed by tidal force before ISCO.

# Conclusion

⇨ Astrophysical uncertainties can be largely reduced by measurements on ABH-SMBH EMRIs.

Mass spectrum and spin distribution of SMBHs.

Help to remove hard cut-off at $z$=1.

⇨ Lighter SMBH may be more useful to look for smaller PBHs.

Larger Frequency Integration Regime (SNR)

Guideline in future LISA-like GW experiments

LIGO opens the era of GW astronomy. (Similar to the time when CMB is observed.)

Plenty astrophysics can be studied, as well as non-SM physics (super-radiance).