1 title & aim

1) In medias res; first about the thesis, title, aims, motivation
2)
   - particle interp.; hypothesised massless spin-2 boson **graviton**
   - Like EM waves, observations in different frequency bands require different instruments and carry different information insight to the universe -> two different "sensory impressions"
   - On Earth, we have been able to see for a long time, but we developed hearing in 2015
   - high-freq: BH binaries [hand gesture]
3)
   - colliding, collapsing or otherwise interacting/imperfect
   - generally relics of PTs, which themselves can produce GW rad.
4)
   - topological defects in context of a first-order late-time (redshift around 2, matter domination) PT

2 motivation

1) *Why interest in cosmological GWs?* —Astrophysical sources cannot explain the GW signal » new physics?
2) *Why theoretical and analytical focus?* —Lack of analytical solutions in generic spacetimes?
3) *(same)*
4) *Why topological defects?*
5) *Why domain walls?* —Intuitive structures
6) With this in mind, let us back up a bit

2 gravitation

1)
2)
   - Also born from GR is modern cosmology.
3)
   - A consequence of this is GWs, which do not have a non-relativistic analogy. (No GWs "at home")
   - Conceptually complicated
   - Will not dig into the formalities of GWs

4 GR

1) "Spacetime tells matter how to move; matter tells spacetime how to curve." —John Wheeler
2) We mention two solutions to this equation when there are one time dimension and three spatial dimensions.

5 GWs

1) Before we move on: Quick look; how this relates to GWs.
2)
   - Choose coords. s.t.
   - EOM for GWs in expanding spacetime!
   - Inhomogeneous (damped) wave eq.
   - 2 physical dofs » 2 polarisations
   - Unlike density perturbations, there is no Newtonian analogy to GWs (other words: conceptually complicated)

6 cosmology

1) Earth not at privileged position
2) The negative pressure of the former is responsible for the current accelerated expansion of the universe, given by the value of the Hubble constant H_0.
3)
4) GR very precise in e.g. solar systems, but there are problems in modern cosmology; one of them has to do with this constant

7 Hubble tension

1)
   - There are problems, but will only address the phenomenologically indifferent accelerated expansion of the universe *today*.
   - direct (distance ladder) vs. indirect (CMB experiments)
   - More precise measurements (about a decade ago) gives no overlap between uncertainties.
2)
   - Often associated with a PT, which in turn can imply the existence of topological defects.
   - Motivates models s.a. scalar-field theories
   - Symmetron: fifth force mediated when symmetry is broken (low-density vacuum)
   - GR accurate in laboratories—fifth force must be screened here

8 symmetron PT

1)
   - Use an effective potential to describe the phase transition.
   - Here, scale factor and energy density are the used "synonymously" (for our purposes, anim with time)
   - coupling to matter restores symmetry in dense regions
2) …which is an attempt at solving a different problem, which we will get back to

9 (drawing) ϕ at PT

1) At PT, random fluctuations around (yellow) vacuum state
2) Shortly after
3) Infinitely long after » domain walls (in truth: fluctuations)

10 DW→GW

1)
   - DW models can be constrained by PTA observations.
   - Colliding, collapsing, decaying, stochastic fluctuations
   - We will look at planar DWs formed during late-time PT in a matter-dominated universe, and specifically how a spatial perturbation can induce GWs
2) Mention a problem...
3) Motivation for asymm, and emphasise the usefulness of considering time-dep. surface tension

11 overview

1)
2)
3)
4) Which will be addressed in the analysis section
5) ...
6) Backing up a bit; mention that curvature affects both directly and by propagation
7) These arrows are not "rigorous;" but they emphasise the (non-linear) thesis methodological steps

12 toy model

1)
   - Introduce terminology, specify example.
   - We discuss only the following specific scenario, to keep the number of free parameters to a minimum.
2)
3) We discuss to various depths the possibility of generalising these parameters of the framework.

13 1st approach

1) Submanifold of two spatial dims (infinitely thin wall)
2)
   - first-order pert. –» induced metric
   - moving on ...
3)
   - Energy times the area swept out by the worldsheet
   - under small variations
   - not the first ones to get here (power-law expansion)
4) Modification, inspo from symmetron

14

1) Expand into eigenvalue solutions
2) Resembles a damped harm. oscillator
3)

15 solution

1) MD + ICs, Neat! (possible for any α)
2)
   - Will not go into detail about how this equation was solved.
   - Comment about singularity?
   - In a region where they overlap.
4)

16 schematic solution

1) ζ and "naive" are same general solution with different initial conditions

17 GWs

1) (power through) Vary NG action ⟶ Analytical expression for SE tensor (with simple function)

18

1)
   - Simple » analytical SE tensor
   - Focus on the time-dependence
2)
3)
   - no particular assumptions about the time-part of epsilon
   - ...which brings us to the second approach

19 2nd approach

1) Compare the above with full field theory sims
2) Highly non-linear equation
3)

20 quasi-static

1) Here are many things I could have done more elegantly in the thesis, but we will not discuss it here.

21

1)
   - Not in fact thin in its initial stages
   - Reason for initialising a few time steps after PT.

22 asymptotic

1)
2) *Sidenote*

23 animation

1)

24 code

1) Will not spend time on this.
2) Donut

25 sims

1)
   - For reference, …
   - We account for the small difference in perturbation from PT to sim. onset.
2) Baseline/benchmark
3) Vary one parameter at a time

26 initial perturbations

1)
2) From here: Will ignore simulations 0 and 6.

27 DW

1)
2) One single solution when normalised and plotted over the time parameter $t_\omega = \omega(s-1)$
3) Intricate way of saying, see next slide
4)
   - Initially defn. not thin, and very close to anti-wall.
   - Spatial resolution might not capture sinus wave.
   - **Inter- and intra-wall forces**
   - Asymptotic field inhabits oscillations that might affect both wall thickness, but more importantly surface tension, and then again the eom for ε.
   - To mention some…

28 animation (sim 2)

1) *Simulation 2:* "Worst one," but visually the clearest
Take the opportunity to point out a few weaknesses: –Inter- and intra-wall forces

29 combi plot

1) This x-axis is not time

30

1)
- lack of summary statistic
- only FT of GWs

4) Only qualitative comparison.

31 gravitational rad.

1) SKIP?

32 peculiarity (sim 1)

1)

33 peculiarity (sim 5)

1)

34 summary (TABLE)

1) Summarise...

3) *Is the time-dependence of the surface tension insignificant?*

4) *Is there a single, common graph when normalised and plotted over t_ω?*

5) Want to mention that the discrepancy does matter when computing the GWs, and that is why we insert this result into the formula for h_+

35 way forward

1)
- With more time... VALIDATION + INSIGHT
- In the thesis, I describe specifics of how to set up new experiments in a consistent and robust way.

2) Or in general, *more* experiments.

6) Can help constrain this model with GW observations.

8) By calculation or simulation

9) This is just a sample; there are many interesting strategies going forward

36 conclusion

1)
- Comprehensive study, might have overreached
- MD, symmetron
- One step closer to analytical estimations of GW spectra
- Groundwork laid for further similar analyses