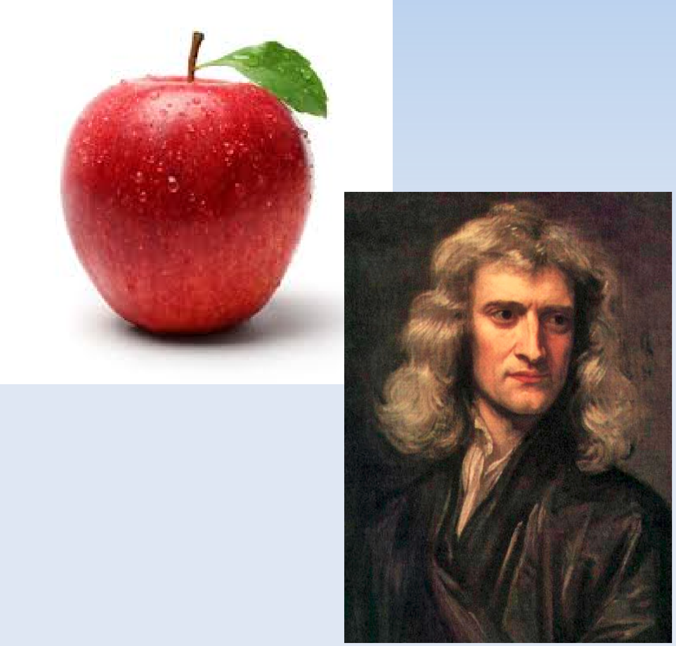
From gravitational waves to particle physics and cosmology

Thomas Konstandin

Oslo, November 8, 2017

Apple Crumble



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H_0 astro physics Λ_{QCD} Λ_{EW} Λ_{GUT} M_{Planck}

References

LIGO / Virgo:

PRL **119** (2017) no.14, 141101
Ann. Phys. **529**, No. 1–2, 1600209 (2017)
PRL **119** (2017) no.16, 161101
Astrophys.J. **848** (2017) no.2, L12
Astrophys.J. **848** (2017) no.2, L13

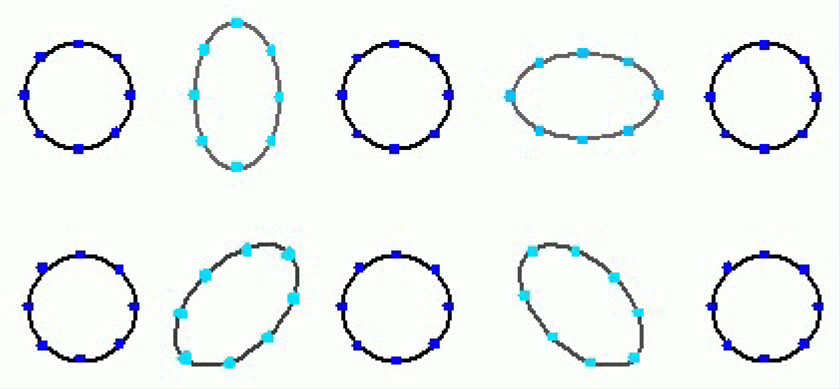
LISA cosmo working group reports:

JCAP **1604** (2016) no.04, 001
JCAP **1604** (2016) no.04, 002
JCAP **1612** (2016) no.12, 026

disclaimer: $\hbar = c = 1 \neq M_{pl}$

Gravitational waves

Gravitational waves (GW) are ripples in space-time that fulfill the wave equation.



For a weak field expansion of the metric *g*

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

One finds an equation of motion of the form

$$\Box h \simeq \frac{8\pi}{c^4} G T$$

For localised sources, the quadrupole moment dominates GW production

$$h_{ij} = 2\frac{G}{d_L}\ddot{Q}_{ij} \qquad Q_{ij} = \int dV \rho(x) \left(x_i x_j - \frac{r^2}{3}\delta_{ij} \right)$$

GWs carry energy-momentum of size (binary system)

$$\dot{E}_{GW} = \frac{32}{5}\frac{G}{c^5}\mu^2 r^4 \omega^6 \longleftarrow$$

$\mu = m_1 m_2/(m_1 + m_2)$

high frequency helps tremendously

Einsteins u-turn

To Max Born:

Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows that the nonlinear field equations can show us more, or rather limit us more, than we have believed up till now.

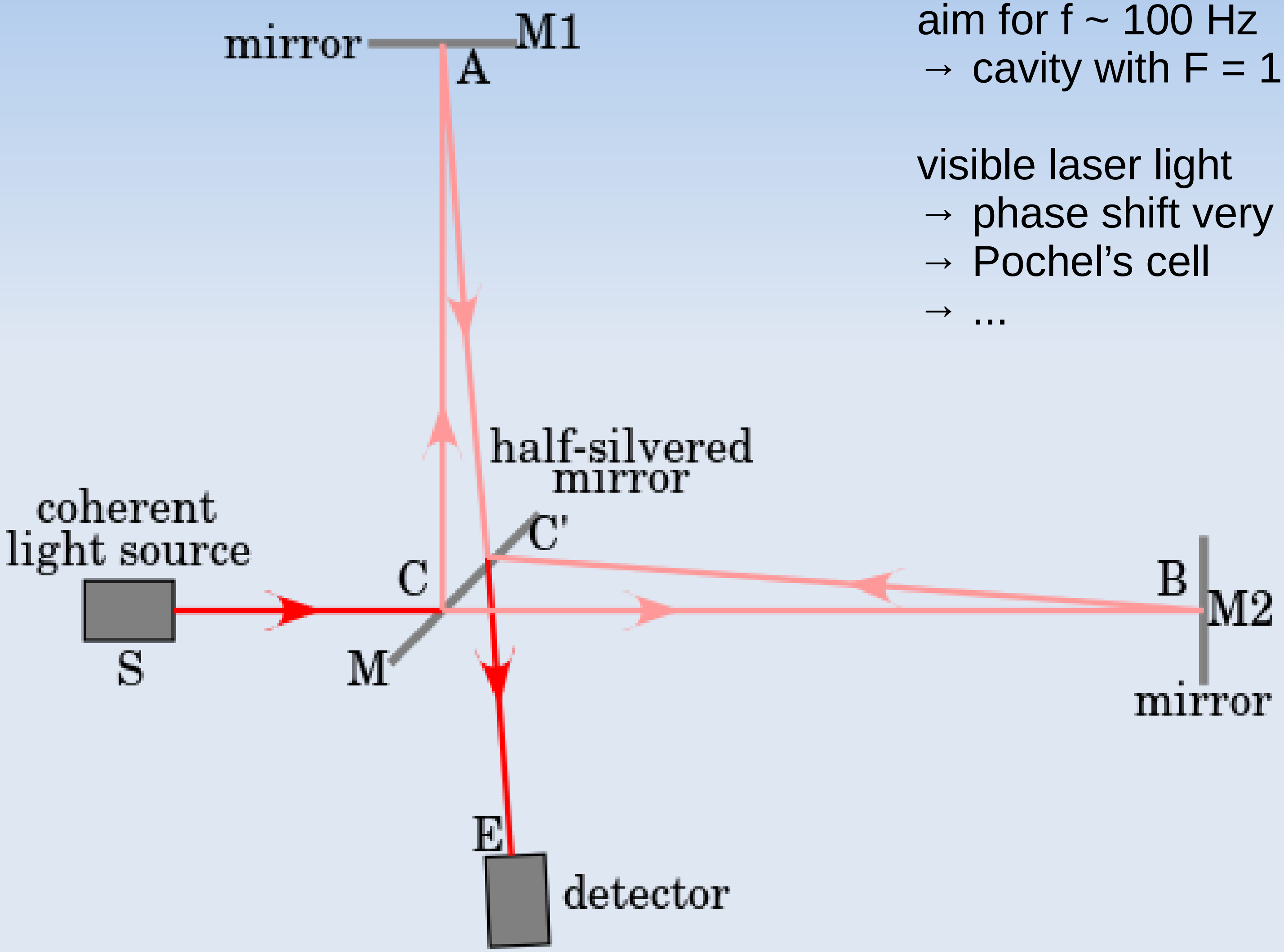
A.E. 1936

We (Mr. Rosen and I) had sent you our manuscript for publication and had not authorized you to show it to specialists before it is printed. I see no reason to address the — in any case erroneous — comments of your anonymous expert. On the basis of this incident I prefer to publish the paper elsewhere.

A.E. 1936

→ 1955, Feynman’s sticky beats argument

Interferometers



aim for f ~ 100 Hz
→ cavity with F = 100

visible laser light
→ phase shift very small
→ Pochel’s cell
→ ...

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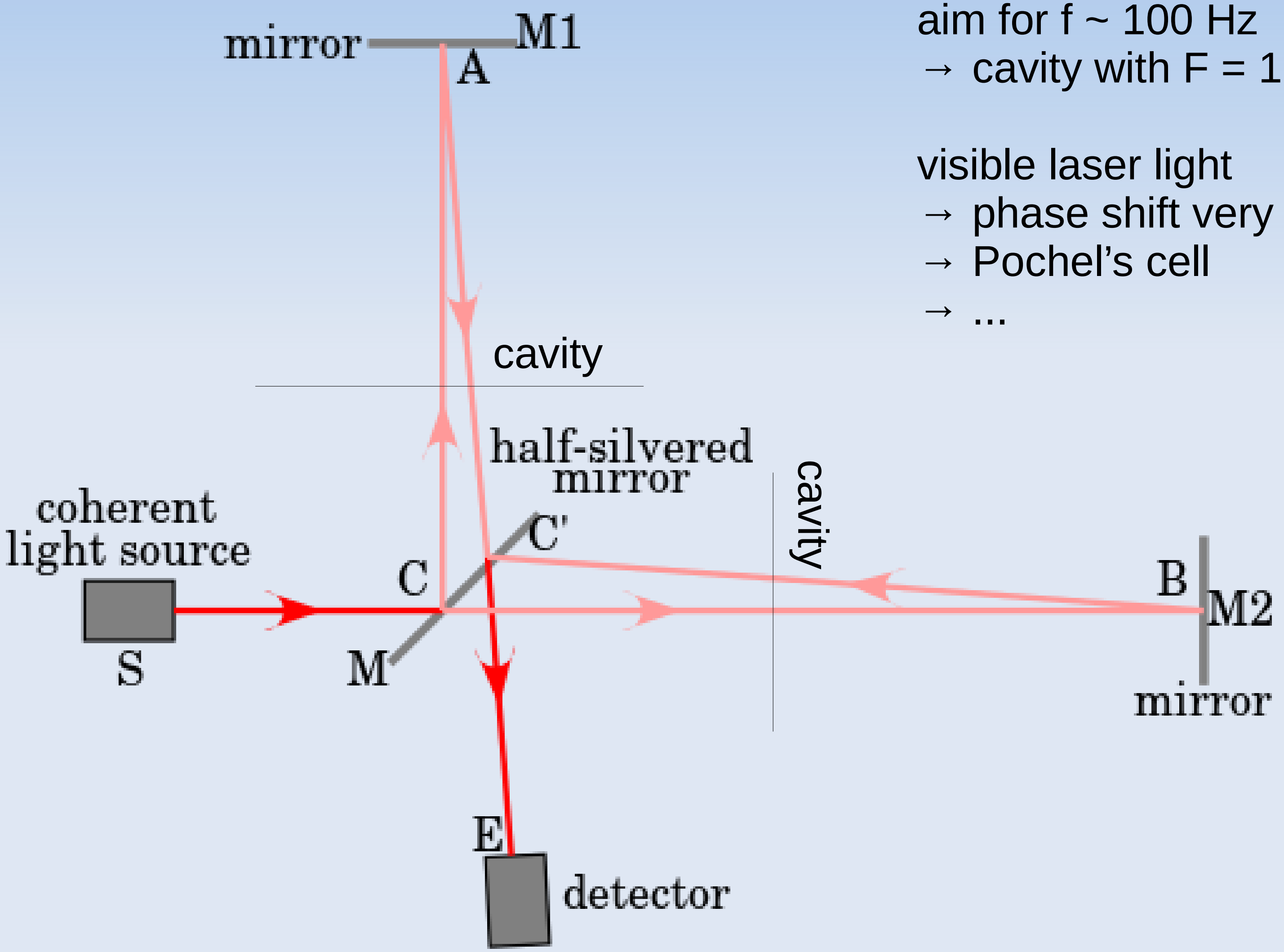
Interferometers



aim for f ~ 100 Hz
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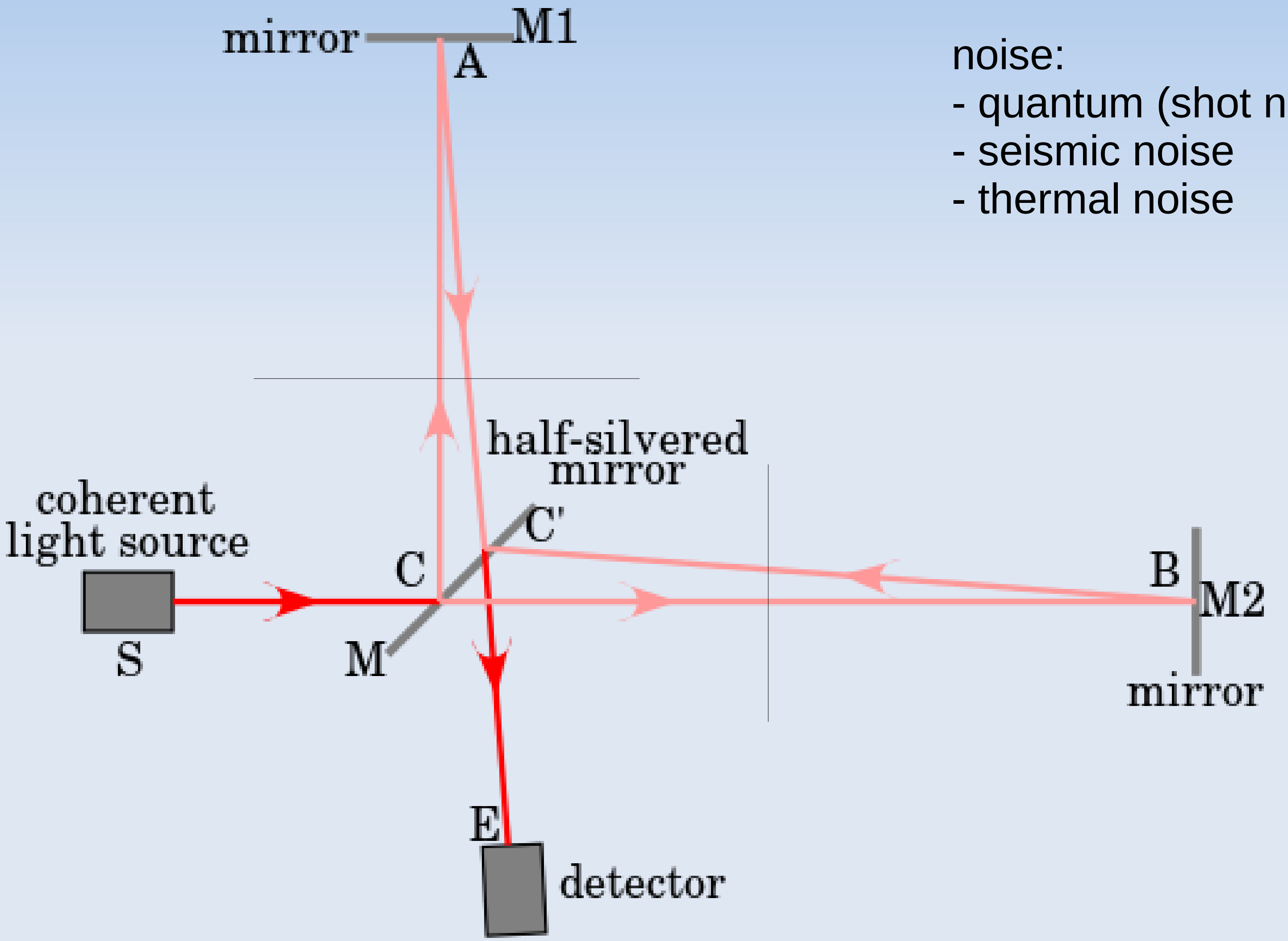
Interferometers



noise:
- quantum (shot noise)
- seismic noise
- thermal noise

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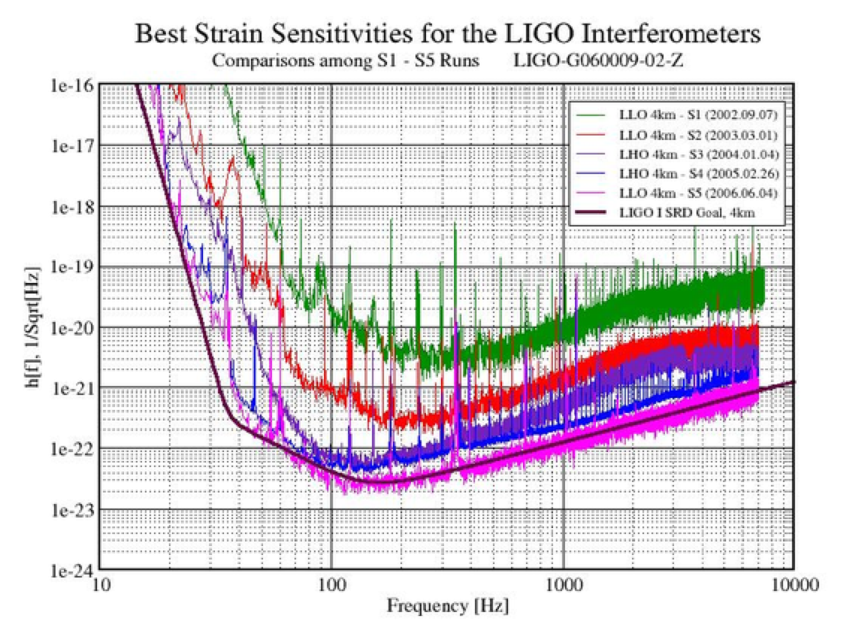
LIGO / Virgo


Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1 - S5 Runs
LIGO-G060009-02-Z
LLO 4km - S1 (2002.09.07)
LLO 4km - S2 (2003.03.01)
LHO 4km - S3 (2004.01.04)
LHO 4km - S4 (2005.02.26)
LLO 4km - S5 (2006.06.04)
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]

Binary mergers

$$\dot{E}_{GW} = \frac{32}{5}\frac{G}{c^5}\mu^2 r^4 \omega^6$$

Large frequency good for GW production, remember Kepler:

$$\omega^2 r^3 = G(m_1 + m_2)$$

and

$$2\pi f_{GW} = 2\omega$$

→ small radius important

The energy loss leads to a change in the frequency according to

$$\dot{f}_{GW}^3 \propto \frac{G^5}{c^{15}} \mathcal{M}^5 f_{GW}^{11}$$

chirp mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

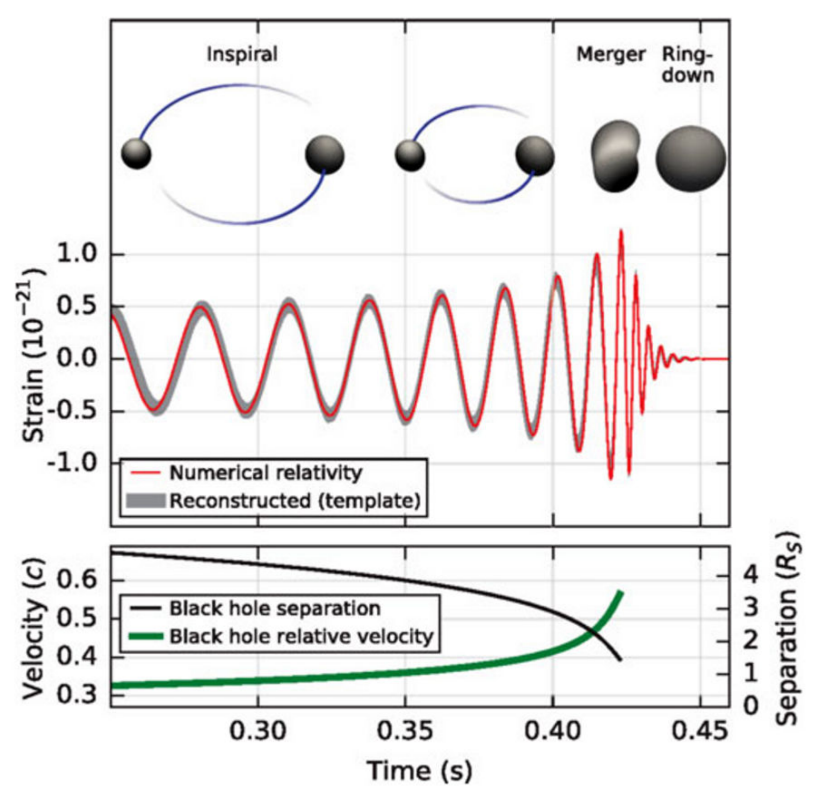
Black holes

Black holes are formed via the collapse of very massive stars $m \gtrsim M_\odot$

Schwarzschild radius

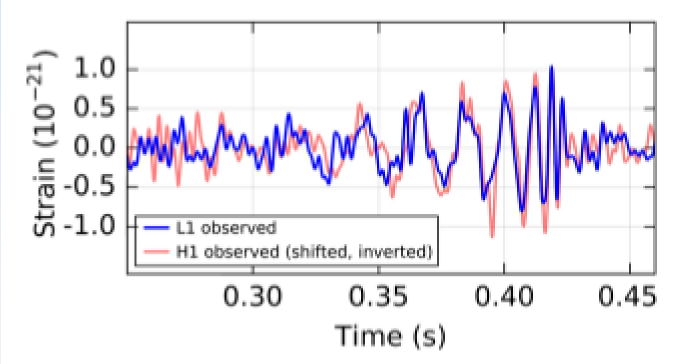
$$r_s = \frac{2Gm}{c^2} = 2.95 \left(\frac{m}{M_\odot} \right) \mathrm{km}$$

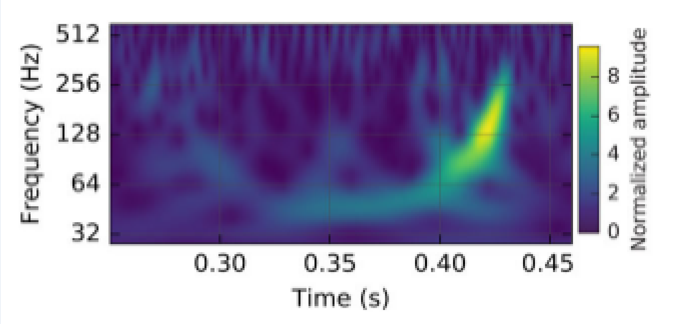
Using this in Keplers law, we see that *v* ~ *c* at the merger and that LIGO can see BHs with ~ 10 solar masses ~ 100 Hz



BH – BH mergers

GW150914



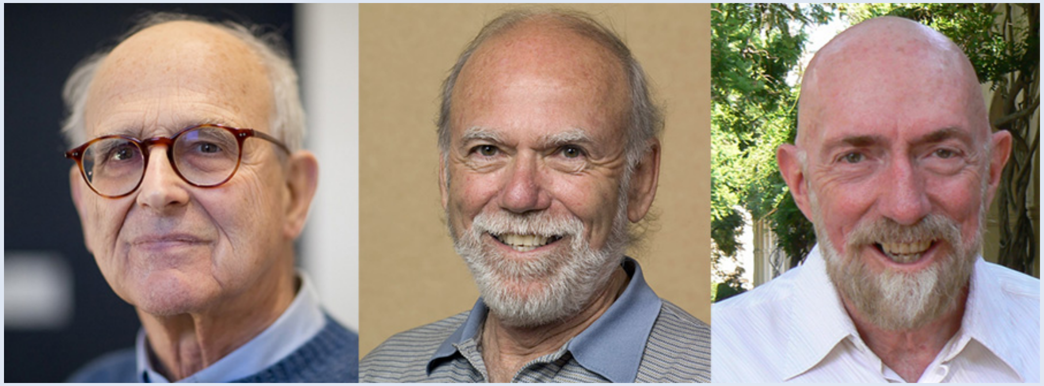


Using the equations from before on finds a chirp mass of ~ $35M_\odot$

Around the peak amplitude the orbital separation of the two bodies was ~ 350 km

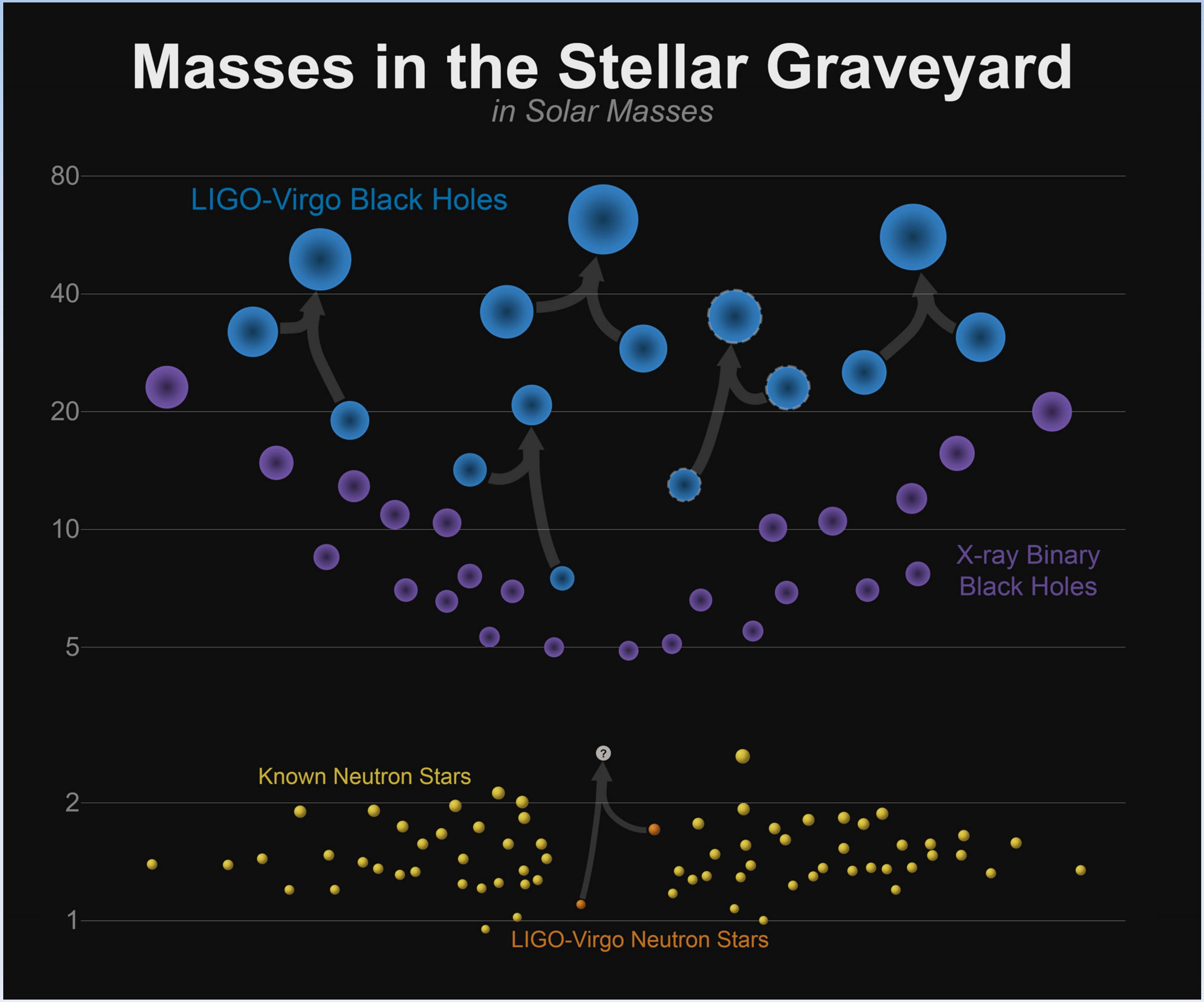
Cannot be neutron stars.

→ must have been two black holes



”for decisive contributions to the LIGO detector and the observation of gravitational waves”

BH – BH mergers



Neutron stars

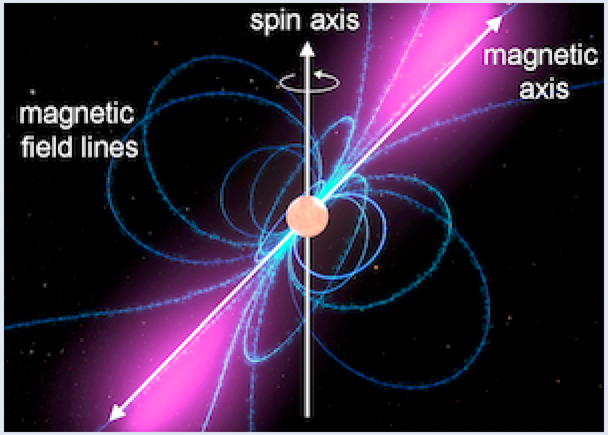
Neutron stars result from the explosion of supernovae with masses of between 10-30 solar masses. Their mass is typically about **2 solar masses** and their radius about **10 km**.

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



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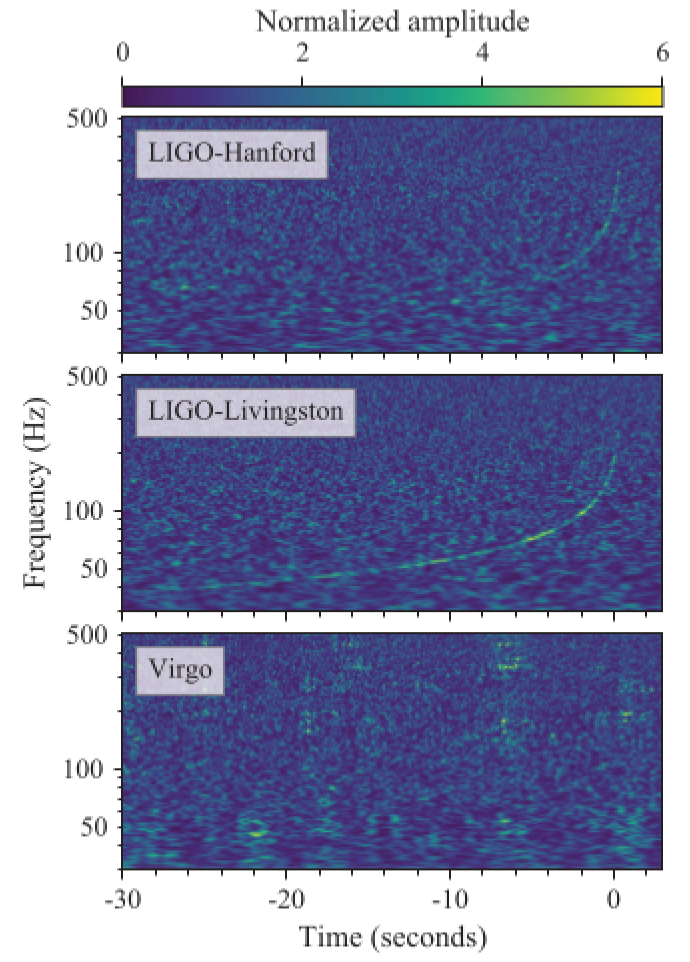
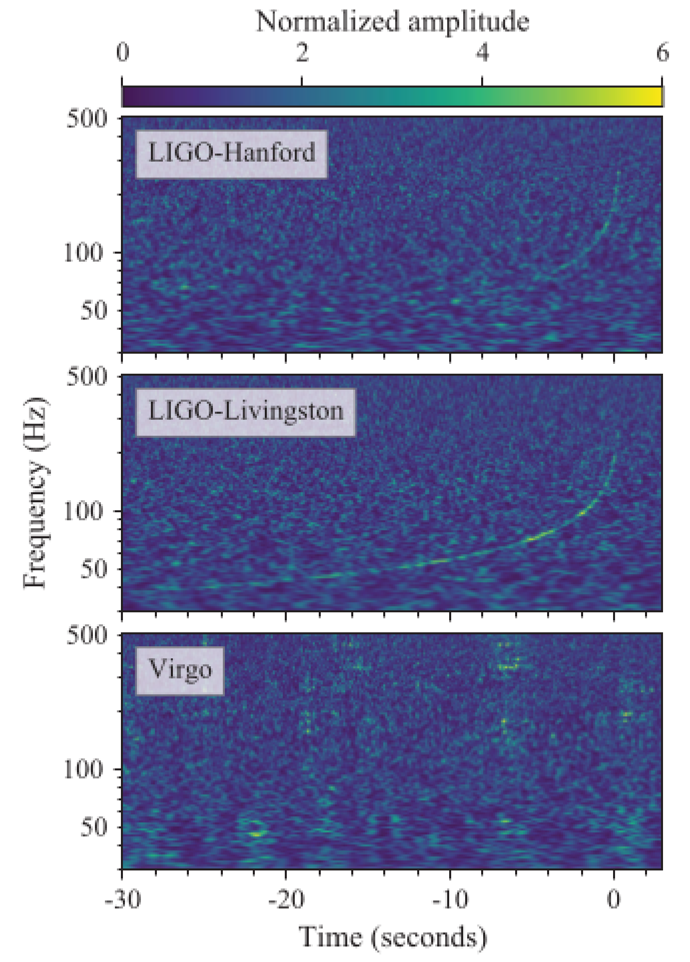
NS – NS mergers

GW170817



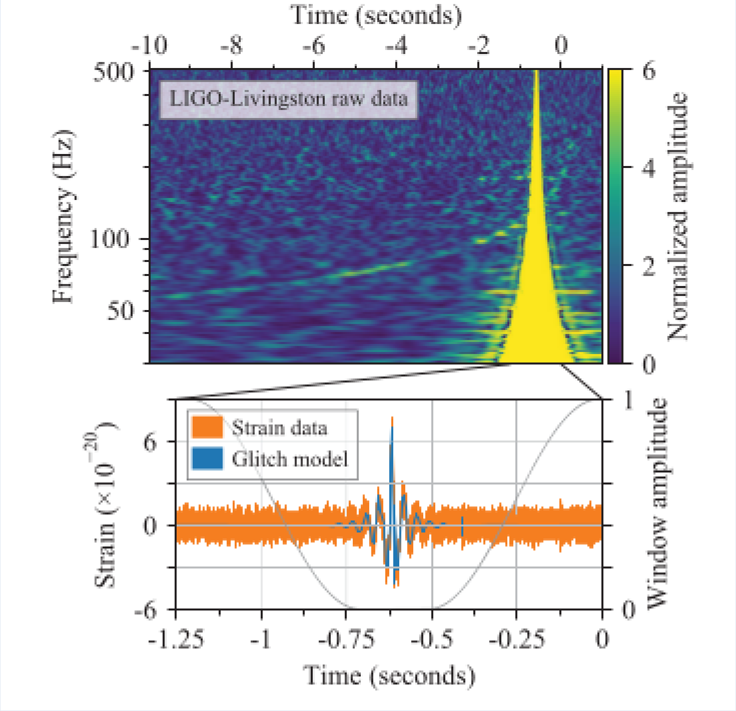
NS – NS mergers

GW170817



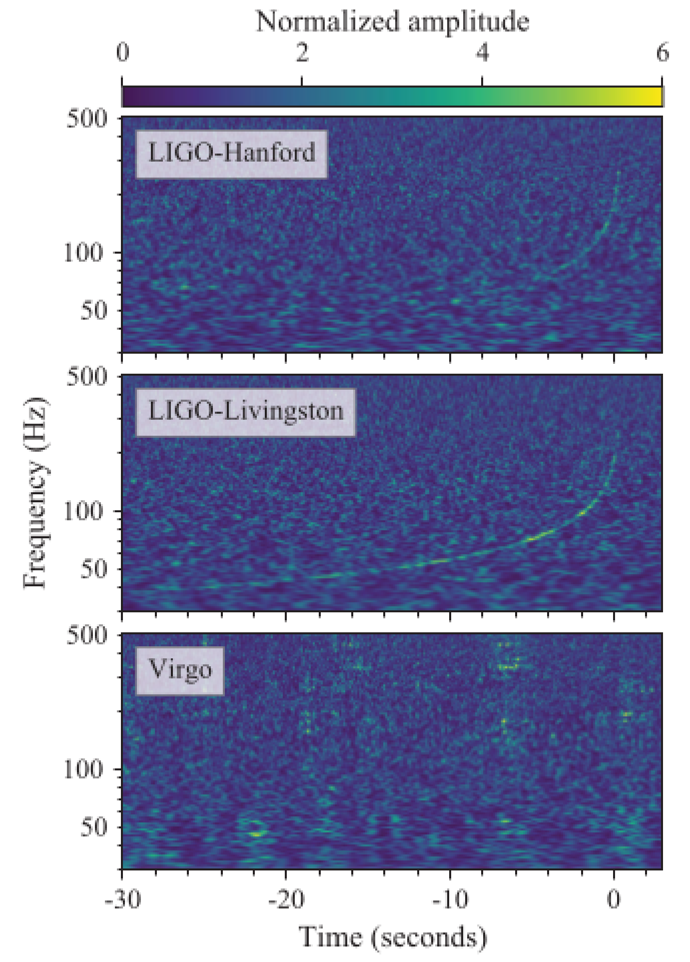
Ooops.

Actually didn’t trigger automatically:



NS – NS mergers

GW170817



SNR > 32

masses are about 1.2 – 1.6 solar masses each

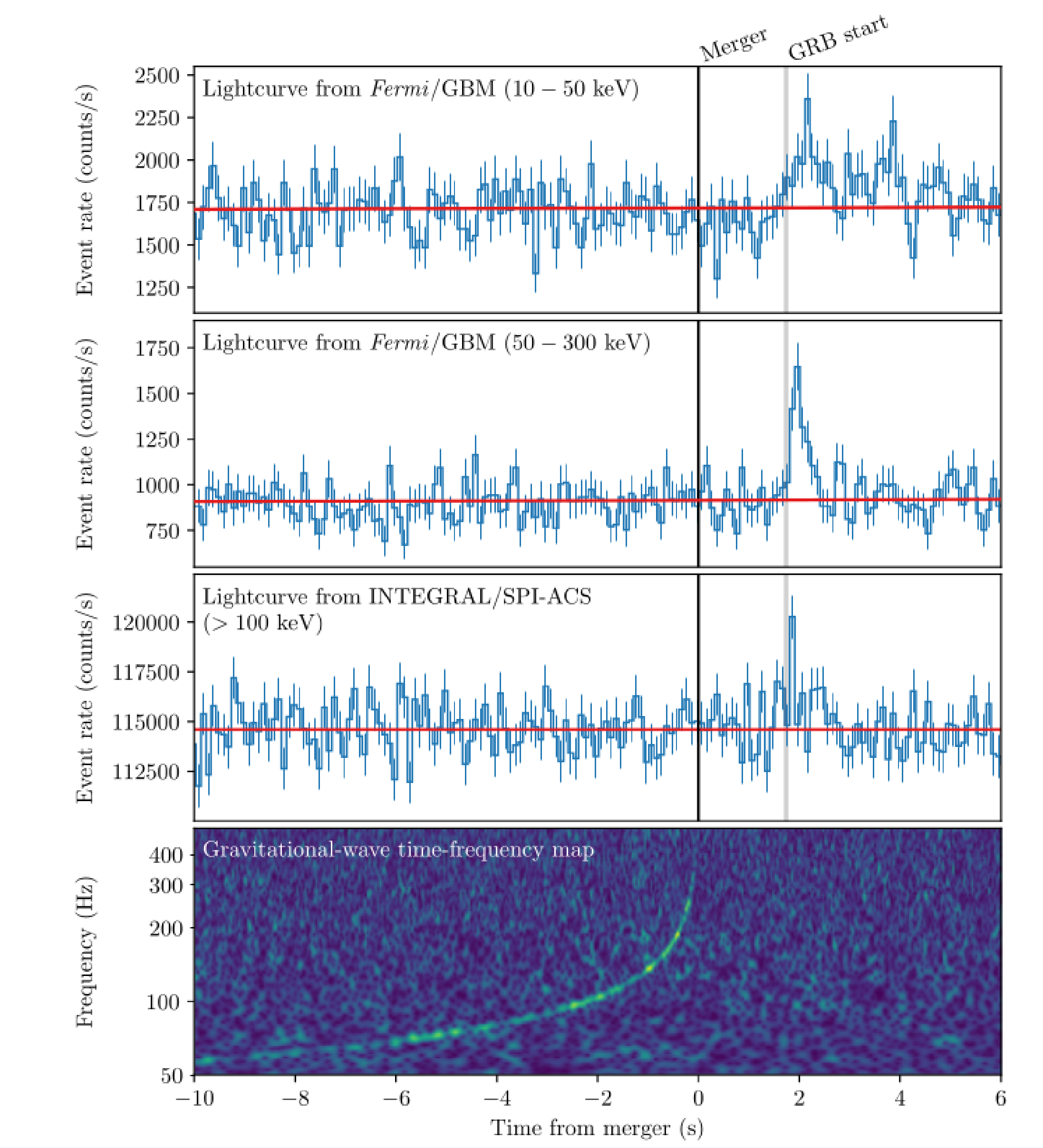
Orbital separation at the end again ~O(100 km). Cannot be black hole.

→ must be neutron stars?

Virgo did’nt see much but was very important
- localisation
- polarisation

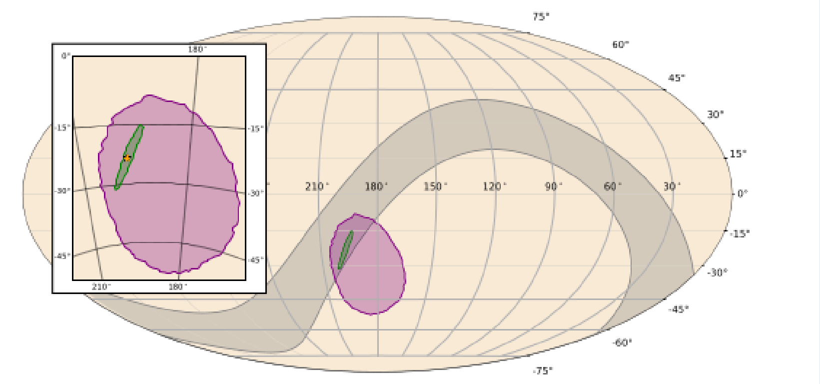
What about EM couterparts?

Gamma ray burst



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

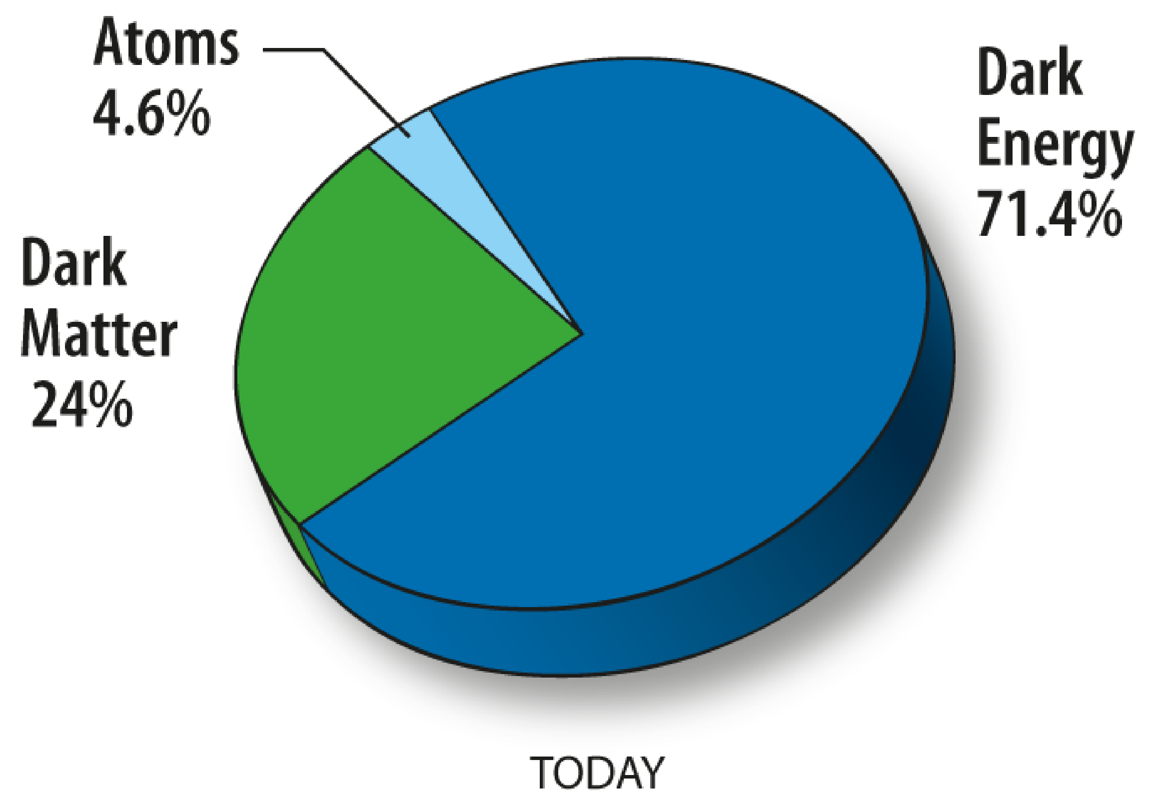
Good localization was possible even though (or because?) the event was in the blind spot of Virgo.



Subsequent EM observations could pinpoint the host galaxy.

→ important for the H_0 measurement

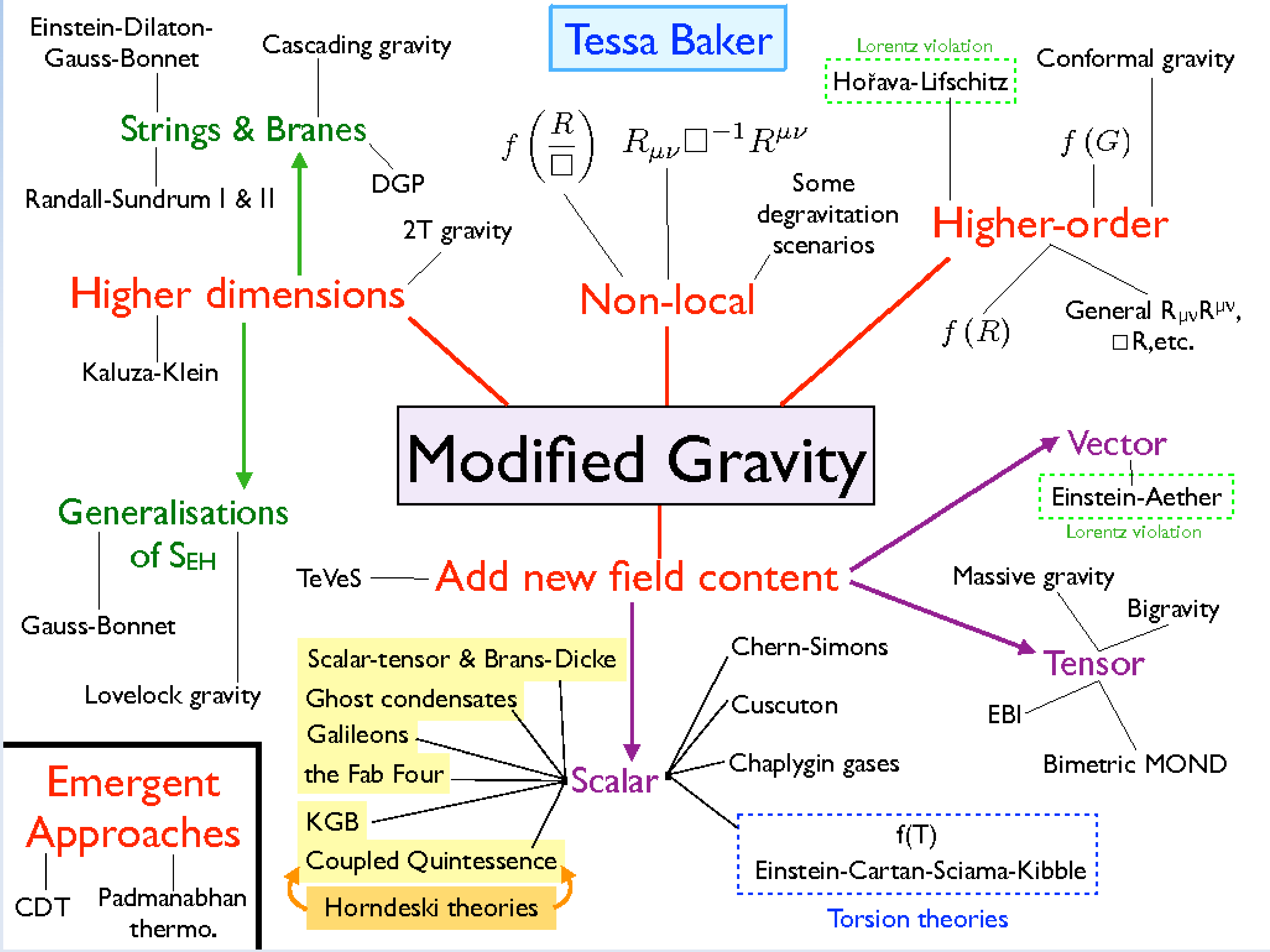
Cosmic pie



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



Tessa Baker

Modified Gravity

Higher dimensions

Strings & Branes

Einstein-Dilaton-Gauss-Bonnet

Cascading gravity

DGP

Randall-Sundrum I & II

2T gravity

Kaluza-Klein

Generalisations of S_{EH}

Gauss-Bonnet

Lovelock gravity

Non-local

$f\left(\frac{R}{\Box}\right)$

$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$

Some degravitation scenarios

Higher-order

Lorentz violation

Hořava-Lifschitz

Conformal gravity

$f(G)$

$f(R)$

General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$,etc.

Add new field content

TeVeS

Vector

Einstein-Aether

Lorentz violation

Tensor

Massive gravity

Bigravity

EBI

Bimetric MOND

Scalar

Scalar-tensor & Brans-Dicke

Ghost condensates

Galileons

the Fab Four

KGB

Coupled Quintessence

Horndeski theories

Chern-Simons

Cuscuton

Chaplygin gases

f(T)

Einstein-Cartan-Sciama-Kibble

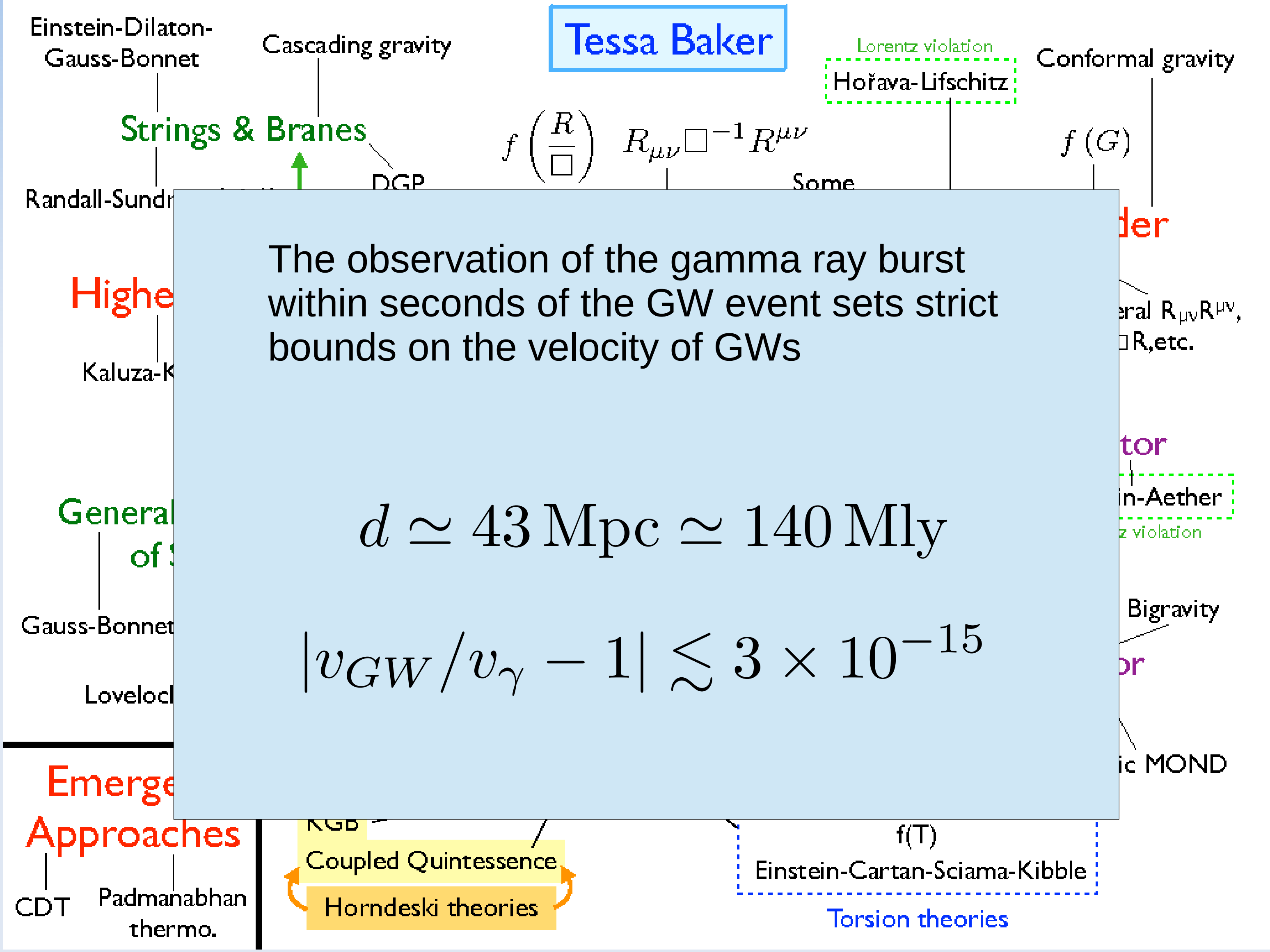
Torsion theories

Emergent Approaches

CDT

Padmanabhan thermo.

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

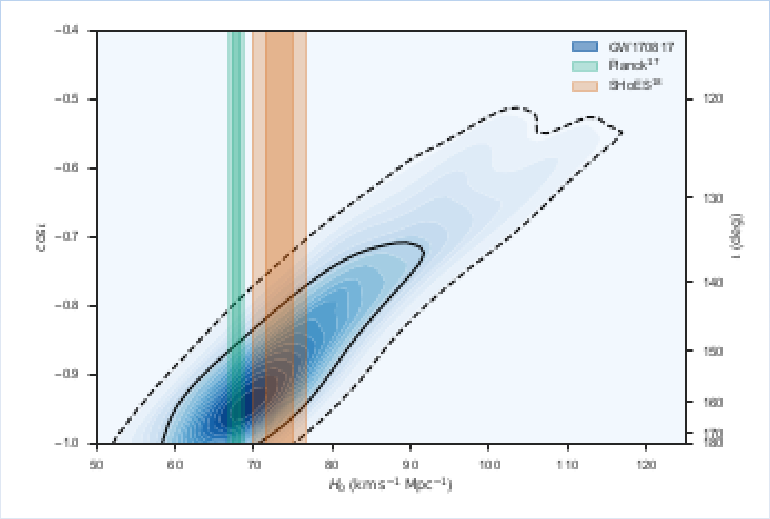
$$v_H = H_0 \, d$$

In order to determine H_0 one needs v_H (via 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 couterparts.

problems:
- pecular motions → LSS catalogues
- *d* degenerate with inclination → polarisation

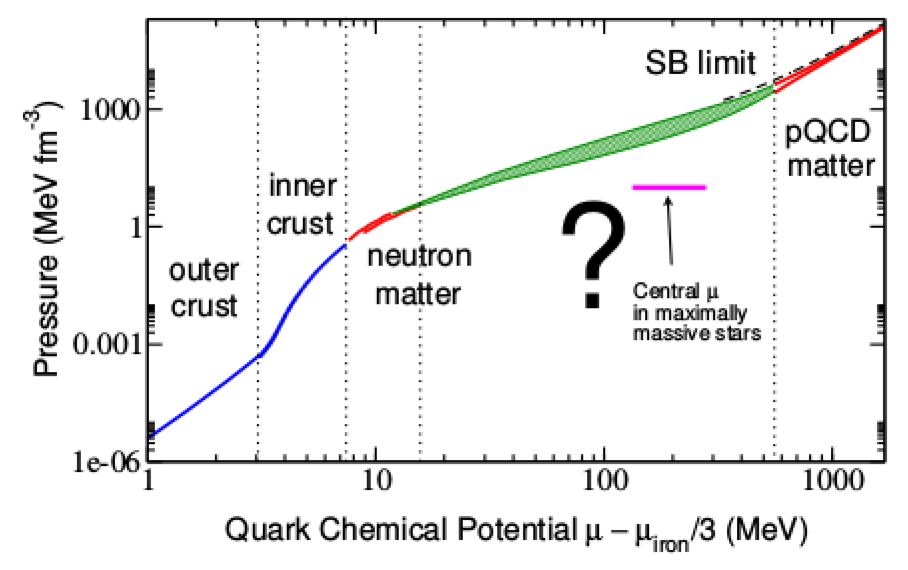


Results are not yet competitive due to degeneracy with inclination. This will change with a larger number of events

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

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

QCD equation of state

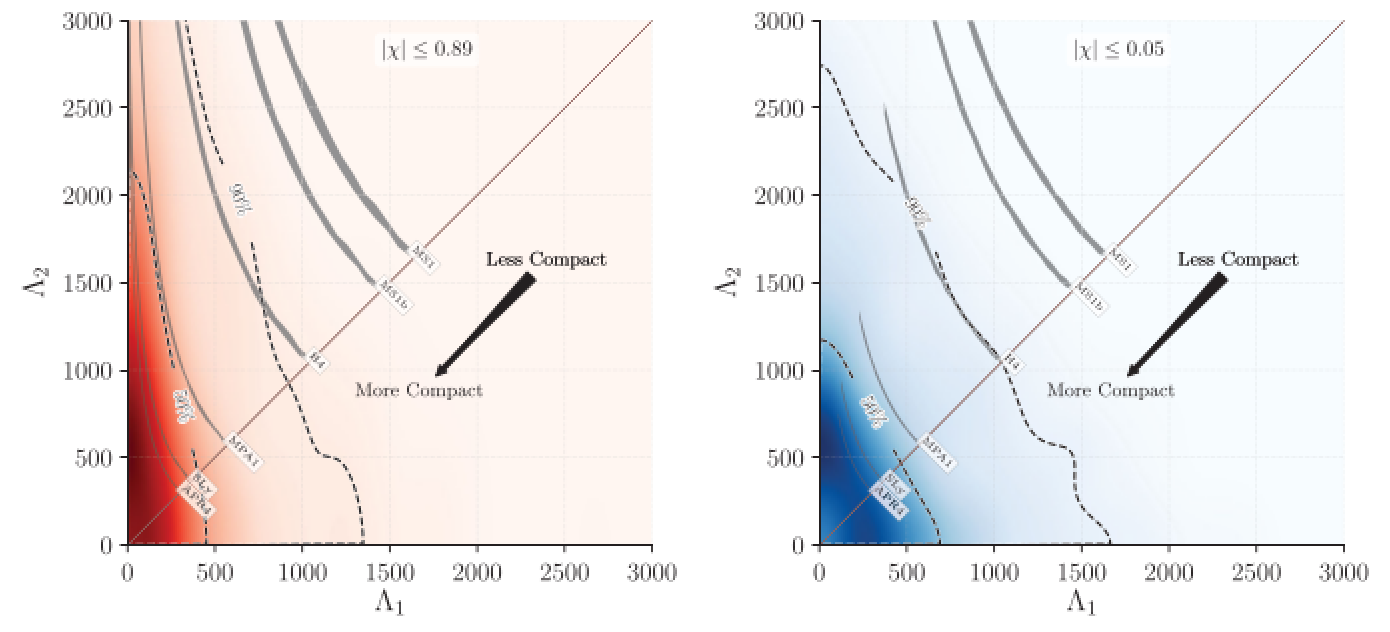


The equation-of-state of quark matter is poorly known for finite chemical potential.

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

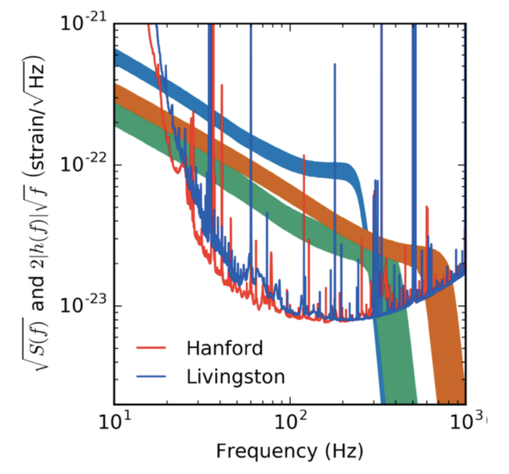
The EoS can in principle be tested via teh GW signal of a neutron star merger from the late stage where finite size effects and tidal forces play a role.

QCD equation of state

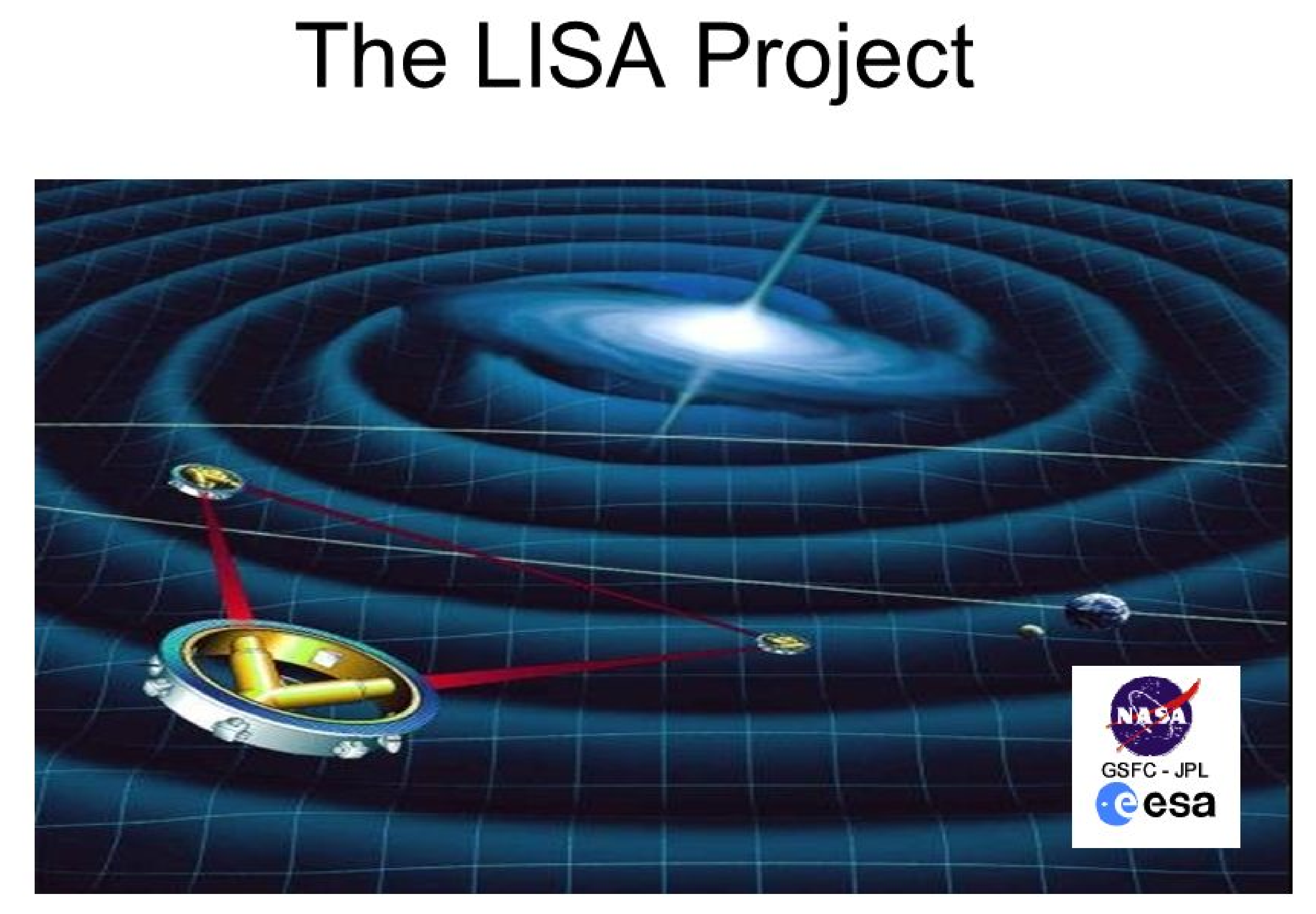


Some bounds obtained from GW170817 on the tidal deformation parameters Λ.

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



Future space spaces telescopes



The LISA Project

Electroweak phase transition

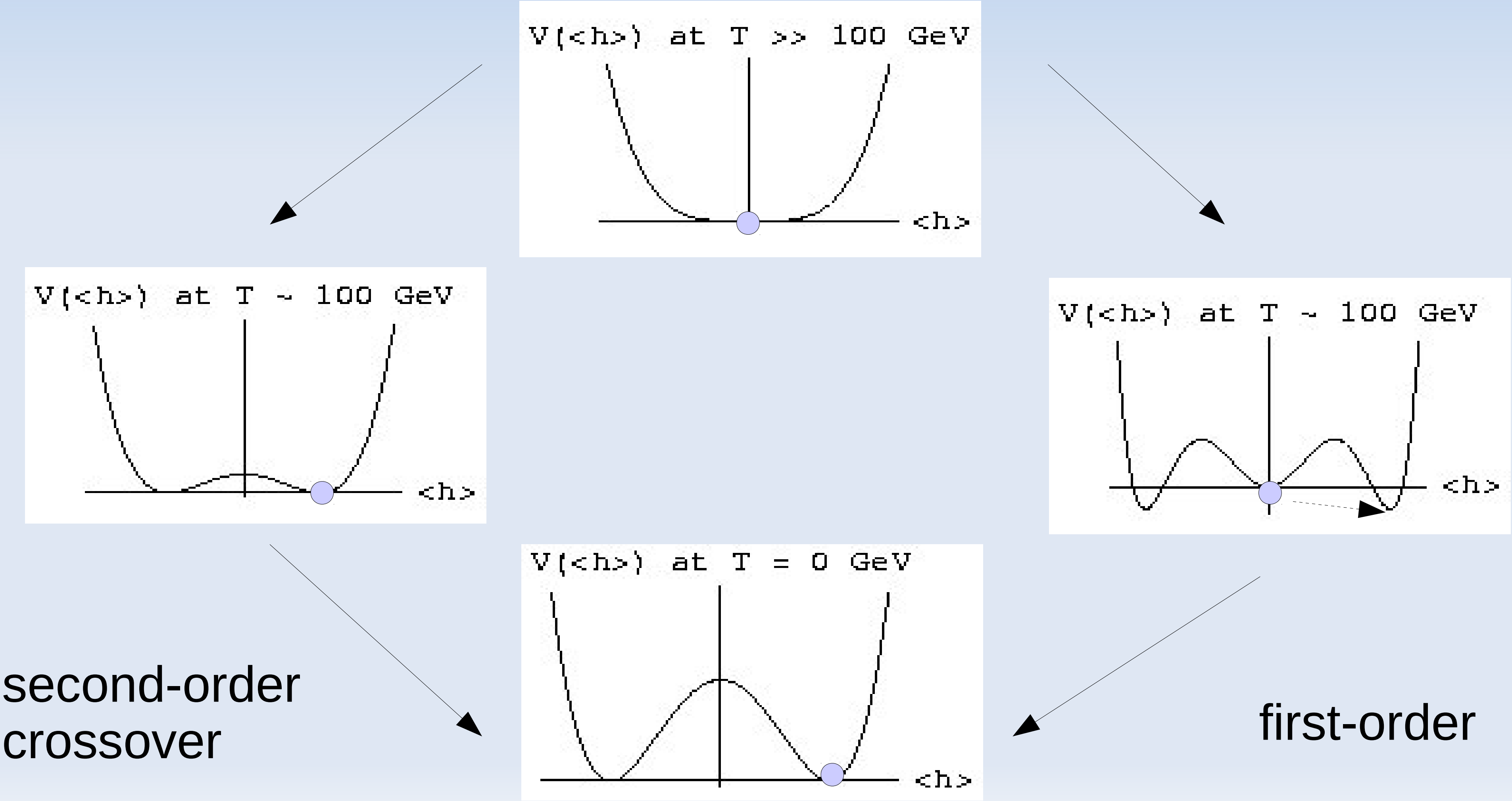
gravitational
waves

baryogenesis

~~eq~~

First-order phase transition

The free energy (as a function of the Higgs vev) decides the nature of the phase transition:



second-order crossover

first-order

First-order phase transitions

- first-order phase transitions proceed by bubble nucleations

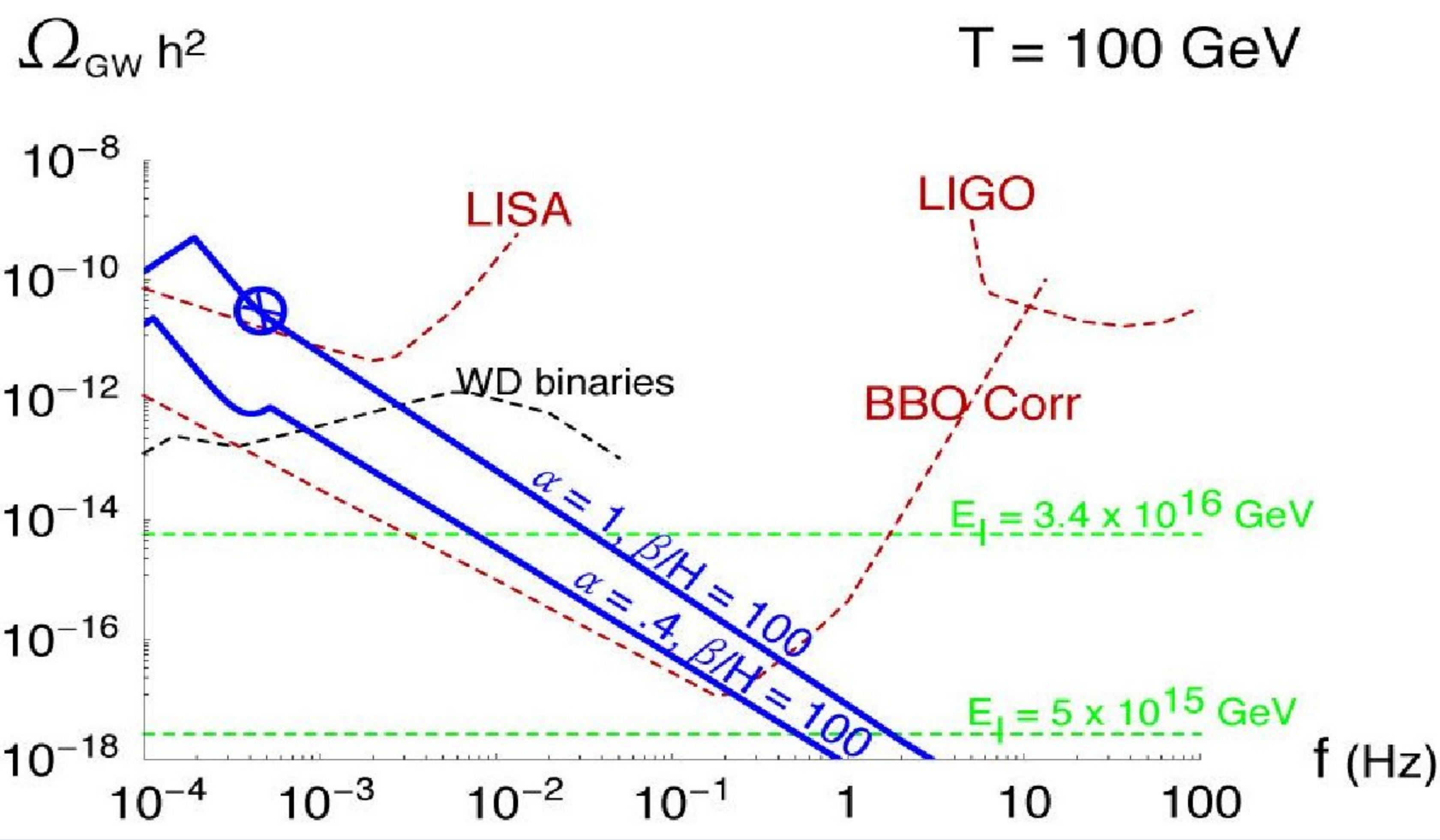
- in case of the electroweak phase transition, the ”Higgs bubble wall” separates the symmetric from the broken phase

- this is a violent process ($v_b = O(1)$) that drives the plasma out-of-equilibrium

- bosons that are strongly coupled to the Higgs tend to make the phase transition stronger

Gravitational waves from the phase transition

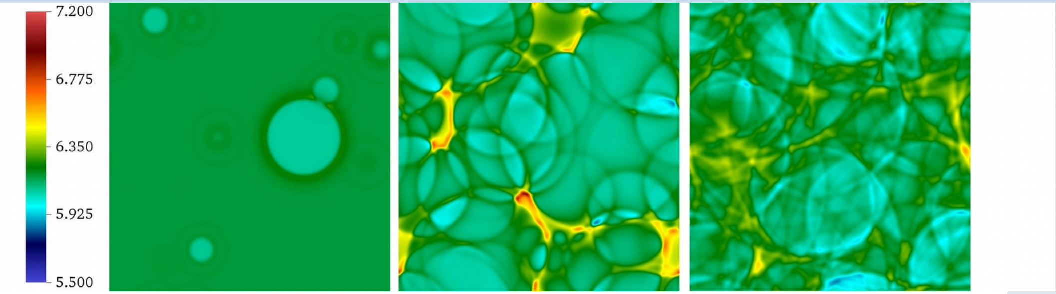
[Grojean, Servant '06] $\alpha = \rho_{vac}/\rho_{rad}, \quad \beta \sim \tau^{-1}, \quad v_b, \quad T$

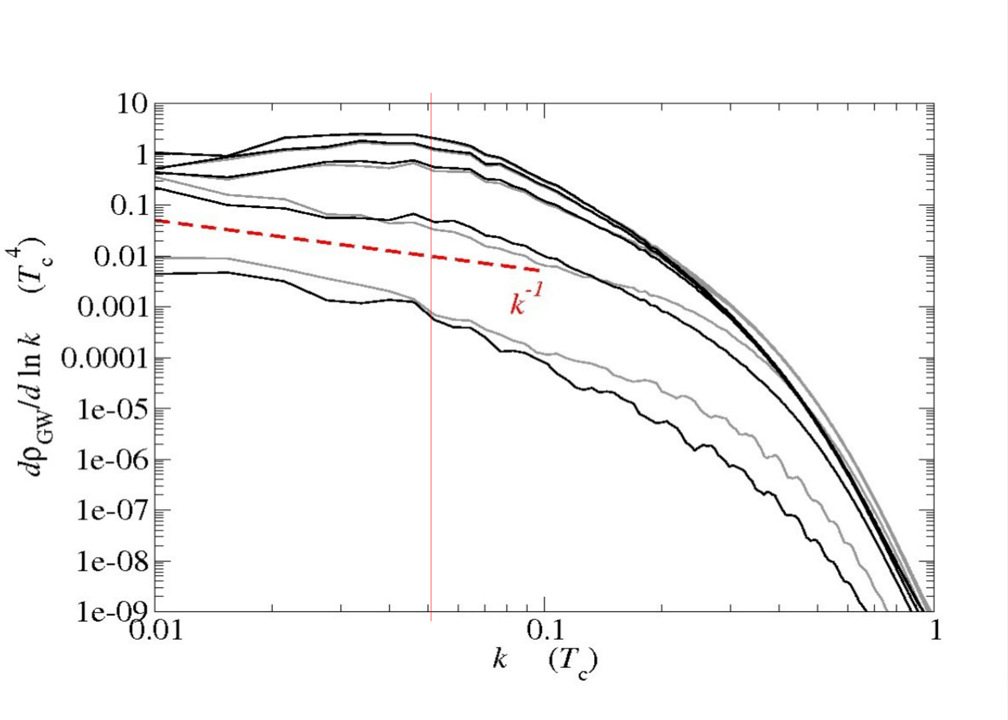


GWs by sound waves

[Hindmarsh et.al. '13]

For small wall velocities, the system can be descibed using hydrodynamics. $v_{wall} \ll c$

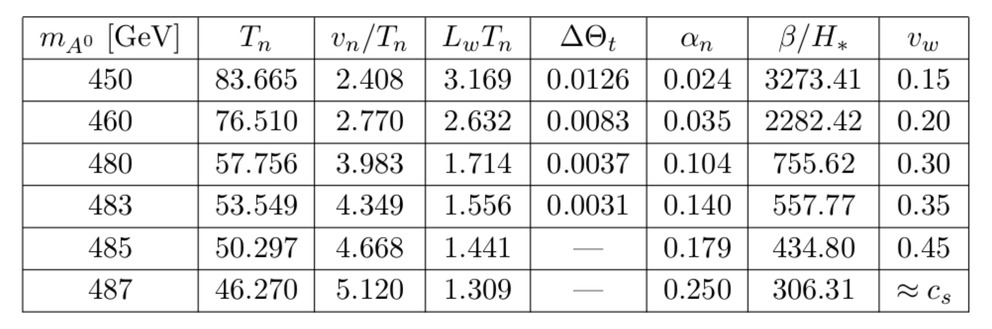




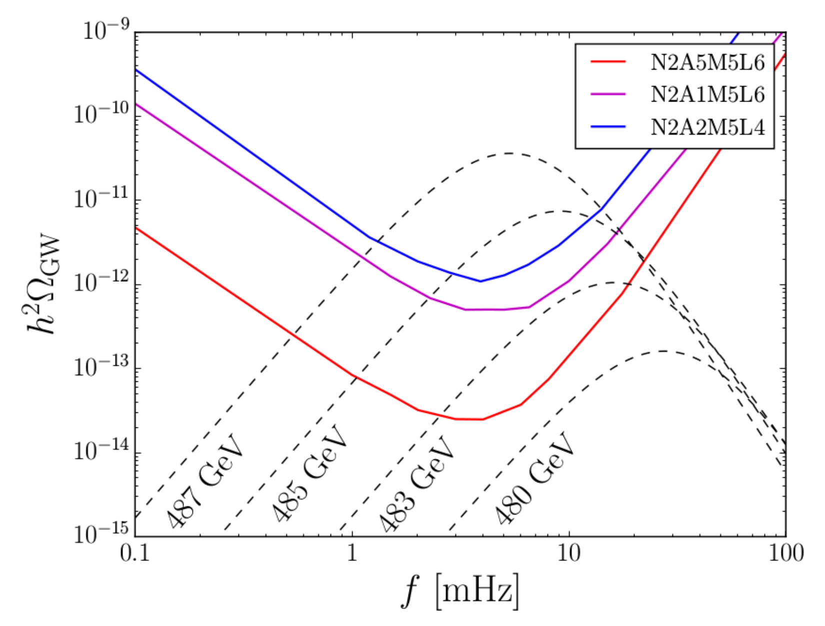
The overall features are quite similar to the envelope approximation.

Amplitude is increased by a factor β/H

Update on sensitivity to stochastic GW background



m_{A^0} [GeV]	T_n	v_n/T_n	$L_w T_n$	$\Delta\Theta_t$	α_n	β/H_*	v_w
450	83.665	2.408	3.169	0.0126	0.024	3273.41	0.15
460	76.510	2.770	2.632	0.0083	0.035	2282.42	0.20
480	57.756	3.983	1.714	0.0037	0.104	755.62	0.30
483	53.549	4.349	1.556	0.0031	0.140	557.77	0.35
485	50.297	4.668	1.441	—	0.179	434.80	0.45
487	46.270	5.120	1.309	—	0.250	306.31	$\approx c_s$

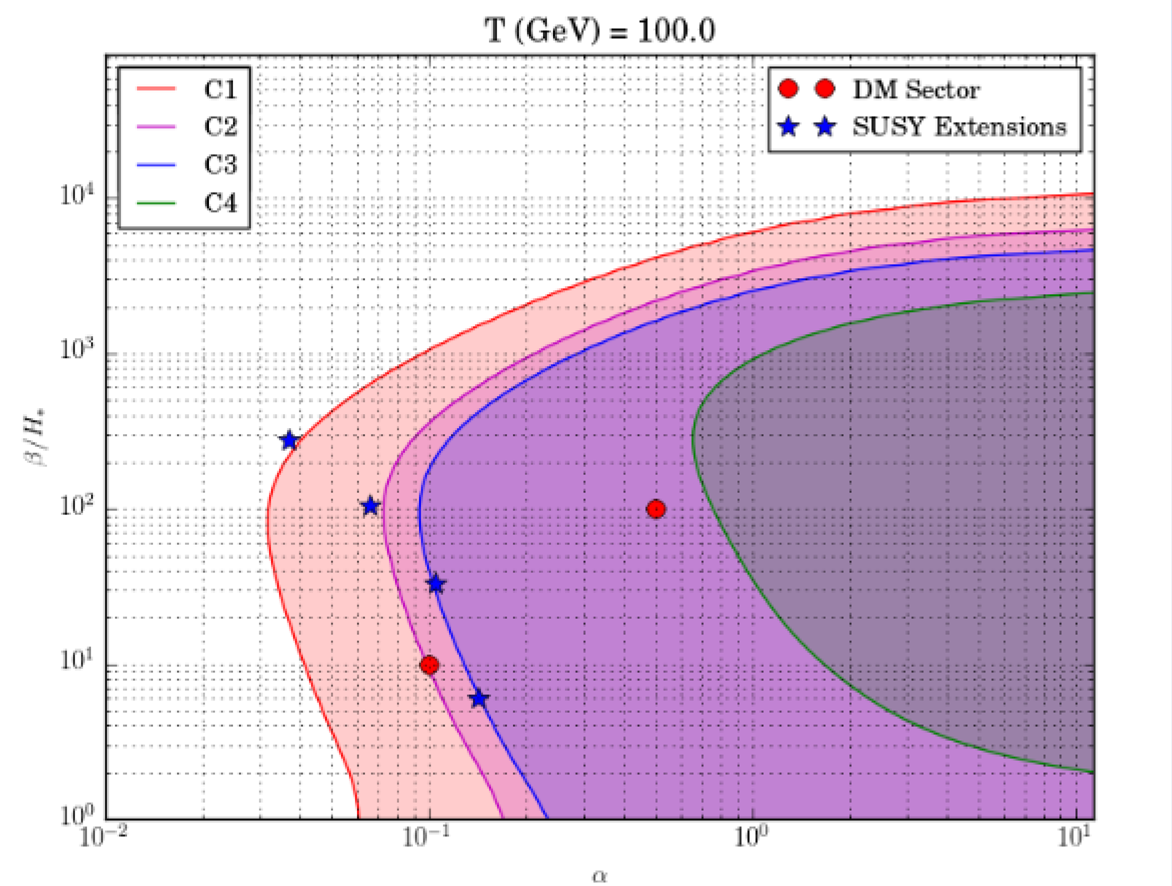


[Dorsch, Huber, TK, No. '16]

[A. Petiteau, unpublished]

A dedicated analysis of the LISA analysis team for stochastic sources increases the sensitivity. **Long lasting, broad** spectra are easier to observe than localized, short-lived sources.

LISA cosmology working group report

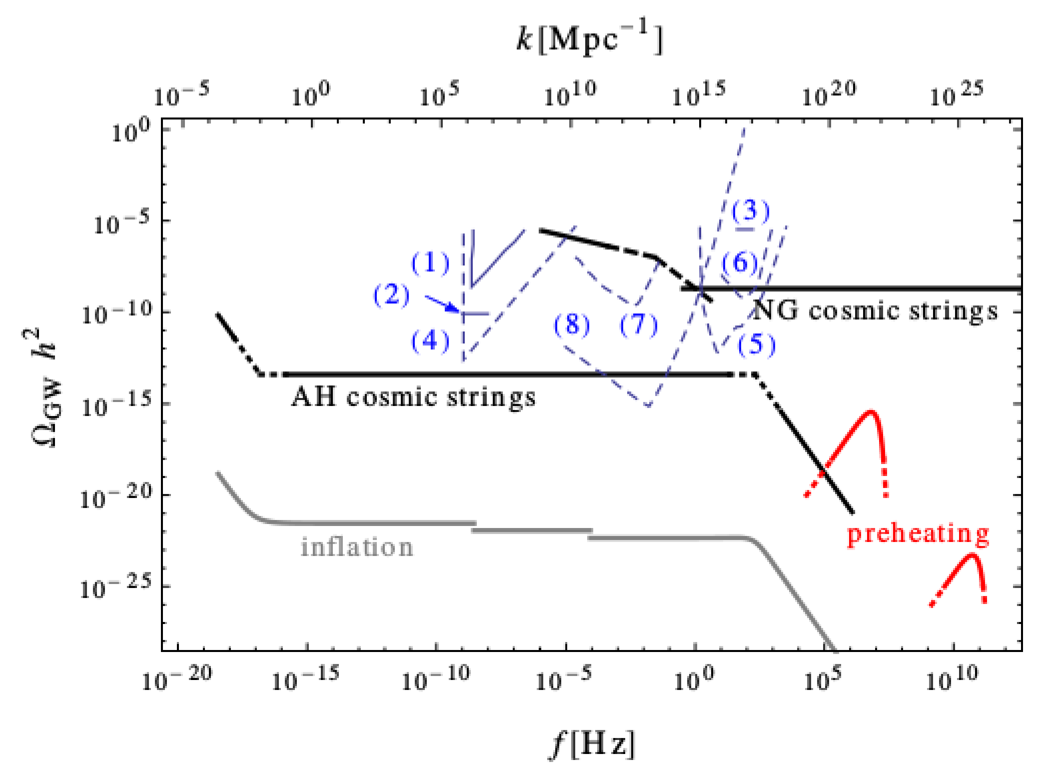


Science with the space-based interferometer eLISA II: Gravitational waves from cosmological phase transitions

[C. Caprini et al. '15]

Cosmic strings

If a grand unified theory (GUT) was broken to the Standard Model gauge group, cosmic strings have been eventually produced

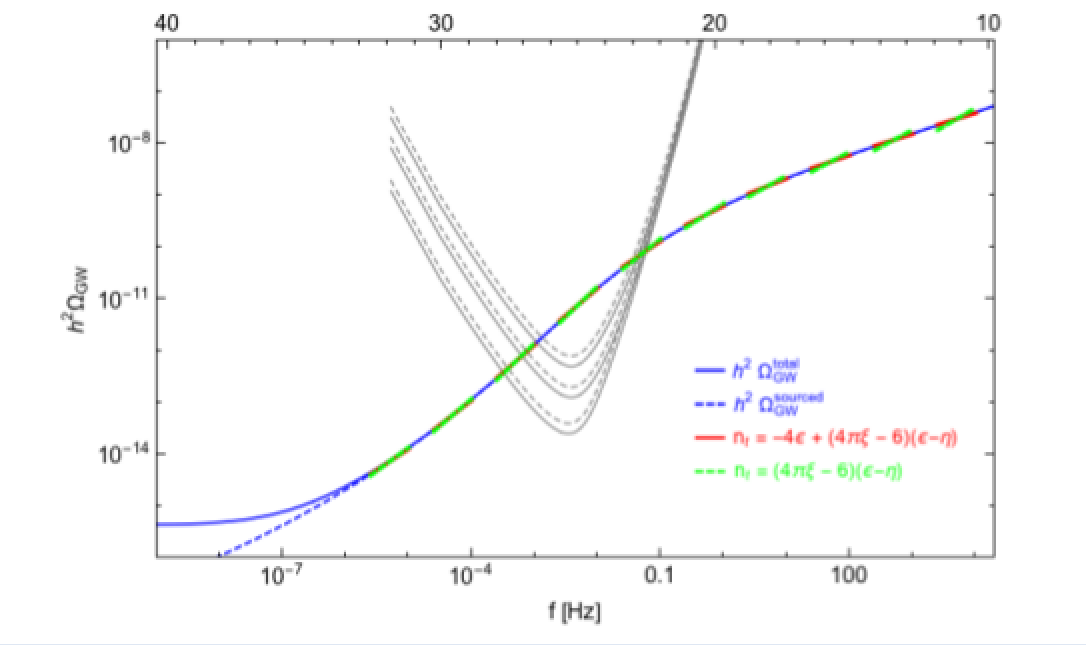


These can produce sizable GWs depending on if they decay mostly gravitationally (Nambu-Goto strings) or into particles (Abelian Higgs strings)

Inflation

Generically, tensor modes (read GWs) from inflation are strongly constrained from CMB observations.

Furthermore, single field inflation predicts a red-tilt in the GW spectrum from inflation due to consistency relations.



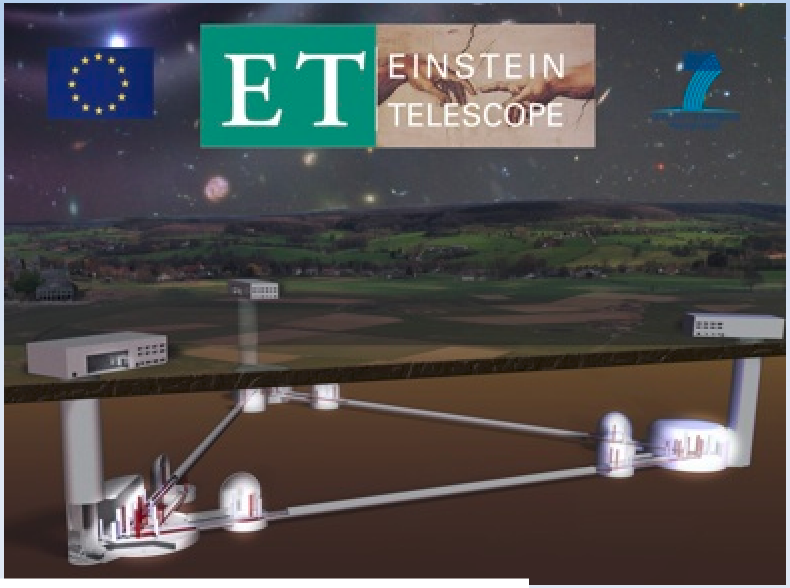
Still, in some models, the late stage of inflation can produce sizable GWs, e.g. though a coupling to vector fields (axion inflation)

Summary

modified gravity
Hubble parameter
QCD equation of state
… astrophysics

cosmological phase transitions
cosmic strings
inflation
… astrophysics

Summary



The LISA Project