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Gravitational waves from first order phase transitions: Using LISA to probe particle physics

Jorinde van de Vis

APEC Seminar, Kavli IPMU
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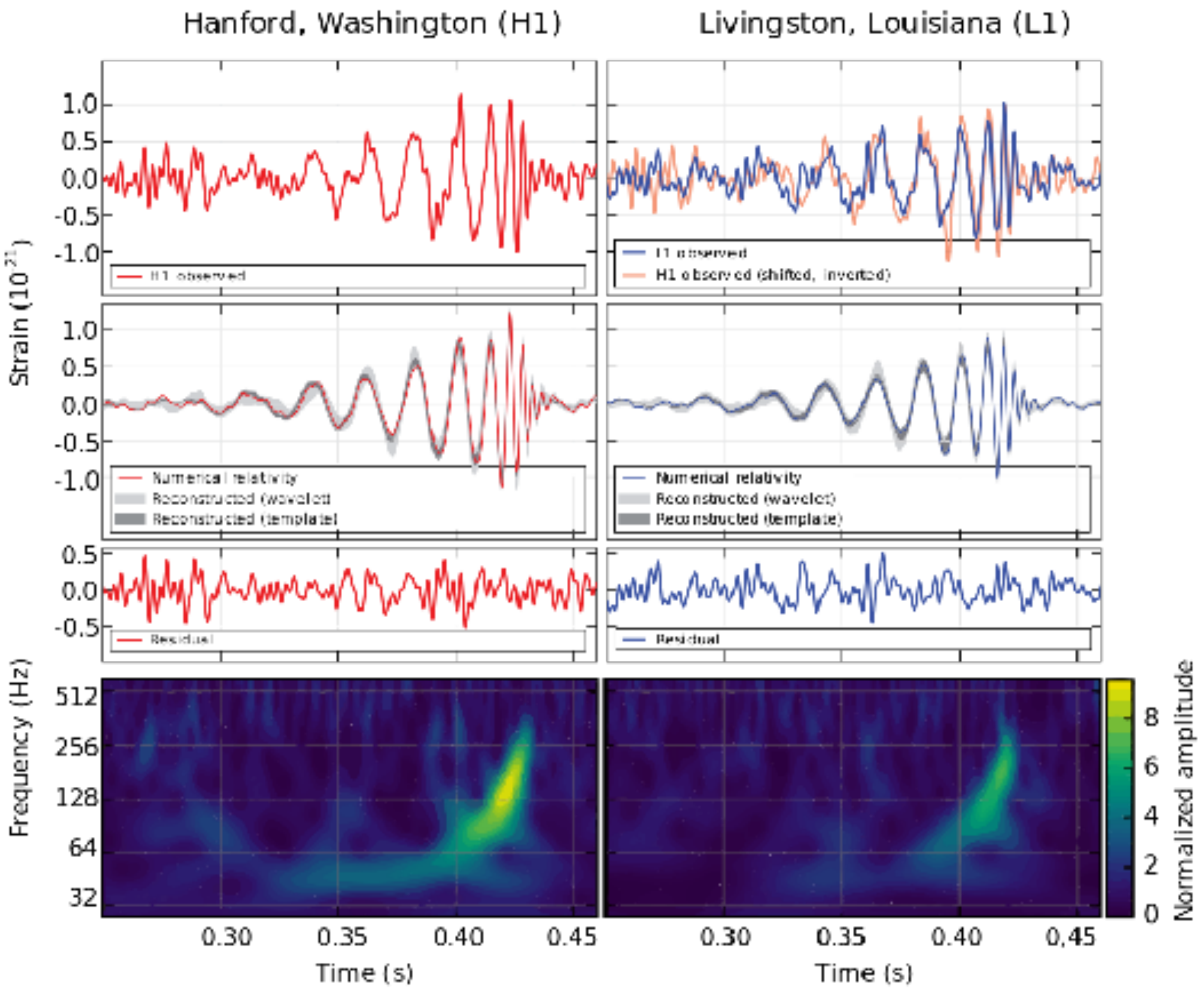
Gravitational waves from first order phase transitions: Using LISA to probe particle physics

T.V.I. Tenkanen, JvdV	*JHEP* 08 (2022) 302	arXiv:2206.01130
R. Jinno, T. Konstandin, H. Rubira, JvdV	*JCAP* 12 (2021) 12, 019	arXiv:2108.11947
F. Giese, T. Konstandin, JvdV	*JCAP* 11 (2021) 002	arXiv:2107.06275
F. Giese, T. Konstandin, K. Schmitz, JvdV	*JCAP* 01 (2021) 072	arXiv:2010.09744
F. Giese, T. Konstandin, JvdV	*JCAP* 07 (2020) 07, 057	arXiv:2004.06995

Gravitational waves

First black hole merger event: GW150914



LIGO/Virgo Collab. 2016

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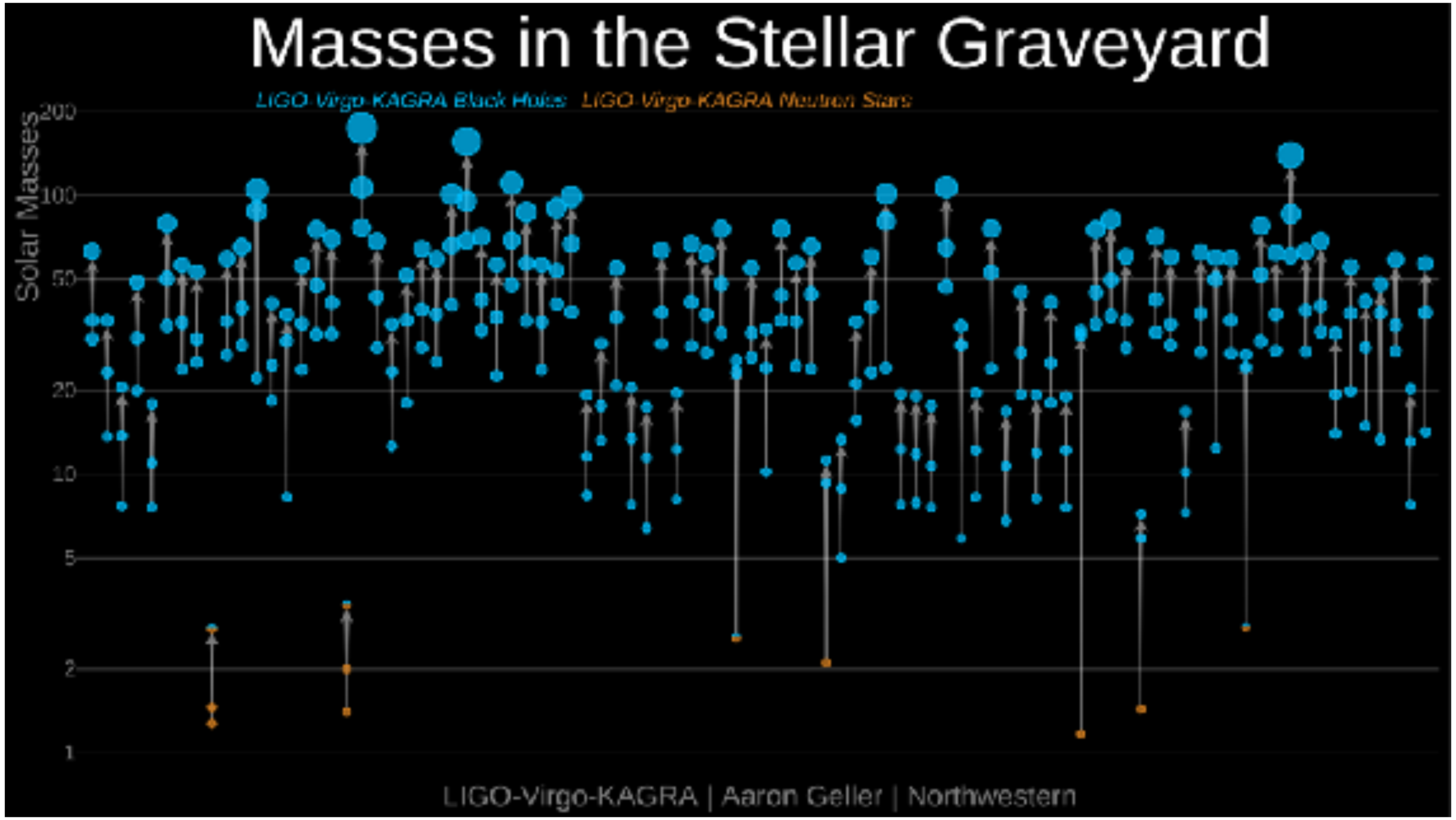
Gravitational waves

November 2021: 90 events



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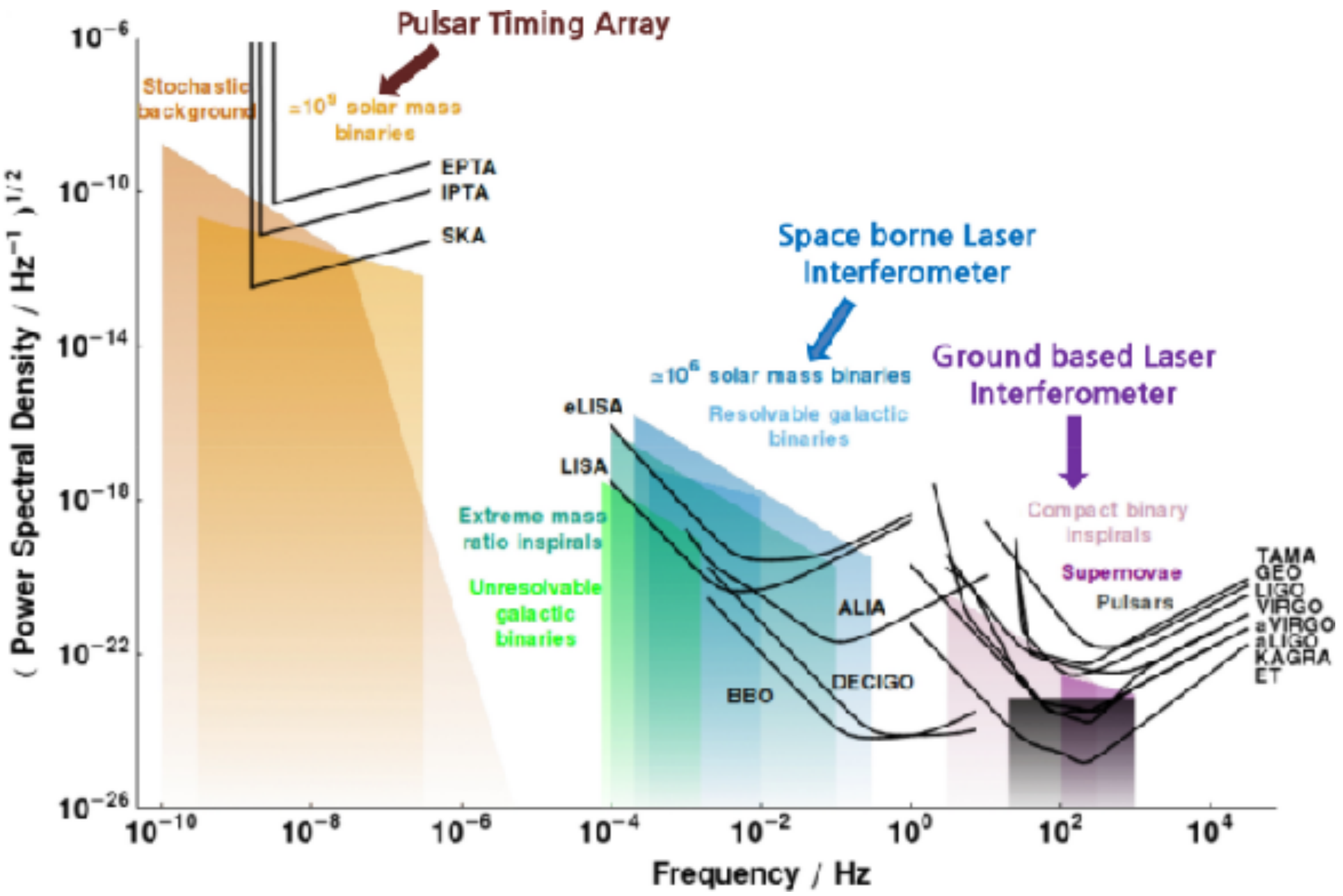
Ongoing and upcoming experiments

- Size of the detector sets f_{detector}
- Time scale and redshift of the source set f_{signal}



Park 2021

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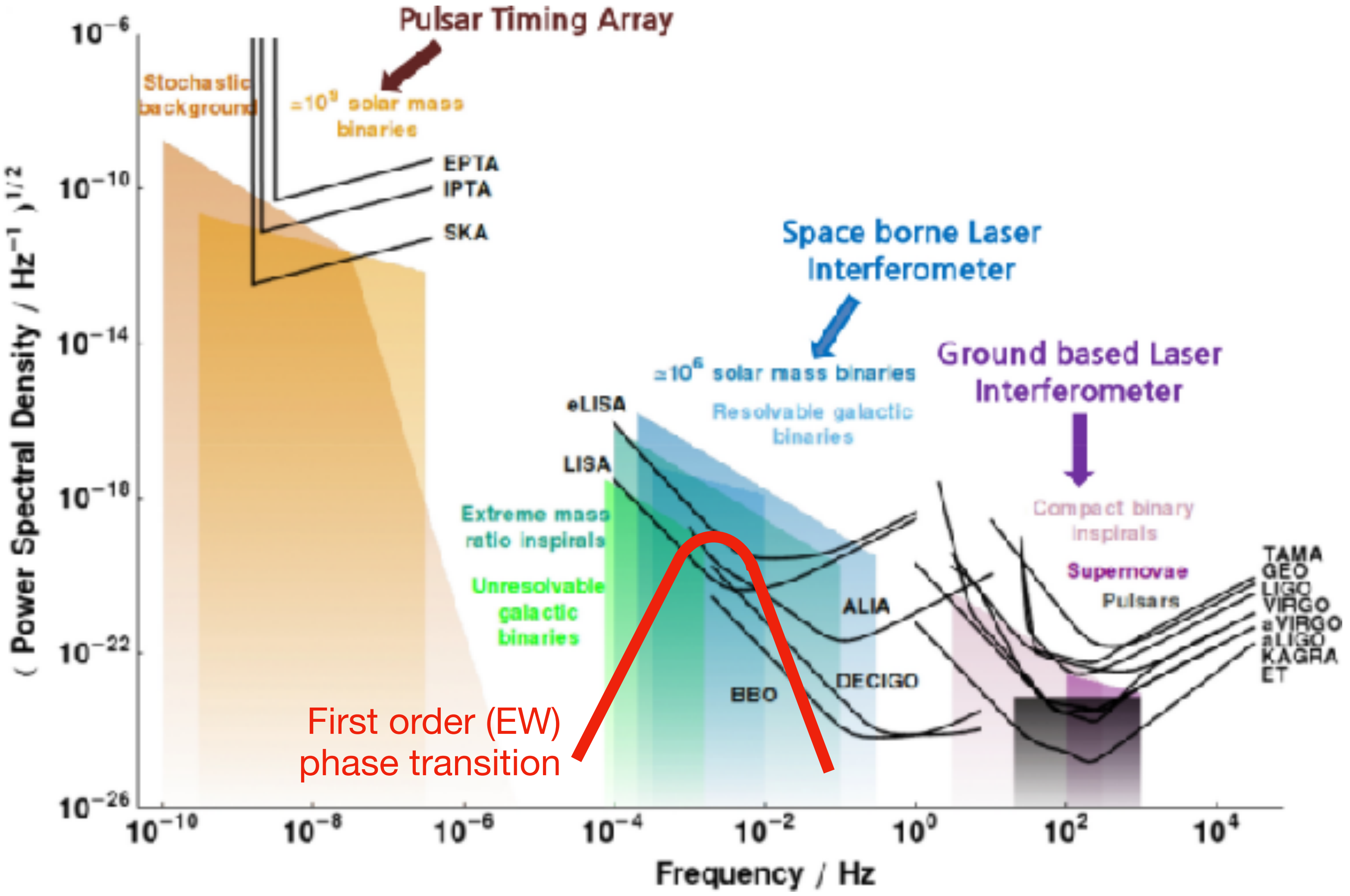

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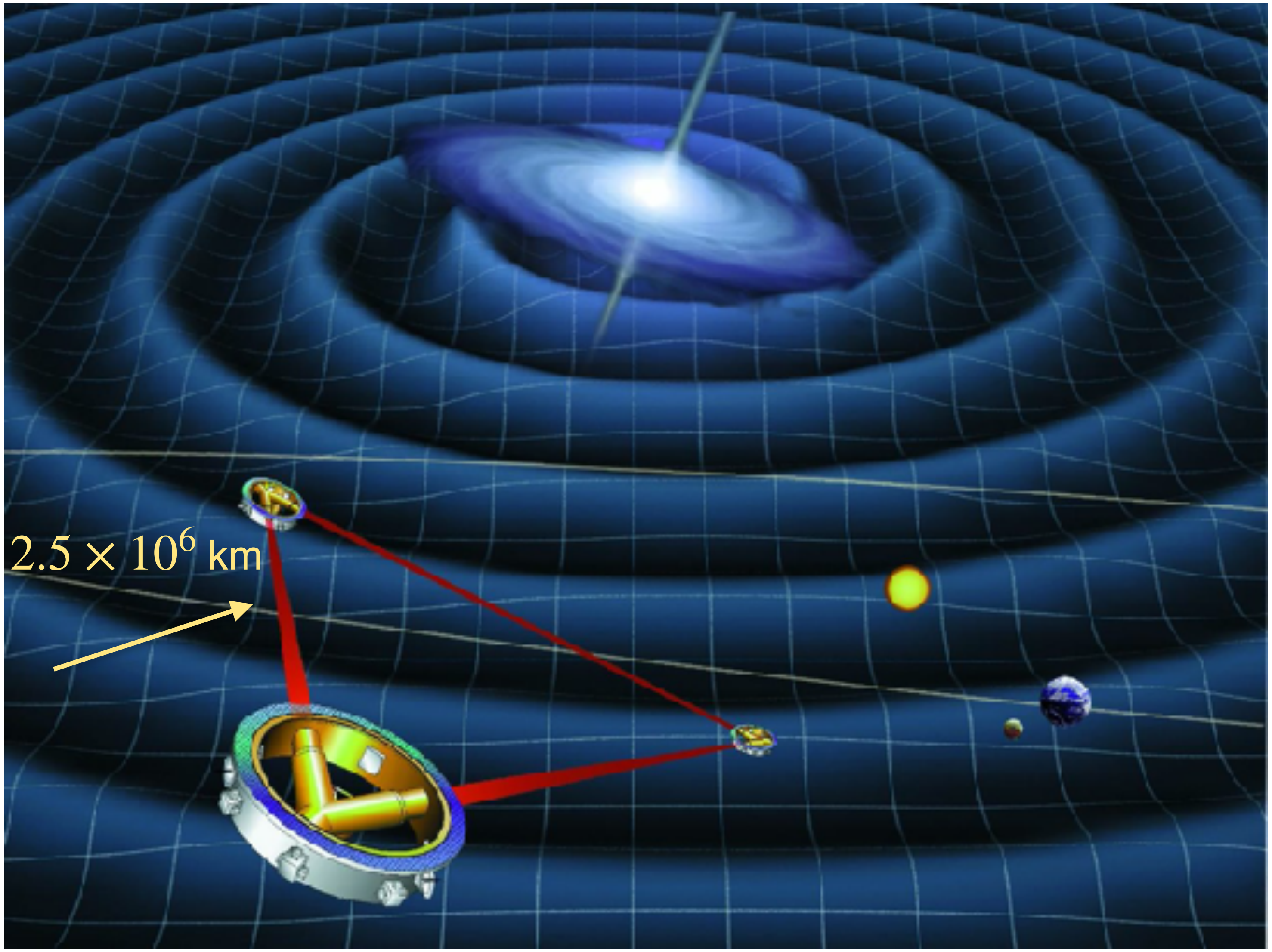
Laser Interferometer Space Antenna (LISA)

ESA mission, planned in mid 2030s



How does a first order phase transition source gravitational waves?

Gravitational waves

Minkowski GW

- Expand the metric: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, with $|h_{\mu\nu}| \ll 1$
- Only the transverse-traceless component of $h_{\mu\nu}$
- Source*: $\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$

Only transverse and traceless part

*In the gauge where $\partial^\nu \bar{h}_{\mu\nu} = 0$, with $\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h$

GWs get sourced by anisotropic stress-energy

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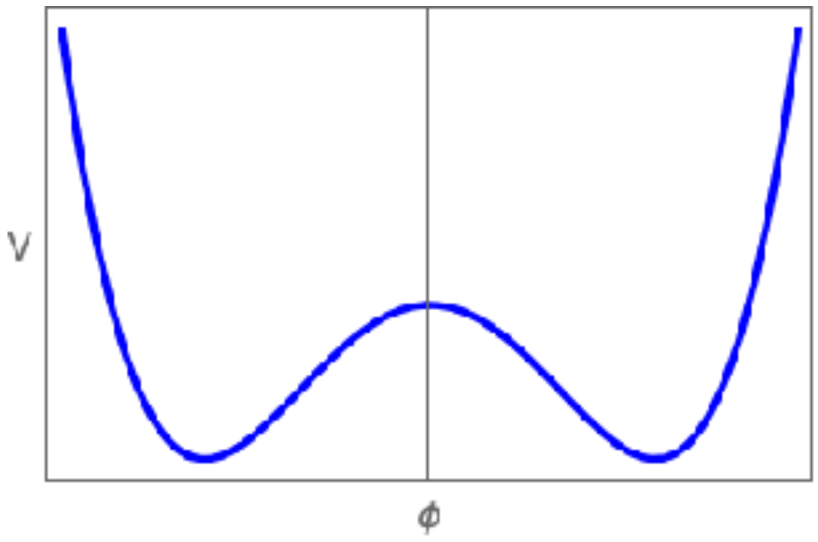
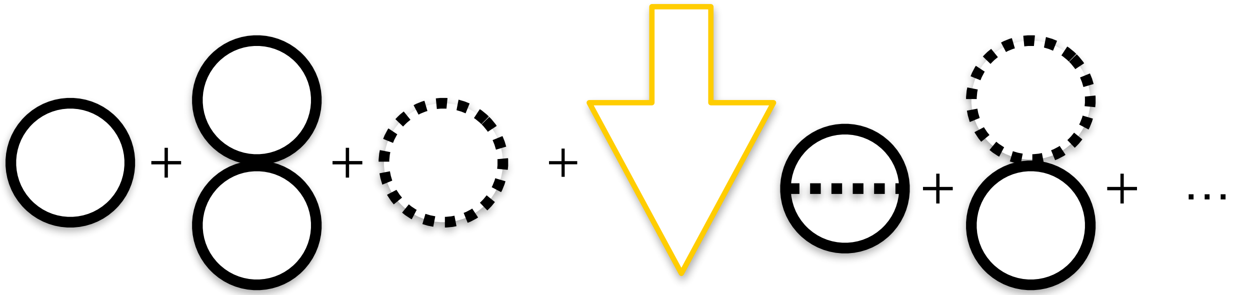
Cosmological phase transition

Temperature-dependent Higgs* potential

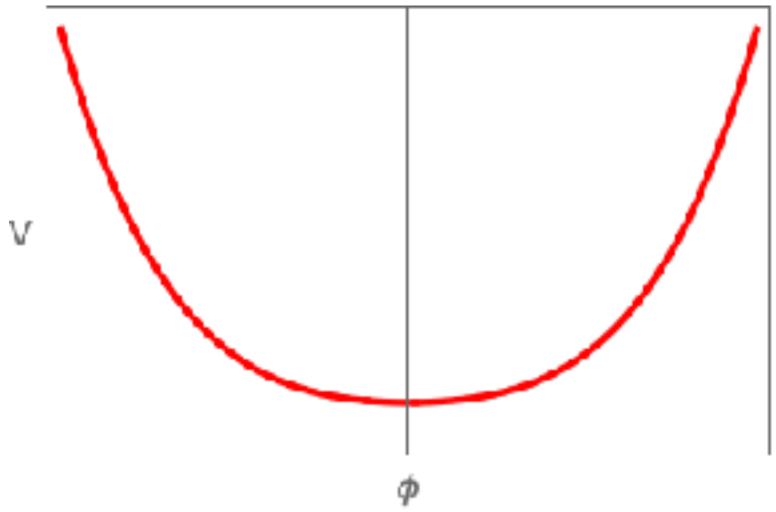
Zero temperature



T-dependent vacuum contributions



Finite temperature



*Or some other field

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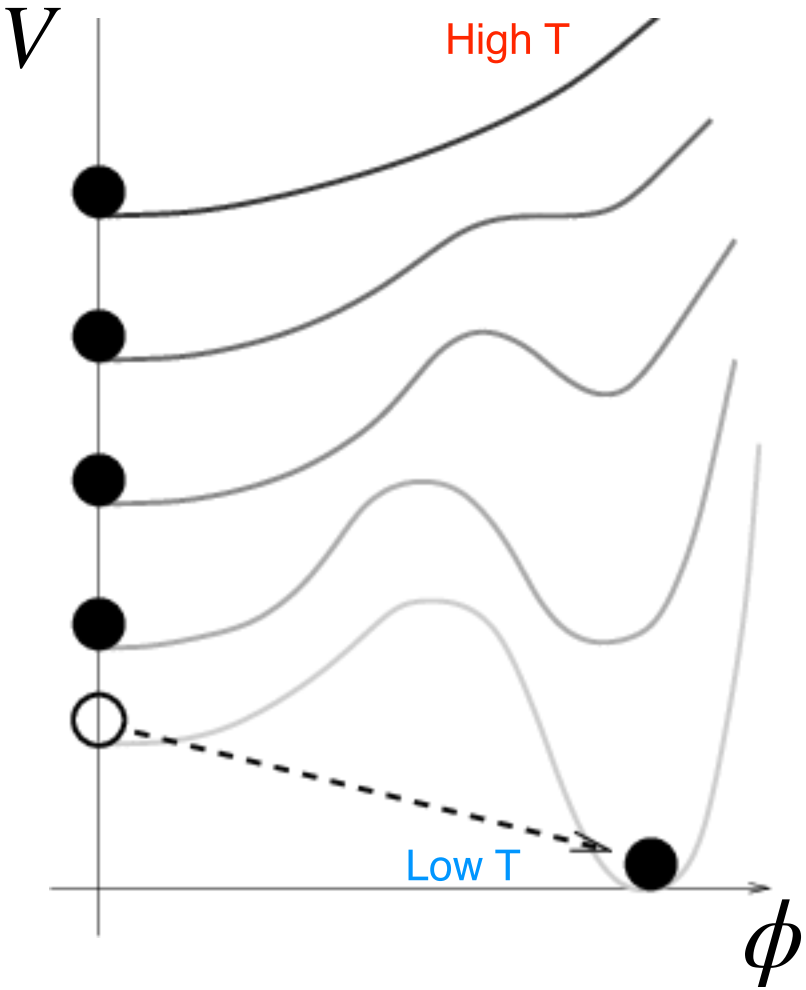
First order phase transition



Rubakov, 2015

Bubble nucleation

Motion in the primordial fluid sourcing gravitational waves

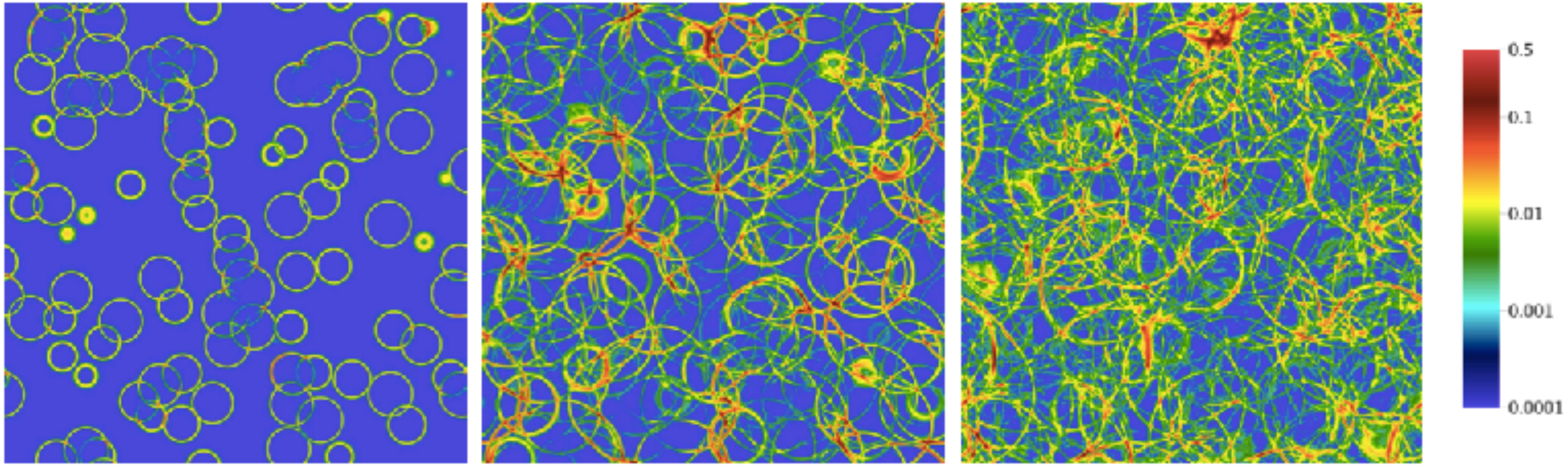
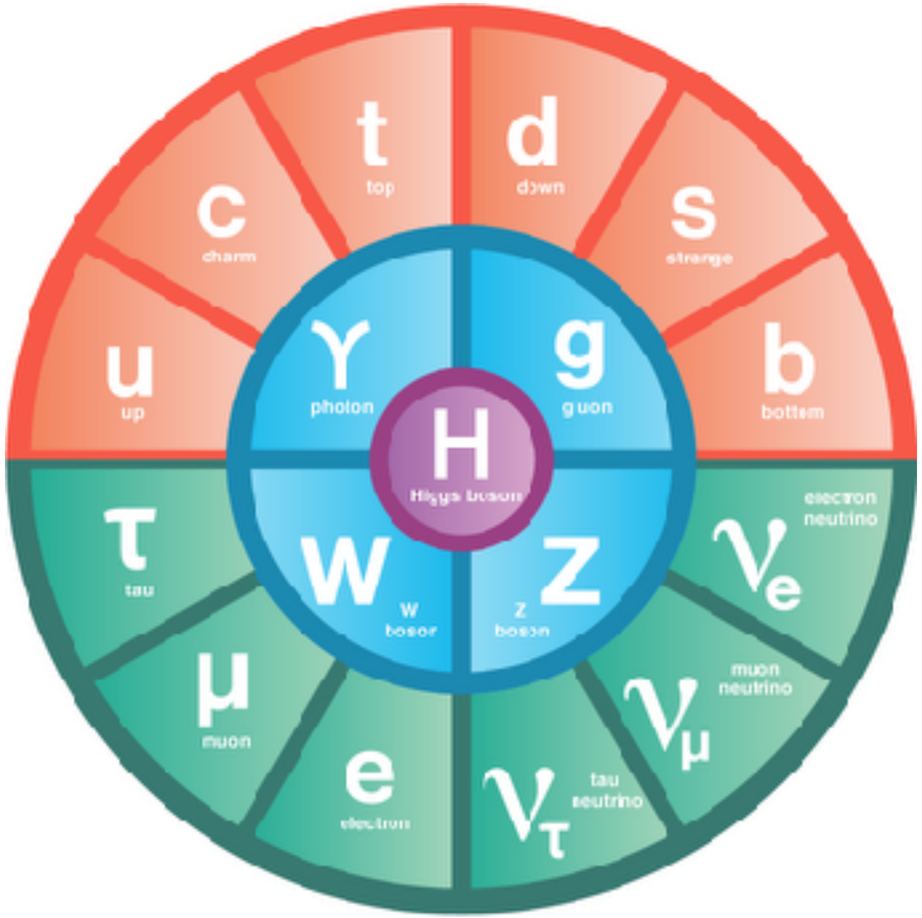


FIG. 4. Slices of fluid kinetic energy density E/T_c^4 at $t = 500\,T_c^{-1}$, $t = 1000\,T_c^{-1}$ and $t = 1500\,T_c^{-1}$ respectively, for the $\eta/T_c = 0.15$, $N_b = 988$ simulation.

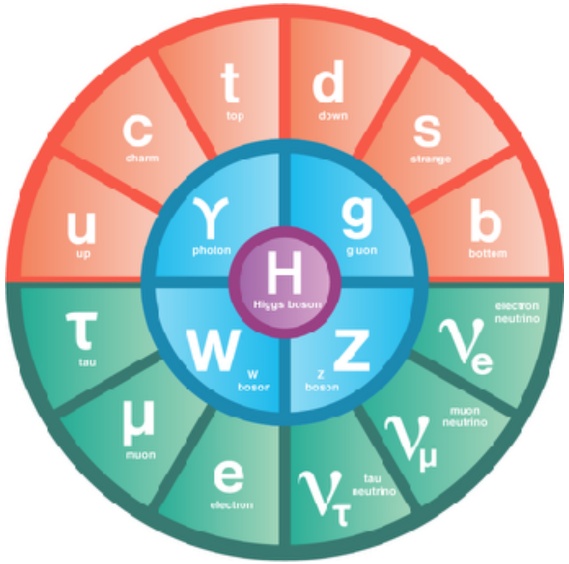
Hindmarsh, Huber, Rummukainen, Weir 2015

Phase transitions in the Standard Model

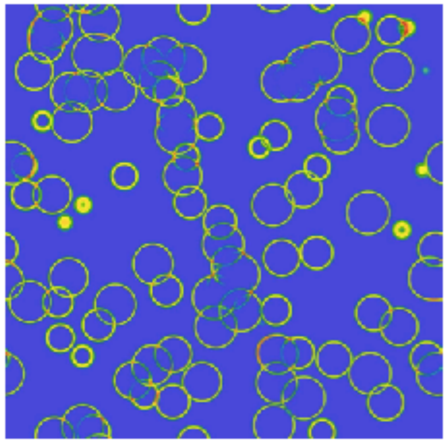
- Electroweak phase transition $(100\,\mathrm{GeV})$
- QCD phase transition $(150\,\mathrm{MeV})$
- Both are cross-overs!



Gravitational waves from first order phase transition: sign of new particles!



+ ? →



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Three contributions to the gravitational wave signal

- Kinetic energy in the bubble walls

  Kosowsky, Turner, Watkins 1992, Kosowsky, Turner 1993, Jinno, Takimoto 2017, Konstandin 2017, Cutting, Hindmarsh, Weir 2018*

- Sound waves

  Hindmarsh, Huber, Rummukainen, Weir 2013, 2015 & 2017, Giblin, Mertens 2013&2014, Cutting, Hindmarsh, Weir 2019

- Turbulence

  Caprini, Durrer, 2006, Kahniashvili, Campanelli, Gogoberidze, Maravin, Ratra 2008&2009, Caprini, Durrer, Servant 2009, Kissinger, Kahniashvili 2015

* A very incomplete list of references

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- Feebly interacting particles: talk on 09/12

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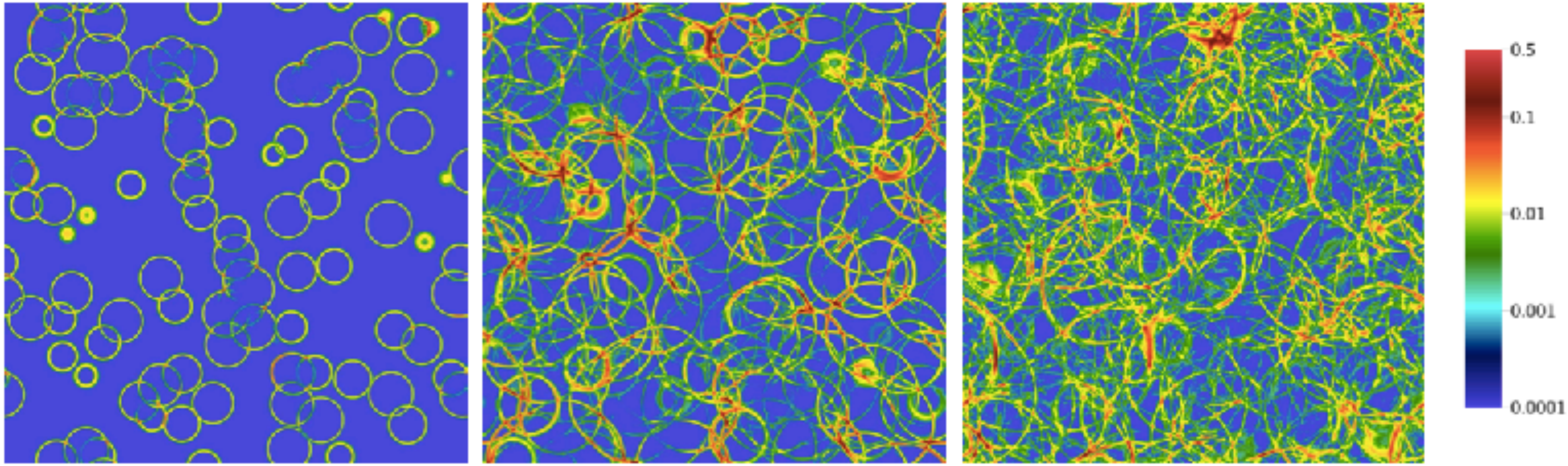
Gravitational waves from many bubbles - hydrodynamic lattice simulations



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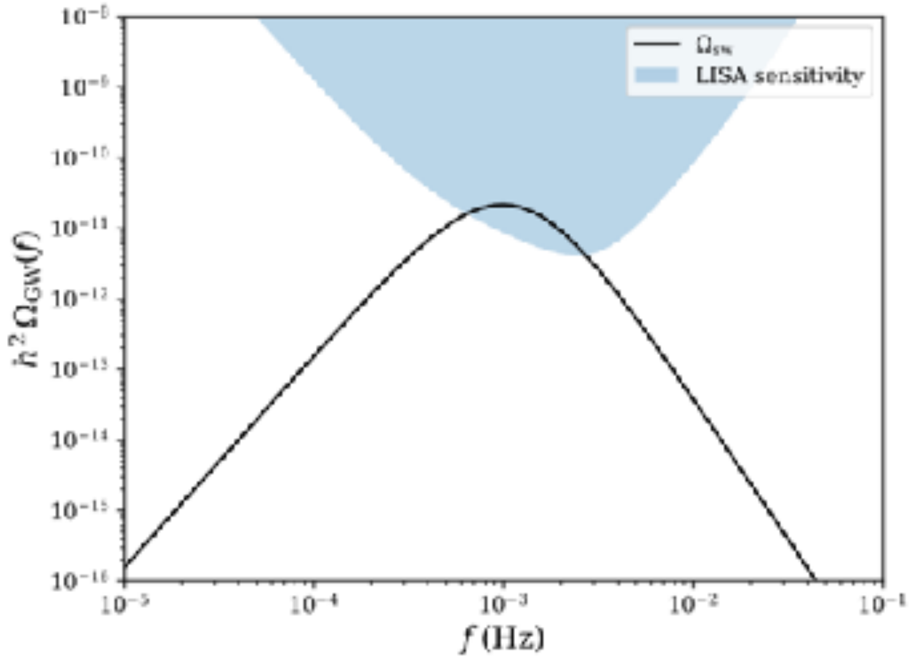
Fit to lattice result

$$\frac{d\Omega_{\rm gw}}{d\ln(f)} = 0.687 F_{\rm gw,0} K^2 H_* R_* / c_s \tilde{\Omega}_{\rm gw} C\left(f/f_{p,0}\right)$$

LISA cosmology working group, 2019 (based on Hindmarsh, Huber, Rummukainen, Weir 2015 & 2017)



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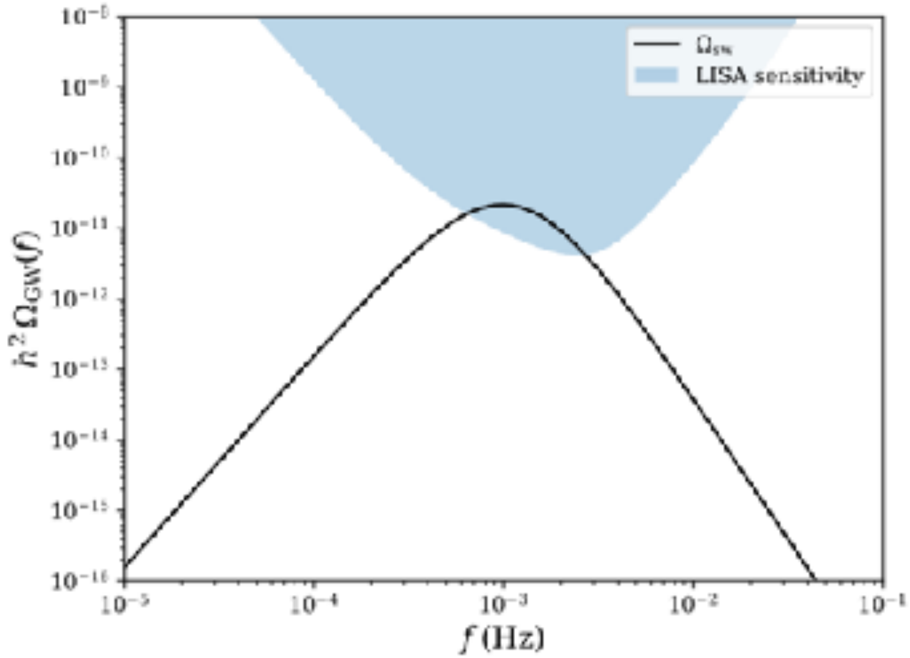
Fit to lattice result

Redshift ($T*$)

$$\frac{d\Omega_{\rm gw}}{d\ln(f)} = 0.687 F_{\rm gw,0} K^2 H_* R_* / c_s \tilde{\Omega}_{\rm gw} C\left(f/f_{p,0}\right)$$

LISA cosmology working group, 2019 (based on Hindmarsh, Huber, Rummukainen, Weir 2015 & 2017)

Relevant parameters:
$T*$



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Fit to lattice result

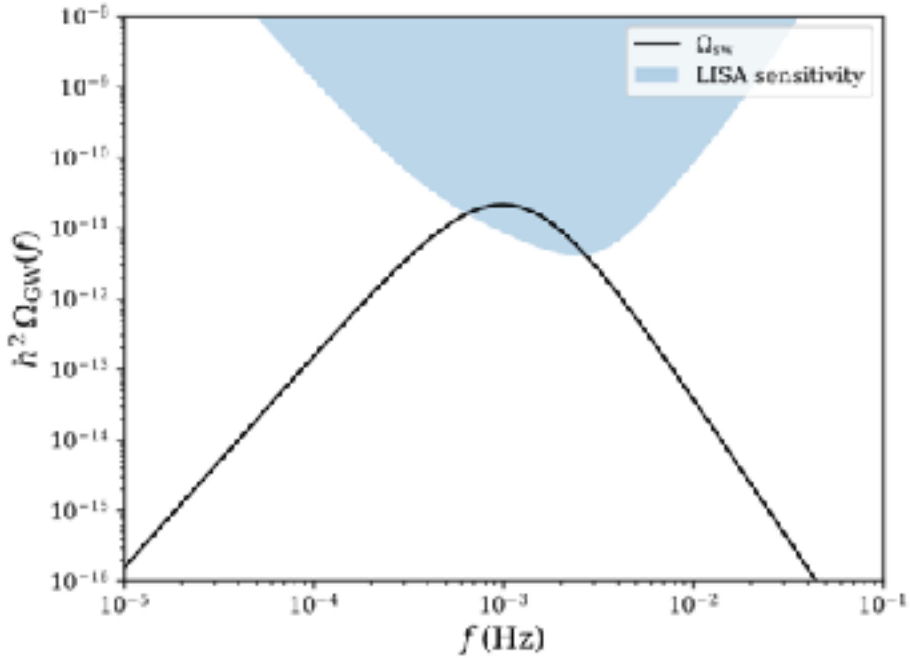
Kinetic energy fraction (α, v_w)

$$\frac{d\Omega_{\rm gw}}{d\ln(f)} = 0.687 F_{{\rm gw},0} K^2 H_* R_* / c_s \tilde{\Omega}_{\rm gw} C\left(f/f_{p,0}\right)$$

LISA cosmology working group, 2019 (based on Hindmarsh, Huber, Rummukainen, Weir 2015 & 2017)

Relevant parameters:

$T*, \alpha, v_w$



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Fit to lattice result

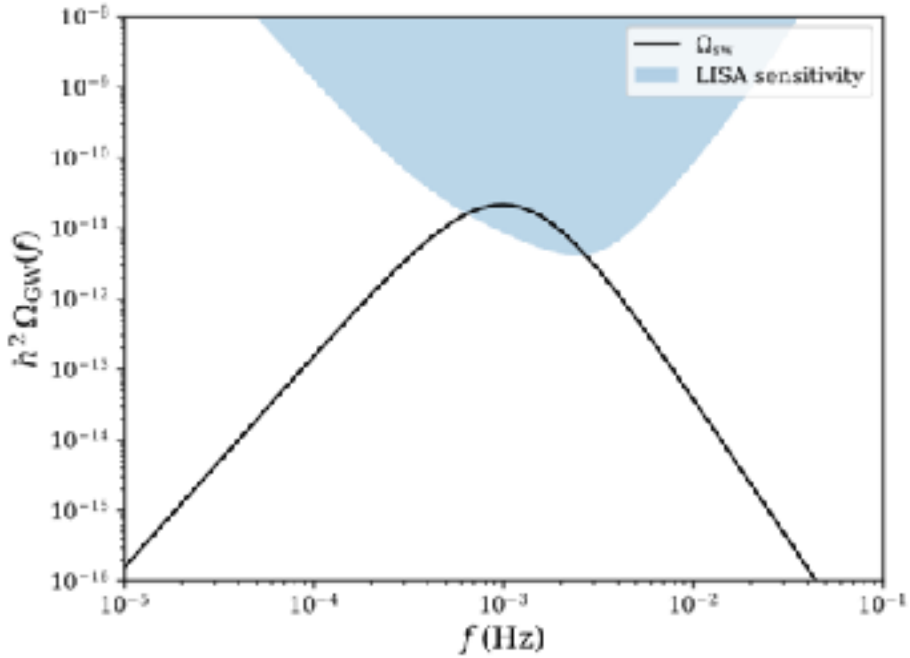
Bubble size (β, v_w)

$$\frac{d\Omega_{\rm gw}}{d\ln(f)} = 0.687 F_{{\rm gw},0} K^2 H_* R_* / c_s \tilde{\Omega}_{\rm gw} C\left(f/f_{p,0}\right)$$

LISA cosmology working group, 2019 (based on Hindmarsh, Huber, Rummukainen, Weir 2015 & 2017)

Relevant parameters:

$T*, \alpha, v_w, \beta$



Fit to lattice result

Sound speed ($c_s^2 \sim 1/3$)

$$\frac{d\Omega_{\rm gw}}{d\ln(f)} = 0.687 F_{\rm gw,0} K^2 H_* R_* / c_s \tilde{\Omega}_{\rm gw} C\left(f/f_{p,0}\right)$$

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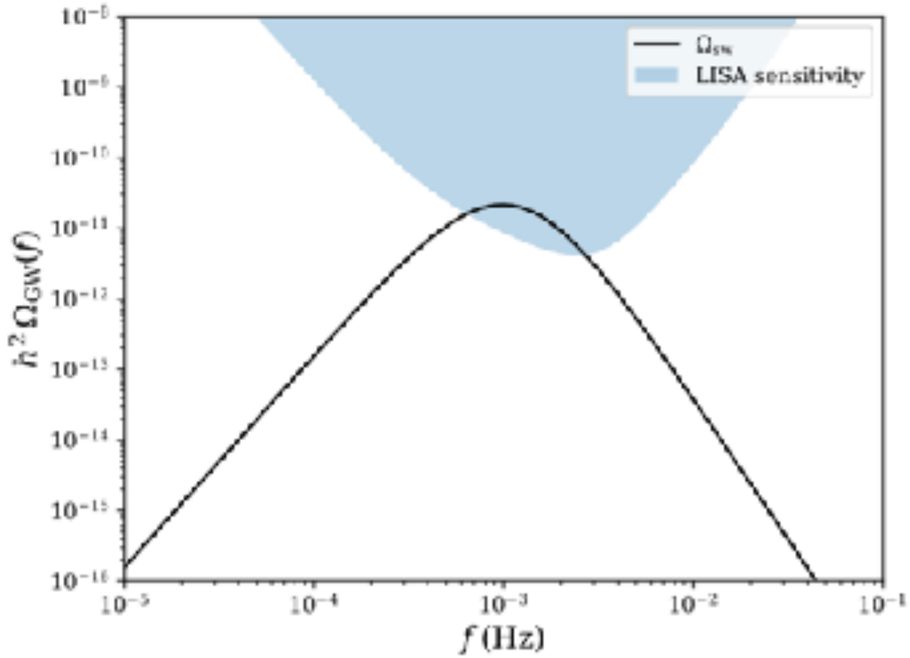

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2 Spectral parameters, set by 4 thermal parameters?

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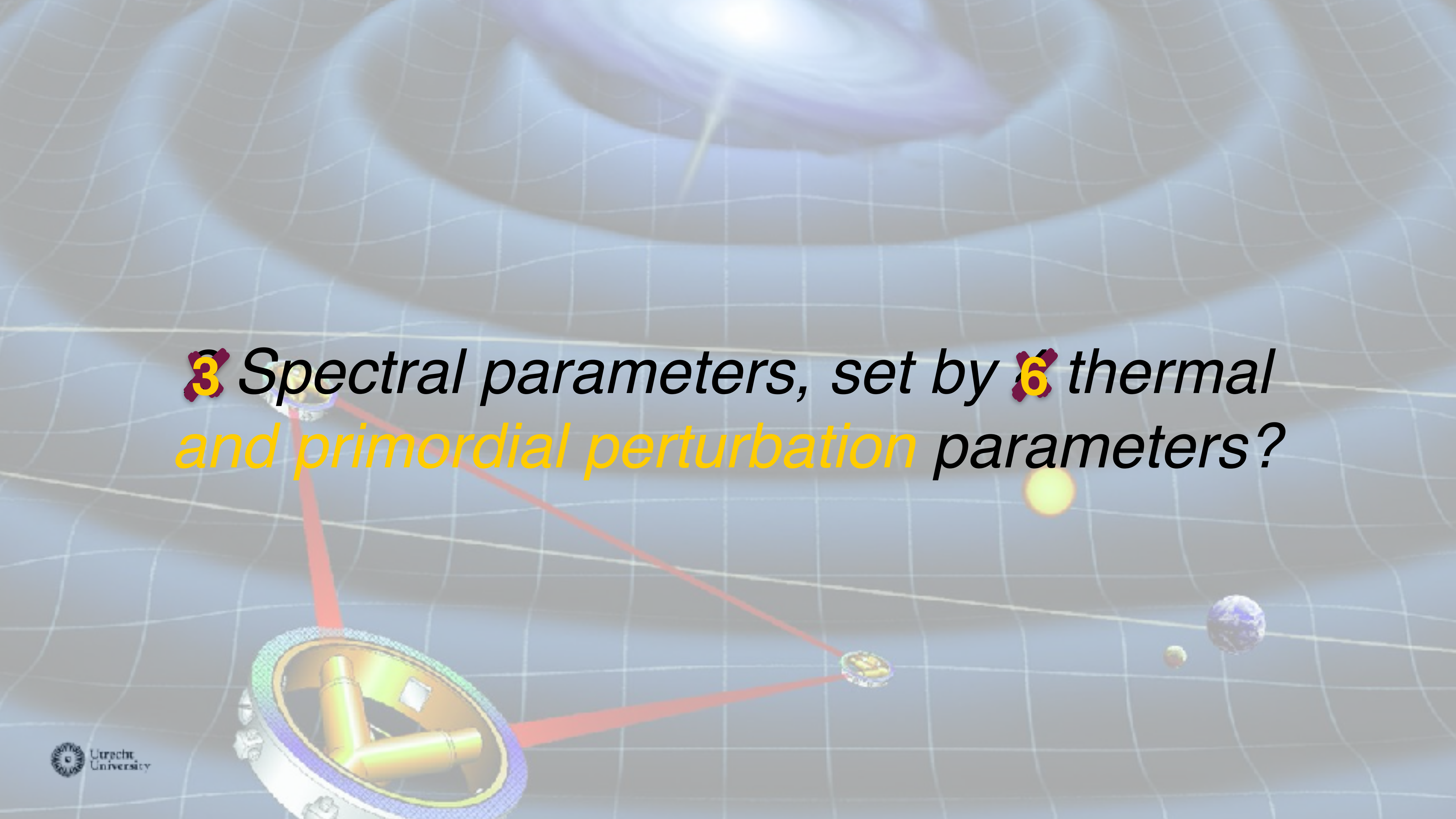
We can improve this picture!



~~2~~ 3 *Spectral parameters, set by* ~~4~~ 6 *thermal and primordial perturbation parameters?*

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Dependence on additional thermal parameters via the kinetic energy fraction

A closer look at the kinetic energy fraction/energy budget

- $$\frac{d\Omega_{\rm gw}}{d\ln(f)} = 0.687 F_{\rm gw,0} K^2 H_* R_*/c_s \tilde{\Omega}_{\rm gw} C\left(f/f_{p,0}\right)$$

- Ratio of kinetic energy in the sound waves over total energy density at nucleation: $K = \dfrac{\rho_{\rm fl}}{e_n}$
- Obtained from single bubble profile

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Single bubble profiles

Perfect fluid

Hydrodynamic equations $\partial_\mu T^{\mu\nu} = 0$

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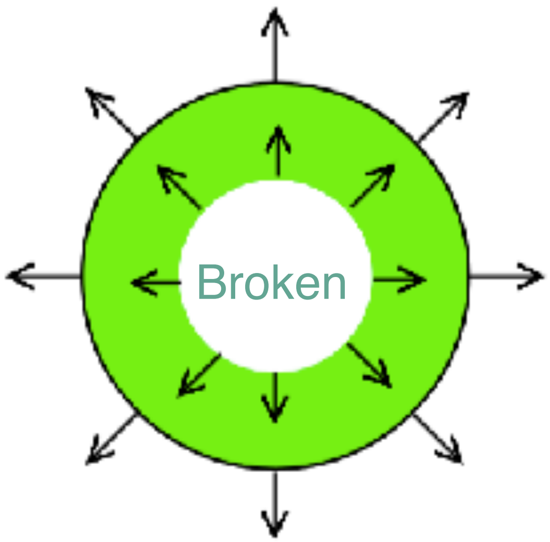
Single bubble profiles

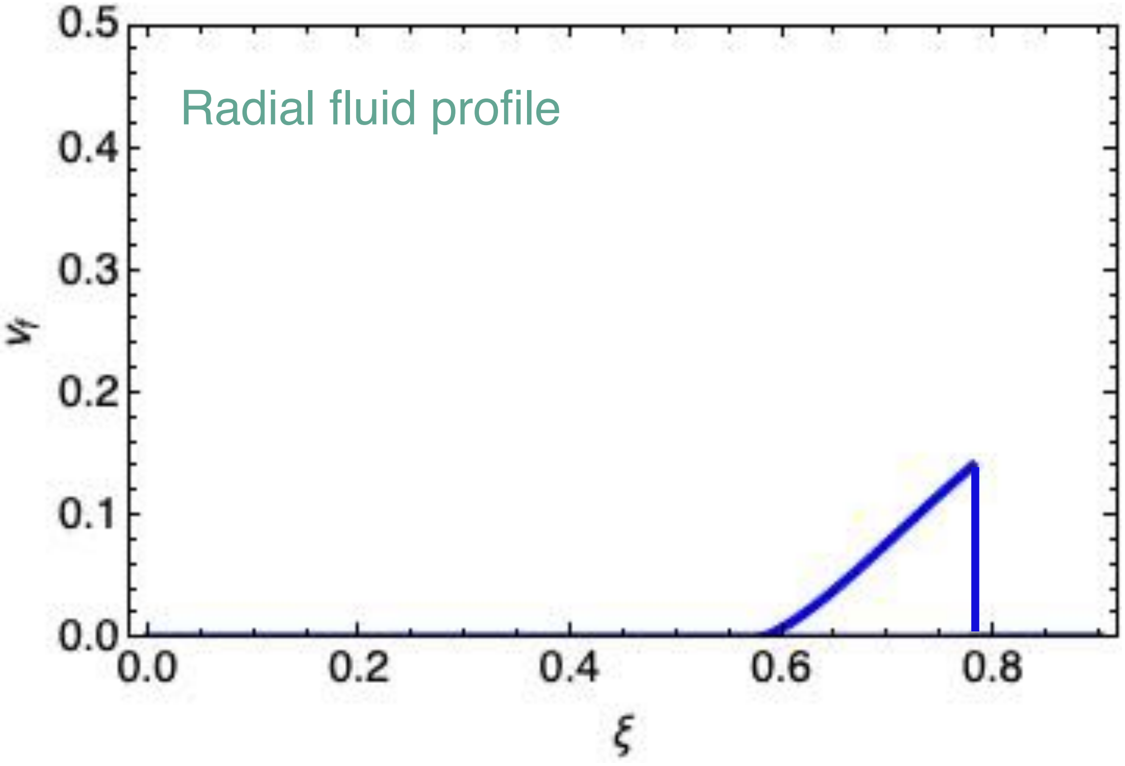
Perfect fluid

Hydrodynamic equations $\partial_\mu T^{\mu\nu} = 0$

J. Espinosa, T. Konstandin, J. No, G. Servant, 2010



Symmetric



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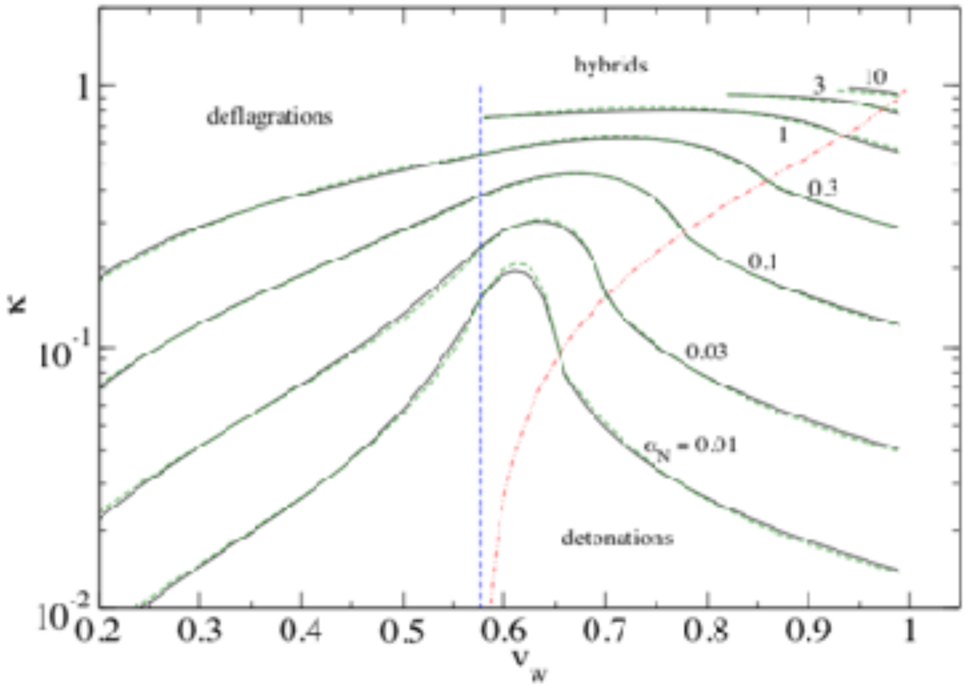
Assumption $K = K(\alpha, v_w)$?

Bag constant

- Relies on bag equation of state: $p = aT^4 + \epsilon$
  Corresponds to $c_s^2 = 1/3$
- Fit of 'efficiency factor' as function of α, v_w
- Bag equation of state is not a realistic equation of state!



J. Espinosa, T. Konstandin, J. No, G. Servant, 2010

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More realistic equation of state can be parameterized by speed of sound

Giese, Konstandin, JvdV 2020, Giese, Konstandin, Schmitz, JvdV 2020

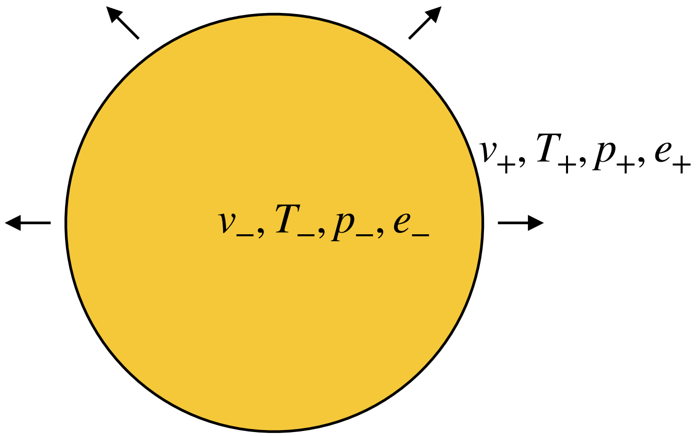
- Sound speed $c_s^2 = \dfrac{dp/dT}{de/dT}$ enters in hydrodynamic equations

$$2\frac{v}{\xi} = \gamma^2(1 - v\xi)\left[\frac{\mu^2}{c_s^2} - 1\right]\partial_\xi v, \quad \frac{\partial_v w}{w} = \left(\frac{1}{c_s^2} + 1\right)\gamma^2 \mu$$

- And matching equations

$$\frac{v_+}{v_-} = \frac{e_b(T_-) + p_s(T_+)}{e_s(T_+) + p_b(T_-)}, \quad v_+ v_- = \frac{p_s(T_+) - p_b(T_-)}{e_s(T_+) - e_b(T_-)}$$

$$\frac{v_+}{v_-} \simeq \frac{v_+ v_-/c_{s,b}^2 - 1 + 3\alpha}{v_+ v_-/c_{s,b}^2 - 1 + 3 v_+ v_- \alpha}$$



Python snippet to compute efficiency (2010.09744)

Compute $\alpha_{\bar\theta}$, both c_s and choose v_w

```
import numpy as np
from scipy.integrate import odeint
from scipy.integrate import simps

def mu(a,b):
  return (a-b)/(1.-a*b)

def getwow(a,b):
  return a/(1.-a**2)/b*(1.-b**2)

def getvm(al,vw,cs2b):
  if vw**2<cs2b:
    return (vw,0)
  cc = 1.-3.*al+vw**2*(1./cs2b+3.*al)
  disc = -4.*vw**2/cs2b+cc**2
  if (disc<0.)|(cc<0.):
    return (np.sqrt(cs2b), 1)
  return ((cc+np.sqrt(disc))/2.*cs2b/vw, 2)

def dfdv(xiw, v, cs2):
```

```
    Krf*= -wow*getwow(vp,vm)
  else:
    Krf = 0
  return (Ksh + Krf)/al
```

$\rightarrow \kappa_{\bar\theta}$

$$K = \frac{D\bar\theta}{4e_n}\kappa_{\bar\theta}$$

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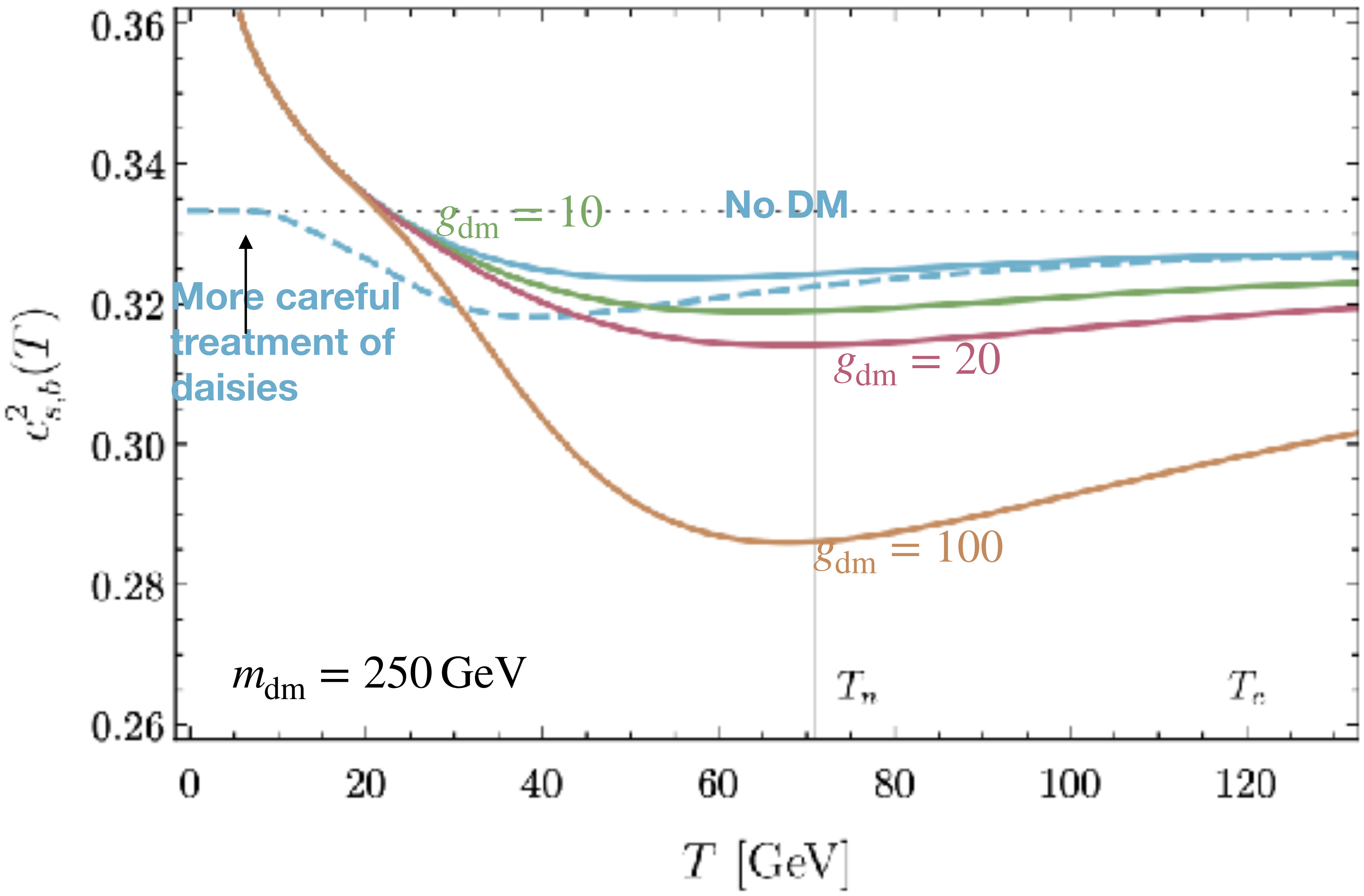
What is the value of the sound speed?

Estimate of 2010.09744
for SM + $g_{\rm dm}$ singlets, with
two-step PT
using on ‘daisy resummation’



We can do better!

- Perturbative loop expansion breaks down at finite temperature due to large occupation of lowest energy state
- Construct an effective field theory for the dynamic modes only (dimensional reduction) Ginsparg 1980, Appelquist, Pisarski 1981
- Consistent expansion in some coupling g
- Daisy resummation corresponds to NLO result
- Significant corrections to phase transition parameters T, α, and GW signal at higher orders Croon, Gould, Schicho, Tenkanen, White 2020

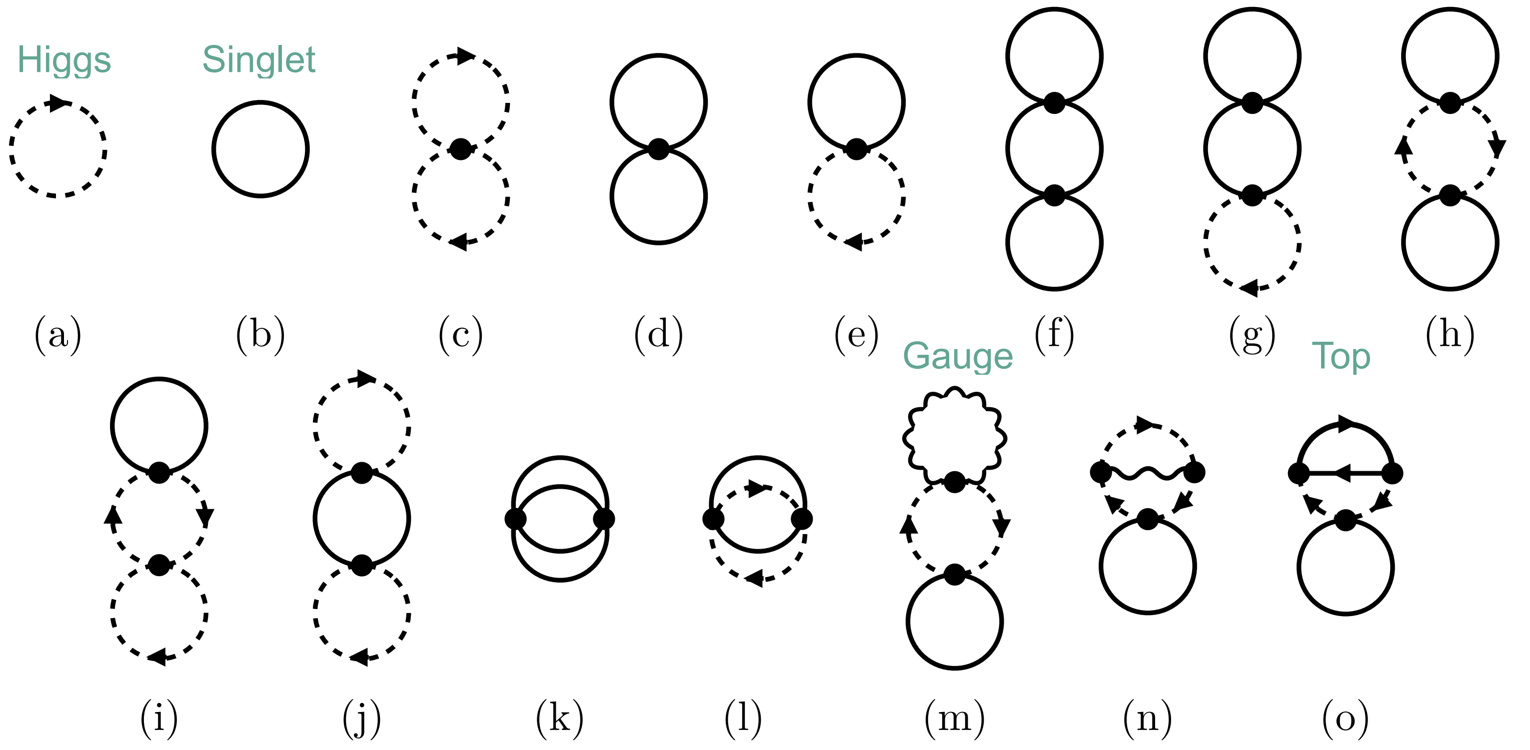
Construct an EFT for the computation of the sound speed for SM + N singlets

Tenkanen, JvdV 2022

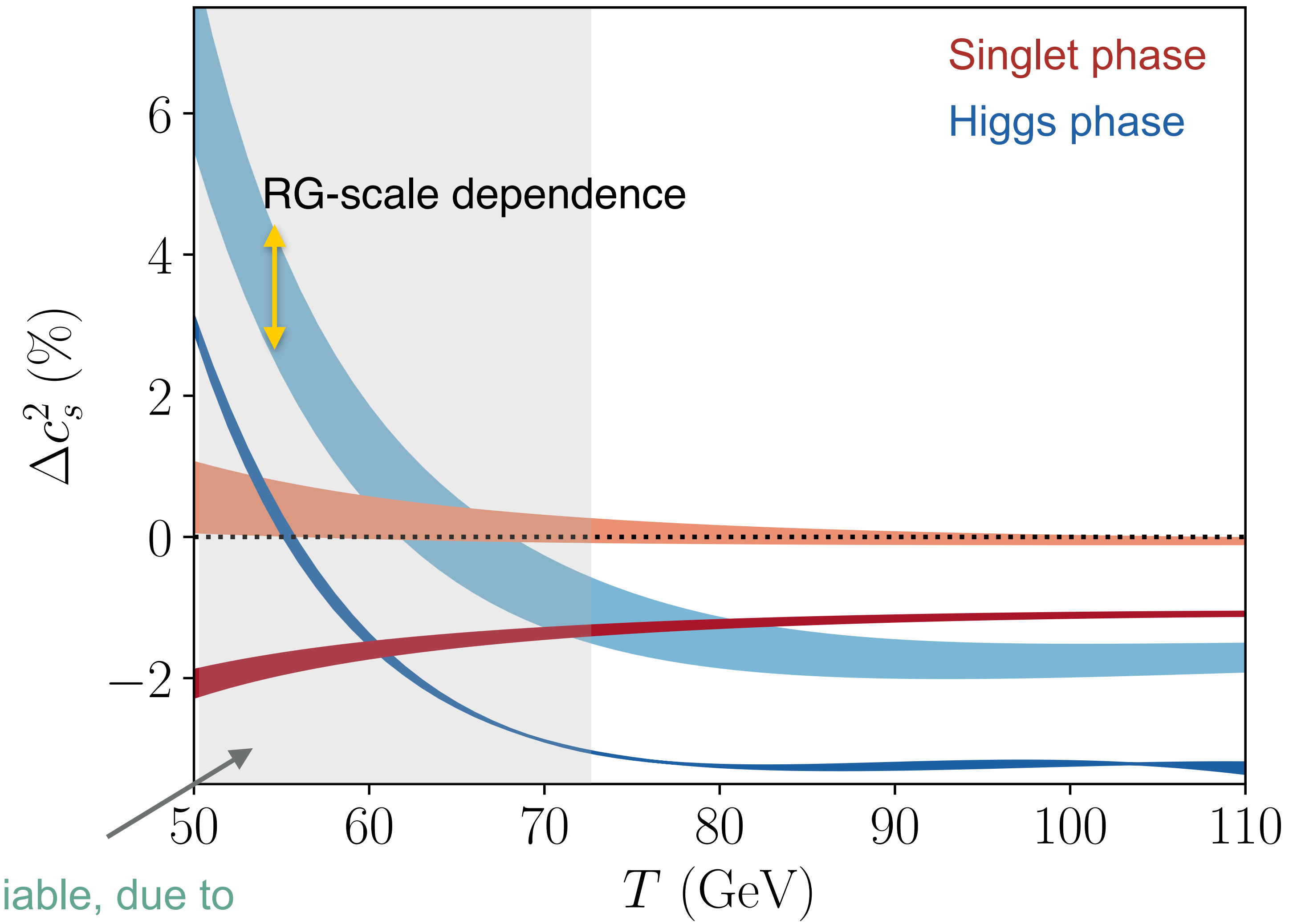
'Matching of the unit operator' for computation of the pressure

For SM part, see

Gynther, Vepsalainen 2005&2006

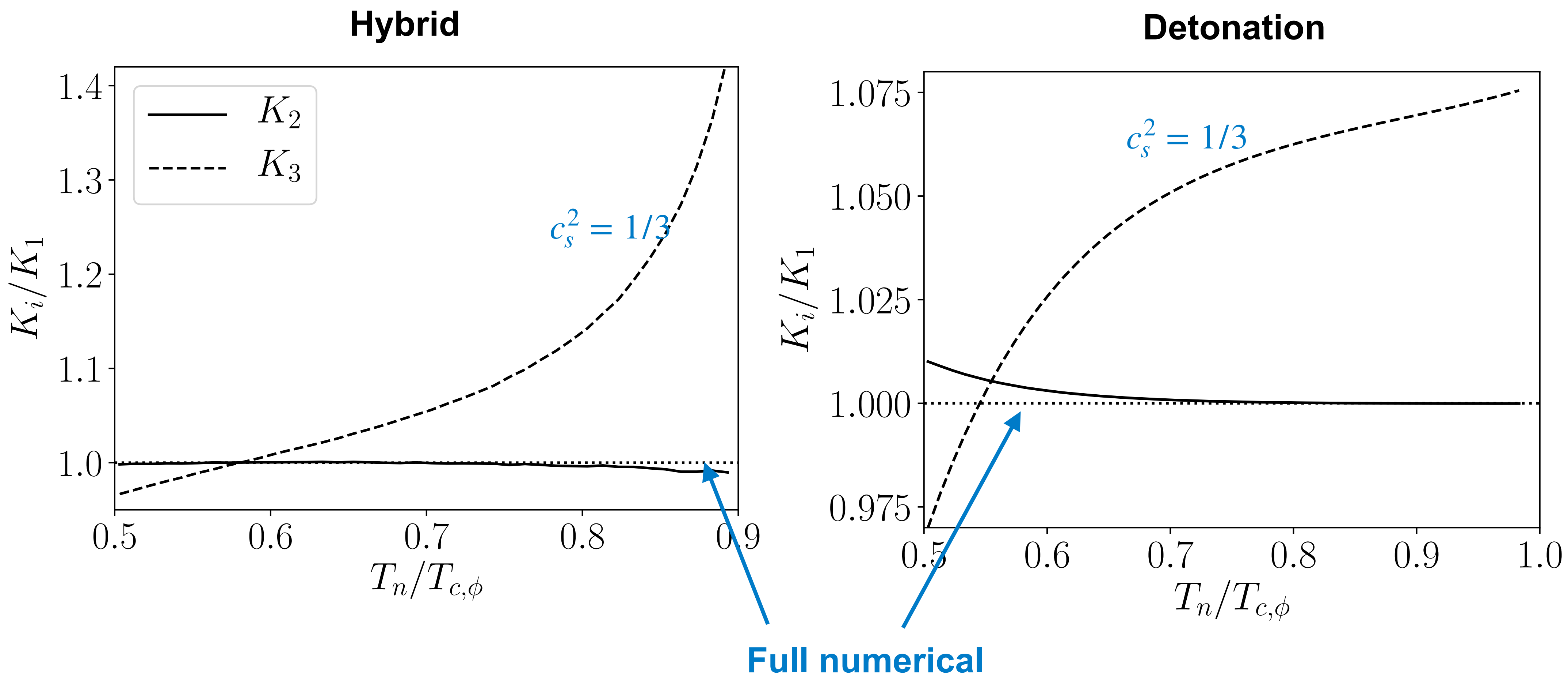


Deviation from $c_s^2 = 1/3$ for N = 1

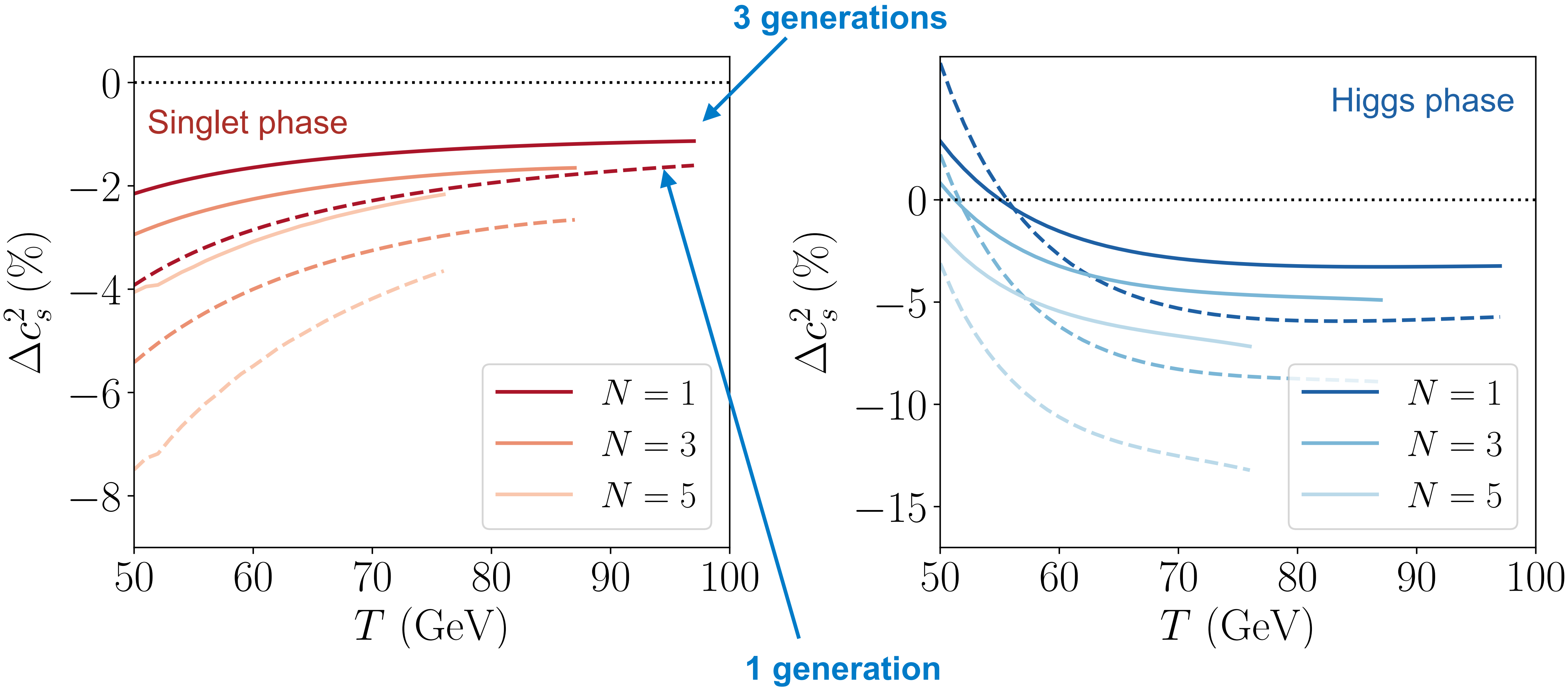


Not so reliable, due to breakdown of high-T expansion

Comparison of K with $c_s^2 = 1/3$ case for N = 1



Modified particle content: fewer fermions



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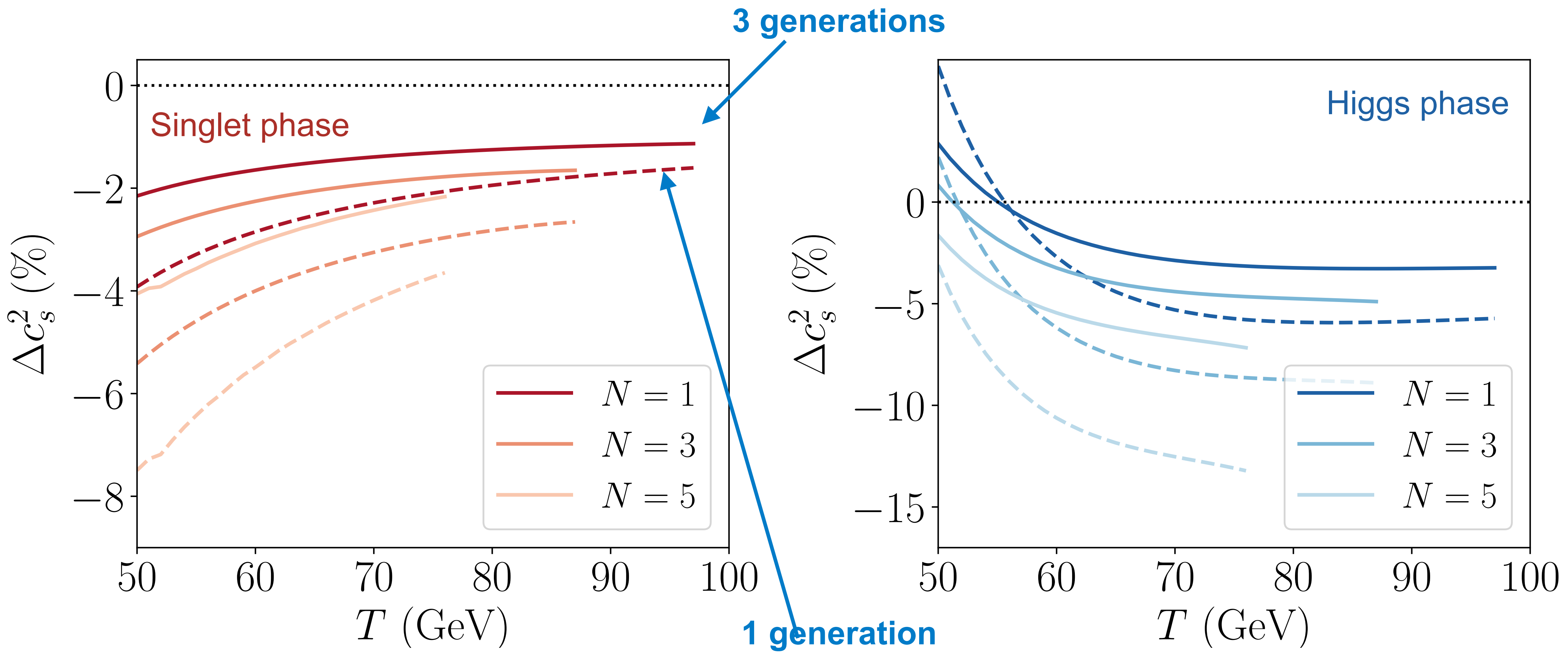

Suppression of GW signal up to order of magnitude

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Summary Part I

- Kinetic energy fraction depends on α, v_w and c_s
- Deviations from $c_s^2 = 1/3$ of $1 - 5\,\%$, causing a suppression in K of up to $40\,\%$
- Deviations in sound speed can be larger for many singlets, or fewer light fermions.
- Sound speed dependence can be very relevant for PT in dark sectors

Spectral shape described by doubly broken power law

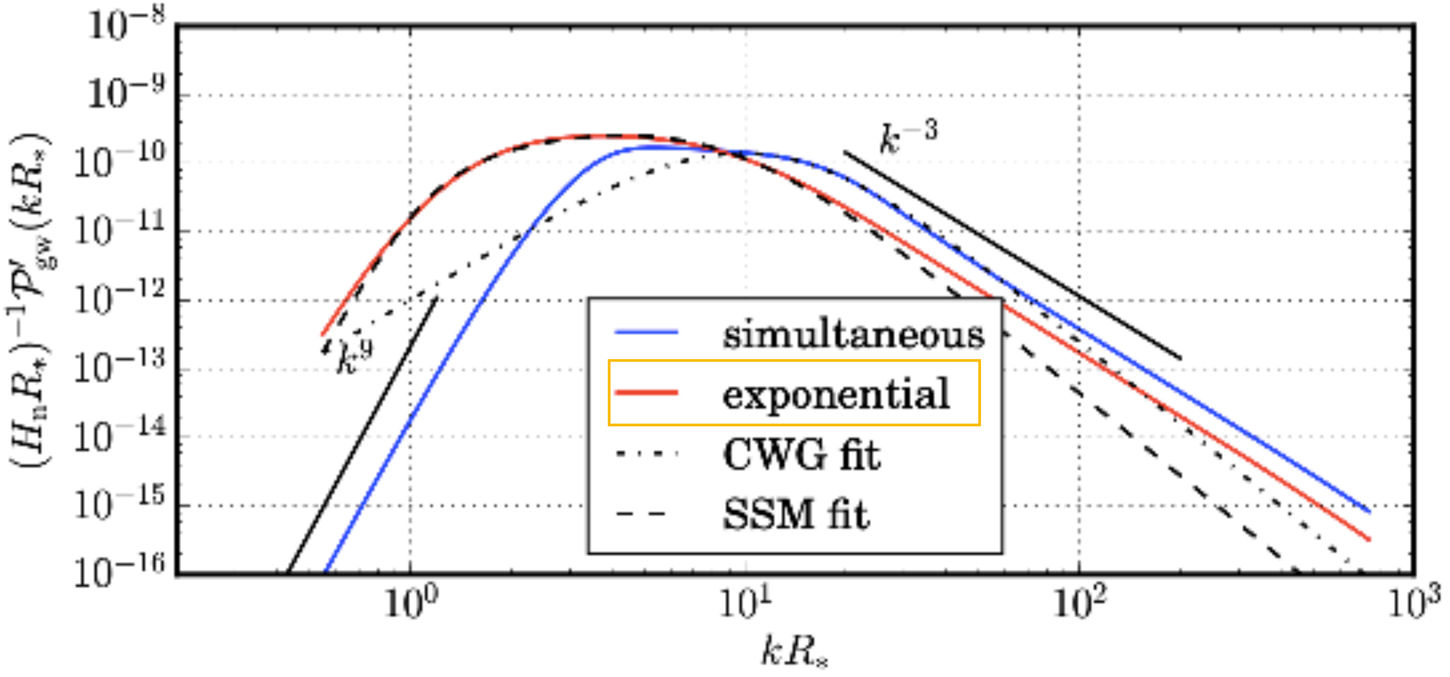
Sound shell model

Description of GW spectrum by linear superposition of single bubble spectra

Hindmarsh 2016, Hindmarsh Hijazi 2019

~Gravitational wave spectrum before redshift

proportional to $h^2\Omega_{\mathrm{gw}}$ →



↑ proportional to f

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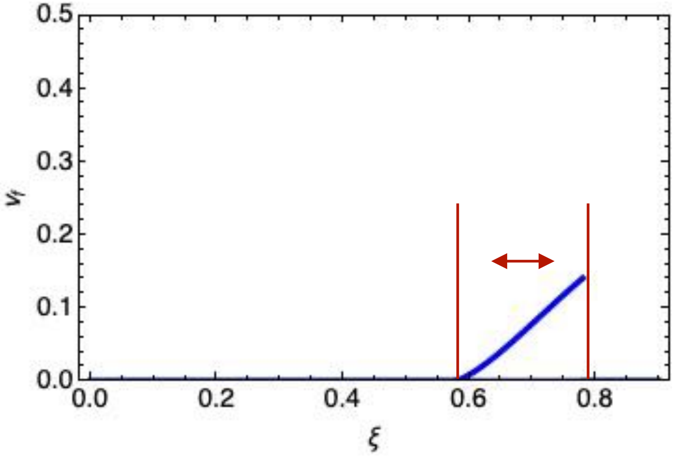
Sound shell model

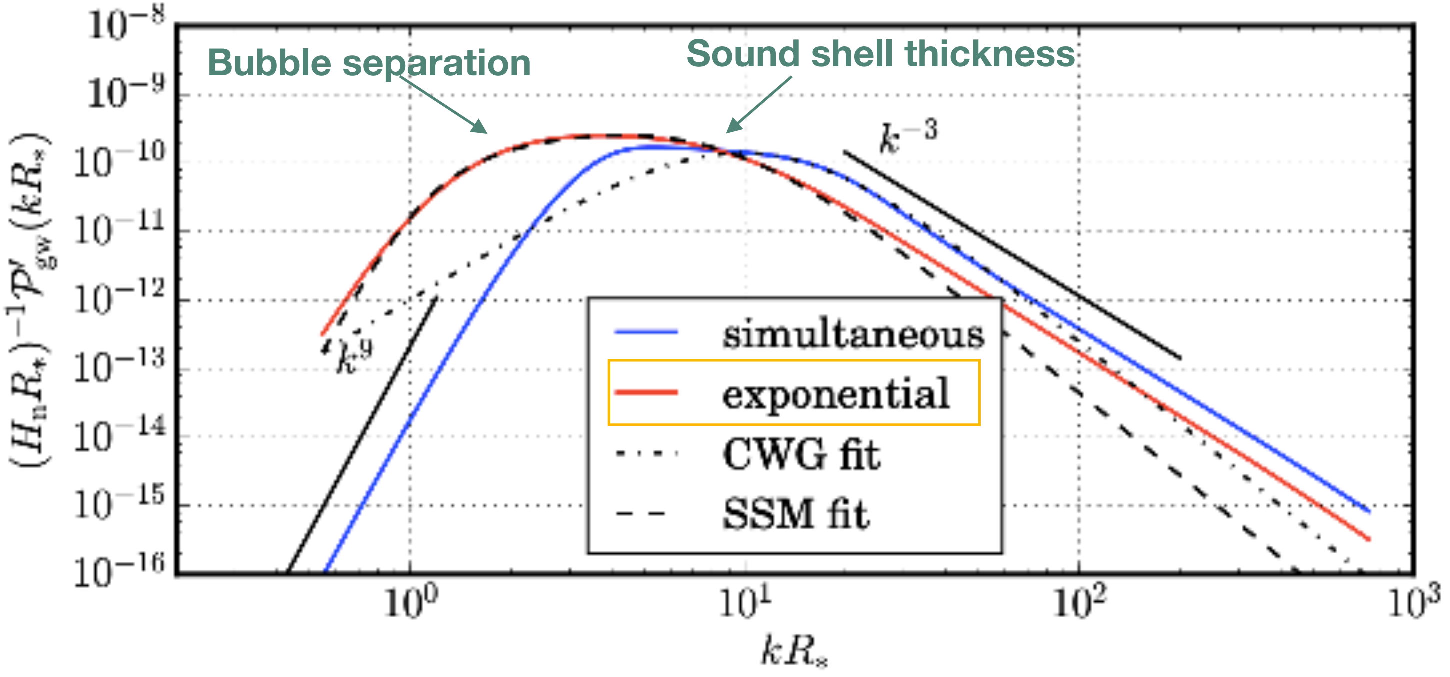
Description of GW spectrum by linear superposition of single bubble spectra

Hindmarsh 2016, Hindmarsh Hijazi 2019



proportional to $h^2\Omega_{\rm gw}$ →

~Gravitational wave spectrum before redshift



↑

proportional to f

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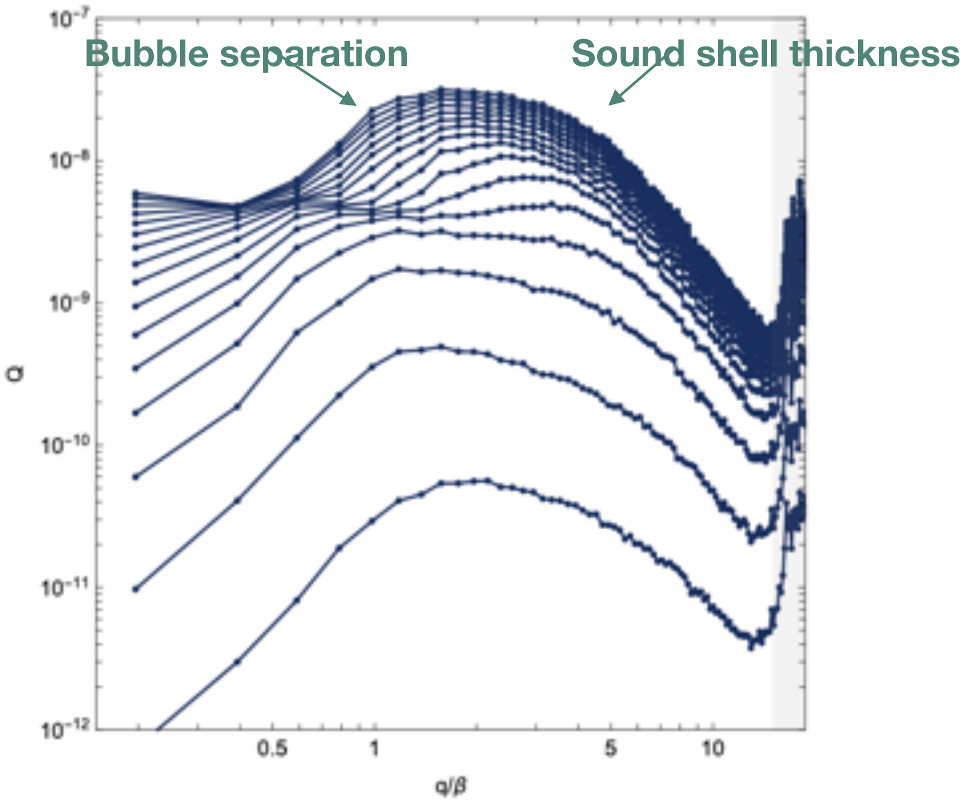
Hybrid/Higgsless simulations

Jinno, Konstandin, Rubira, 2020
Jinno, Konstandin, Rubira, Stomberg, 2022

~Gravitational wave spectrum before redshift



proportional to $h^2\Omega_{\rm gw}$

proportional to f

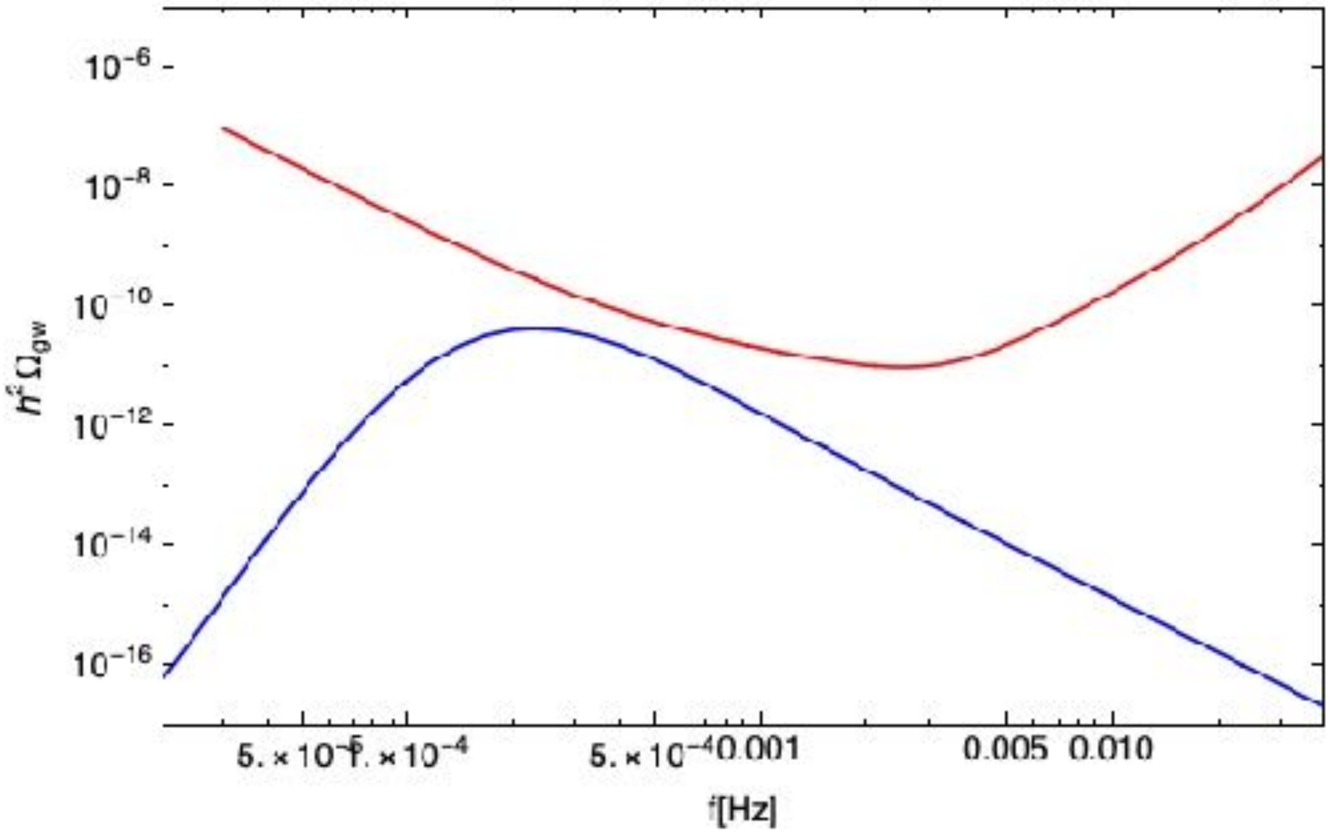
Can LISA detect the doubly broken power law?

Giese, Konstandin, JvdV 2021

- 3 observables: overall amplitude and two break positions
- Approach: generate mock data and try to fit

Step 1: generate LISA mock signal

- Mock data from LISA noise curve and fit from hybrid simulation.
  Caprini, Figueroa, Flauger, Nardini, Peloso, Pieroni, Ricciardone, Tasinato 2019, Flauger, Karnesis, Nardini, Pieroni, Ricciardone, Torrado 2021
- Vary α and v_w
- Relation between α, T^* and β as in 2HDM
  G. Dorsch, J.M. No via PTPlot.org
- Assume $c_s^2 = 1/3$



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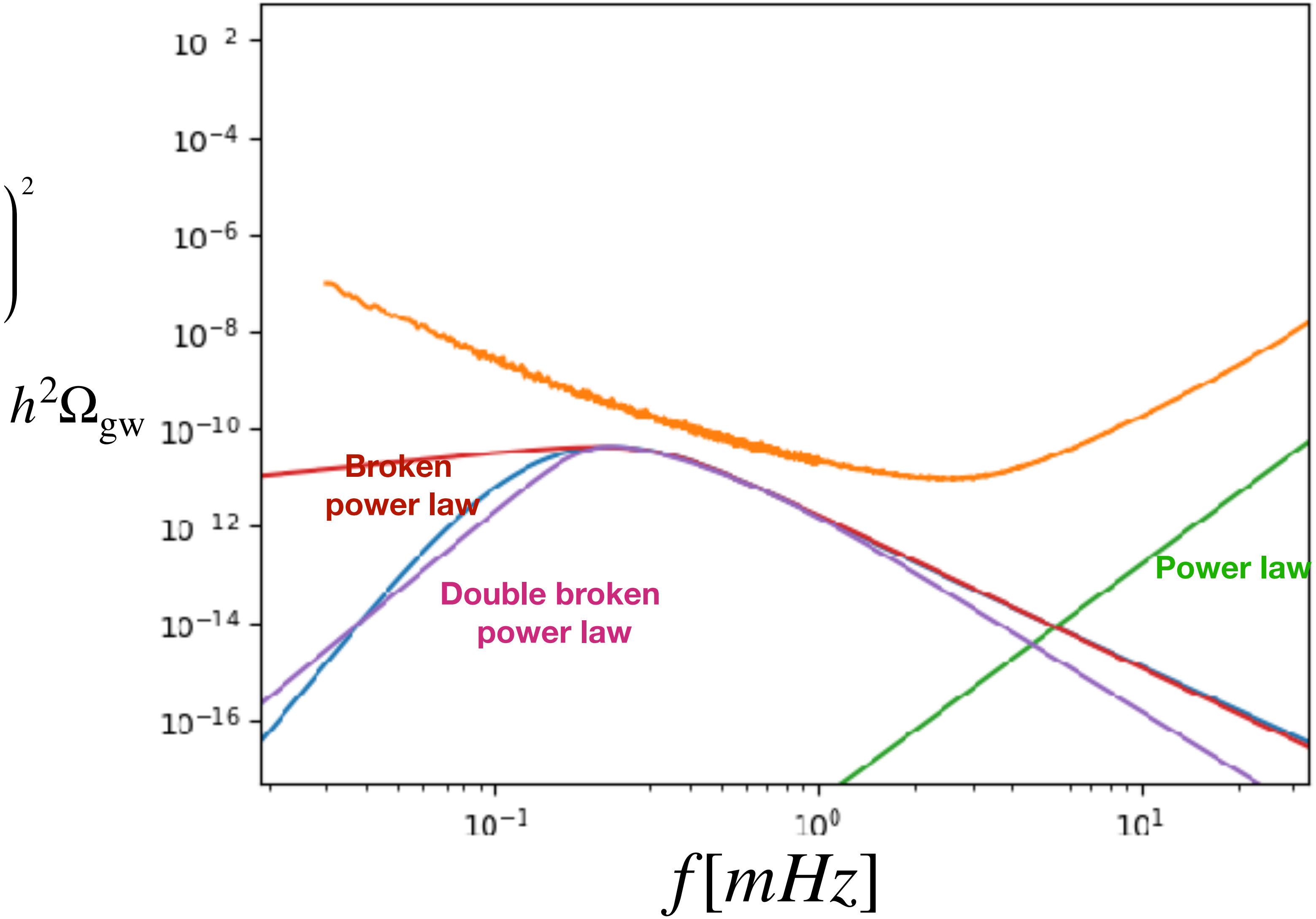
Step 2: fit the signal to noise+GW model

- Minimize χ^2

$$\chi^2 \propto \sum_i \left(\frac{\bar{D}_i - h^2\Omega_{\rm gw}(f_i, \vec{\theta}_s) - h^2\Omega_{\rm noise}(f_i, \vec{\theta}_n)}{\sigma_i} \right)^2$$



Step 3: Determine the best fit

- Avoid overfitting: minimize Akaike information criterion (AIC) Akaike 1974

$$AIC = \chi^2_{\text{best fit}} + 2k$$

Number of fitting parameters

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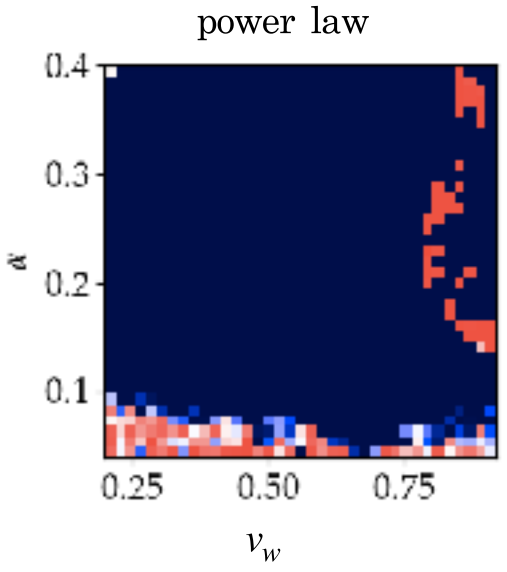
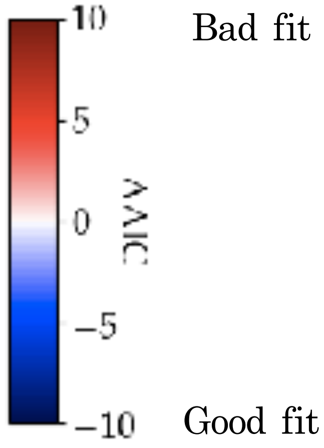
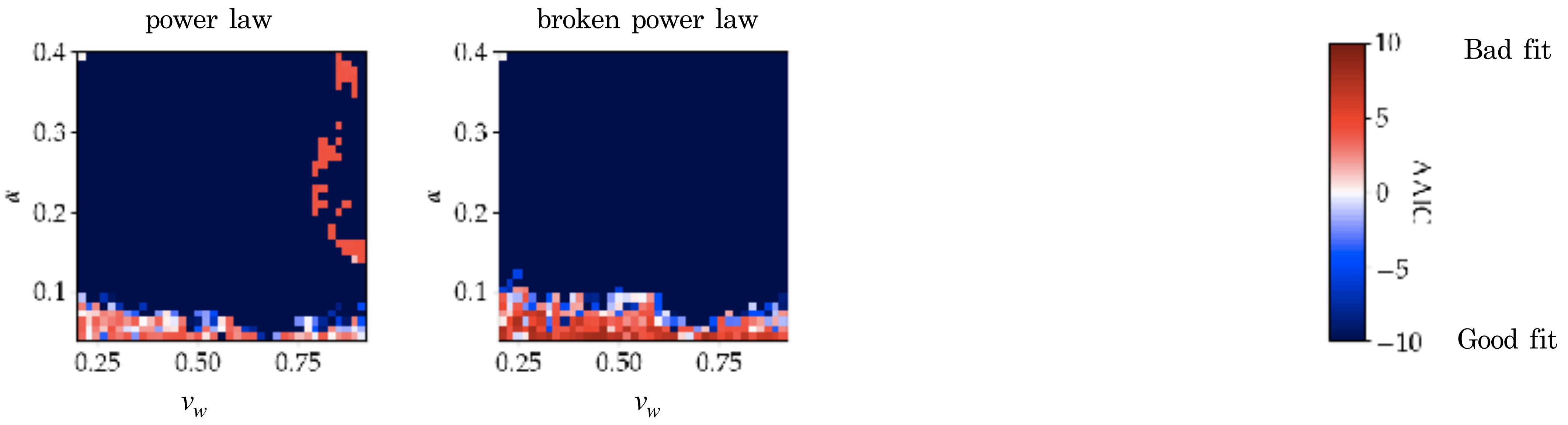
Results





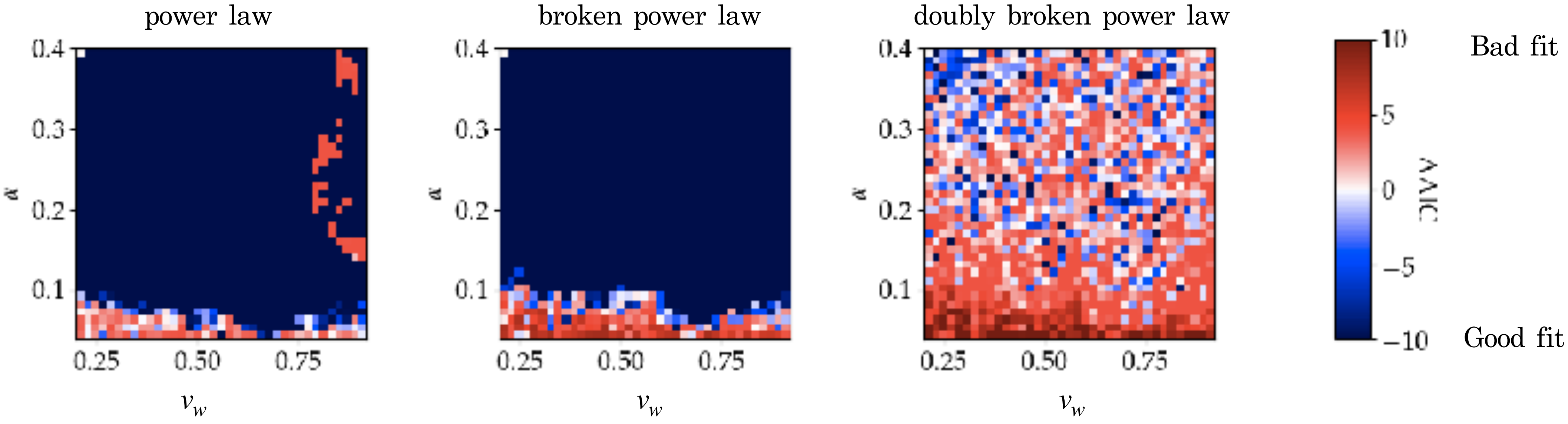
Comparison of AIC with fits with fewer parameters

Results



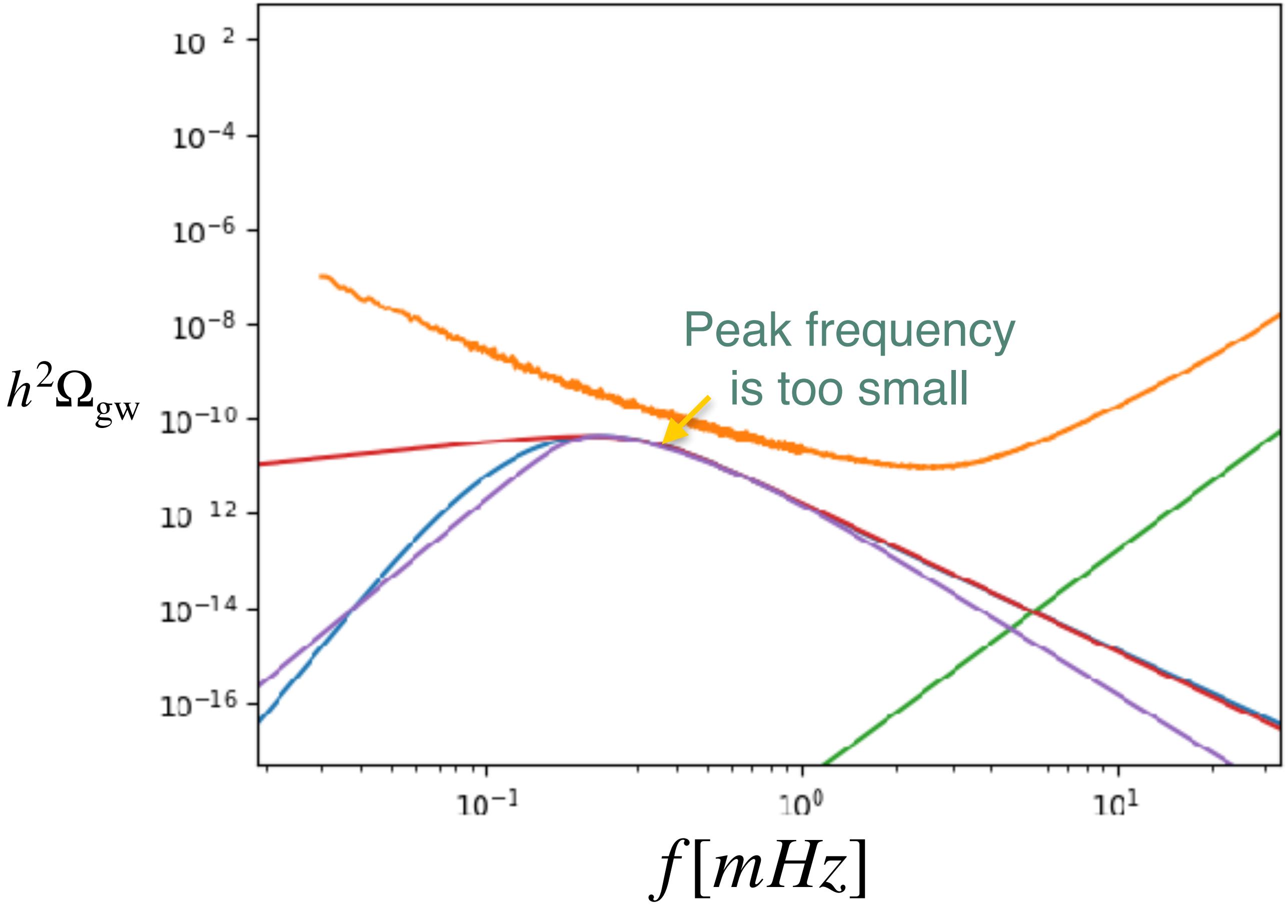
Comparison of AIC with fits with fewer parameters

Results



Comparison of AIC with fits with fewer parameters

Why can’t we reconstruct the full doubly-broken power law?



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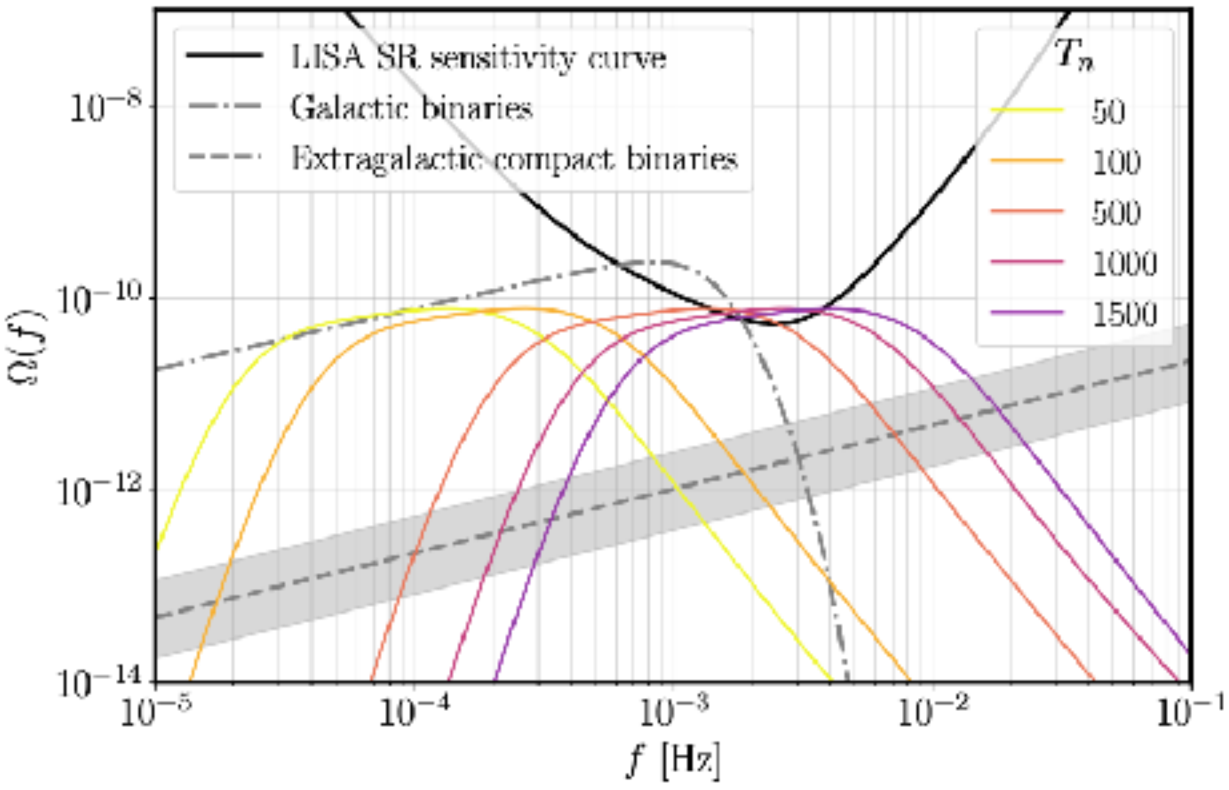
The peak frequency increases with T^*



(d) Fixed: $v_w = 0.6, \quad \alpha = 0.2, \quad r_* = 0.1.$

Gowling, Hindmarsh, 2021

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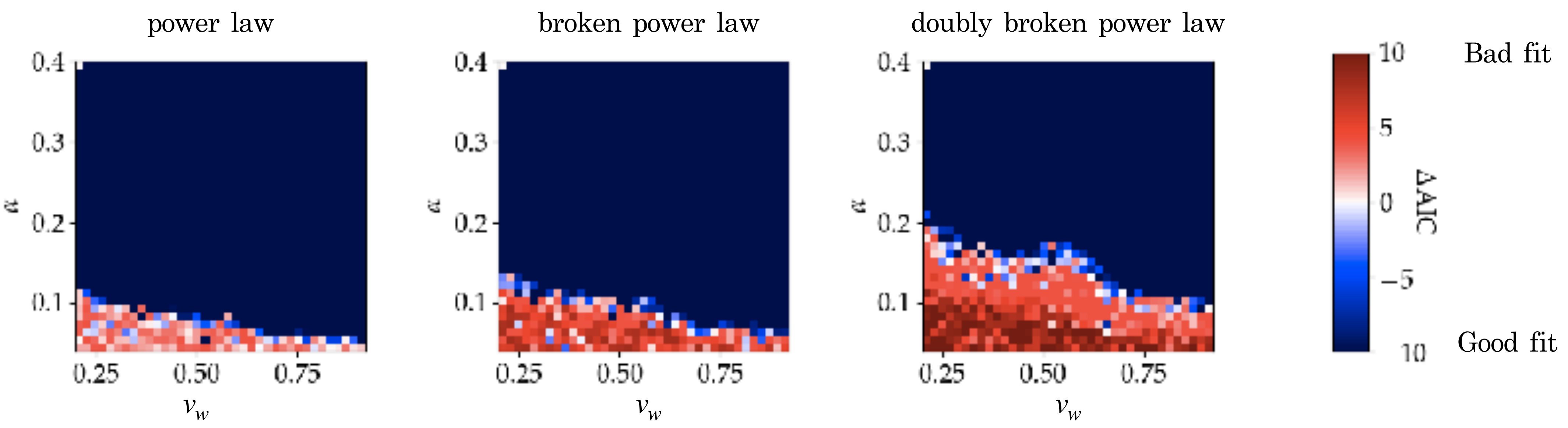
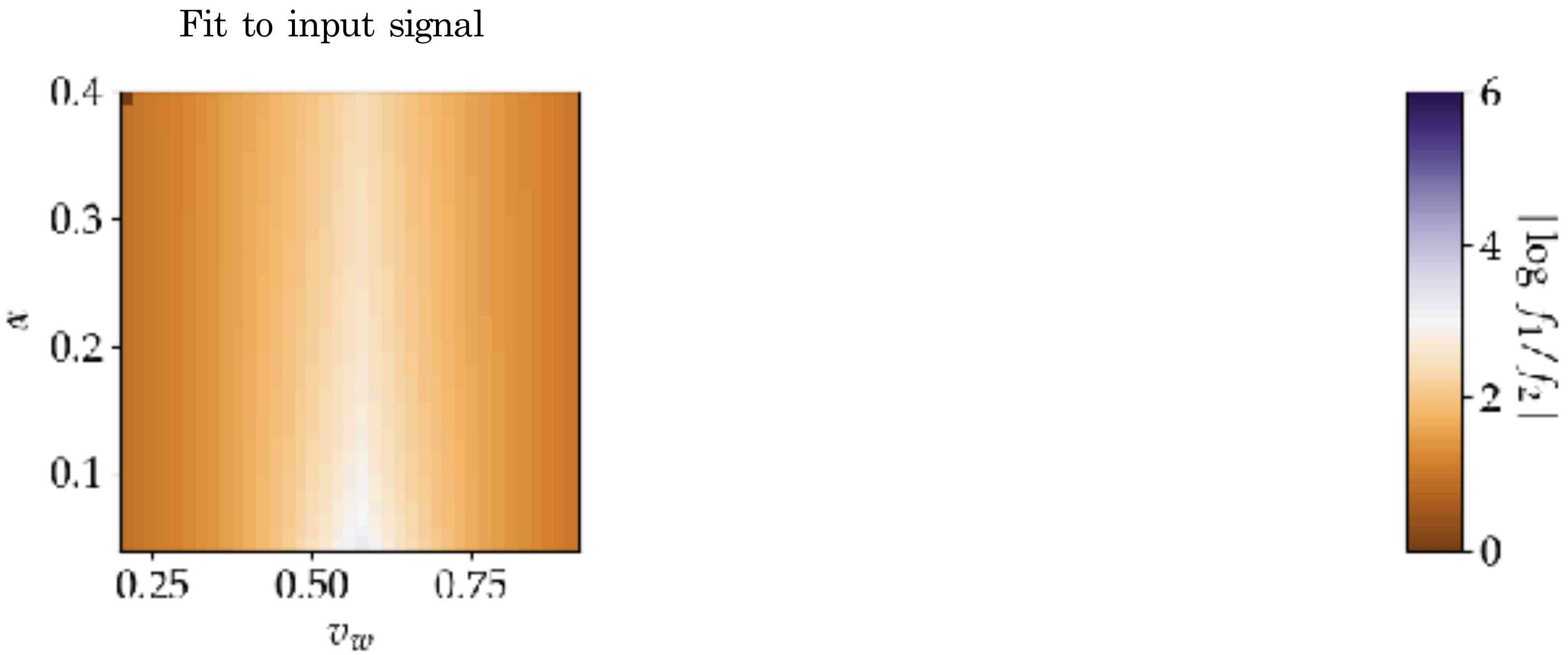
Results for $T^* \to 10T^*$ (composite Higgs, gauged lepton models)

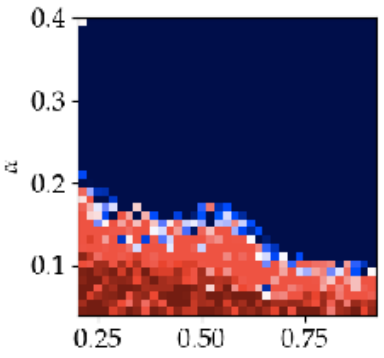


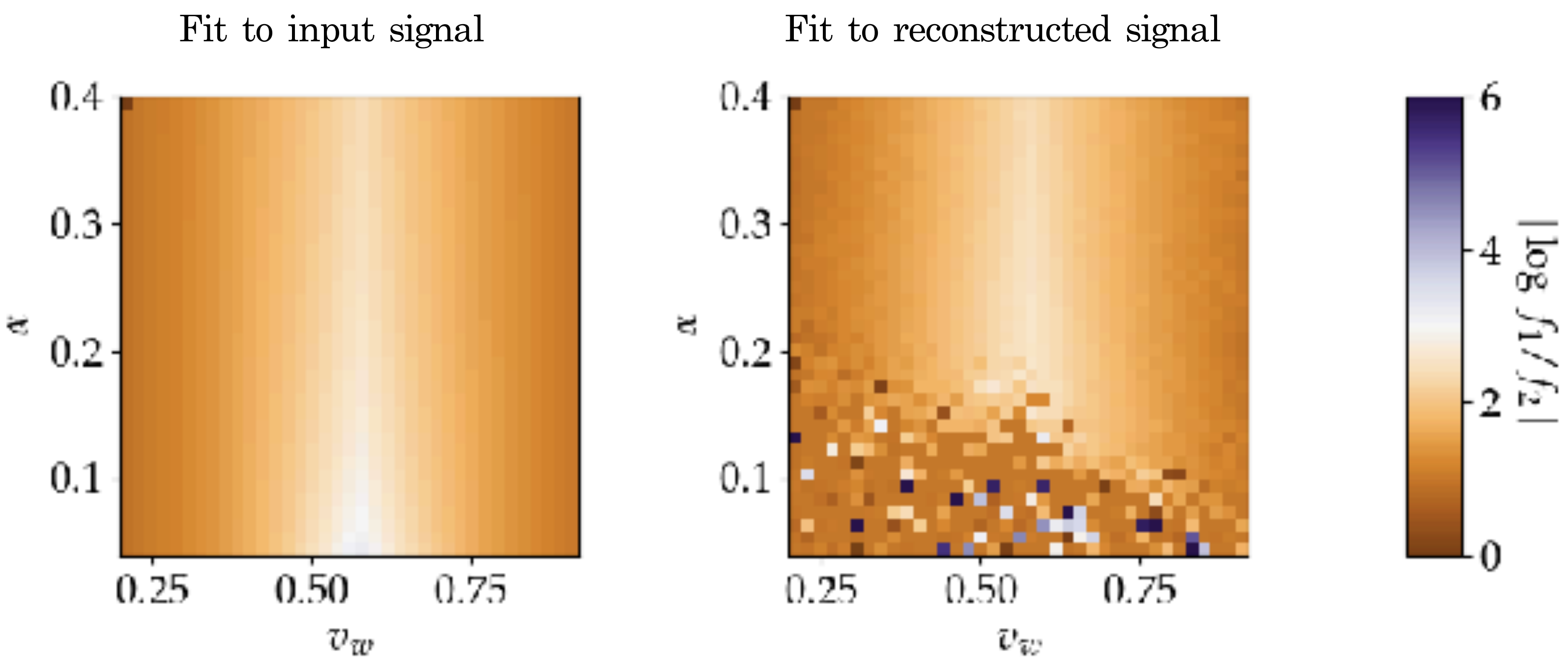
Comparison of AIC with fits with fewer parameters

Break ratio informs us about the wall velocity ($10T^*$ result)



Break ratio informs us about the wall velocity ($10T*$ result)



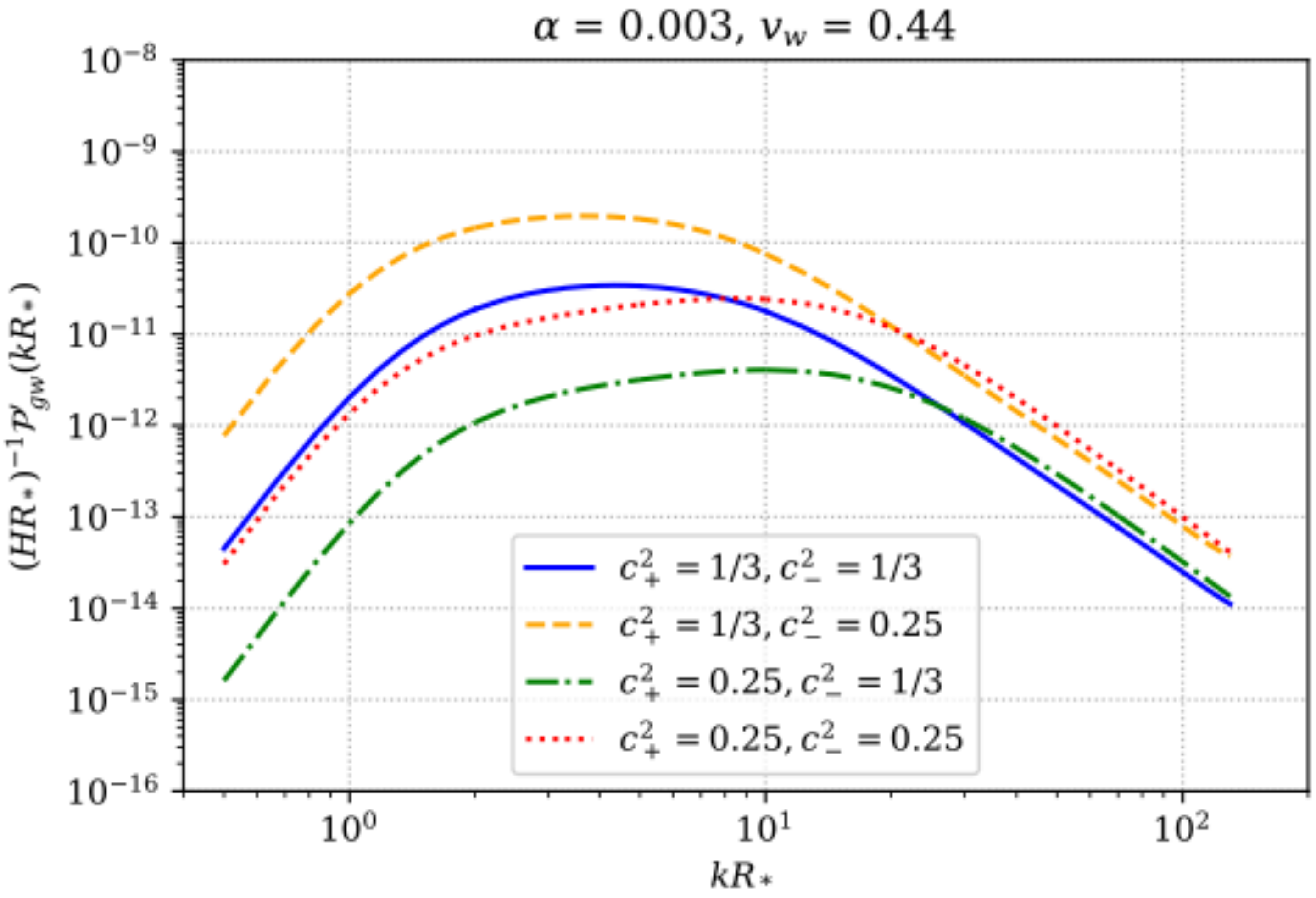


- MCMC: break ratio can be measured with ~10% accuracy

Summary Part II

- GW spectrum likely contains more information than just 2 spectral parameters
- Whether all spectral parameters of a doubly broken power law can be extracted depends on the model
- For larger α and $T*$ reconstruction is more successful
- The break ratio informs about the wall velocity

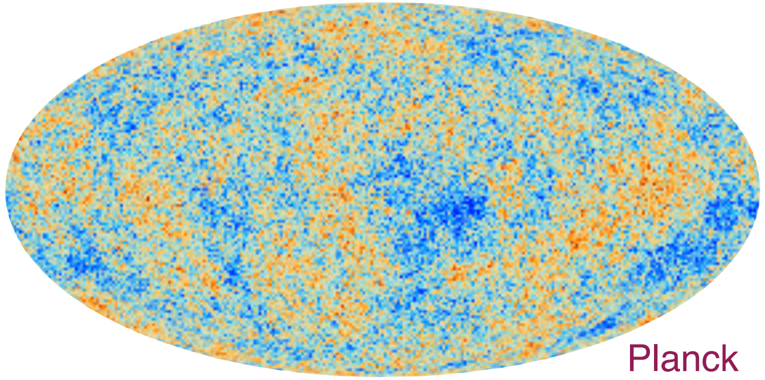
Effect of sound speed on the GW spectrum



Wang, Huang, Li, 2021

(Primordial) temperature perturbations may affect the spectrum

Primordial perturbations



- On CMB scales: $\frac{\delta T}{T} \sim 10^{-4}$
- Maybe $\frac{\delta T}{T}$ is larger on the scale relevant to the phase transition?
- How does that affect the gravitational wave signal?

Nucleation rate with perturbations

- Temperature perturbations can enhance/reduce the nucleation rate
- Tunnelling rate $\Gamma(t) = \Gamma_* \exp\left[\beta(t - t_*) - \frac{\beta}{H_*}\frac{\delta T}{\bar{T}}\right]$
- Perturbations relevant when $\left|\frac{\beta}{H_*}\frac{\delta T}{\bar{T}}\right| \equiv |\delta\tilde{T}| \gtrsim 1$
- $\frac{\beta}{H_*} = \mathcal{O}(100) \rightarrow \frac{\delta T}{\bar{T}}$ can be moderate

Numerical simulations

- Modified version (temperature fluctuation-dependent nucleation rate) of

A hybrid simulation of gravitational wave production in first-order phase transitions

Ryusuke Jinno, Thomas Konstandin and Henrique Rubira

Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany

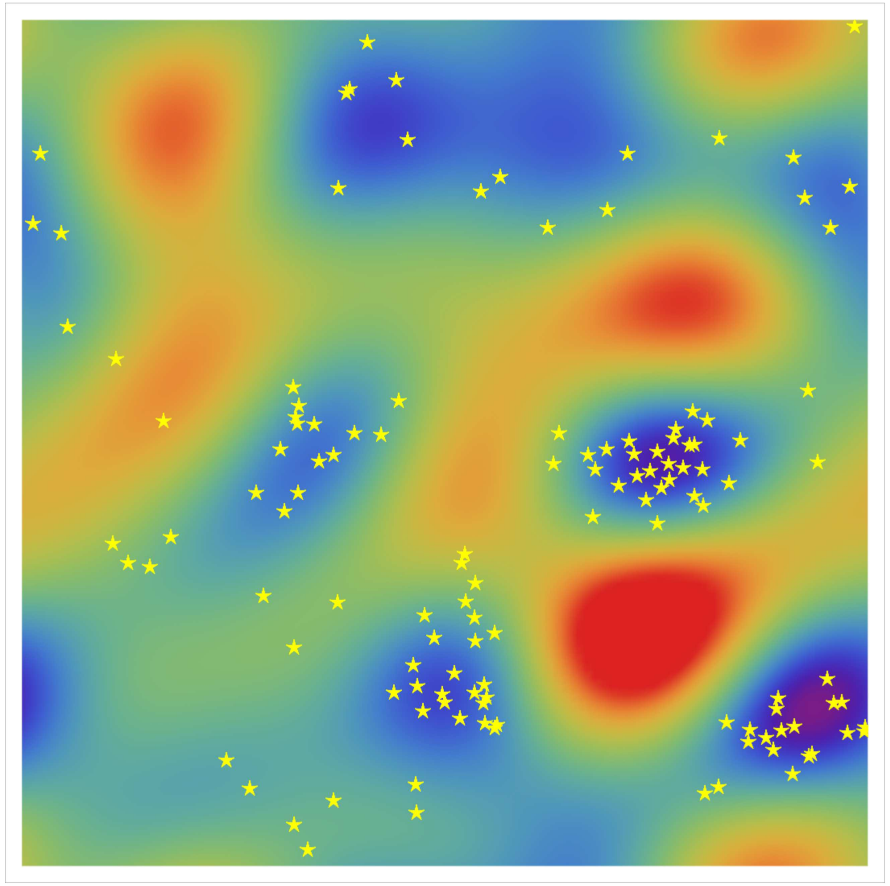
Spectrum of the perturbations

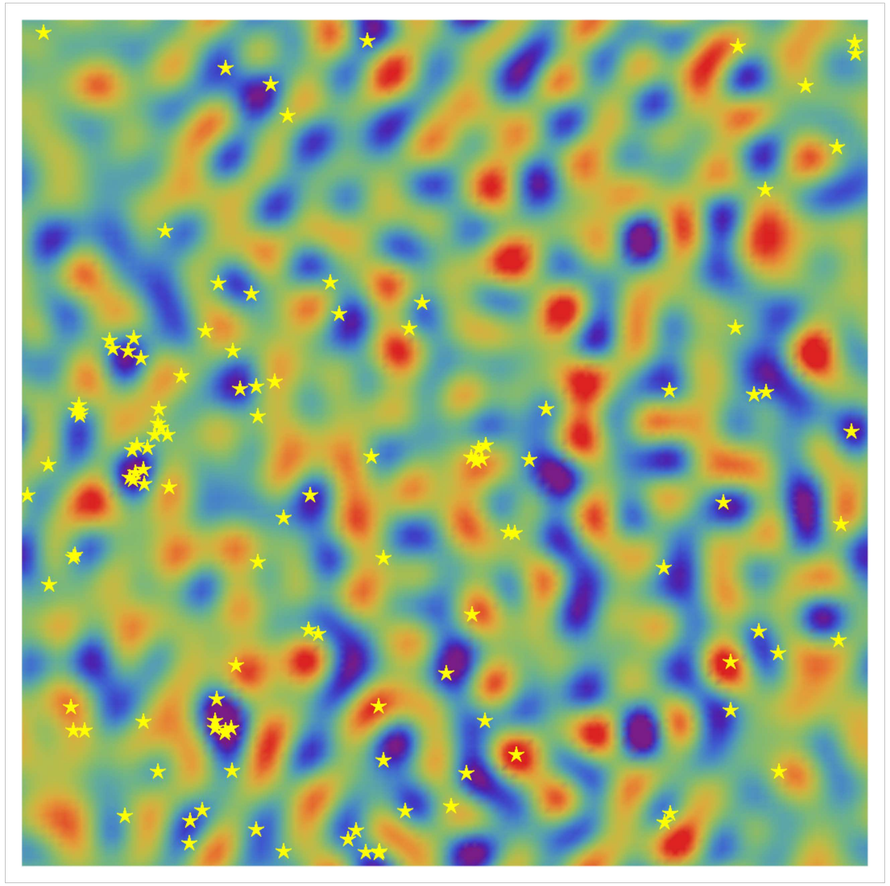
- k-modes move with c_s
- Spectrum: top-hat between k_* and $k_*/2$
- Power in perturbations
$$\sigma^2 = \frac{1}{V}\int d^3x\delta\tilde{T}(x)^2 = \int \frac{d^3k}{(2\pi)^3}\mathscr{P}_{\delta\tilde{T}}(k)$$
- Expect strongest effect for $k_* \sim R_*^{-1} \sim \dfrac{\beta}{(8\pi)^{1/3}}$

↑ $\delta T = 0$

Results: nucleation sites

$\sigma = 3 \qquad L = 40/\beta$





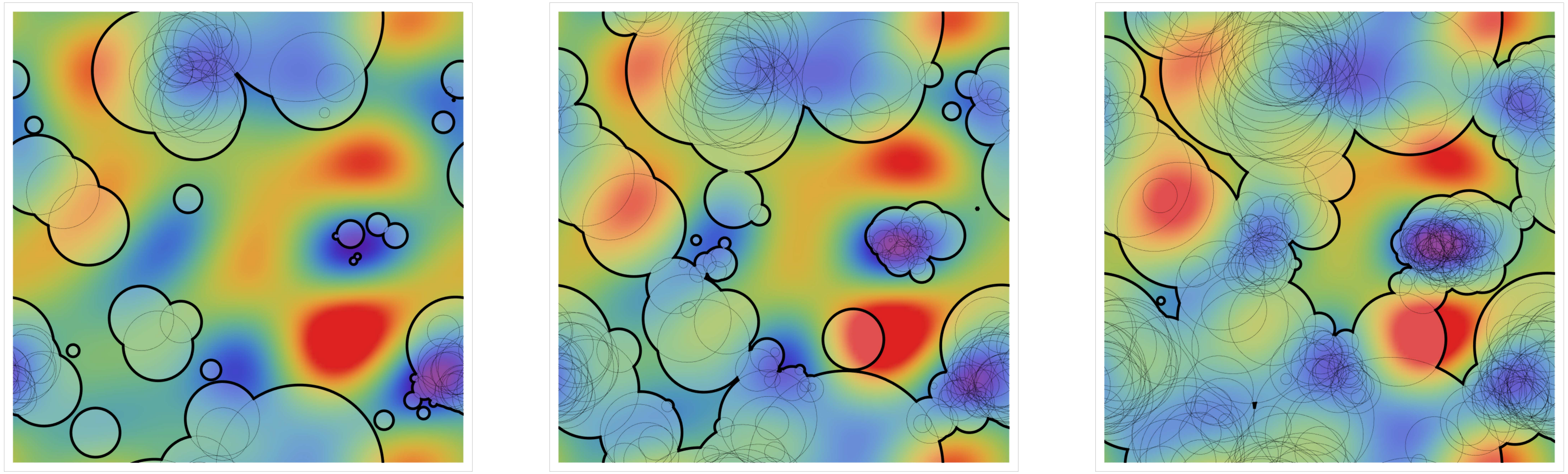
$\Delta z = 2/\beta$

"IR": $4 \times (2\pi/L)$

"UV": $k_* = 16 \times (2\pi/L)$

Results: larger ‘effective bubbles’

$$\sigma = 3, \quad k_* = 4 \times (2\pi/L)$$



$t = -6/\beta$ $t = -5/\beta$ $t = -4/\beta$

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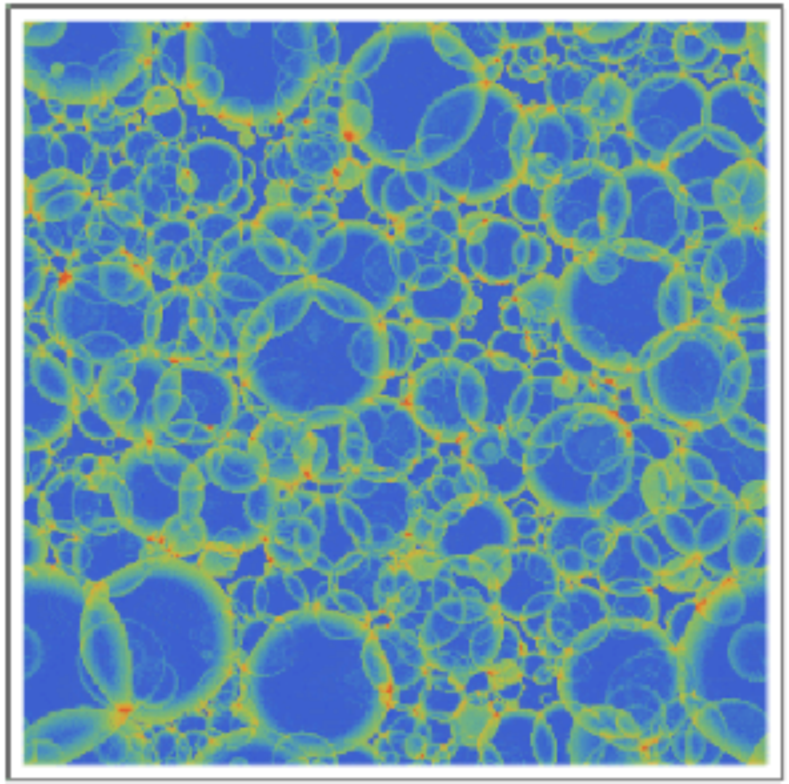
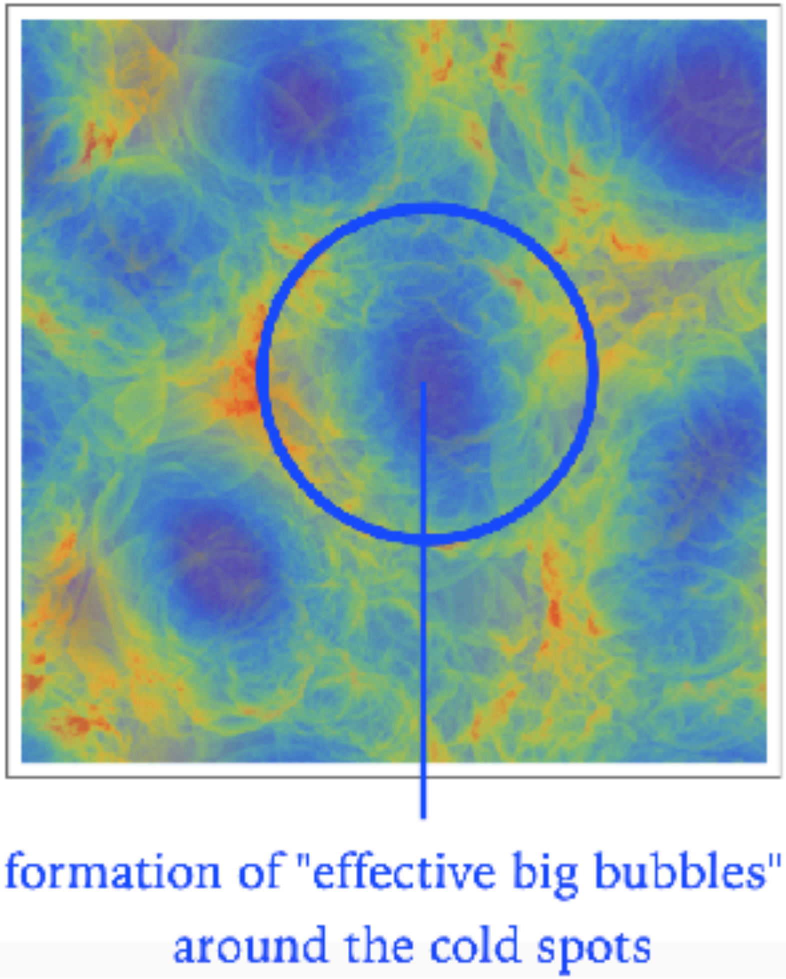
Results: larger ‘effective bubbles’





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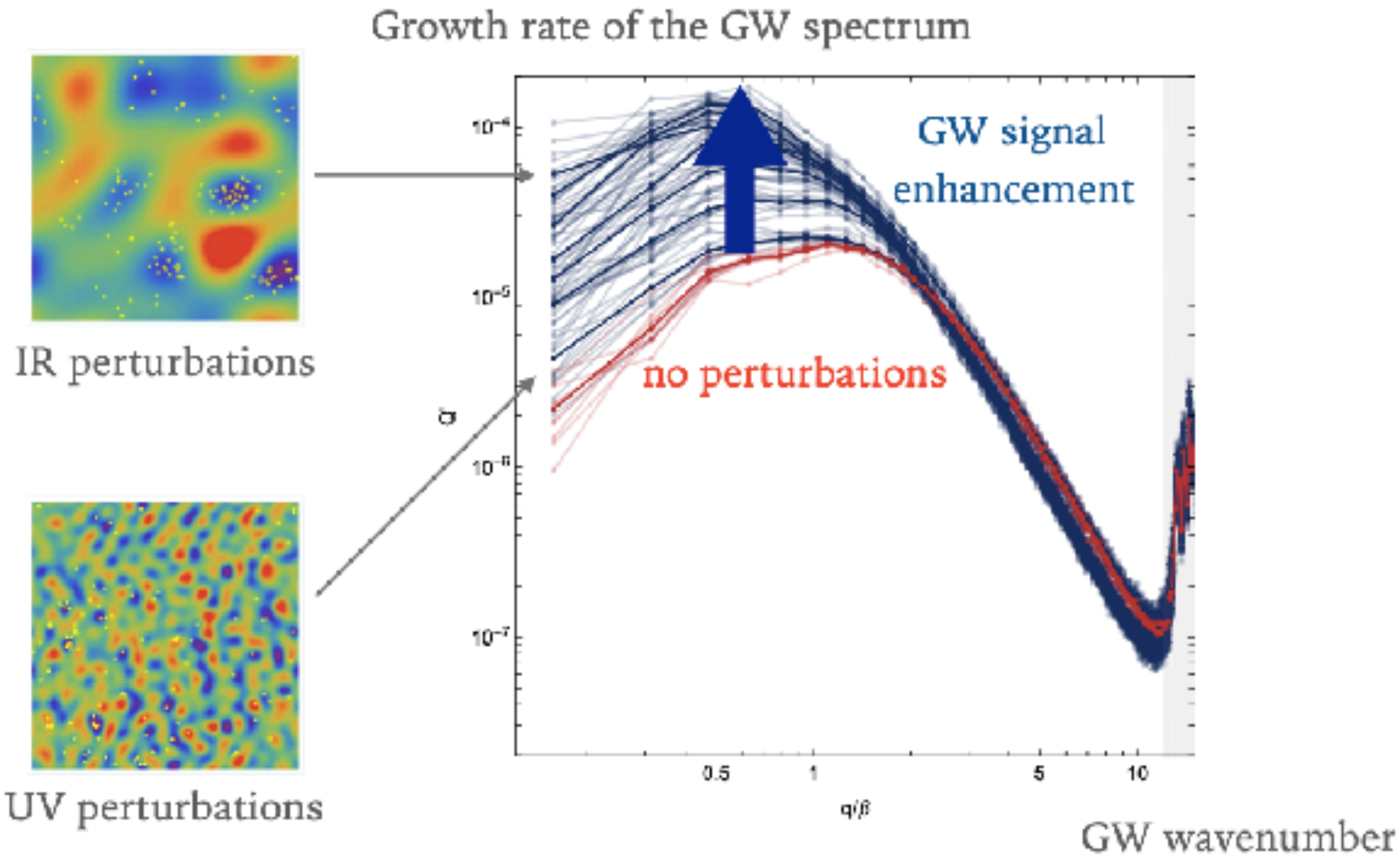
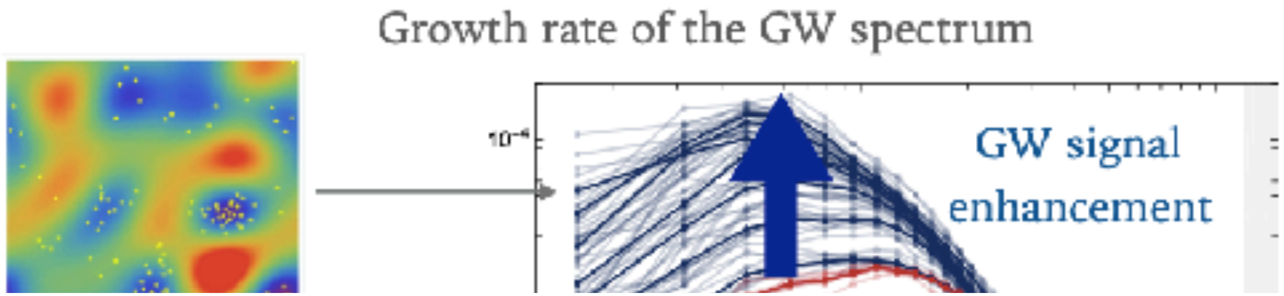
Results: GW signal

- Signal scales as $\Omega_{\mathrm{gw}} \propto \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 R_* H_* / v_w$

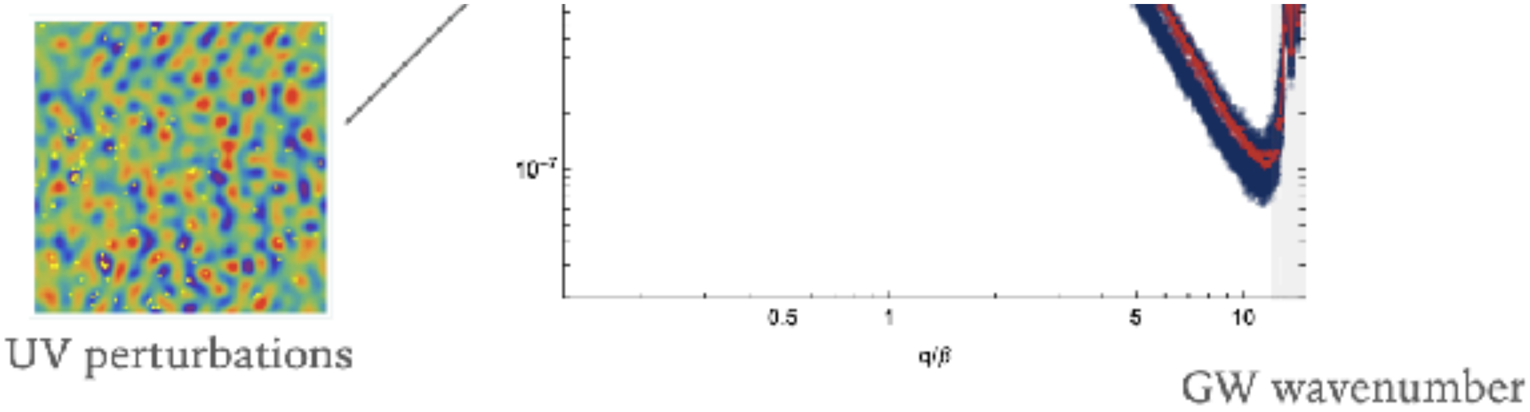
Results: GW signal



Results: GW signal



The strength and wavenumber of the temperature-perturbation affect the signal too!



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Summary & Outlook
Shape of the spectrum

- The GW spectrum is much more interesting than just a single broken power law

- Improvement of GW simulations required:
  - Stronger phase transitions
  - Inclusion of turbulence
  - Sound speed $c_s^2 \neq 1/3$ in numerical simulations
  - …

Summary & Outlook
LISA detection prospects

- Detection prospects depend on PT temperature
- Specific interest in strong PTs and/or $T_{\rm pt} \gtrsim \mathcal{O}(10) \times T_{\rm EW}$
  Models with classical conformal symmetry?

- Realistic estimates require a careful study of foregrounds

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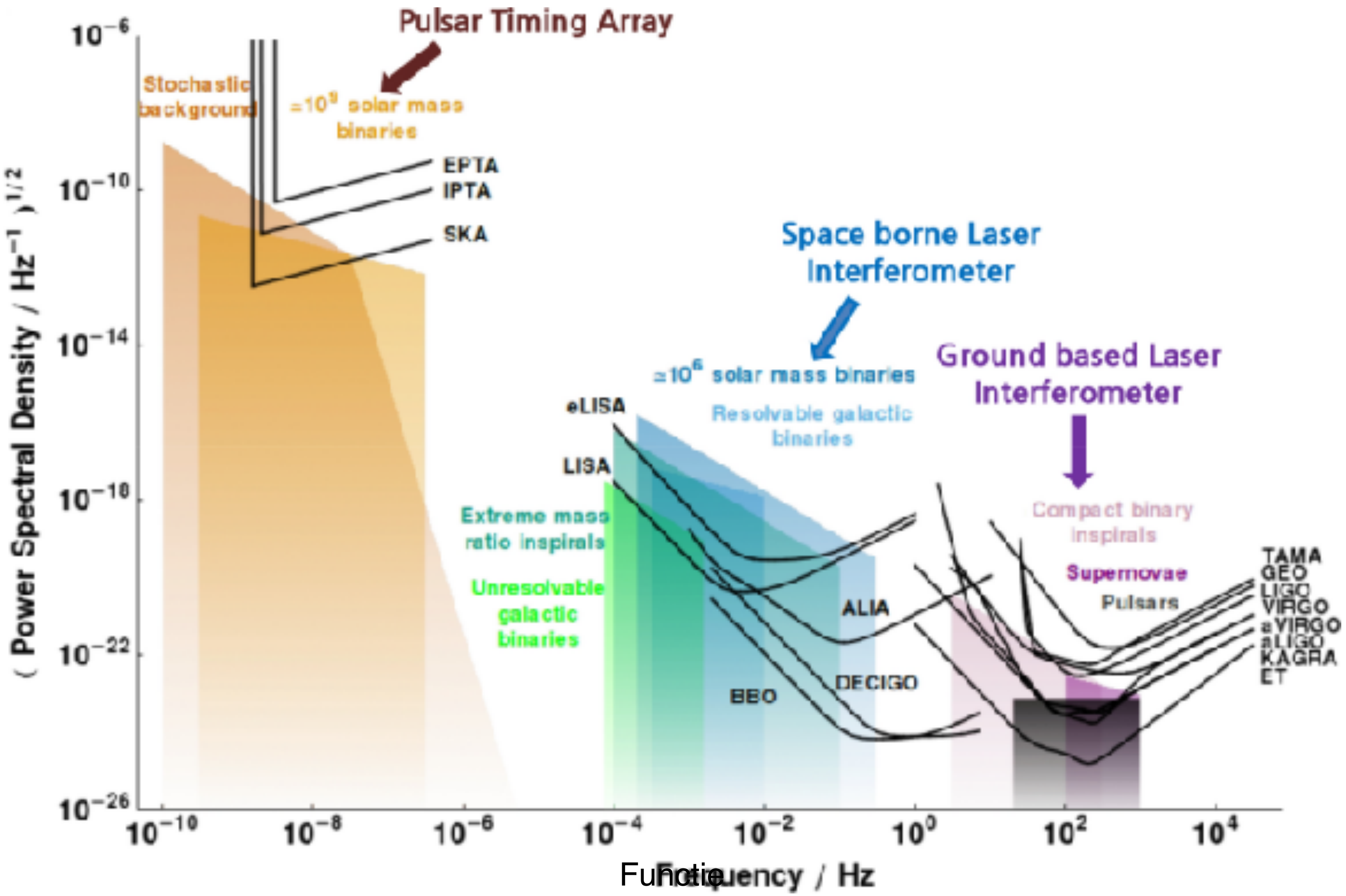

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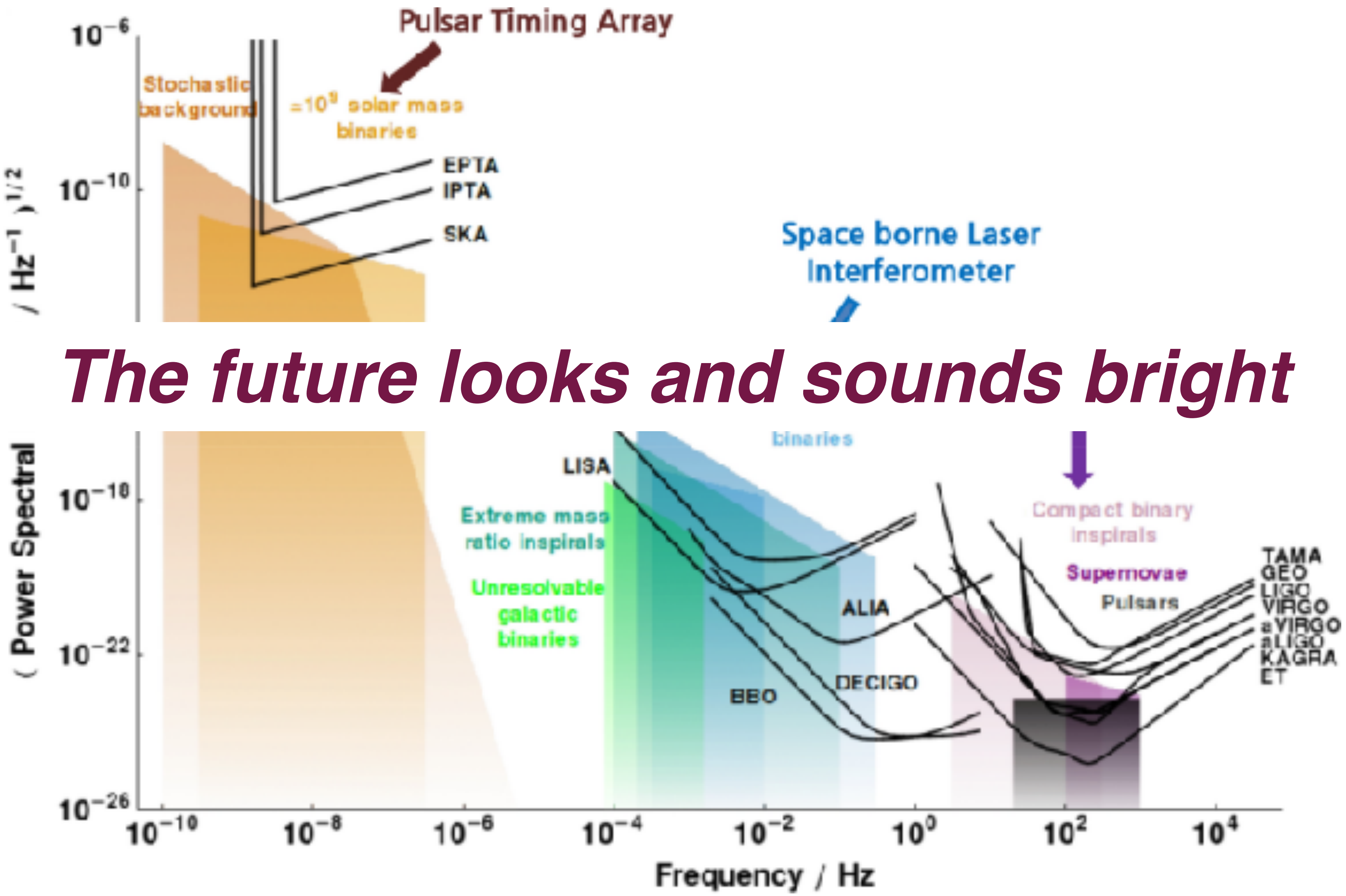
The future looks and sounds bright



Park 2021