# Testing fundamental physics with gravitational waves

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Future colliders for Early-Career Researchers Workshop

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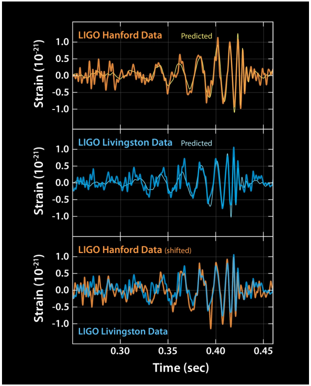
# Overview

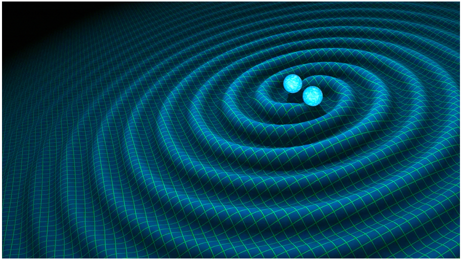

1. Introduction
2. GW sources
    - Individual GW sources
    - Stochastic Gravitational Wave Backgrounds (SGWBs)
3. SGWB detection to constrain HEP
4. Conclusions and outlook

# The dawn of GW astronomy

Gravitational Waves (GWs) are:

- Spacetime perturbations
- Almost free streaming
- The ultimate cosmological probe



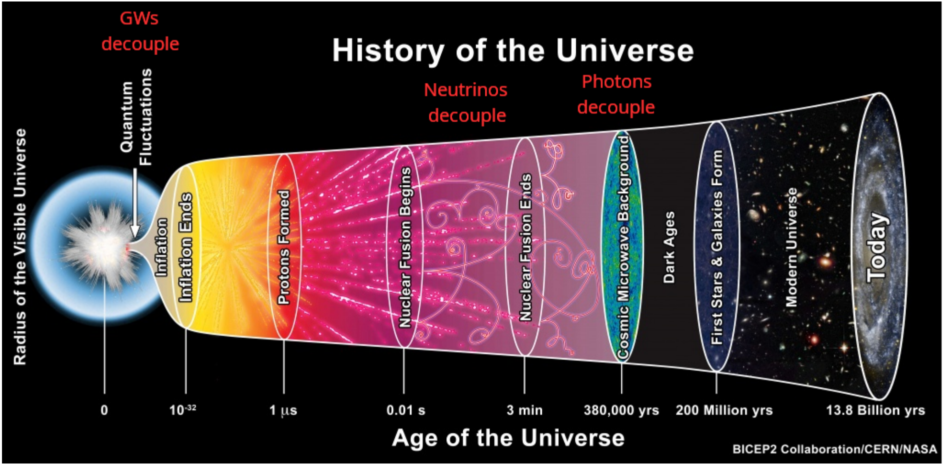



Why GWs are interesting?

- Finally detected (GW150914)! 
- Some detectors are active now
- More will join in the next years
- New window on high energy physics
- Unveil new details on gravity

* Figures from https://www.nasa.gov/sites/default/files/thumbnails/image/ns_gw_art.jpg and https://www.ligo.org/detections/images/ligoGW150914signals-lg.jpg

# Exploring the cosmic history with GWs



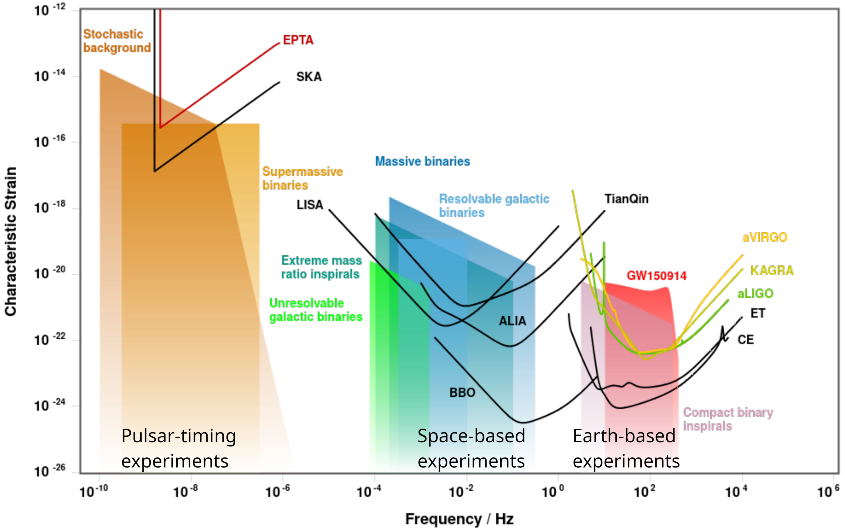

GWs decouple much earlier than photons and neutrinos!

Could bring info on scales we cannot access in any other way

* Figure from https://home.cern/news/series/lhc-physics-ten/recreating-big-bang-matter-earth BICEP2 Collaboration/CERN/NASA

# Present and future GW detectors

Different types of detectors will probe different frequency bands (and sources)




* Figure adapted from GWPlotter

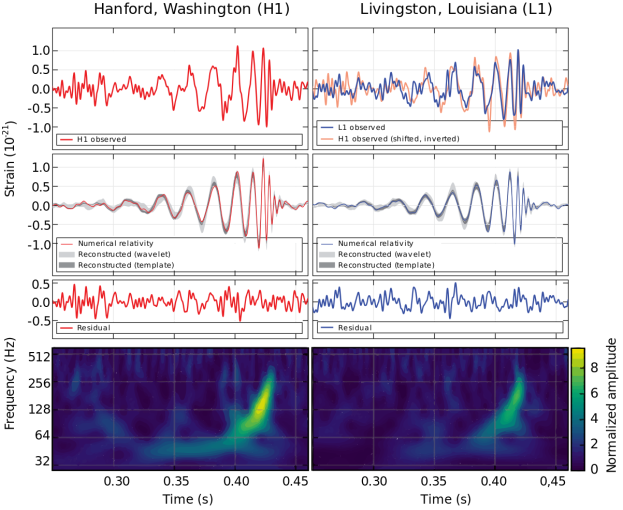
# Individual (and possibly resolvable) sources

Signals having a predictable morphology in time and frequency

Loud sources can be seen individually (like LVK detectors do)

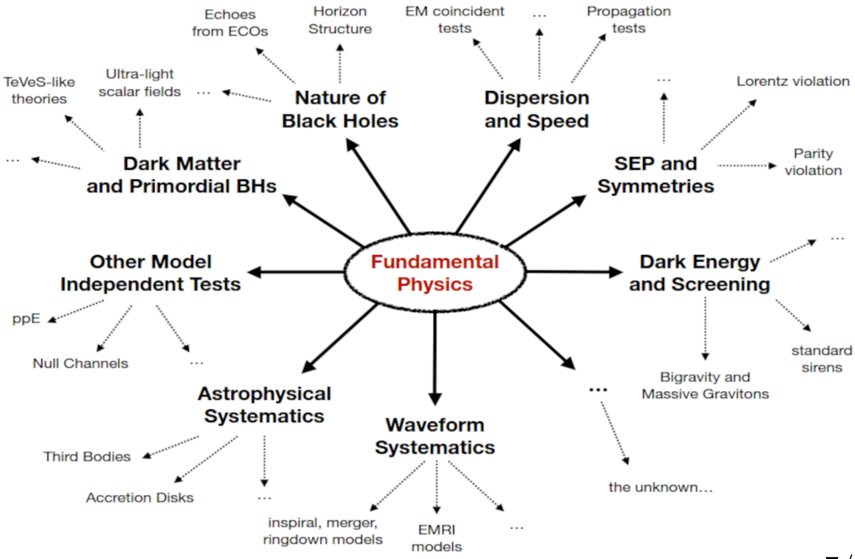
Choose your favourite th template (GR or something beyond) and reconstruct the parameters

Combine single events to constrain the population parameters (or your favourite cosmological model)




* Figure from LIGO Scientific and Virgo Collaborations B.P. Abbott et al., *Phys.Rev.Lett. 116 (2016) 6, 061102*, ArXiv: 1602.03837.

# Some aspects we can probe with individual sources




* LISA Collaboration, K.G. Arun et al. *Living Rev.Rel. 25 (2022) 1, 4*, ArXiv: 2205.0159

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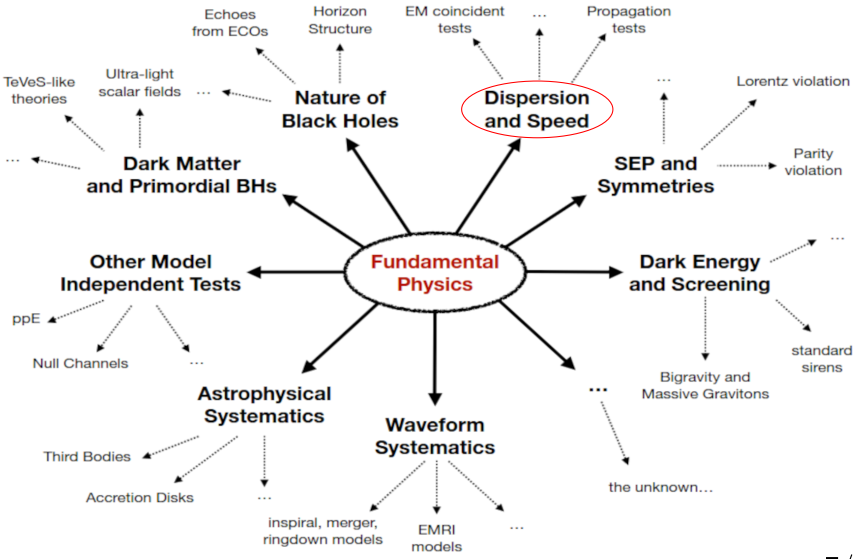


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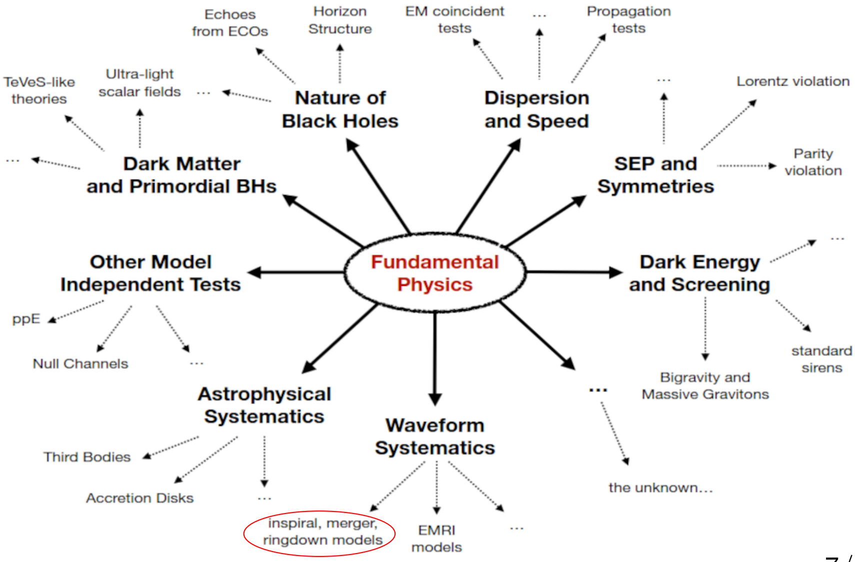


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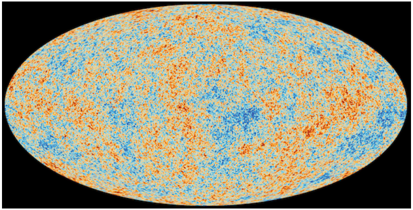
# SGWBs detection and characterization

SGWBs are:

- Stochastic signals from the whole sky
- Either cosmological or astrophysical origin
- Invaluable source of information (HEP!)
- A target for all future detectors



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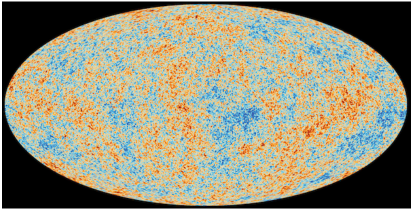

Detection prospects?

- At least two SGWB components (SOBBHs and CGBs) are guaranteed signals for LISA!
- LIGO/Virgo/KAGRA + future Earth-based interferometers (LIGO-India, ET, CE, ...)
- Millisecond pulsars timing to detect GWs (hints for SGWB detection..)

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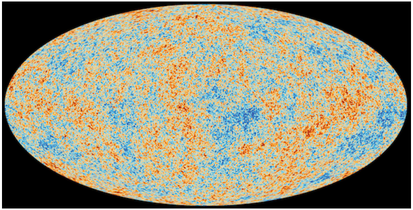

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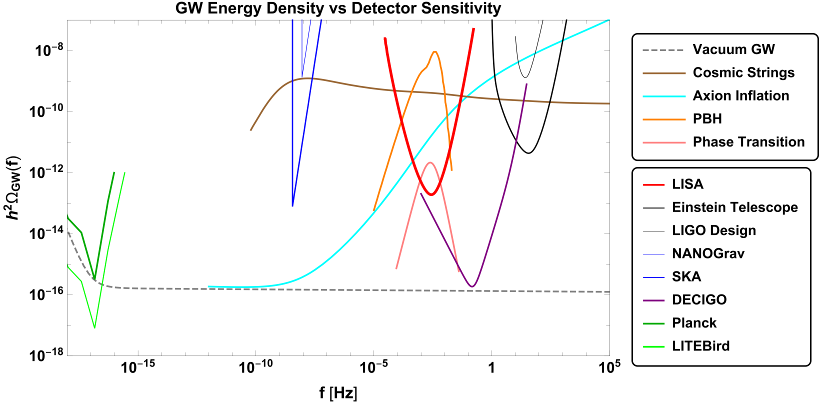
Few characteristics to classify SGWBs: $\longrightarrow$

- **Isotropy / Anisotropy**
- **Stationary / Non-stationary**
- **Polarized / Unpolarized**
- **Statistical properties**
- **Frequency shape**

* Figure from: https://sci.esa.int/web/planck/-/60500-plancks-view-of-the-cosmic-microwave-background

# Sources for SGWBs of cosmological origin



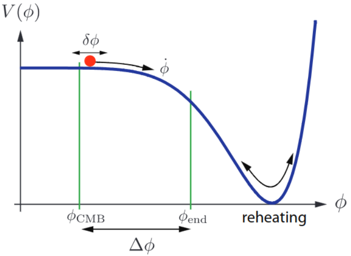

The detection of any of these signals could unveil signatures from HEP:

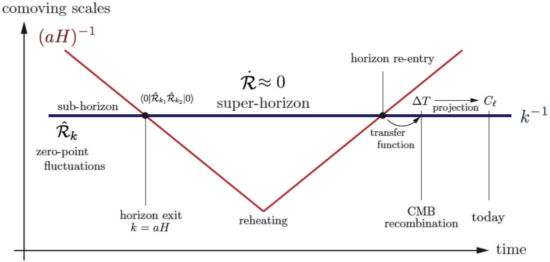
- Inflaton's coupling to other particles?
- Occurrence of first order phase transitions in the ealy Univer?
- Generation (and interactions within networks of) cosmic strings?

* Figure from LISA Cosmology Working Group WP, P. Auclair et al., *Living Rev.Rel. 26 (2023) 1, 5*, ArXiv: 2204.05434

# Inflation

Minimal realization of inflation: $\longrightarrow$ $S = \int \mathrm{d}^4x\sqrt{-g}\left(\frac{R}{2\kappa^2} + \frac{\dot{\phi}^2}{2} - V(\phi)\right).$

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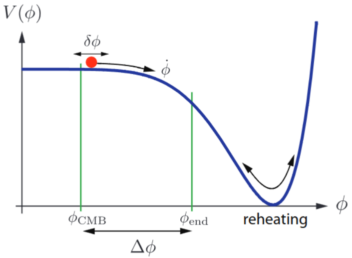


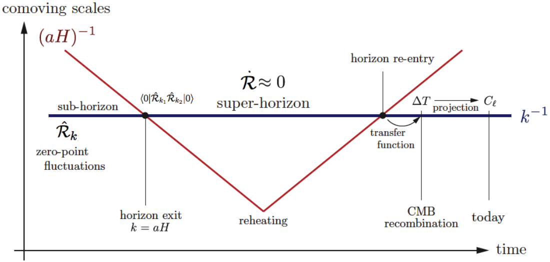


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Things change dramatically in non-minimal scenarios:

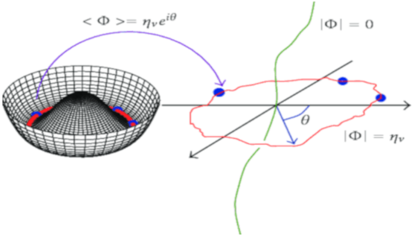
(see, e.g., N. Bartolo et al., *JCAP 12 (2016) 026*, ArXiv: 1610.06481)

- Axion inflation: $\mathcal{L} \supset \frac{\alpha}{4\Lambda}\phi F\tilde{F}$
- Spectator fields: $\mathcal{L} \supset P(\dot{\sigma}, \sigma)$
- Symmetry breaking: $m_h \neq 0$
- ...

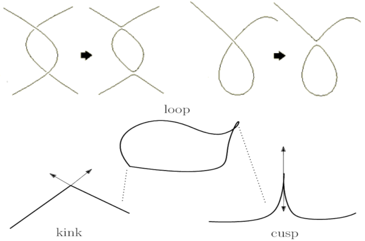
* Figures from Baumann, ArXiv: 0907.5424

# Cosmic Strings

CS might form in the early Universe




Evolution turn long strings into loops

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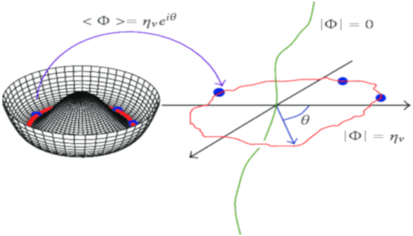


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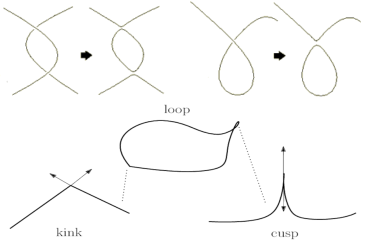


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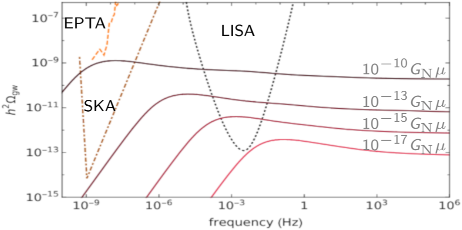
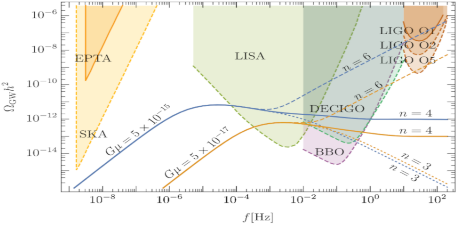
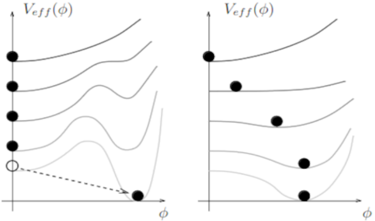



* Figures from Ringeval, *Adv.Astron. 2010 (2010) 380507*, ArXiv: 1005.4842, Shellard and Vilenkin 1994, Gouttenoire, Servant and Simakachorn *JCAP 07 (2020) 032*, ArXiv: 1912.02569, Auclair et al. *JCAP 04 (2020) 034*, ArXiv: 1909.00819, Cui, et al. *Phys.Rev.D 97 (2018) 12, 123505*, ArXiv:1711.03104.

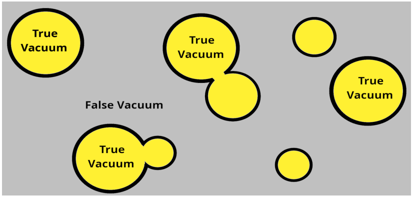
# First order phase transitions

First order Second order




$\Longrightarrow$

FOPT $\rightarrow$ Bubble nucleation

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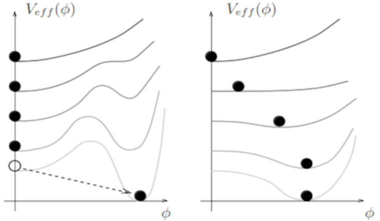


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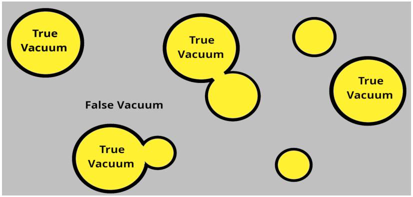


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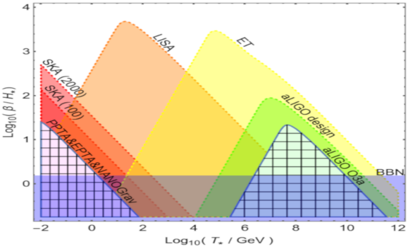
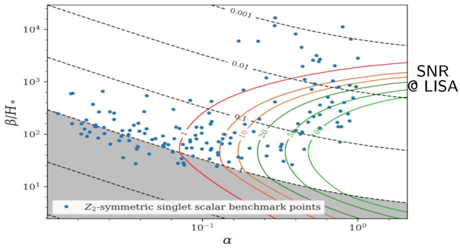
In SM both EW and QCD PTs should be second order $\Longrightarrow$ Detection implies BSM!




* Figures from Rubakov ArXiv:1804.11230, Caprini et al., *JCAP 03 (2020) 024*, ArXiv: 1910.13125, Auclair et al. *Living Rev.Rel. 26 (2023) 1, 5*, ArXiv:2204.05434

# Conclusions and outlook

**Some general conclusions:**

- GWs have a great potential to probe High Energy Physics (HEP)
- Individual sources → direct way to test modifications of gravity
- SGWBs of cosmological origin → new window on BSM!

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## New ideas and tools will be necessary:

- Cross-correlations with other probes (CMB, LSS, ...?)
- Identification of "smoking-gun" observables for the different mechanisms (chirality, anisotropy, time modulations, statistical properties, ...)
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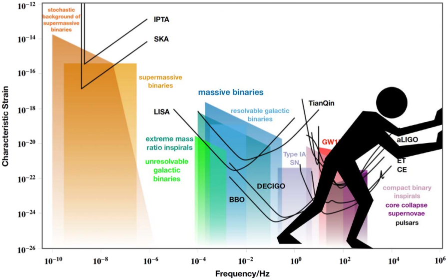
## More detectors to cover all frequencies:

- More Earth-based detectors (also new generation) will join the network
- First space-based detectors: LISA + (maybe ?) Taiji/TianQin
- Others?

# High frequency GWs?

What about high frequency GWs??



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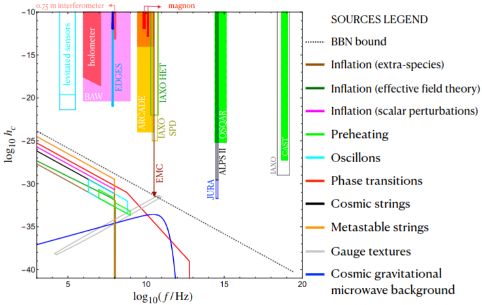
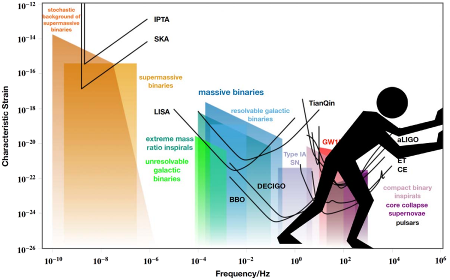
Several mechanisms predict signals at high frequency

⇓




“Ultra-high frequency gravitational waves: where to next?”

Workshop @ CERN, Dec 4 - 8, 2023

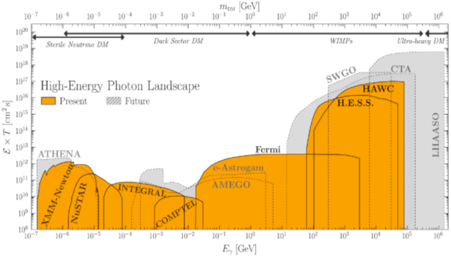
* Figures from https://cerncourier.com/a/exploring-the-early-universe-with-gravitational-waves/
N. Aggarwal et al. *Living Rev.Rel. 24 (2021) 1, 4*, ArXiv: 2011.12414

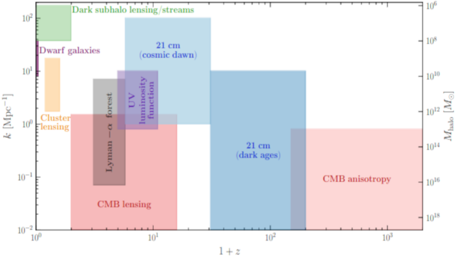
# Other probes?

Some astro/cosmo DM probes:

- Detection of X-rays and $\gamma$-rays
- High-energy neutrinos searches
- Charged cosmic rays
- Axion Indirect Detection
- ...

- CMB (anistropies/distorsions/...)
- 21-cm line at high redshift
- Lyman-$\alpha$ forest
- Gravitational lensing
- ...




* Figures from Snowmass2021 Theory Frontier White Paper, ArXiv:2203.06380

## Last Slide

# The end

Thank you for your attention