Gravitational waves from the early universe

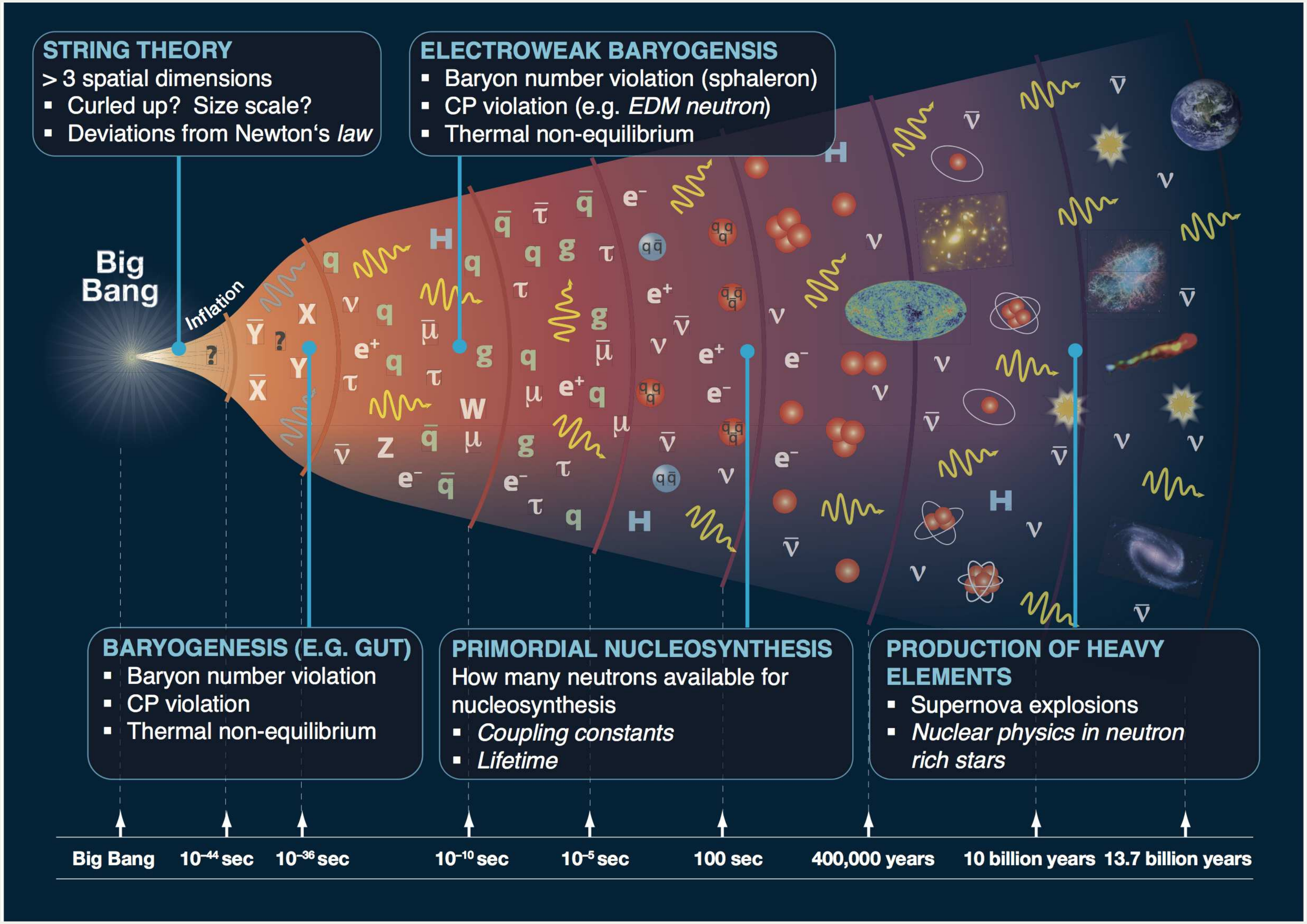
saoghal.net/slides/ppd2018/

David J. Weir - University of Helsinki - davidjamesweir

Particle Physics Day, Jyväskylä, 23.11.2018

What happened in the early universe?

Source: arXiv:1205.2451



What happened in the early universe? when the universe was optically opaque?

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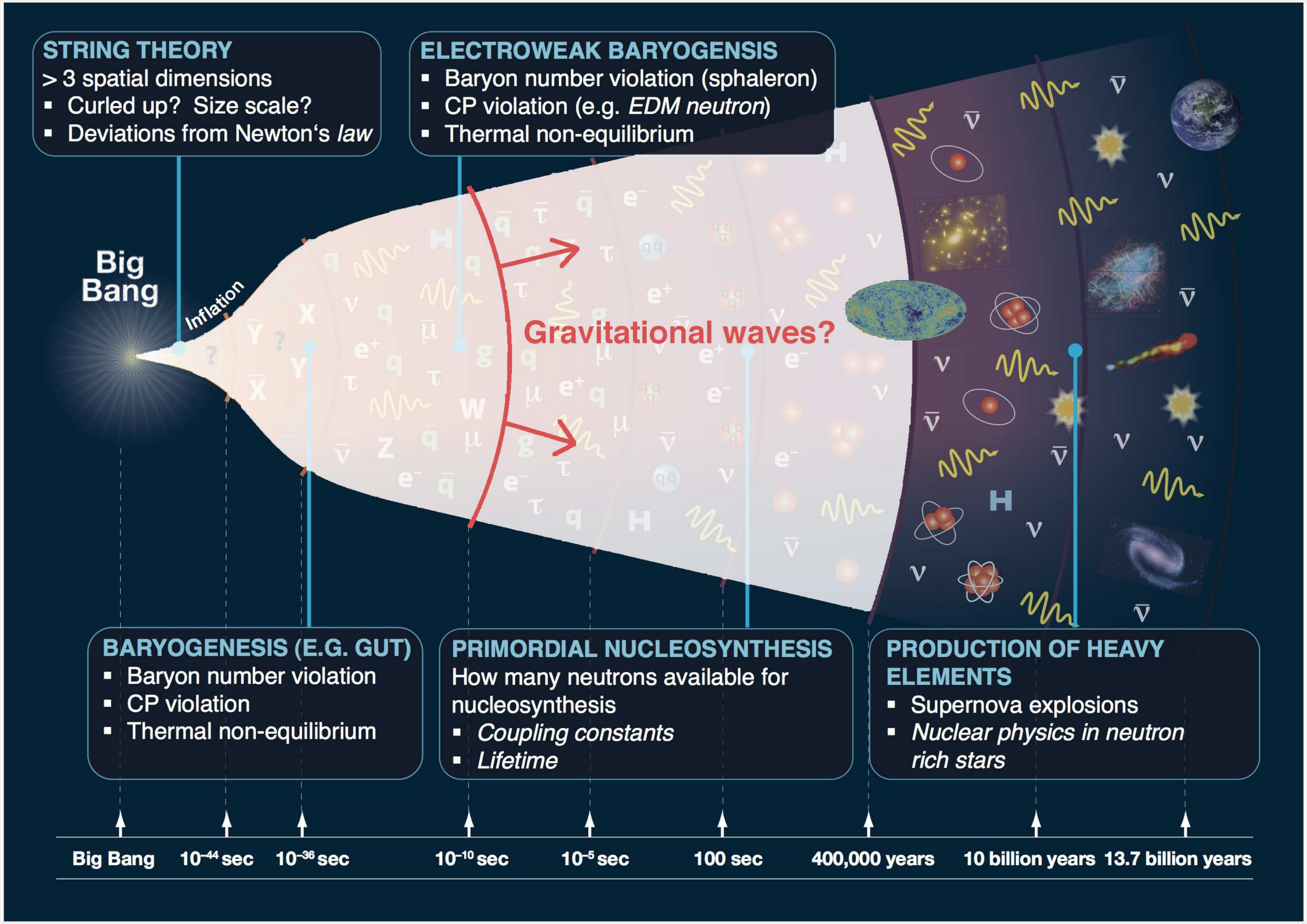

What happened in the early universe? when the universe was optically opaque? in dark sectors?

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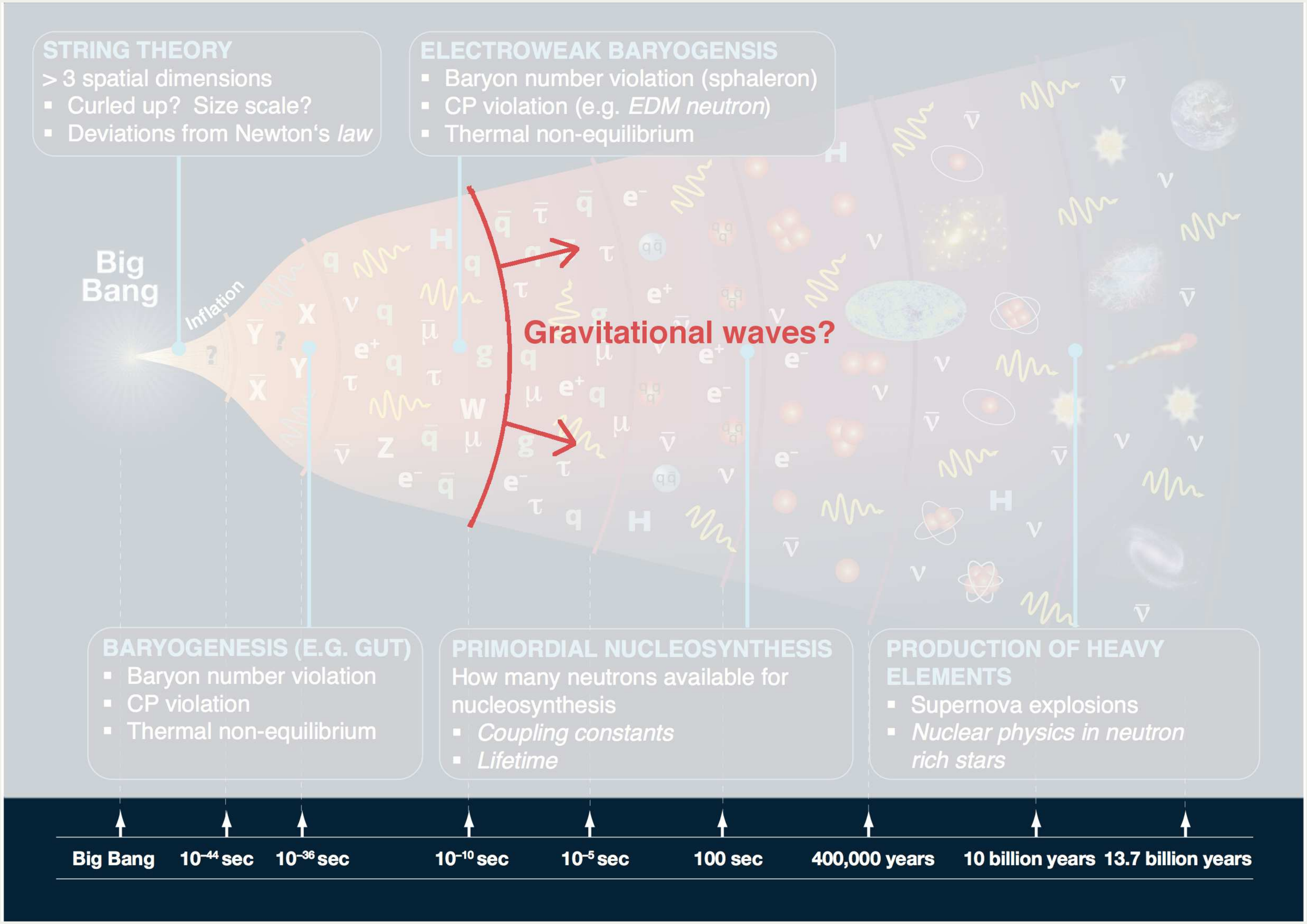
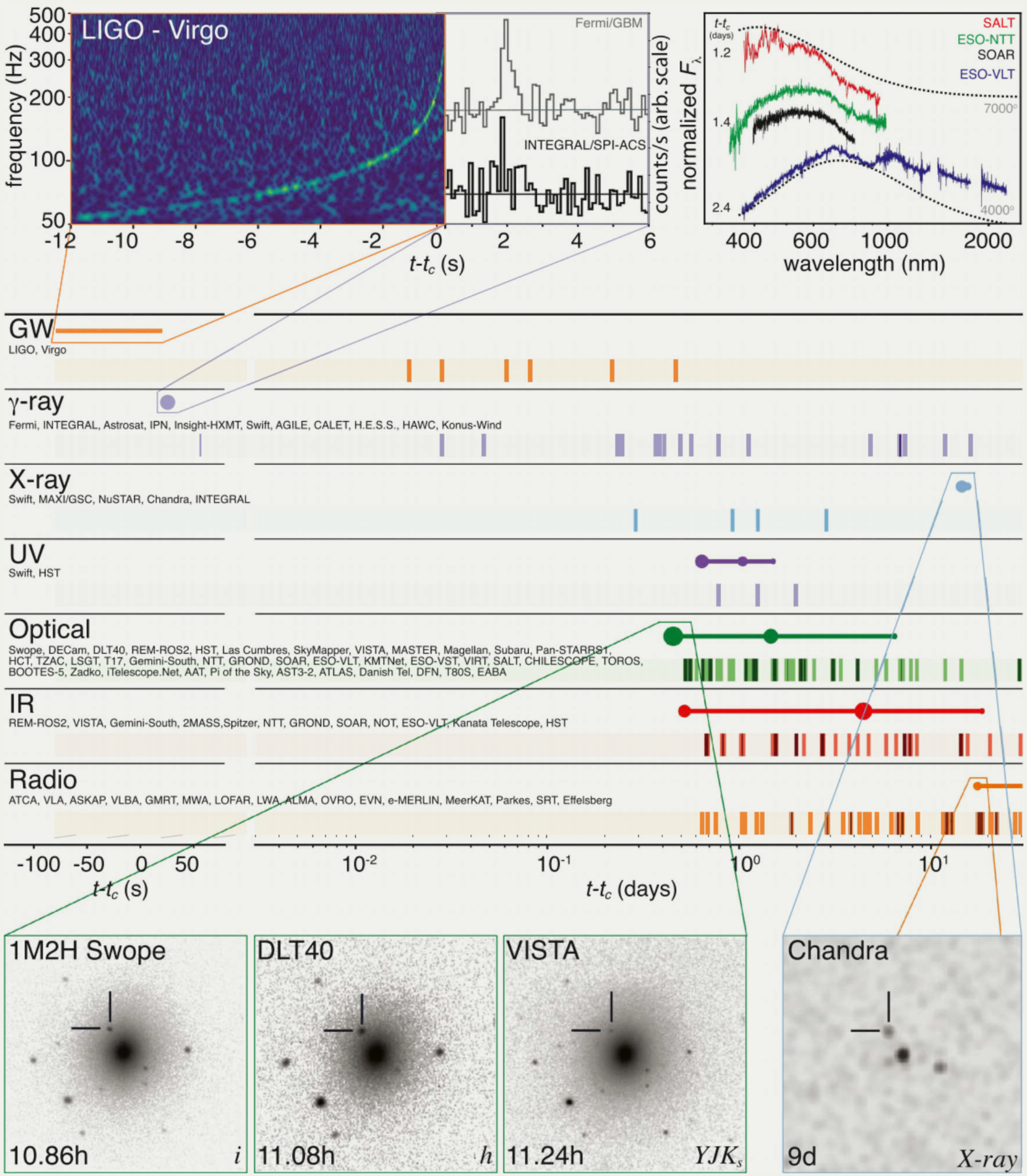


Start of the GW astrophysics era

Source:
 arXiv:1710.05833

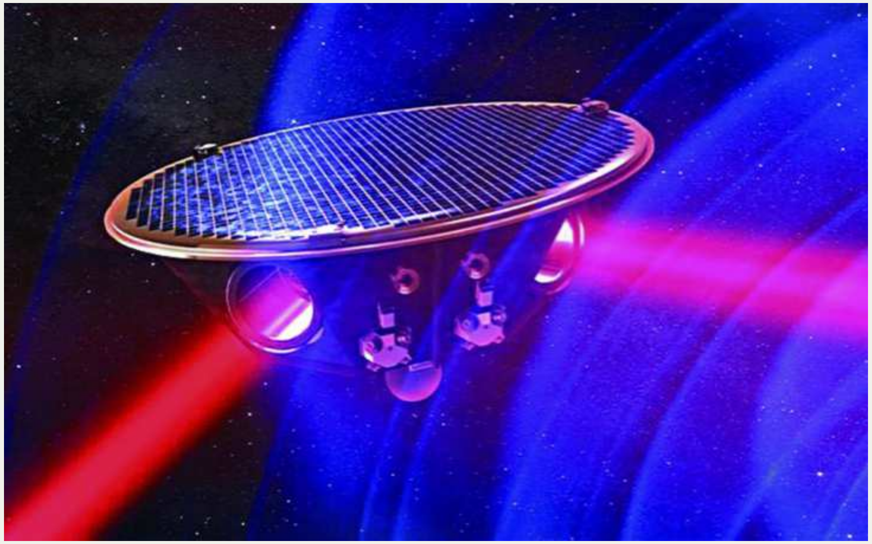


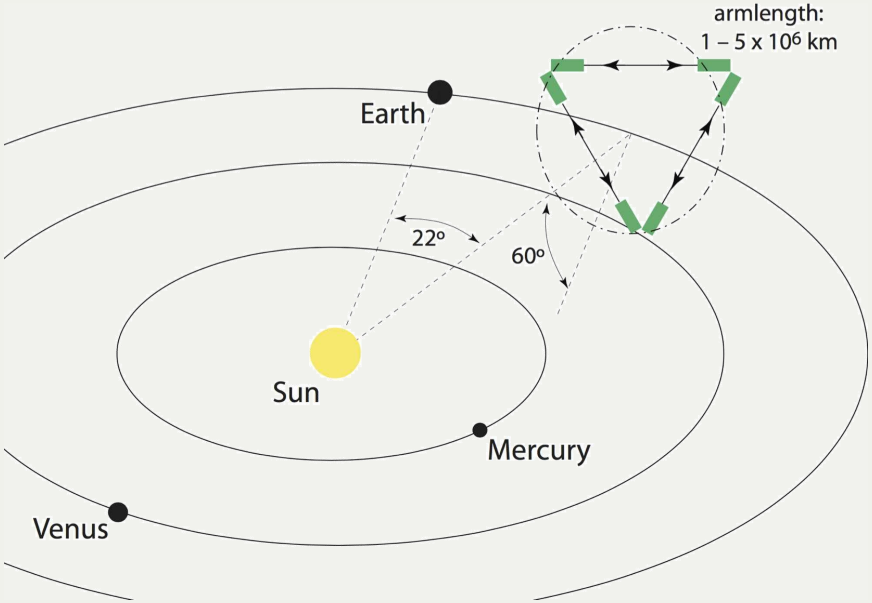
Cosmological sources

Early universe processes that could produce observable GWs:

- Inflation (and how it ended)
  - CMB experiments? *see Elina's talk*
- Cosmic strings and other defects
  - *see Asier's talk*
- First-order phase transitions
  - *this talk!*

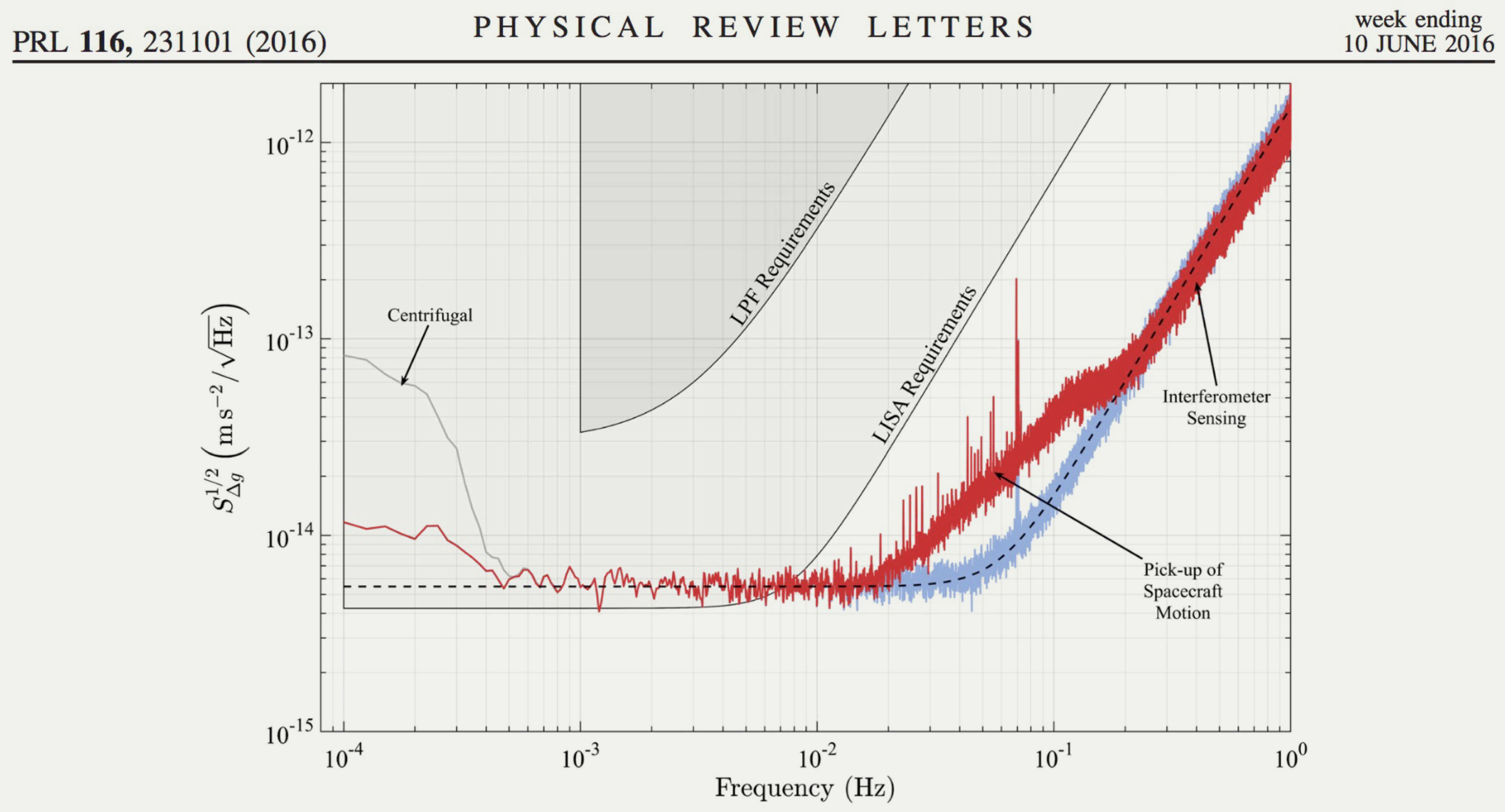
What's next: LISA mission





- 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

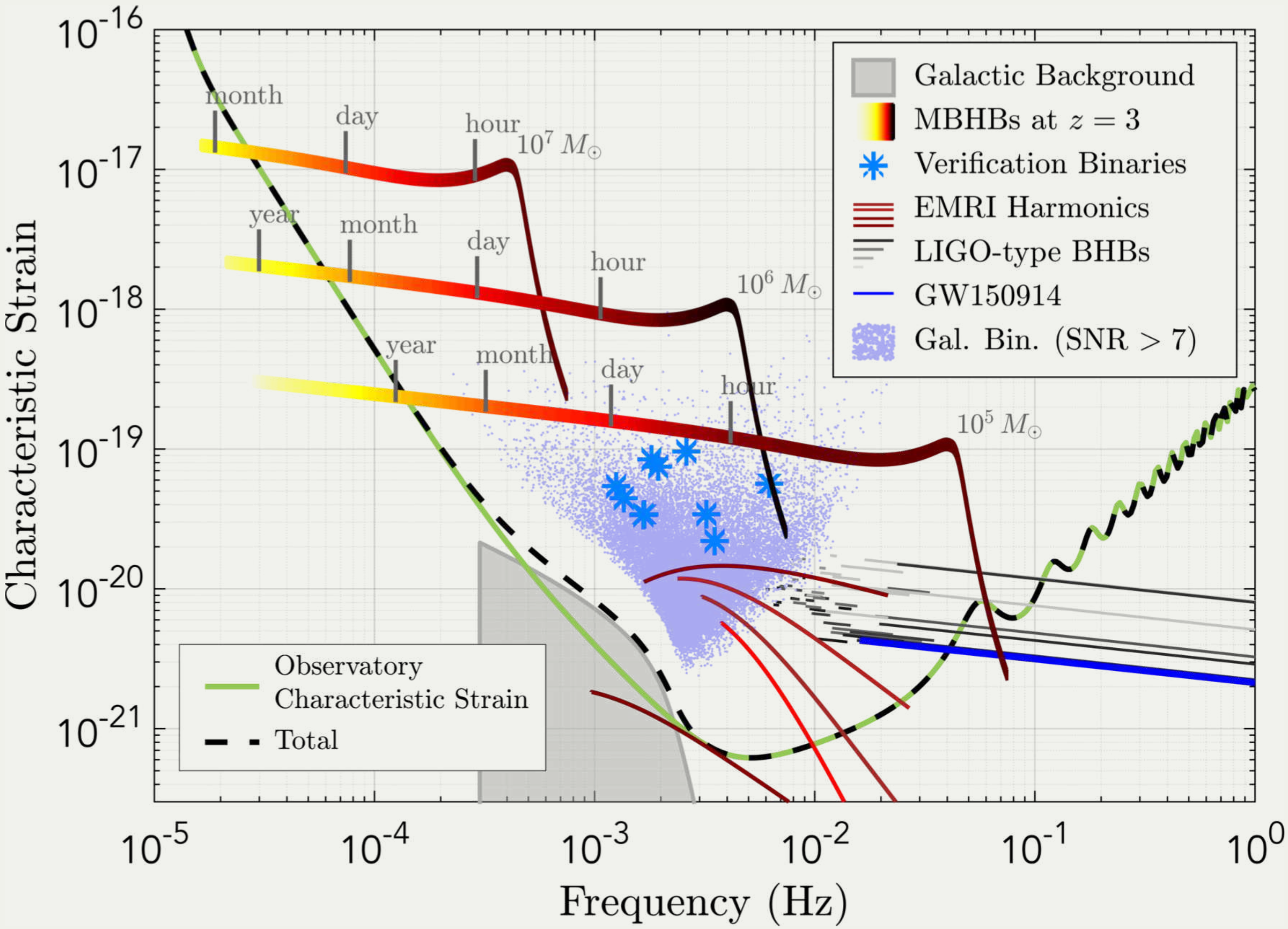
LISA Pathfinder



Exceeded design expectations by factor of five!

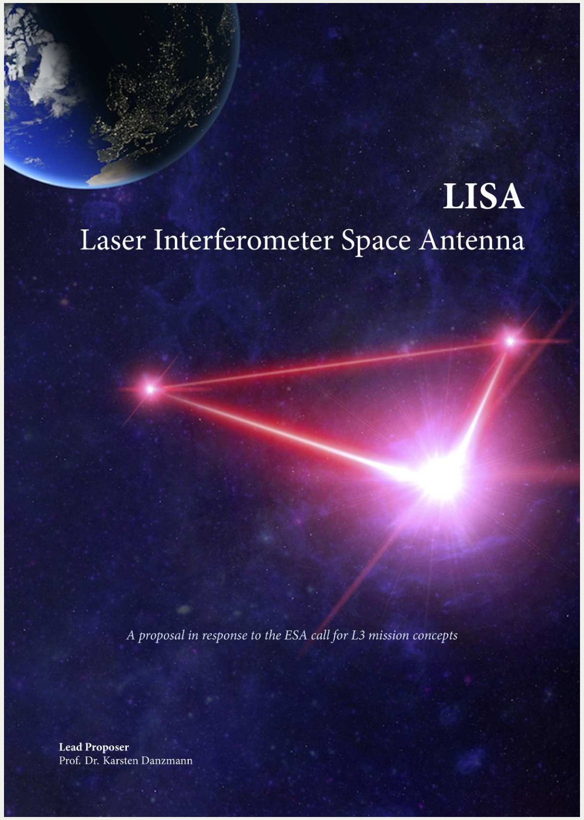
Source: (CC-BY) Phys. Rev. Lett. 116, 231101

Possible signals for LISA



Source: arXiv:1702.00786.

Key science for LISA



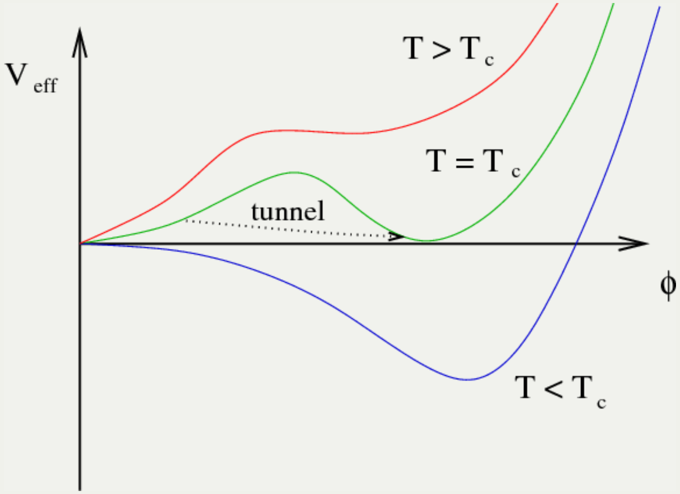
Science Investigation 7.2: Measure, or set upper limits on, the spectral shape of the cosmological stochastic GW background.

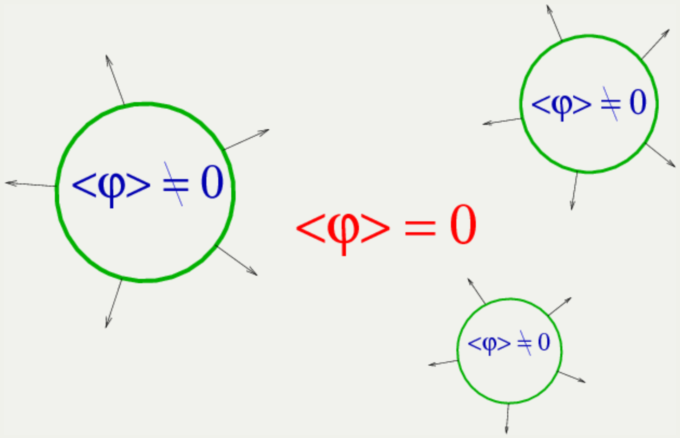
Operational Requirement 7.2: Probe a broken power-law stochastic background from the early Universe as predicted, for example, by first order phase transitions …

Let's focus on these first-order phase transitions...

Electroweak phase transition

- This is the process by which the Higgs 'turned on'
- In the minimal Standard Model it is gentle (crossover)
- It is possible (and theoretically attractive) in extensions that it would experience a first order phase transition

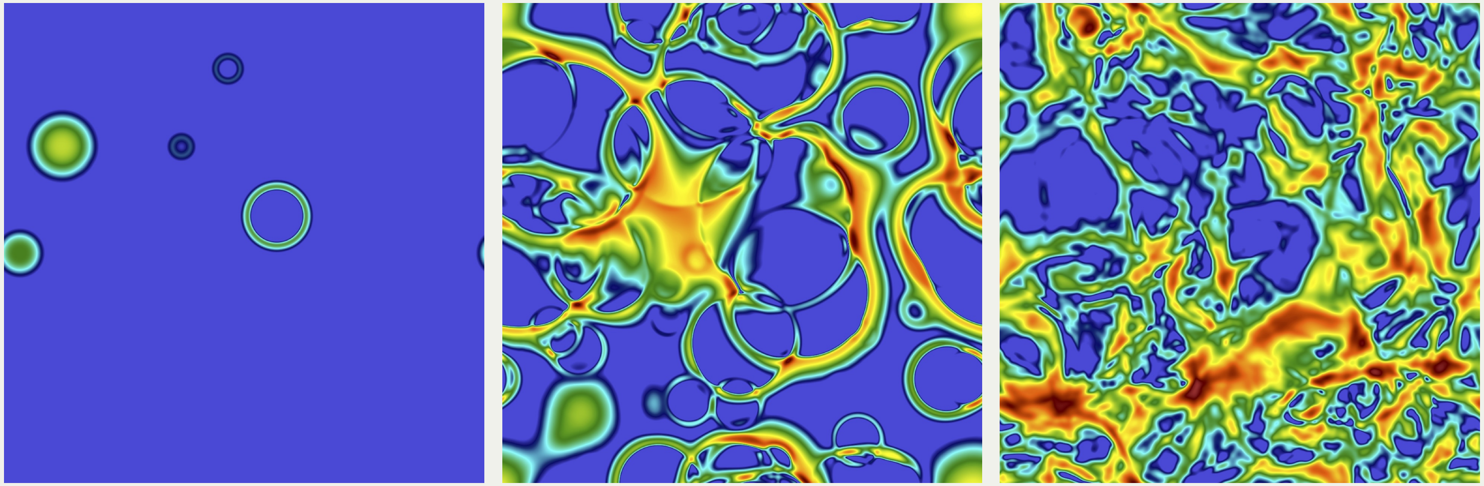




Source: Morrissey and Ramsey-Musolf

Thermal phase transition: what, when?

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 wall moves

- In EWPT: equation of motion is (schematically)

Liu, McLerran and Turok; Prokopec and Moore; Konstandin, Nardini and Rues; ...

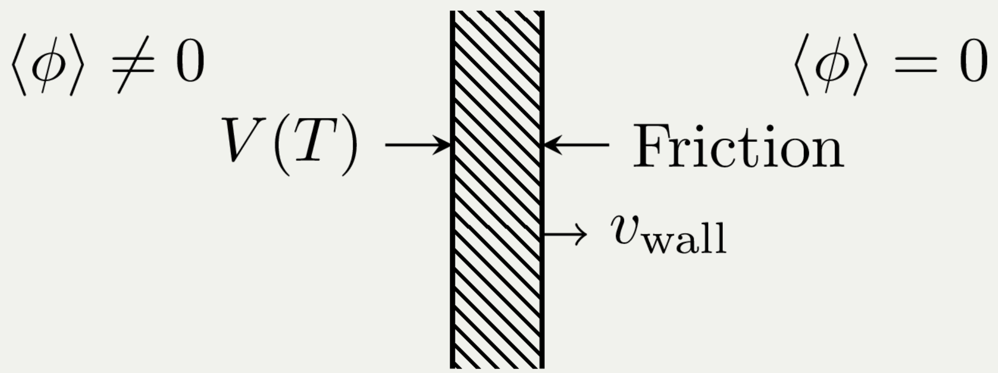
$$\partial_\mu \partial^\mu \phi + V'_{\rm eff}(\phi, T) + \sum_i \frac{dm_i^2}{d\phi} \int \frac{\mathrm{d}^3 k}{(2\pi)^3\, 2E_i} \delta f_i(\mathbf{k}, \mathbf{x}) = 0$$

  - $V'_{\rm eff}(\phi)$: gradient of finite-T effective potential
  - $\delta f_i(\mathbf{k}, \mathbf{x})$: deviation from equilibrium phase space density of ith species
  - m_i: effective mass of ith species:

Force interpretation

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

This equation is the realisation of this idea:



Field-fluid system

Using a flow ansatz for the wall-plasma system:

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

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.

astro-ph/9309059

Detonations vs deflagrations

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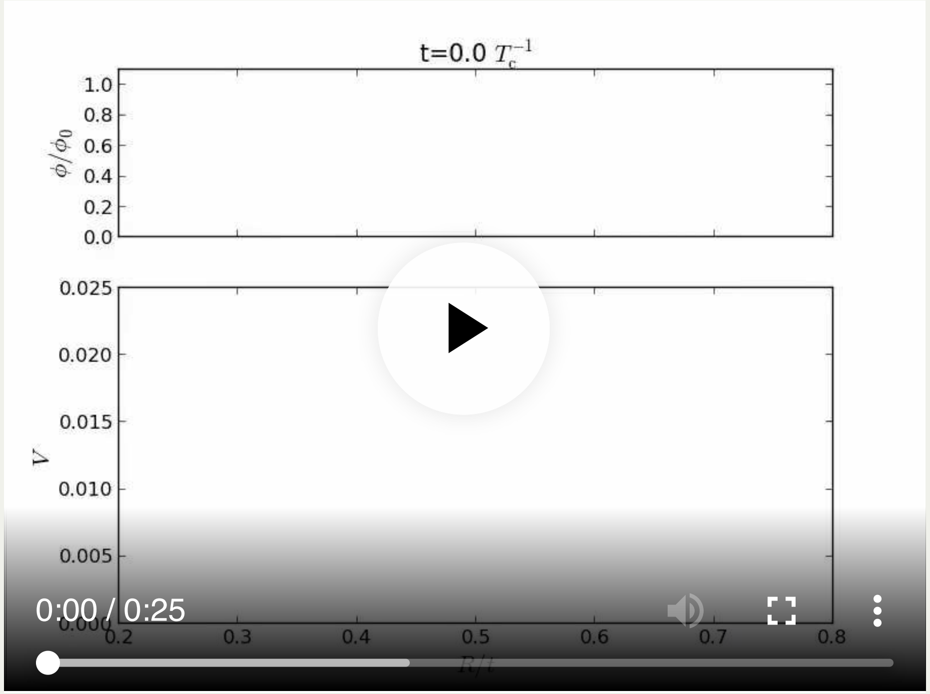
What the makes the GWs at a first-order phase transition?

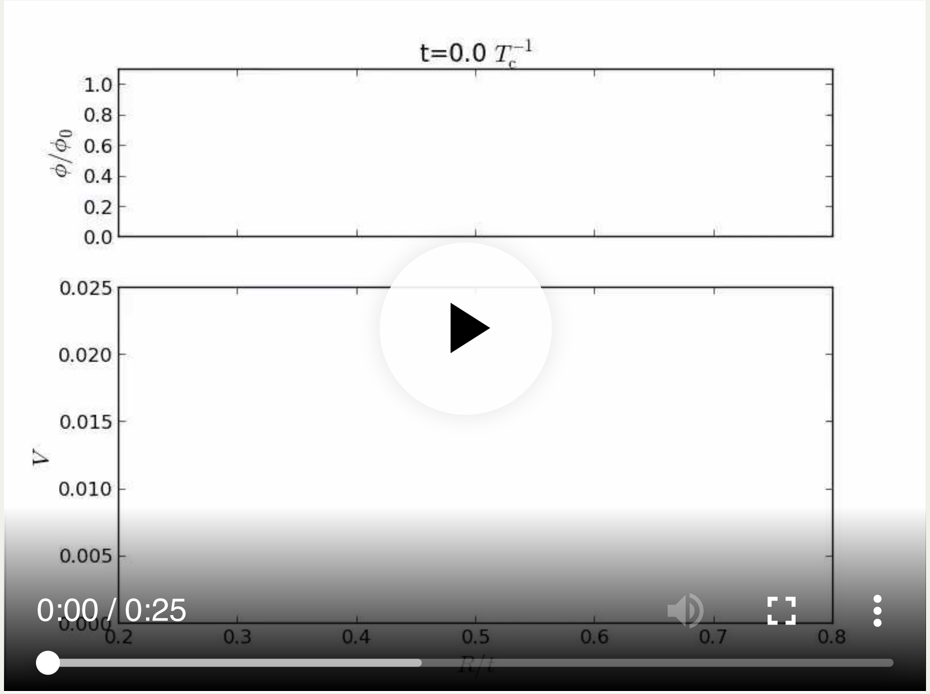
- Bubbles nucleate and expand, shocks form, then:
  1. $h^2\Omega_\phi$ ~~: Bubbles + shocks collide - 'envelope phase'~~
  2. $h^2\Omega_{\rm sw}$: Sound waves set up - 'acoustic phase'
  3. $h^2\Omega_{\rm turb}$: [MHD] turbulence - 'turbulent phase'

- Sources add together to give observed GW power:

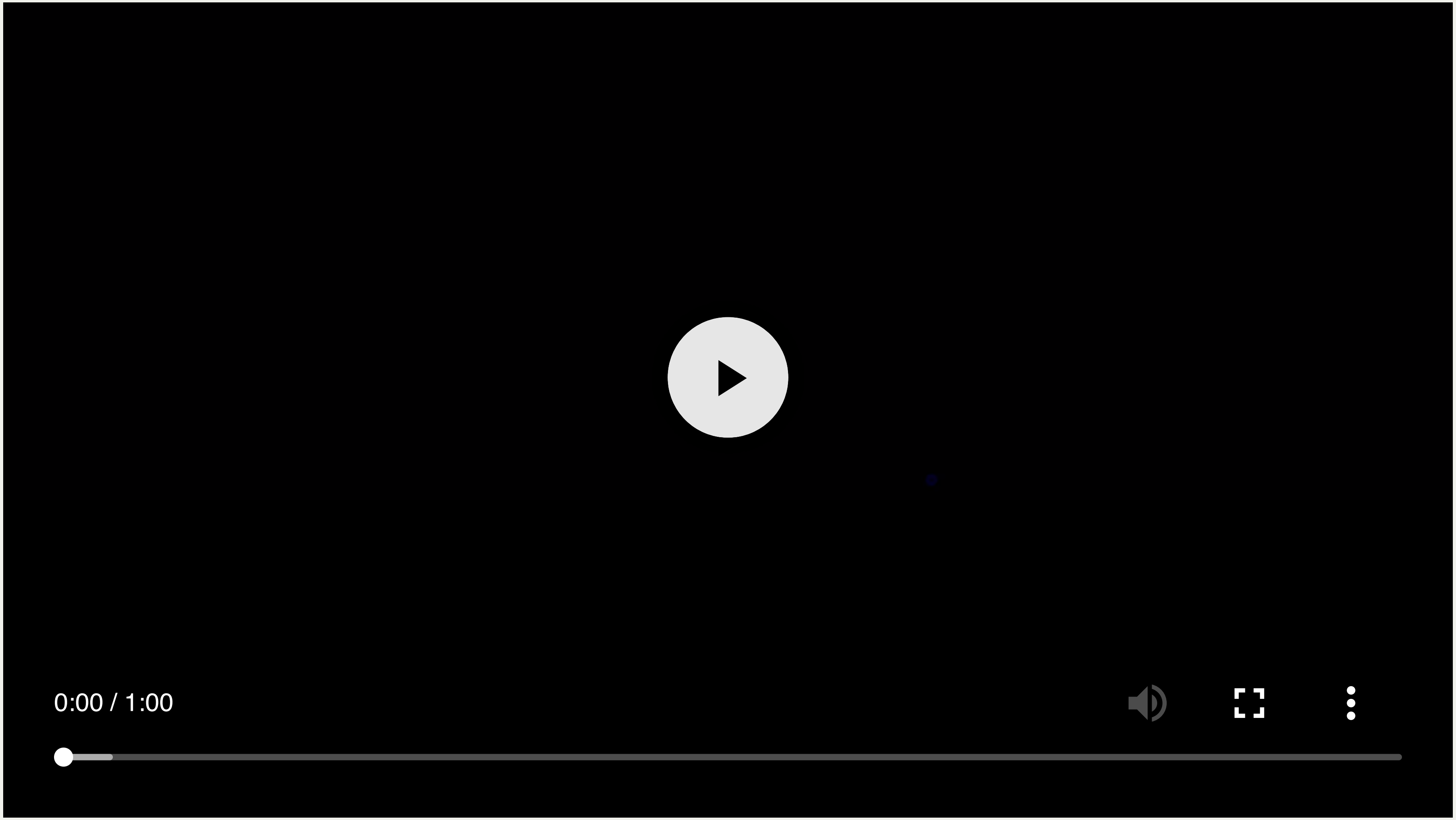
$$h^2\Omega_{\rm GW}\, h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$$

Velocity profile development: detonation vs deflagration



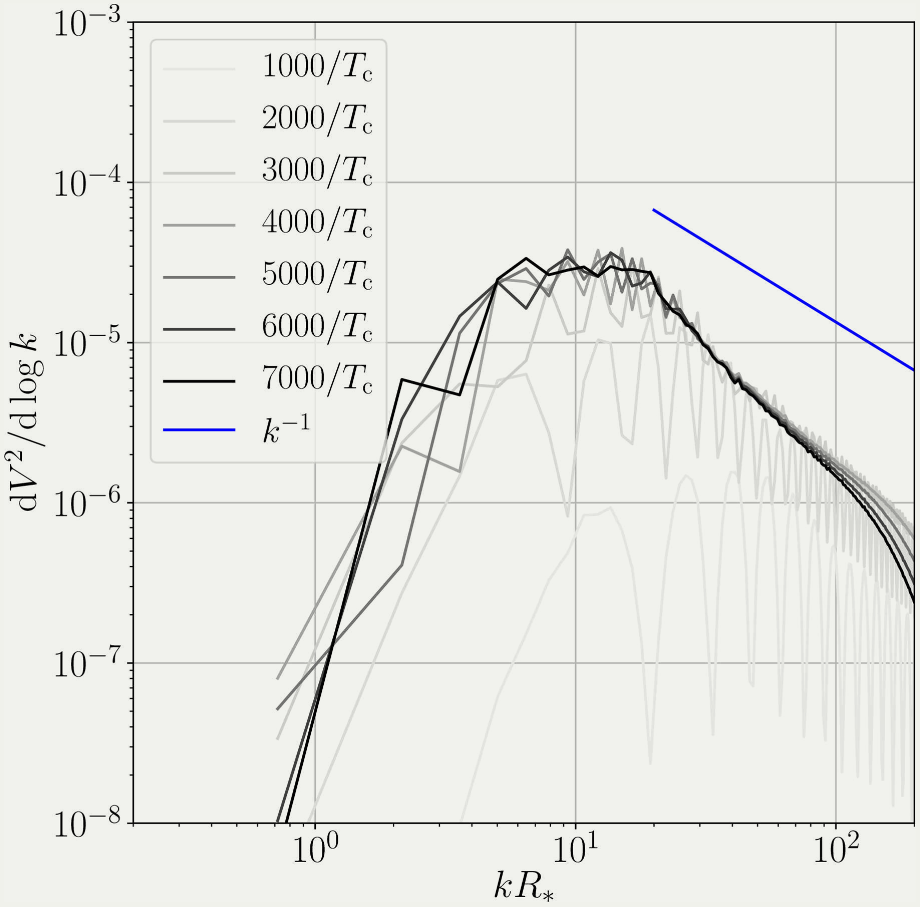


Simulation slice example



Velocity power spectra

$v_\mathrm{w} < c_\mathrm{s}$



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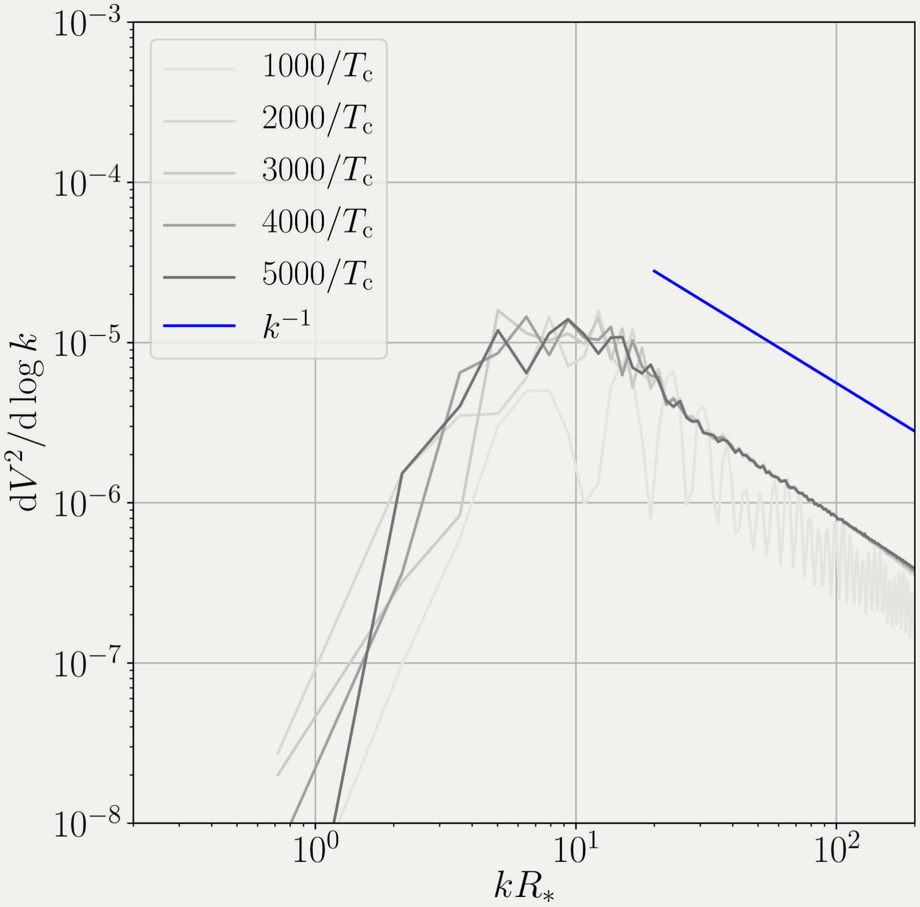
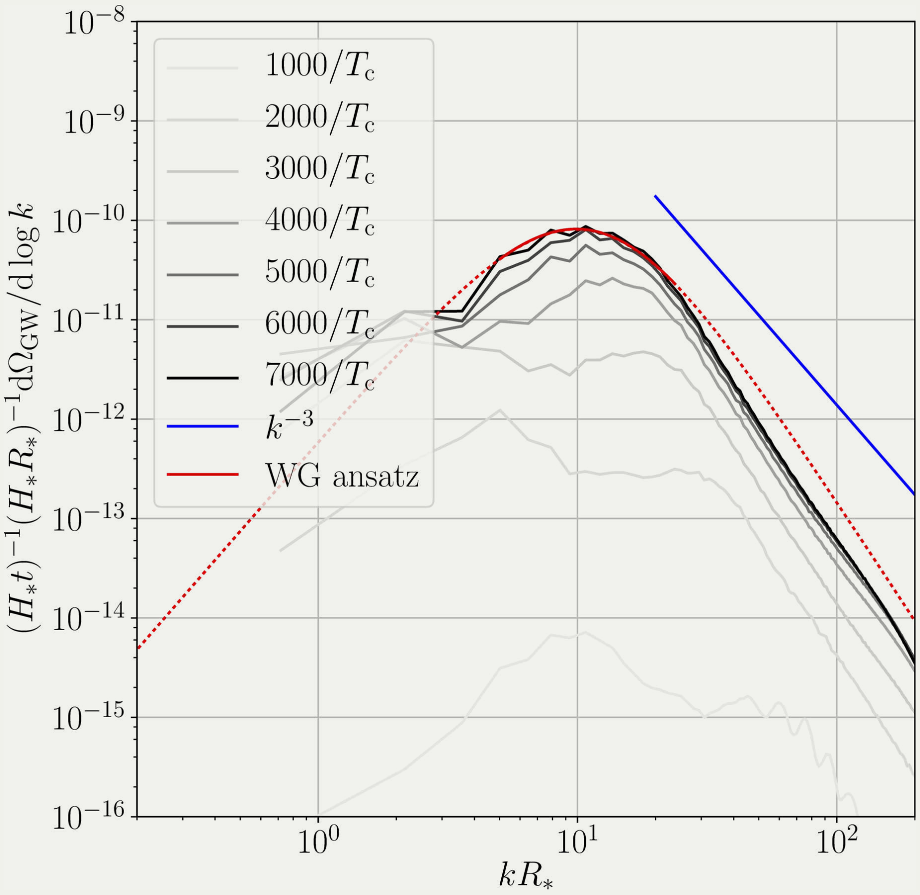


GW power spectra and power laws

$v_w < c_s$



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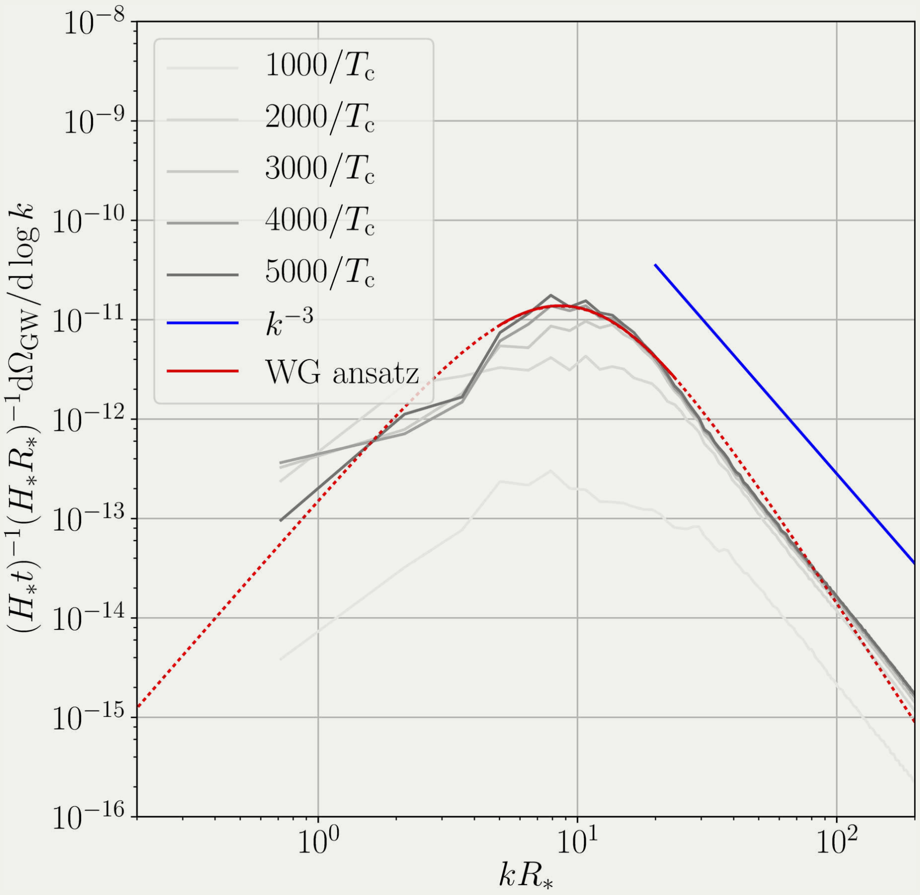
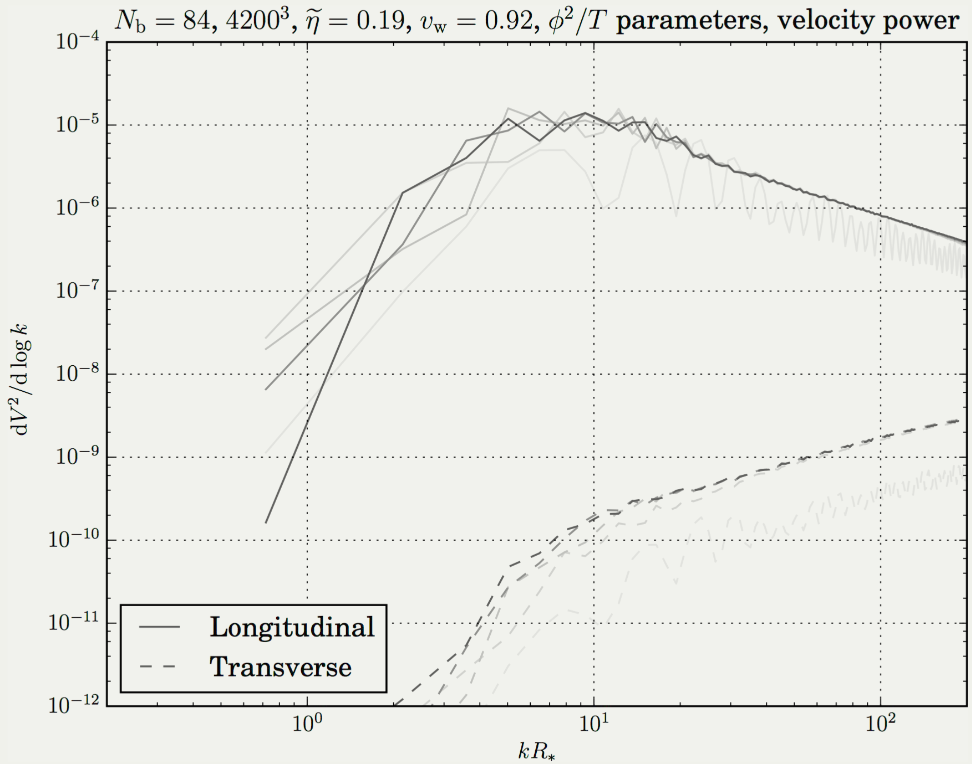


NB: curves scaled by t

Shocks and turbulence?



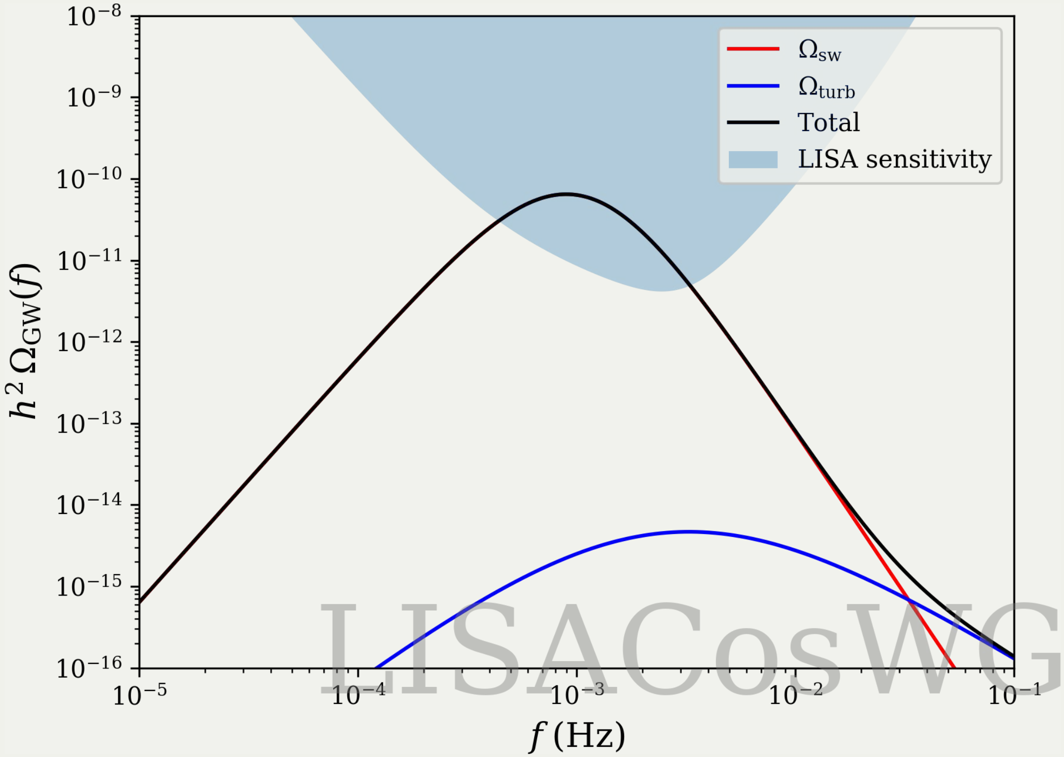
- Require longer timescales (fluid turnover time) $R_*/\overline{U}_f$, thus: may not develop at all
- Plenty of theoretical results, but little agreement

arXiv:0705.1733; arXiv:0909.0622; arXiv:1510.02985; ...

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, $\alpha_{T_*} = 0.066$, $v_{\rm w} = 0.95$, $\beta/H_* = 105.9$)



From ptplot.org (beta!)

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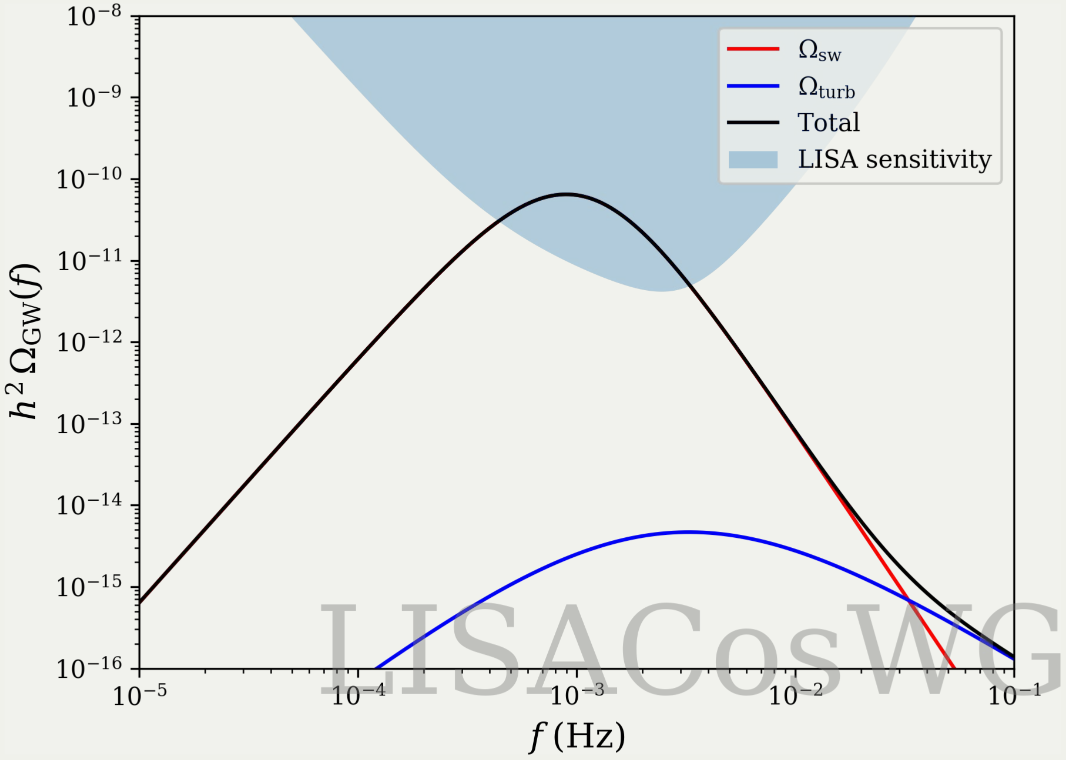

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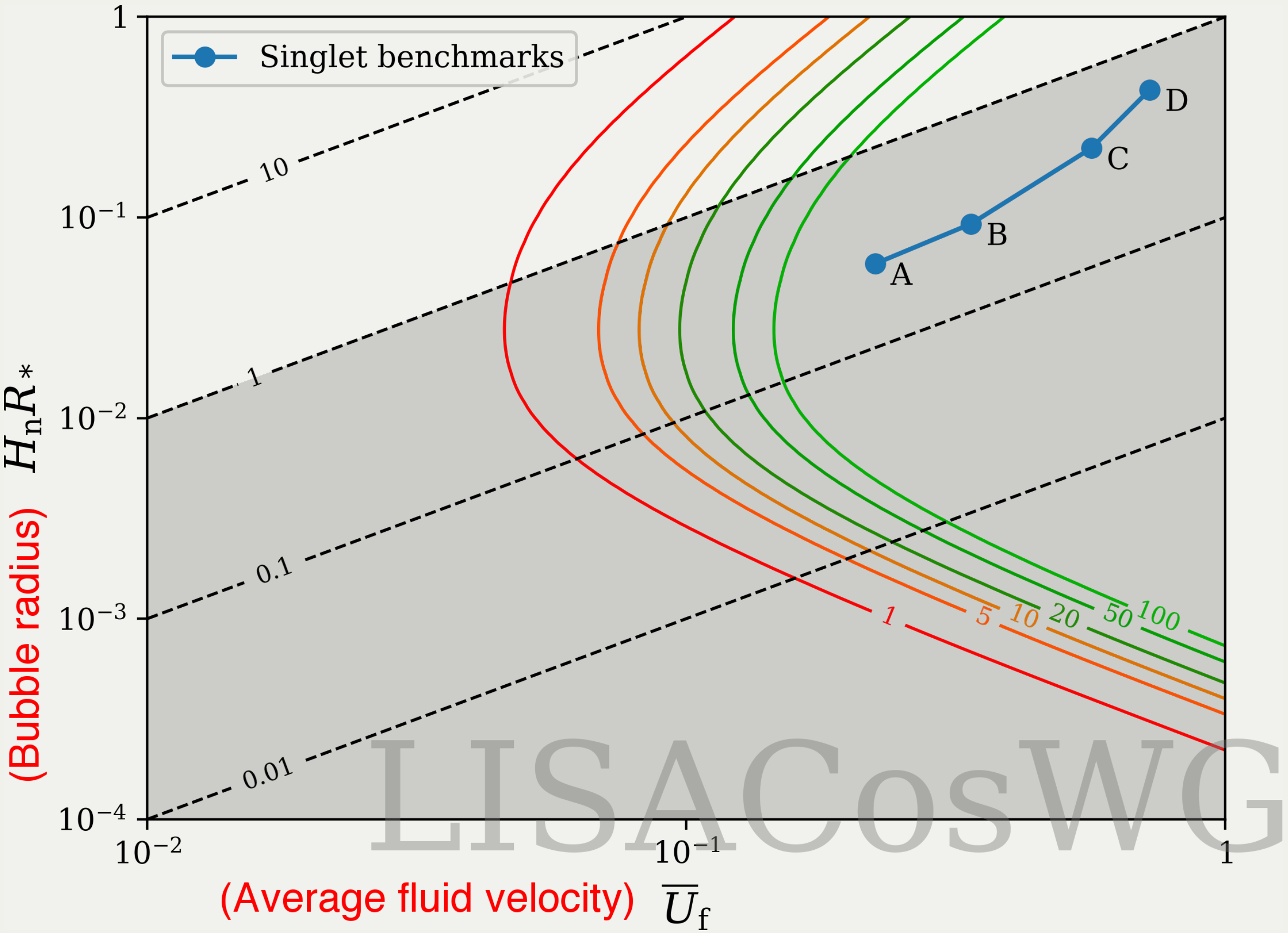
PTPlot.org

$$\text{Model} \longrightarrow (T_*, \alpha_{T_*}, v_\mathrm{w}, \beta) \longrightarrow \text{this plot}$$



Final conclusion

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