Discovering Exotica

PAX IX, King's College London, July 23-25

Your friendly neighbourhood panel members

Sarah Gossan
Hofstra University
Stellar collapse, compact objects

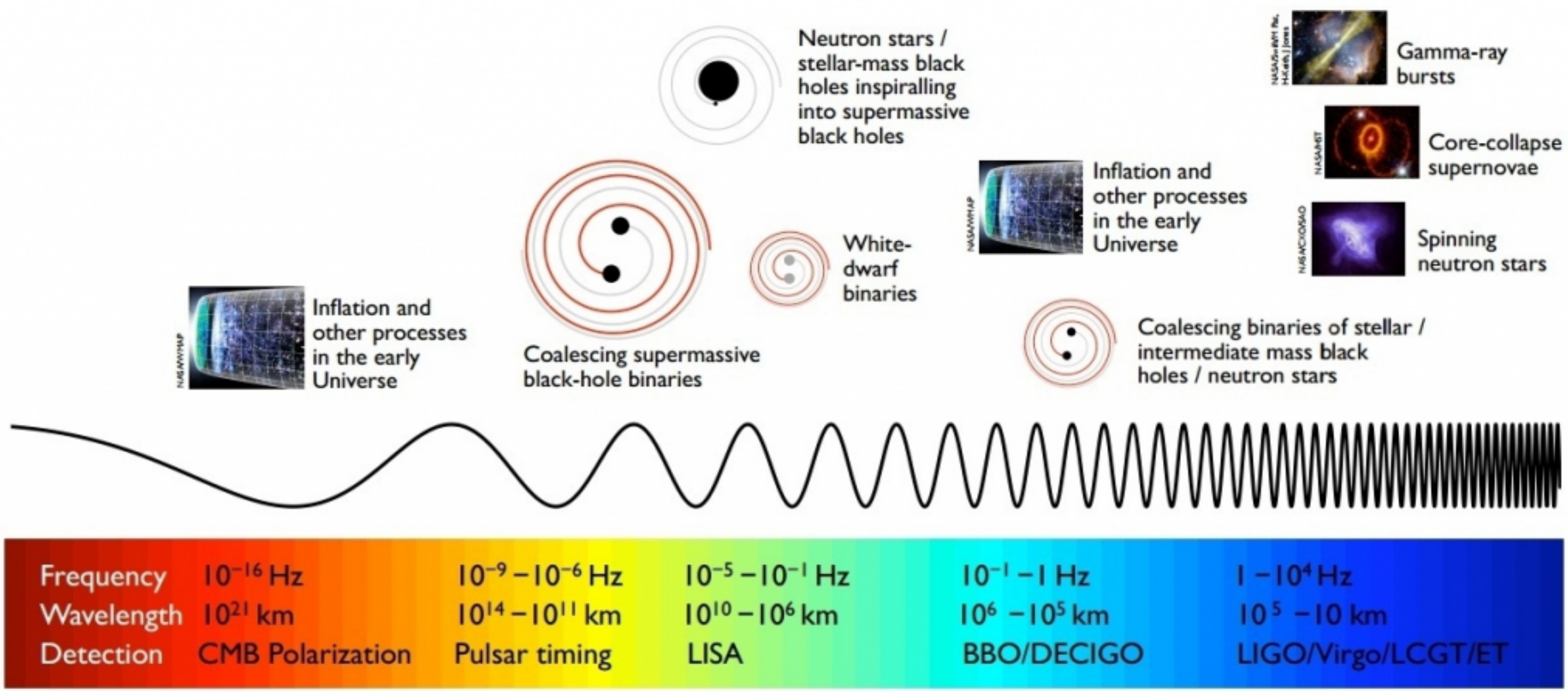
Ani Prabhu
Princeton University
Particles, dark matter, pulsars

José M. Ezquiaga
Niels Bohr Institute
Lensing, cosmology, testing GR

Julian Westerweck
University of Birmingham
Exotic compact objects, ringdowns

+ special guest Chandana Hrishikesh (gamma ray, pulsars)

The Gravitational Wave Menagerie



Credit: LIGO India

Assessing challenges: back-to-basics

Polarization-averaged signal-to-noise ratio (SNR) in a single detector

$$\langle \rho^2 \rangle \propto P(\theta, \phi) \int_0^\infty \mathrm{d}f \, \frac{|\tilde{h}(f)|^2}{S_h(f)}$$

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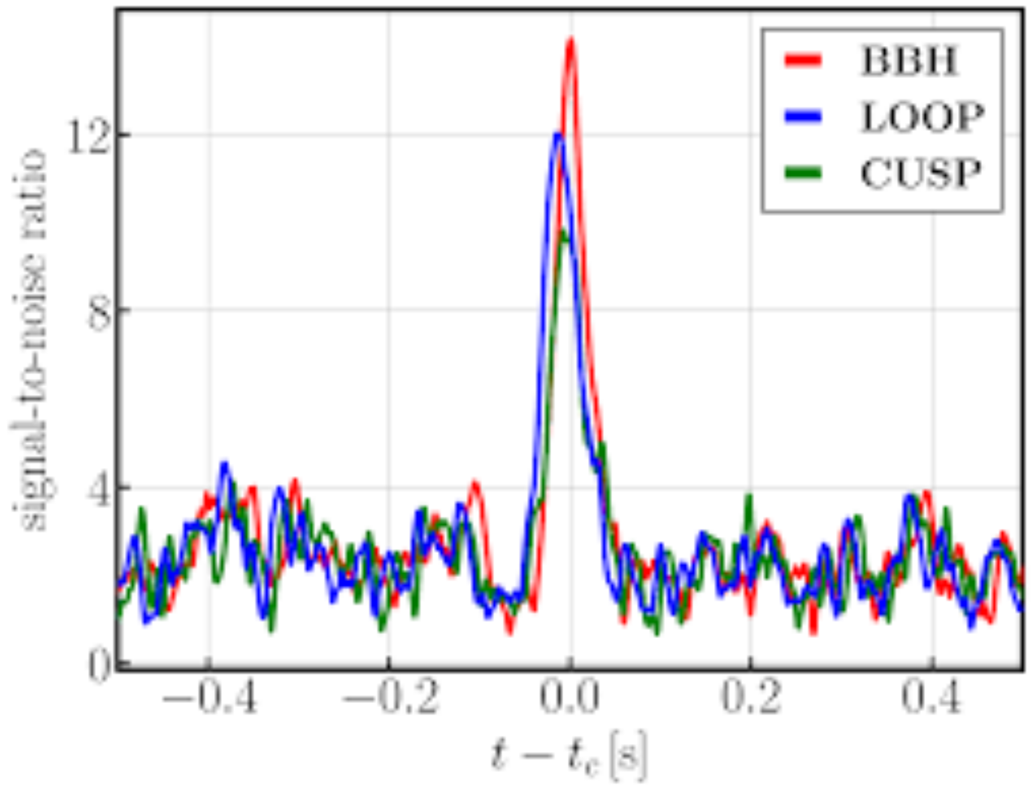
Observed SNR dependent on: **(1) Signal strength**

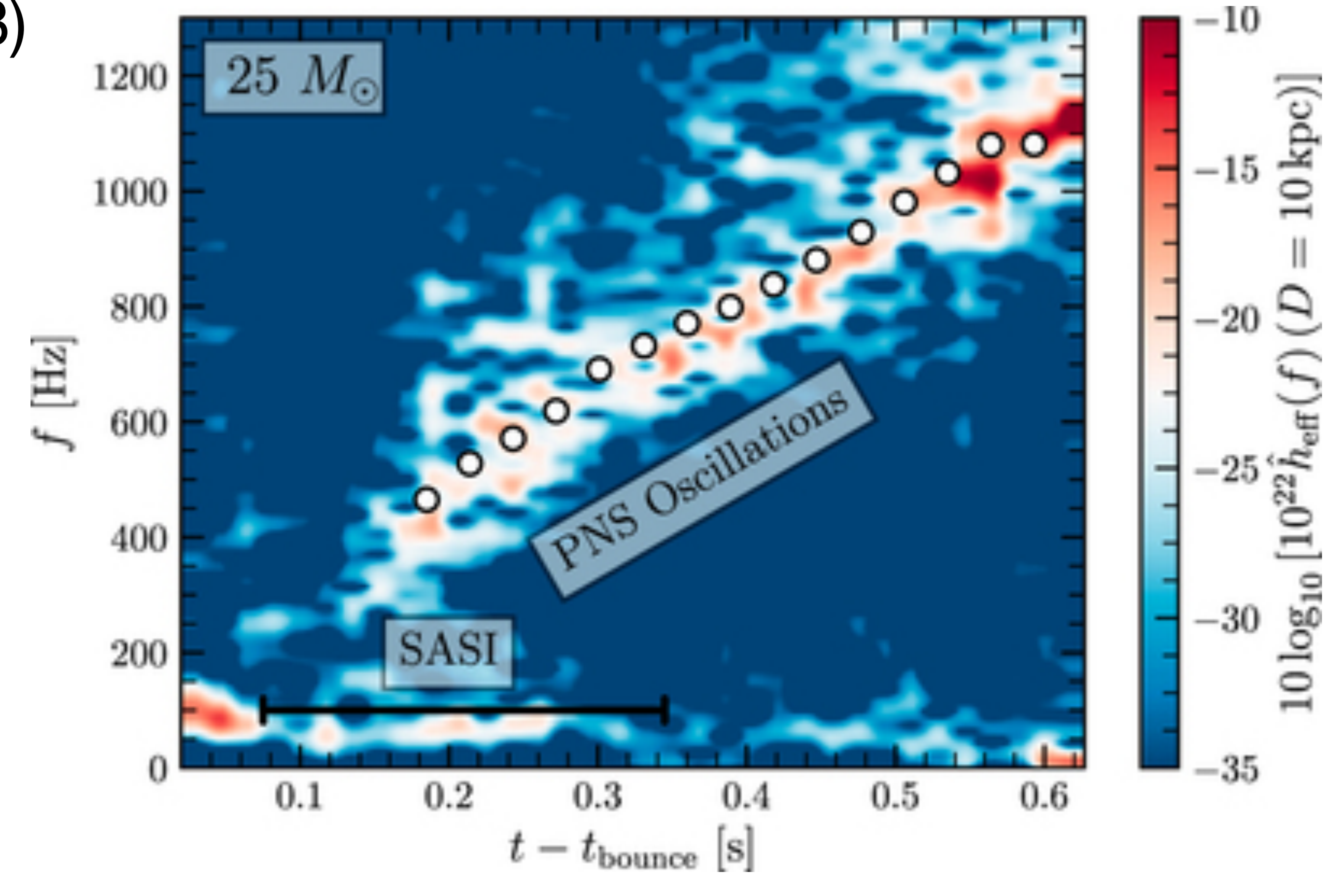
Challenge 1: The Modelling Problem

- Require (at least sort of) realistic signal predictions
- Approaches:
  - Zeroth order: sine-Gaussian/ ringdown/white-noise burst
  - Pen and paper
  - Semi-analytic/phenomenological models
  - State-of-the-art simulations
  - Population studies?

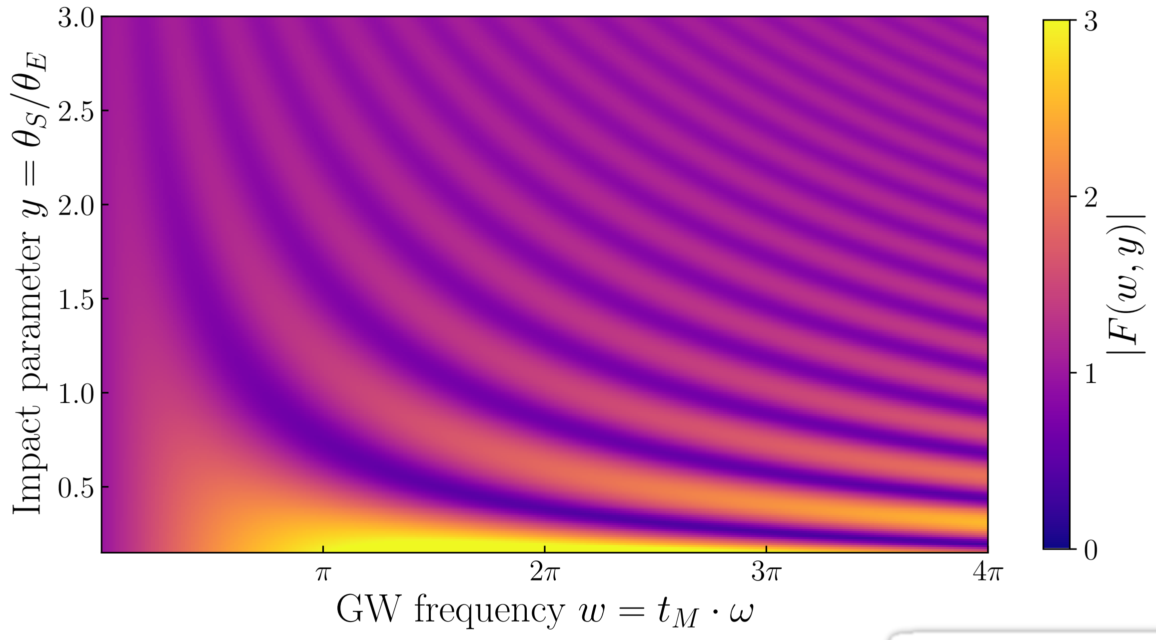
Cosmic string cusps (Aurrekoetxea 2023)



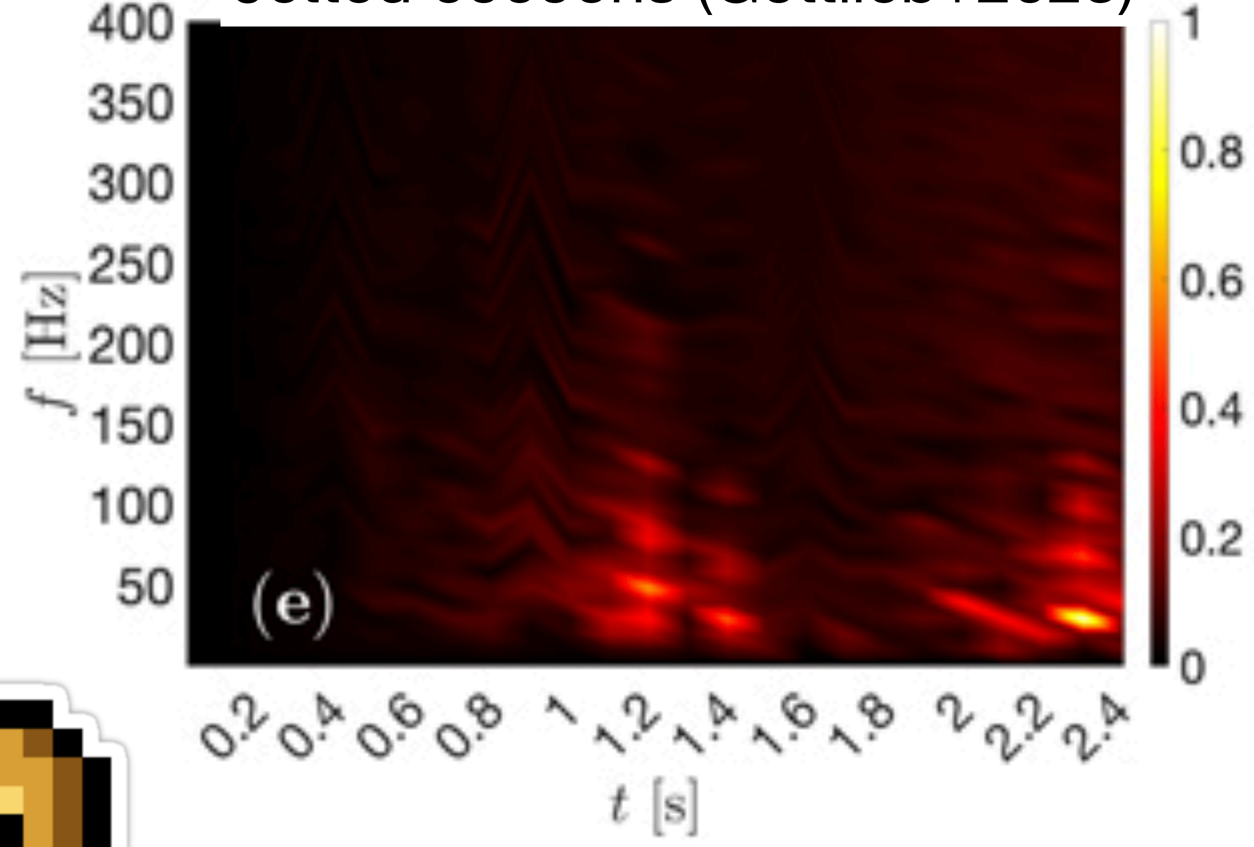
Core-collapse supernova (Radice+2019)



Wave optics diffraction (Ezquiaga)



Jetted cocoons (Gottlieb+2023)



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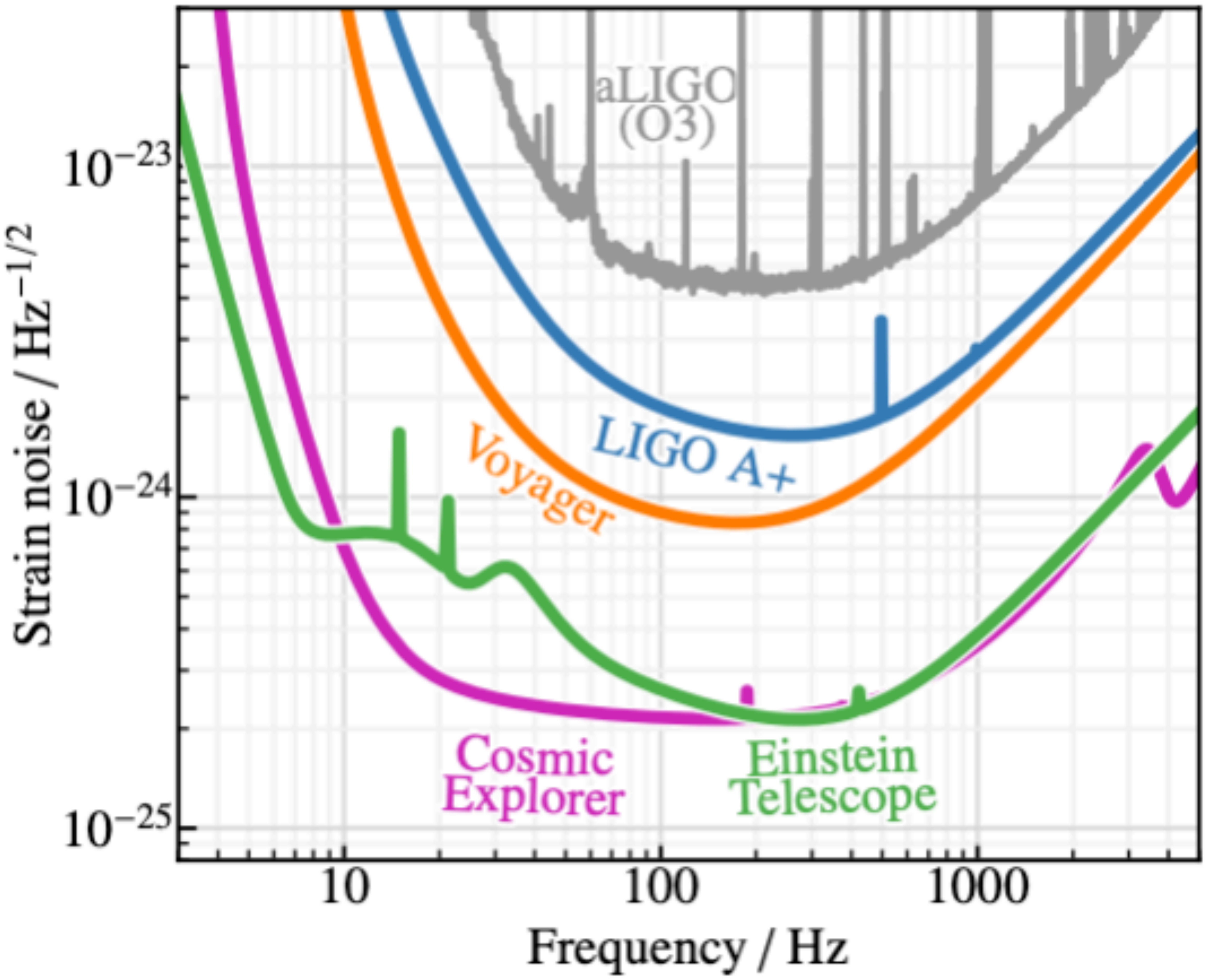
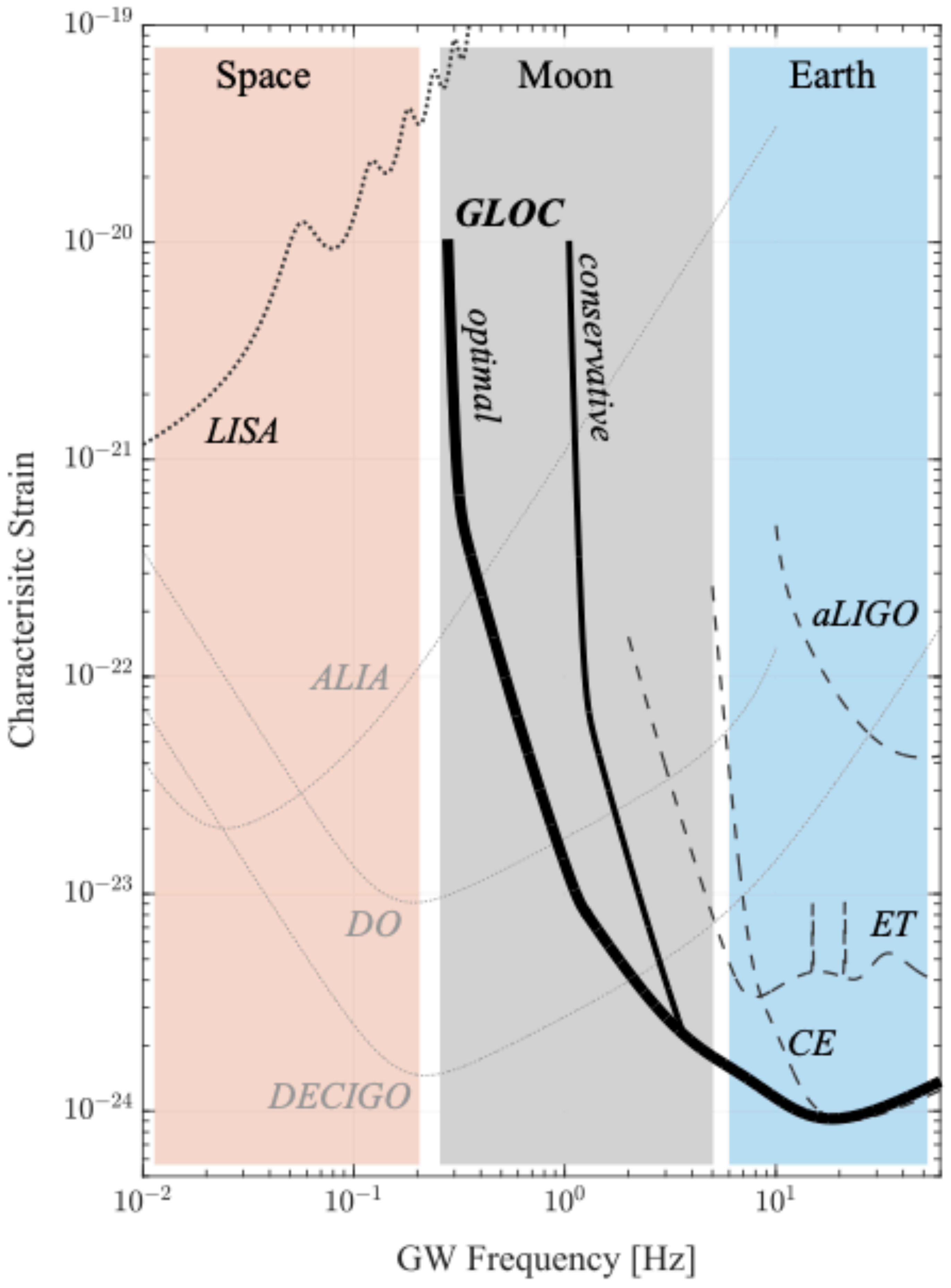
(2) Detector sensitivity

(a) Noise floor

Challenge 2: The Instrument Problem

Approach: Build all the new detectors!





Jani & Loeb (2021)

Challenge 2: The Instrument Problem

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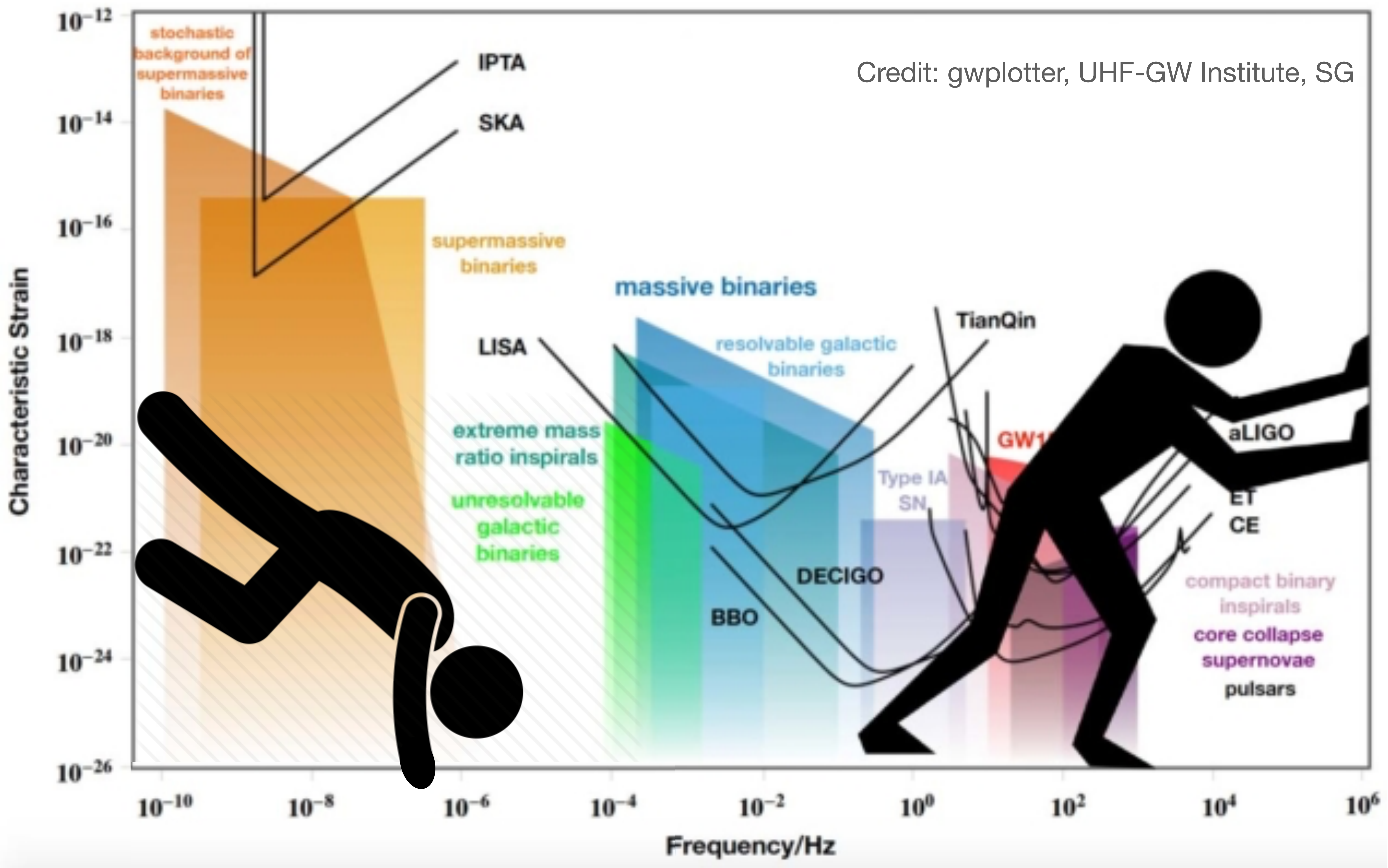

Assessing challenges: back-to-basics

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Observed SNR dependent on: (1) Signal strength

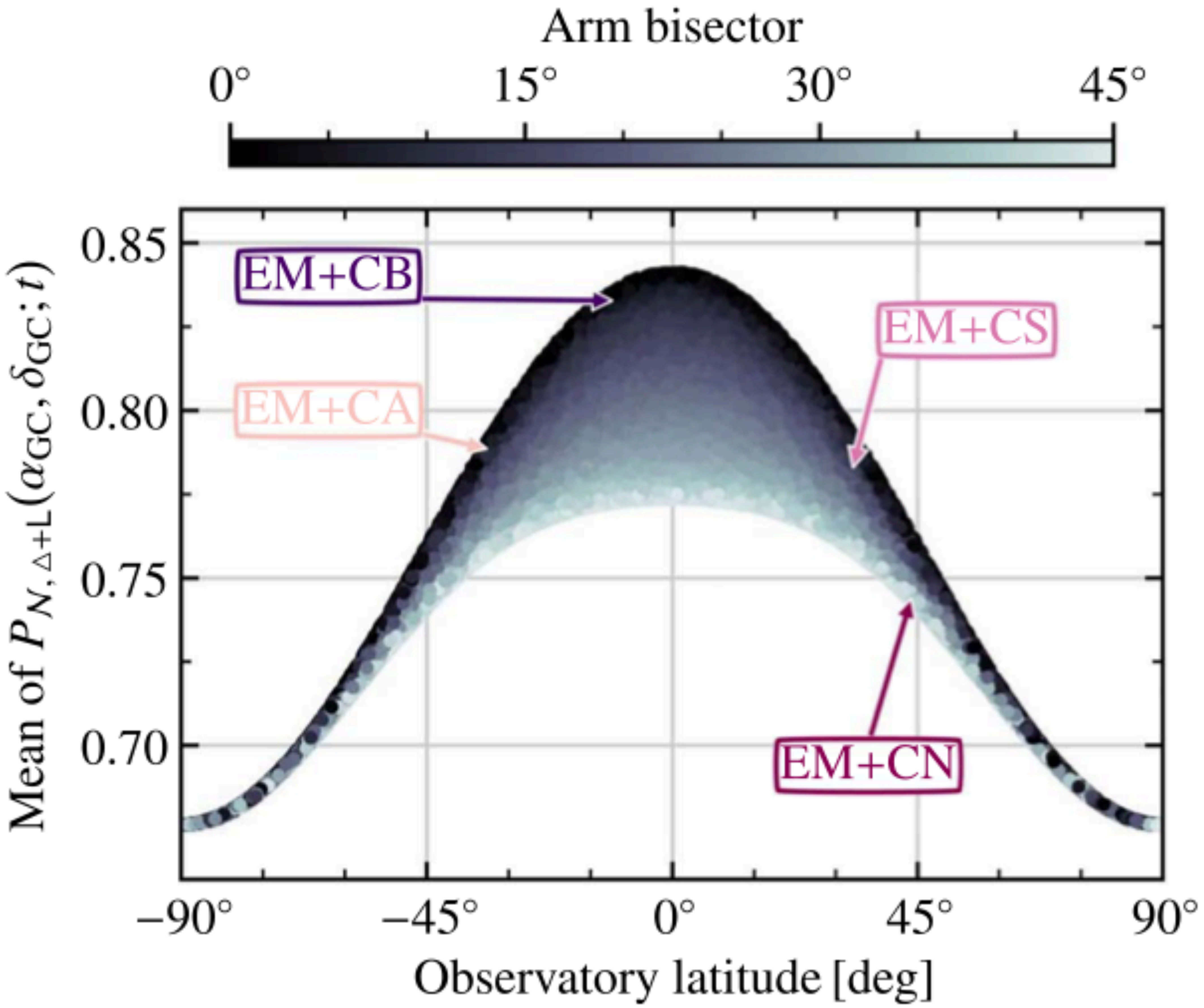
(2) Detector sensitivity

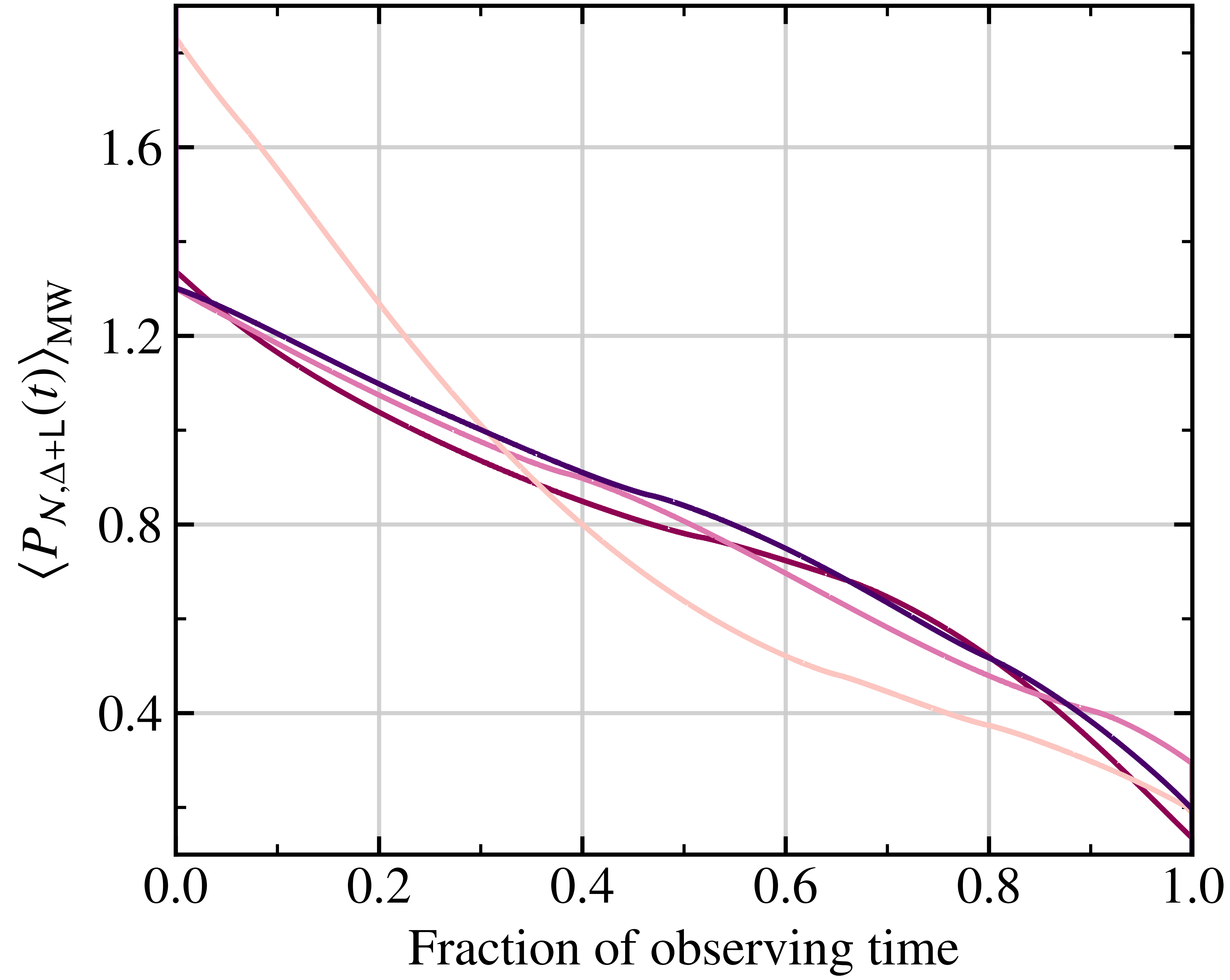
(a) Noise floor

(b) Antenna power

Challenge 2: The Instrument Problem

Approach: Preferential placement for Galactic science





Gossan, Nissanke, Hall (2022)

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Observed SNR dependent on: **(1) Signal strength**

(2) Detector sensitivity

(a) Noise floor

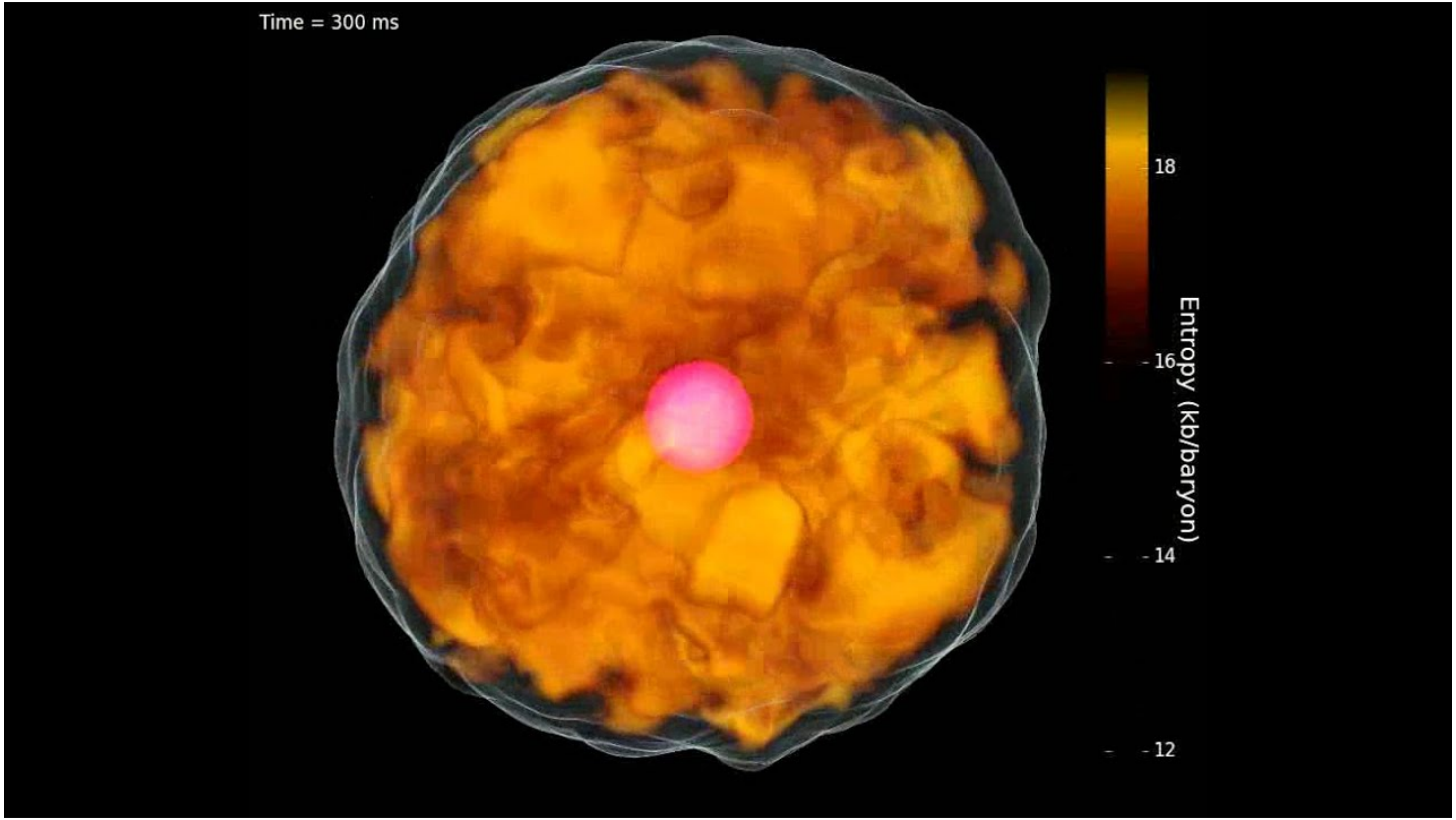
(b) Antenna power

(3) Ability to recover signal from noise

Challenge 3: The Detection Problem

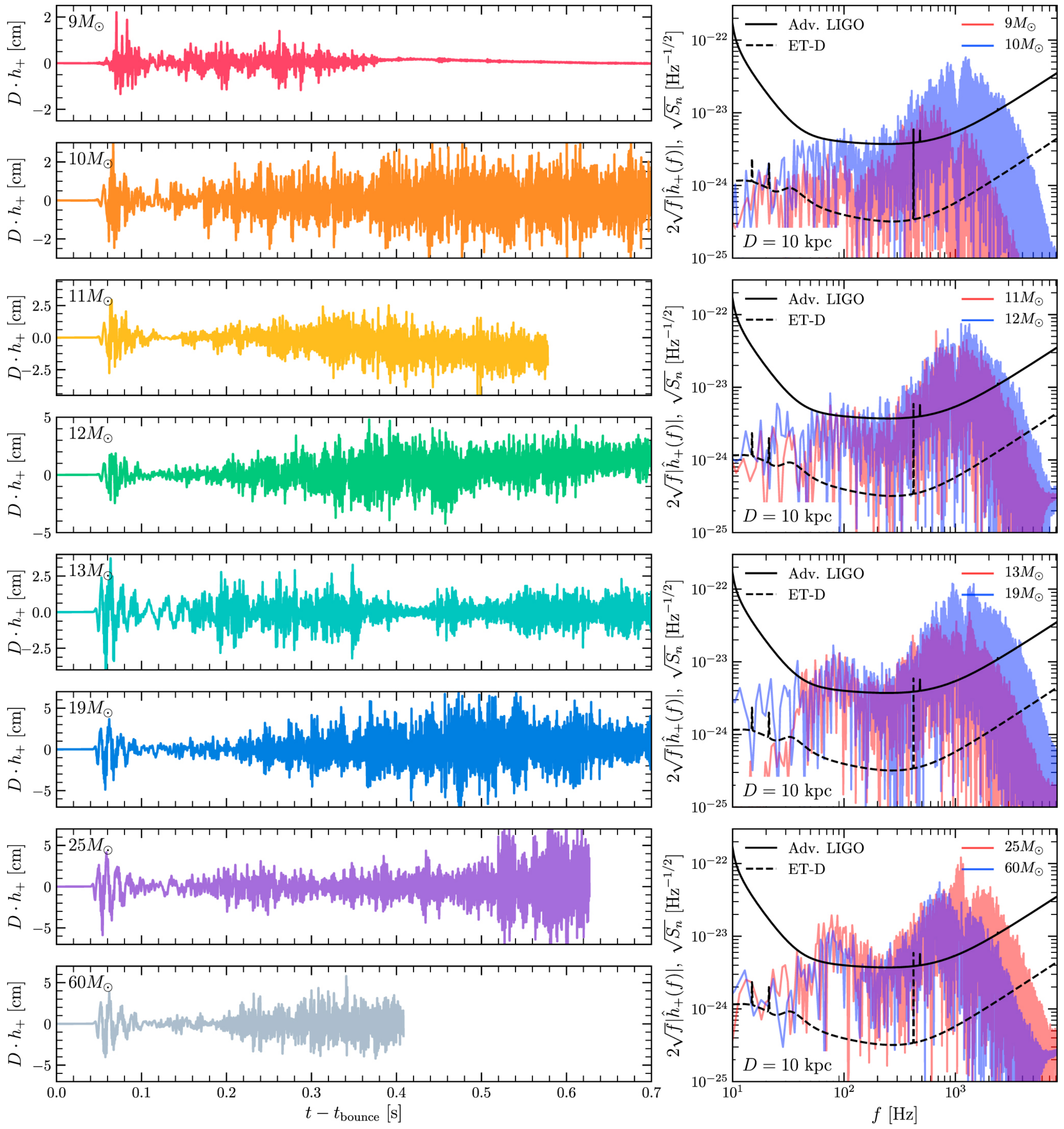
- Need analysis tools capable of recovering the signals from noise without losing significant fraction of signal power
- Approaches:
  - Brute force computation
  - Reducing time-frequency search volume
  - Multi-messenger counterparts to constrain intrinsic source parameters
  - Development of targeted, astrophysically-motivated analysis methods
  - When in doubt, AI/ML?

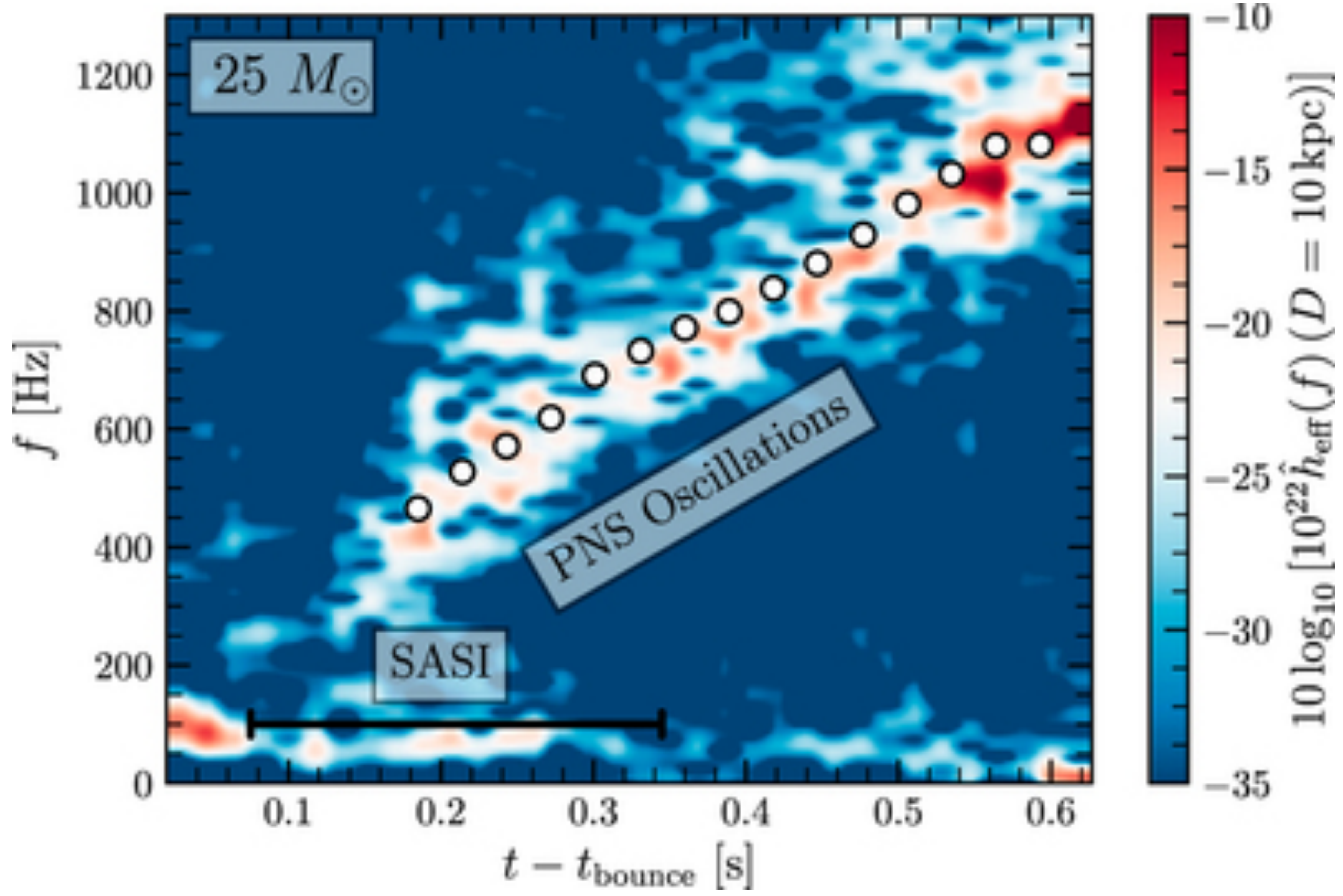
The next nearby core-collapse supernova



Kuo-Chuan Pan

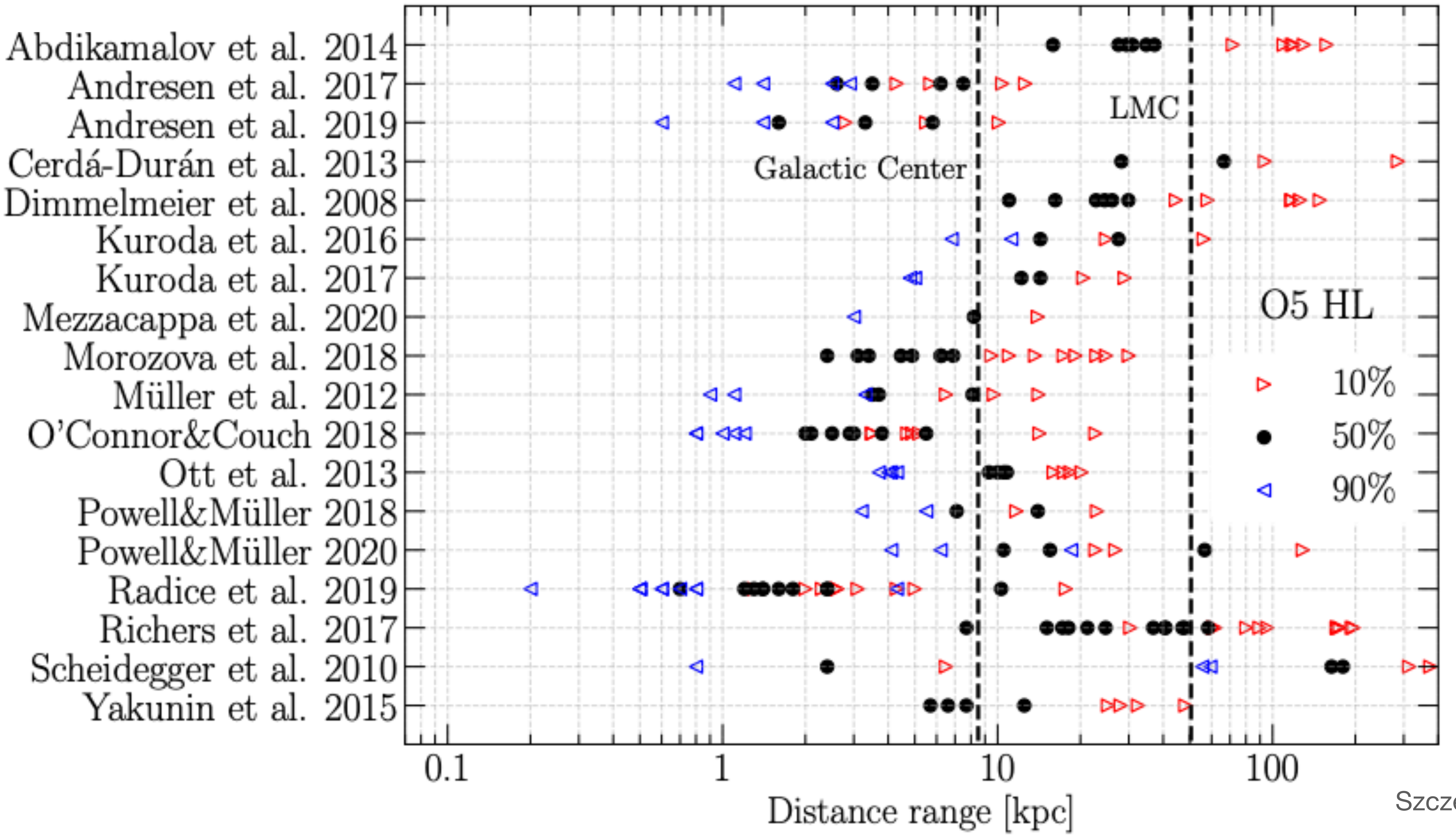
The next nearby core-collapse supernova





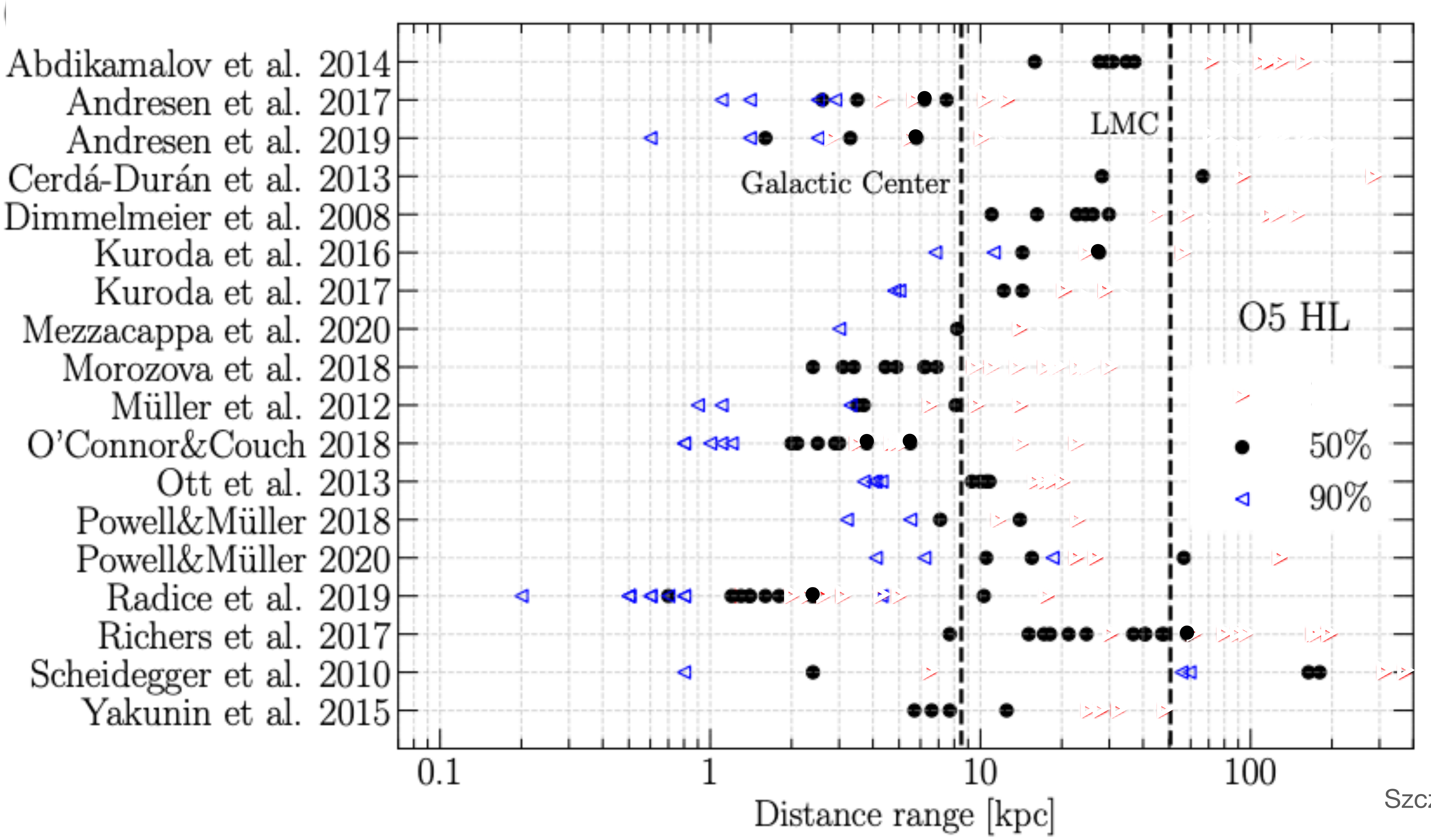
Radice+2019

The next nearby core-collapse supernova



Szczepanczyk+2021

The next nearby core-collapse supernova



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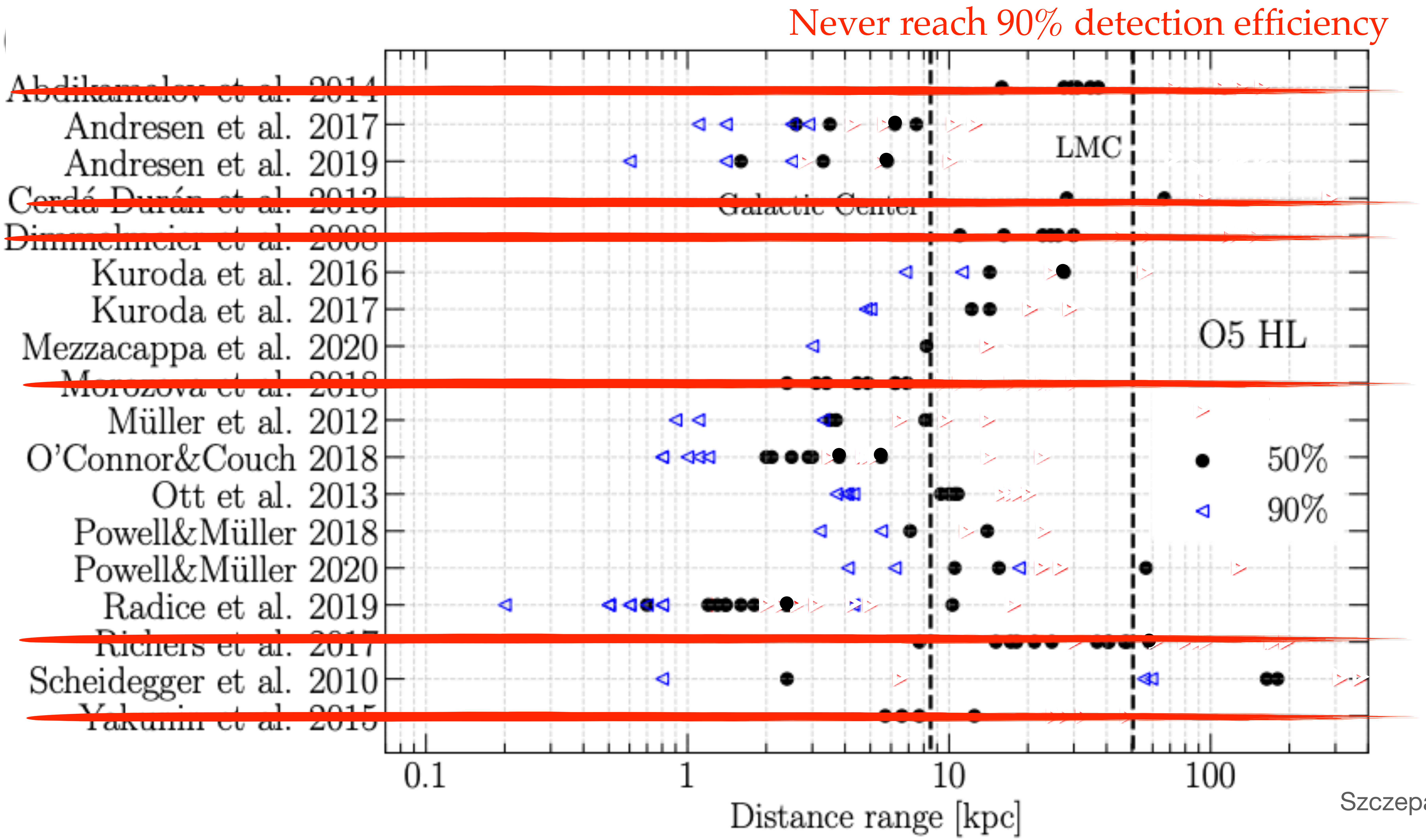

Szczepanczyk+2021

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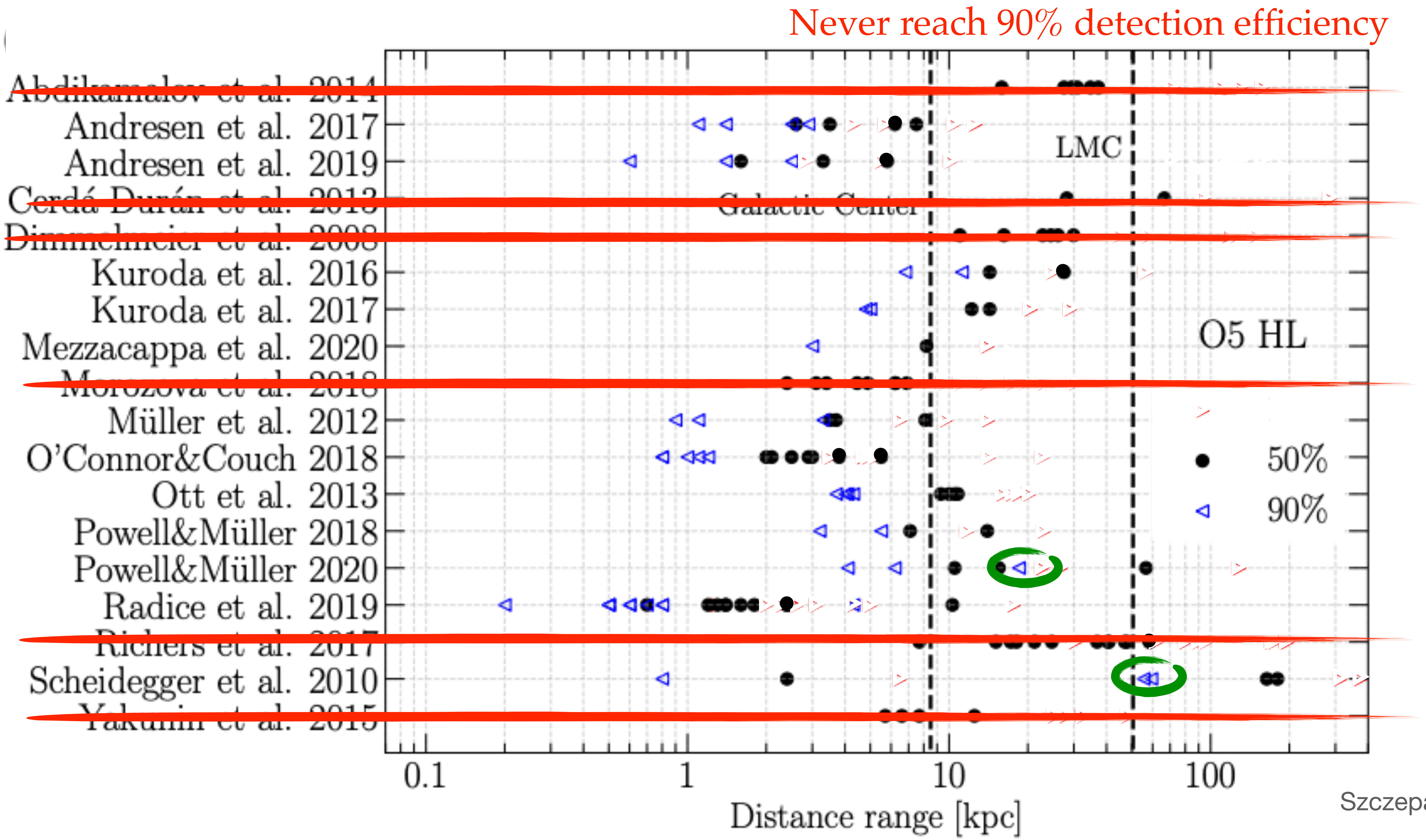

Szczepanczyk+2021

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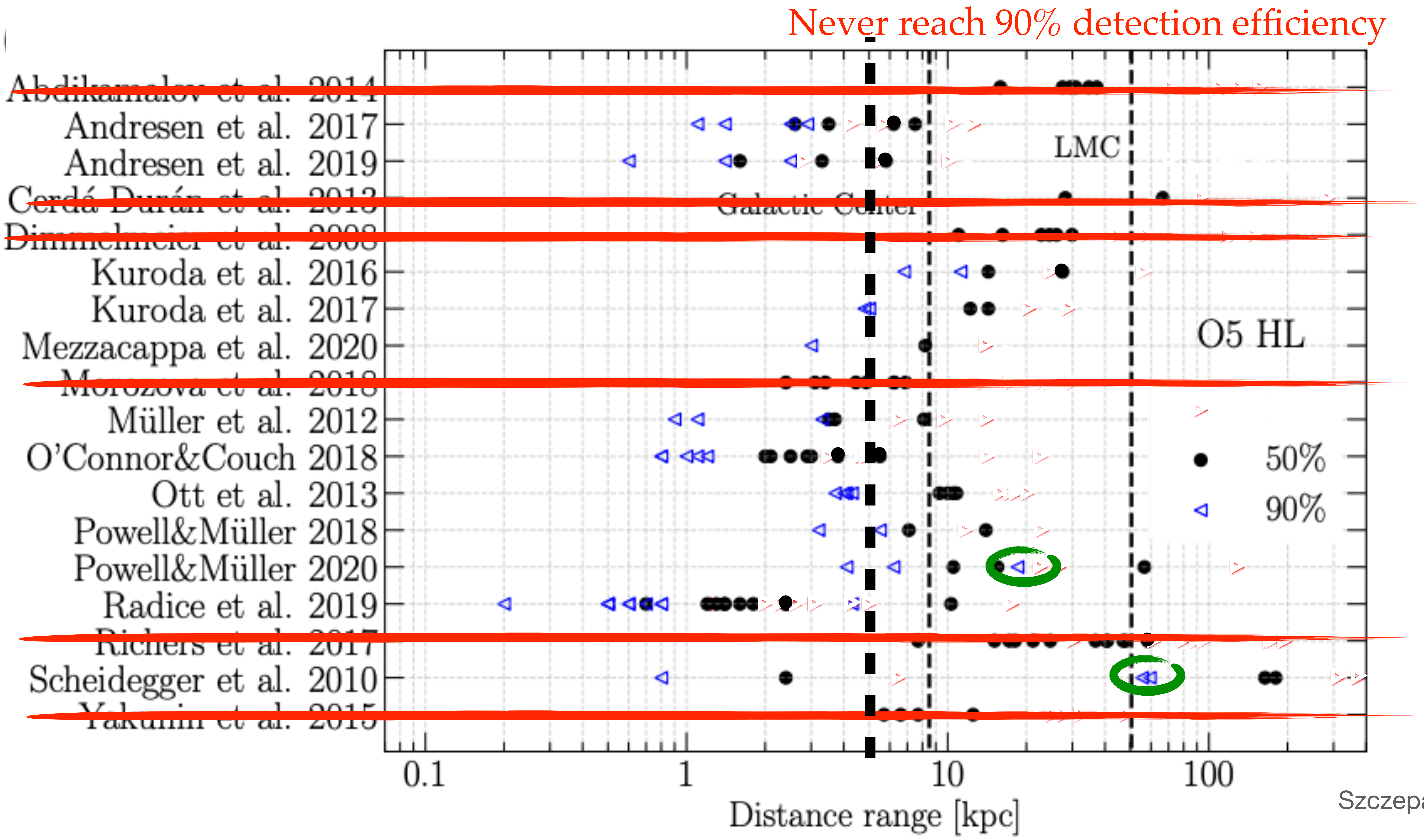
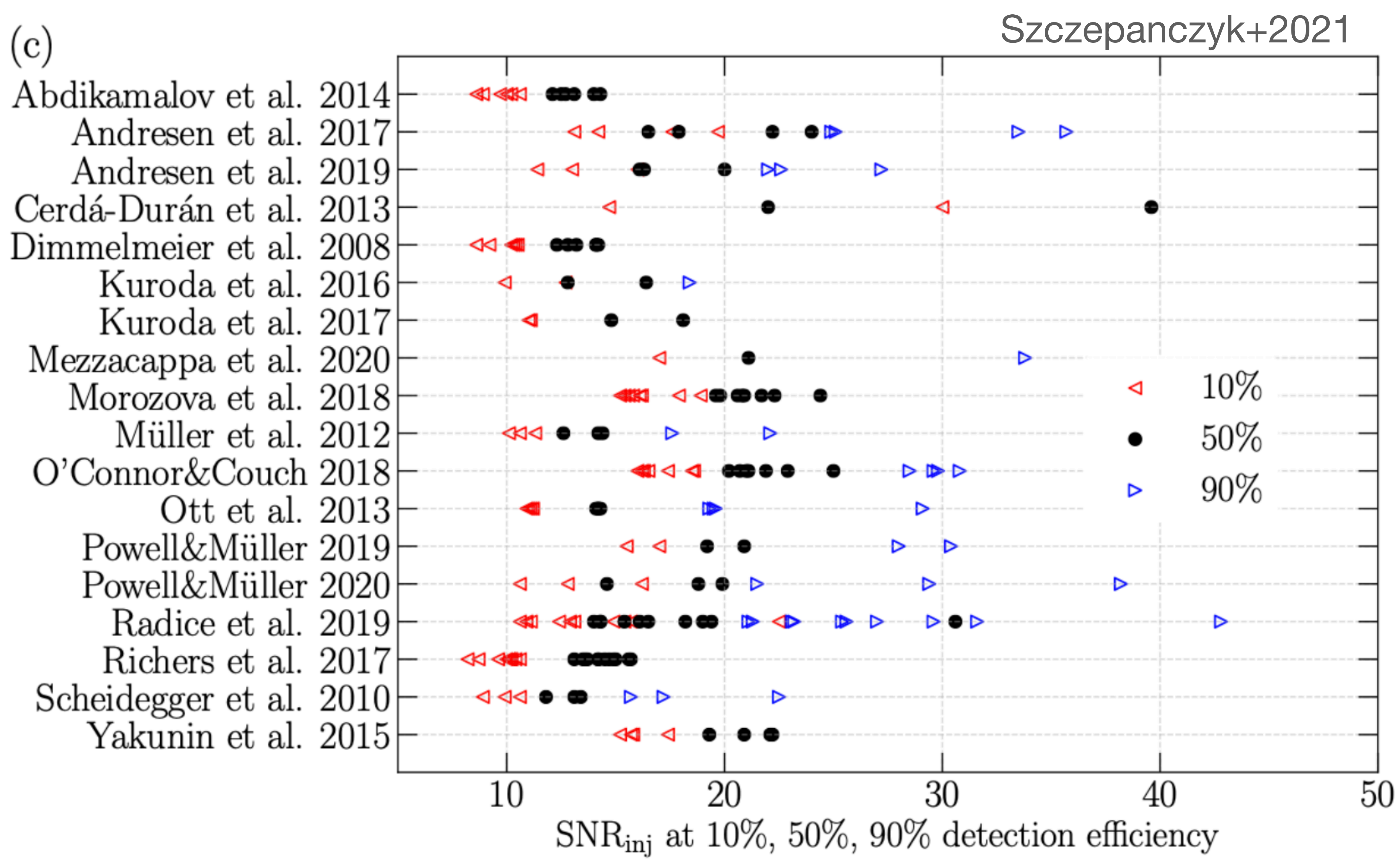
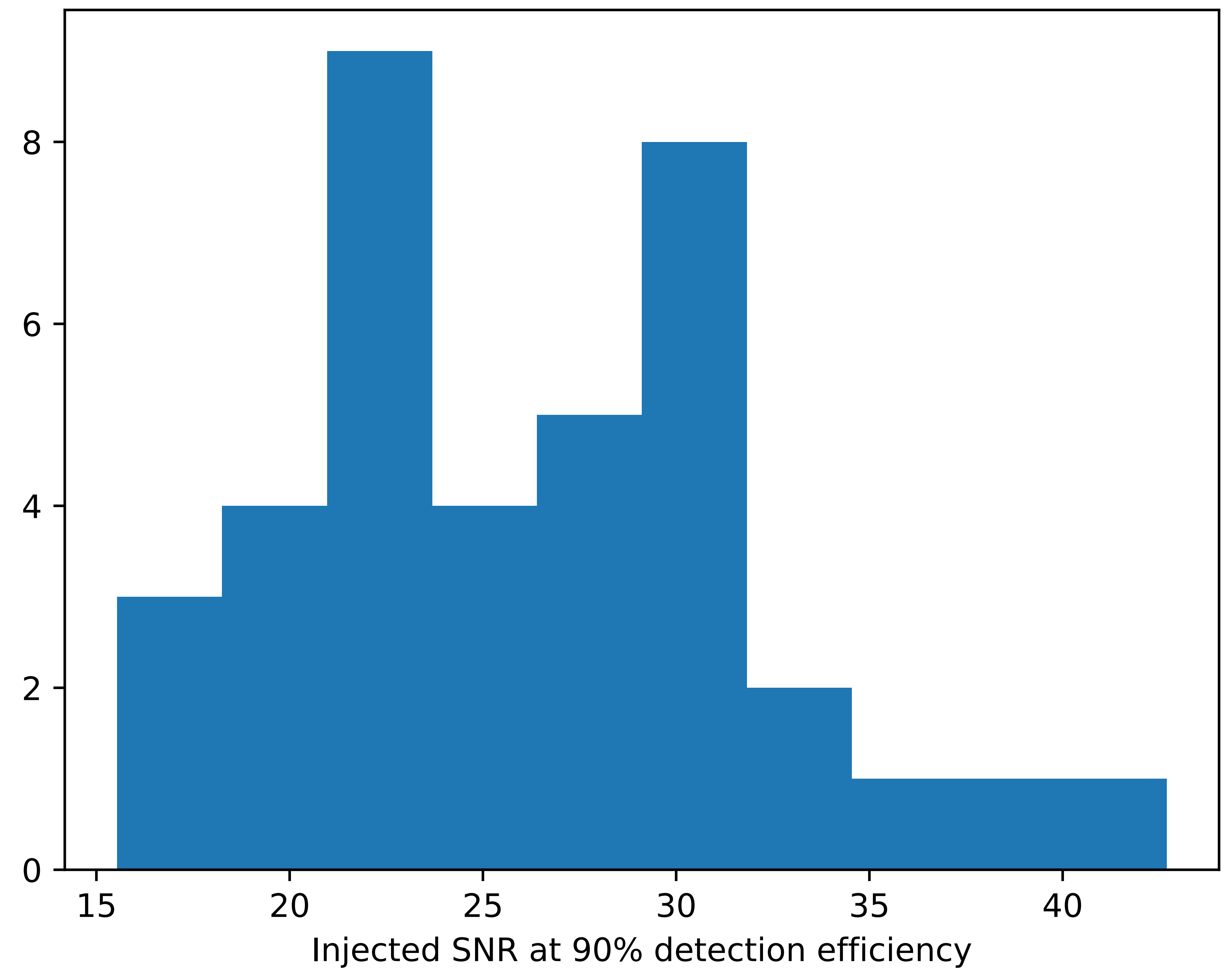


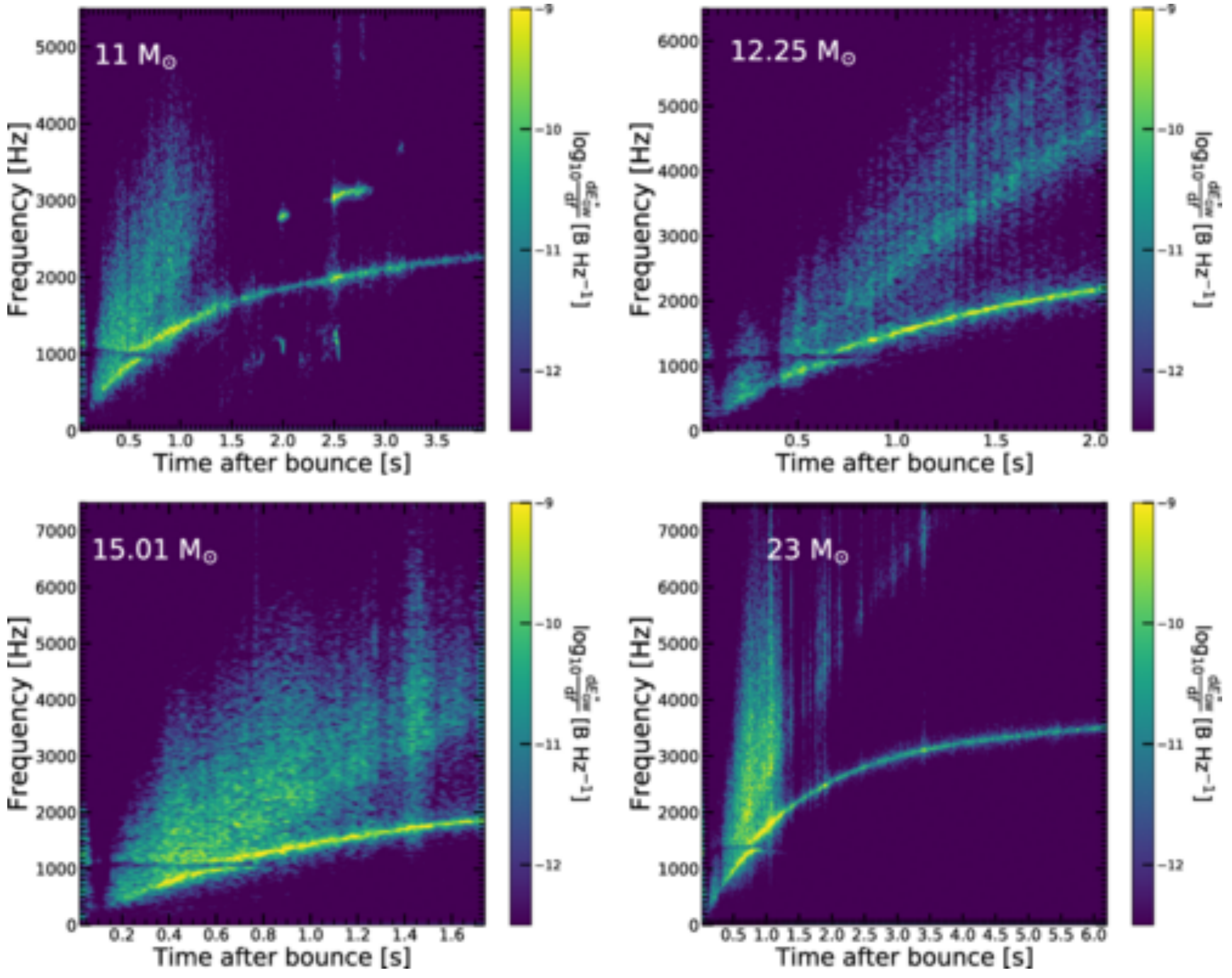
Szczepanczyk+2021

The next nearby core-collapse supernova

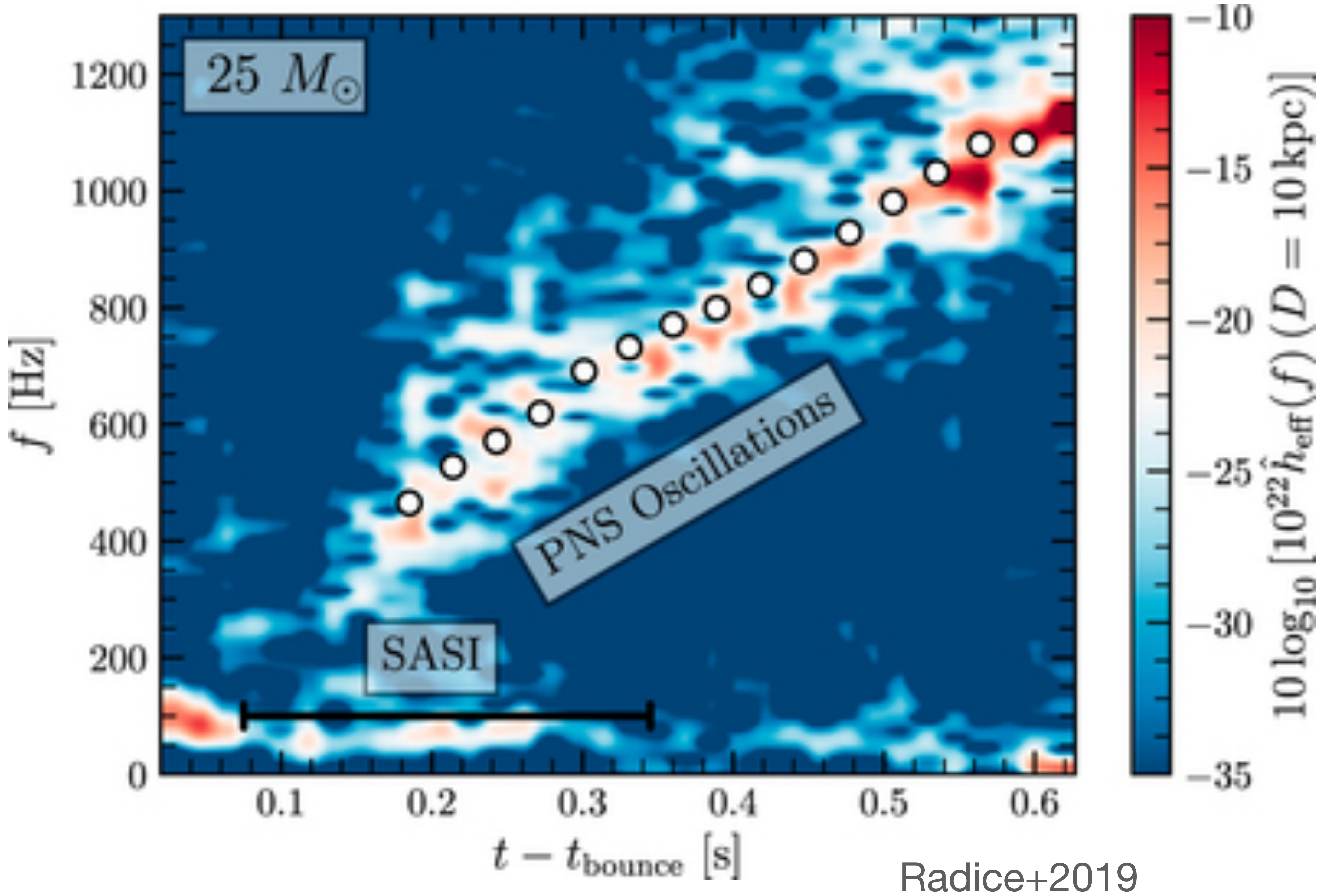




The next nearby core-collapse supernova



Vartanyan+2023



Radice+2019

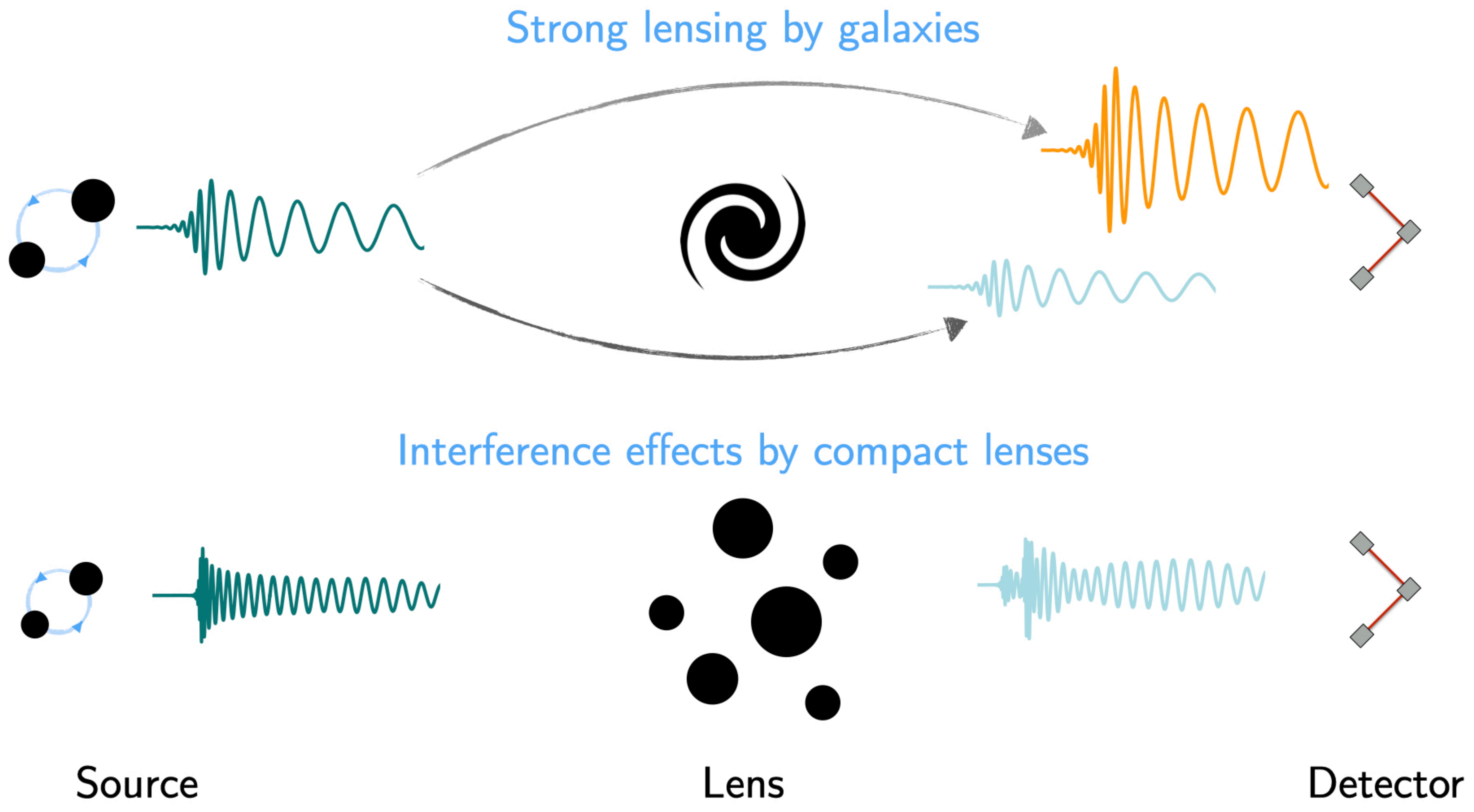
The next nearby core-collapse supernova

- We are not ready. Please help!
- We need:
  - State-of-the-art simulations for larger waveform banks (phenom models)
  - Neutrino signature to pinpoint in time, EM signature to pinpoint in space
  - Improvements to pipelines for broadband, long-duration signals
  - Development of independent search pipelines targeted to CCSN GWs
  - More sensitive detectors (sure, but shouldn’t be first priority)
  - A miracle; maybe Betelgeuse goes off?

GW lensing

jose.ezquiaga@nbi.ku.dk

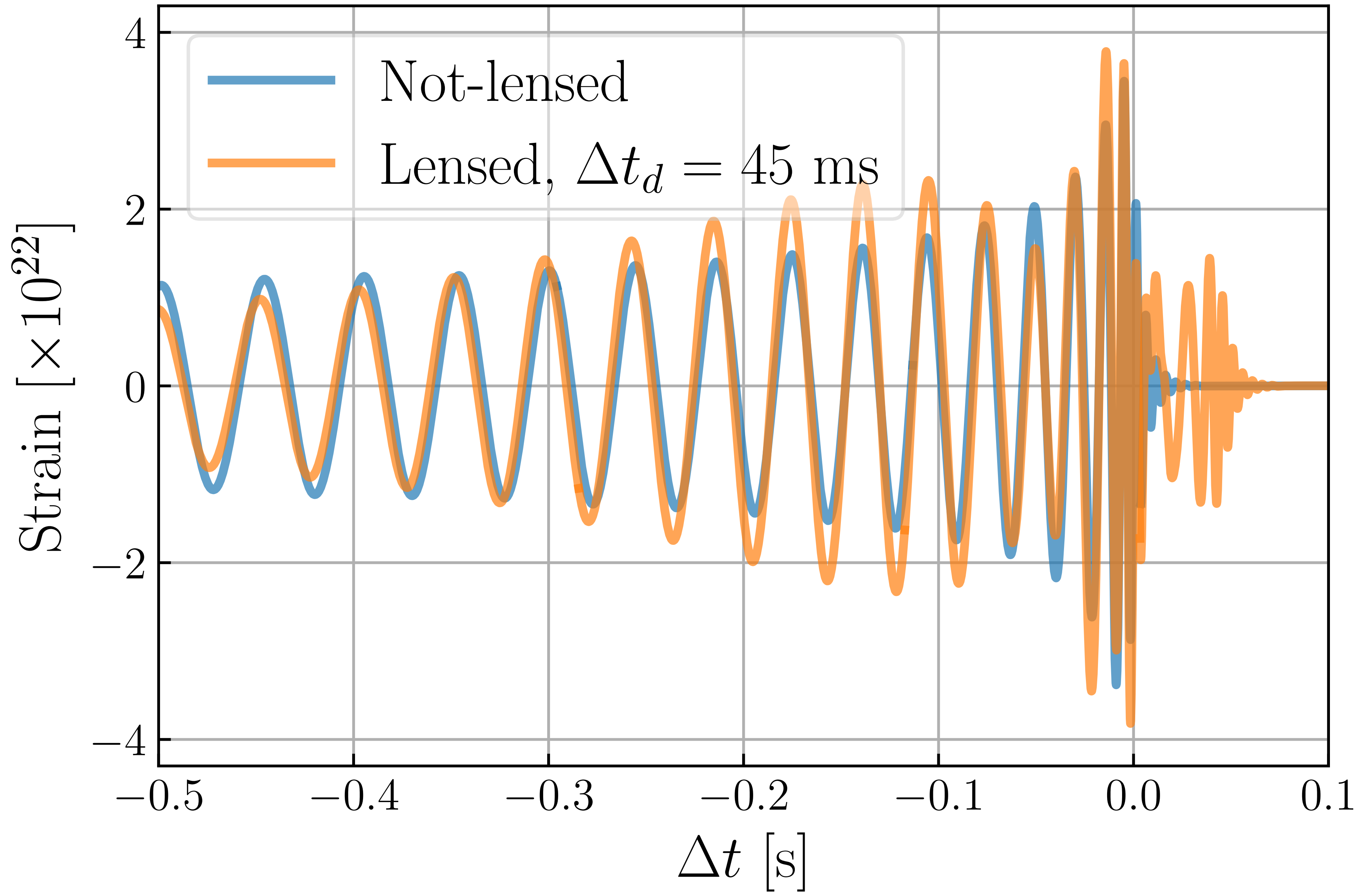
- We **will** detect gravitational lensing of GWs! *("safe-bet" exotica)*
- Big lenses (galaxies/clusters of galaxies): $1/10^4 < N_{gw,lens} < 1/100$
- Small lenses (*e.g.* IMBHs): $N_{gw,lens} < 1/100$
- GWs open **new** regimes in lensing! Lensed GWs **shortcut** to XG!



New frontiers

jose.ezquiaga@nbi.ku.dk

- GW lensing **interference/diffraction** leads to *waveform distortions!*

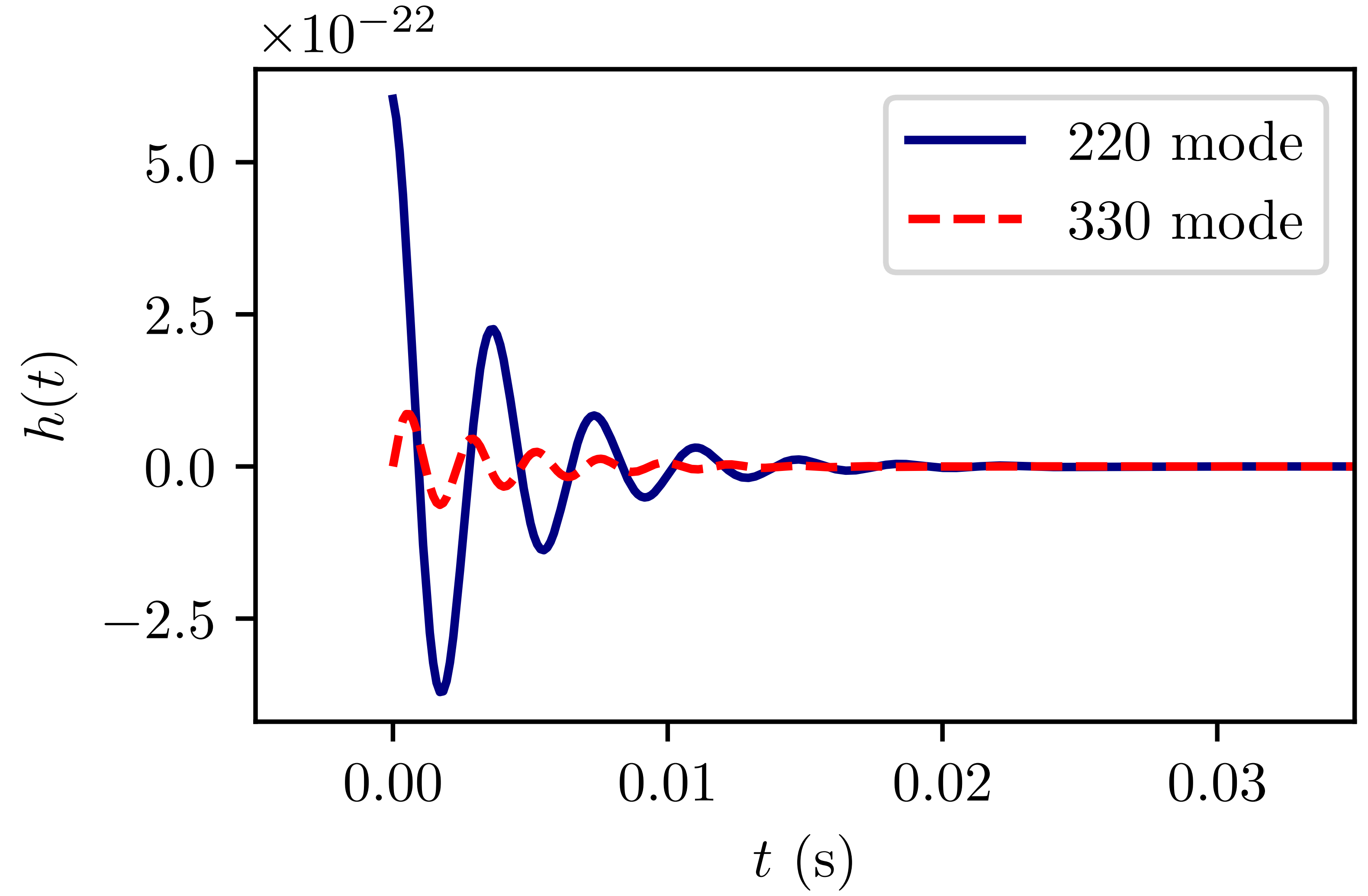


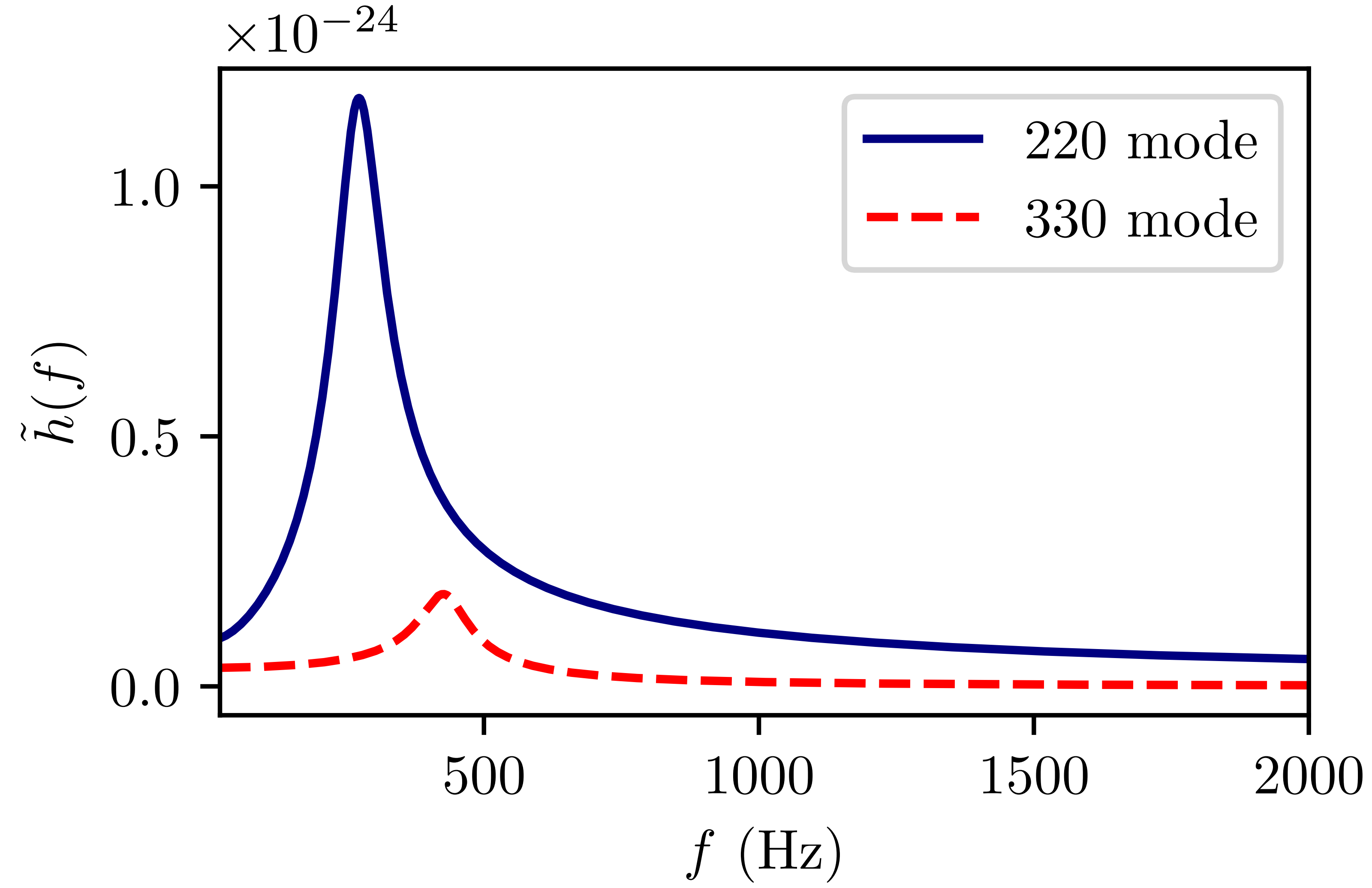
- **Point lenses**
  - Discover IMBHs/PBHs
- **High magnification (caustics)**
  - Relevant **now!**
- **Sub-halos**
  - Exciting for LISA

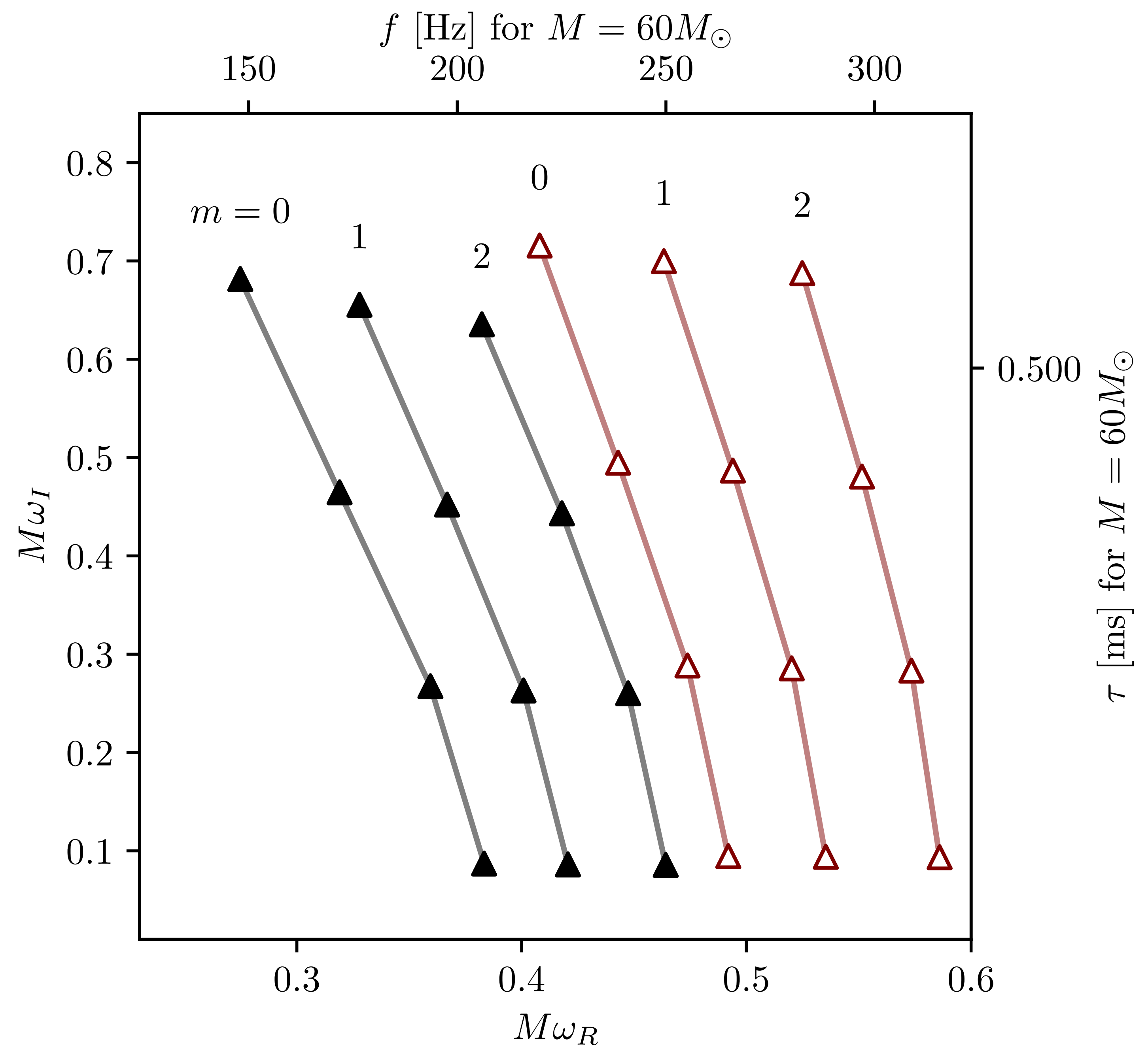
Exotica can be challenging…

- *Template-based searches* could miss these signals
- Beyond GR lensing can lead to birefringence and more

Quasi-normal modes from non-GR black holes?

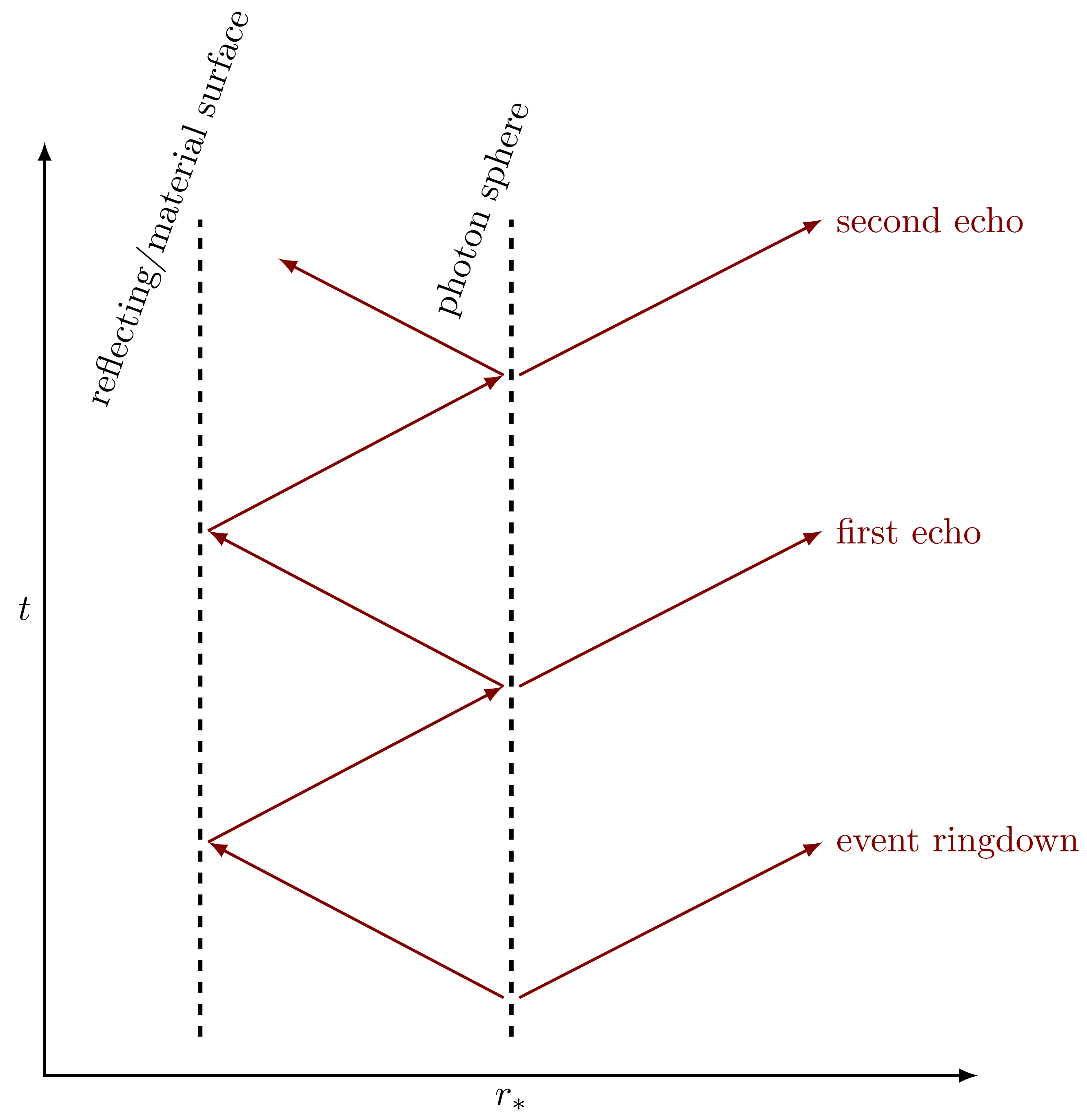


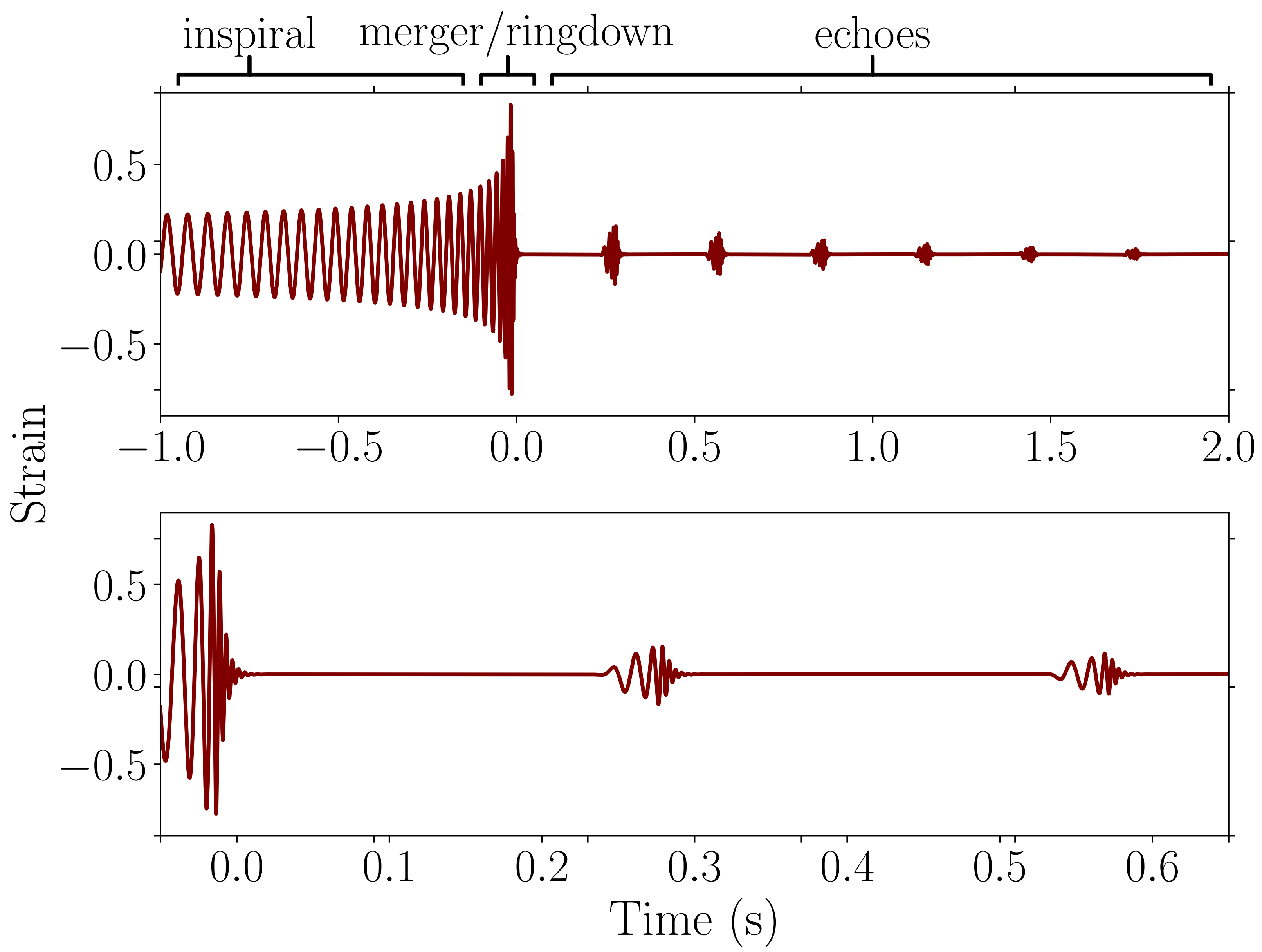


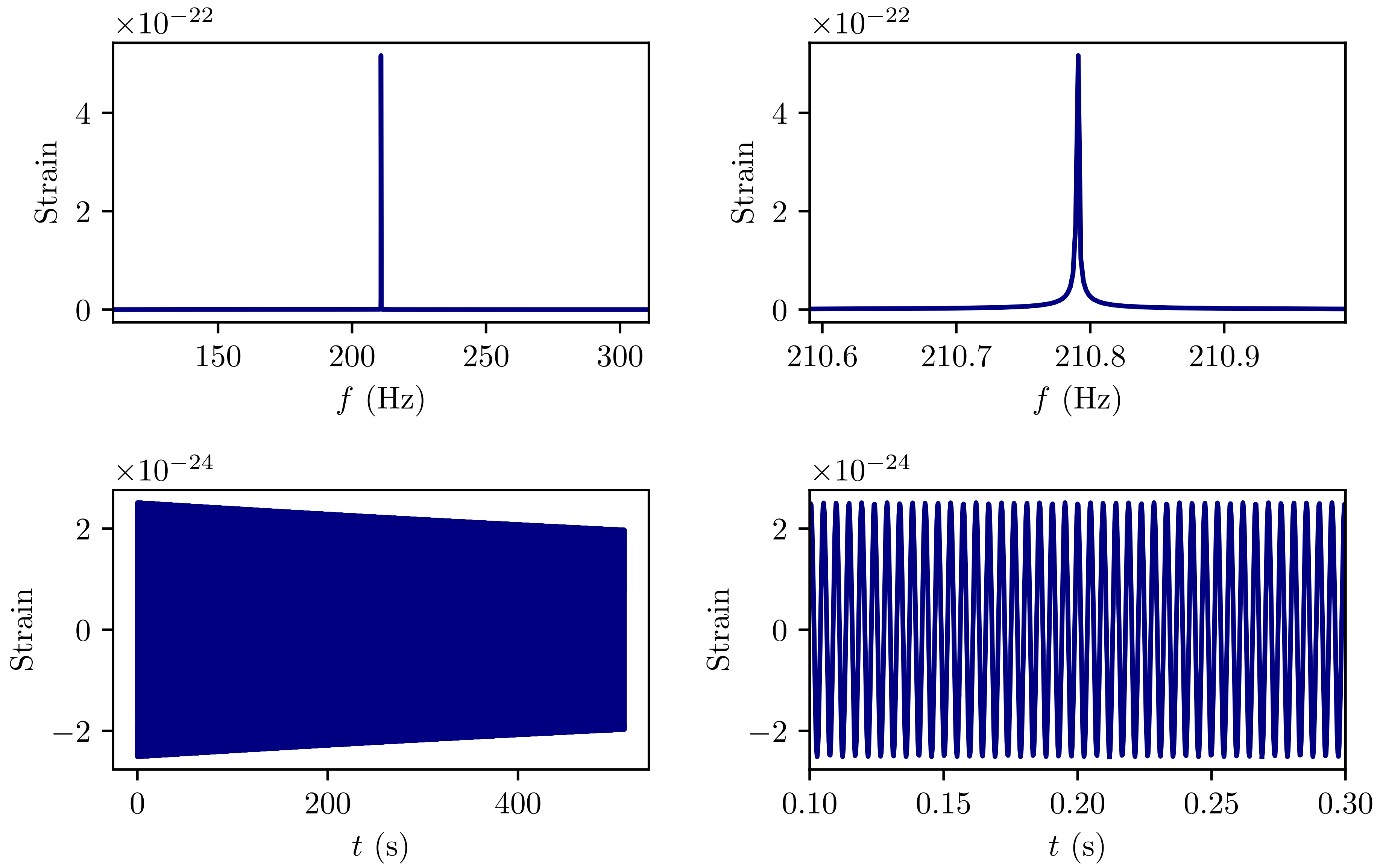


- Black hole quasi-normal mode spectra.
- Quantify deviations from black hole prediction.
- Additional modes from scalar-/vectorfields.
- How to incorporate higher level of complexity in QNMs?

(Not) finding exotic compact objects



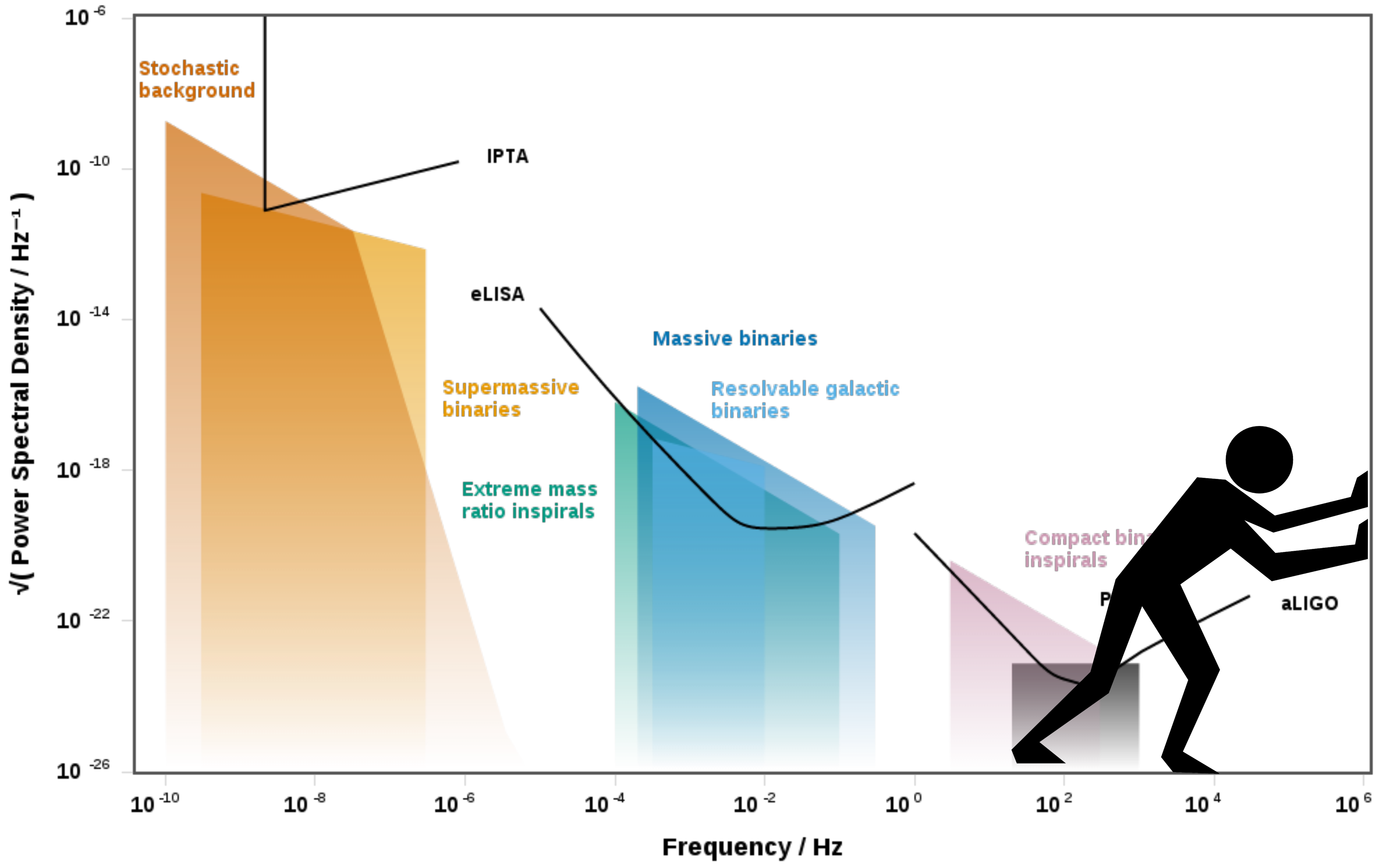




- ➤ Pulsed echoes from trapped GWs.
- ➤ Long-duration QNMs.
- ➤ Bounds from several studies.

- ➤ Relaxing restrictive assumtions?
- ➤ Going beyond post-merger effects?
- ➤ Balance modelling, tolerant searches, trials factors, impatience?

Exotic Physics in Exotic Frequency Ranges?



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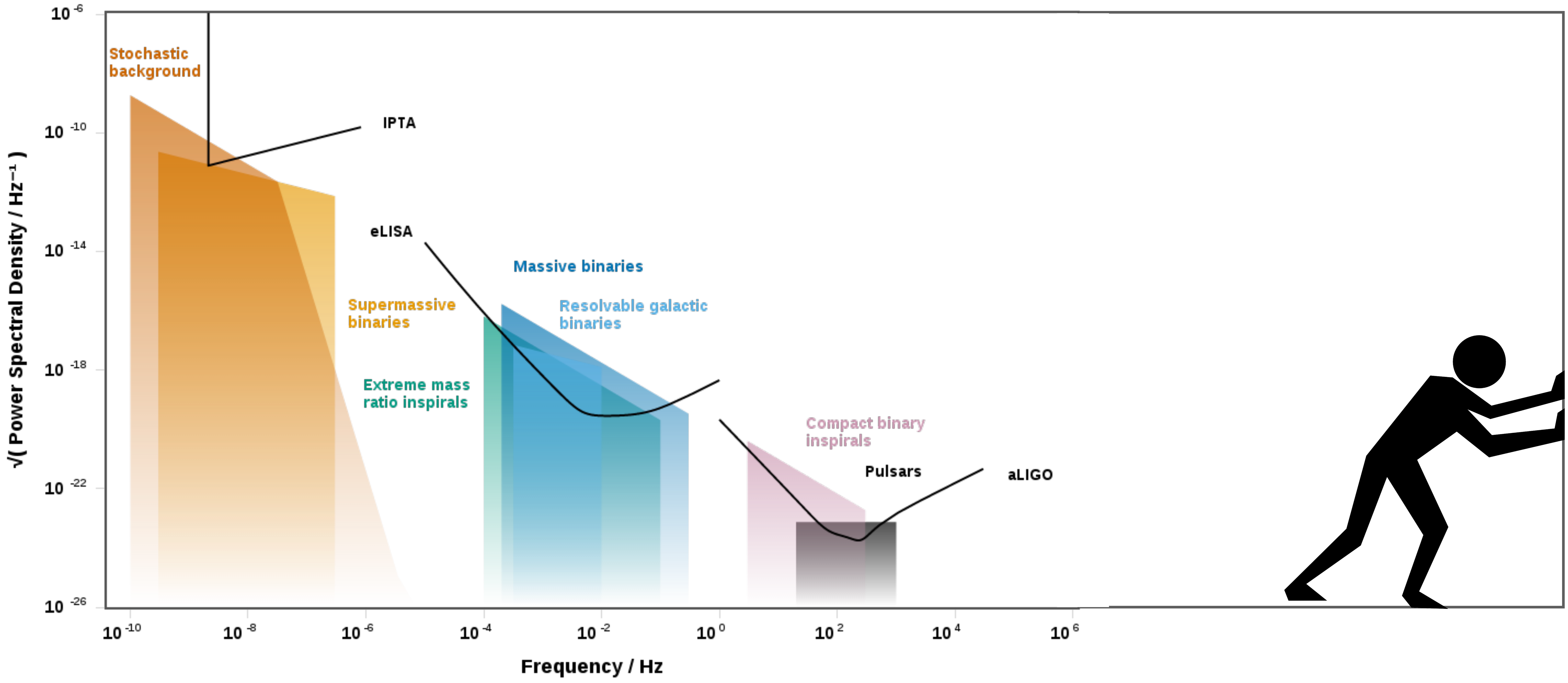
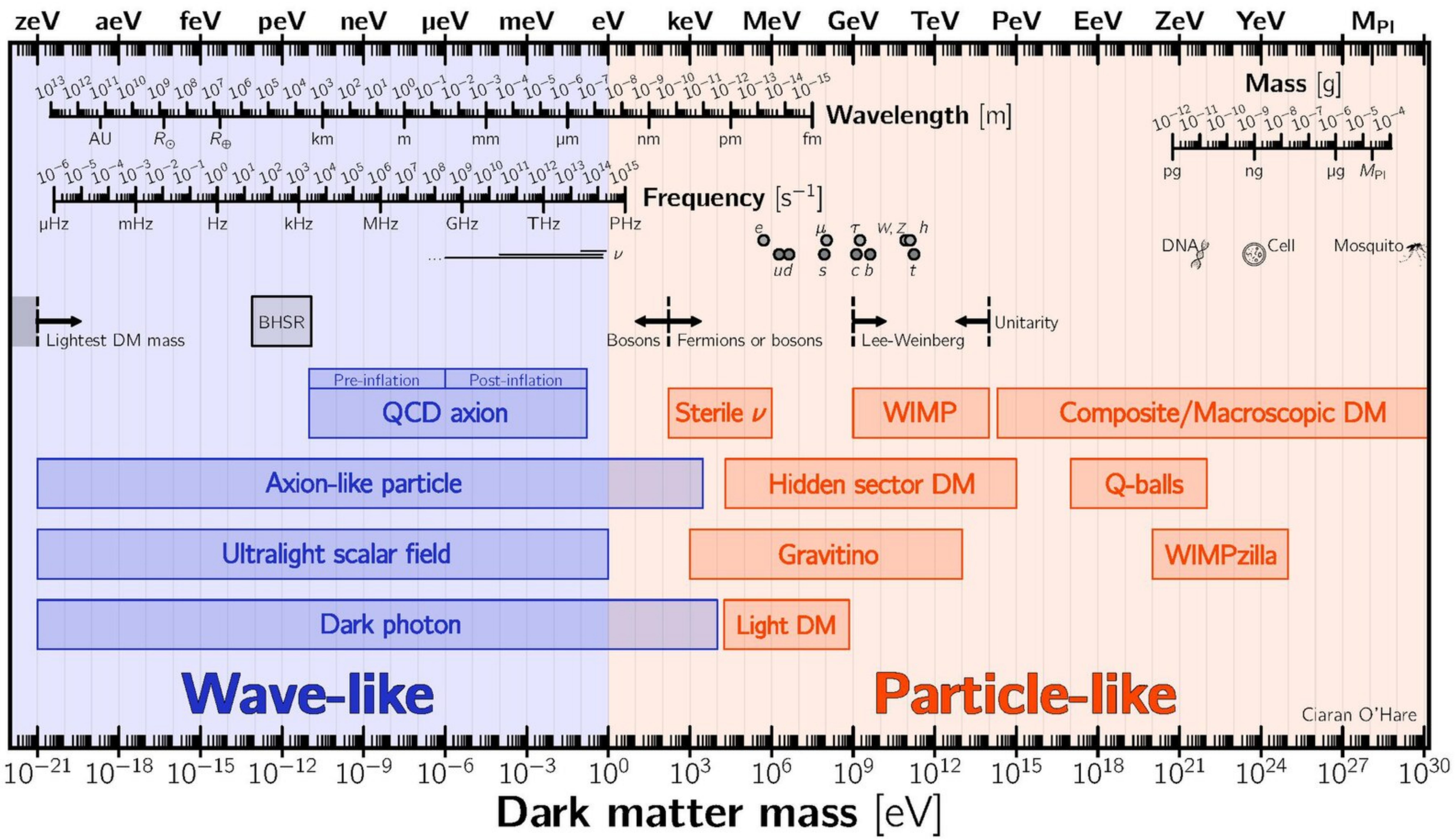


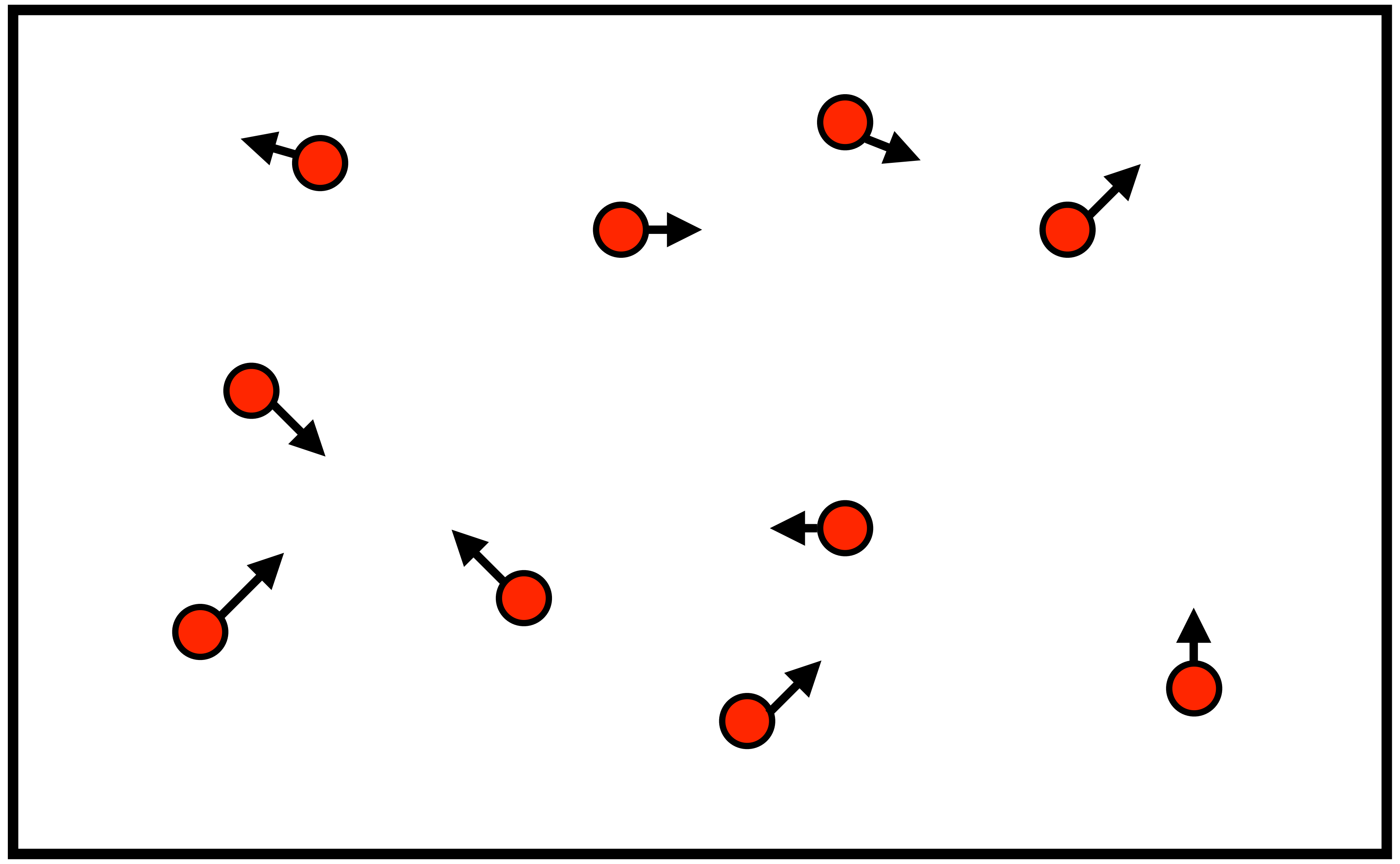
Dark Matter Candidates



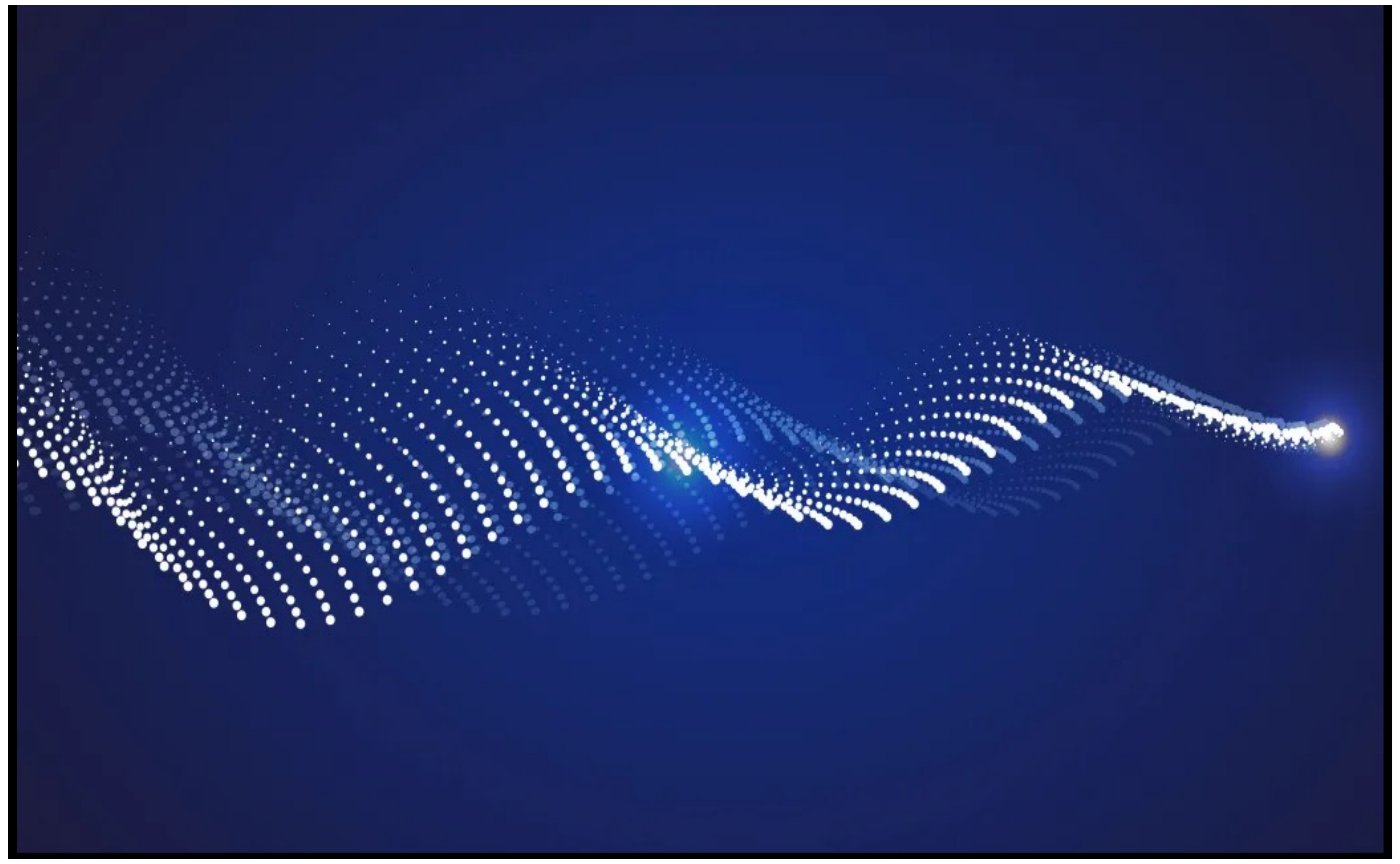
Particles vs. Waves

$$N_{dB} = \frac{\rho}{m}\left(\frac{2\pi}{mv}\right)^3 \approx 100 \left(\frac{\rho}{0.3\ \mathrm{GeV/cm^3}}\right)\left(\frac{m}{10\ \mathrm{eV}/c^2}\right)^{-4}\left(\frac{v}{250\ \mathrm{km/s}}\right)^{-3}$$

Particle dark matter ($N_{dB} \ll 1$)



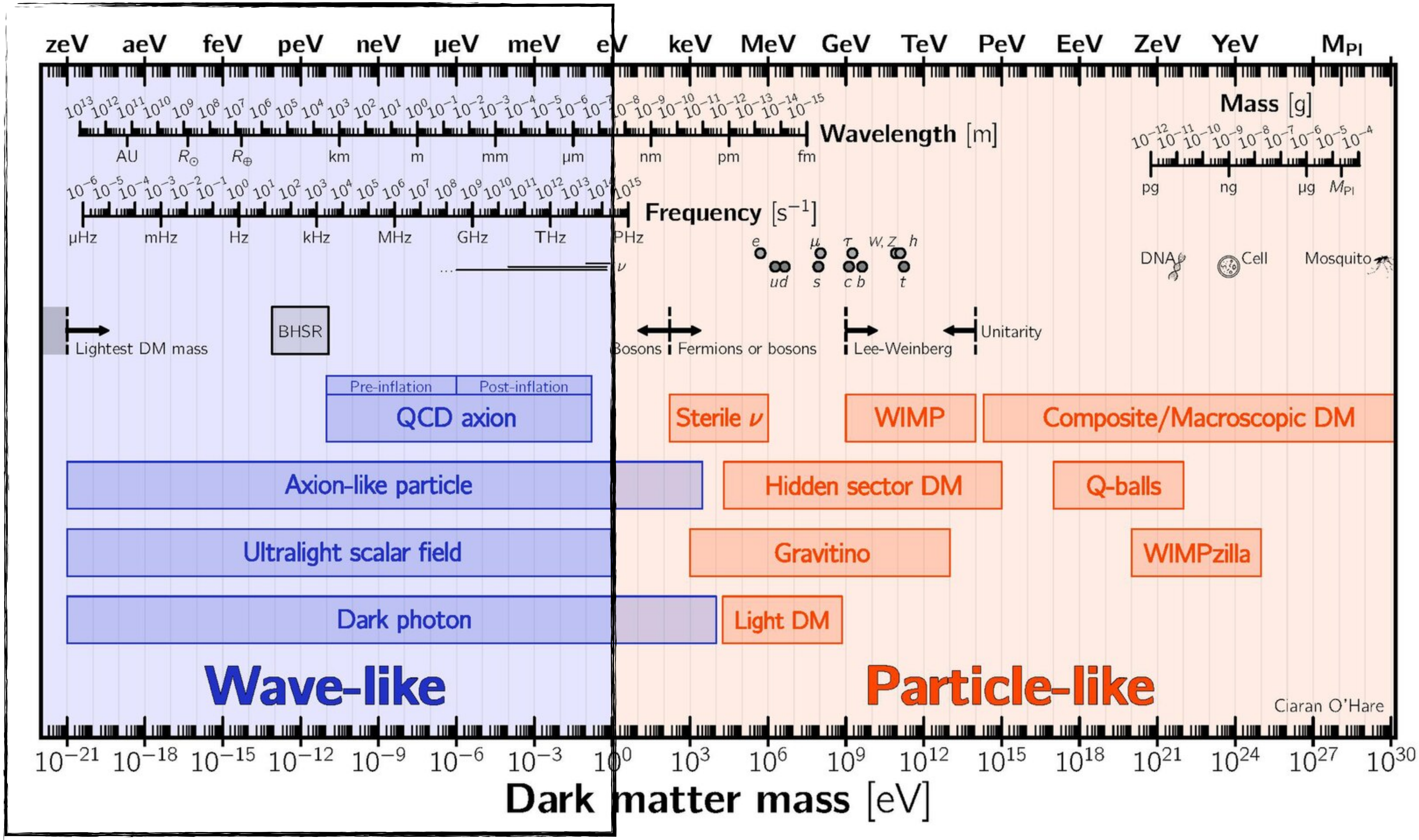
Wave-like dark matter ($N_{dB} \gg 1$)

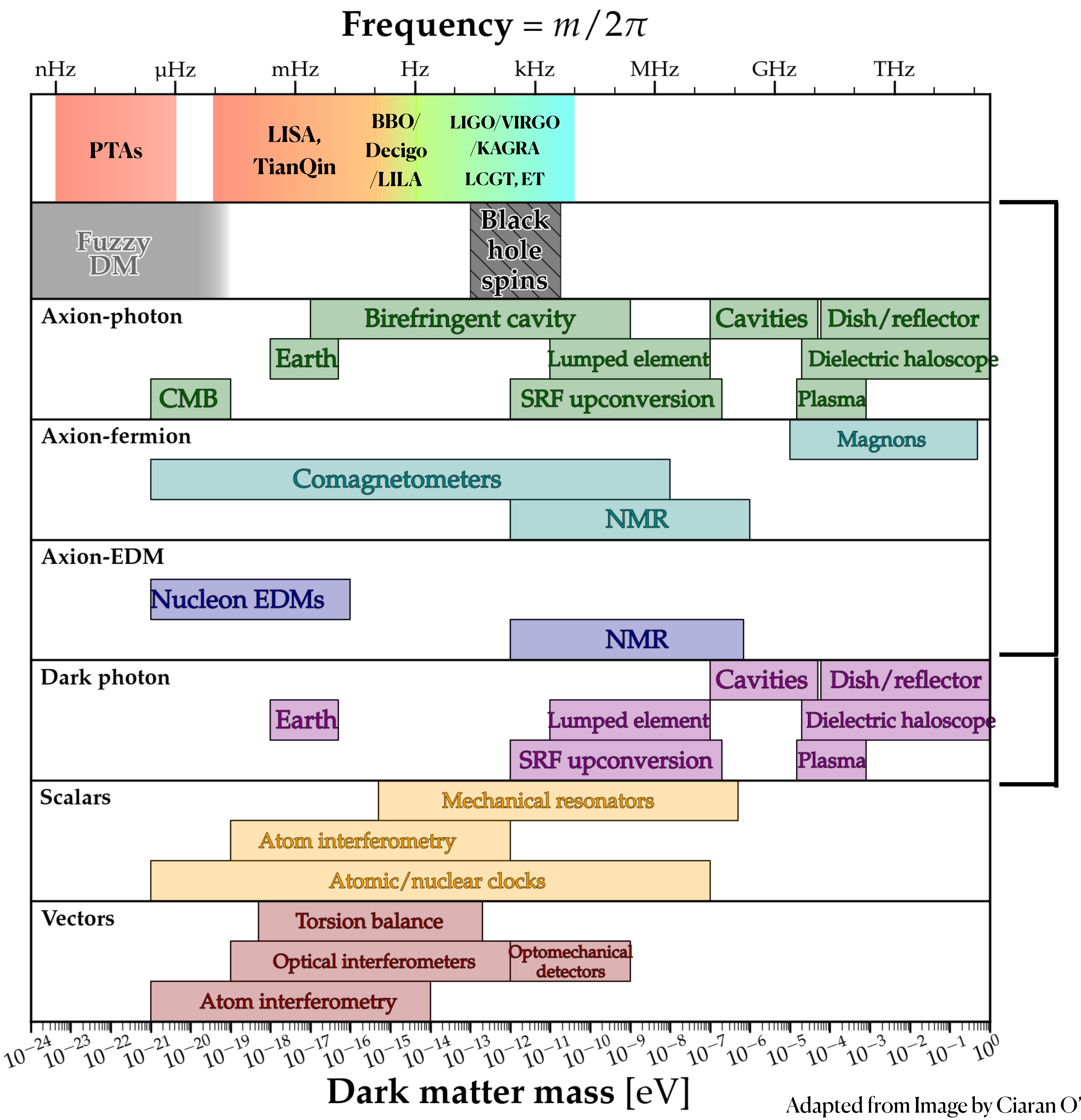


Bosons with $m \lesssim 10\ \mathrm{eV}/c^2$ behave like classical waves

Analogy: The fundamental theory of EM is *quantum*, but states with large numbers of photons behave like classical EM waves.

Dark Matter Candidates





Gravitational Waves

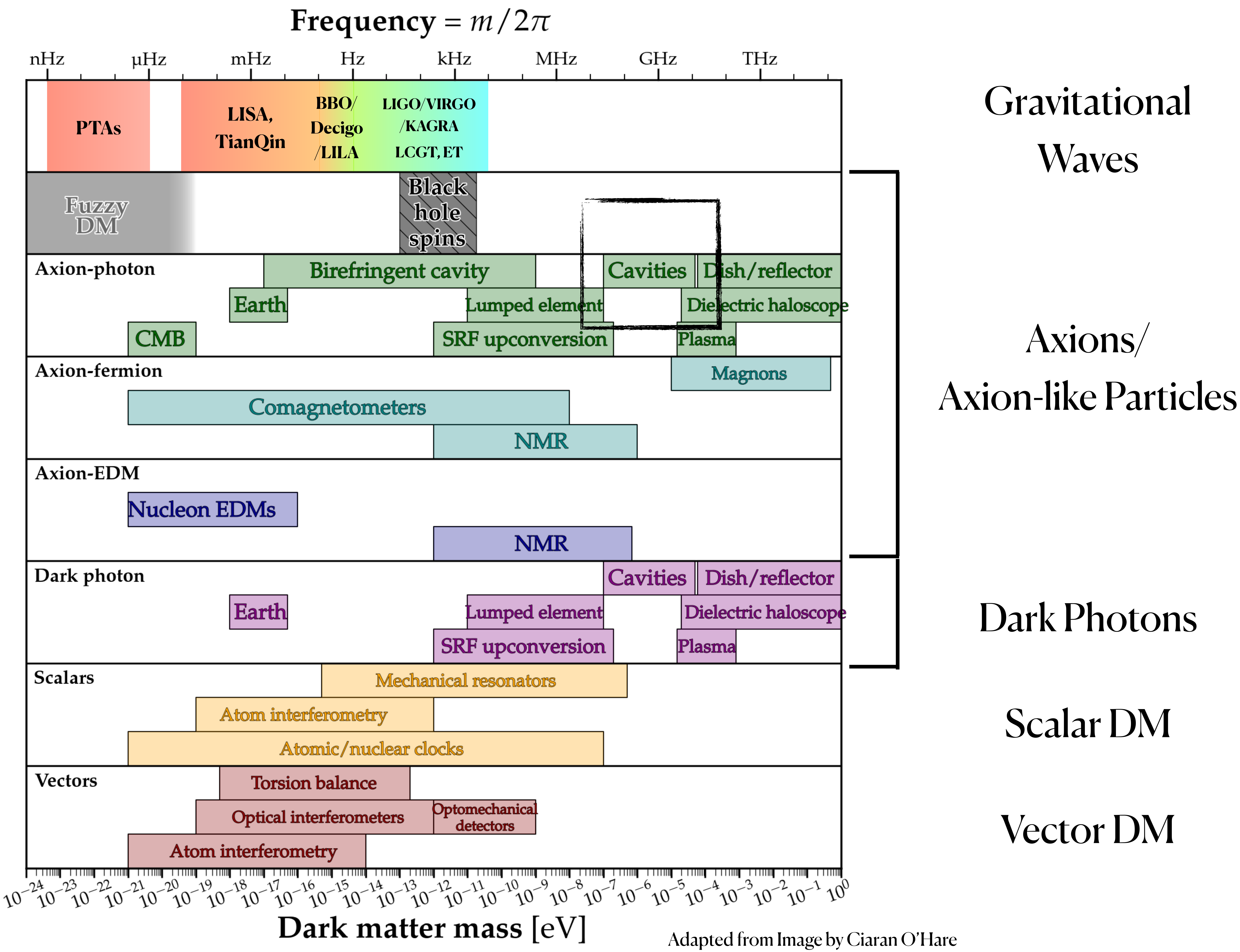
Axions/ Axion-like Particles

Dark Photons

Scalar DM

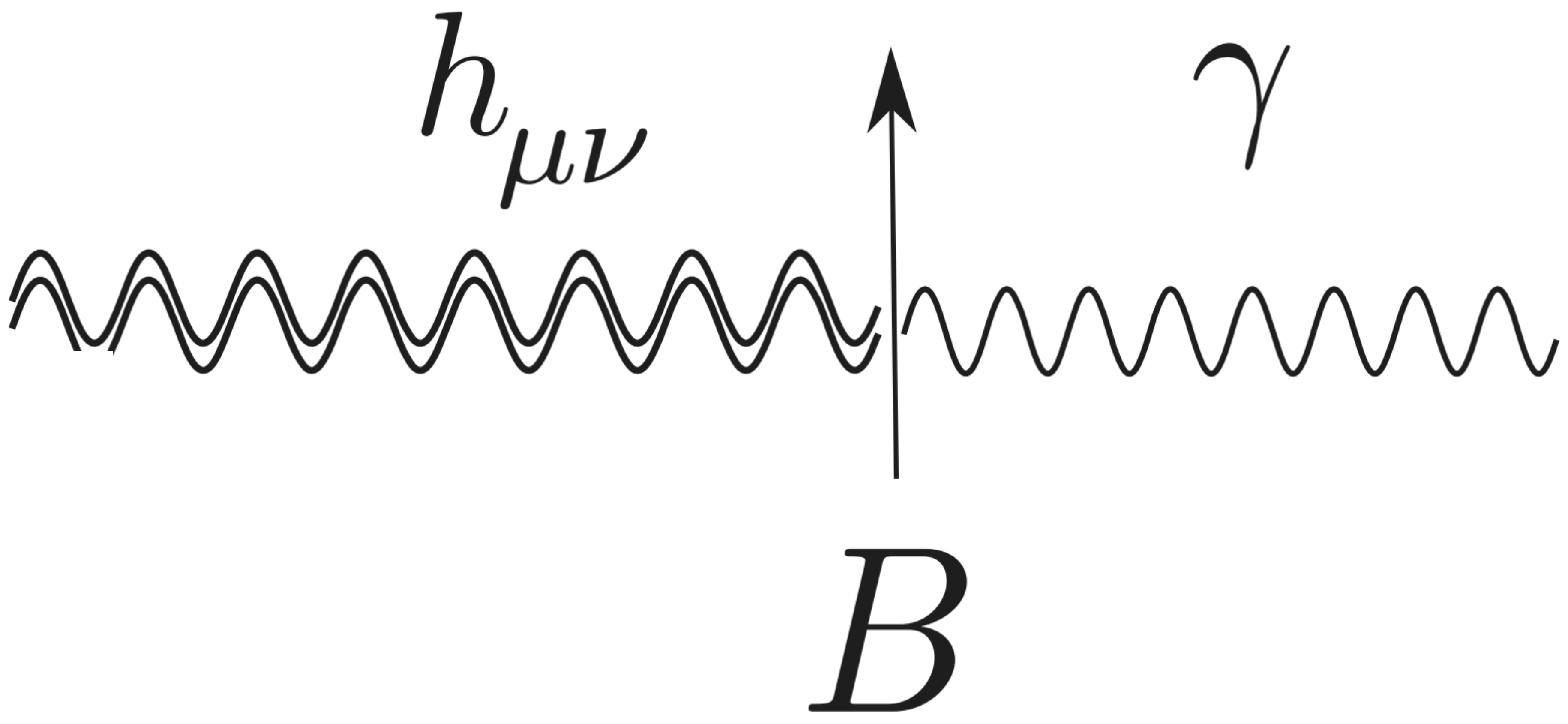
Vector DM

Adapted from Image by Ciaran O'Hare



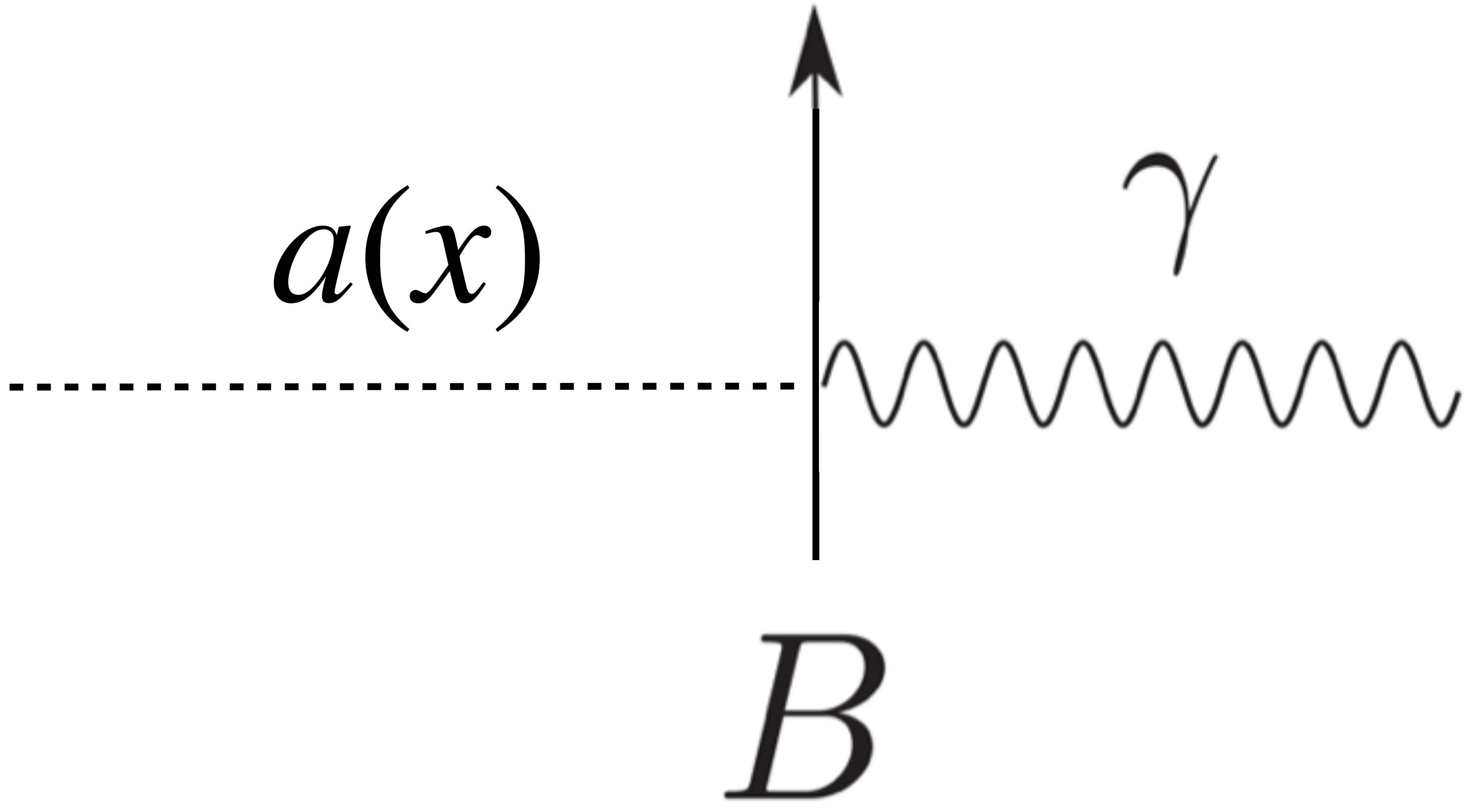
Adapted from Image by Ciaran O'Hare

(Inverse) *Gertsenshtein*



$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{4} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} \right) \to -\frac{1}{2} \int d^4x \, j^{\mu}_{\text{eff}} A_{\mu}$$

$$j^{\mu}_{\text{eff}} \equiv \partial_{\nu} \left(\frac{1}{2} h \, F^{\mu\nu} + h^{\nu}{}_{\alpha} \, F^{\alpha\mu} - h^{\mu}{}_{\alpha} \, F^{\alpha\nu} \right)$$



$$S = \int d^4x \left(-\frac{g_{a\gamma\gamma}}{4} \, a(x) \, F_{\mu\nu} \tilde{F}^{\mu\nu} \right) = \int d^4x \, j^{\mu}_{\text{eff}} A_{\mu}$$

$$j^{\mu}_{\text{eff}} = \epsilon^{\mu\nu\alpha\beta} \, g_{a\gamma\gamma} (\partial_{\nu} a) \partial_{\alpha} A_{\beta}$$

Microwave Cavities (e.g. ADMX)

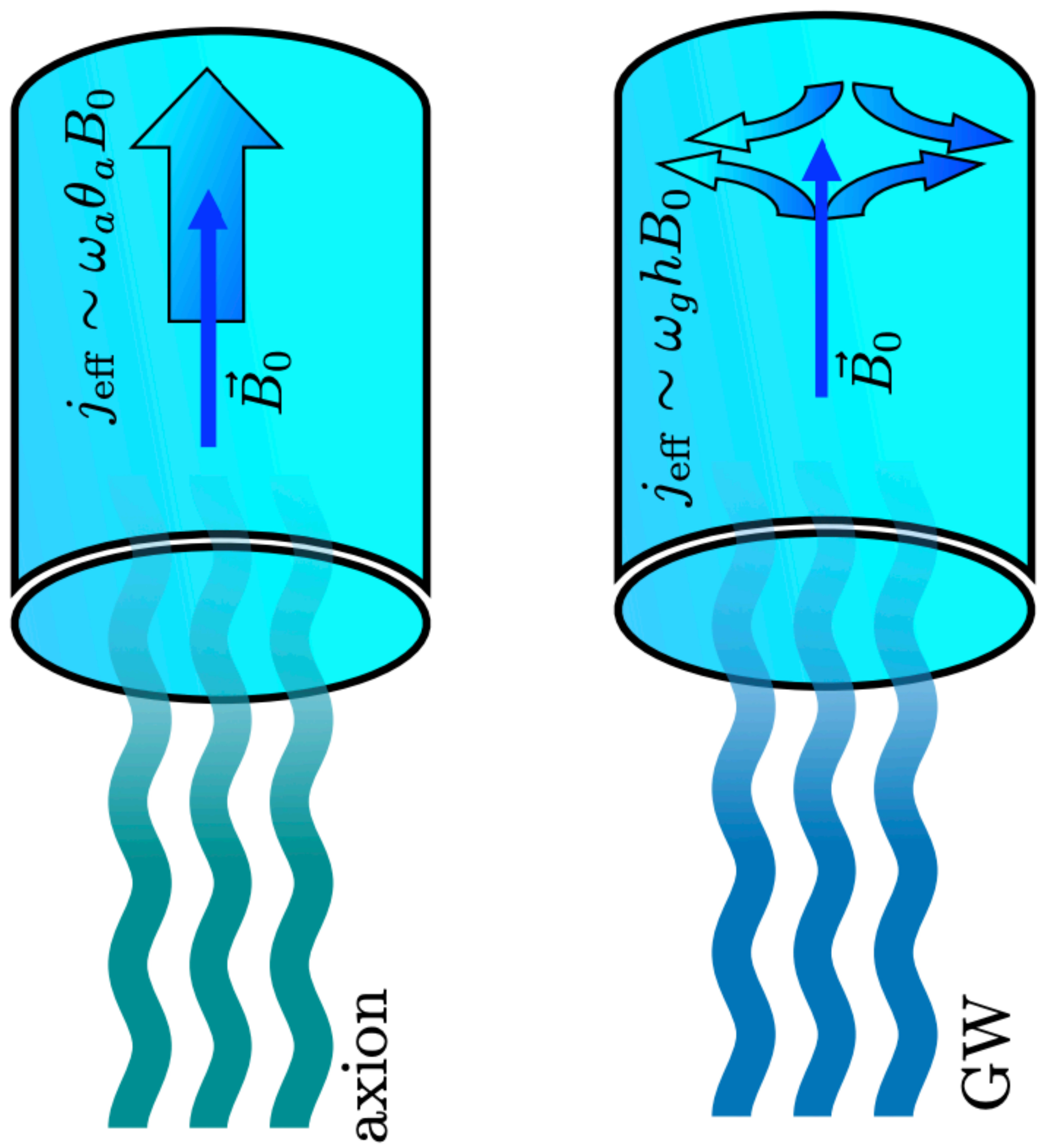
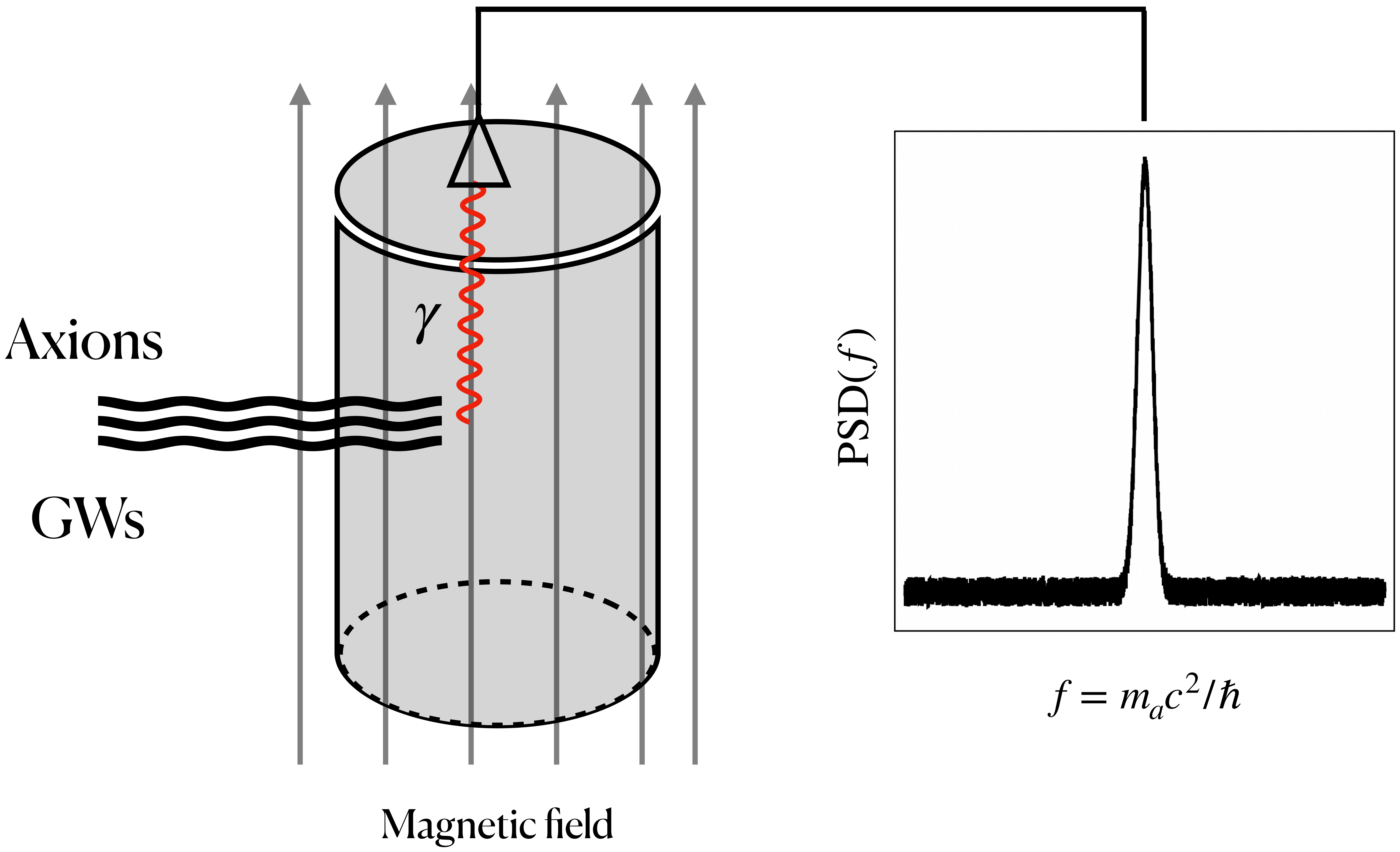


Image: Berlin et al. (2022)



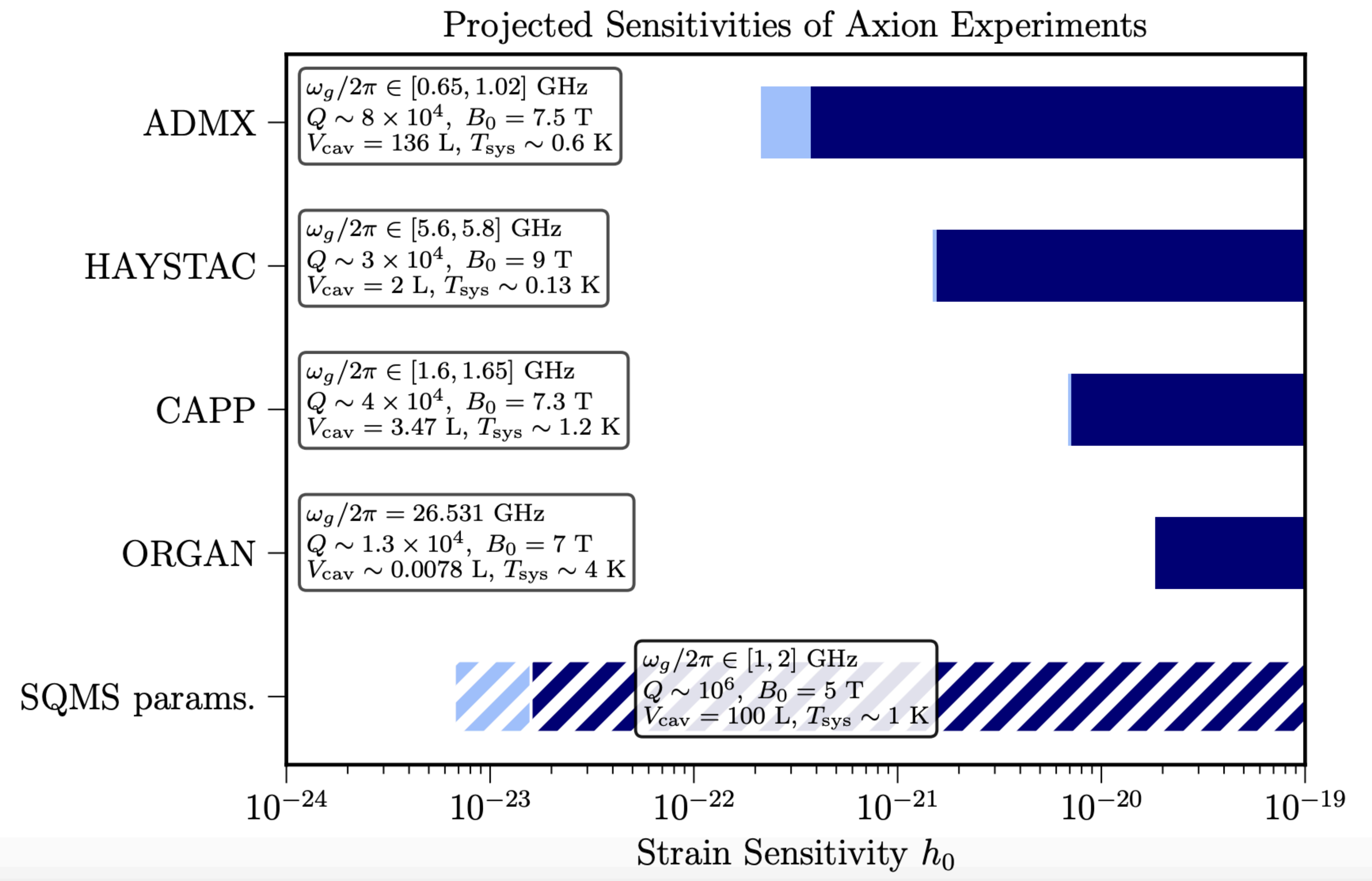
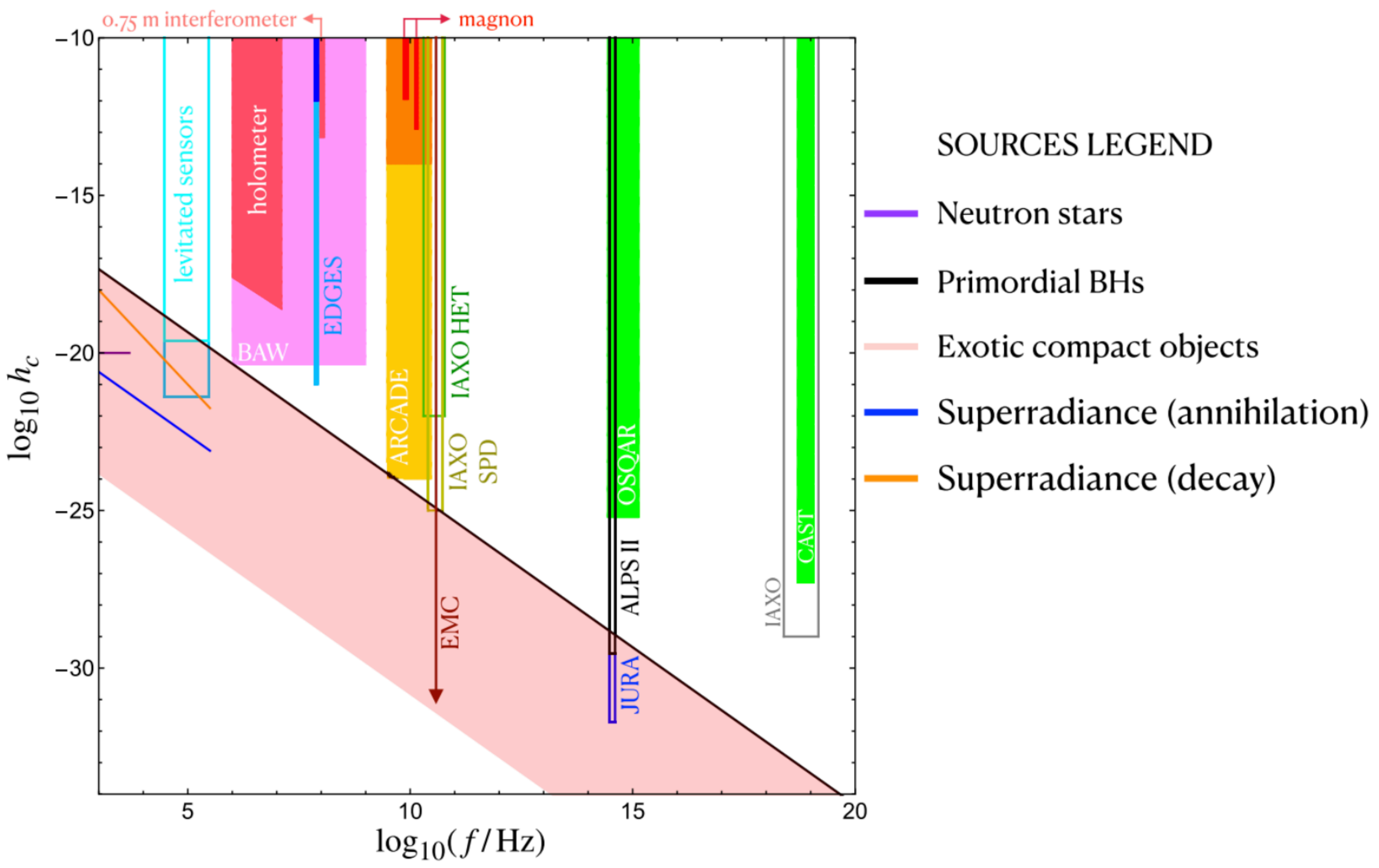


Image: Berlin et al. (2022)



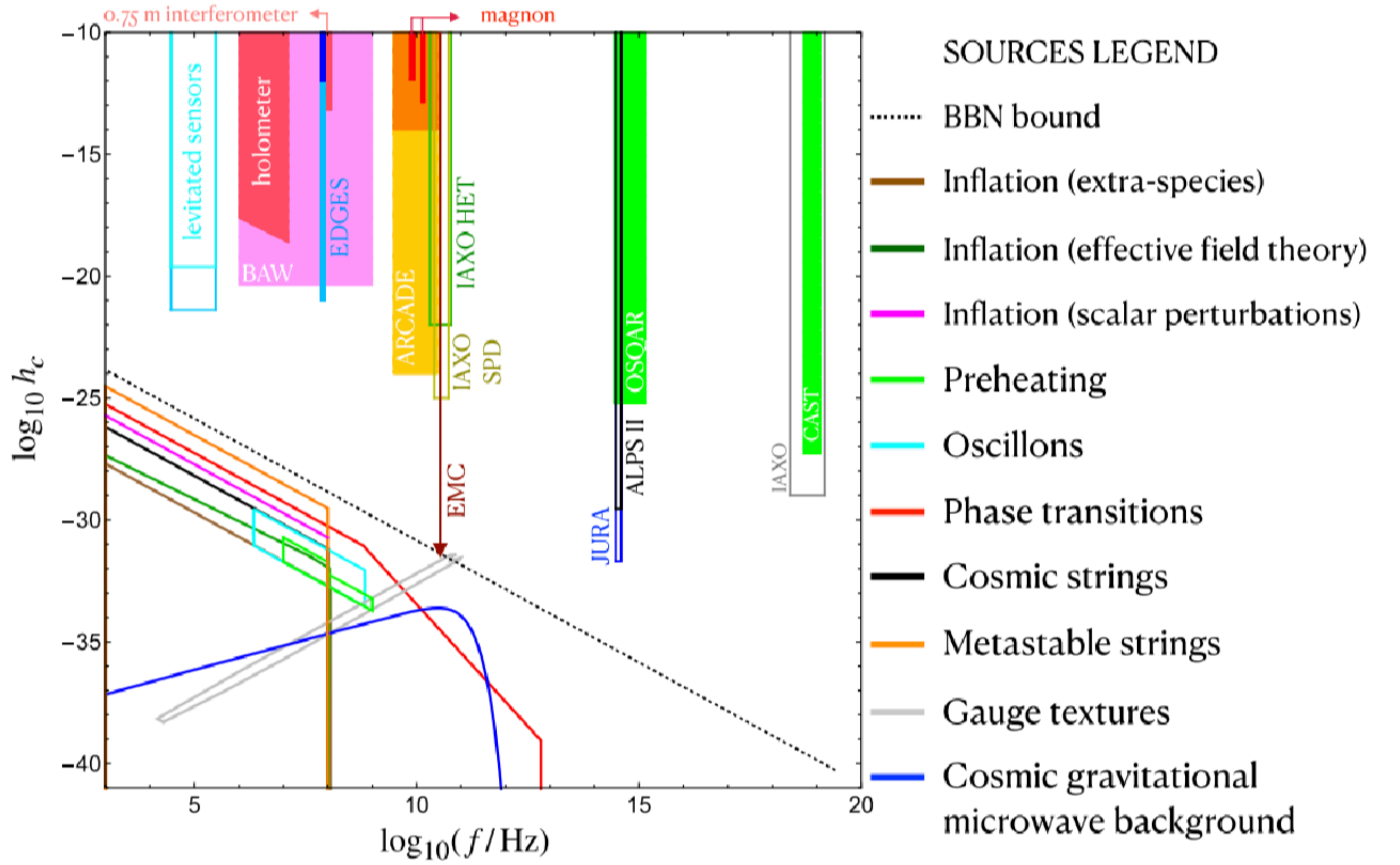
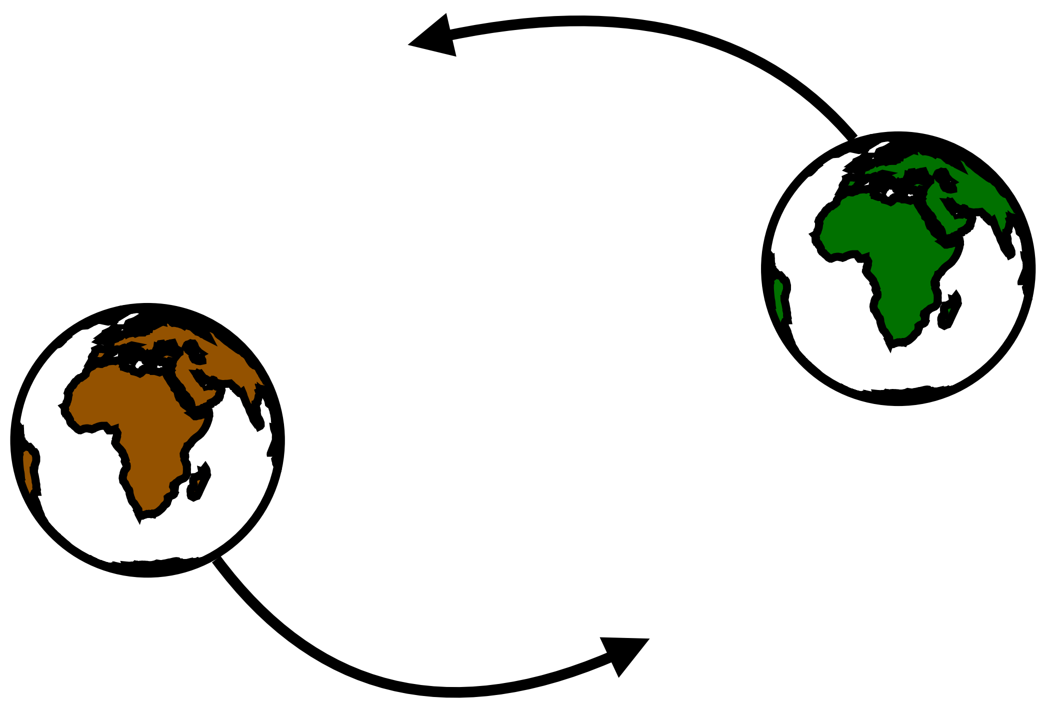
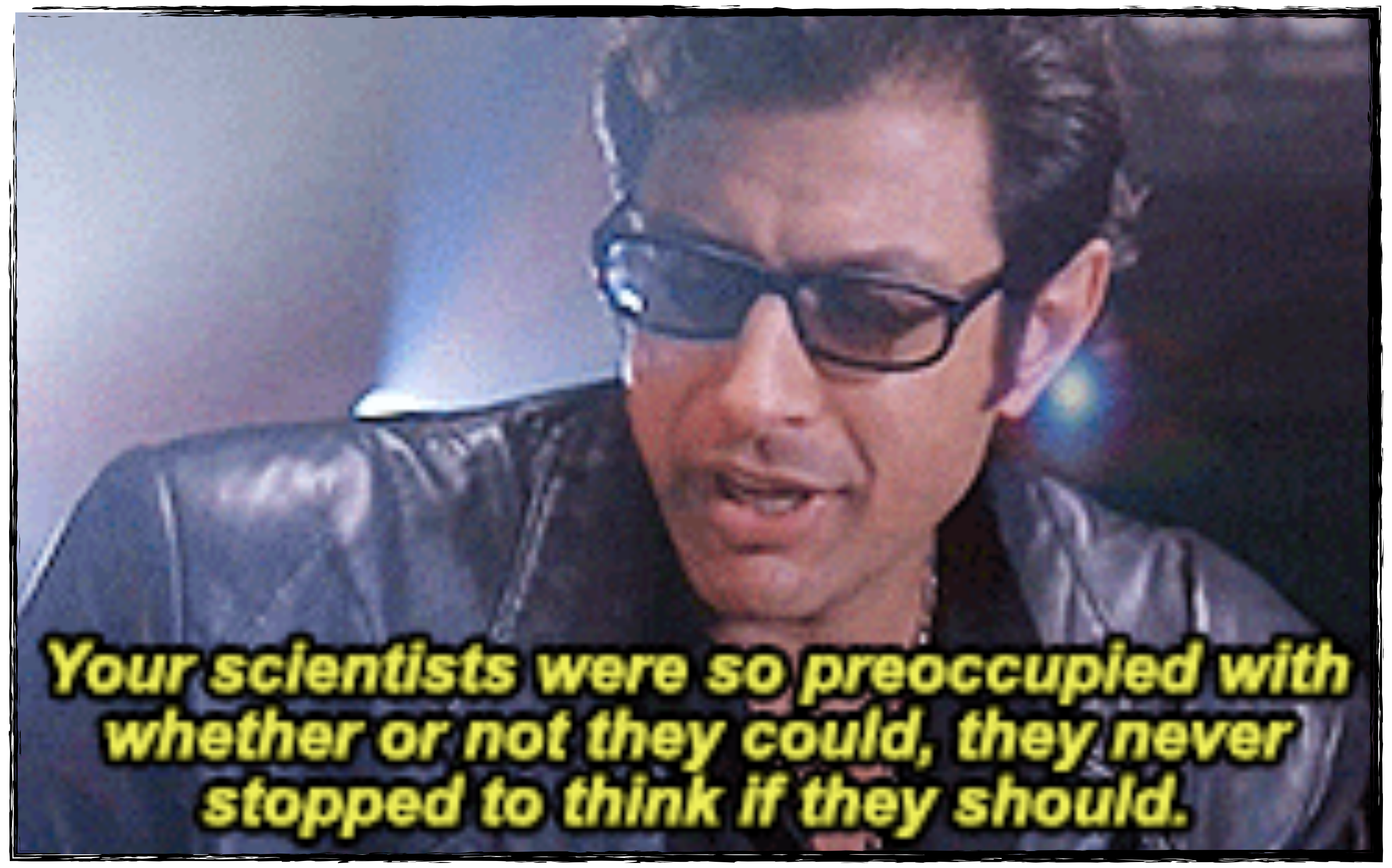


Image: Aggarwal et al. (2021)

Sources?





Primordial Black Holes

$$\omega_g = 14\ \text{GHz} \left(\frac{\mu M_\odot}{M_\odot}\right)\left(\frac{r_{\rm ISCO}}{r}\right)^{3/2}$$

- Modeling the waveform.
- Evolving frequency, resonant experiment?
- Population modeling?

Exotic compact objects

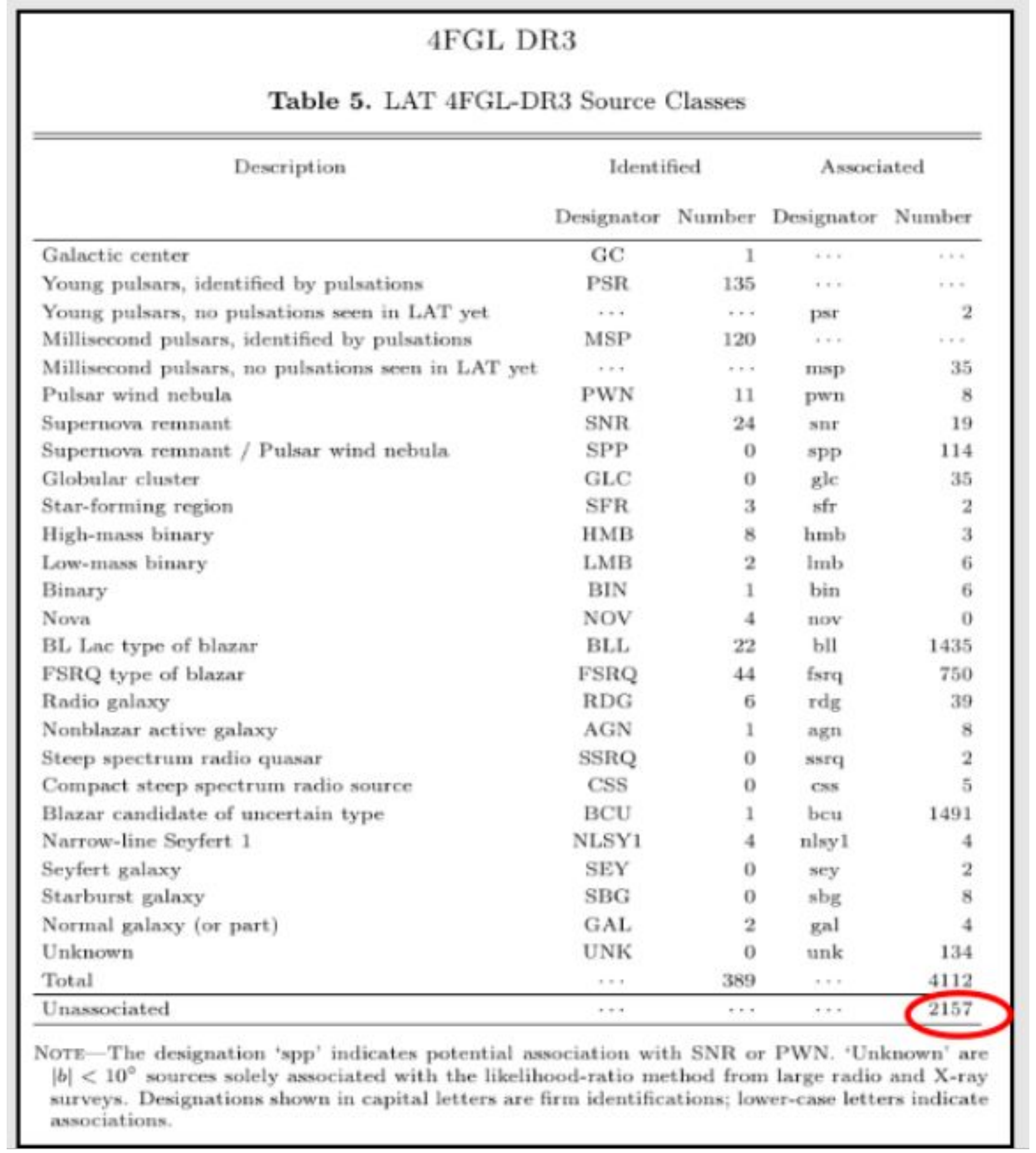
- Boson and fermion stars?
- Superradiant clouds around PBHs.
- Gravistars, gravitino stars?
- DM blobs?
- ....

High-Frequency Stochastic GWs

- First-order phase transitions
- Cosmic string
- Inflation/Preheating
- Thermal Plasma
- .....

Probing Unassociated Fermi-LAT Sources for Potential Gamma Ray Pulsar Detection

- **Unassociated sources** - Gamma-ray sources whose counterparts in other wavelengths (such as radio, X-ray, or optical) have not been identified.
- **Direct search Data Analysis Method (DSDA)** - This is an extension, of a semicoherent pipeline used to analyse Continuous Gravitational waves data, to the Fermi data.
- The collaboration between EM-GW is important to study Pulsars.



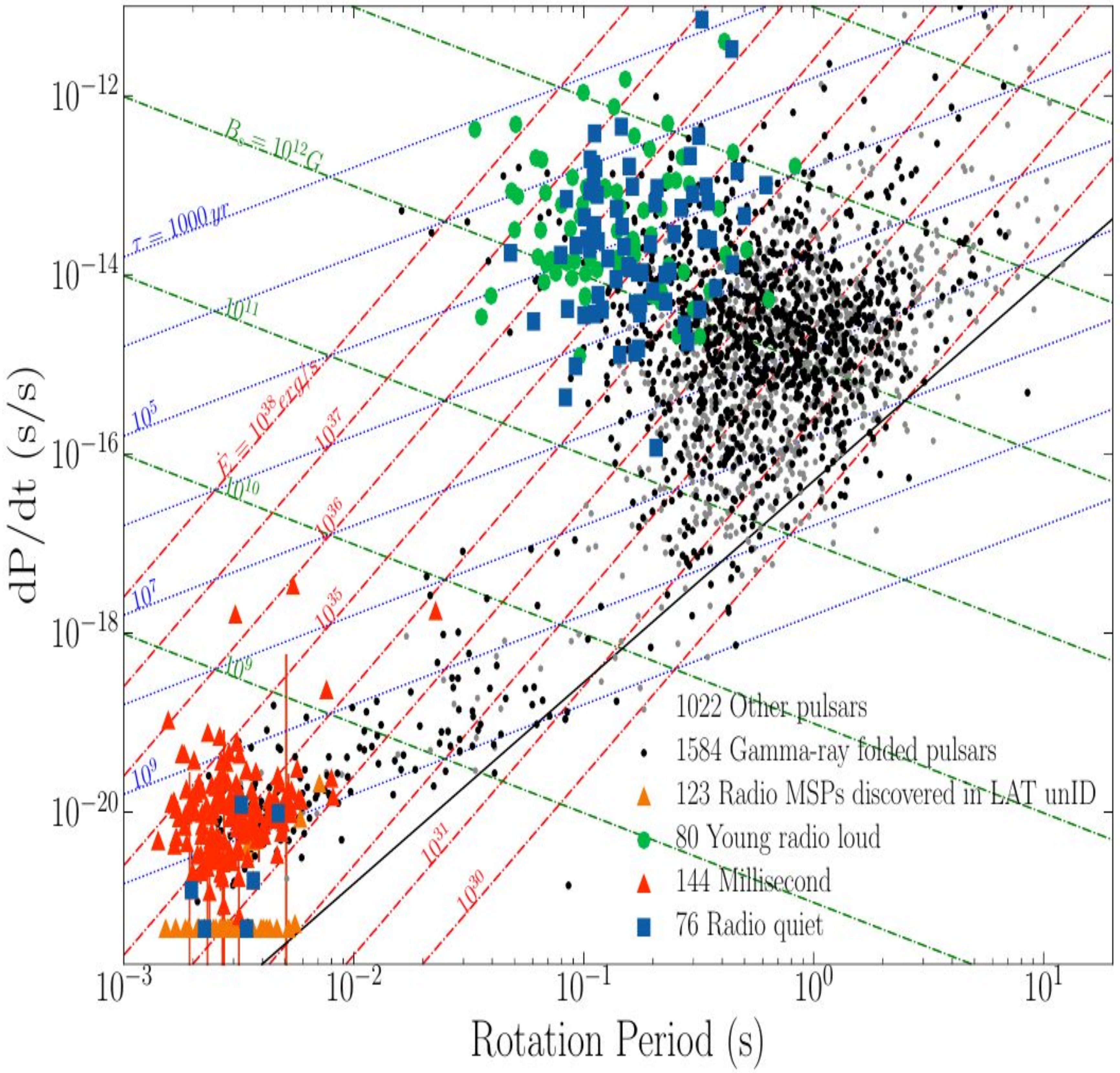
4FGL DR3

Table 5. LAT 4FGL-DR3 Source Classes

Description	Identified		Associated	
	Designator	Number	Designator	Number
Galactic center	GC	1	⋯	⋯
Young pulsars, identified by pulsations	PSR	135	⋯	⋯
Young pulsars, no pulsations seen in LAT yet	⋯	⋯	psr	2
Millisecond pulsars, identified by pulsations	MSP	120	⋯	⋯
Millisecond pulsars, no pulsations seen in LAT yet	⋯	⋯	msp	35
Pulsar wind nebula	PWN	11	pwn	8
Supernova remnant	SNR	24	snr	19
Supernova remnant / Pulsar wind nebula	SPP	0	spp	114
Globular cluster	GLC	0	glc	35
Star-forming region	SFR	3	sfr	2
High-mass binary	HMB	8	hmb	3
Low-mass binary	LMB	2	lmb	6
Binary	BIN	1	bin	6
Nova	NOV	4	nov	0
BL Lac type of blazar	BLL	22	bll	1435
FSRQ type of blazar	FSRQ	44	fsrq	750
Radio galaxy	RDG	6	rdg	39
Nonblazar active galaxy	AGN	1	agn	8
Steep spectrum radio quasar	SSRQ	0	ssrq	2
Compact steep spectrum radio source	CSS	0	css	5
Blazar candidate of uncertain type	BCU	1	bcu	1491
Narrow-line Seyfert 1	NLSY1	4	nlsy1	4
Seyfert galaxy	SEY	0	sey	2
Starburst galaxy	SBG	0	sbg	8
Normal galaxy (or part)	GAL	2	gal	4
Unknown	UNK	0	unk	134
Total	⋯	389	⋯	4112
Unassociated	⋯	⋯	⋯	2157

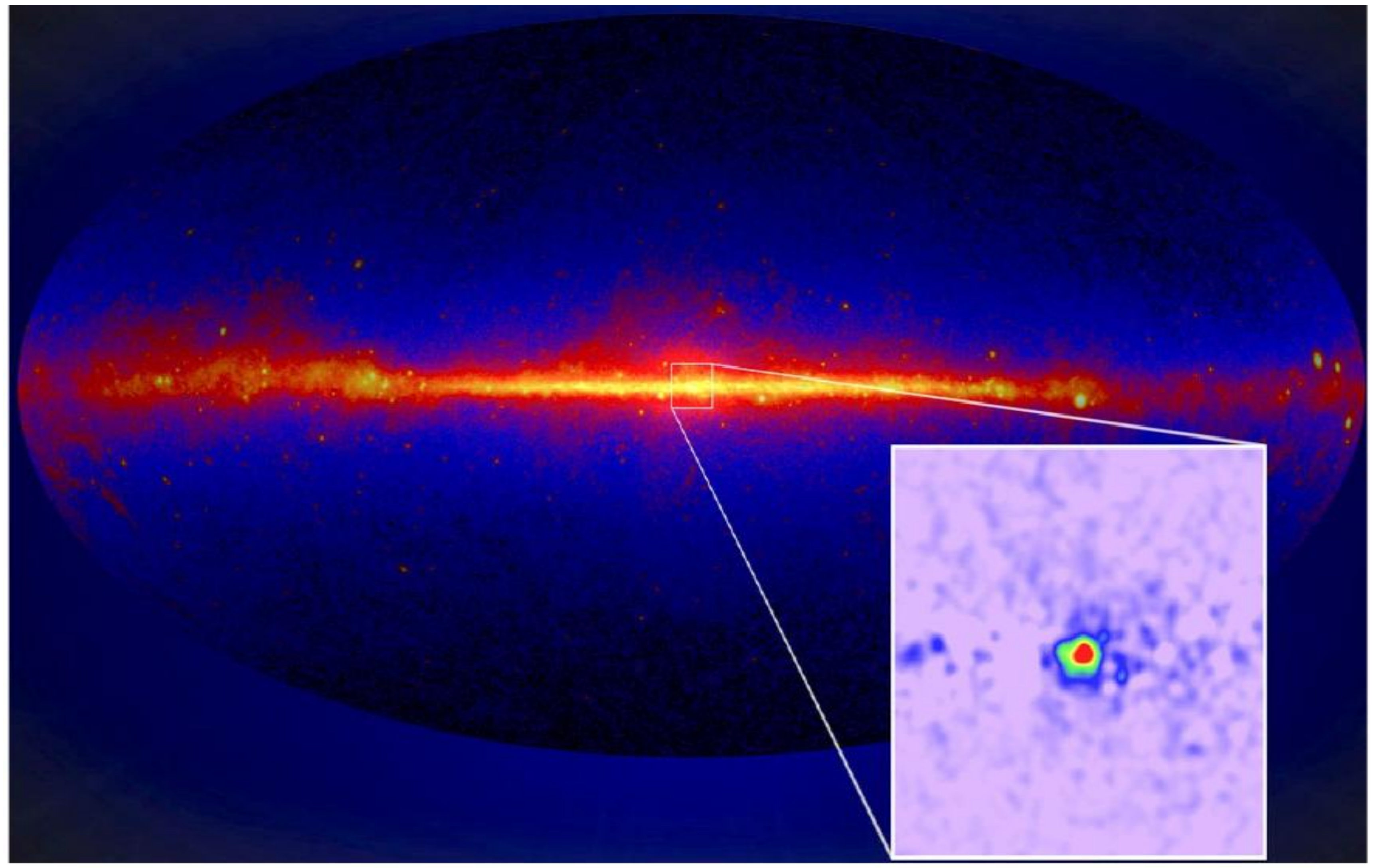
NOTE—The designation 'spp' indicates potential association with SNR or PWN. 'Unknown' are $|b| < 10^\circ$ sources solely associated with the likelihood-ratio method from large radio and X-ray surveys. Designations shown in capital letters are firm identifications; lower-case letters indicate associations.

Image courtesy of Fermi Large Area Telescope (LAT) 4FGL-DR3 data release.

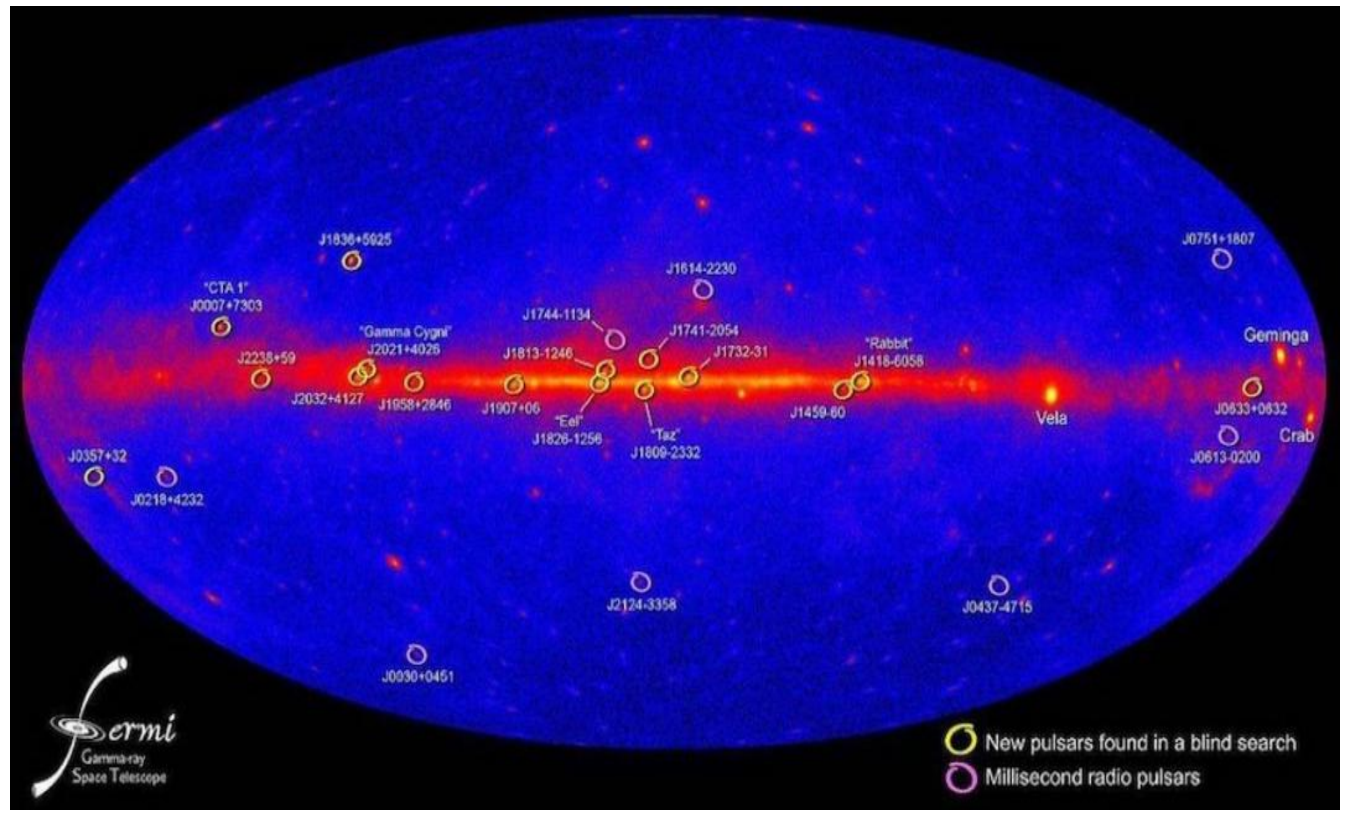


D A Smith et al. 2023, "The Third Fermi Large Area Telescope Catalog of Gamma-ray Pulsars", arXiv:2307.11132v1

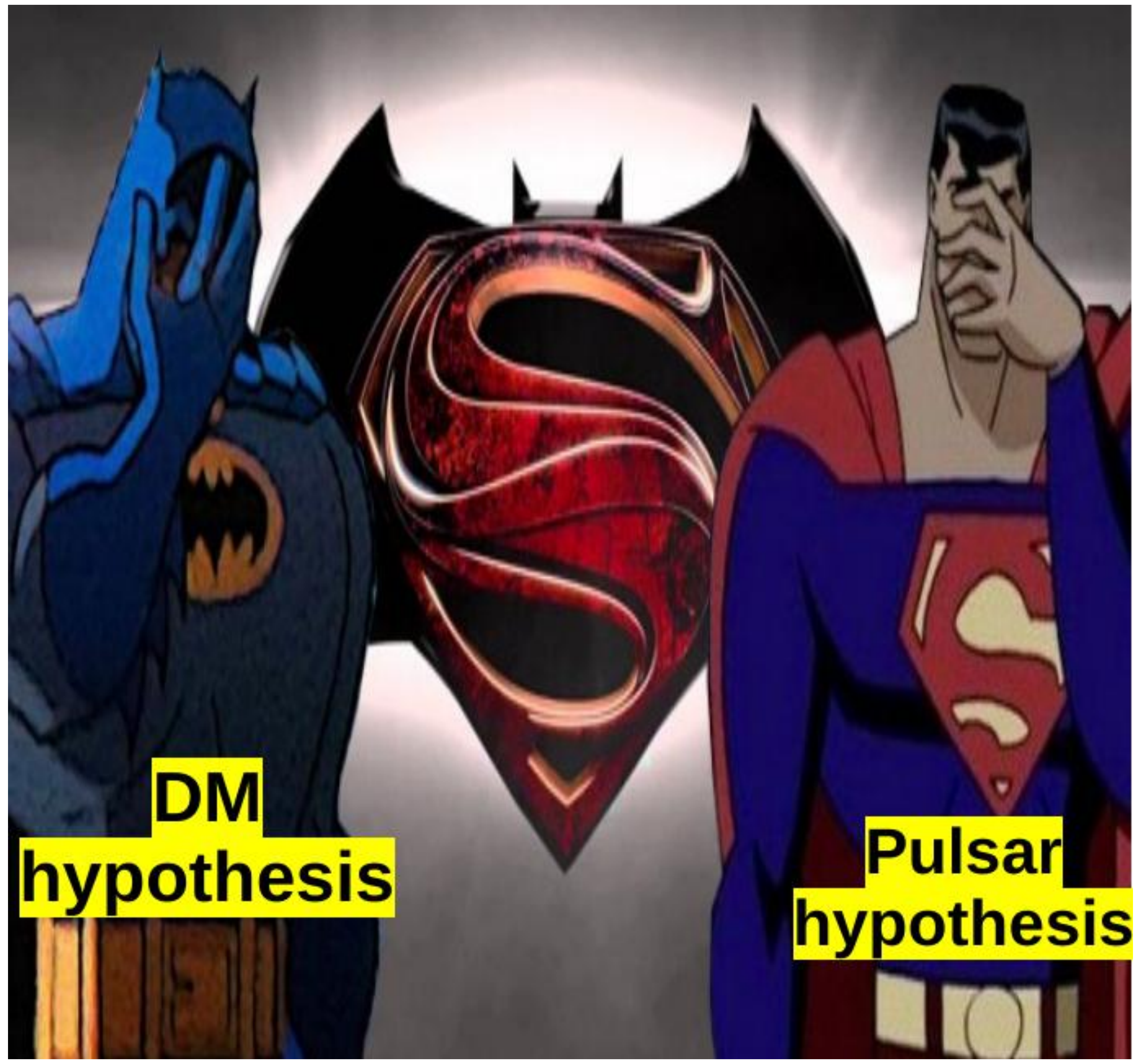
Chandana Hrishikesh

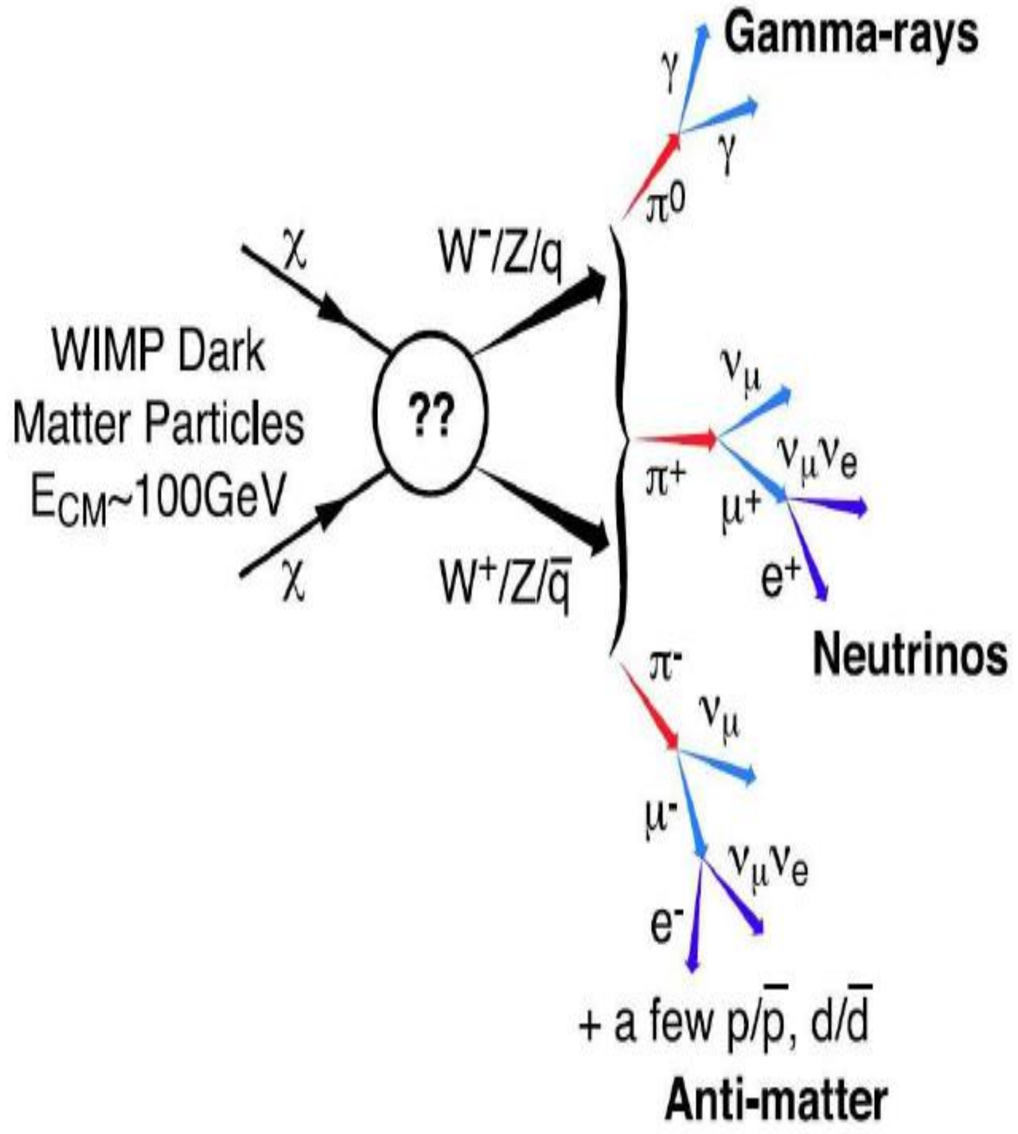


Credit : NASA/DOE/FERMI LAT COLLABORATION;
T. LINDEN/UNIVERSITY OF CHICAGO



High resolution, high-energy map of the sky - showcasing new pulsars and millisecond pulsars. Credit: NASA/DOE/FERMI LAT COLLABORATION





Summary

- Require better understanding (modelling+) of GW exotica to search for it
- Development of source-specific searches may be required to improve detection prospects (esp. for long-duration, broad-band emission)
- Looking forward: do we require better coordination to avoid waste of resources (time, computation,+)
- In the ultra-HF regime (10kHz+): require more sources of interest for GW searches
- New physics: how do we prepare to detect the unknown? Are burst/excess-power pipelines enough?
- What do *you* think will be our first “non-garden variety CBC”/exotic GW detection?