

# FUNDAMENTAL PHYSICS WITH GRAVITATIONAL WAVES

Winter School on Cosmology

Passo del Tonale

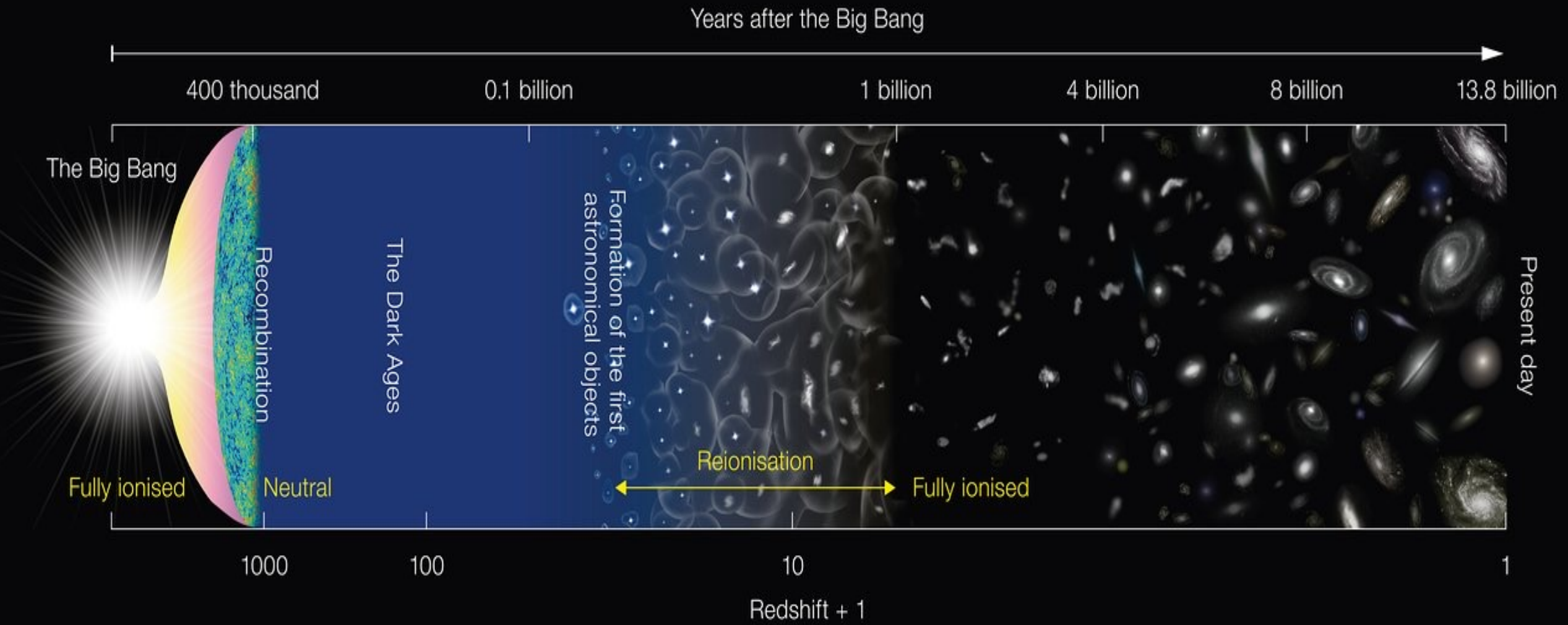
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# Outline

- Gravitational waves as probes of Fund. Physics
- Use GW as a messenger, a window into the origin and evolution of the Universe
- Information is carried & retrieved in their Generation, Propagation and Detection



# Basic Concepts

- Gravity much weaker than the other fundamental forces

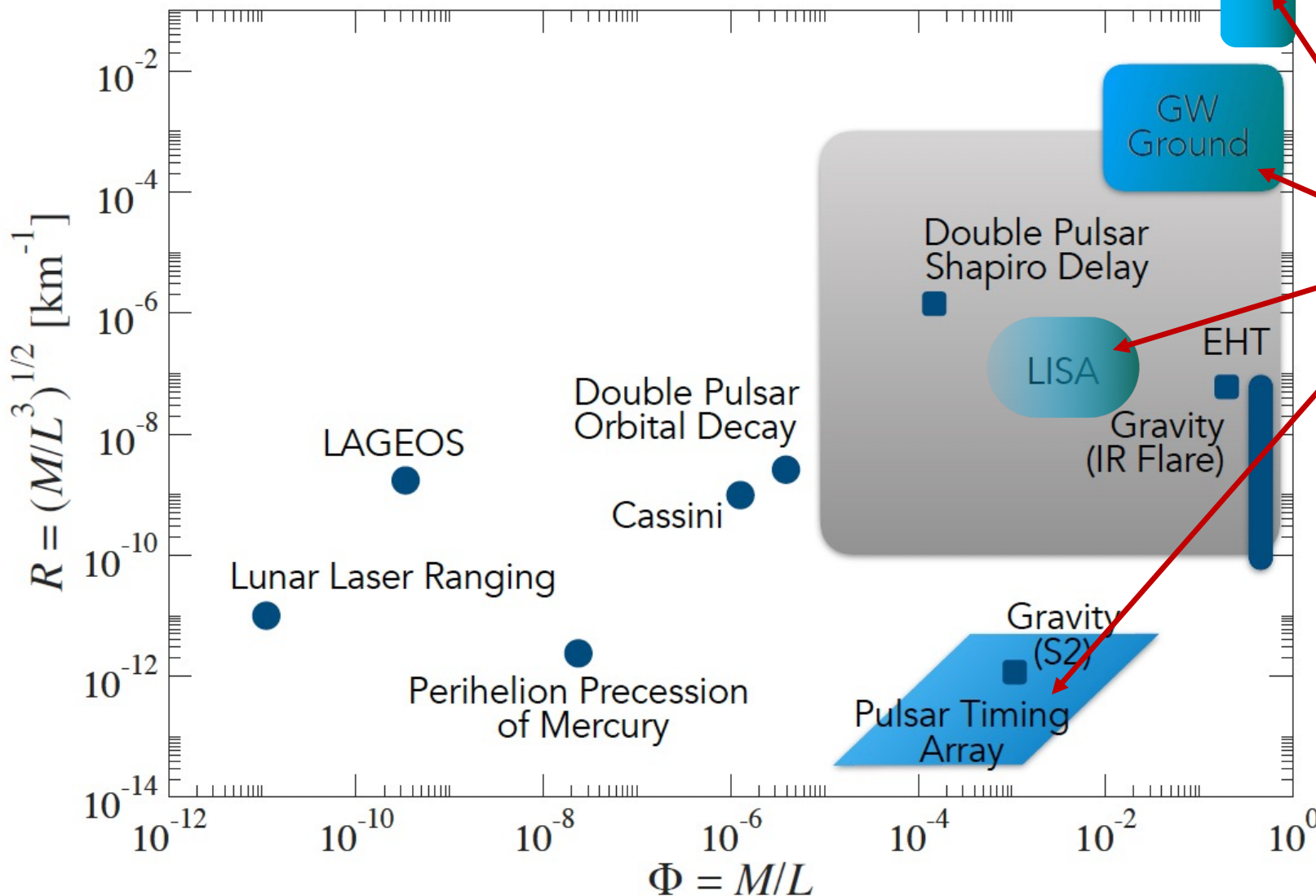
$$\alpha_s = \frac{g^2}{4\pi\hbar c} \simeq 0.1, \quad \alpha_{em} = \frac{e^2}{4\pi\hbar c} = \frac{1}{137},$$

$$\alpha_w = \frac{G_F m_p^2}{\hbar c} \simeq 10^{-11}, \quad \alpha_G = \frac{G_N m_p^2}{\hbar c} \simeq 10^{-38}$$

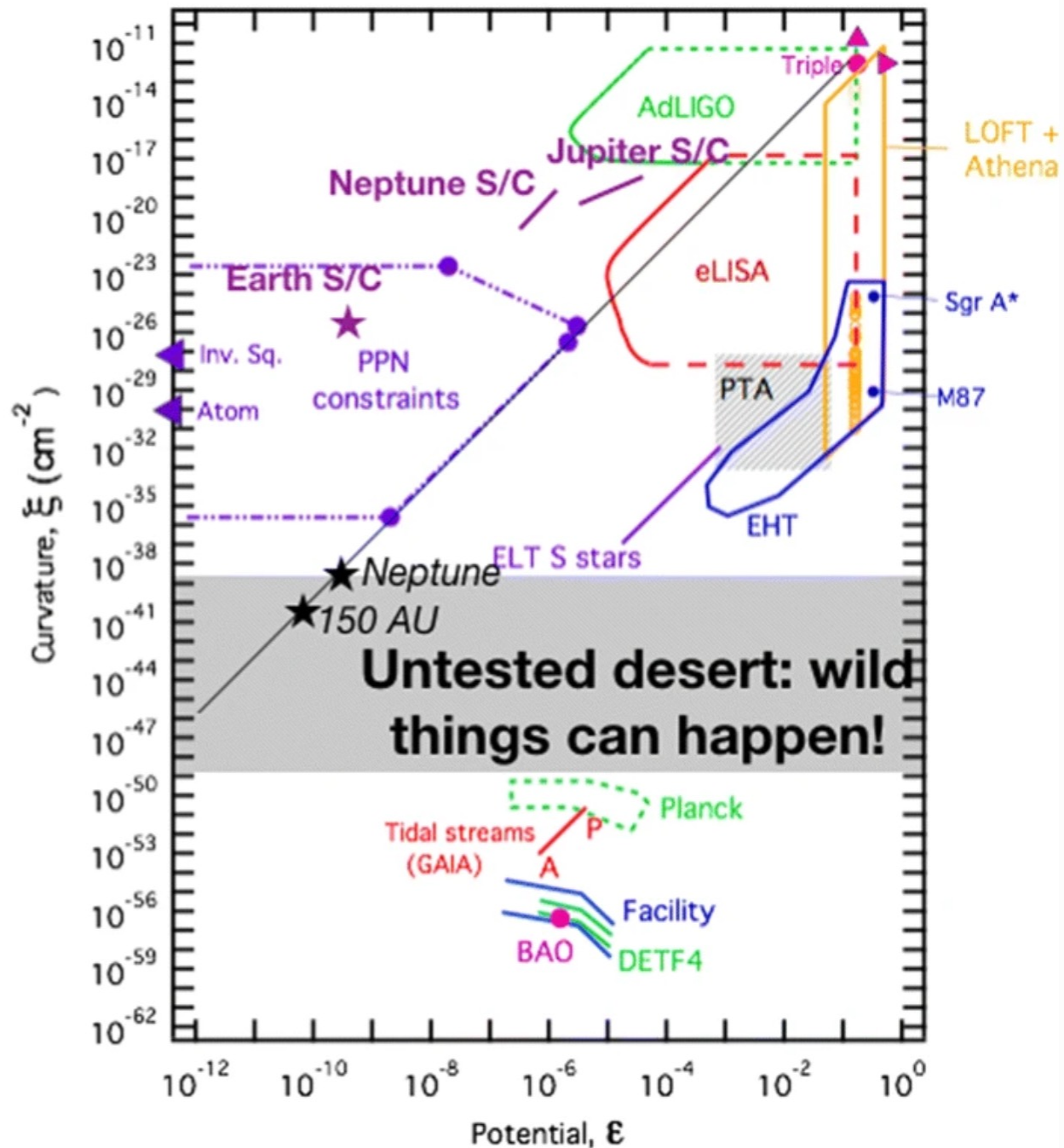
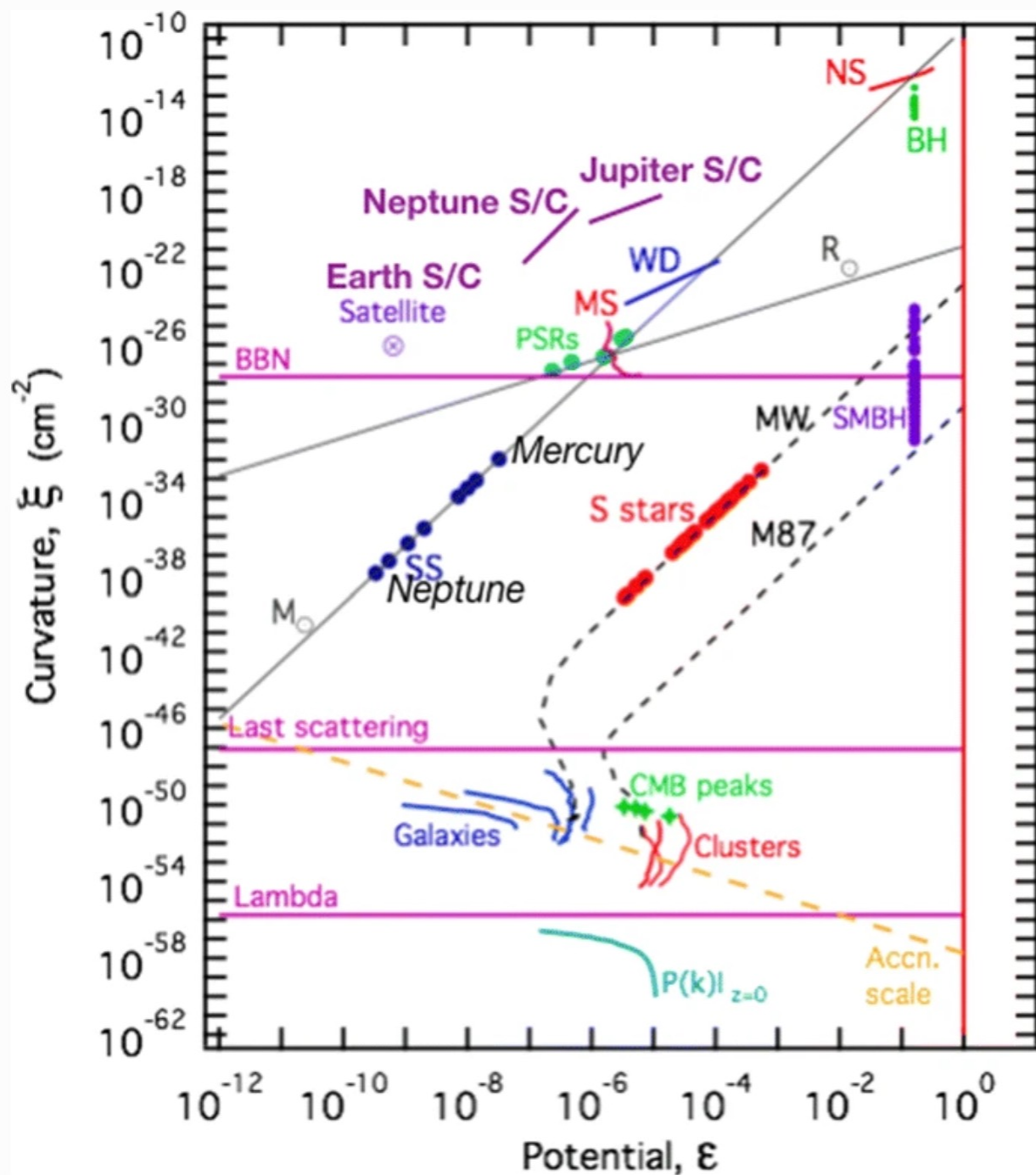


# Probing Gravity at all scales

Spacetime curvature



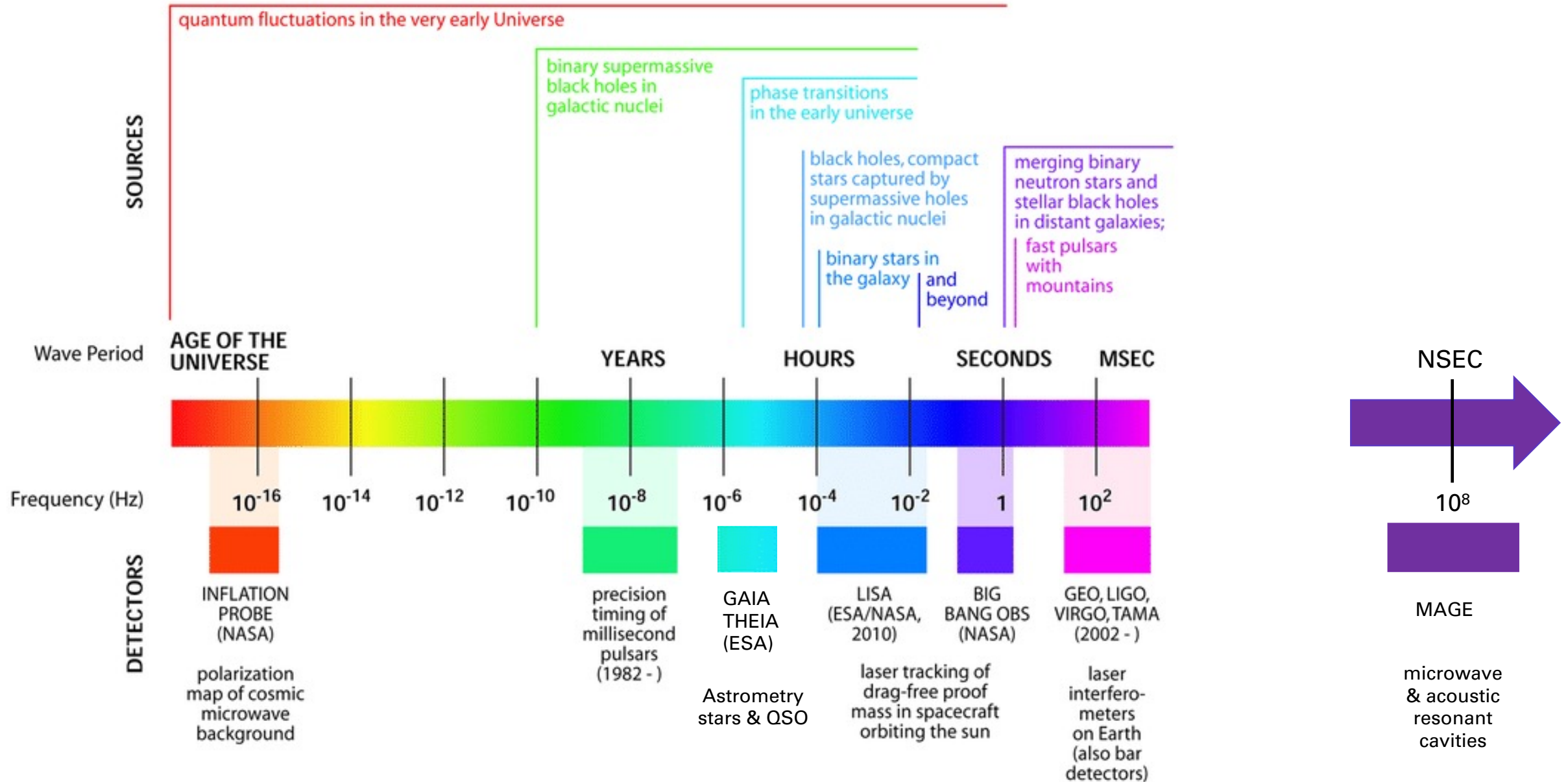
Potential energy



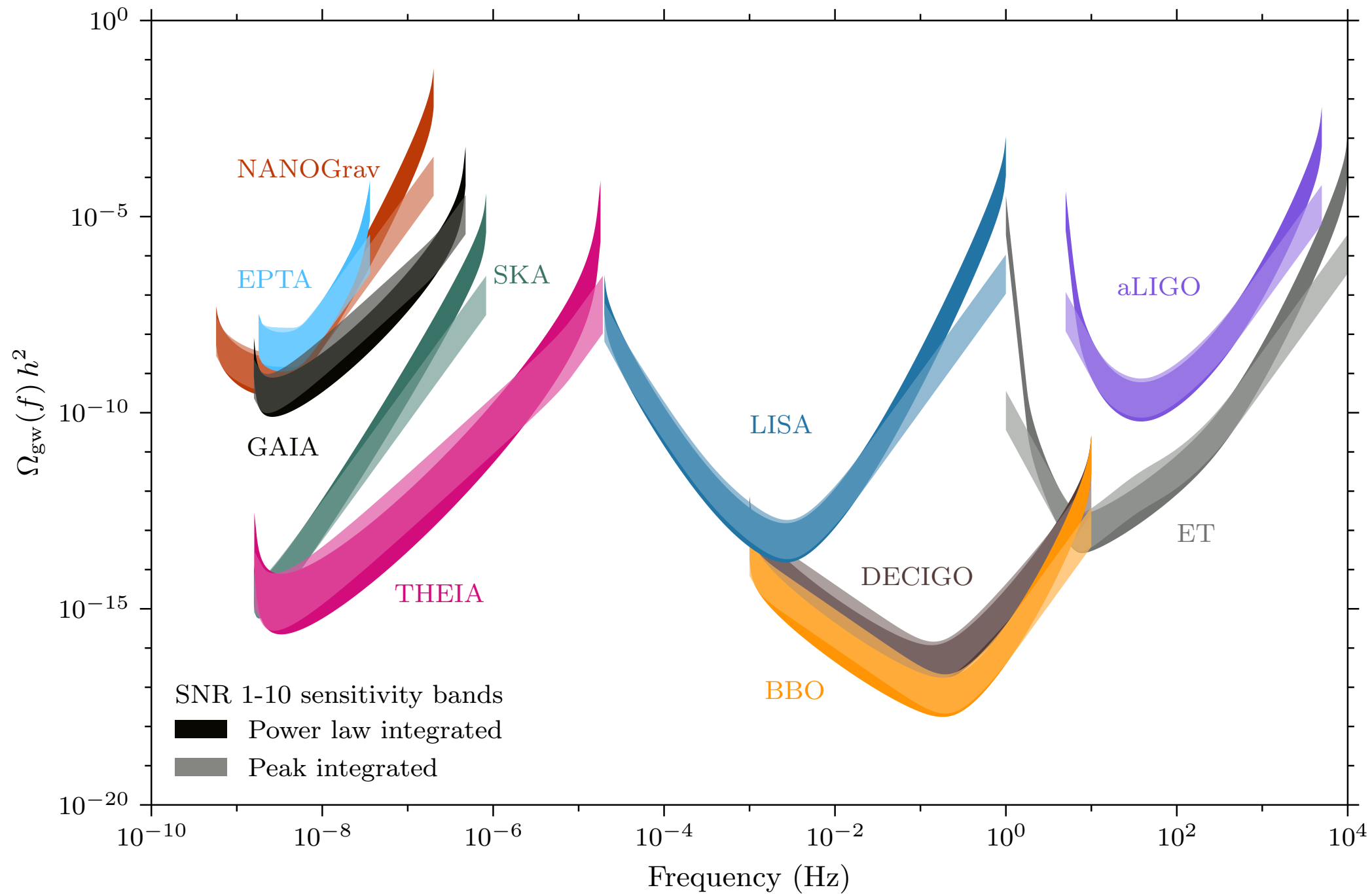
# Basic Concepts

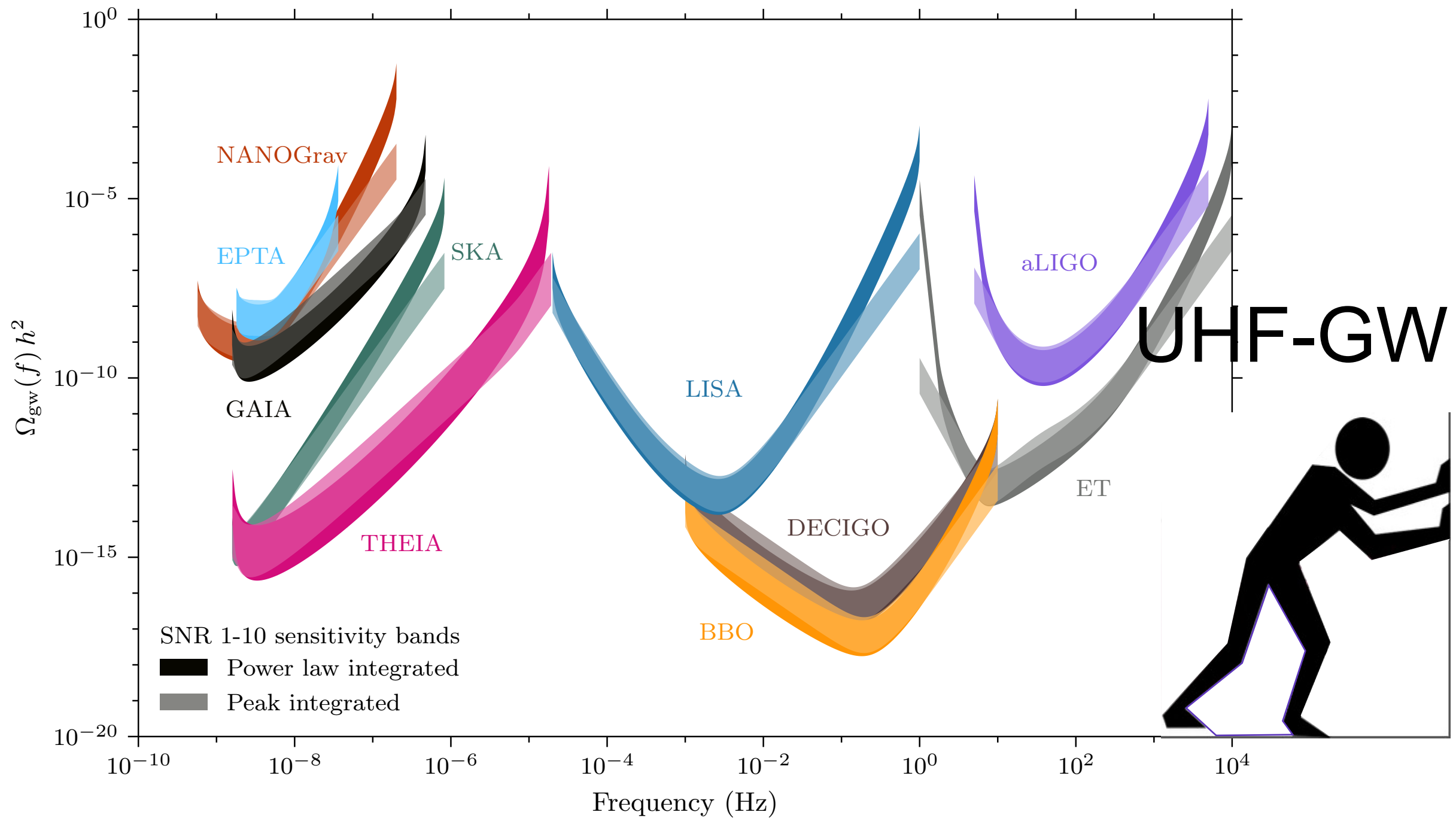
- Broad-band spectrum of GW  
From CMB ( $10^{-18}$  Hz) to crystals (100 GHz)
- Can explore deeper and earlier than any carrier

# THE GRAVITATIONAL WAVE SPECTRUM







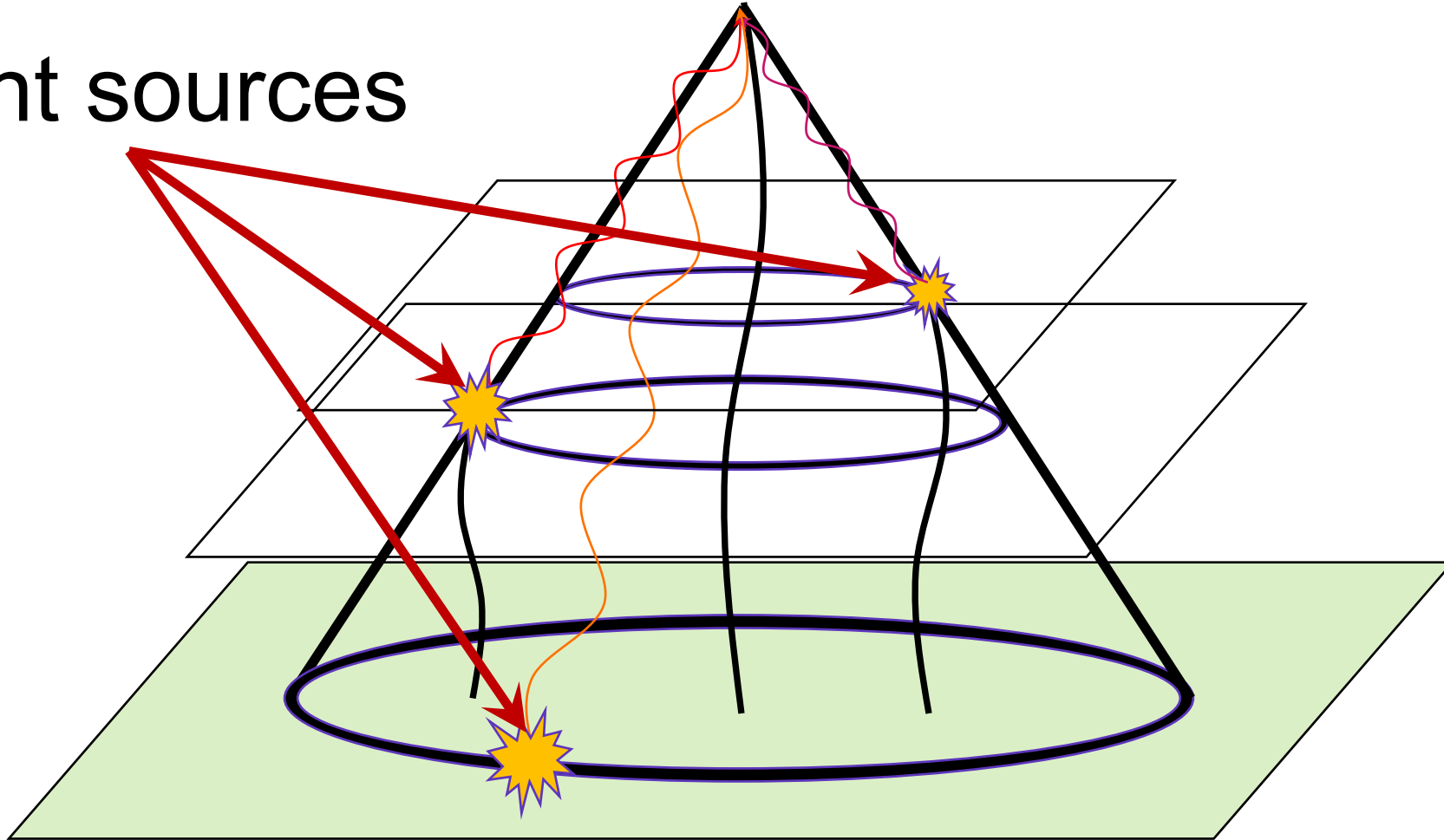


# Basic Concepts

- Causal origin of sources (lightcones)  
(We cannot generate them appreciably on Earth)
- Point sources & Stochastic GW backgrounds

# Past lightcone

Point sources

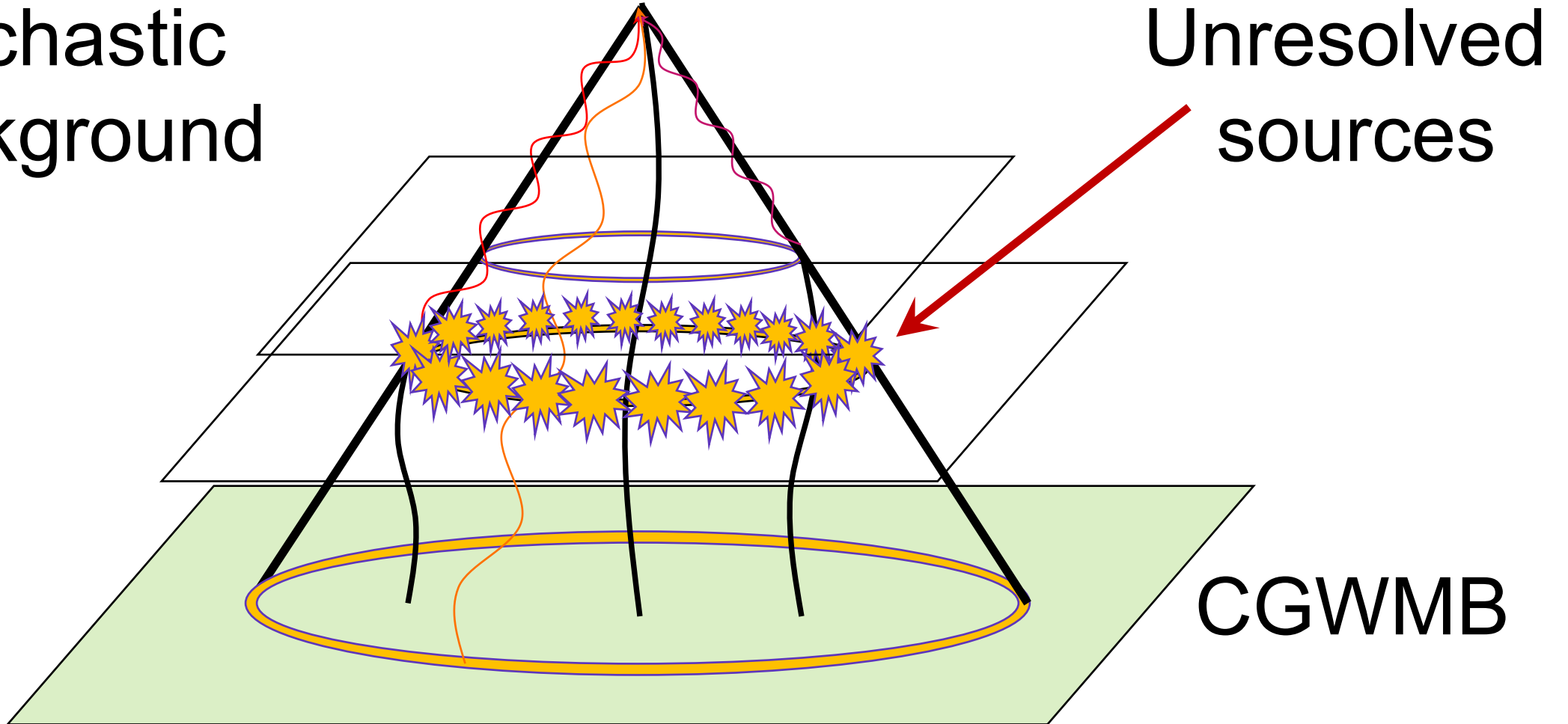




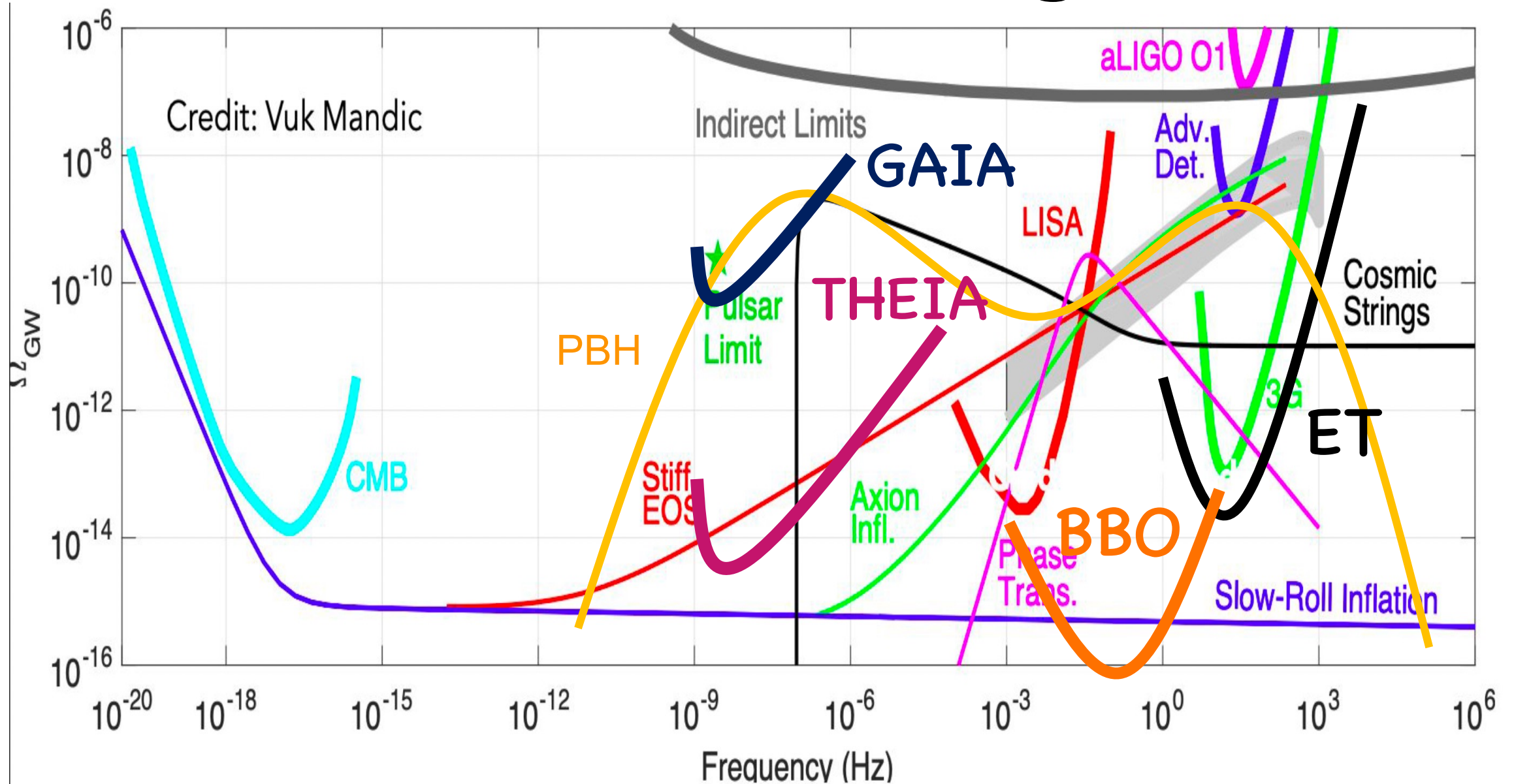
# Past lightcone

Stochastic  
Background

Unresolved  
sources



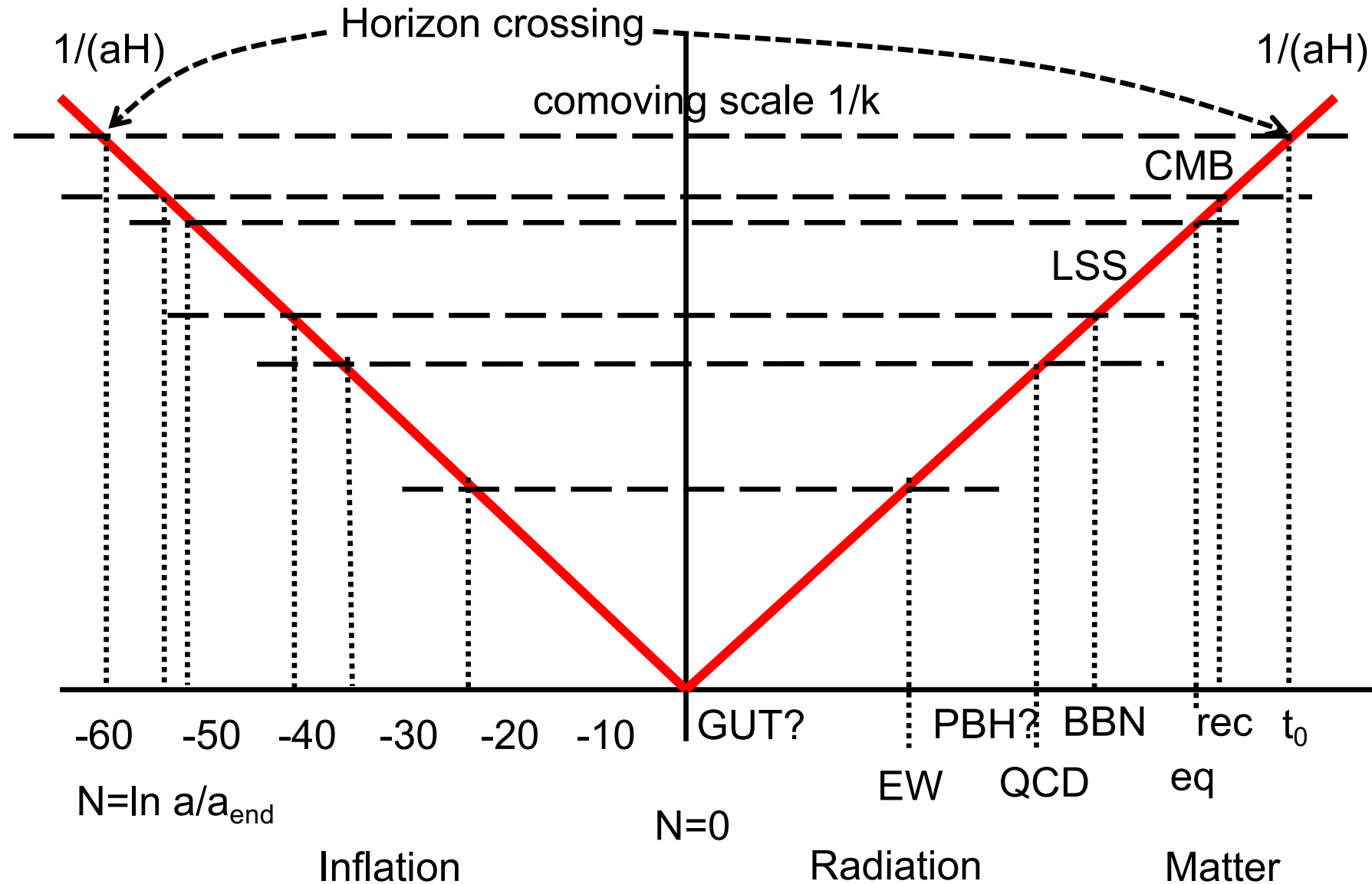
# Stochastic GW Background



# Basic Concepts

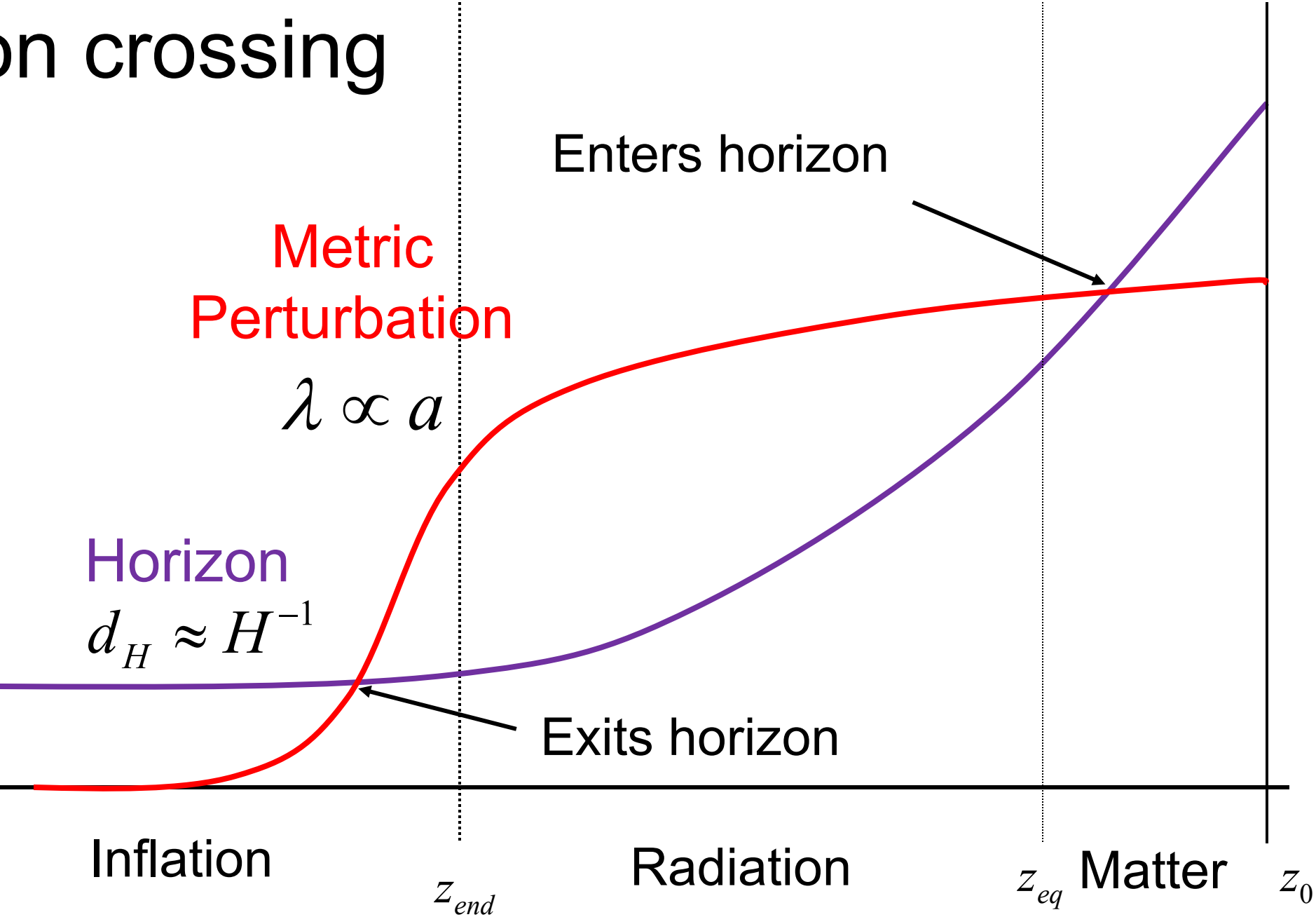
- Causal structure of spacetime  
(origin of scales within inflation)
- Point sources & Stochastic GW backgrounds

# Physical scales

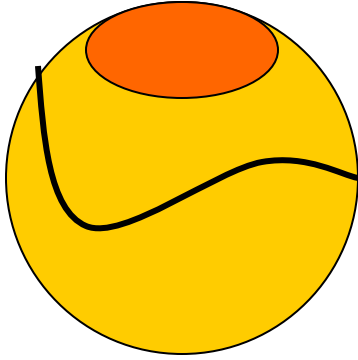




# Horizon crossing

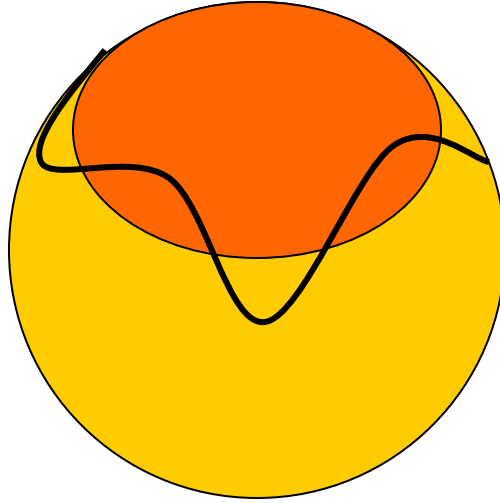


# After Inflation



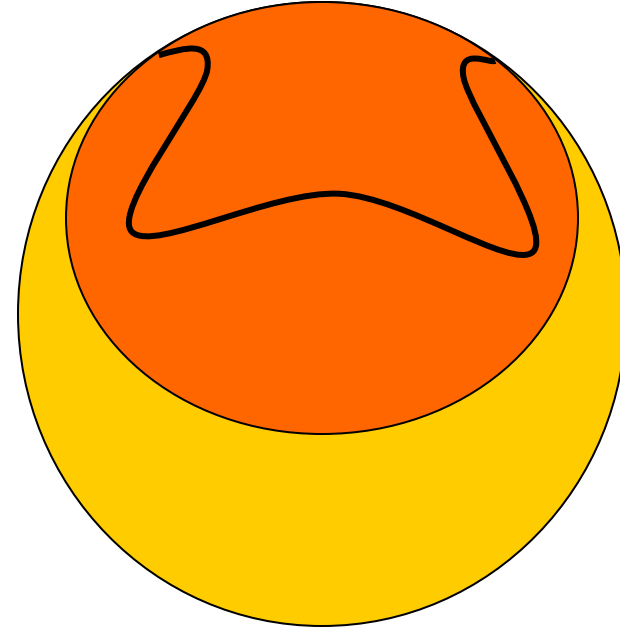
$$\lambda > d_H$$

Outside  
Horizon



$$\lambda \approx d_H$$

Enters the  
Horizon



$$\lambda < d_H$$

Inside  
Horizon

# Basic Concepts

- Generation
- Propagation
- Detection

# Generation GW

## Generation of GW in the Early Universe

- Inflation (Vacuum - QM)
- Preheating after inflation (Resonant - QM)
- Phase transitions (turbulence - classical)
- Cosmic strings and other (non-)topological defects
- Second order scalar perturbations at reentry
- Gravitational collapse of inhomogeneities (classical)
- Thermal plasma from rel. particle momenta (QFT)
- BBN bound (rate of expansion)



# Generation GW

## Generation of GW in the Late Universe

- Generic violent astrophysical phenomena
- Asymmetric Supernova explosions
- Black Hole scattering and collisions (mergers)
- Neutron star collisions (Kilonovas)
- Pulsars
- EMRIs
- Formation and accretion of SMBH of  $10^9 M_{\odot}$

# Propagation GW

## Propagation of GW

- Early Universe

Depends on matter content (EOS  $w = 1, 1/3, 0$ )

- Late Universe

Extra fields, e.g. Horndeski or massive gravity  
(introduced to account for DE)

Weak, Strong and Microlensing of GW

# Detection GW

## Detection of GW

- CMB polarization anisotropies ( $10^{-18}$  Hz). - indirect
- Pulsar timing array (nHz) "
- Astrometry (uHz) "
- Time delay interferometers (mHz). - direct
- Laser Interferometers (kHz) "
- Crystals, microwave cavities (MHz) "
- BEC, atomic interferometry (GHz) "

# Basic Concepts

- Need a mathematical formalism based on GR
- Derive rigorously (gauge choices) GW equations in multiple contexts (Mink. / FLRW / Schw.)
- Origin, propagation and detection opens a door into fundamental physics (GR, QM, TD)



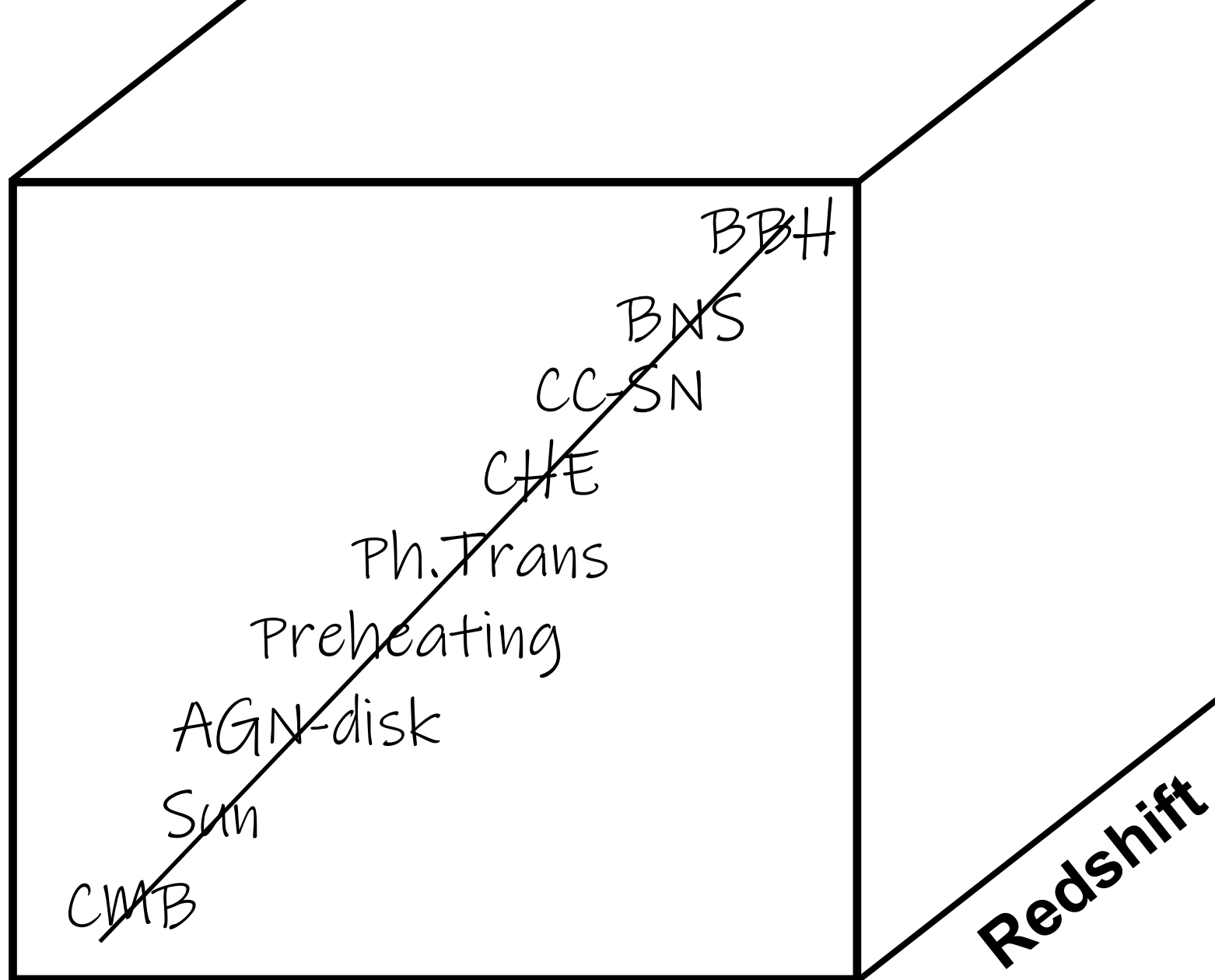
# Formalism

- Linear perturbation of Einstein Eqs.
- Expansion around arbitrary background ( $M$ , FRW)
- Wave equation – quadrupolar formula – energy loss
- Production during inflation (Bogoliubov transf.)
- Production during preheating (QM resonant)
- Second order scalar pert. as source upon reentry
- Non-topological defects as source upon reentry

# Formalism

- Phase transitions + cosmic defects (loops & cusps)
- Thermal plasma stirring (SGWB)
- Pulsar emission as standard clock
- BBH (inspiral + merger + ringdown)
- Primordial vs Astrophysical BH (source confusion?)
- Standard and Dark Sirens (Cosmology)
- Freefall and detectors (gauge coord dependence)
- Gravitational memory effect (linear & non-linear)

**Energy Released**



**Intensity (Flux)**

**Redshift**

# Basic Concepts

- Sources of Information
- Photons versus Gravitons

# Sources of information

- Scientific method is similar to that of Cosmology, and different from particle physics
- Make hypothesis & contrast with observations
- Cannot make GW experiment (e.g. Hertz in EM)
- Multimessengers (e.g. NS, SNe, accretion disks)

# Sources of information

- We measure on Earth (orbit), far from the source
- Inference depends on environment (like Aristotle)
- Astrophysics complicates our inference
- How to calibrate detectors? (e.g. binary pulsar)
- Can we reach precision physics with GW?  
(e.g. masses and spins of BH)



# Example: BNS = Kilonova

- Stiffness of NS under deformations/accelerations
- Equation of state of nuclear matter
- Multilayer structure of inner neutron star
- Velocity propagation of GW =  $c$  (light)
- Rate of expansion of the Universe ( $H_0$ )
- Rates of r-processes nuclear matter high energy
- Abundance rare elements of periodic table
- Matter-energy content of Universe from source

# Example: Detection methods

- CMB polarization (B modes)
- Astrometry (coherent motion stars in sky)
- Time arrival radio pulses from PSR (PTA)
- Time arrival laser pulses satellites (LISA)
- Laser interferometry (LIGO-Virgo-KAGRA)
- Atomic interferometry
- Resonant bar detectors (crystals) + EM cavities
- BEC suspended inside Fabri-Perot interferometer

# Example: GW as tests of GR

- Speed propagation (GW170817)
- Energy loss system (PSR1913+16)
- Structure ST around Kerr BH (EMRI)
- Exotic compact objects (Boson stars)
- Superradiance
- ST inside BH = wormhole?
- Nature of DM (PBH)
- Horndeski/massive gravity in propagation GW

# Photons versus gravitons

## Generation

- EM waves from accelerated charges only –  
photon is neutral
- GW from accelerated asymmetric masses –  
GW also carry energy, thus non-linear

# Photons versus gravitons

## Propagation

- SZE:  $\gamma$  interacts with  $e^-$  in clusters
- GKZ:  $p^+$  interacts with  $\gamma$  in IGM
- ISW:  $\gamma$  interacts with  $\Phi$  in voids
- Gravitational lensing of both  $\gamma$  and GW
- Redshifting and Shapiro time delay of both
- GW mix with grav. d.o.f. in Horndeski
- Event Horizon Telescope and EMRIs

# Photons versus gravitons

## Detection

- At same energy,  $\gamma$  interacts with matter much more strongly than GW
- Need huge energies and luminosities GW
- GW low frequency act as background for matter
- Angular resolution point sources (marcsec, deg)
- SGWB of unresolved sources

















