WISHEPP

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3rd Winter School in HEP

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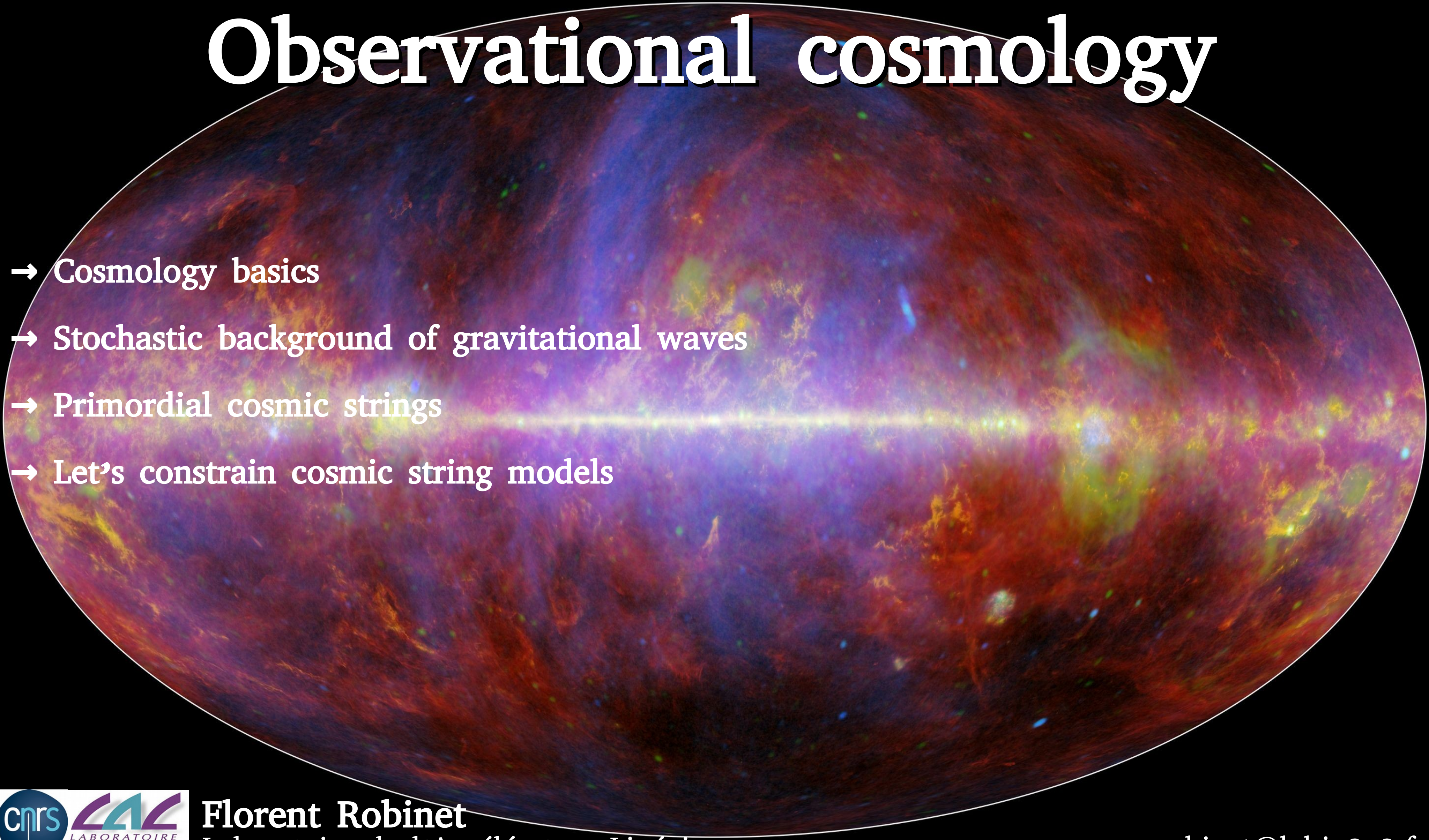
Bruno Mazoyer LAL 2018

Observational cosmology



- → Cosmology basics
- → Stochastic background of gravitational waves
- → Primordial cosmic strings
- → Let's constrain cosmic string models

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Cosmology in a nutshell

→ Cosmological principle:
at large scales (>10 Mpc) the universe is isotropic and homogeneous

→ Distances are measured by integrating the distance element: $ds^2 = g_{\mu\nu} dx^{\mu} dx^{\nu}$

→ Friedmann-Lemaitre-Robertson-Walker metric in spherical coordinates:

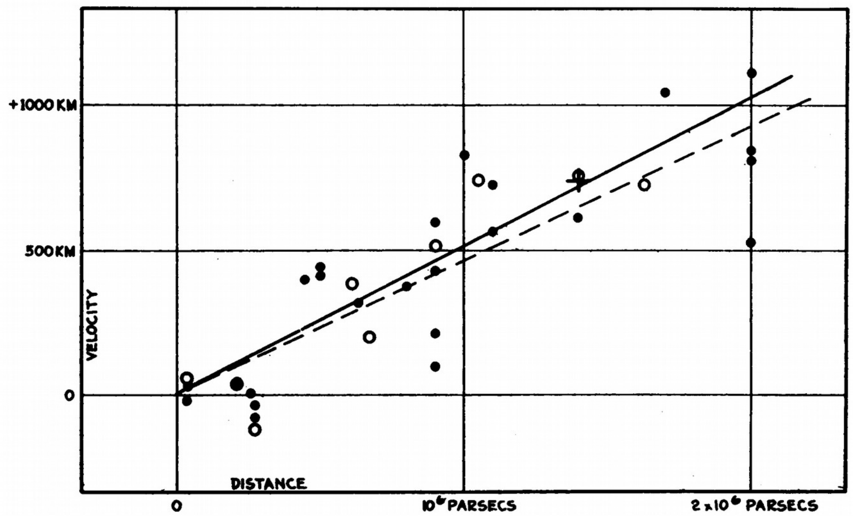
$$ds^2 = dt^2 - a(t)\left[\frac{dr^2}{1-kr^2} + r^2 \sin(\theta) d\theta + d\phi^2\right]$$

$a(t)$= scaling factor (intergalactic distances), normalized such that $a(0)=1$

k = curvature (-1, 0, 1)

→ FLRW metric in Einstein's equation: $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$

→ $H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{a^2}$

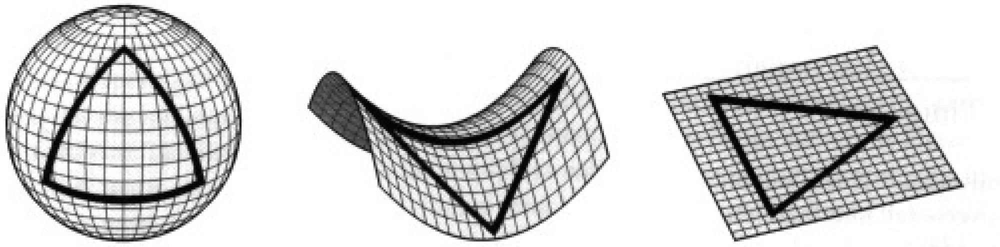


Densities

Critical density: $\rho_c = \frac{3H_0}{8\pi G}$

- → matter $\Omega_{mat} = \frac{\rho_{mat}}{\rho_c}$
- → radiation $\Omega_{rad} = \frac{\rho_{rad}}{\rho_c}$
- → cosmological constant $\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c}$
- → total $\Omega_{tot} = \frac{\rho_{tot}}{\rho_c}$

$\Omega_{tot} > 1$ $\Omega_{tot} < 1$ $\Omega_{tot} = 1$



Positive Curvature Negative Curvature Flat Curvature

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{a^2}$$

↓ Today

$$\Omega_{tot} = 1 + \frac{k}{H_0^2} = \Omega_{mat} + \Omega_{rad} + \Omega_\Lambda$$

State equation

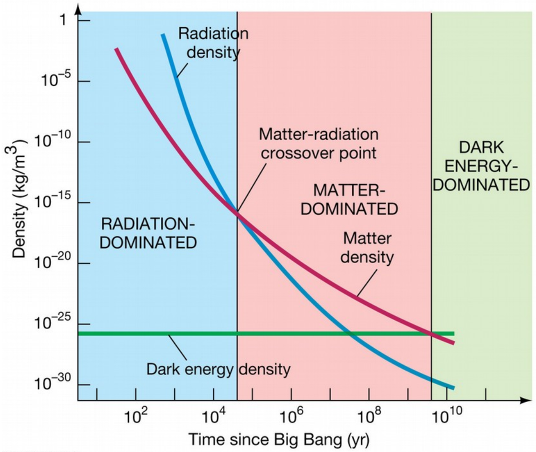
Local conservation of energy $\frac{\partial \rho}{\partial t} = -3(\rho + P)\frac{\dot{a}}{a}$

State equation $P = w\rho$ $\frac{\partial \rho}{\partial t} = -3\rho\frac{\dot{a}}{a}(1+w)$ $\rho = \rho_0 a^{-3(1+w)}$

→ matter $w \approx 0$ $\rho = \rho_0 a^{-3}$

→ radiation $w = 1/3$ $\rho = \rho_0 a^{-4}$

→ cosmological constant $w = -1$ $\rho = \rho_0$



$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{a^2}$$

$$H^2(t) = H_0^2\left[\Omega_{mat} a^{-3} + \Omega_{rad} a^{-4} + \Omega_\Lambda\right]$$

$\Omega_{mat} = 0.308$ $\Omega_{rad} = 9.1 \times 10^{-5}$ $\Omega_\Lambda = 0.692$ $H_0 = 67.8\, km/s/Mpc$

redshift

A photon is emitted at time t with $\lambda=\lambda_e$

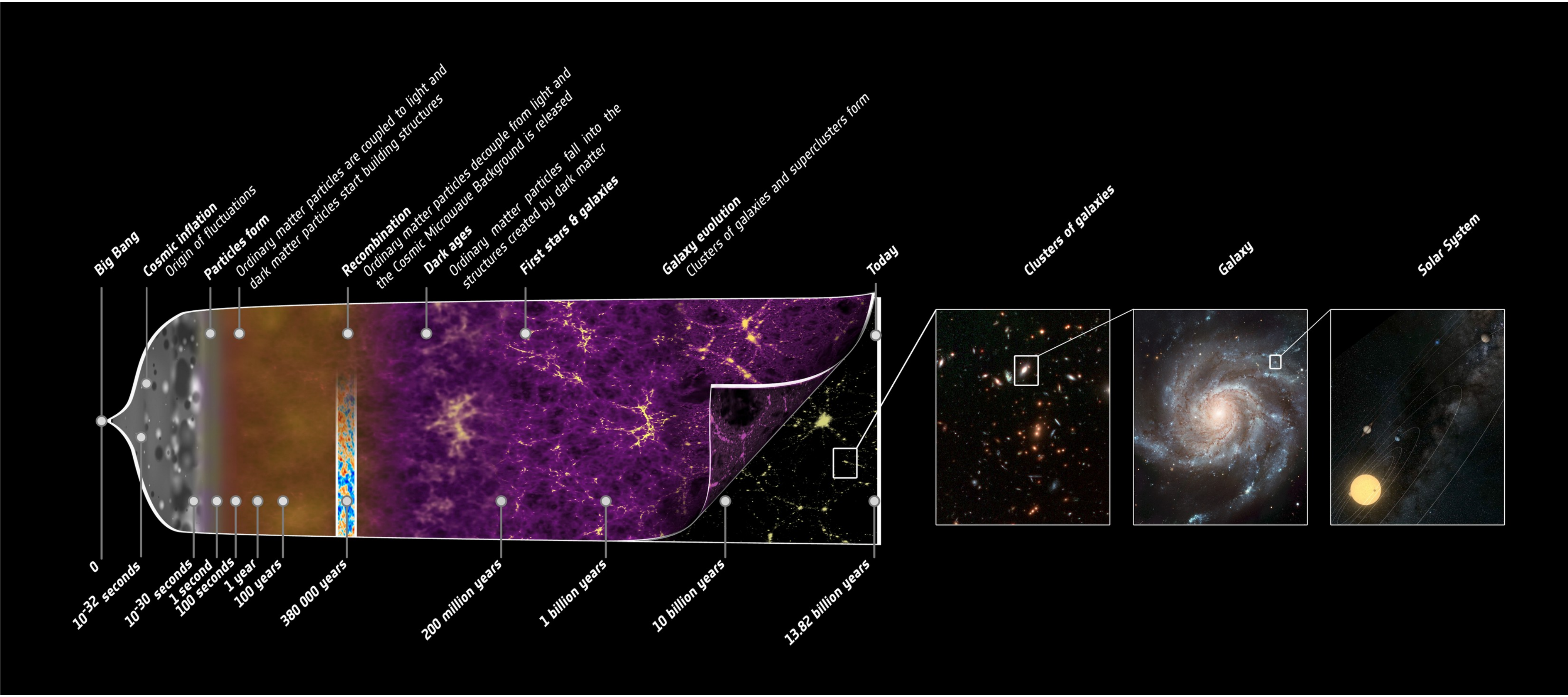
The photon is detected today with $\lambda=\lambda_d$

$$1+z=\frac{\lambda_d}{\lambda_e}=\frac{a(0)}{a(t)}=\frac{1}{a(t)}$$

$$H^2(t)=H_0^2\left[\Omega_{mat}\,z^3+\Omega_{rad}\,z^4+\Omega_\Lambda\right]$$

Lambda-CDM cosmology → standard model for cosmology

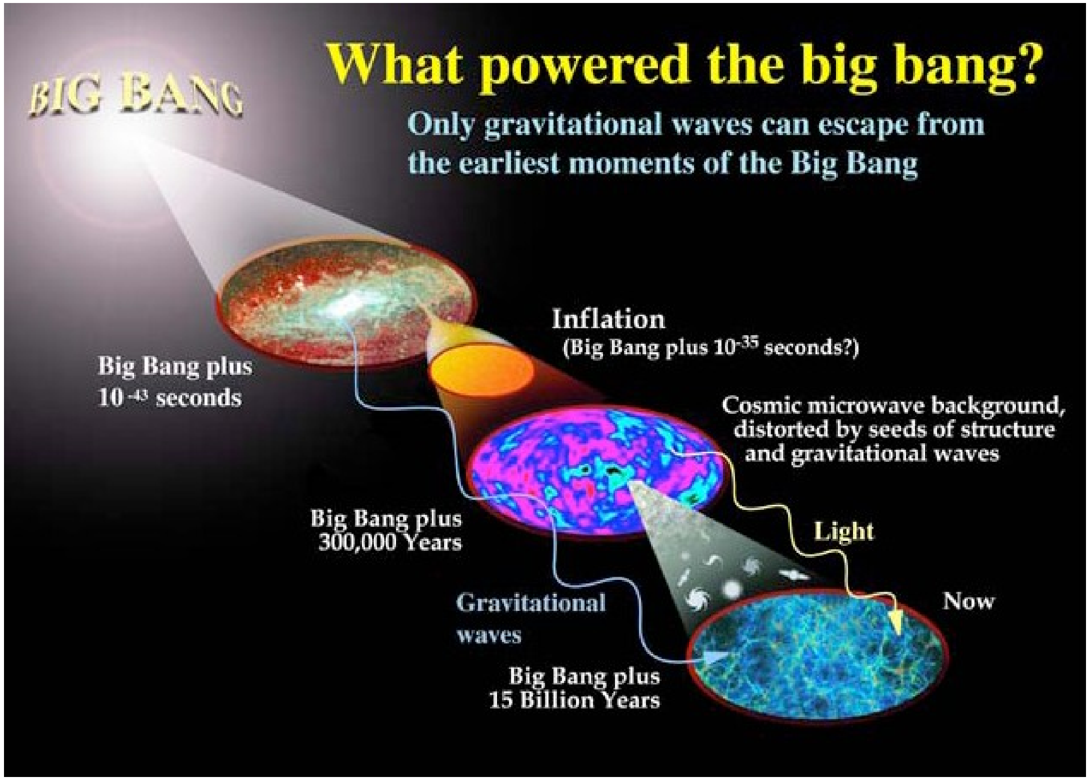
History of the universe



Inflation	$z > 10^{25}$	
Nucleosynthesis	$z \sim 3 \times 10^{8}$	
CMB	$z \sim 1100$	
Dark ages	$20 < z < 1100$	Cosmology
Stars and galaxies formation	$z < 20$	Astrophysics

GW stochastic background

- Incoherent superposition of many unresolved sources.
- Cosmological:
  - Inflationary epoch, preheating, reheating
  - Phase transitions
  - Cosmic strings
  - Alternative cosmologies
- Astrophysical:
  - Supernovae
  - Magnetars
  - Binary black holes
- Potentially could probe physics of the very-early Universe.



$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

GW stochastic background

Assumption : stationary, unpolarized, and Gaussian stochastic background

→ Cross correlate the output of detector pairs to eliminate the noise

$$h_i = n_i + \color{red}{GW_i}$$

$$\langle h_1, h_2 \rangle = \langle GW_1, GW_2 \rangle + \underbrace{\langle n_1, GW_2 \rangle}_{0} + \underbrace{\langle GW_1, n_2 \rangle}_{0} + \underbrace{\langle n_1, n_2 \rangle}_{0}$$

With $\langle x_1, x_2 \rangle = \int_{-\infty}^{+\infty} \tilde{x}_1^*(f)\,\tilde{Q}(f)\,\tilde{x}_2(f)\,df$

Optimal filter:

overlap of antenna pattern

GW spectrum

$\Omega_{GW}(f) = \Omega_\alpha f^\alpha$

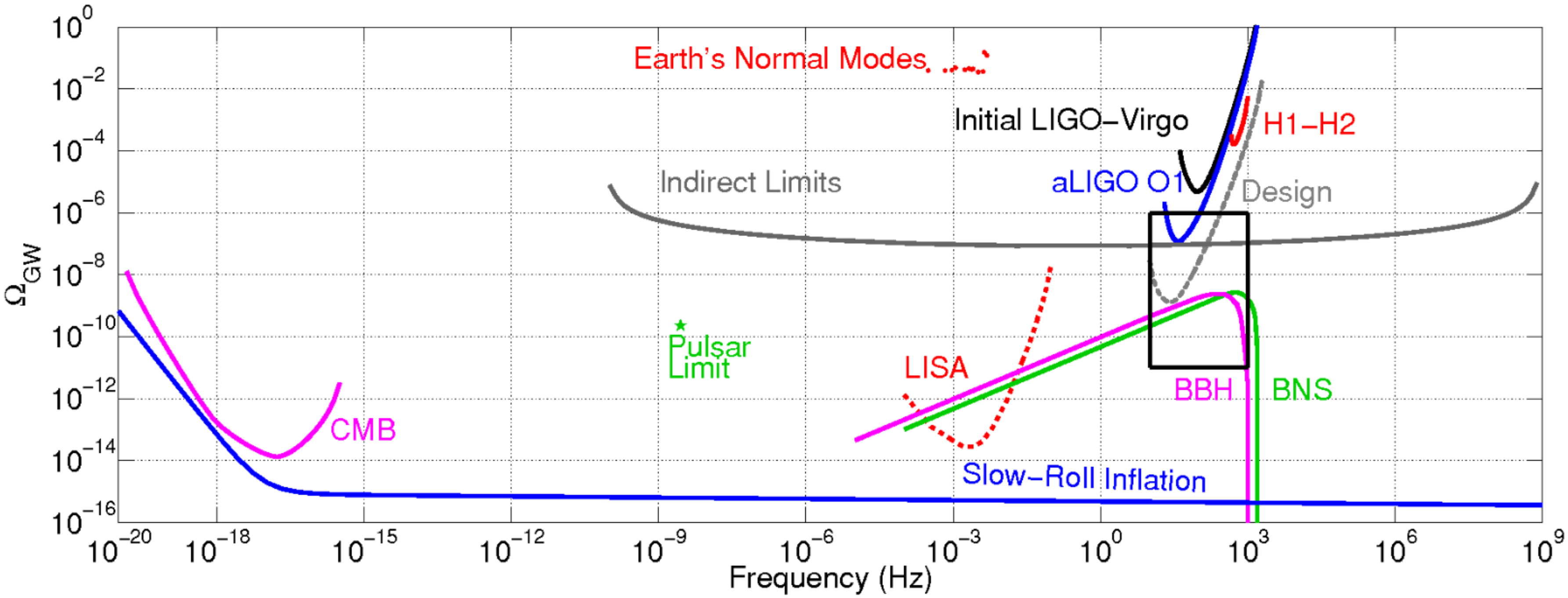
$$\tilde{Q}(f) \propto \frac{\gamma(f)\,\Omega_{GW}(f)}{f^3 S_{n,1}(f)\,S_{n,2}(f)}$$

Detector PSDs

O1 isotropic search, for $\alpha = 0$: $\Omega_{GW}(25\,Hz) < 1.7 \times 10^{-7}$

PRL.118.121101 (2017)

GW stochastic background



Use the LIGO upper limit to constrain the parameters of:
- an astrophysical population, e.g. CBC
- an cosmological model, e.g. inflation models

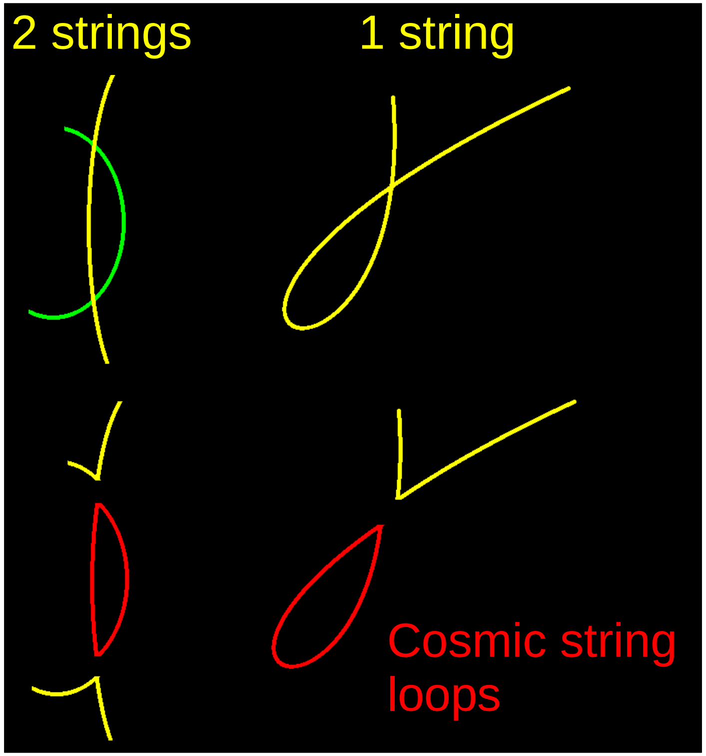
Incoherent superposition of GWs from a population of sources

$$\Omega_{GW}(f)=\frac{4\pi^2}{3H_0^2}f^3\int_0^{h*.}dh\,h^2\int_0^{+\infty}dz\frac{d^2R}{dzdh}(h,z,f)$$

Cosmic strings

Cosmic strings are 1-dimensional topological defects which may have formed in the early universe.

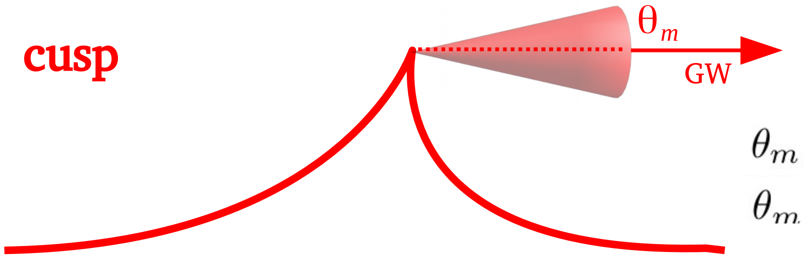
Phase transitions → symmetry breaking → Higgs mechanism → Inflation → topological defects



Loop formation
Loop oscillation → cusps

Models/simulations are used to compute the loop number density:

$$n(l,t)$$



$$d\Omega \sim \pi\theta_m^2$$

$$\theta_m(\ell, z, f) = (g_2 f(1+z)\ell)^{-1/3}$$

$$\theta_m < 1$$

GW waveform:

$$h(\ell, z, f) = A_q(\ell, z) f^{-q}$$

$$A_q(\ell, z) = g_1 \frac{G\mu\ell^{2-q}}{(1+z)^{q-1} r(z)}$$

q = 4/3 for cusps

Cosmic string GW rate

$$\frac{d^2 R}{dV(z)\,dA}(A, z, f)$$

Number density of loops with sizes between l and l+dl: $n(l,t)\,dl$

Period of loop oscillation: $T = l/2$

→ In average we have N cusps produced per loop oscillation

→ number of cusps produced per unit space-time volume
by loops of size in dl at time t?

$$\nu(l,t)\,dl = ?$$

Cosmic string GW rate

$$\frac{d^2 R}{dV(z)\,dA}(A, z, f)$$

Number density of loops with sizes between l and l**+**dl: $n(l,t)\,dl$

Period of loop oscillation: $T = l/2$

→ In average we have N cusps produced per loop oscillation

→ number of cusps produced per unit space-time volume
by loops of size in dl at time t**?**

$$\nu(l,t)\,dl = \frac{2N}{l} n(l,t)\,dl$$

Loop density

$$\Omega_{GW}(f) = \frac{4\pi^2}{3H_0^2} f^3 \int_0^{h^*} dh\ h^2 \int_0^{+\infty} dz \frac{d^2R^M}{dzdh}(h,z,f)$$