Gravitational waves and new physics

Anastasiia Filimonova, Sascha Leonhardt, Thomas Rink
Horizon problem

\[ ds^2 = a(\tau)^2 (-d\tau^2 + dx^2) \]
Horizon problem

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Evolution of the horizon

Standard cosmology
Evolution of the horizon

- Inflaton potential
- Slow-roll
- Reheating
- Standard cosmology
- Hubble Radius \((aH)^{-1}\)
- LSS, CMB
- Inflation
- Radiation Dominated
Quantum fluctuations
Quantum fluctuations
Quantum fluctuations

- **Scalar perturbations**: curvature perturbations induced by spatial fluctuation in scalar field.

\[
\Delta^2(k) = \frac{k^3}{2\pi^2} \langle |R_k|^2 \rangle
\]
Quantum fluctuations

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  \[
  \Delta_r^2(k) = \frac{k^3}{2\pi^2} \langle |R_k|^2 \rangle
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- **Tensor perturbations**: gravitational waves.

  \[
  \Delta_h^2(k) = 2 \frac{k^3}{2\pi^2} \langle |h_{\nu,k}|^2 \rangle
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Quantum fluctuations

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- **Tensor perturbations**: gravitational waves.
  
  \[
  \Delta_{h}^{2}(k) = 2 \frac{k^3}{2\pi^2} \langle |h_{p,k}|^2 \rangle
  \]
  
  Tensor-to-scalar ratio (normalized amplitude)
  
  \[
  r = \frac{\Delta_{h}^{2}(k)}{\Delta_{r}^{2}(k)} \approx \left( \frac{V}{[2 \times 10^{16} \text{ GeV}]^4} \right)
  \]

  \[\Delta_{h}^{2}(k) \text{ is known from } \langle T^2(k) \rangle, \ H^2 \propto V\]
Quantum fluctuations

- **Scalar perturbations**: curvature perturbations induced by spatial fluctuation in scalar field.

- **Tensor perturbations**: gravitational waves.

Power spectrum:

- **Tensor-to-scalar ratio** (normalized amplitude)

Test your favourite model!
Also classical production possible!
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If large and coherent
Also classical production possible!

Non-perturbative processes

If large and coherent
Also classical production possible!

If large and coherent, non-perturbative processes may occur, leading to time-dependent inhomogeneities in the energy-density.
Also classical production possible!

If large and coherent

Non-perturbative processes

Time-dependent inhomogeneities in the energy-density.

Non-trivial quadrupole moments.
Why interesting?
Why interesting?
Why interesting?

Model-independent evidence of inflation!
A small motivation for indirect detection
The CMB - A Screenshot of Primordial Gravitational Waves
GWs ↔ CMB

- Primordial GWs too faint to detect directly
- GWs generate anisotropies in the matter distribution
- At the time of decoupling this results in anisotropies of CMB
- Indistinguishable from (more dominant) scalar quantum fluctuations
- However: B-mode polarization of CMB is unique to GWs!
- Power of B-polarized CMB waves (in inflationary low frequency band) gives tensor-to-scalar ratio $r$
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Detection of B-modes proves existence of primordial GWs!
What are E- and B-Modes?
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- Information in CMB: temperature \( T(\hat{n}) \) and polarization as function of position \( \hat{n} = (\theta, \phi) \)
- Polarization measured by symmetric, traceless tensor:

\[
\mathcal{P}_{ab}(\hat{n}) = \begin{pmatrix}
Q(\hat{n}) & U(\hat{n}) \\
U(\hat{n}) & -Q(\hat{n})
\end{pmatrix}
\]

\[\hat{n}(\theta, \phi)\]

\[Q(\hat{n}) \quad U(\hat{n})\]

wikipedia: Stokes parameters
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- Just like we decompose

$$V_a = \nabla_a E + \varepsilon_{ab} \nabla_b B$$

$$\mathcal{P}_{ab} = \nabla_a \nabla_b E + \varepsilon_{ac} \nabla_b \nabla_c B$$

(+ symmetrization - trace), where $E(\hat{n})$ is “the gradient” and $B(\hat{n})$ is “the curl”.

wikipedia: Stokes parameters
Anisotropies in CMB induce two types of polarization: gradient E- and curl B-modes
Reminder: Thomson Scattering
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\[ \frac{I}{I'} \frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi} |\hat{e}' \cdot \hat{e}|^2 \]
Reminder: Thomson Scattering

\[
\frac{I}{I'} \frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi} |\hat{\epsilon}' \cdot \hat{\epsilon}|^2
\]

unpolarized photons

polarized CMB

last scattering surface
Reminder: Thomson Scattering

\[ \frac{I}{I'} \frac{\Delta \Omega}{\Delta \Omega} = \frac{d \sigma}{d \Omega} = \frac{3 \sigma_T}{8 \pi} |\hat{\epsilon}' \cdot \hat{\epsilon}|^2 \]

\[ I_x^2 + I_y^2 = I = \frac{3 \sigma_T}{16 \pi} I'(1 + \cos^2(\theta))d\Omega \]

\[ I_x^2 - I_y^2 = Q = \frac{3 \sigma_T}{16 \pi} I' \sin^2(\theta)d\Omega \neq 0 \]

last scattering surface

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\[ I_x^2 - I_y^2 = Q = \frac{16\pi I'}{3\sigma_T} \]

\[ U = \ldots \]

polarized CMB

unpolarized photons

last scattering surface
CMB with a monochromatic scalar perturbation
CMB with a monochromatic GW
Why are B-Modes only generated by GWs? (qualitatively)
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- from the picture we read off that $Q(\hat{n})$ is an even and $U(\hat{n})$ is an odd function under $P = \{ x \rightarrow -x \}$.
- with this one checks that $E(\hat{n})$ is even and $B(\hat{n})$ is odd.
- since scalar perturbations give rise to (even) scalar functions like $T(\hat{n})$, they cannot source (qualitatively)
Why are B-Modes only generated by GWs?

- from the picture we read off that $Q(\hat{n})$ is an even and $U(\hat{n})$ is an odd function under $P = \{ x \rightarrow -x \}$
- with this one checks that $E(\hat{n})$ is even and $B(\hat{n})$ is odd
- since scalar perturbations give rise to (even) scalar functions like $T(\hat{n})$ they cannot source
- consider x-polarized GW:

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2 + 2h_x dx dy$$

$P \rightarrow -dt^2 + dx^2 + dy^2 + dz^2 - 2h_x dx dy$

read off: amplitude $h_x$ is odd under parity!

- GWs are odd and can therefore source B-modes!
Why are B-Modes only generated by GWs? (quantitatively)
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- any anisotropy in spatial photon power density creates polarization:
  \[ Q(\hat{n}) - iU(\hat{n}) \propto \int d\theta' d\phi' \sin^2 \theta' e^{2i\phi'} I'_1(\hat{n}, \theta', \phi') \]

- can be decomposed into E- and B-modes after plugging into and into \textbf{spherical harmonics} \[ P_{ab} \]
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\[ Y_{lm}(\theta, \phi) \]

- density (scalar) quadrupole rotationally symmetric about plane wave axis

GW (tensor) quadrupole not rotationally symmetric

- LHS of (1) contains E and B, RHS of (1) contains sources such as GWs;

find: B-modes only sourced by GWs

\[ \propto Y_{22} \]

\[ \propto Y_{20} \]
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- GW (tensor) quadrupole not rotationally symmetric \( \propto Y_{22} \)

- LHS of (1) contains E and B, RHS of (1) contains sources such as GWs; find: B-modes only sourced by GWs \( \propto Y_{22} \)

- difficulty: B-mode creation after decoupling via gravitational lensing
What we learn about GWs
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● spectrum of GWs extracted from B-modes test theories of primordial GWs, this not only includes GWs from fluctuations during inflation, but also phase transitions* (eternal inflation, EW phase transition)

● correlations larger than horizon at the time of decoupling are a test of inflation

*see Thomas’ talk
What we learn about GWs

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What we learn about our Universe today

- we also learn about where and how much dust is in the universe, see BICEP2

*see Thomas’ talk
Phase transitions in the early Universe

[T.Prokopec, Lecture notes for cosmology, 2008]
Phase transitions in the early Universe

QCD phase transition: $T \sim O(100)$ MeV

- deconfinement: " $SU(3)_C \times U(1)_Q \rightarrow U(1)_Q$ "
- chiral SB:

$SU(3)_L \times SU(3)_R \rightarrow SU(3)_{L-R}$

$\longrightarrow$ Second order phase transition!

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Second order phase transition!

Electroweak phase transition: $T \sim O(100)$ GeV
- Higgs mechanism:
$$SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_Q$$
- eff. scalar potential $V_{\text{eff}}(v)$

LHC:
$$m_H = 125.09 \pm 0.24 \text{ GeV}$$

[T.Prokopec, Lecture notes for cosmology, 2008]
Recap: Phase transitions (PT) in toy models

**Second order PT:**
- real scalar field in Mexican hat
  \[
  \mathcal{L} = \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - \frac{\lambda}{4} (\phi^2 - v^2)^2
  \]
- ground state (T=0):
  \[
  \lambda(\phi^2 - v^2) \phi = 0
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- @ high T: symmetry restoration

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- field decomposition: \( \phi(x) \rightarrow \phi_0 + \delta \phi(x) \)
  \[ \lambda (\phi_0^2 + 3 (\delta \phi^2) - v^2) \phi_0 = 0 \]
- thermal contribution:
  \[ \langle \delta \phi^2 \rangle \simeq \frac{T^2}{12} + \mathcal{O}(T) \]
- effective scalar potential:
  \[ V_{\text{eff}}(\phi_0) = \lambda \left( \frac{\phi_0^4}{4} + \frac{\phi_0^2}{2} \left( \frac{T^2}{4} - v^2 \right) \right) \]

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[T.Prokopec, Lecture notes for cosmology, 2008]

- continuous in the order parameter
- thermal equilibrium
- no bubbles for \( T < T_c \)
Recap: Phase transitions (PT) in toy models

First order PT:
- scalar QED:
  \[ \mathcal{L} = D_\mu \phi^* D^\mu \phi - \frac{\lambda}{4} (\phi^* \phi)^2 - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} \]
- field decomposition (wlog):
  \[ \phi_1 = \phi_0 + \delta \phi_1 \]
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- ground state (averaged fluctuations):
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- effective potential:
  \[
  V_{\text{eff}}(\phi_0) = \frac{1}{2} \left[ \left( \frac{\lambda}{3} + \frac{g^2}{4} T^2 - \lambda v^2 \right) \phi_0^2 - \frac{g^3 T}{4\pi} \phi_0^3 + \frac{\lambda}{4} \phi_0^4 \right]
  \]

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Recap: Phase transitions (PT) in toy models

First order PT:
- scalar QED:

\[ L = D_\mu \phi^a D^\mu \phi + \frac{\lambda}{4}(\phi^a \phi^a - v^2)^2 + \frac{1}{4} F_{\mu \nu} F^{\mu \nu} \]

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\[ V_{\text{eff}}(\phi_0) = \frac{1}{2} \left[ \left( \frac{\lambda}{3} + \frac{g^2}{4} T^2 - \lambda v^2 \right) \phi_0^2 - \frac{g^3 T}{4n} \phi_0^3 + \frac{\lambda}{4} \phi_0^4 \right] \]

[T.Prokopec, Lecture notes for cosmology, 2008]

- \( T < T_c \): maxima develop – barriers
- \( T < T_n \): barriers become smaller, tunnelling probability increases
- bubble formation in background of false vacuum
Generic picture: GW from cosmological first order PT

1. bubble nucleation into low-T phase
   - tunnelling or thermal fluctuations

1. bubble expansion & bubble collision:
   - latent heat rises $T_{\text{plasma}}$ & $E_{\text{kin}}$ of bubble wall and bulk

[D.J.Weir, Phil.Trans.Roy.Soc.Lond. A376, 2018]
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Bubble formation & collision

Youtube: https://www.youtube.com/watch?v=Ggs2fQL0ICU0
Bubble collision and origin of gravitational waves

GW production through 1OPT can be divided into three stages:

1. initial collision of scalar field shells (generally subdominant)

2. wave of kinetic energy within plasma

3. shocks & turbulence (typical time- and length-scales?)

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Bubble collision and origin of gravitational waves

GW production through 1OPT can be divided into three stages:

1. initial collision of scalar field shells (generally subdominant)
   \[
   \hbar^2 \Omega_{esc}(f) \approx 1.65 \cdot 10^{-7} \Delta(v_{sw}) \left( \frac{H_+}{\beta} \right) \left( \frac{\eta_{\rho} \alpha T_+}{1 + \alpha T_+} \right)^2 \epsilon_{env} \left( \frac{f}{f_{esc}} \right) 
   \]
   \[f_{esc} \approx 16.5 \mu Hz \left( \frac{\beta}{H_+} \right) \left( \frac{v_{sw}}{\epsilon_{env}} \right)\]

1. wave of kinetic energy within plasma
   \[
   \hbar^2 \Omega_{ew}(f) \approx 8.5 \cdot 10^{-6} \bar{U}_f(\alpha f, \alpha T_+)^4 \left( \frac{H_+}{\beta} \right) \nu_{sw} \epsilon_{ew} \left( \frac{f}{f_{sw}} \right) 
   \]
   \[f_{sw} \approx 8.9 \mu Hz \left( \frac{1}{\nu_{sw}} \right) \left( \frac{\beta}{H_+} \right)\]

1. shocks & turbulence (typical time- and length-scales?)
   \[
   \hbar^2 \Omega_{tur}(f) \approx 3.35 \cdot 10^{-1} \left( \frac{H_+}{\beta} \right) \left( \frac{\eta_{\rho} \alpha T_+}{1 + \alpha T_+} \right) \nu_{sw} \epsilon_{tur} \left( \frac{f}{f_{tur}} \right) 
   \]
   \[f_{tur} \approx 27 \mu Hz \left( \frac{1}{\nu_{sw}} \right) \left( \frac{\beta}{H_+} \right)\]

[D.J. Weir, Phil.Trans.Roy.Soc.Lond. A376, 2018]
Key parameter of GW spectrum

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1) Change of bubble nucleation rate:

- free energy of critical bubble:

$$S_3 = 4\pi \int r^2dr \left( \frac{1}{2} \left( \frac{d\phi_b}{dr} \right)^2 + V(\phi_b, T) \right)$$

- bounce solution:

$$\frac{d^2\phi_b}{dr^2} + \frac{2}{r} \frac{d\phi_b}{dr} - \frac{\partial V}{\partial \phi_b} = 0 \quad \text{with} \quad \frac{d\phi_b}{dr} \bigg|_{r=0} = \Omega, \quad \phi_b \bigg|_{r=\infty} = 0$$

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2) Latent heat to energy density ratio: \[ \epsilon = \frac{\Delta \rho}{\rho_{\text{ad}}} \]
   - two contributions to latent heat:
   \[ \epsilon = -\Delta V - T \Delta s = \left( -\Delta V + T \frac{\partial V}{\partial T} \right)_{T_0} \]

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     \]

GW are insensitive to:
- internal bubble structure
- small scale field configuration in the collision region

Detection possibilities of future experiments

- LISA sensitive to 10 TeV
- LIGOIII, LISA & BBO will probe $T \sim 100-10^7$ GeV
- GW from PTs around 10-100 TeV could entirely screen signals from inflation!


Phase transitions & BSM physics

Search: GW from first order PT

1. Modification of electroweak PT
   - electroweak baryogenesis
   - Higgs portals

1. First order PT in new (yet hidden) sectors
   - new scalars
   - new forces & symmetry breaking
Conclusion:

- If inflation took place, GWs produced during that time, would actually survive until CMB and can be even observed.
- Primordial GWs would be a model-independent evidence of the concept of inflation.
- GWs leave a unique imprint on the CMB in the form of polarization.
- The extracted spectrum can give hints to their origins (e.g. low frequencies for inflationary GWs).
- GW from particle physics PT directly related to associated scalar potential.
- “New”/old tool for future particle phenomenology!
Thank you!
WE CAN HEAR BLACK HOLES!