Gravitational waves and particle physics

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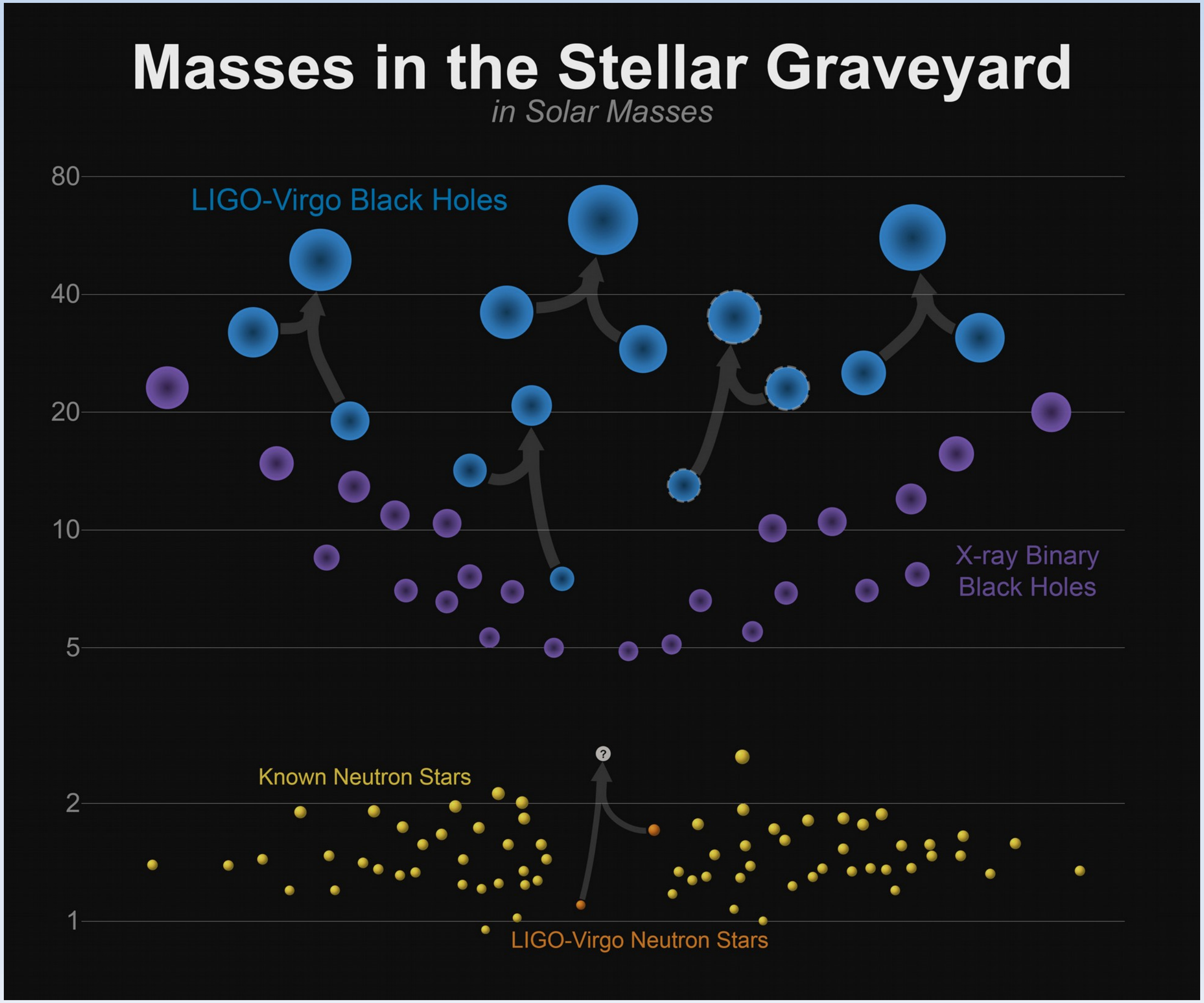
IPMU, Nov 11, 2020

Part I: binary mergers and particle physics

Observation of black hole merges put GW astrophysics and multi-messanger 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

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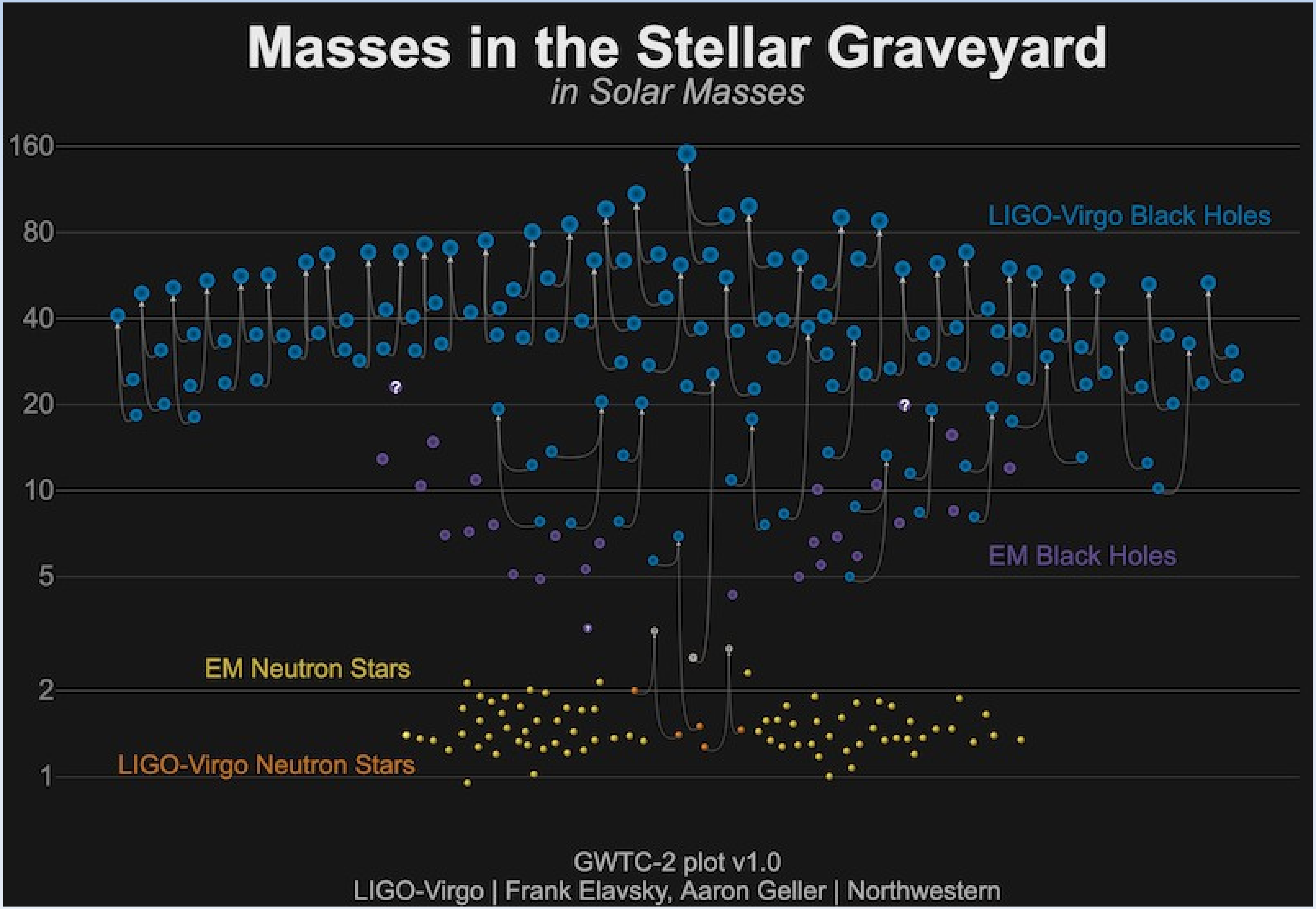
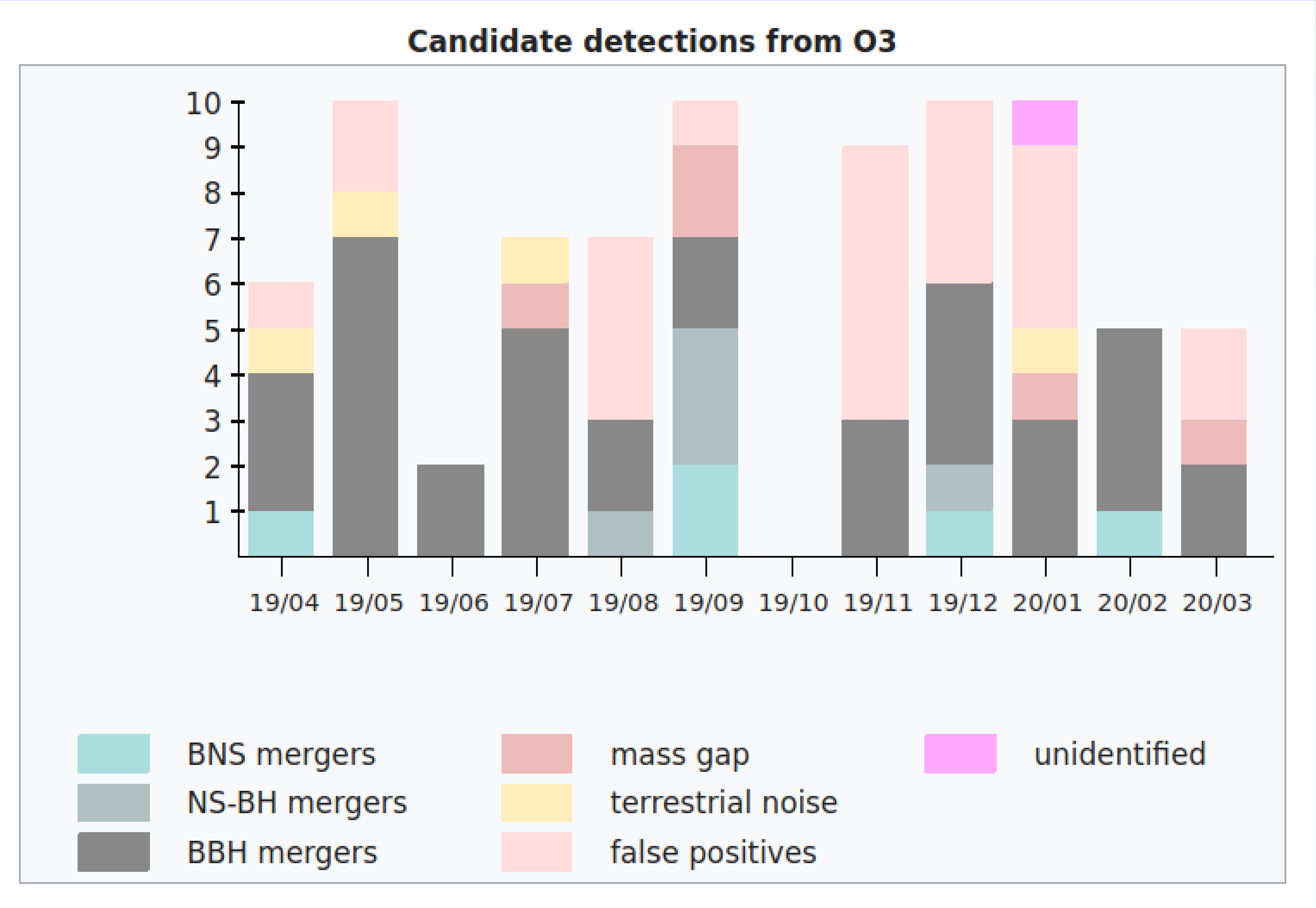


binary mergers



Corona shutdown ongoing

Neutron stars

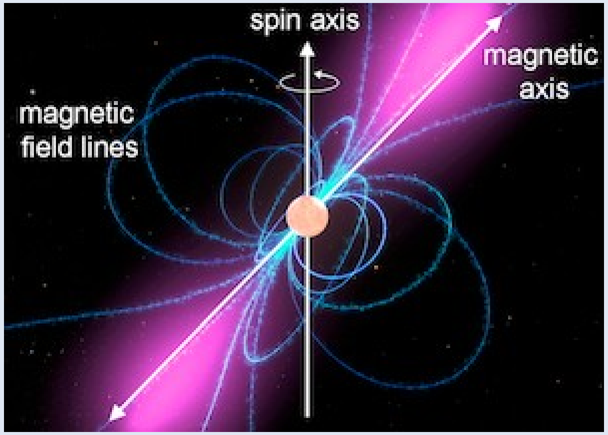
Neutron stars result from the explosion of supernovae with masses of between 10-30 solar masses. Their mass is typically about **2 solar masses** and their radius about **10 km**.

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**.

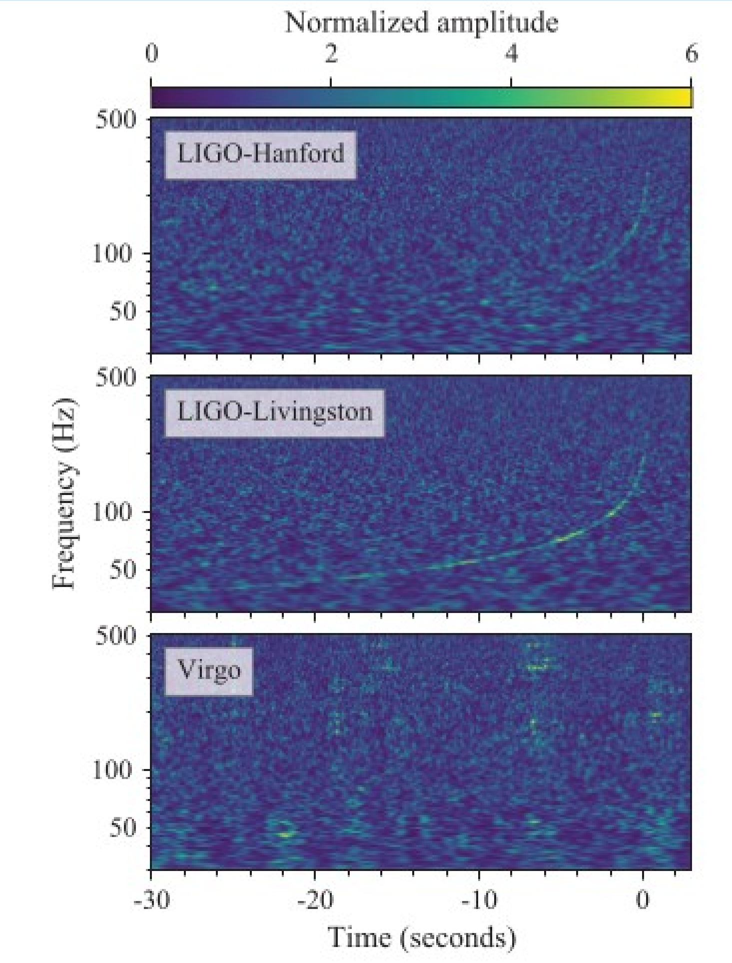
Neutron stars are believed to constitute the observed (milli sec) pulsars.

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



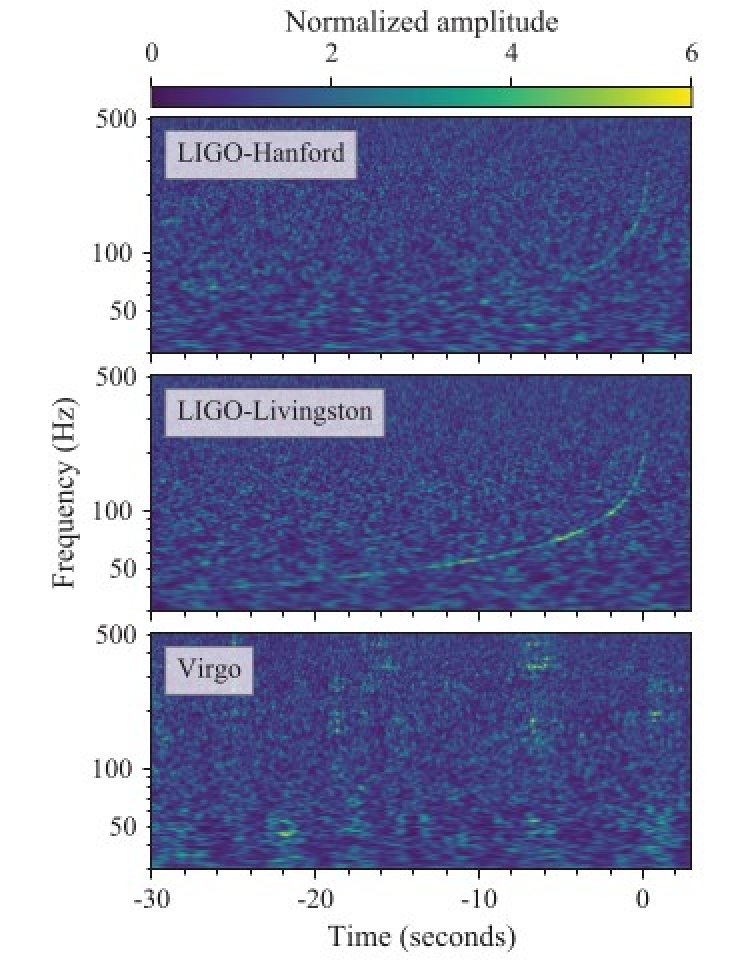
NS – NS mergers

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



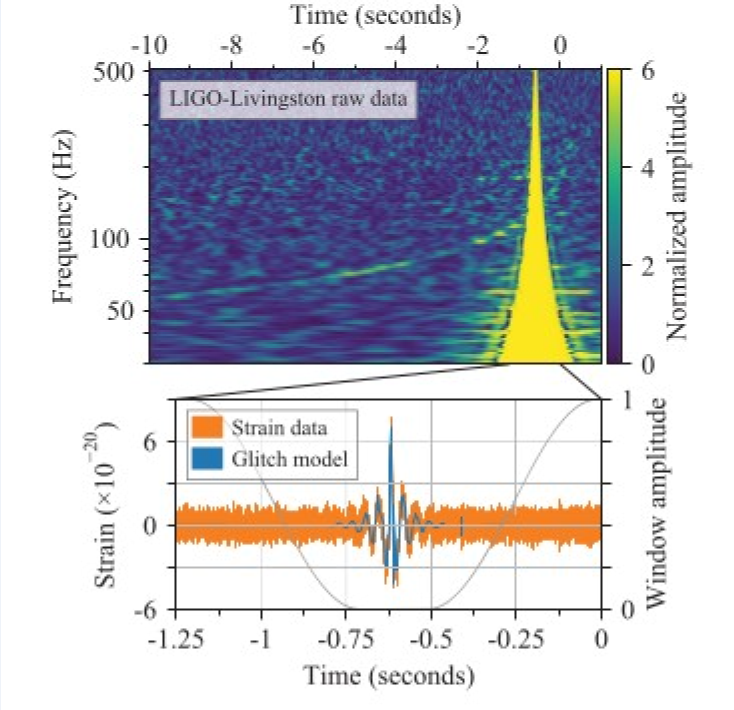
NS – NS mergers

GW170817



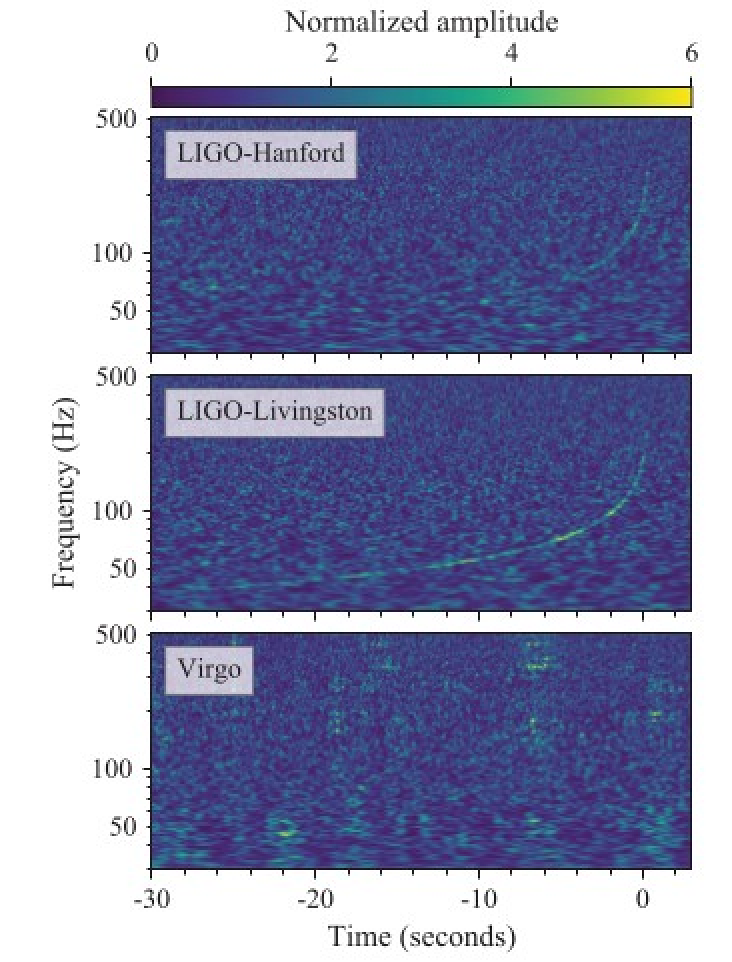
Ooops.

Actually didn't trigger automatically:



NS – NS mergers

GW170817



SNR > 32

masses are about 1.2 and 1.5 solar masses each

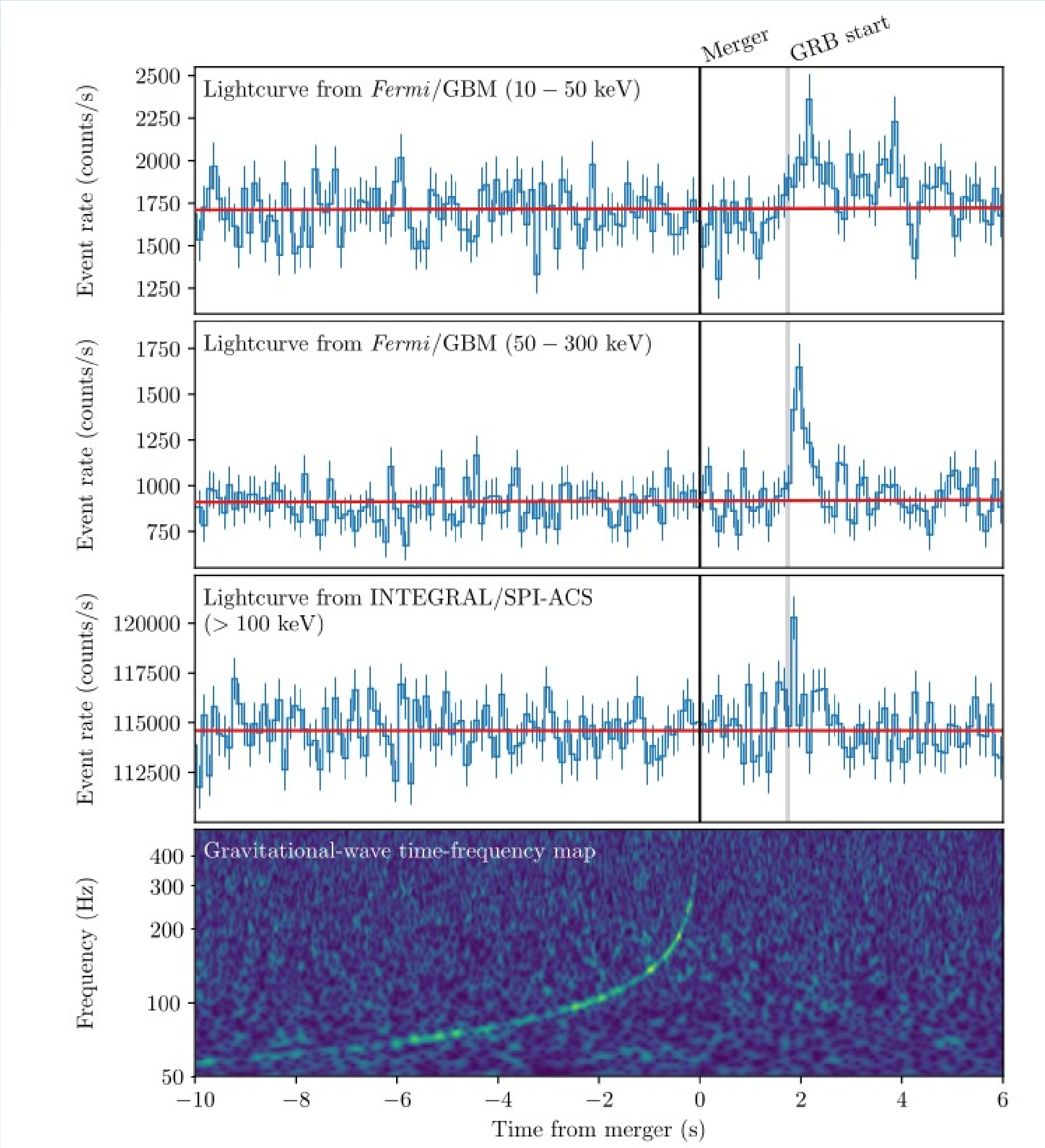
Orbital separation at the end again ~O(100 km). Cannot be normal star; one cannot be black hole.

→ must be neutron stars?

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

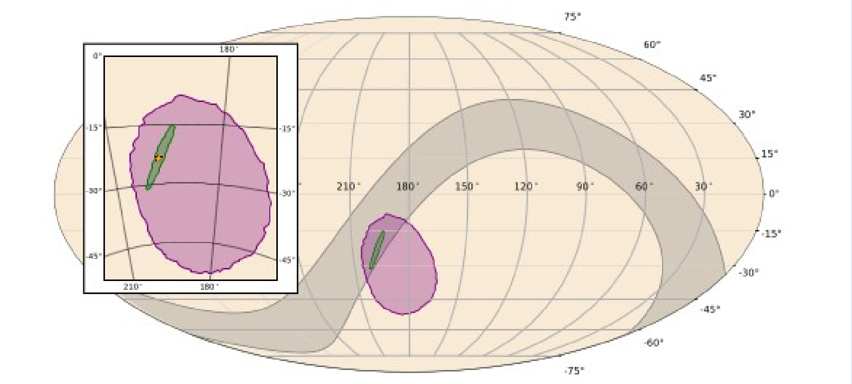
What about EM couterparts?

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 rather because) the event was in the blind spot of Virgo.

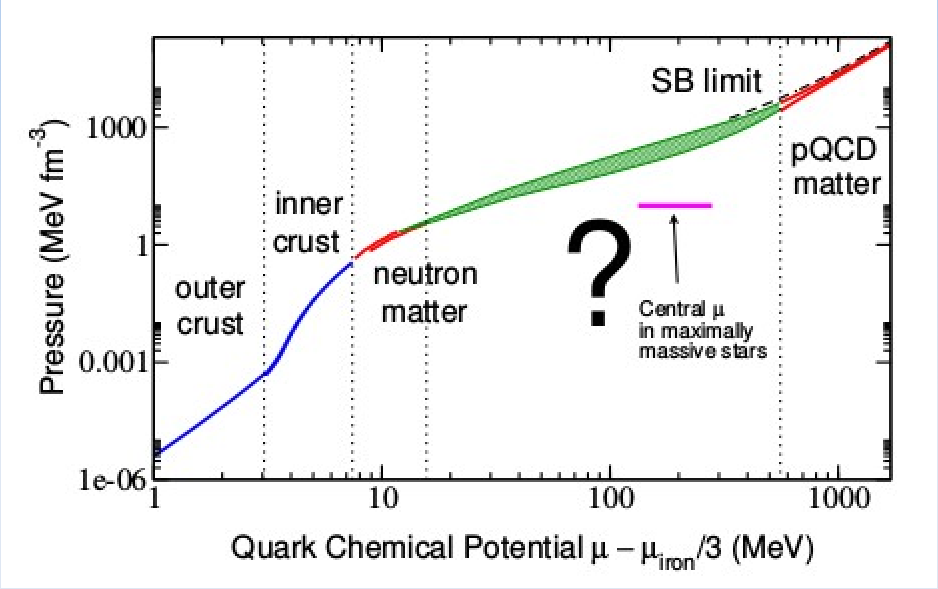


Subsequent EM observations could pinpoint the host galaxy.

→ important for the H_0 measurement

QCD equation of state

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



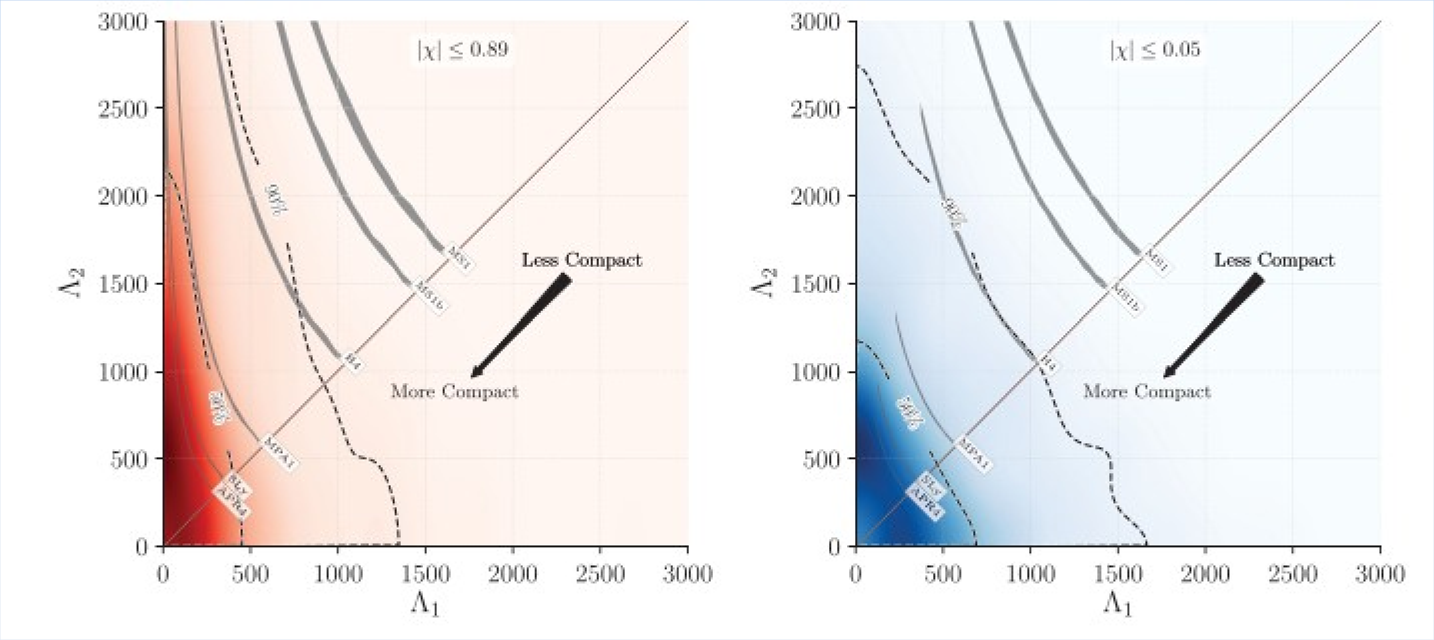
The equation-of-state of quark matter is poorly known for finite chemical potential.

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

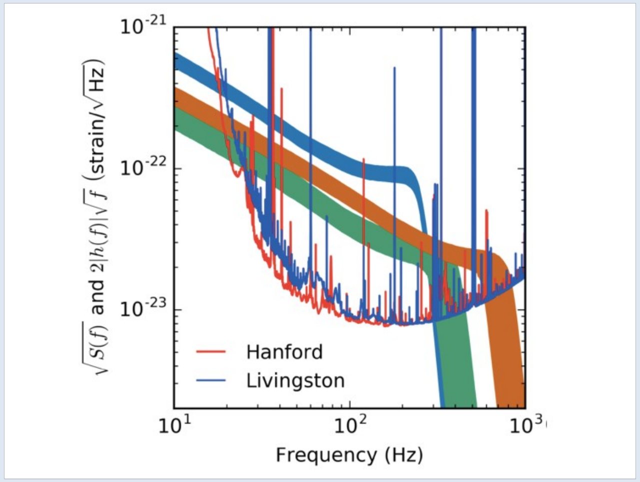
QCD equation of state

[LIGO '2017]

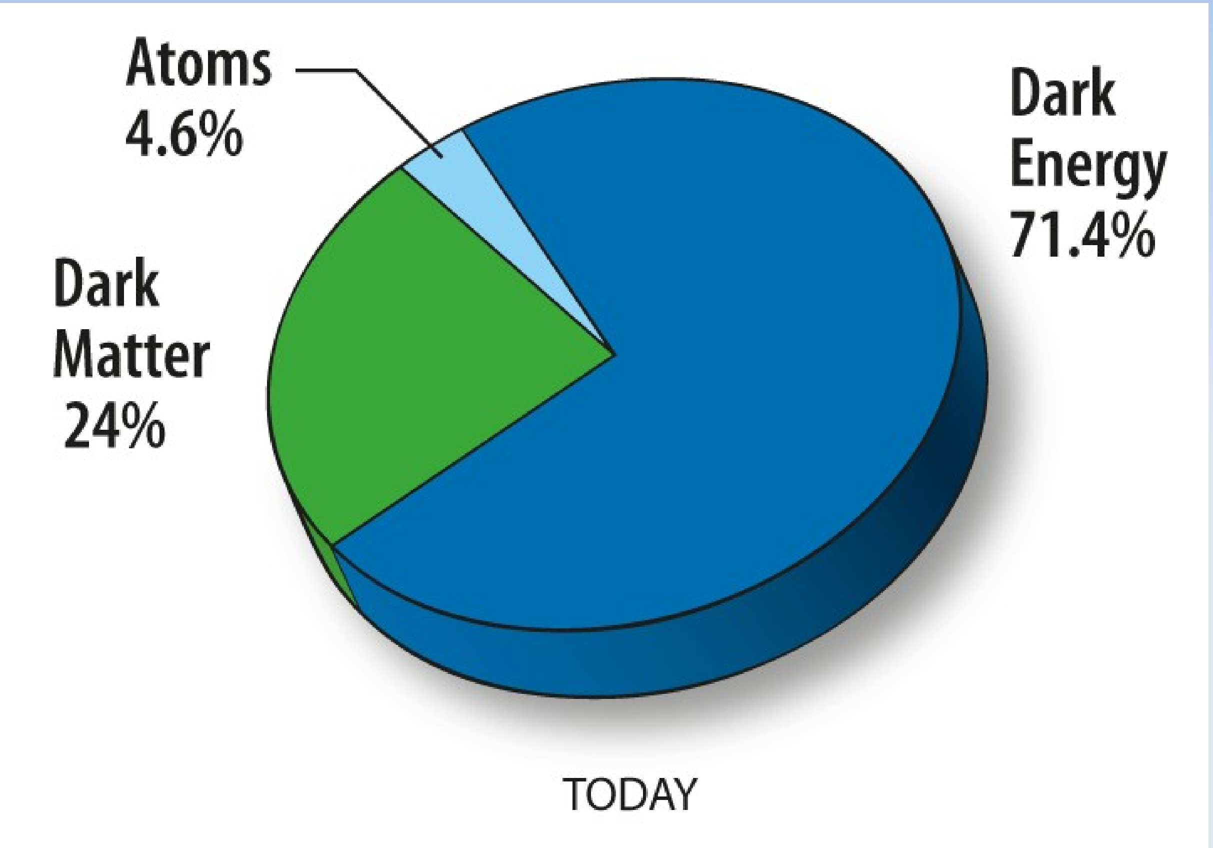


Some bounds obtained from GW170817 on the tidal deformation parameters Λ.

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



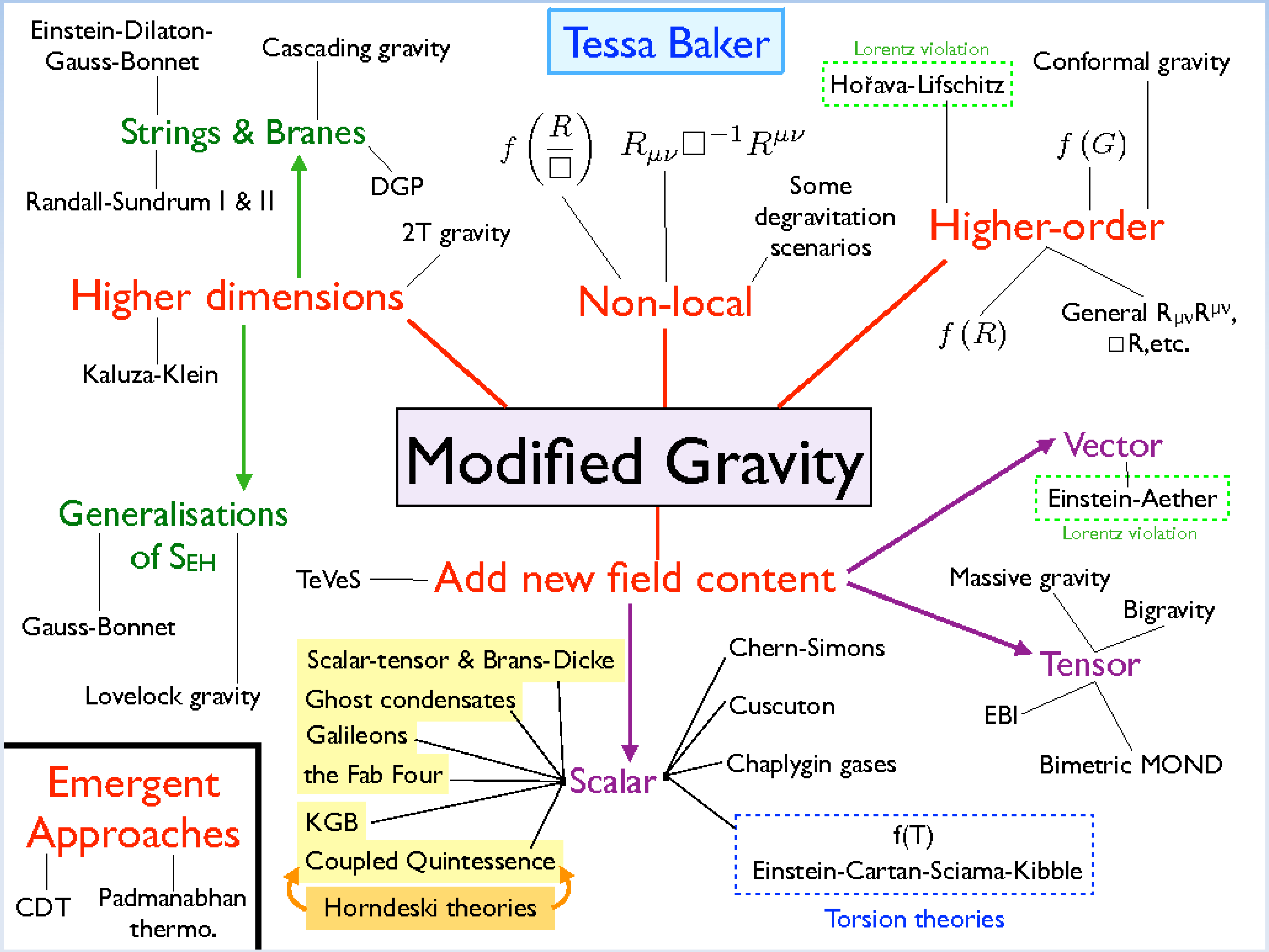
Cosmic pie



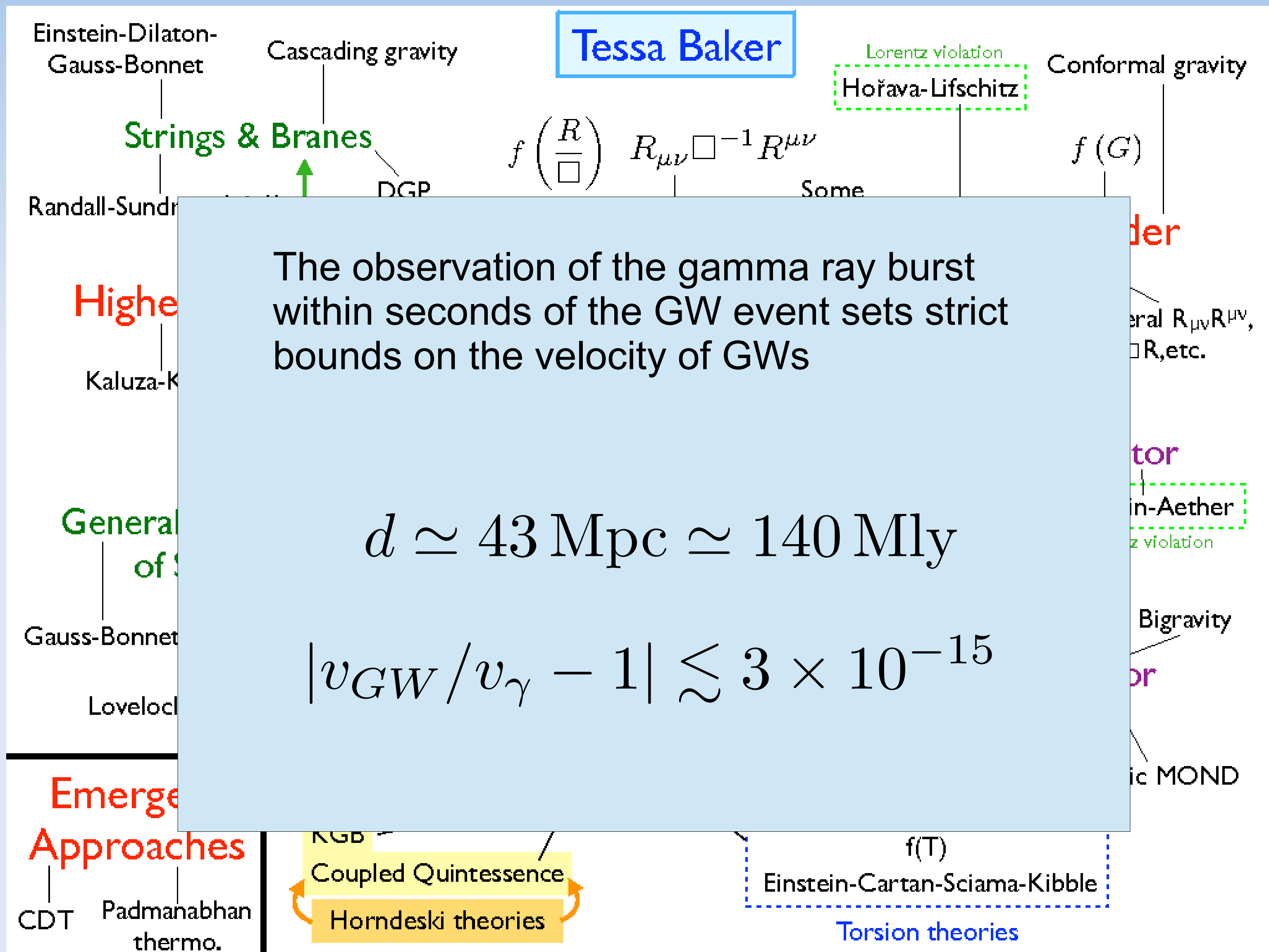
Dark energy and dark matter is only observed through their gravitational forces. CC problem.

Do we really need them?
Perhaps modified gravity can accout for it?

Modified gravity landscape



Modified gravity landscape



The observation of the gamma ray burst within seconds of the GW event sets strict bounds on the velocity of GWs

$$d \simeq 43\,\mathrm{Mpc} \simeq 140\,\mathrm{Mly}$$

$$|v_{GW}/v_\gamma - 1| \lesssim 3 \times 10^{-15}$$

Hubble parameter

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

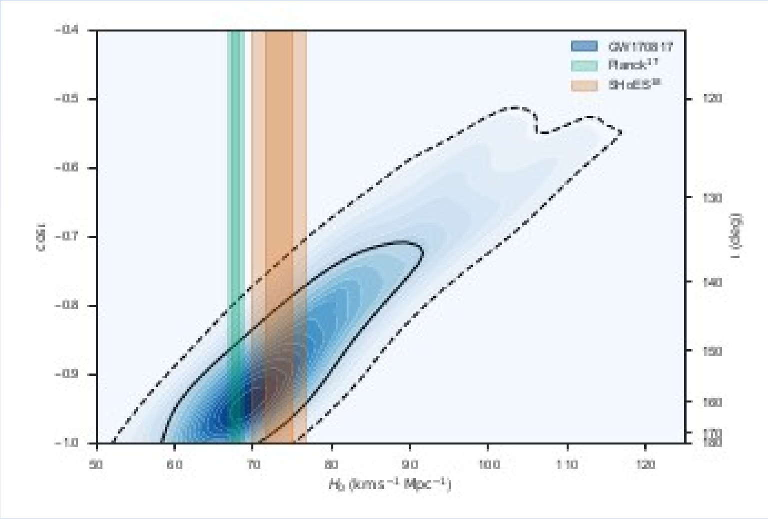
$$v_H = H_0 \, d$$

In order to determine H_0 one needs v_H (via the redshift) 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 can be measured by identifying the host galaxy which in this case was easy due to the EM couterparts.

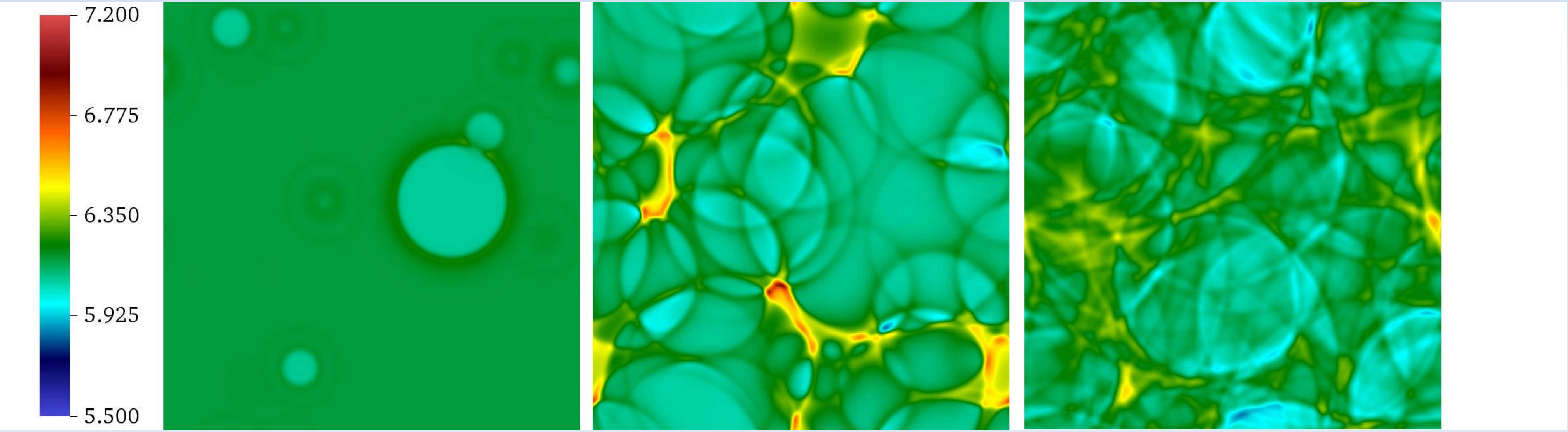
problems:
- peculiar motions (Doppler effect)
  → LSS catalogues
- *d* degenerate with inclination → polarisation



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

$$v_H \simeq 3000\,\mathrm{km/s}$$
$$d \simeq 43\,\mathrm{Mpc}$$

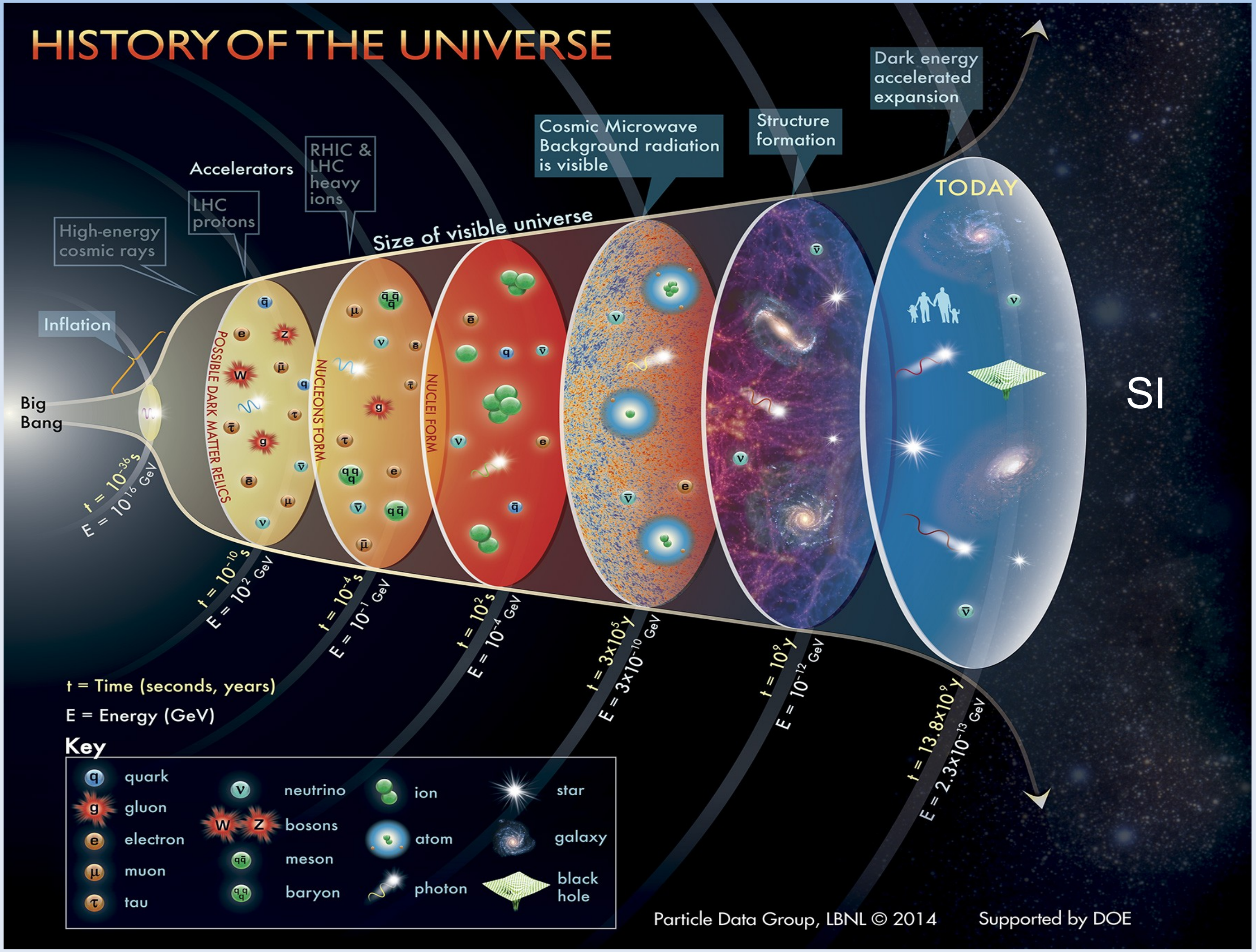
Part II : GWs from cosmological phase transitions



Future space telescopes

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

Standard Cosmology

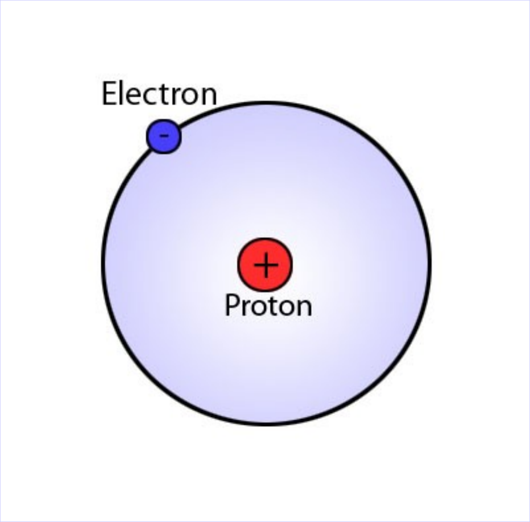


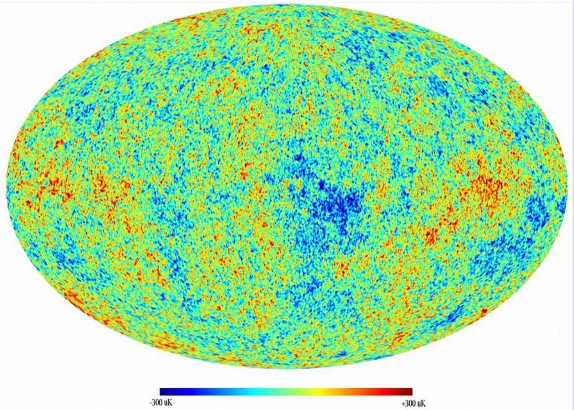
SI

time →

← temperature

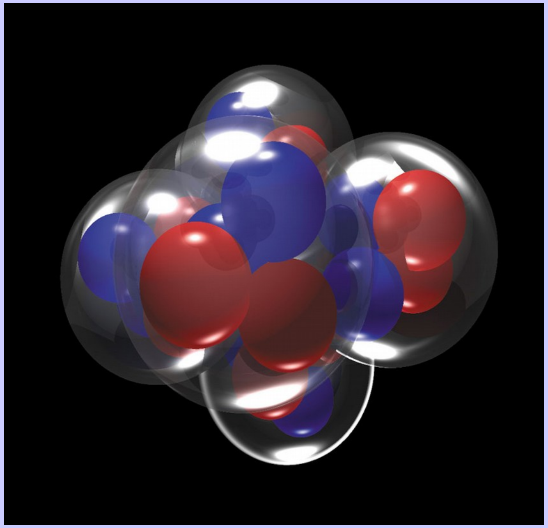
Atomic physics at T~eV

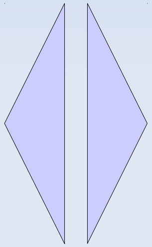


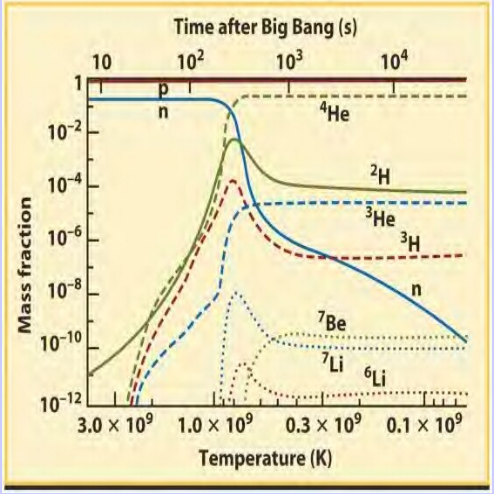


The Cosmic Microwave Background **links** atomic physics to cosmology at temperature T~eV

Nuclear physics at T~MeV

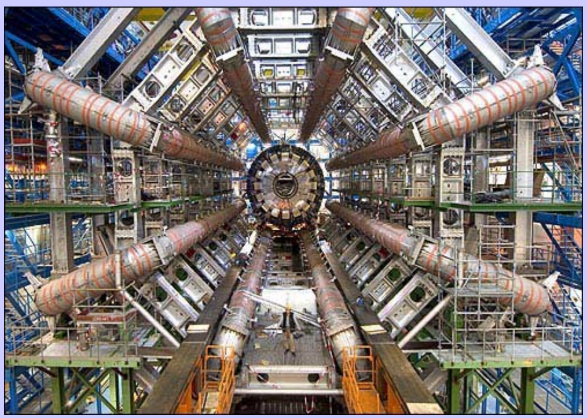


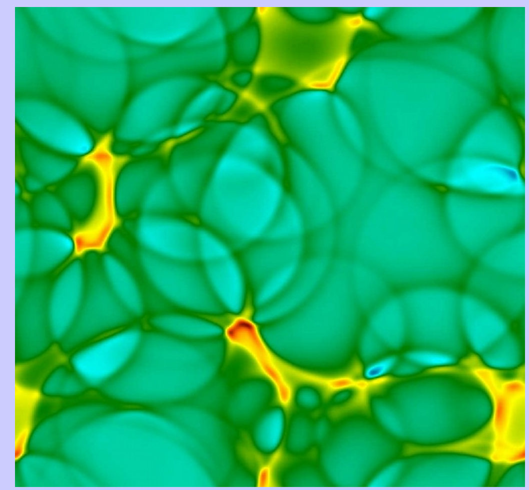




Big bang nucleosynthesis **links** nuclear physics to cosmology at temperature T~MeV

Phase transition at T~100 GeV?





Possibly, the electroweak phase transition drove the Universe **out-of-equilibrium** if it was of first order**.**

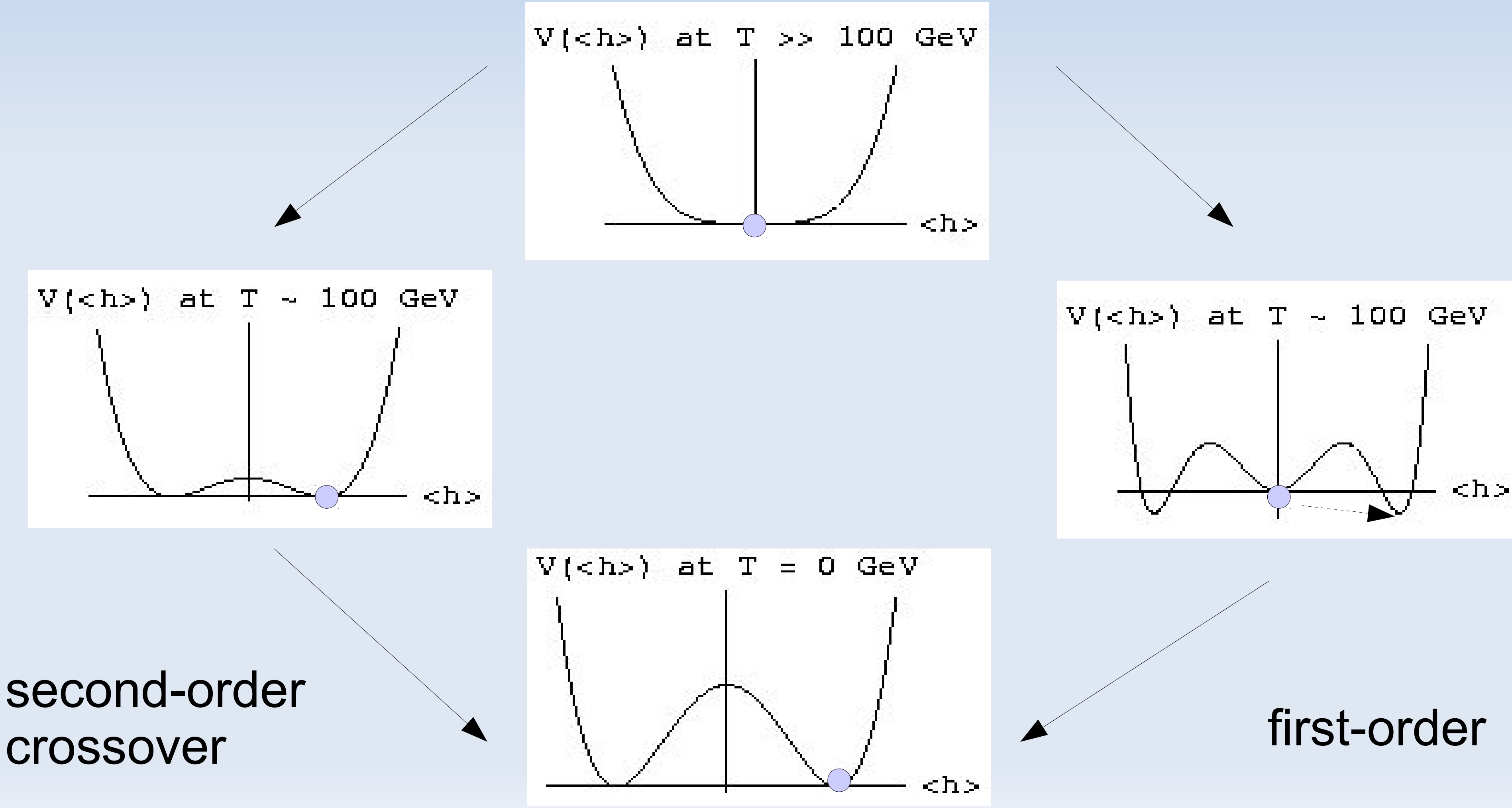
Electroweak phase transition

gravitational
waves

baryogenesis

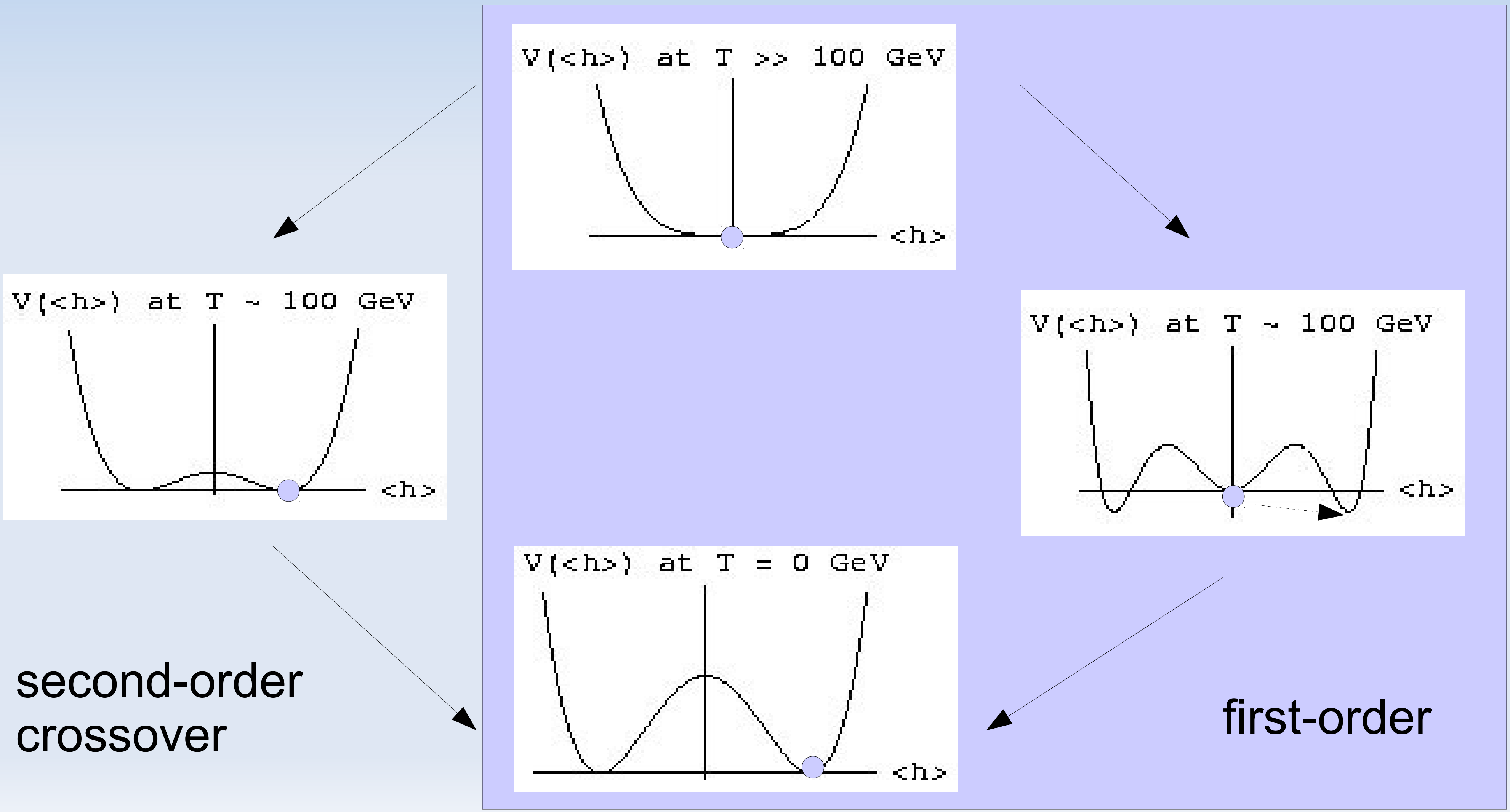
Electroweak symmetry breaking

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



Electroweak symmetry breaking

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

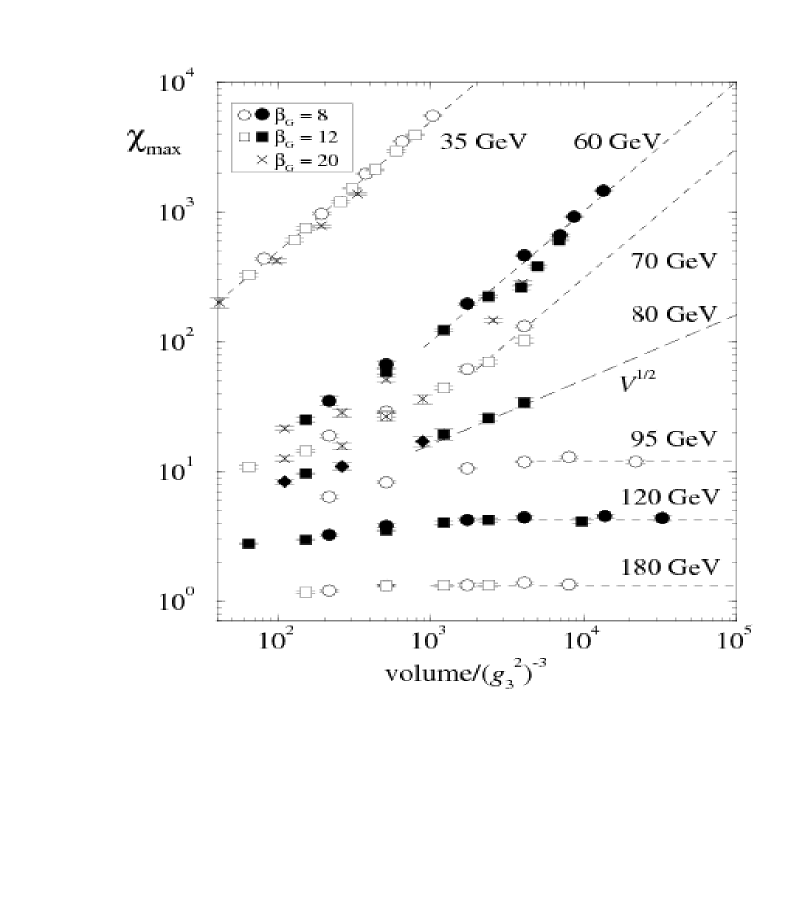


Electroweak phase transition in the SM

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.



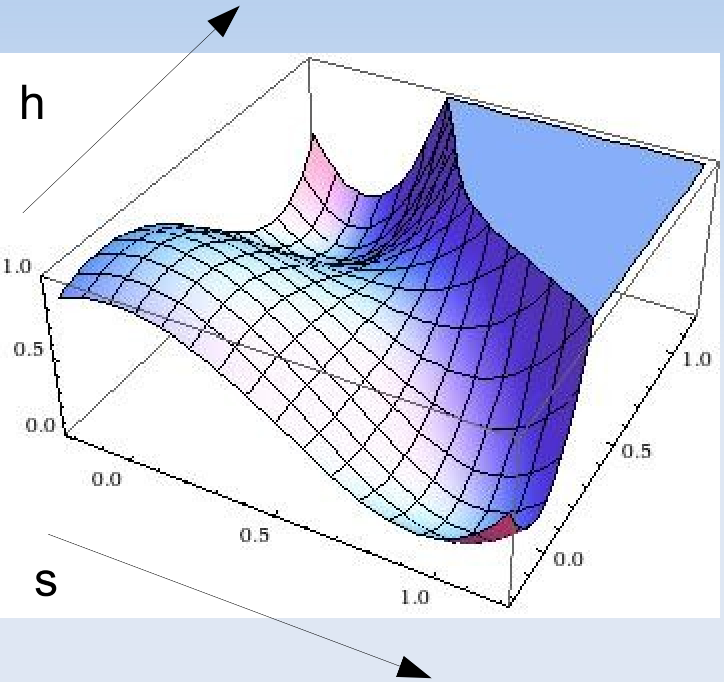
[Kajantie, Laine, Rummukainen, Shaposhnikov '96]
[Buchmuller, Fodor, Helbig, Walliser '93]

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:

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



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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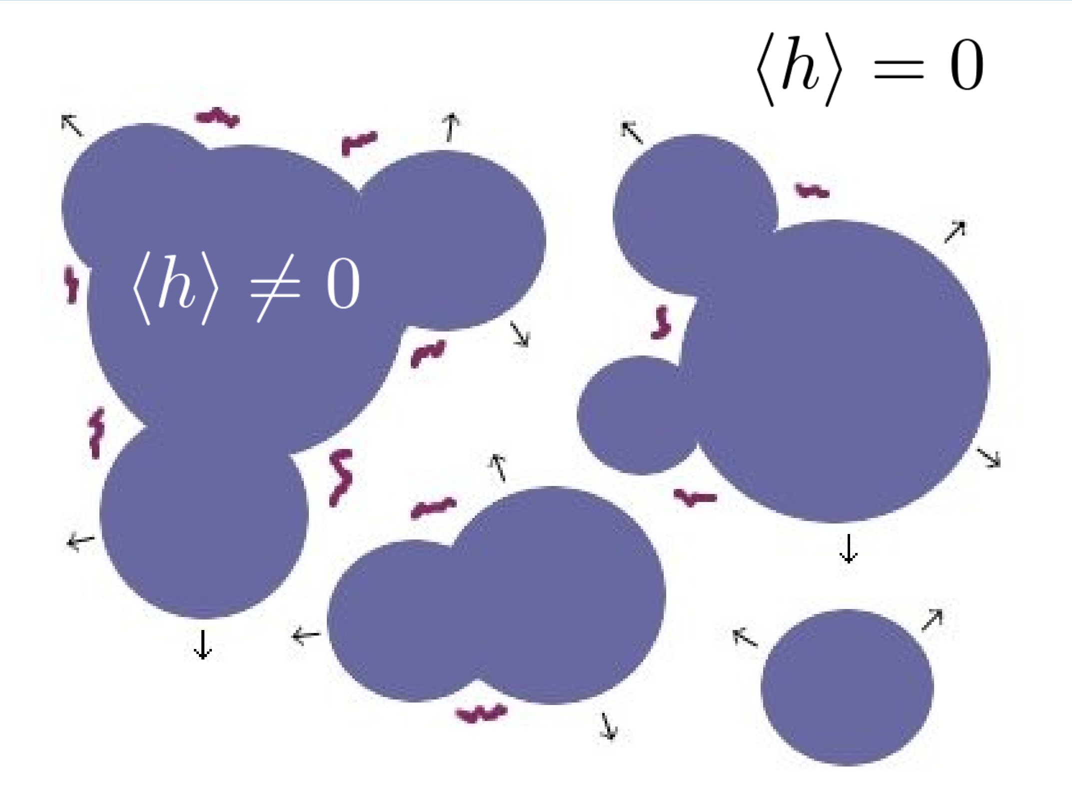
First-order phase transitions

- 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

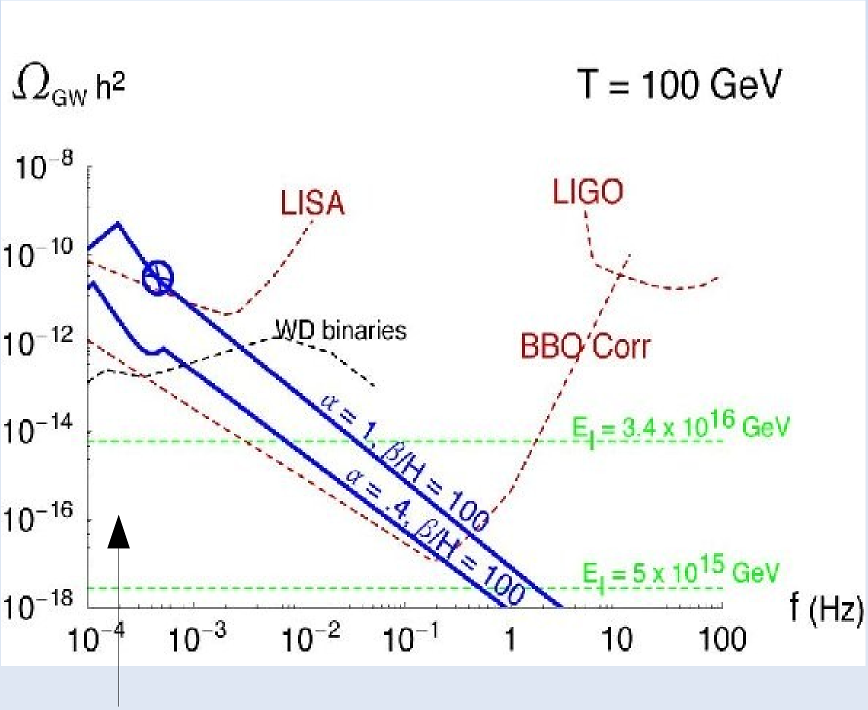


During the first-order phase transitions, the nucleated bubbles expand. Finally, the colliding bubbles generate stochastic gravitational waves.

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 ~ 100 GeV

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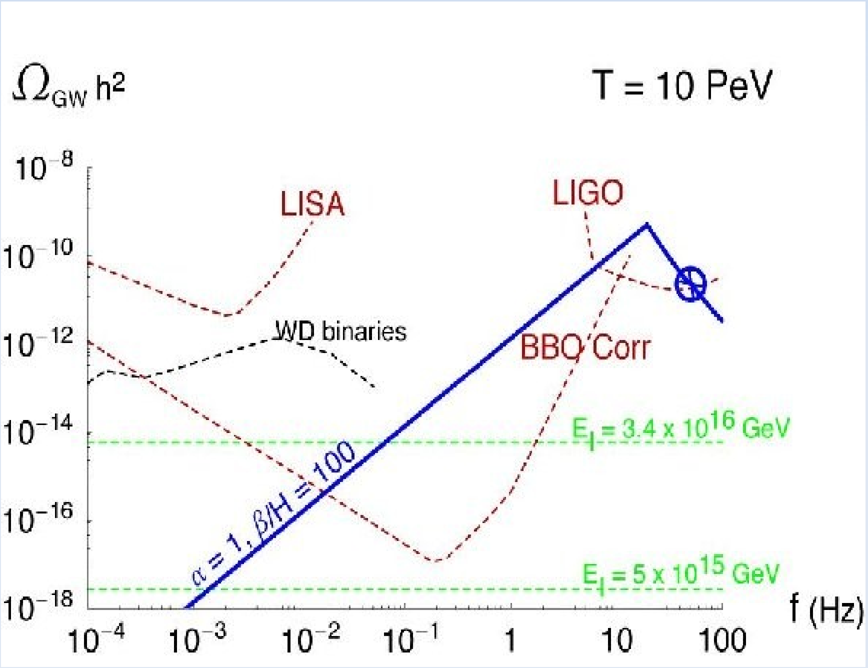
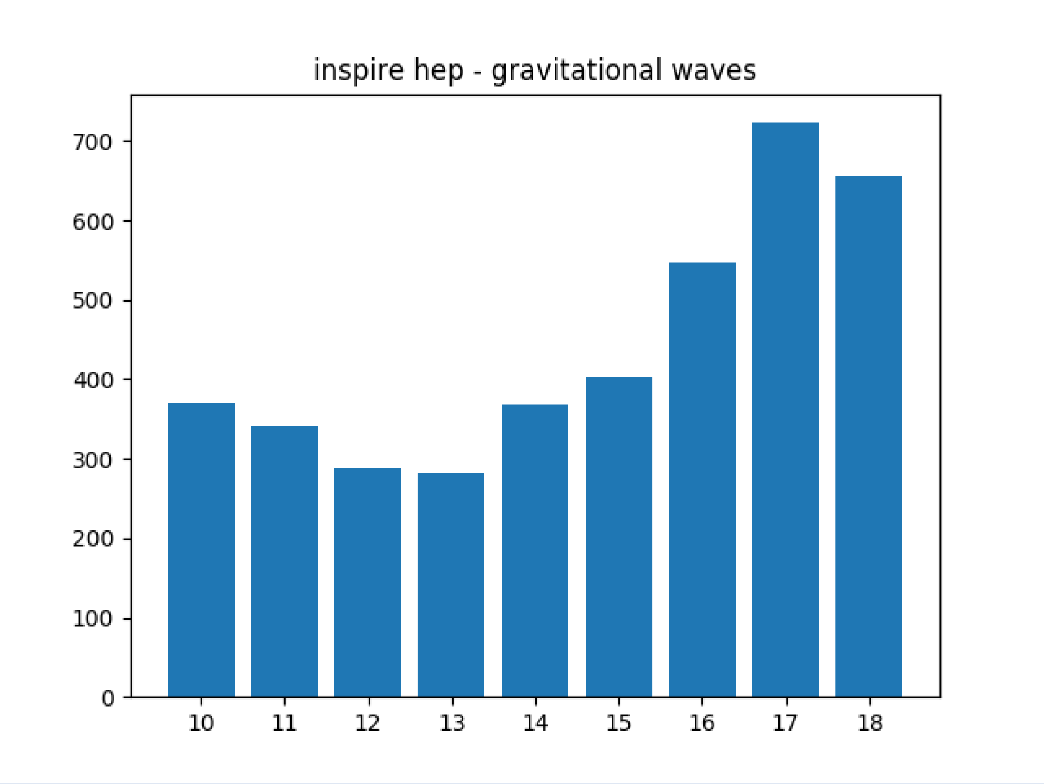
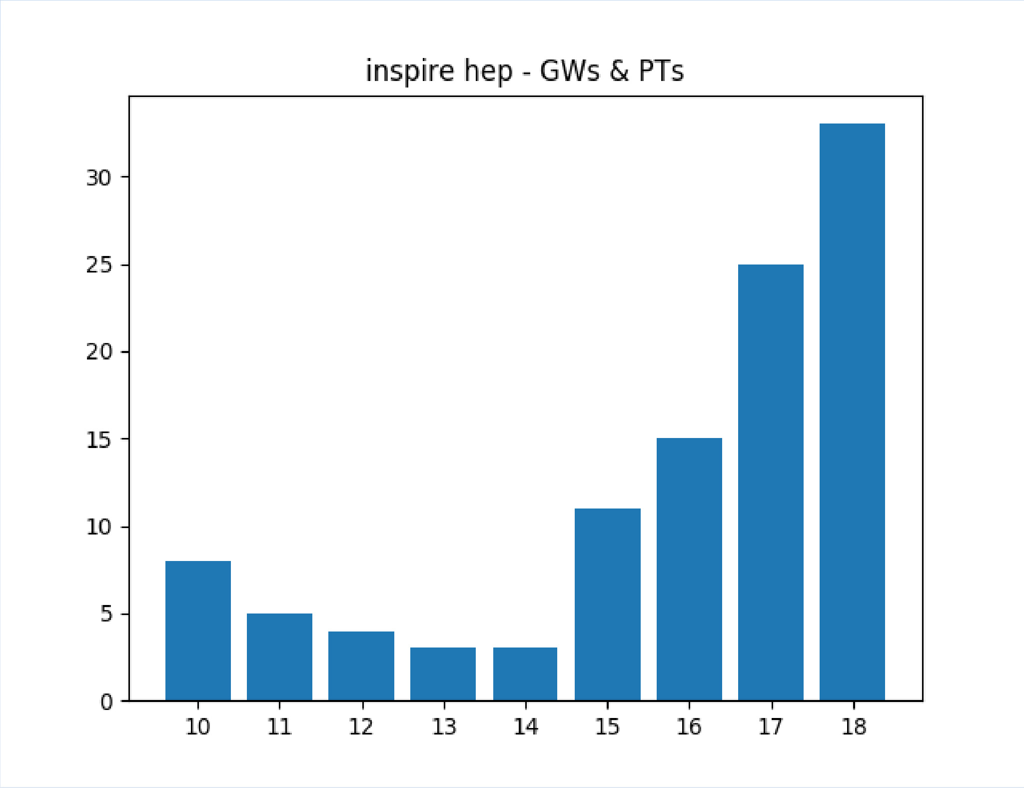


Strong phase transition at larger temperatures produce the same energy fraction of gravitational waves but at higher frequencies.

GWs from PTs

ArXiv activity:





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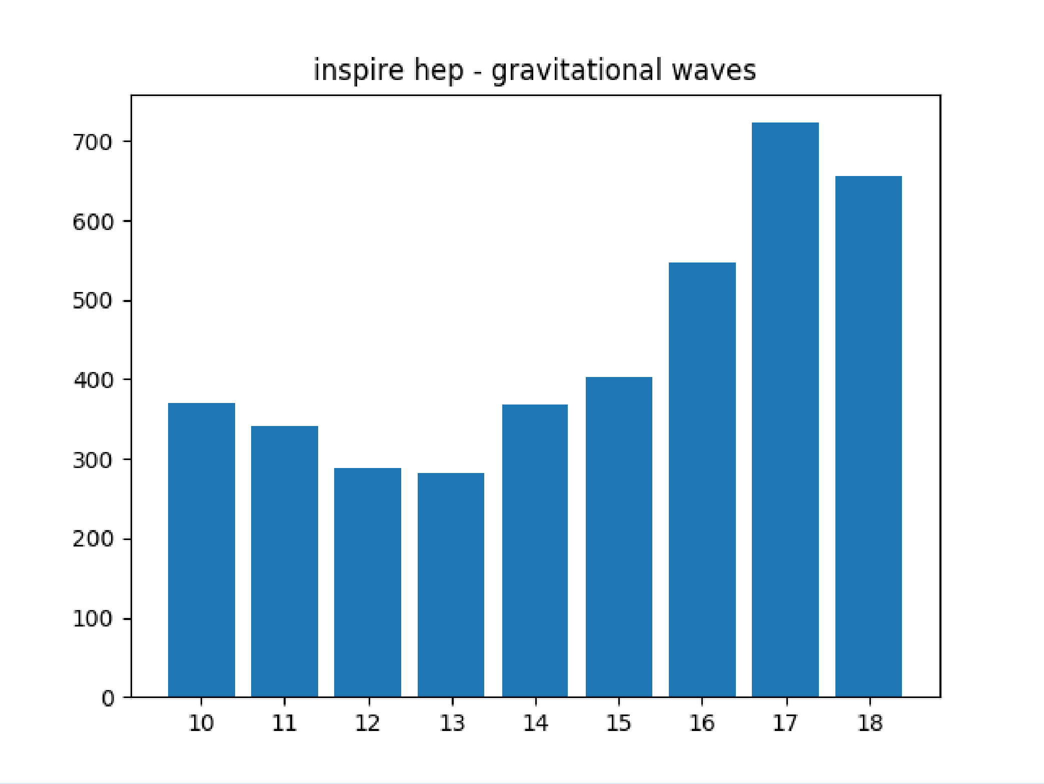
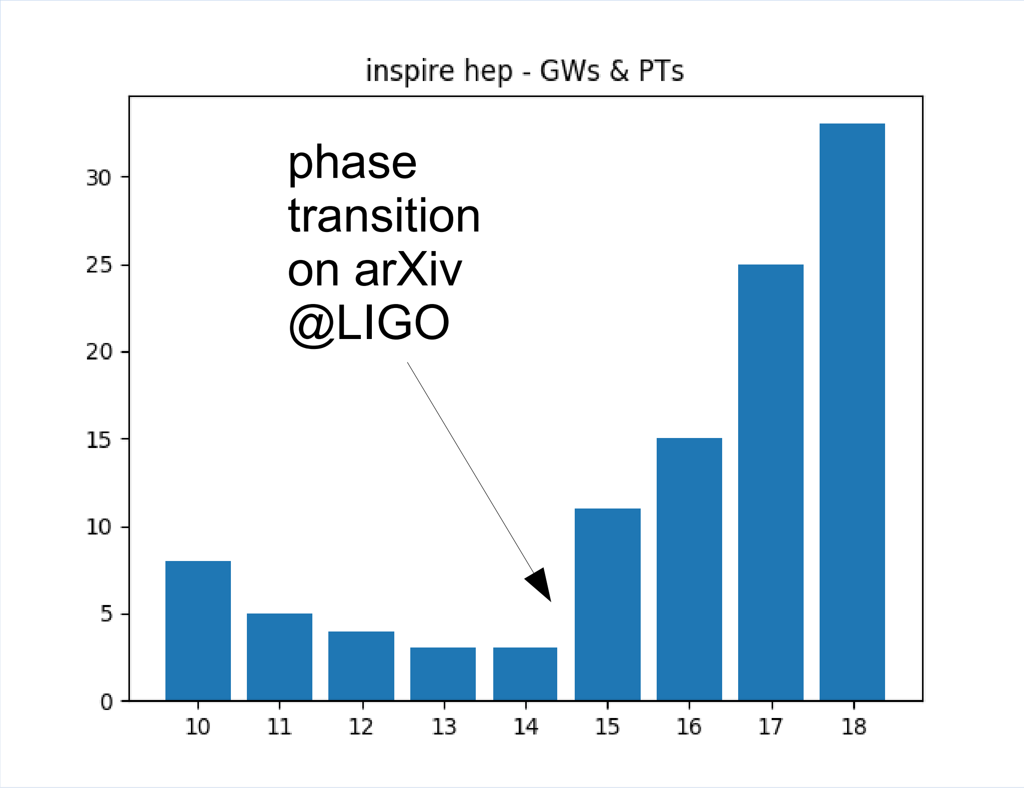




Sources of GWs from PTs

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

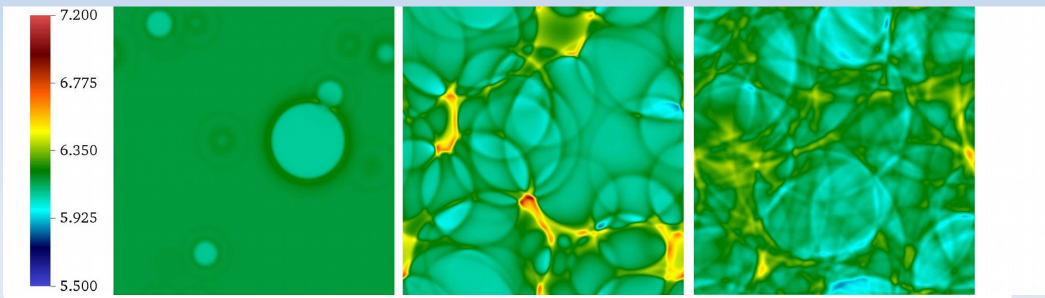
- Collisions of the scalar field configurations / initial fluid shells
- Sound waves after the phase transition (long-lasting → dominant source)
- Turbulence
- Magnetic fields

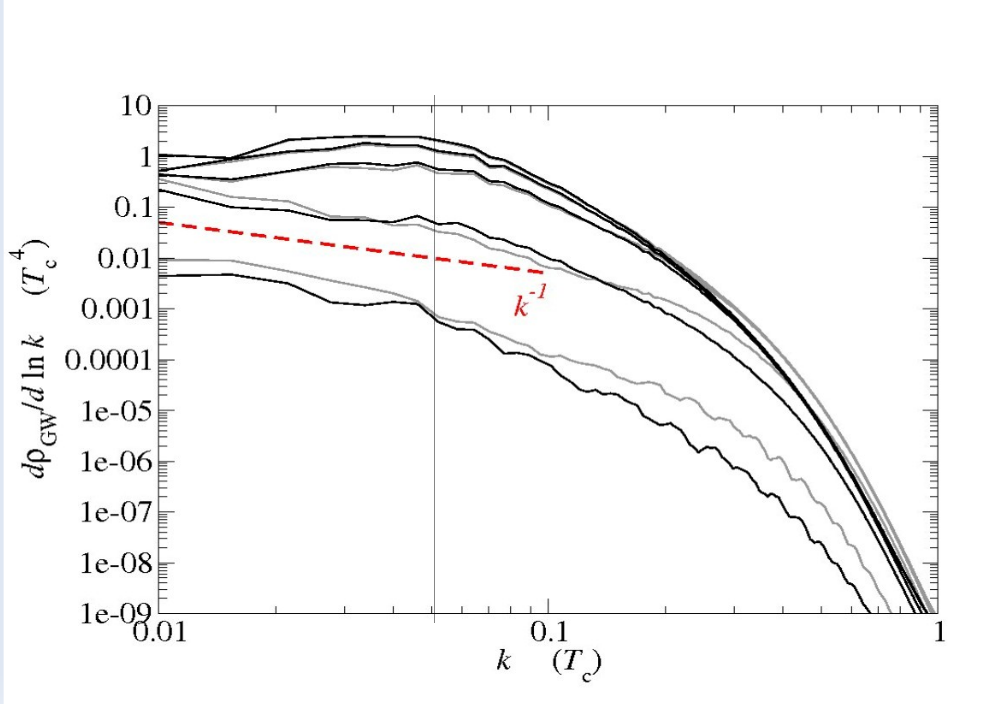
Which source dominates depends on the characteristics of the PT

State-of-the-art

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

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

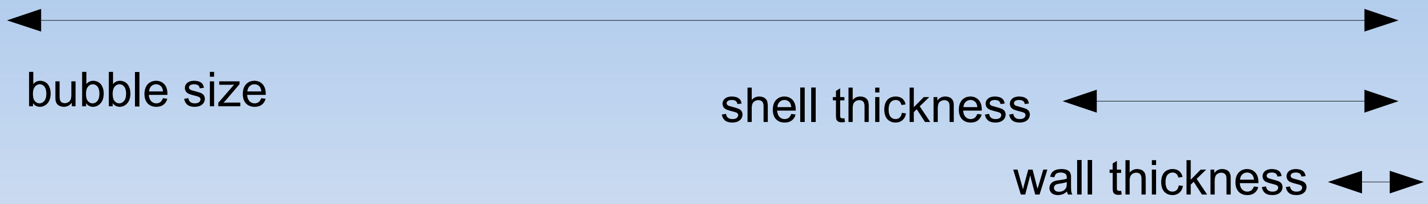




The produced GW spectrum can be read off from the simulation.

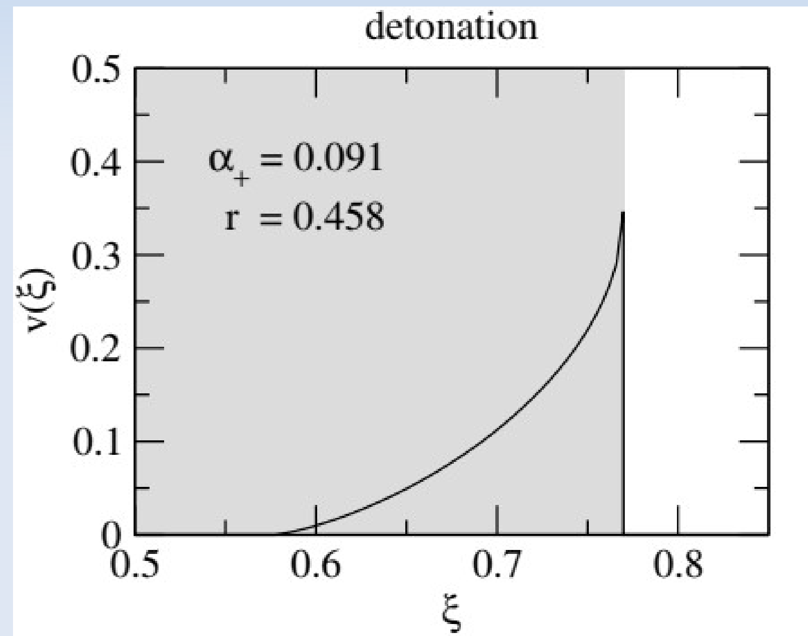
Really robust results but how to extrapolate to other models and realistic wall thickness?

Length scales



One technical main problem of the simulations is that they have to resolve diffrent length scales: the bubble size, the sound shell thickness and the bubble wall thickness.

In particular, the bubble wall thickness is many orders smaller than the bubble size, so extrapolations to the physical point have to be used.

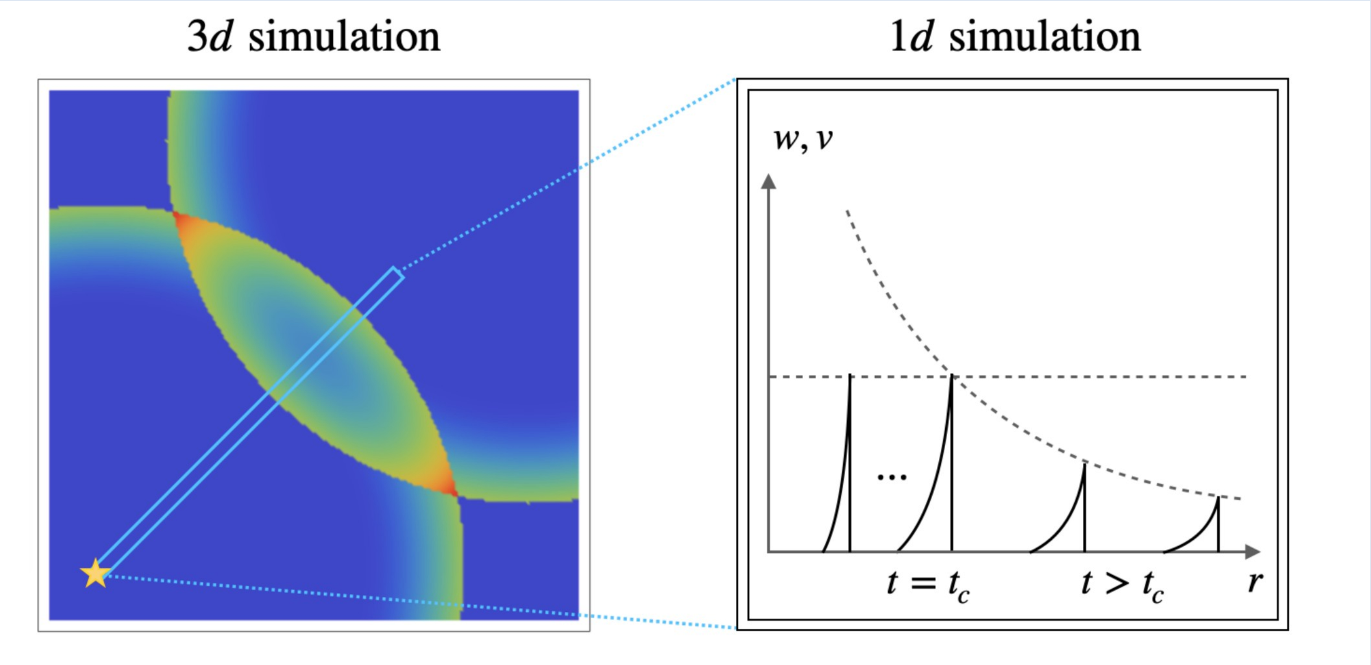


$$\xi = \frac{r}{t}$$

Novel simulations

We are concieving new simulations where the bubble wall thickness only enters through the boundary conditions of the simulation. We achieve this by doing simulations of colliding 1D bubbles and then embed these bubbles into a 3D grid.

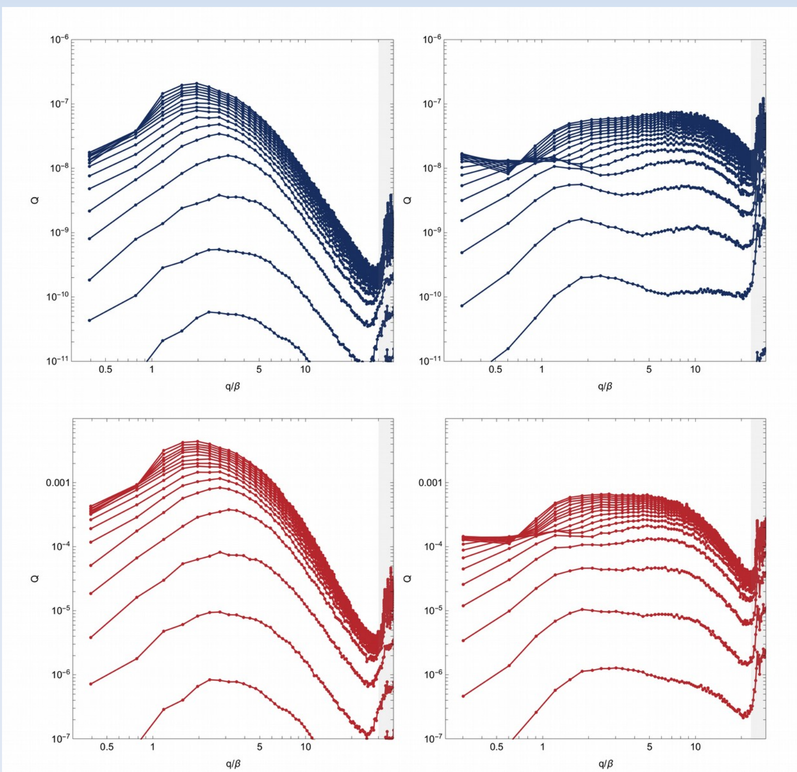
This assumes relatively weak phase transitions (and linear superposition of sound waves) but is valid for very thin shells and relativistic bubble wall velocities.

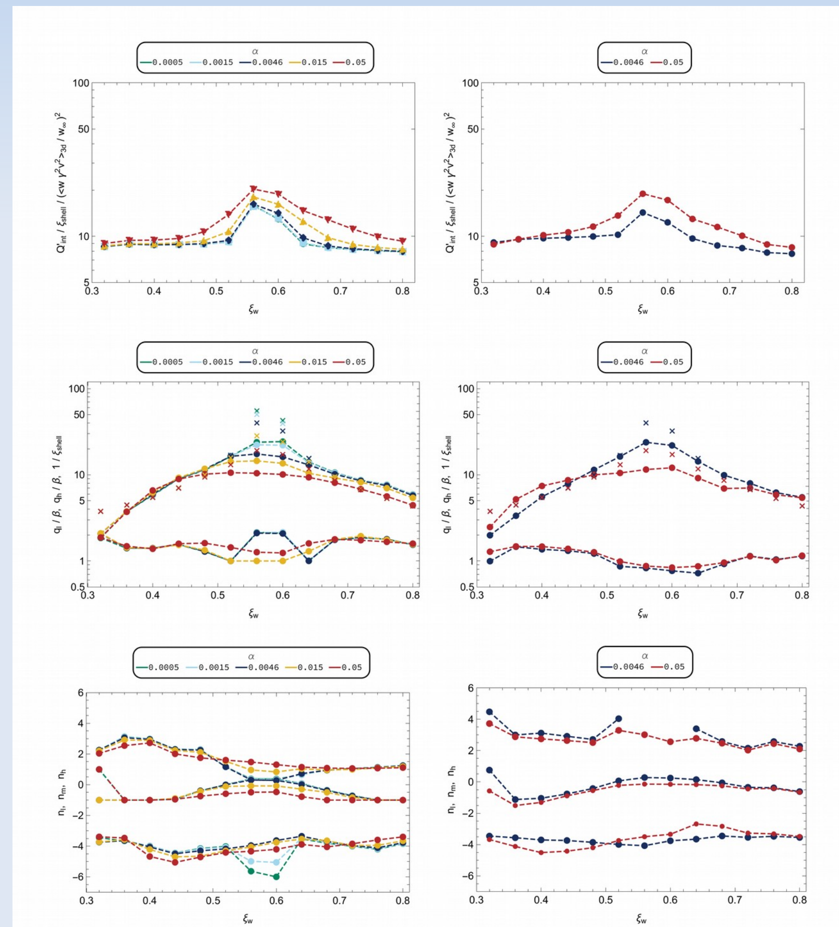


show cool video here

Final spectra

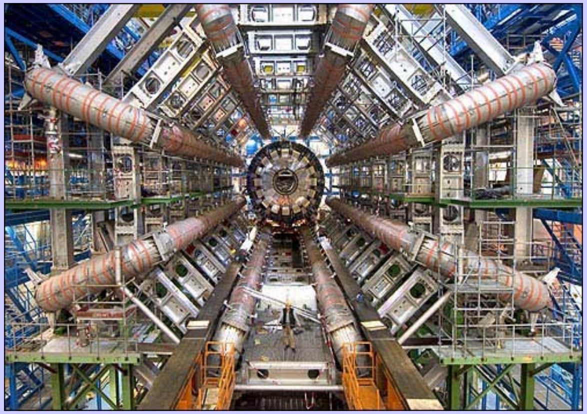
Many of these light-weight simulations can be performed and the relevant parameters of the GW spectra can be extracted. This also – for the first time – gives access to phase transitions with thin shells and large wall velocities.

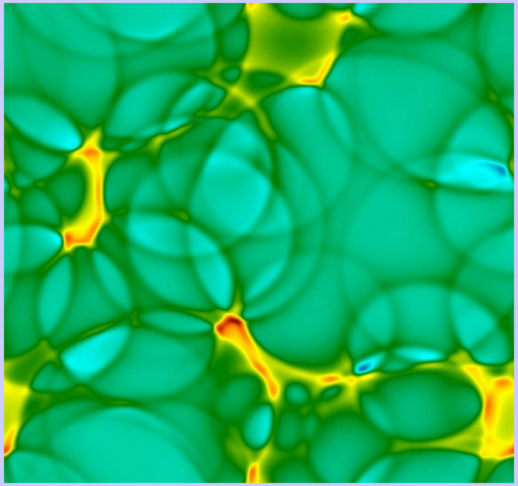




[Jinno, TK, Rubira ’20]

How to connect models and simulations?





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

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

rest of the talk

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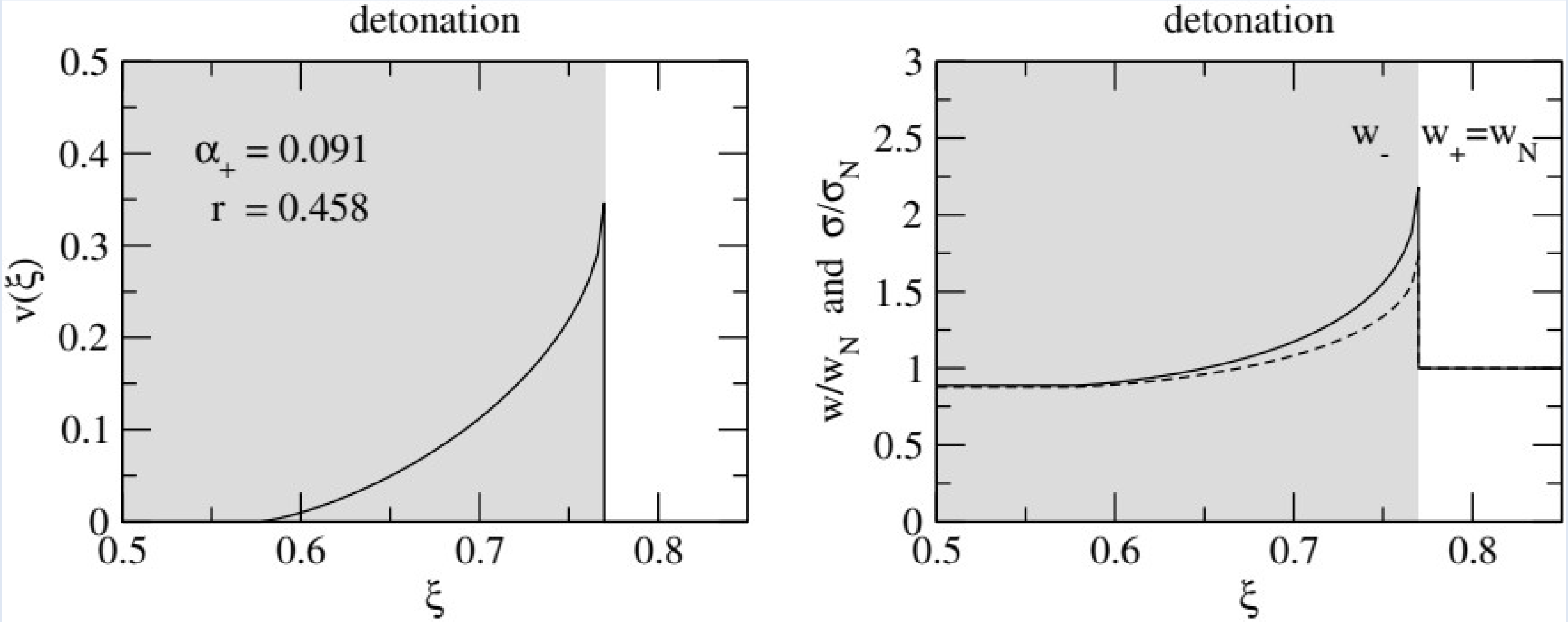
Kinetic energy with spherical symmetry

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

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



$$\xi = r/t$$

Bag model

[Kosowsky, Turner , Watkins, '92]
[Espinosa, TK, No, Servant '10]

The kinetic enregy 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

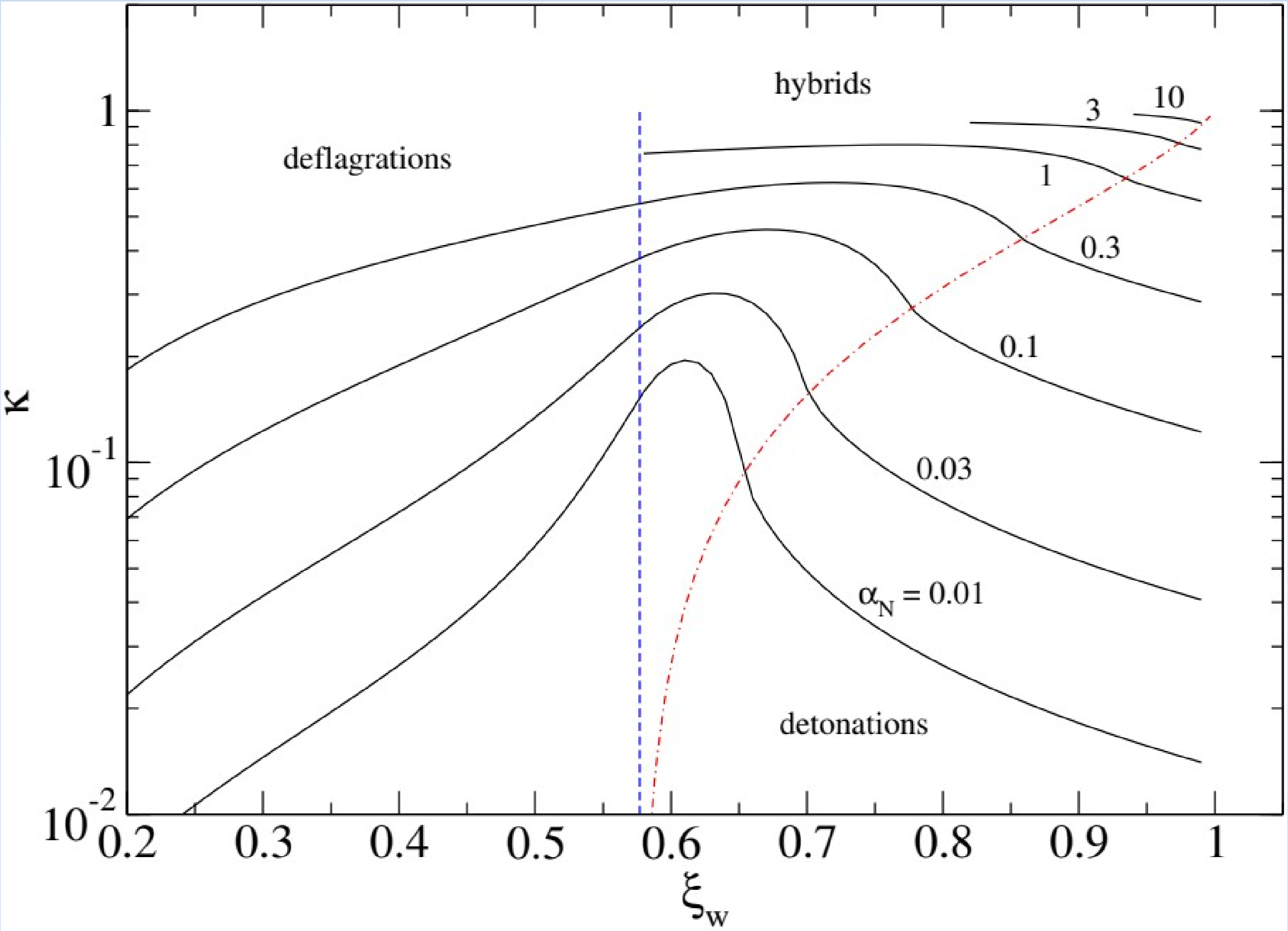
The strength of the phase transition is characterized by

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

Kinetic energy fraction and efficiency coefficient

[Espinosa, TK, No, Servant '20]

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



wall velocity

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 simluations

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 %

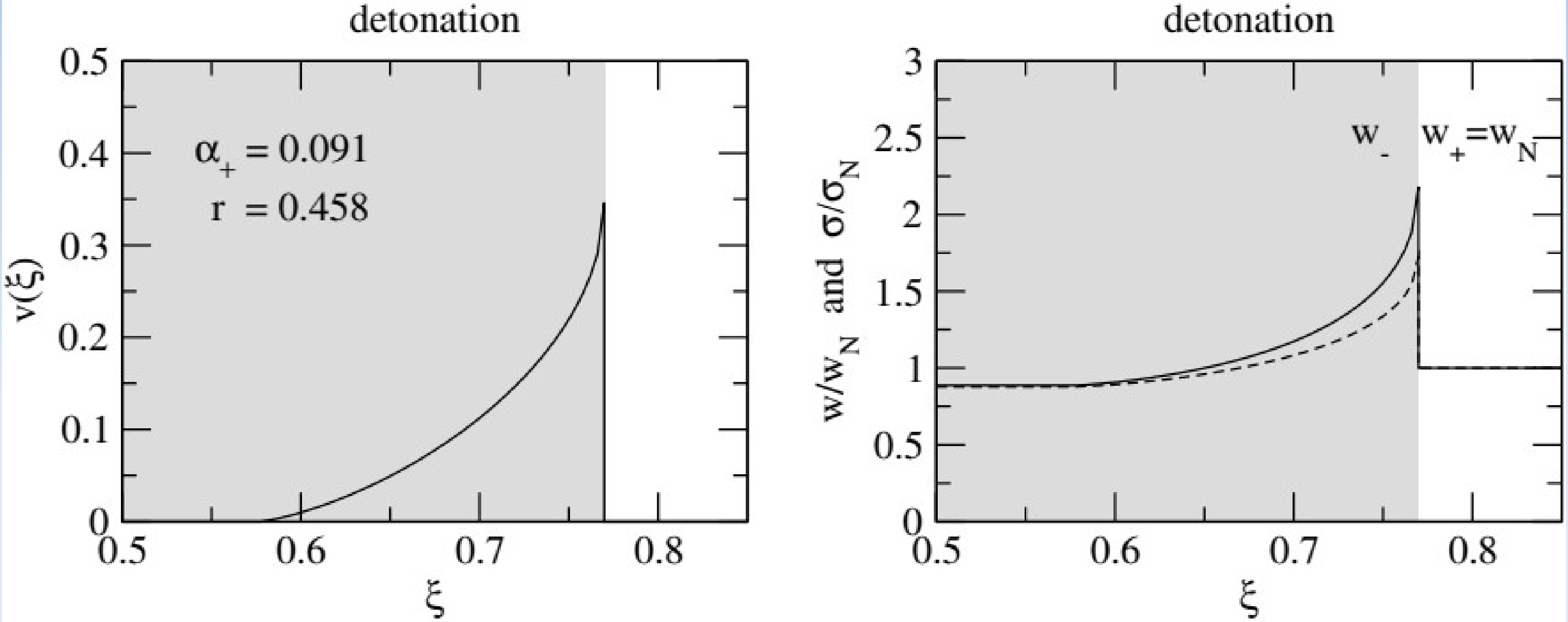
Table 4: Relative errors of the methods M2-M6 compared to the fully numerical result M1. The model parameters are given in Table 1 and 2 and a wall velocity of $\xi_w = 0.9$ was used.

	M3	M4	M5	M6
	$\Delta\theta$	$\Delta\theta$	Δp	Δe

new approach

methods used in the literature

The matching equation



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

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

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*

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

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*

K should only depend on these two quantities!

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

A sound argument to go beyond the bag model

[Leitao and Megevand '14] v-model

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

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

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 %

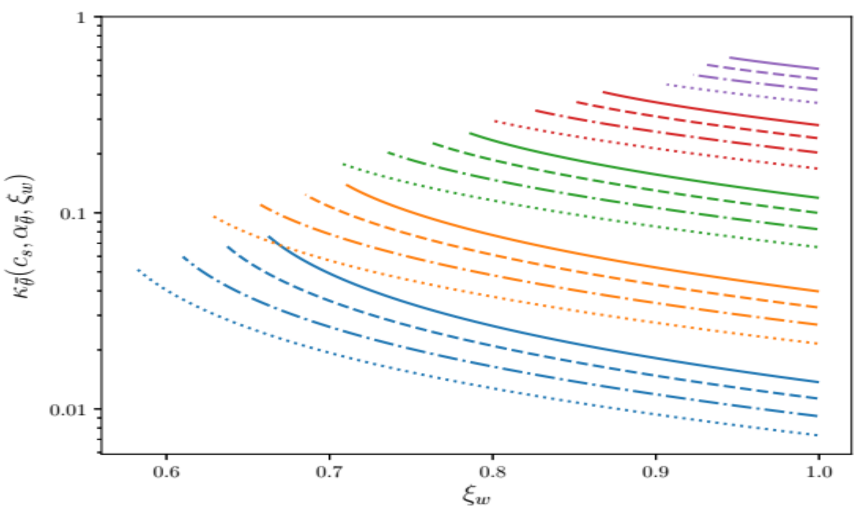


Table 4: Relative errors of the methods M2-M6 compared to the fully numerical result M1. The model parameters are given in Table 1 and 2 and a wall velocity of $\xi_w = 0.9$ was used.

Coding the kinetic energy fraction

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

def kappaNuModel(cs2,al,vp):
  nu = 1./cs2+1.
  tmp = 1.-3.*al+vp**2*(1./cs2+3.*al)
  disc = 4*vp**2*(1.-nu)+tmp**2
  if disc<0:
    print("vp too small for detonation")
    return 0
  vm = (tmp+np.sqrt(disc))/2/(nu-1.)/vp
  wm = (-1.+3.*al+(vp/vm)*(-1.+nu+3.*al))
  wm /= (-1.+nu-vp/vm)

  def dfdv(xiw, v, nu):
    xi, w = xiw
    dxidv = (((xi-v)/(1.-xi*v))**2*(nu-1.)-1.)
    dxidv *= (1.-v*xi)*xi/2./v/(1.-v**2)
    dwdv = nu*(xi-v)/(1.-xi*v)*w/(1.-v**2)
    return [dxidv,dwdv]

  n = 501 # change accuracy here
  vs = np.linspace((vp-vm)/(1.-vp*vm), 0, n)
  sol = odeint(dfdv, [vp,1.], vs, args=(nu,))
  xis, ws = (sol[:,0],-sol[:,1]*wm/al*4./vp**3)

  return simps(ws*(xis*vs)**2/(1.-vs**2), xis)
```

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

Summary

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(few %) using the Python code snippet.

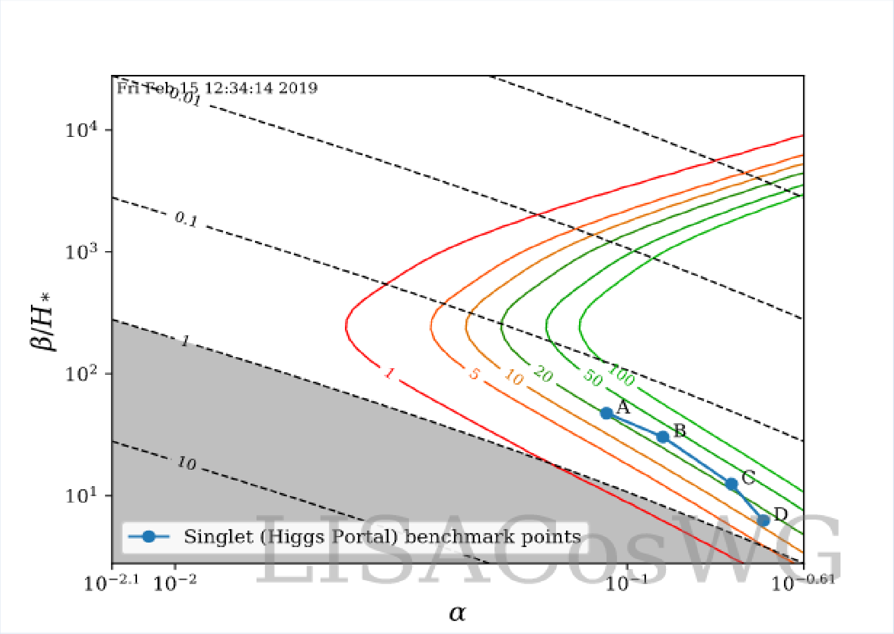
Putting it all together

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

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

Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions
Caprini et al.
arxiv/1512.06239

Detecting ravitational waves from cosmological phase transitions with LISA: an update
Caprini et al.
arxiv/1910.13125



Conclusions

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.

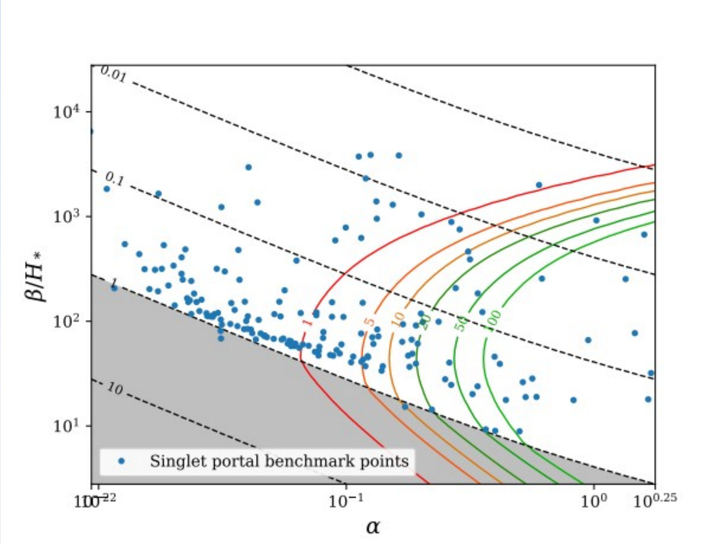
In principle, experiments as LISA/LIGO/DECIGO allow to test phase transitions (and hence particle physics) from EW scales up to very high scales ~ 10^6 GeV.

KAGRA will join the LIGO/VIRGO network soon.

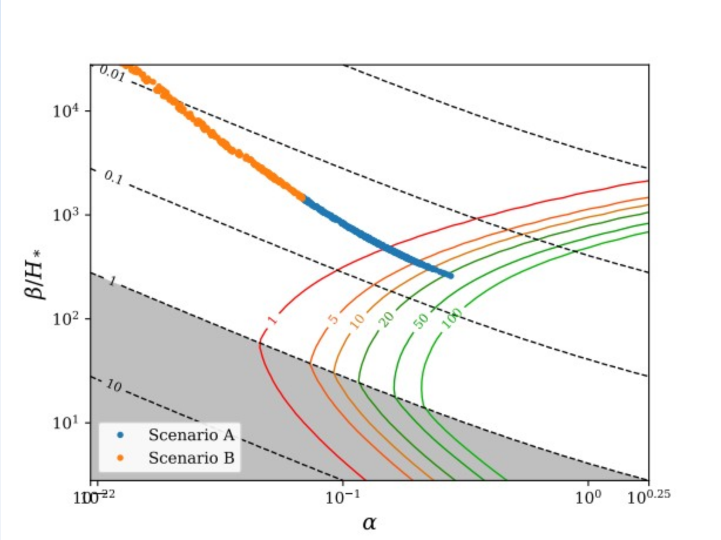
LISA will fly in the 2030s and cover a large range of cosmological phase transitions in terms of strength and temperatures close to electroweak scales.

Thank you

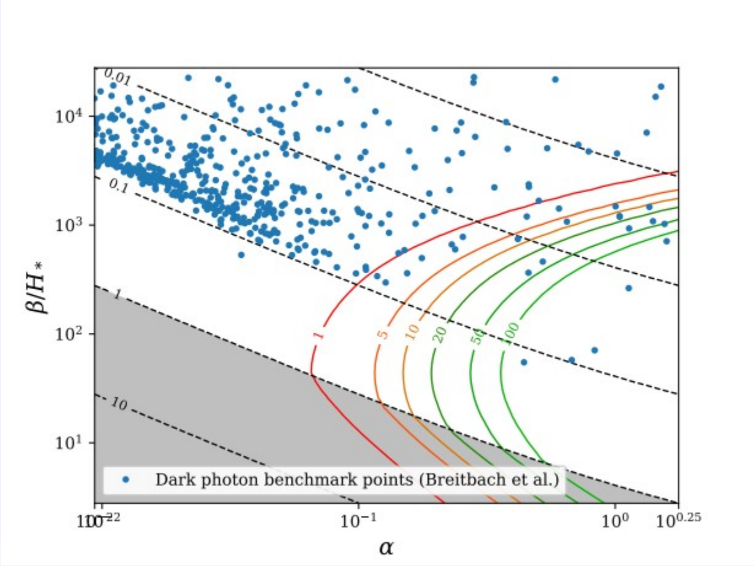
singlet portal model



SM EFT



dark photon



THD