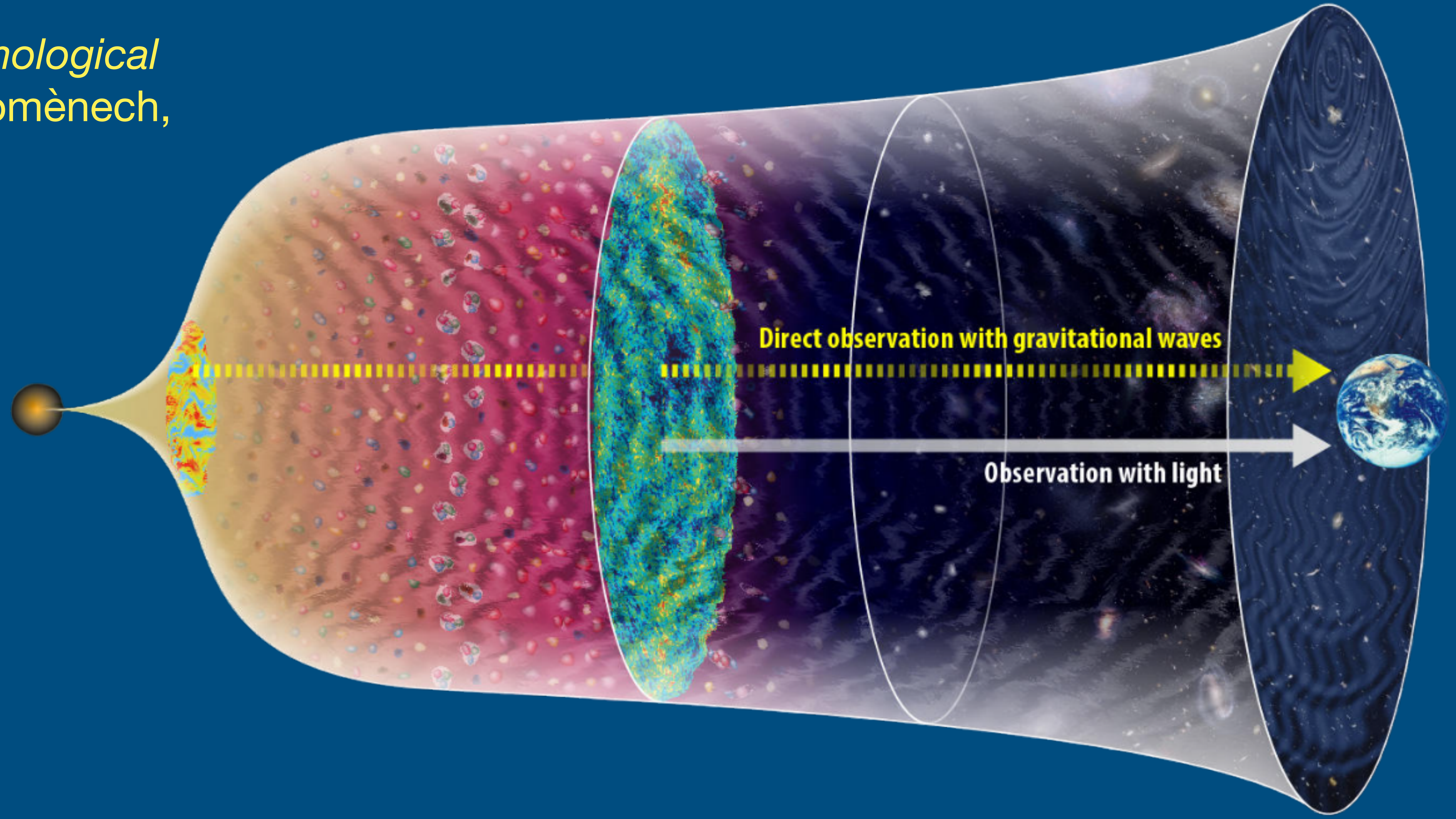
Cosmological gravitational wave background anisotropies

PRD 107 (2023), "*New universal property of cosmological GW anisotropies*" with E. Dimastrogiovanni, G. Domènech, M. Fasiello and G. Tasinato



NASA/WMAP Science Team

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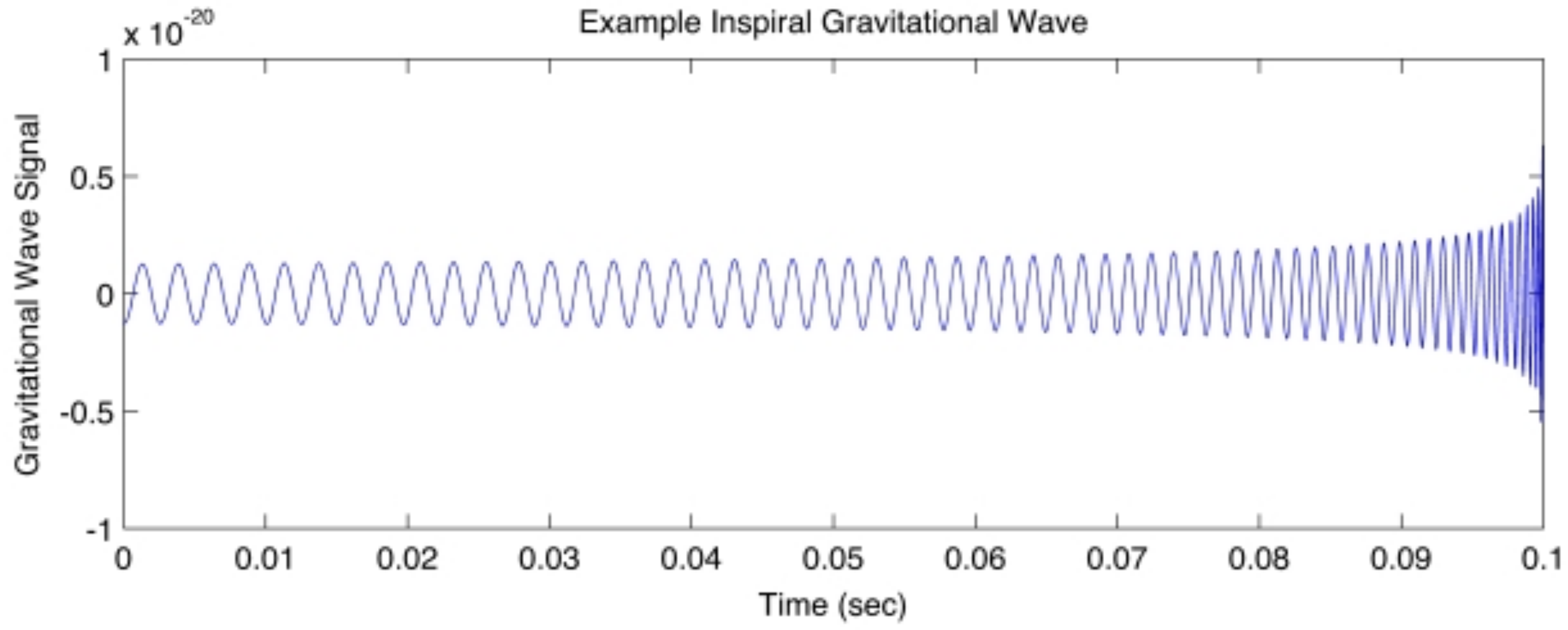
Cosmology from Home 2023

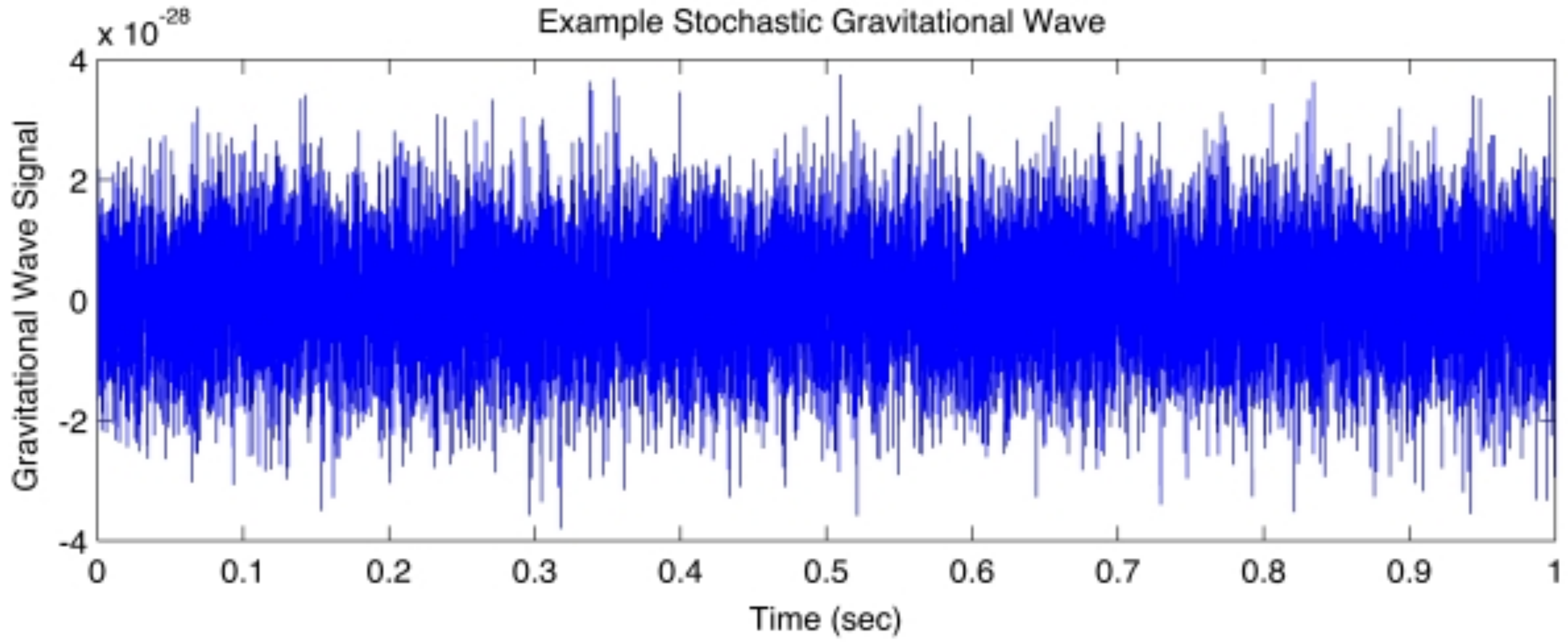
Outline

- SGWB overview
- SGWB anisotropies
    - Line of sight formalism
    - Adiabatic initial conditions
    - Isocurvature initial conditions
- Summary

SGWB

- Stochastic signals appear similar to noise
- Superposition of signals too weak to be resolved individually e.g. compact object mergers
- Nature of generation process e.g. primordial sources inflation, PT…



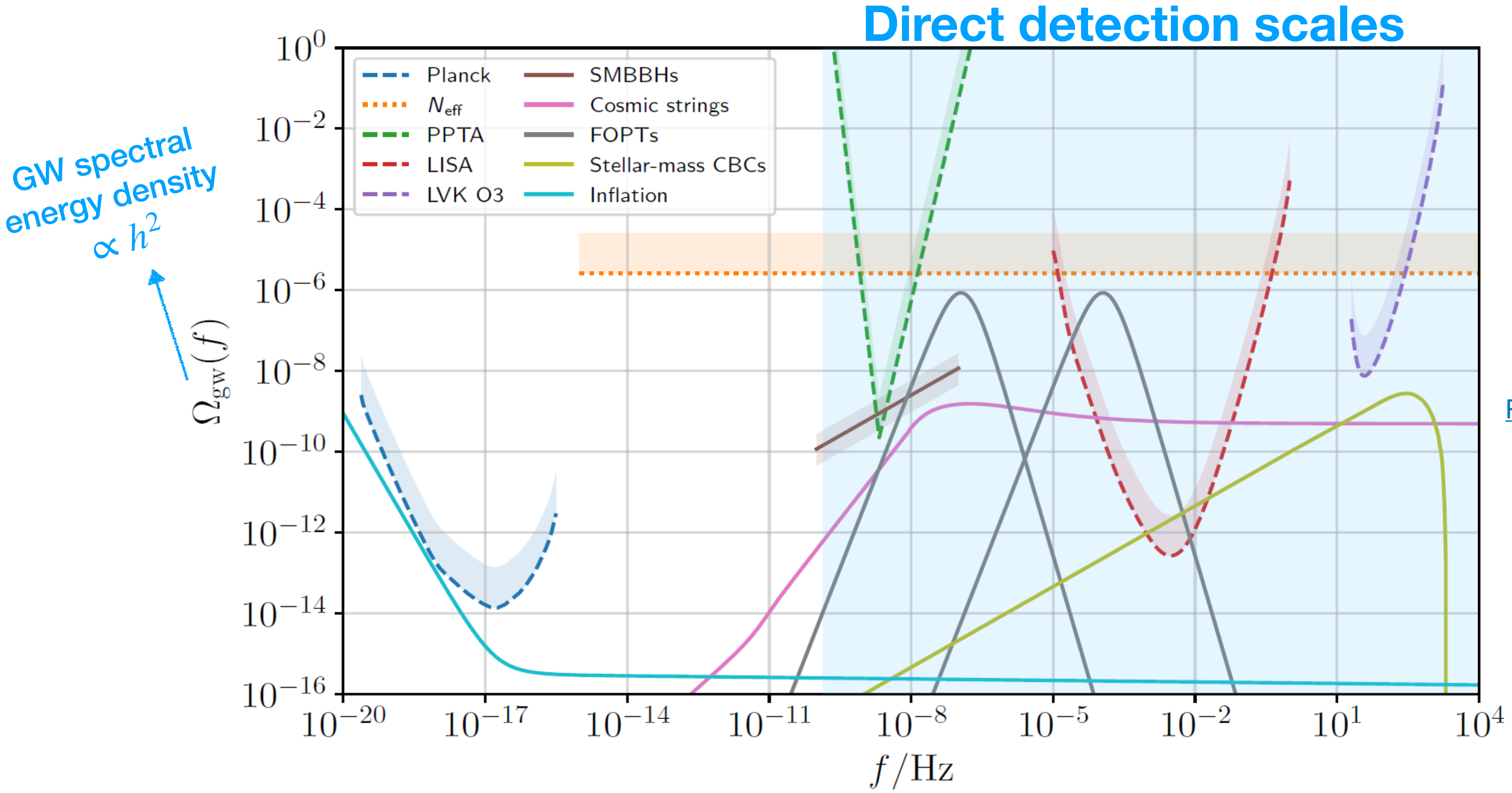


[Images: A. Stuver/LIGO]

SGWB

- SGWB characterised in terms of their statistical properties
  - 2-point (intensity/energy density) + higher order correlations
  - Spectral shape
  - Polarisation (circular/linear)
  - **Anisotropies**

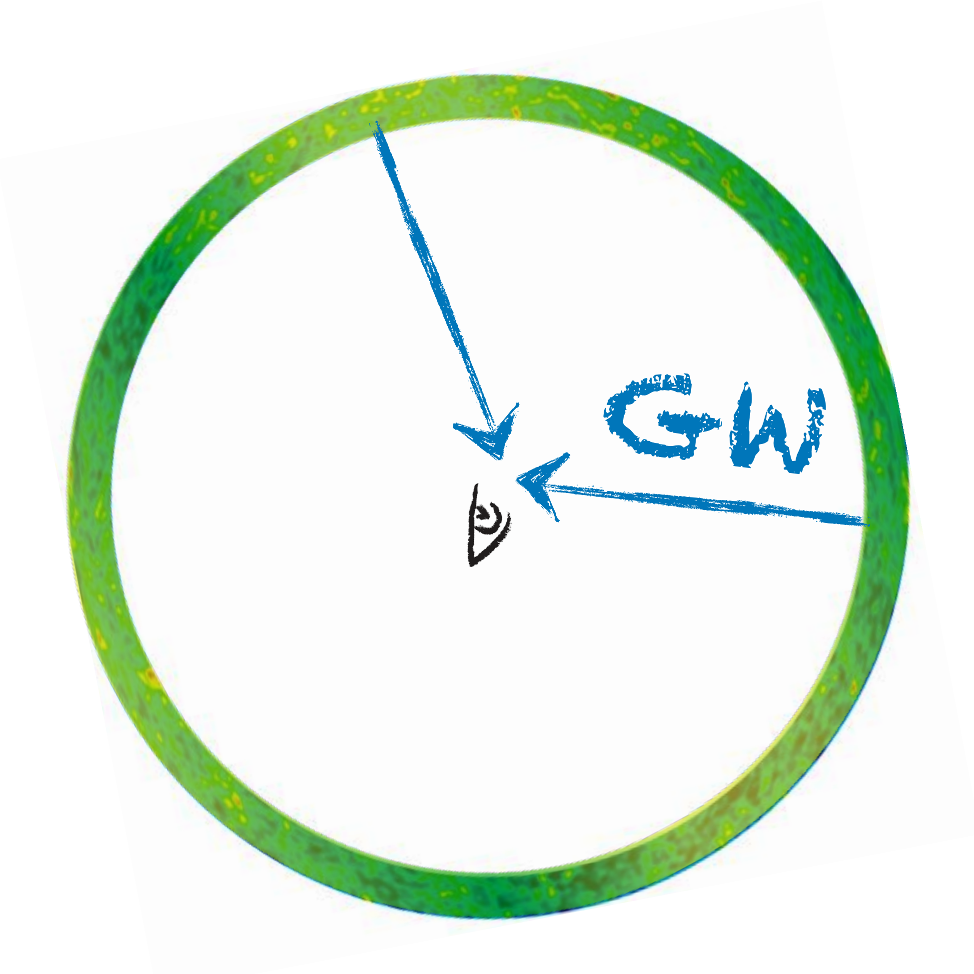
SGWB Landscape



Renzini et al. 2022

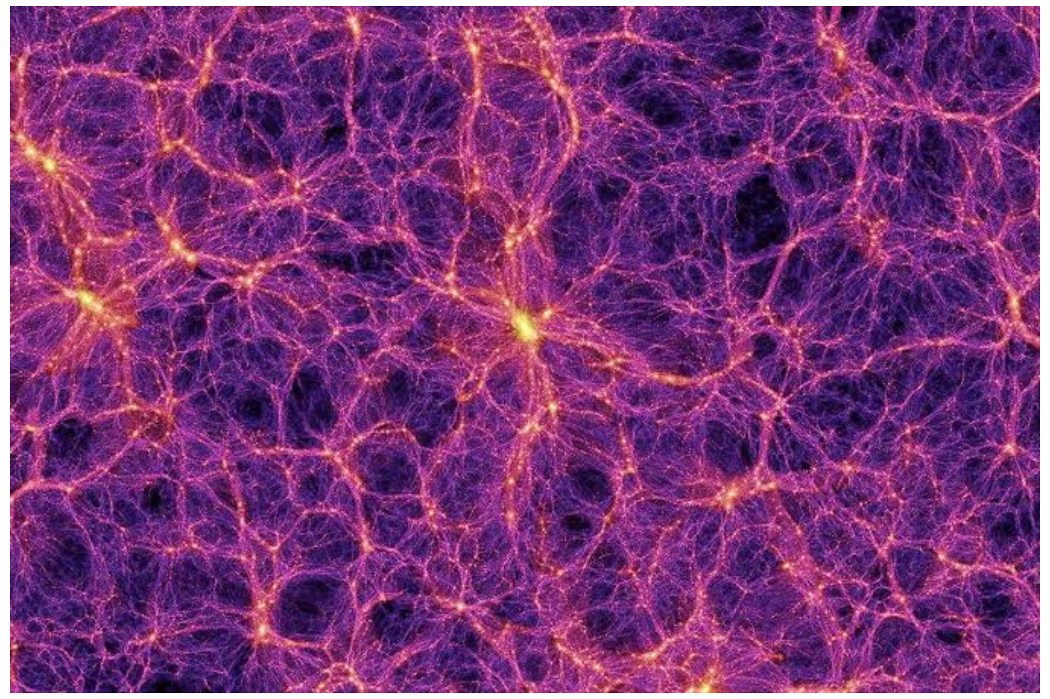
SGWB Anisotropies

GW Production



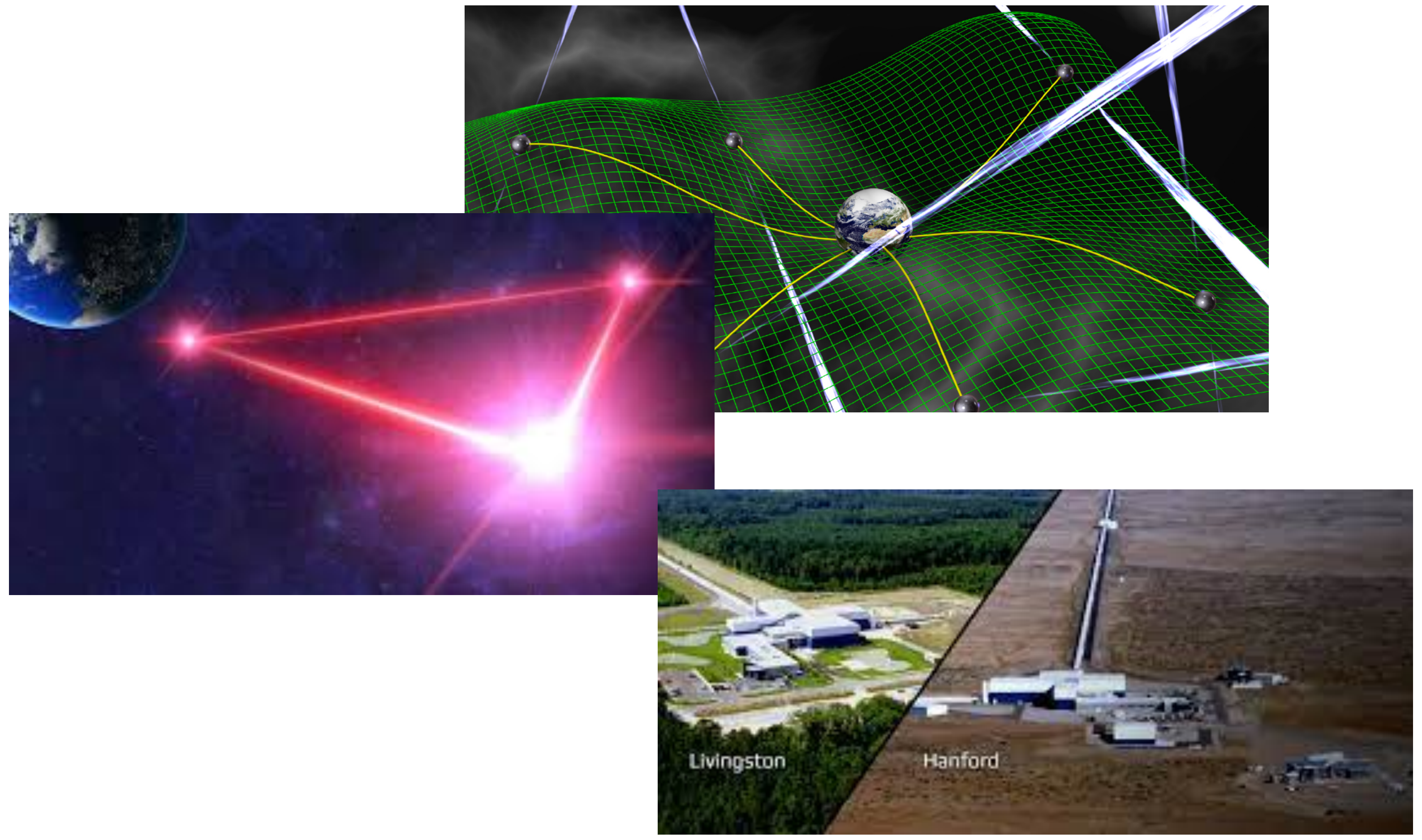
Primordial source properties imprinted on anisotropies
(Inflation, PT, PBH…)

GW Propagation



Propagation through large scale density perturbations

Detection



Characterising SGWB, parameter inference + model constraints

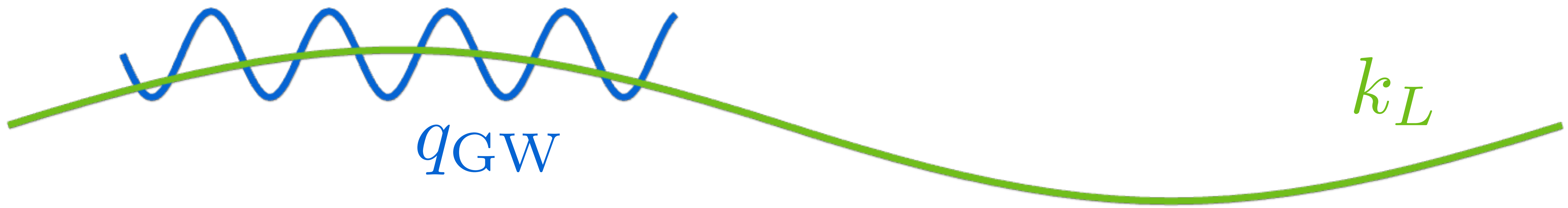
$t \approx 0$

Today

See review by LISA CosWG (2022)

SGWB line-of-sight formalism

GW propagating along null geodesics of background spacetime with large scale perturbations



Described by distribution function $f(\eta, \vec{x}, q^{\mu})$ with $q =$ comoving momentum, $\eta =$ conformal time

[Alba & Maldacena 2015, Contaldi 2017; Bartolo et al. 2019a, 2019b]

SGWB line-of-sight formalism

Zeroth order term + perturbation

$$f(\eta, \vec{q}, \vec{x}) \equiv \bar{f}(\eta, q) - \Gamma(\eta, \vec{x}, q, \hat{n}) \frac{d\bar{f}}{d\ln q}$$

The isotropic and anisotropic parts of the energy density are

$$\bar{\Omega}_{\rm GW} = \frac{4\pi}{\rho_{\rm cr}} \left(\frac{q}{a_0}\right)^4 \bar{f}(\eta, q), \quad \delta_{\rm GW} = \left[4 - \frac{\partial \ln \bar{\Omega}_{\rm GW}(q)}{\partial \ln q}\right] \Gamma(\eta, \vec{x}, q, \hat{n})$$

[Alba & Maldacena 2015, Contaldi 2017; Bartolo et al. 2019a, 2019b]

SGWB line-of-sight formalism

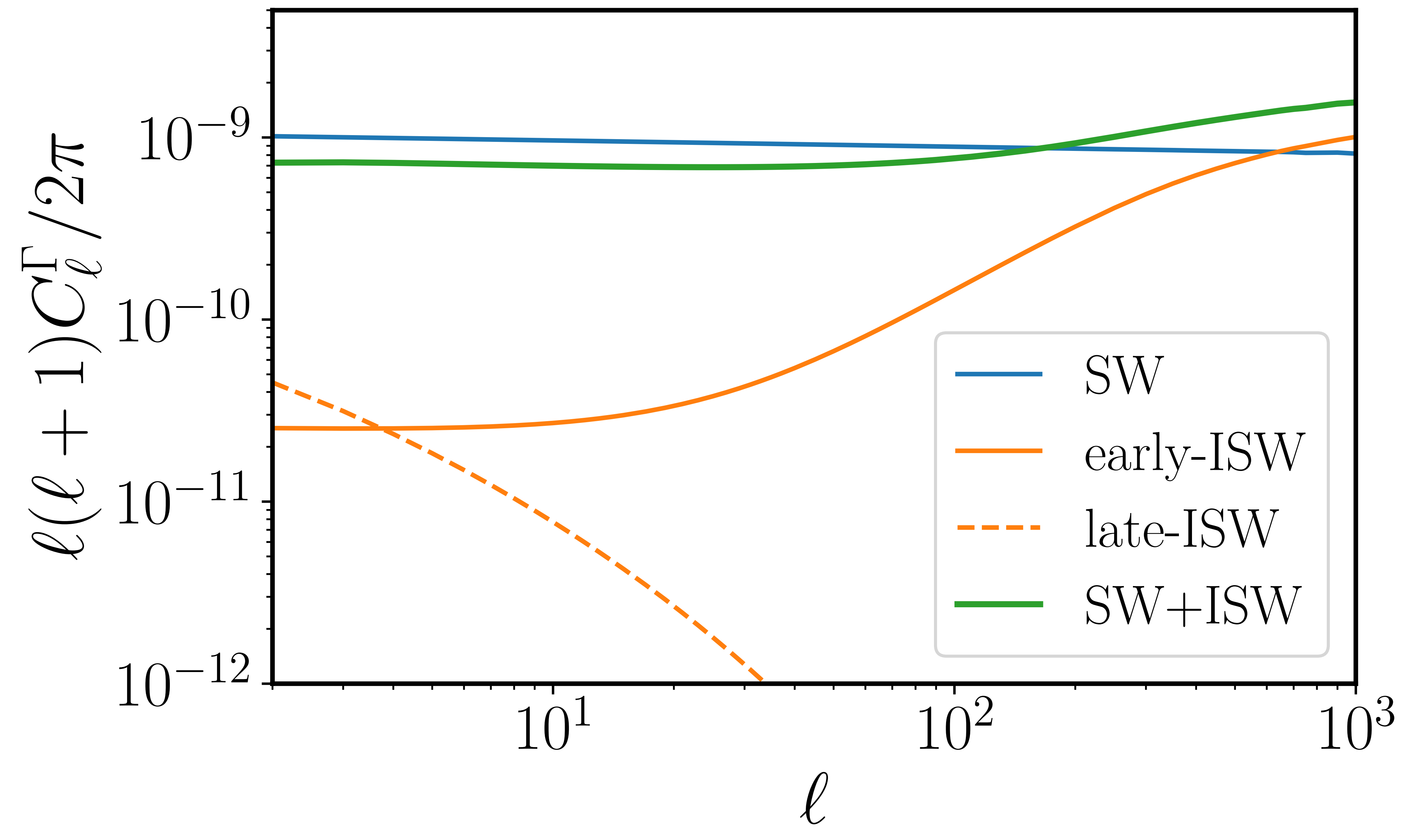
Solution in terms of Newtonian gauge potentials

$$\underbrace{\Gamma(\eta_0, k, f, \hat{n})}_{\text{“}\Delta T/T\text{” for GW}} = \Gamma_I + \Phi_I + \int_{\eta_i}^{\eta_0} d\eta \left\{\Phi'(k,\eta) + \Psi'(k,\eta)\right\} e^{-i\hat{k}\cdot\hat{n}(\eta_0-\eta)}$$

$\Gamma_I \equiv \Gamma(\eta_i, k, f, \hat{n}) \rightarrow$ initial perturbation

$\Phi_I \equiv \Phi(k, \eta_i) \rightarrow$ SW

$\Phi'(k,\eta) + \Psi'(k,\eta) \rightarrow$ ISW

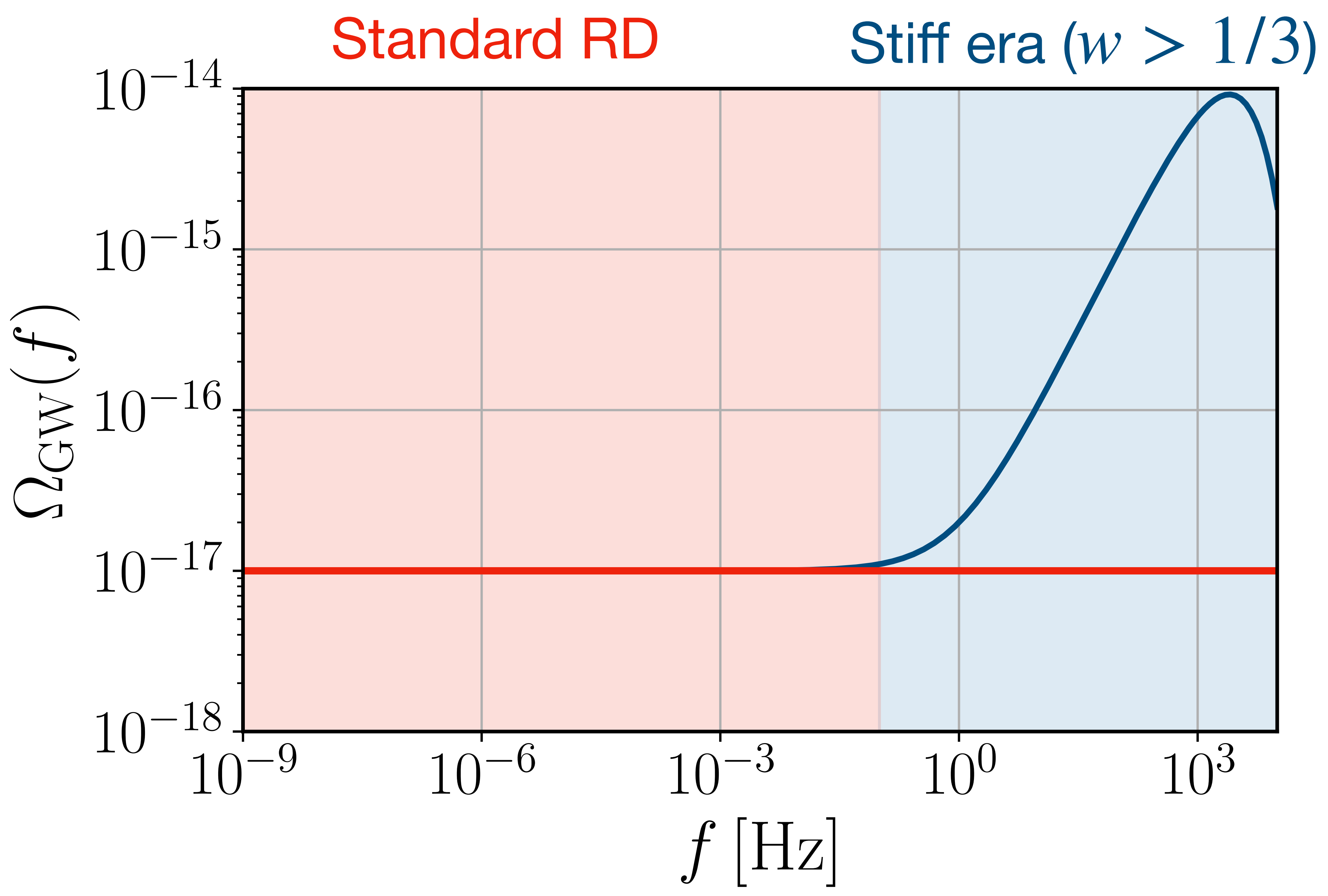


[Alba & Maldacena 2015, Contaldi 2017; Bartolo et al. 2019a, 2019b]

Adiabatic initial conditions - non standard w

- Equation of state of universe before BBN unknown - possible kination, eMD…
- SGWB spectral shape can tell us the expansion history
- However, possible degeneracies with other production mechanisms
- Can anisotropies help?

See Allahverdi et al. 2020 for a review



Adiabatic initial conditions

- SGWB produced/horizon re-entry during an epoch with equation of state w

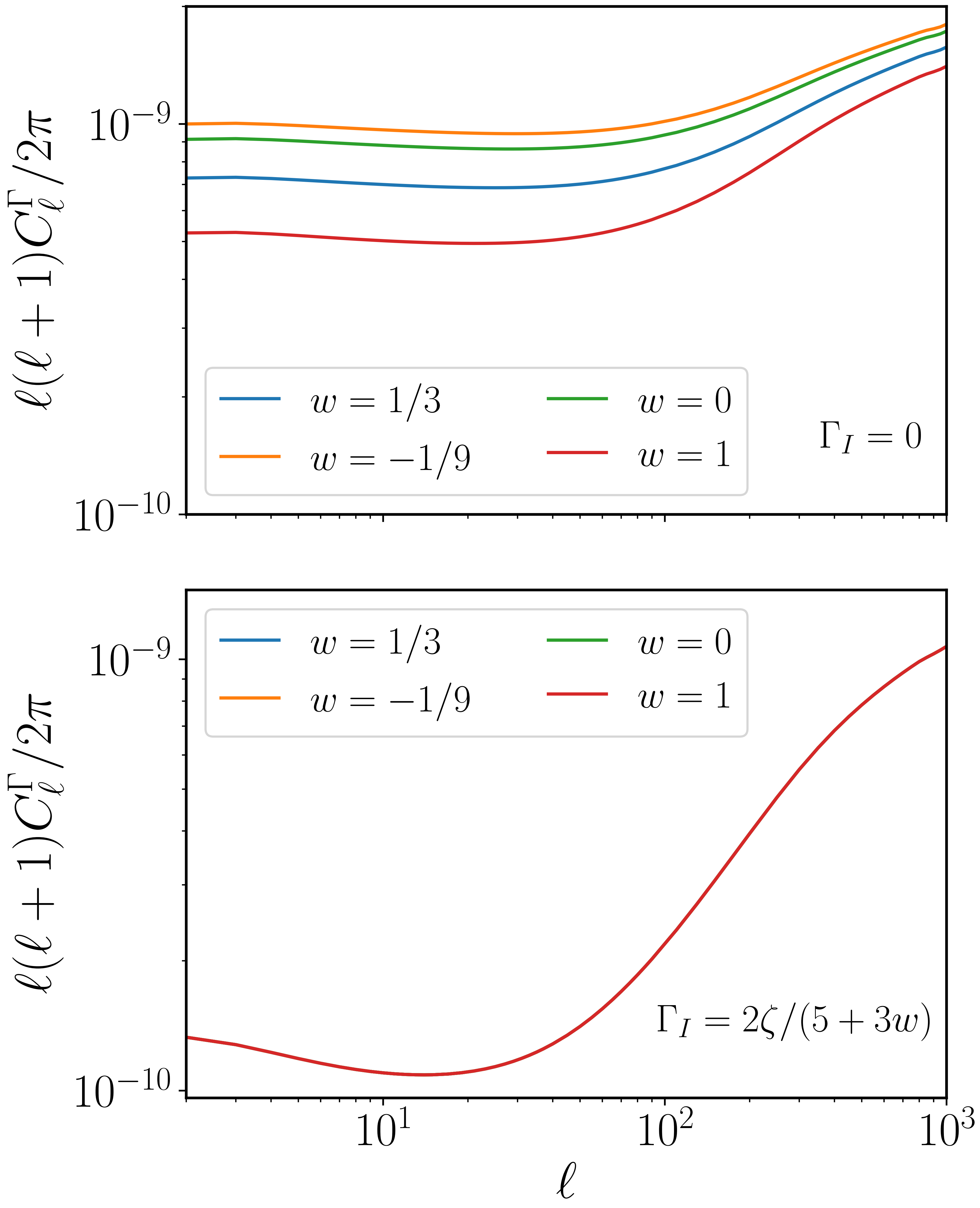
- For adiabatic initial conditions $$\Gamma_I = \frac{2\zeta}{5+3w}, \qquad \Phi_I = -\frac{3(1+w)}{(5+3w)}\zeta$$

- What is the effect on the anisotropies?

Adiabatic initial conditions

- **No** effect on anisotropies from non-standard w
- Adiabaticity $\implies \zeta$ conserved on superhorizon scales

$$C_\ell^\Gamma \propto \left[-\frac{1}{3}\zeta j_\ell(k\eta_0) + \mathrm{ISW}\right]^2$$

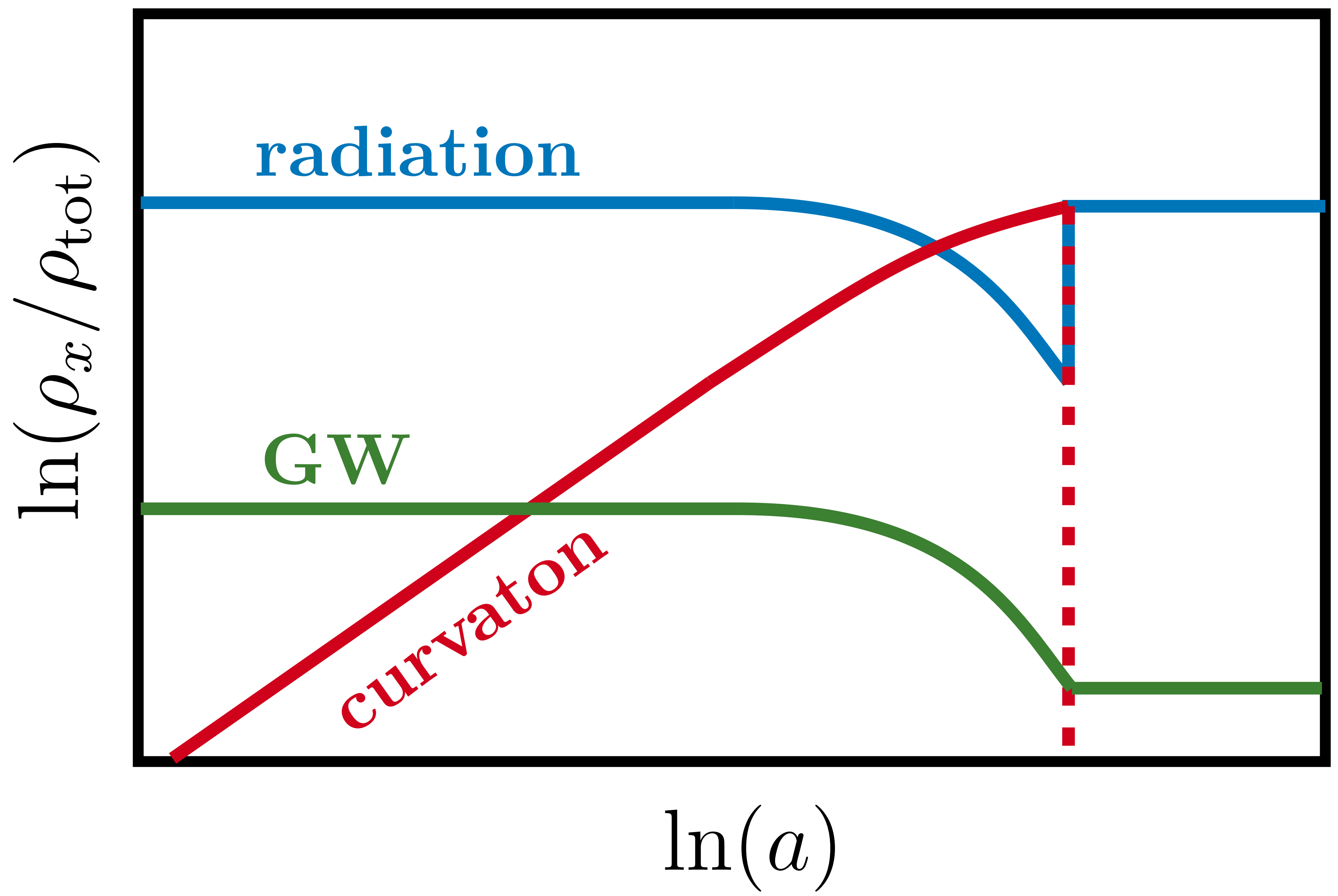


Isocurvature via curvaton mechanism

- Additional scalar field besides the inflaton, subdominant during inflation [Enqvist & Sloth, Lyth & Wands, Moroi & Takahashi (2002)]
- Post-inflation, it behaves like dust and may dominate the energy density of the universe
- Resulting isocurvature depends on the decay products of the curvaton

Curvaton scenario I

- Curvaton dominates $\rho_{\rm tot}$ then decays entirely into radiation
- Fluctuation amplitude fixed by CMB normalisation

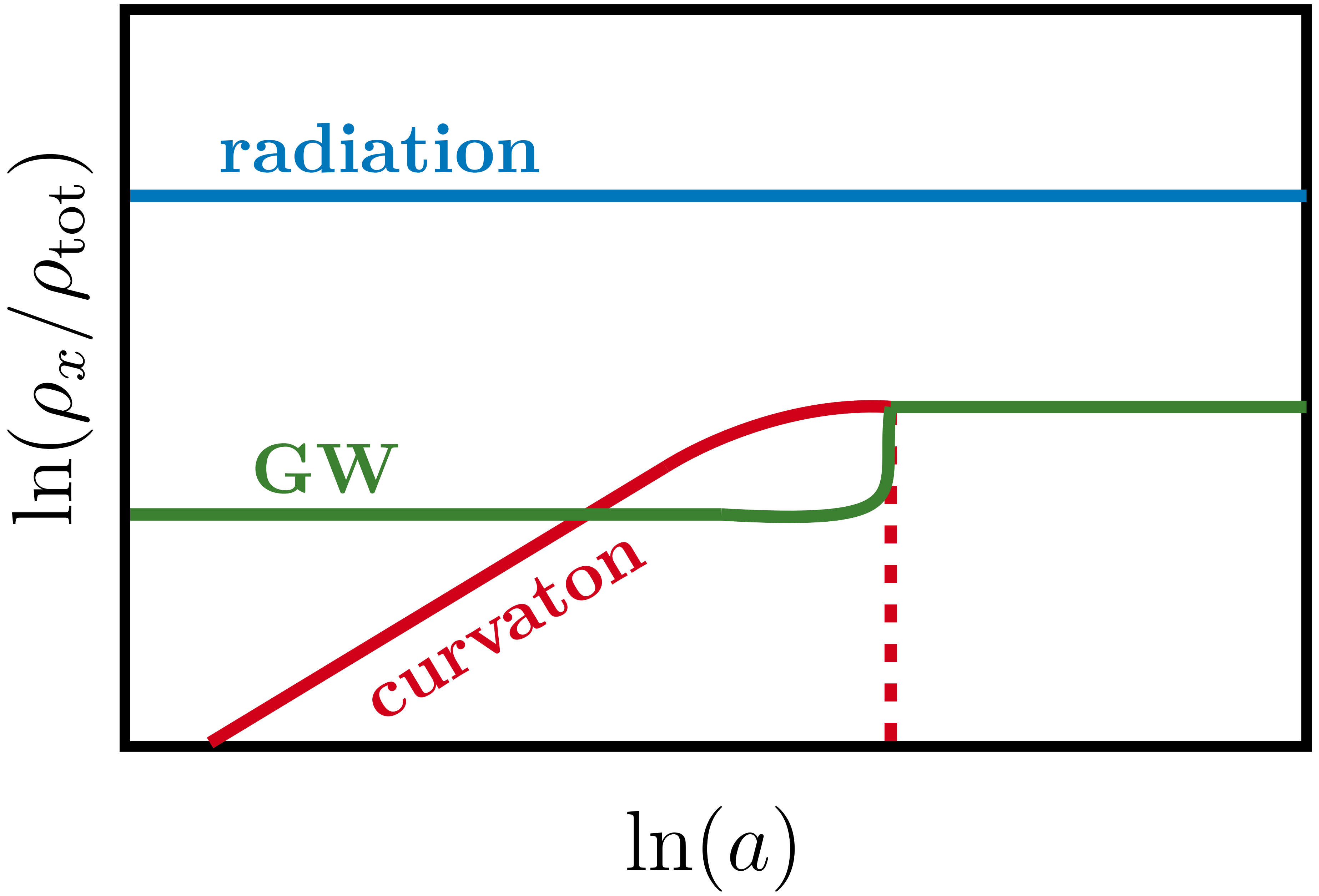


$$C_\ell^\Gamma \propto \left[-\frac{4}{3}\zeta_r\, j_\ell[k\eta_0] + \mathrm{ISW} \right]^2$$

4x adiabatic term

Curvaton scenario II

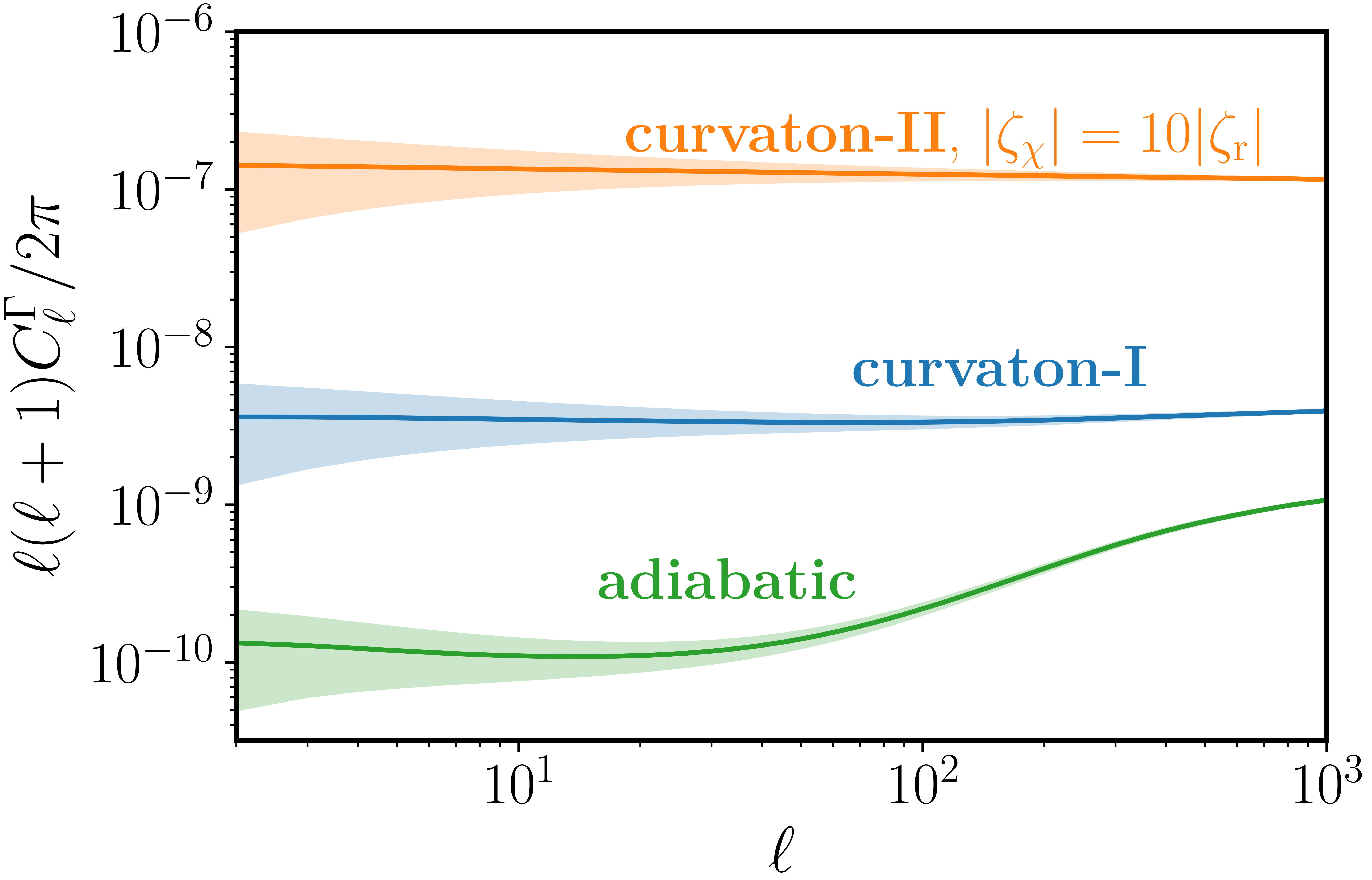
- Curvaton remains subdominant and decays entirely into GW
- Fluctuation amplitude not fixed



$$C_\ell^\Gamma \propto \left\{ \left[\frac{(1+w_\chi)}{(1+w_r)}\zeta_\chi - \frac{1}{3}\zeta_r \right] j_\ell[k\eta_0] + \text{ISW} \right\}^2$$

independent curvaton fluctuations

Curvaton summary plot



Summary

- Anisotropies a key property for characterising SGWB
- Adiabatic anisotropies independent of primordial equation of state
- Distinct predictions for isocurvature anisotropies based on curvaton mechanism

Thank you!

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