Gravitational waves from cosmological phase transitions:

Using LISA to probe particle physics

S@INT seminar - University of Washington

05/05/2022

Jorinde van de Vis

Based on:

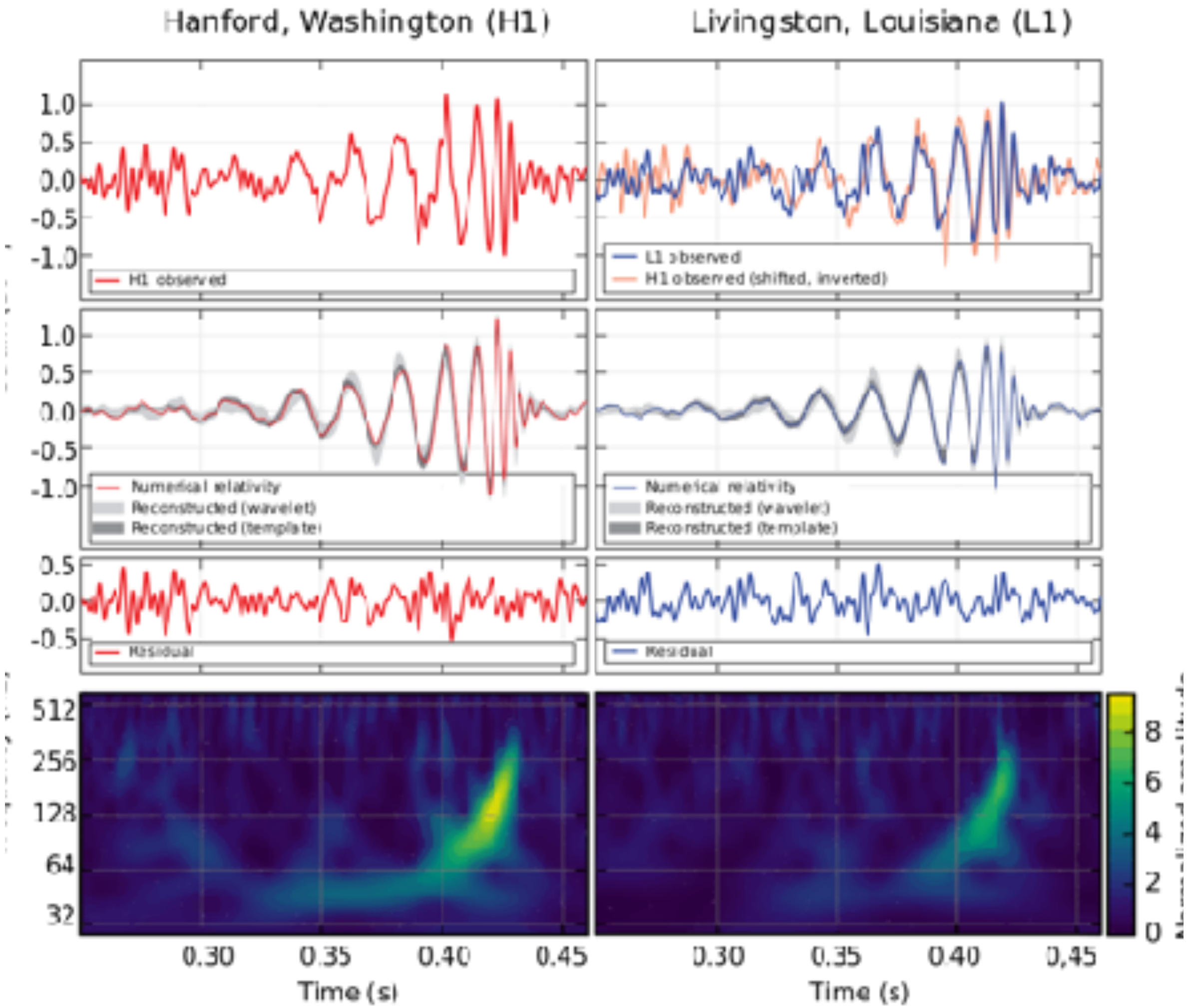
R. Jinno, T. Konstandin, H. Rubira, JvdV	*JCAP* 12 (2021) 12, 019	arXiv:2108.11947
F. Giese, T. Konstandin, JvdV	*JCAP* 11 (2021) 002	arXiv:2107.06275
F. Giese, T. Konstandin, K. Schmitz, JvdV	*JCAP* 01 (2021) 072	arXiv:2010.09744
F. Giese, T. Konstandin, JvdV	*JCAP* 07 (2020) 07, 057	arXiv:2004.06995

HELMHOLTZ

DESY.

Gravitational waves

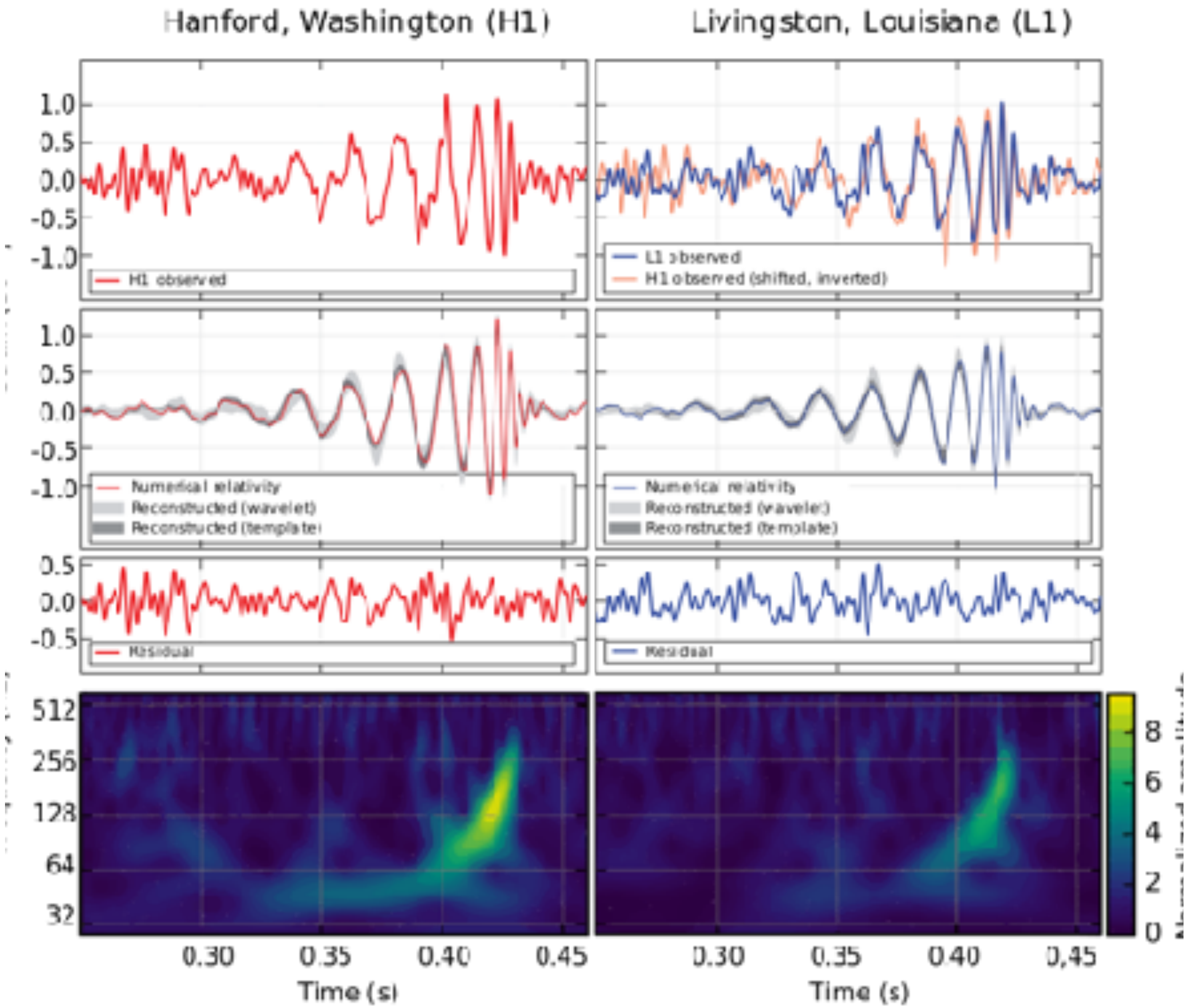
First black hole GW merger event: GW150914



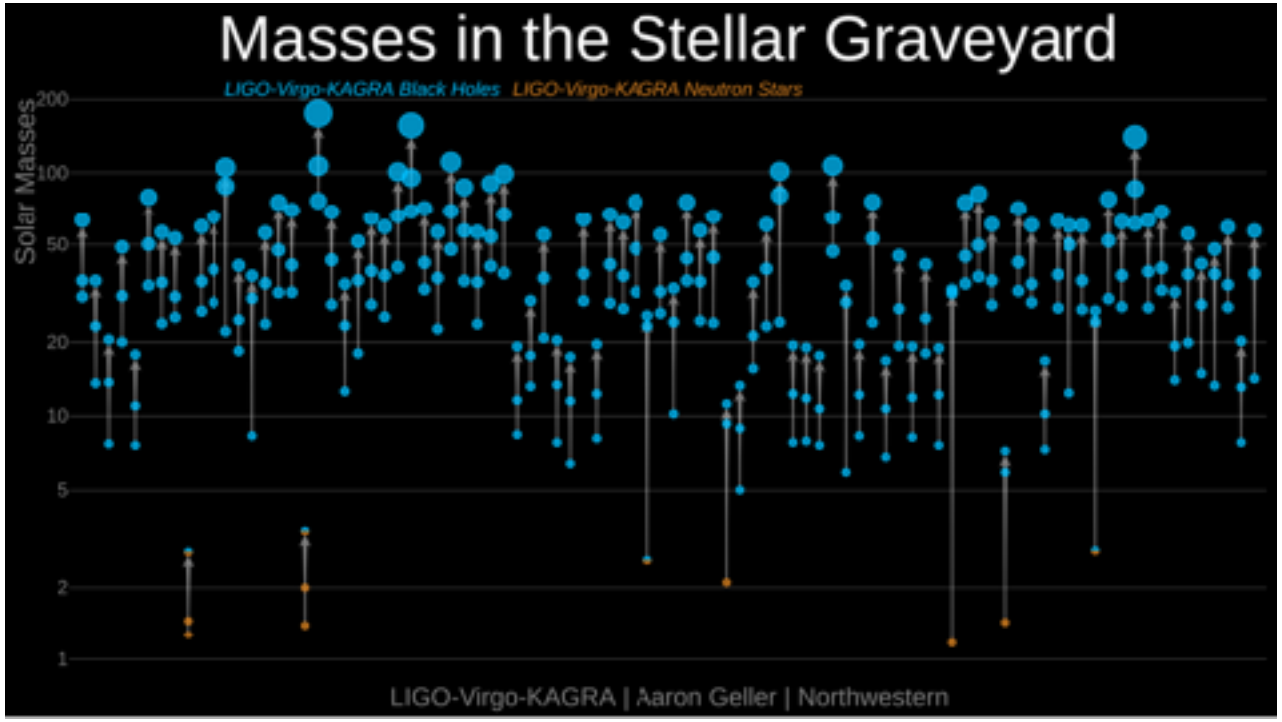
LIGO/Virgo Collab. 2016

Gravitational waves

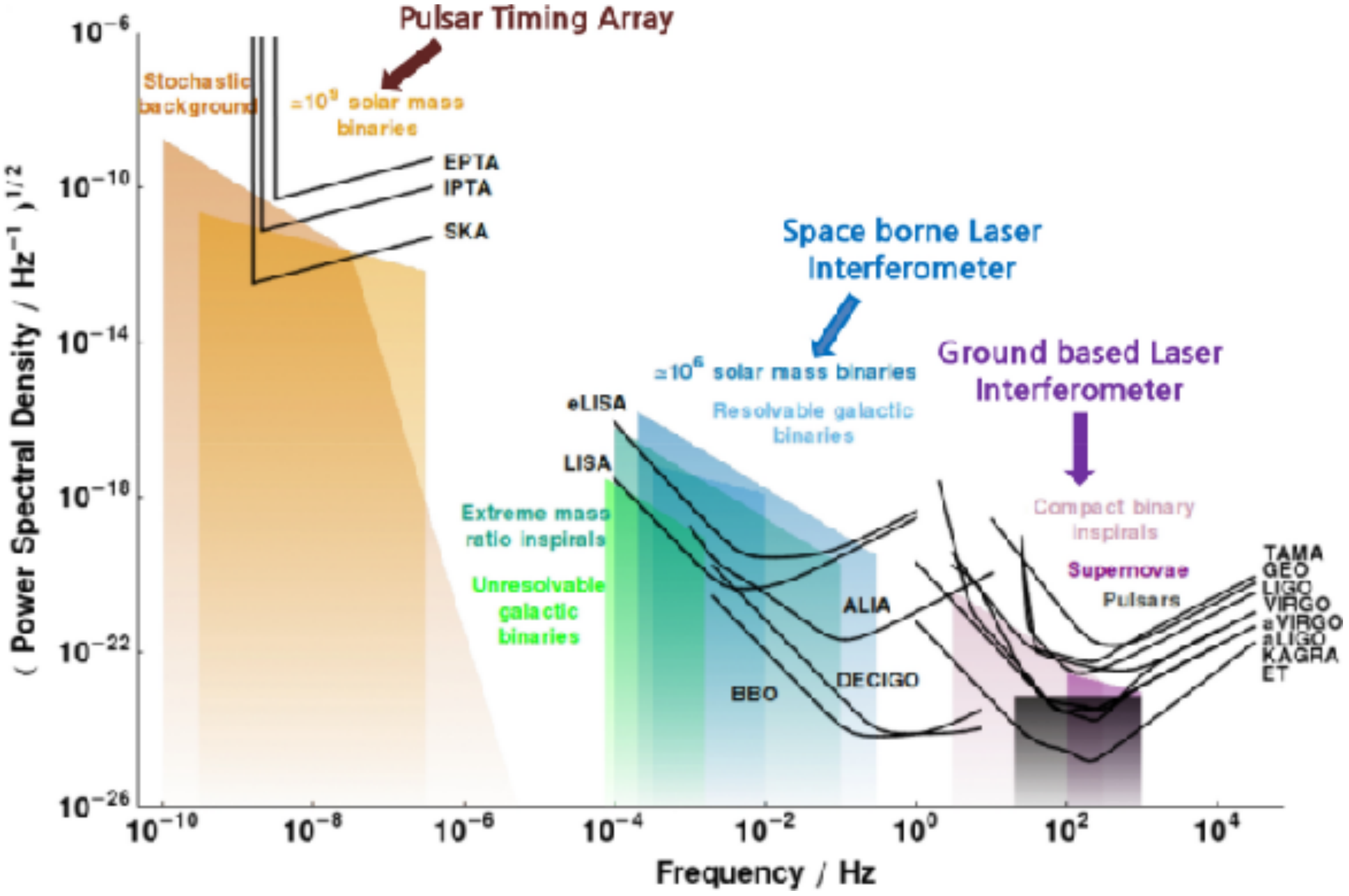
November 2021: 90 events



LIGO/Virgo Collab. 2016

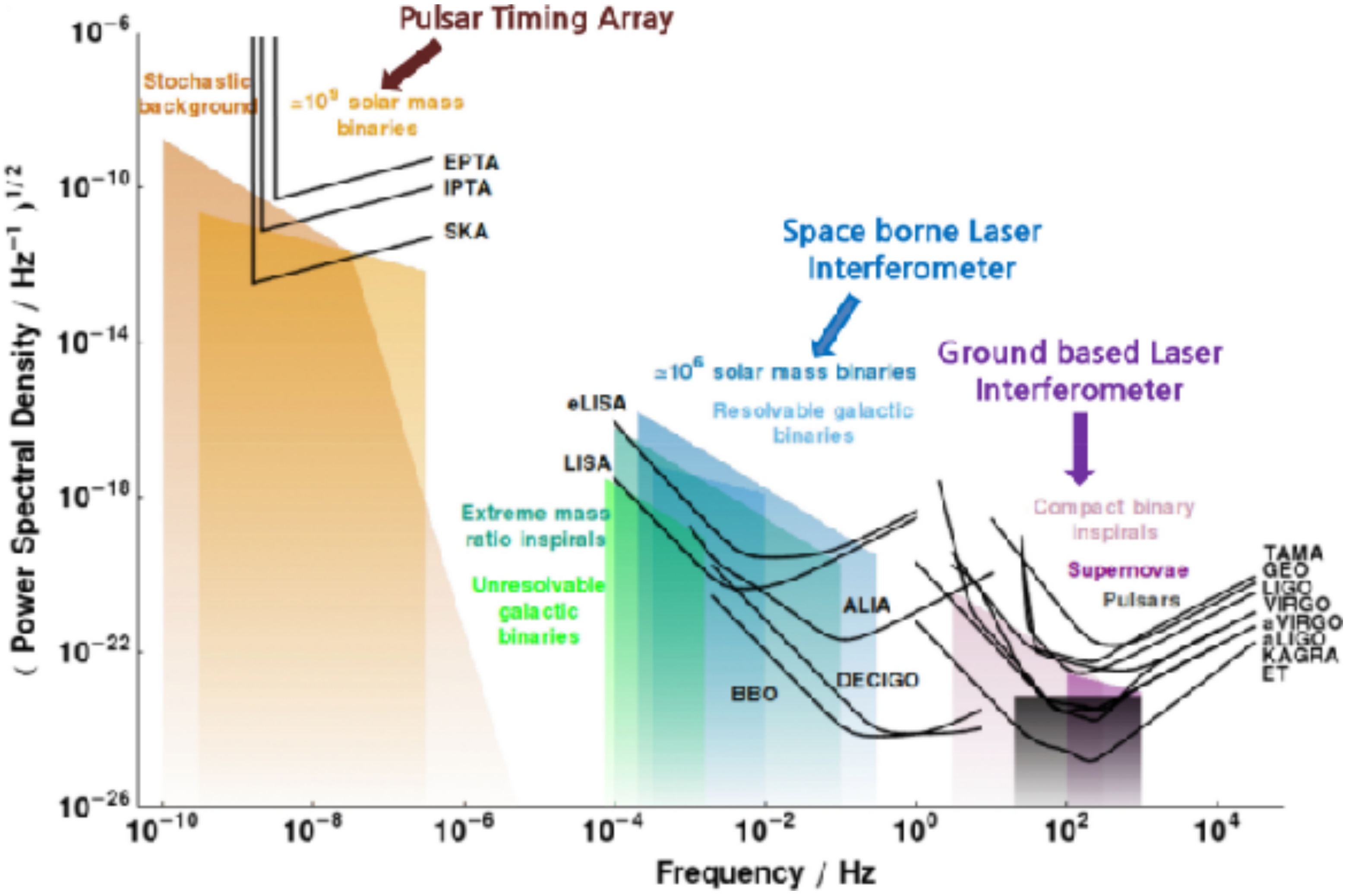


Ongoing and upcoming experiments



Park 2021

Ongoing and upcoming experiments

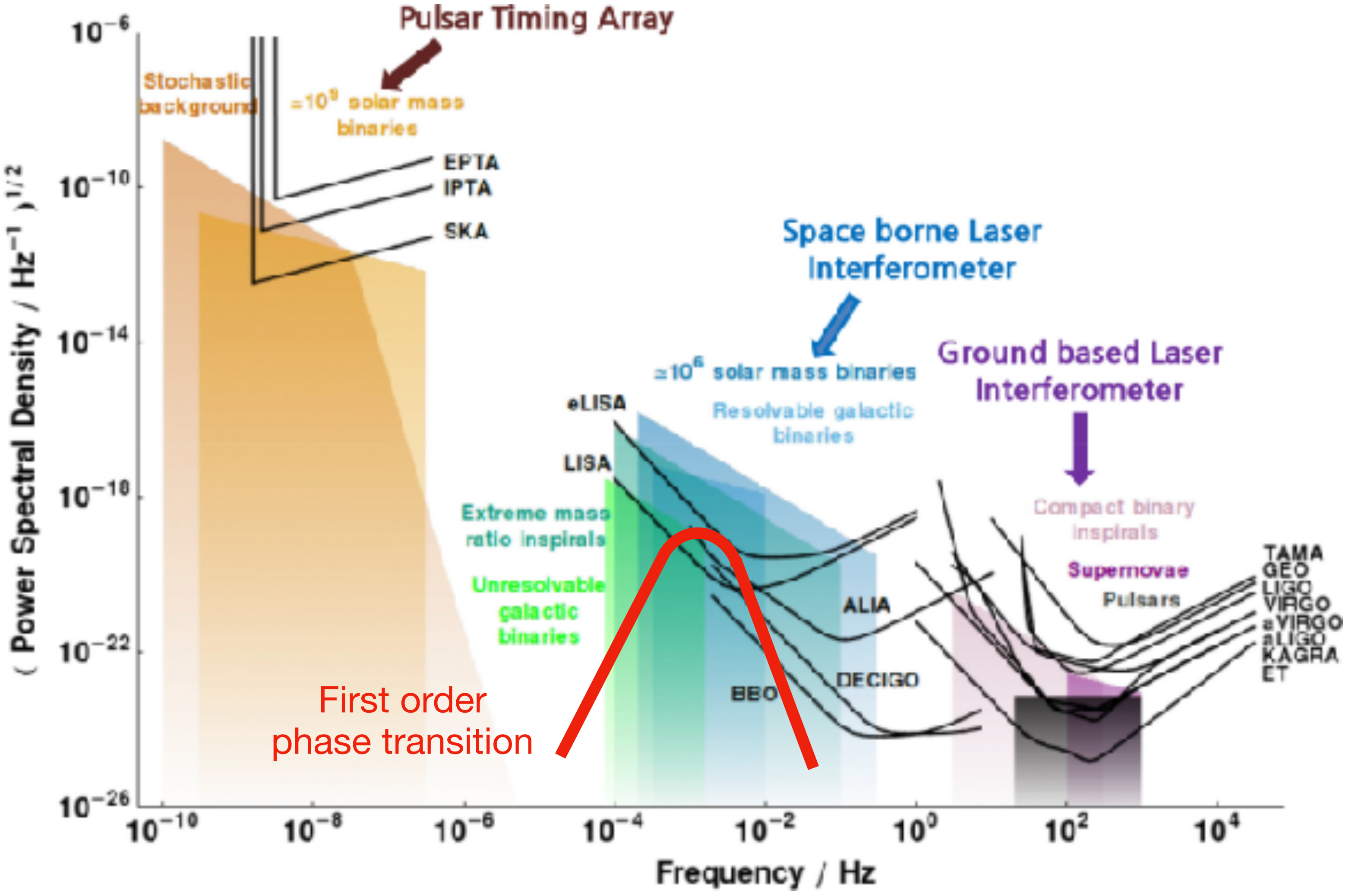


- Size of the detector sets f_{detector}
- Typical time scale and redshift of source set f_{signal}

Park 2021

Ongoing and upcoming experiments

Cosmological phase transition: observable with LISA?

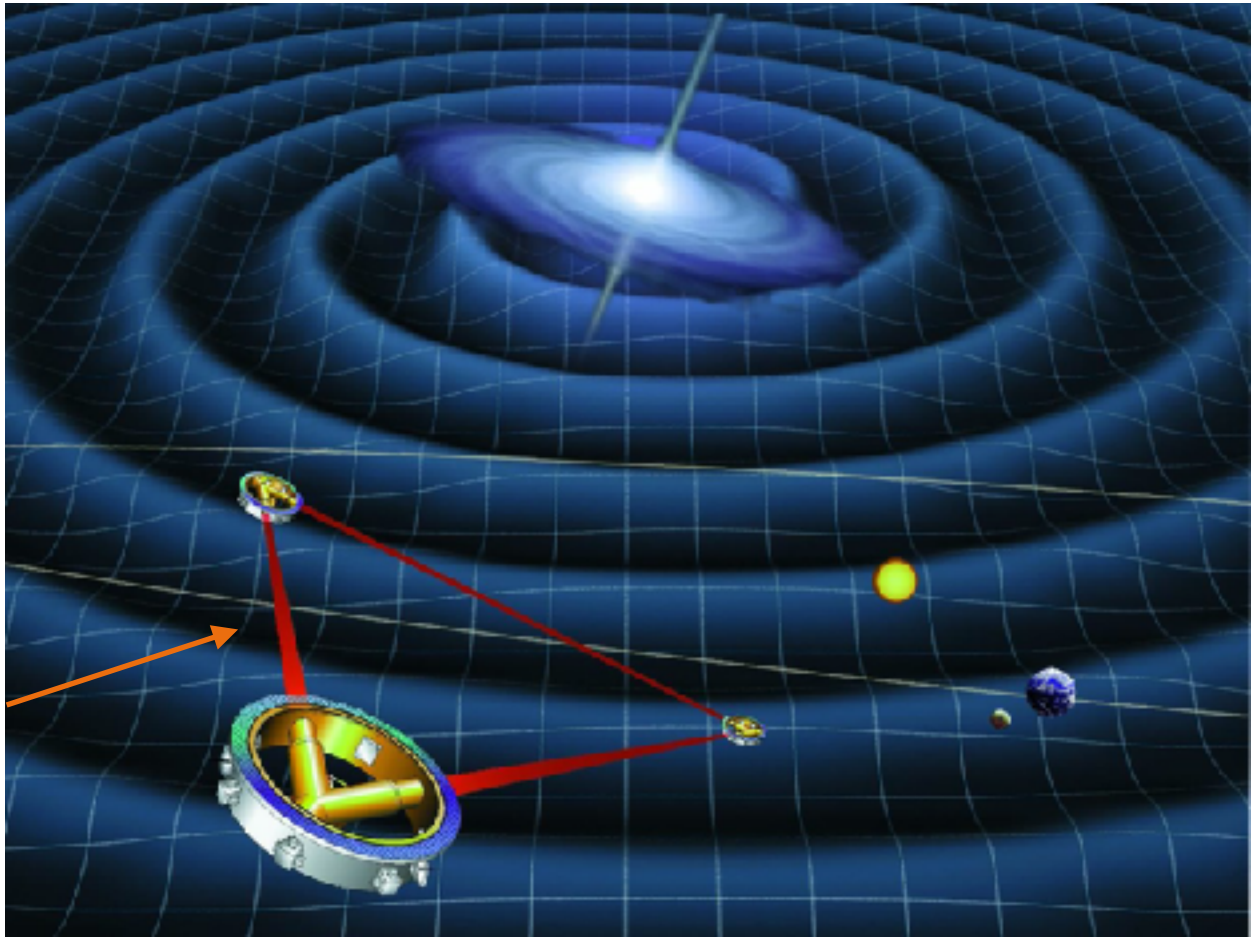


Park 2021

Laser Interferometer Space Antenna (LISA)

ESA mission, planned in the 2030s

2.5×10^6 km



NASA

Gravitational waves

Expand the metric: $g_{\mu\nu} = \underset{\text{Minkowski}}{\eta_{\mu\nu}} + \underset{\text{GW}}{h_{\mu\nu}}, \qquad |h_{\mu\nu}| \ll 1$

Gravitational waves

Expand the metric: $\underbrace{g_{\mu\nu} = \overset{\text{Minkowski}}{\eta_{\mu\nu}} + \underbrace{h_{\mu\nu}}_{\text{GW}}}$, $\quad |h_{\mu\nu}| \ll 1$

$h_{\mu\nu}$: only transverse and traceless component

Gravitational waves

Minkowski

Expand the metric: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \qquad |h_{\mu\nu}| \ll 1$

GW

$h_{\mu\nu}$: only transverse and traceless component

Source*: $\Box \bar{h}_{\mu\nu} = -\dfrac{16\pi G}{c^4} T_{\mu\nu}$

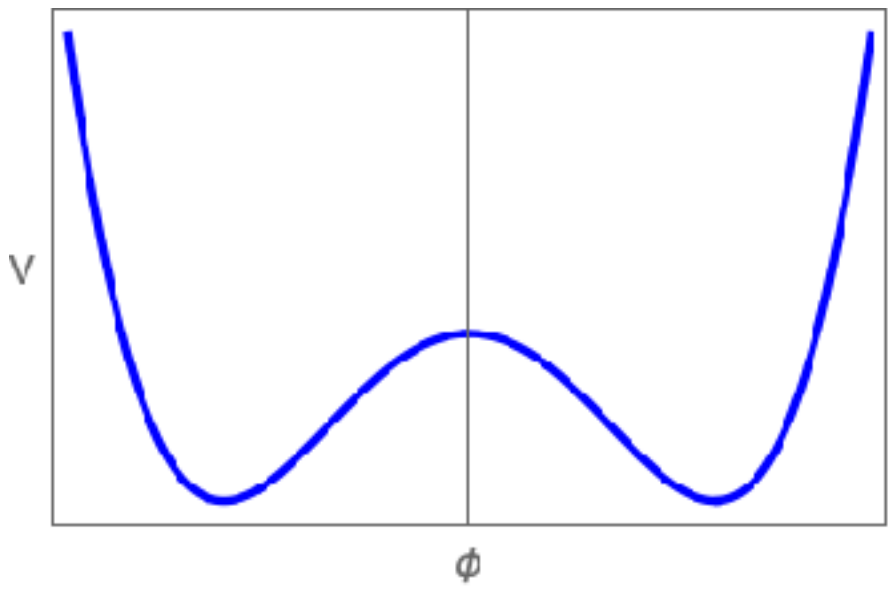
*In the gauge where $\partial^\nu \bar{h}_{\mu\nu} = 0$, with $\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h$

How can a cosmological phase transition source gravitational waves?

Cosmological phase transition

Temperature-dependent Higgs* potential

Zero temperature Higgs potential

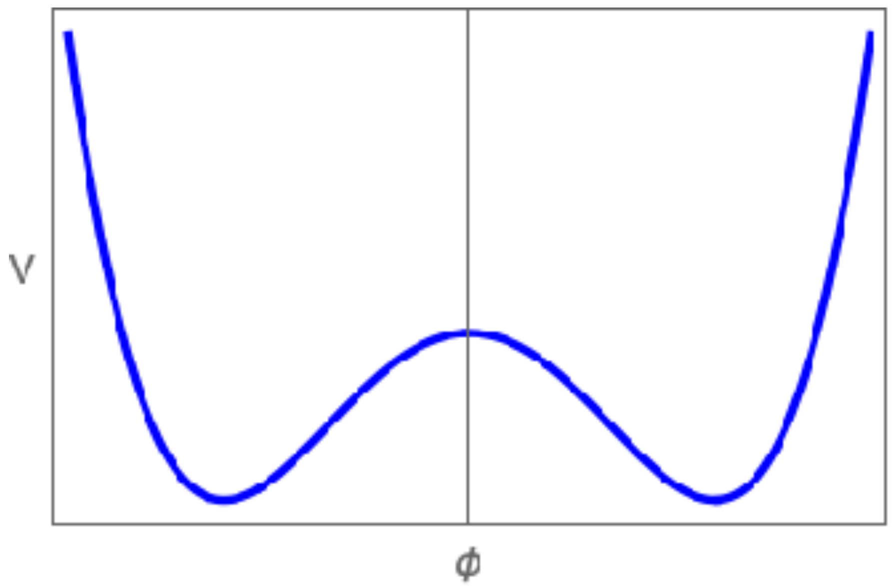


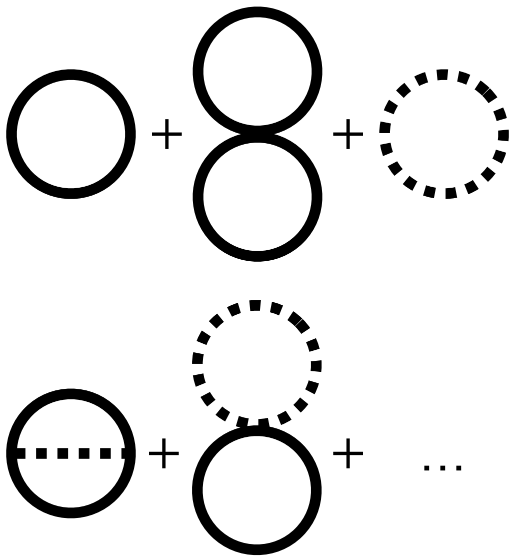
*Or some other scalar field

Cosmological phase transition

Temperature-dependent Higgs* potential

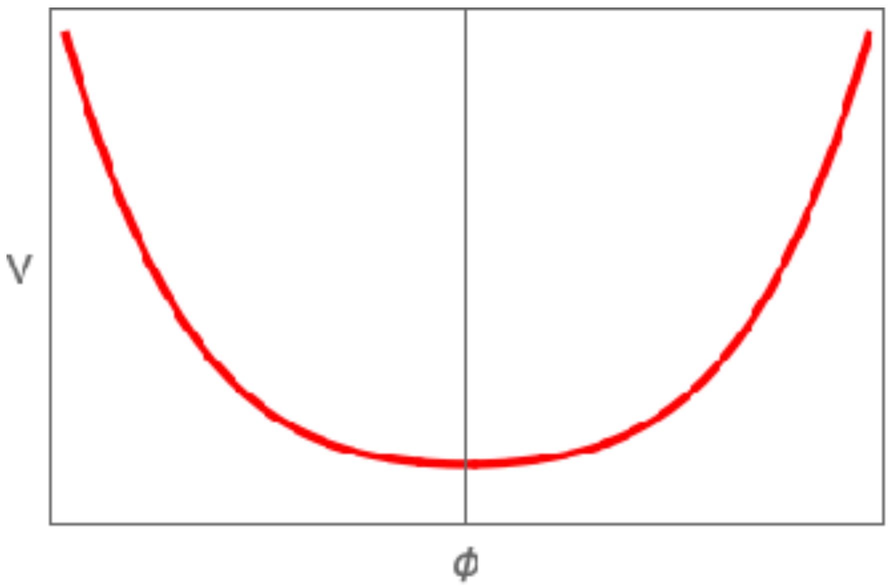
Zero temperature Higgs potential





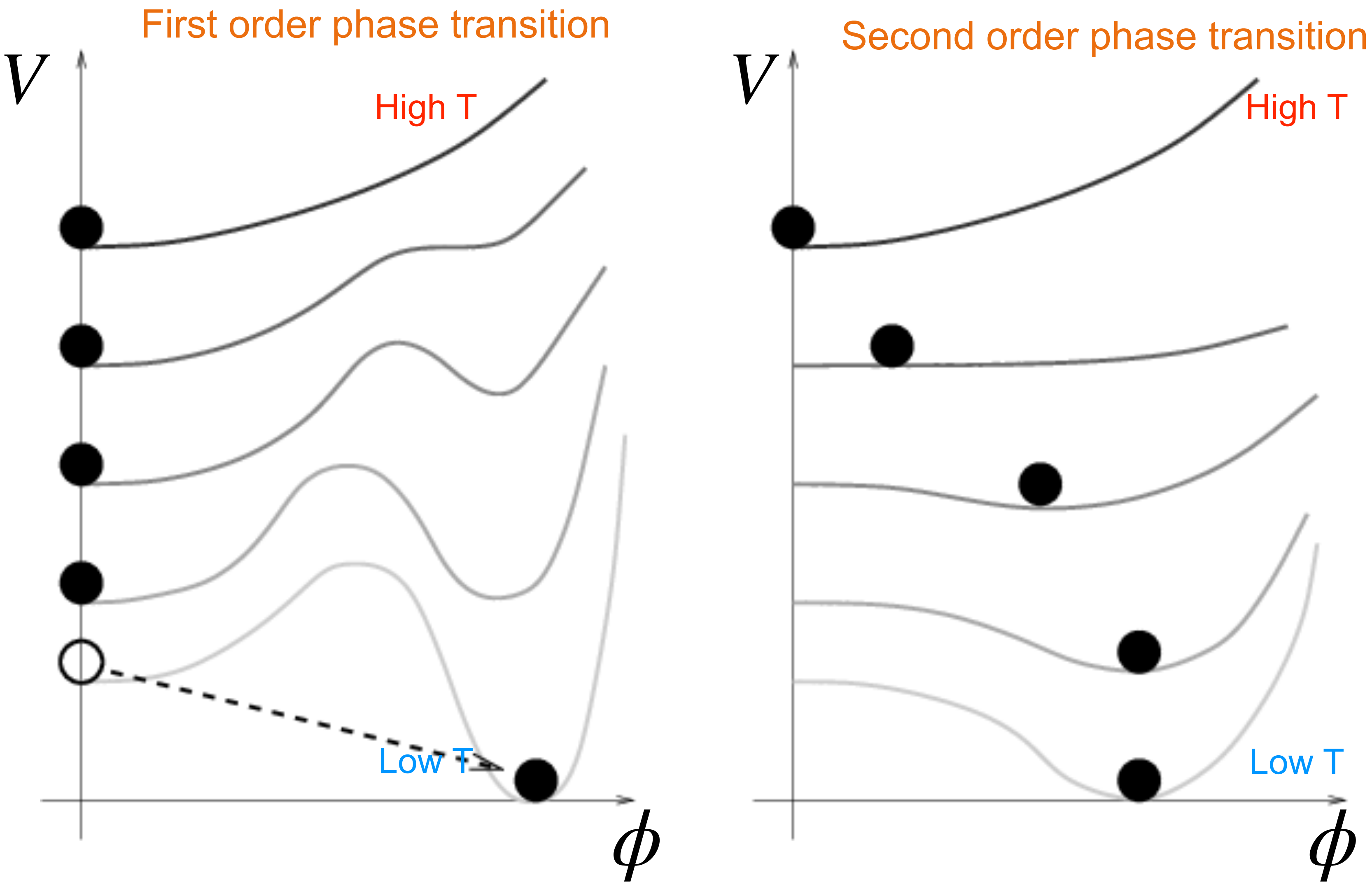
(Temperature-dependent) vacuum bubbles

High temperature Higgs potential



DESY. *Or some other scalar field

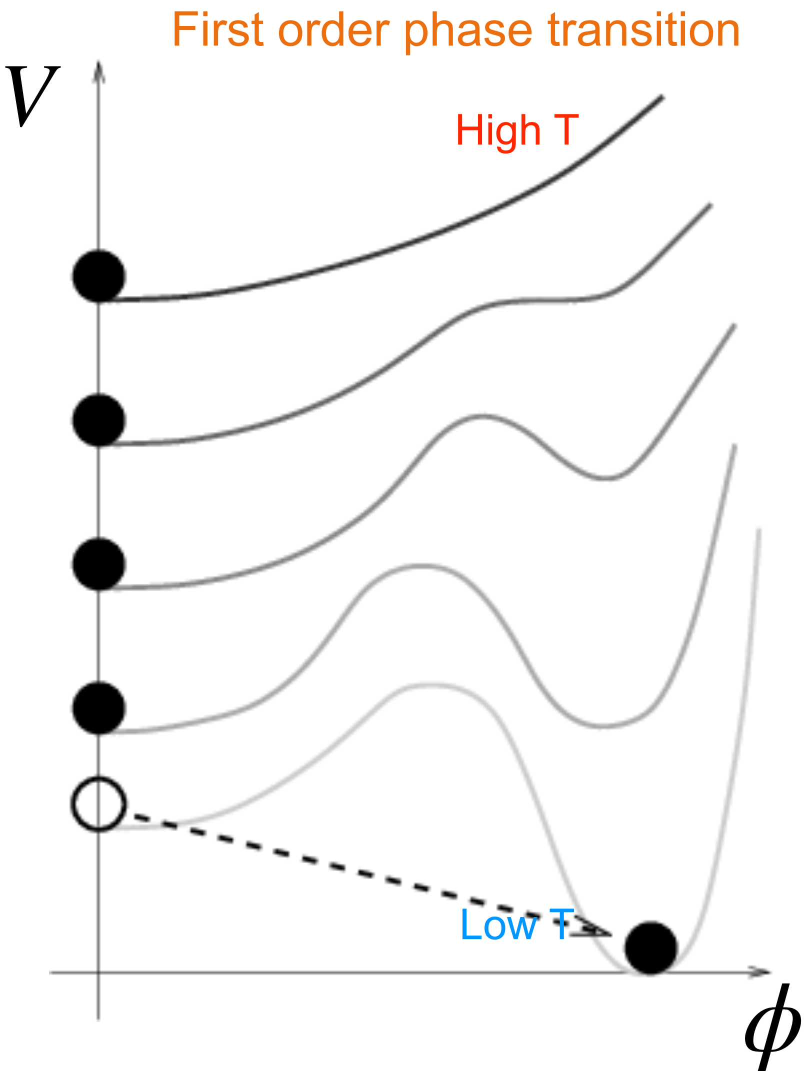
First order versus second order



Rubakov, 2015

First order phase transition

Bubble nucleation



Rubakov, 2015

Motion in the primordial fluid sourcing gravitational waves

Hydrodynamic simulations

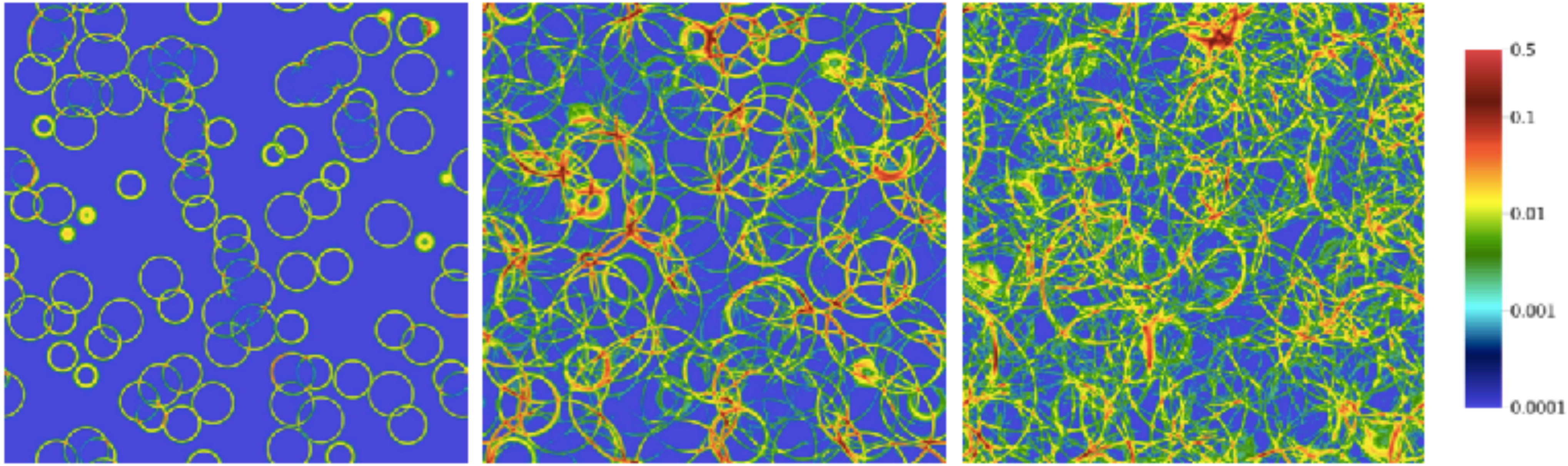
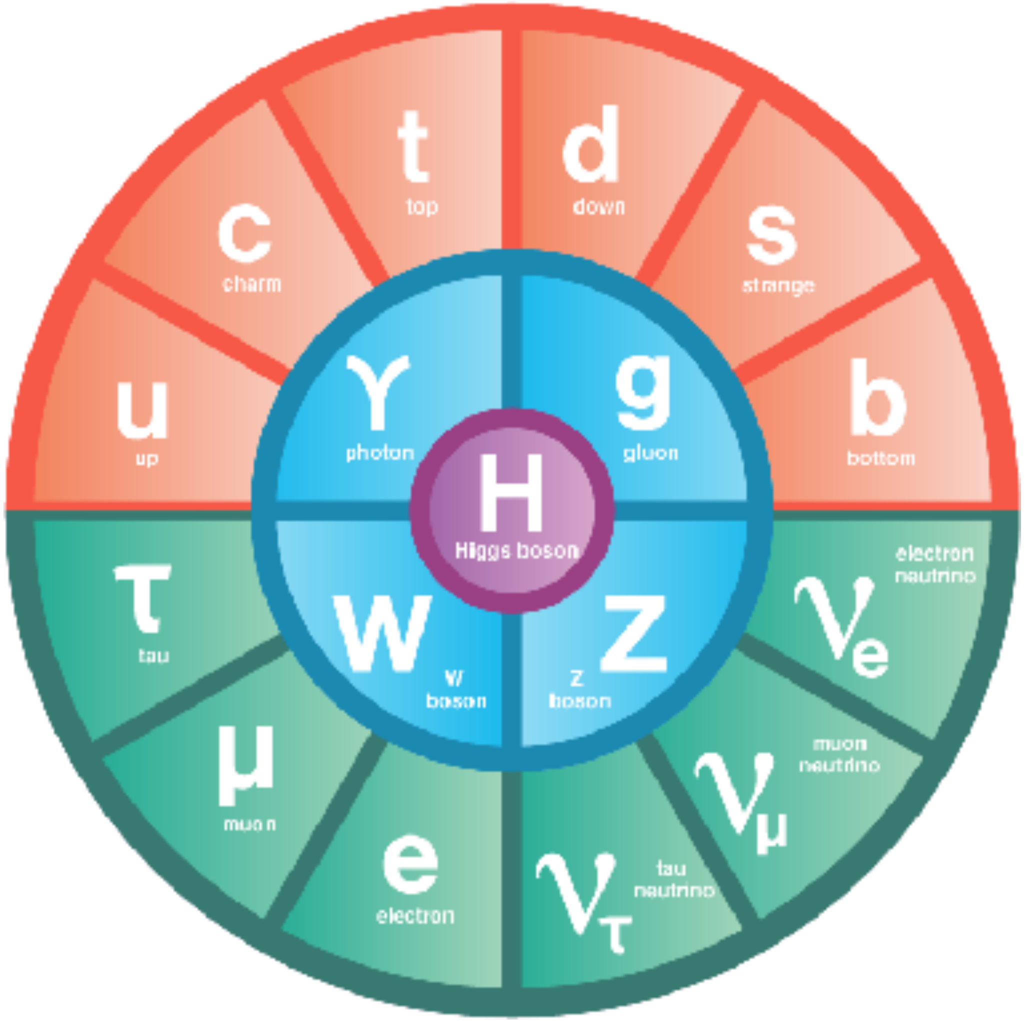


FIG. 4. Slices of fluid kinetic energy density E/T_c^4 at $t = 500\,T_c^{-1}$, $t = 1000\,T_c^{-1}$ and $t = 1500\,T_c^{-1}$ respectively, for the $\eta/T_c = 0.15$, $N_b = 988$ simulation.

Hindmarsh, Huber, Rummukainen, Weir 2015

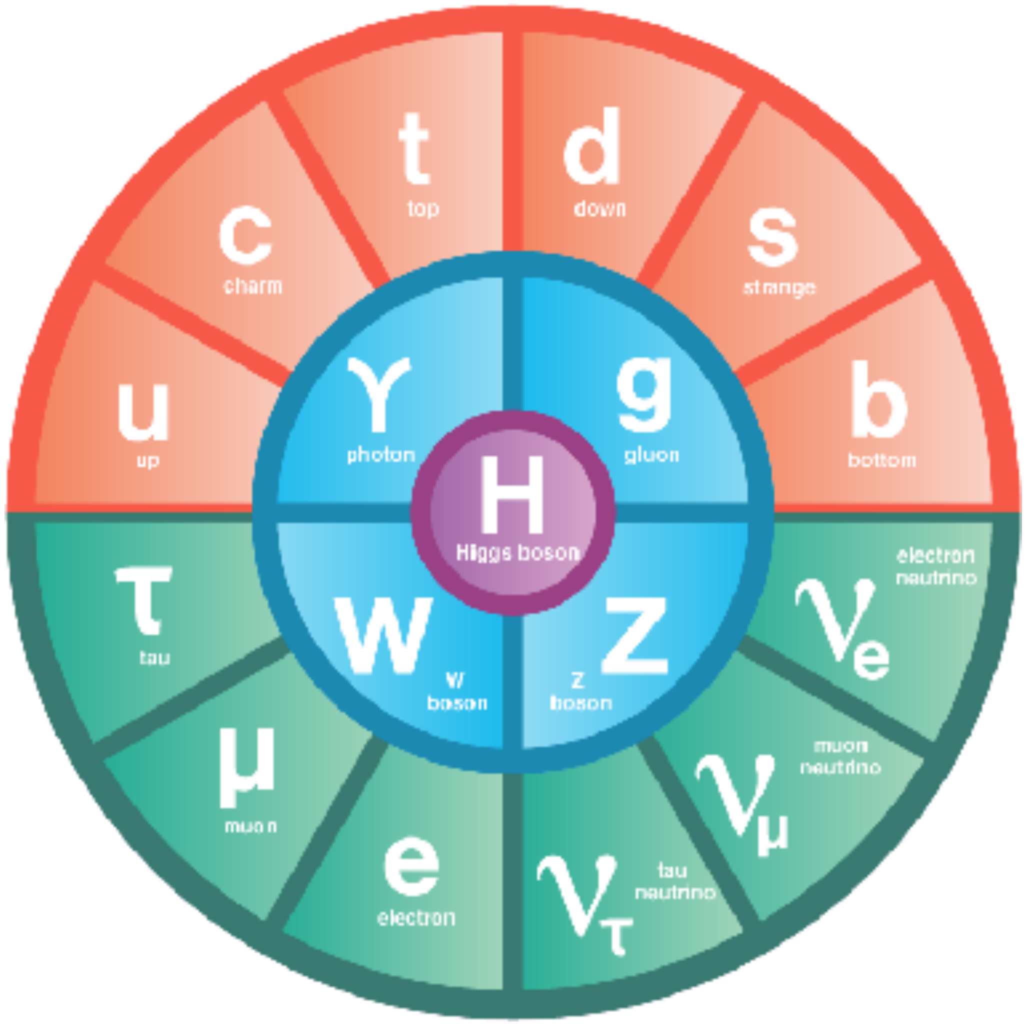
Phase transitions in the Standard Model of Particle Physics

- Electroweak phase transition around $100\,\mathrm{GeV}$
- QCD phase transition around $150\,\mathrm{MeV}$



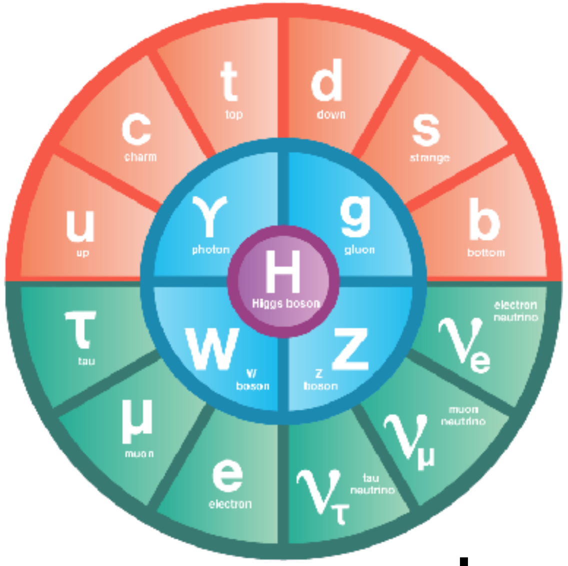
Phase transitions in the Standard Model of Particle Physics

- Electroweak phase transition around $100\,\mathrm{GeV}$
- QCD phase transition around $150\,\mathrm{MeV}$
- None of them is first order

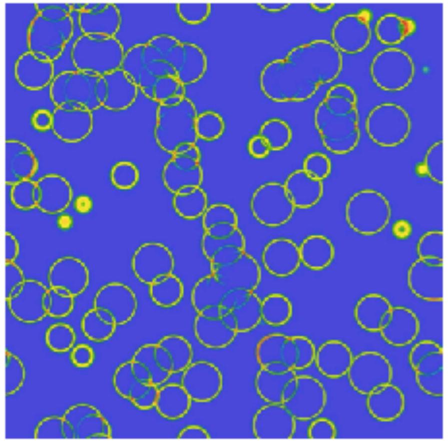


Gravitational waves from first order phase transition: sign of new particles!

- New particle interacting with the Higgs can make the phase transition first order
- Phase transition in a dark sector?
- Relation to the asymmetry between matter and antimatter (electroweak baryogenesis)?



+ ?



The ideal world

The ideal situation

- We know exactly what the gravitational wave spectrum looks like
- There are enough model-dependent features to distinguish between different BSM models
- The GW signal can be completely reconstructed by LISA
- We can infer the particle physics model from the signal

The ideal situation

- We know exactly what the gravitational wave spectrum looks like
- There are enough model-dependent features to distinguish between different BSM models

Part I

- The GW signal can be completely reconstructed by LISA
- We can infer the particle physics model from the signal

The ideal situation

- We know exactly what the gravitational wave spectrum looks like
- There are enough model-dependent features to distinguish between different BSM models
- The GW signal can be completely reconstructed by LISA
- We can infer the particle physics model from the signal

Part II

What does the gravitational wave signal look like?

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

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

Gravitational waves from many bubbles

Hydrodynamic lattice simulations

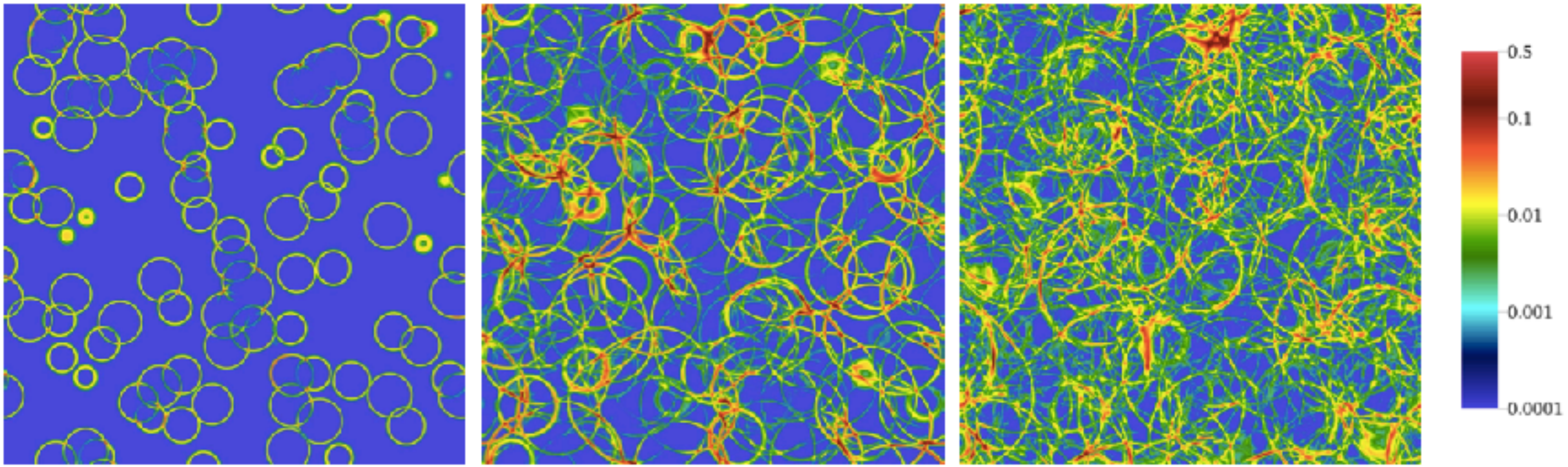


FIG. 4. Slices of fluid kinetic energy density E/T_c^4 at $t = 500\,T_c^{-1}$, $t = 1000\,T_c^{-1}$ and $t = 1500\,T_c^{-1}$ respectively, for the $\eta/T_c = 0.15$, $N_b = 988$ simulation.

Hindmarsh, Huber, Rummukainen, Weir 2015

Do I have to run a new simulation for every model that predicts a first order phase transition?

Fit to lattice result

Gravitational wave power spectrum

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

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

Fit to lattice result

Redshift (temperature T_*)

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

- Relevant parameters: T_*

Fit to lattice result

Kinetic energy fraction (phase transition strength α, wall velocity v_w)

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

- Relevant parameters: T_*, α, v_w

Fit to lattice result

Bubble size at collision (v_w, phase transition duration β^{-1})

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

- Relevant parameters: T_*, α, v_w, β

Fit to lattice result

Sound speed $\sim 1/\sqrt{3}$

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

- Relevant parameters: T_*, α, v_w, β

Fit to lattice result

Peak frequency (T_*, β)

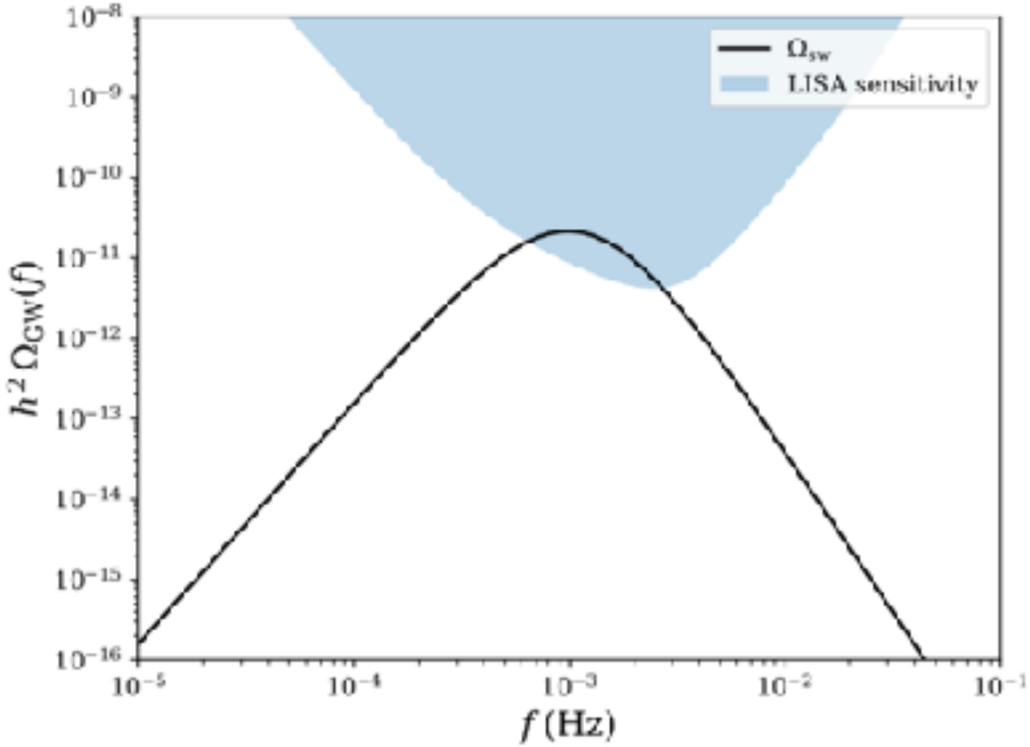
$$\frac{d\Omega_{\rm gw}}{d\ln(f)} = 0.687 F_{\rm gw,0} K^2 H_* R_* / c_s \tilde{\Omega}_{\rm gw} C\left(f/\boxed{f_{p,0}}\right)$$

- Relevant parameters: T_*, α, v_w, β

Fit to lattice result

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

- Relevant parameters: T_*, α, v_w, β



Computation of the power spectrum - common procedure

- Choose a BSM model with a first order phase transition (Higgs + singlet, 2HDM, composite Higgs…)

Computation of the power spectrum - common procedure

- Choose a BSM model with a first order phase transition
- Analyze at finite temperature and determine T_*, α, β *

* $\alpha \sim \dfrac{\Delta p}{\rho_{\text{tot}}}$

Computation of the power spectrum - common procedure

- Choose a BSM model with a first order phase transition
- Analyze at finite temperature and determine T_*, α, β
- Compute the wall velocity v_w

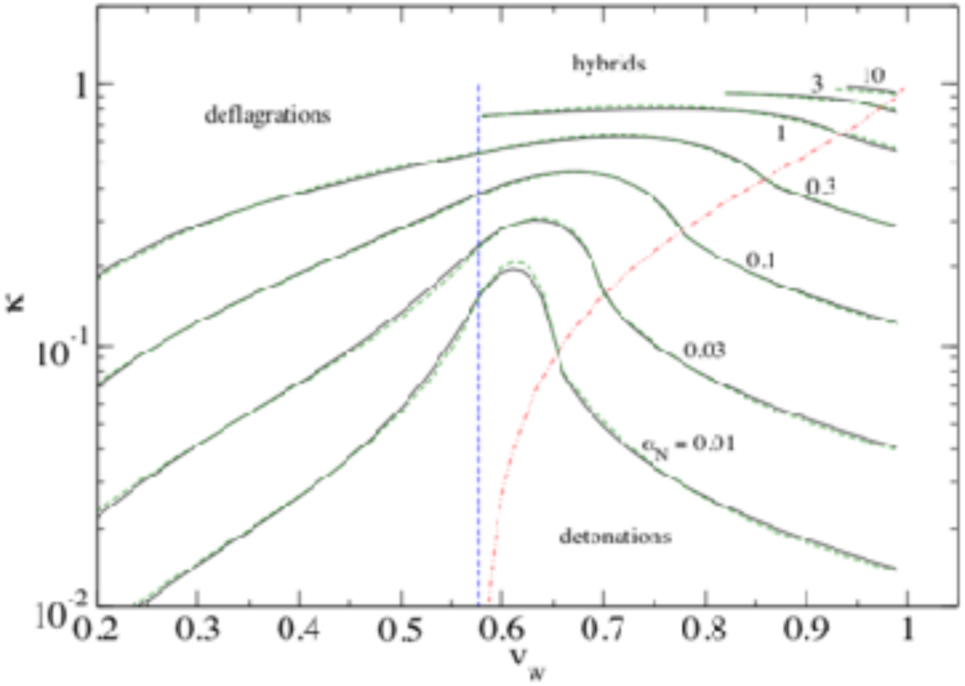
Computation of the power spectrum - common procedure

- Choose a BSM model with a first order phase transition
- Analyze at finite temperature and determine T_*, α, β
- Compute the wall velocity v_w
- Determine the kinetic energy fraction

Common determination of kinetic energy fraction

- Obtain from a fit provided by Espinosa et al.
- Fit is based on the bag model

Fit of 'efficiency factor' as function of v_w and α



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

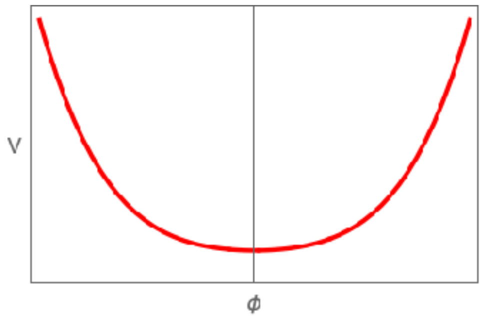
Computation of the power spectrum - common procedure

- Choose a BSM model with a first order phase transition
- Analyze at finite temperature and determine T_*, α, β
- Compute the wall velocity v_w
- Determine the kinetic energy fraction
- Plug everything into $$\frac{d\Omega_{\mathrm{gw}}}{d\ln(f)} = 0.687 F_{\mathrm{gw},0} K^2 H_* R_* / c_s \tilde{\Omega}_{\mathrm{gw}} C\left(f/f_{p,0}\right)$$

Improved computation of K: (2004.06995, 2010.09744)

Hydrodynamics of a single bubble

Thermodynamic quantities



- Pressure $$p = -F$$
- Energy density $$e = T\frac{\partial p}{\partial T} - p$$
- Enthalpy $$w = T\frac{\partial p}{\partial T} = e + p$$
- Speed of sound $$c_s^2 = \frac{dp/dT}{de/dT}$$
- Energy-momentum tensor of the fluid $$T^{\mu\nu} = u^\mu u^\nu w + \eta^{\mu\nu} p$$

fluid velocity

Hydrodynamics of a single bubble

Hydrodynamic equations

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

  v: fluid velocity

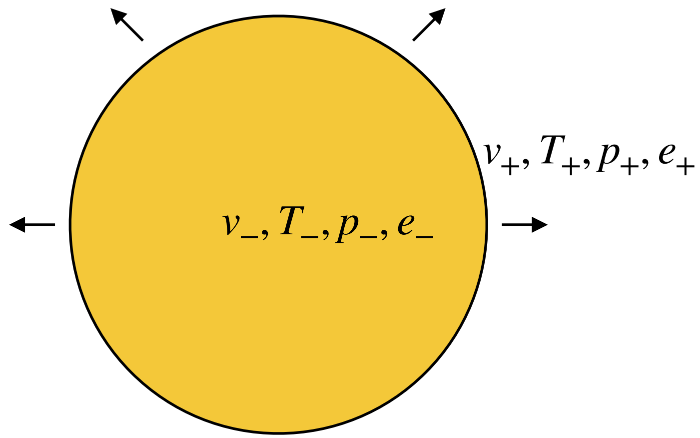
  ξ: radial coordinate

  $$\mu = \frac{\xi - v}{1 - \xi v}$$

Hydrodynamics of a single bubble

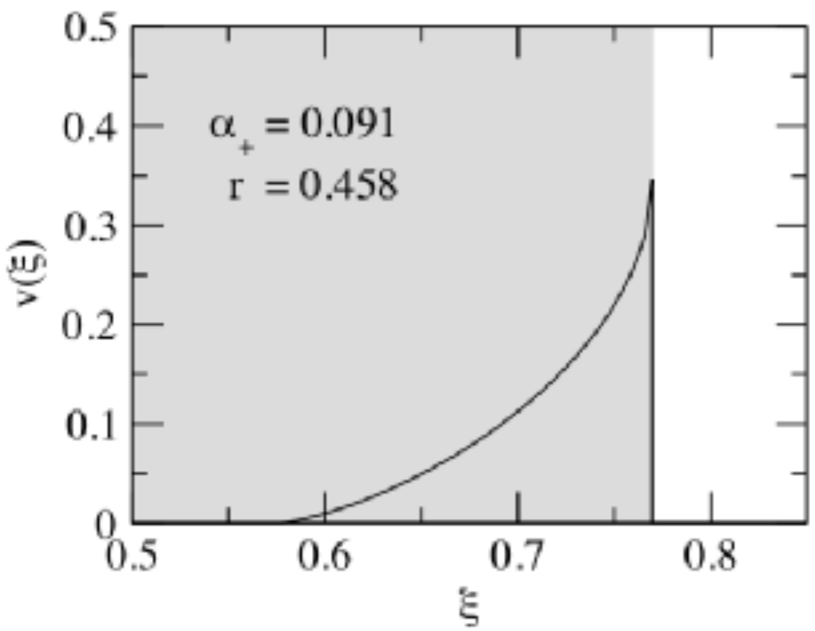
Hydrodynamic equations

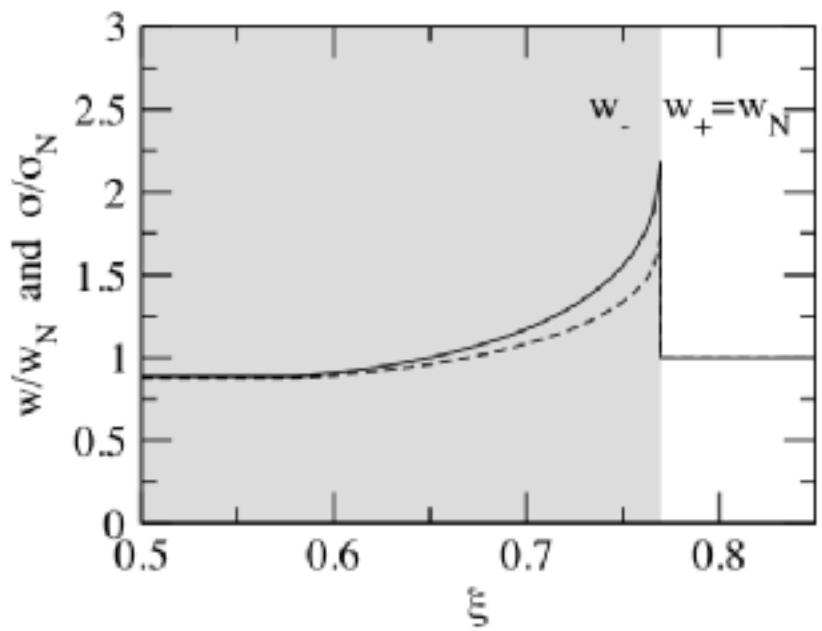
- $$2\frac{v}{\xi} = \gamma^2(1 - v\xi)\left[\frac{\mu^2}{c_s^2} - 1\right]\partial_\xi v\,, \qquad \frac{\partial_v w}{w} = \left(\frac{1}{c_s^2} + 1\right)\gamma^2\mu$$
- Boundary conditions:
  $$w(T_n) = w_n$$
- Matching
  $$\frac{v_+}{v_-} = \frac{e_b(T_-) + p_s(T_+)}{e_s(T_+) + p_b(T_-)}\,, \quad v_+v_- = \frac{p_s(T_+) - p_b(T_-)}{e_s(T_+) - e_b(T_-)}$$



Hydrodynamics of a single bubble

Solution: velocity and enthalpy profiles

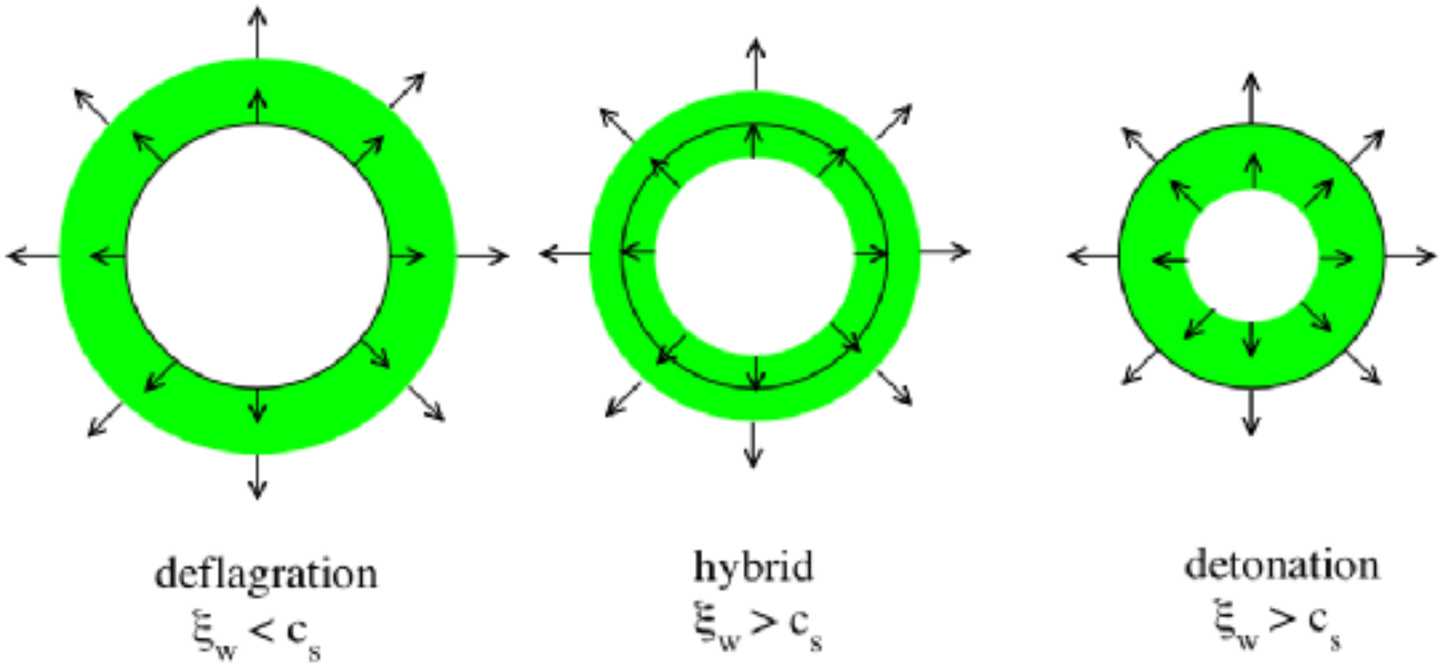




J. Espinosa, T. Konstandin, J. No, G. Servant, 2010

Hydrodynamics of a single bubble

Three types of solutions



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

Kinetic energy fraction

- Kinetic energy in the fluid $$\rho_{fl} = \frac{3}{v_w^3} \int d\xi \, \xi^2 \, v^2 \, \gamma^2 w$$
- Kinetic energy fraction $$K = \frac{\rho_{fl}}{e_n}$$

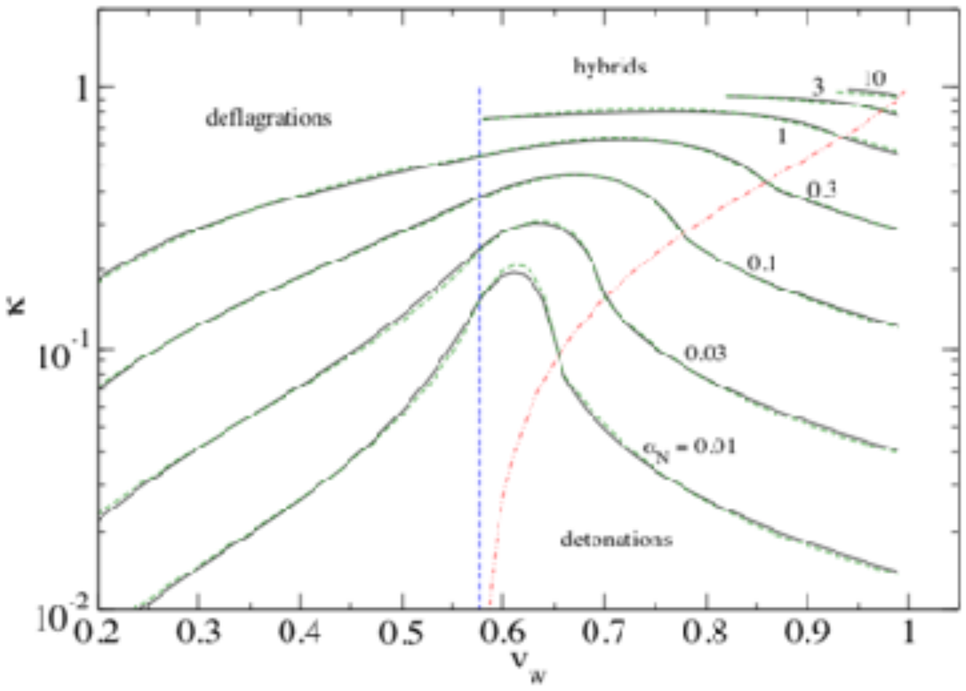
Can we solve these equations “once and for all”?

Solution in the bag model

- $p_s = \frac{1}{3}a_+T^4 - \epsilon \qquad e_s = a_+T^4 + \epsilon$

  $p_b = \frac{1}{3}a_-T^4 \qquad e_b = a_-T^4$

- Bag constant ϵ independent of temperature
- Sound speed $c_s = 1/\sqrt{3}$
- Phase transition strength $\alpha_\epsilon = \frac{4\epsilon}{3w_n}$
- $K = \frac{\alpha_\epsilon \kappa_\epsilon}{\alpha_\epsilon + 1}$ completely determined by α_ϵ and v_w



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

Shortcomings in the bag model

- $\boxed{\begin{array}{ll} p_s = \frac{1}{3}a_+T^4 - \epsilon & e_s = a_+T^4 + \epsilon \\ p_b = \frac{1}{3}a_-T^4 & e_b = a_-T^4 \end{array}}$
- Bag constant ϵ independent of temperature
- ~~Sound speed $c_s = 1/\sqrt{3}$~~
- Phase transition strength $\alpha_\epsilon = \frac{4\epsilon}{3w_n}$
- $K = \frac{\alpha_\epsilon \kappa_\epsilon}{\alpha_\epsilon + 1}$ completely determined by α_ϵ and ξ_w

Not a realistic model

Shortcomings in the bag model

- $$\boxed{\begin{aligned} p_s &= \frac{1}{3}a_+T^4 - \epsilon & \qquad e_s &= a_+T^4 + \epsilon \\ p_b &= \frac{1}{3}a_-T^4 & \qquad e_b &= a_-T^4 \end{aligned}}$$
- Bag constant ϵ independent of temperature
- ~~Sound speed $c_s = 1/\sqrt{3}$~~
- Phase transition strength $\boxed{\alpha_\epsilon = \dfrac{4\epsilon}{3w_n}}$
- $K = \dfrac{\alpha_\epsilon \kappa_\epsilon}{\alpha_\epsilon + 1}$ completely determined by α_ϵ and ξ_w

Not a realistic model

How does this get generalized?

Beyond the bag model

Model-independent matching

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

Beyond the bag model

Model-independent matching

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

Beyond the bag model

Model-independent matching

- $$\frac{v_+}{v_-} = \frac{e_b(T_-) + p_s(T_+)}{e_s(T_+) + p_b(T_-)}, \qquad v_+ v_- = \frac{p_s(T_+) - p_b(T_-)}{e_s(T_+) - e_b(T_-)}$$
- Assume $T_+ \sim T_-$
- $$\frac{v_+}{v_-} \simeq \frac{(v_+ v_- / c_{s,b}^2 - 1) + 3\alpha_{\bar{\theta}}}{(v_+ v_- / c_{s,b}^2 - 1) + 3 v_+ v_- \alpha_{\bar{\theta}}}$$
- $$\bar{\theta} \equiv e - \frac{p}{c_{s,b}^2} \qquad \alpha_{\bar{\theta}} \equiv \frac{D\bar{\theta}}{3 w_n}$$

Beyond the bag model

Model-(in)dependent hydrodynamic equations

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

Take constant in broken and symmetric phase

Model-independent hydrodynamics

- All model-dependence is captured by $v_w, \alpha_{\bar{\theta}}, c_{s,b}, c_{s,s}$ *
- Determine $\kappa_{\bar{\theta}} = \dfrac{4\rho_{fl}}{D\bar{\theta}}$ model-independently
- Find $K = \dfrac{D\bar{\theta}}{4e_n}\kappa_{\bar{\theta}}$

* As long as $T_- \sim T_+$ is reasonable

Template model

Model with speed of sound $c_s \neq 1\sqrt{3}$ (but constant)

- $$p_s = \frac{1}{3}a_+T^\mu - \epsilon \qquad e_s = a_+(\mu - 1)T^\mu + \epsilon$$
  $$p_b = \frac{1}{3}a\_T^\nu \qquad e_b = \frac{1}{3}a\_(\nu - 1)T^\nu$$

L. Leitao,
A. Megevand, 2015

- $$\nu = 1 + \frac{1}{c^2_{s,\text{broken}}}, \quad \mu = 1 + \frac{1}{c^2_{s,\text{symm}}}$$

Python snippet (2010.09744) computes efficiency factor

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
```

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

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

How well does this work?

Two toy models

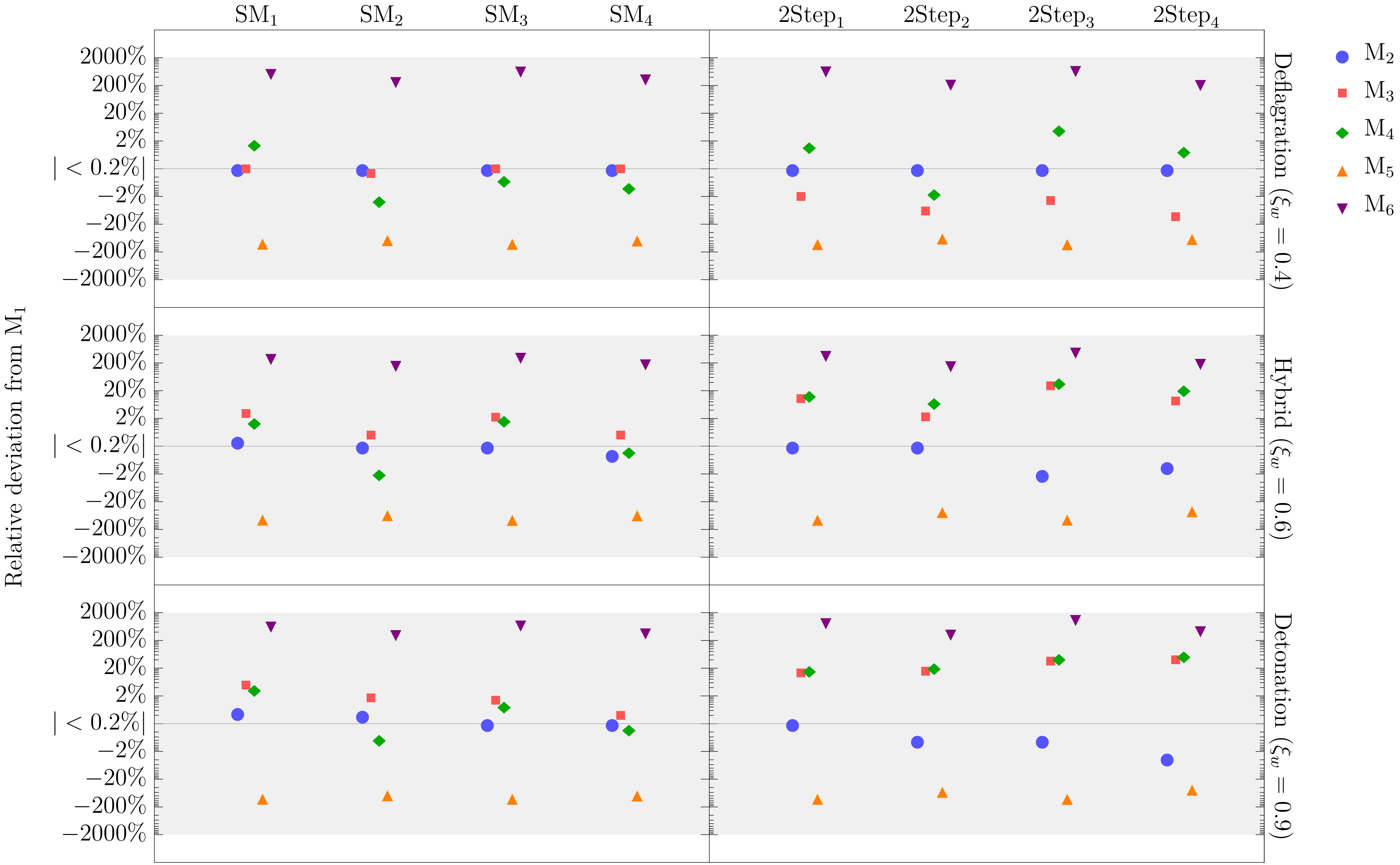
- SM with a light Higgs
- Two-step phase transition
- Choose nucleation temperature manually

Model	T_+/T_{cr}	$\alpha_{\bar{\theta}}$	c_s^2
SM_1	0.9	0.0297	0.326
SM_2	0.8	0.0498	0.331
SM_3	0.9	0.00887	0.331
SM_4	0.8	0.0149	0.333

Model	T_+/T_{cr}	$\alpha_{\bar{\theta}}$	c_s^2
$2\mathrm{step}_1$	0.9	0.0156	0.312
$2\mathrm{step}_2$	0.7	0.0704	0.297
$2\mathrm{step}_3$	0.9	0.0254	0.282
$2\mathrm{step}_4$	0.7	0.159	0.245

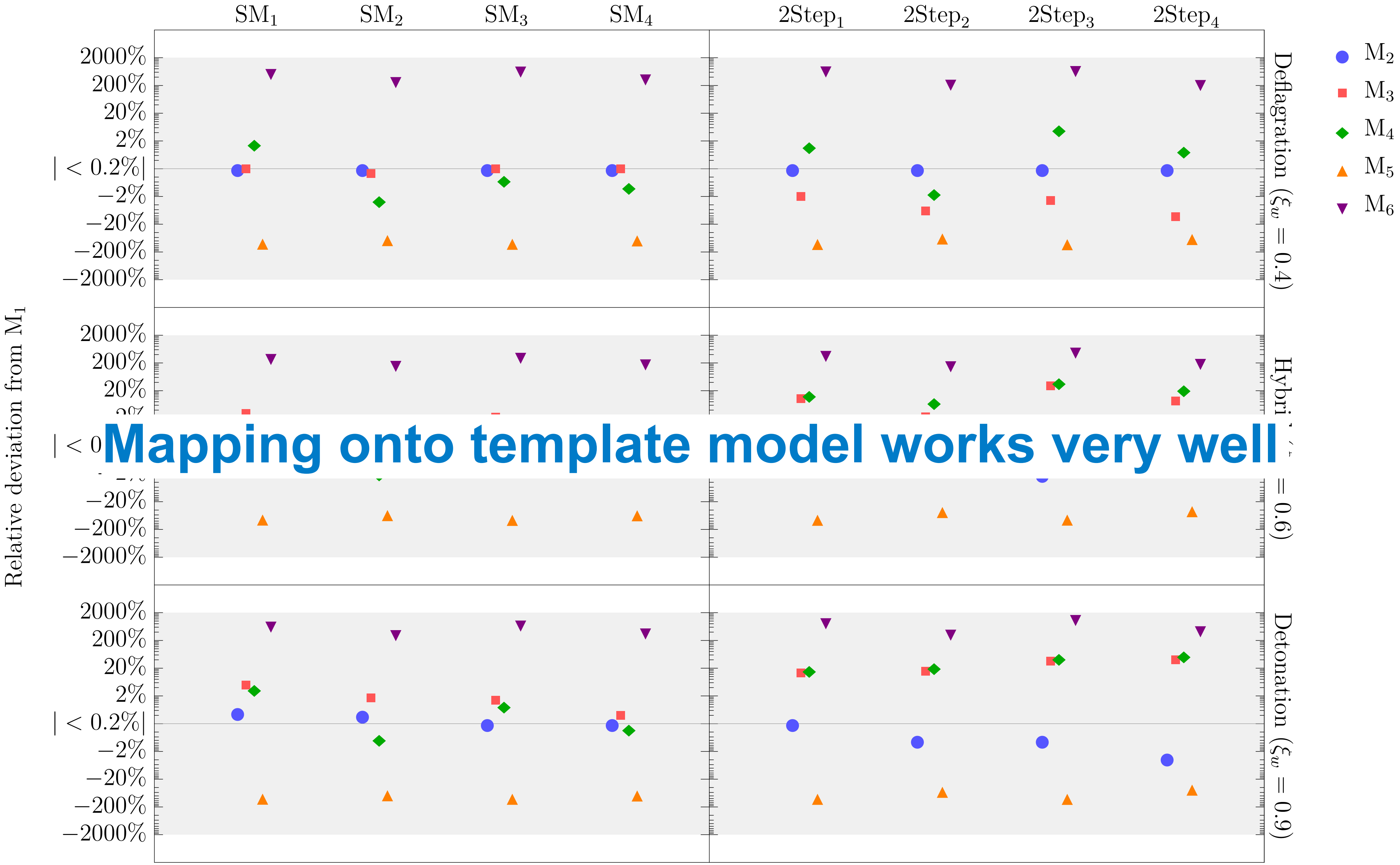
Six different methods to determine K

M1	Full numerical solution
M2	Mapping onto template model
M3 & M4	Mapping onto bag model via trace of energy-momentum tensor
M5	Mapping onto bag model via pressure difference
M6	Mapping onto bag model via energy-density difference



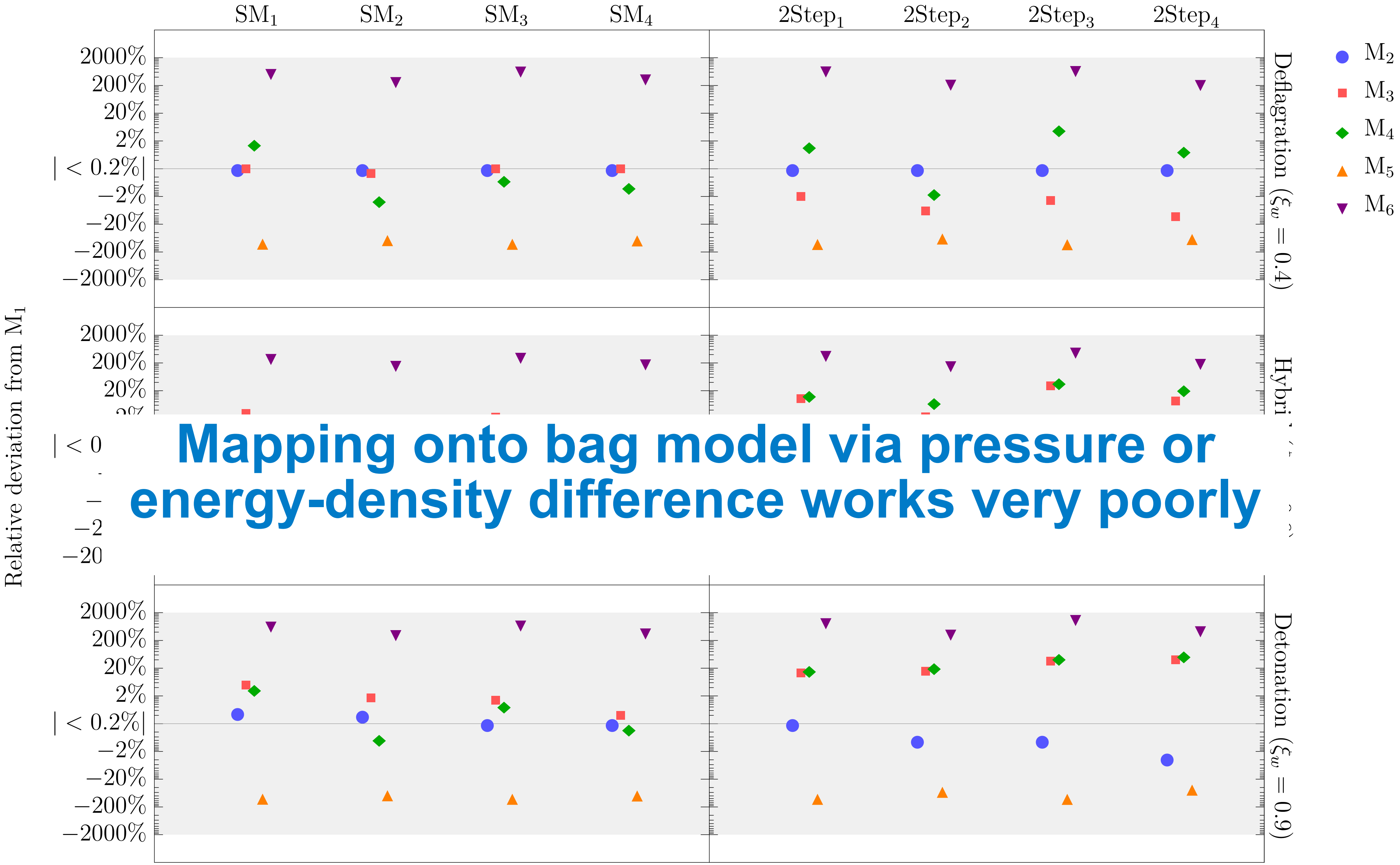
SM$_1$
SM$_2$
SM$_3$
SM$_4$
2Step$_1$
2Step$_2$
2Step$_3$
2Step$_4$
Relative deviation from M$_1$
2000%
200%
20%
2%
$|<0.2\%|$
-2%
-20%
-200%
-2000%
Deflagration ($\xi_w = 0.4$)
Hybrid ($\xi_w = 0.6$)
Detonation ($\xi_w = 0.9$)
M$_2$
M$_3$
M$_4$
M$_5$
M$_6$

DESY.



Mapping onto template model works very well

Mapping onto bag model via pressure or energy-density difference works very poorly



Beyond the toy model: two-step revisited

What is a realistic value for the sound speed?

- $$V_{\rm tree}(h,s) = -\frac{\mu_h^2}{2}h^2 + \frac{\lambda_h}{4}h^4 - \frac{\mu_s^2}{2}s^2 + \frac{\lambda_s}{4}s^4 + \frac{\lambda_{hs}}{4}h^2 s^2 + \Delta V_h$$
- $$V_T(h,s) = \frac{T^4}{2\pi^2}\sum_\alpha N_\alpha \int_0^\infty dx x^2 \log\left[1 \pm e^{-\sqrt{x^2 + M_\alpha^2(h,s)/T^2}}\right] + \frac{T}{12\pi}\sum_{\text{bosons }\alpha} N_\alpha \left[M_\alpha^3(h,s) - M_{T,\alpha}^3(h,s,T)\right]$$

Heavy particles

Light particles

- $$V_{\delta T} = -\frac{\pi^2}{90} g'_* T^4, \qquad g'_* = \frac{345}{4}$$
- $$V_{\rm eff} = V_{\rm tree} + V_{cw} + V_{ct} + V_T + V_{\delta T}$$

Beyond the toy model: two-step revisited

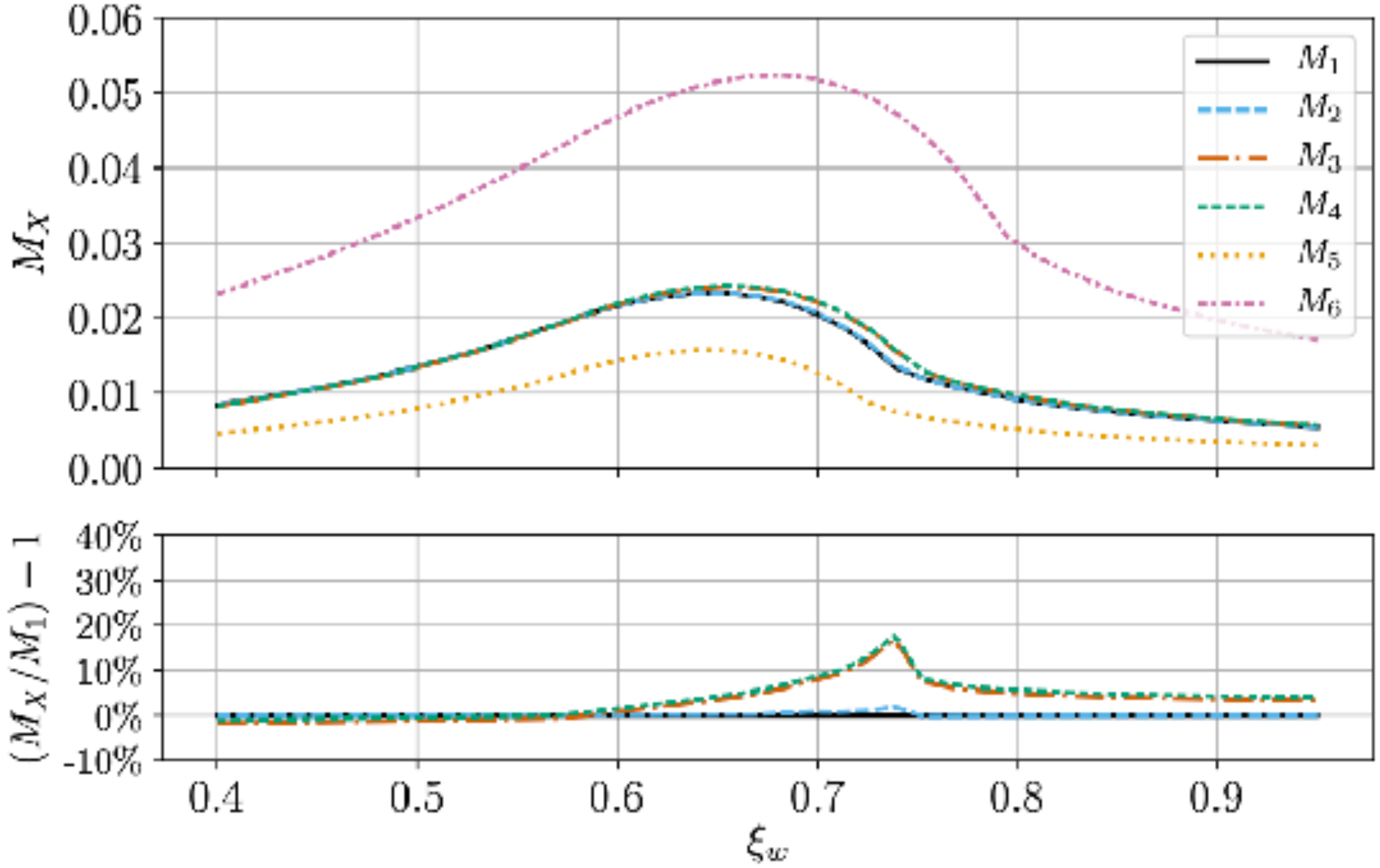
What is a realistic value for the sound speed?

- Find nucleation temperature via $\frac{S_3}{T} \approx 140$ (one bubble per Hubble)

m_s(GeV)	λ_s	λ_{hs}	T_n(GeV)	β/H_*	α_e	$\alpha_{\bar{\theta}n}$	$c^2_{s,b}$	$c^2_{s,s}$
300	1.90	3.50	87.3	288	0.070	0.035	0.324	0.333
250	2.80	2.80	71.1	152	0.126	0.075	0.325	0.334
250	0.40	2.26	98.9	367	0.051	0.022	0.325	0.333
170	2.80	1.80	69.5	335	0.119	0.065	0.324	0.334

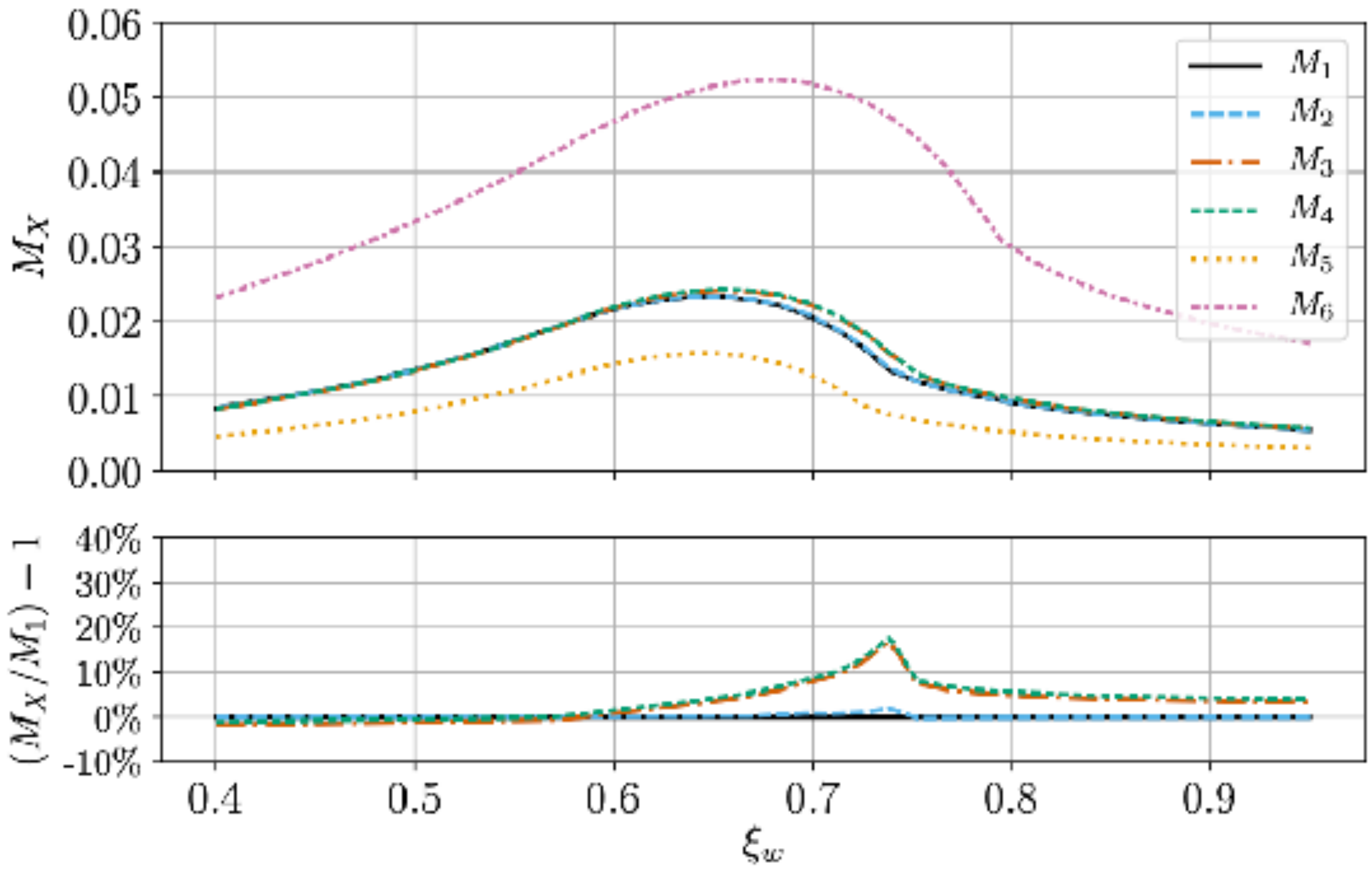
$\sim 1/3...$

Beyond the toy model: two-step revisited



$m_s = 170\,\mathrm{GeV}$

Beyond the toy model: two-step revisited



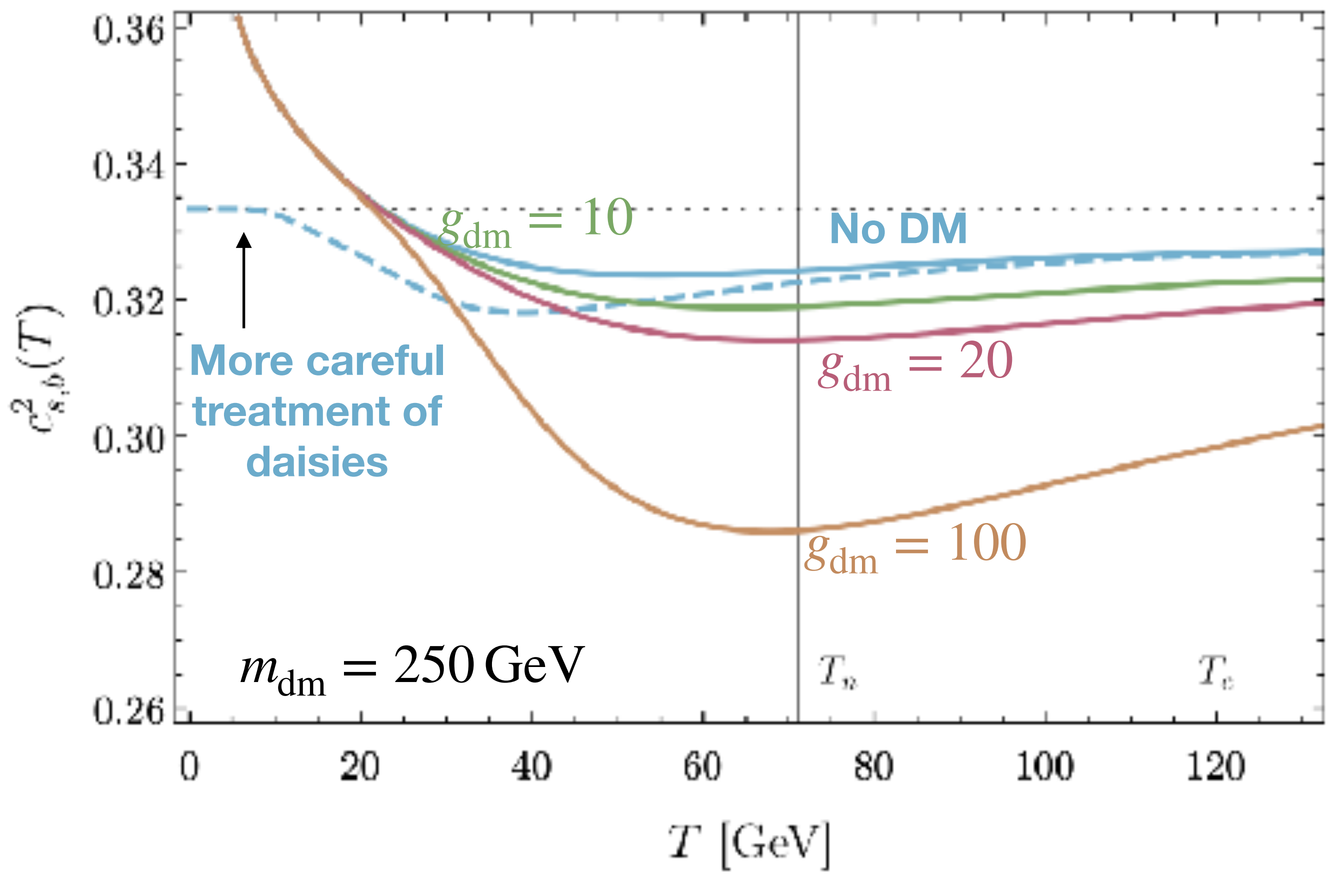
$m_s = 170\,\mathrm{GeV}$

Note that $\Omega_{\mathrm{tot}} \propto K^2$ or $K^{3/2}$

Deviations in sound speed from $c_s^2 \sim 1/3$

Sound speed affected by presence of heavy particles

- Many relativistic particles in the SM
- Presence of massive particles suppresses the sound speed



Beyond the toy model: two-step revisited revisited

Problems with Daisy resummation!

- Daisy resummation can be very inaccurate (e.g. Croon, Gould, Schicho, Tenkanen, White 2020)
- Ongoing work with T. Tenkanen: computation of the sound speed using Dimensional Reduction

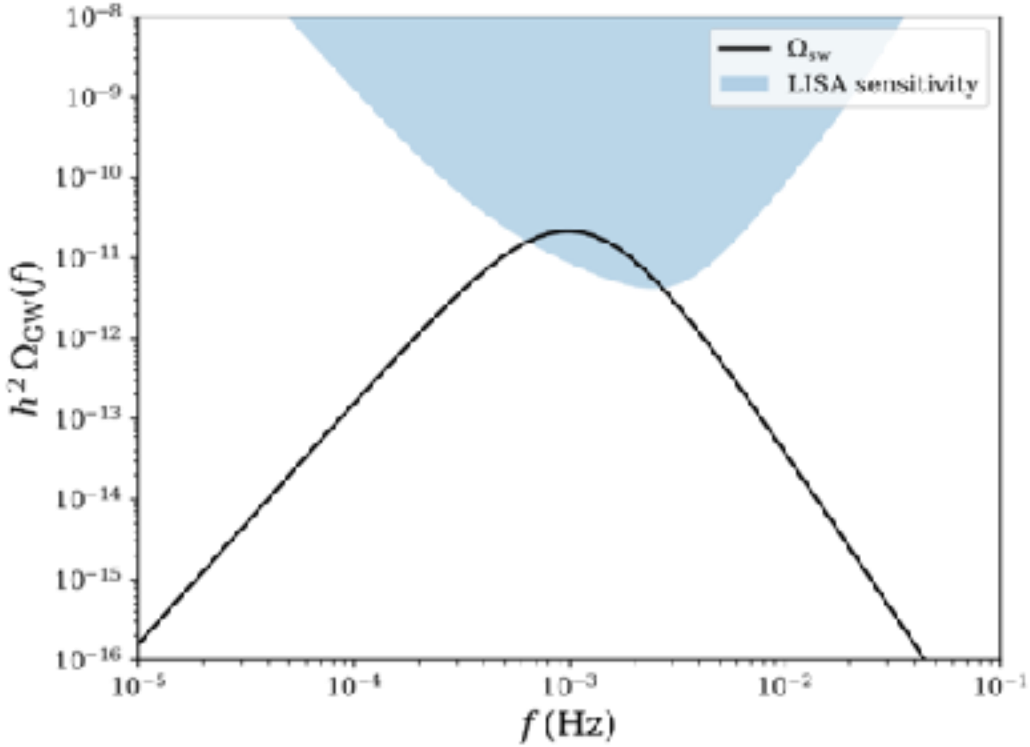
What does this mean for the gravitational wave signal?

Fit to lattice result

Effect on amplitude only

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

Lattice computation assumed
$c_s = 1/\sqrt{3}$



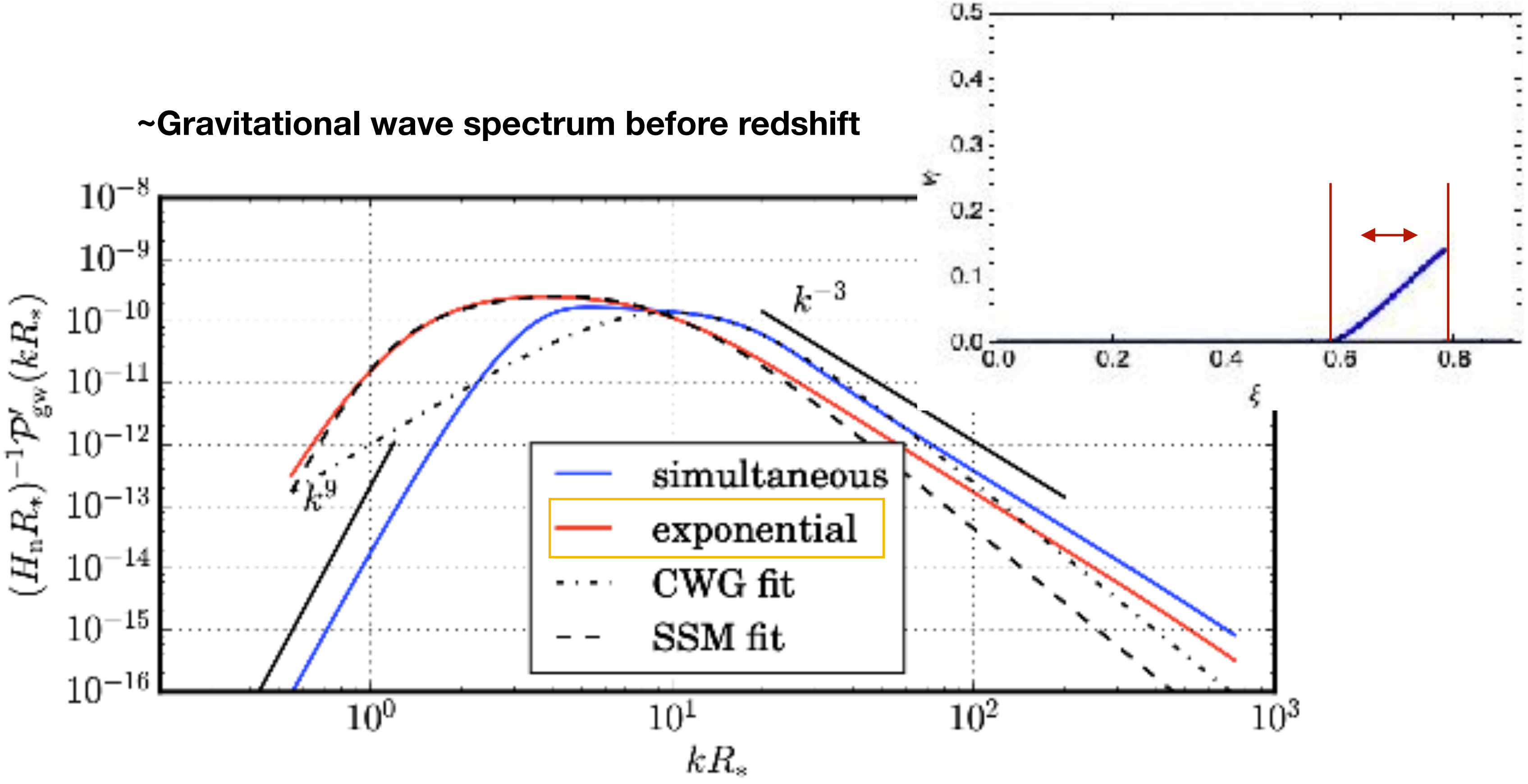
Sound-shell model (alternative to lattice simulations)

Thickness of fluid profile affects shape of the spectrum

Hindmarsh 2016
Hindmarsh, Hijazi 2019

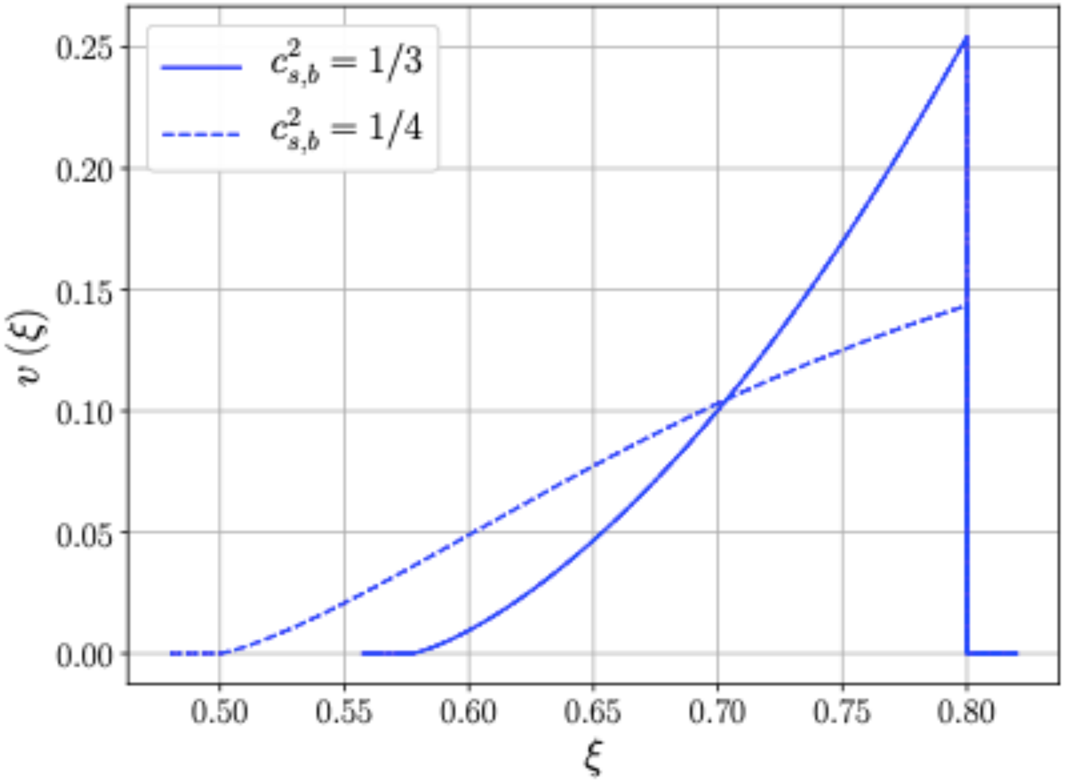
~Gravitational wave spectrum before redshift

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

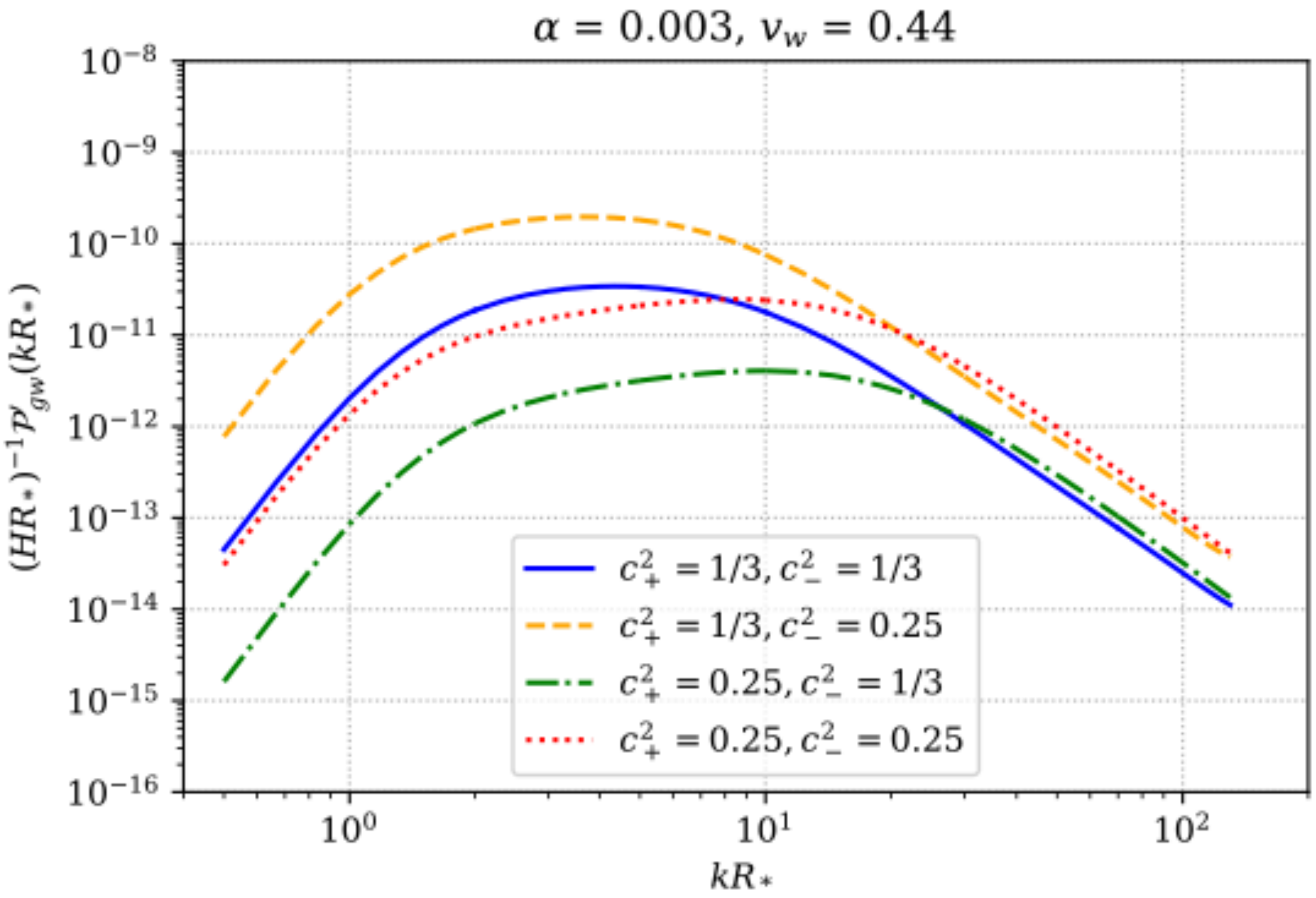


proportional to f

Effect of the sound speed on fluid profile



Effect of the sound speed on gravitational wave spectrum (sound shell model)



Wang, Huang, Li, 2021

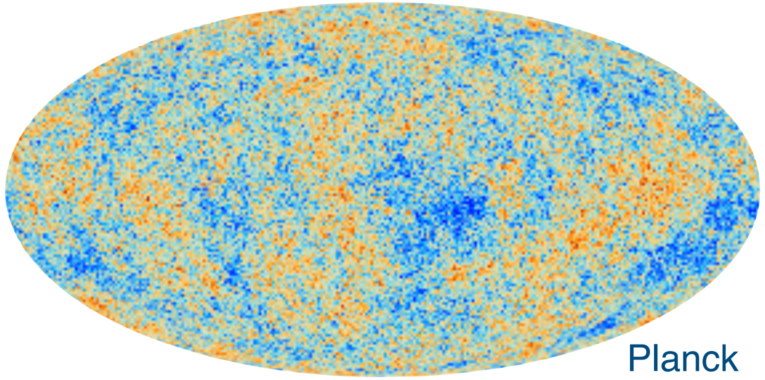
In addition to T_*, β, α, v_w, also $c_{s,b}$ and $c_{s,s}$ affect the gravitational wave spectrum.

In addition to T_*, β, α, v_w, also $c_{s,b}$ and $c_{s,s}$ affect the gravitational wave spectrum.

But more parameters come into play… (2108.11947)

Primordial perturbations

- On CMB scales: $\dfrac{\delta T}{T} \sim 10^{-4}$
- Maybe $\dfrac{\delta T}{T}$ 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 $\left|\frac{\beta}{H_*}\frac{\delta T}{\bar{T}}\right| \equiv |\delta\tilde{T}| \gtrsim 1$
- $\frac{\beta}{H_*} = \mathcal{O}(100) \to \frac{\delta T}{\bar{T}}$ can be moderate

Numerics

- 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

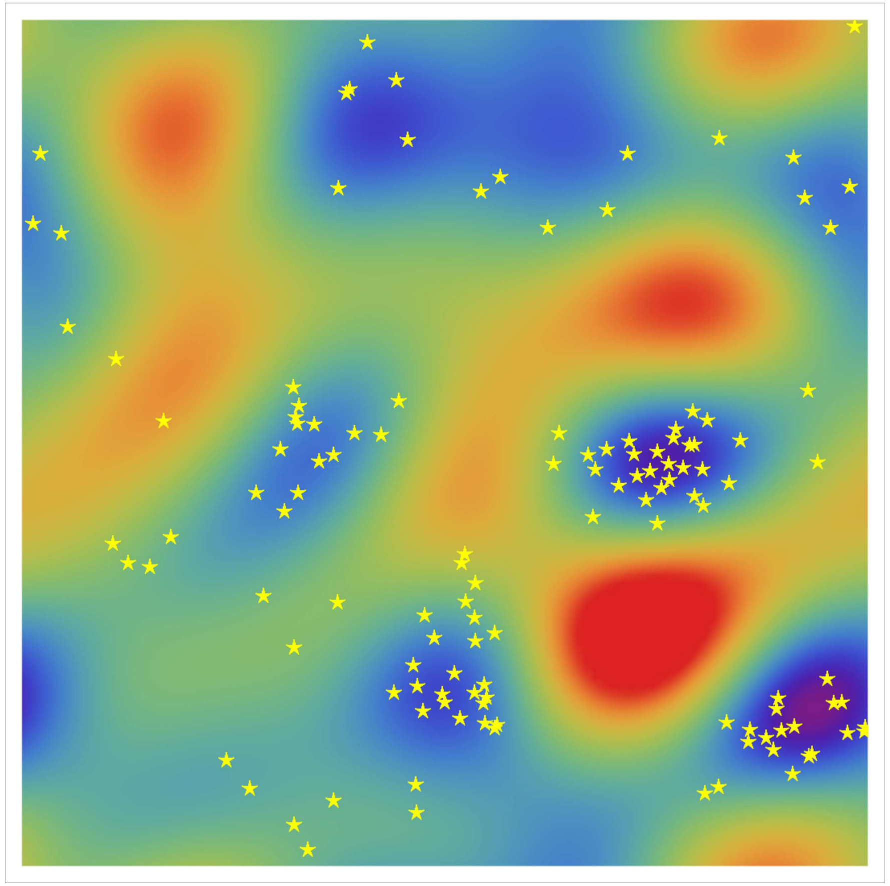
- k-modes move with c_s
- Spectrum: top-hat between k_* and $k_*/2$
- Power in perturbations $\sigma^2 = \frac{1}{V}\int d^3x\delta\tilde{T}(x)^2 = \int \frac{d^3k}{(2\pi)^3}\mathscr{P}_{\delta\tilde{T}}(k)$
- Expect strongest effect for $k_* \sim R_*^{-1} \sim \frac{\beta}{(8\pi)^{1/3}}$

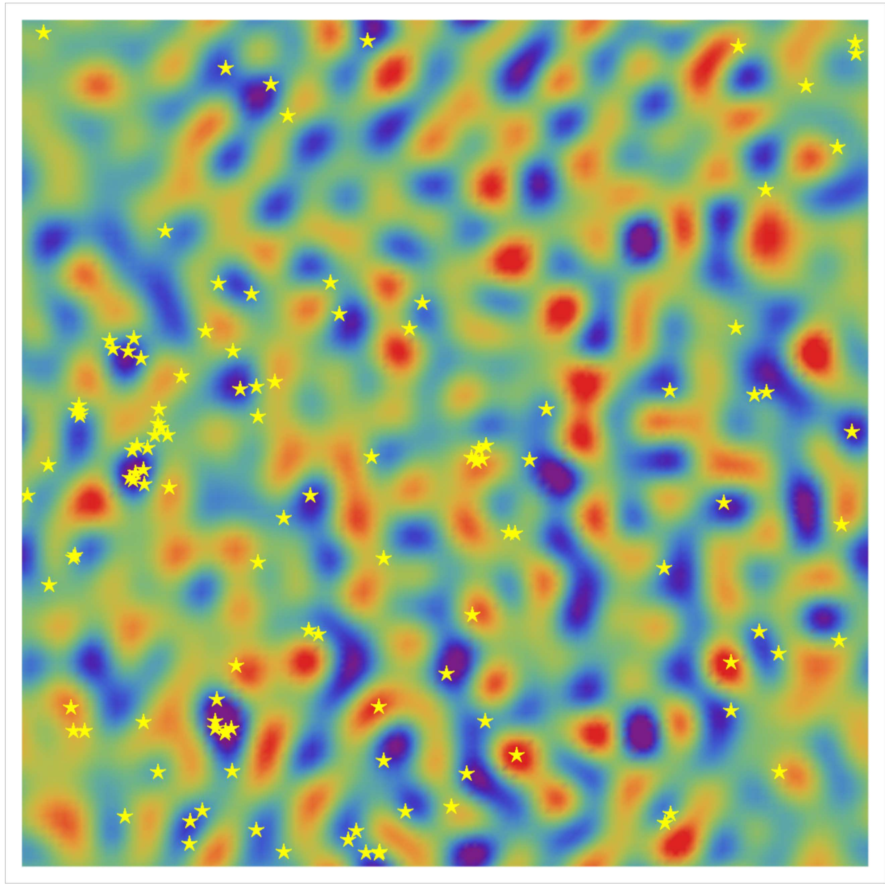
$\delta T = 0$

Results

Nucleation sites

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





$\Delta z = 2/\beta$

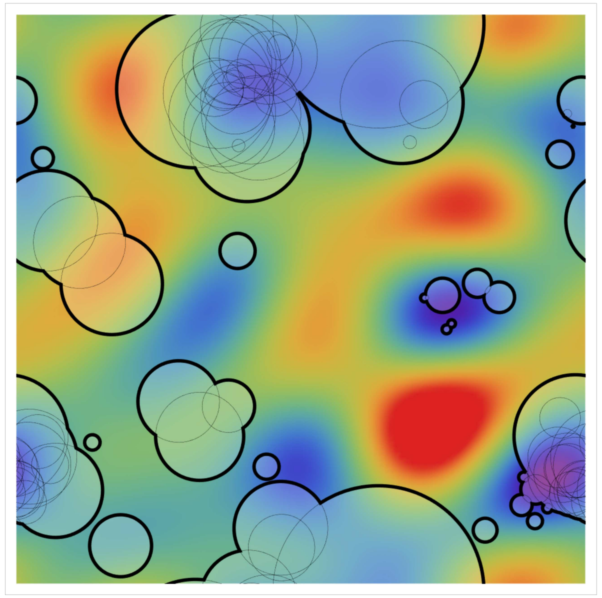
"IR": $4 \times (2\pi/L)$

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

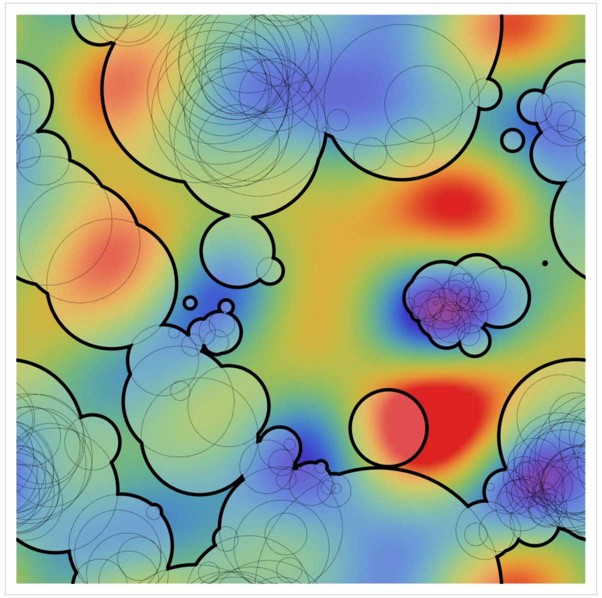
Results

Larger effective bubbles

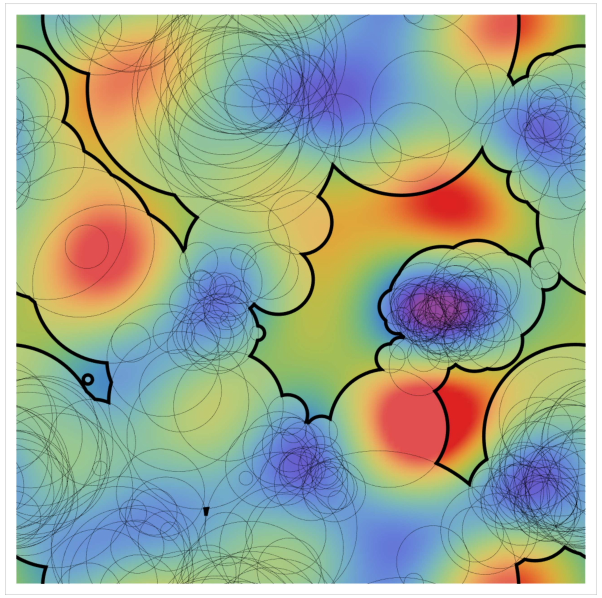
$$\sigma = 3, \quad k_* = 4 \times (2\pi/L)$$



$t = -6/\beta$



$t = -5/\beta$

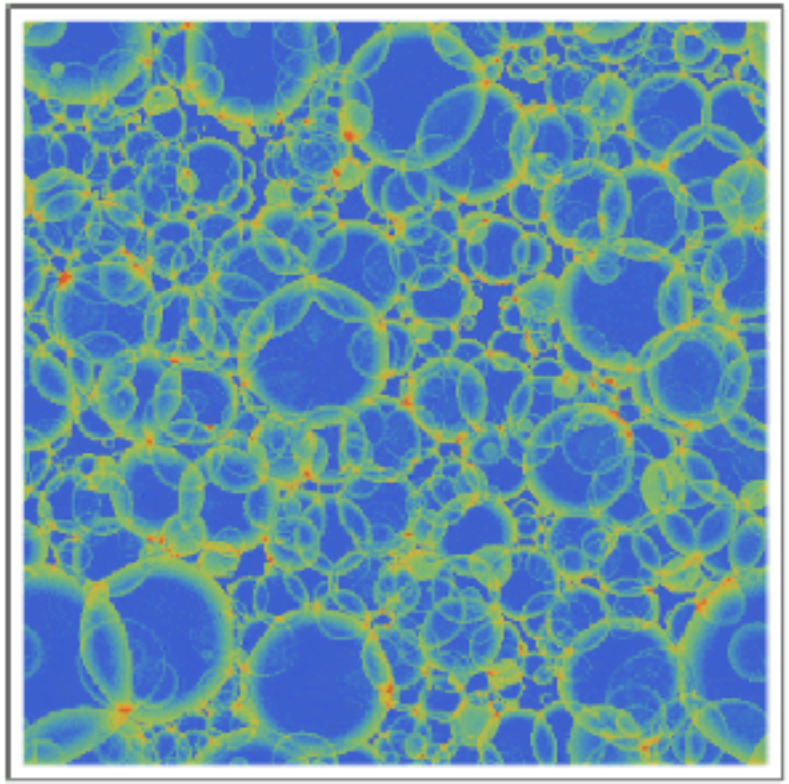


$t = -4/\beta$

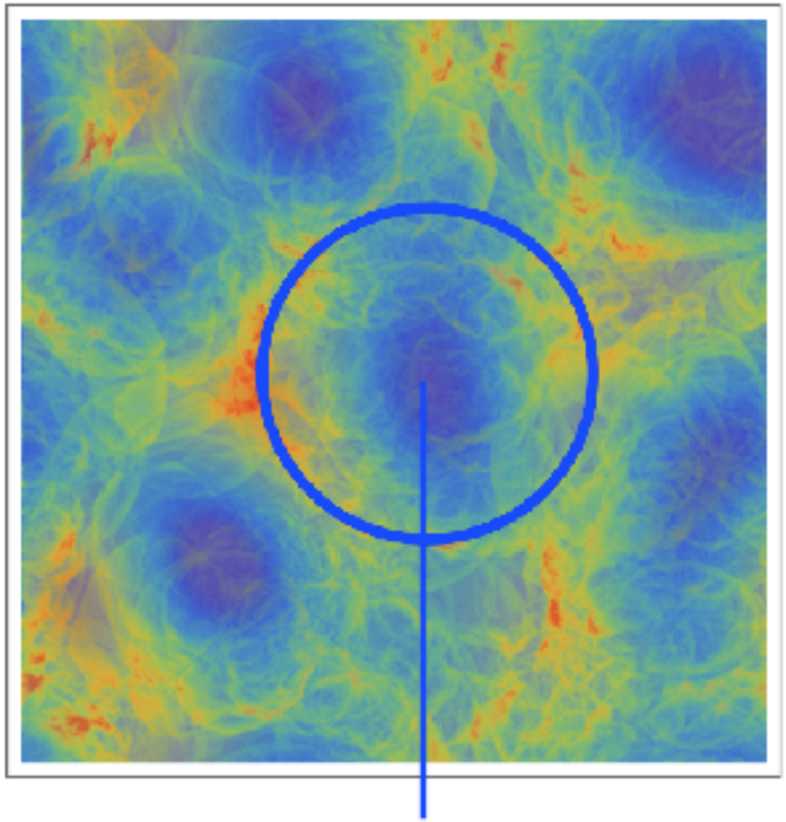
Results

Larger effective bubbles

From R. Jinno



No temperature fluctuations



formation of "effective big bubbles" around the cold spots

Results

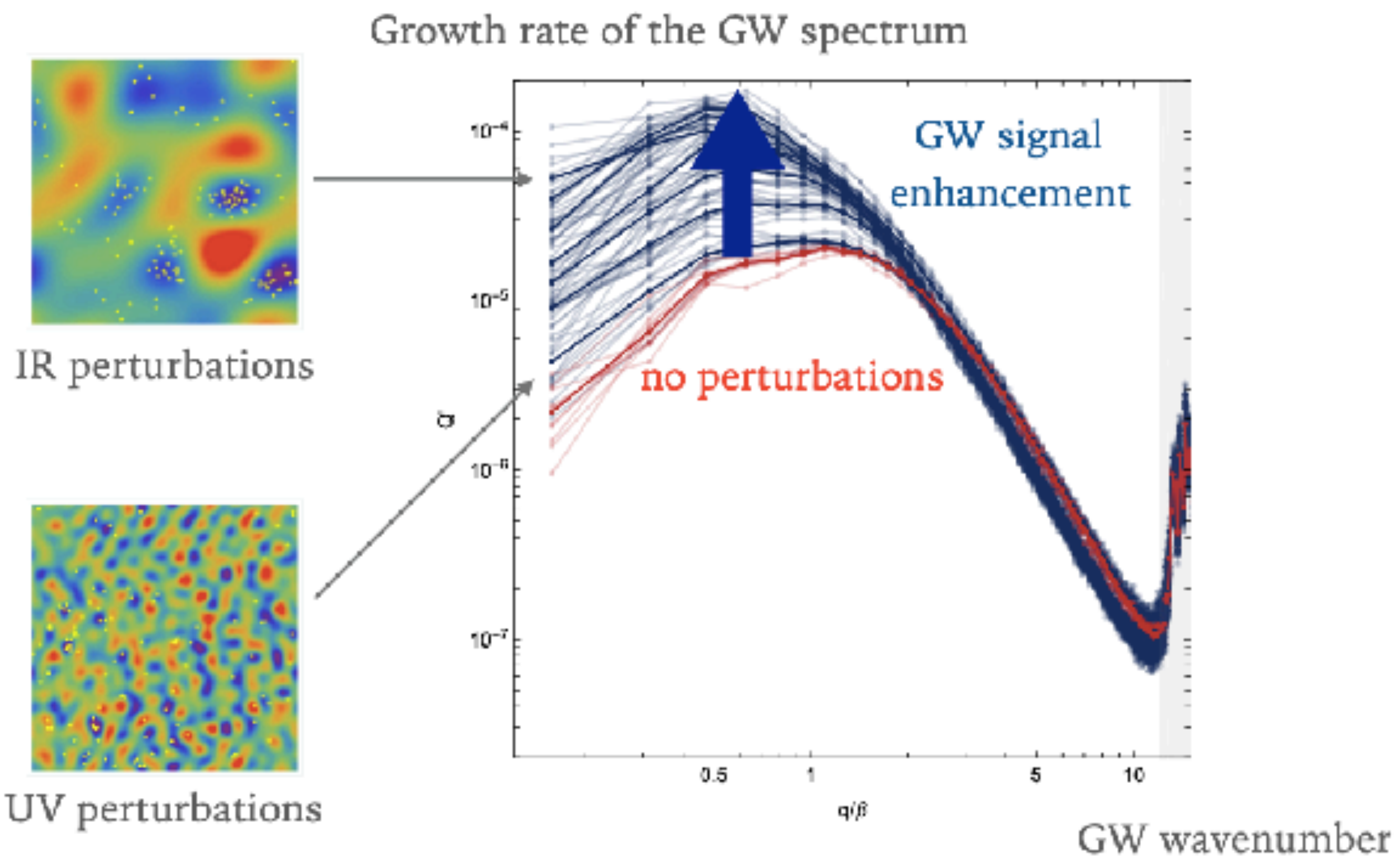
Gravitational wave signal

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

Results

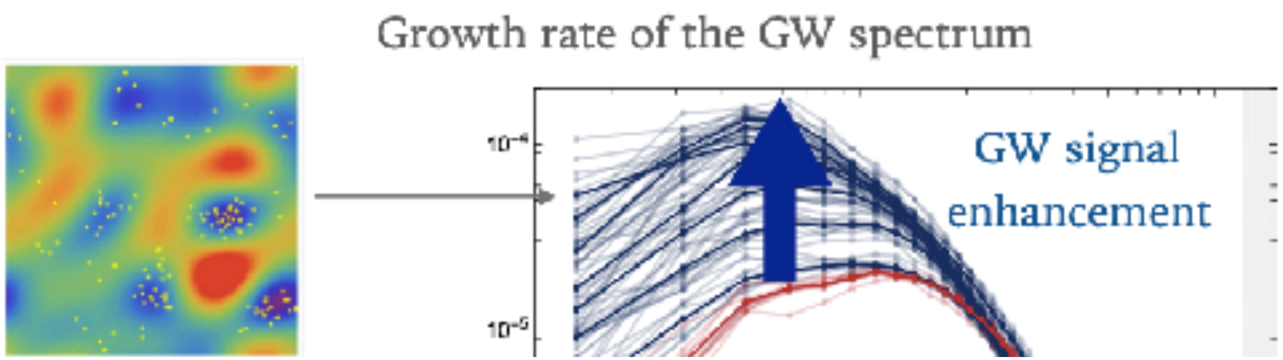
Gravitational wave signal

From R. Jinno



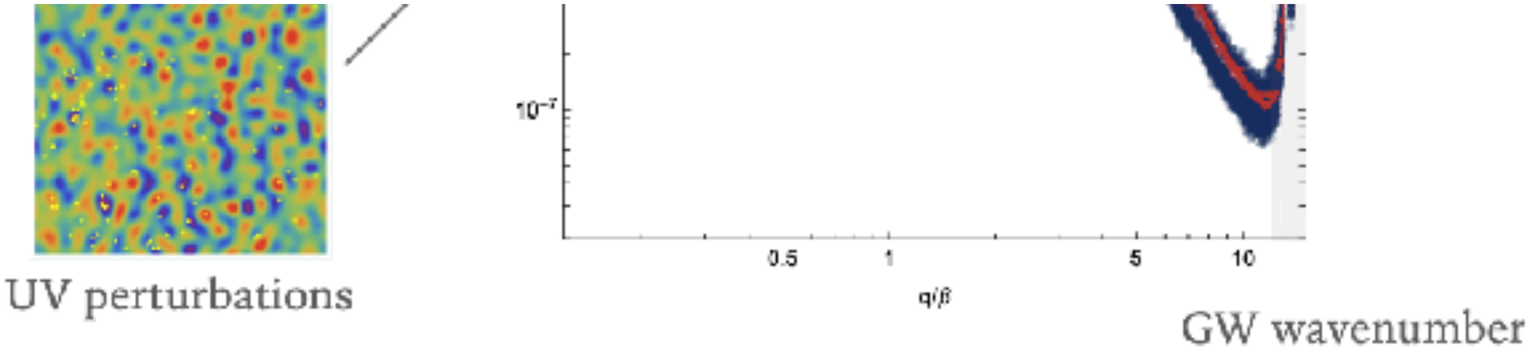
Results

Gravitational wave signal



From R. Jin

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



The ideal situation - how close are we?

- We know exactly what the gravitational wave spectrum looks like
- There are enough model-dependent features to distinguish between different BSM models

- We are making progress!

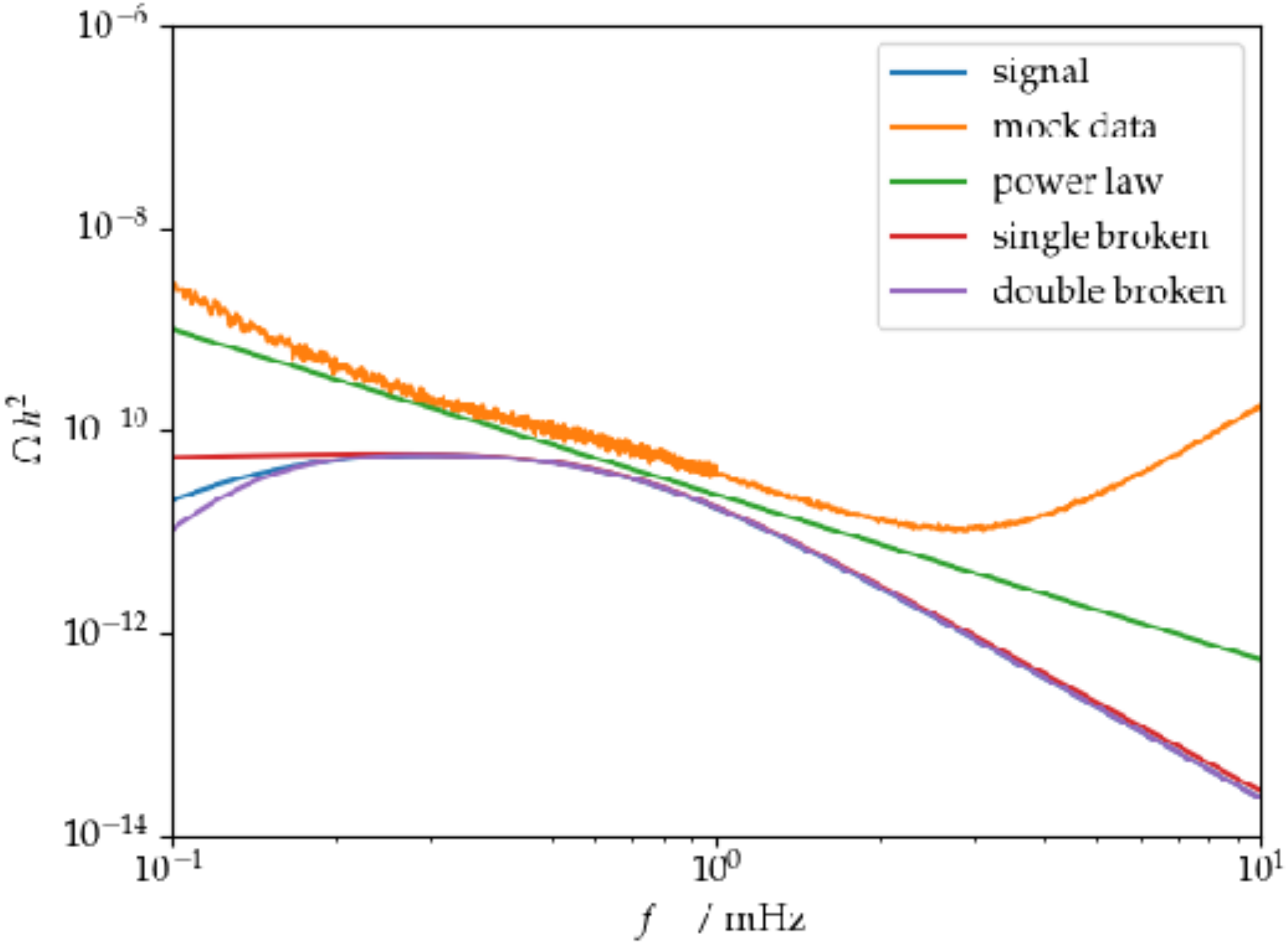
The ideal situation - how close are we?

- We know exactly what the gravitational wave spectrum looks like
- There are enough model-dependent features to distinguish between different BSM models

- Challenges ahead:
- Improved simulations
- Simulations combining different effects
- Accurate computation of phase transition parameters
- Computation of the wall velocity

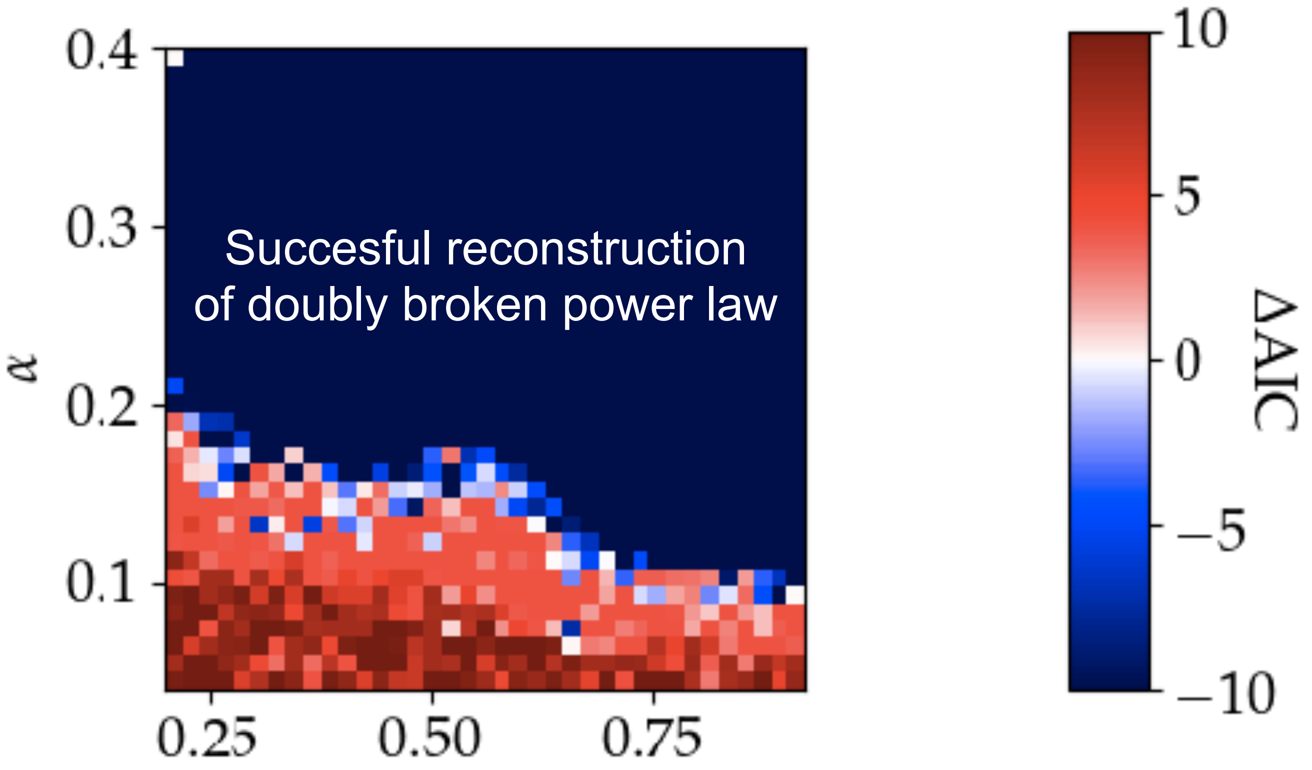
Can all of this be measured?

Can LISA reconstruct a doubly broken power law? 2107.06275



Reconstruction of the doubly broken power law

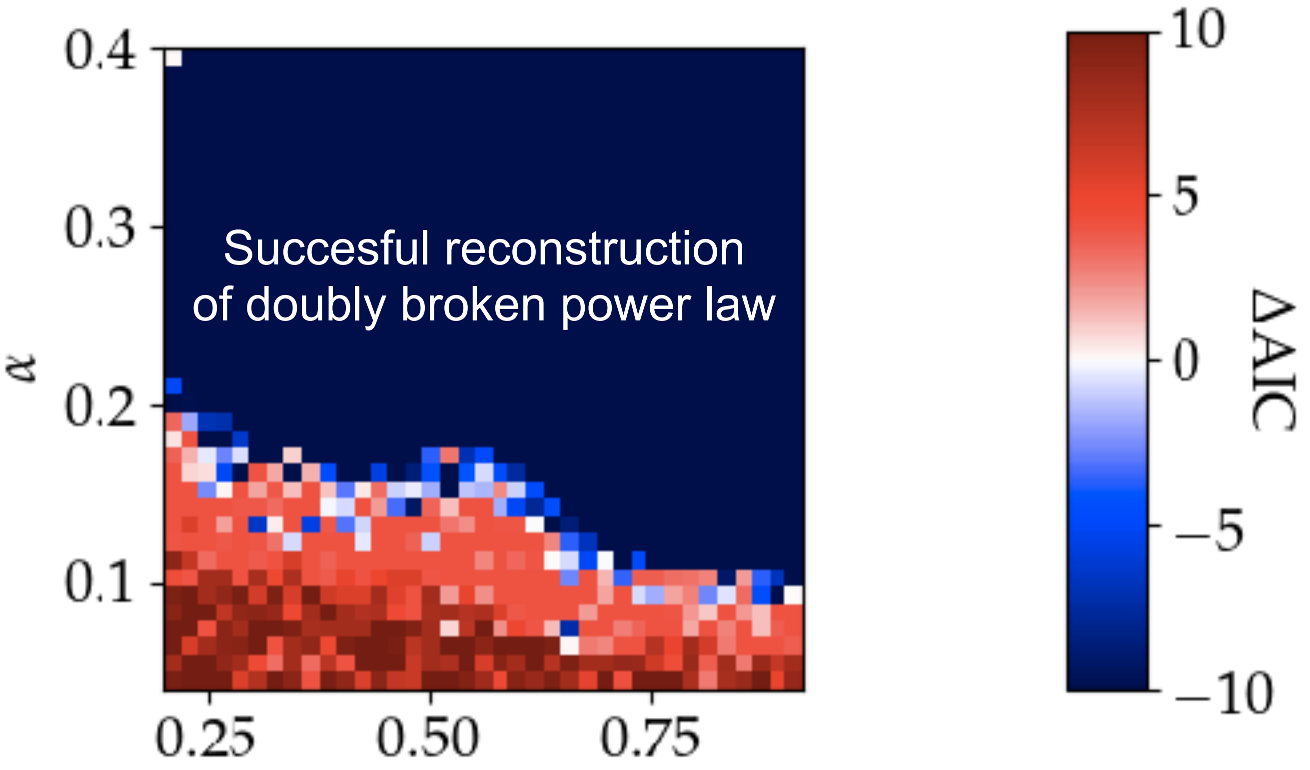
Composite Higgs/gauged lepton models



But for other extensions of the SM, reconstruction is not successful.

Reconstruction of the doubly broken power law

Composite Higgs/gauged lepton models



But for other extensions of the SM, reconstruction is not successful.
Reconstruction of all relevant parameters is not likely with LISA.

The ideal situation - how close are we?

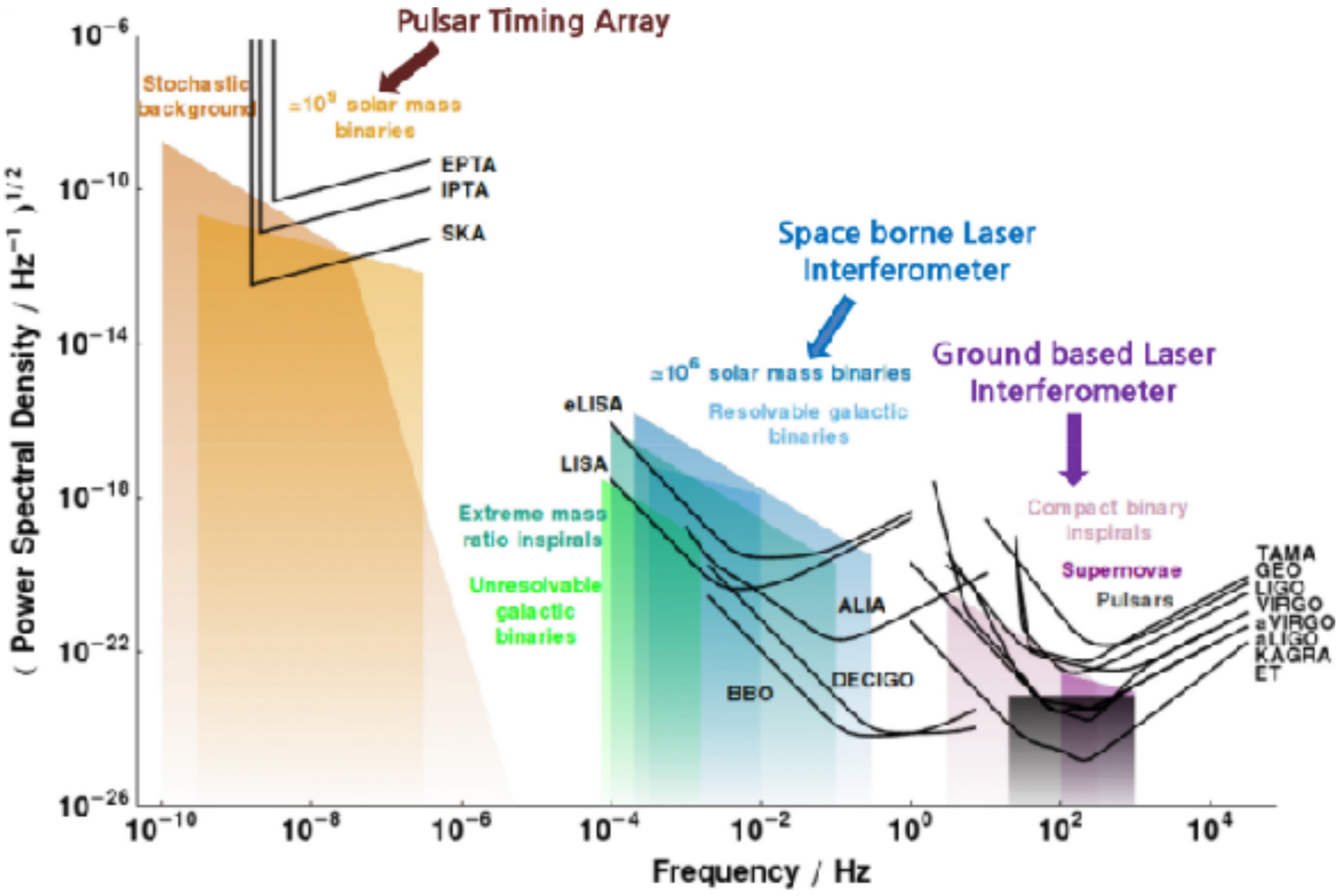
- The GW signal can be completely reconstructed by LISA
- We can infer the particle physics model from the signal

- Maybe we need a more sensitive detector…
- Need to develop a strategy to infer the model from the GW signal

Conclusion

- The sound wave gravitational wave spectrum depends on $T_*, \beta, \alpha, v_w, c_{s,b}, c_{s,s}$.
- Hydrodynamic equations can easily be solved in the template model.
- Realistic computation of sound speed is work in progress.
- Primordial perturbations can enhance and deform the signal.
- Not all of these effects have been simulated simultaneously.
- If LISA detects a gravitational wave signal, degeneracies likely remain.

The future looks (and sounds) bright!



Park 2021