Cosmological backgrounds

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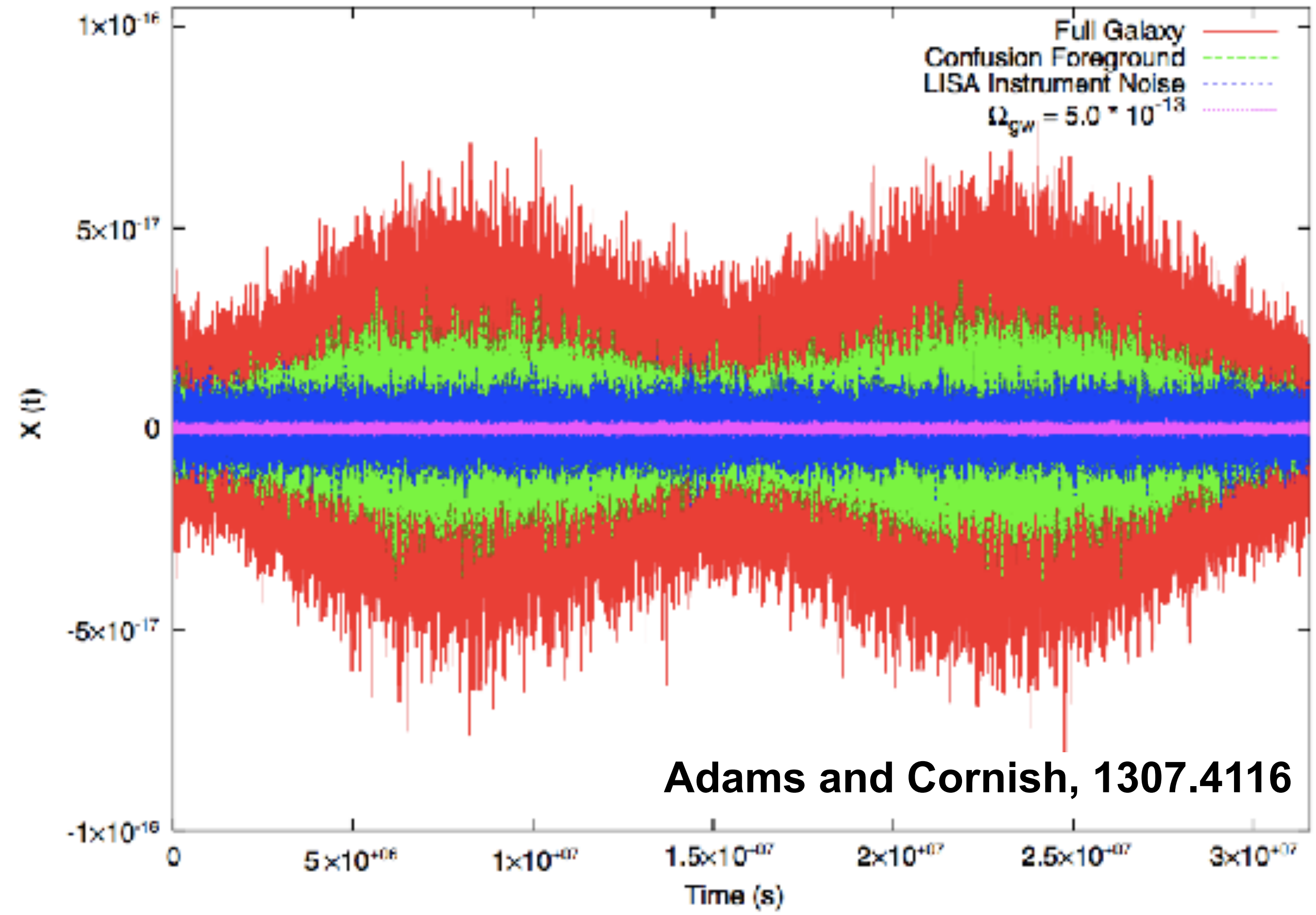
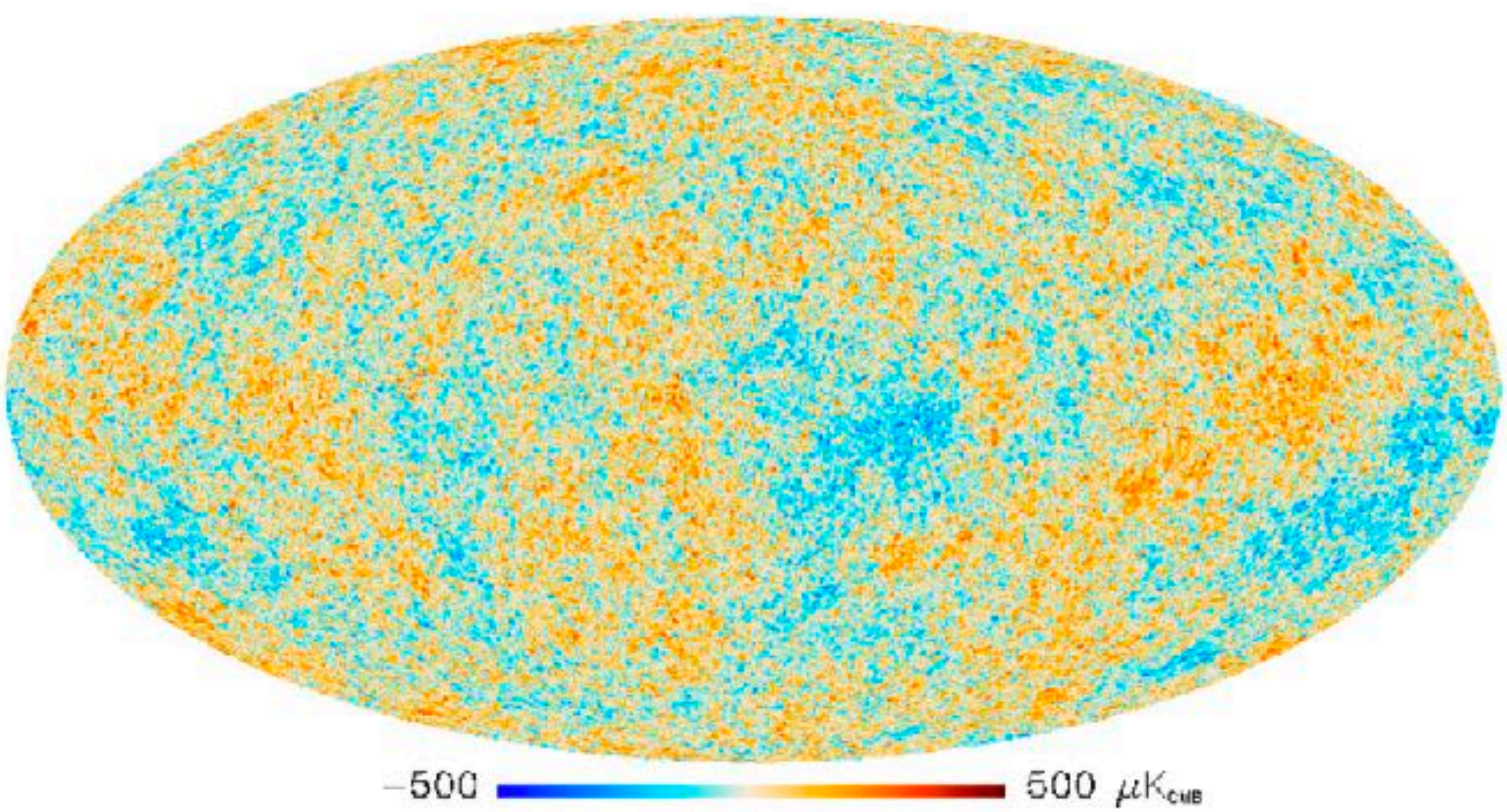




the questions (hopefully) answered by this seminar

- what are cosmological backgrounds? why are they formed?
- what can we use them for? what information do they bring to us?
- in a nutshell, the physics of the Cosmic Microwave Background
- in more detail, the physics of the Stochastic Gravitational Wave Background

the questions that remain open

what are CBs and why are they formed

description of the universe in the context of General Relativity

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu} - \Lambda g_{\mu\nu} \qquad\qquad \nabla_\mu T^{\mu\nu} = 0$$

COSMOLOGICAL PRINCIPLE:
the universe is homogenous and isotopic

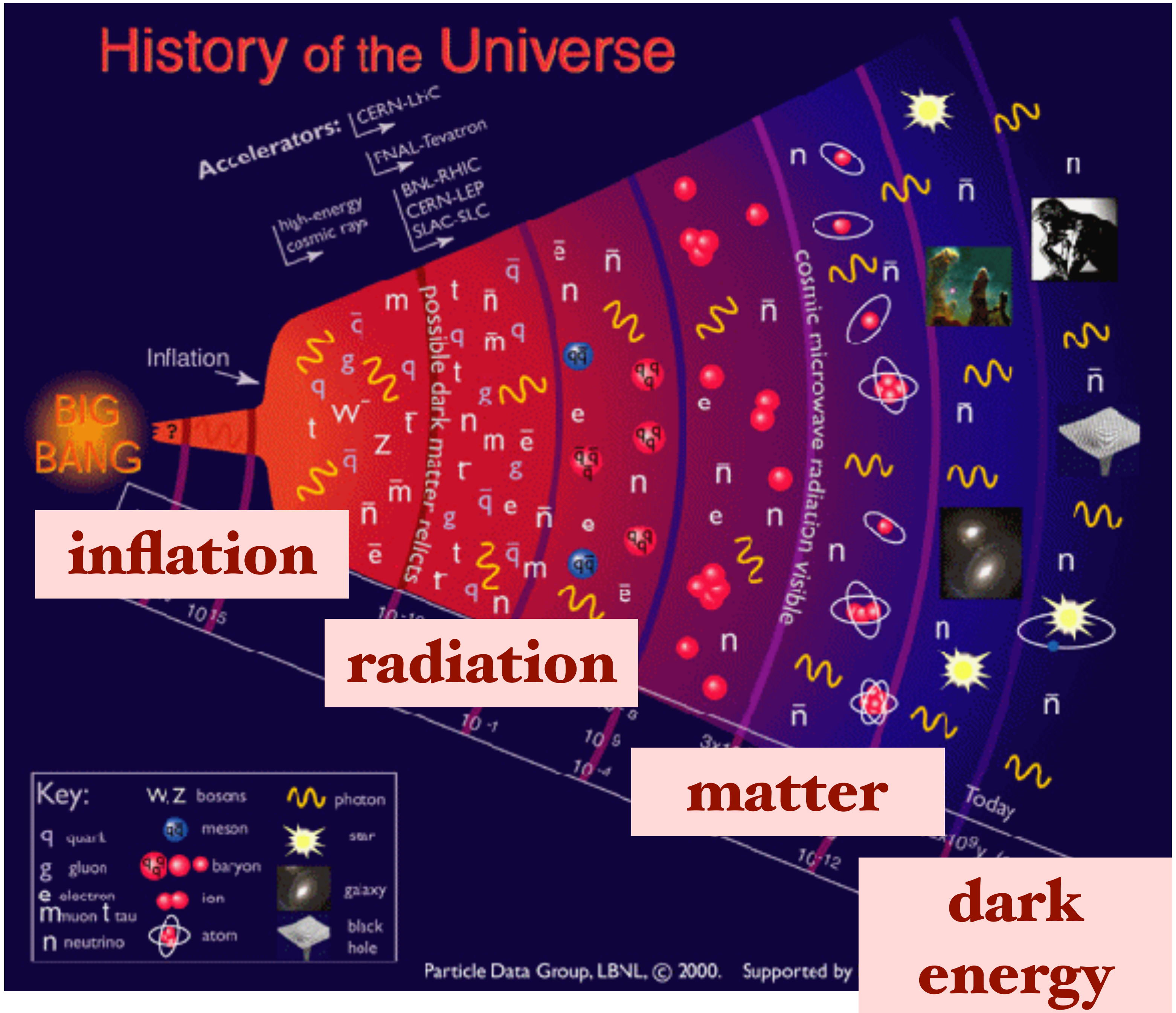
FLRW metric $$ds^2 = a^2(\eta)(-d\eta^2 + \delta_{ij}dx_i dx_j)$$

$$T_{\mu\nu} = (\rho + p)u_\mu u_\nu + p g_{\mu\nu} \qquad\qquad p = w\,\rho$$

linear equation of state

- phase of inflation (scalar field)
- phase of radiation domination
- phase of matter domination
- phase of cosmological constant domination (?)

what are CBs and why are they formed

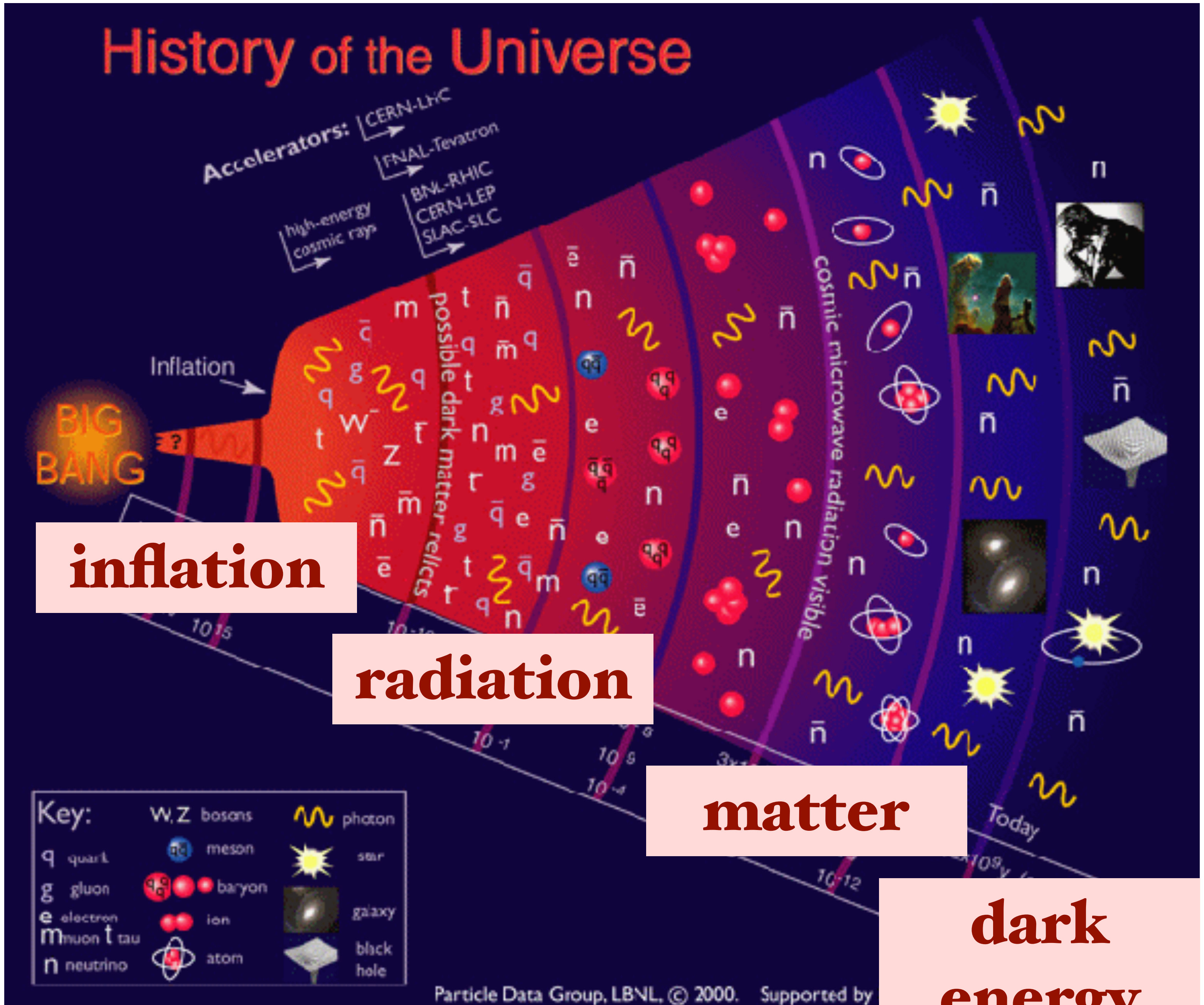


- the universe is in *thermal equilibrium* and undergoes *adiabatic expansion*

time →

← temperature

what are CBs and why are they formed



inflation

radiation

matter

dark energy

- the universe is in *thermal equilibrium* and undergoes *adiabatic expansion*
- as the universe expands particles can get out of thermal equilibrium: *freeze-out*

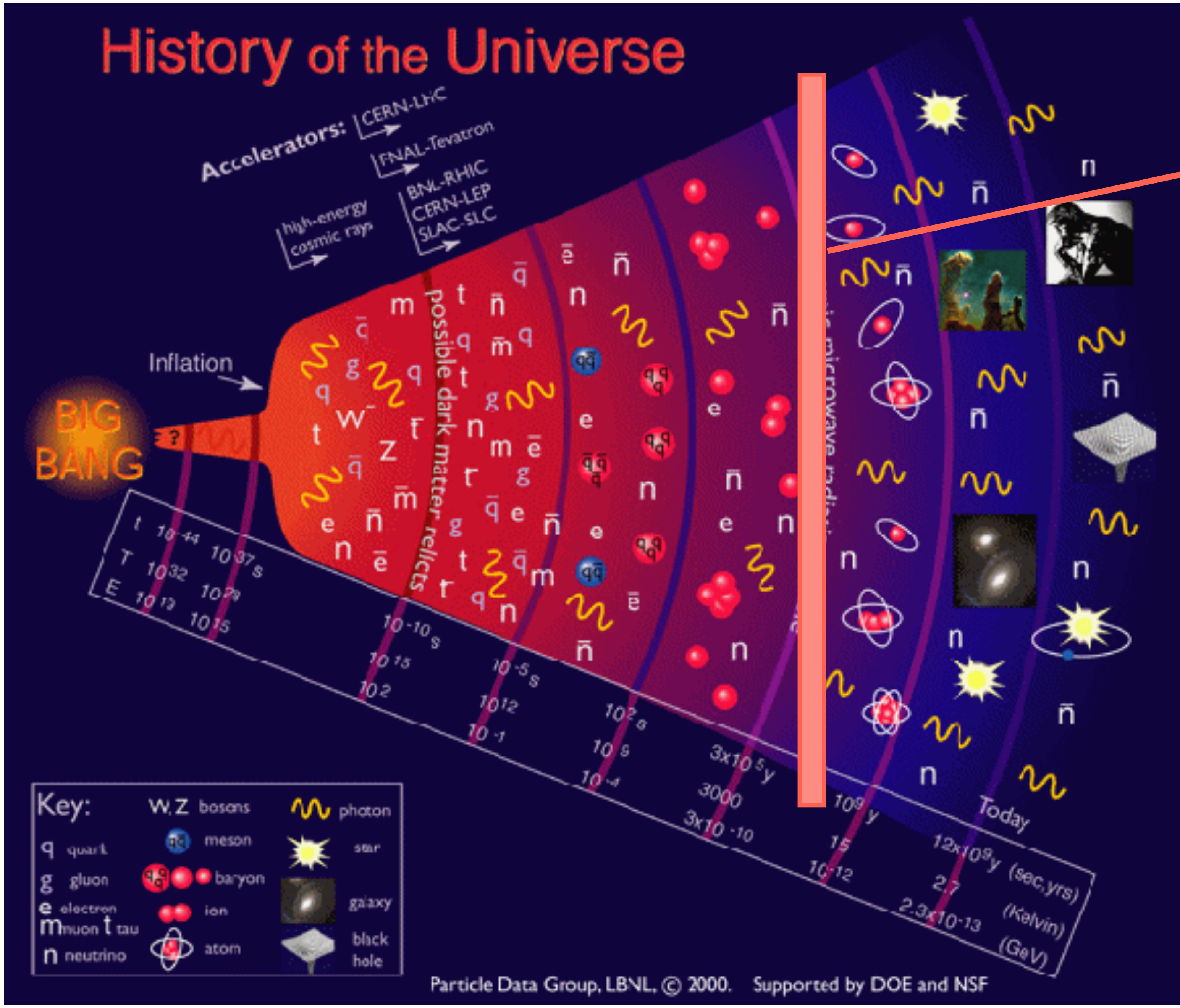
$$\frac{\Gamma(T)}{H(T)} < 1$$

rate of expansion of the universe

rate of the interaction maintaining thermal equilibrium

$$\Gamma = n\,\sigma\,v$$

what are CBs and why are they formed



$$T_{\mathrm{dec}} \simeq 0.25\,\mathrm{eV}$$

freeze-out of

$$e + p \leftrightarrow H + \gamma$$

$$e + \gamma \rightarrow e + \gamma$$

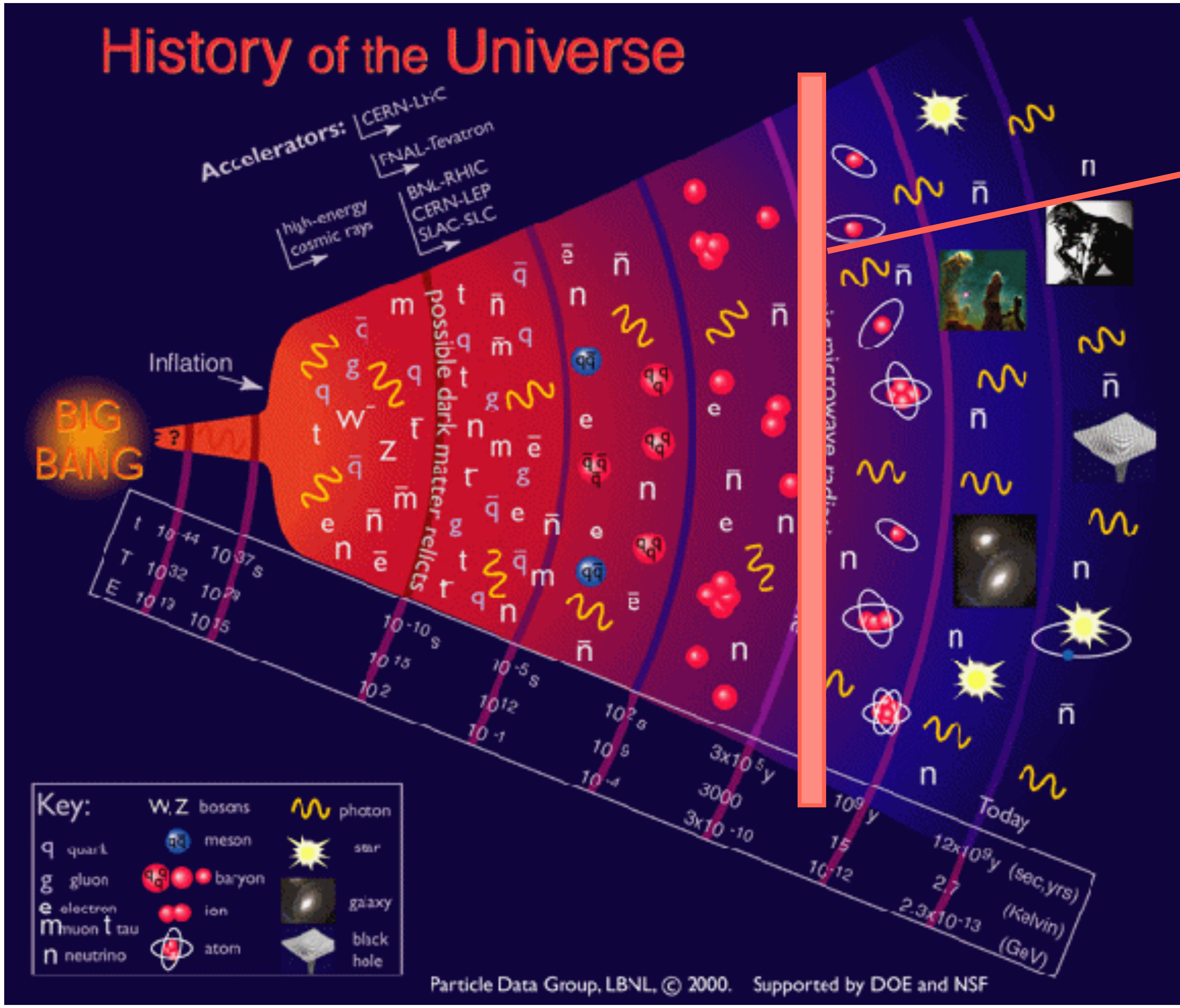
photons are decoupled thereafter:

COSMIC MICROWAVE BACKGROUND

today: $T_0 \simeq 2 \cdot 10^{-4}\,\mathrm{eV}$

recombination: $T_{\mathrm{rec}} \simeq 0.3\,\mathrm{eV}$

what are CBs and why are they formed



$$T_{\rm dec} \simeq 0.25\,{\rm eV}$$

freeze-out of

$$e + p \leftrightarrow H + \gamma$$

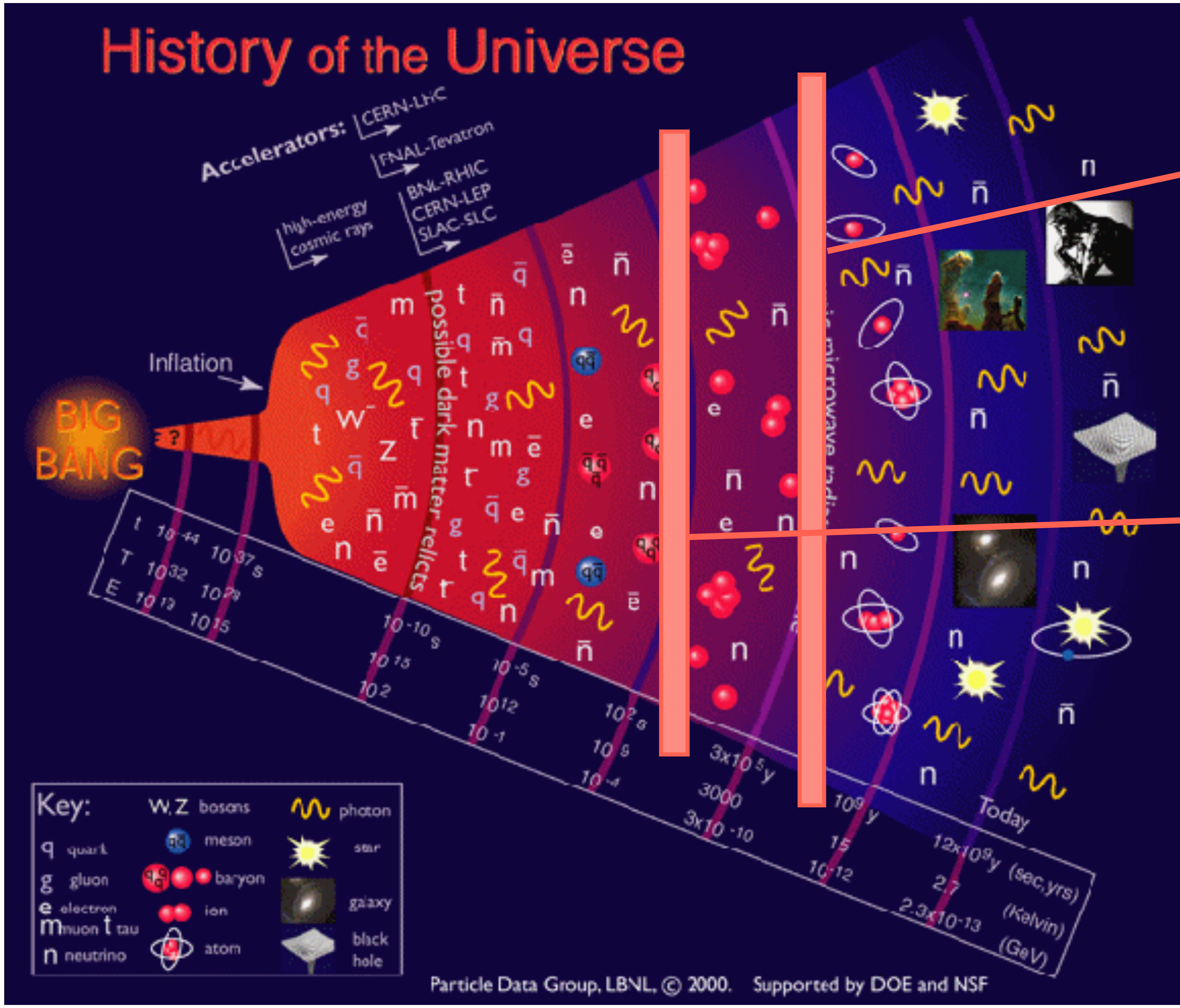
$$e + \gamma \to e + \gamma$$

photons are decoupled thereafter:

COSMIC MICROWAVE BACKGROUND

particles that decouple at temperature $T_{\rm dec}$ carry direct information about the status of the universe at that temperature

what are CBs and why are they formed



$$T_{\rm dec} \simeq 0.25\,{\rm eV}$$

photons decouple: CMB

$$T_{\rm dec} \simeq 1.4\,{\rm MeV}$$

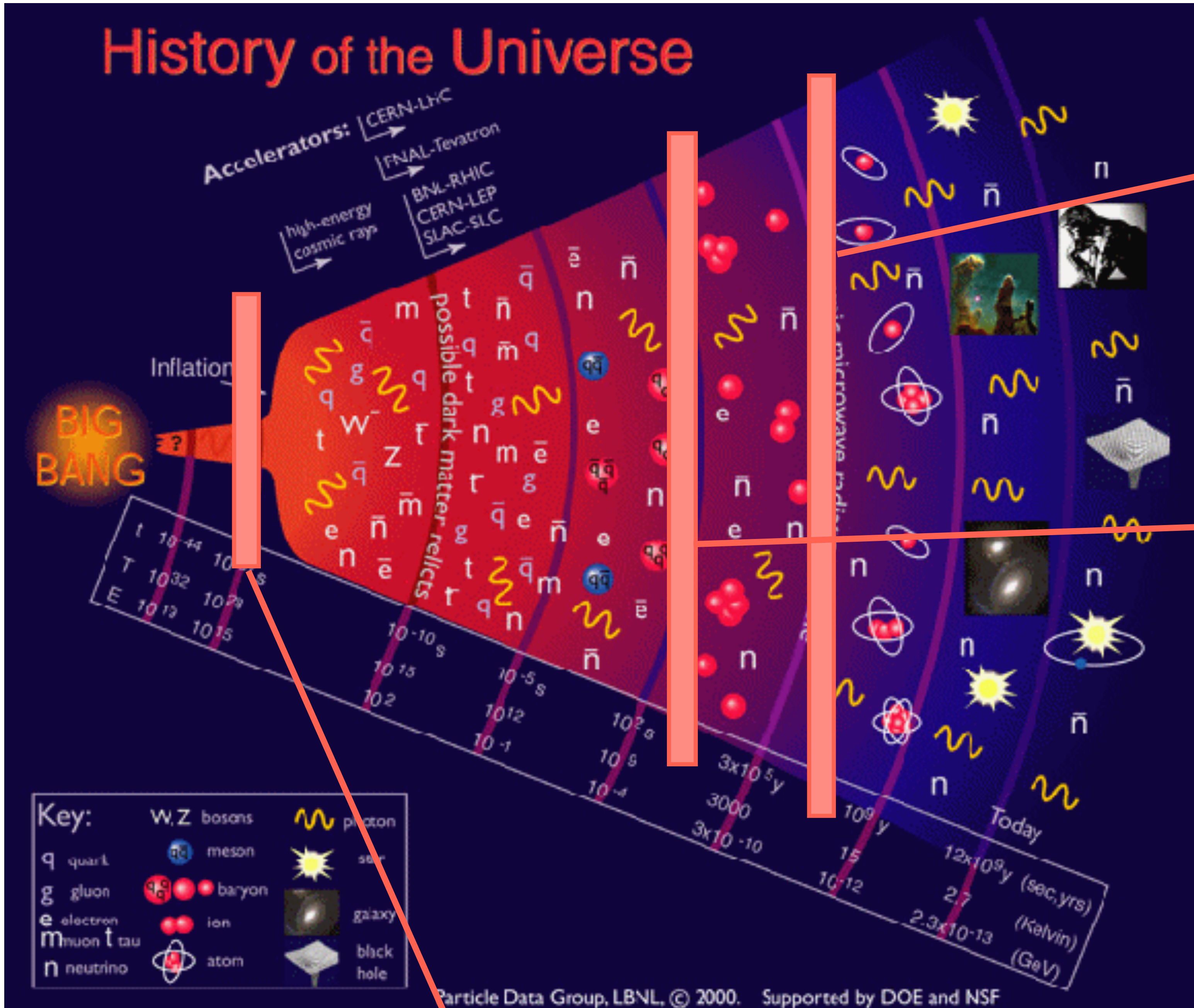
freeze-out of weak interactions

$$e + \bar{\nu} \leftrightarrow e + \bar{\nu}$$

COSMIC NEUTRINO BACKGROUND

- indirect evidence: CMB, structure formation, Big Bang Nucleosynthesis

what are CBs and why are they formed



$$T_{\rm dec} \simeq 0.25\,{\rm eV}$$

photons decouple: CMB

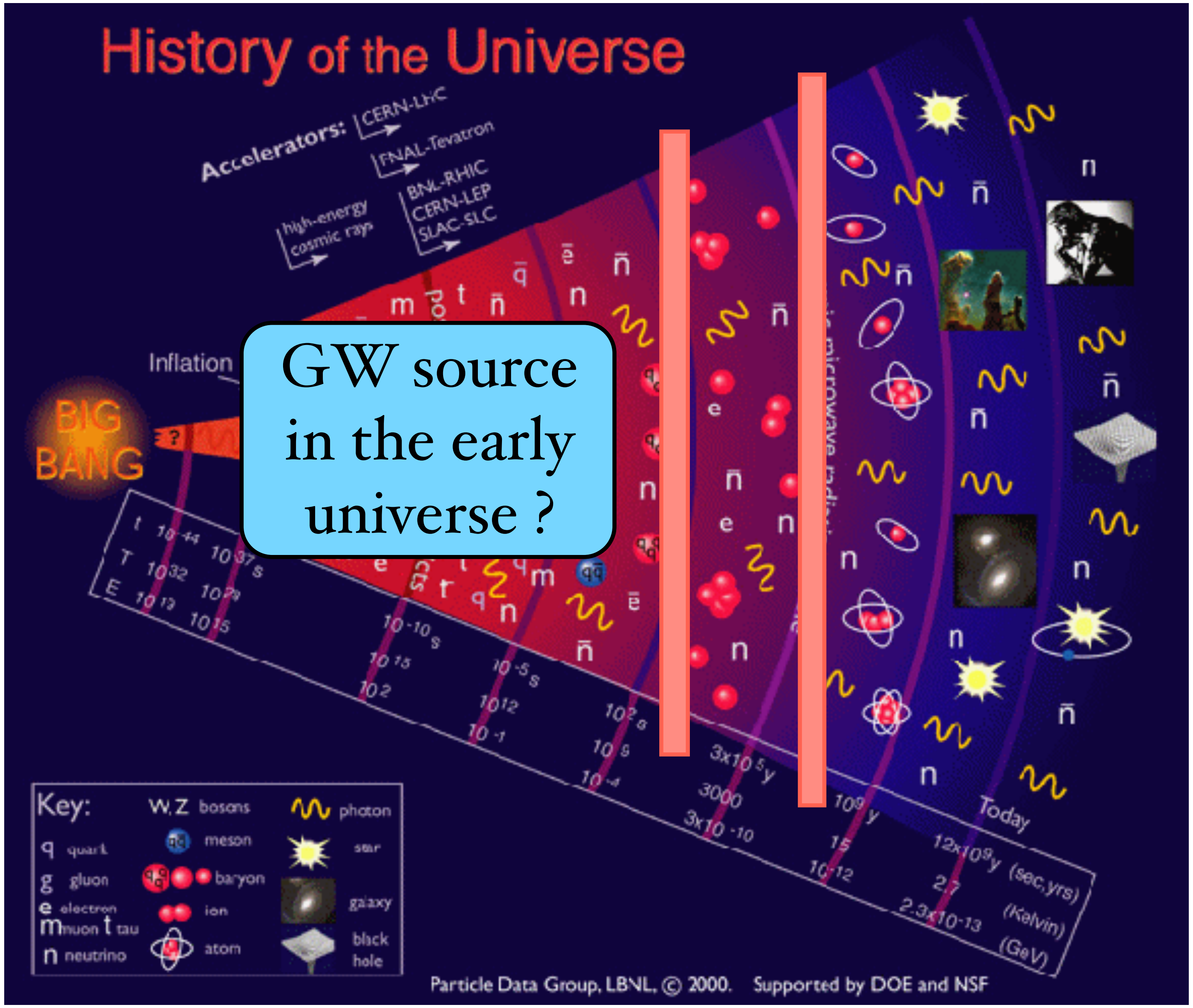
$$T_{\rm dec} \simeq 1.4\,{\rm MeV}$$

neutrinos decouple: CNB

for gravitons the decoupling temperature would be

$$\frac{\Gamma(T)}{H(T)} \sim \frac{G^2\,T^5}{T^2/M_{Pl}} \sim \left(\frac{T}{M_{Pl}}\right)^3 < 1$$

what are CBs and why are they formed



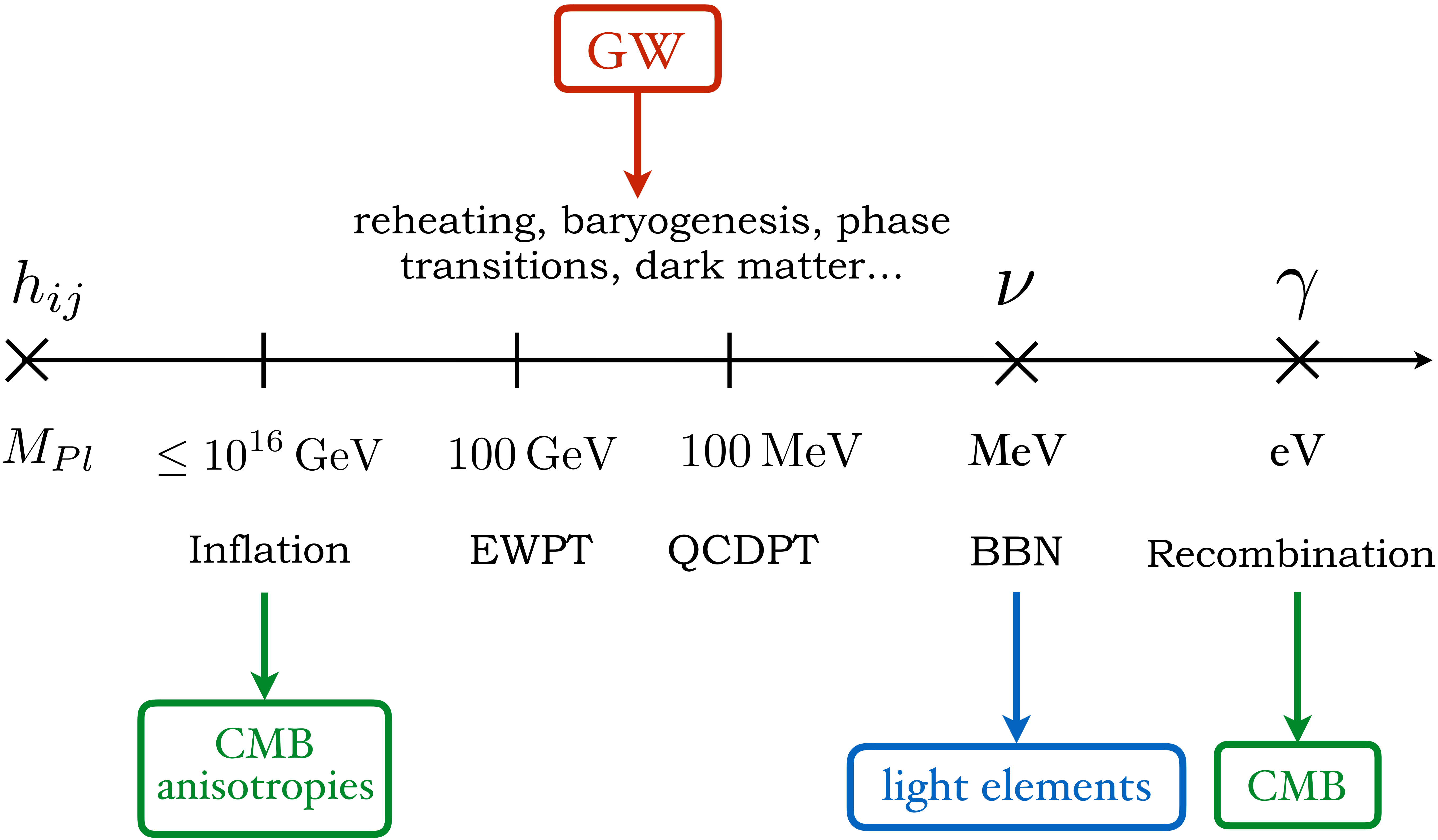
because of the weakness of the gravitational interaction GW propagate freely in the early universe

processes in the early universe could have created a

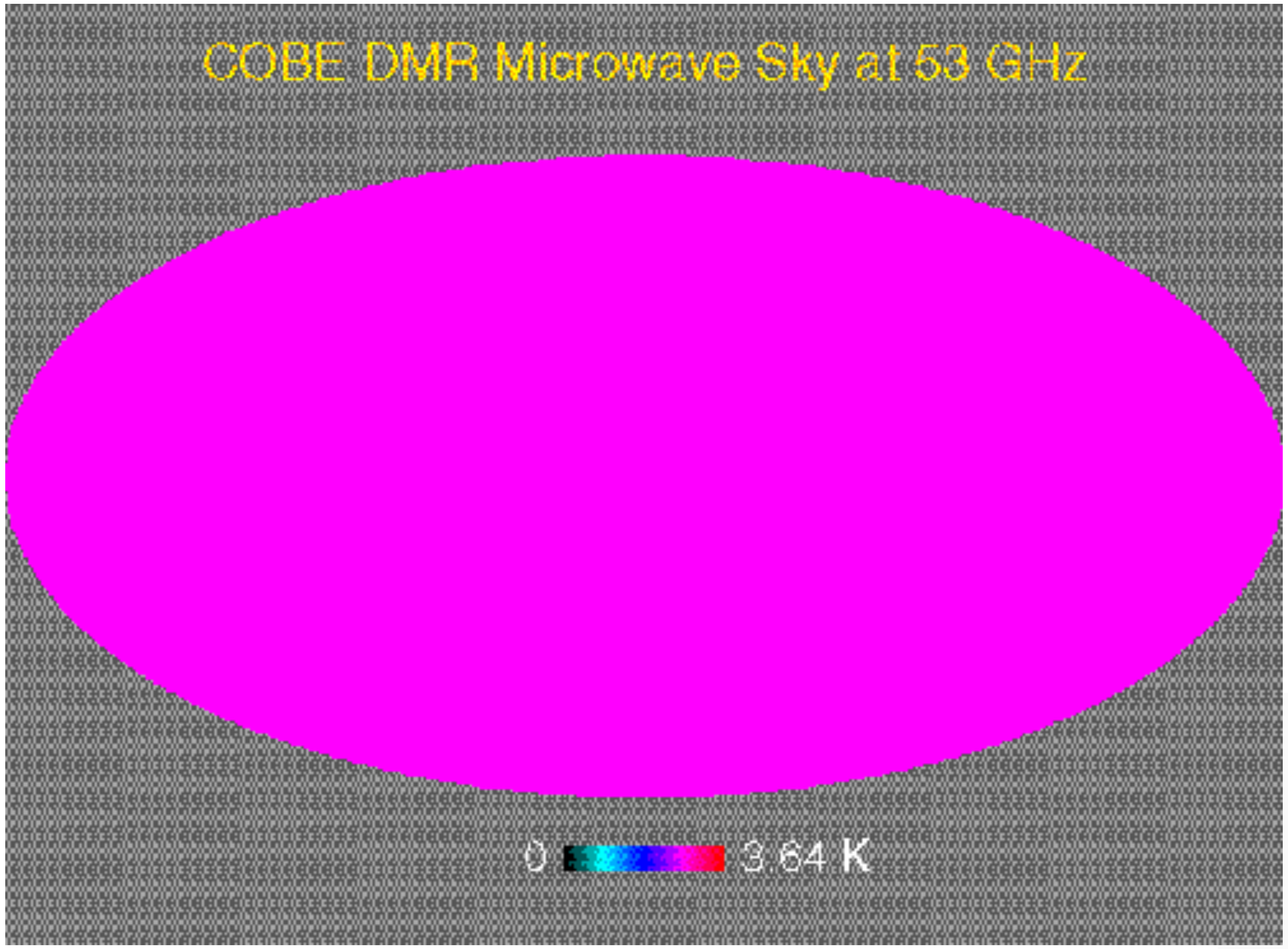
STOCHASTIC GW BACKGROUND

the detection of the SGWB would be a big step forward in our knowledge of the very early universe

CB: what can we use them for? what information do they bring to us?

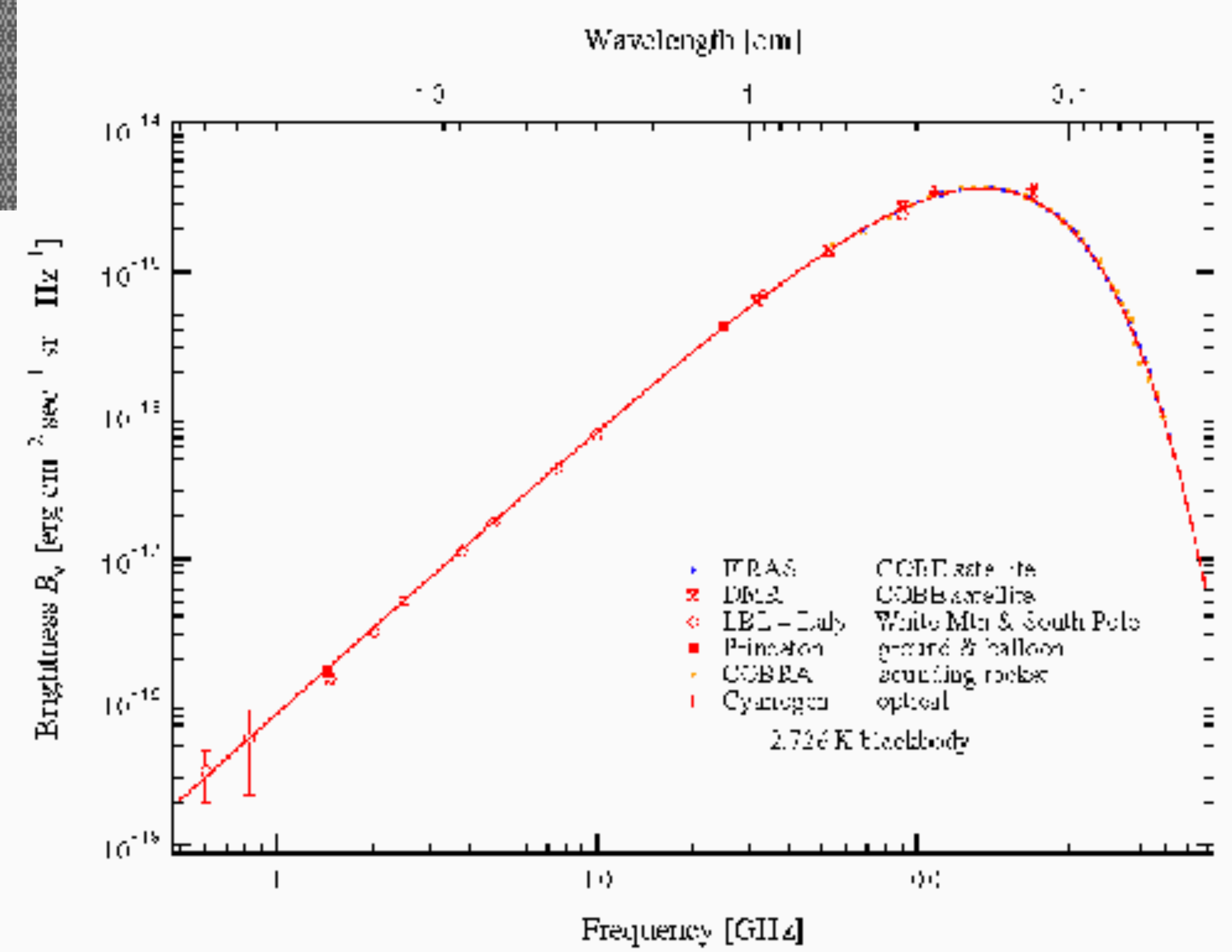


CMB in a nutshell



marked the birth of modern cosmology

spectacular confirmation of the Big Bang theory

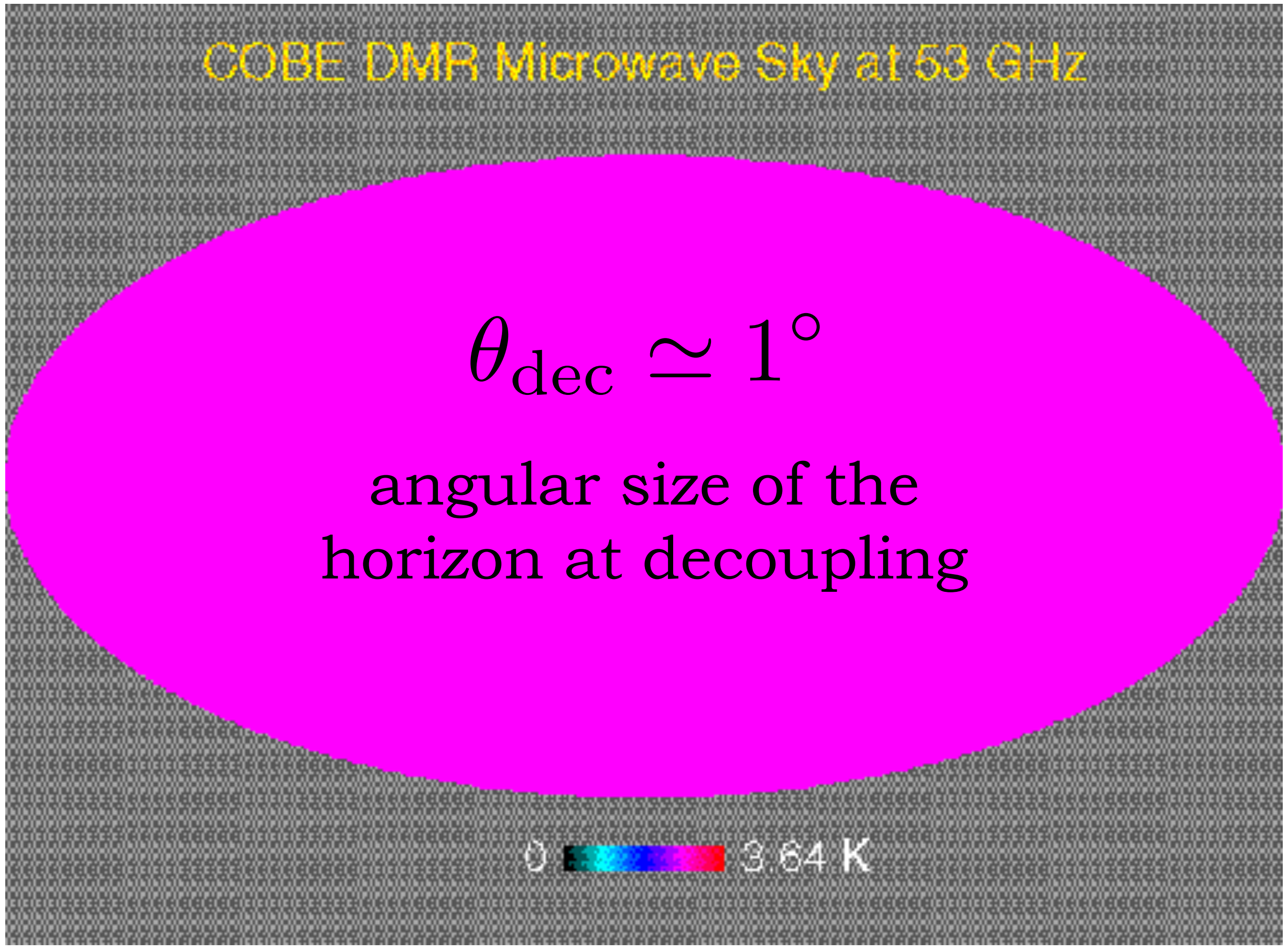


http://cosmology.berkeley.edu

all interactions changing the photon number froze-out at 1keV before photon decoupling

$$T = (2.725 \pm 0.001)\, K$$

CMB in a nutshell



$$\theta_{\rm dec} \simeq 1^\circ$$

angular size of the horizon at decoupling

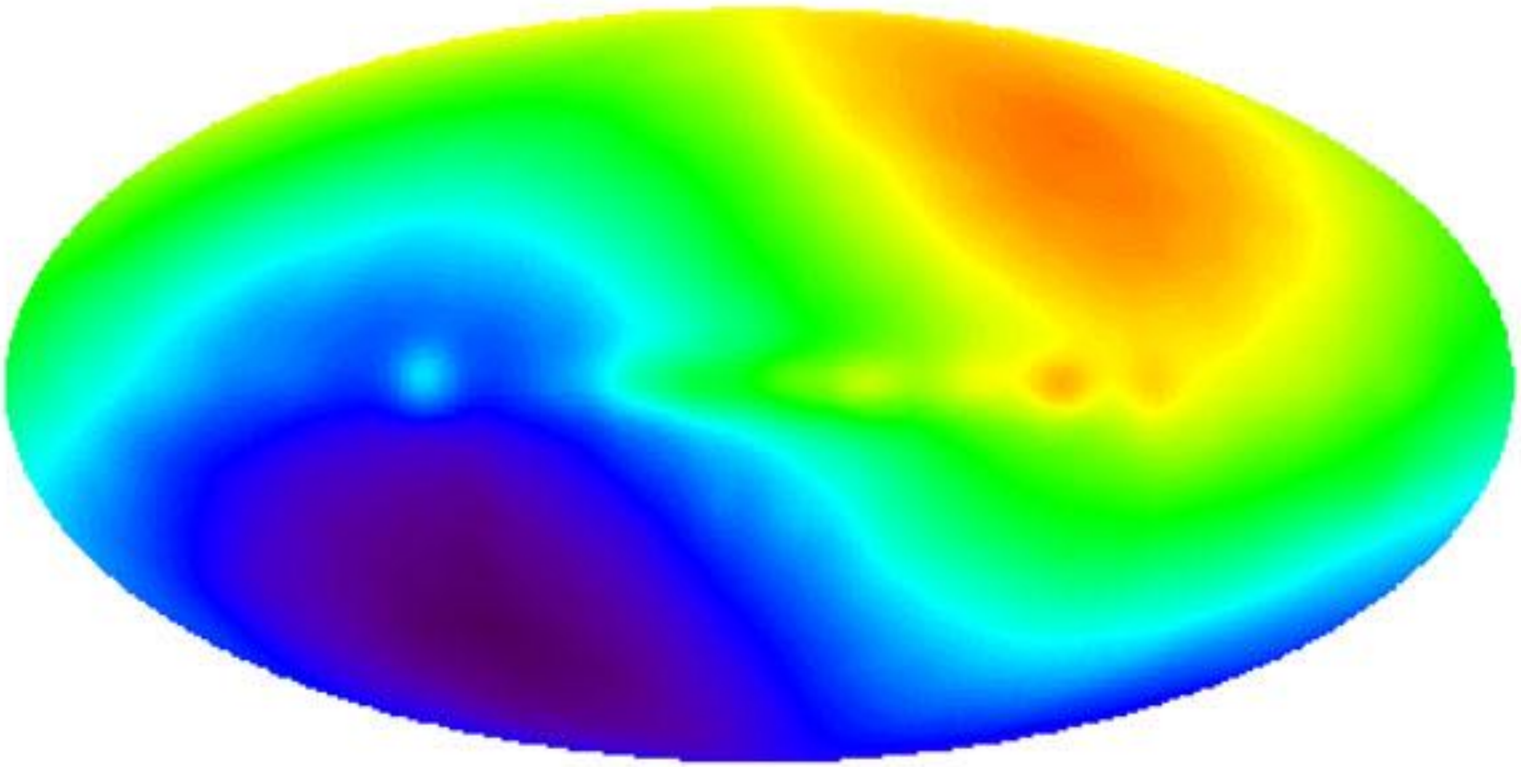
marked the birth of modern cosmology

spectacular confirmation of the Big Bang theory

why is this radiation so isotropic?

the CMB monopole contains 10^4 causally disconnected regions all at the same temperature

CMB in a nutshell

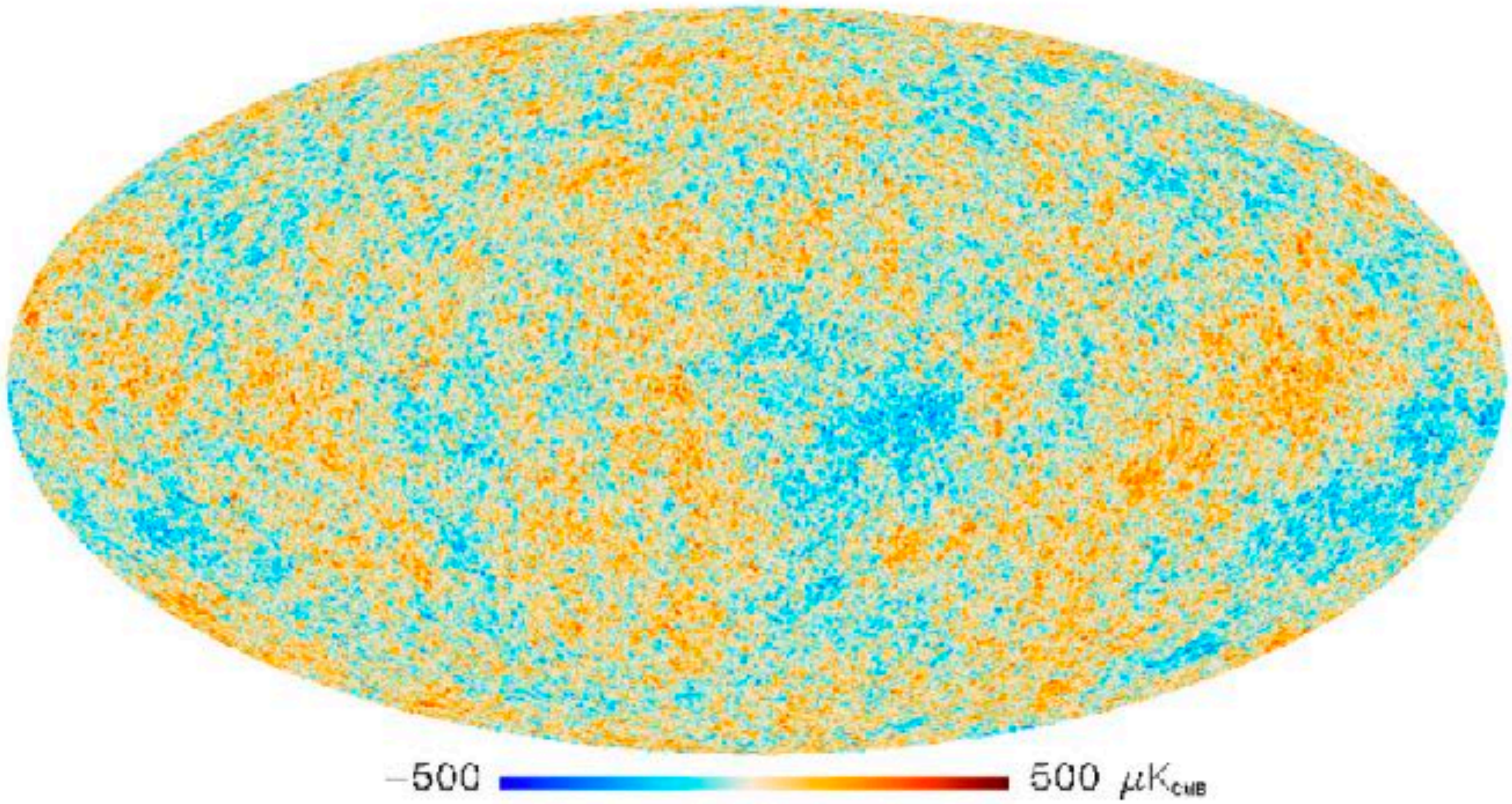


COBE satellite
https://apod.nasa.gov/apod/ap010128.html

dipole due to Doppler effect of Earth's movement

$$\frac{\delta T}{T} = |\mathbf{v}| = 1.23 \times 10^{-3}$$

CMB in a nutshell

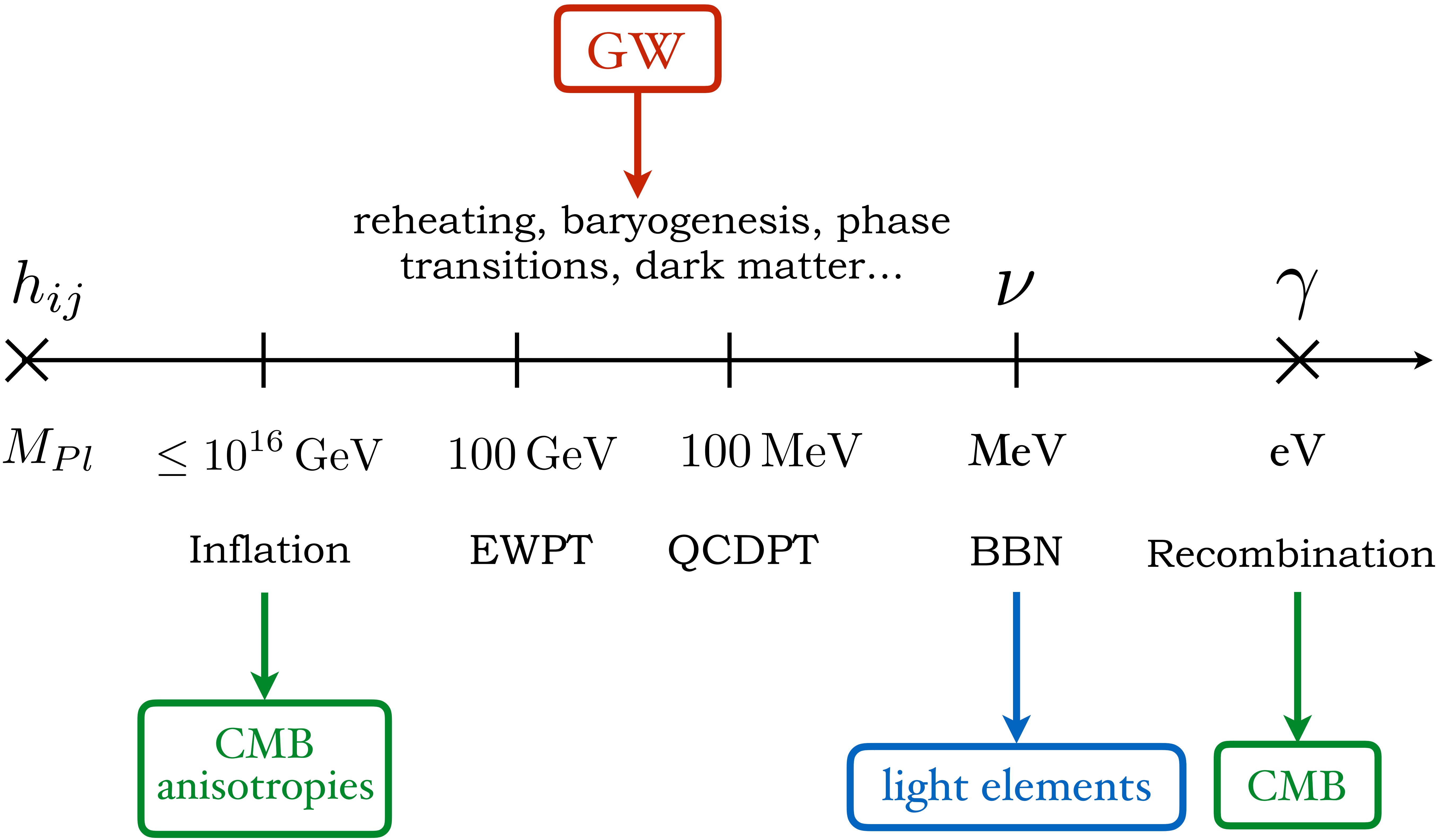


Planck satellite
arXiv:1303.5062

multipoles >2 all with amplitude

$$\frac{\delta T}{T} \sim 10^{-5}$$

CB: what can we use them for? what information do they bring to us?



CMB in a nutshell

Inflation provides a model for the "initial conditions" of the observed universe
it is a phase of accelerated expansion isotropising the universe

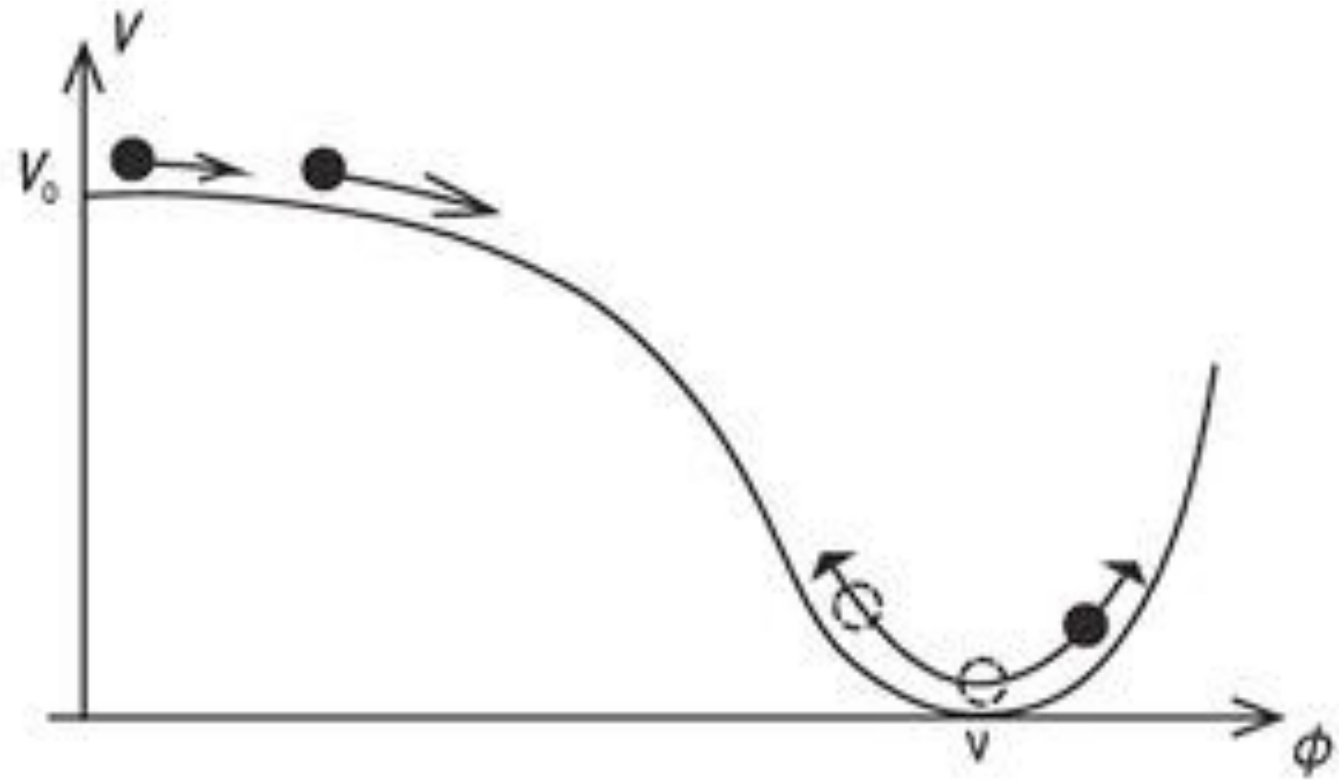
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) > 0$$

Phase dominated by a scalar field in a sufficiently flat potential

$$\rho_\phi = \cancel{\frac{1}{2}\dot{\phi}^2} + \cancel{\frac{1}{2}(\nabla\phi)^2} + V(\phi)$$

$$p_\phi = \cancel{\frac{1}{2}\dot{\phi}^2} - \cancel{\frac{1}{6}(\nabla\phi)^2} - V(\phi)$$

$$p_\phi \simeq -\rho_\phi$$



CMB in a nutshell

Inf … e “initial conditions” of the observed universe
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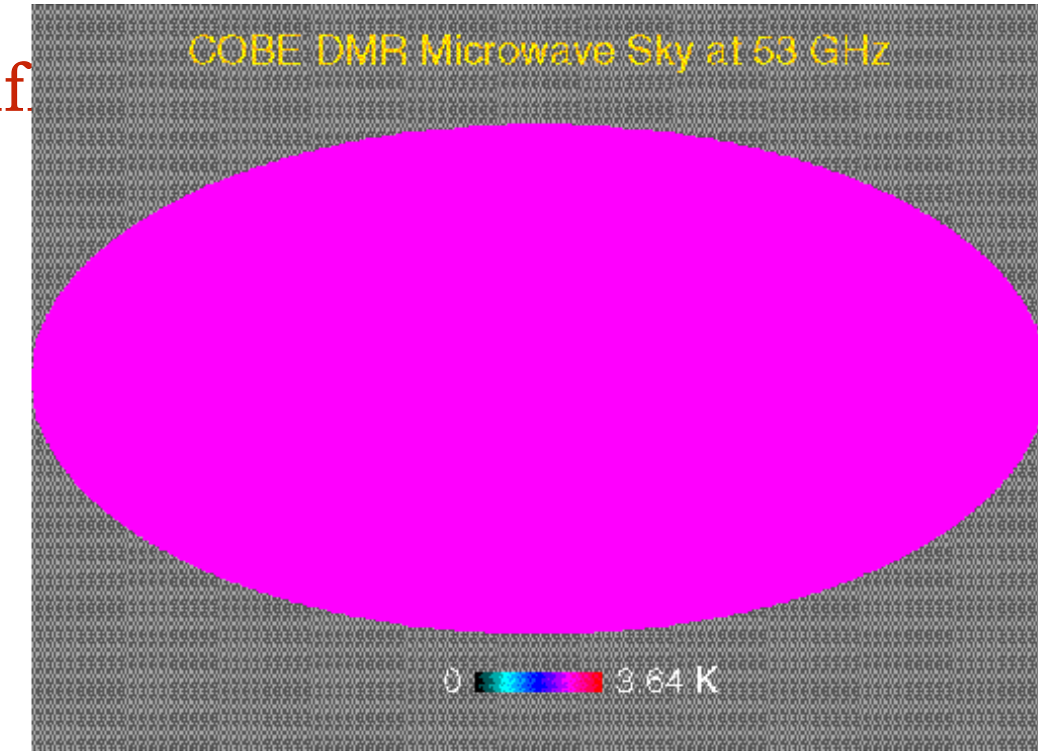

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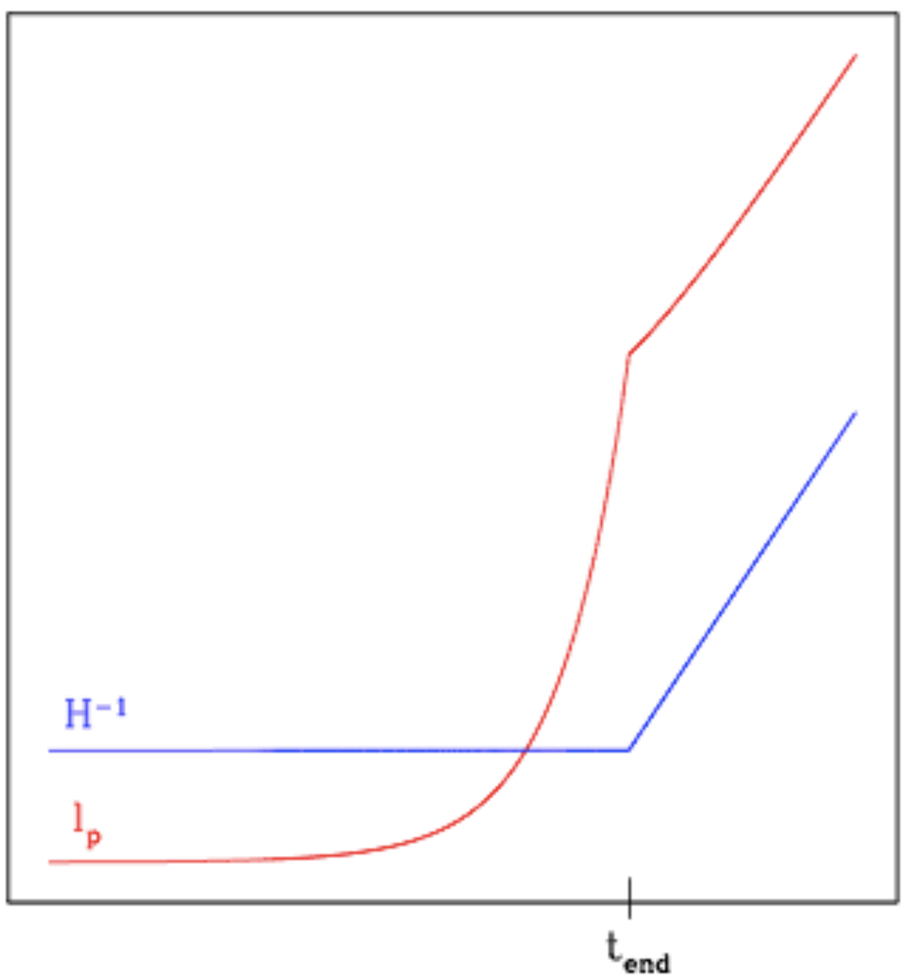
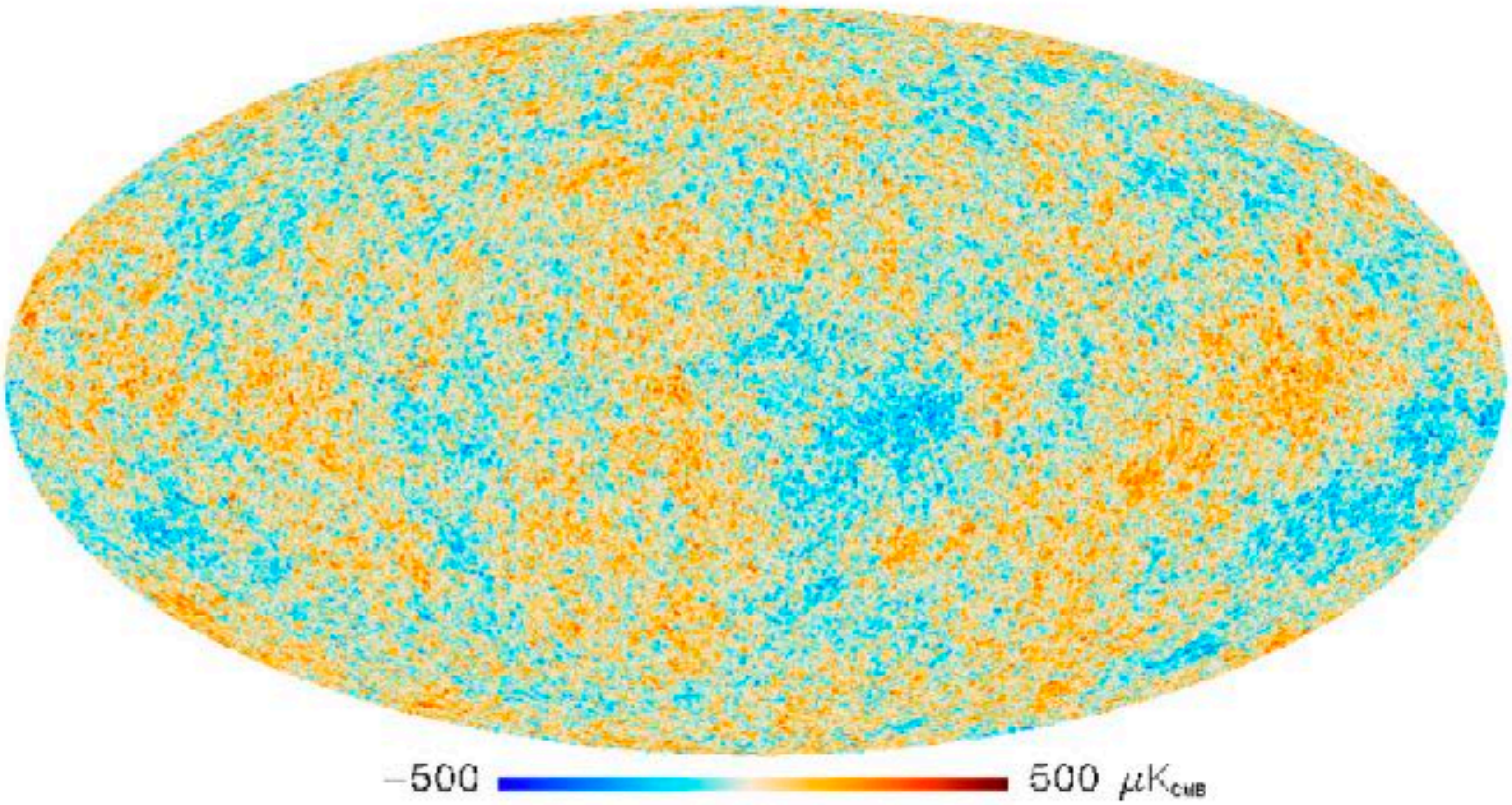


during a phase which is
not accelerating:

$$\ell_p \simeq 1/H$$

during an accelerating phase the
particle horizon grows
exponentially
at the end it is much larger than
if inflation had not been there

CMB in a nutshell



Planck satellite
arXiv:1303.5062

Inflation also provides an explanation for the small temperature anisotropies in the CMB

CMB in a nutshell

the phase of accelerated expansion amplifies and stretches out of the horizon quantum fluctuations

- scalar modes: quanta of the inflaton field $\phi = \bar{\phi} + \delta\phi$
- tensor modes: quanta of the gravitational field $g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}$

CMB in a nutshell

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<u>scalar modes</u>: field fluctuations perturb the metric
photons and baryons evolve in the fluctuating potential

$$ds^2 = a^2(\eta)[-(1+\Phi)d\eta^2 + (1-\Psi)d\mathbf{x}^2 + (\delta_{ij} + h_{ij})dx^i dx^j]$$

$$\delta\phi \to (\Psi,\, \Phi) \to \left(\frac{\delta\rho}{\rho},\, \mathbf{v}\right) \to \frac{\delta T}{T}$$

CMB in a nutshell

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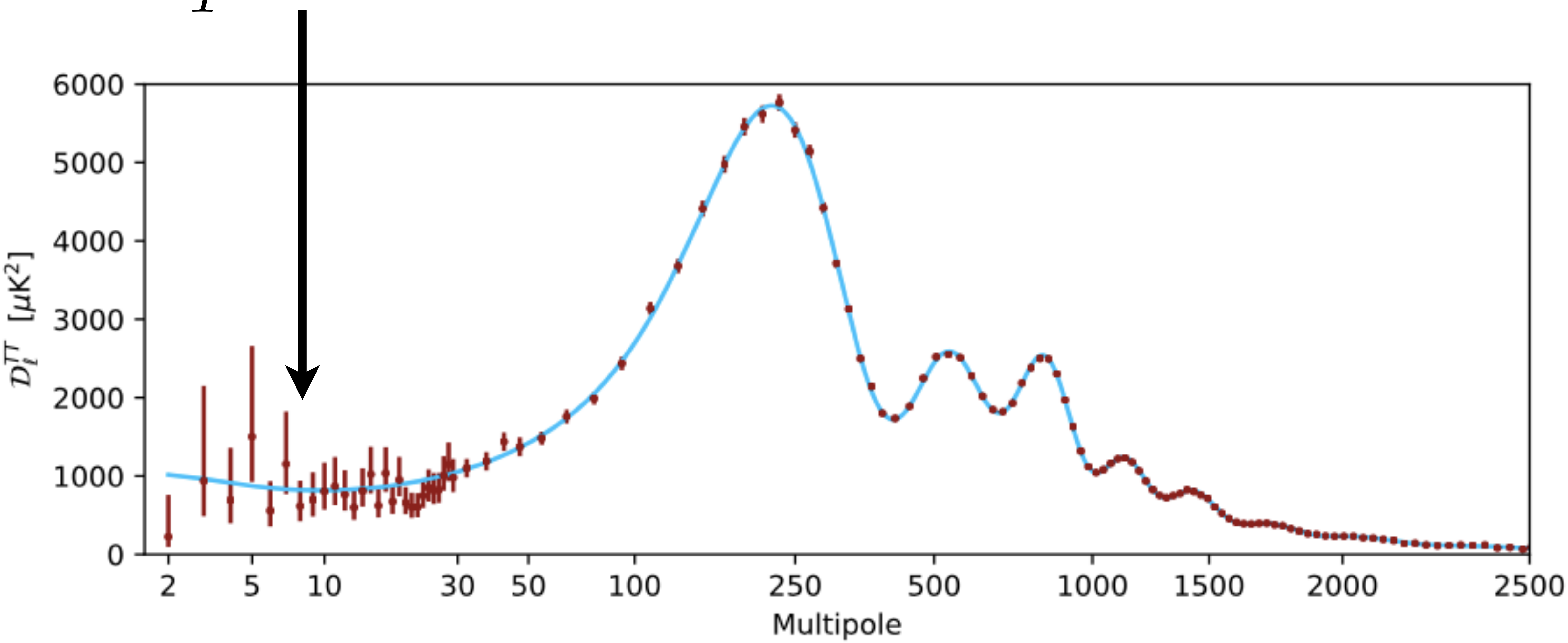
$$\frac{\delta T}{T} \sim 10^{-5}$$



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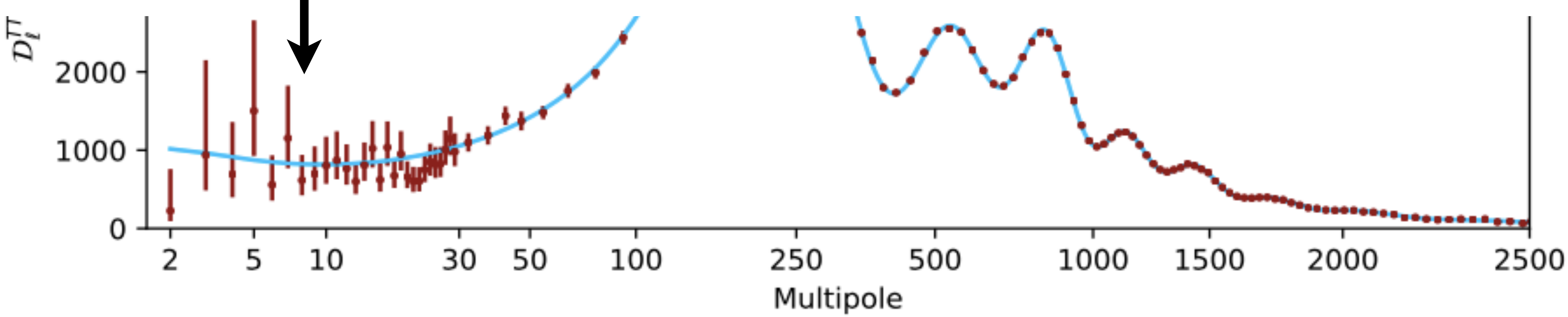
- content of the universe (ΛCDM)
- confirmation that inflation works
- information on structure formation
- constraints on H_0, neutrinos, dark energy…



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GW from early universe sources

tensor perturbations of FRW metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

$$|h_{ij}| \ll 1$$

$$h^i_i = \partial_j h^j_i = 0$$

GW from early universe sources

tensor perturbations of FRW metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

$$G_{\mu\nu} = 0$$

WAVE EQUATION

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 0$$

GW from early universe sources

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amplification of metric vacuum fluctuations during inflation

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WAVE EQUATION

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 0$$

amplification of metric vacuum fluctuations during inflation

- ✓ canonically normalised free field $v_\pm = a\,M_{Pl}\,h_\pm$
- ✓ quantisation
- ✓ homogeneous wave equation: harmonic oscillator with *time dependent* frequency

$$v''_\pm(t) + (k^2 - a^2 H^2)v_\pm(t) = 0$$

GW from early universe sources

tensor perturbations of FRW metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

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amplification of metric vacuum fluctuations during inflation

$$v''_{\pm}(t) + (k^2 - a^2 H^2)v_{\pm}(t) = 0$$

$k \gg a\,H$ sub-Hubble modes

$$\omega^2(t) = k^2$$

free field in vacuum
zero occupation number

$k \ll a\,H$ super-Hubble modes

$$\omega^2(t) = -a^2 H^2$$

super-Hubble modes have very large occupation number

GW from early universe sources

tensor perturbations of FRW metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

WAVE EQUATION

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\, h_{ij} = 16\pi G\, \Pi_{ij}^{TT}$$

source: Π_{ij}^{TT} tensor anisotropic stress

GW from early universe sources

tensor perturbations of FRW metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

WAVE EQUATION

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 16\pi G\,\Pi_{ij}^{TT}$$

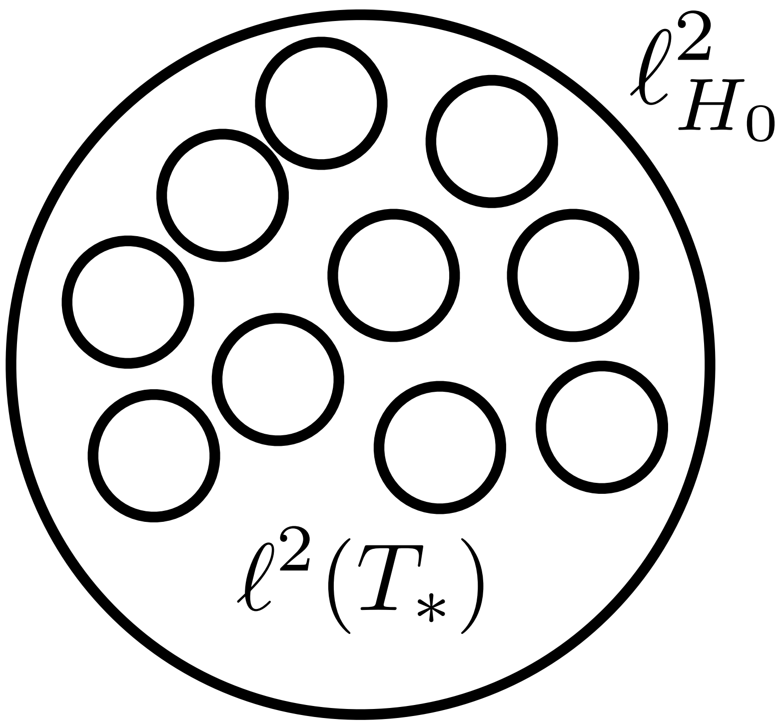
source: Π_{ij}^{TT} tensor anisotropic stress

- fluid $\quad \Pi_{ij} \sim \gamma^2(\rho + p)\,v_i v_j$
- electromagnetic field $\quad \Pi_{ij} \sim (E^2 + B^2)\dfrac{\delta_{ij}}{3} - E_i E_j - B_i B_j$
- scalar field $\quad \Pi_{ij} \sim \partial_i \phi\,\partial_j \phi$

stochastic GW background

- inflation: intrinsic, quantum fluctuations that become classical (stochastic) outside the horizon

- causal source: of GW cannot operate beyond the horizon (Hubble scale) signal visible today originated from many independent horizon volumes



GW energy density power spectrum

$$\Omega_{\rm GW} = \frac{\rho_{\rm GW}}{\rho_c} = \frac{\langle \dot{h}_{ij}\dot{h}_{ij}\rangle}{32\pi G\,\rho_c} = \int \frac{{\rm d}f}{f}\frac{{\rm d}\Omega_{\rm GW}}{{\rm d}\ln f}$$

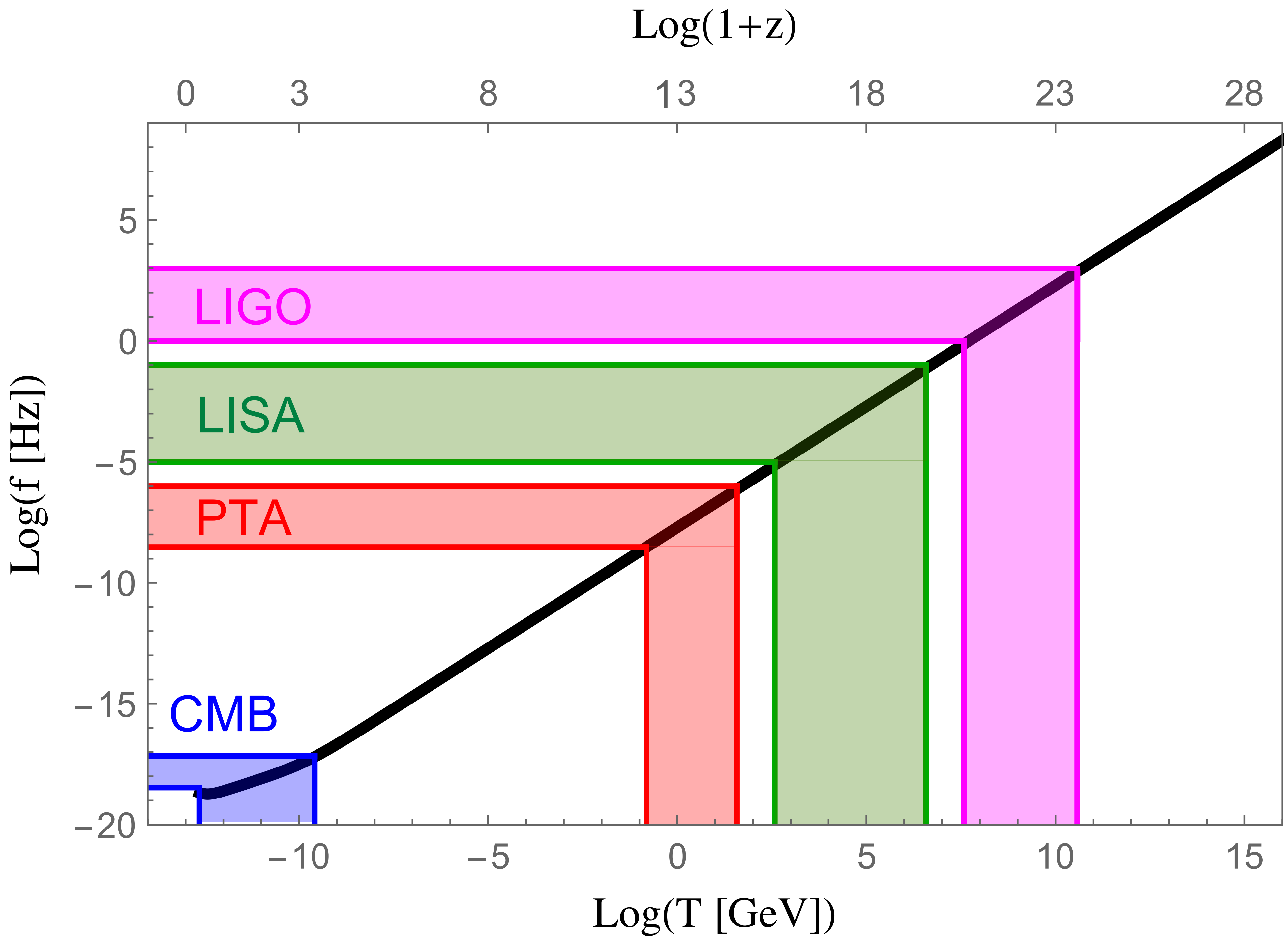
stochastic GW background

Characteristic frequency for *causal sources*

$$f_* = \frac{H(T_*)}{\epsilon_*}$$

$$\epsilon_* = 1$$

parameter depending on the characteristic scale of source



Advanced LIGO/Virgo interferometers

arm length L = 4 km

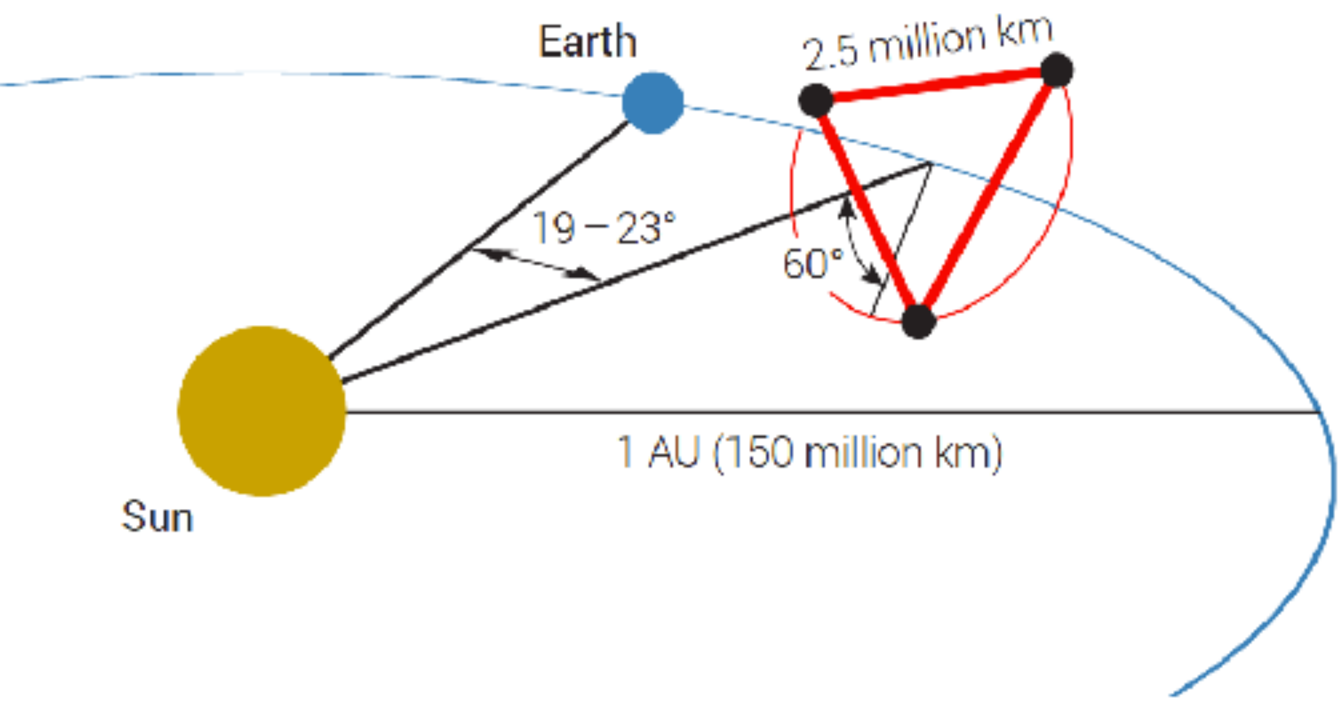
frequency range of detection: $10\,\mathrm{Hz} < f < 5\,\mathrm{kHz}$

- Black hole coalescing binaries of masses few to dozens solar masses
- Neutron Star and NS-BH binaries
- Stochastic GW background

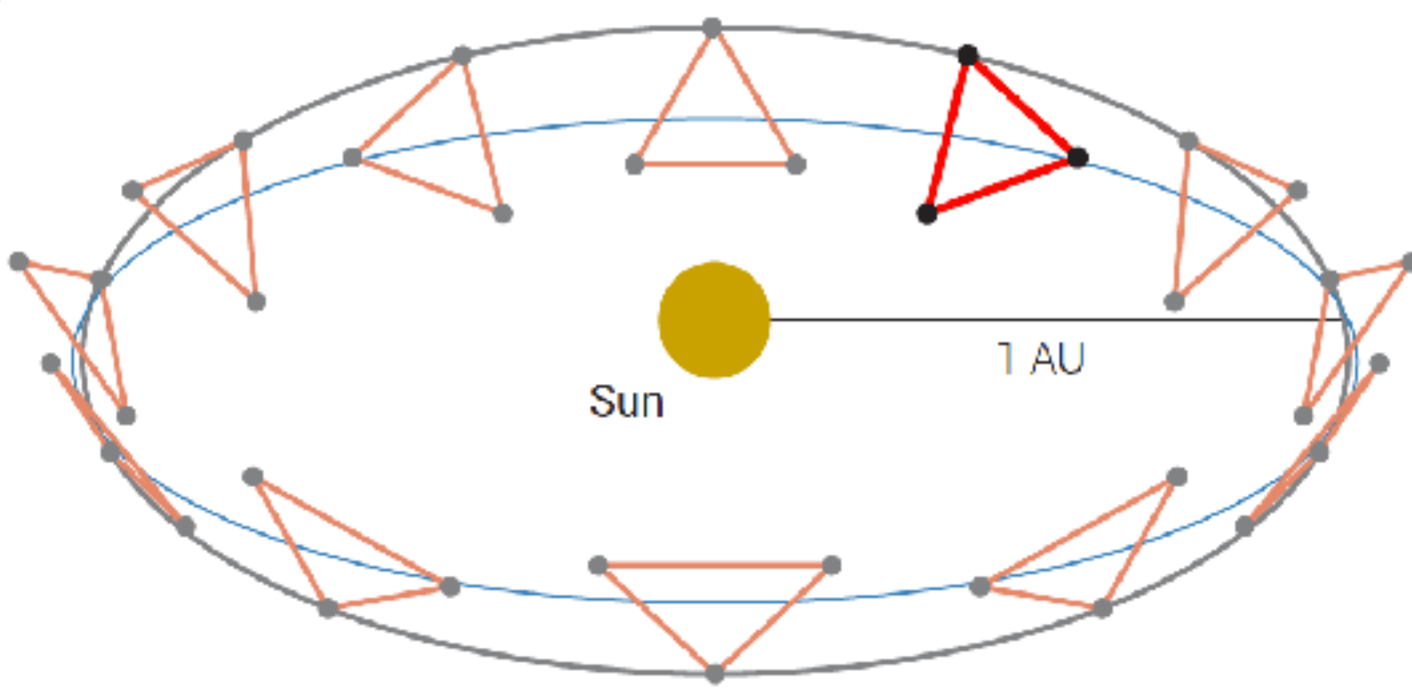
LISA: Laser Interferometer Space Antenna

- no seismic noise
- much longer arms than on Earth

frequency range of detection: $10^{-4}\,\mathrm{Hz} < f < 1\,\mathrm{Hz}$



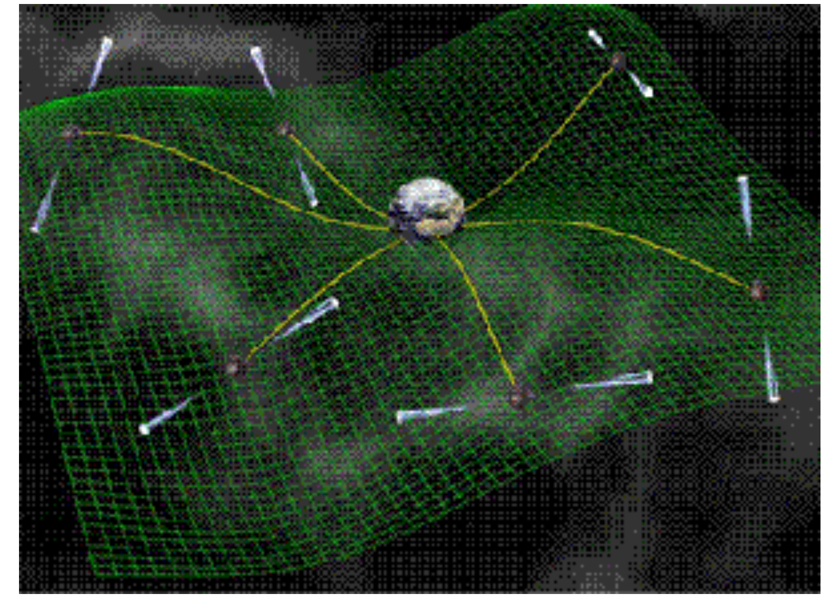
- Launch in ~2032
- two masses in free fall per spacecraft
- 2.5 million km arms
- picometer displacement of masses



Pulsar timing array

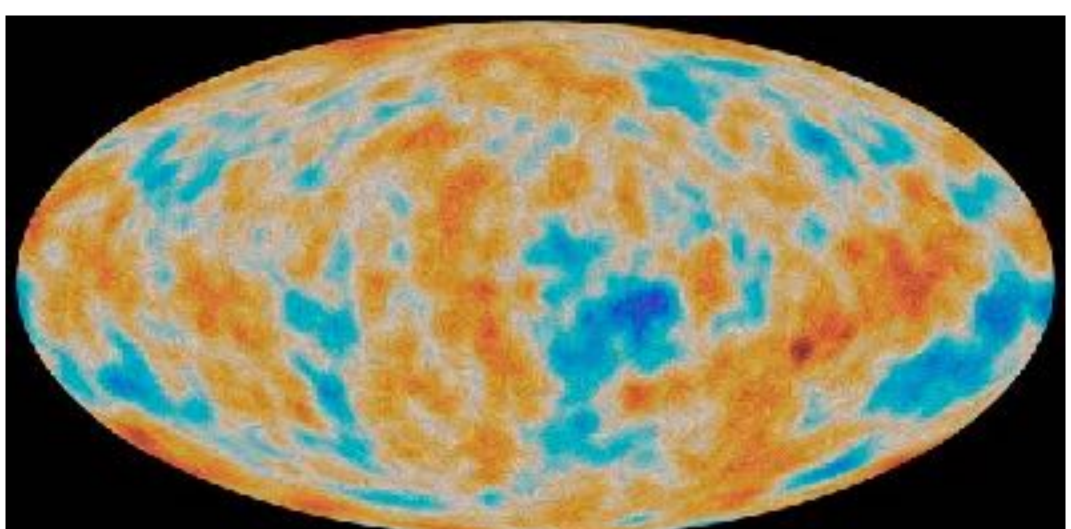
frequency range of detection: $10^{-9}\,\mathrm{Hz} < f < 10^{-7}\,\mathrm{Hz}$

- target: stochastic background from inspiralling SMBH binaries (masses of order 10^9 solar masses)



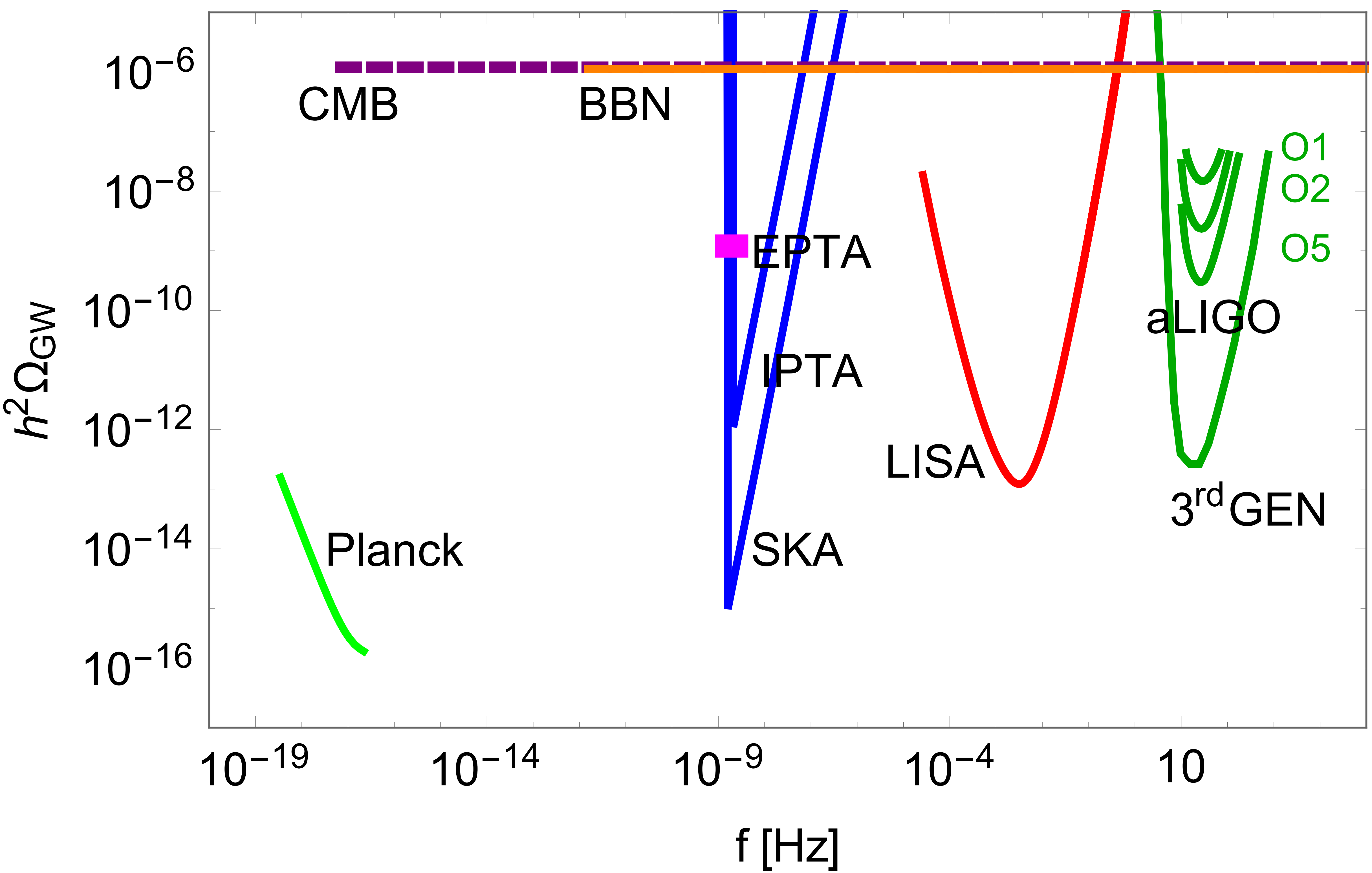
Cosmic microwave background

frequency range of detection: $10^{-18}\,\mathrm{Hz} < f < 10^{-16}\,\mathrm{Hz}$



- target: temperature fluctuations and B polarisation

SGWB bounds and detectors

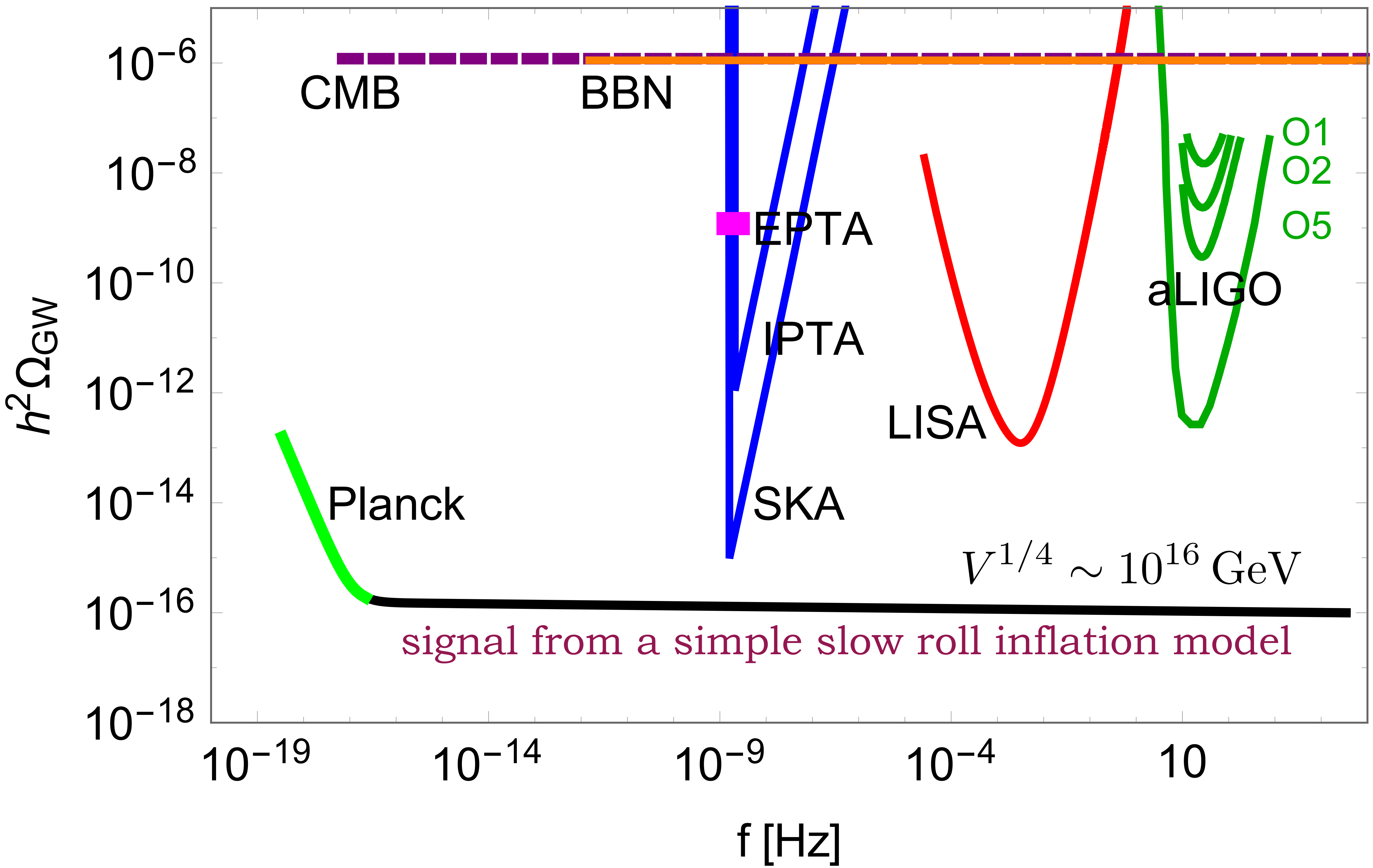


SGWB from slow roll inflation

$$\Omega_{\rm GW}(f) = \frac{3}{128}\,\Omega_{\rm rad}\,r\,\mathcal{P}^*_{\mathcal{R}}\left(\frac{f}{f_*}\right)^{n_T}\left[\frac{1}{2}\left(\frac{f_{\rm eq}}{f}\right)^2 + \frac{16}{9}\right]$$

- tensor to scalar ratio $\quad r = \mathcal{P}_h/\mathcal{P}_{\mathcal{R}} \qquad r_* \leq 0.07$
- scalar amplitude at CMB pivot scale $\quad \mathcal{P}^*_{\mathcal{R}} \simeq 2\cdot 10^{-9} \qquad k_* = \frac{0.05}{\rm Mpc}$
- tensor spectrum $\quad \mathcal{P}_h = \frac{2}{\pi}\frac{H^2}{m_{Pl}^2}\left(\frac{k}{aH}\right)^{-2\epsilon} \qquad n_T \simeq -2\epsilon$
- transfer function from inflation to today

SGWB from slow roll inflation



GW influence CMB photons and leave an imprint in CMB anisotropies

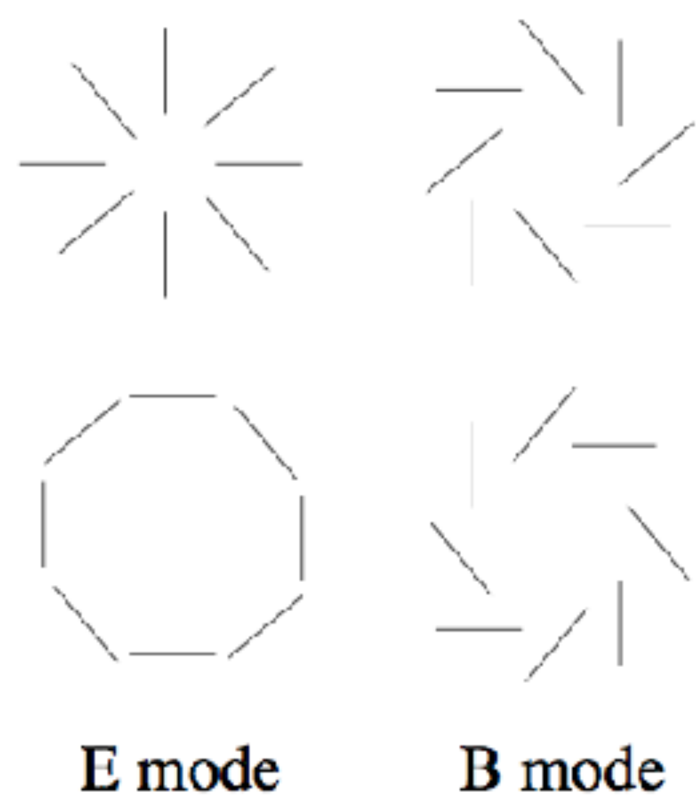
- temperature : limit by COBE, WMAP, Planck

$$\frac{\delta T}{T} = -\int_{t_{\rm dec}}^{t_0} \dot{h}_{ij}\, n^i n^j\, dt$$

- polarisation: BB spectrum measured by BICEP2 and Planck generated at photon decoupling time, from Thomson scattering of electrons by a quadrupole temperature anisotropy in the photons

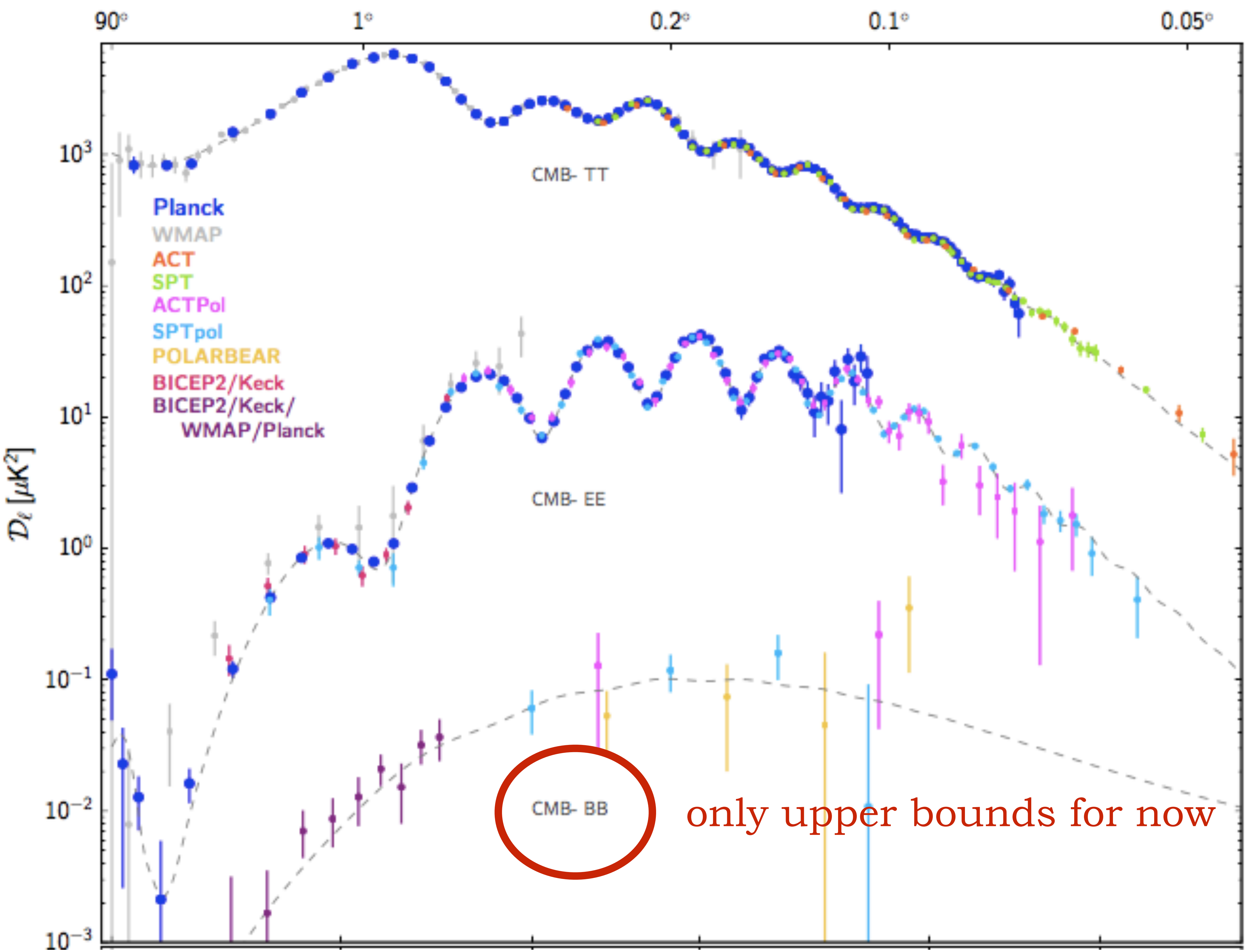
polarisation patterns

generated by primordial scalar and tensor perturbations

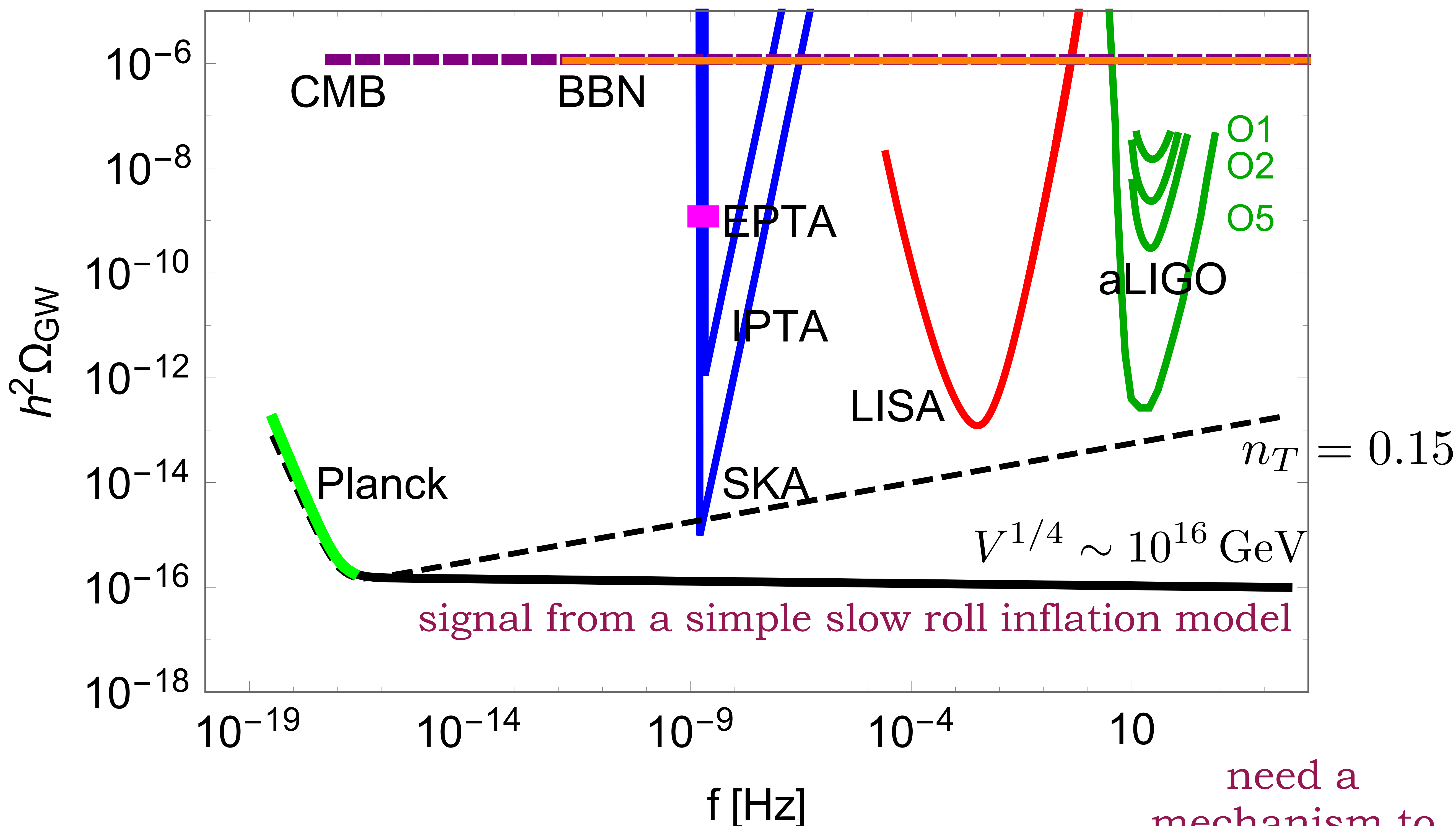


generated only by primordial tensor perturbations or by foregrounds

GW influence CMB photons and leave an imprint in CMB anisotropies



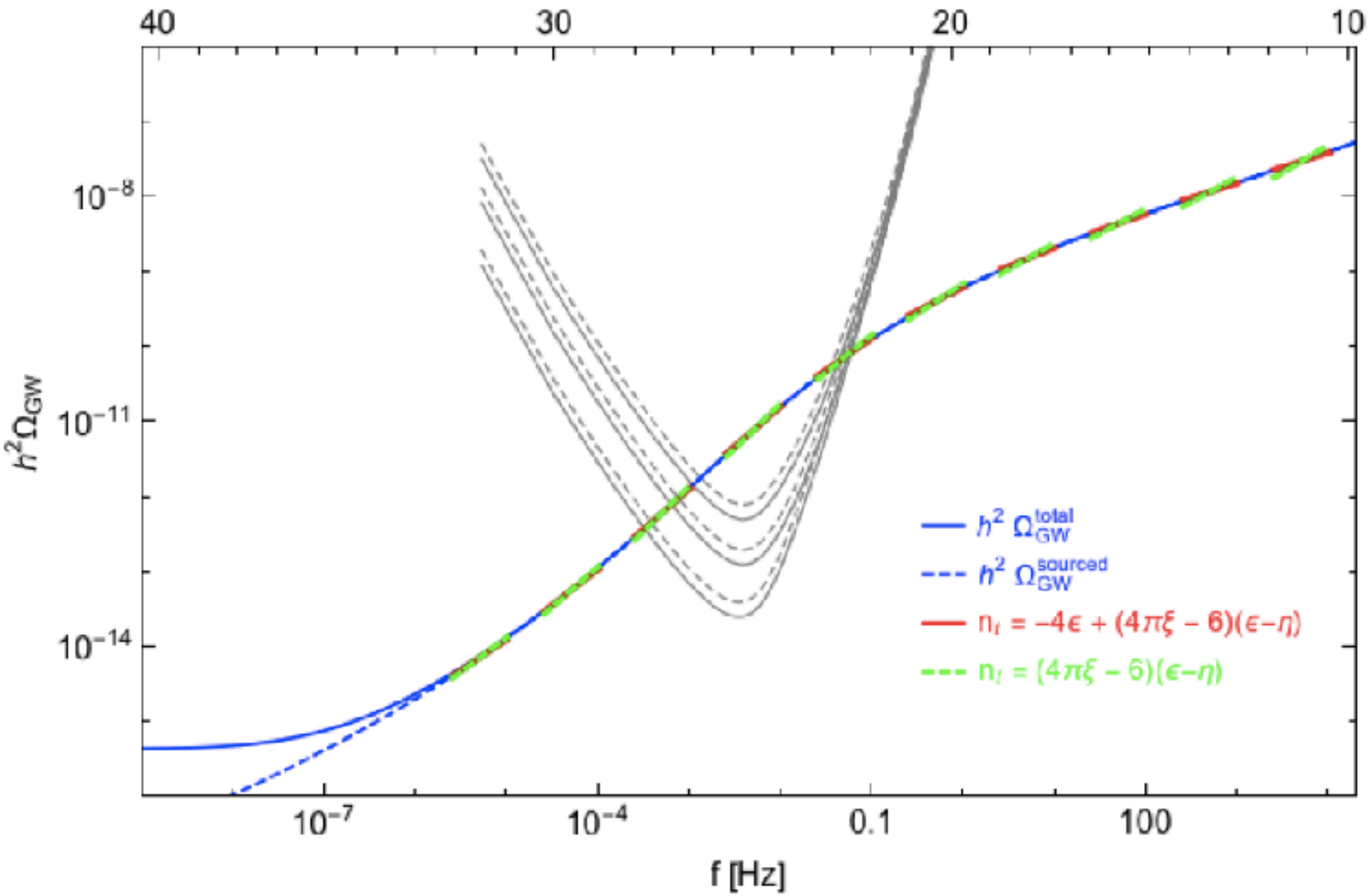
SGWB from slow roll inflation



need a mechanism to enhance it!

just one example: inflaton-gauge field coupling

$$\Delta\mathcal{L} = -\frac{1}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



$$\Lambda = \frac{M_{Pl}}{35}$$

quadratic inflaton potential

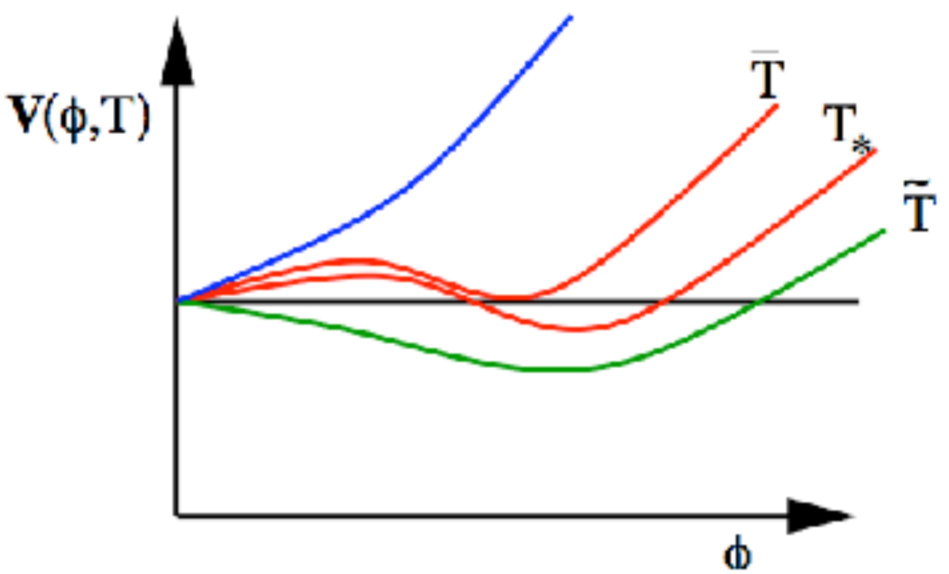
OTHER SIGNATURES:
non-gaussianity, chirality

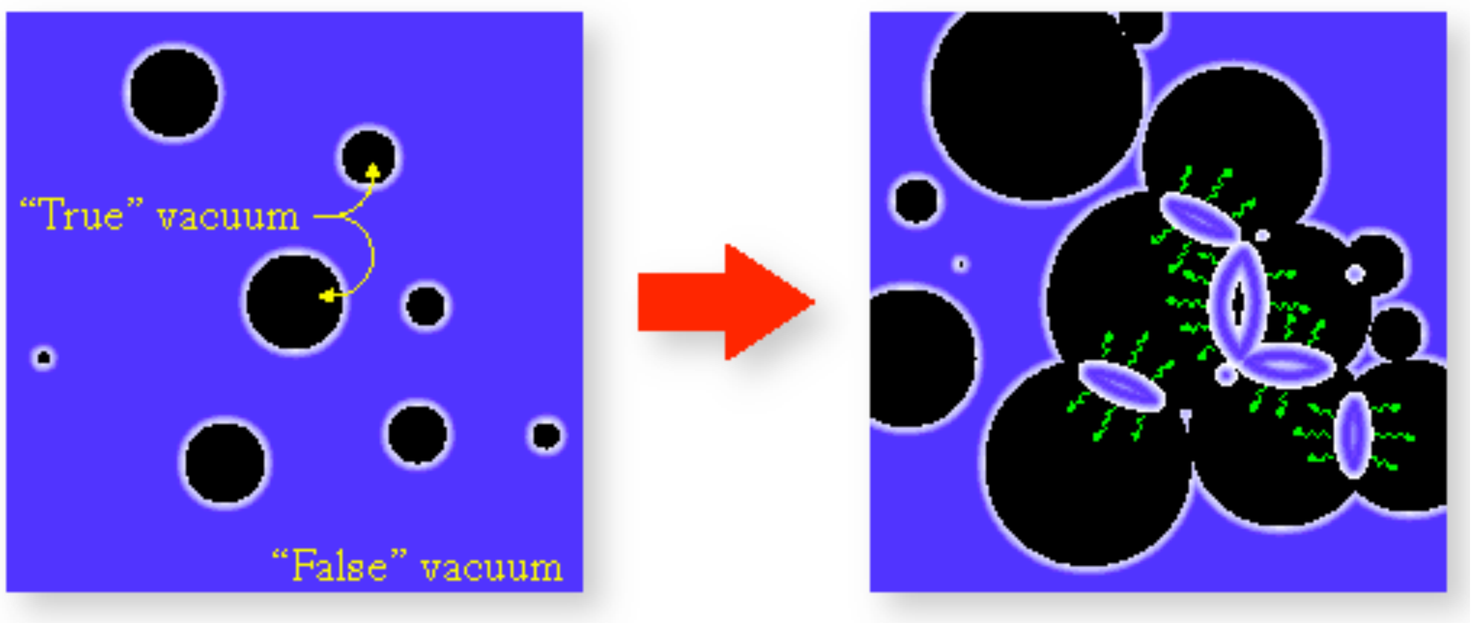
SGWB from first order phase transitions

in the course of its adiabatic expansion, the universe might have undergone several PTs, maybe of first order

potential barrier separates true and false vacua

quantum tunneling across the barrier : nucleation of bubbles of true vacuum





- QCD and EWPT (beyond the standard paradigm)
- higher temperature PTs (extra dimensions, dark matter models...)

SGWB from first order phase transitions

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 16\pi G\,\Pi_{ij}^{TT}$$

- collisions of bubble walls $\Pi_{ij} \sim \partial_i\phi\,\partial_j\phi$
- sound waves and turbulence in the fluid $\Pi_{ij} \sim \gamma^2(\rho + p)\,v_i v_j$
- primordial magnetic fields (MHD turbulence)

$$\Pi_{ij} \sim (E^2 + B^2)\frac{\delta_{ij}}{3} - E_i E_j - B_i B_j$$

SGWB from first order phase transitions

$$f_* = \frac{H(T_*)}{\epsilon_*}$$

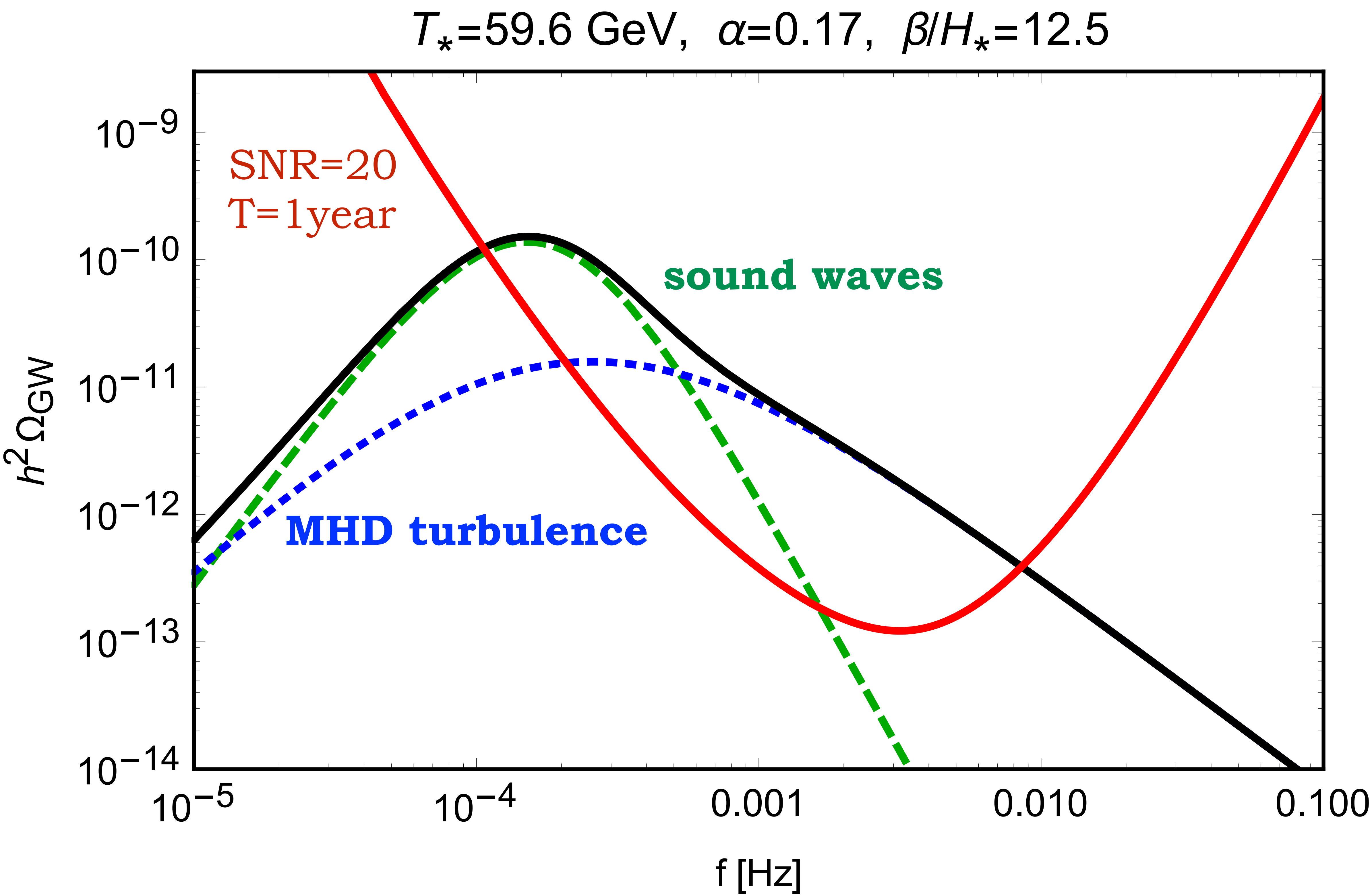
- LISA (mHz) is sensitive to energy scales around the **TeV scale**, so it can can probe the EWPT in BSM models and more exotic PTs beyond the EWPT

connections with baryon asymmetry, dark matter : LISA as a probe of BSM physics, complementary to colliders

- Pulsar Timing Array (nanoHertz) can probe the **QCDPT scale** at 100 MeV

- Earth-based detectors (100 Hz) can probe more exotic PTs possibly occurring around 10^5 GeV

Example of signal from FO EWPT in LISA



Conclusions and open questions

- Cosmological backgrounds are an amazing source of information to understand the early universe and consequently fundamental physics

- the Cosmic Microwave Background is one of the neatest observational probes of the standard cosmological model

- the Stochastic GW Background has the same potential, carrying with itself information on high energy physics beyond the standard model of particle physics

Conclusions and open questions (SGWB)

- how probable is the existence of early universe GW sources leading to an *observable* signal?

- both for the CMB and for the SGWB, the next observational challenge concerns the removal of “foregrounds”
  - there are expected SGWBs from binaries which are too numerous to be individually detected
  - there are all the other GW sources which need to be subtracted to high enough precision

- once a SGWB is detected, how can we ascertain its origin?
  - can we make sure it is cosmological (and not astrophysical, remember BICEP)?
  - can we understand from which process it comes from?
  - connected challenge: there is the need to make very precise predictions on the expected signals, and it is difficult since the generation mechanisms are based on BSM physics

GW sources in the early universe : inflation-related

- irreducible SGWB from inflation
  - also sourced by second order scalar perturbations
- beyond the irreducible SGWB from inflation
  - particle production during inflation (scalar, gauge fields… coupled to the inflaton)
  - spectator fields
  - breaking symmetries (space-dependent inflaton, massive graviton…)
  - modified gravity during inflation (massive GWs with $c \neq 1$)
  - primordial black holes
- alternatives to inflation
  - pre big-bang, cyclic/ekpirotic, string gas cosmology…
- preheating and non-perturbative phenomena
  - parametric amplification of bosons/fermions
  - symmetry breaking in hybrid inflation
  - decay of flat directions
  - oscillons

GW sources in the early universe : phase transition-related

- first order phase transition
  - true vacuum bubble collision
  - sound waves
  - turbulence

- cosmic topological defects
  - irreducible SGWB from topological defect networks
  - decay of cosmic string loops