

Gravitational waves and particle physics

Thomas Konstandin



Ljubljana, June 16, 2020

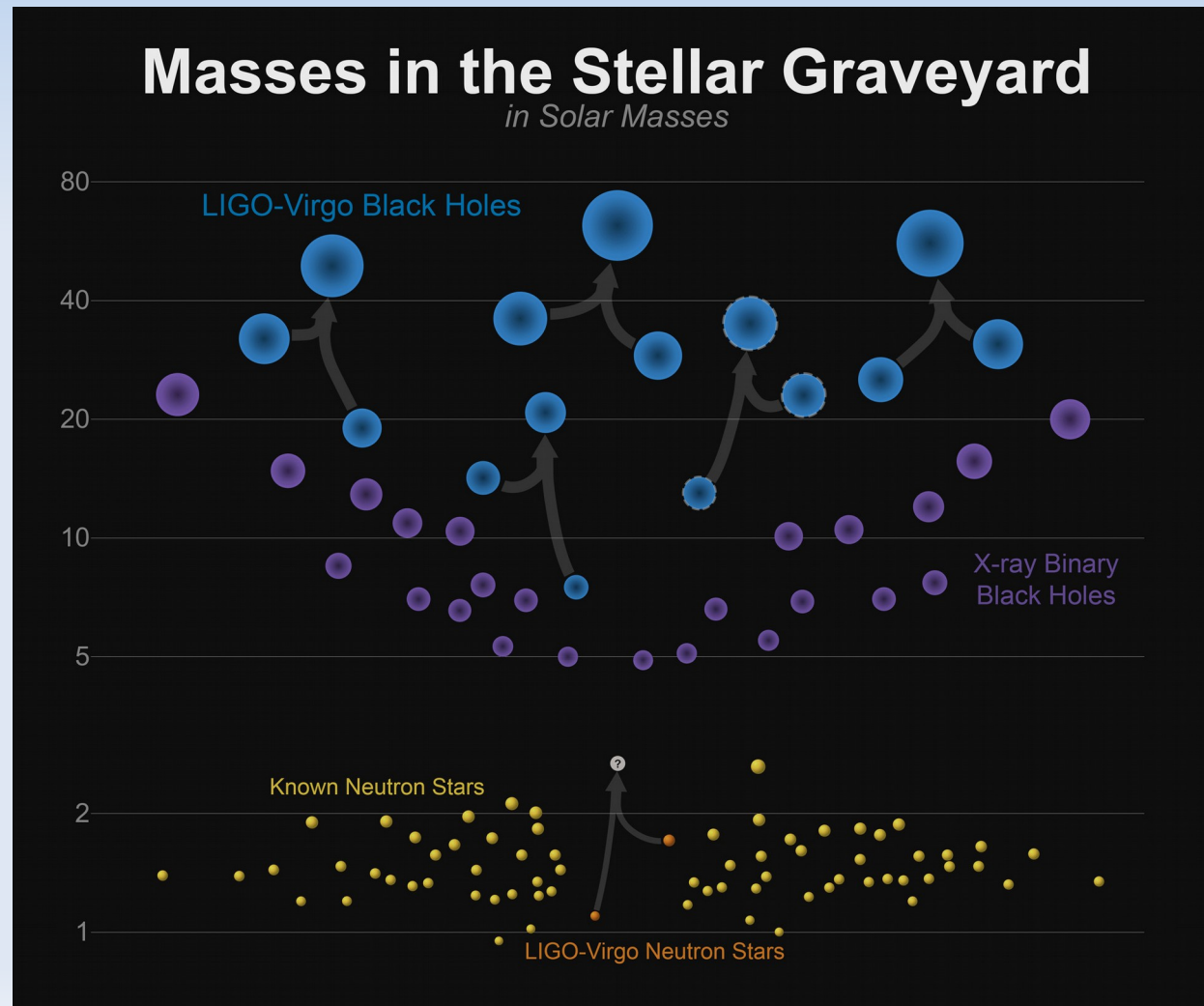
Part I: binary mergers and particle physics

Observation of black hole merges put GW astrophysics and multi-messenger astronomy firmly on the physics landscape. But what can we learn in particle physics and cosmology?

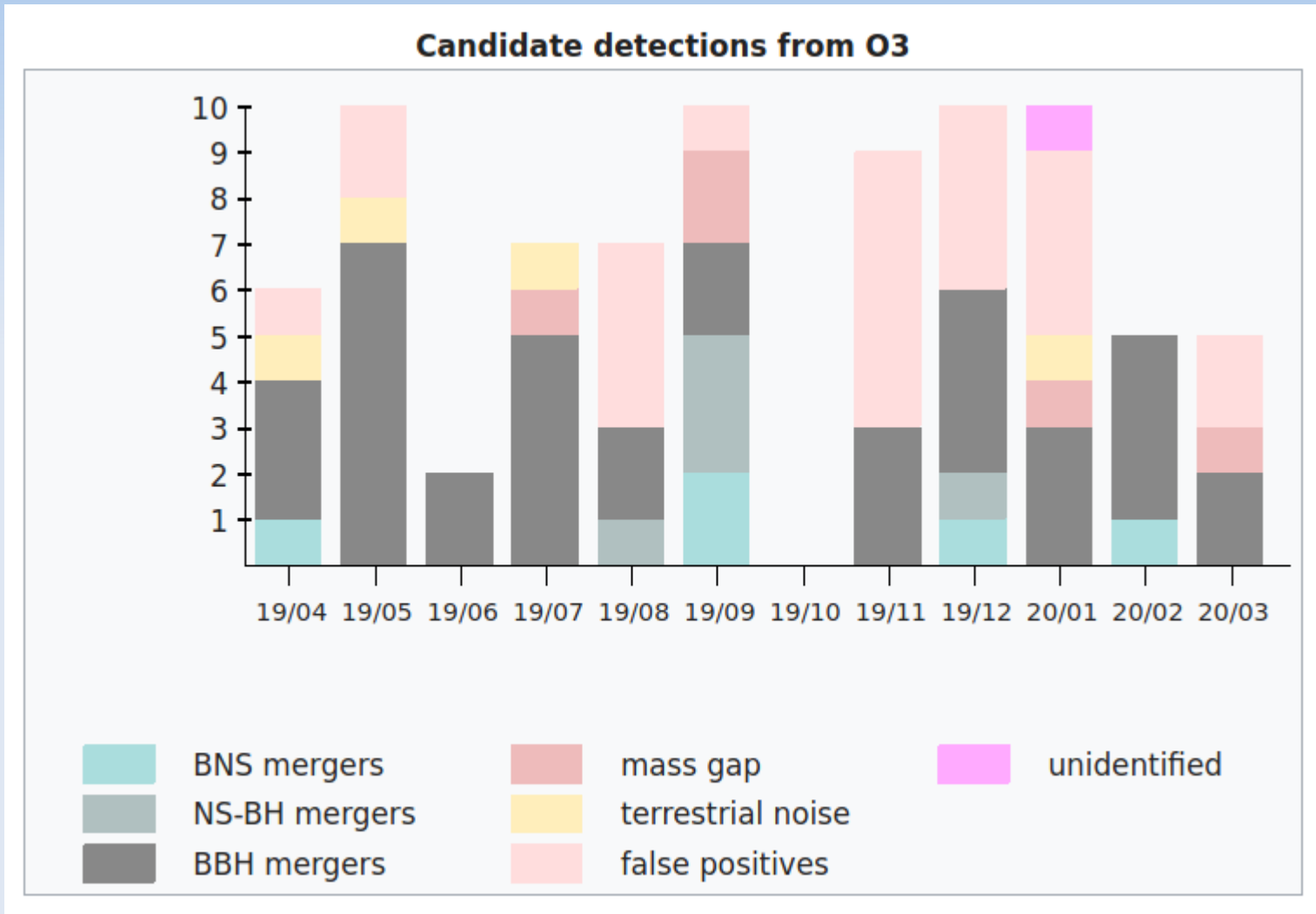


binary mergers

The stellar graveyard is ever expanding, neutron stars are especially interesting from a particle physics perspective.



binary mergers



Corona shutdown ongoing

Neutron stars

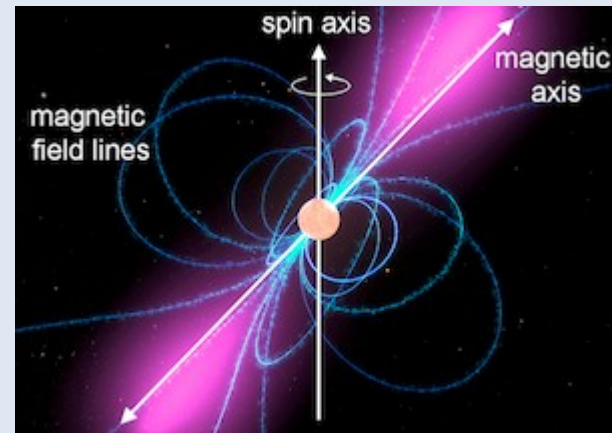
Neutron stars result from the explosion of supernovae with masses of between 10-30 solar masses. Their mass is typically about **2 solar masses** and their radius about **10 km**.

They can be understood as a super large nucleus with 10^{60} neutrons and no protons.

The structure of the neutron star is due to the balance of the strong force and the gravitational force → **neutron star equation of state** determines the relation between **mass and radius**.

Neutron stars are believed to constitute the observed (milli sec) pulsars.

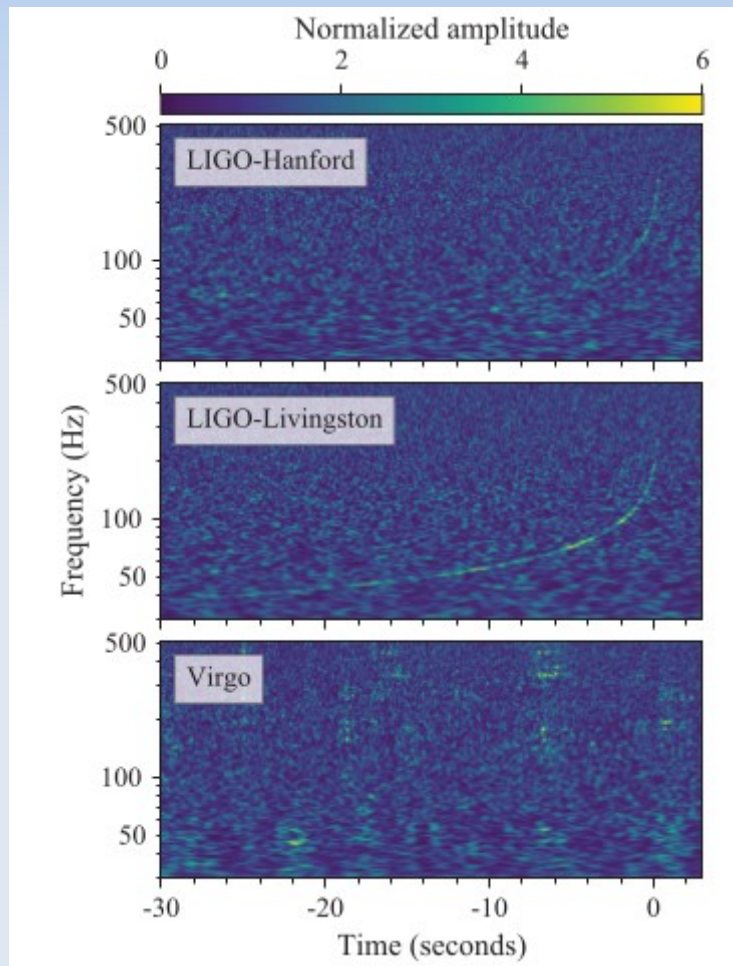
Pulsars lead to the first **indirect observation** of GWs in the 70s
→ Hulse-Taylor binary



© NASA

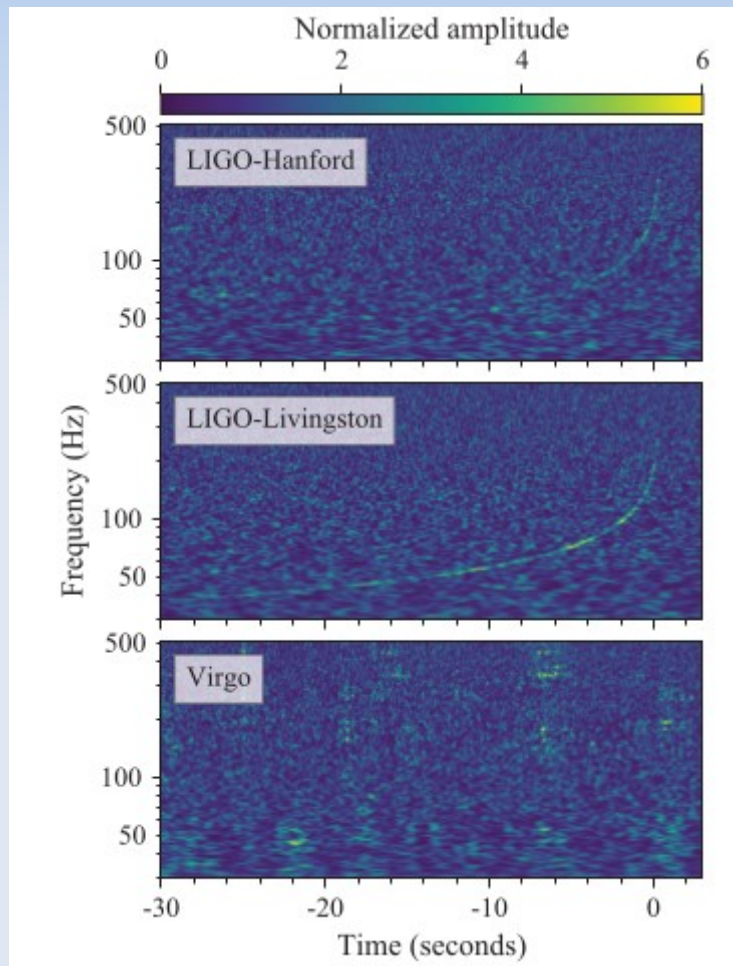
NS – NS mergers

GW170817 → (almost) only event with EM counterpart so far



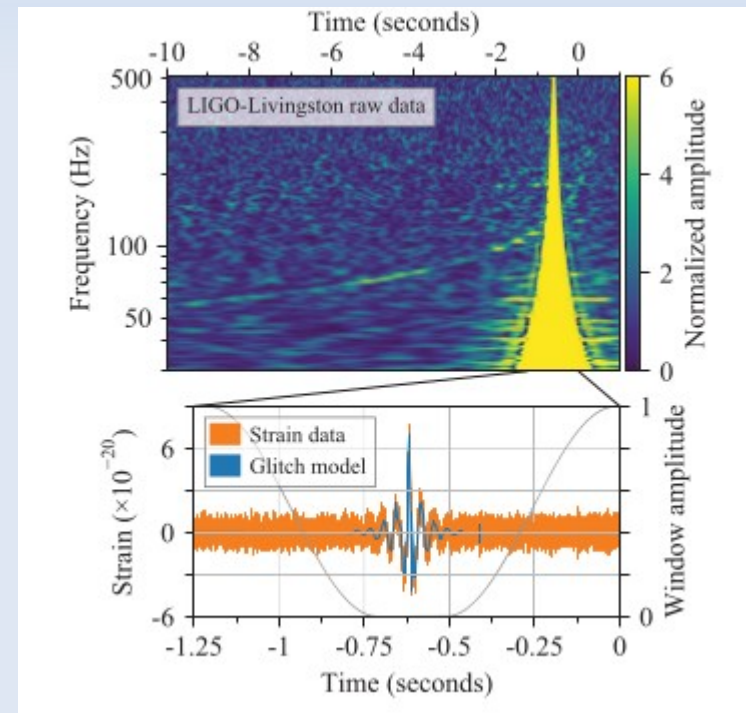
NS – NS mergers

GW170817



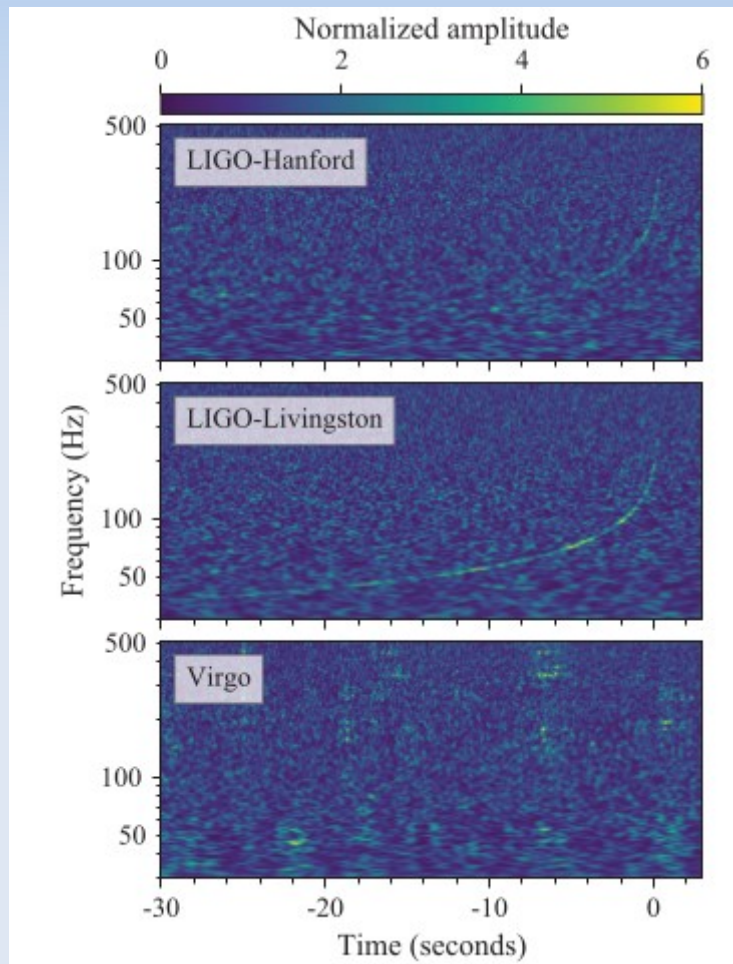
Ooops.

Actually didn't trigger automatically:



NS – NS mergers

GW170817



SNR > 32

masses are about 1.2 and 1.5 solar masses each

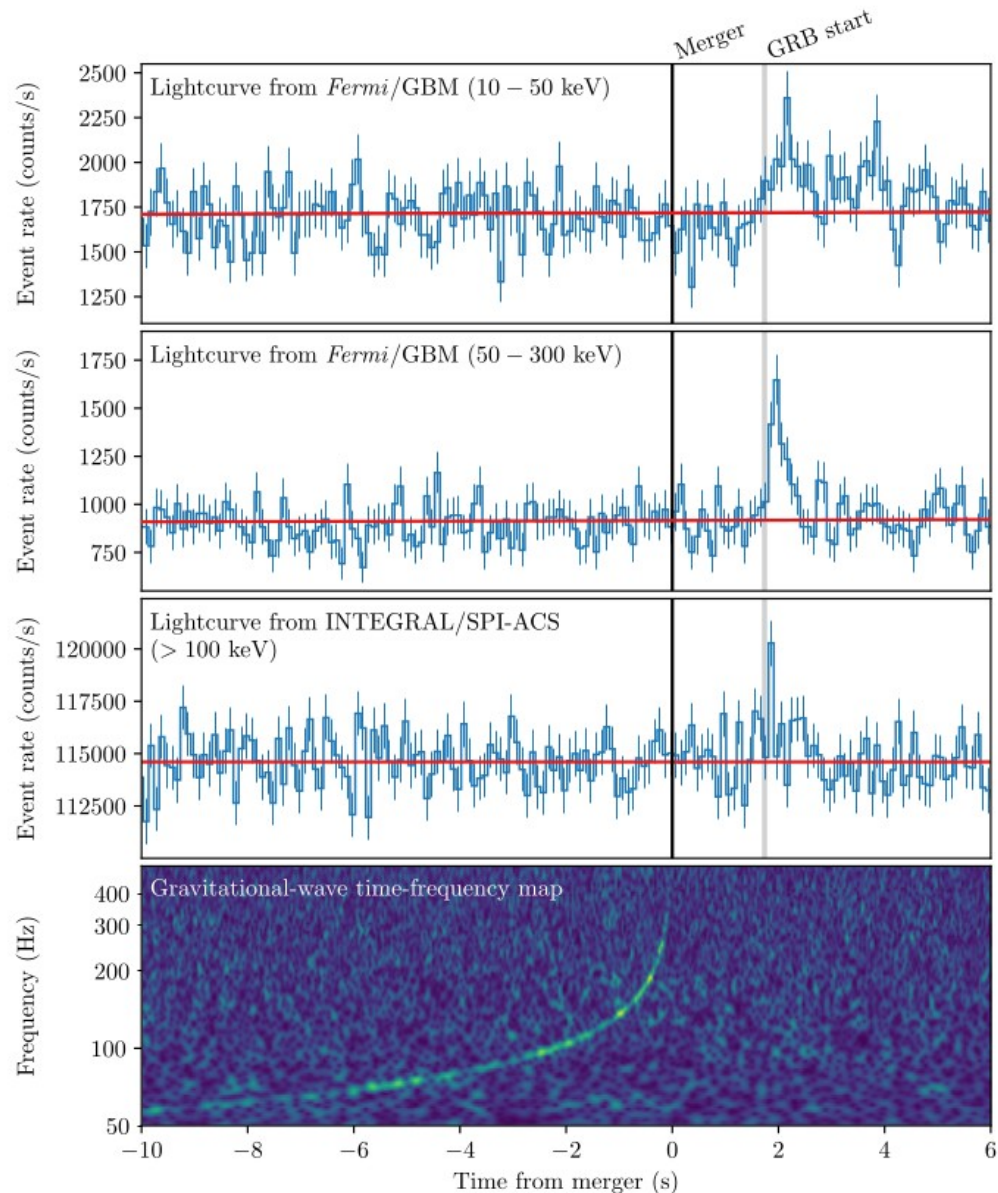
Orbital separation at the end again $\sim O(100 \text{ km})$. Cannot be normal star; one cannot be black hole.

→ must be neutron stars?

Virgo didn't see much but was very important for localisation

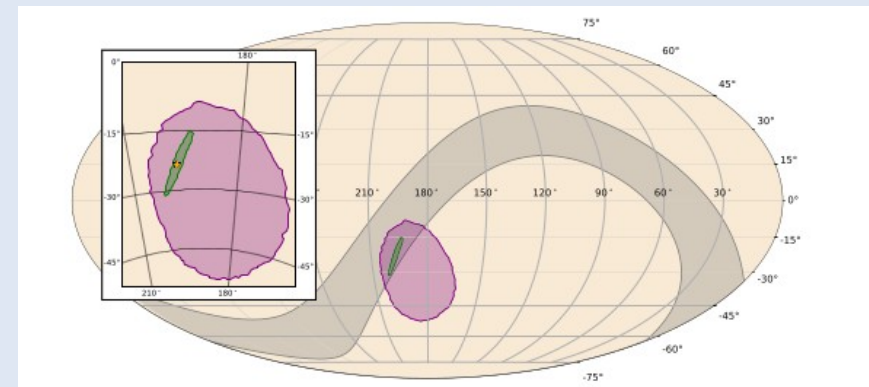
What about EM counterparts?

Gamma ray burst



A strong (not so strong actually considering the distance) gamma ray burst was seen shortly after the GW signal.

Good localization was possible even though (or because?) the event was in the blind spot of Virgo.

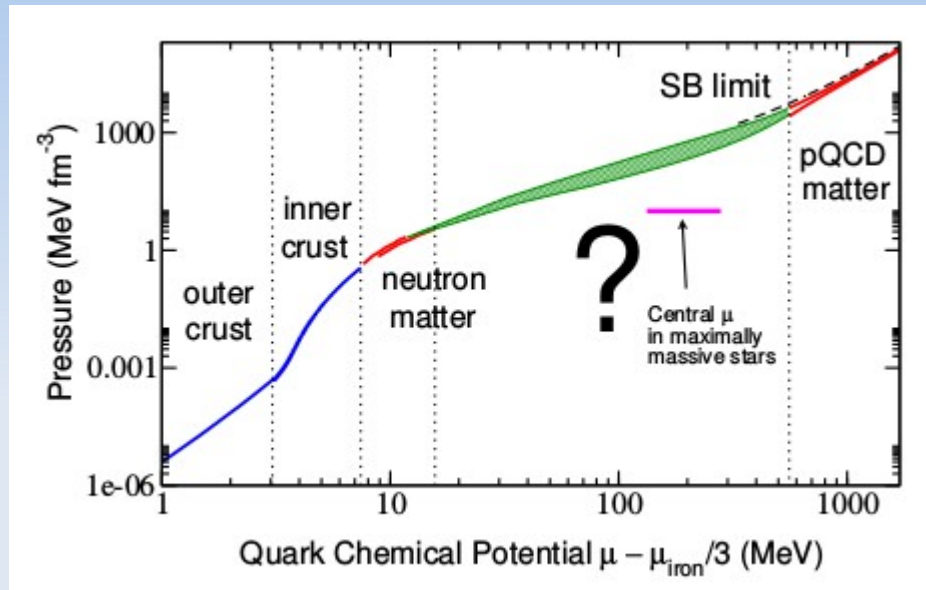


Subsequent EM observations could pinpoint the host galaxy.

→ important for the H_0 measurement

QCD equation of state

[Kurkela, Fraga, Schaeffer-Bilich, Vuorinen '14]



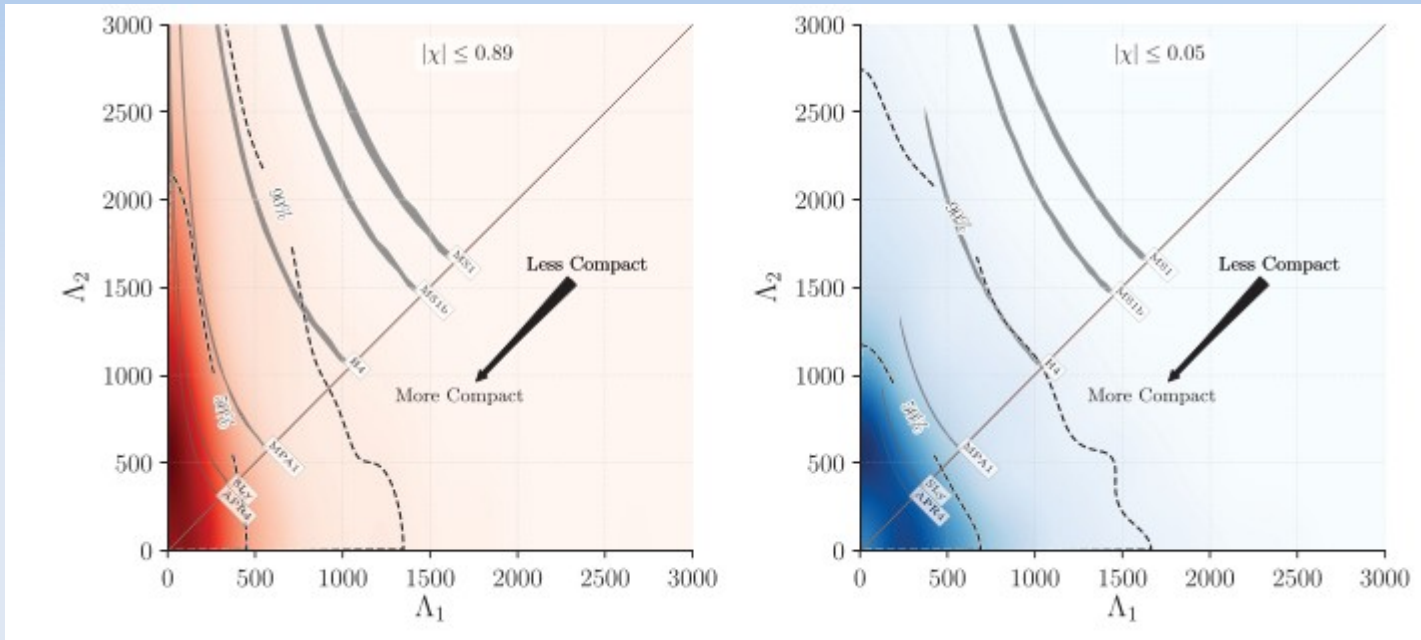
The equation-of-state of quark matter is poorly known for finite chemical potential.

These properties are important for neutron stars, in particular the relation between mass and radius and the maximal mass that is stable against gravitational collapse into a BH.

The EoS can in principle be tested via the GW signal of a neutron star merger from the late stage where finite size effects and tidal forces play a role.

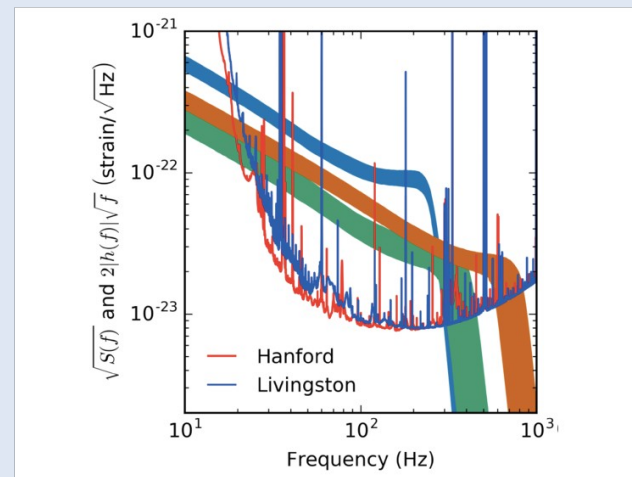
QCD equation of state

[LIGO '2017]

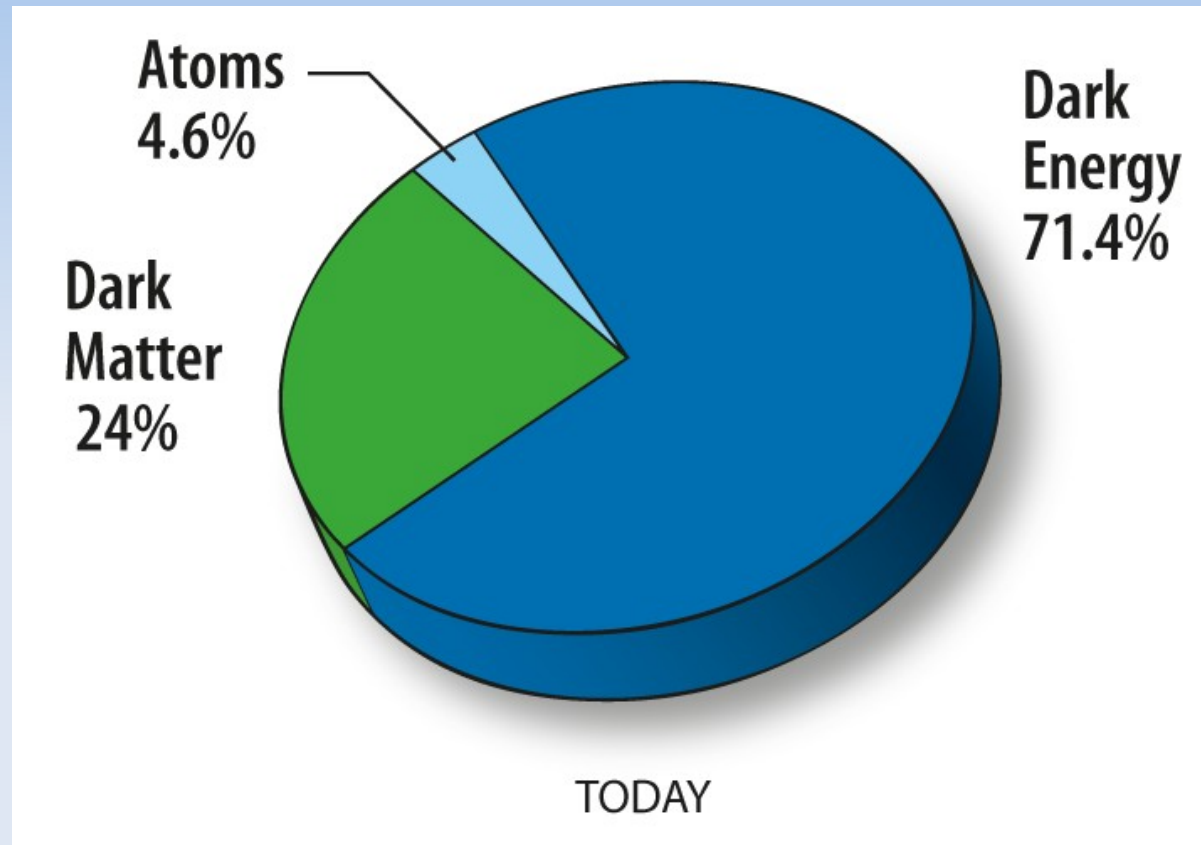


Some bounds obtained from GW170817 on the tidal deformation parameters Λ .

Unfortunately, the very last stage of the merger could not be observed and much stronger bounds can be expected from future events.



Cosmic pie

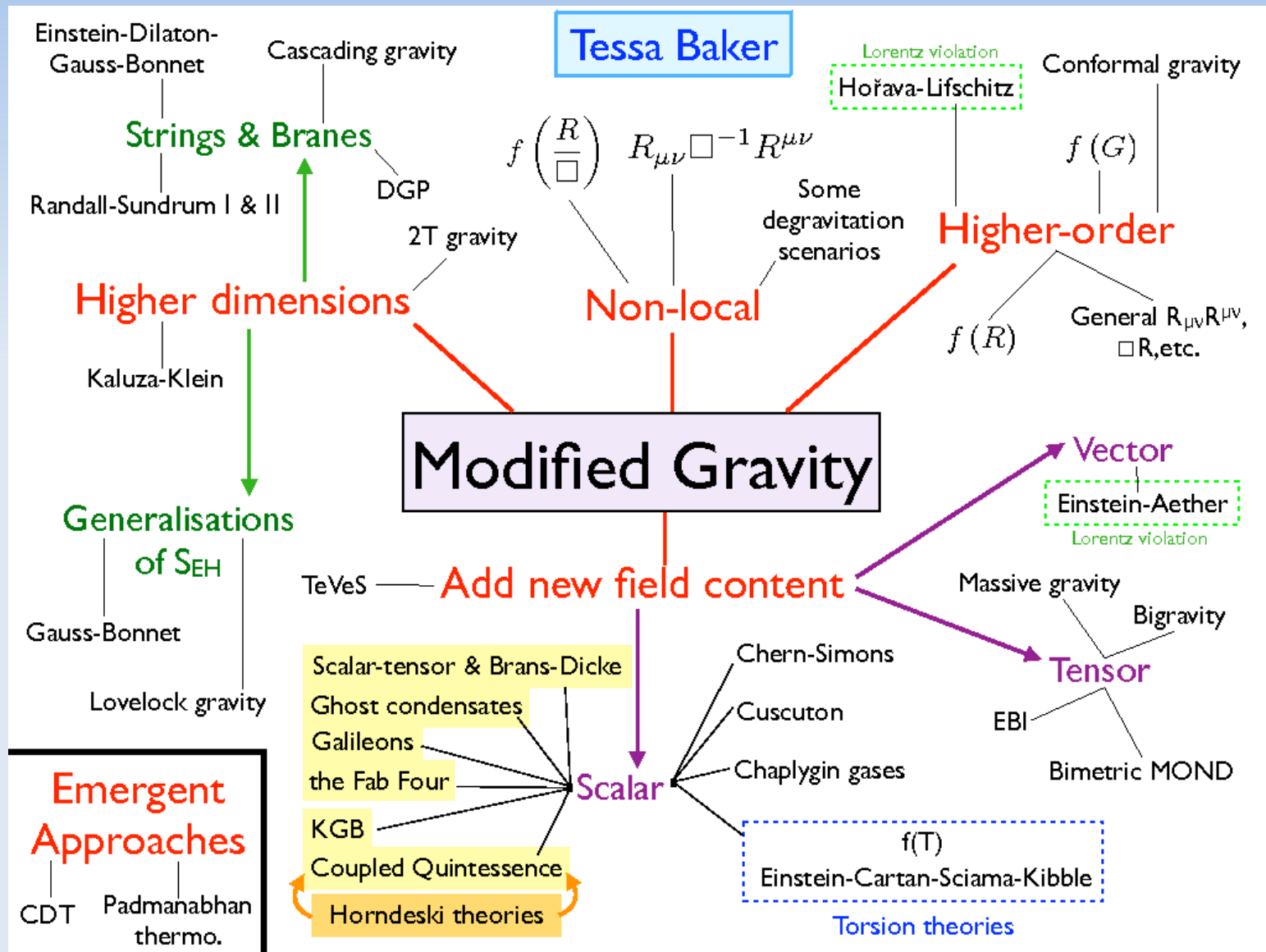


Dark energy and dark matter is only observed through their gravitational forces. CC problem.

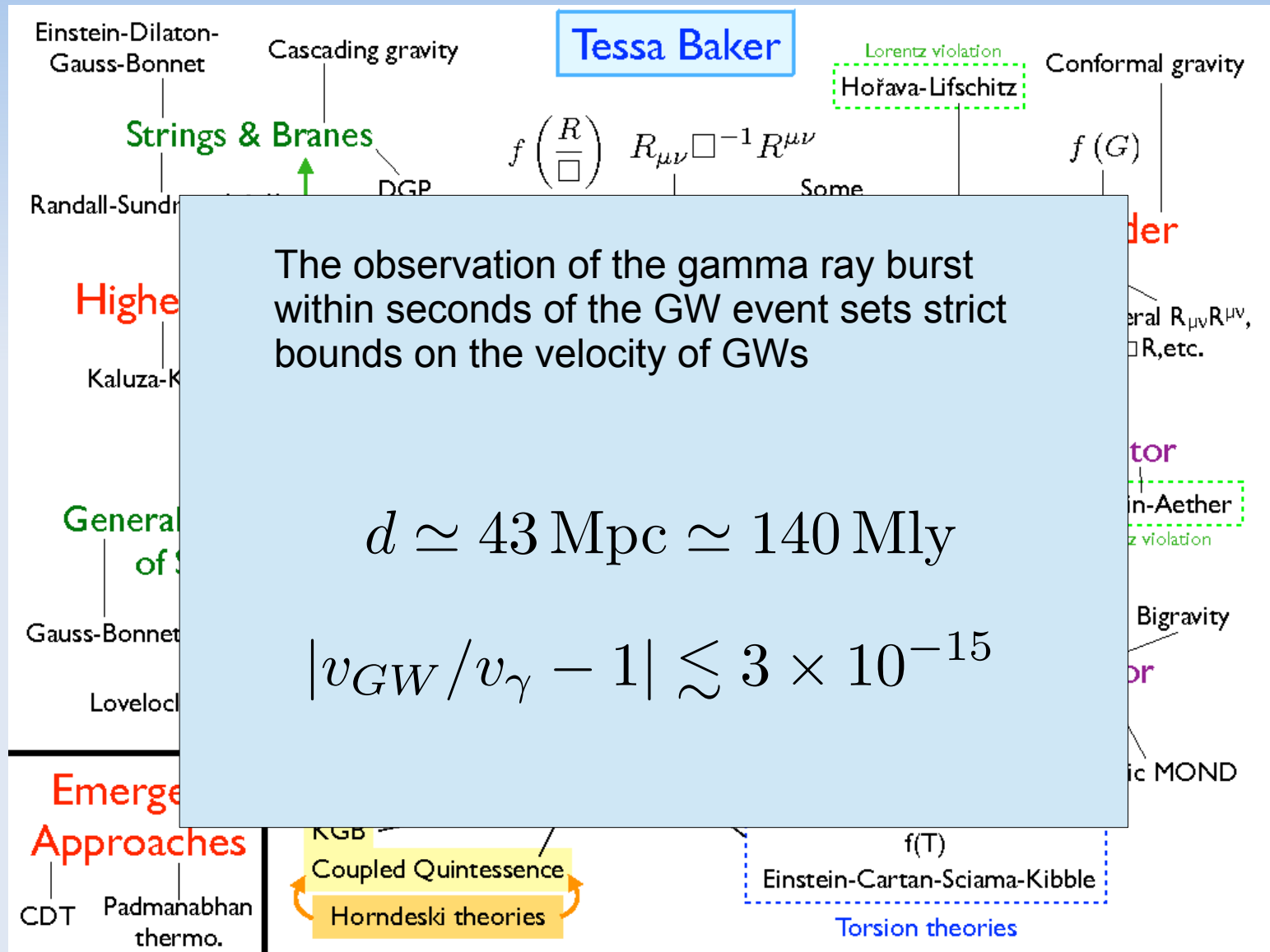
Do we really need them?

Perhaps modified gravity can account for it?

Modified gravity landscape



Modified gravity landscape



Hubble parameter

Due to the expansion of the Universe, distant objects seem to recede from any observer according to the Hubble law

$$v_H = H_0 d$$

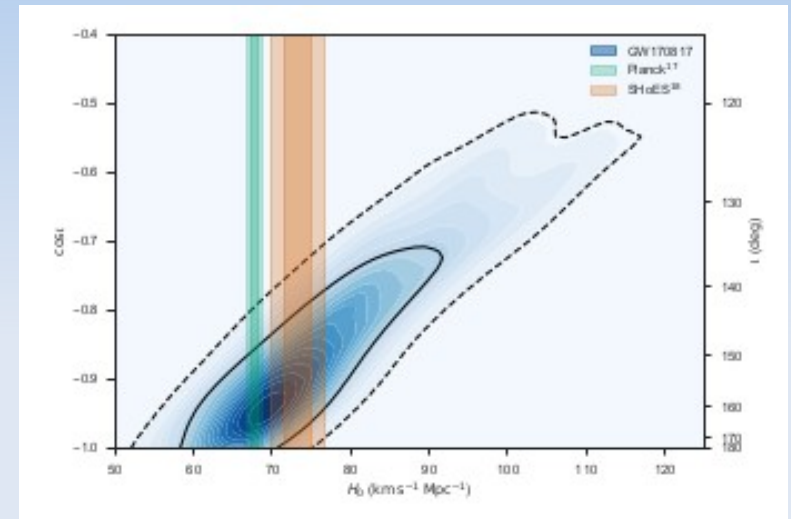
In order to determine H_0 one needs v_H (via Doppler effect) and d .

GW events can act as **standard sirens** since their signal in principle encodes their distance. (c.f. standard candles of supernovae)

The redshift (Doppler) can be measured by identifying the host galaxy which in this case was easy due to the EM counterparts.

problems:

- peculiar motions \rightarrow LSS catalogues
- d degenerate with inclination \rightarrow polarisation

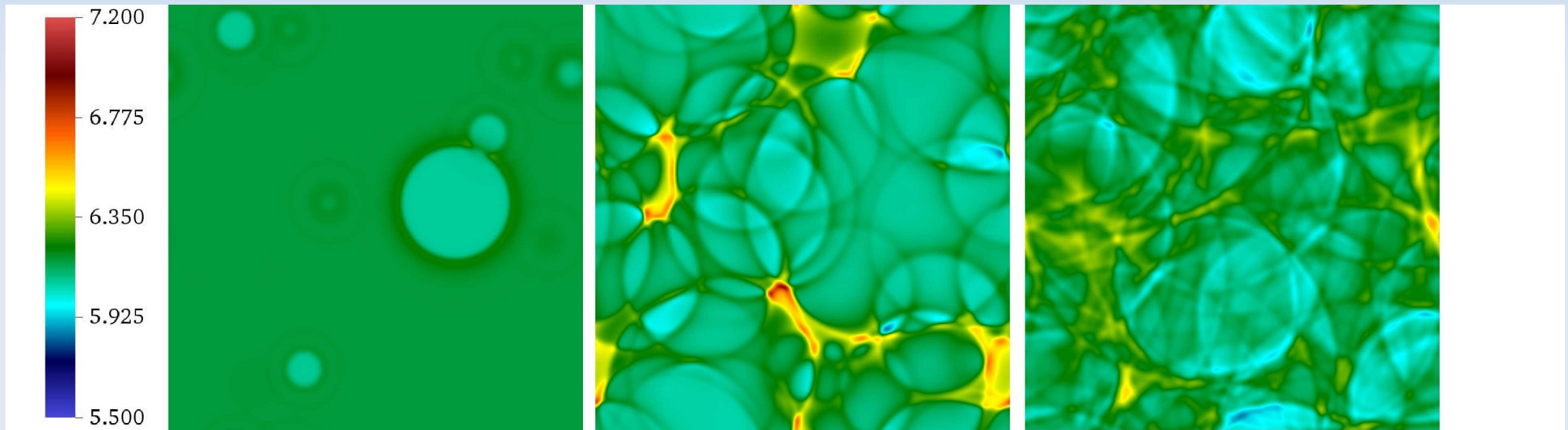


Results are not yet competitive due to degeneracy with inclination. This will change with a larger number of events

$$v_H \simeq 3000 \text{ km/s}$$

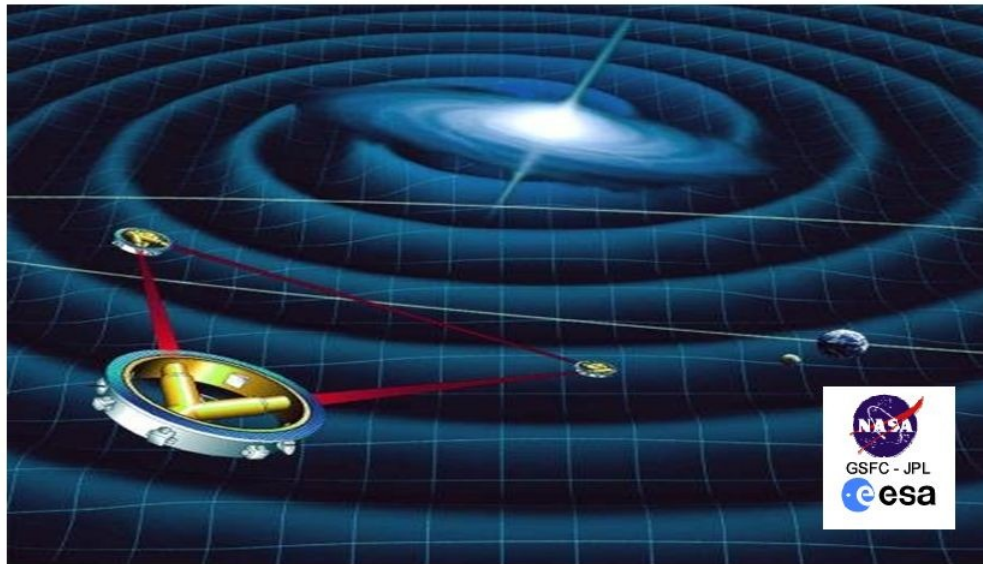
$$d \simeq 43 \text{ Mpc}$$

Part II : GWs from cosmological phase transitions



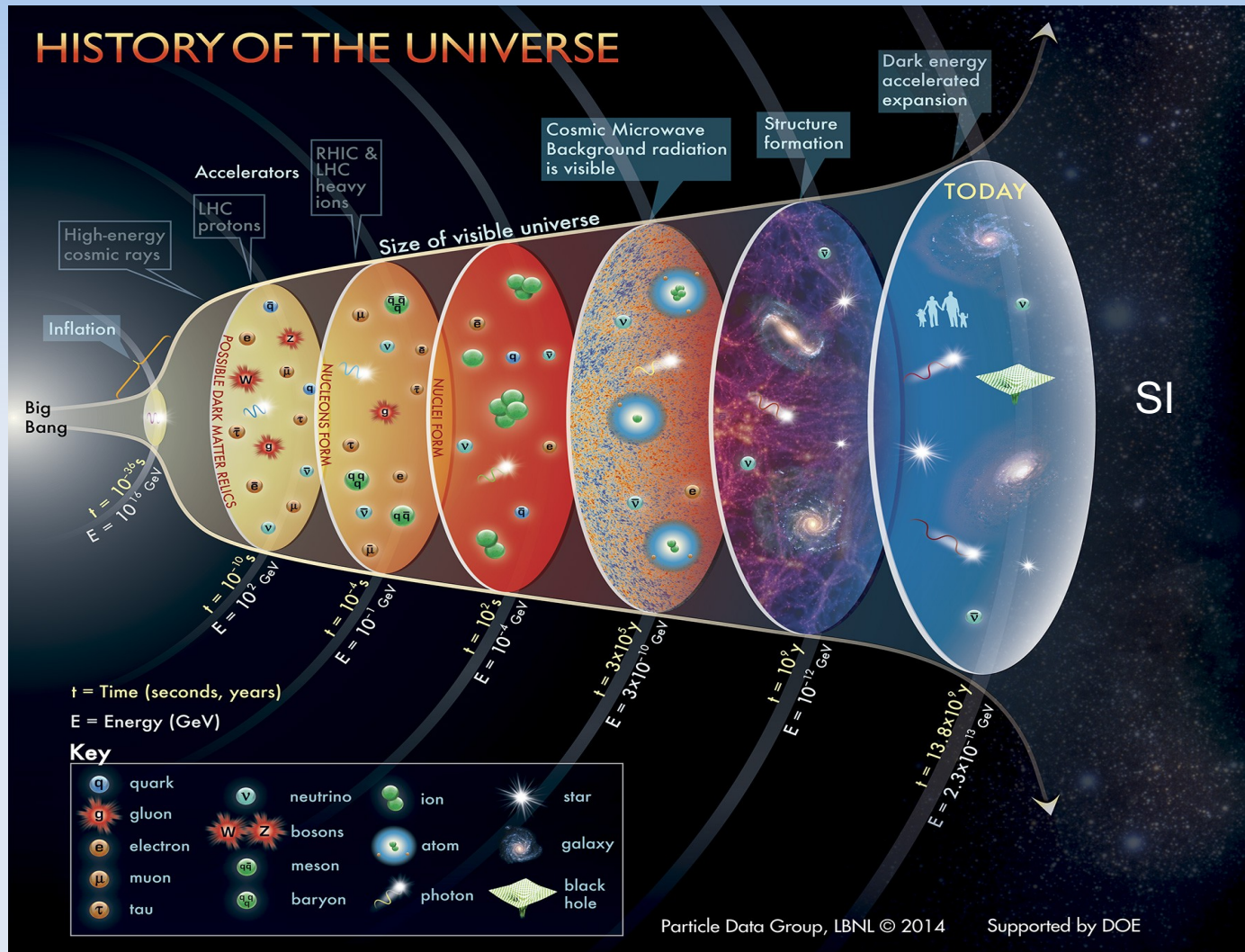
Future space telescopes

The LISA Project



Space based experiments are sensitive to smaller frequencies where stochastic backgrounds GWs can provide a link to EW physics.

Standard Cosmology

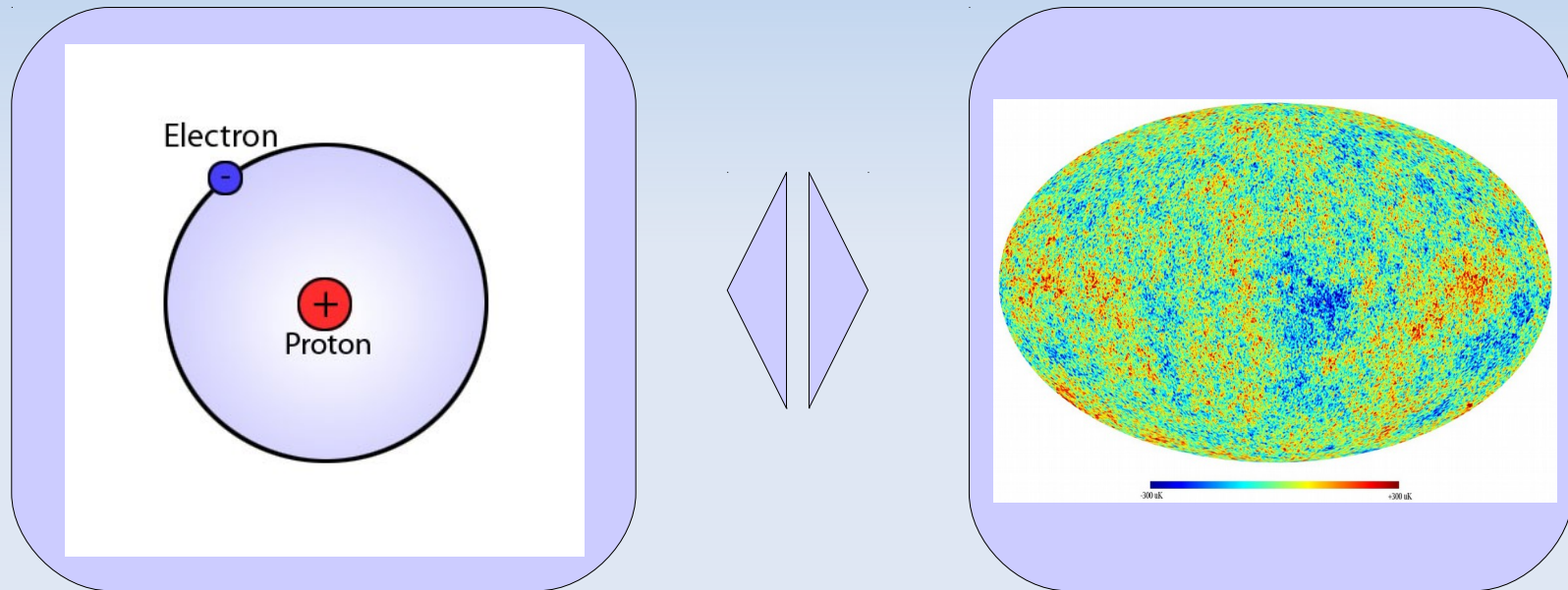


time



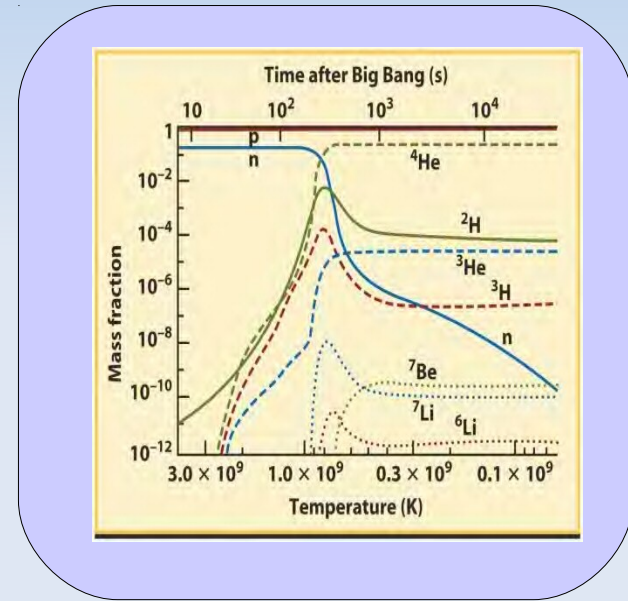
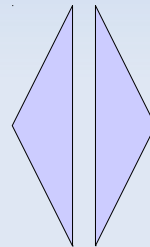
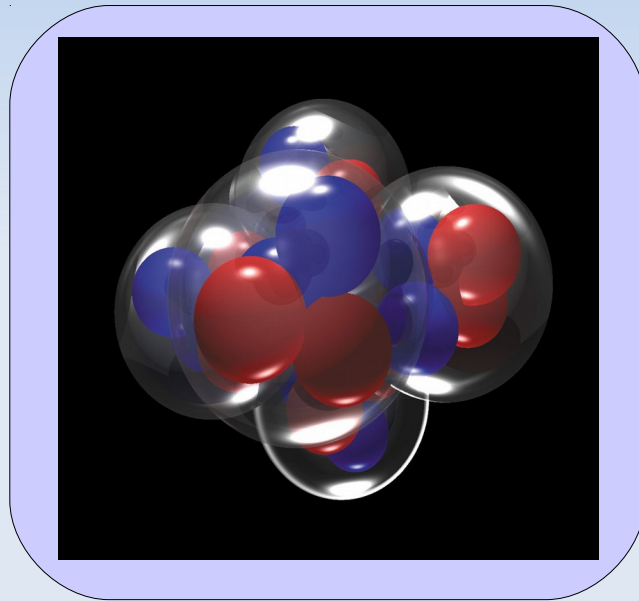
temperature

Atomic physics at $T \sim eV$



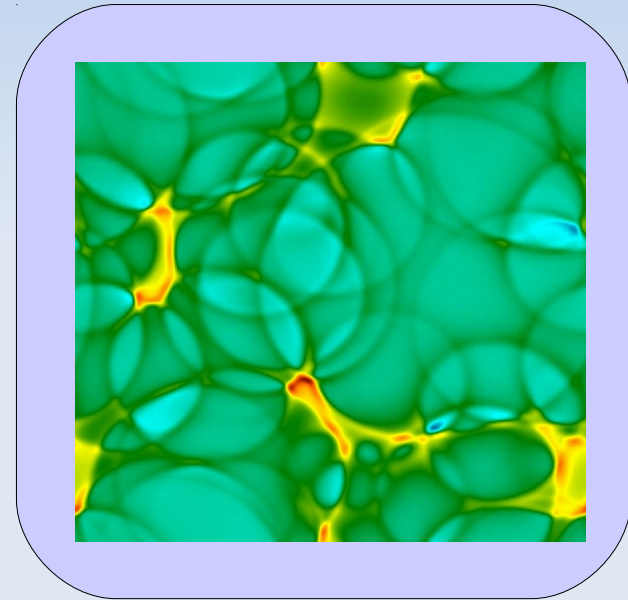
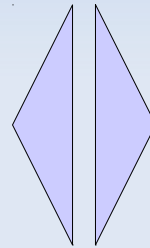
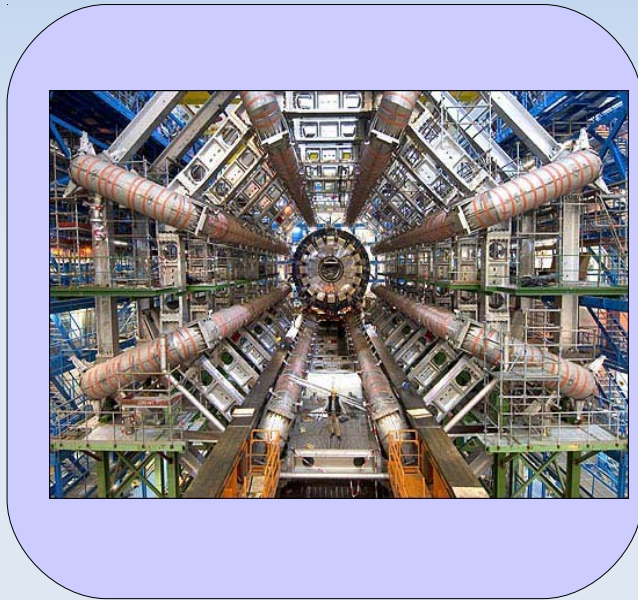
The Cosmic Microwave Background **links** atomic physics to cosmology at temperature $T \sim eV$

Nuclear physics at $T \sim \text{MeV}$



Big bang nucleosynthesis **links** nuclear physics to cosmology at temperature $T \sim \text{MeV}$

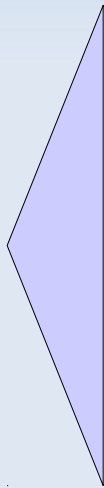
Phase transition at $T \sim 100$ GeV?



Possibly, the electroweak phase transition drove the Universe **out-of-equilibrium**.

Electroweak phase transition

gravitational
waves

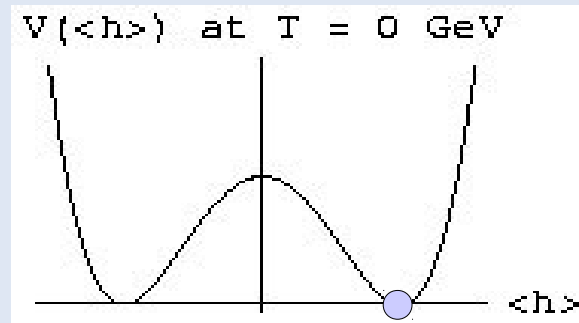


baryogenesis

Electroweak symmetry breaking

The **Mexican hat** potential is designed to lead to a finite Higgs vacuum expectation value (VEV) and break the electroweak symmetry

$$V(h) = \frac{\lambda}{4} (h^2 - v^2)^2$$

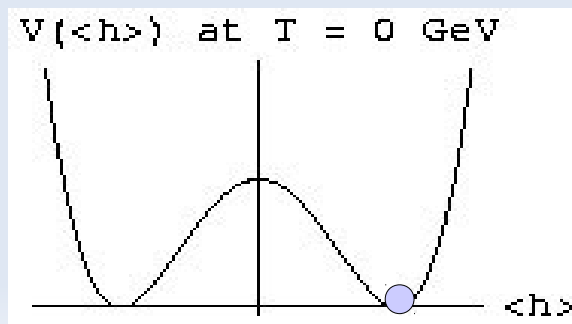
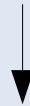
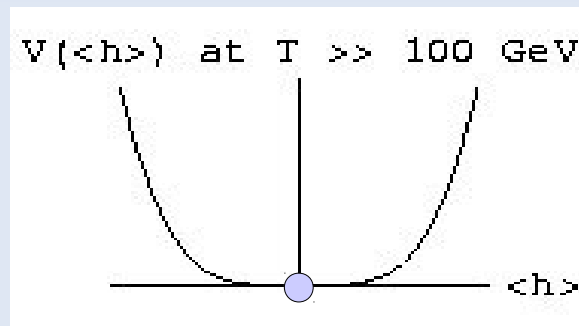


Electroweak symmetry breaking

[Weinberg '74]

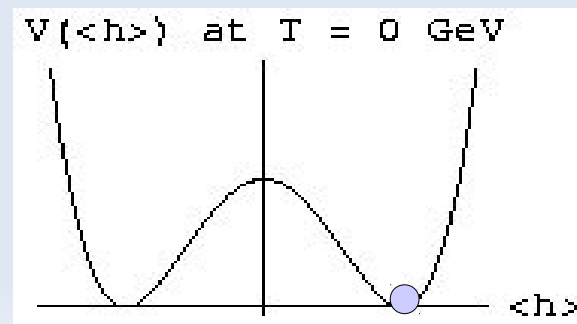
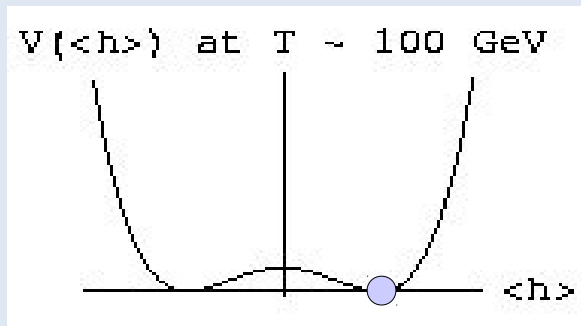
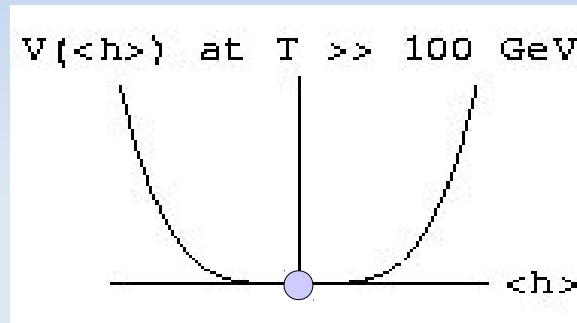
At large temperatures the symmetry is restored

$$V(h, T) = \frac{\lambda}{4} (h^2 - v^2)^2 + \text{const} \times h^2 T^2 + \text{details}$$



Electroweak symmetry breaking

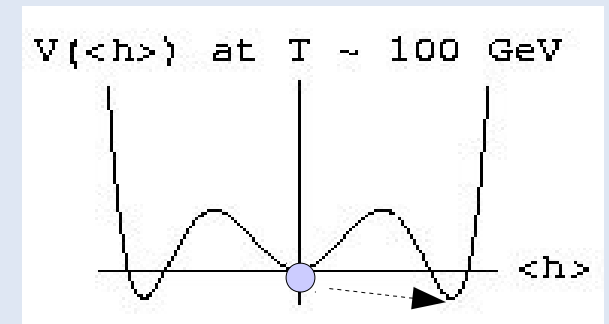
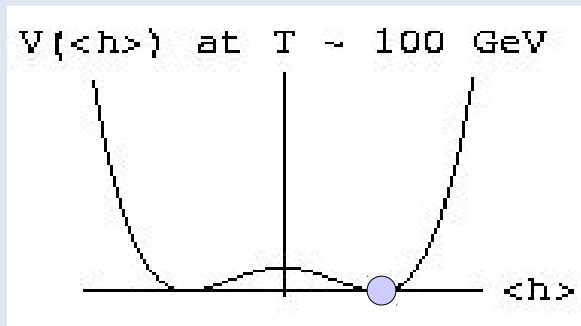
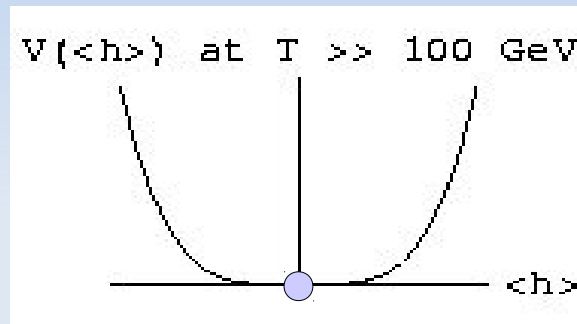
Depending on the details, the phase transition can be very weak or even a cross over



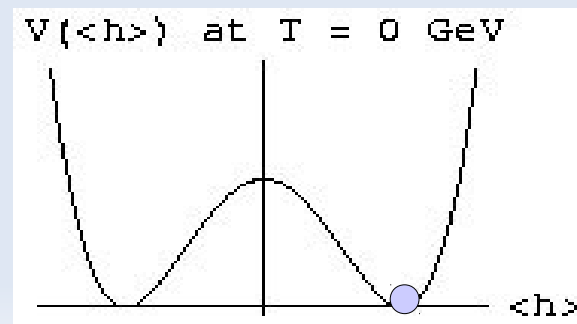
second-order
crossover

Electroweak symmetry breaking

It can also be a strong phase transition if a **potential barrier** separates the new phase from the old phase



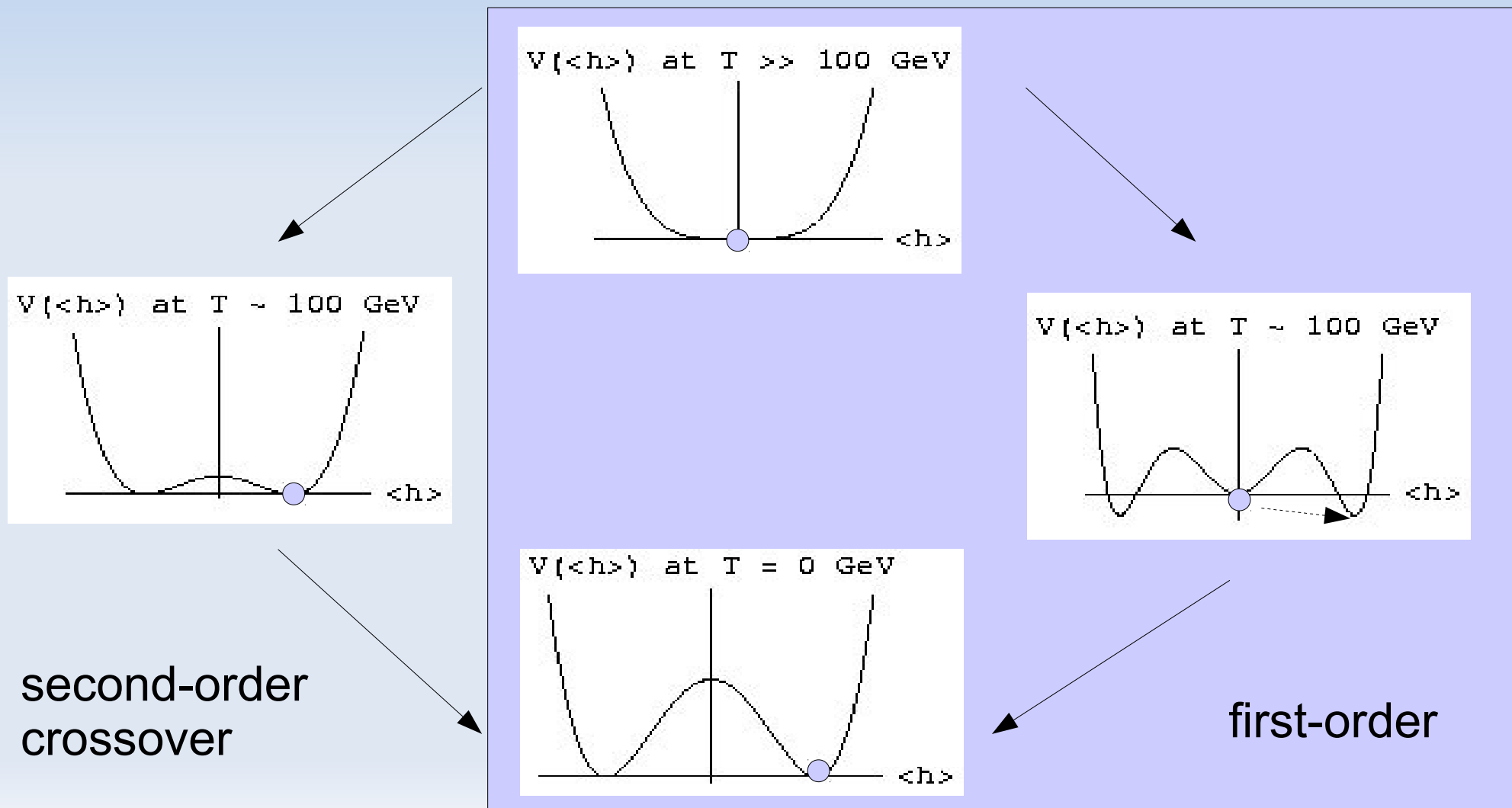
second-order
crossover



first-order

Electroweak symmetry breaking

It can also be a strong phase transition if a **potential barrier** separates the new phase from the old phase

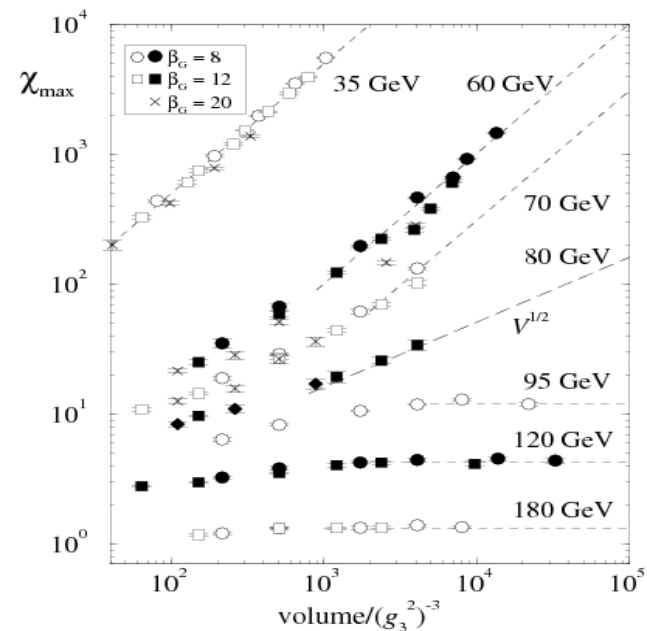


Electroweak phase transition in the SM

The effective potential is the standard tool to study phase transition at finite temperature.

Lattice studies show that there is a crossover in the SM.

A light Higgs would lead to a 1st-order PT.

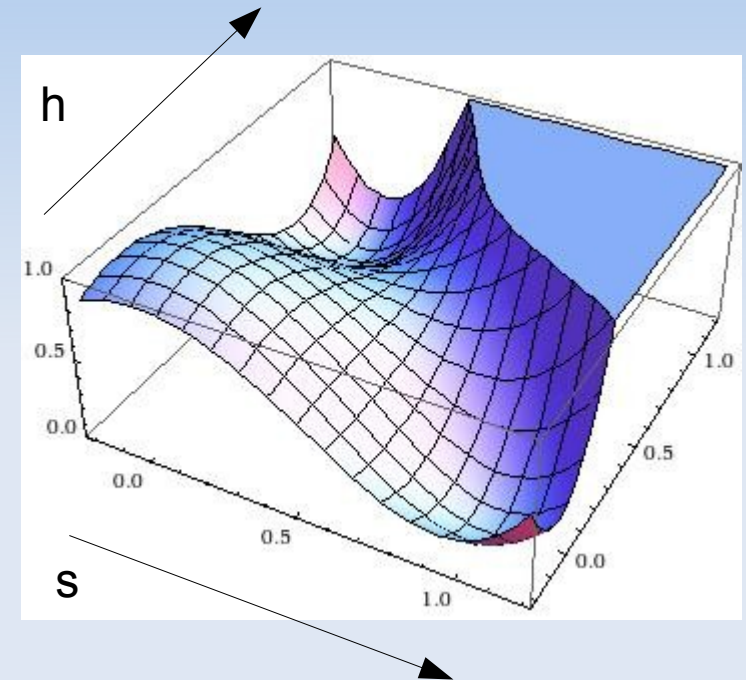


Singlet extension

The Standard Model only features a electroweak crossover.

A potential barrier and hence first-order phase transitions are quite common in extended scalar sectors:

$$V(h, s) = \frac{\lambda}{4} (h^2 - v^2)^2 + m_s^2 s^2 + \lambda_s s^4 + \lambda_m s^2 h^2$$



The singlet field has an additional \mathbb{Z}_2 symmetry and is a viable DM candidate.

The phase transition proceeds via

$$(h, s) = (0, w) \rightarrow (h, s) = (v, 0)$$

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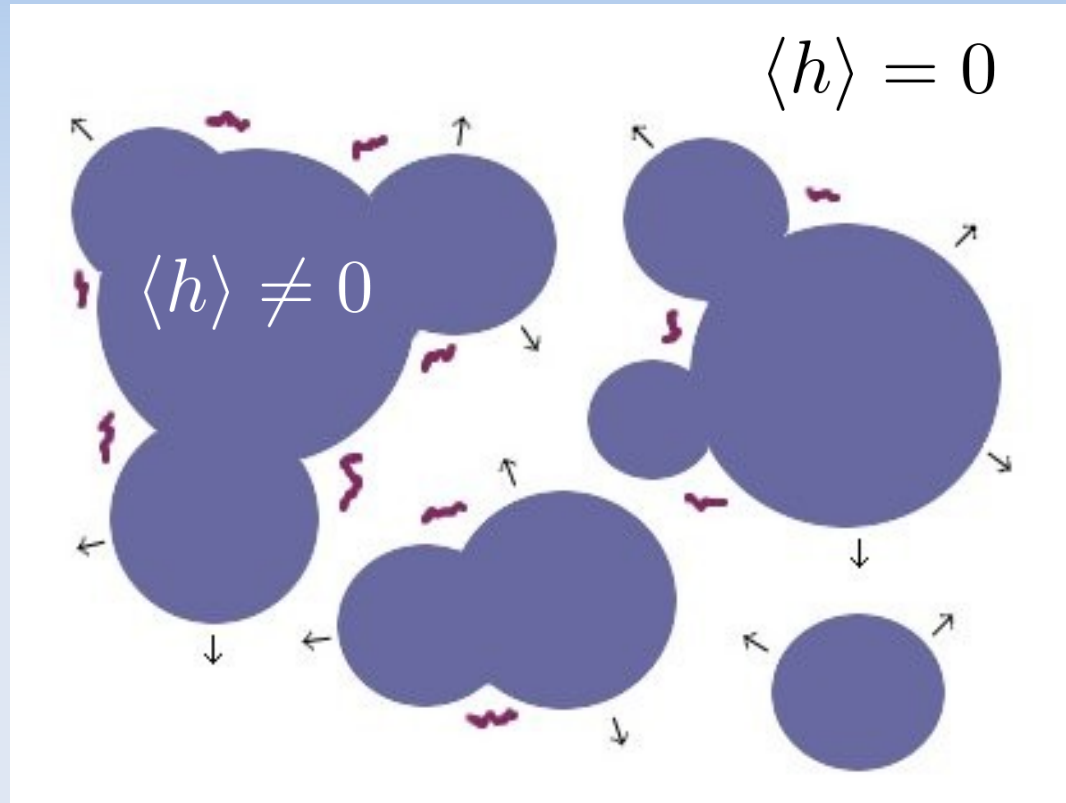


First-order phase transitions



- first-order phase transitions proceed by bubble nucleations
- in case of the electroweak phase transition, the "Higgs bubble wall" separates the symmetric from the broken phase
- this is a violent process ($v_{wall} \simeq O(c)$) that drives the plasma out-of-equilibrium and set the fluid into motion

Gravitational waves

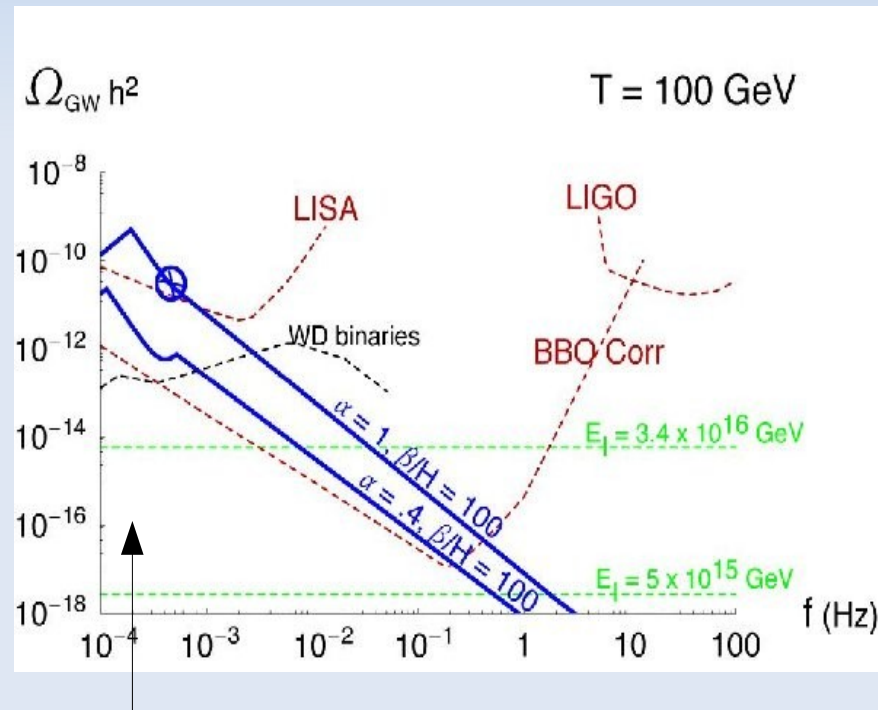


During the first-order phase transitions, the nucleated bubbles expand. Finally, the colliding bubbles generate **stochastic gravitational waves**.

Observation

[Grojean&Servant '06]

The produced gravitational waves can be observed with laser interferometers in space

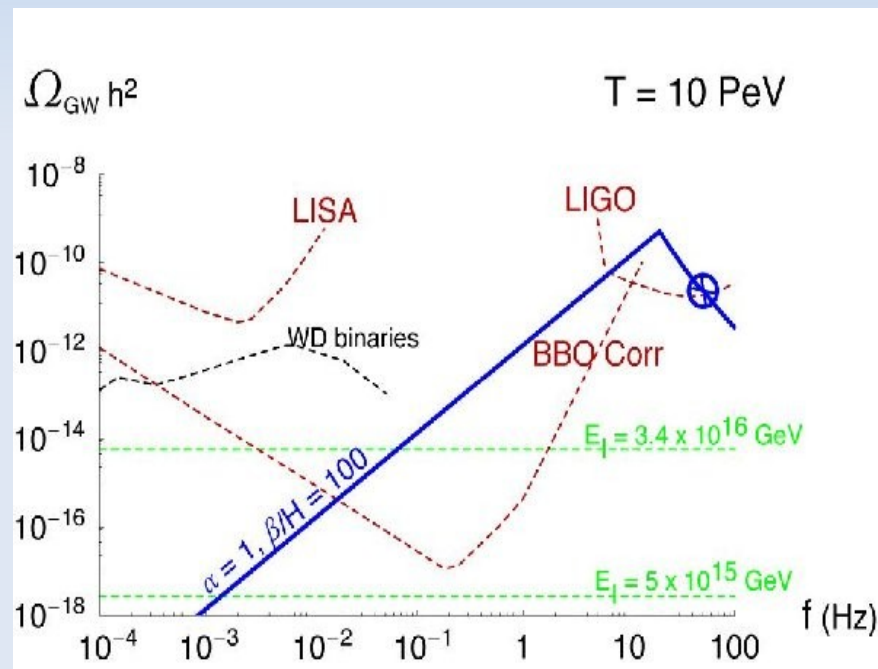


redshifted **Hubble horizon** during a phase transition at $T \sim 100$ GeV

Observation

[Grojean&Servant '06]

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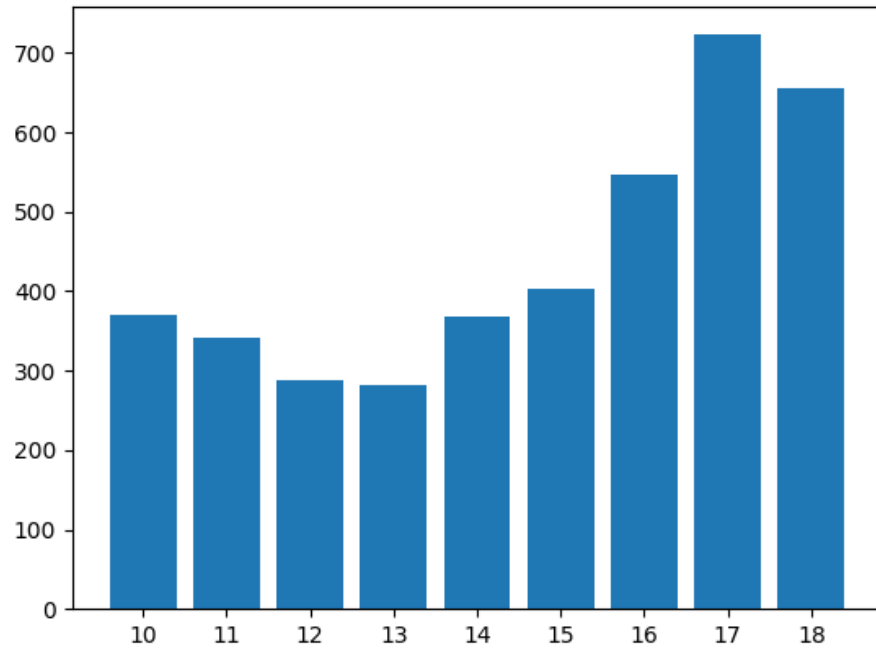


Strong phase transition at **larger temperatures** produce the same energy fraction of gravitational waves but at **higher frequencies**.

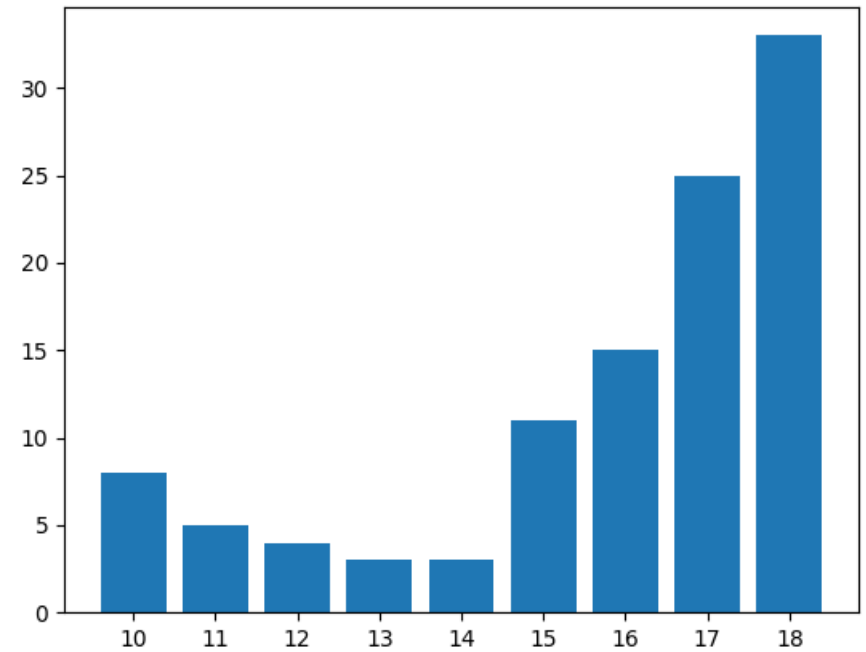
GWs from PTs

ArXiv activity:

inspire hep - gravitational waves



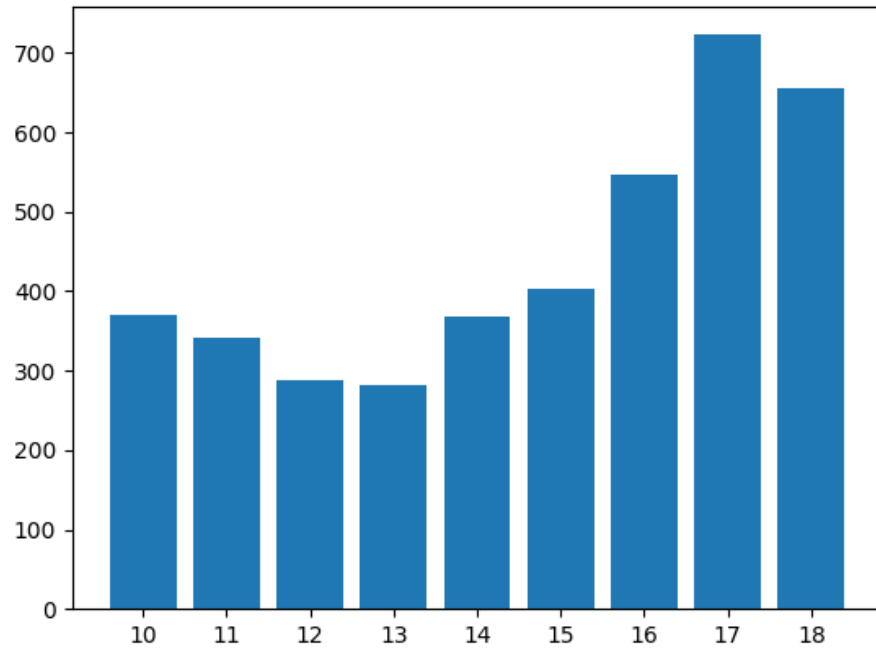
inspire hep - GWs & PTs



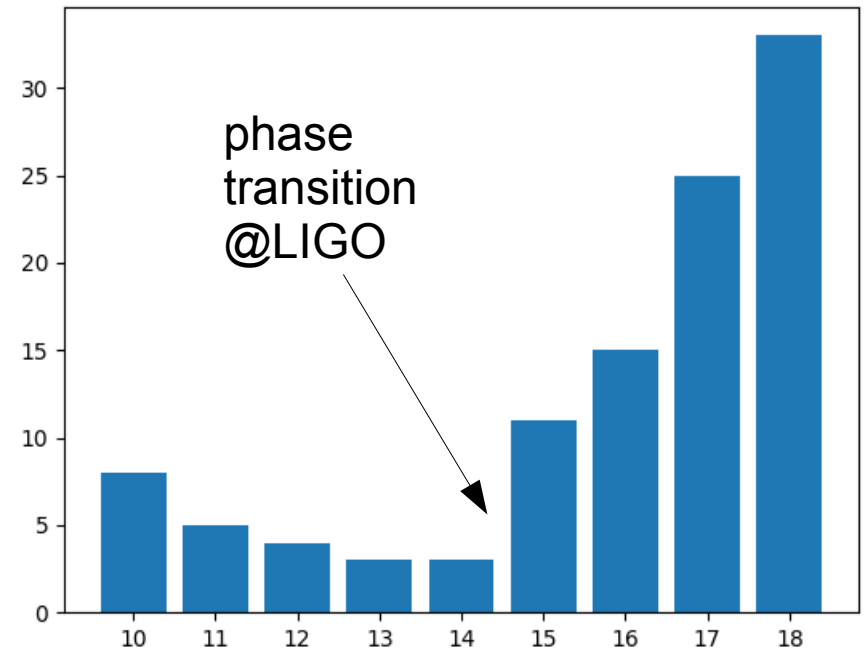
GWs from PTs

Arxiv activity:

inspire hep - gravitational waves



inspire hep - GWs & PTs



Sources of GWs from PTs

During and after the phase transition, several sources of GWs are active

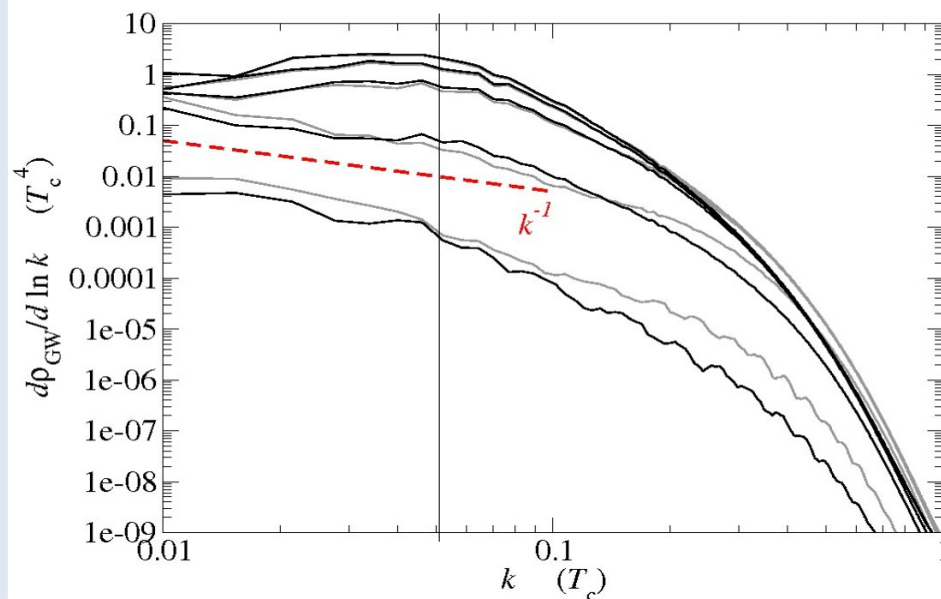
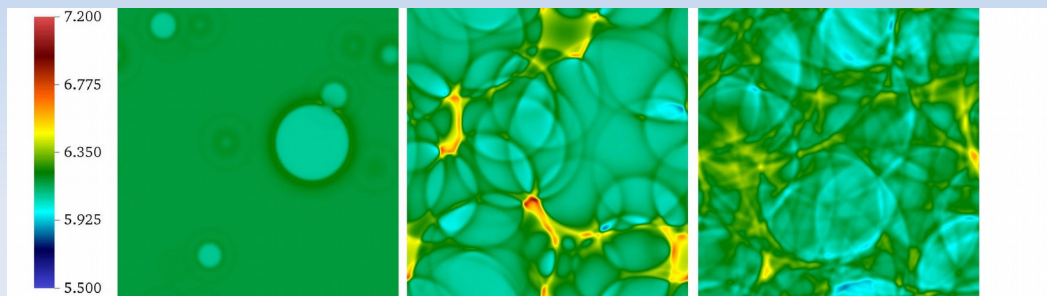
- Collisions of the scalar field configurations / initial fluid shells
- Sound waves after the phase transition
(long-lasting → dominant source)
- Turbulence
- Magnetic fields

Which source dominates depends on the characteristics of the PT

State-of-the-art

[Hindmarsh, Huber, Rummukainen, Weir '13, '15, '17]

After the PT, the system can be described using hydrodynamics (fluid + Higgs).



The produced GW spectrum can be read off from the simulation.

Really robust results but how to **extrapolate** to other models?

Model-dependence

The Weinberg master formula determines how stochastic gravitational waves are produced

$$\frac{dE_{GW}}{d\omega d\Omega} = 2G\omega^2 \Lambda_{ij,lm}(\hat{\mathbf{k}}) T_{ij}^*(\hat{\mathbf{k}}, \omega) T_{lm}(\hat{\mathbf{k}}, \omega),$$

And generally the energy fraction in GWs scales as

$$\Omega_{GW*}(f) \propto K^2$$

where \mathbf{K} denotes the **kinetic energy fraction** in the fluid after the phase transition that is where the **model-dependence** will enter for most parts.

Model-dependence

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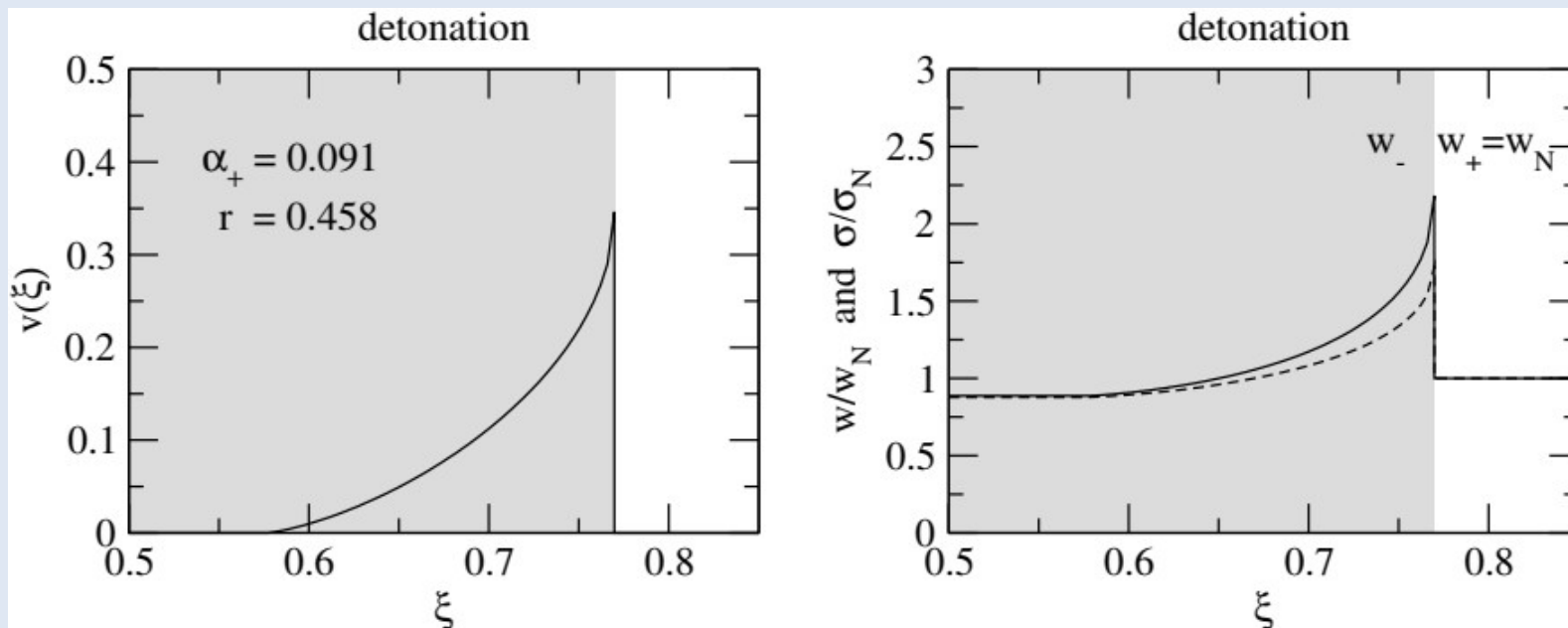
$$\Omega_{GW*}(f) \propto K^2 \leftarrow \text{rest of the talk}$$

where \mathbf{K} denotes the **kinetic energy fraction** in the fluid after the phase transition that is where the **model-dependence** will enter for most parts.

Kinetic energy

The bulk kinetic energy depends on the enthalpy w and the fluid velocity v and can be determined from an isolated **spherical bubble** before collision

$$K \equiv \frac{\rho_{kin}}{e}, \quad \rho_{kin} = \frac{1}{V} \int dV v^2 \gamma^2 w.$$



$$\xi = r/t$$

Bag model

[Kosowsky, Turner , Watkins, '92]
[Espinosa, TK, No, Servant '20]

The kinetic energy fraction has been calculated in the bag model

$$p_s = \frac{1}{3}a_+T^4 - \epsilon, \quad p_b = \frac{1}{3}a_-T^4.$$

$$e_s = a_+T^4 + \epsilon, \quad e_b = a_-T^4,$$


bag
constant

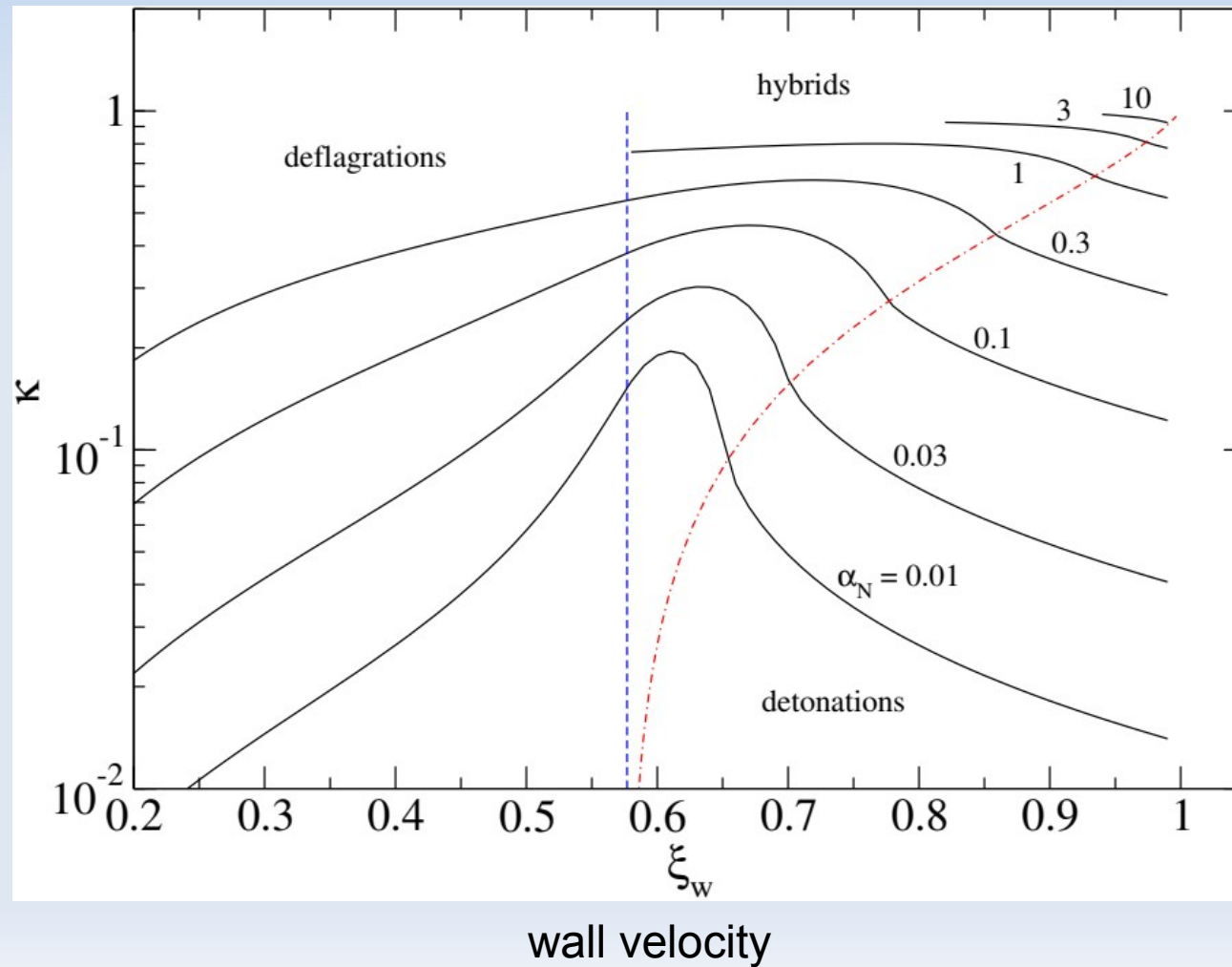
The strength of the phase transition is characterized by

$$\alpha = \frac{\epsilon}{a_+T^4}$$

Kinetic energy fraction and efficiency coefficient

[Espinosa, TK, No, Servant '20]

$$K = \frac{\alpha}{\alpha + 1} \kappa$$



How to match to other models?

Fitting functions of these results are used in phenomenological analysis but what is the strength parameter in a general models? In particular if only quantities at nucleation temperature are used?

$$DX = (X_s(T_n) - X_b(T_n))$$

$$\alpha \propto Dp$$

If the pressure difference vanishes, the bubble becomes static

$$\alpha \propto De$$

The energy difference fuels the kinetic motion of the bulk fluid

$$\alpha \propto D\theta \propto (De - 3Dp)$$


The trace difference is the bag constant in the bag model and also comes about naturally in lattice simulations

A model comparison

[Giese, TK, van de Vis '20]

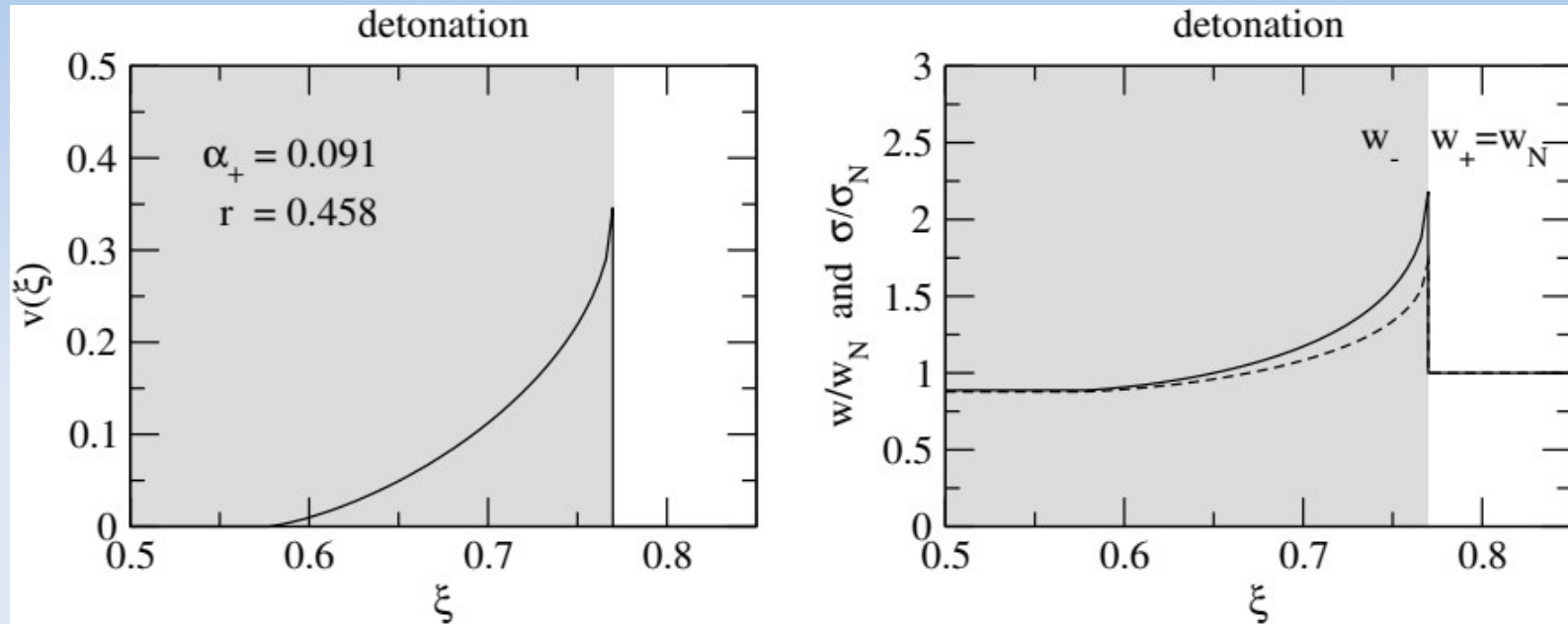
model/method	M1	M2	M3	M4	M5	M6
SM ₁	0.00143		4.99 %	3.55 %	-88.45 %	713.34 %
SM ₂	0.00401		1.70 %	-0.72 %	-66.69 %	351.90 %
SM ₃	0.00014		1.37 %	0.94 %	-89.16 %	779.35 %
SM ₄	0.00039		0.42 %	-0.32 %	-67.85 %	405.11 %
2step ₁	0.00036		13.61 %	17.39 %	-89.52 %	945.17 %
2step ₂	0.00563		15.68 %	21.90 %	-50.01 %	366.20 %
2step ₃	0.00070		35.97 %	47.28 %	-89.85 %	1235.34 %
2step ₄	0.01576		40.05 %	58.29 %	-41.80 %	485.16 %

Table 4: Relative errors of the methods M2-M6 compared to the fully numerical result M1. The model parameters are given in Table [1](#) and [2](#) and a wall velocity of $\xi_w = 0.9$ was used.


 new approach

$\Delta\theta$ $\Delta\theta$ Δp Δe
 methods used in the
 literature

The matching equation



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

These equations determine T_- and v_- as functions of $v_+ = v_w$ and $T_+ = T_{\text{nucleation}}$

The matching equation

[Giese, TK, van de Vis '20]

The temperature T_- can be eliminated using

$$\frac{p_b(T_+) - p_b(T_-)}{e_b(T_+) - e_b(T_-)} \simeq \left. \frac{dp_b/dT}{de_b/dT} \right|_{T_n} \equiv c_s^2.$$

This then leads to

$$\frac{v_+}{v_-} \simeq \frac{(v_+v_-/c_s^2 - 1) + (De - Dp/c_s^2)/w_+}{(v_+v_-/c_s^2 - 1) + v_+v_-(De - Dp/c_s^2)/w_+}.$$

$$DX = (X_s(T_n) - X_b(T_n))$$

This motivates the following definition of the strength parameter in terms of the *pseudotrace*

$$\bar{\theta} \equiv e - p/c_s^2, \quad \alpha_{\bar{\theta}} \equiv \frac{D\bar{\theta}}{3w_+},$$

The matching equation

[Giese, TK, van de Vis '20]

The temperature T_- can be eliminated using

$$\frac{p_b(T_+) - p_b(T_-)}{e_b(T_+) - e_b(T_-)} \simeq \left. \frac{dp_b/dT}{de_b/dT} \right|_{T_n} \equiv c_s^2.$$

This then leads to

$$\frac{v_+}{v_-} \simeq \frac{(v_+v_-/c_s^2 - 1) + (De - Dp/c_s^2)/w_+}{(v_+v_-/c_s^2 - 1) + v_+v_-(De - Dp/c_s^2)/w_+}.$$

$$DX = (X_s(T_n) - X_b(T_n))$$

This motivates the following definition of the strength parameter in terms of the *pseudotra*

$$\bar{\theta} \equiv e - p/c_s^2, \quad \alpha_{\bar{\theta}} \equiv \frac{D\bar{\theta}}{3w_+},$$

K should only depend on these two quantities!

A sound argument to go beyond the bag model

[Leitao and Megevand '14] v-model

$$p_s = \frac{1}{3}a_+T^4 - \epsilon, \quad e_s = a_+T^4 + \epsilon, \quad c_s^2 = \frac{1}{\nu - 1}$$

$$p_b = \frac{1}{3}a_-T^\nu, \quad e_b = \frac{1}{3}a_-(\nu - 1)T^\nu,$$

model/method	M1	M2
SM ₁	0.00143	0.45 %
SM ₂	0.00401	0.43 %
SM ₃	0.00014	0.04 %
SM ₄	0.00039	0.04 %
2step ₁	0.00036	-0.21 %
2step ₂	0.00563	-0.80 %
2step ₃	0.00070	-0.77 %
2step ₄	0.01576	-3.52 %

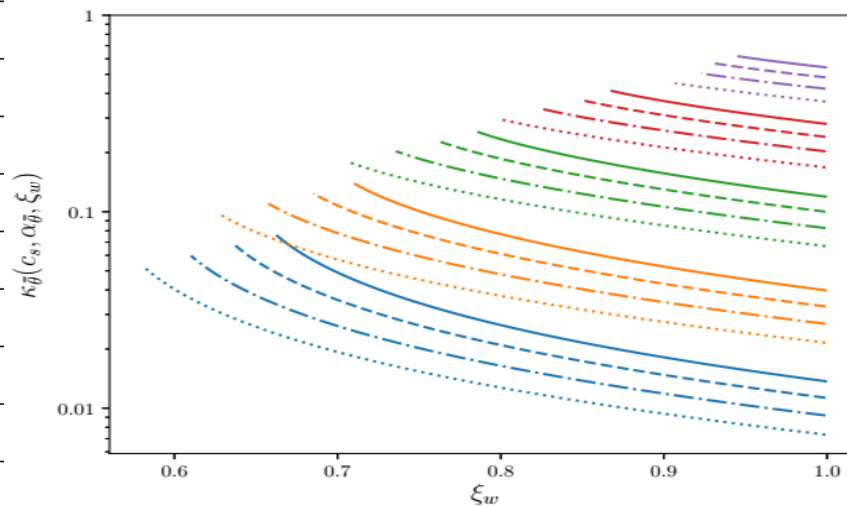


Table 4: Relative errors of the methods M2-M6 compared to the fully numerical result M1. The model parameters are given in Table 1 and 2 and a wall velocity of $\xi_w = 0.9$ was used.

Coding the kinetic energy fraction

```
01 import numpy as np
02 from scipy.integrate import odeint
03 from scipy.integrate import simps
04
05 def kappaNuModel(cs2,al,vp):
06     nu = 1./cs2+1.
07     tmp = 1.-3.*al+vp**2*(1./cs2+3.*al)
08     disc = 4*vp**2*(1.-nu)+tmp**2
09     if disc<0:
10         print("vp too small for detonation")
11         return 0
12     vm = (tmp+np.sqrt(disc))/2/(nu-1.)/vp
13     wm = (-1.+3.*al+(vp/vm)*(-1.+nu+3.*al))
14     wm /= (-1.+nu-vp/vm)
15
16     def dfdv(xiw, v, nu):
17         xi, w = xiw
18         dxidv = (((xi-v)/(1.-xi*v))**2*(nu-1.)-1.)
19         dxidv *= (1.-v*xi)*xi/2./v/(1.-v**2)
20         dwdv = nu*(xi-v)/(1.-xi*v)*w/(1.-v**2)
21         return [dxidv,dwdv]
22
23     n = 501 # change accuracy here
24     vs = np.linspace((vp-vm)/(1.-vp*vm), 0, n)
25     sol = odeint(dfdv, [vp,1.], vs, args=(nu,))
26     xis, ws = (sol[:,0],-sol[:,1]*wm/al*4./vp**3)
27
28     return simps(ws*(xis*vs)**2/(1.-vs**2), xis)
```

Table 5: Python code to calculate $\kappa_{\bar{\nu}}$ in the ν -model as a function of the speed of sound squared c_s^2 , the strength of the phase transition $\alpha_{\bar{\nu}}$ and the wall velocity ξ_w .

Summary I

To extrapolate the results from hydrodynamic simulations to other models one needs the energy fraction of a single expanding bubble.

In the literature this is typically done by matching the bag model where the energy fraction is known (as a fit).

This leads to errors of order $O(1)$ or $O(10)$.

A model-independent approach suggests to use the *speed-of-sound* in the broken phase and the *pseudo-trace* in the strength parameter of the matching.

This reduces the error to $O(\text{few } \%)$ using the Python code snippet.

Putting it all together

The different sources and the relation to particle physics model building is discussed in publications by the LISA cosmology working group on GWs from cosmological phase transitions:

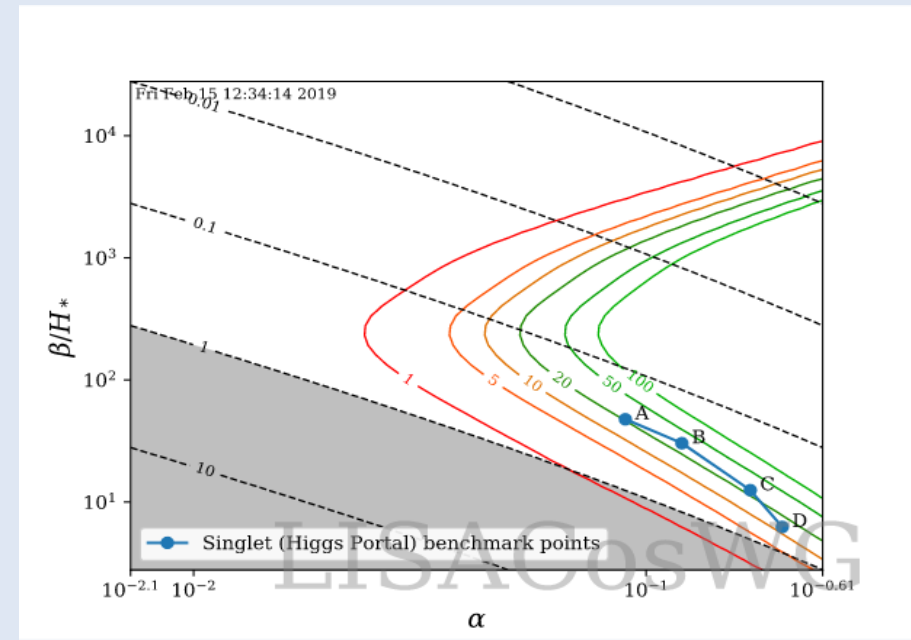
Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions

Caprini et al.
arxiv/1512.06239

Detecting gravitational waves from cosmological phase transitions with LISA: an update

Caprini et al.
arxiv/1910.13125

web-tool by *David Weir*
<http://www.ptplot.org>



Summary II

The observation of Gravitational Waves started a new era in astro physics.

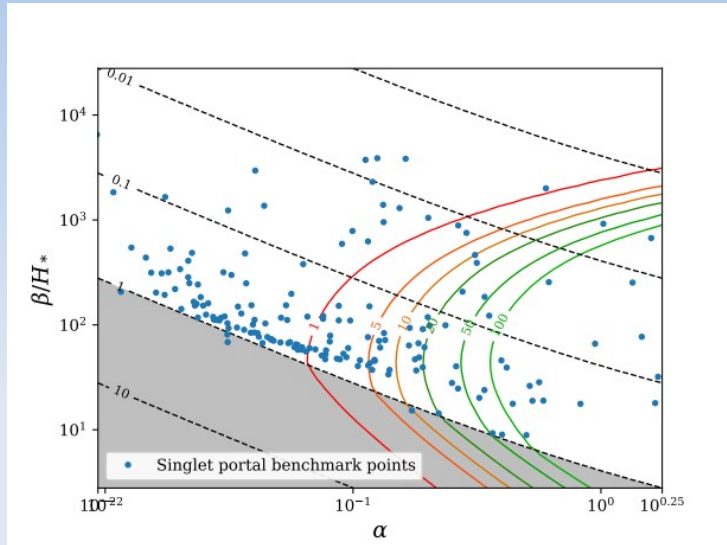
The main appeal of these observations is that one can **probe** the era before **electromagnetic decoupling**.

In principle, experiments as LISA/LIGO/DECIGO allow to test phase transitions (and hence particle physics) from **EW scales** up to **very high scales** $\sim 10^6$ GeV.

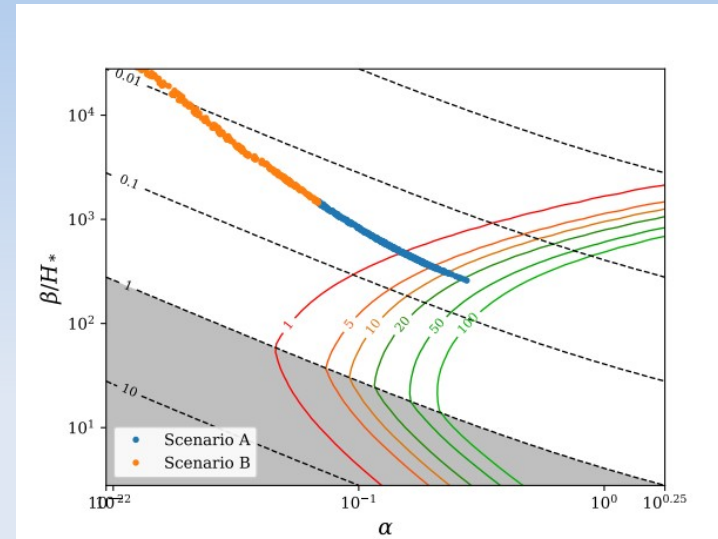
LISA will fly in the 2030s and cover a large range of cosmological phase transitions in terms of strength and temperatures close to electroweak scales.

Thank you

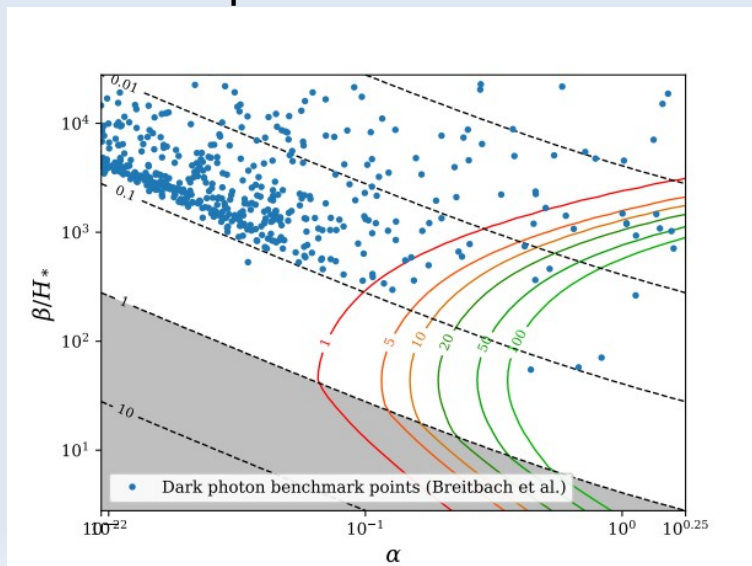
singlet portal model



SM EFT



dark photon



THD

