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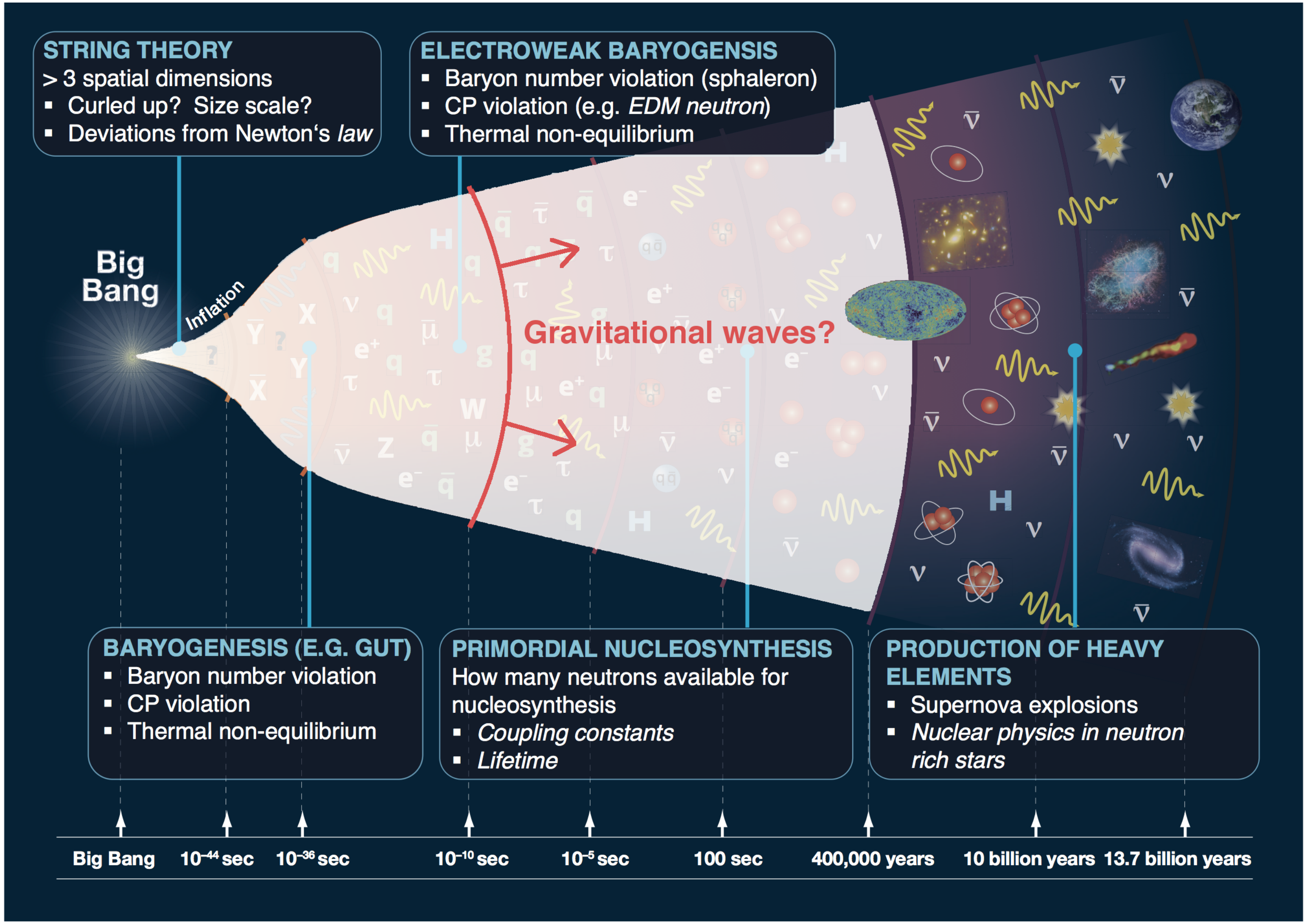
Higgs physics and cosmology: Gravitational waves from the EWPT

saoghal.net/slides/charged2018/

David J. Weir - University of Helsinki - davidjamesweir

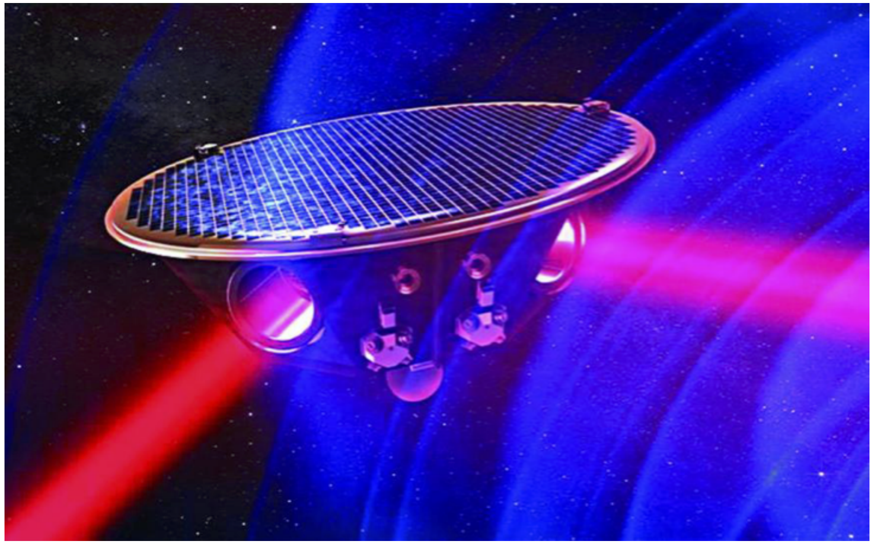
cH$^{\pm}$arged 2018

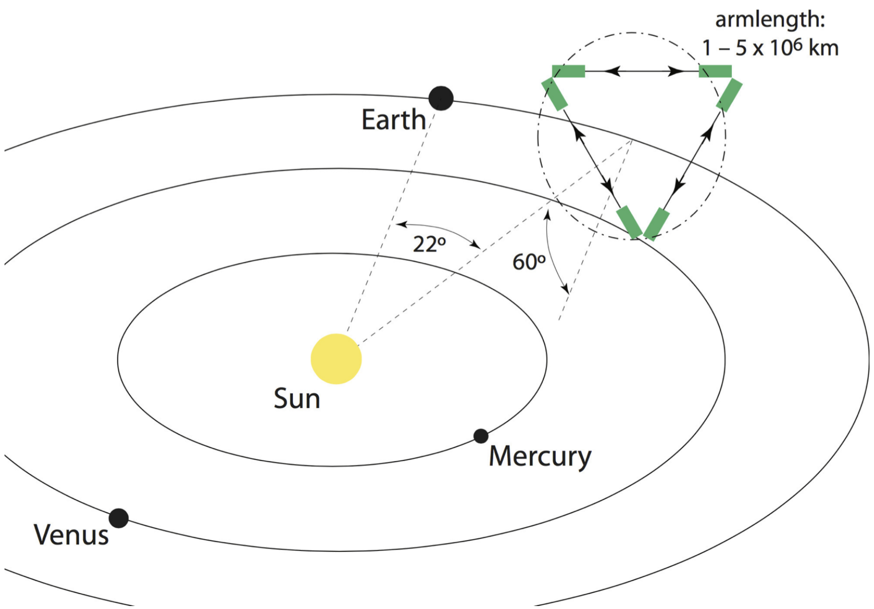
What happened when the universe was optically opaque?



Source: arXiv:1205.2451

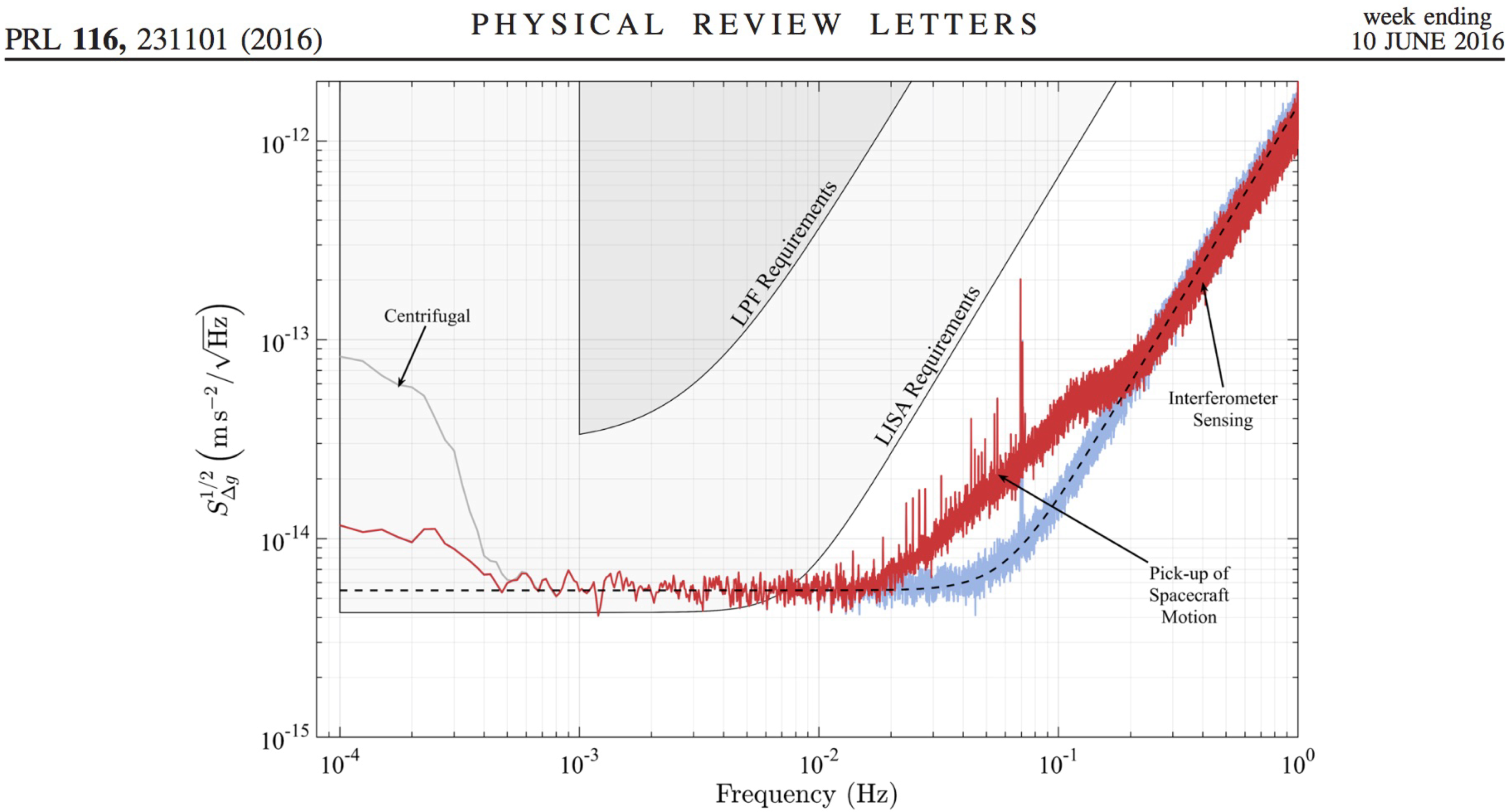
What's next: LISA mission





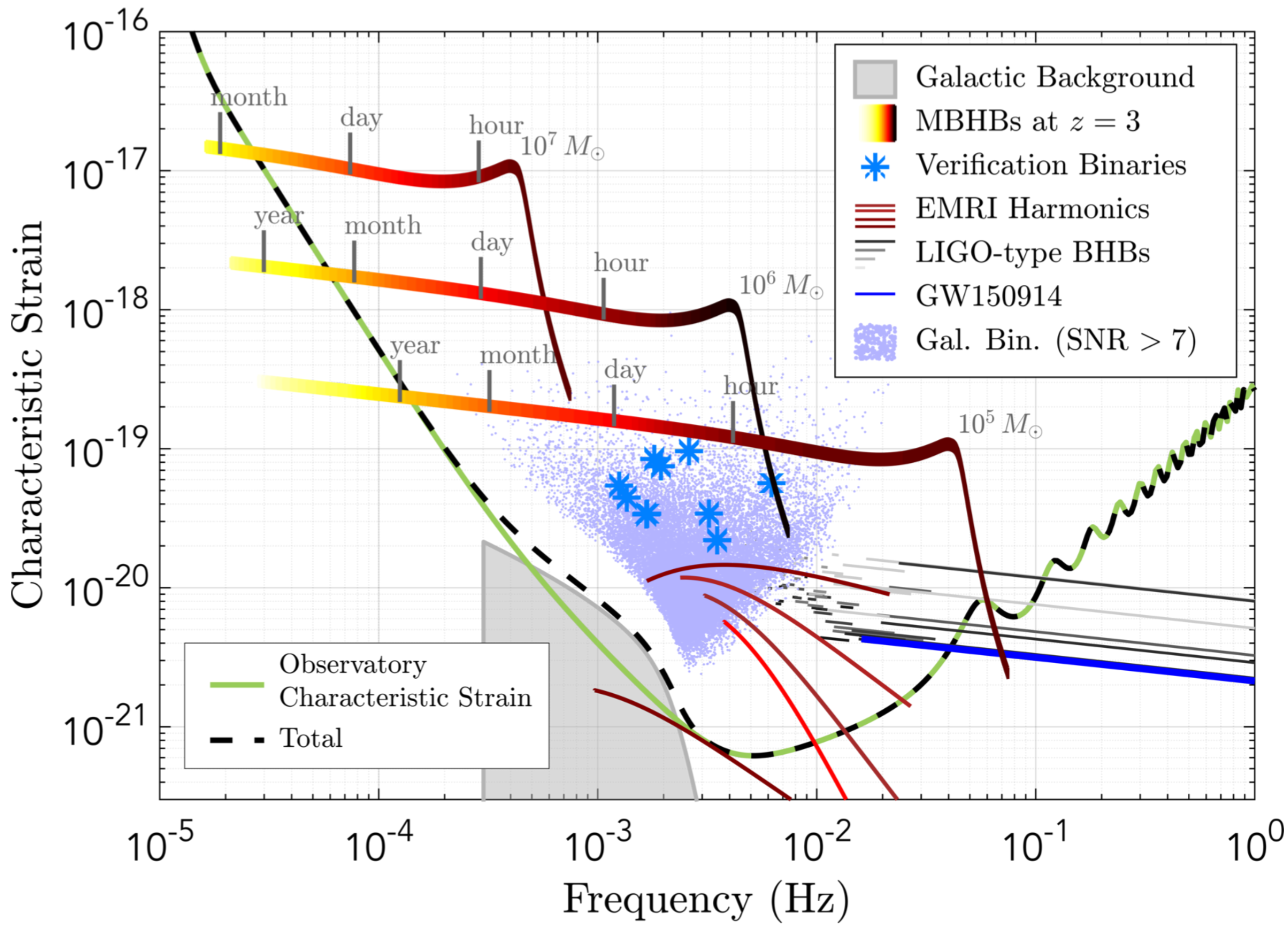
- Three laser arms, 2.5 M km separation
- ESA-NASA mission, launch by 2034
- Proposal submitted last year arXiv:1702.00786
- Officially adopted on 20.6.2017

LISA Pathfinder



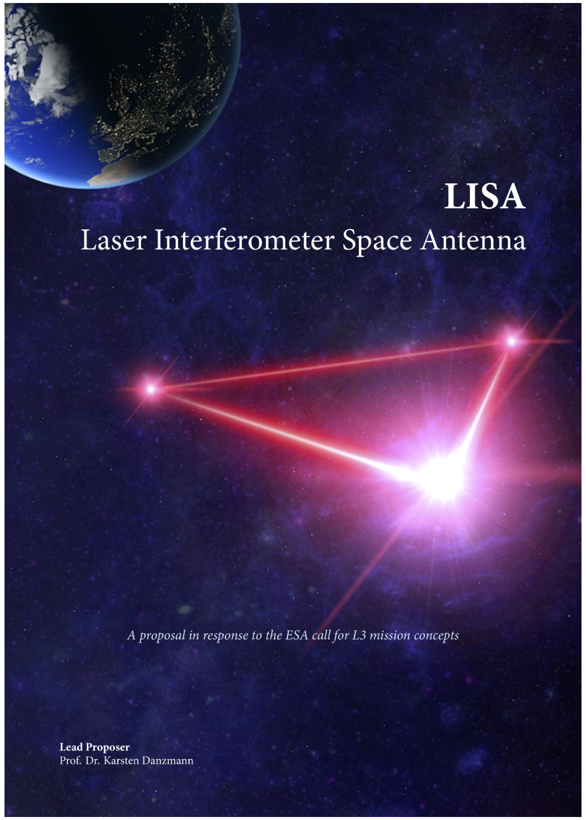
Exceeded design expectations by factor of five!

Possible signals



Source: arXiv:1702.00786.

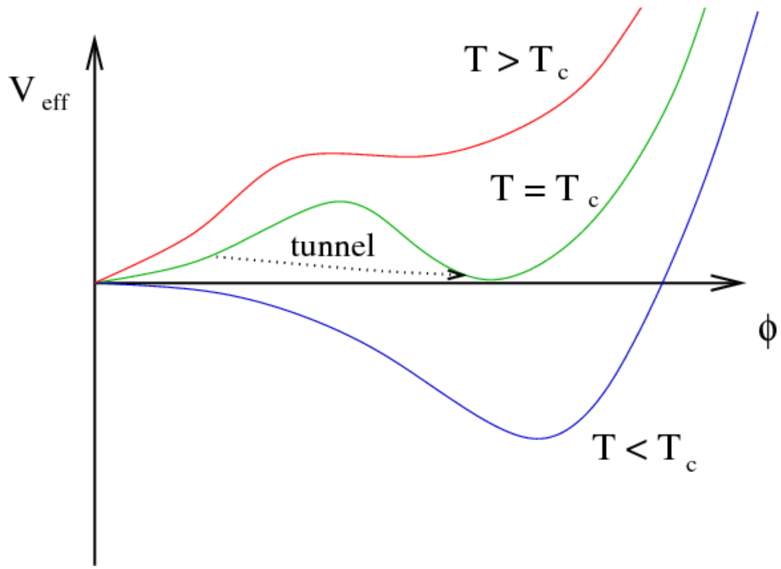
Key science for LISA

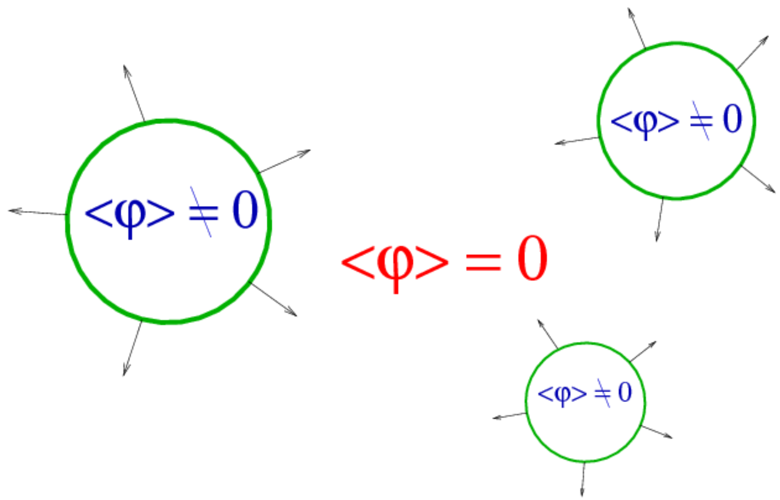


Science Investigation 7.2: Measure, or set upper limits on, the spectral shape of the cosmological stochastic GW background.

Operational Requirement 7.2: Probe a broken power-law stochastic background from the early Universe as predicted, for example, by first order phase transitions ...

Electroweak phase transition

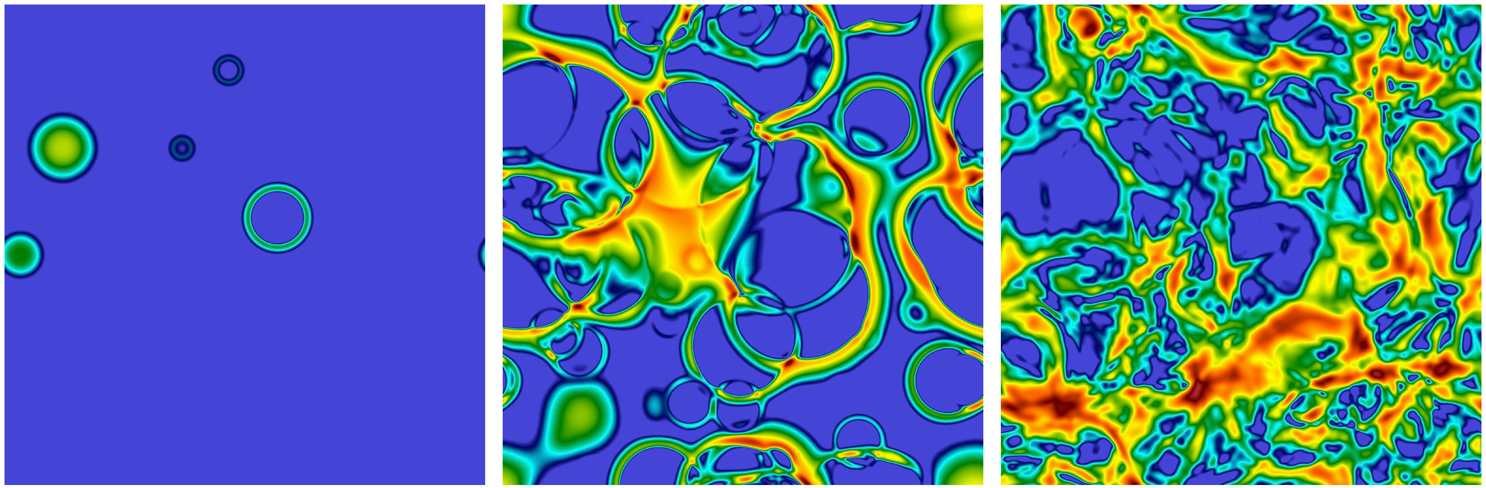




Source: arXiv:1206.2942

First order thermal phase transition

1. Bubbles nucleate and grow
2. Expand in a plasma - create reaction fronts
3. Bubbles + fronts collide - violent process
4. **Sound waves** left behind in plasma
5. Turbulence; damping



Key parameters for GW production

4 numbers parametrise the transition:

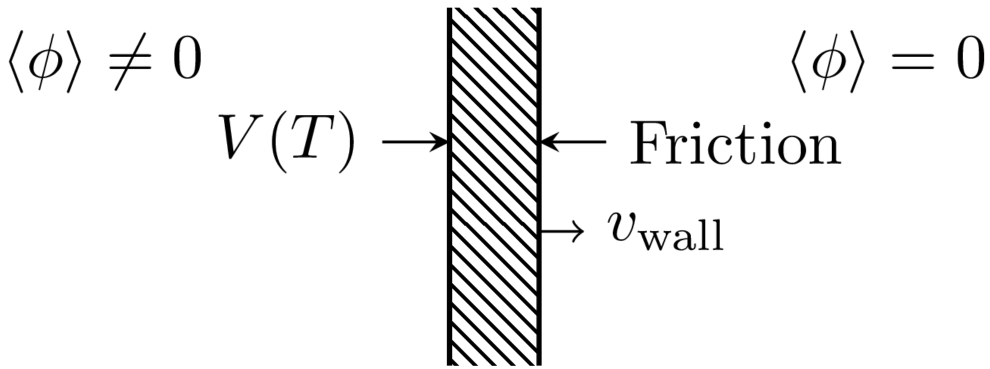
- T_*, temperature ($\approx T_\mathrm{n} \lesssim T_\mathrm{c}$)
- α_{T_*}, vacuum energy fraction
- v_w, bubble wall speed
- β/H_*:
  - β, inverse phase transition duration
  - H_*, Hubble rate at transition

How the bubble wall moves

$$\overbrace{\partial_\mu T^{\mu\nu}}^{\text{Force on }\phi} - \overbrace{\int \frac{d^3k}{(2\pi)^3} f(\mathbf{k}) F^\nu}^{\text{Force on particles}} = 0$$

Phys. Rev. D 46, 2668

This equation is the realisation of this idea:



Yet another interpretation:

$$\overbrace{\partial_\mu T^{\mu\nu}}^{\text{Field part}} - \overbrace{\int \frac{d^3k}{(2\pi)^3} f(\mathbf{k}) F^\nu}^{\text{Fluid part}} = 0$$

i.e.:

$$\partial_\mu T^{\mu\nu}_\phi + \partial_\mu T^{\mu\nu}_{\text{fluid}} = 0$$

Can simulate as effective model of field ϕ + fluid u^μ.

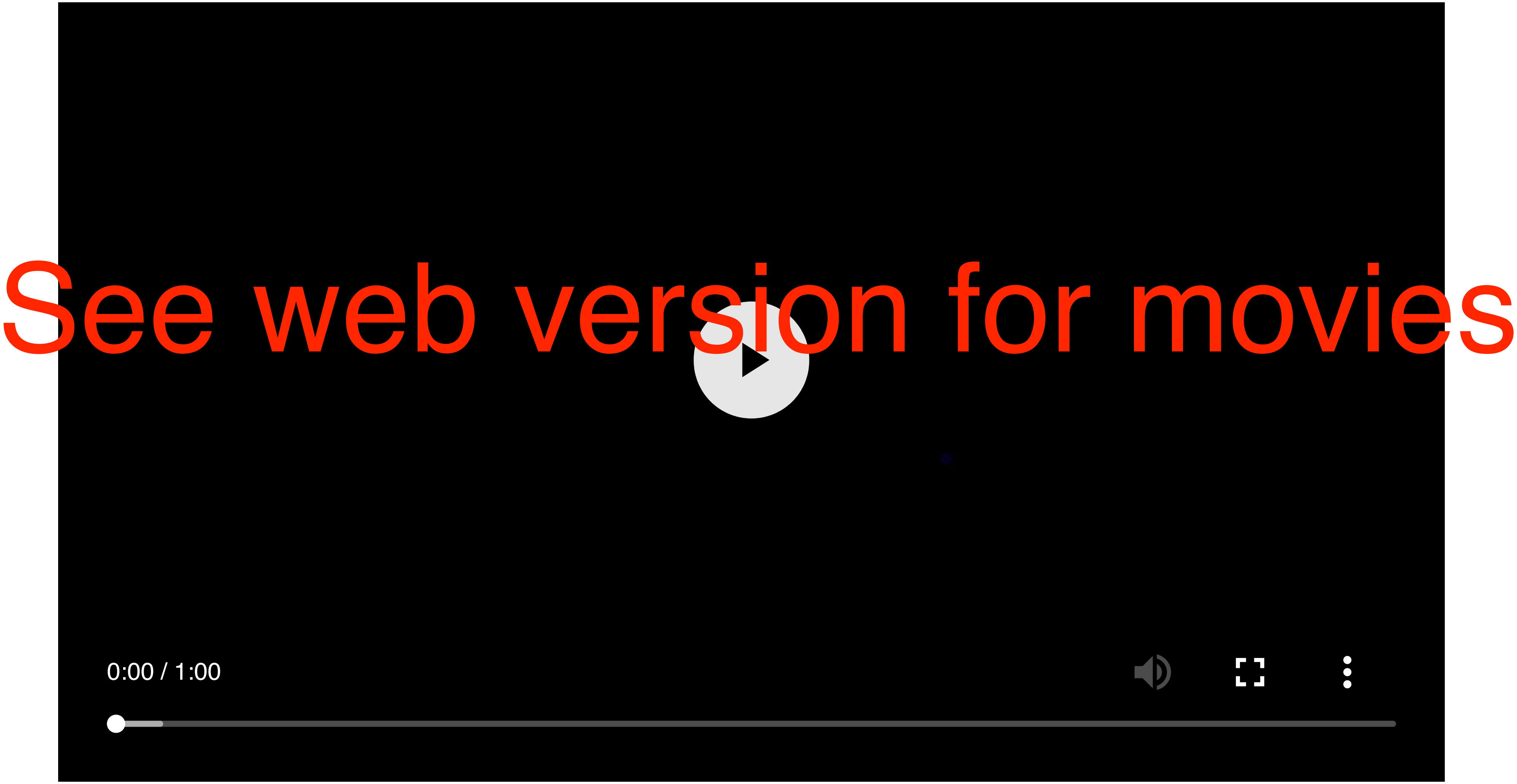
Detonations vs deflagrations

- If ϕ wall moves *supersonically* and the fluid u^μ enters the wall at rest, we have a *detonation*
  ☛ Good for GWs, bad for BG
- If ϕ wall moves *subsonically* and the fluid u^μ enters the wall at its maximum velocity, it's a *deflagration*
  ☛ Bad for GWs, good for BG

Velocity profile development: detonation vs deflagration

See web version for movies

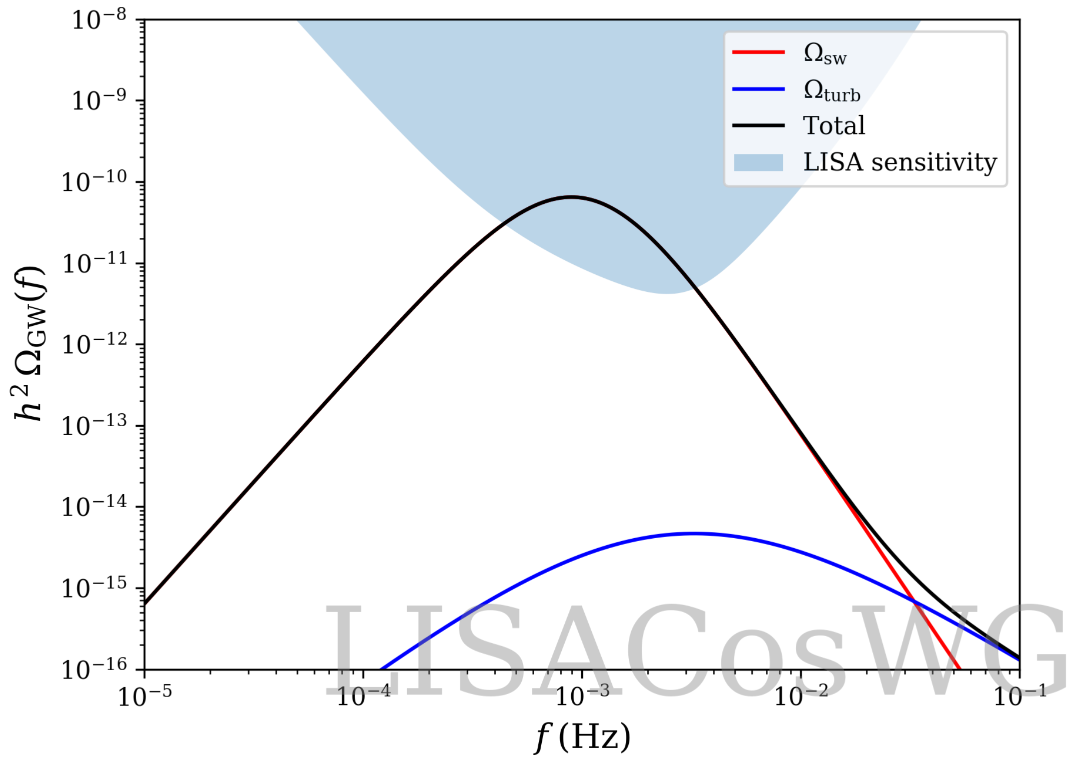
Simulation slice example



Putting it all together - $h^2\Omega_{\rm gw}$

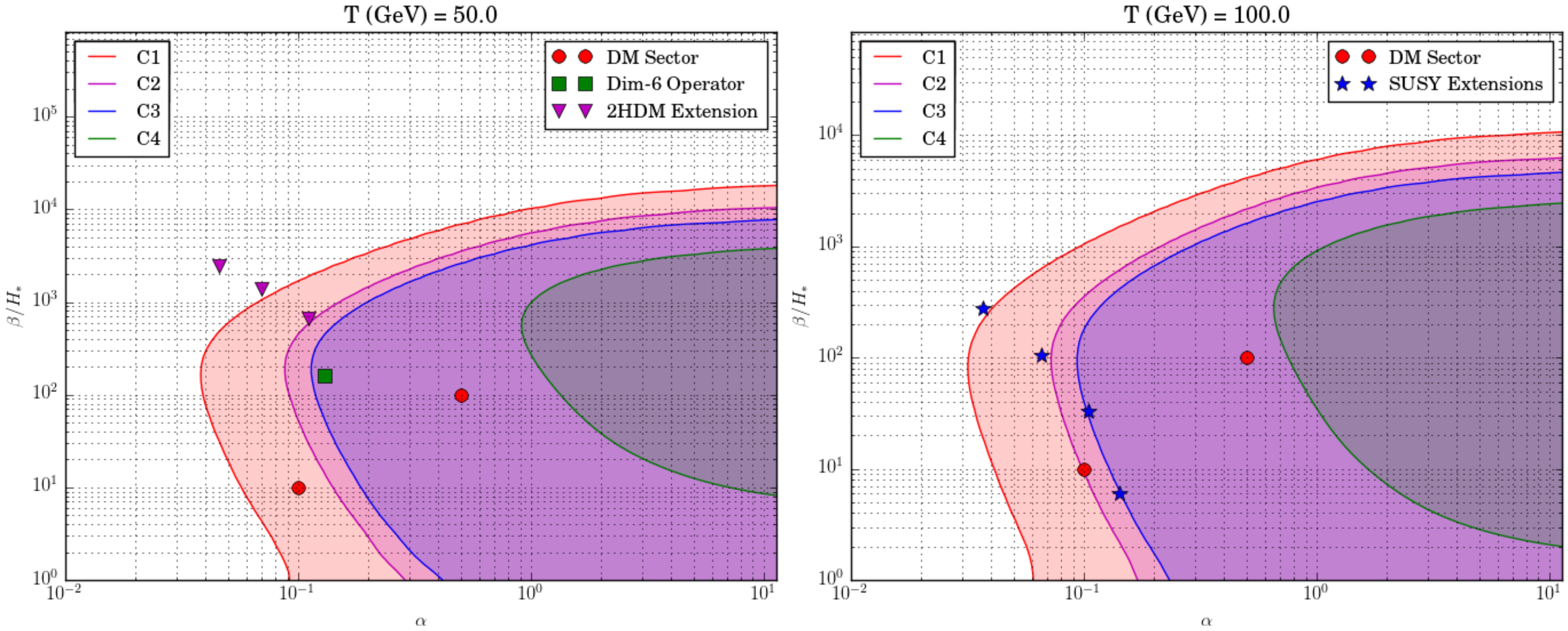
- For any given theory, can get T_*, α_{T_*}, β/H_*, $v_{\rm w}$ arXiv:1004.4187
- It's then easy to predict the signal...

(example, $T_* = 94.7$ GeV, $\alpha_{T_*} = 0.066$, $v_{\rm w} = 0.95$, $\beta/H_* = 105.9$) SNR = 95 ☺️



CosWG report arXiv:1512.06239

- Results for a variety of models, at "benchmark points"
- Key result: parametric plots with contours at SNR_{thr}

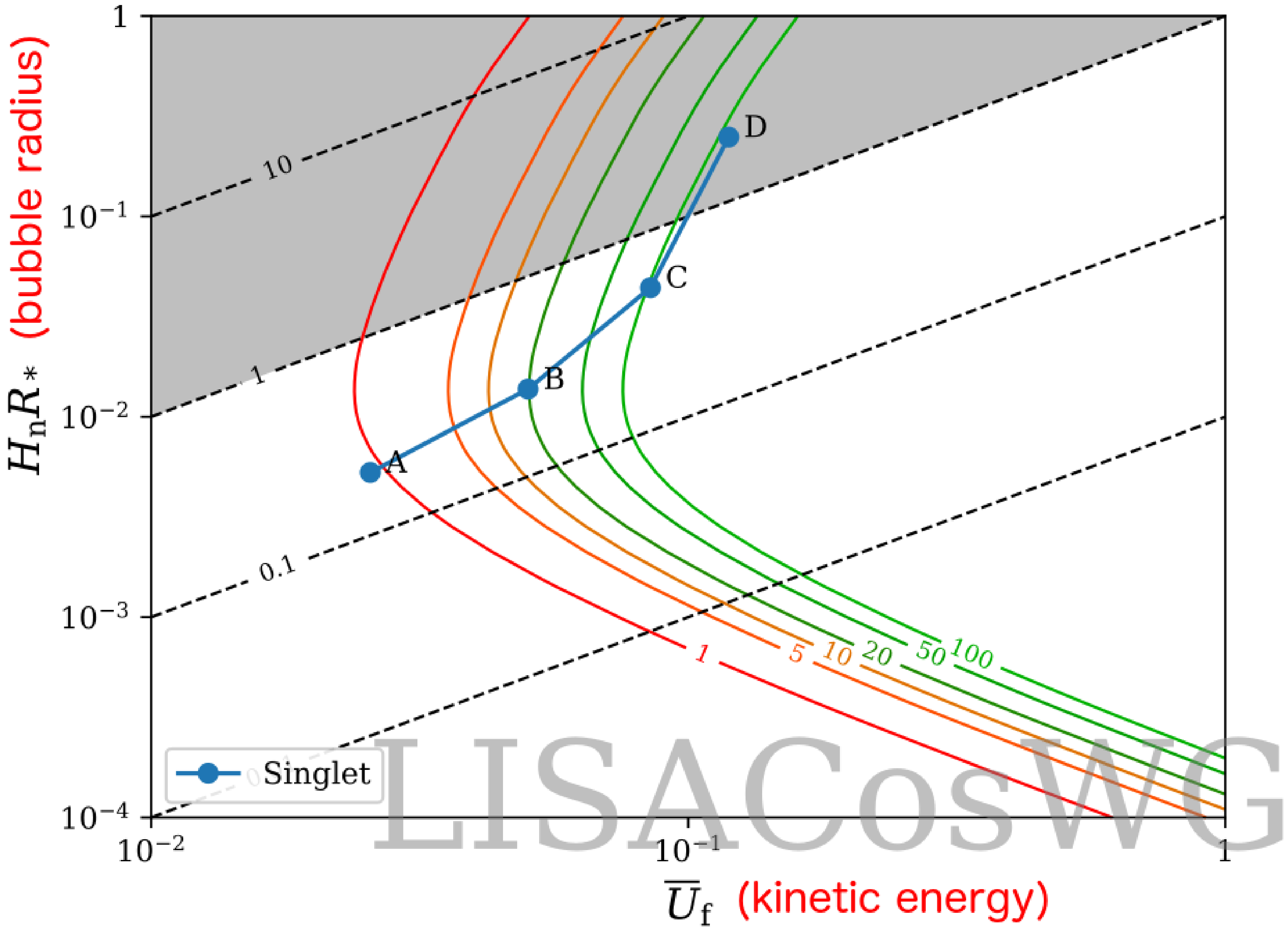


$$\text{Model} \longrightarrow (T_*, \alpha_{T_*}, v_{\rm w}, \beta) \longrightarrow \text{SNR}$$

Current EWPT work in LISA CosWG

- In preparation: update to first report on PTs (arXiv:1512.06239)
  - "Final" sensitivity curve
  - Updated model 'showcase'
  - New theoretical work (including no runaways)
- PTPlot web tool for computing SNR
  - Modular, containerised
  - Code will be open, can be run locally
- Coming soon 😅

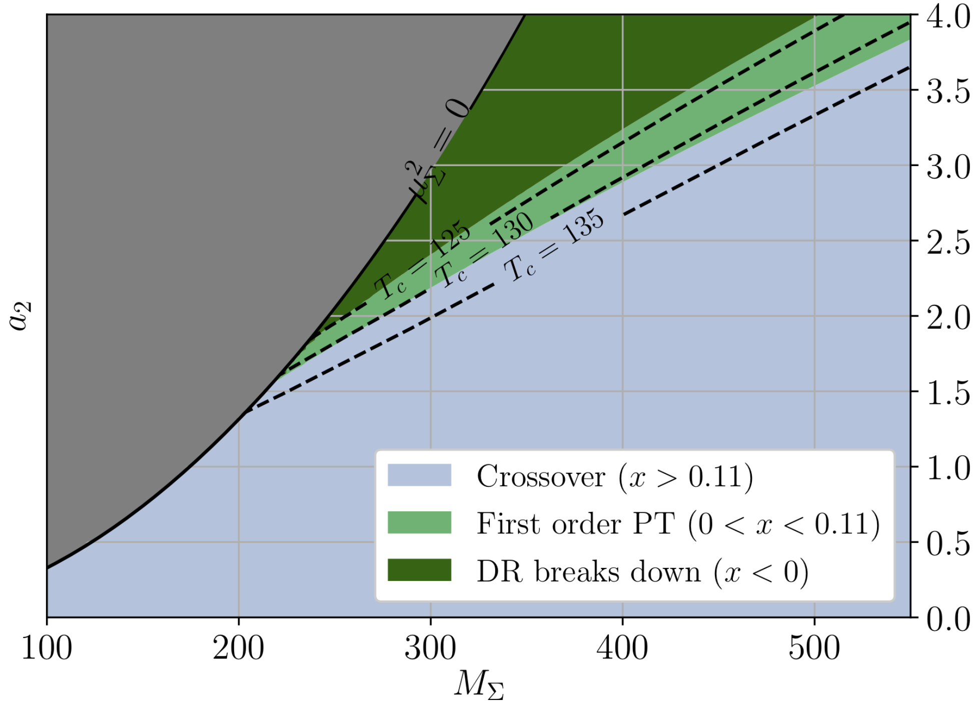
PTPlot.org



1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
1
$H_n R_*$ (bubble radius)
$\overline{U}_f$ (kinetic energy)
10
1
0.1
1
5
10
20
50
100
A
B
C
D
Singlet
LISACosWG

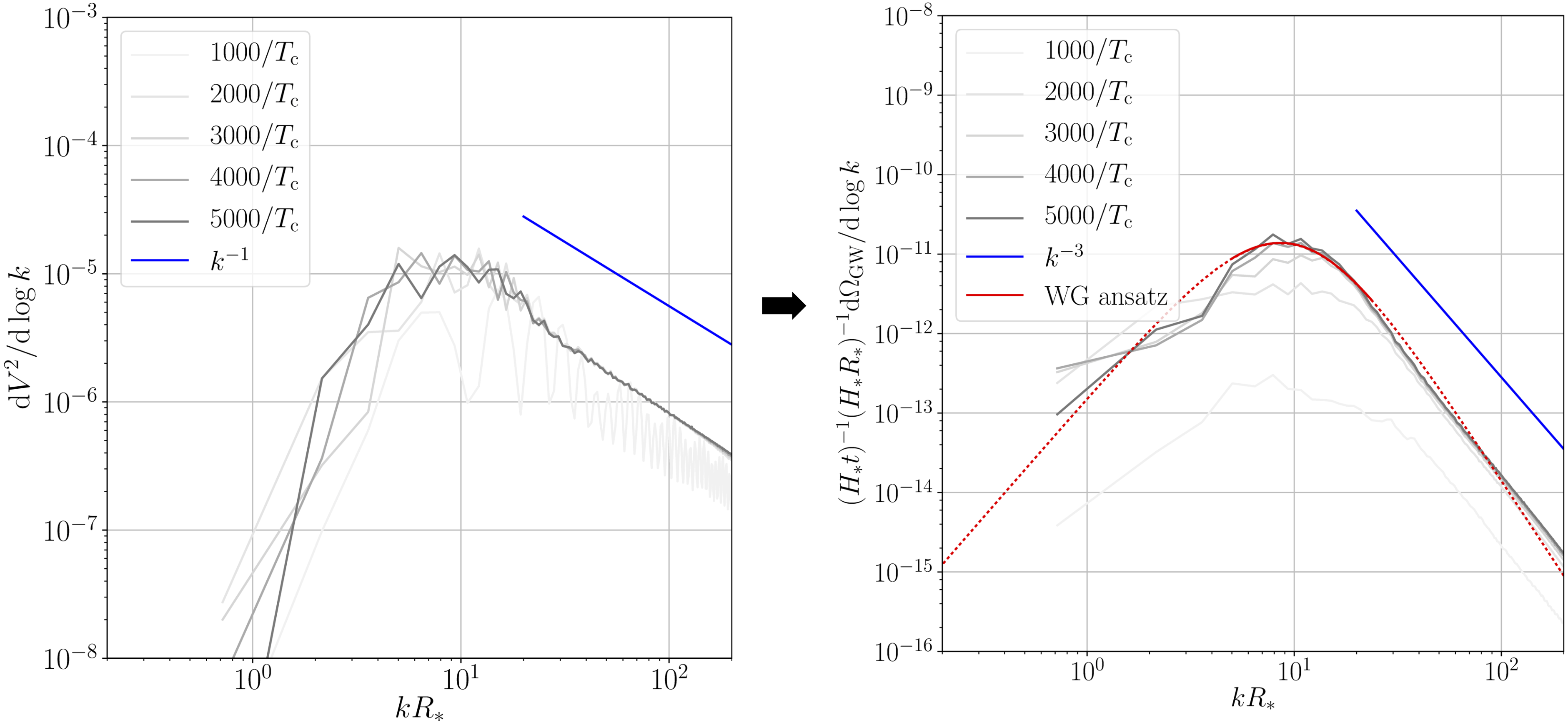
Recent results 1: parameter space

- "Non-perturbative" results for triplet model arXiv:1802.10500
- Dimensional reduction, mapping to existing theory
- Light green region - first order phase transition
- Dark green + gray regions - new simulations required



Recent results 2: spectral shape

- Each simulation: ~1M CPU hours arXiv:1704.05871
- Validate spectral shape used in WG reports



A pipeline

1. Choose your model (e.g. SM, xSM, 2HDM, ...)
2. Dim. red. model
   Kajantie et al.
3. Phase diagram (α_{T_*}, T_*);
   lattice: Kajantie et al.
4. Nucleation rate (β);
   lattice: Moore and Rummukainen
5. Wall velocities ($v_{\rm wall}$)
   Moore and Prokopec; Kozaczuk
6. GW power spectrum $\Omega_{\rm gw}$
7. Sphaleron rate

Very leaky, even for SM!

What I am thinking about

- Turbulence
  - MHD or no MHD?
  - Timescales $H_* R_* / \overline{U}_{\mathrm{f}} \sim 1$, sound waves and turbulence?
  - More simulations needed?

- Complementarity of GW signal and BG
  - Competing wall velocity dependence of BG and GWs?
  - Sphaleron rates in extended models?

- The best possible determinations for xSM, 2HDM, ΣSM, ...
  - What is the phase diagram?
  - Nonperturbative nucleation rates?

Final conclusion

- Now have good understanding of thermal history of first-order electroweak phase transitions
- Can make good estimates of the GW power spectrum
- Turbulence still a challenge
- Recently appreciated contributions, like acoustic waves, enhance the source considerably.
- LISA provides a model-independent probe of first-order phase transitions around 100 GeV