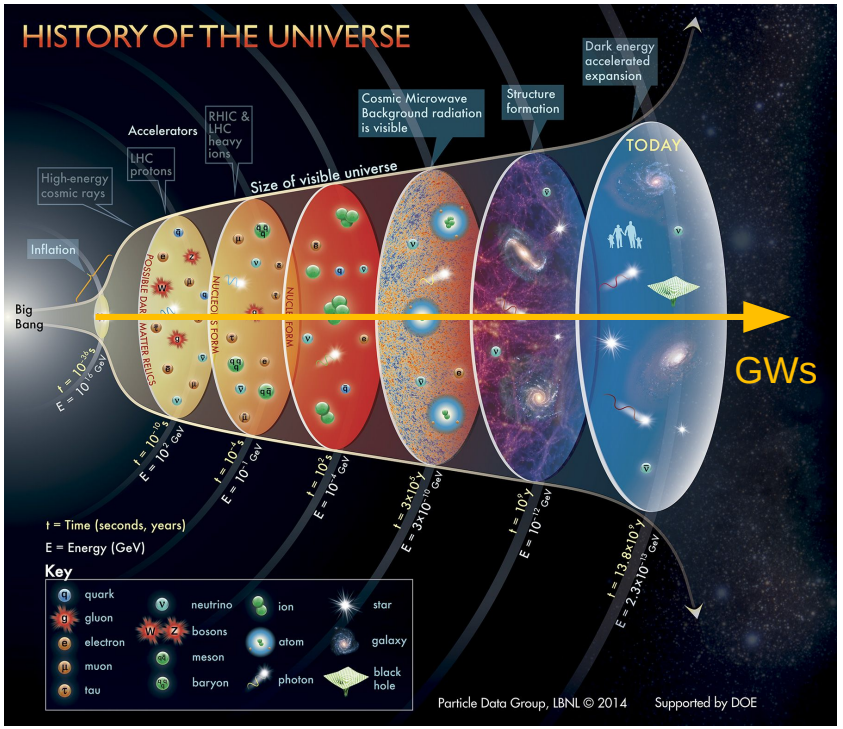
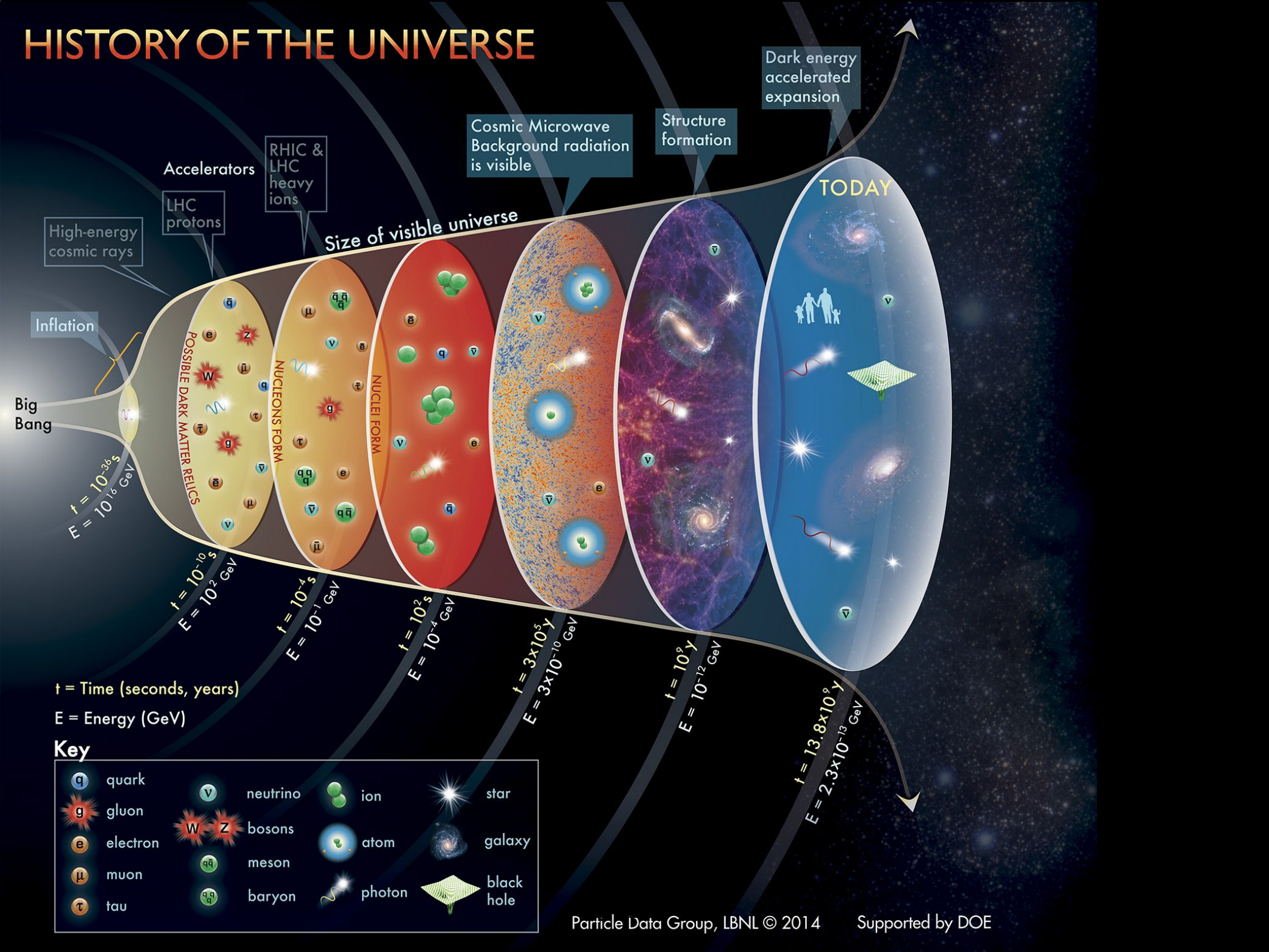
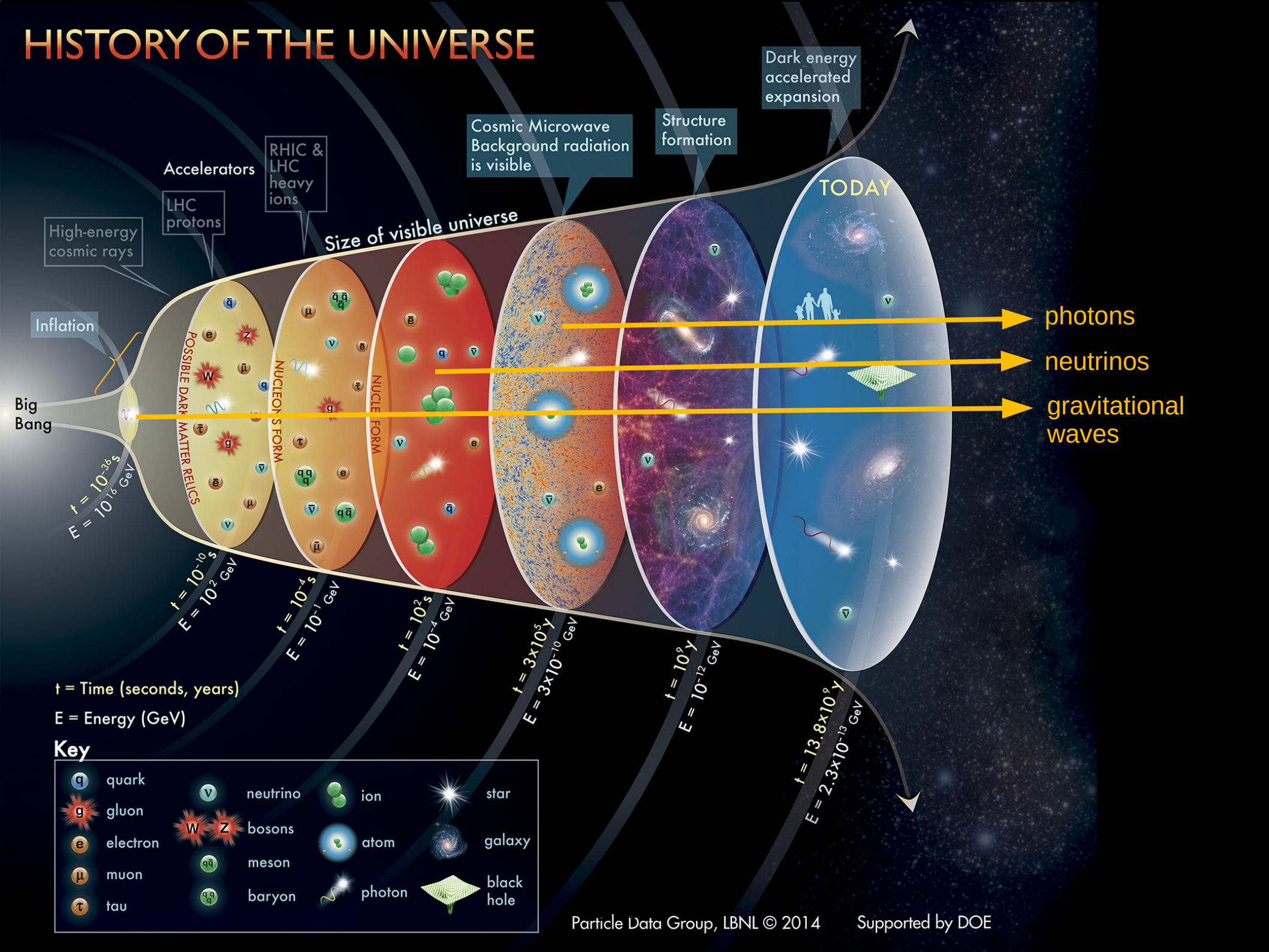
Gravitational waves from cosmic inflation



Valerie Domcke
CERN/EPFL

DESY Theory Workshop
September 21 – 24, 2021


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE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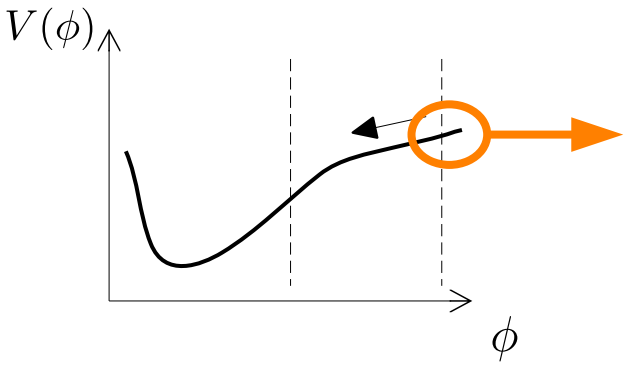
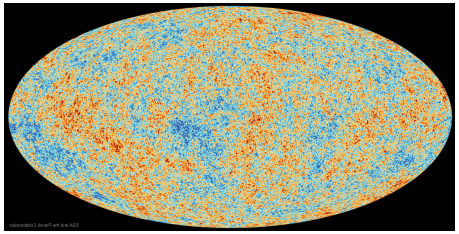
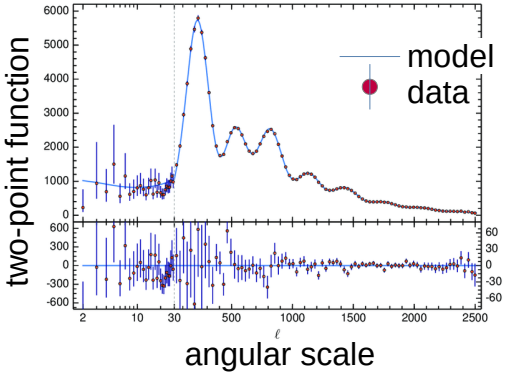
Cosmic inflation in a nutshell





Planck collaboration `18

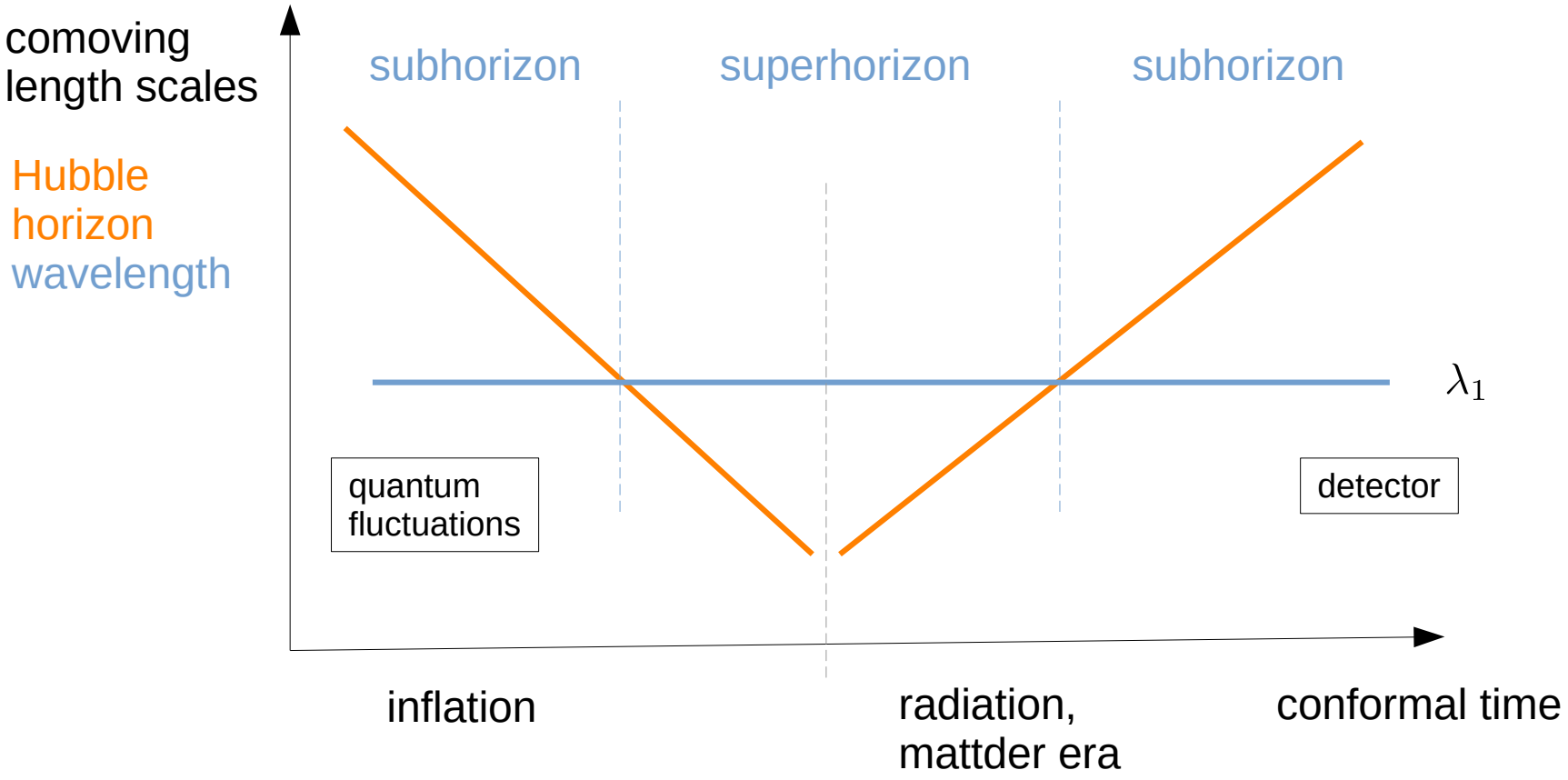


large vacuum energy → exponential expansion → homogeneity of CMB

quantum fluctuations → become classical → tiny anisotropies in CMB

very successful paradigm, but very many possible realizations

scales and horizons



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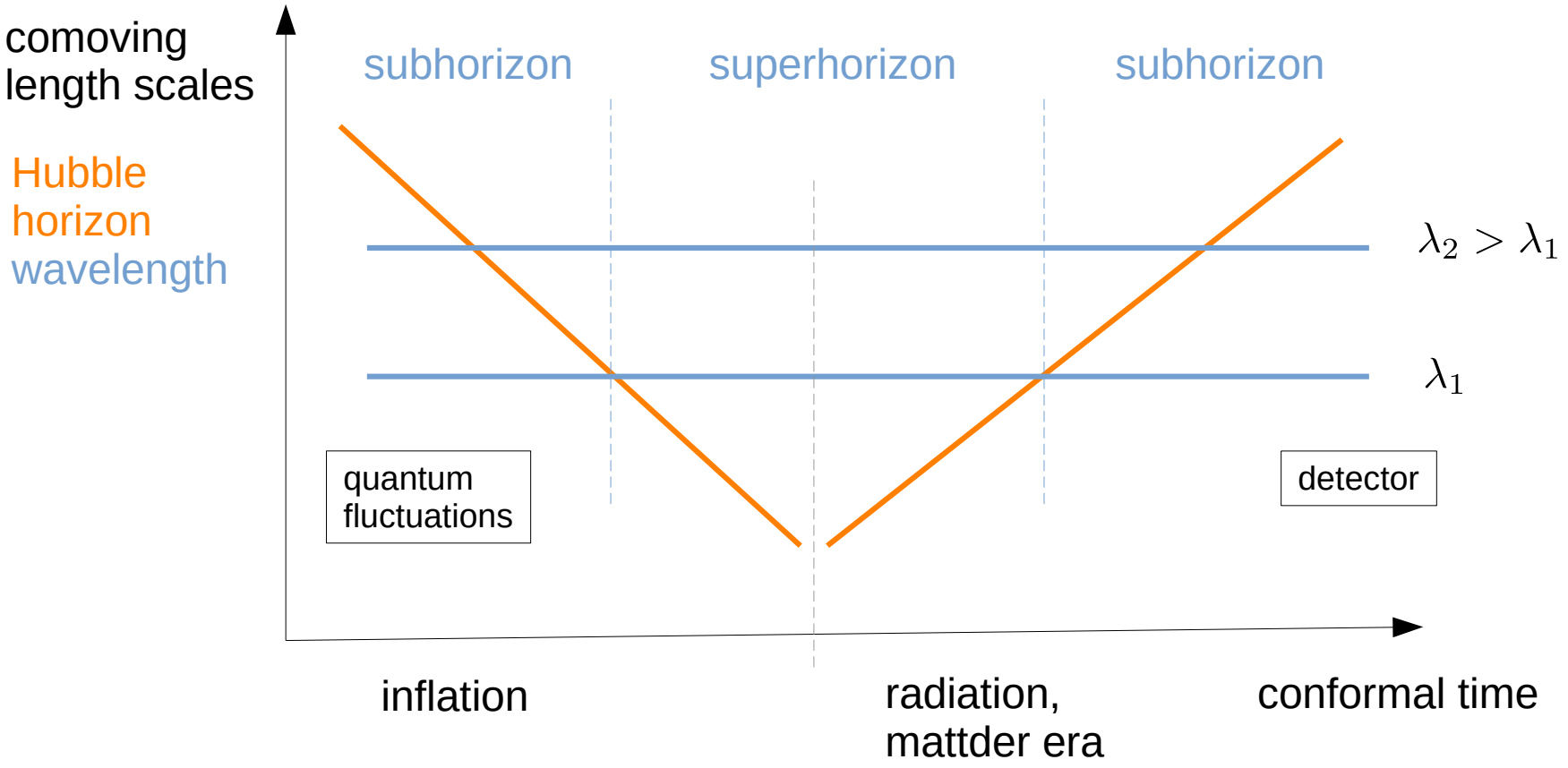


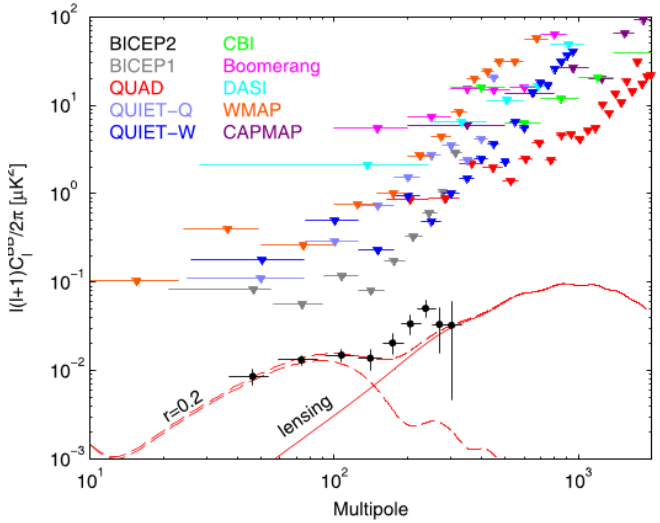
high frequency fluctuations leave horizon late (during inflation) and re-enter (early) after inflation

→ 1:1 correlation between frequency and time (during/after inflation)

Searching for GWs from inflation

CMB polarization

- $\lambda_{\rm gw} \sim (aH)^{-1}$
  at CMB decoupling
- upper bound
  $r \lesssim 0.06$



hypothetical signal with r = 0.2 [BICEP `14]

GW frequency

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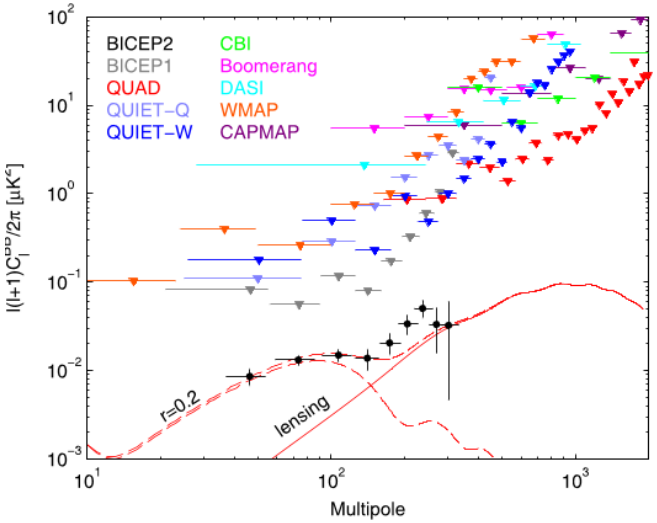
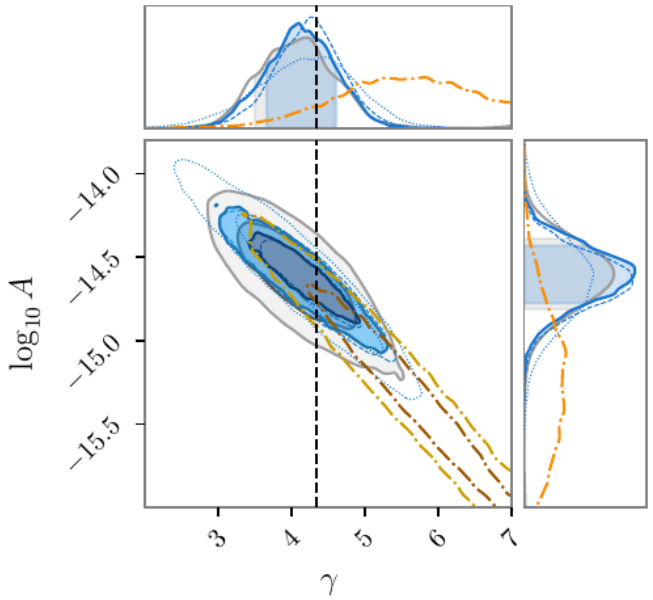


hypothetical signal with r = 0.2 [BICEP `14]

direct GW detection

- pulsar timing arrays
- GW interferometers



NANOGrav `20 / PPTA `21

GW frequency

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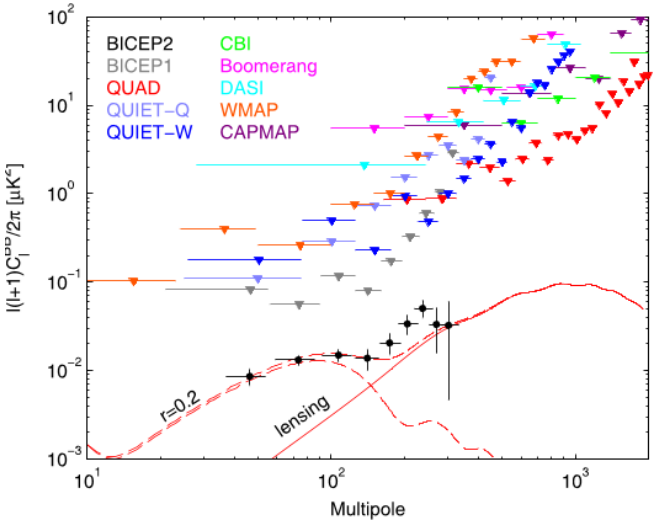

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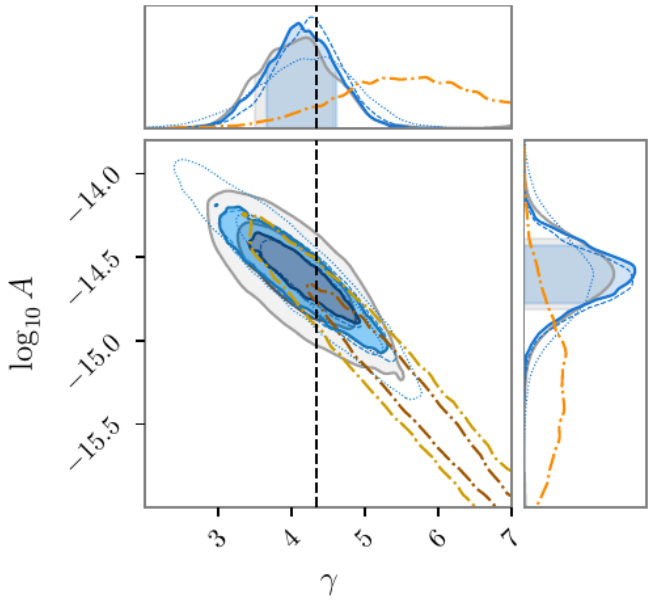


NANOGrav `20 / PPTA `21

BBN / CMB bounds on extra radiation

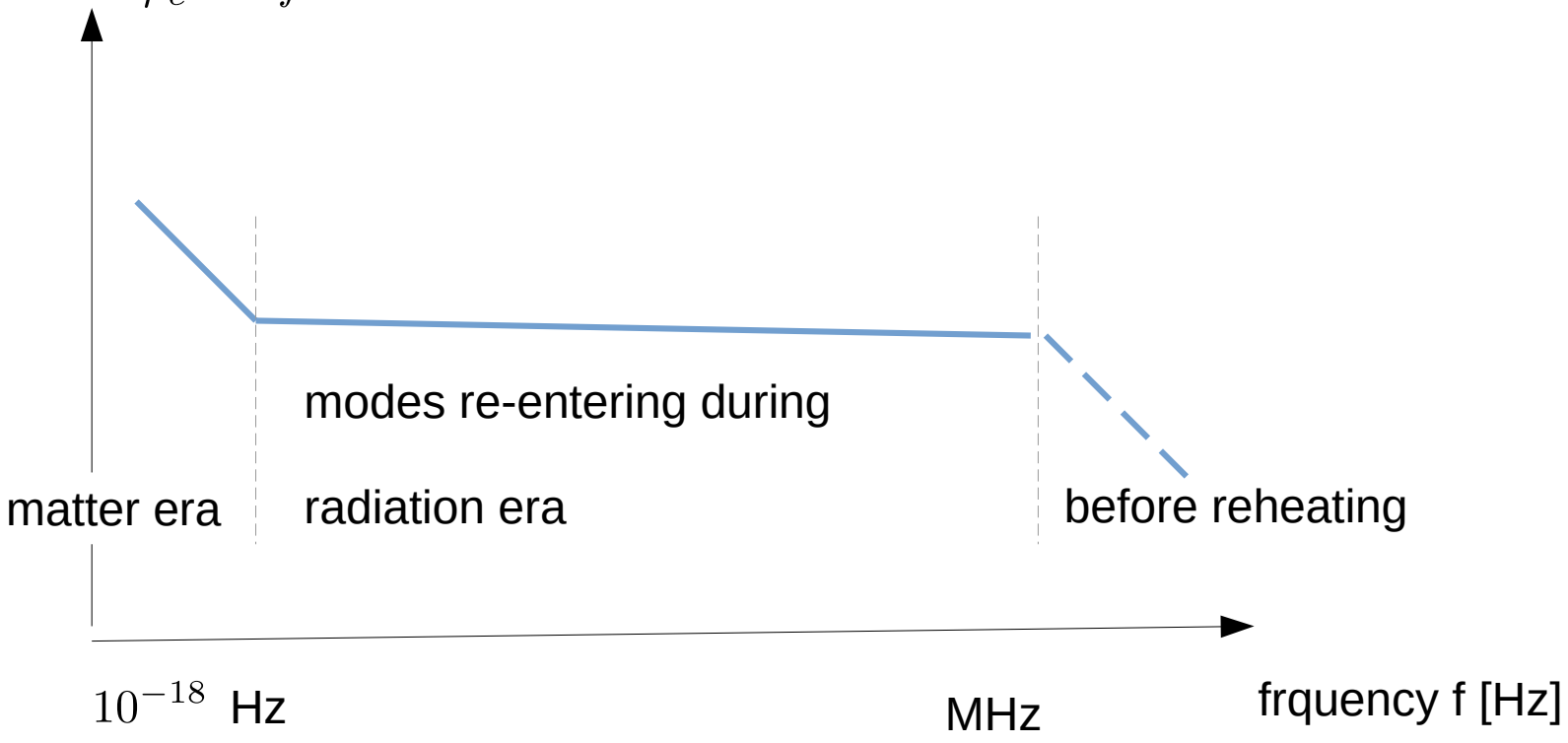
- significant extra radiation $\rho_{\rm gw}/\rho_\gamma \gtrsim \mathcal{O}(0.1)$ changes cosmic expansion
- $\Delta N_{\rm eff} \lesssim 0.5$
- bound on energy (not displacement)
  → particularly relevant for high frequencies

GW frequency

Single-field slow roll inflation

vacuum fluctuations: scale invariant GW spectrum generated during inflation

$$\Omega_{\rm gw}(f) = \frac{\partial \rho_{\rm gw}}{\rho_c \, \partial \ln f}$$



[for non-standard cosmic expansion history → see P. Simakachorn`s talk]

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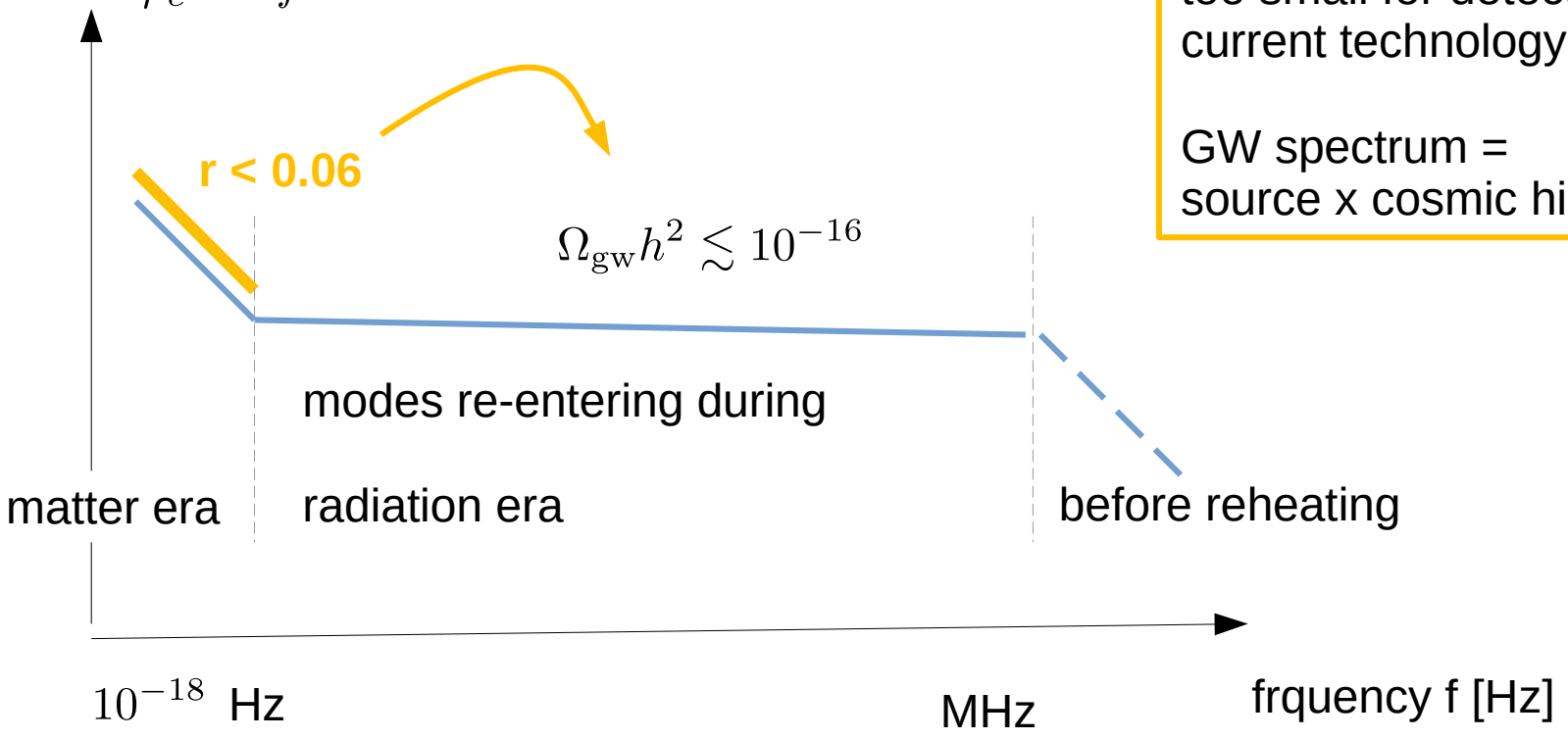

too small for detection with current technology

GW spectrum = source x cosmic history

[for non-standard cosmic expansion history → see P. Simakachorn`s talk]

``axion" inflation

slow-roll inflation → very flat scalar potential

reheating after inflation → coupling to the SM

inflaton as Pseudo Goldstone Boson (PNGB, ALP) with shift-symmetric couplings, i.e. invariant under $\phi \mapsto \phi + c$

$\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$

$(\partial_\mu \phi)\bar{\psi}\gamma^\mu\gamma^5\psi$ J_5^μ

‘axion’ inflation

- a minimal setup for SM + inflation:

axion with scalar potential | (hyper charge) U(1) gauge field | massless (SM) fermions | axion gauge field coupling

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_\alpha \bar{\psi}_\alpha(i\partial\cdot\gamma - gQA\cdot\gamma)\psi_\alpha + \frac{\alpha\phi}{4\pi f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$(\partial_\mu\phi)\bar{\psi}\gamma^\mu\gamma^5\psi$$

SM chiral anomaly

non-abelian gauge fields: VD, Mares, Muia, Pieroni `18; VD, Ema, Mukaida, Sato `18; VD, Sandner `19
massive fermions: VD, Ema, Mukaida `19; VD, Ema, Mukaida `21

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- axion – hypercharge coupling leads to exponential helical gauge field production (ignoring fermion backreaction for the moment):

$$\frac{d^2}{d\tau^2}A_\pm(\tau,k) + \left[k^2 \pm 2k\frac{\xi}{\tau}\right]A_\pm(\tau,k) = 0\,, \qquad \xi = \frac{\alpha\dot{\phi}}{2Hf_a}$$

Turner, Widrow `88
Garretson, Field, Caroll `92

- gravitational waves, primordial black holes, ….

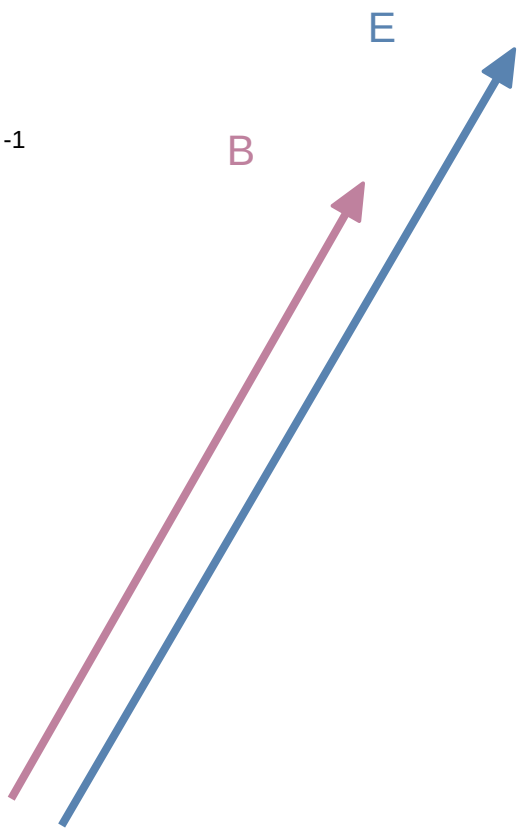
VD, Pieroni, Binétruy `16,
VD, Muia, Pieroni, Witkowski `17

fermion production

VD, Mukaida `18

helical gauge field production

- one gauge field helicity acquires tachyonic mass
- parallel E & B fields, constant & homogeneous on scales << H^{-1}



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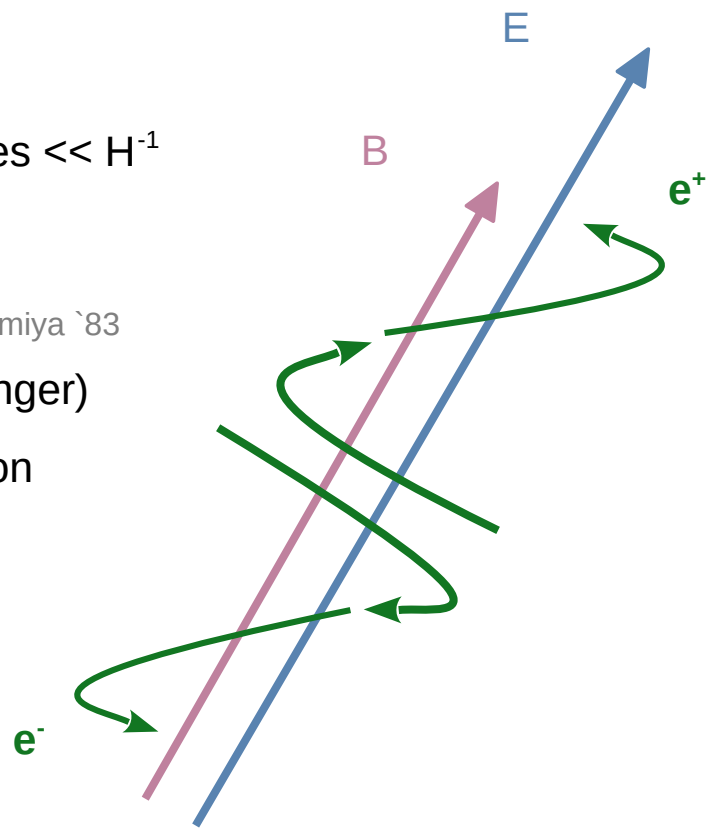
(chiral) fermion production

Nielsen, Ninomiya `83

- fermion production in constant E,B background (Schwinger)
- asymmetric production consistent with anomaly equation



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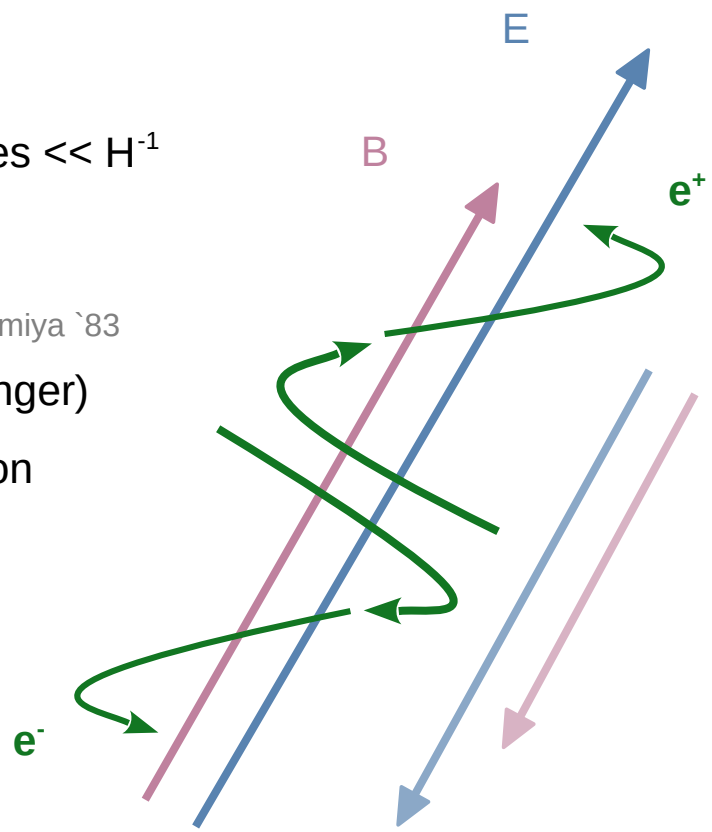
backreaction on gauge field production

- fermions are accelerated in gauge field background
- induced current inhibits gauge field production



any light charged particles will be produced and induce backreaction

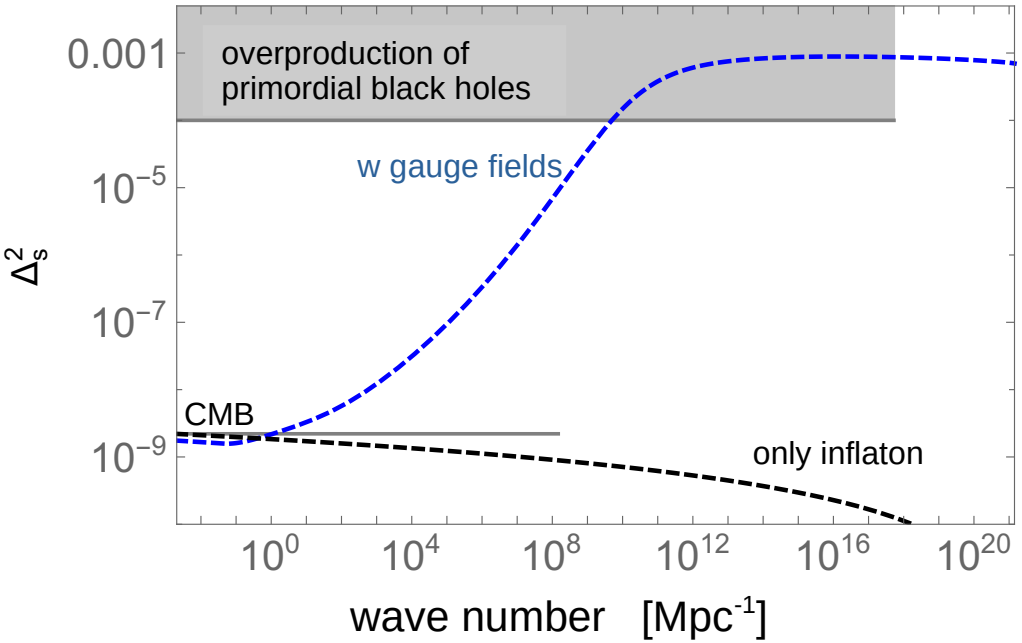
implications for axion inflation

$V(\phi) = \mu^3 \phi\,, \quad \mu \sim 10^{-3} M_P$

$\alpha/(\pi f_a) = (0.02\, M_P)^{-1}$

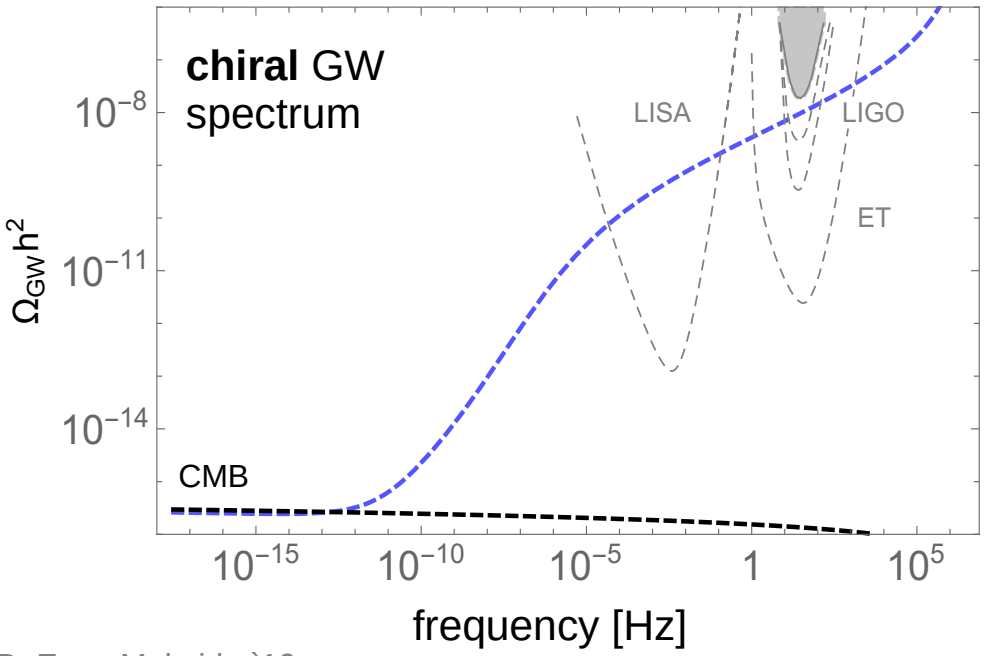
scalar power spectrum

maximal/ equ. solution for EB



tensor power spectrum

equilibrium solution for EB



VD, Mukaida `18, **VD**, Ema, Mukaida `19

probing particle physics behind inflation with gravitational waves

see also **VD**, Guidetti, Welling, Westphal `20 for resonance effects

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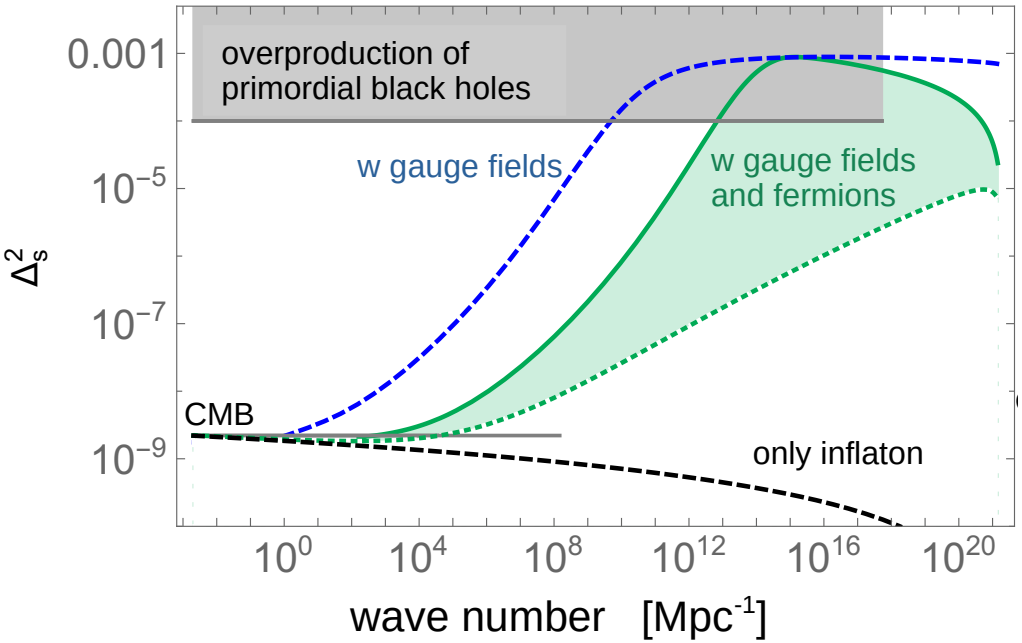

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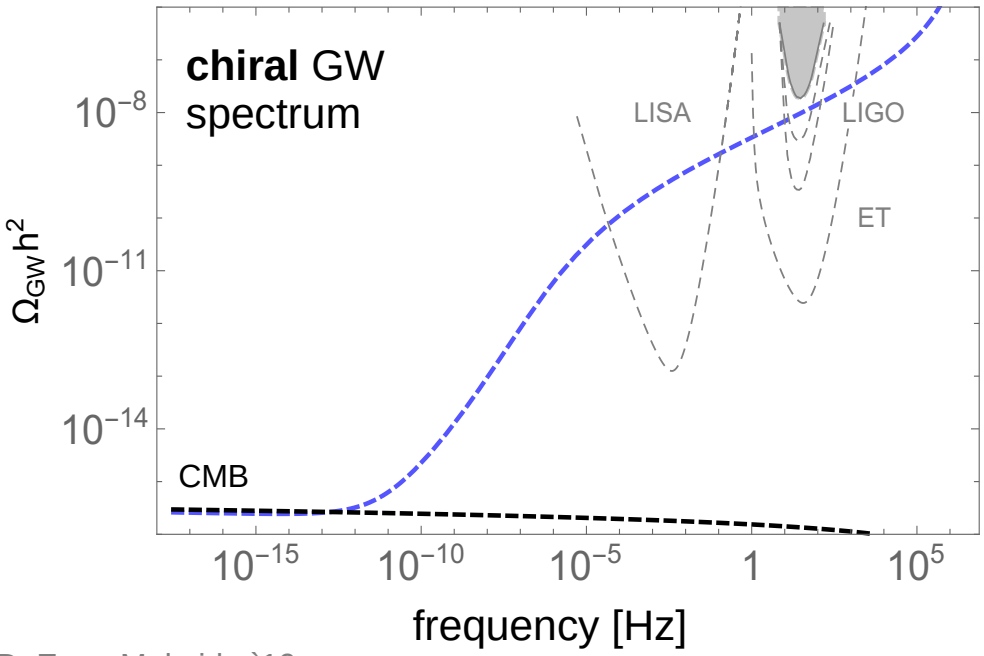

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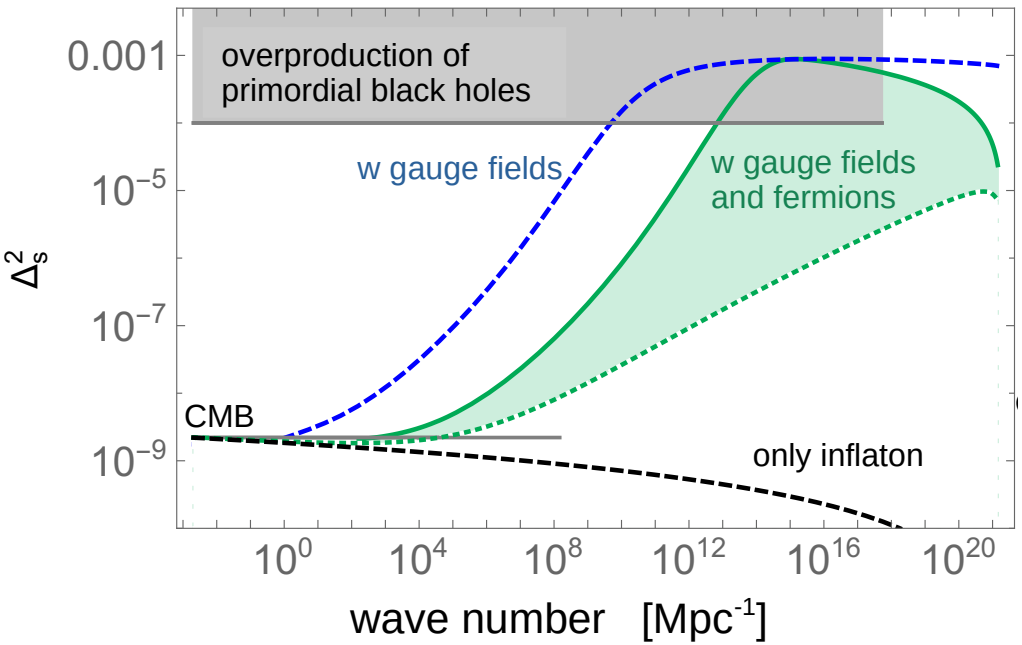

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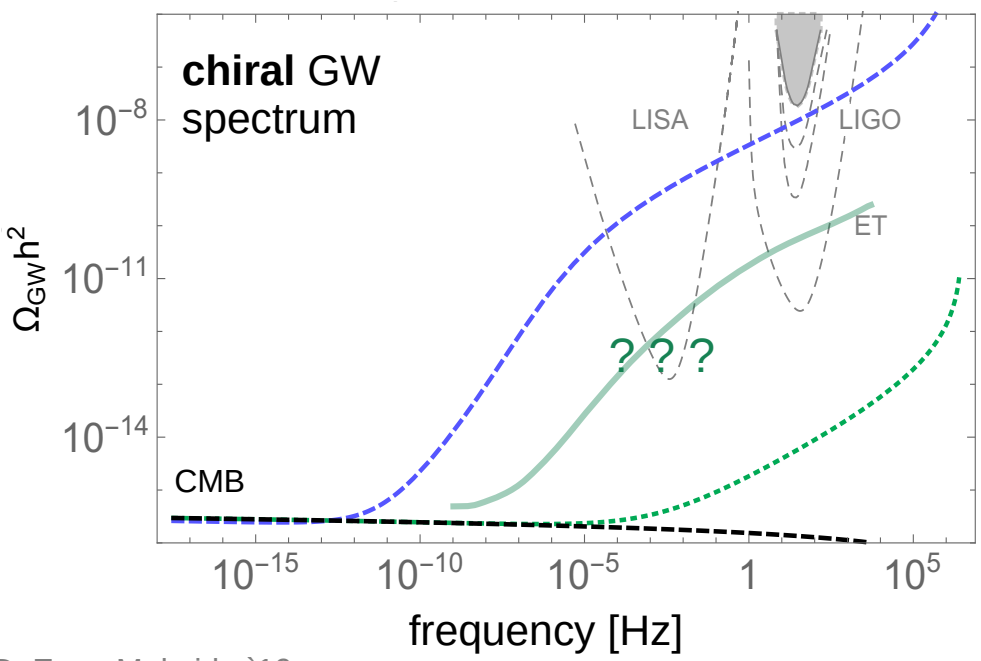

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VD, Garcia-Bellido, Peloso, Pieroni, Ricciardone, Sorbo, Tasinato `19 [LISA Cosmology WG]

measuring chirality of the SGWB

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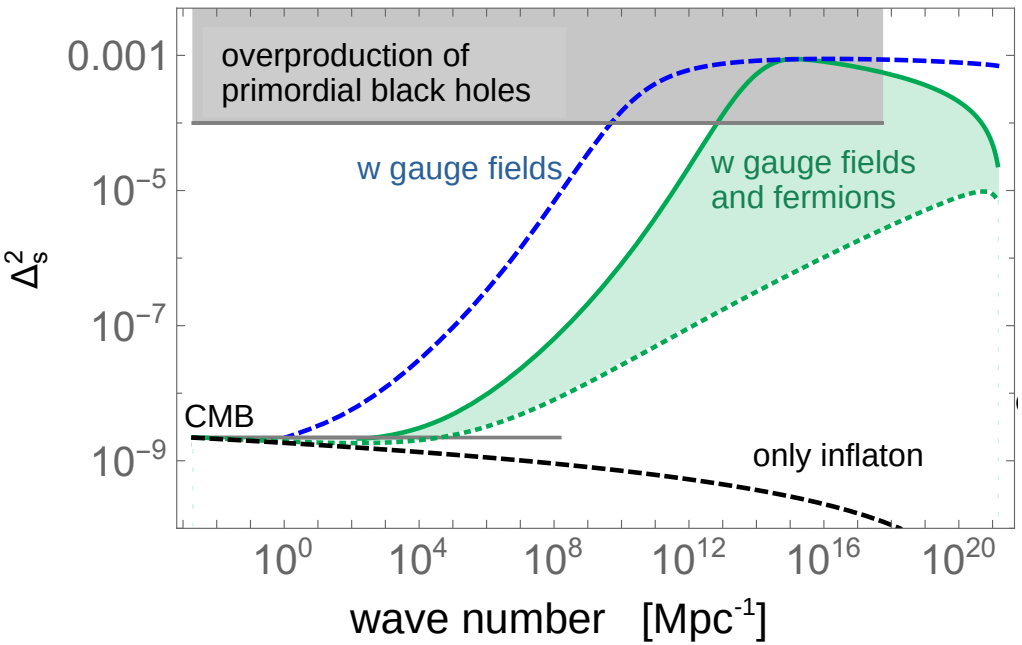

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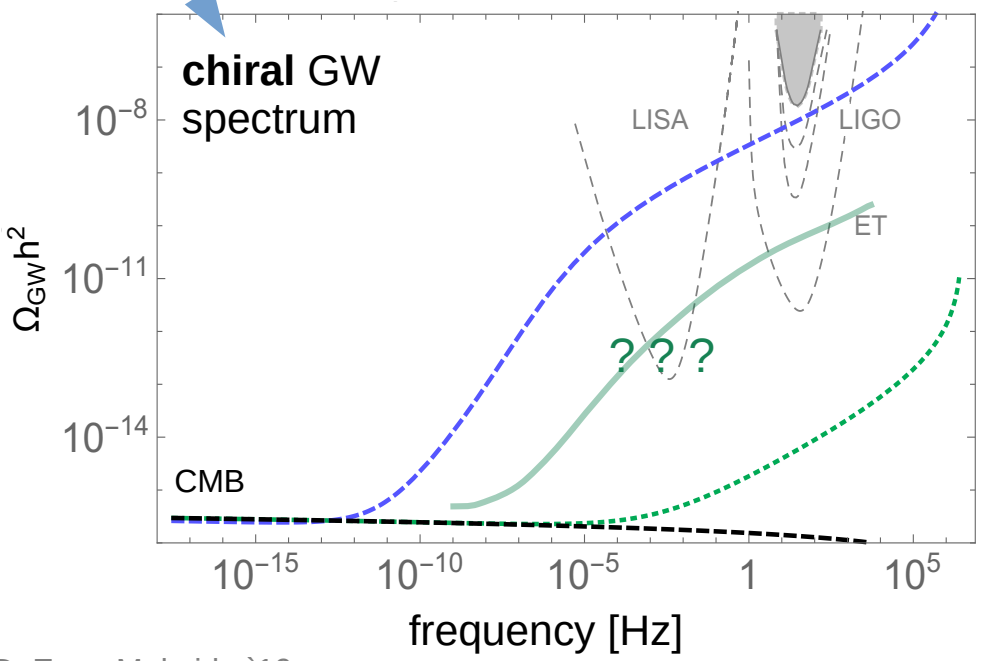

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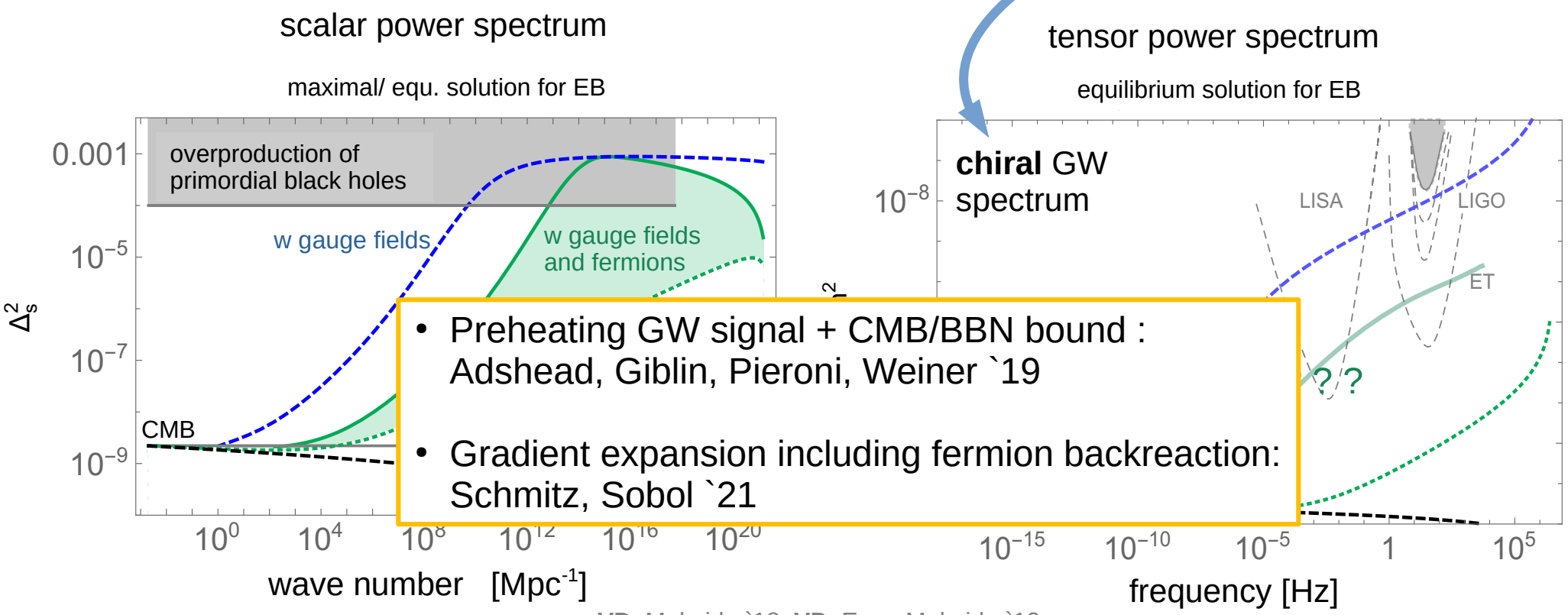

- Preheating GW signal + CMB/BBN bound : Adshead, Giblin, Pieroni, Weiner `19
- Gradient expansion including fermion backreaction: Schmitz, Sobol `21

VD, Mukaida `18, **VD**, Ema, Mukaida `19

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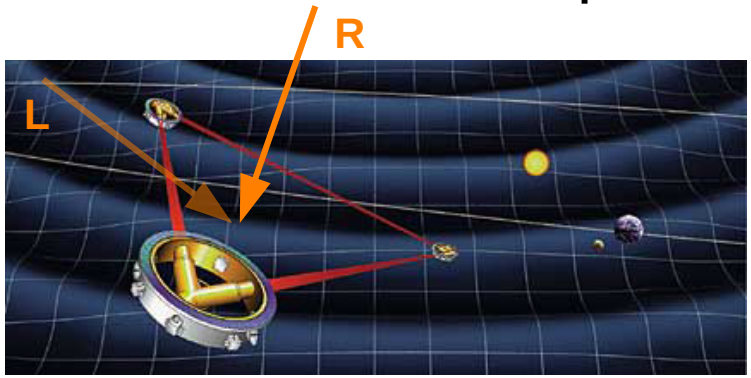
detecting chiral gravitational waves

axion inflation predicts a **chiral** stochastic gravitational wave (GW) spectrum

⇝ a **planar** detector cannot distinguish left- and right-handed GWs from an **isotropic** source

LIGO Livingston - US



LISA (launch 2030s)

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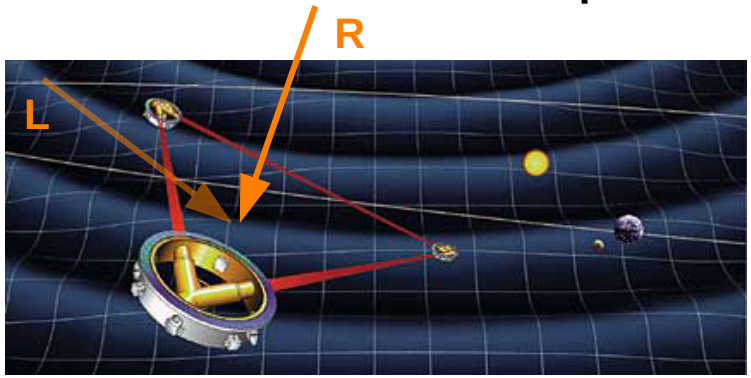
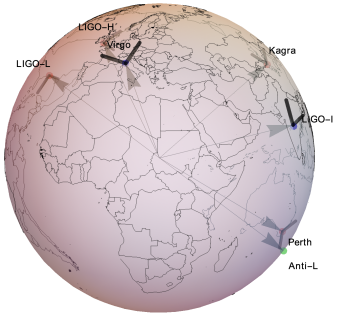


LISA (launch 2030s)

VD, Garcia-Bellido, Peloso, Pieroni, Ricciardone, Sorbo, Tasinato `20 [LISA Cosmology WG]

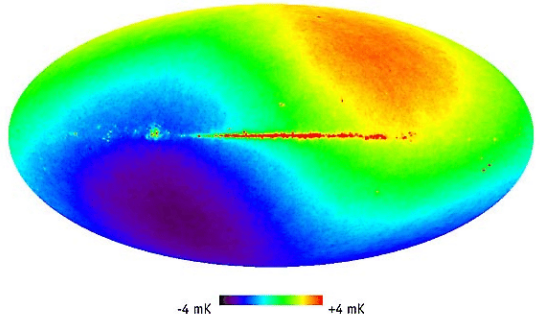
ground-based detectors:
network breaks
Seto, Taruya `07; Crowder et al `12

→ sensitive to maximally chiral scale-invariant spectrum if SNR > 10^3



LISA (or single ET): Seto `06
kinematic cosmic dipole breaks isotropy

→ sensitive to maximally chiral scale-invariant spectrum if SNR > 10^3



possible for SNR > 10^3

topics I did not have time to cover:

- axion inflation: non-abelian gauge fields, massive fermions, resonance effects,…
- GWs in the framework of EFTs of broken spatial reparametrization
- GWs from primordial black holes sourced during inflation
- Preheating, oscillons
- … your favourite model?

Conclusions

- Multi-band GW searches probe different epochs of cosmic inflation
- GW interferometers probe later stages → complementary to CMB polarizaton
- Axion inflation: dual production of gauge fields and fermions during inflation

  → GW signal sensitively depends on microphysics during inflation

See also review of LISA Cosmology WG,
arxiv: 1610.06481

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Questions?

See also review of LISA Cosmology WG,
arxiv: 1610.06481

fermion backreaction

VD, Mukaida `18

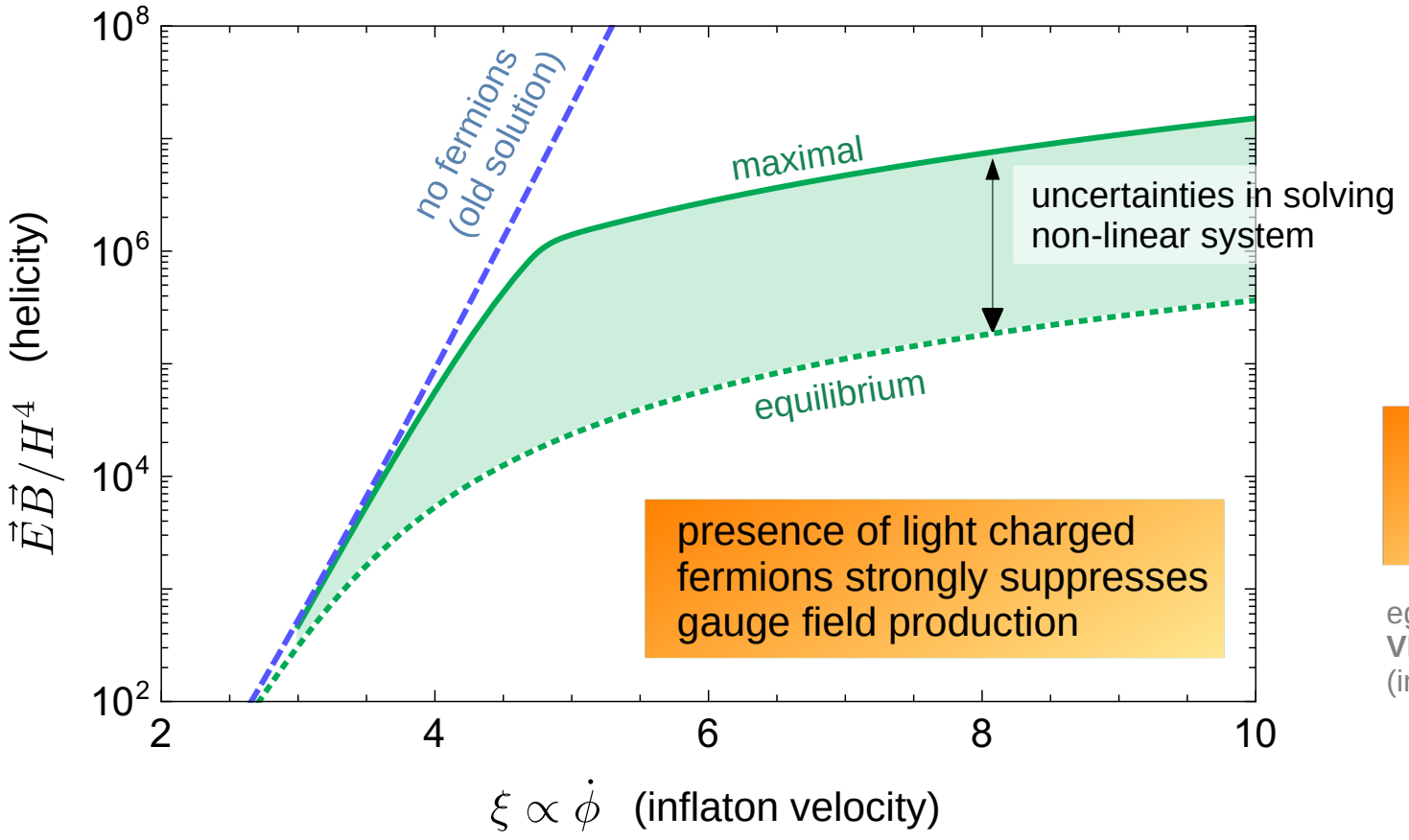
fermion production inhibits gauge field production

$$0 = \dot{\rho}_A = -4H\rho_A + 2\xi H \vec{E}\cdot\vec{B} - \vec{E}gQ\langle\vec{J}_\psi\rangle$$

from solving Dirac equation

$$\langle|J^z_\psi|\rangle \propto \coth\left(\frac{\pi B}{E}\right) EB$$

→ non-linear system, search for stationary solution :



applies to all ALP models !

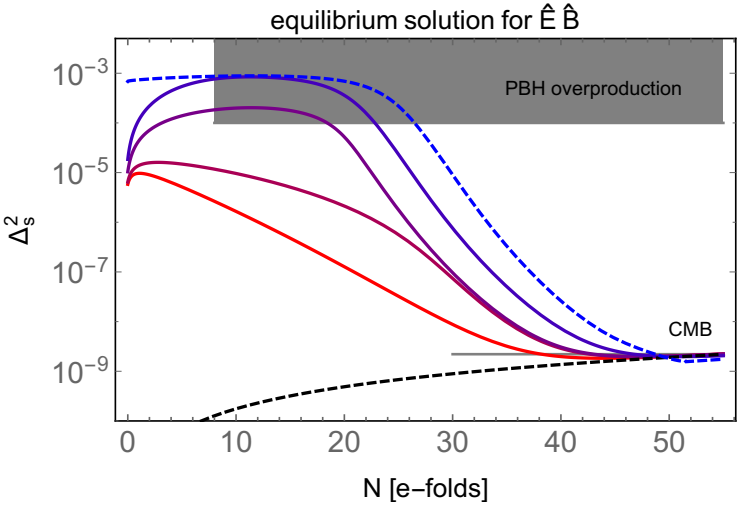
eg the relaxion, **VD**, Schmitz, You (in preparation)

massive fermions & non-abelian gauge fields

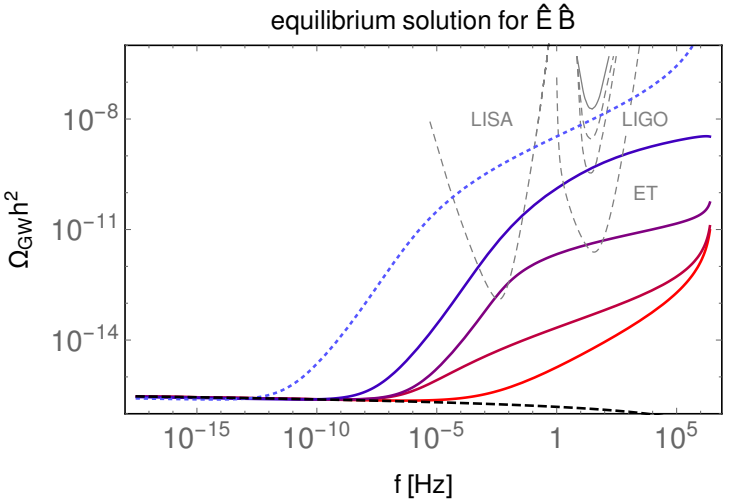
massive fermions $\partial_\mu J_5^\mu = -\frac{g^2Q^2}{8\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + 2ima\bar{\psi}\gamma_5\psi \simeq \frac{g^2Q^2}{2\pi^2}EB\exp\left(\frac{-\pi m^2a^2}{gQE}\right)$

VD, Ema, Mukaida `19

scalar power spectrum



gravitational wave spectrum



no gauge fields,
no fermions,
fermions with
m/H = 0, 10, 30, 100

non-abelian gauge groups [SU(2)]

- gauge field self-interactions allow for formation of non-zero isotropic vev, which is a local attractor solution

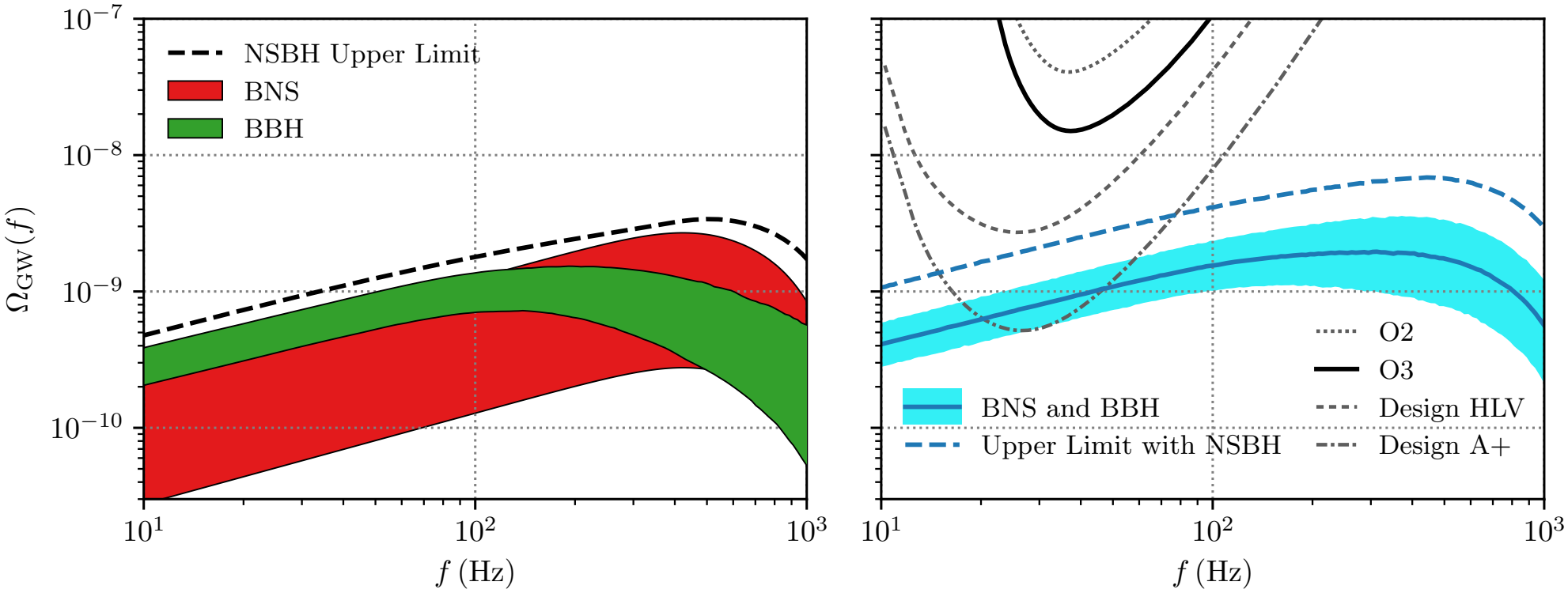
  VD, Mares, Muia, Pieroni `18
- theoretical consistency and perturbativity tightly constrain the parameter space of interest

  VD, Sandner `19
- fermion backreaction sub-dominant compared to gauge field self-interaction

  VD, Ema, Mukaida, Sato `18

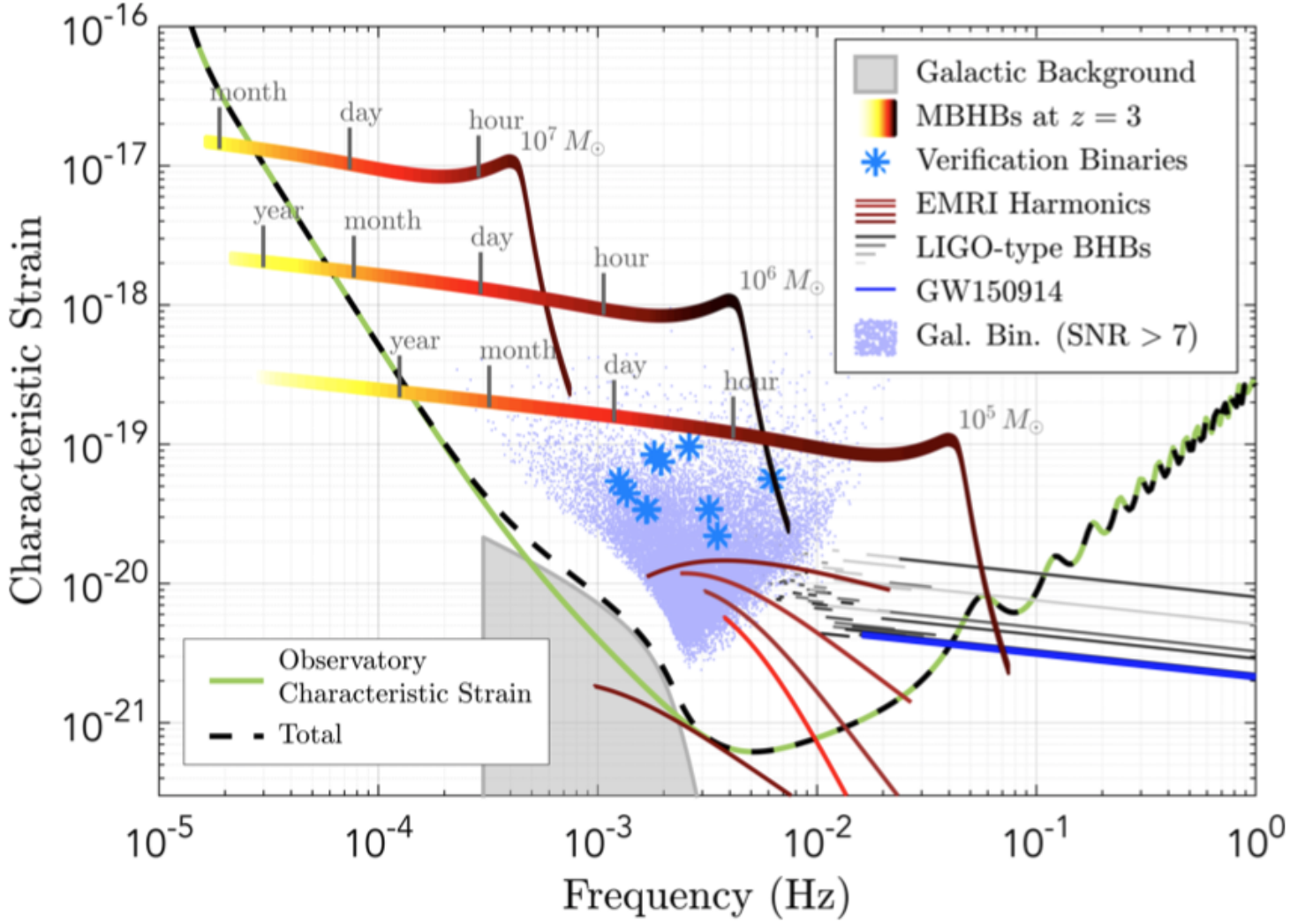
LIGO stochastic backgrounds

LIGO VIRGO O3 run, 2021



- possibly within reach of advanced LIGO / VIRGO / KAGRA
- not an intrinsically stochastic background: ET / Cosmic Explorer can resolve all BBHs in the Universe

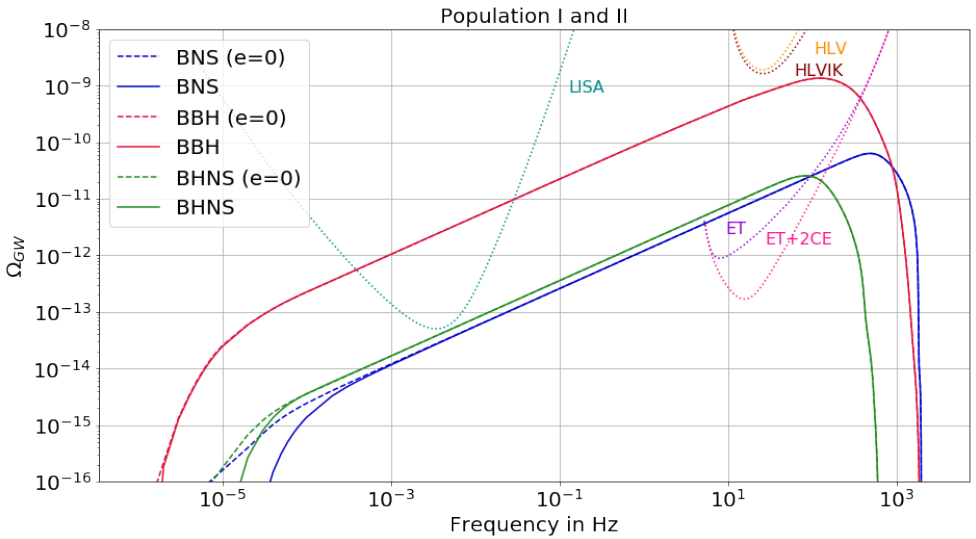
LISA sources

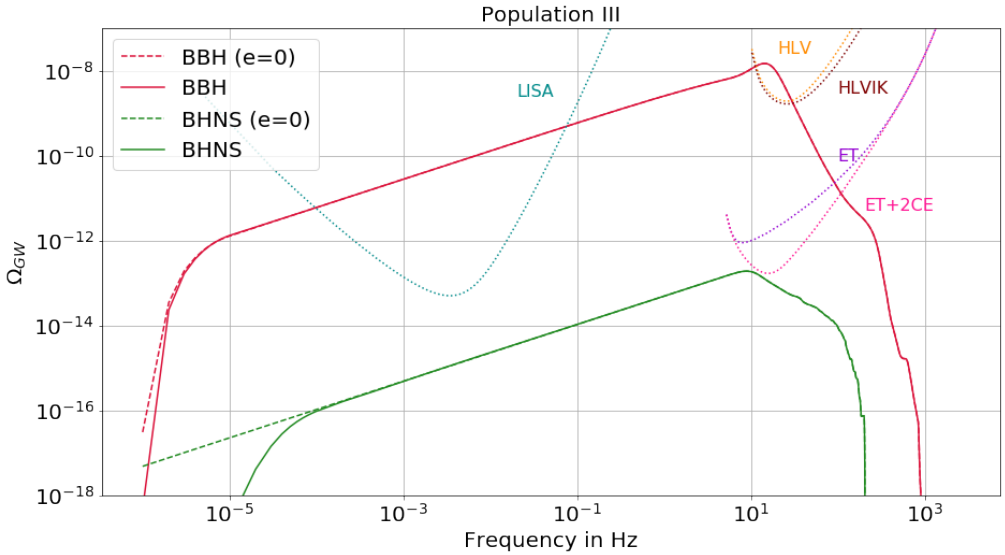


LISA mission proposal `17

LISA stochastic backgrounds

Périgois, Belczynski, Bulik, Regimbeau `21





- merger rate will be well measured by LIGO/VIRGO/KAGRA
- thousands of resolved BHBs, millions of unresolved BHBs [Sesana `16]
- overlapping signals → confusion noise. Isotropic? Gaussian? ...