Gravitational waves from inflation

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Talk based on papers in collaboration with:

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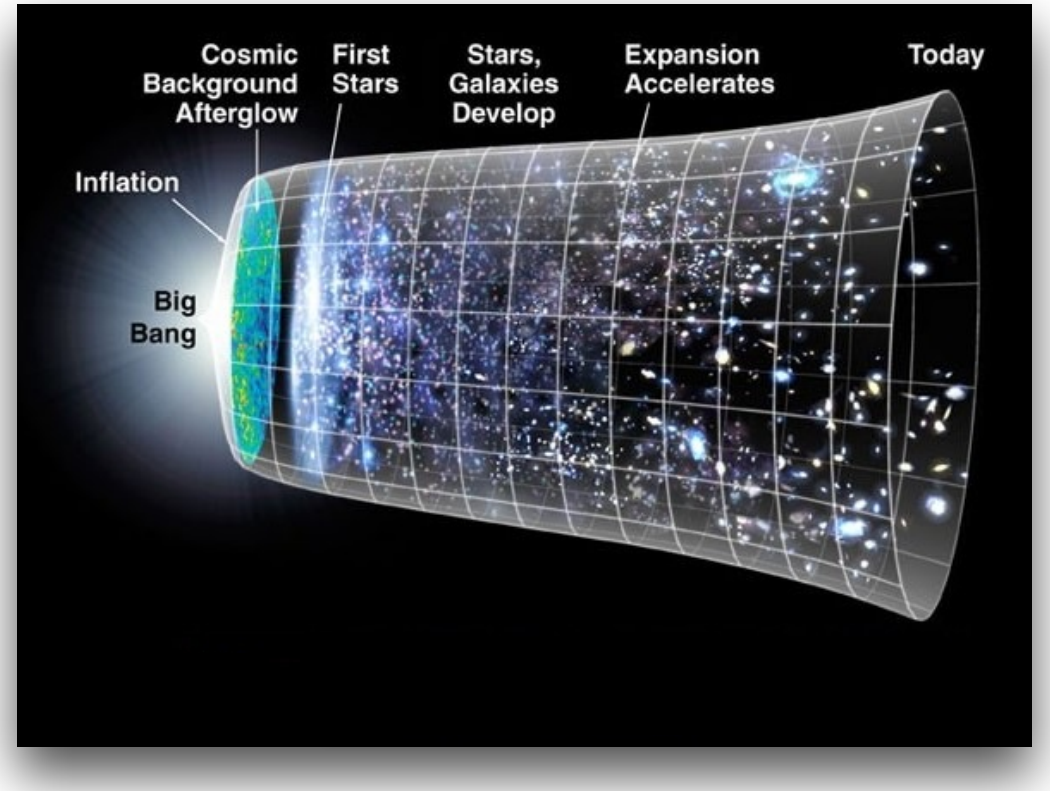
Marc Kamionkowski, Eugene Lim, Ameek Malhotra,
Daan Meerburg, Giorgio Orlando, Maresuke Shiraishi,
Gianmassimo Tasinato



Inflation predicts a stochastic gravitational wave background

- How does it look like?
- What info does it provide on inflation?
- How do we characterise it (and distinguish it from other SGWBs)?

— Frequency profile
— Chirality
— Non-Gaussianity
— Anisotropies

Stochastic background of gravitational waves

Cosmological sources:

- **Inflation**
- Reheating
- Phase transitions
- Cosmic strings

…

Astrophysical sources:

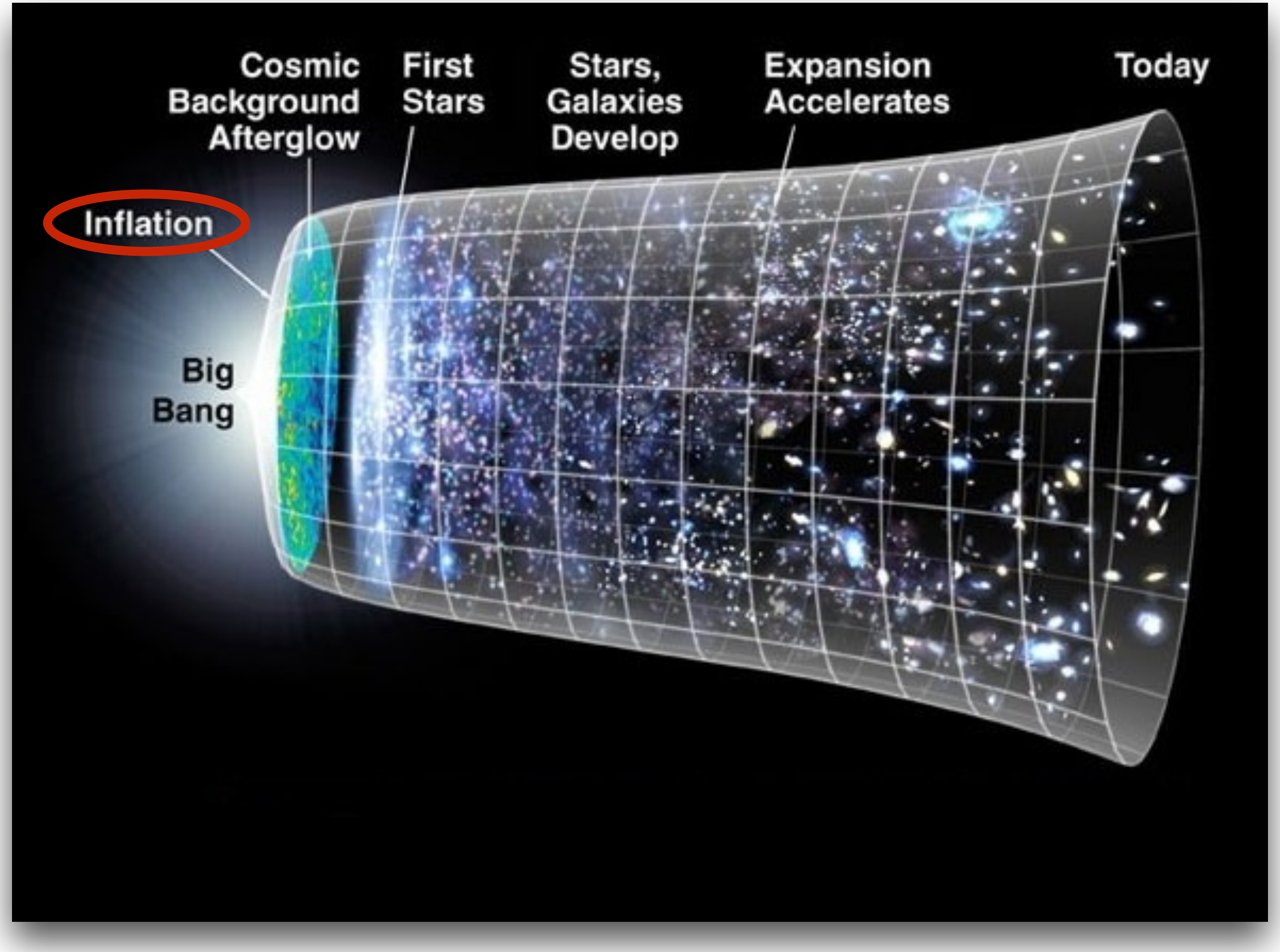
a stochastic gravitational wave background is expected, due e.g. to the superposition of signals from a large number of astrophysical sources (e.g. mergers of black holes, neutron stars,…)

Introduction and motivations: cosmic inflation and primordial gravitational waves

Inflation

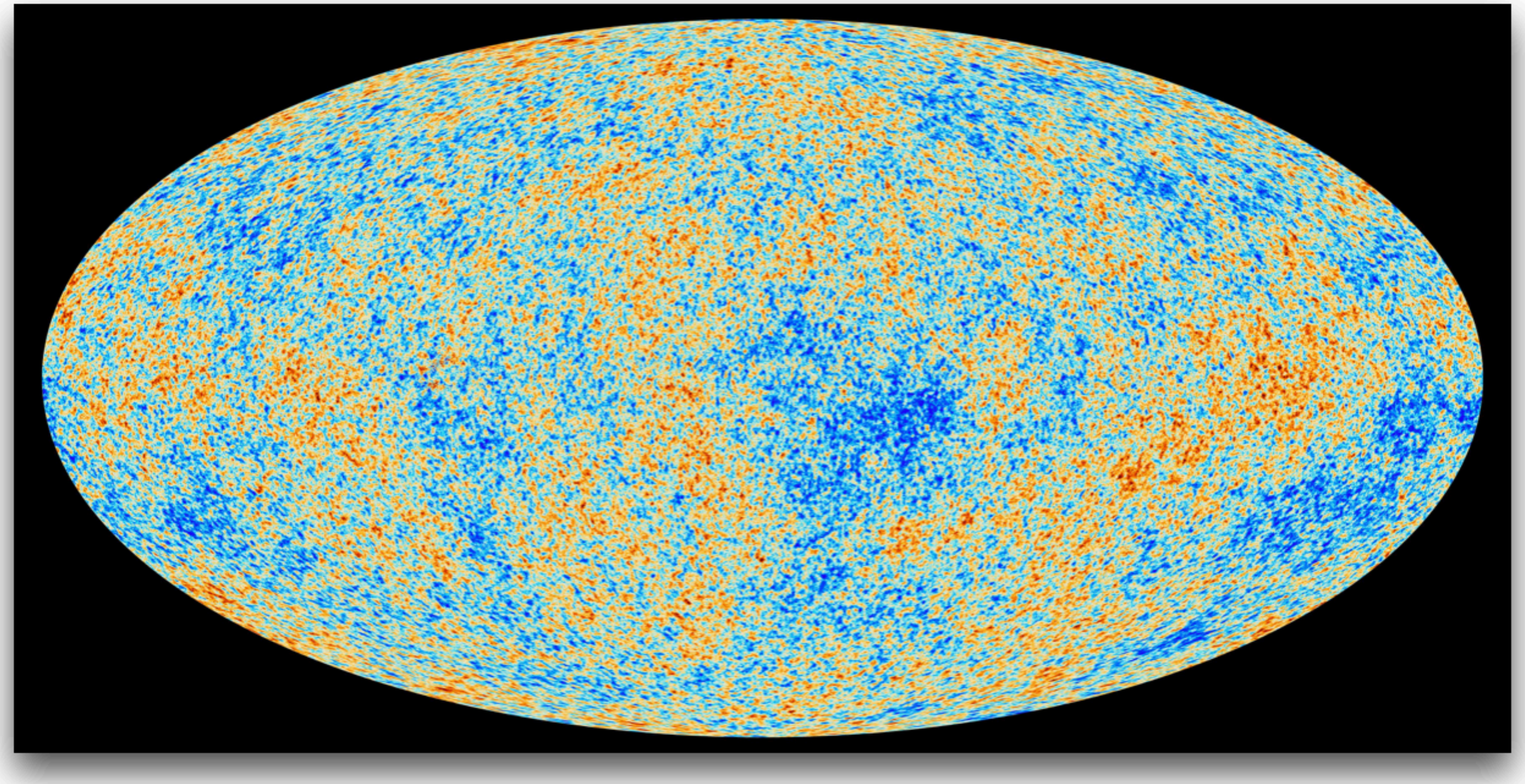
- era of accelerated (exponential) expansion

The universe over time



Inflation

- era of accelerated (exponential) expansion
- explains why CMB is nearly uniform



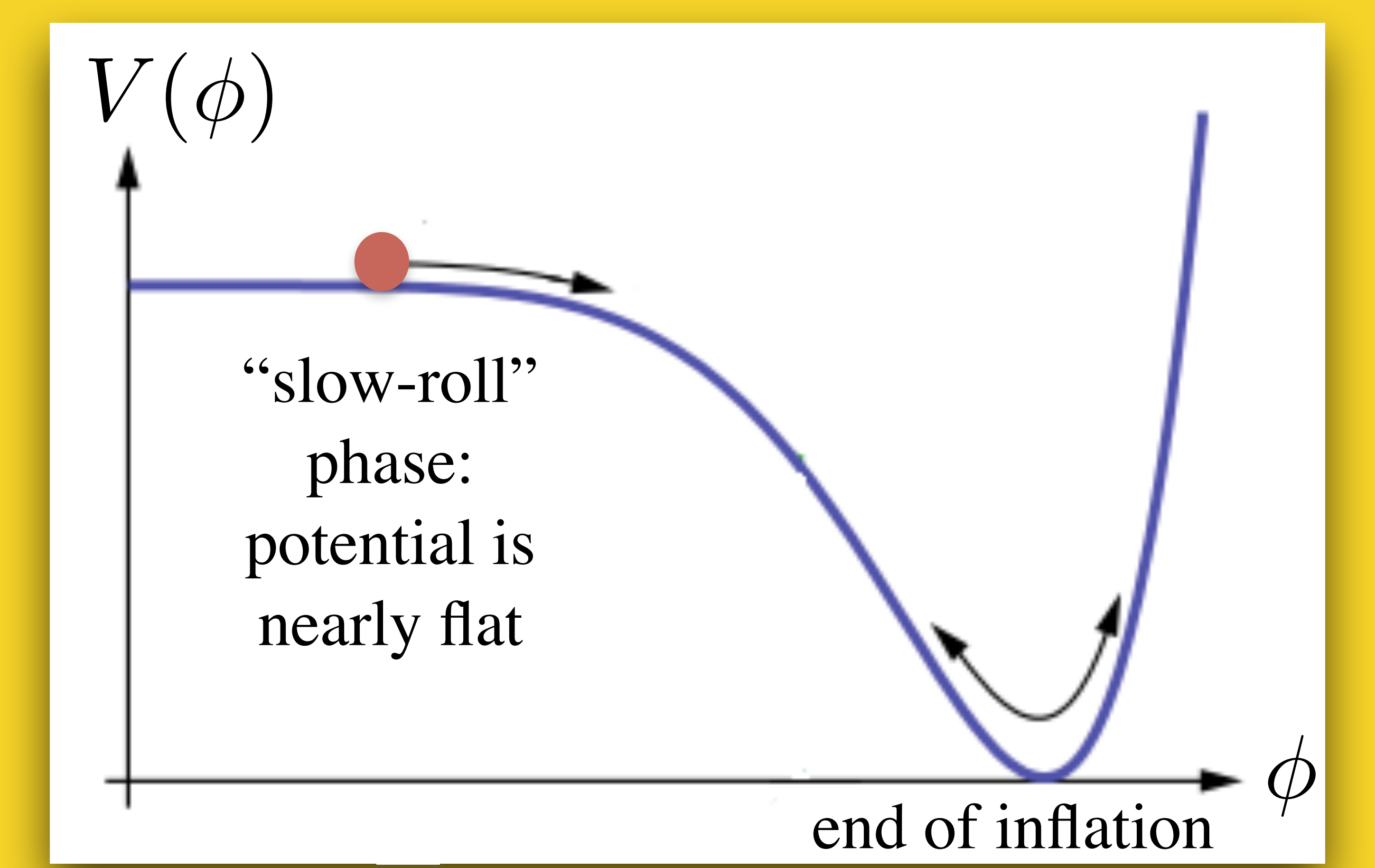
blackbody spectrum: $\bar{T}_{CMB} \sim 2.7\, K$

nearly isotropic: $\Delta T \sim 10^{-5}$

Inflation

- era of accelerated (exponential) expansion
- explains why CMB is nearly uniform
- explains how those fluctuations are generated

Simplest realization: single-scalar field in slow-roll (SFSR)



Inflation

- era of accelerated exponential expansion
- explains why CMB is nearly uniform
- explains how those fluctuations are generated

$$\varphi(\vec{x},t) = \phi(t) + \delta\phi(\vec{x},t)$$

classical homogeneous background

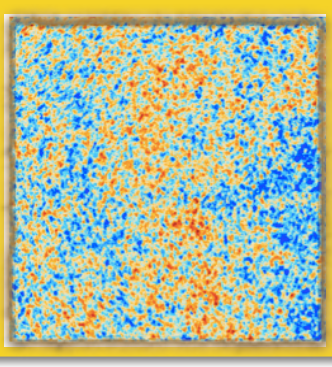
quantum fluctuations

perturbation modes are stretched by the expansion, become super horizon and freeze out to their value at horizon exit

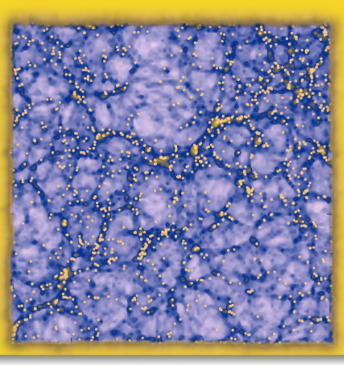
$$\lambda = a(t)\lambda_c$$

cosmological perturbations

ΔT

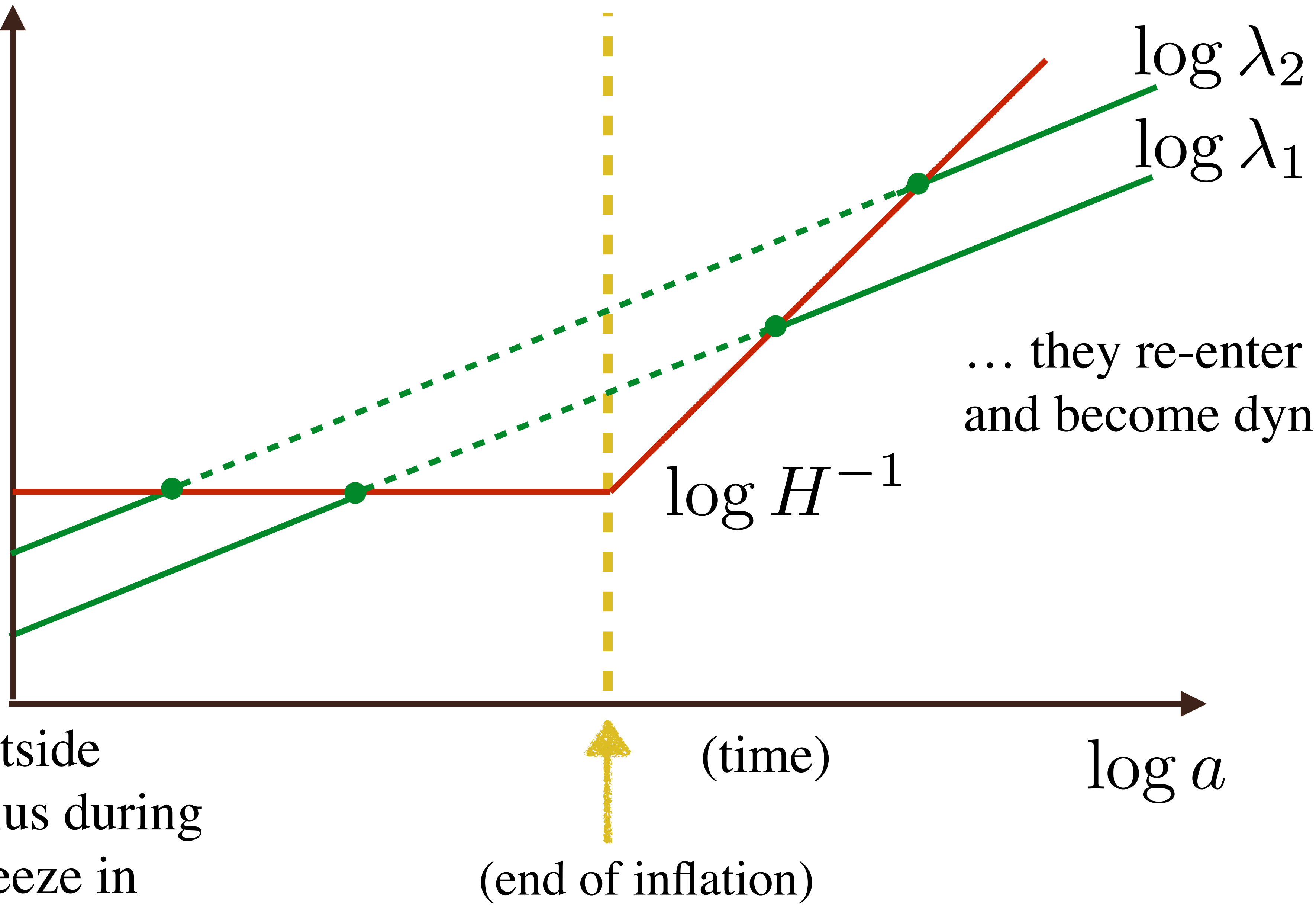


$\delta\rho$



Scales

wavenumber k → e-folding N_k → time of re-entry



… they re-enter after inflation and become dynamical again

Perturbation modes cross outside the Hubble radius during inflation and freeze in

Gravitational waves

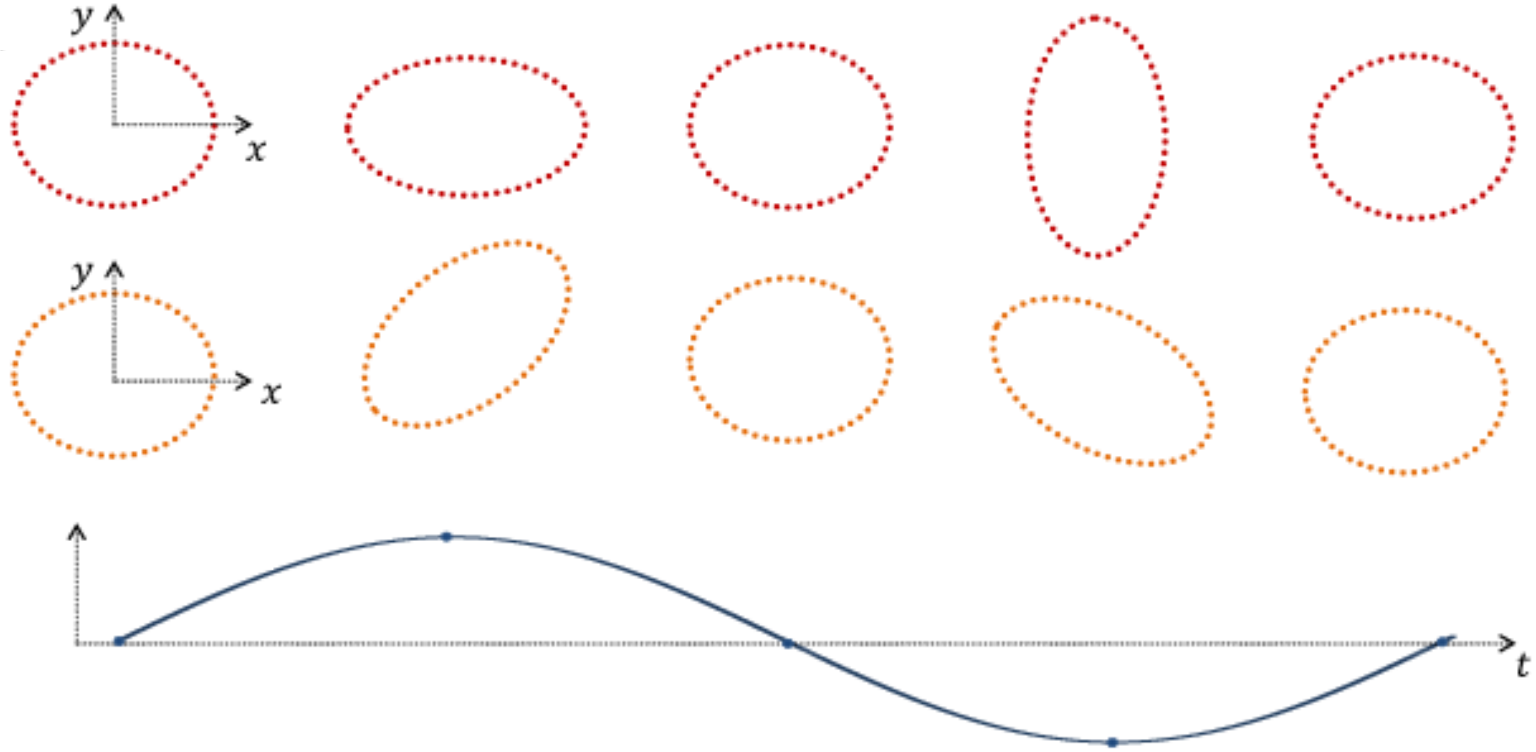
Einstein equations:

$$\underbrace{G_{\mu\nu}}_{\text{geometry}} = 8\pi G \underbrace{T_{\mu\nu}}_{\text{matter/source}}$$

Perturbation around FRLW (homogenous&isotropic) background

$$ds^2 = -dt^2 + a^2(t)\left(\delta_{ij} + \enclose{circle}{\gamma_{ij}}\right) dx^i dx^j$$

$$\gamma^i_i = \partial_i \gamma_{ij} = 0 \longrightarrow$$ **two polarization states of the graviton: +,×**



Gravitational waves

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

- **homogeneous** solution: GWs from **vacuum fluctuations**

Production of gravitons out of the vacuum
in an expanding universe!

- **inhomogeneous** solution: GWs from **sources**

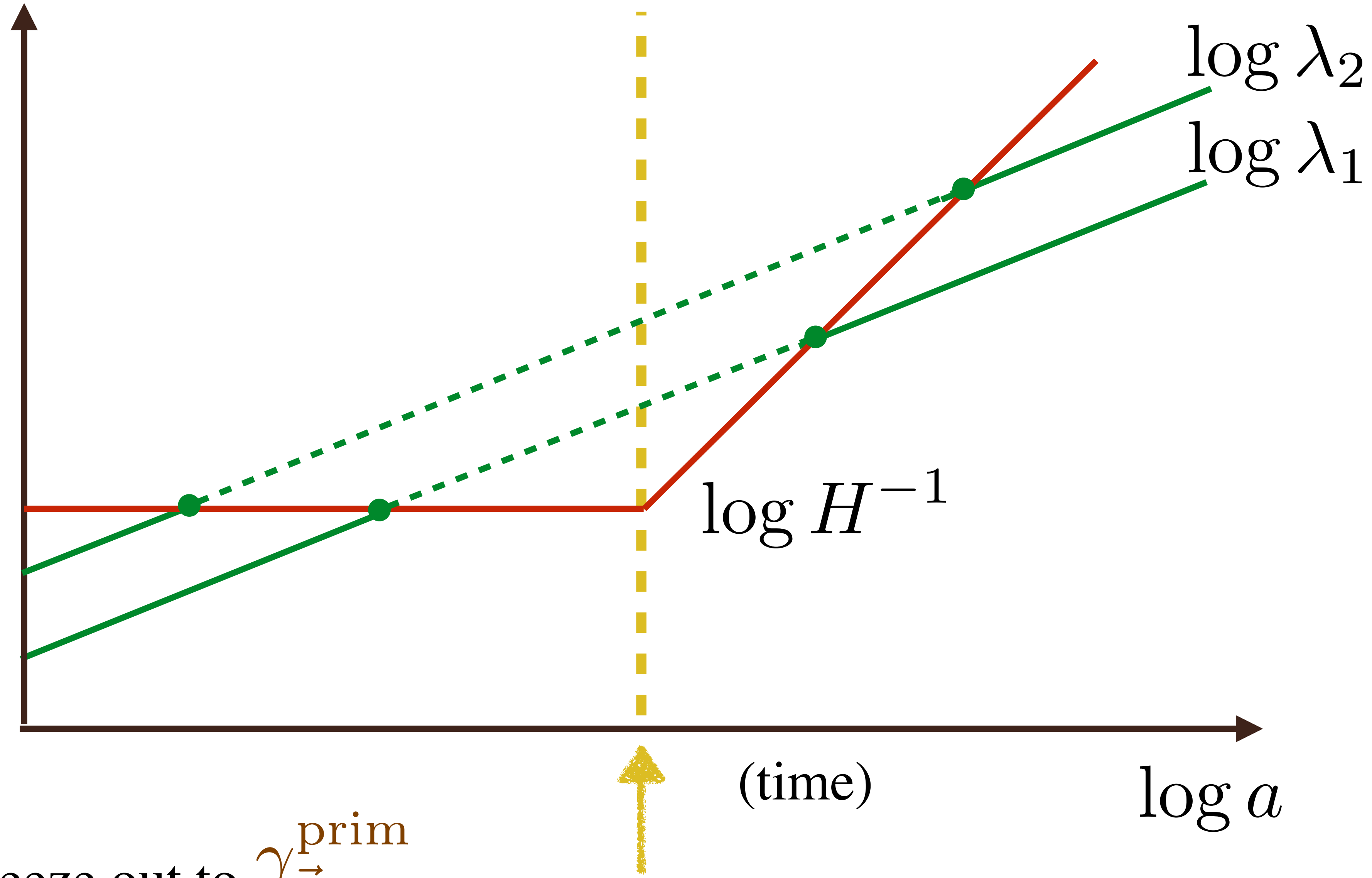
$\Pi_{ij}^{TT} \propto$ {scalar fields, vector fields, fermions, tensors … }

Scales

… they re-enter after inflation
and become dynamical again

$$\gamma_{\vec{k}}(\tau) = T(\tau, k)\gamma_{\vec{k}}^{\text{prim}}$$

transfer function
(subhorizon evolution)



Perturbation
modes leave
horizon during
inflation and freeze out to $\gamma_{\vec{k}}^{\text{prim}}$

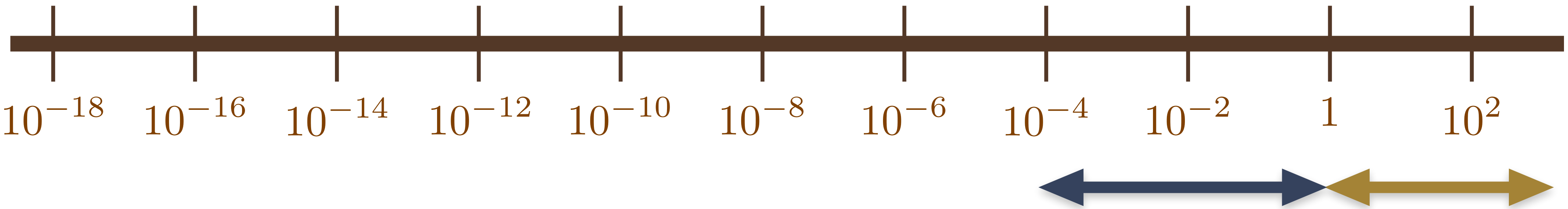
Current bounds and detectability

Direct detection

Gravitational waves travel freely until today

Space get distorted as gravitational wave passes by a detector

Scales — Experiments



time between wave peaks

(age of the universe)

(years)

(hours)

(secs)

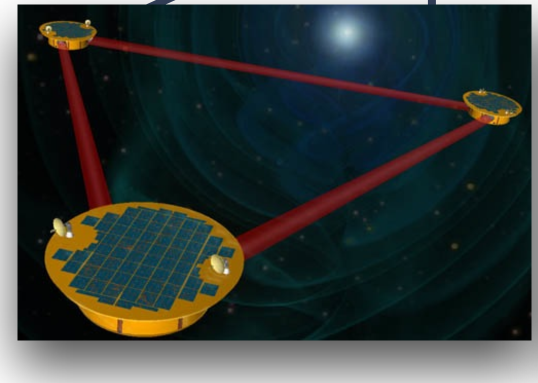
(millisecs)

wave frequency (Hz)

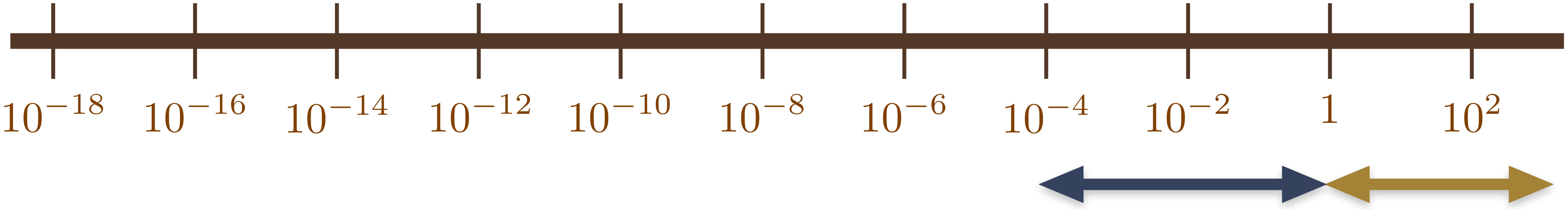
10^{-18} 10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}

space-based interferometers

terrestrial interfer.



Scales — Experiments



Inflationary e-foldings

60 50 40 30 20 10

wave frequency (Hz)

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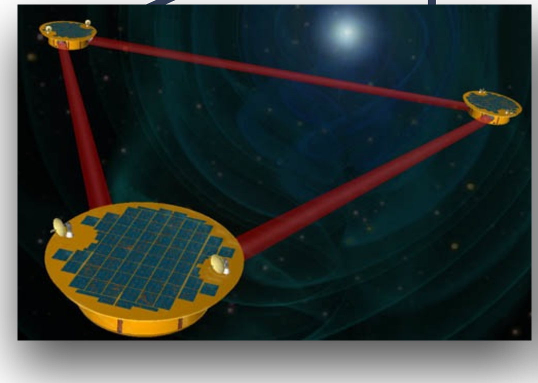
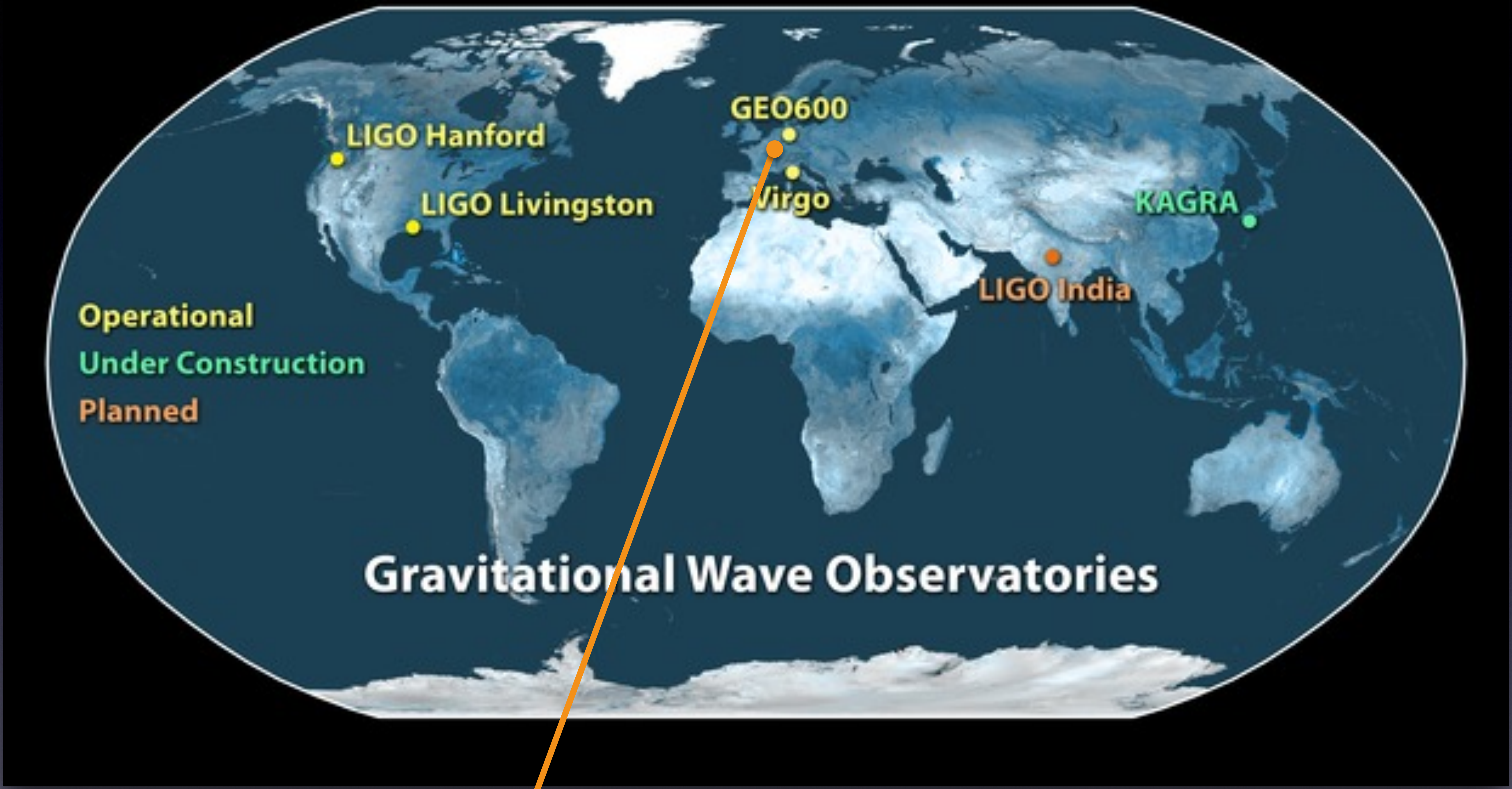
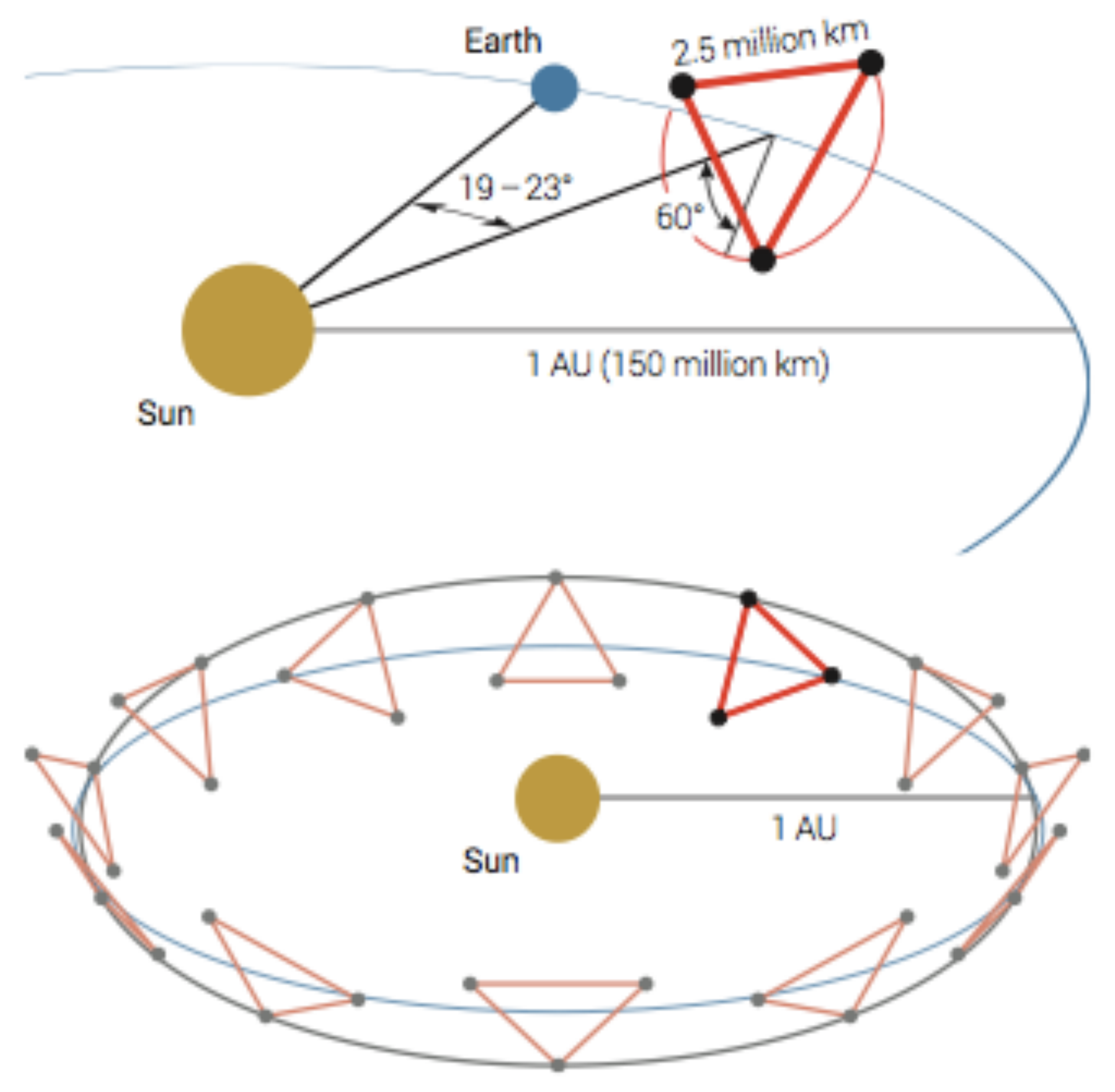




Einstein Telescope (ET)

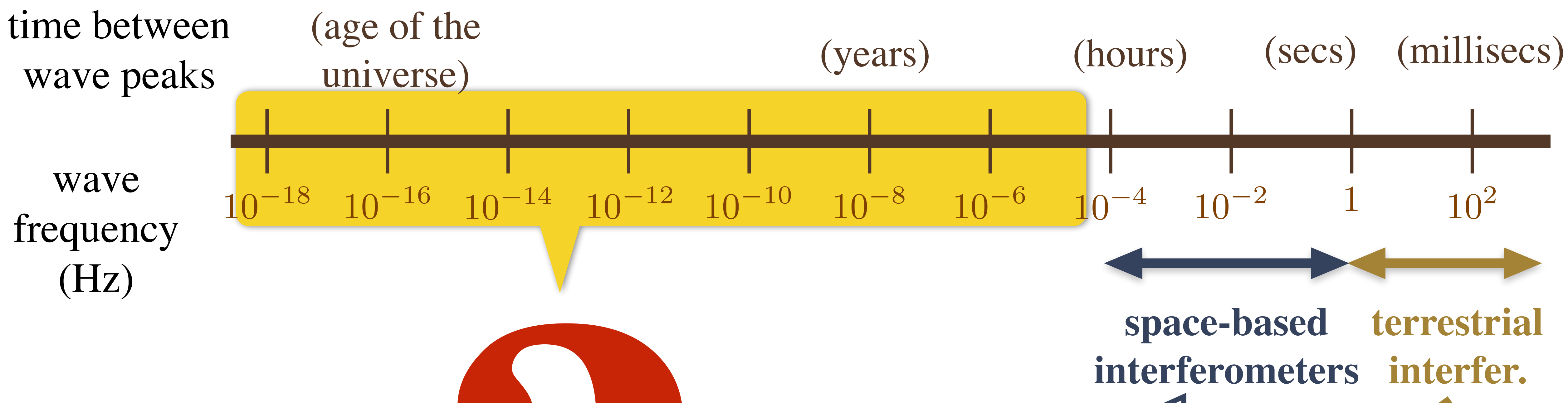
LIGO website

LISA: laser interferometer space antenna



LISA collaboration, 1702.00786

Scales — Experiments



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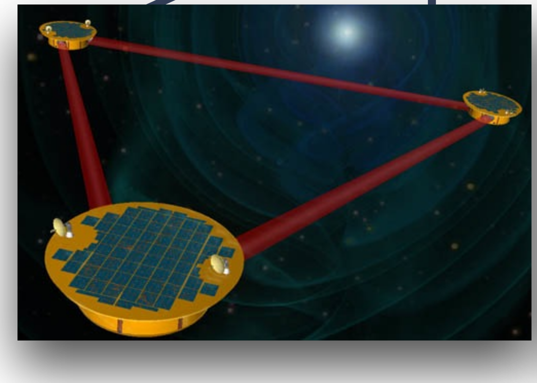
?



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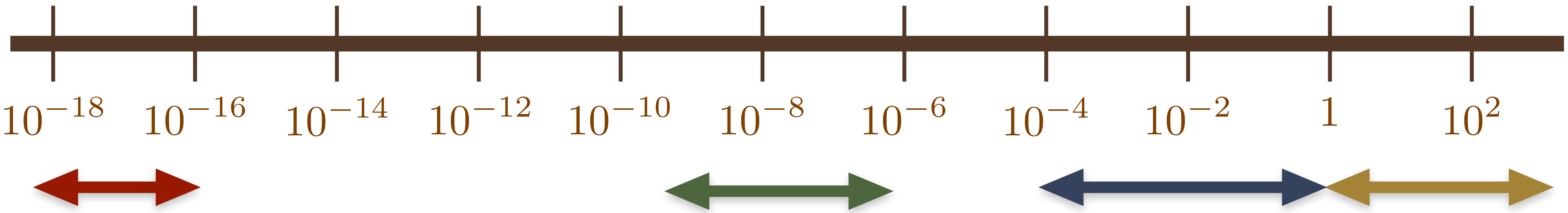

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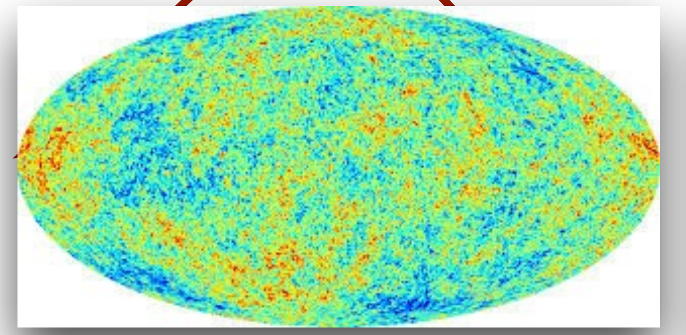
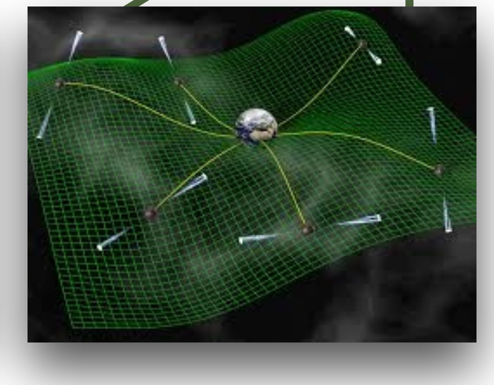
CMB anisotropies

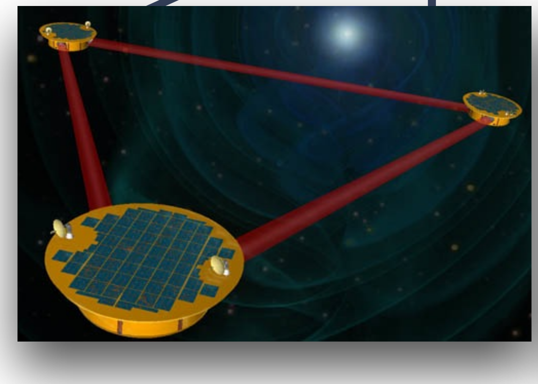
pulsar timing arrays

space-based interferometers

terrestrial interfer.







indirect detection

Primordial GW: indirect detection

In the presence of GW photon propagation occurs along the perturbed geodesics

↓

temperature anisotropies

Thomson scattering of radiation with quadrupole anisotropy by free electrons

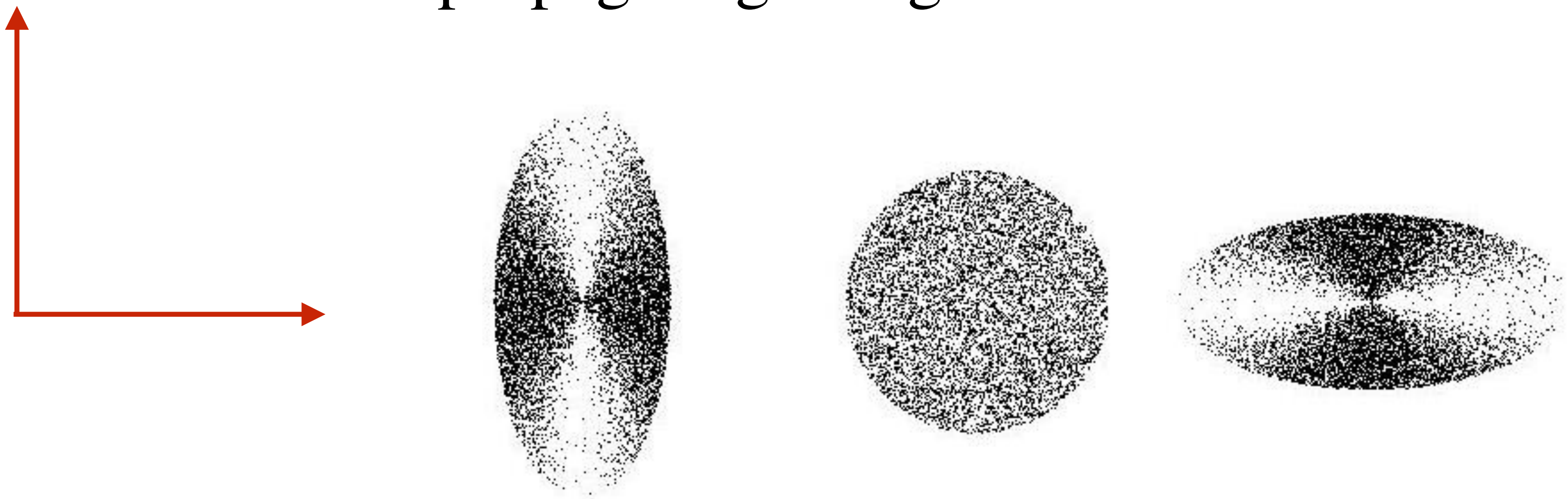
↓

net **linear polarization** for the scattered radiation

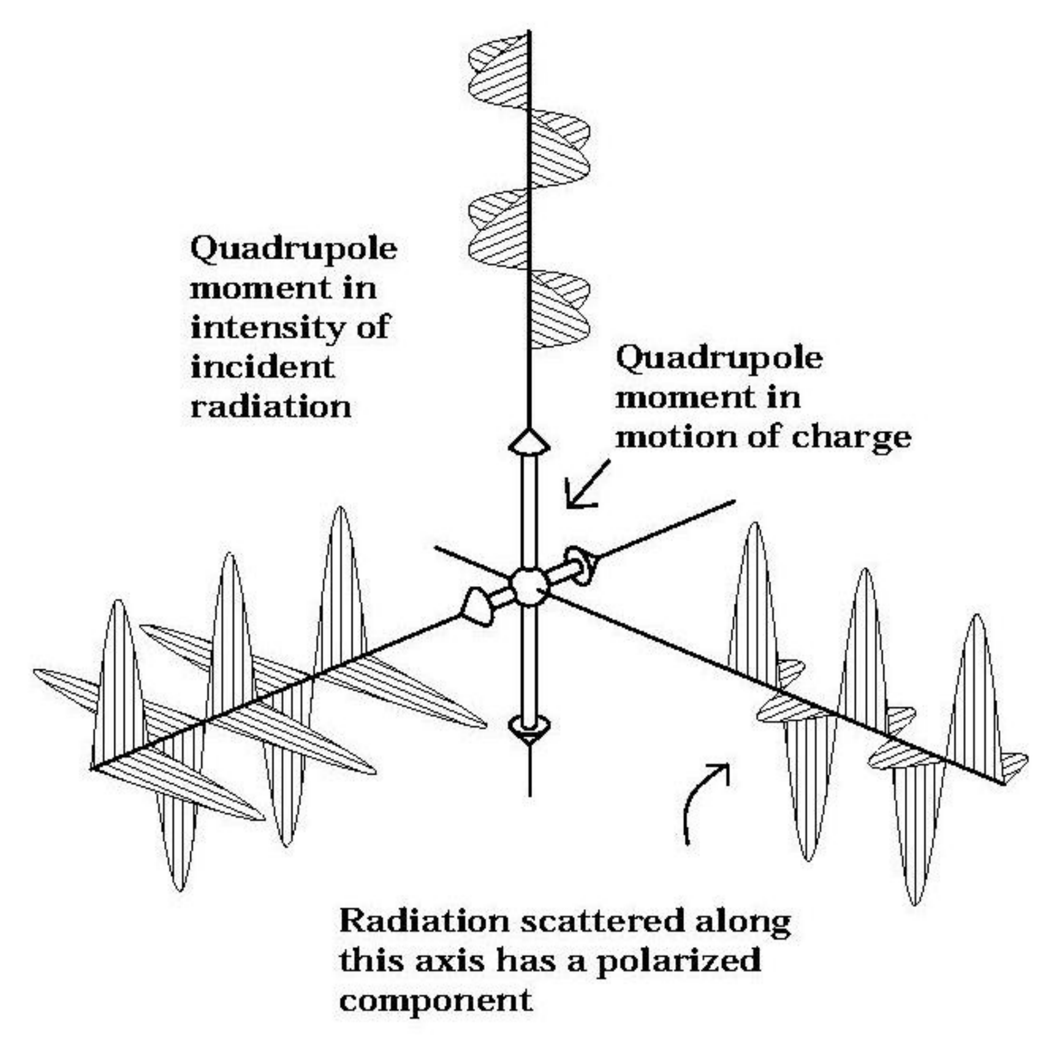
↓

B modes

Distortion of a circular patch of homogenous plasma due to the passing of a gravitational wave: wavelength of photons propagating along the two axis are also distorted!



Thomson scattering



Observational bounds/sensitivities

$$r_{0.002\,\mathrm{Mpc}^{-1}} < 0.056 \longrightarrow V^{1/4} \lesssim 1.6 \times 10^{16}\mathrm{GeV}$$

(Planck+BICEP2/KECK)

Upper bound on the energy scale of inflation

More to come:
BICEP Array, SPT-3G,
Simons Observatory, CMB-S4,
LiteBIRD, PICO, …

What info do gravitational waves provide on inflation?

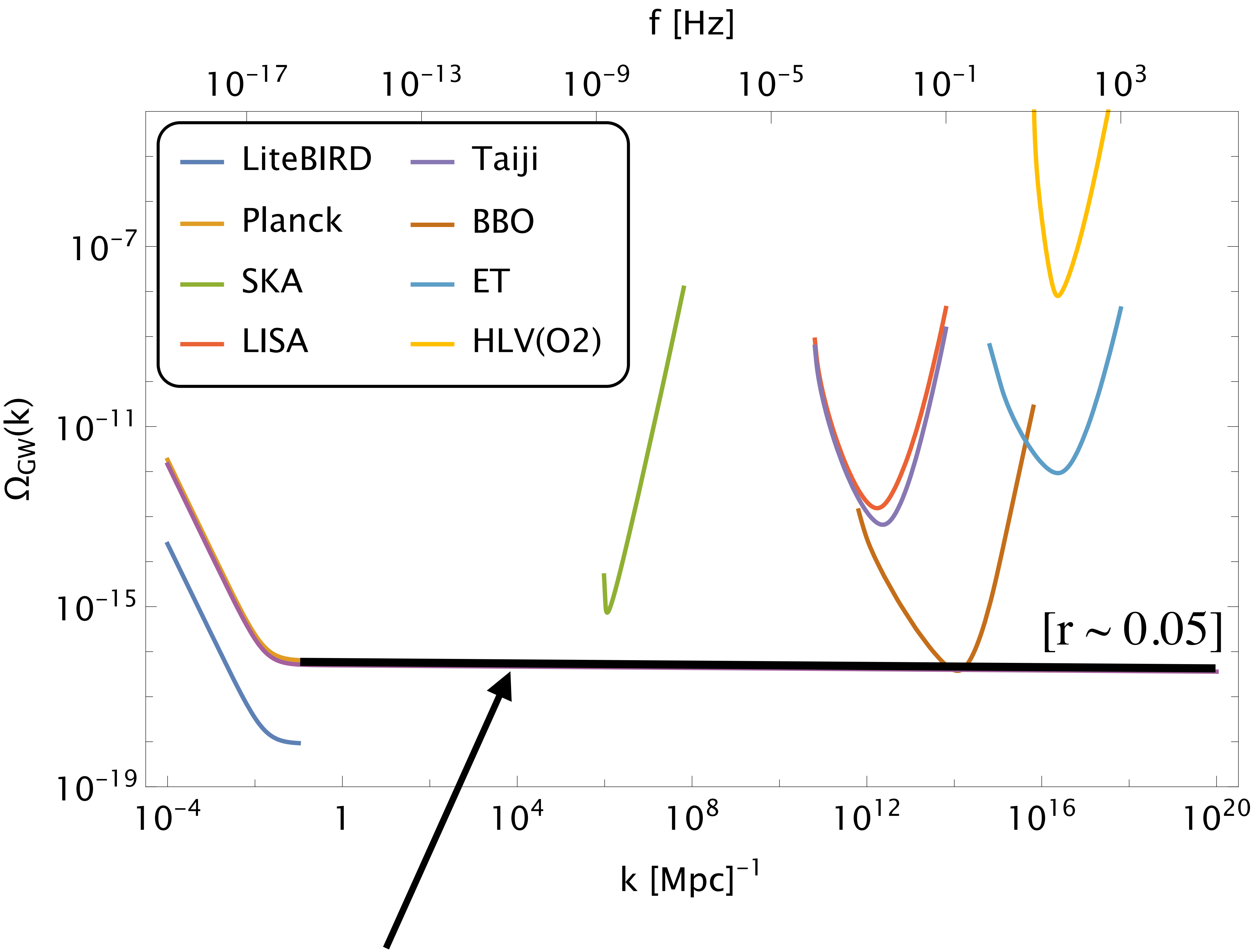
GW can tell us a whole lot about inflation: examples

- GW from the amplification of vacuum fluctuations

$$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + k^2\gamma_{ij} = 0$$

Production of gravitons out of the vacuum
in an expanding universe!

Prediction and sensitivity limits



Standard SFSR would go undetected at small scales (**red tilt**)

Inflationary GW from vacuum fluctuations (SFSR)

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- Generation of GW from additional fields during inflation

GW can tell us a whole lot about inflation: examples

- GW from the amplification of vacuum fluctuations
- Generation of GW from additional fields during inflation

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

anisotropic stress-energy tensor

- Axion-gauge field models $\frac{\lambda\chi}{4f}F\tilde{F}$

  [Anber - Sorbo 2009, Cook - Sorbo 2011, Barnaby - Peloso 2011, Adshead - Wyman 2011, Maleknejad - Sheikh-Jabbari, 2011, ED - Fasiello - Tolley 2012, ED - Peloso 2012, Namba - ED - Peloso 2013, Adshead - Martinec -Wyman 2013, ED - Fasiello - Fujita 2016 Agrawal - Fujita - Komatsu 2017, Caldwell - Devulder 2017, Domcke et al. 2018, …]

- GW from extra non-minimally coupled spin-2 field (EFT formulation)

  [Bordin et al, 2018; …]

- Spectator fields with small sound speed

  $$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + k^2\gamma_{ij} = 16\pi G\,\Pi_{ij}^{TT} \propto \partial_i\sigma\partial_j\sigma$$

  [Biagetti, Fasiello, Riotto 2012, Biagetti, ED, Fasiello, Peloso 2014, …]

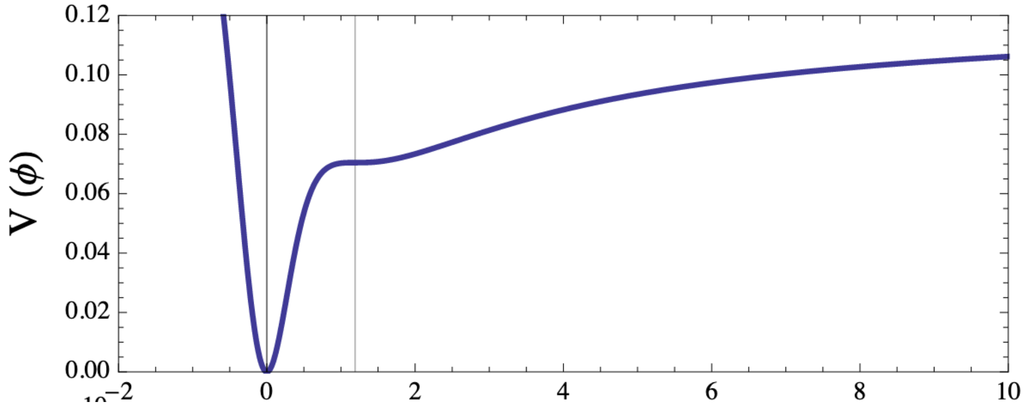
- . . .

GW can tell us a whole lot about inflation:

- GW from the amplification of vacuum fluctuations
- Generation of GW from additional fields during inflation
- Second order GW from peaks in the scalar power spectrum

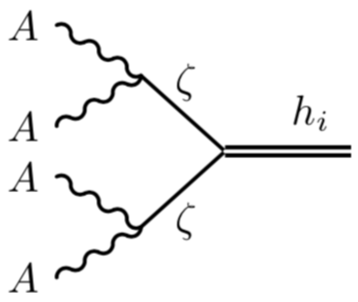
[Ananda et al - 2007, Baumann et al - 2007, …]

- ○ Potentials with inflection points



[Garcia-Bellido, Morales 2017]

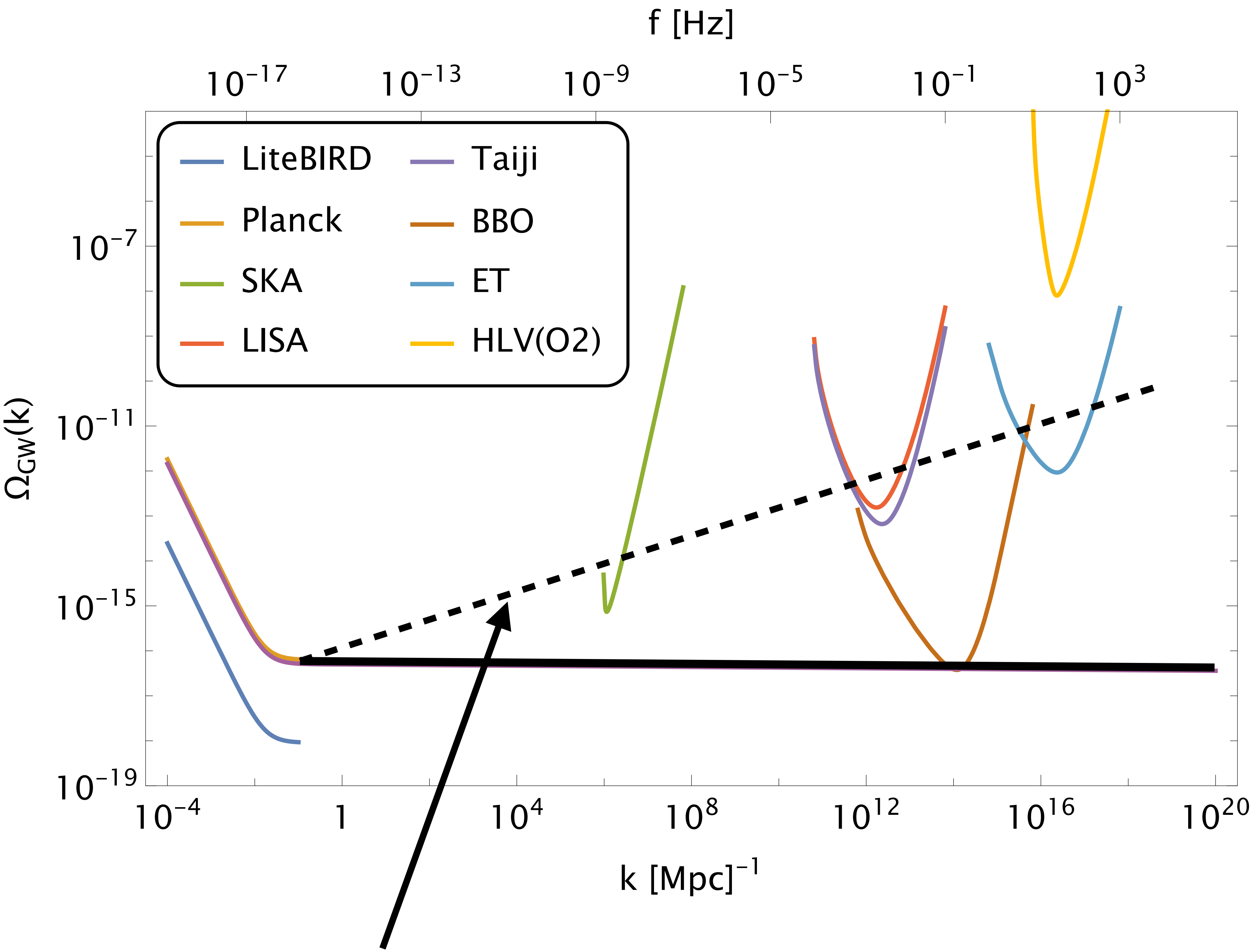
- ○ Inflation with axion and gauge fields



[Garcia-Bellido, Peloso, Unal 2017]

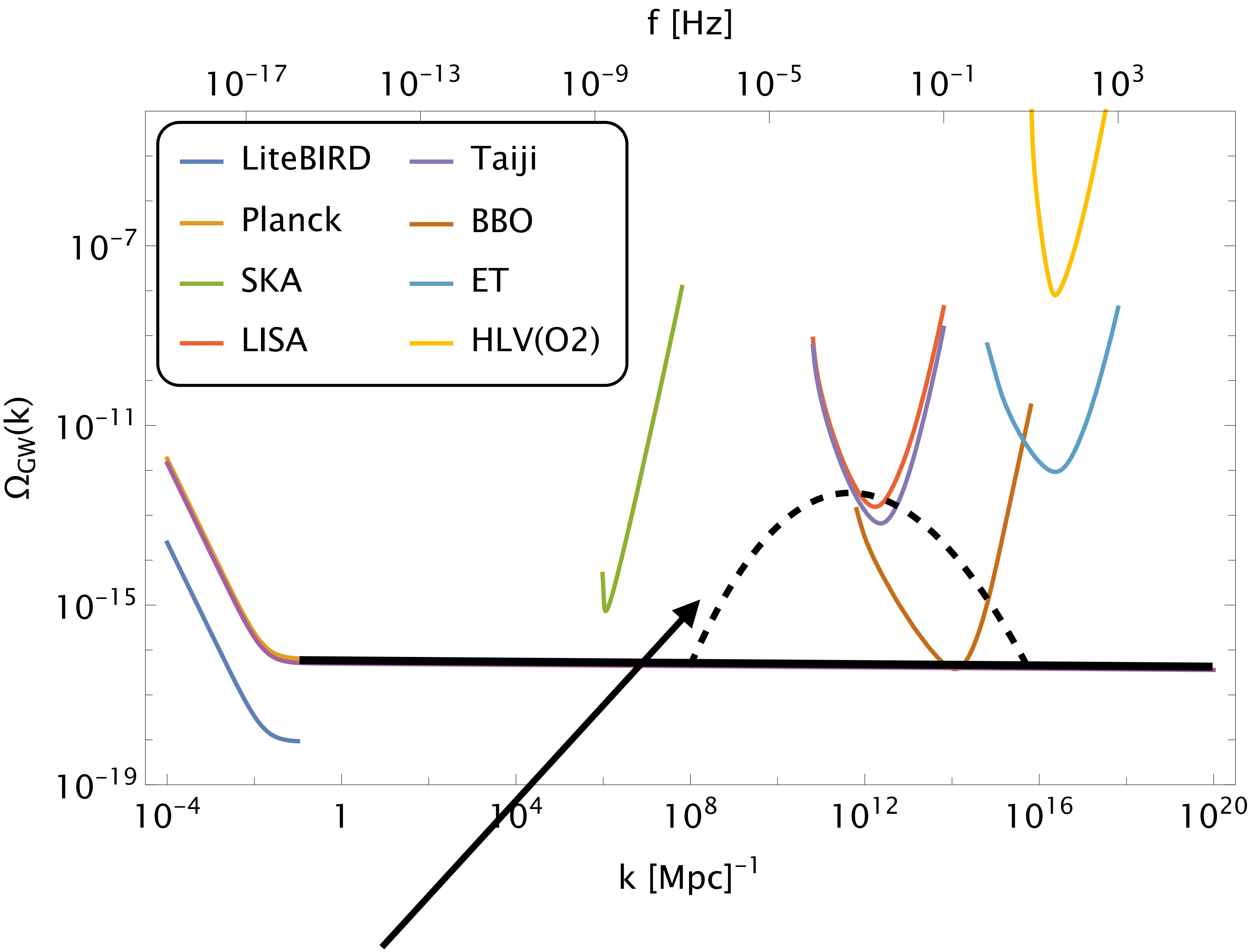
- ○ . . .

Prediction and sensitivity limits



Power spectrum larger at small scales: e.g. **blue tilt**

Prediction and sensitivity limits



Power spectrum larger at small scales: e.g. **bump**

Axion-Gauge fields models: Chern-Simons coupling

$$g(\phi)\ F\ \tilde{F}$$

gauge-field strength and its dual

axion-like field

- naturally light inflaton
- support reheating
- mechanism for baryogenesis
- primordial black holes formation
- **sourced chiral gravitational waves**

[Freese - Frieman - Olinto 1990, Anber - Sorbo 2009, Cook - Sorbo 2011, Barnaby - Peloso 2011, Adshead - Wyman 2011, Maleknejad - Sheikh-Jabbari, 2011, ED - Fasiello - Tolley 2012, ED - Peloso 2012, Namba - ED - Peloso 2013, Adshead - Martinec -Wyman 2013, ED - Fasiello - Fujita 2016, Garcia-Bellido - Peloso - Unal 2016, Agrawal - Fujita - Komatsu 2017, Fujita - Namba - Obata 2018, Domcke - Mukaida 2018, Kaloper-Westphal 2021, Iarygina - Sfakianakis 2021, …]

Axion-Gauge fields models: SU(2)

$$\mathcal{L} = \underset{\substack{\big\downarrow \\ P_{\gamma,\text{vacuum}}}}{\mathcal{L}_{\text{inflaton}}} \overbrace{\underbrace{-\frac{1}{2}(\partial\chi)^2 - U(\chi) - \frac{1}{4}FF + \frac{\lambda\chi}{4f}F\tilde{F}}_{\mathcal{L}_{\text{spectator}} \rightarrow P_{\gamma,\text{sourced}}}}^{\text{[Adshead - Wyman 2011]}}$$

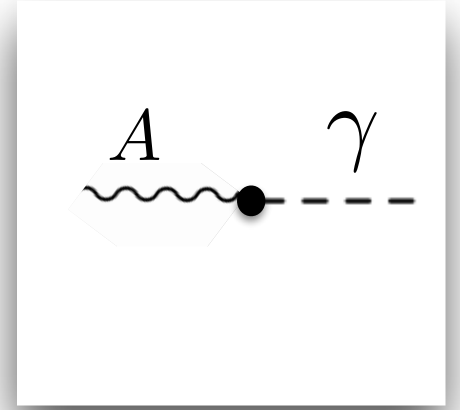
- Inflaton field dominates energy density of the universe
- Spectator sector contribution to curvature fluctuations negligible

$$\boxed{\begin{aligned} A_0^a &= 0 \\ A_i^a &= aQ\delta_i^a \end{aligned}}$$

slow-roll background attractor solution

$$\boxed{\delta A_i^a = t_{ai} + \ldots}$$

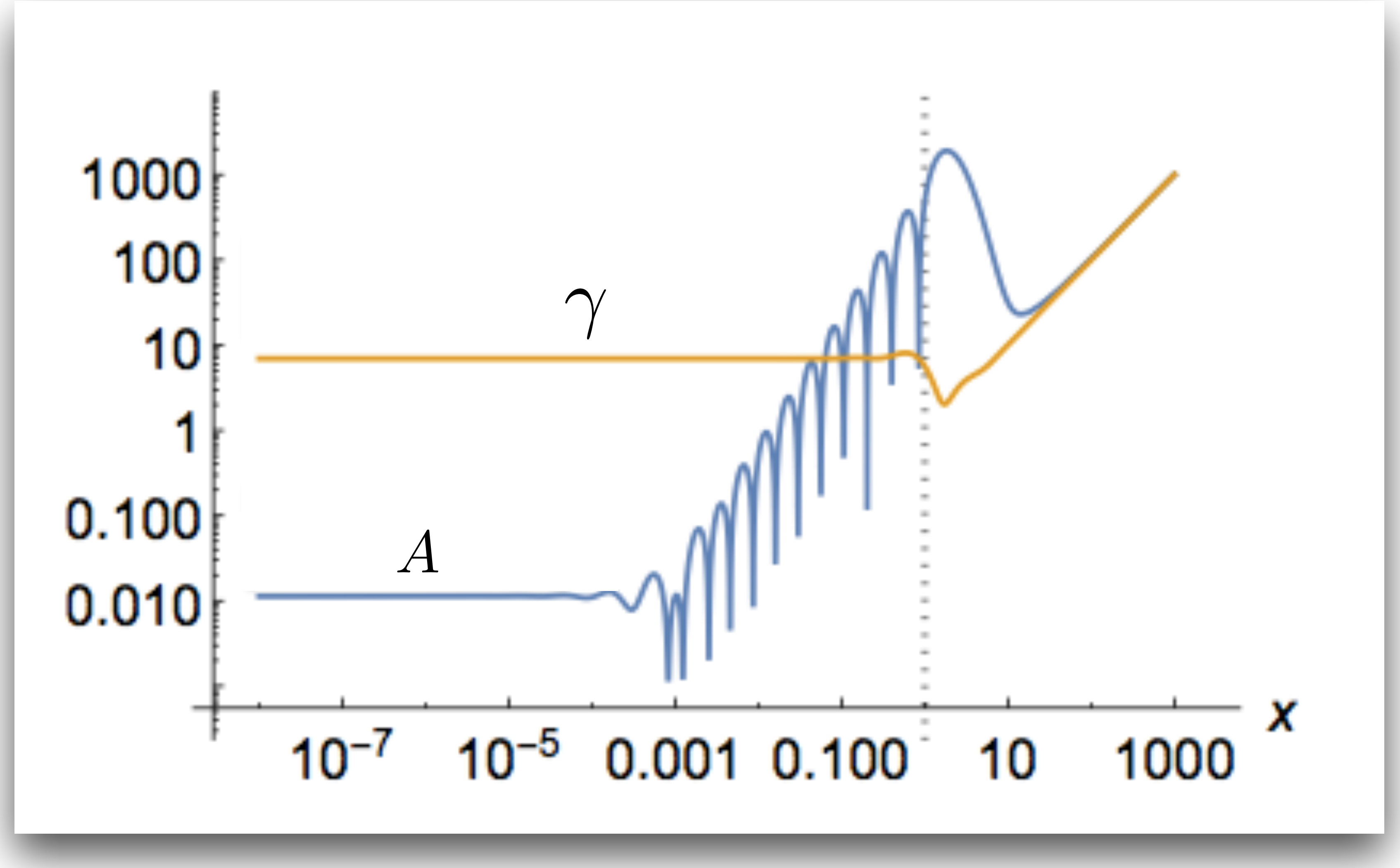
TT-component



[ED-Fasiello-Fujita 2016]

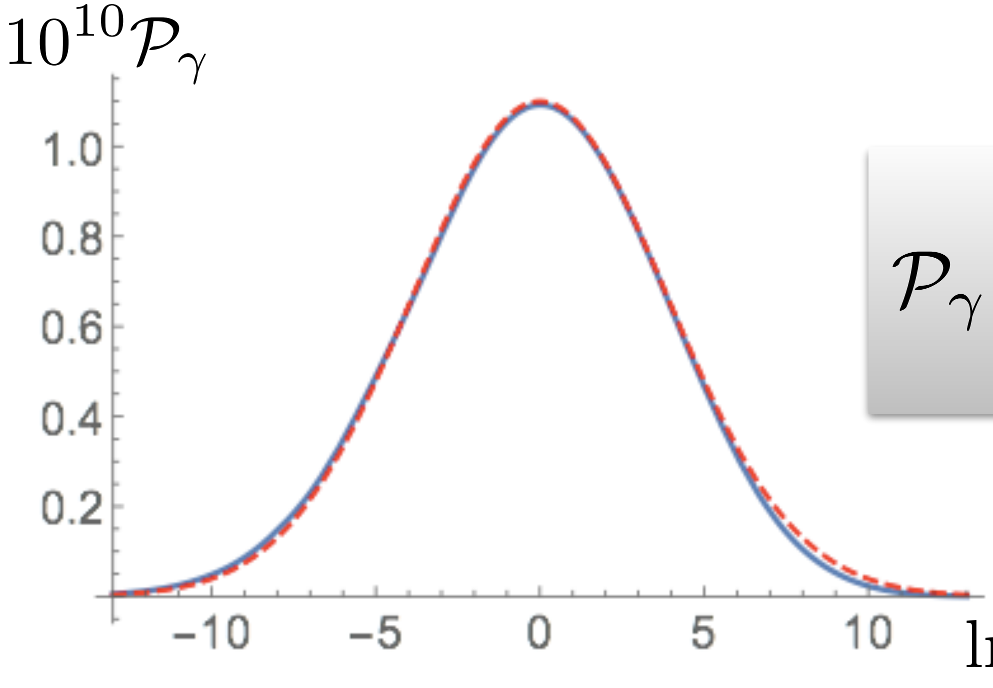
Axion-Gauge fields models: SU(2)

One helicity of the gauge field fluctuations is amplified from coupling with axion → the same helicity of the tensor mode is amplified



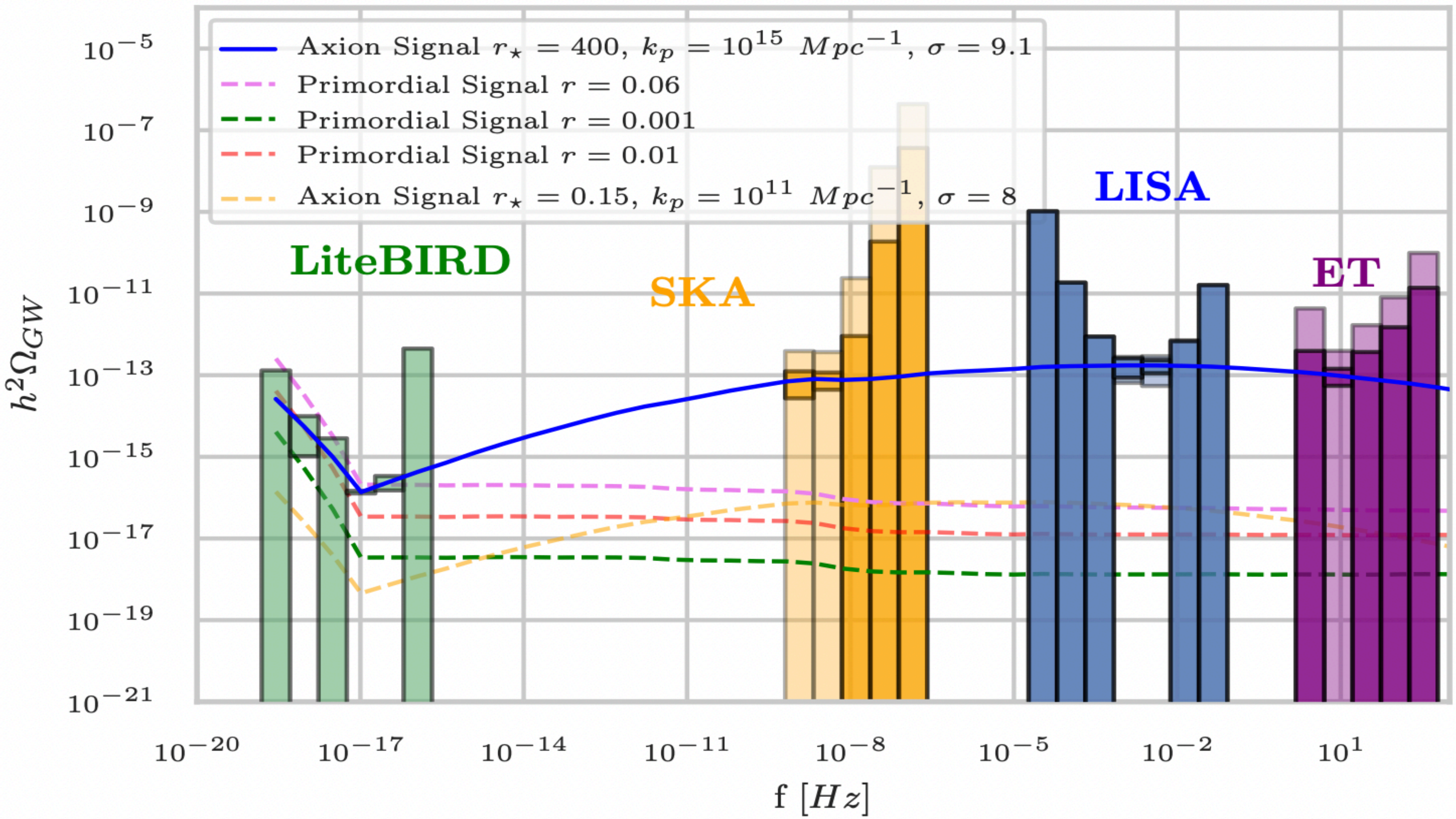
[ED-Fasiello-Fujita 2016]

Axion-Gauge fields models: SU(2)



$$\mathcal{P}_\gamma(k) = \mathcal{P}^{(\text{sourced})}_{\gamma,\,L}(k) = r_*\,\mathcal{P}_\zeta(k)e^{-\frac{1}{2\sigma^2}\ln^2(k/k_\text{p})}$$

[ED-Fasiello-Fujita, 2016 — Thorne et al, 2017]



[Campeti et al, 2020]

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- ~~Red~~ **~~tilt~~**: $n_T \simeq -2\epsilon = -r/8$

- Non-**~~chiral~~**: $P_L = P_R$

- Nearly **Gaussian**: $f_{\rm NL} \ll 1$

How do we detect chirality?

CMB angular power spectra & chirality

$$\mathcal{C}_\ell^{XY} = \int dk\, \Delta_\ell^X(k,\eta_0)\Delta_\ell^Y(k,\eta_0)\left[\mathcal{P}_\gamma^R(k) + \epsilon\cdot\mathcal{P}_\gamma^L(k)\right]$$

$$X,\, Y = T,\ E,\ B$$

$$\epsilon = \begin{cases} \text{1 for TT, EE, BB, TE} \\ \text{-1 for TB, EB} \end{cases}$$

For parity-conserving theories $\langle TB\rangle,\, \langle EB\rangle = 0$

For parity-violating theories $\langle TB\rangle,\, \langle EB\rangle \neq 0$

[See Komatsu et al 2017 for forecasts on chirality from our model with LiteBIRD]

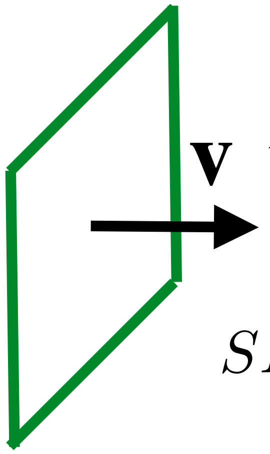
Constraining chirality at high frequencies (interferometers)

A **planar** detector cannot distinguish L from R
for an isotropic SGWB

An ‘effective’ **non-planar** geometry can be realised by:

— using different (non co-planar) detectors at once → monopole

— exploiting the motion of a detector → higher multiples



use of kinematically induced dipole:

$$SNR \simeq \frac{v}{10^{-3}} \, \frac{\Omega_{\mathrm{GW},R} - \Omega_{\mathrm{GW},L}}{1.4 \cdot 10^{-11}} \sqrt{\frac{T}{3\,\mathrm{years}}}$$

(LISA, ET)

* For (networks of) space-based interferometers see: Domcke et al, 2020 - Orlando et al., 2021

* For ground-based networks see, e.g. : Seto-Taruya, 2007— Smith-Caldwell, 2017

* For PTA: Belgacem-Kamionkowski, 2020

[See also Seto 2006-2007]

[See Komatsu et al 2017 for forecasts on chirality from our model with interferometers]

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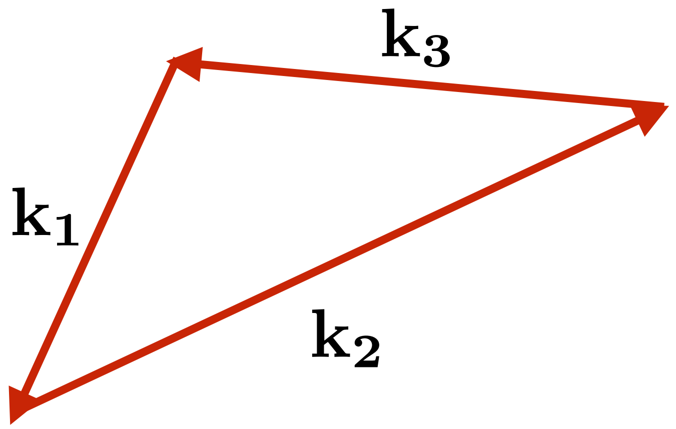
Primordial non-Gaussianity and anisotropies in the GW energy density

Non-Gaussianity: beyond the power spectrum

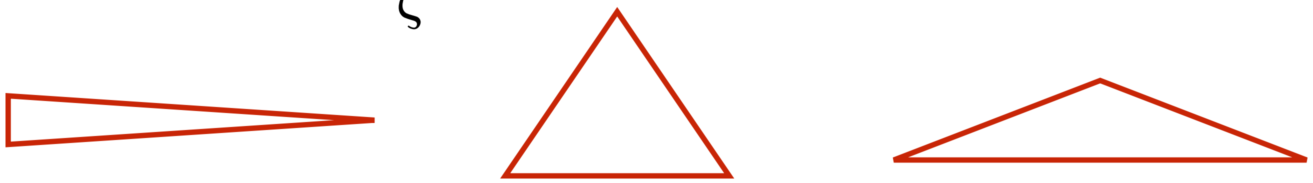


$$\langle \gamma^{\lambda_1}_{\mathbf{k_1}} \gamma^{\lambda_2}_{\mathbf{k_2}} \gamma^{\lambda_3}_{\mathbf{k_3}} \rangle = (2\pi)^3 \delta^{(3)}(\mathbf{k_1} + \mathbf{k_2} + \mathbf{k_3}) B_\gamma^{\lambda_1 \lambda_2 \lambda_3}(k_1, k_2, k_3)$$

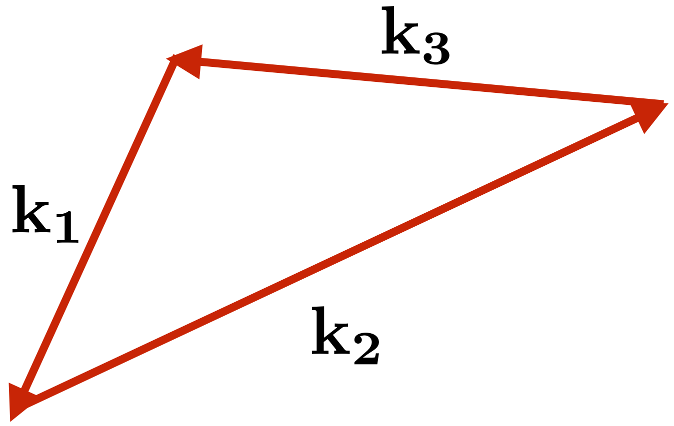
tensor bispectrum

amplitude: $f_{NL} = \dfrac{B}{P_\zeta^2}$

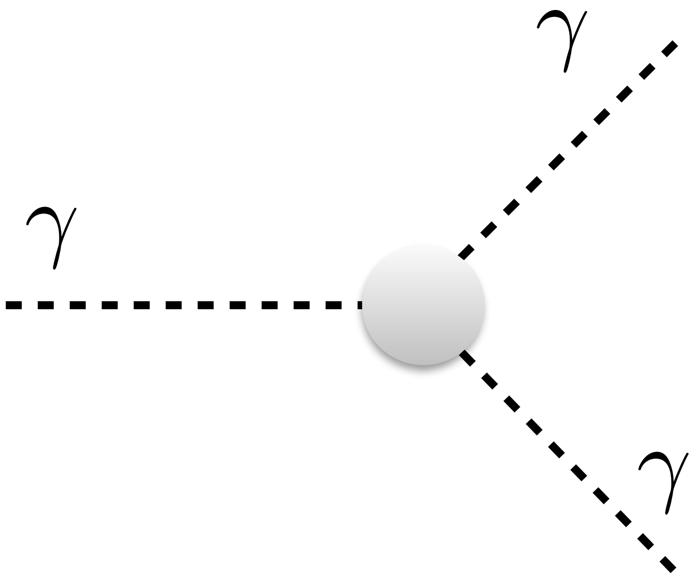
shape:



Tensor non-Gaussianity

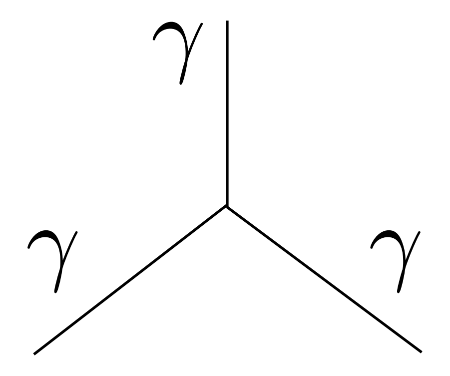


from interactions of the tensors with other fields or from self-interactions



Tensor non-Gaussianity

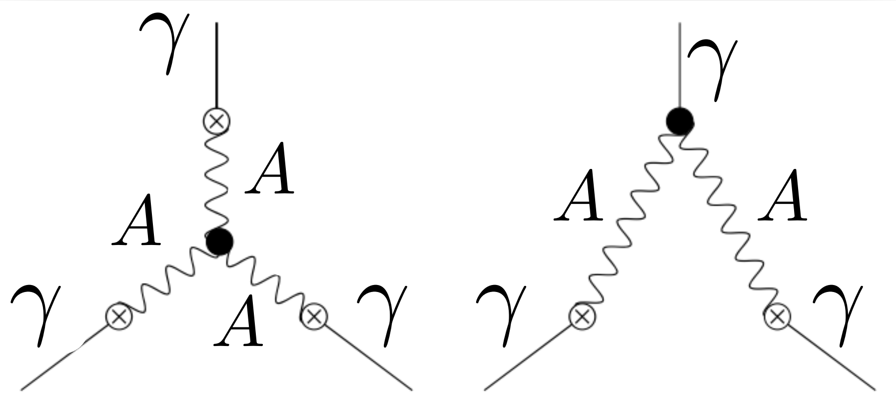
basic single-field inflation



$$f_{NL} = \mathcal{O}(r^2)$$

too small for detection

axion-gauge fields models



$$f_{NL} = r^2 \cdot \frac{25}{\Omega_A} \gtrsim \mathcal{O}(r^2 \cdot 10^6)$$

- detectable by upcoming CMB space missions

[Agrawal - Fujita - Komatsu 2017]

Non-Gaussianity (tensor / mixed): CMB constraints

- We do have constraints from CMB anisotropies and future B mode observations are expected to bring important improvements

Example: LiteBIRD-like experiment could detect an O(1) signal for

$$f_{\rm NL}^{tss,{\rm sq}} \quad f_{\rm NL}^{ttt,{\rm sq}} \quad f_{\rm NL}^{ttt,{\rm eq}}$$

[Shiraishi, 2019]

- The formalism for constraining non-Gaussianity with CMB anisotropies is by now well developed

Non-Gaussianity at interferometers

Shapiro time delay:

$$\gamma'' + 2\mathcal{H}\gamma' - [1 + (12/5)\zeta]\,\gamma_{,kk} = 0$$

GW propagating in FRW background
+ long-wavelength perturbations

$$\gamma_{ij} = A_{ij}\, e^{ik\tau + ik\cdot 2\int^{\tau} d\tau'\,\zeta[\tau',(\tau'-\tau_0)\hat{k}]}$$

GW from different directions
undergo different phase shift
due to intervening structure

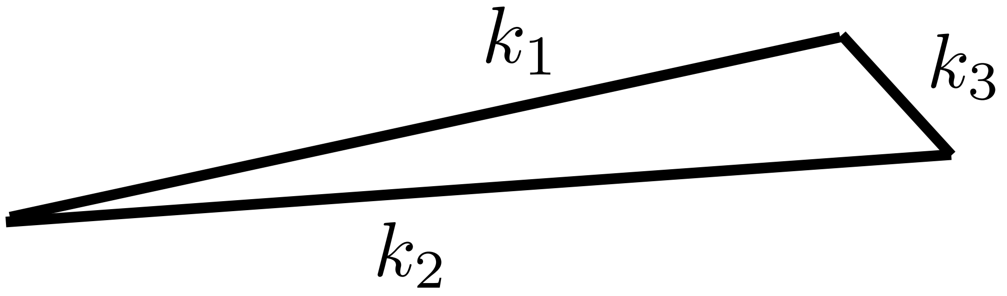
→ decorrelation → cannot measure bispectrum directly with interferometers

[Bartolo, De Luca, Franciolini, Lewis, Peloso, Riotto 2018]

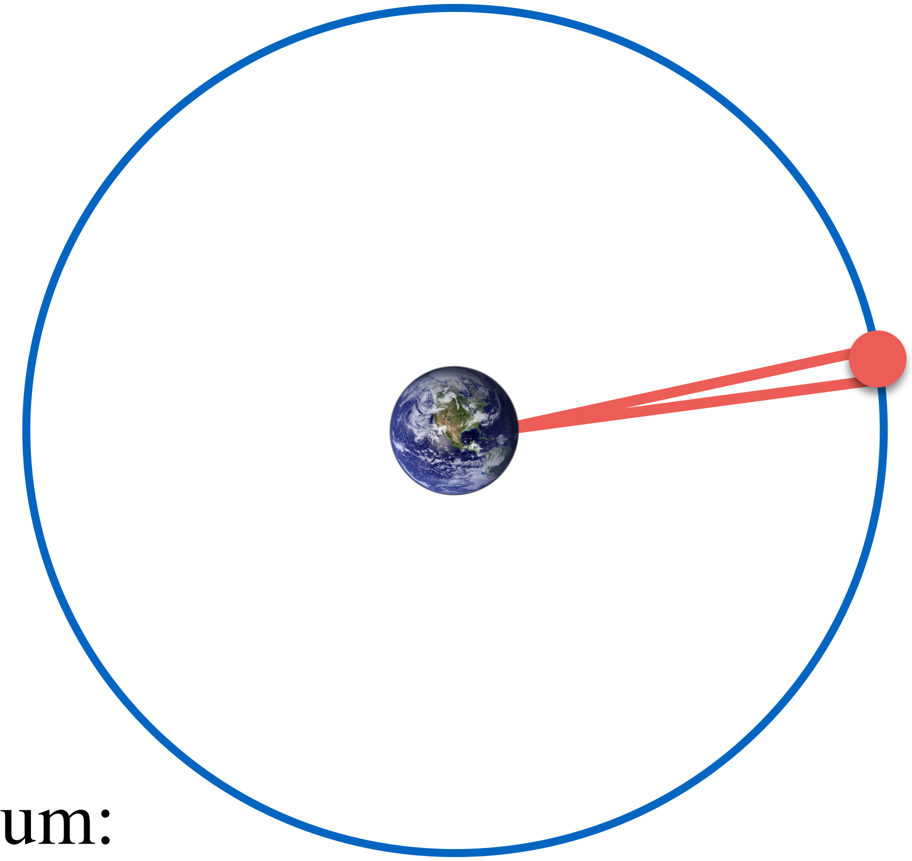
Note: signal measured by an interferometer arises from the superposition
of signals from a large number of Hubble patches (CLT)

[Adshead, Lim 2009 — Caprini, Figueroa 2018 — Bartolo, De Luca, Franciolini, Lewis, Peloso, Riotto 2018]

Ultra squeezed non-Gaussianity



Correlation among two short-wavelength modes (e.g. interferometer scale) and
1 very long-wavelength mode:
the latter has not undergone propagation!



Signals originate from the same patch!

How do we constrain this ultra-squeezed bispectrum:

Look for anisotropies in the SGWB!

$$\Omega_{\rm GW}(k) = \bar{\Omega}_{\rm GW}(k) \left[1 + \frac{1}{4\pi} \int d^2\hat{n}\, \delta_{\rm GW}(k,\hat{n}) \right]$$

[ED, Fasiello, Tasinato, PRL 124(2020)6 061302]

SGWB anisotropies from primordial non-Gaussianity

$$\Omega_{\rm GW}(k) = \bar{\Omega}_{\rm GW}(k)\left[1+\frac{1}{4\pi}\int d^2\hat{n}\,\delta_{\rm GW}(k,\hat{n})\right]$$

isotropic component

anisotropic component

$$\Omega_{\rm GW}(k) \equiv \frac{1}{\rho_{\rm cr}}\frac{d\rho_{\rm GW}}{d\ln k}$$

energy density spectrum
for the stochastic GW background

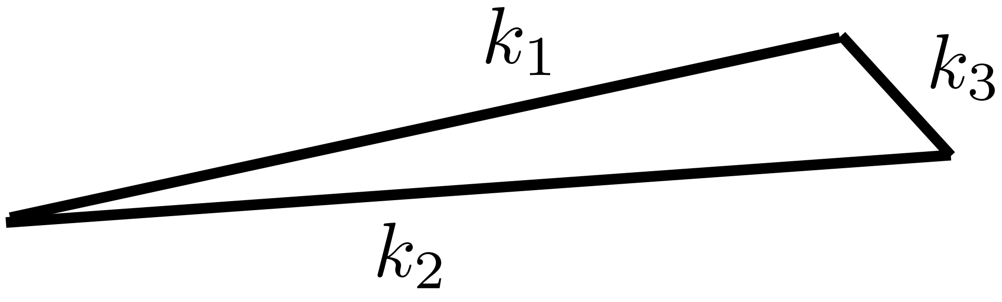
k= comoving wavenumber (proportional to the observed frequency)

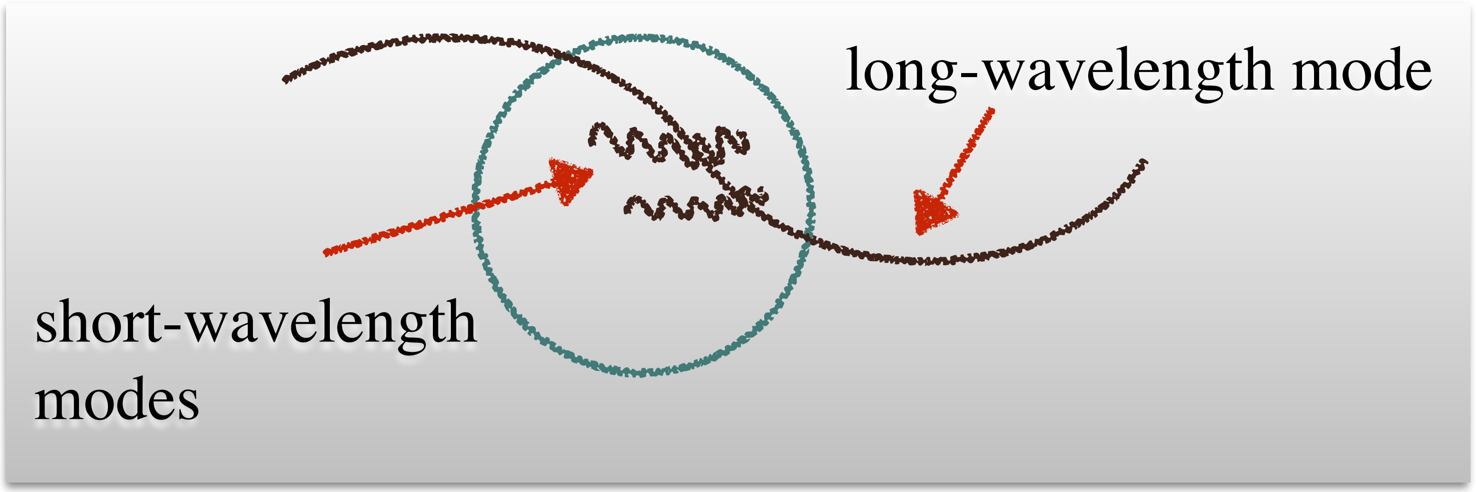
$\hat{n}$= direction of incoming graviton

How do SGWB anisotropies relate to non-Gaussianity?

Soft limits and ‘fossils’

$k_1 \simeq k_2 \gg k_3$





long wavelength modes introduces a modulation
in the primordial power spectrum of the short wavelength modes

$$B^{F\gamma\gamma} \equiv \langle F_L \gamma_S \gamma_S \rangle' \sim F_L \cdot \langle \gamma_S \gamma_S \rangle'_{F_L}$$

$$\downarrow$$

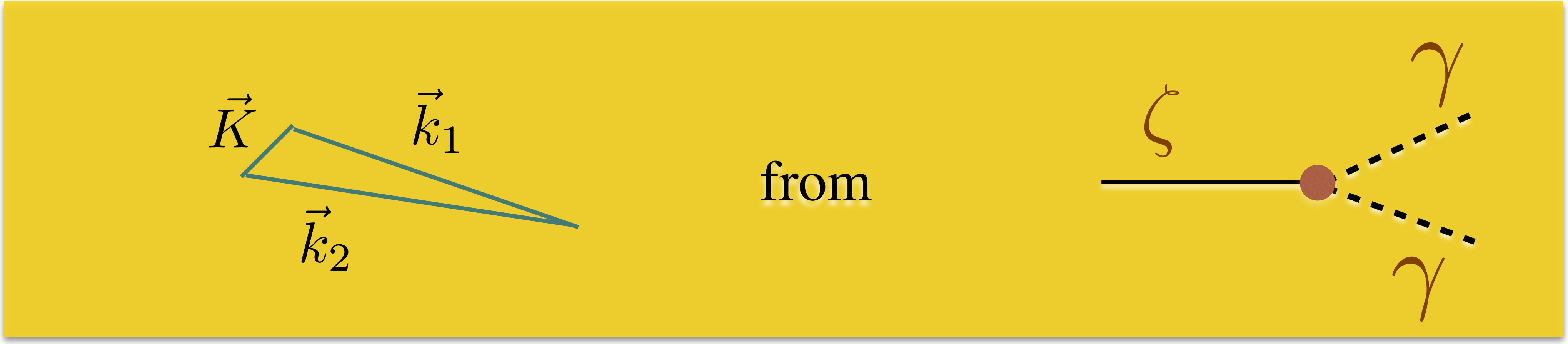
$$\delta\langle \gamma_S \gamma_S \rangle \equiv \langle \gamma_S \gamma_S \rangle_{F_L} \sim \frac{B^{F\gamma\gamma}}{P_F(k_3)} \cdot F_L^* = P_\gamma(k_1) \cdot \overset{f_{\mathrm{NL}}^{F\gamma\gamma}}{\boxed{\frac{B^{F\gamma\gamma}}{P_F(k_3) P_\gamma(k_1)}}} \cdot F_L^*$$

$$\downarrow$$

$$\boxed{\langle \gamma_S \gamma_S \rangle'_{\mathrm{total}} = P_\gamma(k_1) \left(1 + f_{\mathrm{NL}}^{F\gamma\gamma} \cdot F_L^* \right)}$$

[ED, Fasiello, Jeong, Kamionkowski - 2014, ED, Fasiello, Kamionkowski - 2015, …]

Soft limits and fossils



$$\delta_{\rm GW}(k,\hat{n}) = \int \frac{d^3q}{(2\pi)^3} e^{-id\hat{n}\cdot\mathbf{q}} \zeta(\mathbf{q}) F_{\rm NL}^{\rm stt}(\mathbf{k},\mathbf{q})$$

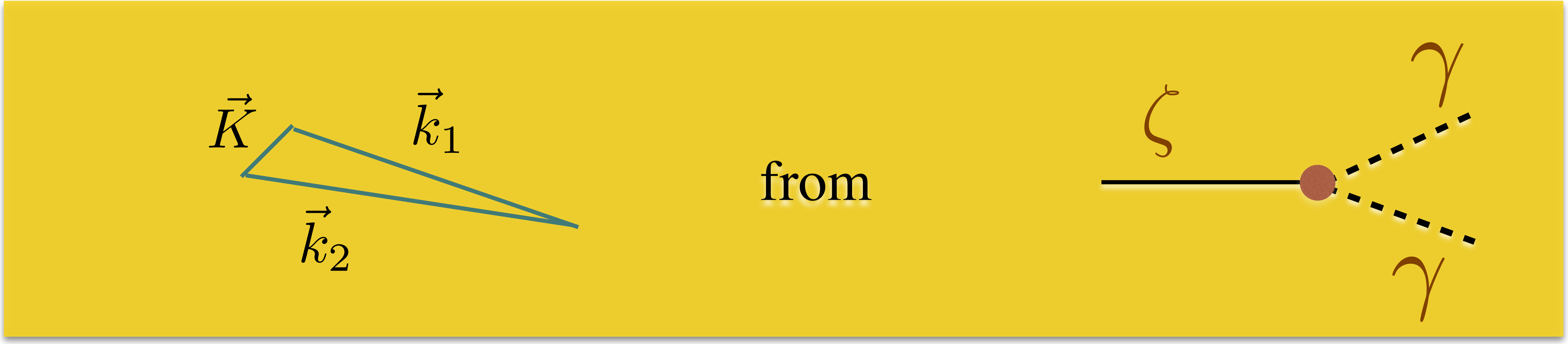
large scale variation large scale variations in the energy density of GW

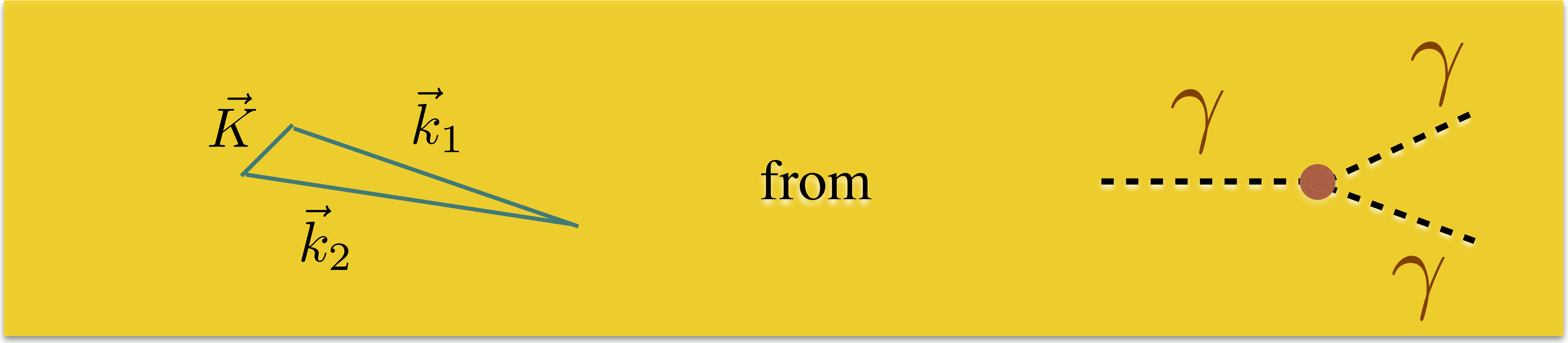
$$\mathbf{d} = -(\eta_0 - \eta_{\rm in})\hat{n}$$

$$\Omega_{\rm GW}(k) = \bar{\Omega}_{\rm GW}(k) \left[1 + \frac{1}{4\pi}\int d^2\hat{n}\, \delta_{\rm GW}(k,\hat{n})\right]$$

[ED, Fasiello, Tasinato, PRL 124(2020)6 061302]

Soft limits and fossils





[ED, Fasiello, Tasinato, PRL 124(2020)6 061302]

for derivation with in-in formalism and applications:

see: **[ED, Fasiello, Pinol, 2022]**

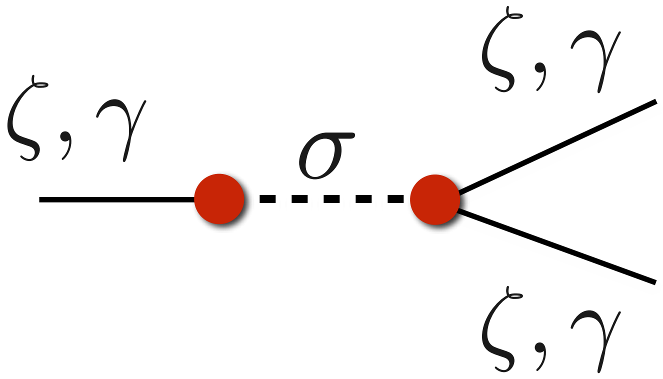
Soft limits in inflation

- ***Extra*** *fields* / superhorizon ***evolution***

  [Chen - Wang 2009, Baumann - Green 2011, Chen et al 2013,
  ED - Fasiello - Kamionkowski 2015, …]

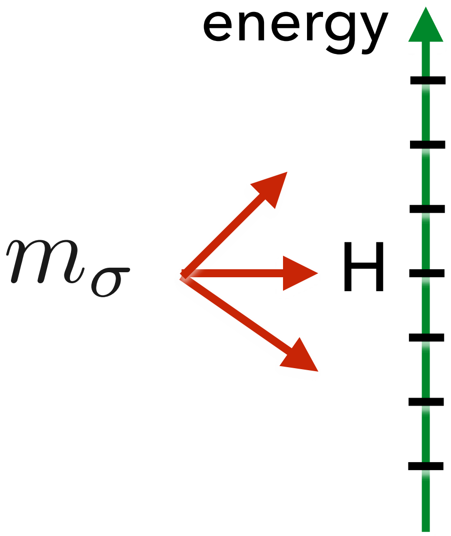
Soft limits in inflation

- ***Extra** fields*



Soft limits reveal (extra) fields mediating inflaton or graviton interactions

squeezed bispectrum delivers info on mass spectrum!!!



Soft limits in inflation

- ***Extra*** *fields* / superhorizon ***evolution***

  **[Chen - Wang 2009, Baumann - Green 2011, Chen et al 2013,
  ED - Fasiello - Kamionkowski 2015, …]**

- ***Non-Bunch Davies*** initial states

  [Holman - Tolley 2007, Ganc - Komatsu 2012, Brahma - Nelson - Shandera 2013, …]

- ***Broken space diffs***
  (e.g. space-dependent background)

  [Endlich et al. 2013, ED - Fasiello - Jeong - Kamionkowski 2014, Celoria - Comelli - Pilo - Rollo 2021…]

Ideal probe for (extra) fields, pre-inflationary dynamics, (non-standard) symmetry patterns

SGWB anisotropies from primordial non-Gaussianity

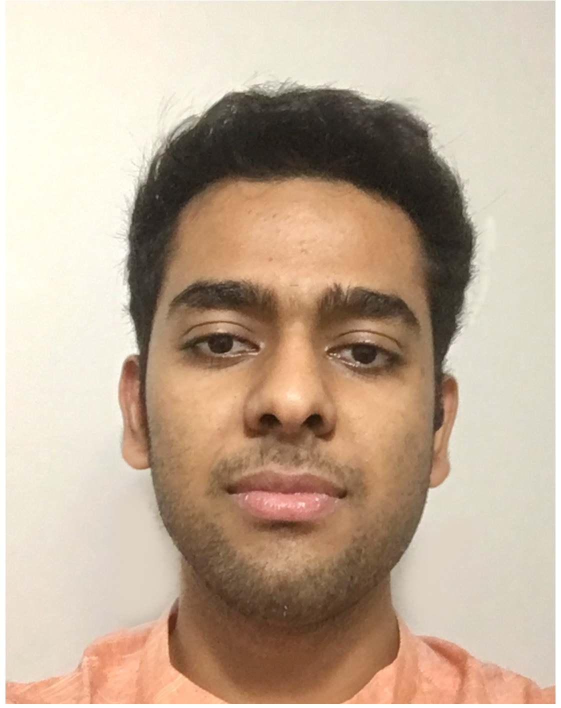
- Typical amplitude of these anisotropies:

$$\delta_{\rm GW}^{\rm tss} \sim F_{\rm NL}^{\rm tss} \sqrt{A_{\rm S}}$$

$$\delta_{\rm GW}^{\rm ttt} \sim F_{\rm NL}^{\rm ttt} \sqrt{r\, A_{\rm S}}$$

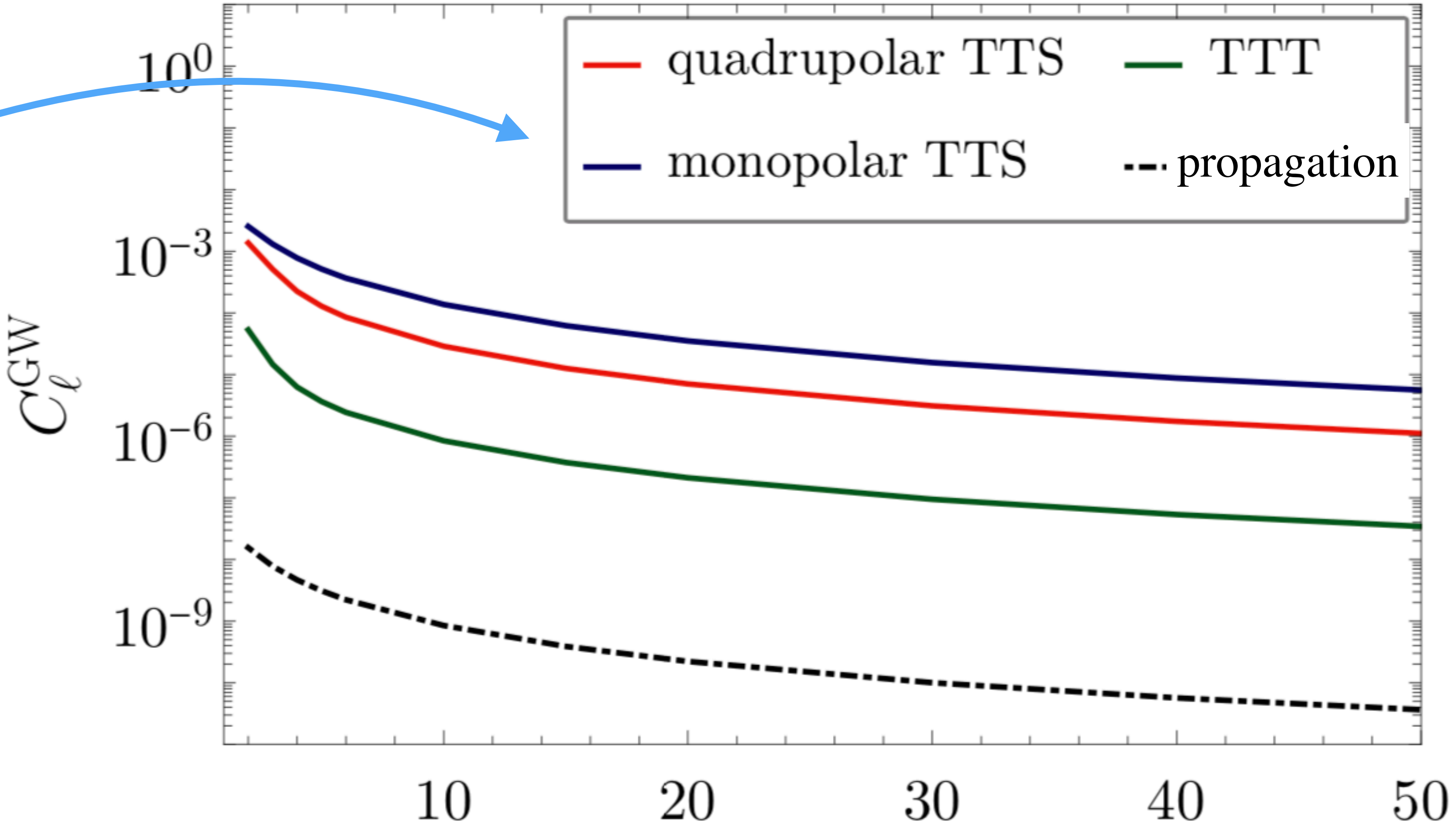
scalar power spectrum amplitude at CMB scales

tensor-to-scalar ratio



angular dependence of $F_{\rm NL}(\mathbf{k}, \mathbf{q})$

(scale-invariant case)

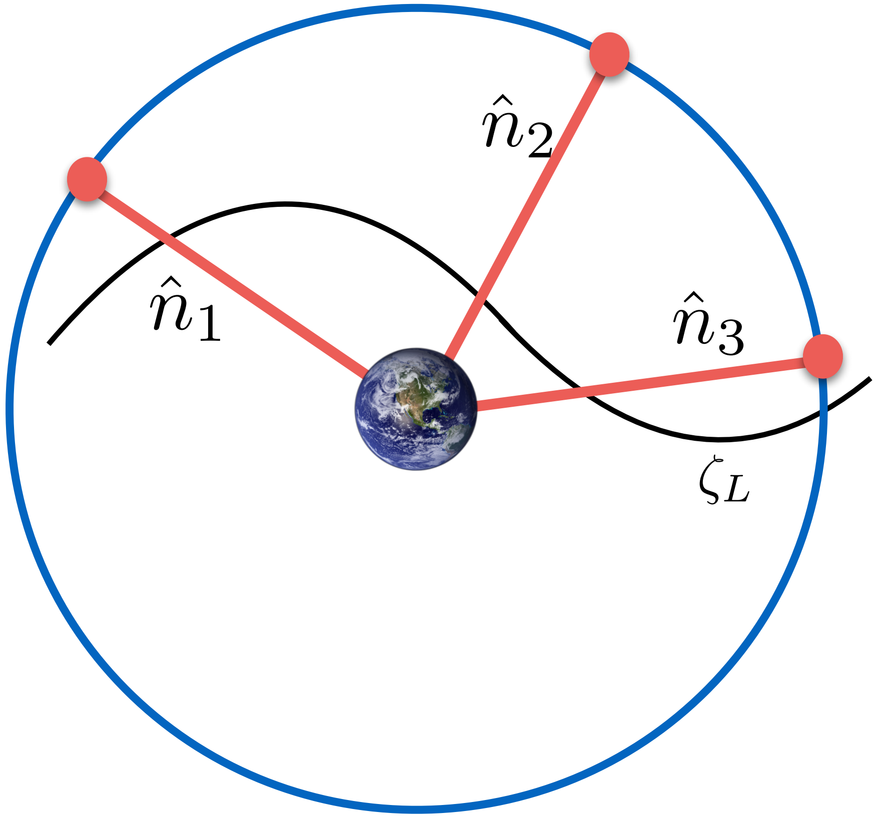


$\langle \delta_{{\rm GW},\ell_1 m_1} \delta_{{\rm GW},\ell_2 m_2} \rangle$

[Malhotra, ED, Fasiello, Shiraishi 2020 - ED, Fasiello, Malhotra, Meerburg, Orlando 2021]

Anisotropies from propagation

GW propagate through the perturbed universe ⟶ subject to Sachs-Wolfe / integrated Sachs-Wolfe …, just like CMB photons



Large-scales: SW dominates

$$\boxed{\frac{\delta f(\hat{n})}{f} = \frac{1}{5}\left[\zeta_{L(\mathrm{today})} - \zeta_L(\hat{n}\cdot\eta_0)\right]}$$

Gravitational redshift/blueshift of gravitons

[Alba - Maldacena, 2015]

$$\zeta_L(\hat{n}_1\cdot\eta_0) \neq \zeta_L(\hat{n}_2\cdot\eta_0)$$

$\downarrow$

Direction-dependent frequency shift

$\downarrow$

Anisotropy in the GW energy density

$$\boxed{\delta_{\rm GW} \sim \left(\frac{\partial \ln \Omega_{\rm GW}}{\partial \ln k}\right) \zeta_{\rm L}}$$

$\downarrow$

$$\delta_{\rm GW} \simeq \mathcal{O}(1)\, \zeta_{\rm L} \simeq 10^{-5}$$ (for SFSR Inflation)

[See Contaldi, 2017- Bartolo et al 2019 - for full Boltzmann treatment; see also: Pitrou et al, 2020]

Boltzmann treatment for gravitational waves

FRLW in Poisson gauge: $ds^2 = a^2(\eta)\left[-e^{2\Phi}d\eta^2 + (e^{-2\Psi}\delta_{ij} + \chi_{ij})dx^i dx^j\right]$

Boltzmann equation for
the distribution function of gravitons
($\delta_{\mathrm{GW}} \propto \Gamma$)

$$\Gamma(\eta_0, \vec{x}_0, \hat{n}, q) = \underbrace{\Gamma(\eta_{\mathrm{i}}, \vec{x}_i, q)}_{\Gamma_I} + \underbrace{\Phi(\eta_{\mathrm{i}}, \vec{x}_i) + \int_{\eta_{\mathrm{i}}}^{\eta_0} d\eta(\Phi' + \Psi')}_{\Gamma_S}$$

Initial perturbations

From propagation in the
inhomogeneous universe
(SW + ISW)

$$\vec{x}_i = \vec{x}_0 - (\eta_0 - \eta_i)\hat{n}$$

Time and position
of the observer

Time of emission

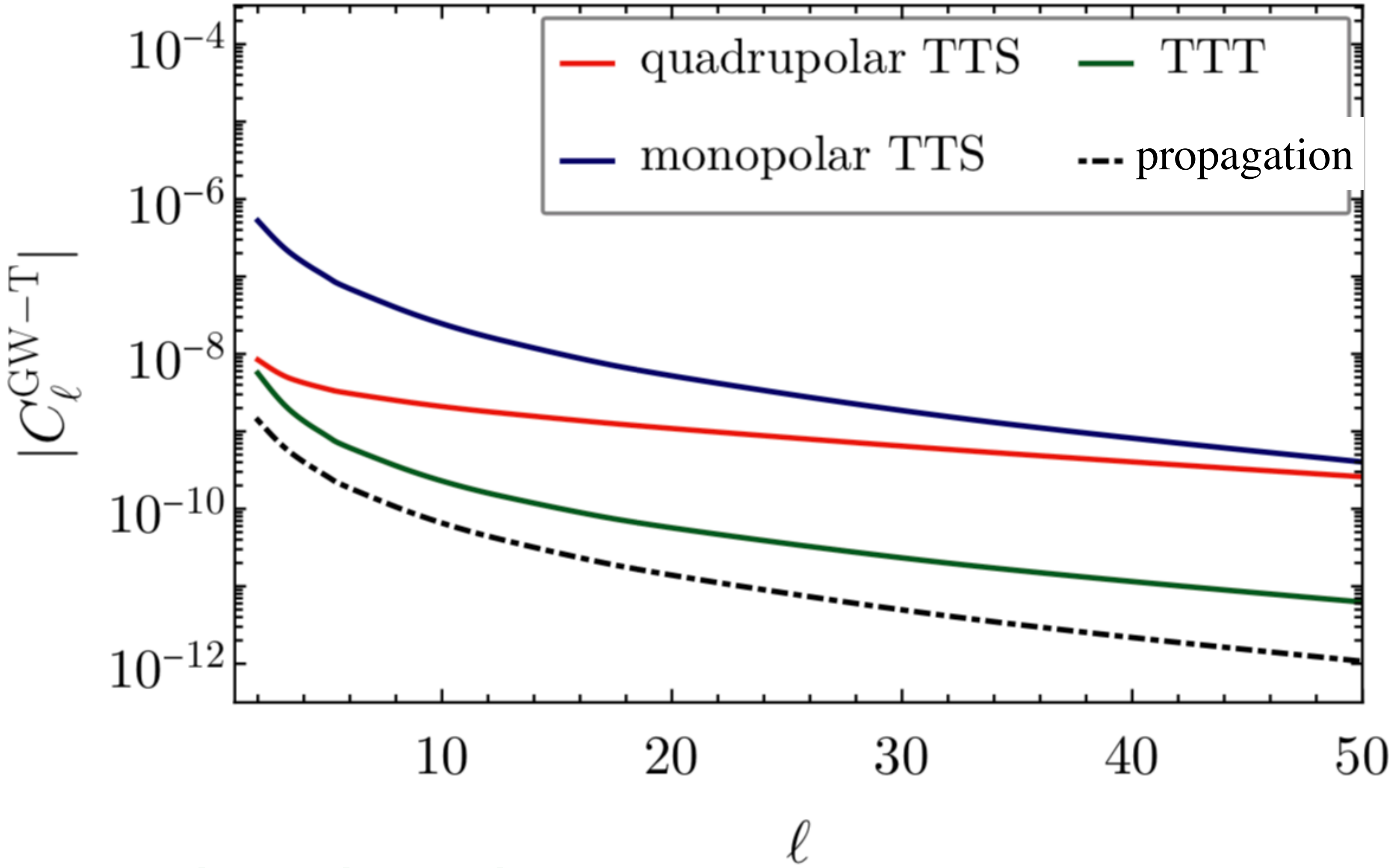
[Bartolo et al 2019]

Cross-correlations of GW and CMB anisotropies

$$\delta_{\rm GW}^{\rm propagation} \sim \zeta_L$$

$$\delta_{\rm GW}^{\rm stt} \sim F_{\rm NL}^{\rm stt} \cdot \zeta_L$$

$$\left.\begin{array}{l} \delta_{\rm GW}^{\rm stt} \sim F_{\rm NL}^{\rm stt} \cdot \zeta_L \\ \dfrac{\Delta T}{T} \sim \zeta_L \end{array}\right\} C_\ell^{\text{GW-T}} \sim F_{\rm NL}^{\rm stt} \cdot C_\ell^{TT}$$



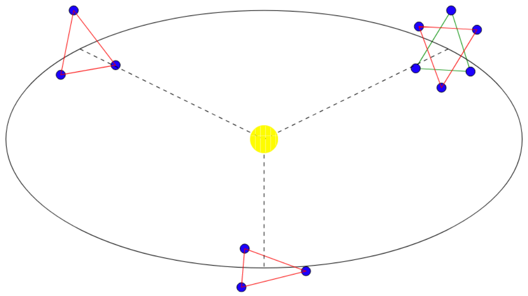
[Adshead, Afshordi, ED, Fasiello, Lim, Tasinato 2020
Malhotra, ED, Fasiello, Shiraishi 2020
ED, Fasiello, Malhotra, Meerburg, Orlando 2021]

Projected constraints on $F_{\rm NL}^{\rm tss}$

$$F_{ij} = \sum_{XY} \sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} \frac{\partial C_\ell^X}{\partial \theta_i} \left(\mathcal{C}_\ell^{XY}\right)^{-1} \frac{\partial C_\ell^Y}{\partial \theta_j} \qquad X, Y = \{\text{TT,GW,GW-T}\}$$

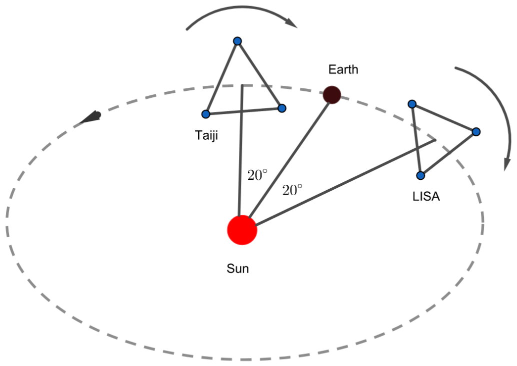
$$\mathscr{C}_\ell = \frac{2}{2\ell+1} \begin{bmatrix} (C_\ell^{\rm TT})^2 & (C_\ell^{\rm GW-T})^2 & C_\ell^{\rm TT} C_\ell^{\rm GW-T} \\ (C_\ell^{\rm GW-T})^2 & (C_\ell^{\rm GW})^2 & C_\ell^{\rm GW} C_\ell^{\rm GW-T} \\ C_\ell^{\rm TT} C_\ell^{\rm GW-T} & C_\ell^{\rm GW} C_\ell^{\rm GW-T} & \frac{1}{2}(C_\ell^{\rm GW-T})^2 + \frac{1}{2} C_\ell^{\rm TT} C_\ell^{\rm GW} \end{bmatrix}$$

- BBO: 4 LISA-like constellations



[Crowder - Cornish, 2005]

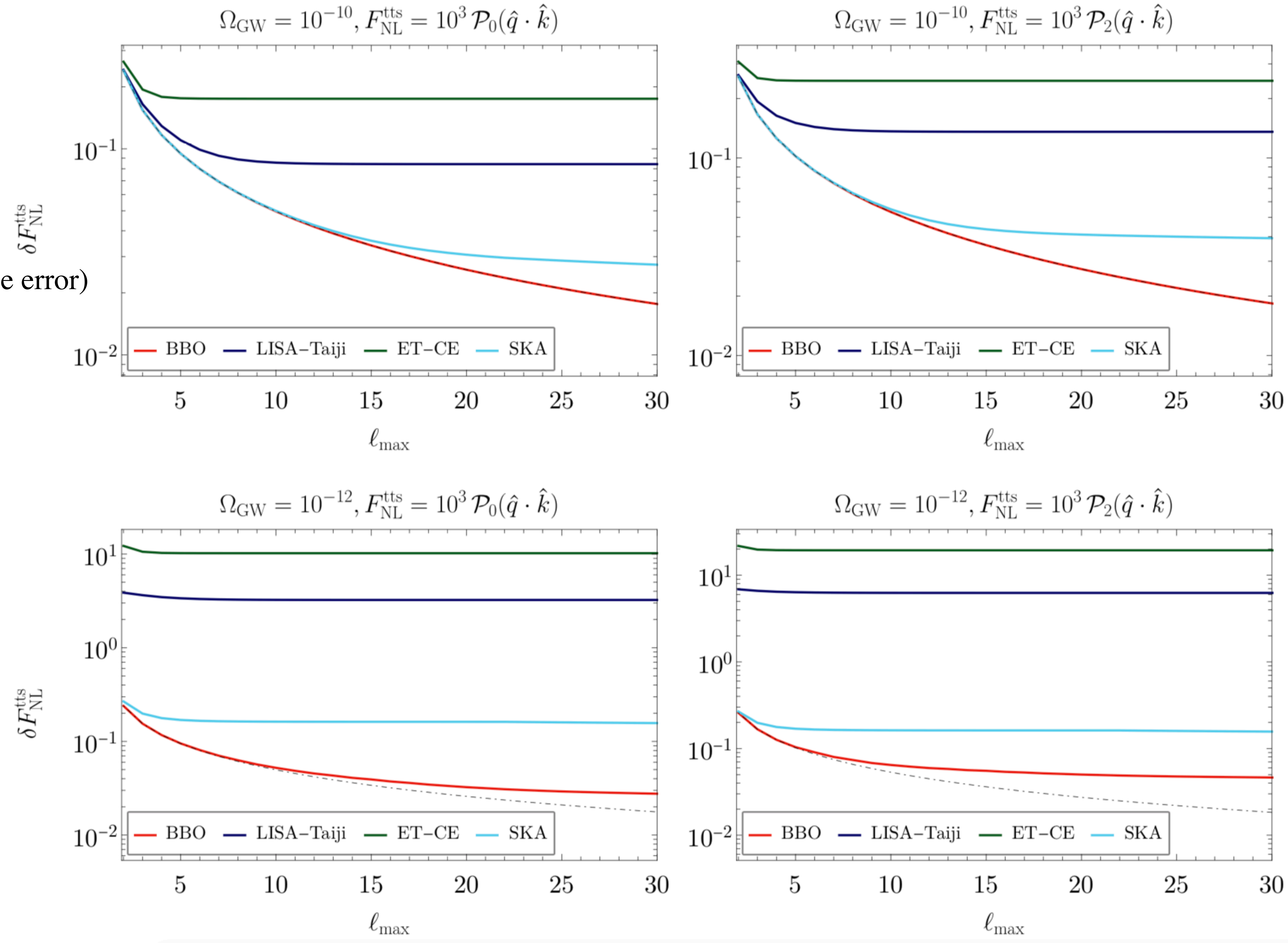
- LISA+Taiji



[Ruan et al, 2020]

- ET + CE
- SKA (assumed 50 identical pulsars)

Projected constraints on $F_{\rm NL}^{\rm tss}$



(relative error)

[ED, Fasiello, Malhotra, Meerburg, Orlando 2021]

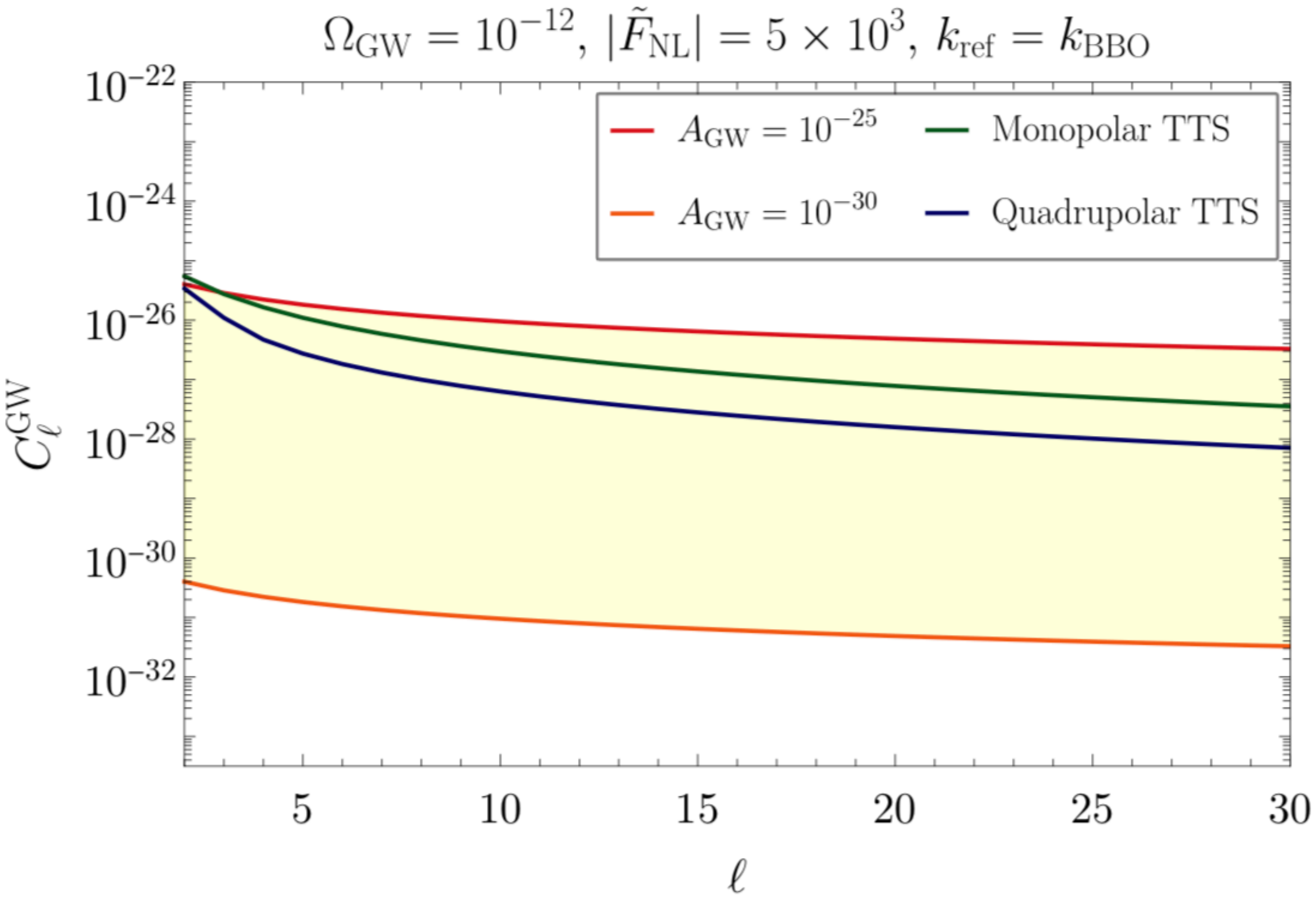
SGWB anisotropies: astrophysical sources

- SGWB from superposition of signals from black holes, neutron star binaries
- ASGWB also expected to be anisotropic due to the distribution of sources
- Anisotropies in the ASGWB can inform us about many things (e.g. start formation model, mass distribution, etc) **[see e.g. Cusin et al, 2018-19-20]**
- On large scales anisotropies in the ASGWB do not correlate strongly with CMB, (cross-correlations with LSS observables much more effective) **[Ricciardone et al, 2021]**

↓

GW-CMB correlation excellent probe of cosmological SGWB!

Astrophysical foregrounds

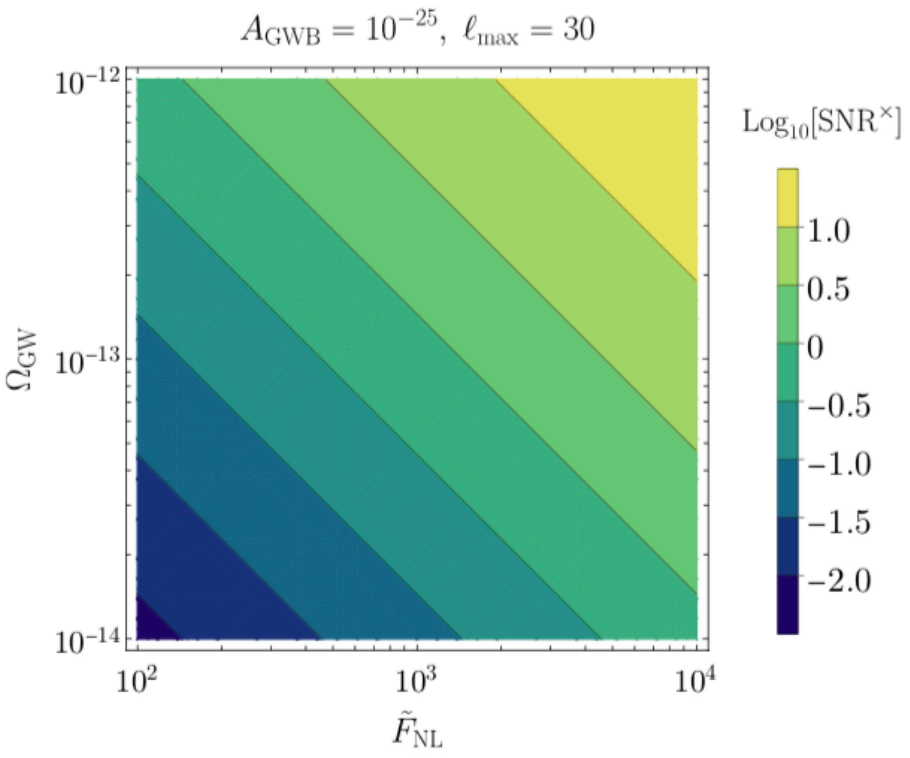


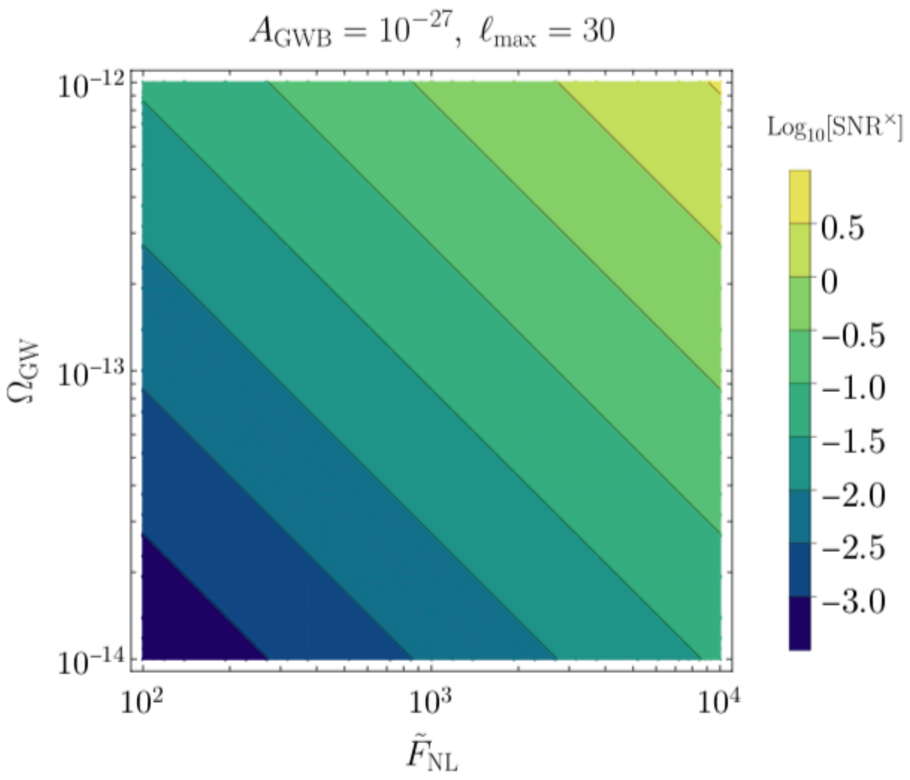
SNR for GW-CMB cross-correlations:

$$\mathrm{SNR}^{\times} = \left[\sum_{\ell_{\min}}^{\ell_{\max}} (2\ell+1) \frac{\left(\mathrm{C}_\ell^{\mathrm{GW-T,signal}}\right)^2}{\left(\mathrm{C}_\ell^{\mathrm{GW-T,total}}\right)^2 + \mathrm{C}_\ell^{\mathrm{GW,total}} \mathrm{C}_\ell^{\mathrm{TT}}}\right]^{1/2}$$

$$\begin{aligned} C_\ell^{\mathrm{GW-T,signal}} &= C_\ell^{\mathrm{GW-T,tts}} \\ C_\ell^{\mathrm{GW-T,total}} &= C_\ell^{\mathrm{GW-T,signal}} + C_\ell^{\mathrm{GW-T,induced}}\,, \\ C_\ell^{\mathrm{GW,total}} &= C_\ell^{\mathrm{GW,tts}} + C_\ell^{\mathrm{GW,induced}} + C_\ell^{\mathrm{GW,astro}} + N_\ell^{\mathrm{GW}} \end{aligned}$$

Monopolar
stt bispectrum

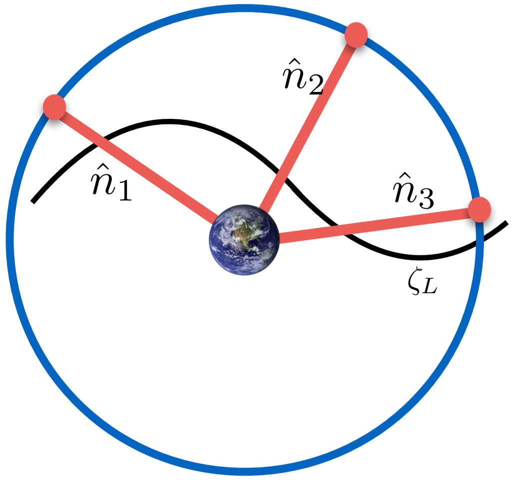




Quadrupolar
stt bispectrum

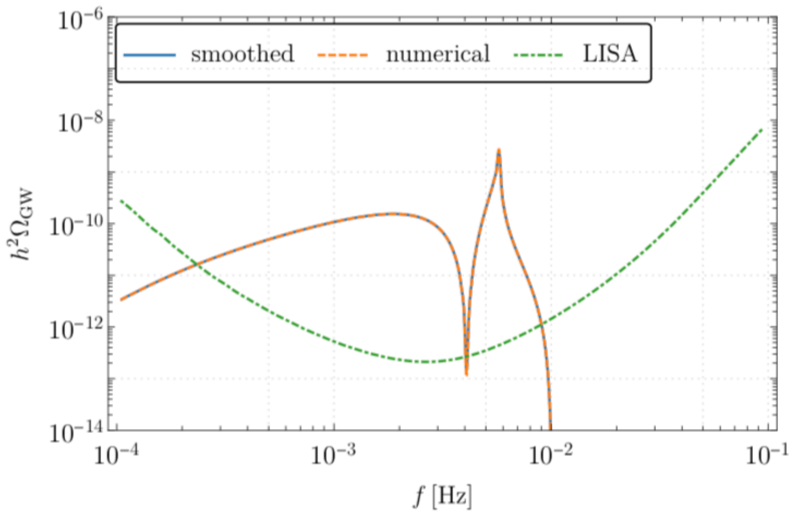
[ED, Fasiello, Malhotra, Meerburg, Orlando 2021]
Modeling of astrophysical background using results in [Cusin, Dvorkin, Pitrou, Uzan 2018-2019]

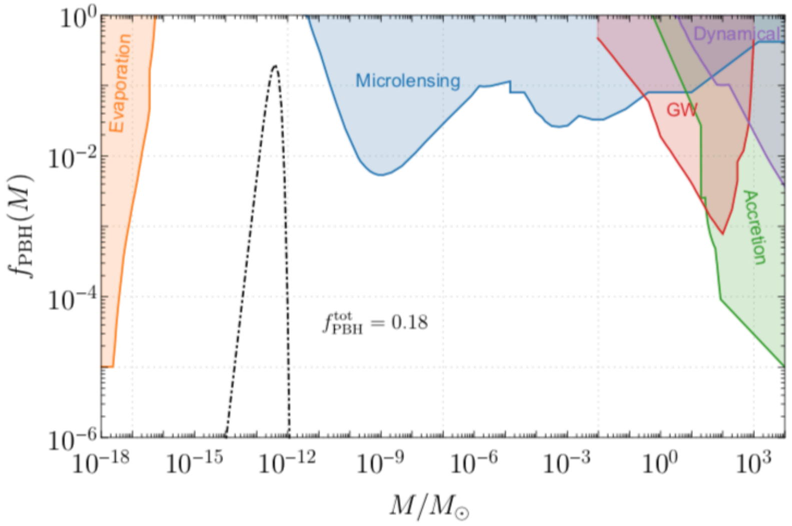
Anisotropies from propagation



Models with sharp peaks in the scalar power spectrum (e.g. PBH production)

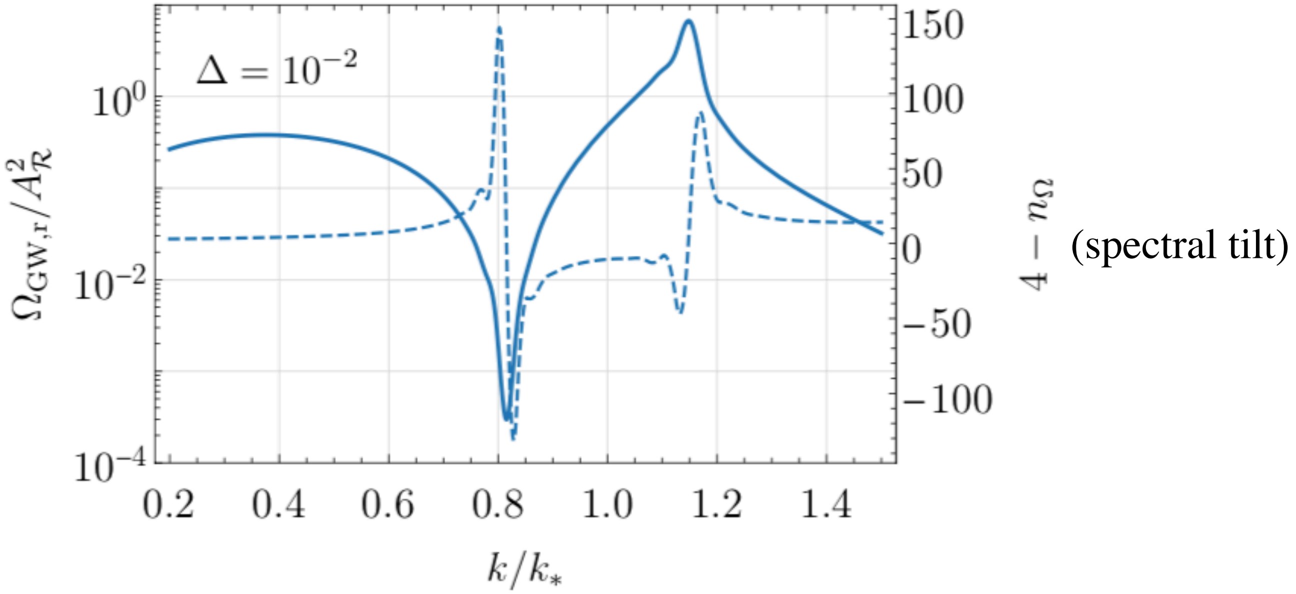
- a large GW background with sharp peaks induced at second order from scalar perturbations



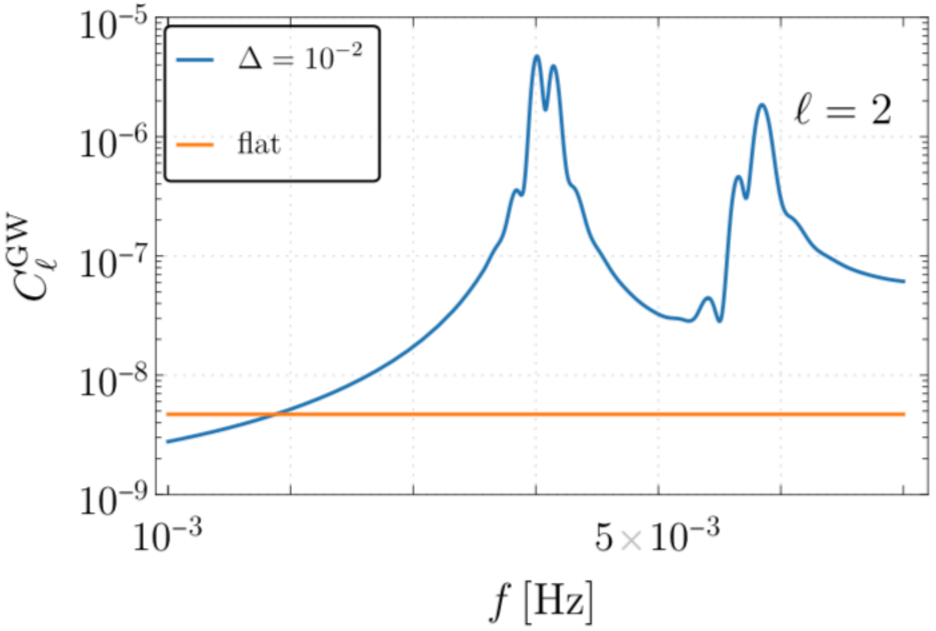


- the anisotropies can be typically enhanced by O(10-100)

$$\delta_{\rm GW} \sim \left(\frac{\partial \ln \Omega_{\rm GW}}{\partial \ln k}\right) \zeta_{\rm L}$$



- the angular power spectrum of the SGWB anisotropies inherits the frequency dependence



[ED, Fasiello, Malhotra, Tasinato 2022]

Primordial gravitational waves

- Different production mechanisms during inflation lead to a variety of signals

- We can characterise the various GW sources from inflation using:
  - spectral shape
  - chirality
  - non-Gaussianity
  - SGWB anisotropies

- Powerful observables with the potential to disentangle inflationary GW from those generated in the post-inflationary universe