Gravitational-wave cosmology over 29 decades in frequency

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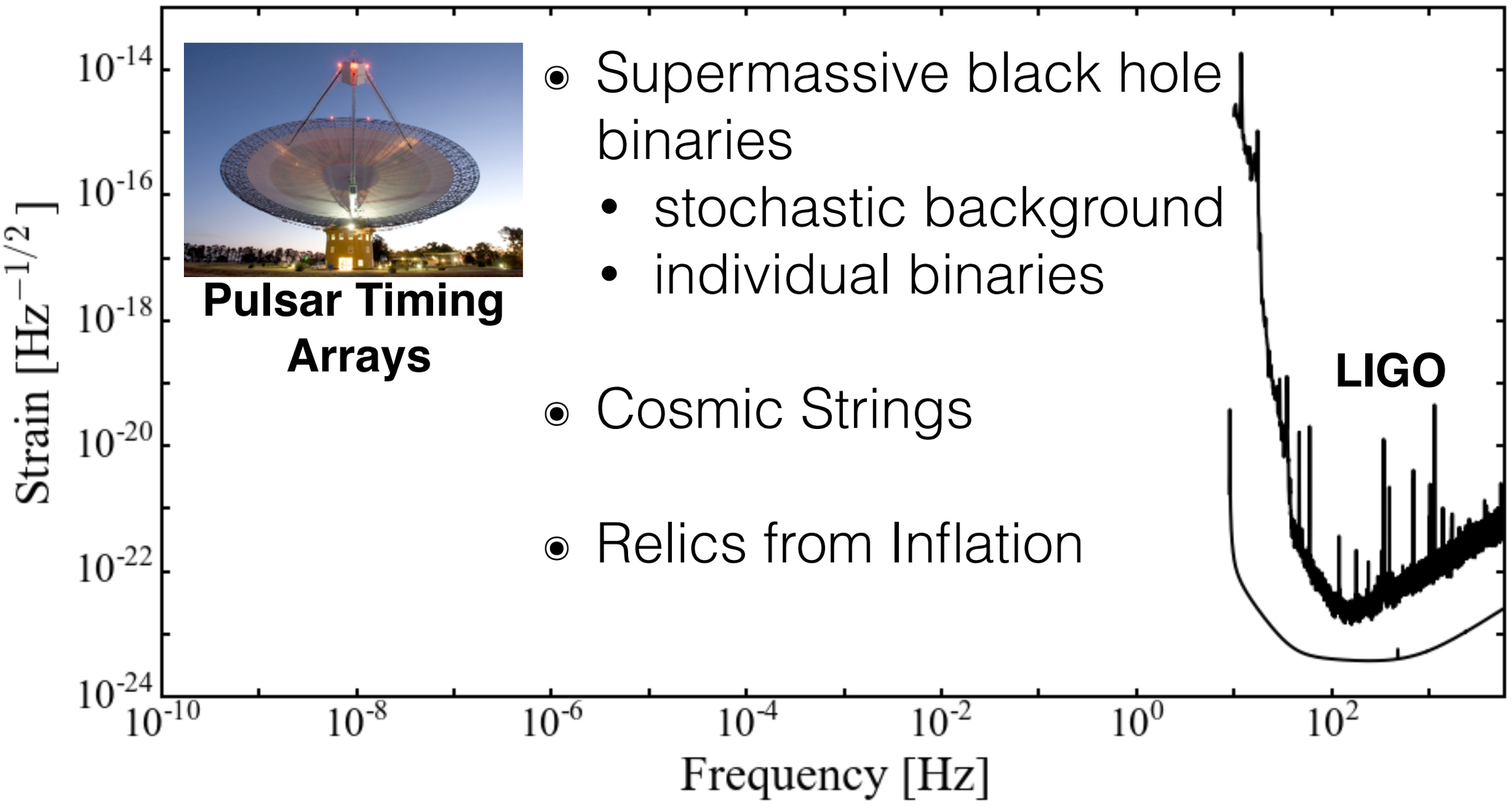
PPTA

Pulsar Timing Arrays

- Supermassive black hole binaries
  - stochastic background
  - individual binaries
- Cosmic Strings
- Relics from Inflation



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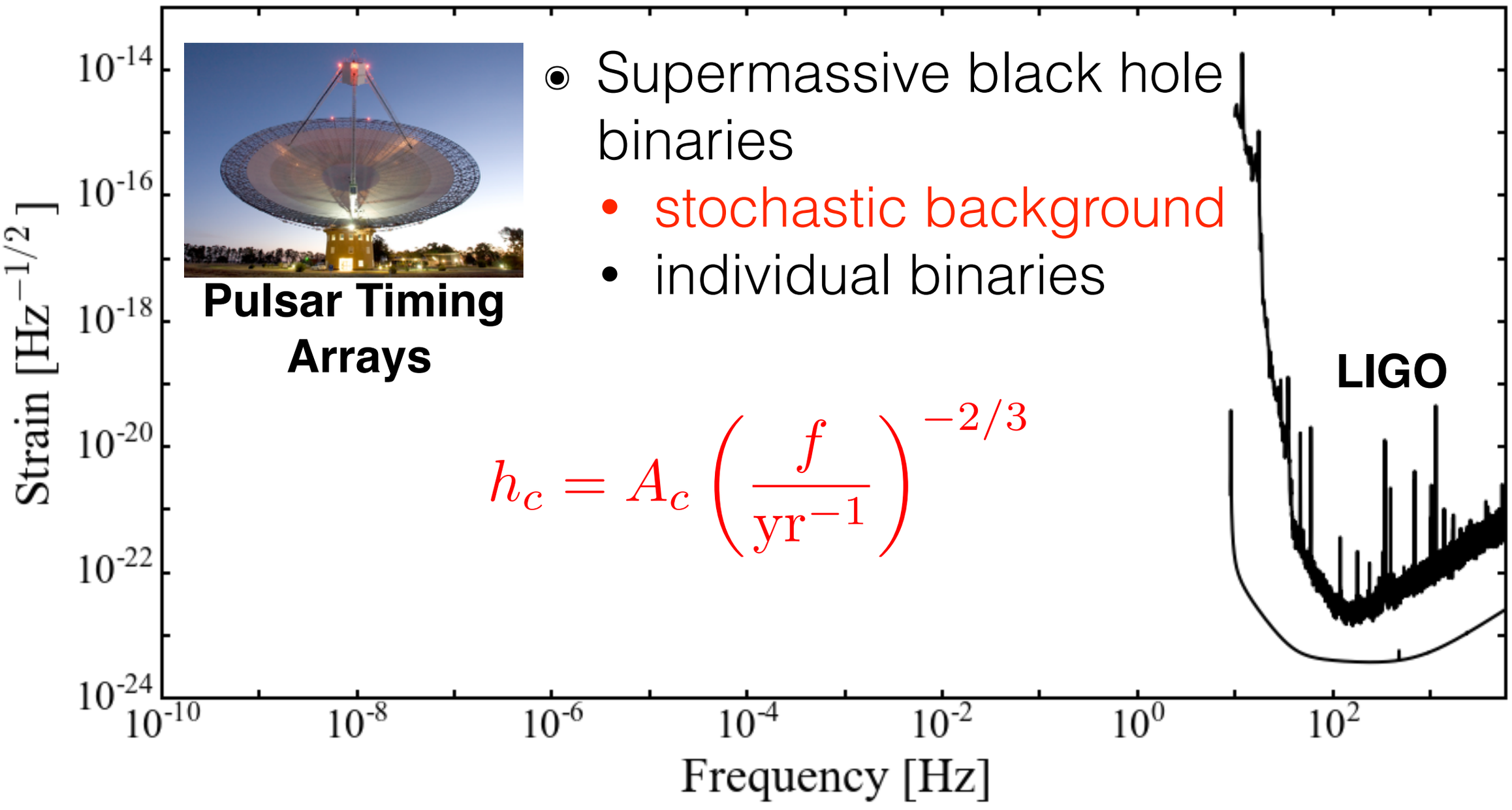
$$h_c = A_c \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-2/3}$$



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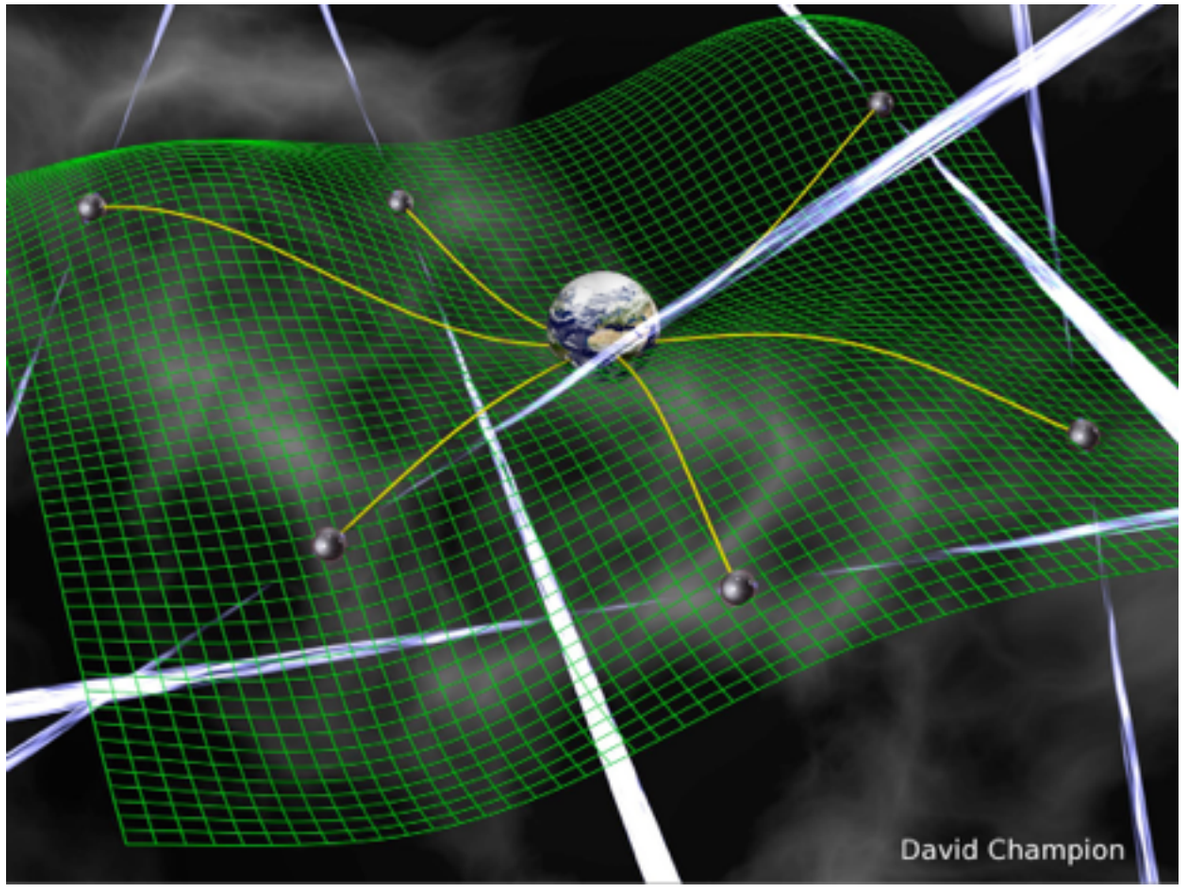
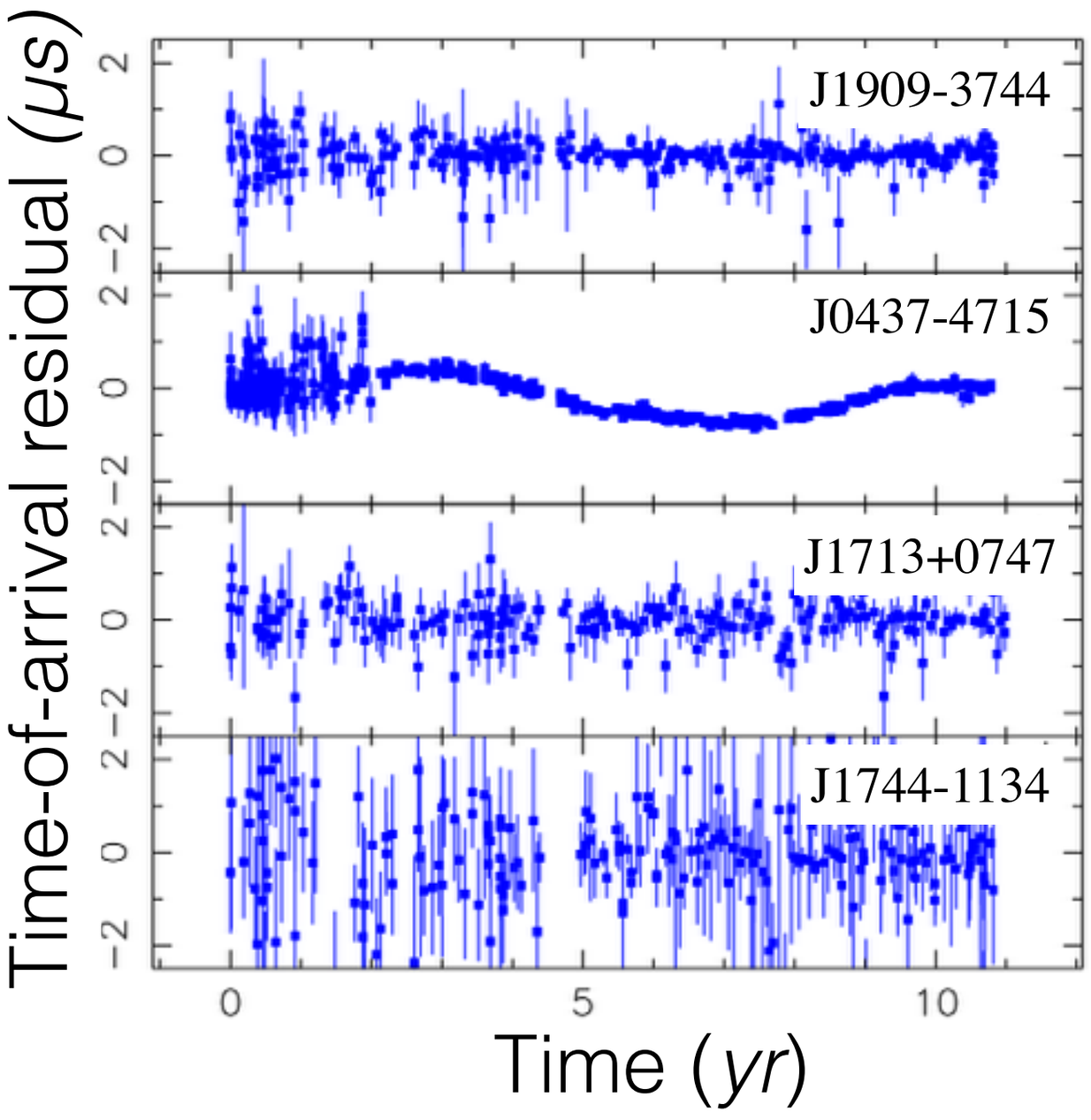

David Champion


Time-of-arrival residual (μs)
J1909-3744
J0437-4715
J1713+0747
J1744-1134
2
0
−2
0
5
10
Time (yr)

Supermassive black hole mergers

- Assume all galaxies host a SMBH
- Use observed BH-Galaxy mass relations
- Assume BH merger rate traces galaxy merger rate
- Assume GW dominated mergers (circular, …)
- …
- Sum up contribution from all SMBHs mergers in Universe

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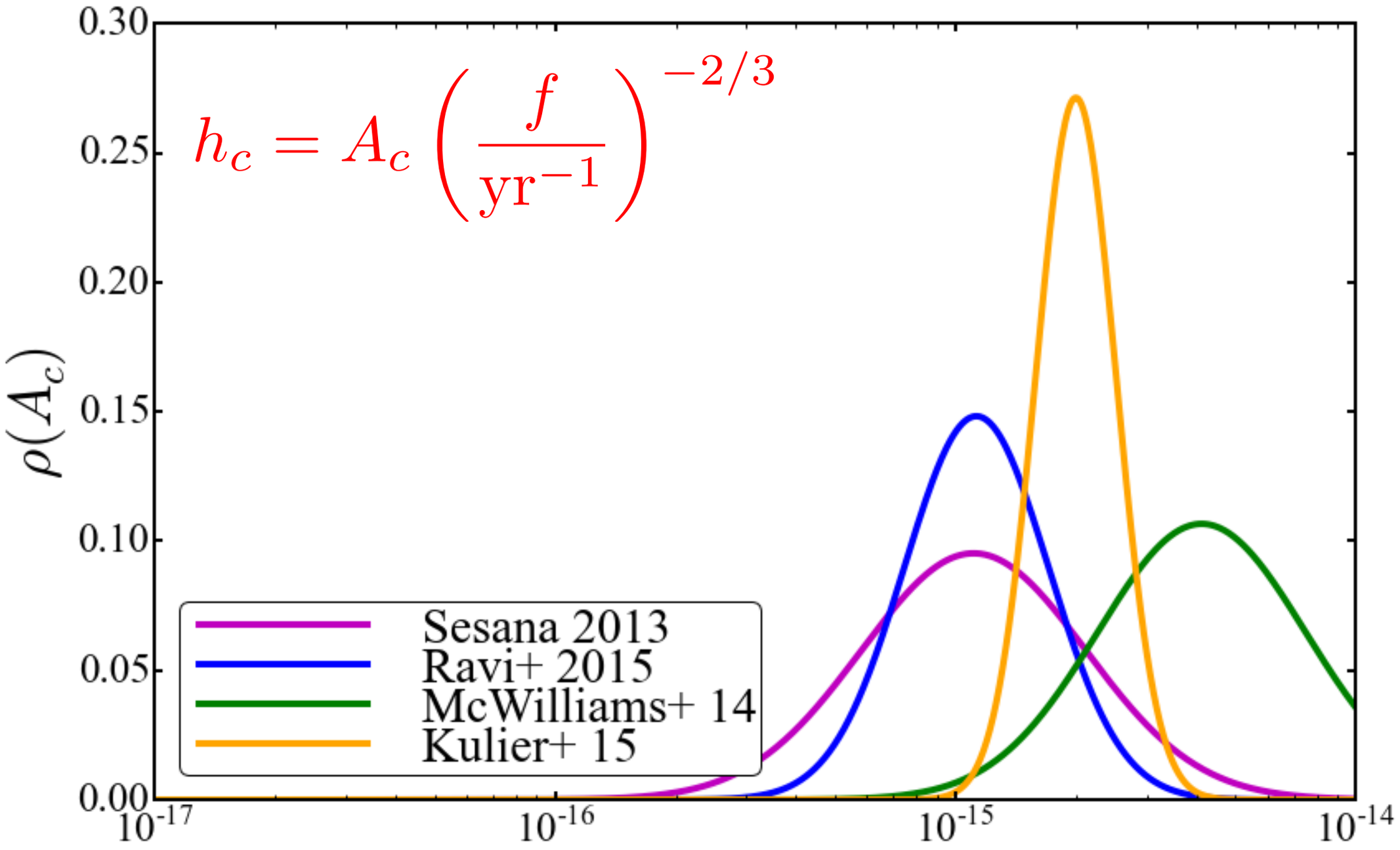

shared assumptions

- all binaries have circular orbits
- all binaries driven through band by GW emission

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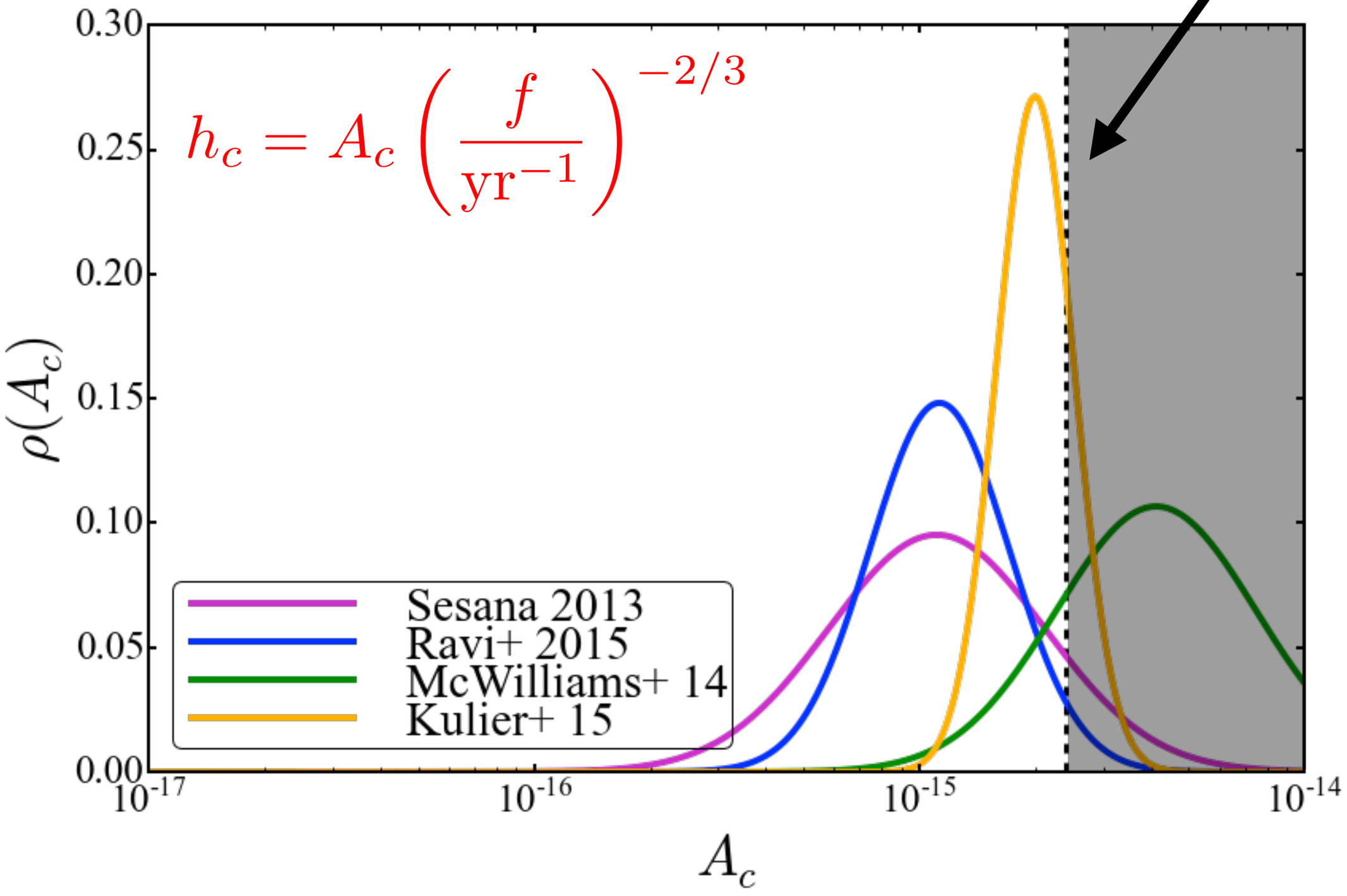
Shannon et al. (2013)



PSR J1909-3744

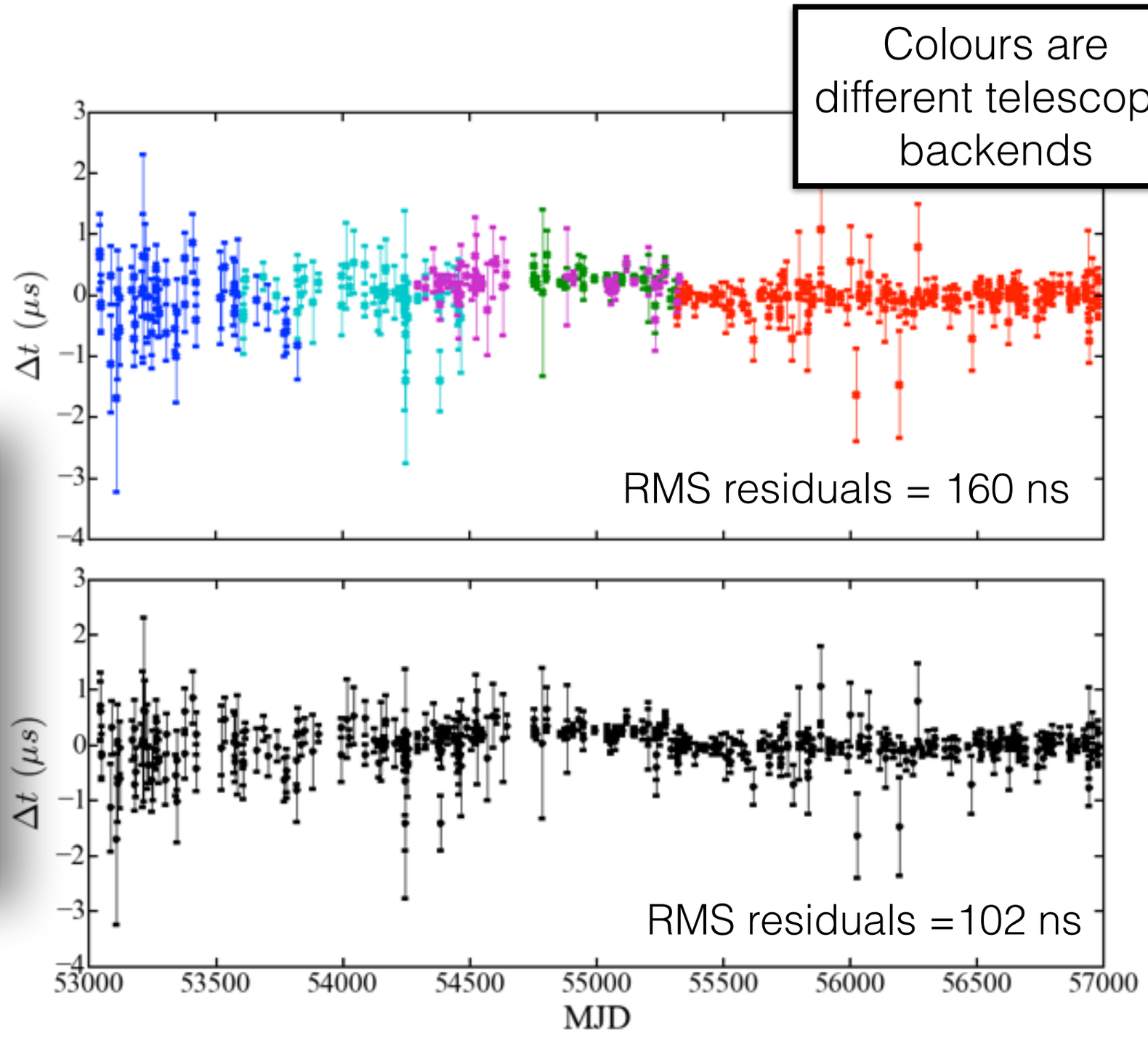
$$f = 339.315687288245 56 \pm 0.000000000000016\,\mathrm{Hz}$$

$$\mathrm{DM} = 10.4\,\mathrm{pc\,cm^{-3}}$$

Shannon et al. (2015)

3 improvements

- longer baseline (+3yr)
- discrete phase offsets
- short λ obs. only



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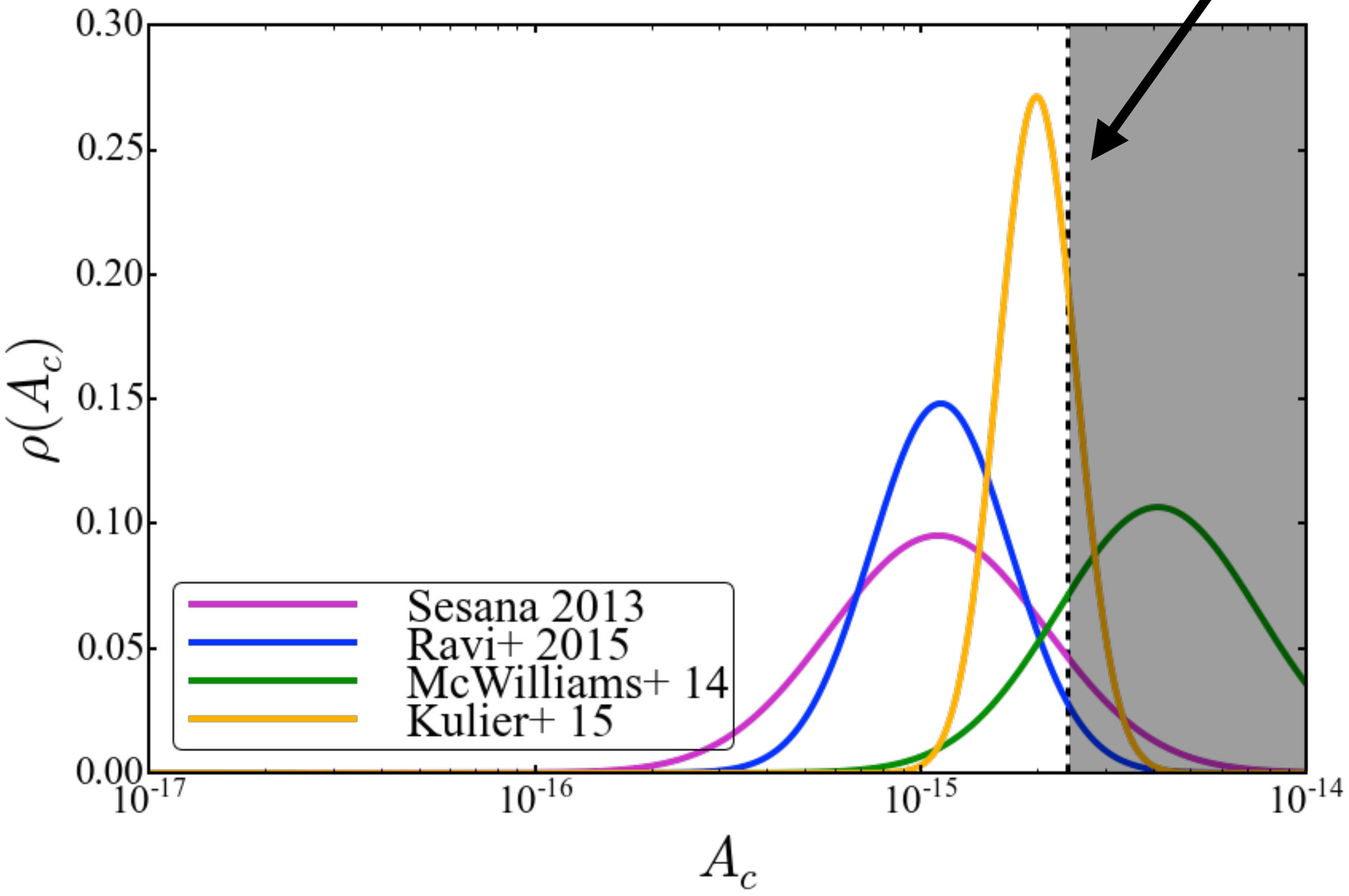
Shannon et al. (2013)



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Shannon et al. (2015)

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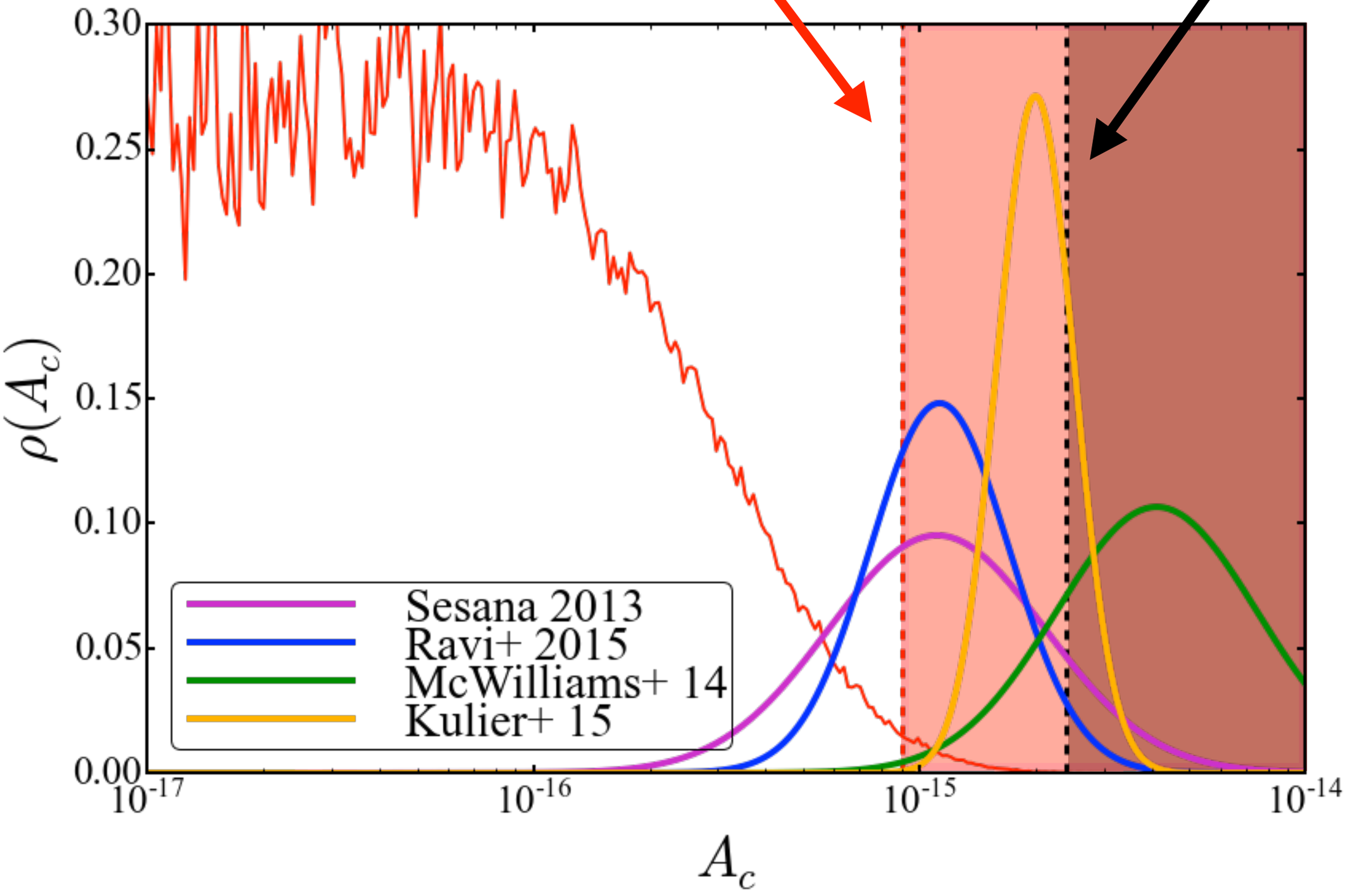

P_{model}	0.09	0.06	0.002	0.005

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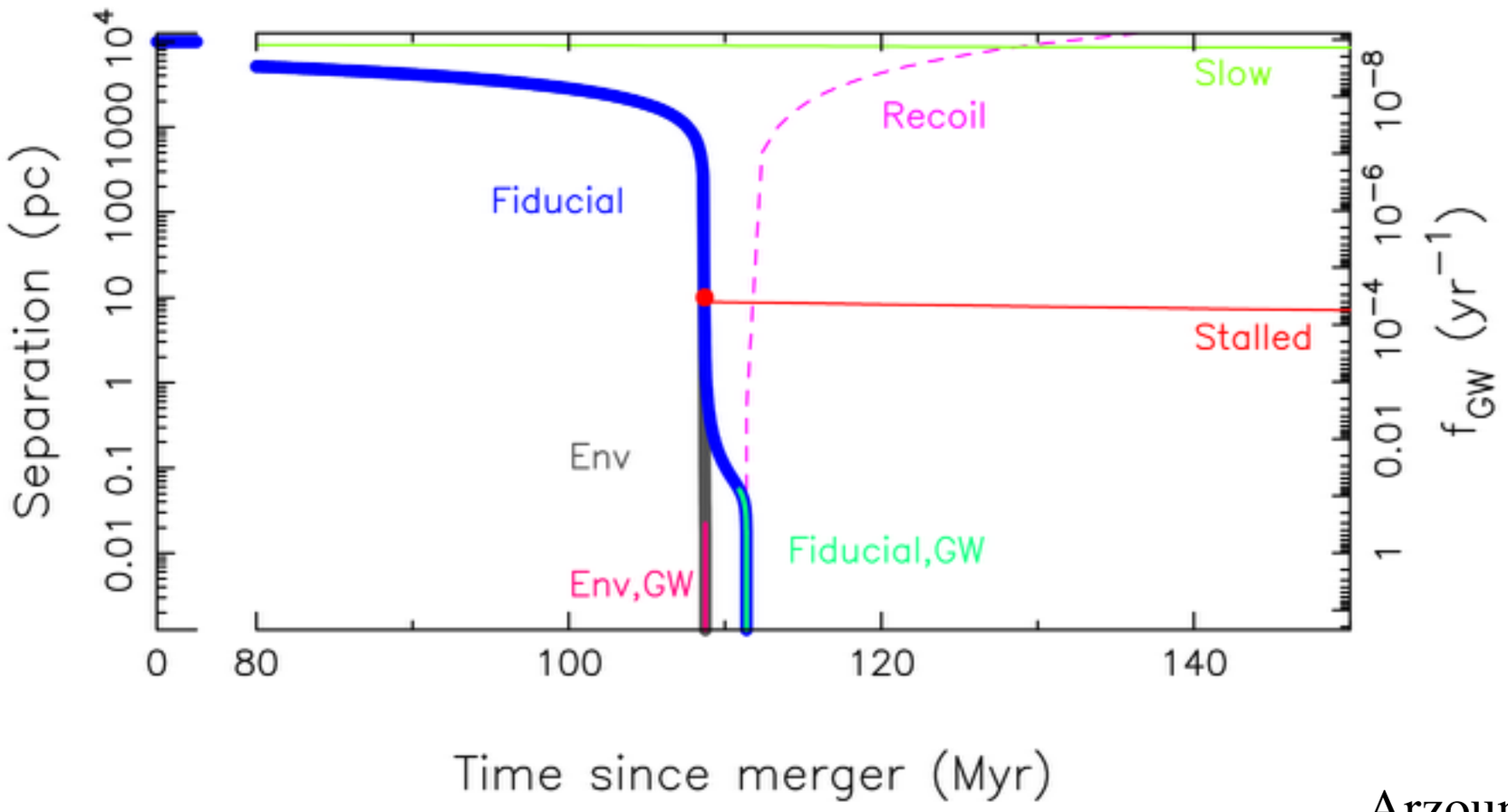
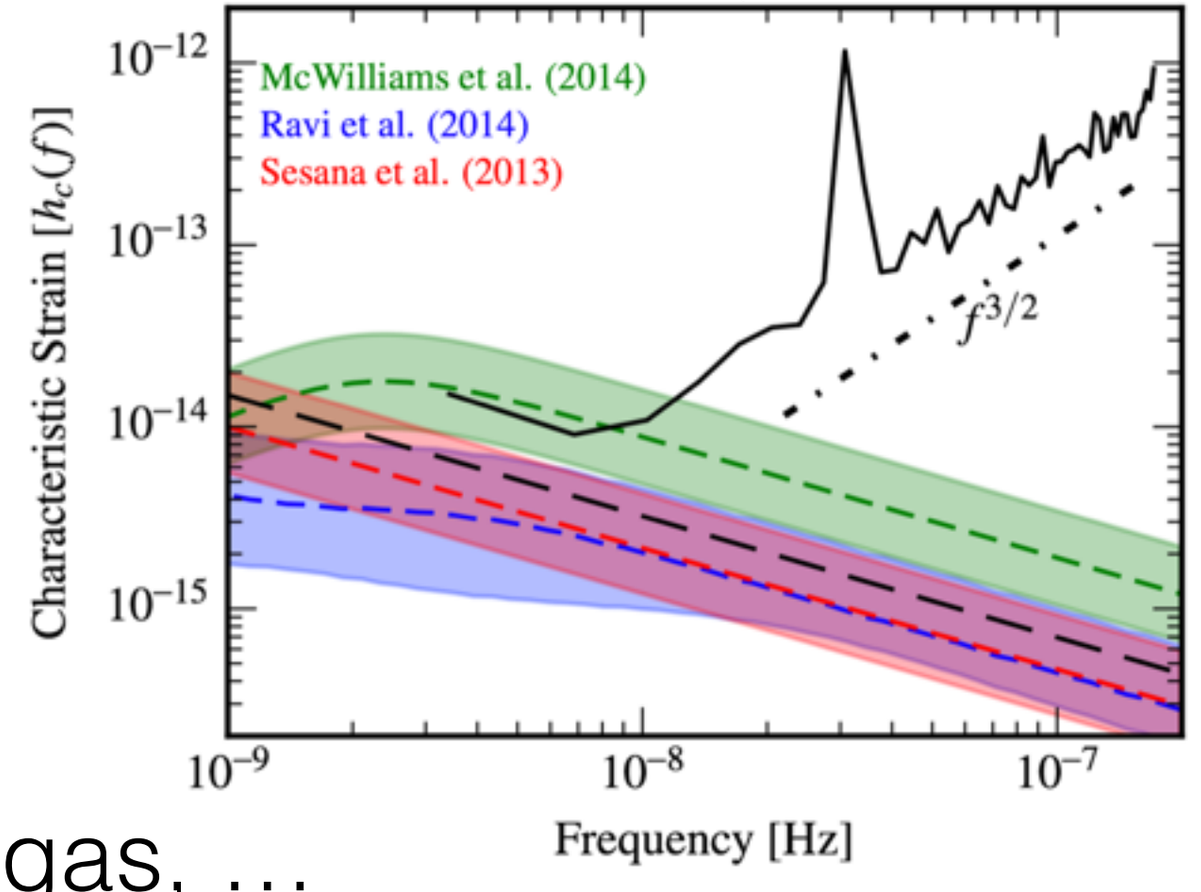


Arzoumanian et al. (2015; NANOGrav)

Astrophysical Inference

- Black hole mass function at z ~ 2?
- Galaxy merger rate?
- Environmental factors: stars, gas, …



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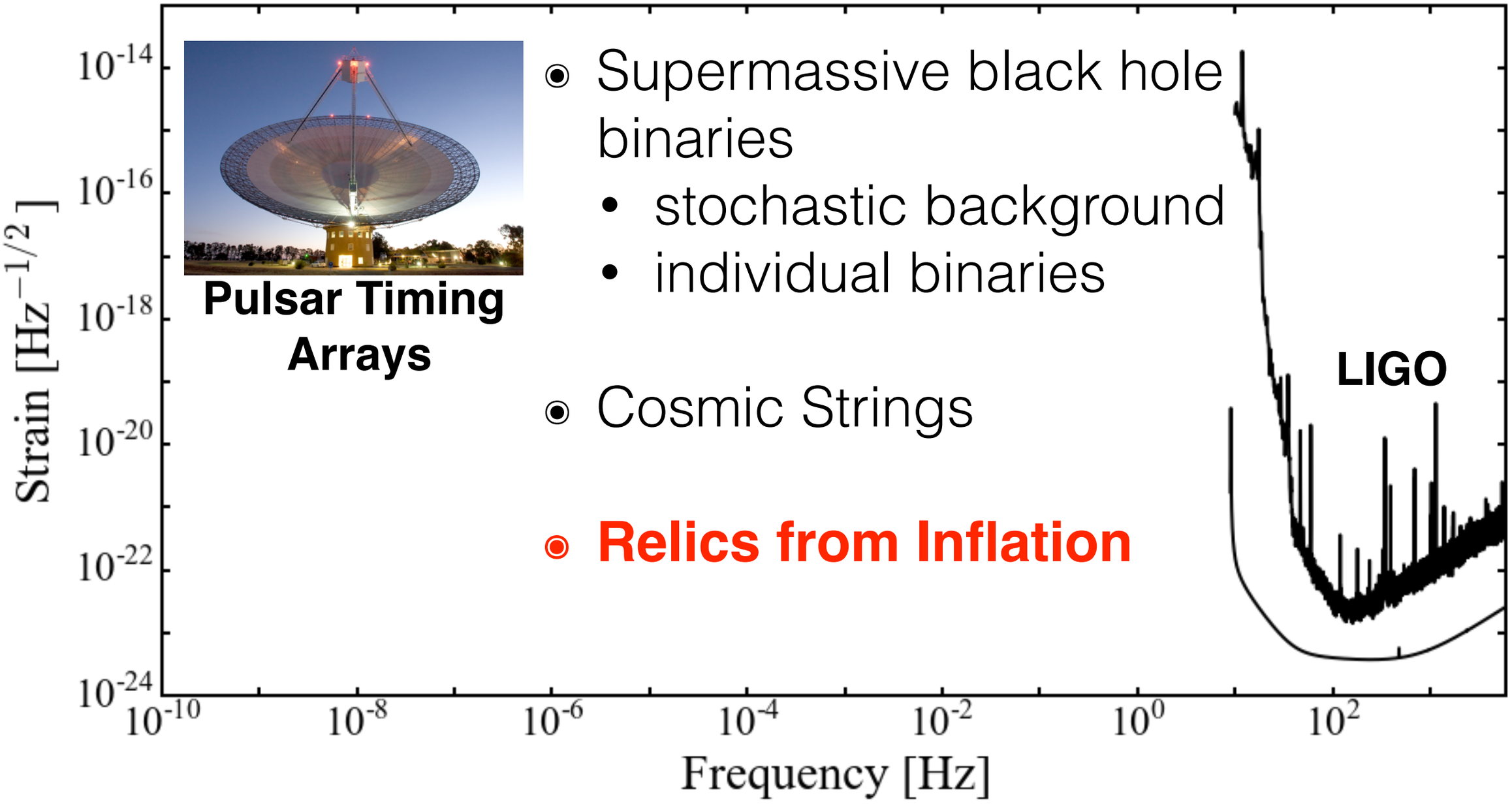
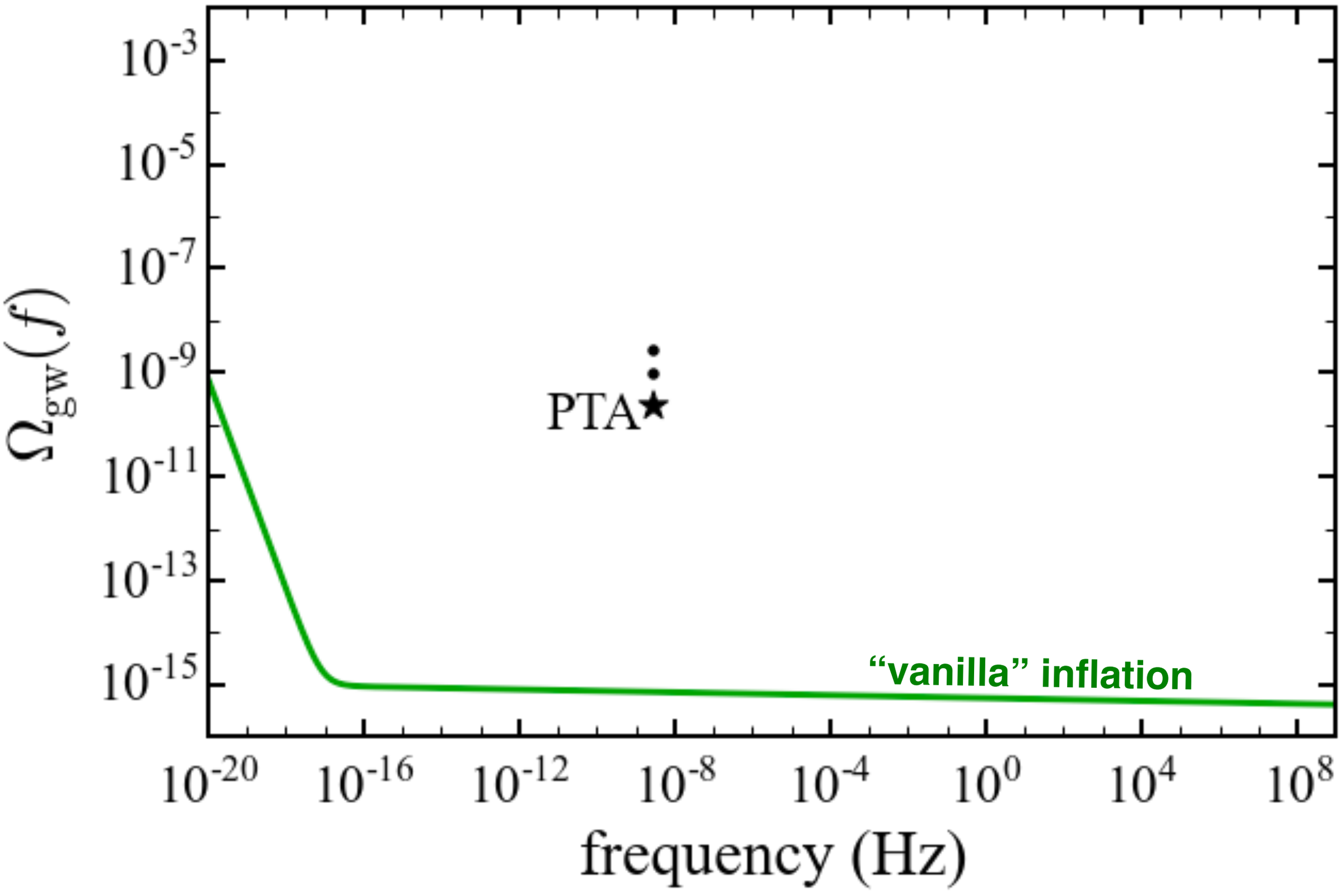
  - stochastic background
  - individual binaries
- Cosmic Strings
- **Relics from Inflation**



Lasky et al. (2015; submitted)



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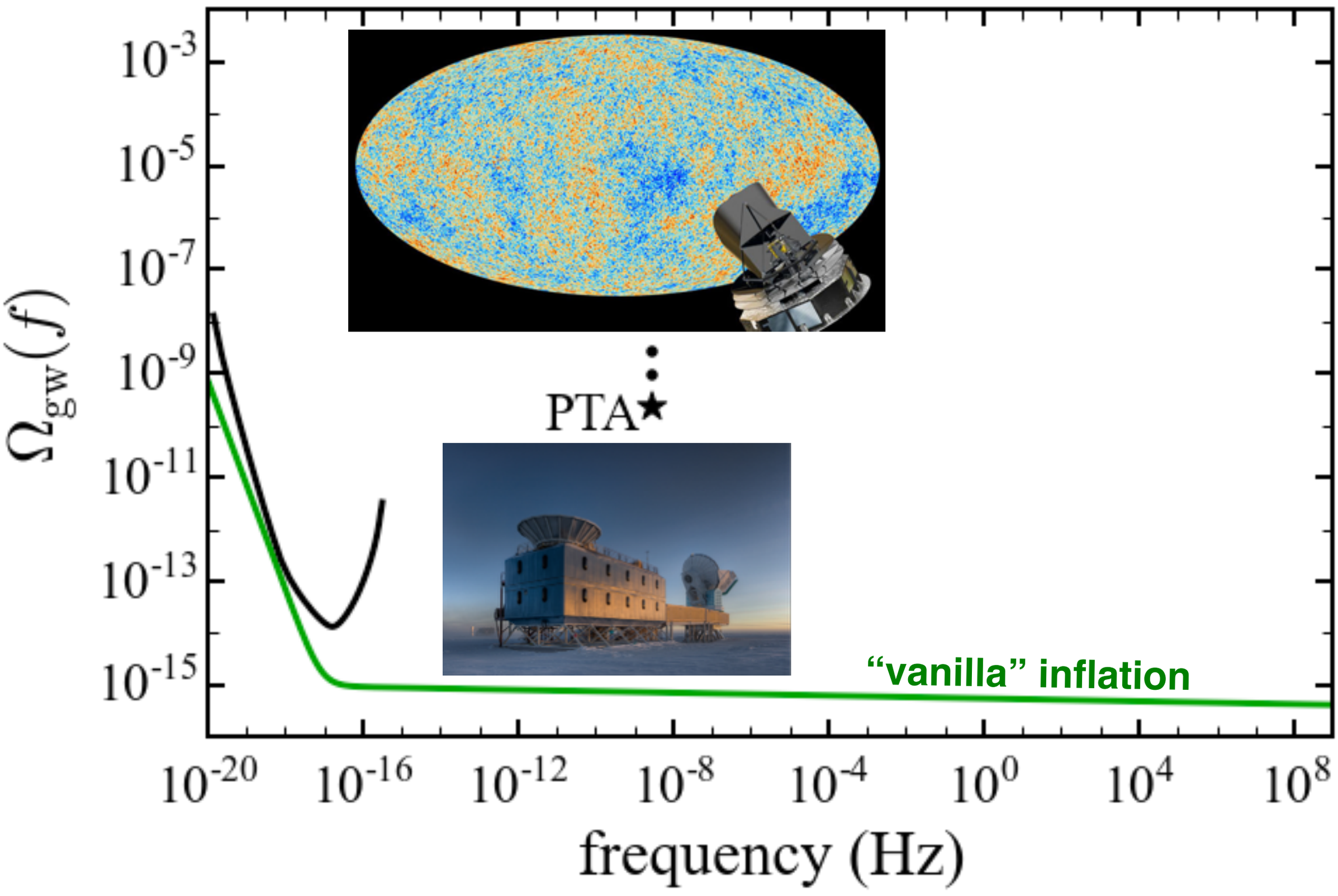

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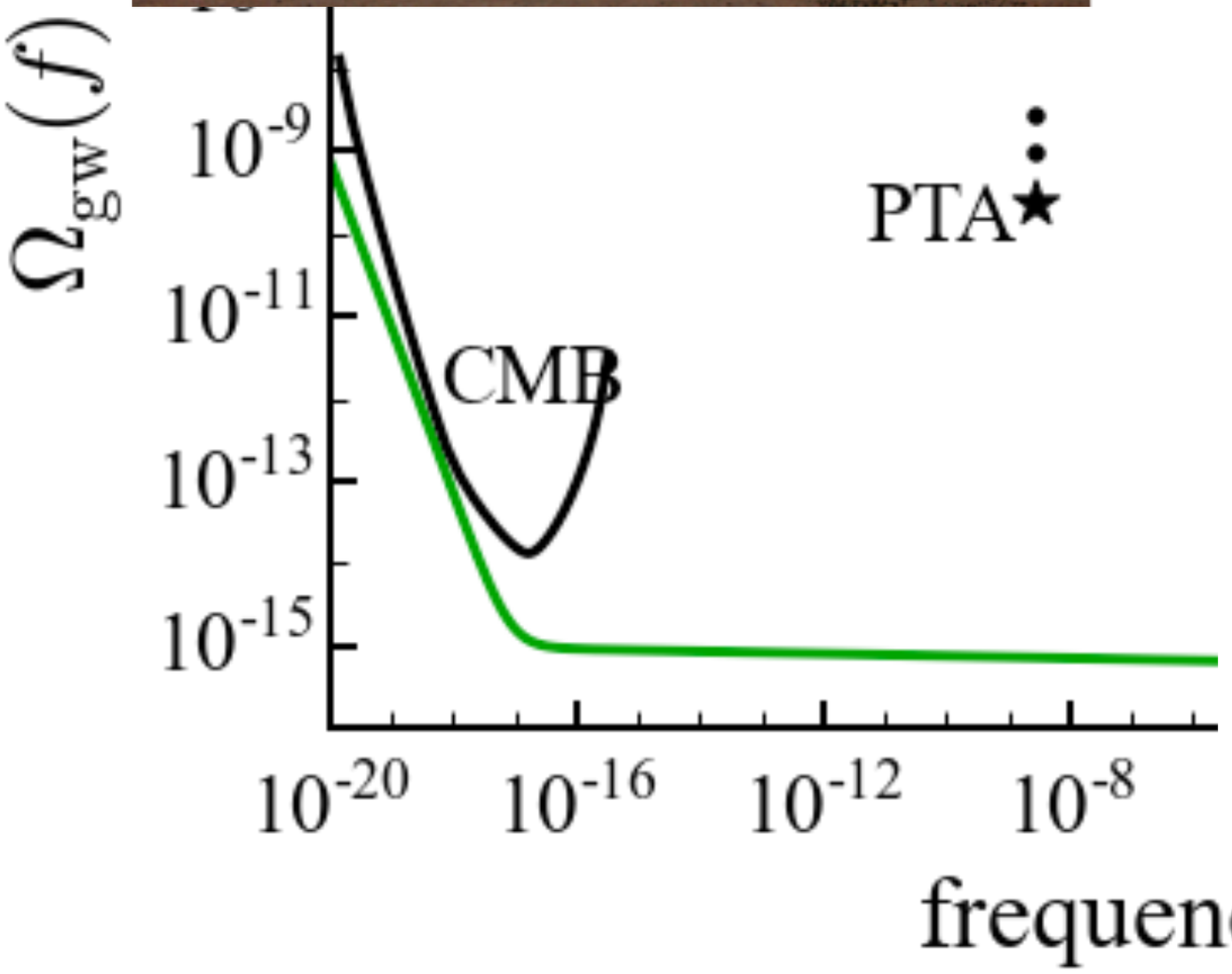
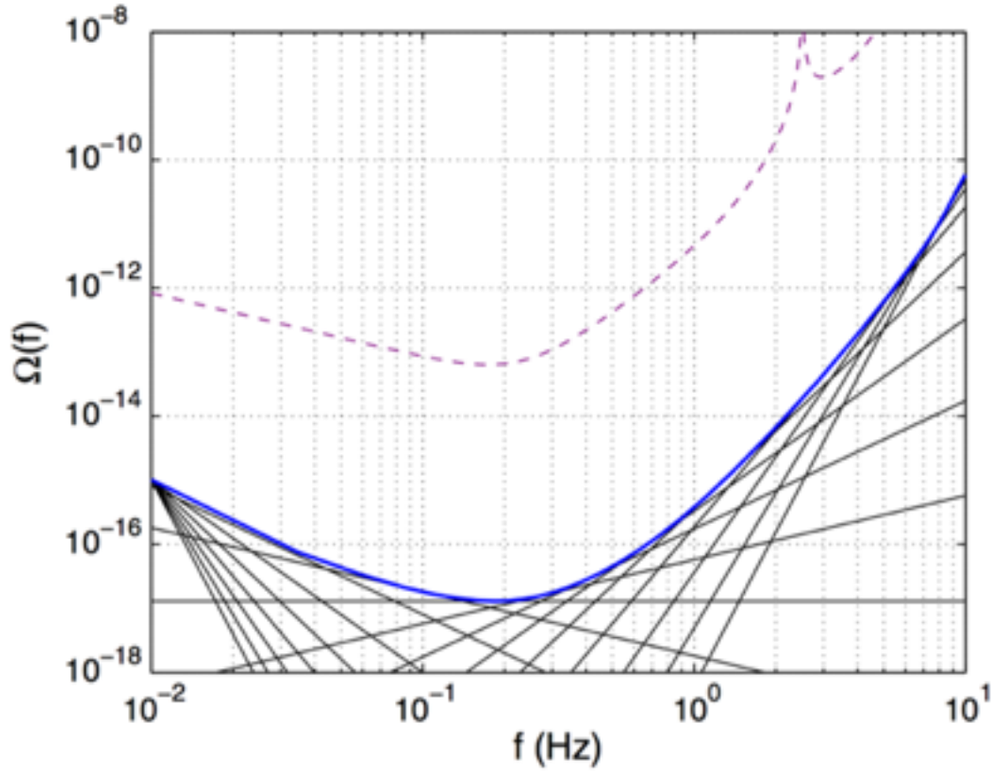
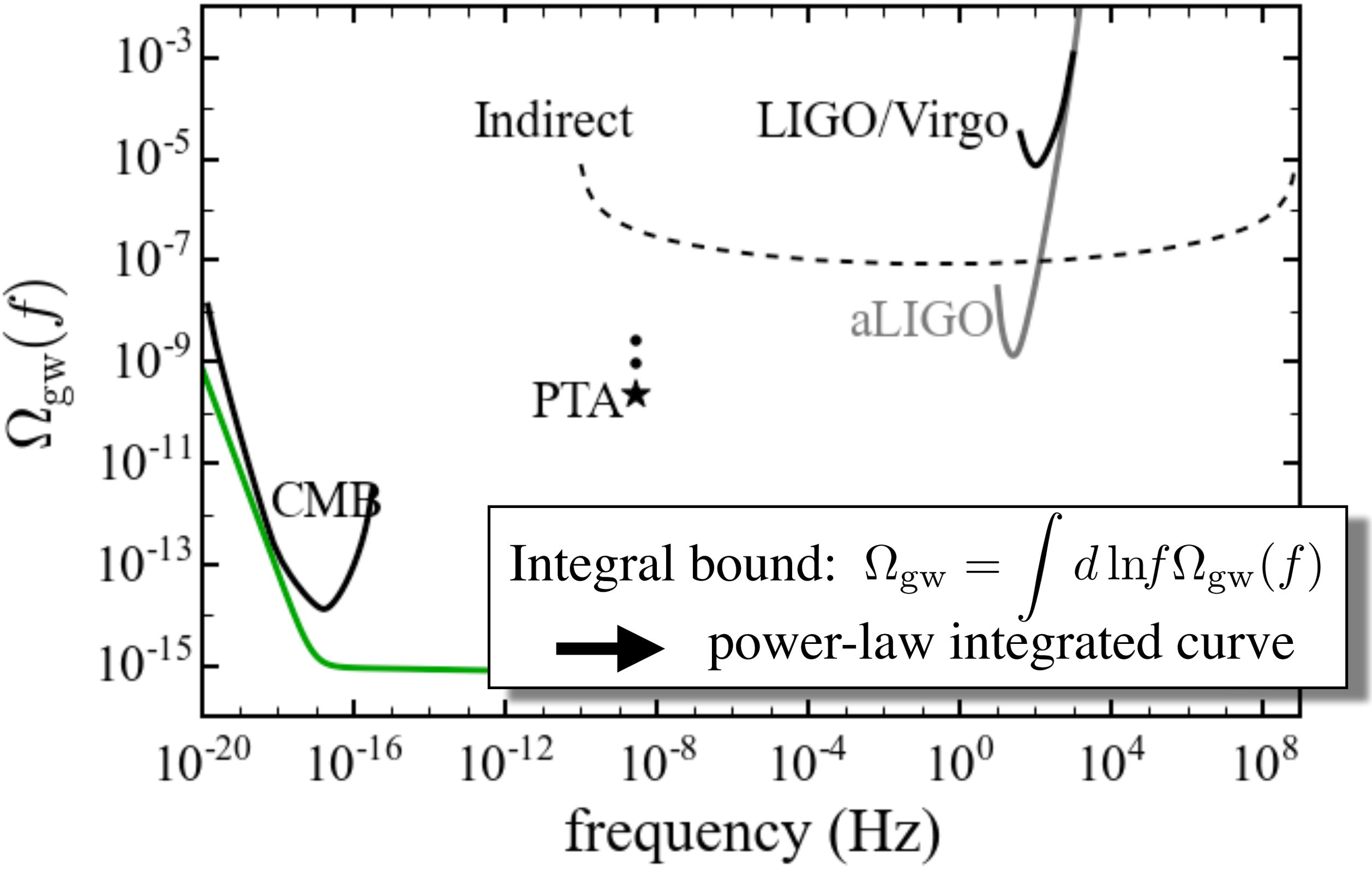




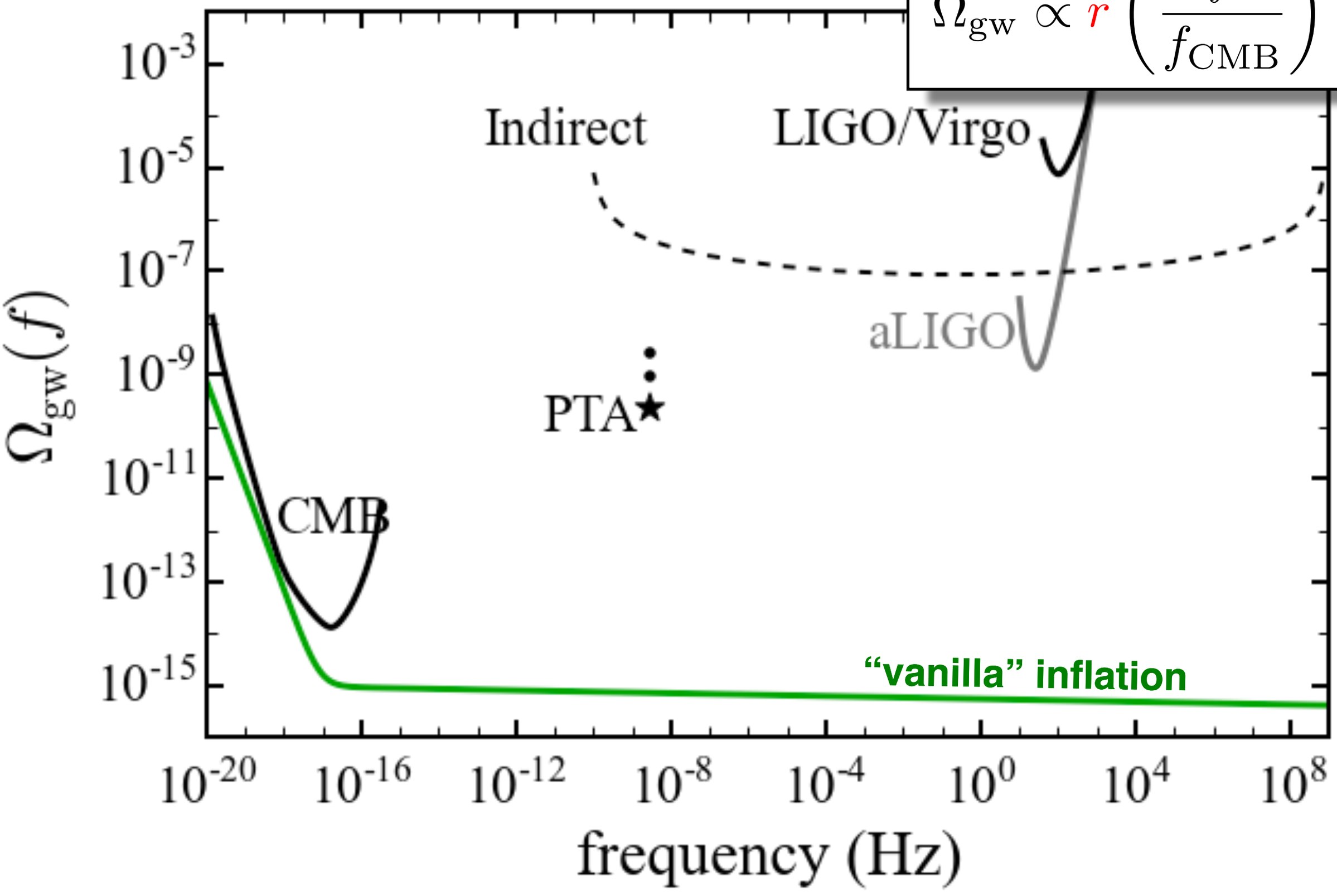
Thrane & Romano 2013

Lasky et al. (2015; submitted)



Lasky et al. (2015; submitted)

$$\Omega_{\rm gw} \propto r \left(\frac{f}{f_{\rm CMB}} \right)^{n_t}$$



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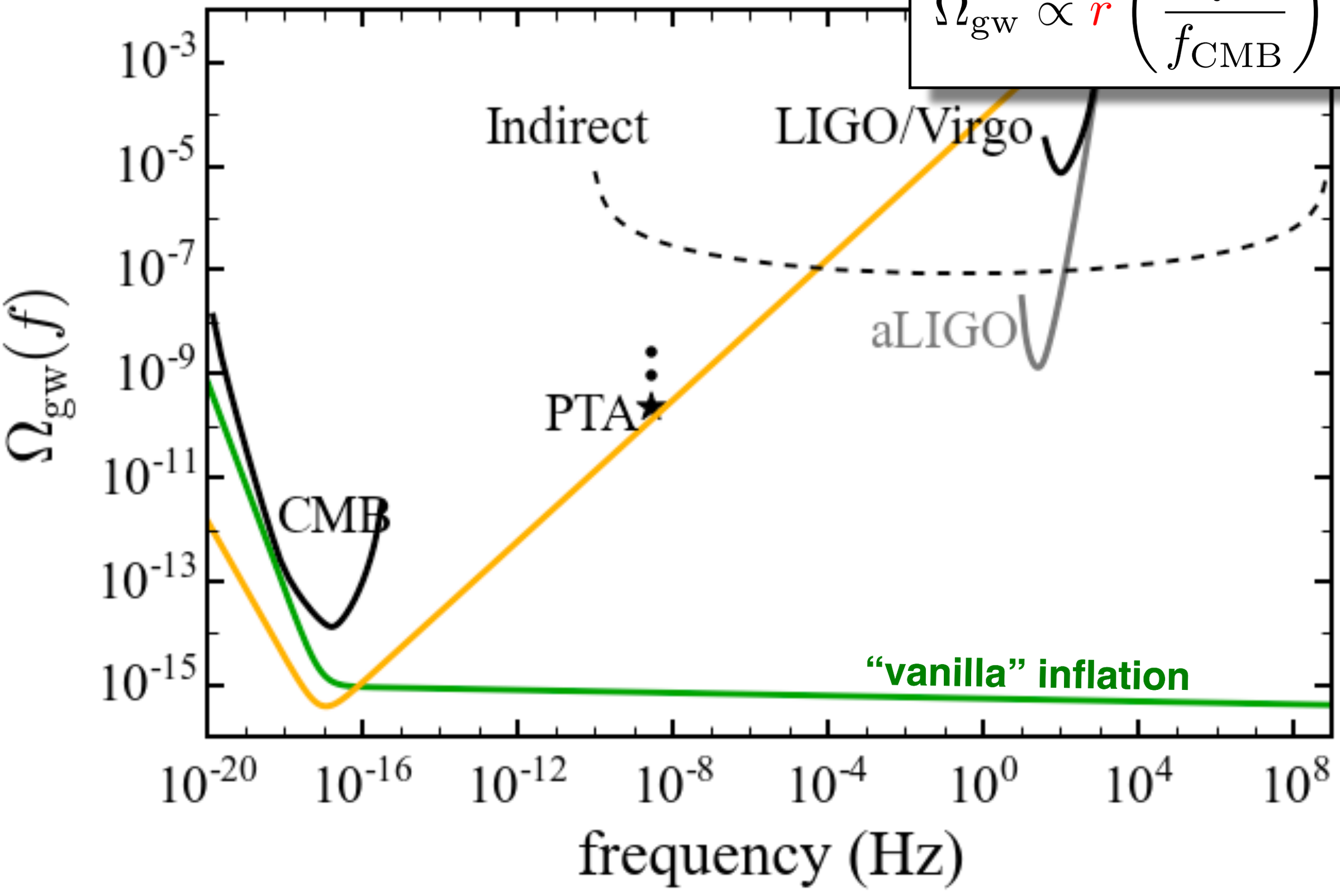

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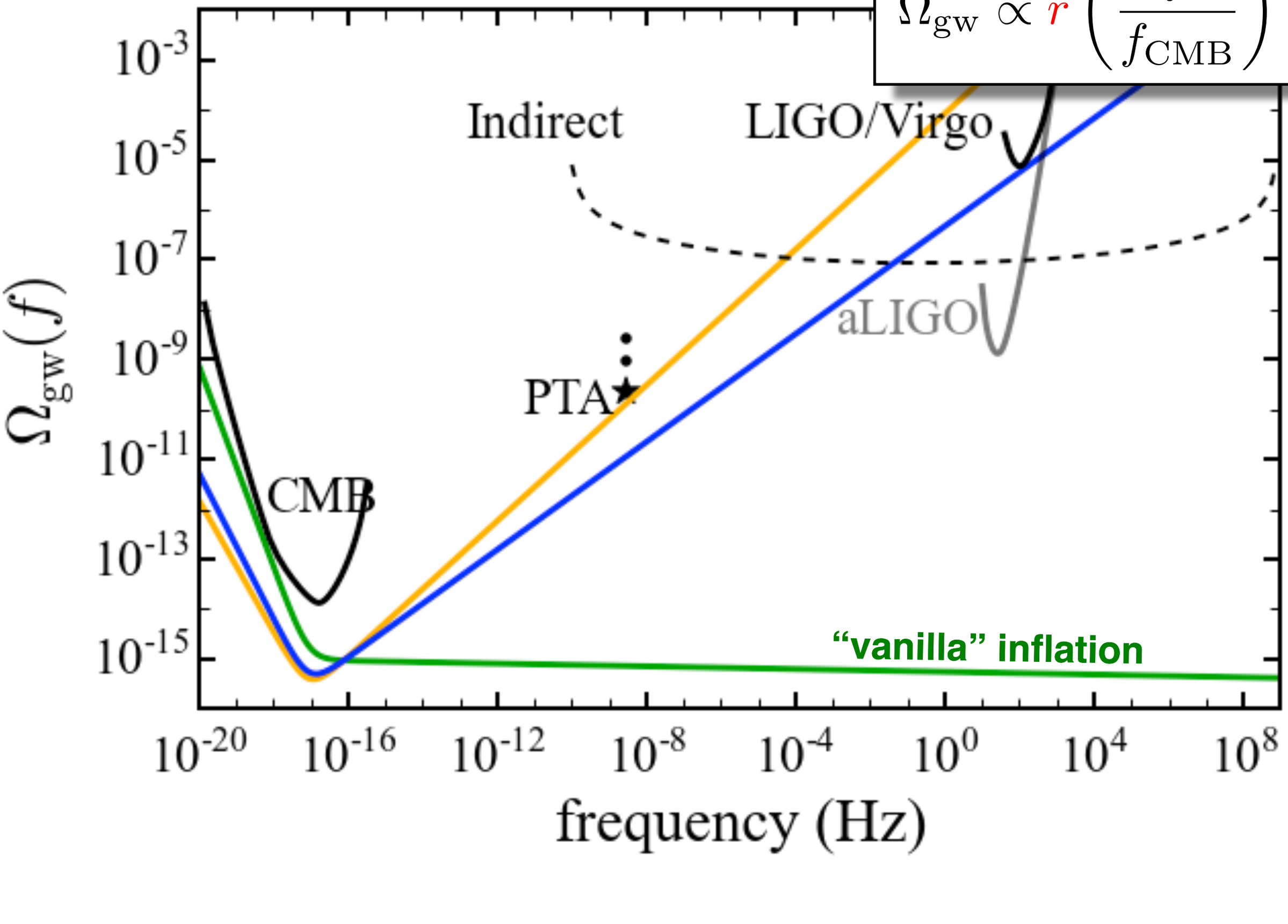

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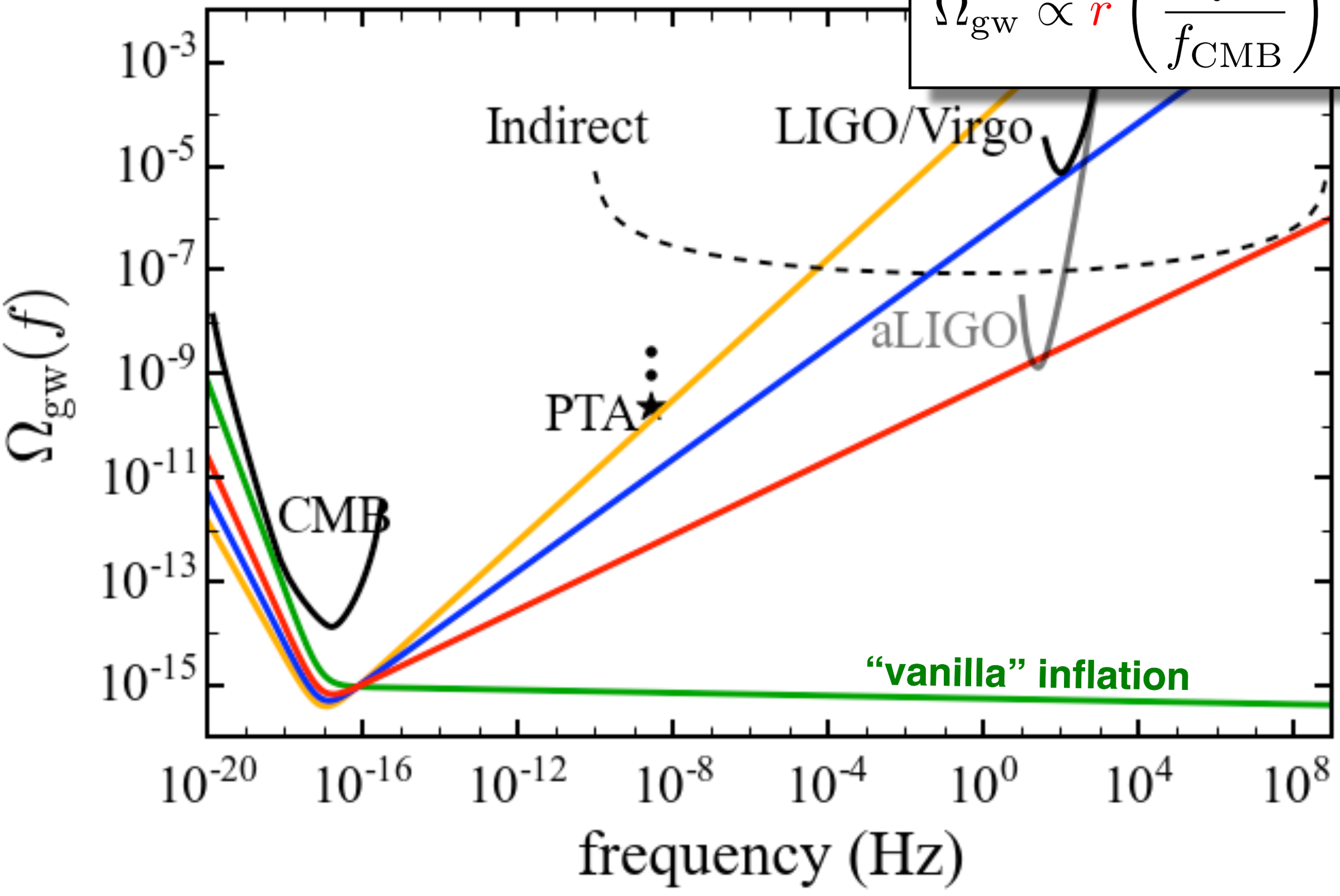

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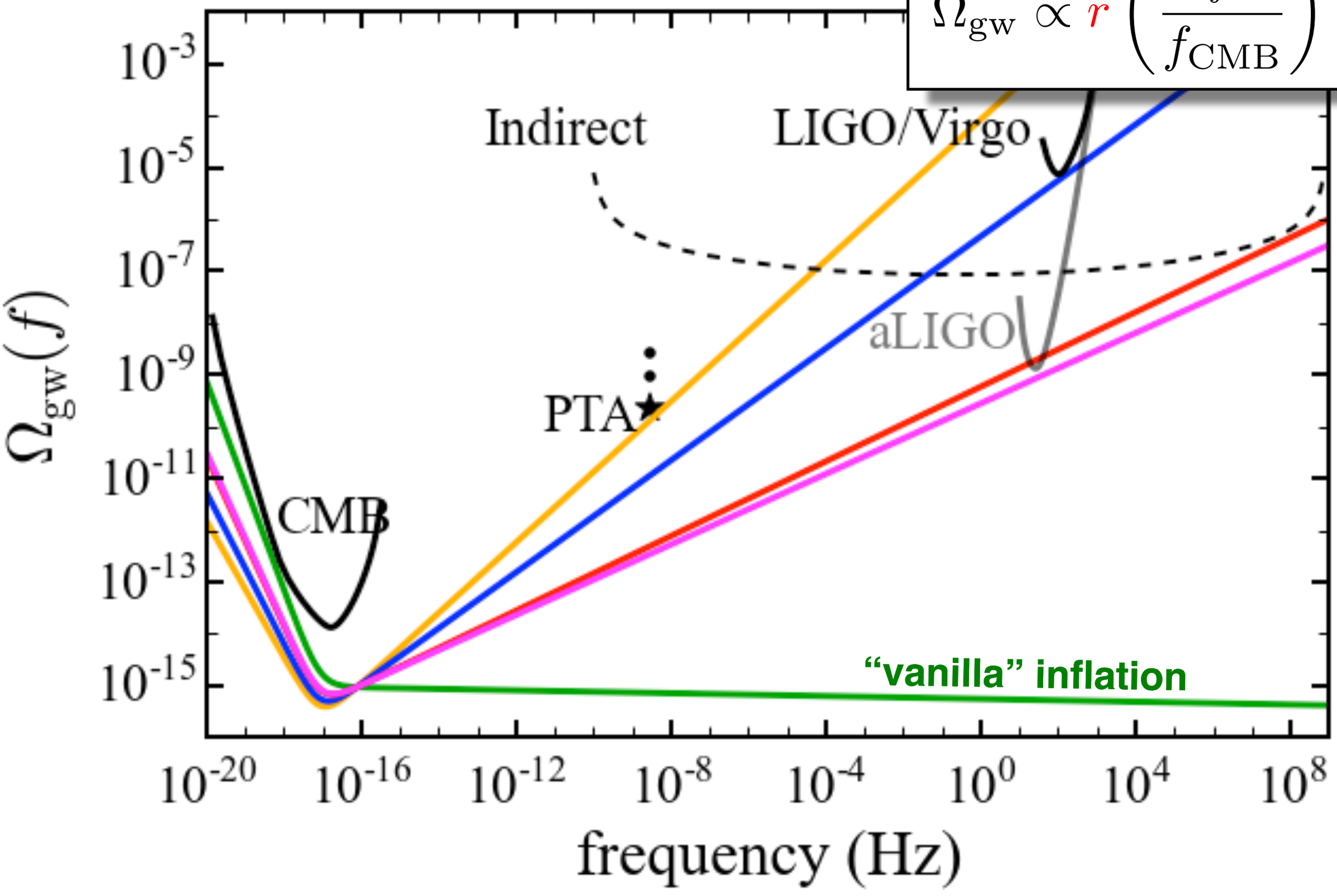


But… physics!?

Canonical inflation:

General relativity + spatially flat metric ⟶ red spectrum ($n_t < 0$)

Blue alternatives:

- ‘Super inflation’ (null energy violating field)
- string-gas cosmologies
- inflation with modified Einstein-Hilbert action
- ekpyrosis
- …

Our philosophy:

‘Let’s let the data decide!’

Lasky et al. (2015; submitted)

tilt of the spectrum

$$\Omega_{\rm gw} \propto r \left(\frac{f}{f_{\rm CMB}} \right)^{n_t}$$

tensor-to-scalar ratio

$\log r$

n_t

Lasky et al. (2015; submitted)

Planck

… + BICEP2

… + SPTpol

$\log_{10} r$

1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0

−1 0 1 2 3 4 5 6

n_t

Lasky et al. (2015; submitted)

PPTA

Planck

… + BICEP2

… + SPTpol

CMB + PPTA

$\log r$

n_t

1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−1
0
1
2
3
4
5
6

Lasky et al. (2015; submitted)

PPTA

LIGO

Planck

… + BICEP2

… + SPTpol

CMB + PPTA

… + LIGO

$\log r$

n_t

1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−1
0
1
2
3
4
5
6

Lasky et al. (2015; submitted)

PPTA

LIGO

Planck

… + BICEP2

… + SPTpol

CMB + PPTA

… + LIGO

… + indirect

$\log r$

n_t

1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−1
0
1
2
3
4
5
6

Lasky et al. (2015; submitted)

PPTA

LIGO

Planck

… + BICEP2

… + SPTpol

CMB + PPTA

… + LIGO

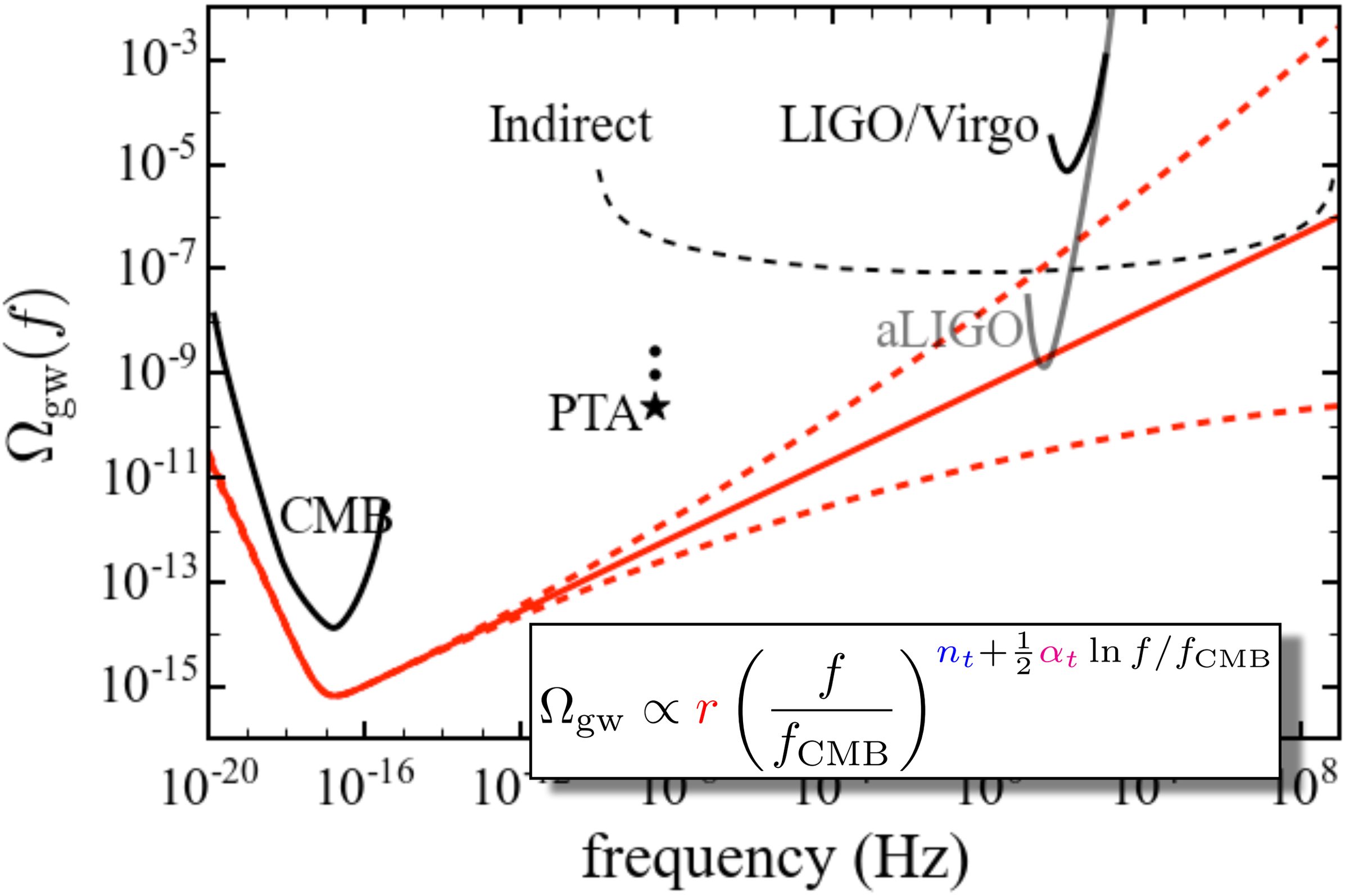
… + indirect

… + aLIGO + PPTA (2020)

$\log r$

n_t

1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−1
0
1
2
3
4
5
6


Indirect
LIGO/Virgo
aLIGO
PTA
CMB
$\Omega_{\rm gw}(f)$
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-20}
10^{-16}
10^{8}
frequency (Hz)
$\Omega_{\rm gw} \propto r \left(\frac{f}{f_{\rm CMB}} \right)^{n_t + \frac{1}{2}\alpha_t \ln f/f_{\rm CMB}}$

Conclusions

- **PPTA currently doing cosmology with non-detections!**
  - Our understanding of galaxy/black hole evolution needs updating
  - excellent probe of galactic cores, including environment of binary system
- **Doing gravitational-wave cosmology over 29 decades in frequency!**
  - Only the combination of experiments can constrain this parameter space
  - Not clear how important this parameter space is to inflationary theorists:
    - they have very little experimental data!
    - (they have creative tendencies without data…)

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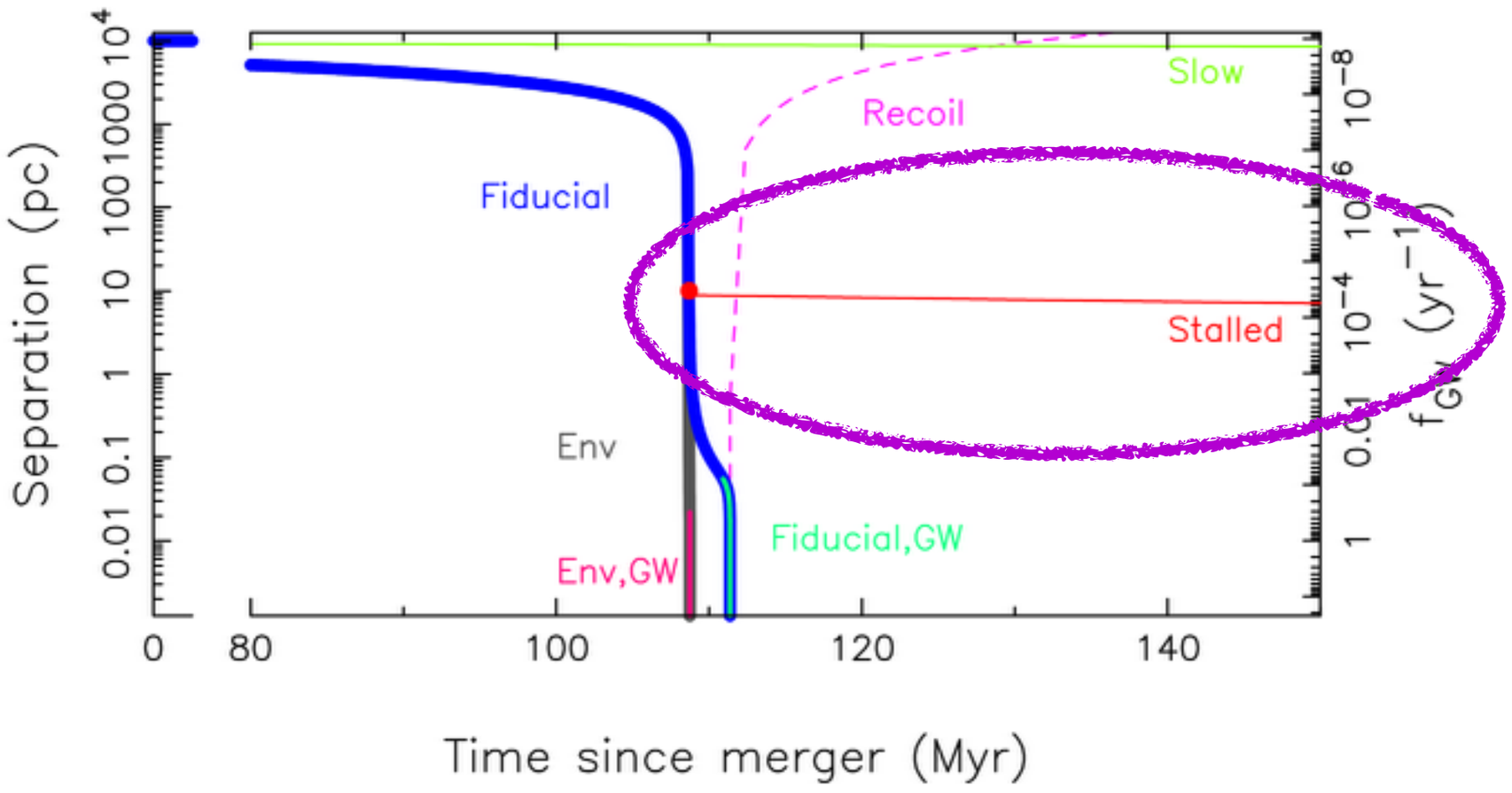
Extra Slides



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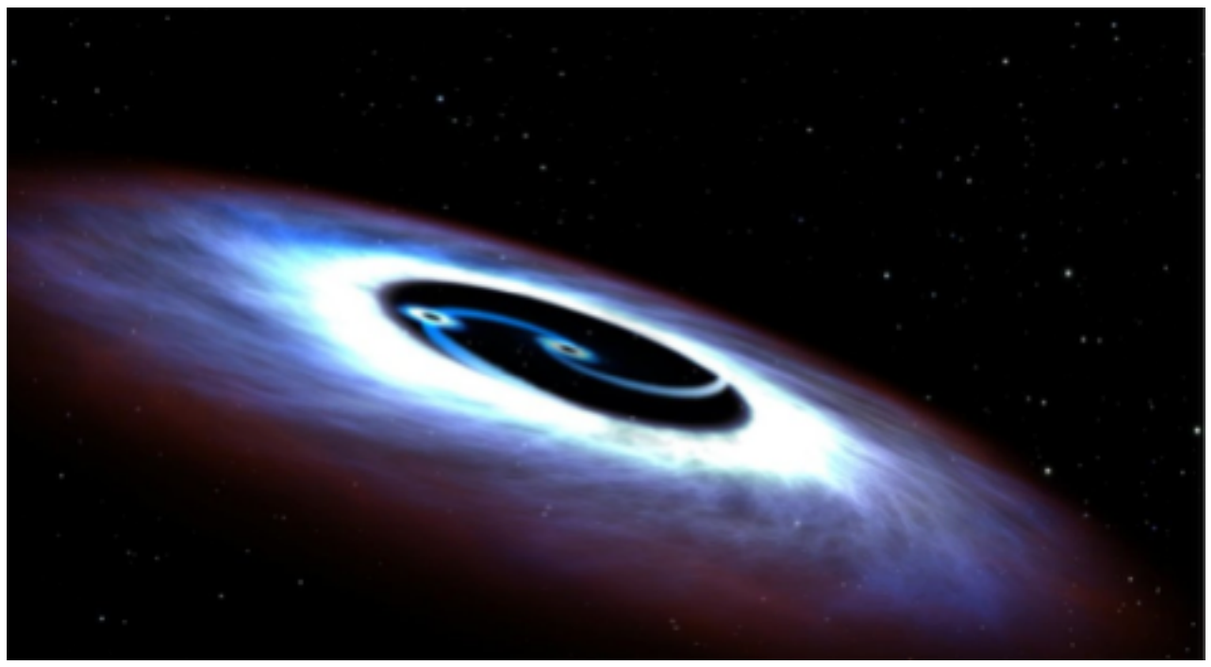
Is the final parsec problem solved?

sciencedaily.com



Stalled evolution:

- many binary systems
- rogue, isolated BHs from 3-body interactions

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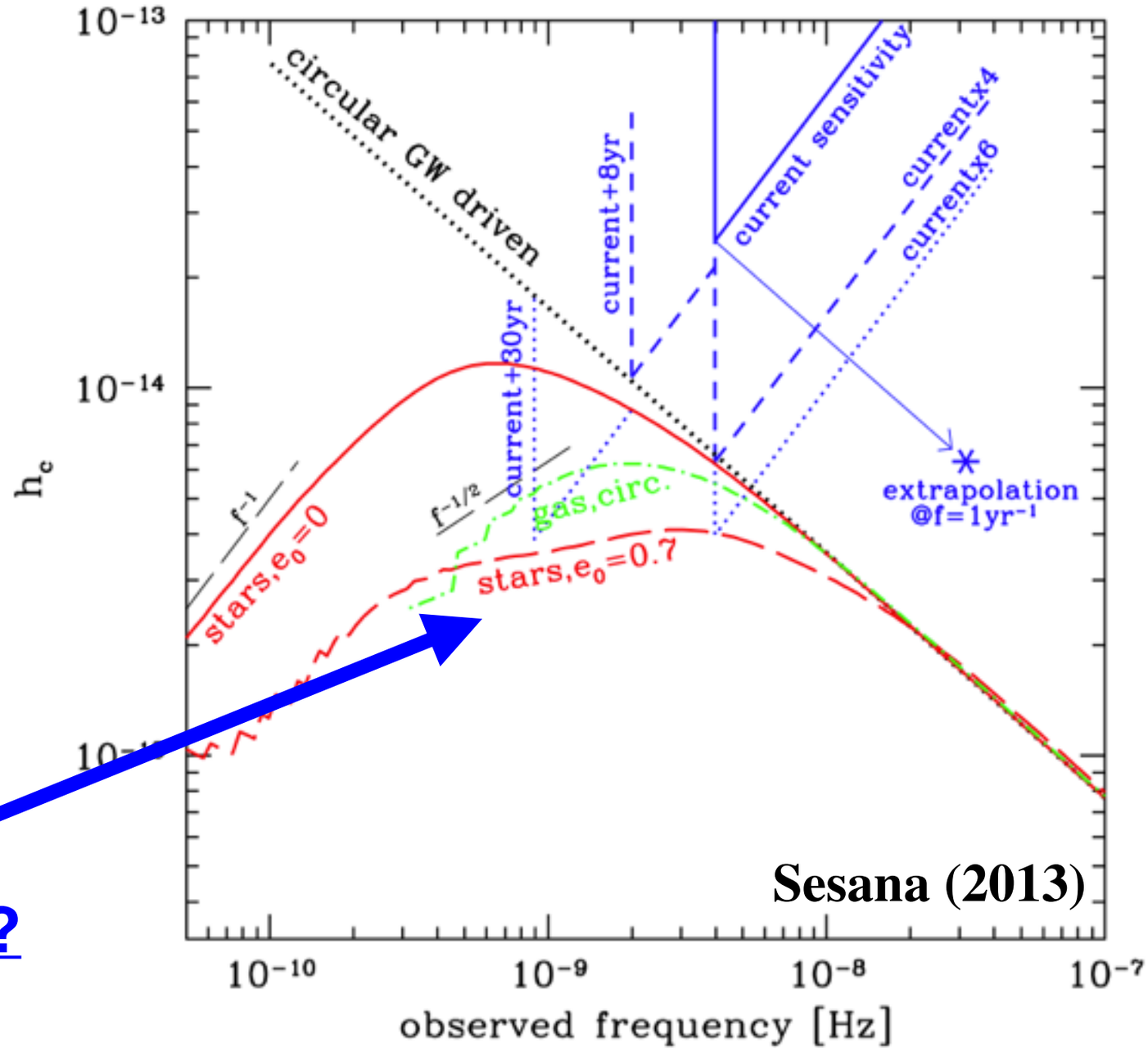
The Environment

Circular inspiral

GWs: $h_c \propto f^{-2/3}$

Stars: $h_c \propto f$

Gas: $h_c \propto f^{1/2}$



Where is the 'knee'?

need to understand:

- gas/stellar density in galactic cores?
- actual masses of supermassive BHs?
- ....

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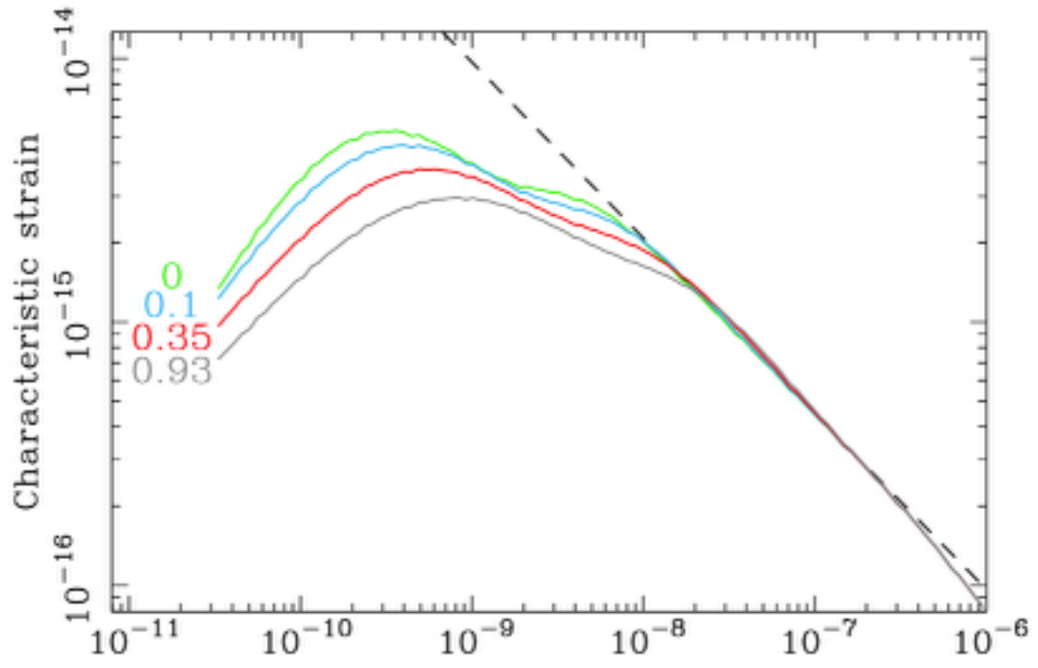
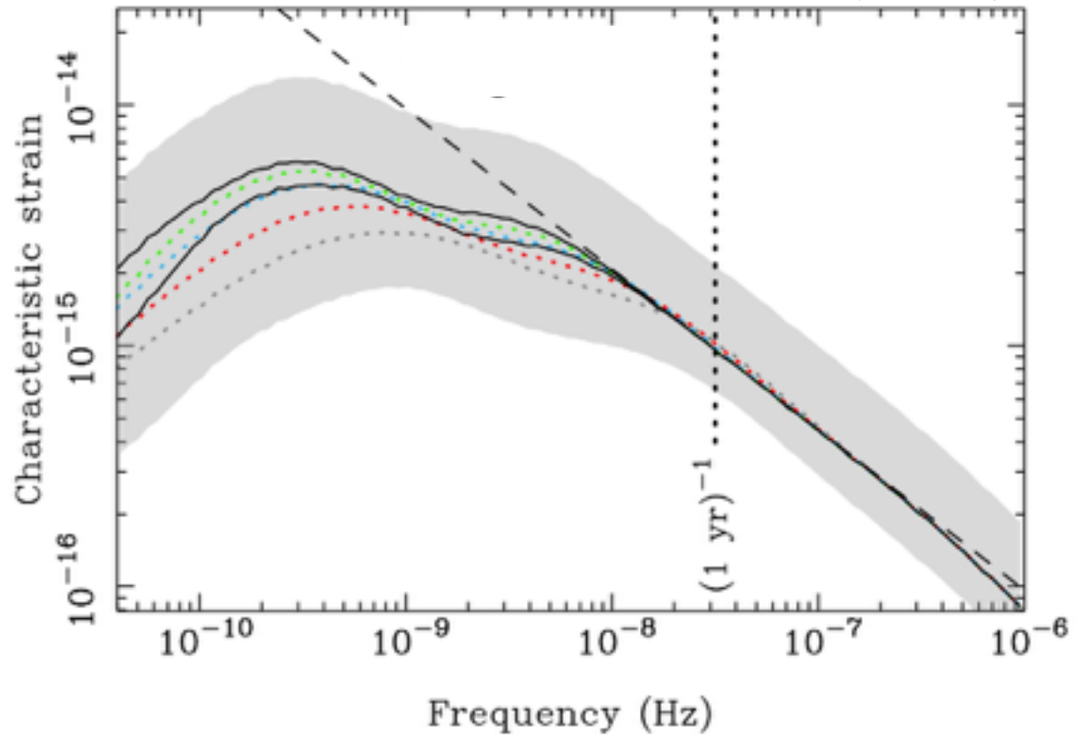
The Environment

non-zero eccentricities

GWs circularise orbits

some other effects drive eccentricity up:
e.g., retrograde circumbinary accretion, …

Enoki & Nagashima (2007)



Ravi et al. (2014)