Gravitational wave measurements: future insights on cosmology and particle physics

University of Zurich

25/9/2018

Germano Nardini

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EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

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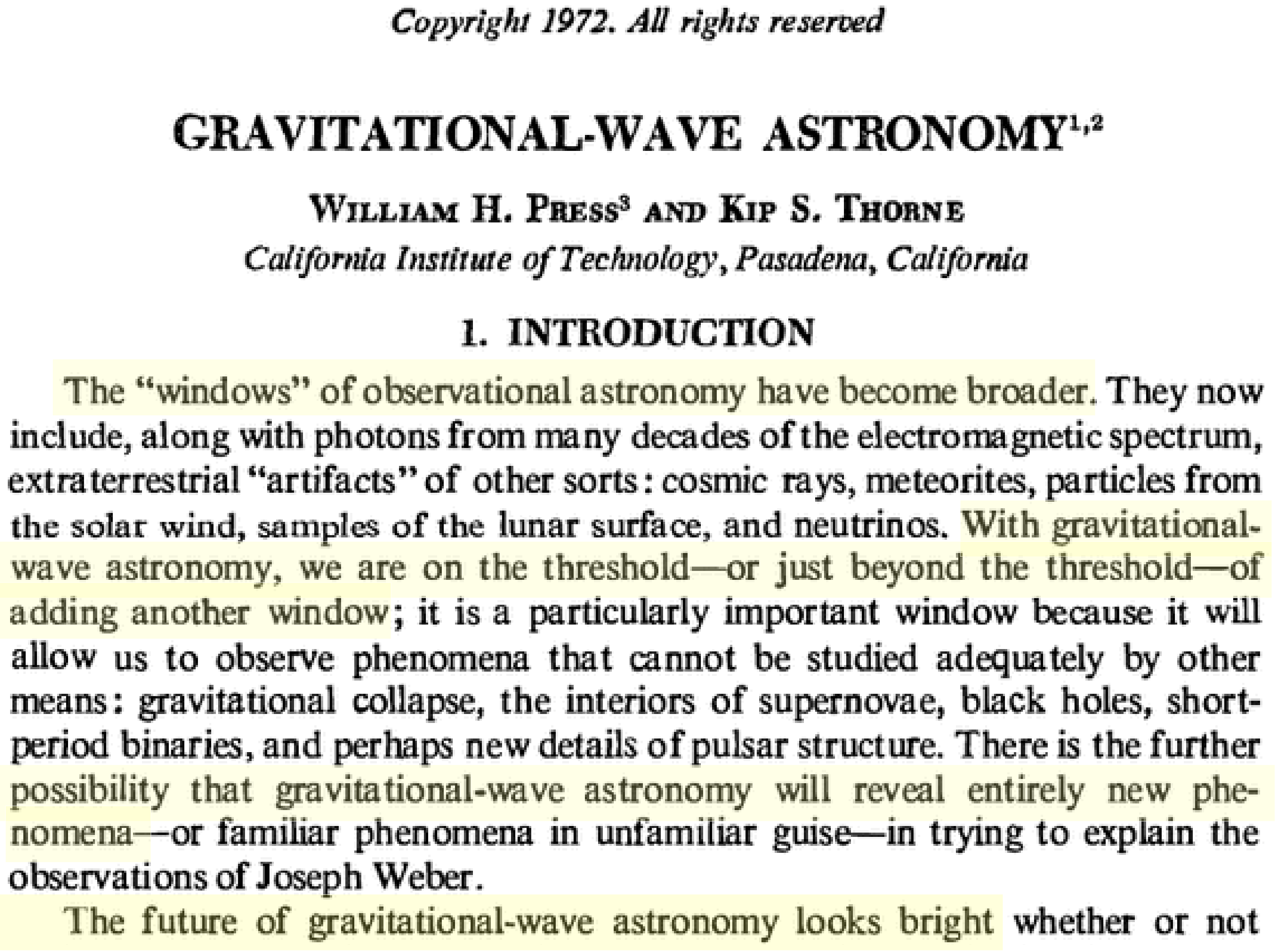
i Stavanger

Gravitational Waves & Astrophysics



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GRAVITATIONAL-WAVE ASTRONOMY[1,2]

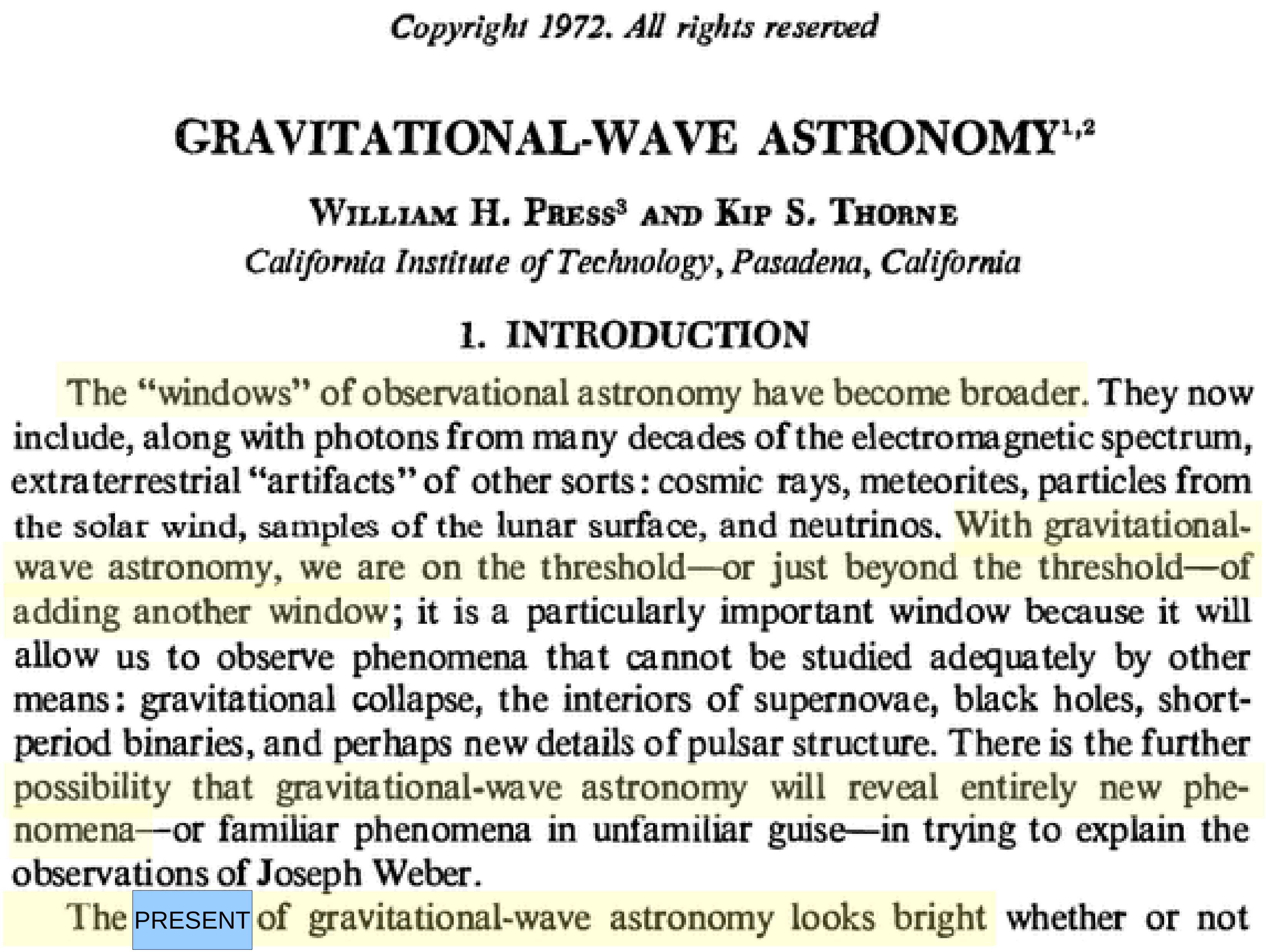
WILLIAM H. PRESS[3] AND KIP S. THORNE
California Institute of Technology, Pasadena, California

1. INTRODUCTION

The "windows" of observational astronomy have become broader. They now include, along with photons from many decades of the electromagnetic spectrum, extraterrestrial "artifacts" of other sorts: cosmic rays, meteorites, particles from the solar wind, samples of the lunar surface, and neutrinos. With gravitational-wave astronomy, we are on the threshold—or just beyond the threshold—of adding another window; it is a particularly important window because it will allow us to observe phenomena that cannot be studied adequately by other means: gravitational collapse, the interiors of supernovae, black holes, short-period binaries, and perhaps new details of pulsar structure. There is the further possibility that gravitational-wave astronomy will reveal entirely new phenomena—or familiar phenomena in unfamiliar guise—in trying to explain the observations of Joseph Weber.

The future of gravitational-wave astronomy looks bright whether or not

Gravitational Waves & Astrophysics



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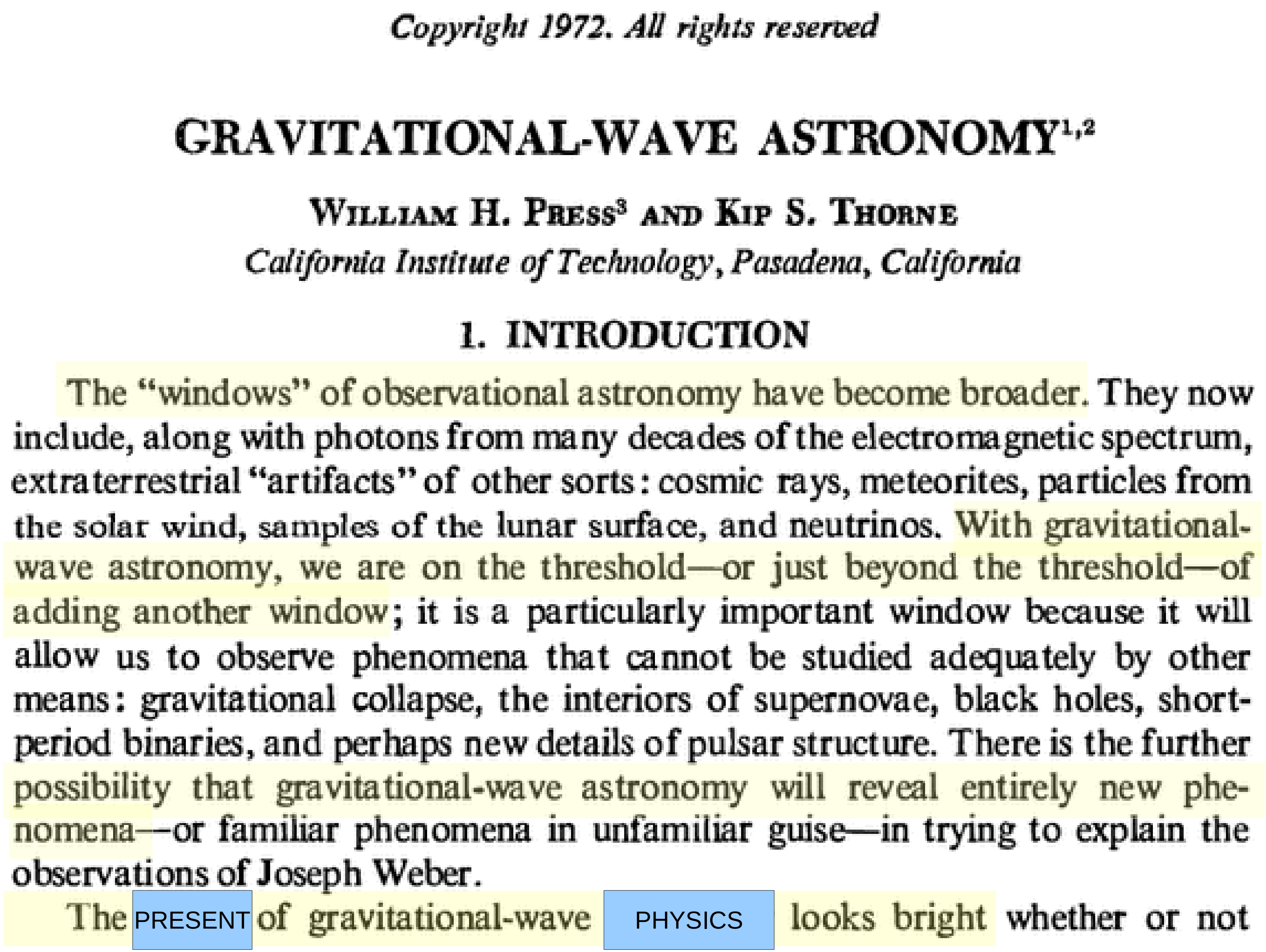
The PRESENT of gravitational-wave astronomy looks bright whether or not

Gravitational Waves & Astrophysics



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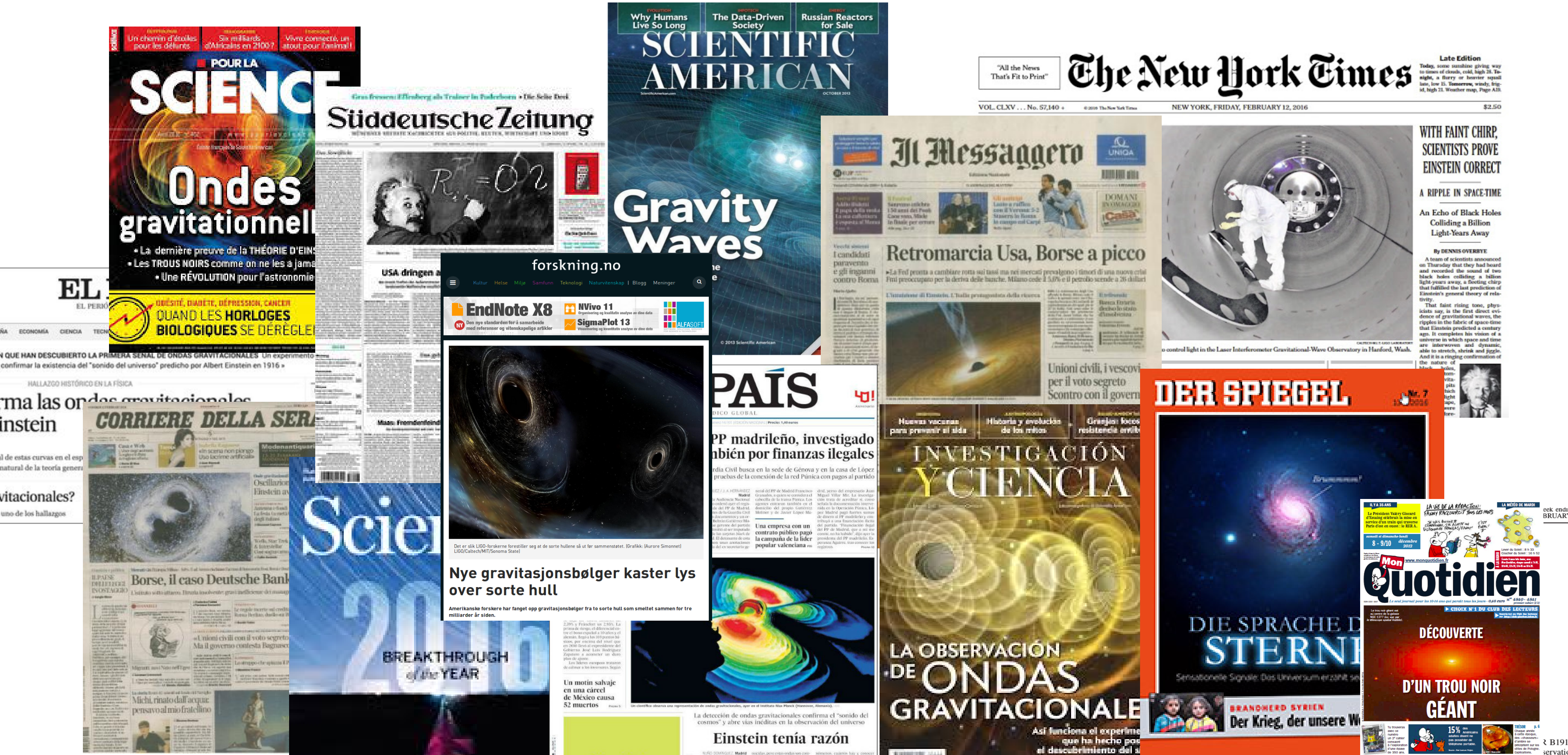
The PRESENT of gravitational-wave PHYSICS looks bright whether or not

Gravitational Waves

- In January 2016, great announcement ...
- … first *direct* detection of GWs. Event dubbed GW150914

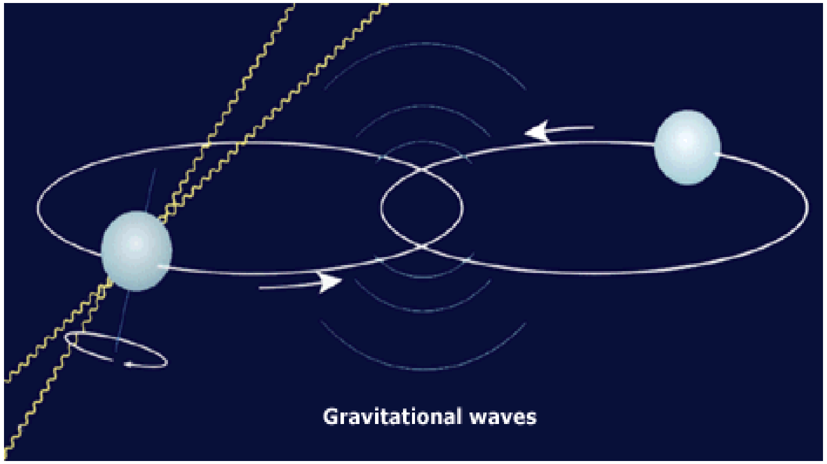


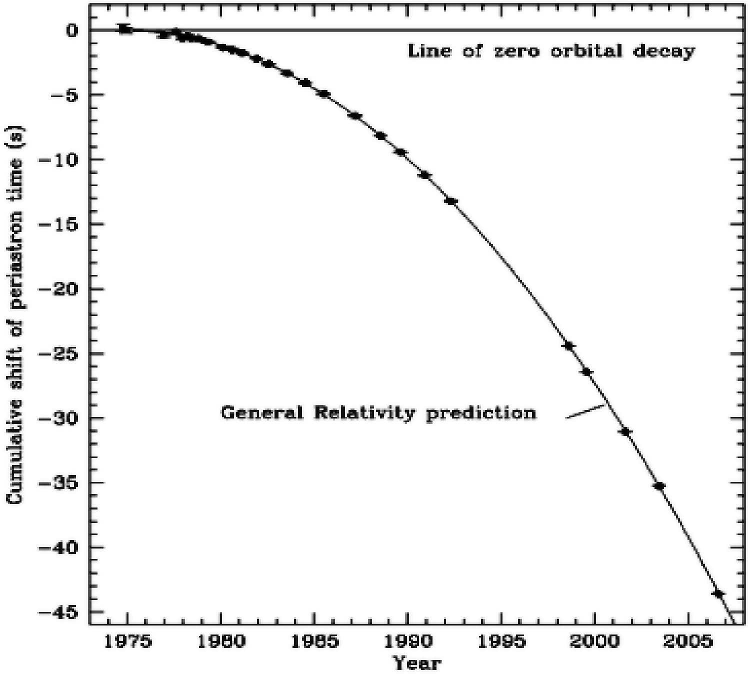
Gravitational Waves

- The first *indirect* detection that GWs exist was obtained by observerving the Hulse-Taylor binary system

- GR predicts that accelerating masses (varying its quad. momentum) produce a spacetime perturbation that propagates (“ripples in spacetime”). These are called GWs and carry energy.

- A system emitting GWs loses energy

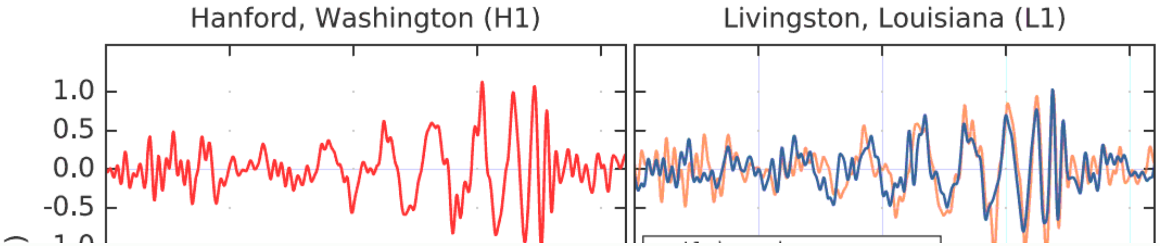


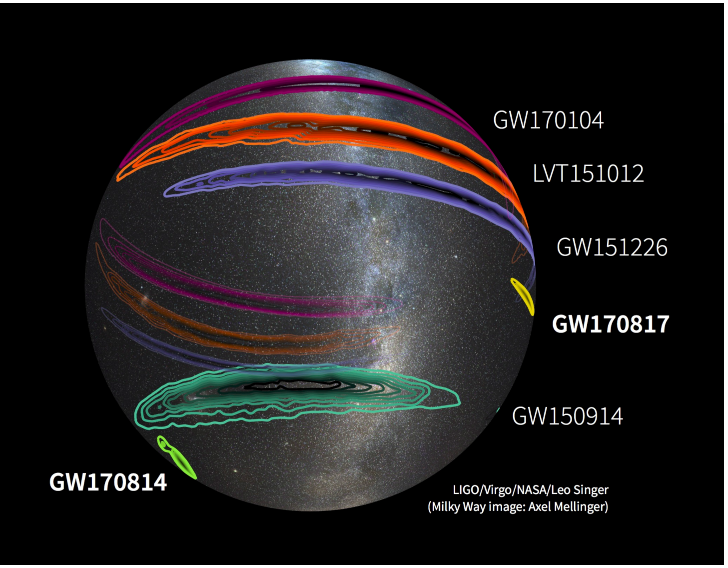


Gravitational Waves

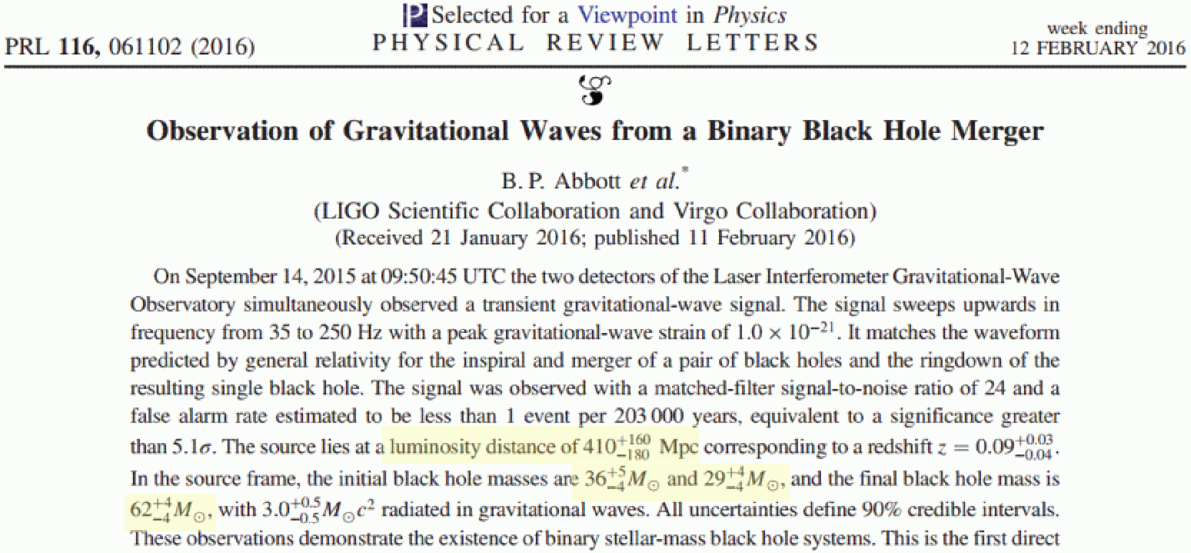
> So, why the first (and subsequent) *direct* observations so interesting?

- Indirect observations may rely on debatable interpretations
- So precise that we can accurately detail the sources
- ….





LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

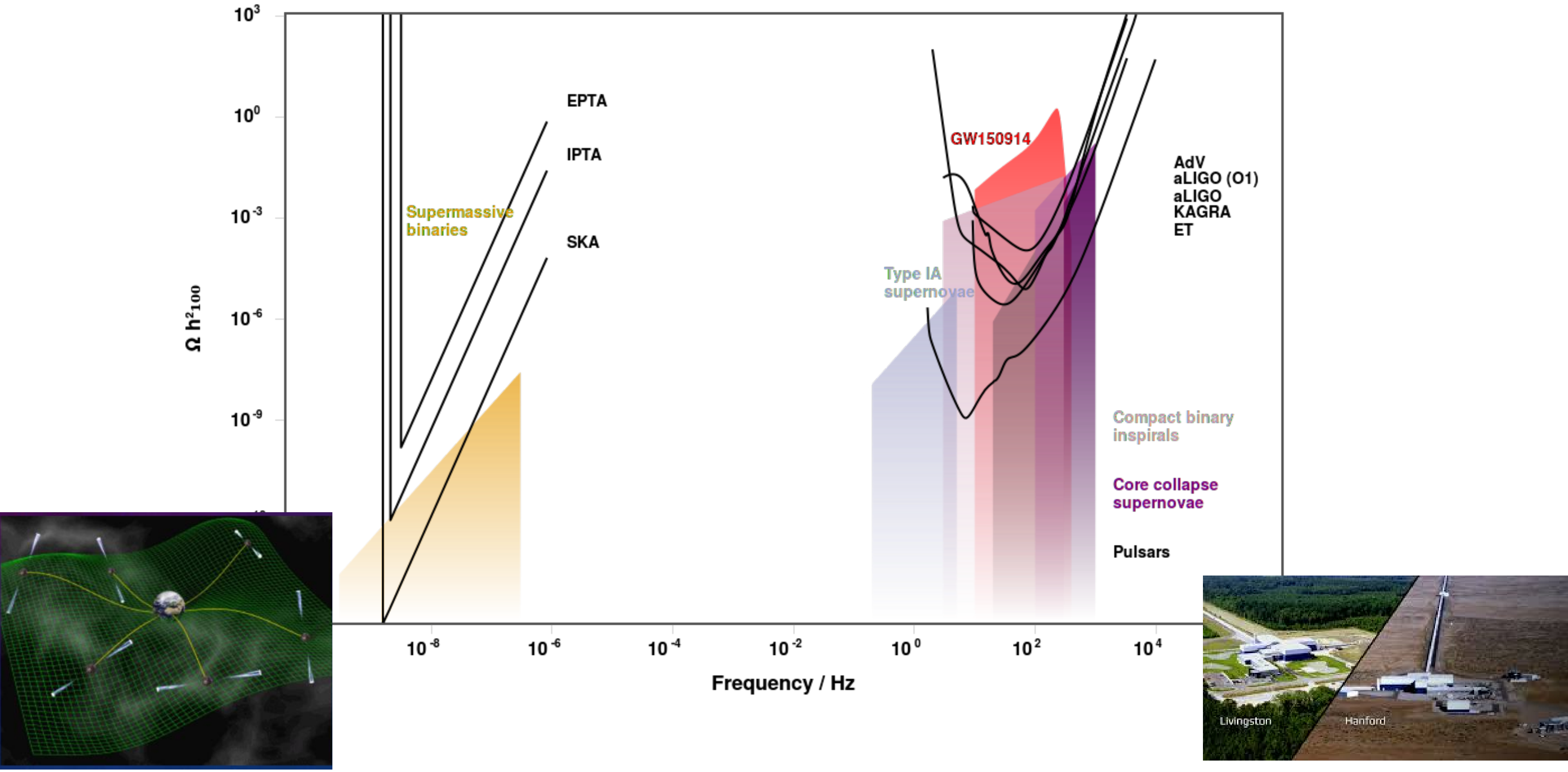
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct

Gravitational Waves & Astrophysics

- Present technique is based on antenna arrays and ground-based interferometers covering the GW frequency ranges 10^{-9}–10^{-6} and 10^{0}–10^{4} Hz
- What kind of (astro)physics are we missing at the 10^{-4}–10^{0} Hz frequencies?



Gravitational Waves & Astrophysics

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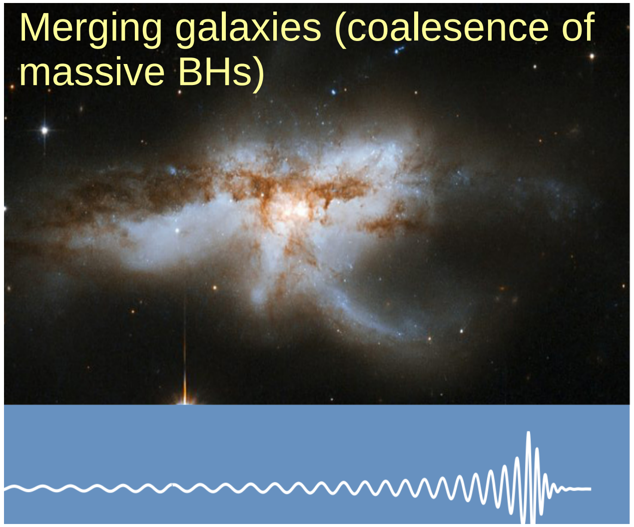
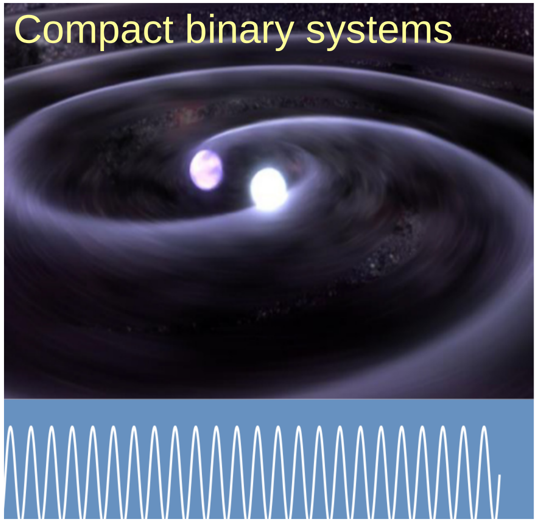
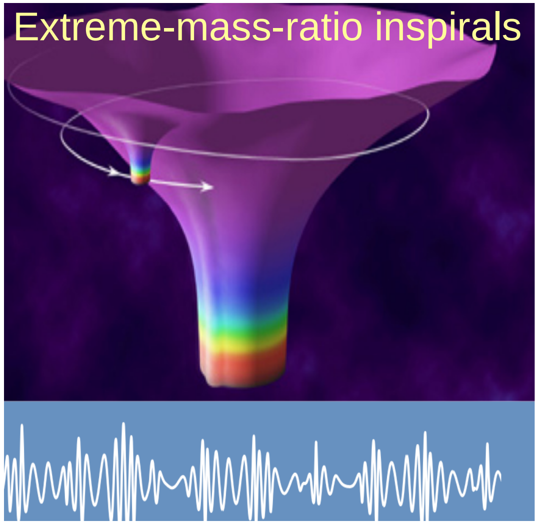
- What kind of (astro)physics are we missing at the 10^{-4}–10^{0} Hz frequencies?

- Typical objects: Binaries of white dwarfs and 10^4–$10^8\ M_\odot$ black holes


Merging galaxies (coalesence of massive BHs)


Compact binary systems


Extreme-mass-ratio inspirals

Gravitational Waves & Astrophysics

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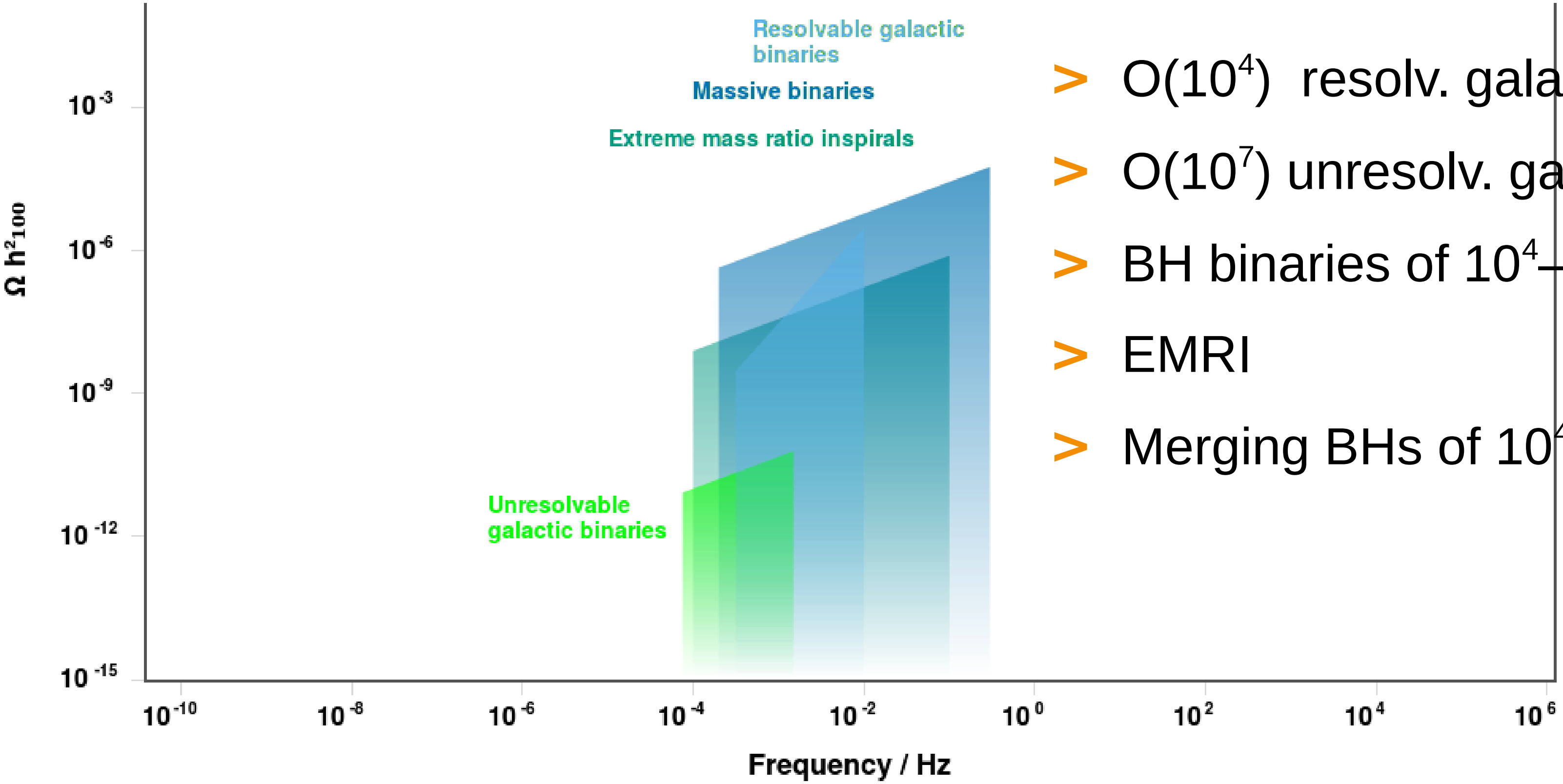
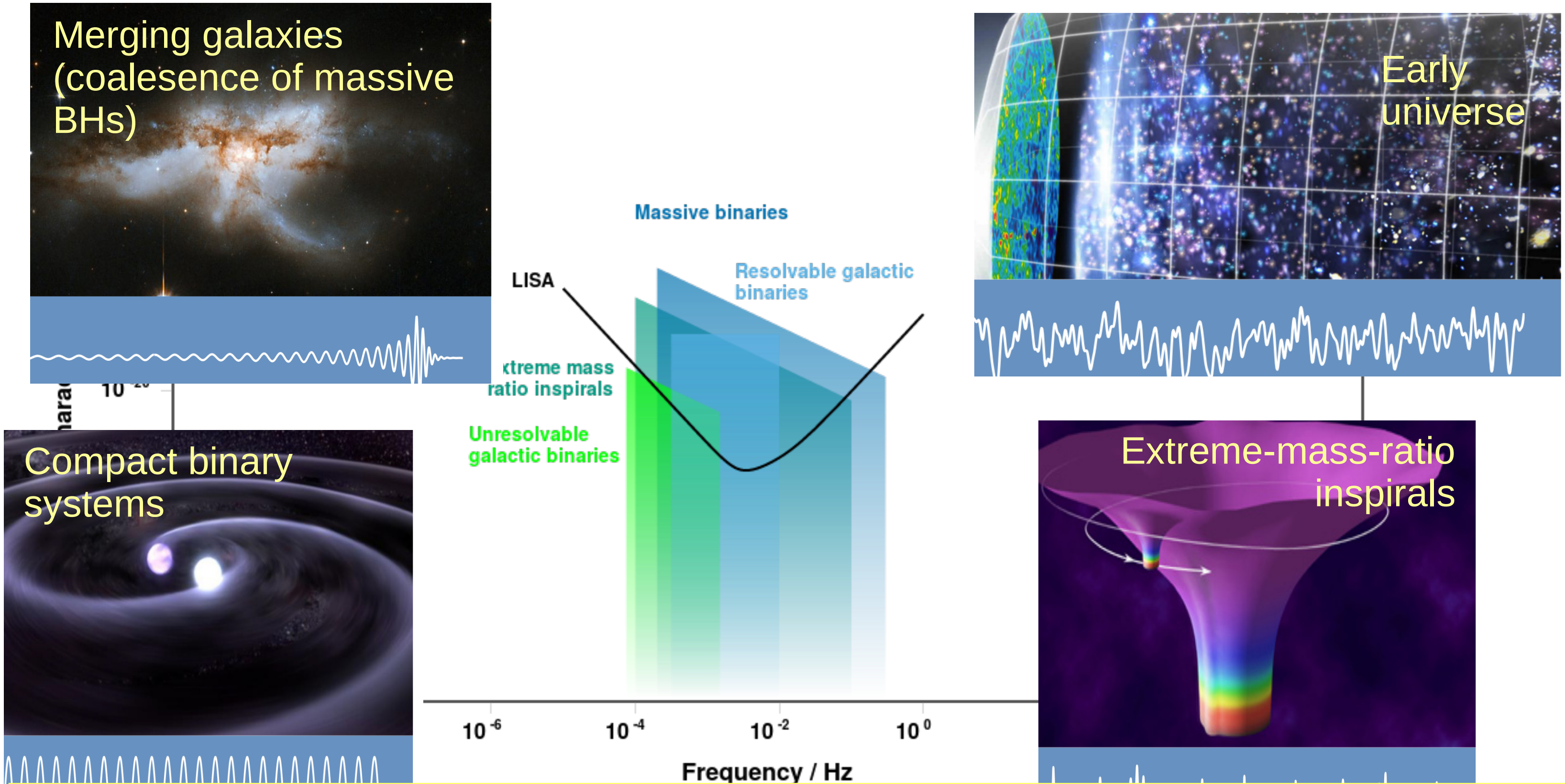


- O(10^4) resolv. galac. binaries
- O(10^7) unresolv. galac. binaries
- BH binaries of 10^4–10^8 $M_\odot$
- EMRI
- Merging BHs of 10^4–10^8 $M_\odot$

Gravitational Waves

- Present techniques are based on antenna arrays and ground-based interferometers covering the GW frequency ranges 10^{-9}–10^{-6} and 10^{0}–10^{4} Hz

- How to detect GWs of 10^{-5}–10^{0} Hz frequencies?



Merging galaxies (coalesence of massive BHs)

Early universe

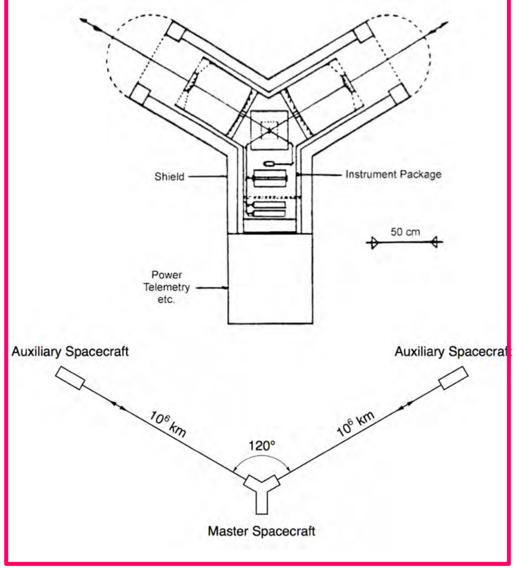
Compact binary systems

Extreme-mass-ratio inspirals

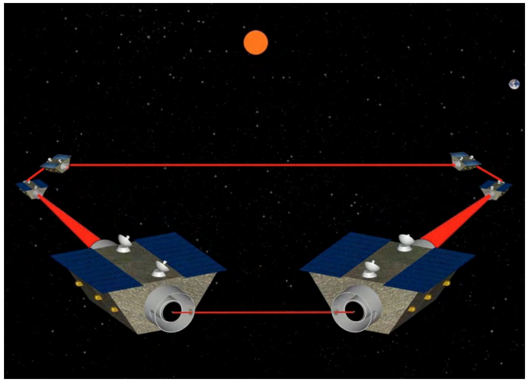
Some sources are guaranteed, others would be a breakthrough. Any experiment able to probe this fr. band?

The Novel of the Laser Interferometer Space Antenna (LISA)

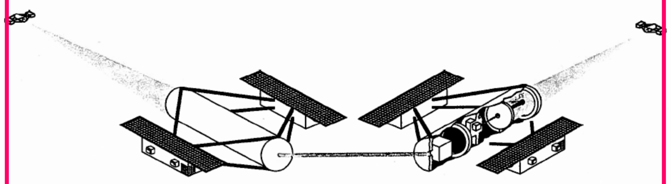
1981: LAGOS



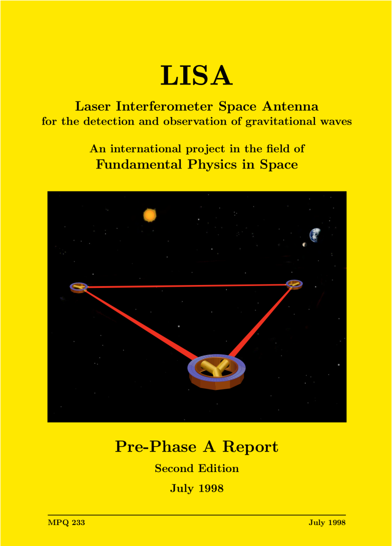
1993: LISAG



1983: LISA



1998: LISA



LISA

Laser Interferometer Space Antenna
for the detection and observation of gravitational waves

An international project in the field of
Fundamental Physics in Space

Pre-Phase A Report

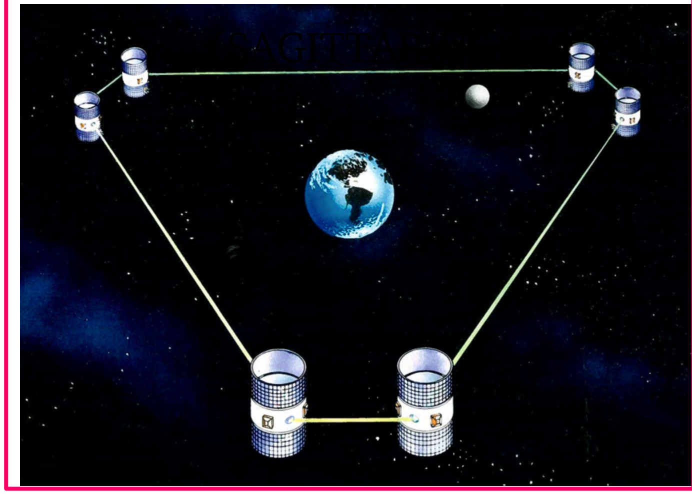
Second Edition

July 1998

MPQ 233 **July 1998**

1993:

Spaceborne Astronomical Gw Interferometer To Test Aspects of Relativity and Investigate Unknown Sources

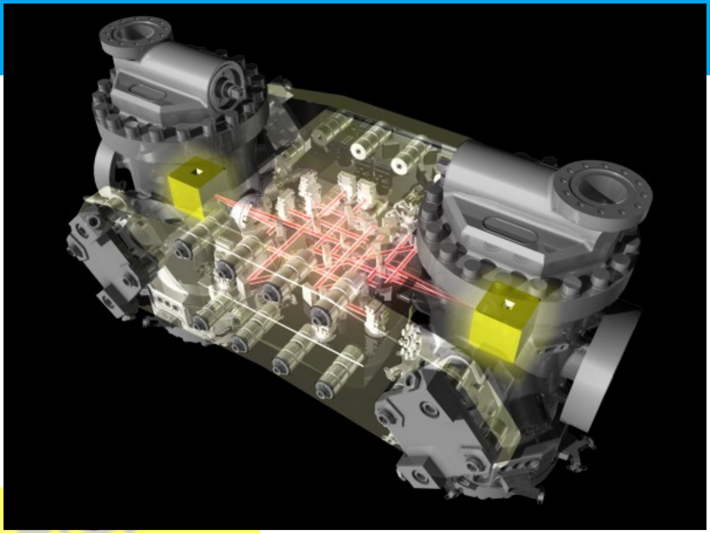


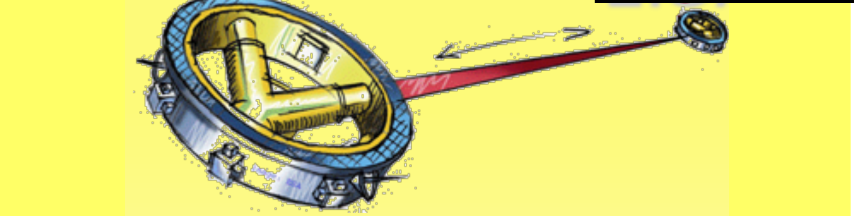
…. quite long story ….

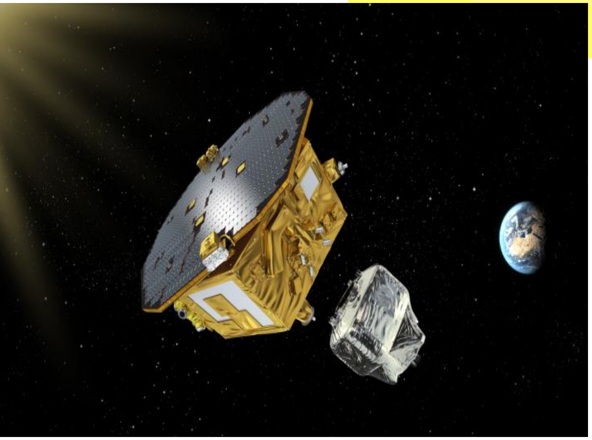
LISA PathFinder

✗ Testing LISA technology in space

✗ Take one arm of LISA, squeeze it into one spacecraft







✗ Launched on 3 Dec. 2015

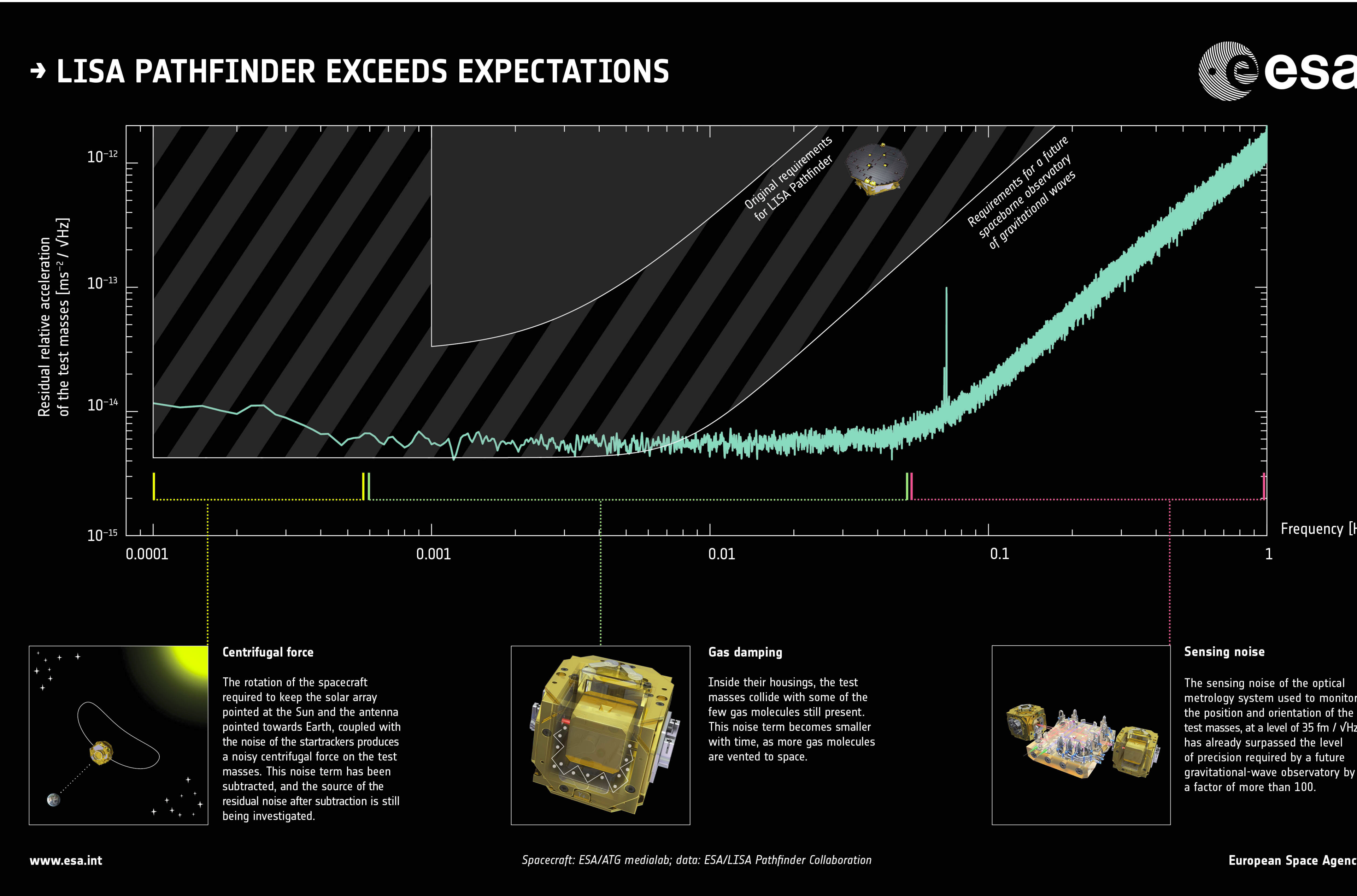
✗ Took data till 18th July 2017

✗ Now switched off

LISA PathFinder (2016 result)

...and 2017 data even better

M.Armano et al., PRL 120 (2018)



→ LISA PATHFINDER EXCEEDS EXPECTATIONS

Centrifugal force

The rotation of the spacecraft required to keep the solar array pointed at the Sun and the antenna pointed towards Earth, coupled with the noise of the startrackers produces a noisy centrifugal force on the test masses. This noise term has been subtracted, and the source of the residual noise after subtraction is still being investigated.

Gas damping

Inside their housings, the test masses collide with some of the few gas molecules still present. This noise term becomes smaller with time, as more gas molecules are vented to space.

Sensing noise

The sensing noise of the optical metrology system used to monitor the position and orientation of the test masses, at a level of 35 fm / √Hz has already surpassed the level of precision required by a future gravitational-wave observatory by a factor of more than 100.

www.esa.int

Spacecraft: ESA/ATG medialab; data: ESA/LISA Pathfinder Collaboration

European Space Agenc

The Novel of the Laser Interferometer Space Antenna (LISA)

By the end of 2016:

✗ PathFinder more than successful

✗ LIGO announces its discovery

✗ Several analyses determining the eLISA/LISA scientific return

✗ NASA + other countries express interest

✗ ESA call deadline: 17th Jan 2017

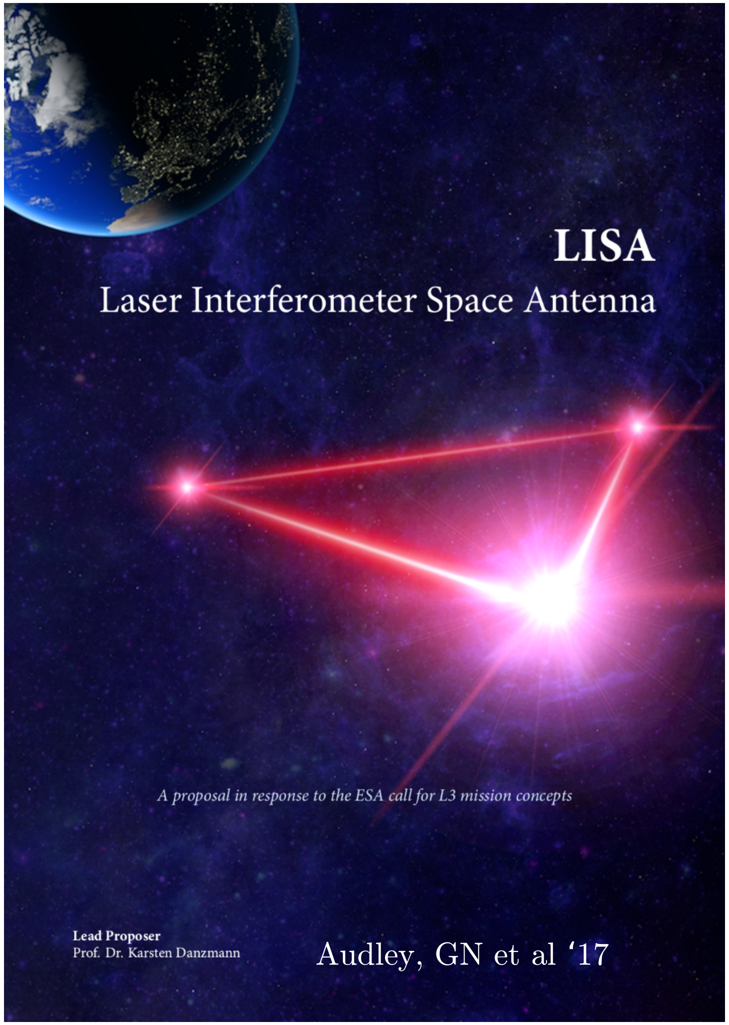
“Science with the space-based interferometer eLISA/LISA” papers

20th June 2017:

✗ The preliminary ESA feasibility study is finished

✗ ESA can decide and …

Jan. 2017:



LISA

Laser Interferometer Space Antenna

A proposal in response to the ESA call for L3 mission concepts

Lead Proposer
Prof. Dr. Karsten Danzmann

Audley, GN et al ‘17

~~e~~LISA proposal in response to the ESA L3 call

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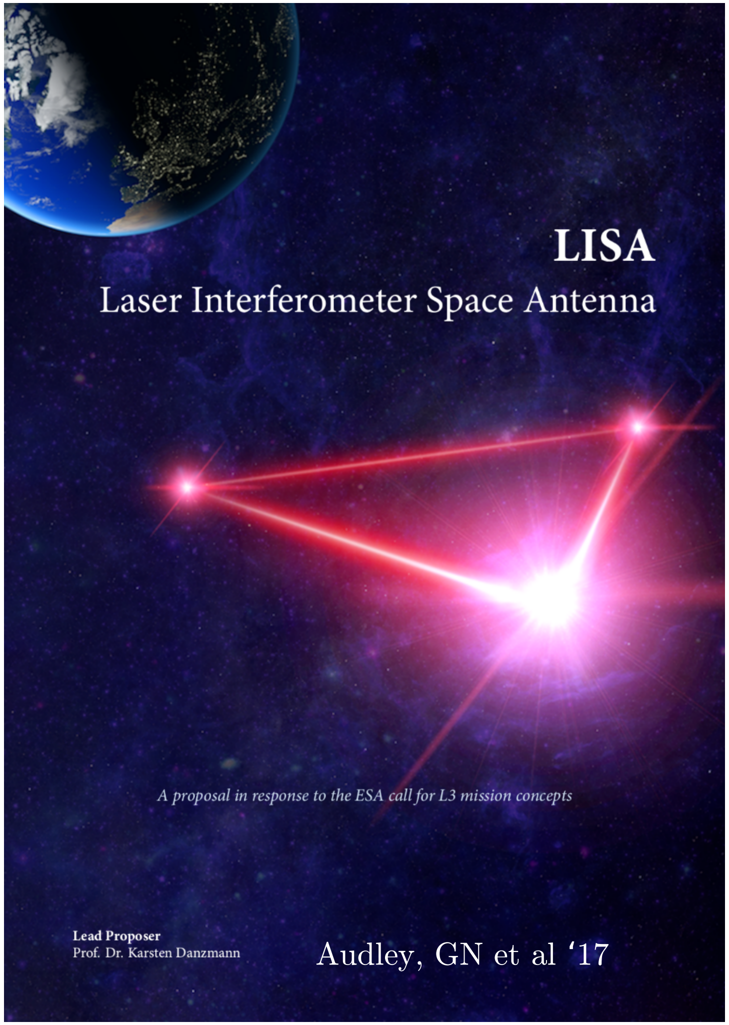
The mission selected for the L3 launch is LISA.

Launch between 2028 and 2034

Jan. 2017:



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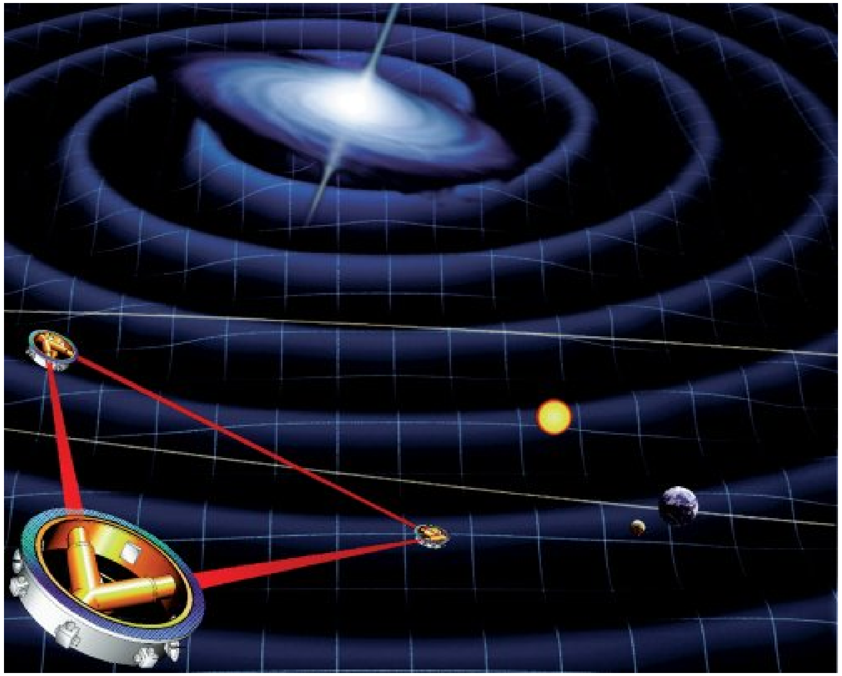
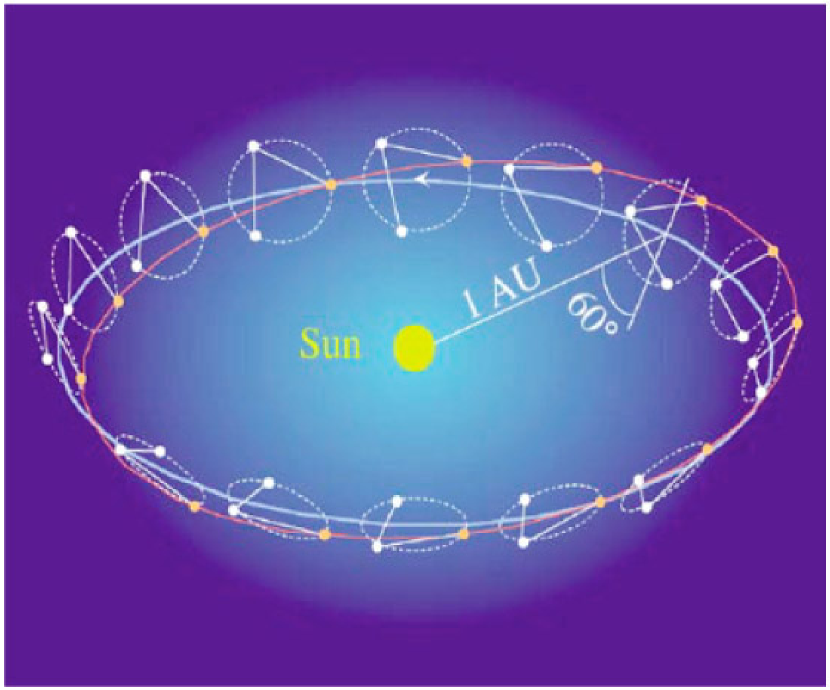
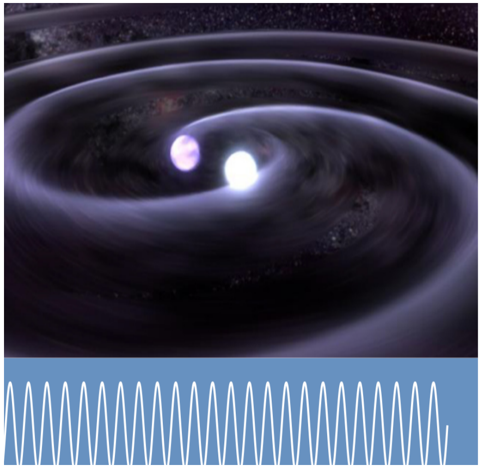
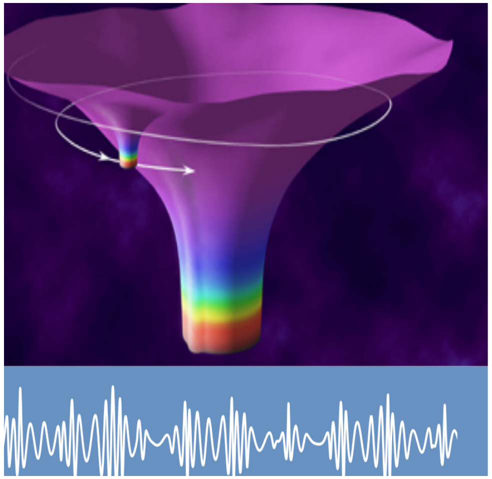


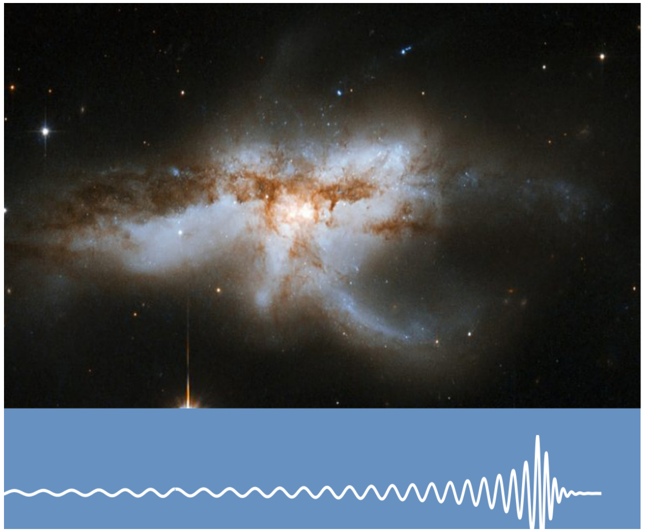


- LISA is kind of a scaled-up version of two LIGO detectors
- The relative displacements of free-fall masses at L1 are measured by means of laser interferometry
- A GW passing through LISA displaces the free-fall masses
- Three arms that are 2.5 Gm long
- Taking data for at least 4 (but expected ~10) years

The Main Astrophysics Science behind GW detections







Astroph. Objectives :

- Formation and evolution of the astro. population
- Primordial black holes ?
- BHs as a relevent DM component?
- Tests of GR
- QCD under extreme conditions
- Surprises ?

But besides astrophysics….

… there is much more

- Particle content and early history of the Universe
- Hubble law

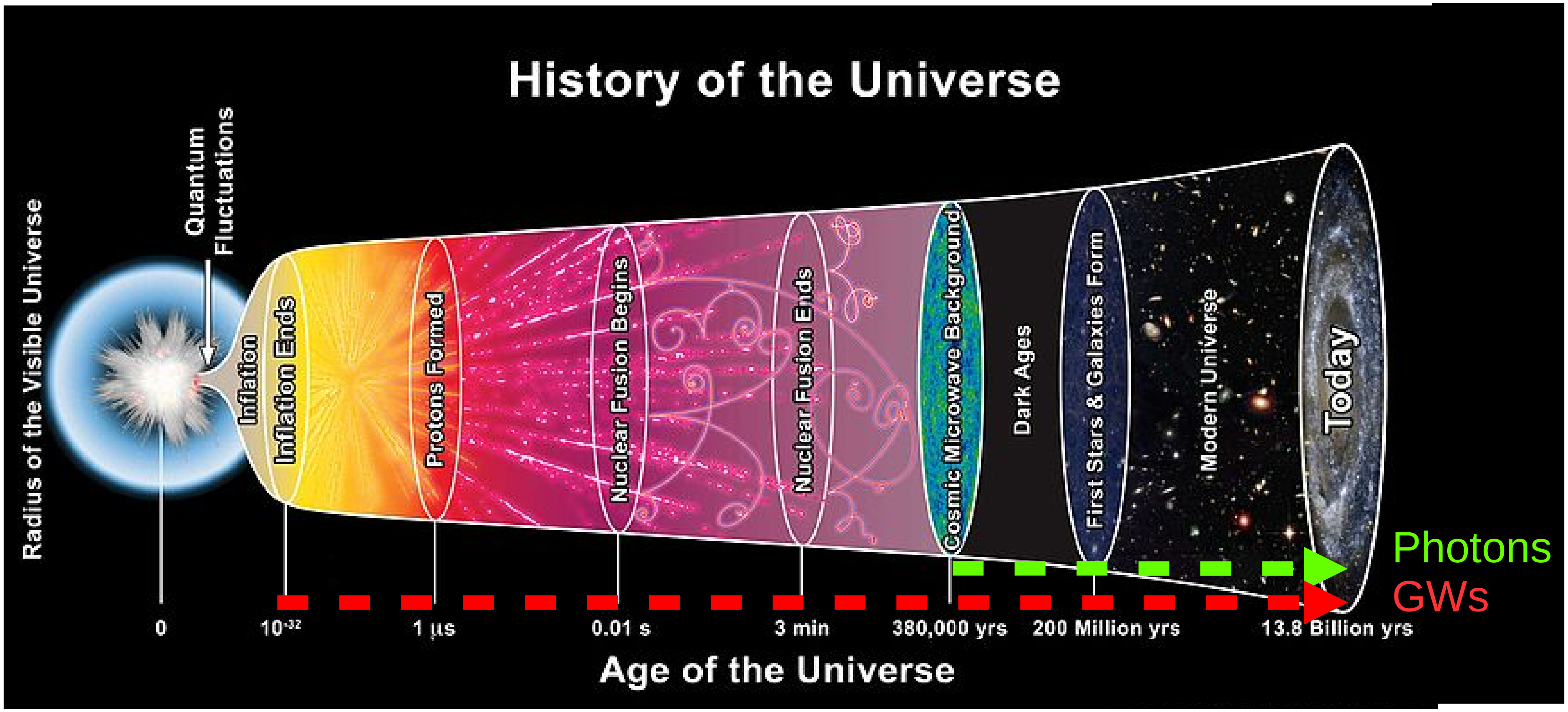
But besides astrophysics….

… there is much more

- ***Particle content and early history of the Universe***
- Hubble law

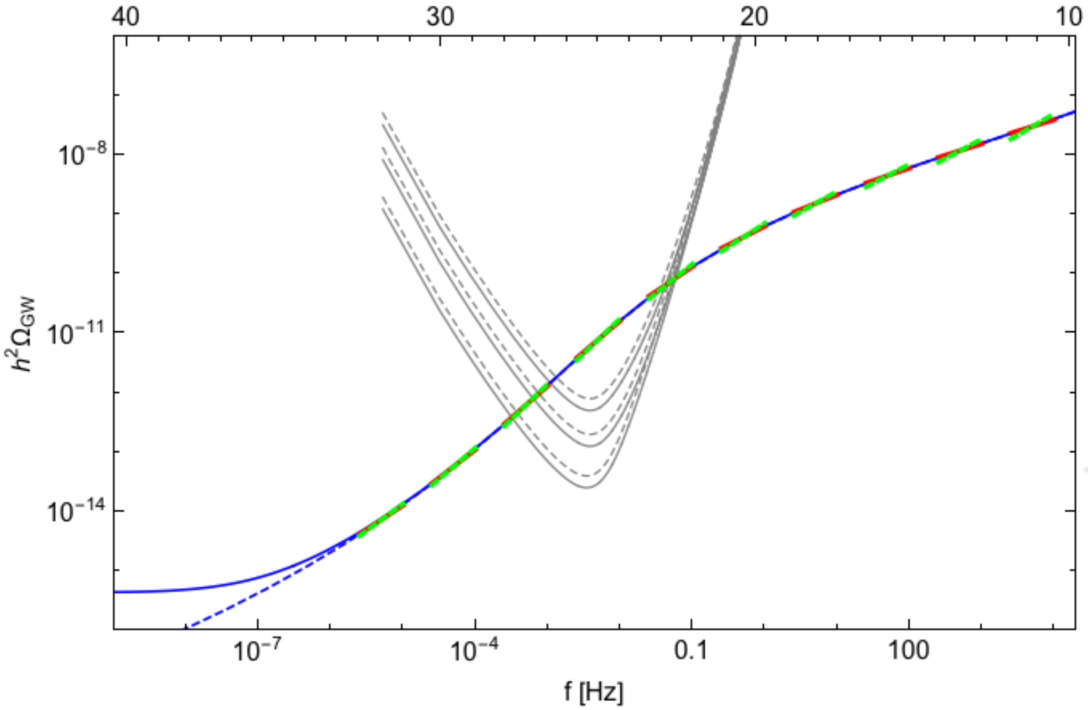
Gravitational Waves & Cosmology

- Not only astrophysical sources! By means of the GW messengers, we directly access the pre-CMB epoch for the first time!
- Early-universe GW sources (inflationary epoch, topological defects, **phase transitions**, ...) generate a stochastic GW background



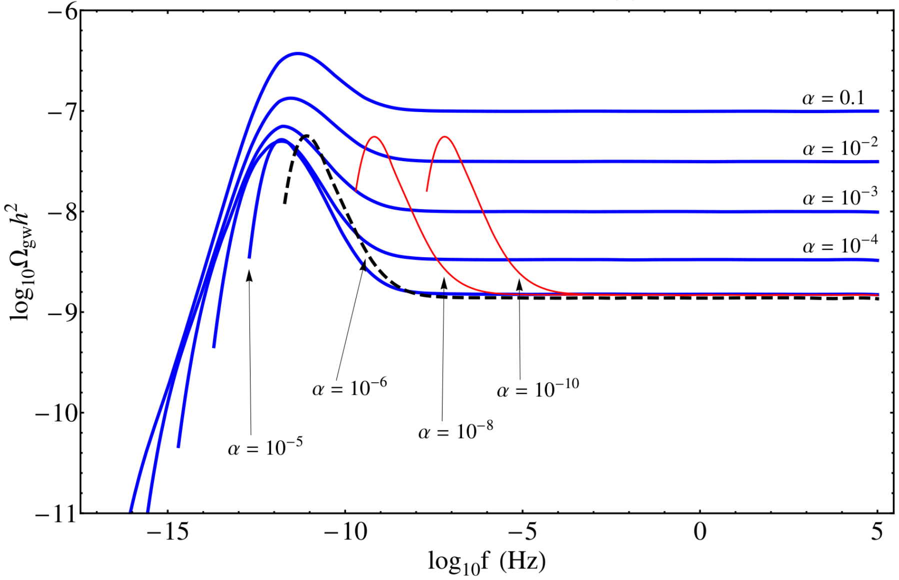
SGWB from the early universe: <u>inflation</u>

- Inflation is expected for many reasons (e.g. horizon/flatness/relics problems)
- By far not detectable in the simplest scenario, but many other possibilities

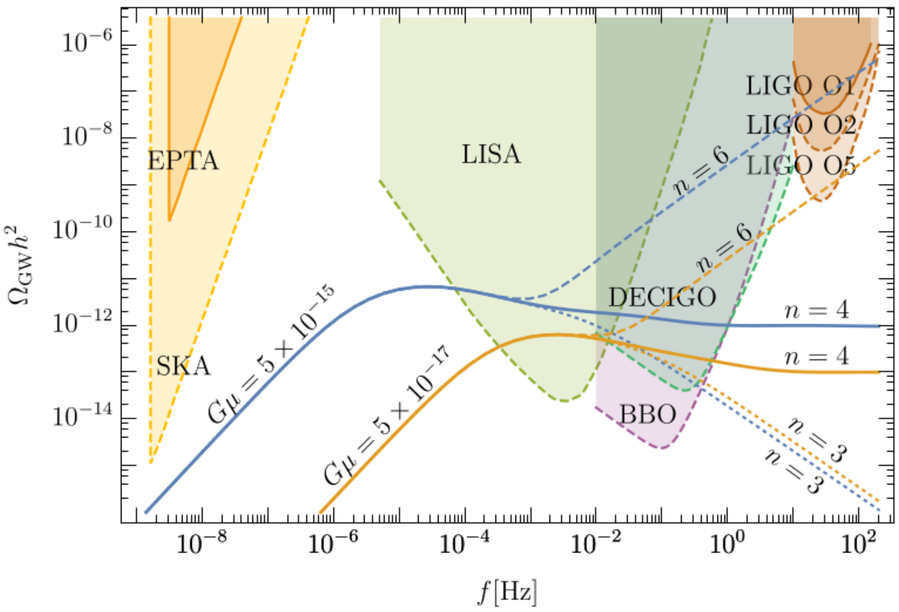


SGWB from the early universe: <u>topological defects</u>

Nambu-Goto string in
Standard Cosmology



Nambu-Goto string in
non-Standard Cosmology (n ≠ 4)

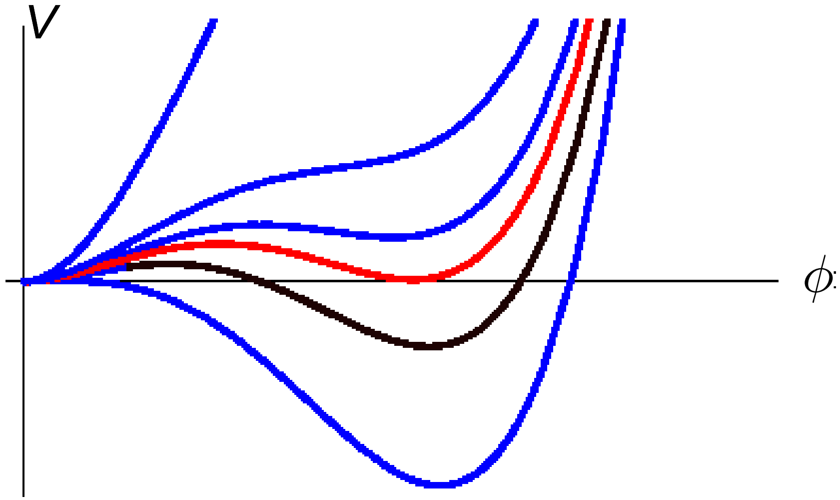


S. Sanidas et al. '12
CosWG internal note
Y.Cui et al.'17

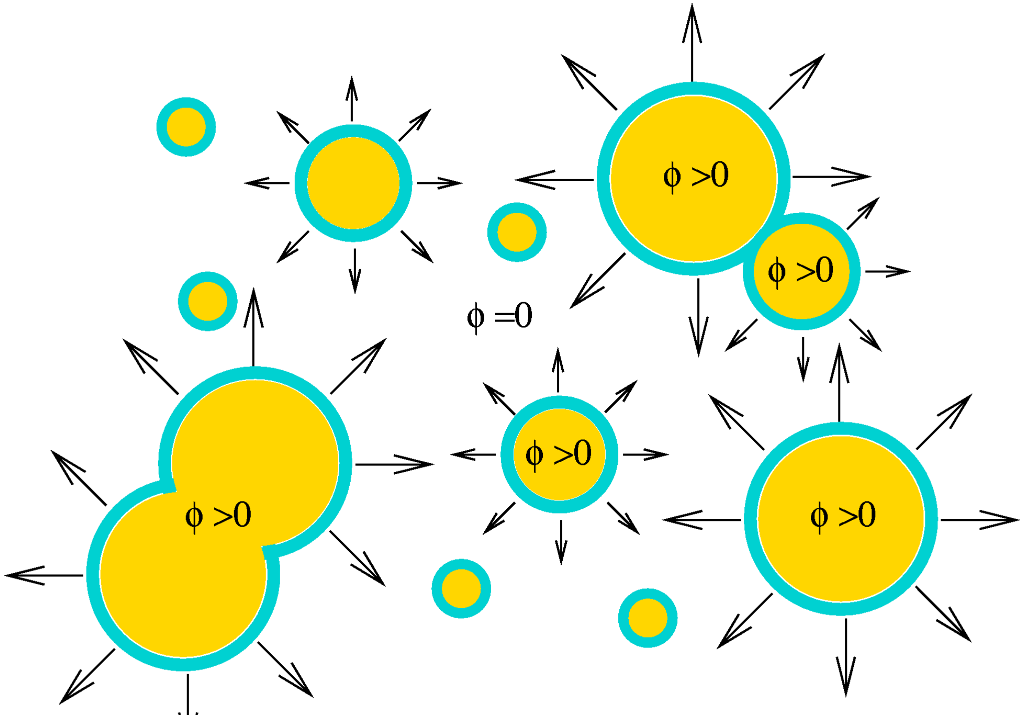
A given SGWB is sensitive to the cosmology history

Gravitational Waves from 1st-Order PT

- When the transition is of first order...



$$V(\phi, T) \approx D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \lambda(T)\phi^4$$



Gravitational Waves from 1st-Order PT

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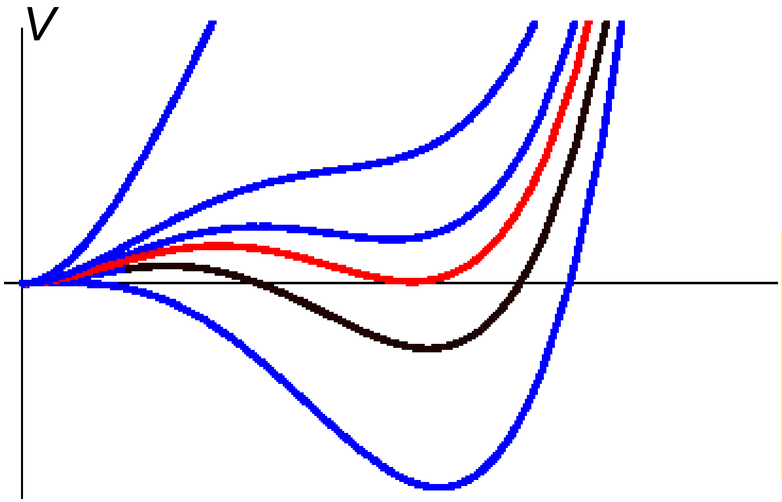
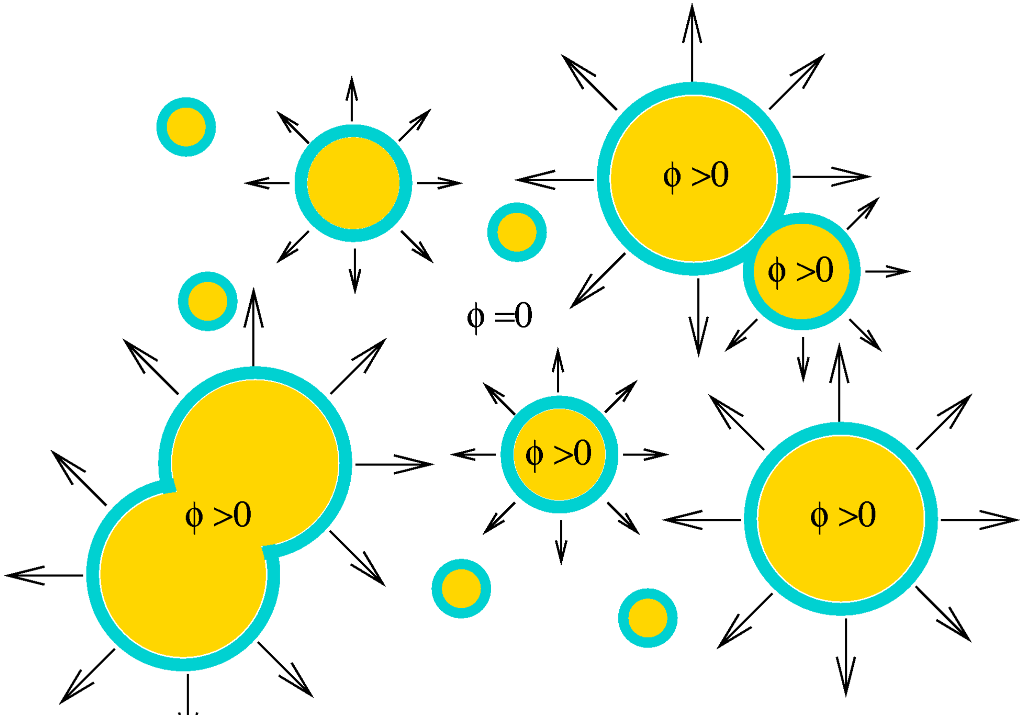


$$V(\phi,T) \approx D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \lambda(T)\phi^4$$

$\alpha(T_n)$: ~normalized difference btw. the minima

$\beta(T_n)$: ~how fast the minimum goes down



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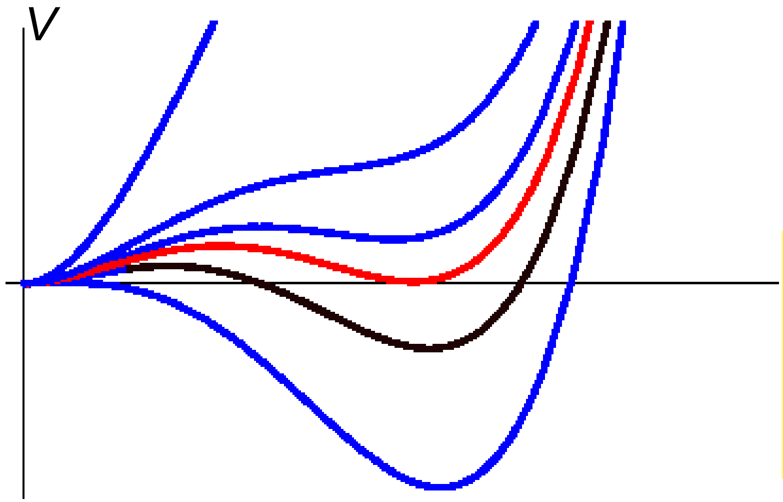

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$\beta(T_n)$: ~how fast the minimum goes down

- When bubbles collide, they convert part of their kinetic energy (of the expanding wall + turbulent fluid) into gravitational waves (GWs)!

M. Kamionkowski et al., ’94

- So, the more energy is available (→ supercooling), the stronger the GW signal

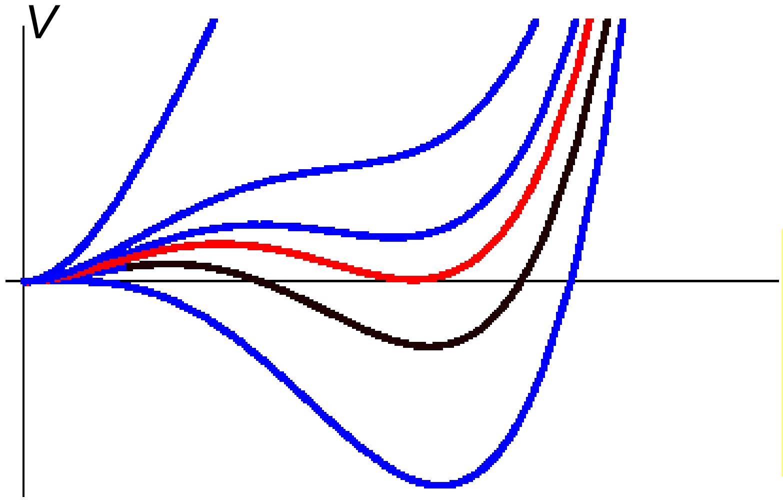
- This available energy is related to

$$\epsilon(T_n) \simeq V(\phi_{sym}, T_n) - V(\phi_{brok}, T_n)$$

which we normalize to the radiation energy: $\alpha = \epsilon(T_n) / \left(\frac{\pi^2}{30} g_* T_n^4 \right)$

Gravitational Waves from 1st-Order PT

- When the transition is of first order...



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$\alpha(T_n)$: ~normalized difference btw. the minima

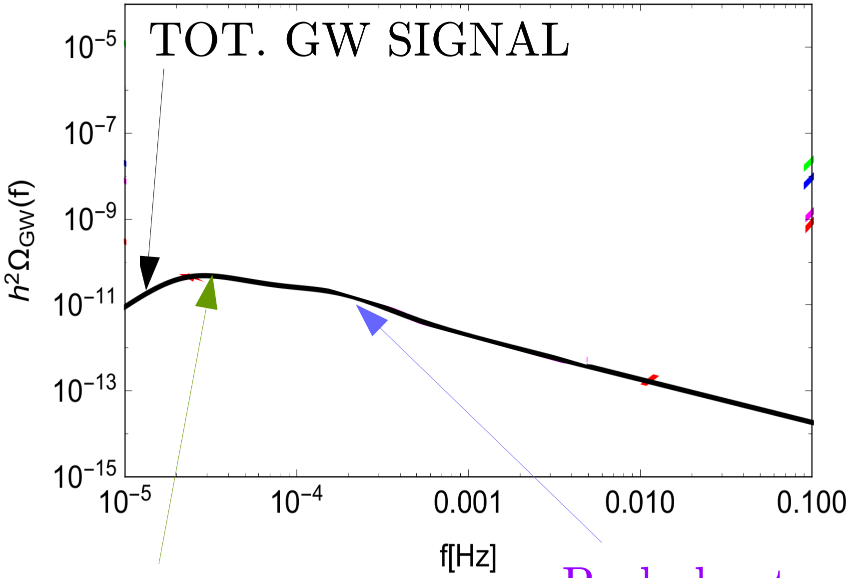
$\beta(T_n)$: ~how fast the minimum goes down

$\alpha(T_n)\ large:$ large supercooling, thus large amount of energy can go into GWs

$\beta(T_n)/H\ large:$ many bubbles, thus high frequency of collisions

Gravitational Waves from 1^{st}-Order PT

C.Caprini, G. Nardini et al '16



$$f_{peak} \approx \mathrm{mHz} \left(\frac{\beta/H}{100}\right)\left(\frac{T_n}{100\mathrm{GeV}}\right)$$

$$h_0^2\Omega_{GW} \approx 10^{-10}\kappa^2(\alpha)\left(\frac{100}{\beta/H}\right)^2\left(\frac{\alpha}{\alpha+1}\right)^2$$

$\alpha(T_n)$: ~normalized difference btw. the minima

$\beta(T_n)$: ~how fast the minimum goes down

Peak due to
SOUND WAVES
CONTRIBUTION

M.Hindmarh,S.Huber,
K.Rummukainen,D.Weir,'13,'15

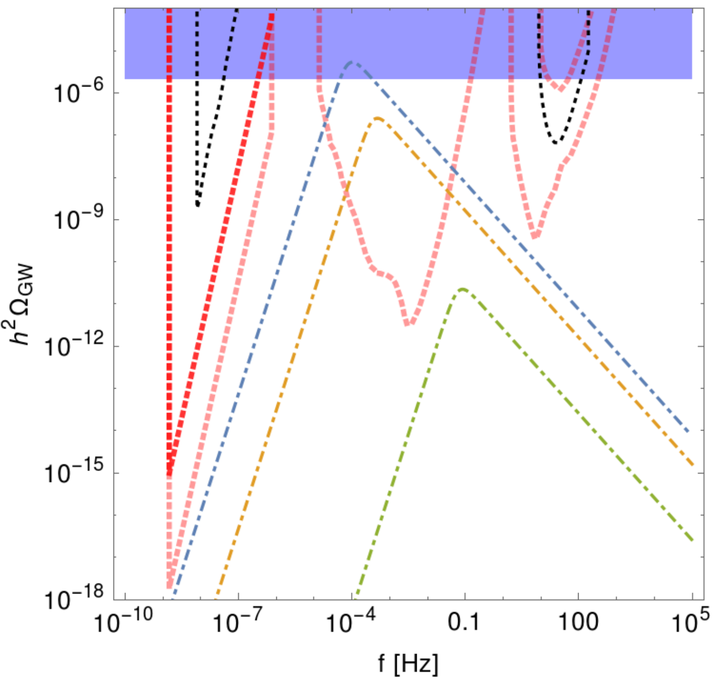
Peak due to
TURBULENCE
CONTRIBUTION

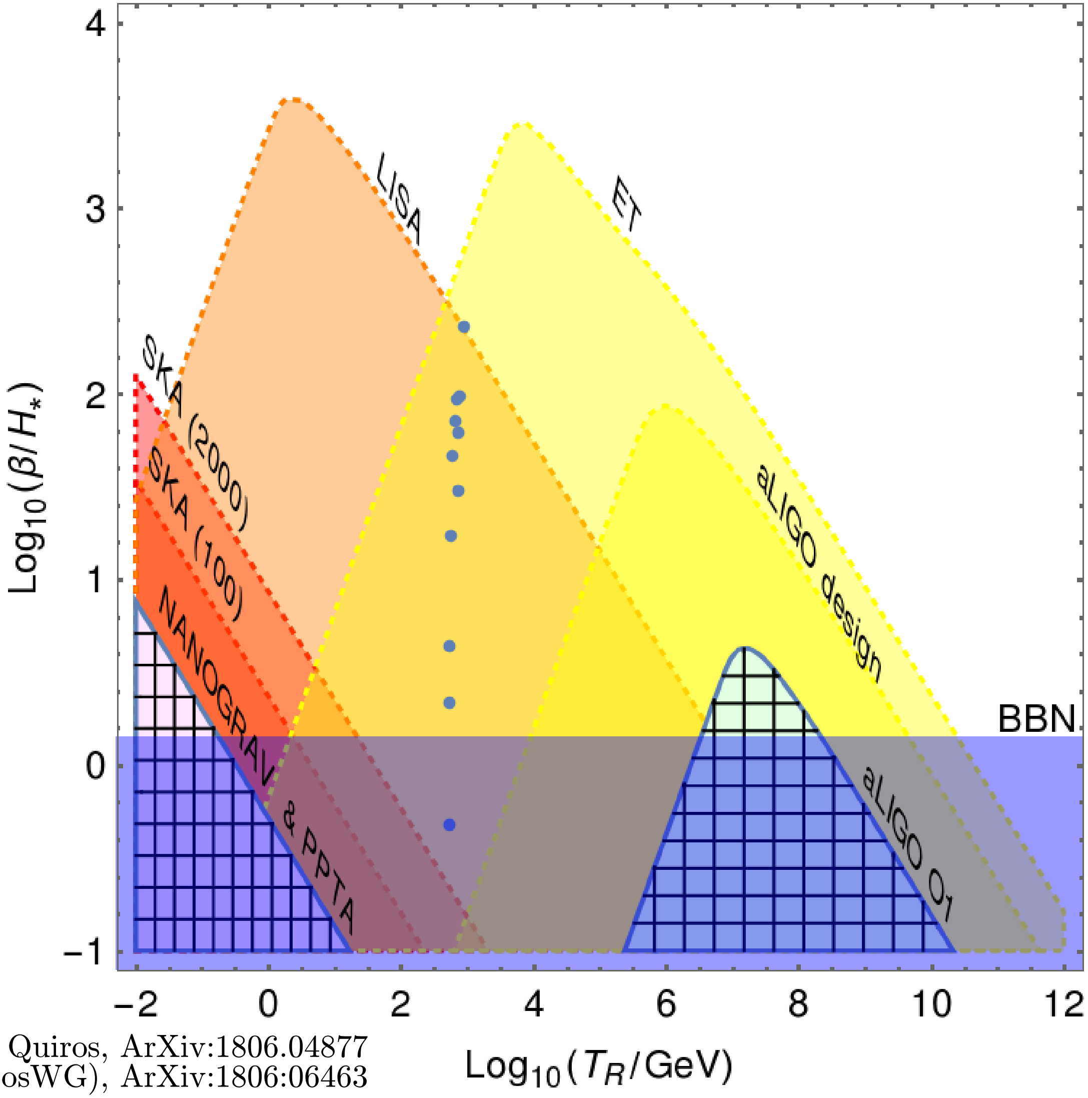
P.Binetruy,A.Bohe,C.Caprini,J.Dufaux,'12
C.Caprini,R.Durrer,G.Servant, '09

1^{st}-Order PT vs. GW detectors (without plasma effects)

- Using the “without plasma” result (i.e. underestimating the spectrum typically)

$$g_* = 100$$
$$v_w = 0.95$$





E. Megias, GN, M. Quiros, ArXiv:1806.04877
D.G.Figueroa et al. (CosWG), ArXiv:1806:06463

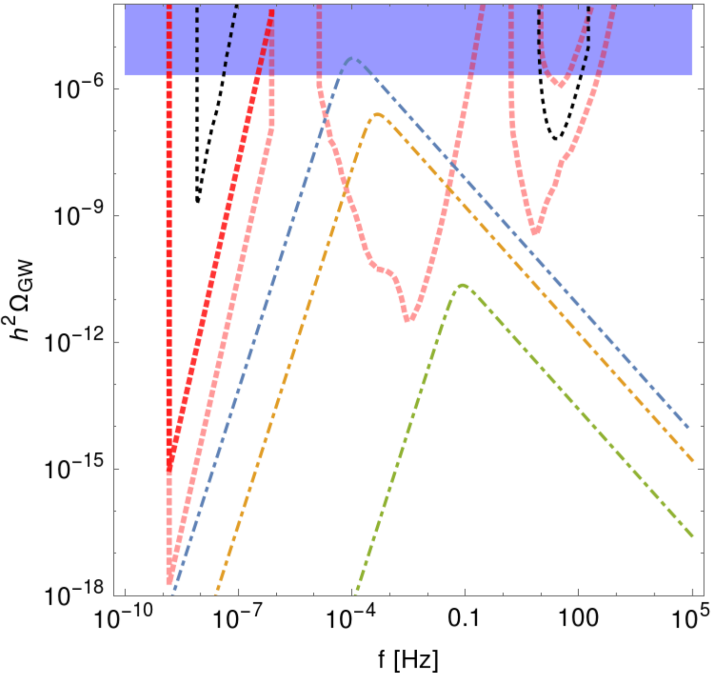
1^{st}-Order PT vs. GW detectors (without plasma effects)

- Using the “without plasma” result (i.e. underestimating the spectrum typically)

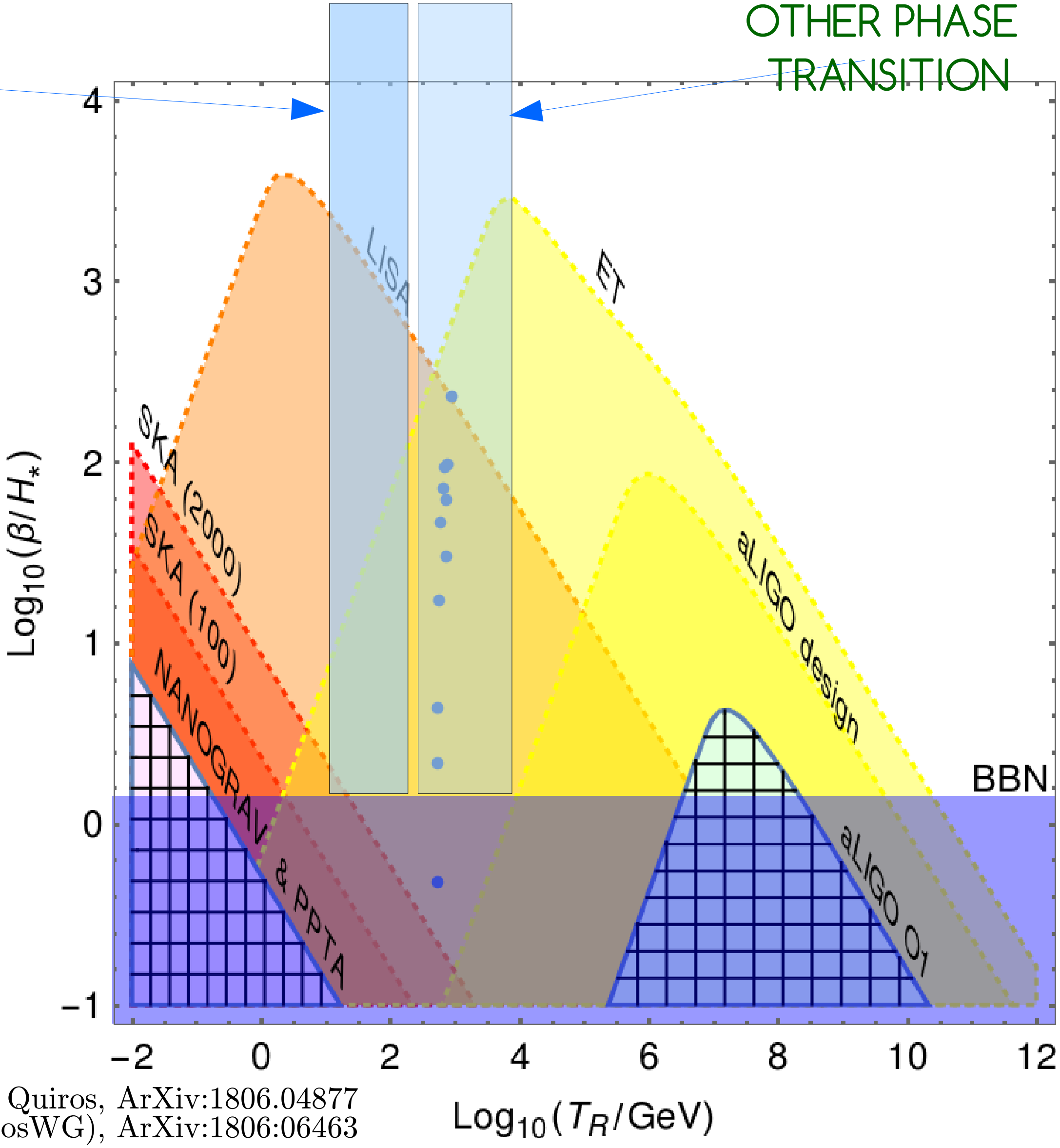
ELECTROWEAK PHASE TRANSITION

$g_* = 100$

$v_w = 0.95$



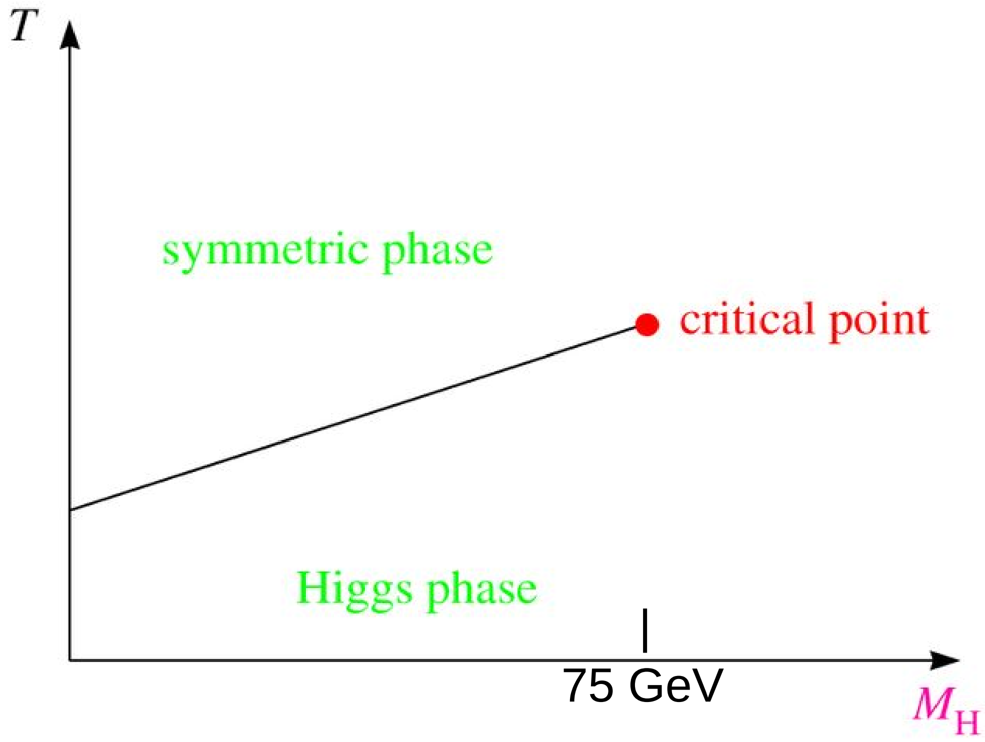
OTHER PHASE TRANSITION



E. Megias, GN, M. Quiros, ArXiv:1806.04877
D.G.Figueroa et al. (CosWG), ArXiv:1806:06463

Electroweak Phase Transition in the SM

No 1st order phase transition in the SM !!!



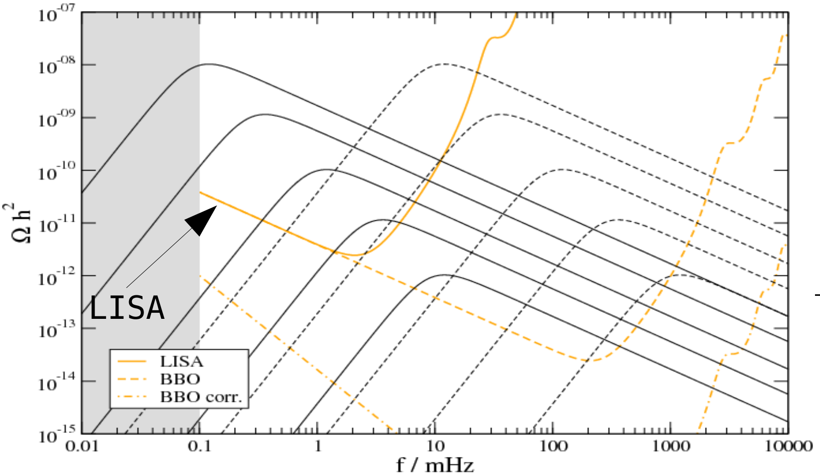
Kajantie,Laine,Rummukainen,Shaposhnikov, '96;
Karsh,Neuhaus,Patkos '96; Csikor,Fodor,Hietger '98;
D'Onofrio, Rummukainen, Tranberg, '14.

Electroweak Phase Transition in BEYOND the SM

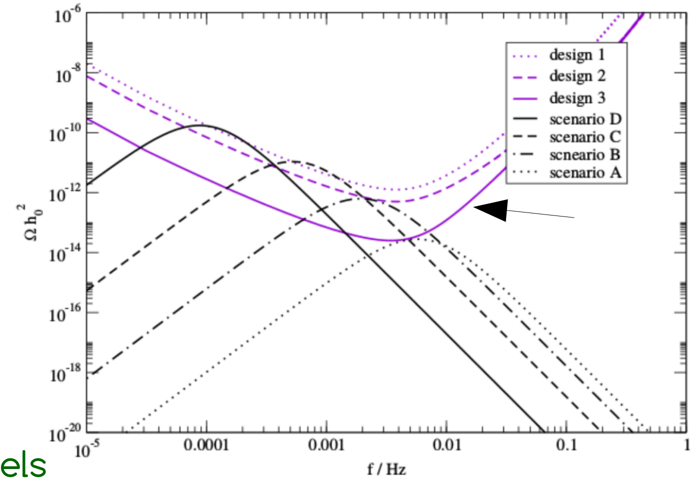
- In the SM the EWPT is not of first-order, i.e. no bubbles

- This feature can be different if the EW sector is modified by BSM physics introducing new finite-temperature radiative corrections or/and new Higgs fields. In practice BSM physics at the ~TeV scale

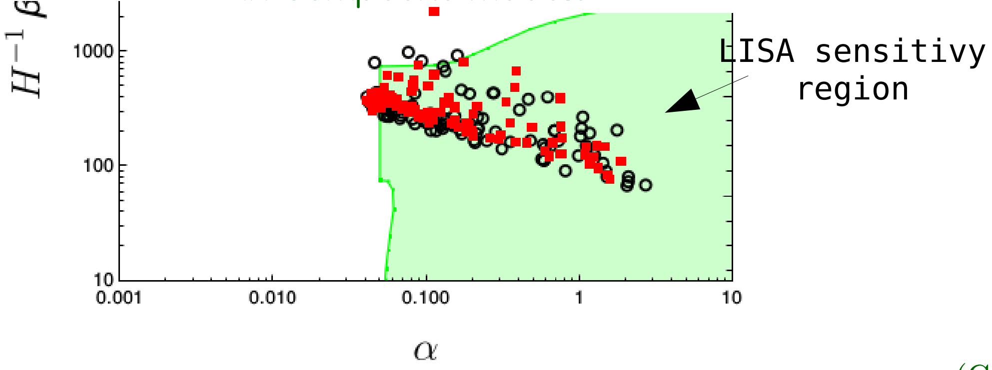
First order in Randall Sundrum



First order in SUSY



First order in Composite Models



Complementarity with the LHC

Nardini et al.'07
Konstandin et al.'10
Huber et al.'15
Chala et al.'16
(CosWG)Caprini et al.'16

From GWs to Particle Physics

- LISA sensitive to 1st order PTs of *1 GeV– 1000 TeV* scale physics
- SKA+LISA+ET sensitive to 1st order PTs of *1 MeV– 1000 PeV* scale physics
- The SM of particle physics predicts that no strong phase transitions ever occurred
- If we detect GWs from strong phase transitions, we have discovered BSM physics

- Synergy among LHC, future colliders and GW observatories

Some key questions requiring also (astro)particle physics skills

1) Does LHC forbid a 1st order PT ? If not, will such a PT detectable in the next years ?

2) Can GW experiment discover BSM physics earlier than colliders ?

3) Can the PT be the only signature of a DM/hidden sector ?

4) Can the PT be connected to baryogenesis ?

But besides astrophysics….

… there is much more

- Particle content and early history of the Universe
- ***Hubble law***

Starting point

If you assume GR and the LFRW metric, ...

… the Hubble rate H(z) provides the evolution of the Universe content along its history

$$H(t)^2 = \left[\frac{\dot{a}(t)}{a(t)}\right]^2 = \frac{8\pi G}{3}\rho(t) = \frac{8\pi G}{3}\sum_{i=M,\Lambda,\ldots}\rho_i(t)$$

How to measure H(z)?

$$d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$$

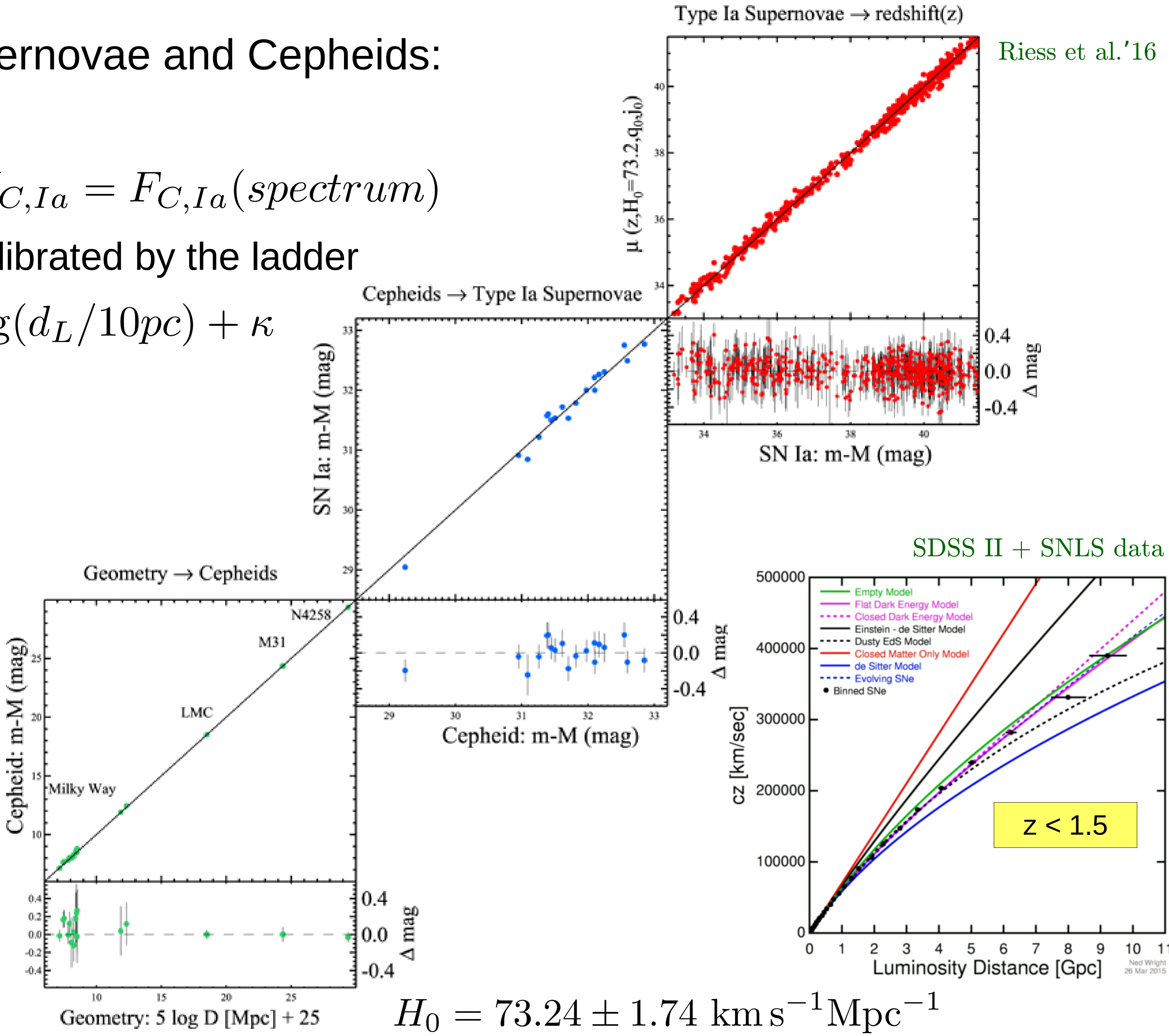
$$H_0 d_L = z + \frac{1}{2}(1-q_0)z^2 + f(q_0, j_0)z^3 + \cdots$$

$$a = \frac{1}{1+z} \equiv \frac{\lambda_{emit}}{\lambda_{obs}}$$

Late Universe: standard candles

For Type Ia Supernovae and Cepheids:

- For d_L
  - Empirically $M_{C,Ia} = F_{C,Ia}(spectrum)$
  - F_C and F_{Ia} calibrated by the ladder
  - $m - M = 5\log(d_L/10pc) + \kappa$
- For z
  - spectroscopy



Riess et al.'16

SDSS II + SNLS data

z < 1.5

$$H_0 = 73.24 \pm 1.74 \ \mathrm{km\,s^{-1}Mpc^{-1}}$$

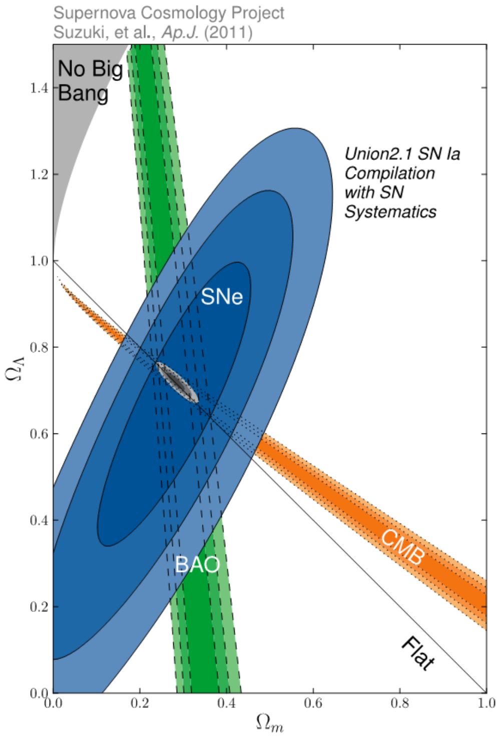
Late Universe: standard candles vs CMB

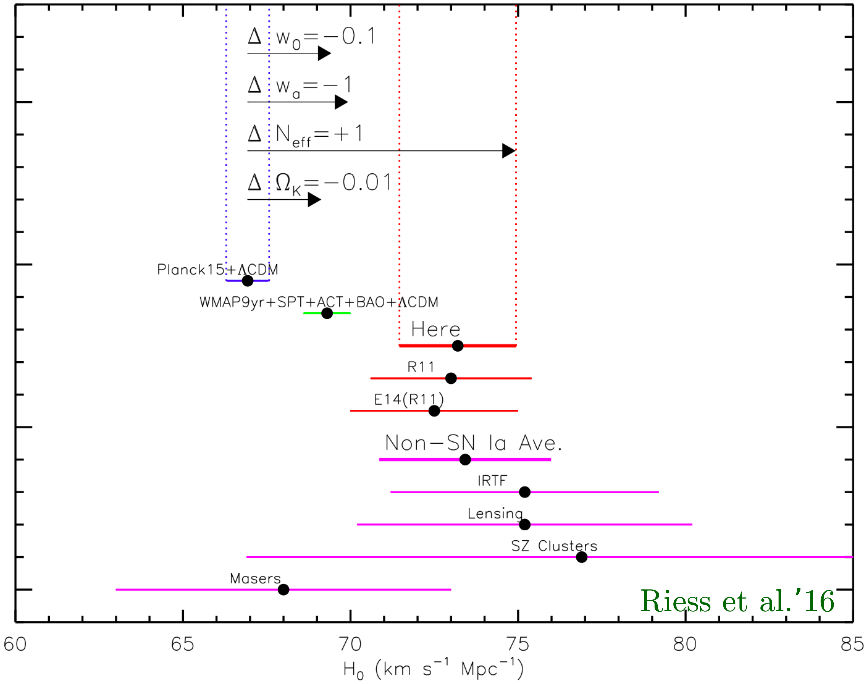
For CMB:

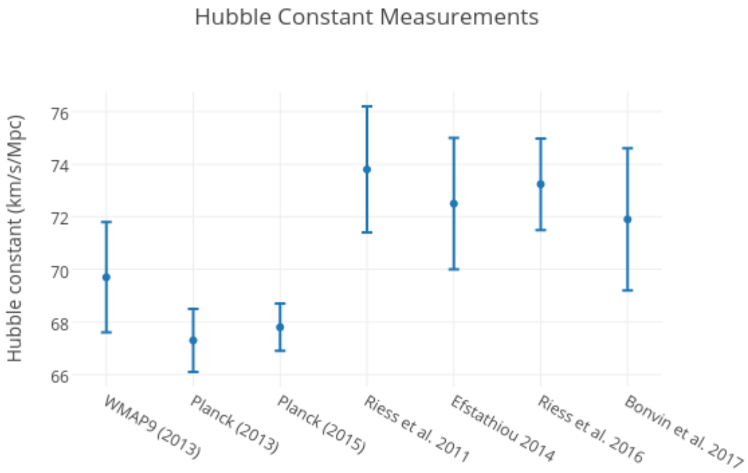
- Not trivial but from first principles
- LCDM fits very well

$$H = H_0\sqrt{\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda}$$

CMB, with LCDM, in tension with stand.candles.
What is wrong?







Late Universe: standard candles vs CMB

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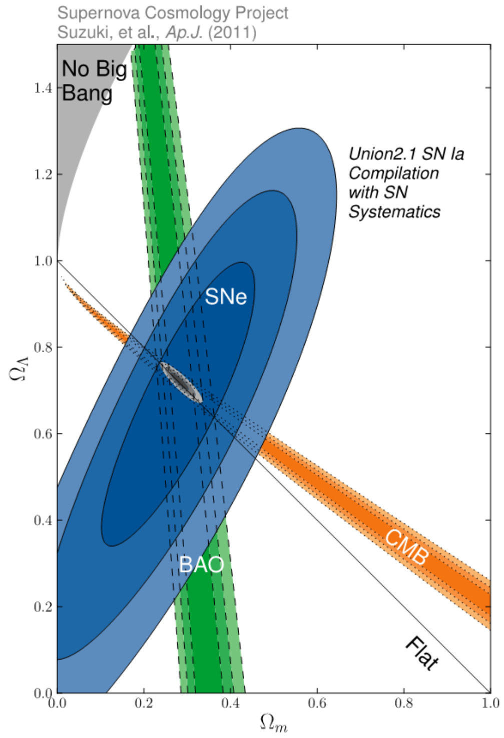

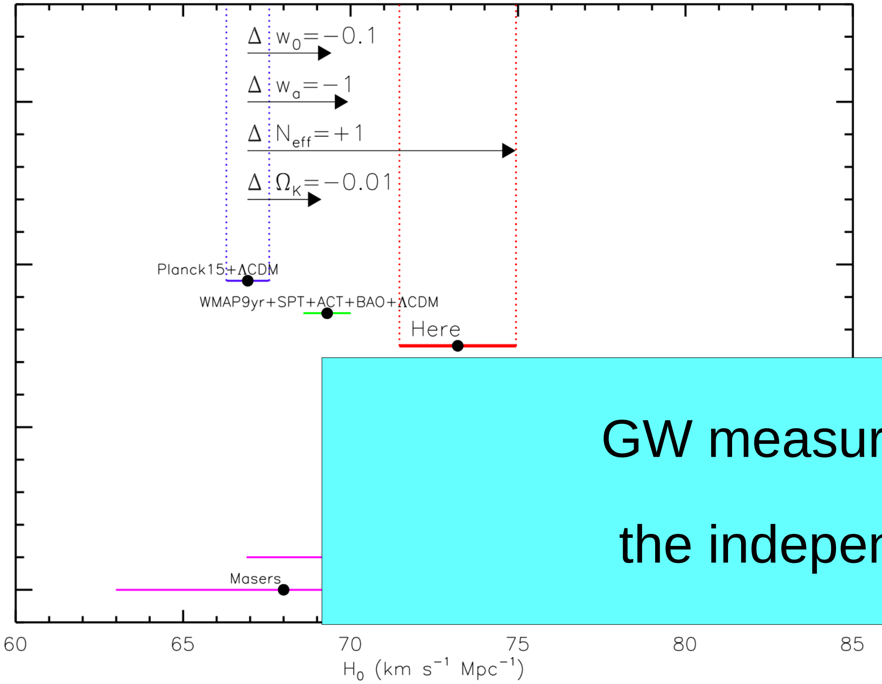

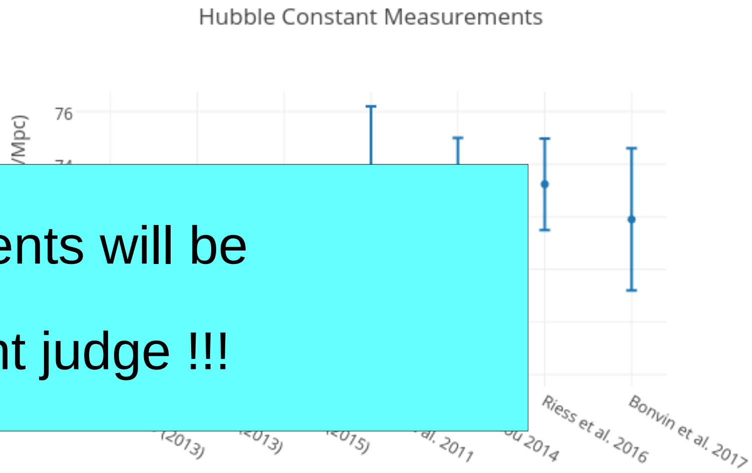

GW measurements will be

the independent judge !!!

Late Universe: standard sirens

For a binary system:

$$h_\times(t) \overset{\text{If GR}}{=} \frac{1}{d_L} f(t, \dots) \overset{\text{Using accurate waveform}}{=} \frac{M_z^{5/3} f(t)^{2/3} F(angles) \sin[\Phi(t)]}{d_L}$$

with $M_z = (1+z)\frac{(m_1 m_2)^{3/5}}{(m_1 m_2)^{1/5}}$

(BH) binaries are scale free → z cannot be measured

The configurations $\{m_1, m_2\}$ and $\{m_1/(1+z)\,,\ m_2/(1+z)\}$ produce the same signal

Late Universe: standard sirens

For a binary system:

$$h_\times(t) \overset{\text{If GR}}{=} \frac{1}{d_L} f(t,\dots) \overset{\text{Using accurate waveform}}{=} \frac{M_z^{5/3} f(t)^{2/3} F(angles)\sin[\Phi(t)]}{d_L}$$

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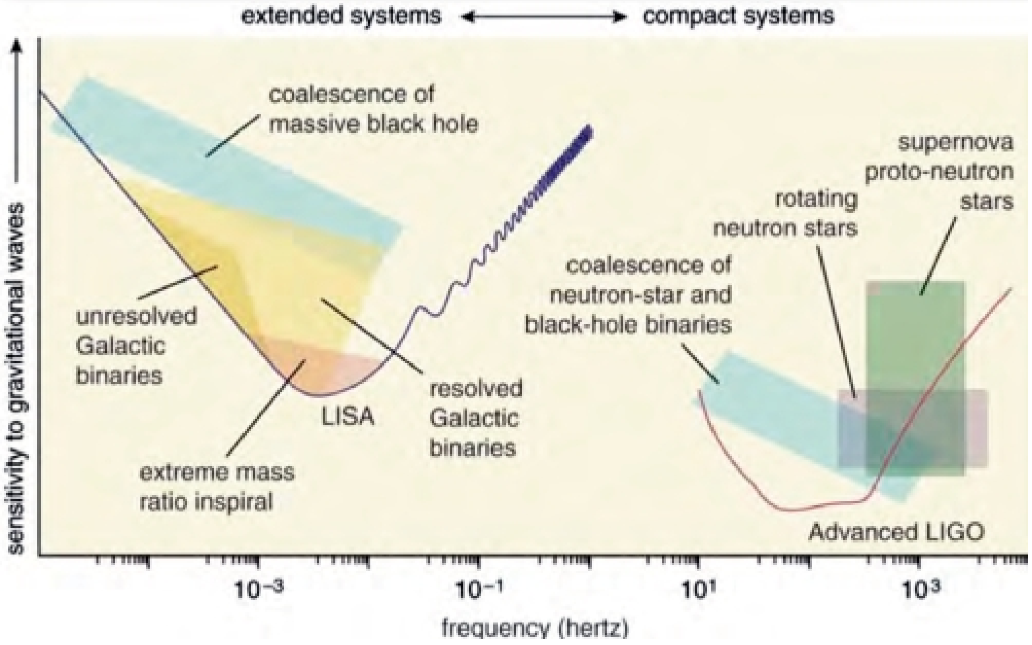
(BH) binaries are scale free → z cannot be measured

The configurations $\{m_1, m_2\}$ and $\{m_1/(1+z)\ ,\ m_2/(1+z)\}$ produce the same signal

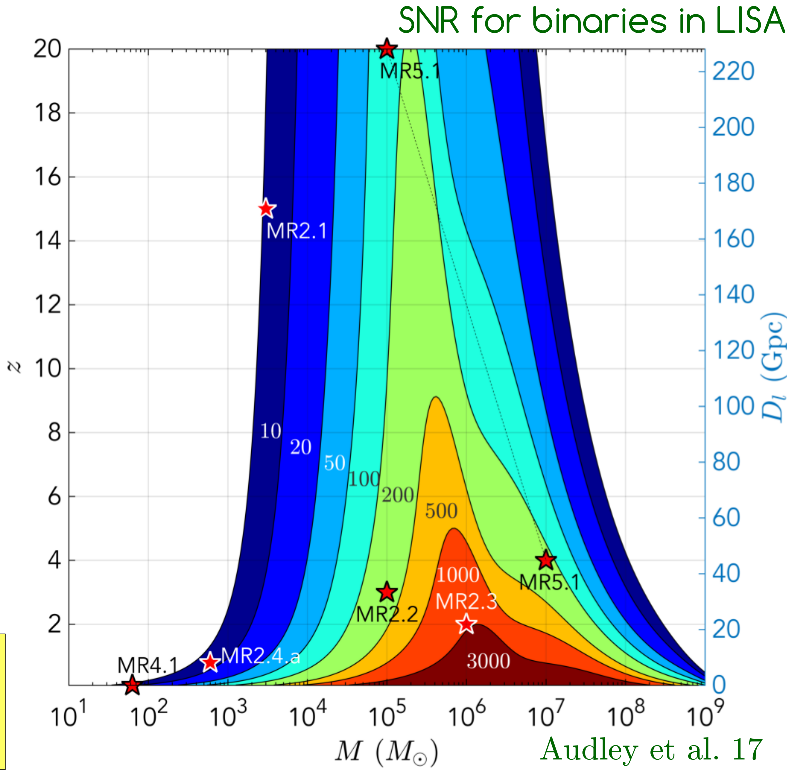
	Stand. candles	Stand. sirens
“Easy”	z (< 1.5)	d_L
Challenging	d_L	z
Method	ladder	???

Late Universe: standard siren zoo

- Surrounding medium for binaries of $(10^4 – 10^7 M_\odot)$ massive BH or NS – NS/BH
- Stellar-origin BHBs and EMRI are maybe isolated systems



EM counterpart is not guaranteed



SNR for binaries in LISA

Audley et al. 17

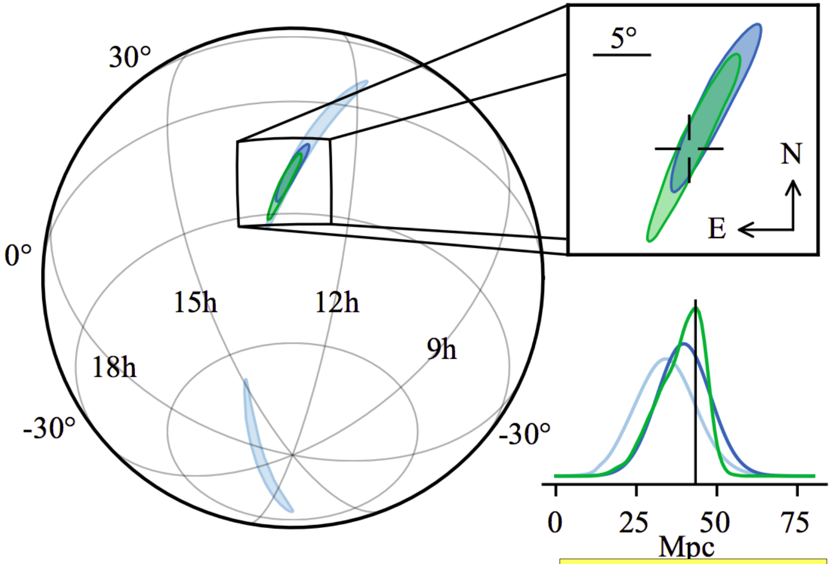
Loud events at redshifts z >> 1, impossible with SN Ia

Late Universe: standard sirens with counterpart

Holz & Hughes '05
Dalal et al. '06
Cutler & Holz '09
Nissanke et al. '10,'13
Nishizawa '17

Recipe:

- Detect the GW signal
- Analyze the data in "real time" and reach a good sky localization asap
  - Precise wave forms
- Point the telescopes and ...



Late Universe: standard sirens with counterpart

Holz & Hughes '05
Dalal et al. '06
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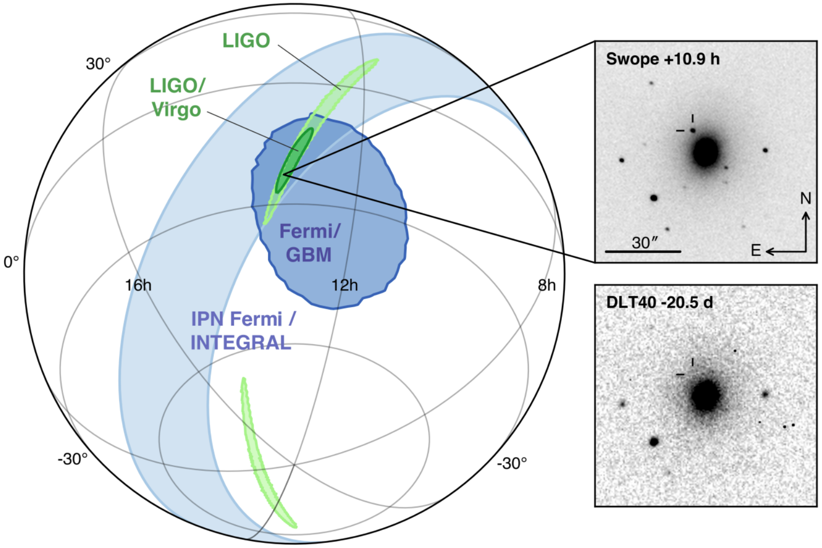
Nissanke et al. '10,'13
Nishizawa '17

Recipe:

- Detect the GW signal
- Analyze the data in “real time” and reach a good sky localization asap
  - Precise wave forms
- Point the telescopes and ... look for the (EM) counterpart transient
  - If the sky localization requires the merging and ringdown phase, maybe you alert too late
- Find the host galaxy
- Consider peculiar velocity/lensing
  - Precise catalogs/issue

Holz & Hughs, '05
Bonvin et al.'05
Shang & Zoltan '10
Bonvin et al.'17

- You now know z and analyze again



Late Universe: standard sirens with counterpart

Holz & Hughes '05
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Holz & Hughs, '05
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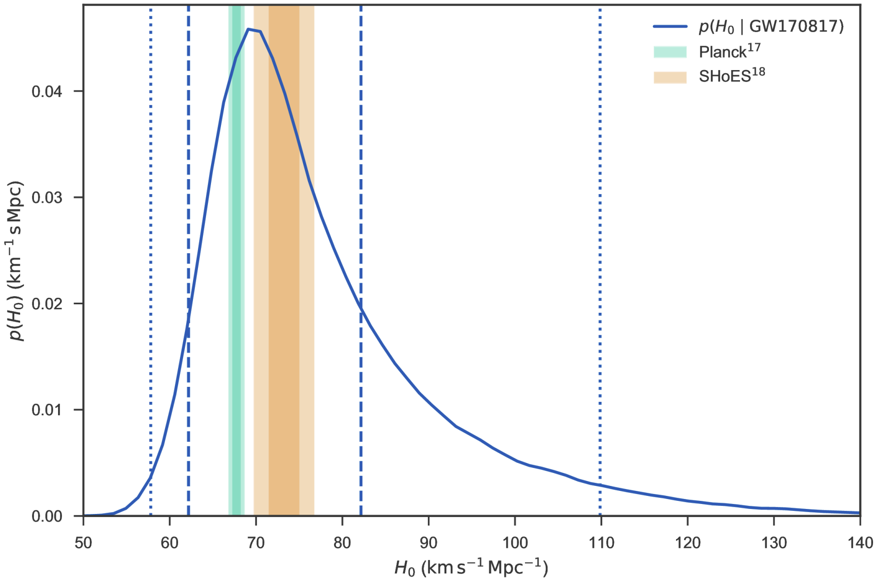


And obtain cosmo. parameters!

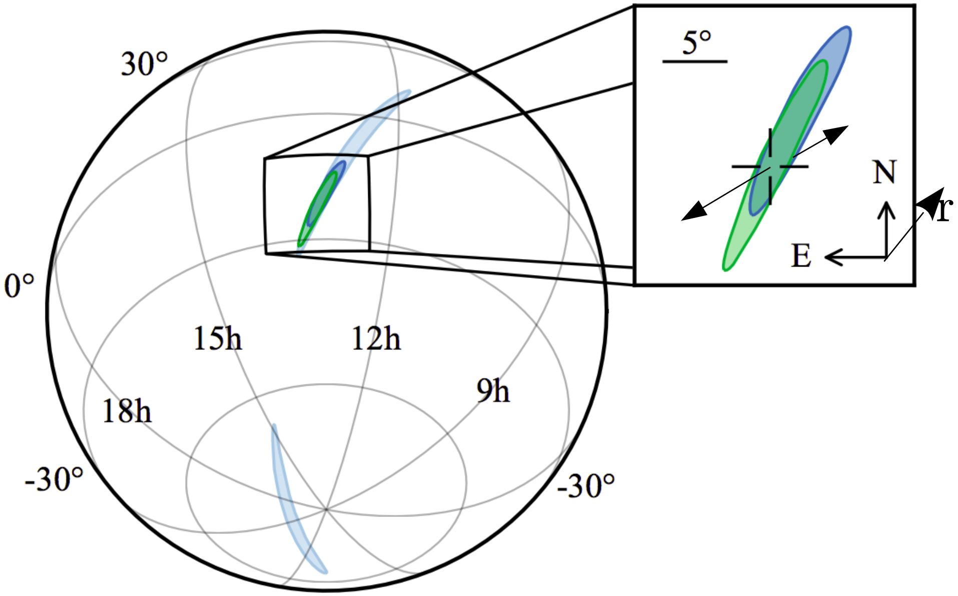
(for small errors, many detections)

Late Universe: standard sirens without counterpart

Schultz '86
Del Pozzo '12
Messenger et al.' 14
Del Pozzo et al. '17

Recipe:

- > Detect the GW signal
- > Analyze the data in "~~real time~~" and reach a good sky localization ~~asap~~ (Ω)
  - Precise wave forms
- ✔ Take LCDM ± error and determine z. The source is in the box (Ω x z ± error)



Late Universe: standard sirens without counterpart

Schultz ‘86
Del Pozzo ‘12
Messenger et al.’ 14
Del Pozzo et al. ‘17

Recipe:

- Detect the GW signal
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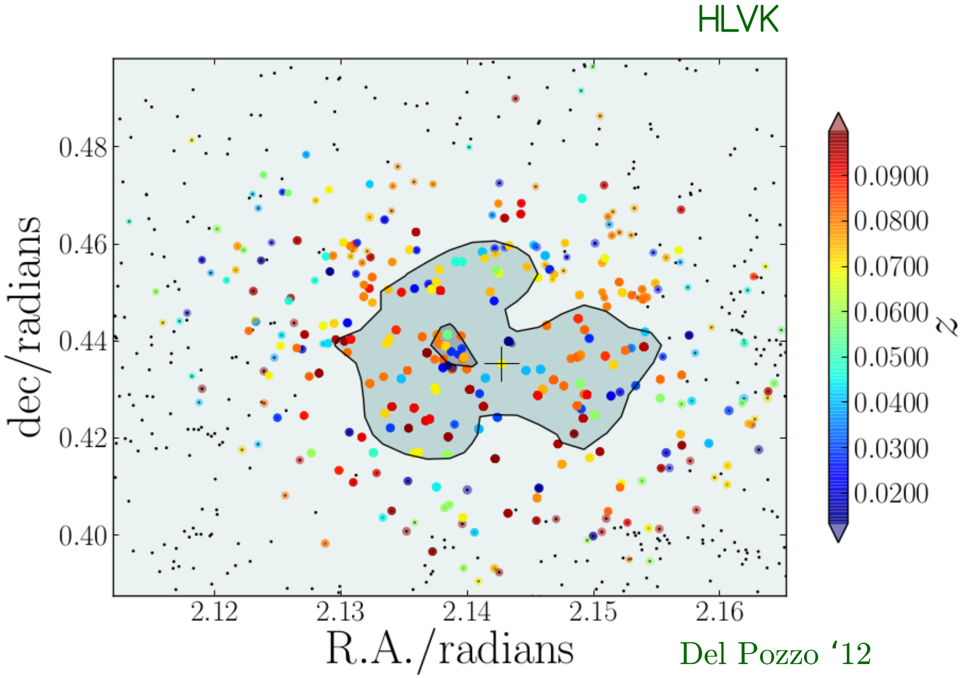
- ✔ Take LCDM ± error and determine z. The source is in the box (Ω x z ± error)
- ✔ Find statistically the host galaxy in the box (Ω x z) in your catalog
  - ✔ Good sky localization is crucial



Del Pozzo ‘12

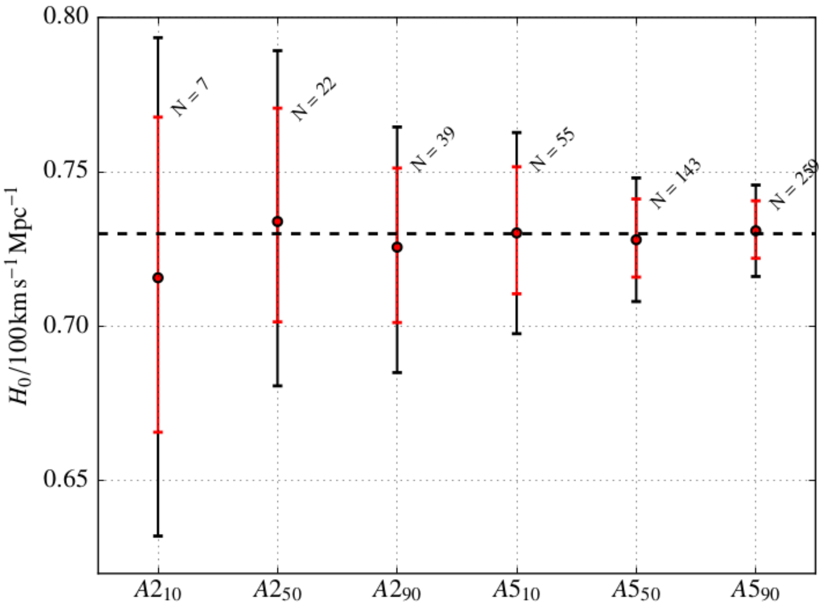
Late Universe: standard sirens without counterpart

Schultz '86
Del Pozzo '12
Messenger et al.' 14
Del Pozzo et al. '17

Recipe:

- > Detect the GW signal
- > Analyze the data in "~~real time~~" and reach a good sky localization ~~asap~~ (Ω)
  - ▪ Precise wave forms
- ✔ Take LCDM ± error and determine z. The source is in the box (Ω x z ± error)
- ✔ Find statistically the host galaxy in the box (Ω x z) in your catalog
  - ✔ Good sky localization is crucial
- > Consider peculiar velocity/lensing
  - ▪ Precise catalogs/issue
- > You now know z and analyze again

And obtain cosmo. parameters
if enough statistics

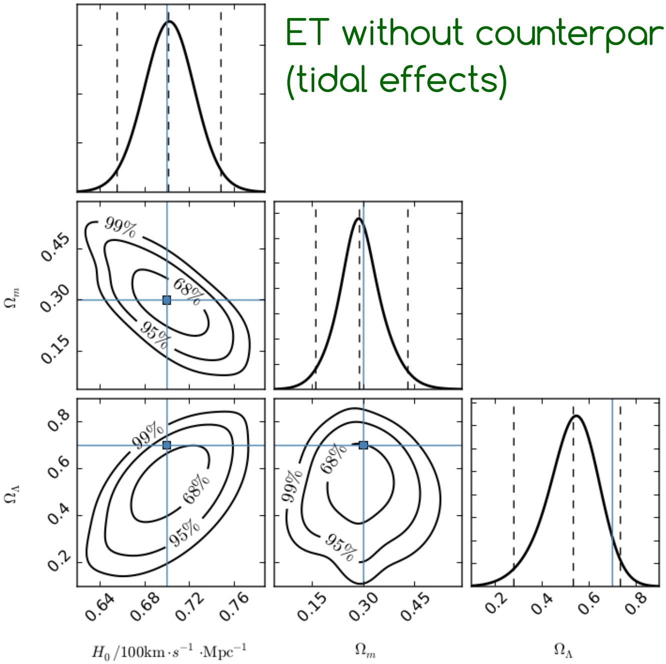


SOBHB in LISA

Del Pozzo et al. '17

Late Universe: standard siren forecasts

Del Pozzo et al. '17



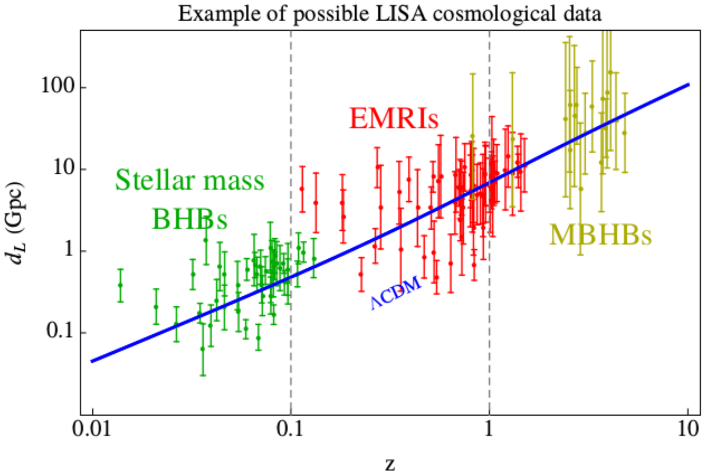
ET without counterpart
(tidal effects)

ET and LISA
will also measure other cosmo. parameter

(the latter at unexplored redshifts)

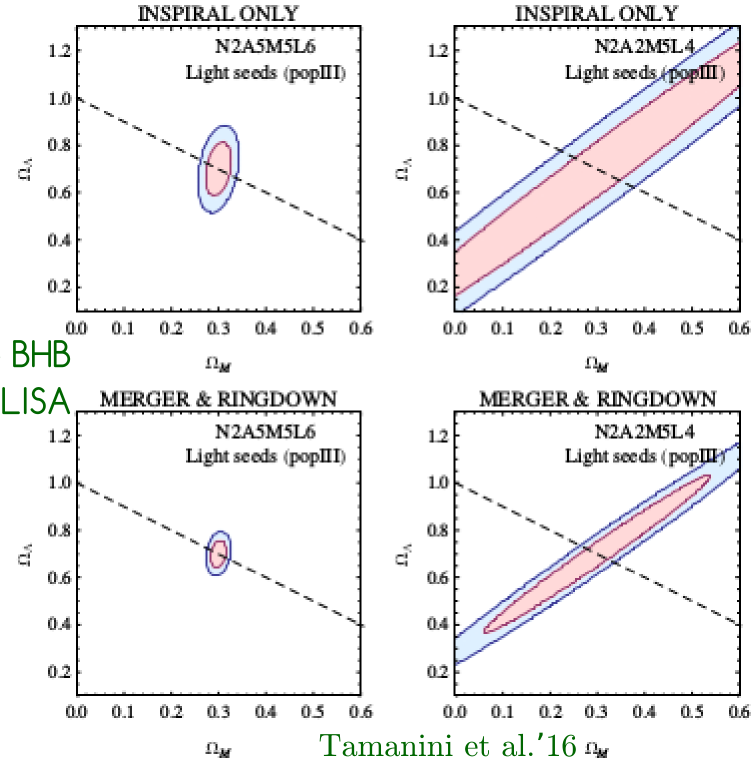
See Tamanini's talk

For SOBHB see Del Pozzo et al.'17



BHB sources up to high redshift

Massive BHB
in LISA



Tamanini et al.'16

From GWs to the Hubble parameter and beyond

- Some tension between present measurements of the Hubble parameter
- Possibility to use binaries as “standard sirens”
- Hubble parameter can be reconstruct with or without an EM counterpart
- Possibility of measuring d(z) at z >> 1 , thus the reconstruction of H(z) at z, inaccessible via SNIa, is feasible

Some key steps requiring skills in cosmology, “QCD in extreme conditions” and data analysis

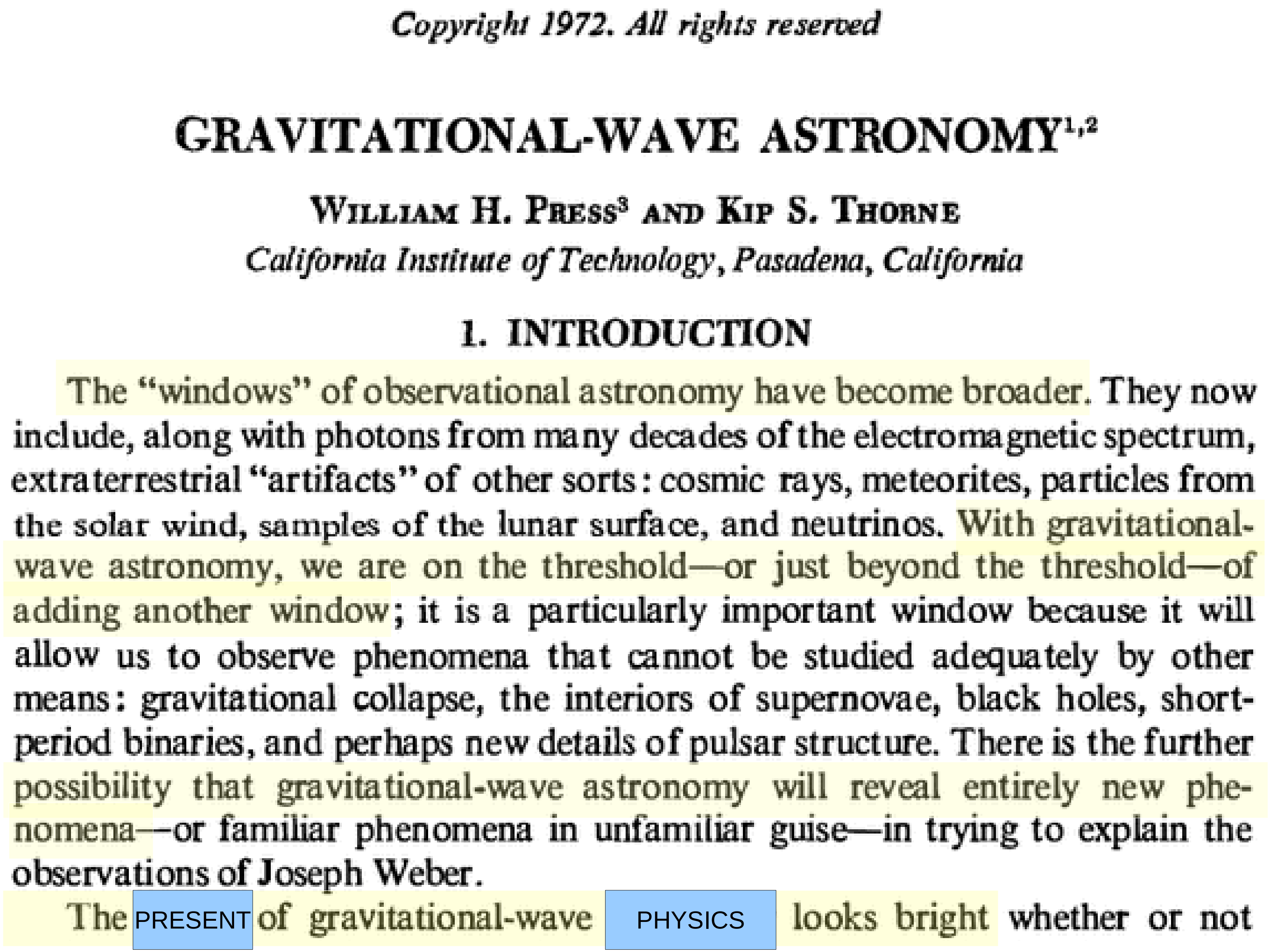
1) Better galactic catalogs with associated lensing and peculiar velocities

2) Waveform and tidal effects

3) Theoretical understanding of the EM counterpart

“Trivial” implication: constraints of the GW speed and thus models of modified GR

Conclusions



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GRAVITATIONAL-WAVE ASTRONOMY[1,2]

William H. Press[3] and Kip S. Thorne
California Institute of Technology, Pasadena, California

1. INTRODUCTION

The "windows" of observational astronomy have become broader. They now include, along with photons from many decades of the electromagnetic spectrum, extraterrestrial "artifacts" of other sorts: cosmic rays, meteorites, particles from the solar wind, samples of the lunar surface, and neutrinos. With gravitational-wave astronomy, we are on the threshold—or just beyond the threshold—of adding another window; it is a particularly important window because it will allow us to observe phenomena that cannot be studied adequately by other means: gravitational collapse, the interiors of supernovae, black holes, short-period binaries, and perhaps new details of pulsar structure. There is the further possibility that gravitational-wave astronomy will reveal entirely new phenomena—or familiar phenomena in unfamiliar guise—in trying to explain the observations of Joseph Weber.

The PRESENT of gravitational-wave PHYSICS looks bright whether or not