Detecting DM Decay into Gravitons

Theory and Forecasts

Now on the arXiv! [2510.18958]

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Table of Contents

1. DM decay

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[Poulin+ 2016]

1. DM decay

- Is DM stable? **We don't know!**

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Fraction of Decaying DM

[Poulin+ 2016]

- Why DM decay?
  - H_0 and σ_8 [Pandey+ 2019 ; Vattis+ 2019]
  - Small-scale structure [Wang+ 2014]
  - Positron excess in cosmic rays [Ibarra & Tan 2009 ; Farzan & Rajaee 2019]

1.1. DM decay into gravitons

- DM interacts gravitationally: **Gravitational decay?**

$$\mathrm{DM} \rightarrow \quad \text{gravitons} + \text{other DM}$$

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- $\phi \rightarrow 2h$ (bosonic DM)

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- Just one channel: $\Gamma = \Gamma_{\phi hh}$
- Just one DM: ϕ
- Assume ΛCDM

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Phenomenological approach

Parameters

- m_ϕ (DM mass)
- $\tau_\phi = 1/\Gamma_\phi$ (DM lifetime)
- n_{DM} (DM # density)

Set by cosmo/astro observations

1.2. $\phi \to 2h$: contributions

Two contributions:

- DM fluid $\to$ **Extragalactic contribution**
- DM halo $\to$ **Local contribution**

Flux of gravitons

(per unit energy and solid angle)

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{4\pi}\int \mathrm{d}s \frac{2n_\phi(\mathbf{s},\boldsymbol{\Omega})}{\tau_\phi} \times \text{Energy dependence}$$

$\downarrow$

Different GW descriptions

$$H_0^2\Omega_{\mathrm{GW}}(f) = \frac{2\pi^2}{3}f^3 S_h(f) = \frac{2\pi^2}{3}f^2 h_c^2(f) = \frac{8\pi G}{3c^2} f S_E(f)$$

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 # Density: DM fluid

- **Homogeneous & Isotropic**

$$n_\phi(t) = \frac{\rho_c \Omega_{\mathrm{DM}}}{m_\phi} e^{-(t-t_0)/\tau_\phi}$$

Redshift

- **At cosmo. distances the redshift is relevant**

$$\delta\left(E - a(t)\frac{m_\phi}{2}\right)$$

1.2. $\phi \to 2h$: contributions

Two contributions:

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- DM halo → **Local contribution**

Flux of gravitons
(per unit energy and solid angle)

$$\frac{d\Phi}{dE\,d\Omega} = \frac{1}{4\pi}\int ds\,\frac{2n_\phi(\mathbf{s},\mathbf{\Omega})}{\tau_\phi} \times \text{Energy dependence}$$

 # Density: DM halo

- **Inhomogeneous and anisotropic**
- **Plug in your favourite DM profile** *(we use Einasto)*

***Approximation**: we will consider the sky-averaged local flux, so we won't be taking into account the anisotropy in the detection*

Doppler broadening

- **Doppler broadening due to velocity dispersion of DM.**
- **Modeled by Gaussian with mean** $m_\phi/2$

2. Detecting SGWBs

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DM decay: stochastic process → **Stochastic GW Background**

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A SGWB is seen in detector as an **additional source of noise.** ⟶

1. **Characterize with extreme precision the noise**
2. **Cross-correlate between detectors**

2. Detecting SGWBs

DM decay: stochastic process → **Stochastic GW Background**

A SGWB is seen in detector as an **additional source of noise.** →

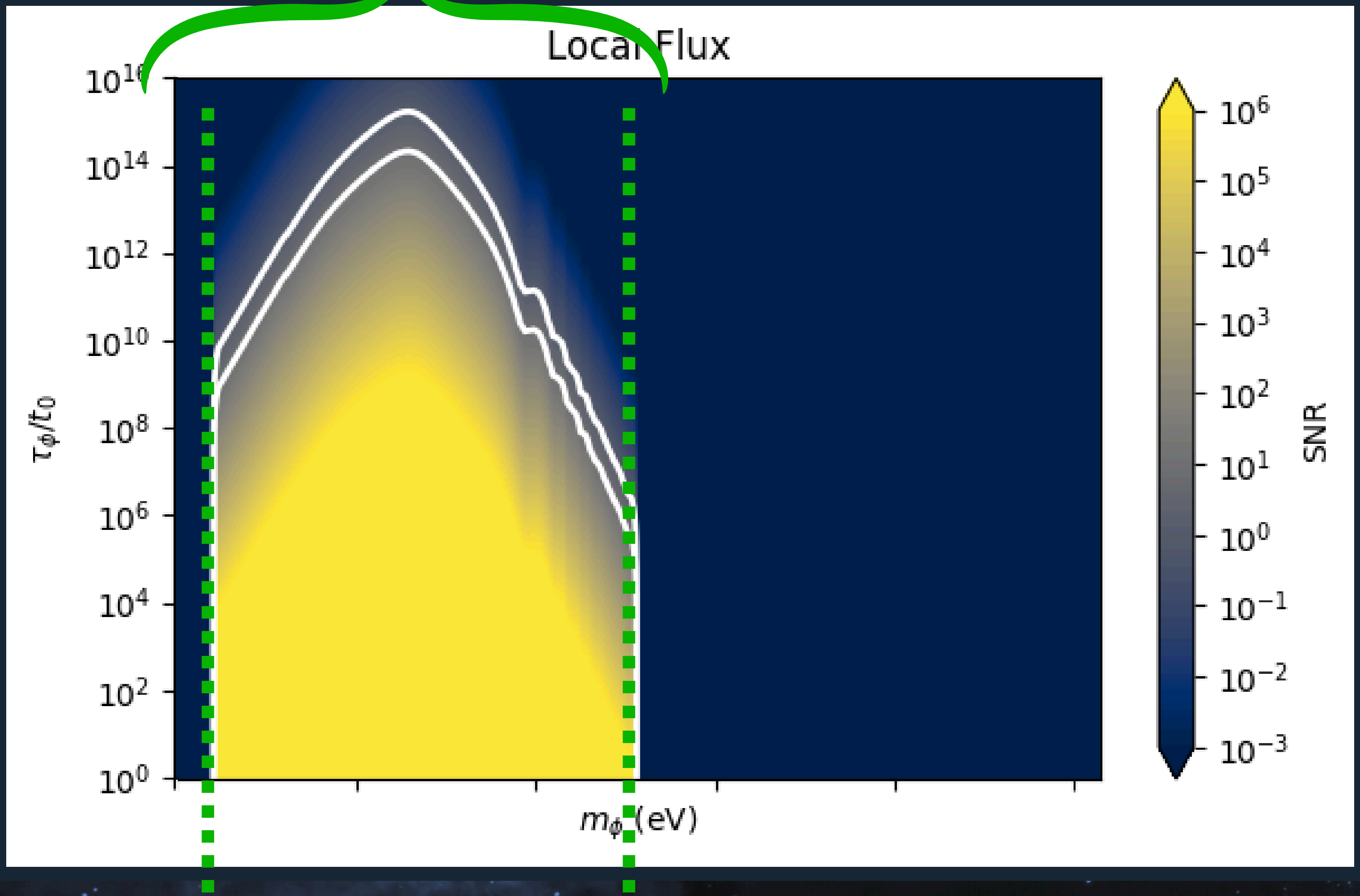
1. **Characterize with extreme precision the noise**
2. **Cross-correlate between detectors**

$$\mathrm{SNR} \sim \sqrt{\mathrm{Obs.\ time}} \times \left[\int_0^\infty \sum_{I,J \in \{\mathrm{Det.}\}} \frac{\mathrm{Corr}_{IJ} \times \mathrm{Signal}^2}{\mathrm{Sens}_I \mathrm{Sens}_J} \mathrm{d}f \right]^{1/2} > 8$$

3. Forecasts

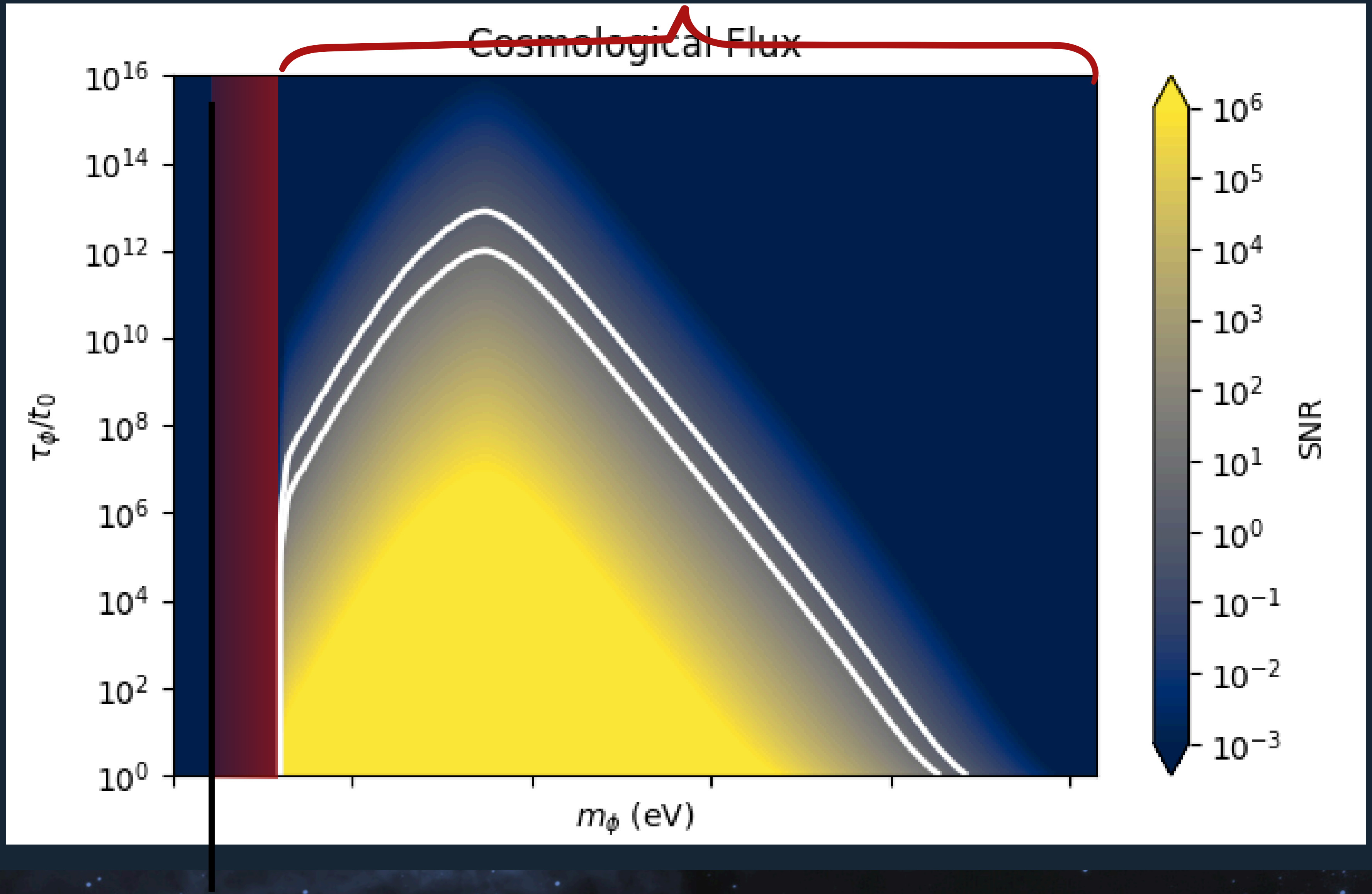
3. Forecasts: LISA

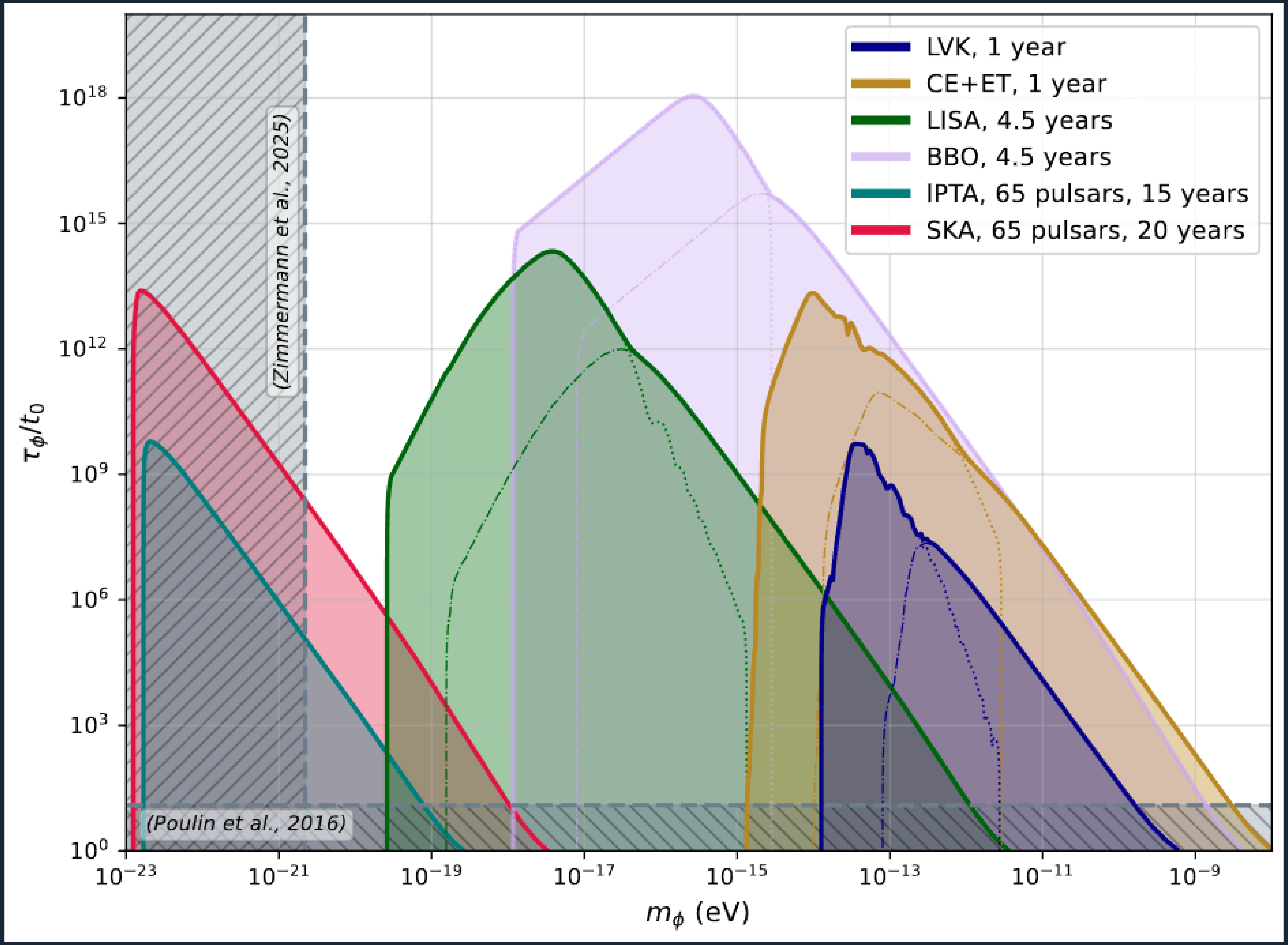
Range of masses ~ $[\hbar f_{min}, \hbar f_{max}]$

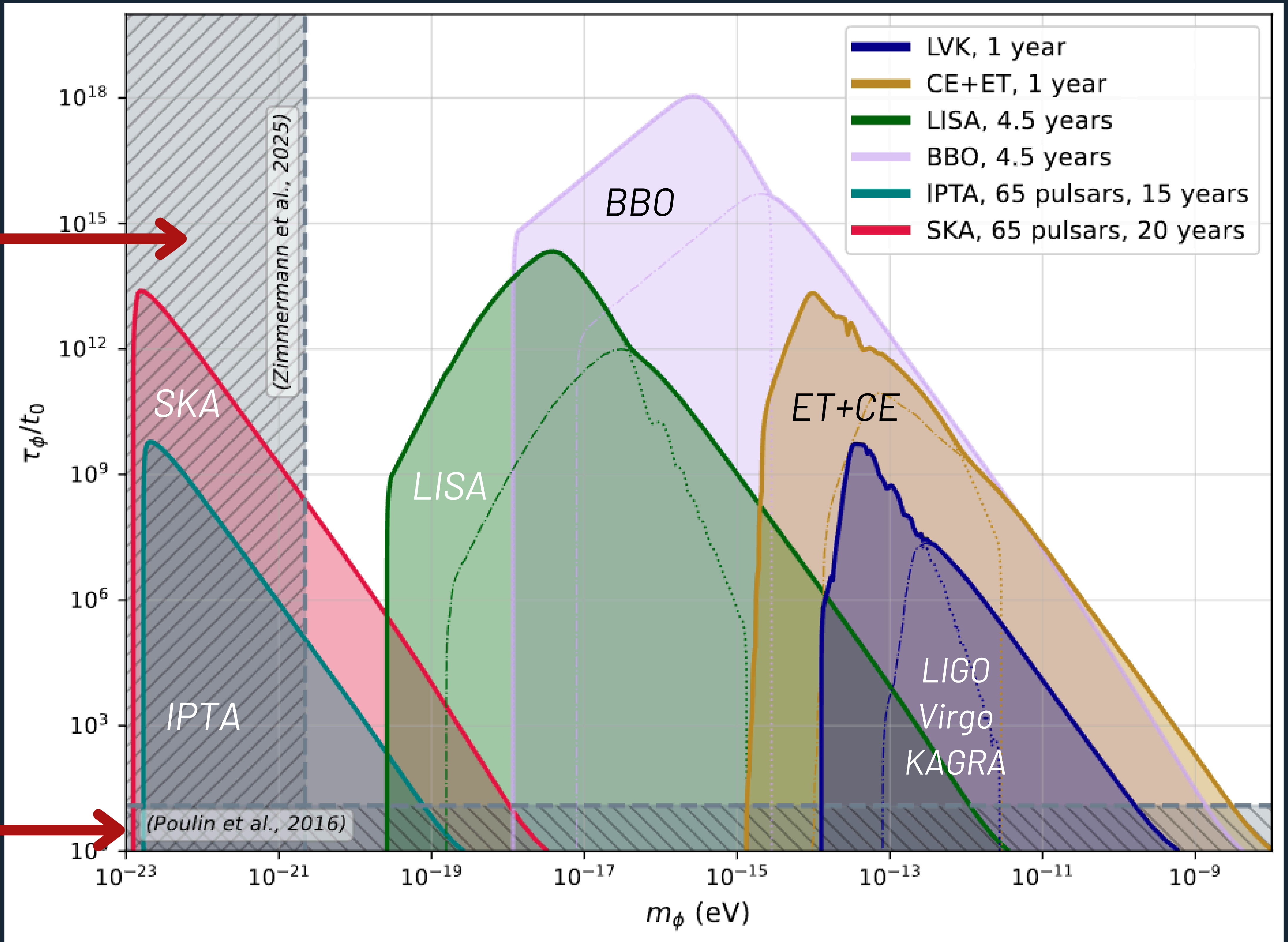


3. Forecasts: LISA

Redshifted towards higher masses

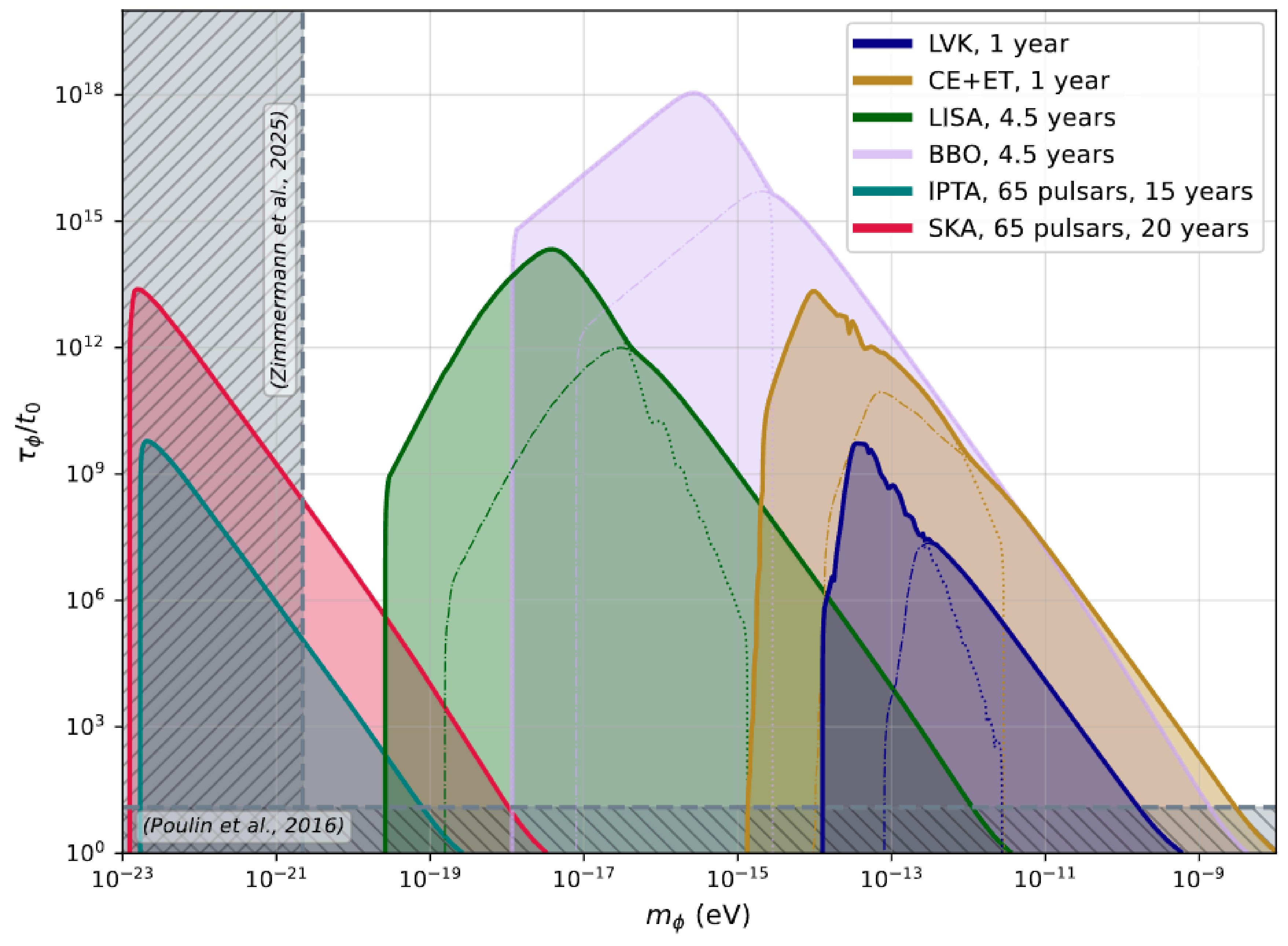



LVK, 1 year
CE+ET, 1 year
LISA, 4.5 years
BBO, 4.5 years
IPTA, 65 pulsars, 15 years
SKA, 65 pulsars, 20 years
(Zimmermann et al., 2025)
(Poulin et al., 2016)
τ_ϕ/t_0
m_ϕ (eV)



Previous Constraints

3. Forecasts



Some remarks:

- PTA not sensible to changes in # pulsars
- PTAs peak under dwarf-galaxy constraints.

- $m_\phi < 3 \times 10^{-9}\,\mathrm{eV}$ (from CE+ET)

- LISA will cover a whole new region, connecting the mass ranges of ground based interferometers and PTAs

Conclusions

- Forecasted detectability of $\phi \to 2h$ decays with current and future GW detectors.
- Next-generation detectors (LISA, ET, CE, SKA) provide continuous mass coverage and improved lifetime reach.
- Sensitive to masses $m_\phi \sim 10^{-23} - 10^{-9}\,\mathrm{eV}$ and lifetimes up to $\tau_\phi \sim 10^{18} t_0$.
- We do not expect the results to change substantially when generalizing to decay to N gravitons $\phi \to Nh$

BACKUP SLIDES

Backup: DM model

Direct decay: EFT model

[Alonso-Artiles+ (2016)]
[Ema+ (2022)]
[Landini & Strumia (2025)]

$$\mathcal{L} \sim \frac{\phi}{\Lambda} R^{\mu\nu\alpha\beta} R_{\mu\nu\alpha\beta} + \frac{\phi}{\tilde{\Lambda}} R^{\mu\nu\alpha\beta} \tilde{R}_{\mu\nu\alpha\beta}$$

Interaction strongly suppressed

$(m_\phi / M_{\rm Pl})^5$

Extremely high-frequency GWs

↓

~~**Direct detection**~~

Indirect: $h \to \gamma$
[Dunsky+, 2025]

$\phi \to 2h$ (Extragalactic contribution)

Two contributions:

- Extragalactic contribution
- Local contribution

Extragalactic contribution

- Produced by DM at cosmo. dist.
- Homogeneous & Isotropic

$$n_\phi(t) = \frac{\rho_c \Omega_{\rm DM}}{m_\phi} e^{-(t-t_0)/\tau_\phi}$$

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$$\frac{\mathrm{d}\Phi_{\rm E}}{\mathrm{d}E} = \int_0^{t_0} c\mathrm{d}t \frac{2n_\phi(t)}{\tau_\phi} \delta(E - a(t) m_\phi/2)$$

$\phi \to 2h$ (Local contribution)

Two contributions:

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- Local contribution

Local contribution

- Produced by galactic DM halo
- Inhomogeneous & Anisotropic

$$\Phi_L = \frac{1}{4\pi} \int \mathrm{d}\Omega \int_0^\infty \mathrm{d}s \frac{2n_\phi(r(s,\psi))}{\tau_\phi}$$

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(Einasto profile)

$$n_\phi(r) = \frac{1}{m_\phi}\frac{M_0}{4\pi r_s^3}\exp\left[-(r/r_s)^\alpha\right],$$

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$$\frac{d\Phi_L}{dE} = \Phi_L \frac{1}{\sqrt{2\pi}\sigma_E}\exp\left[-\frac{(E-m_\phi/2)^2}{2\sigma_E^2}\right]$$

$$\sigma_E \sim \frac{\sigma_v}{c}E \sim 10^{-3}\frac{m_\phi}{2}$$

(Doppler broadening due to vel. disp.)

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Sky-averaged flux: Won't consider the anisotropy in the detection

$$\frac{d\Phi_L}{dE} = \Phi_L \frac{1}{\sqrt{2\pi}\sigma_E}\exp\left[-\frac{(E-m_\phi/2)^2}{2\sigma_E^2}\right]$$

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2.a) Optimal SNR

With two detectors we can use a modified matched filtering

(Optimal SNR from cross-correlation of pairs of N detectors)

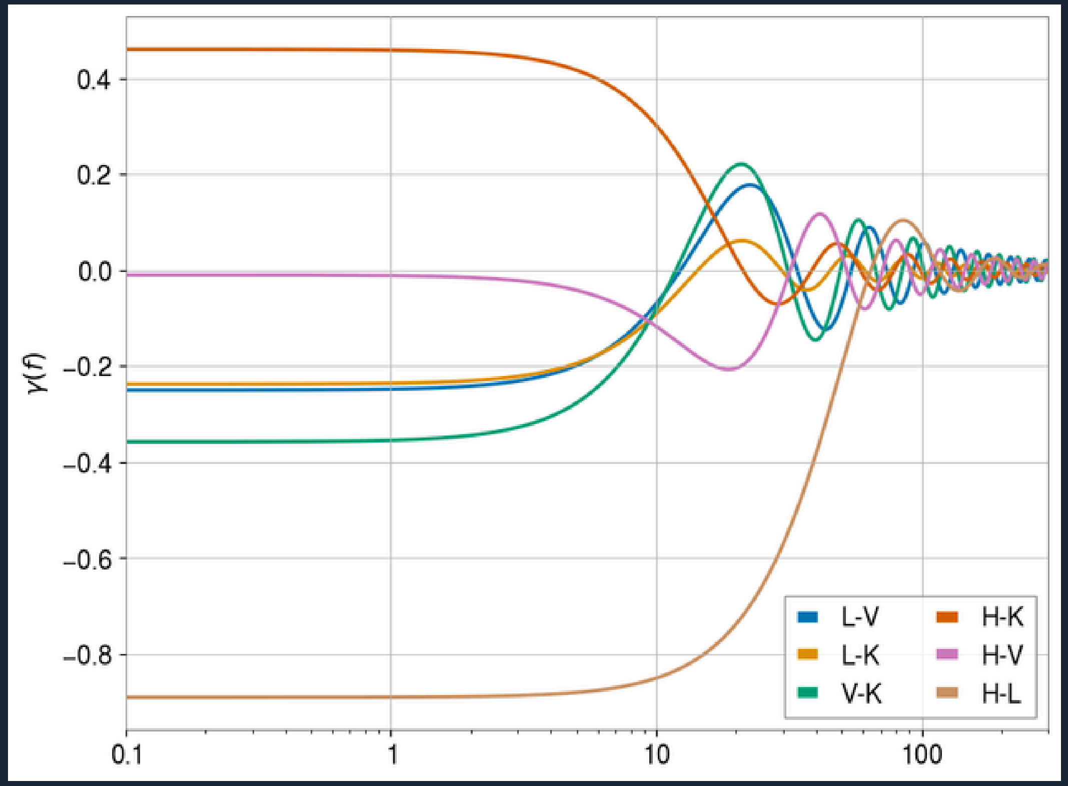
$$\mathrm{SNR} = \sqrt{2T}\left[\int_0^\infty \mathrm{d}f \sum_{I=1}^{N}\sum_{J>I}^{N} \frac{\Gamma_{IJ}^2(f)\, S_h^2(f)}{P_{nI}(f)\,P_{nJ}(f)}\right]^{1/2}$$

Observation time

Noise PSDs of the detectors

Γ_{IJ} **: Overlap Reduction Function (ORF)** encodes the relative geometry and separation of the detectors.

For PTAs Γ_{IJ} *~ Hellings-Downs factors* ζ_{IJ}



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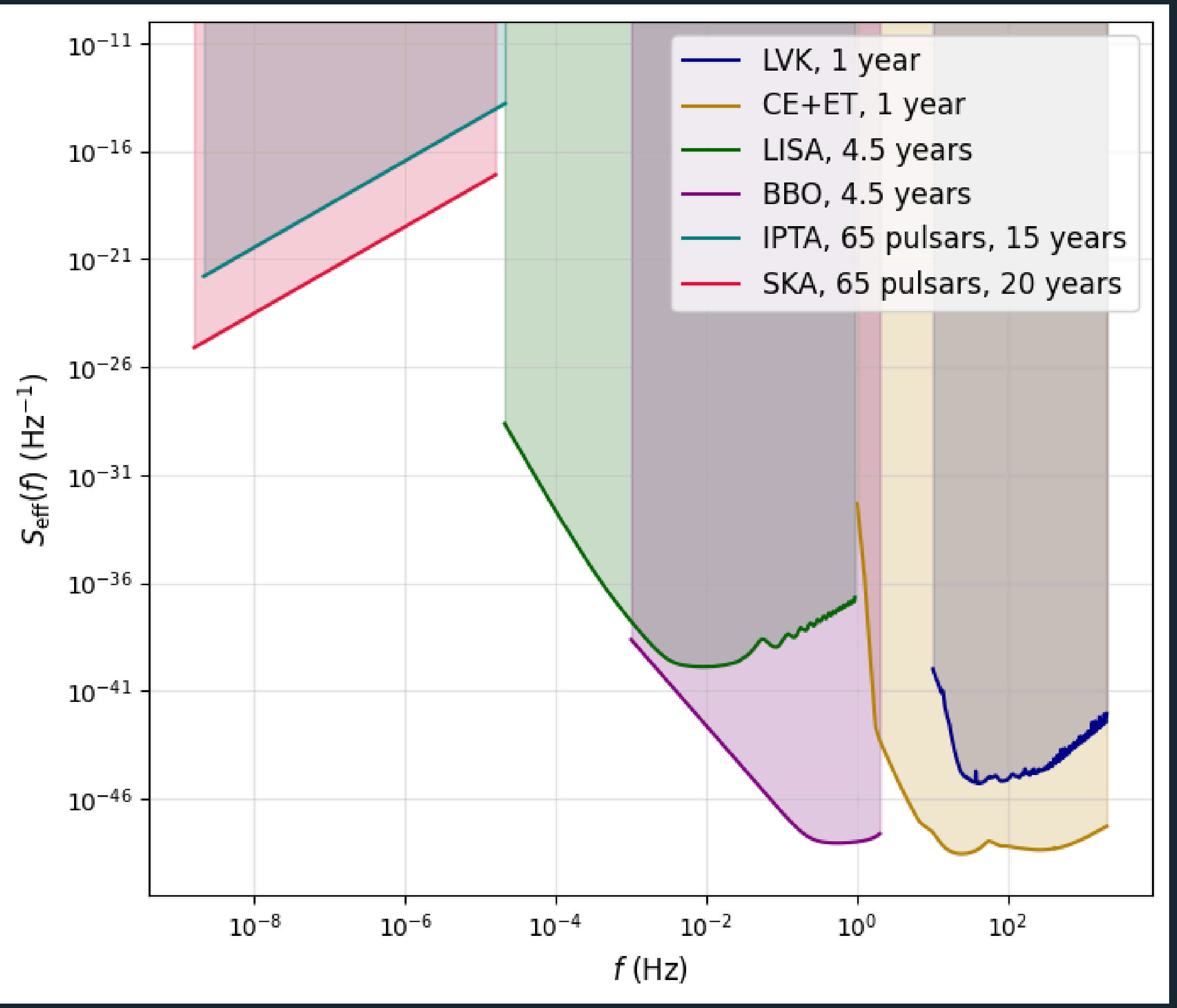
$$= \sqrt{2T}\left[\int_0^\infty \mathrm{d}f \frac{S_h^2(f)}{S_{\mathrm{eff}}^2(f)}\right]^{1/2}$$

[Allen & Romano 1999]

Not the same as coherent signals!!



2.b) Optimal SNR for LISA

Very suppressed response to GWs:
Excellent noise measurement!

LISA is a bit peculiar...

- **Three noise-orthogonal (synthetic) channels: A, E** and **T**

However... A and E are uncorrelated for $f \ll 3 \times 10^{-2}\,\mathrm{Hz}$ [Cutler 1998]

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Luckily, we may use T as a noise reference → Subtract noise

Similar to previous SNR, but without factor $\sqrt{2}$

$$\mathrm{SNR} = \boxed{\sqrt{T}}\left[\int_0^\infty \mathrm{d}f\,\frac{S_h^2(f)}{S_n^2(f)}\right]^{1/2}$$

[Thrane&Romano 2013]

(Optimal SNR assuming perfect noise subtraction)