Comunidad de Madrid

UNIVERSIDAD AUTONOMA DE MADRID

Probing the EW epoch With LISA

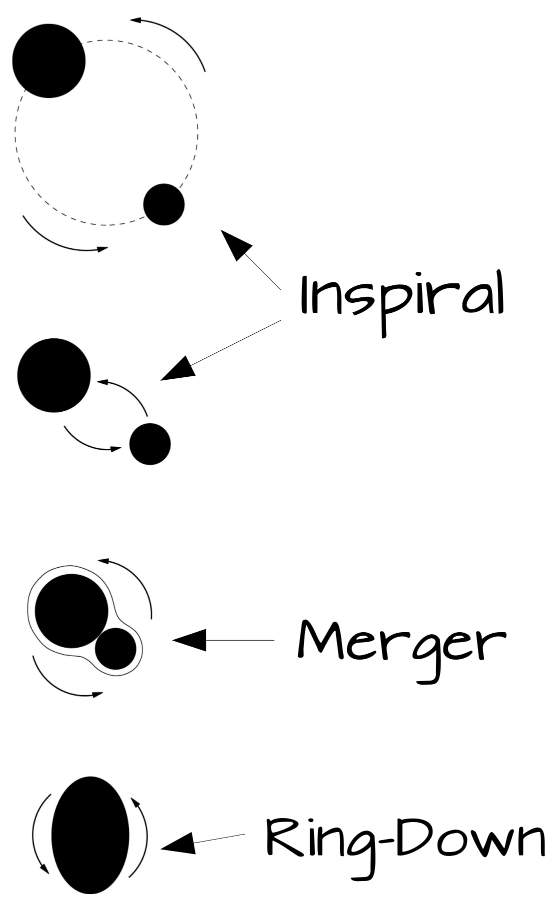
Jose Miguel No
IFT-UAM/CSIC, Madrid

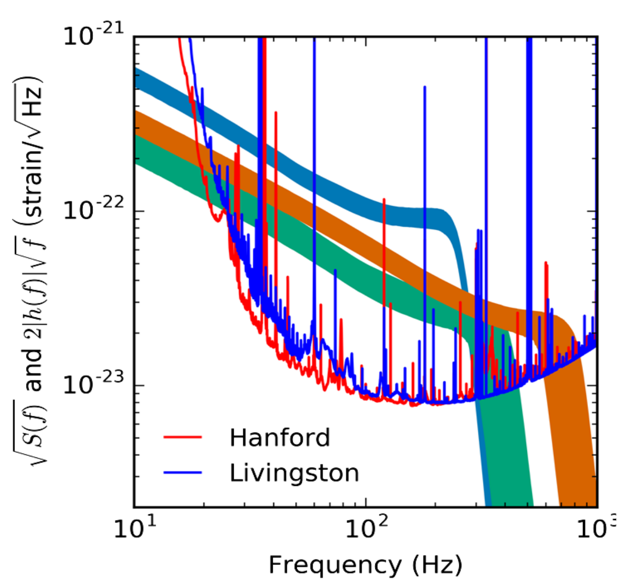
The future of Particle Physics
KIT 02/10/18

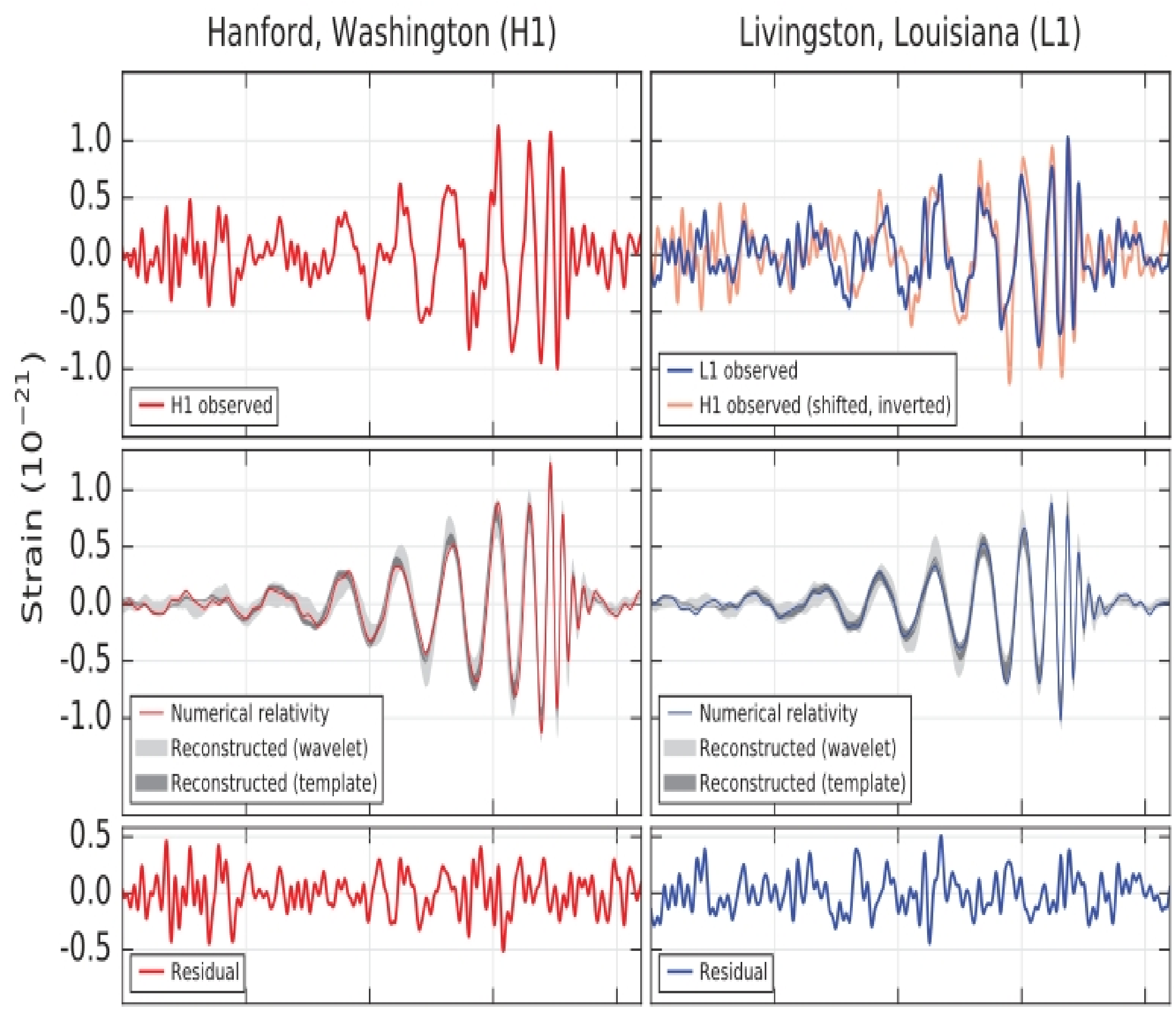
Instituto de Física Teórica
UAM-CSIC

First DIRECT observation of GWs (aLIGO): **GW150914**

Beginning of Gravitational Wave Astronomy…





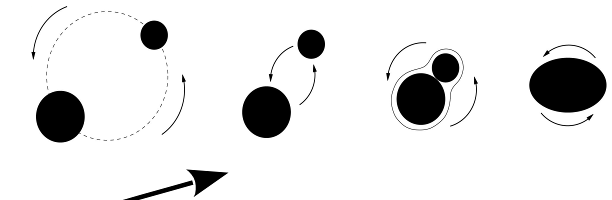


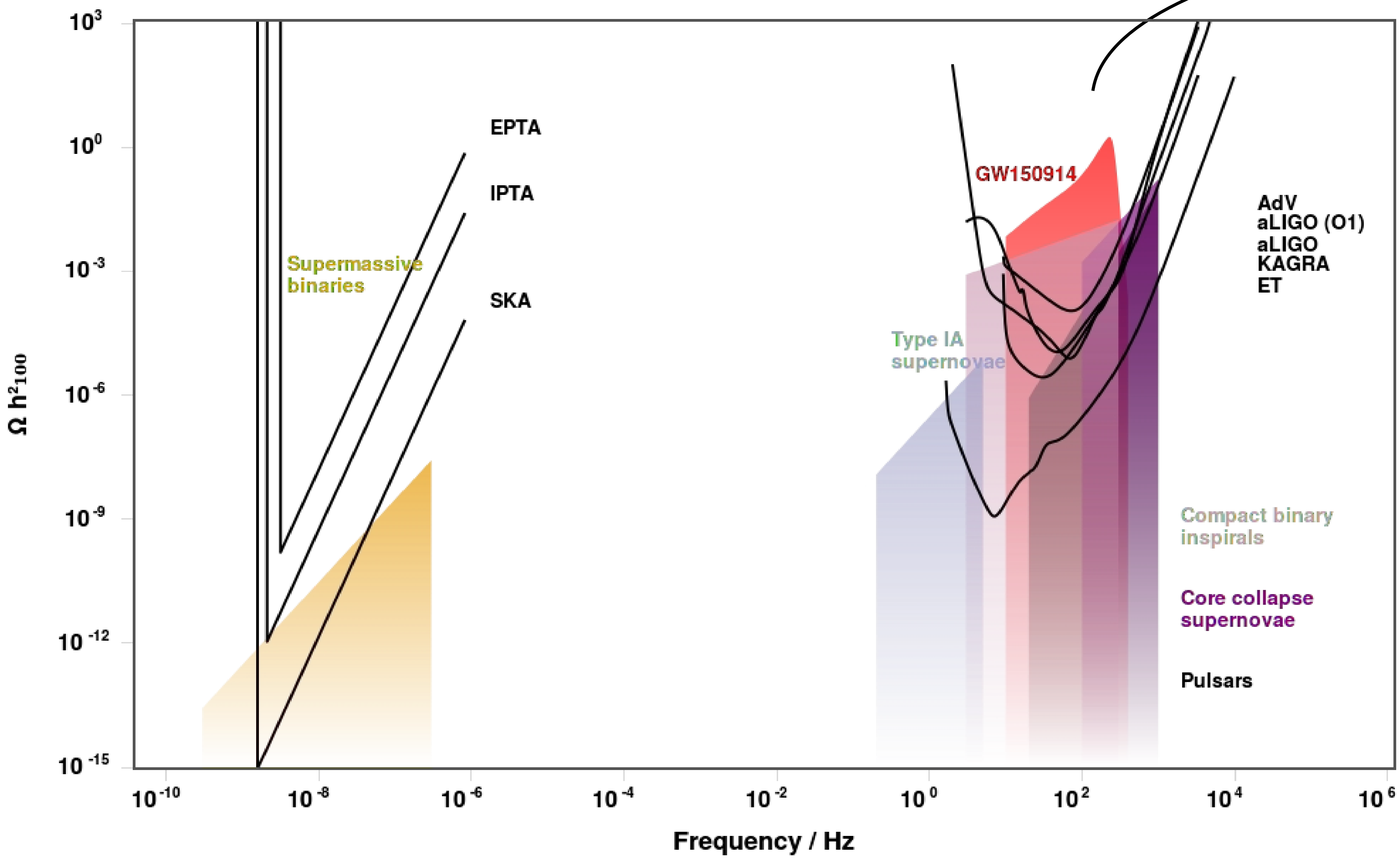
Present technology based on:

Ground-based interferometers covering frequency range 1 – 10^4 Hz

Antenna arrays (PTAs) covering frequency range 10^{-9} – 10^{-6} Hz

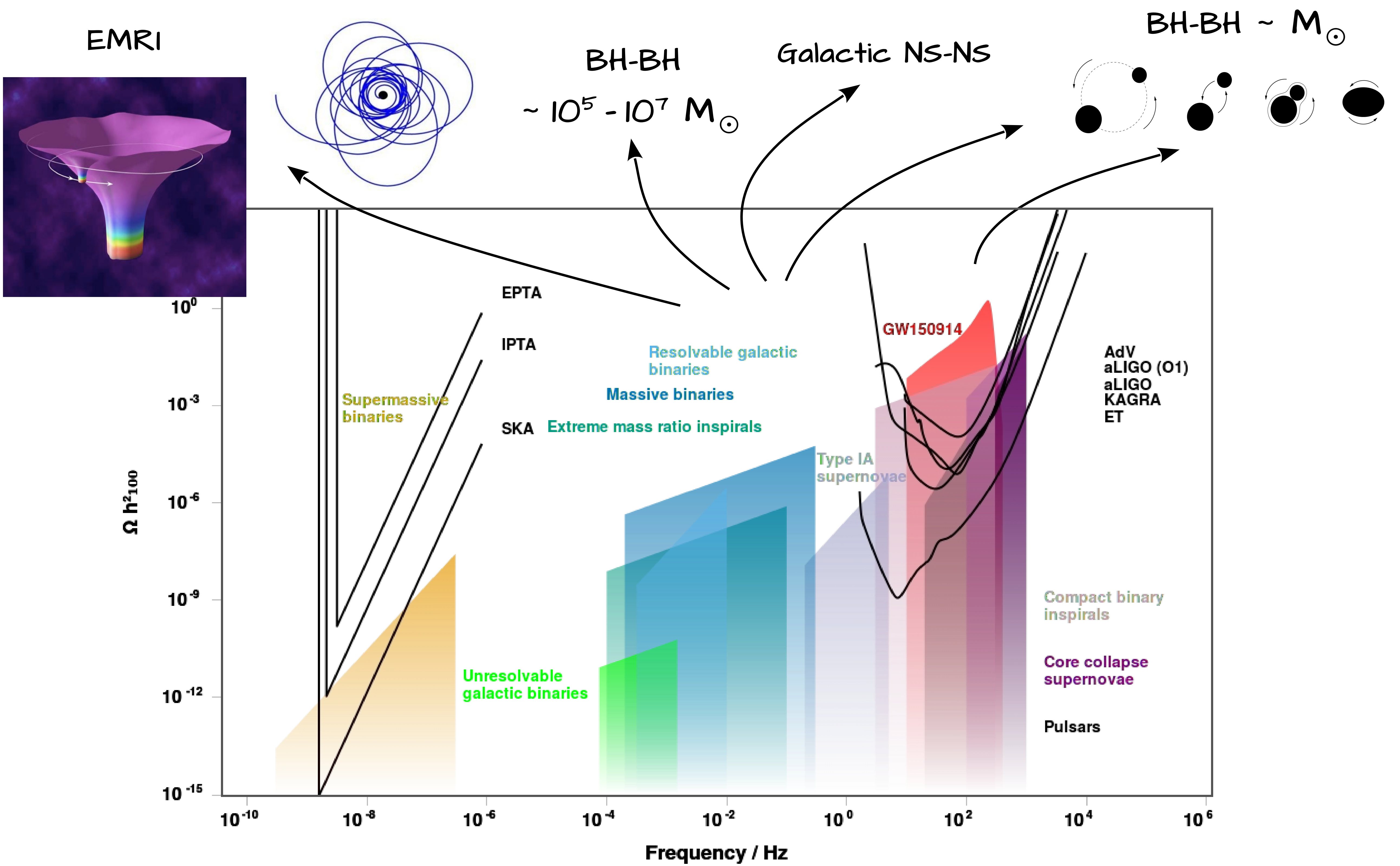
BH-BH ~ $M_\odot$



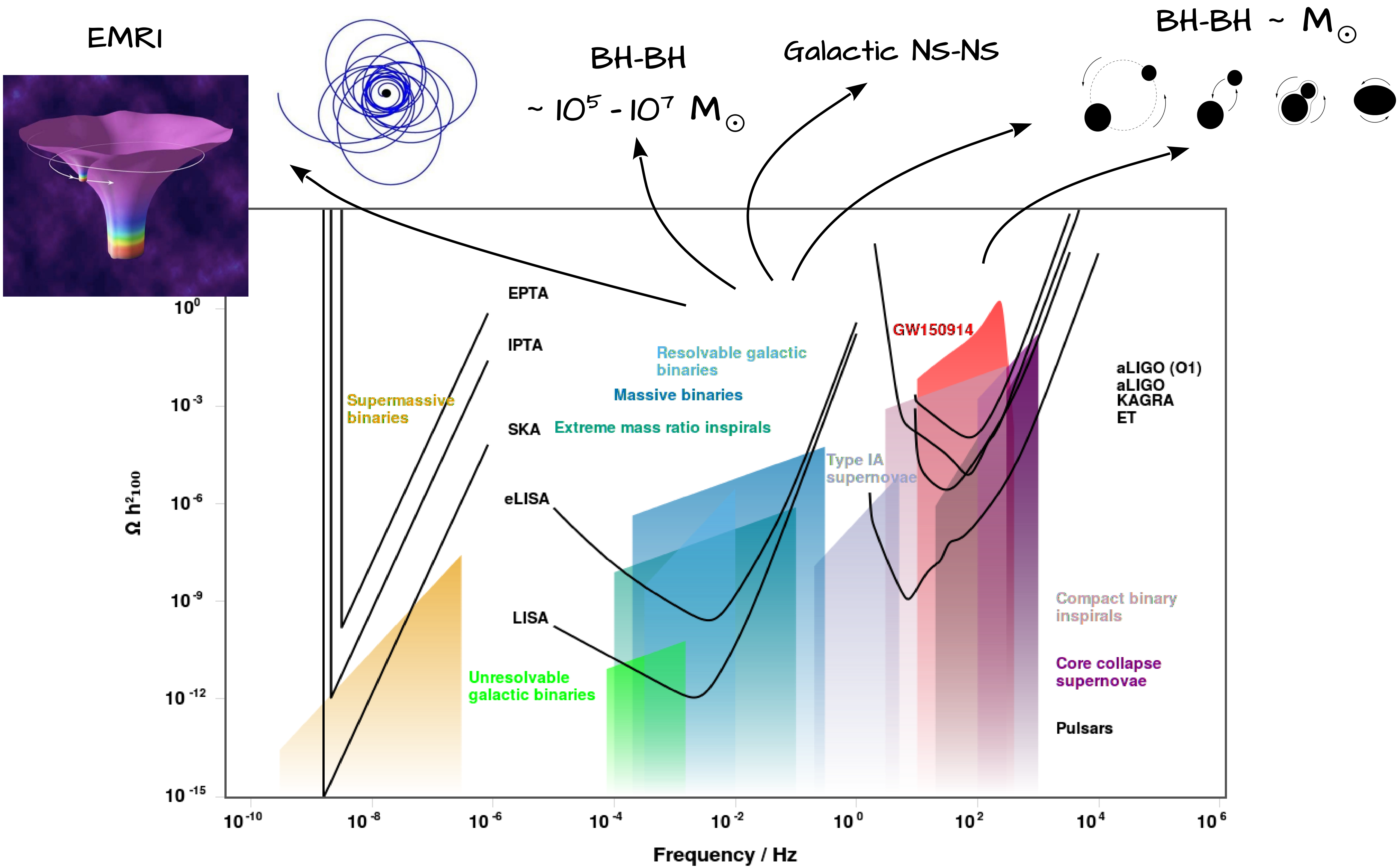


Courtesy of C. Moore, R. Cole, C. Berry (Cambridge)
http://rhcole.com/apps/GWplotter/

Many (astrophysical) GW sources in frequency range 10^{-4} – 1 Hz

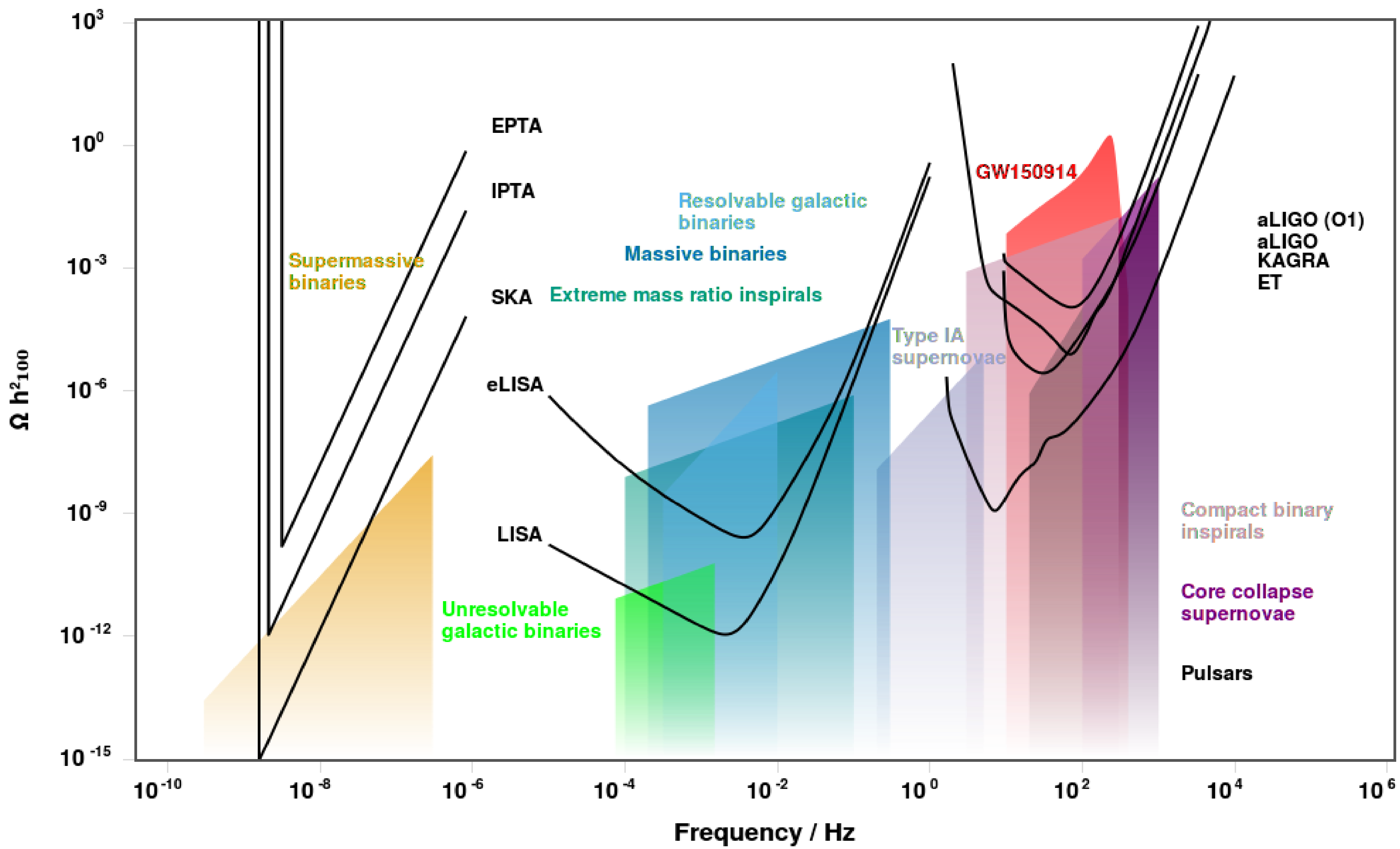


Many (astrophysical) GW sources in frequency range 10^{-4} – 1 Hz



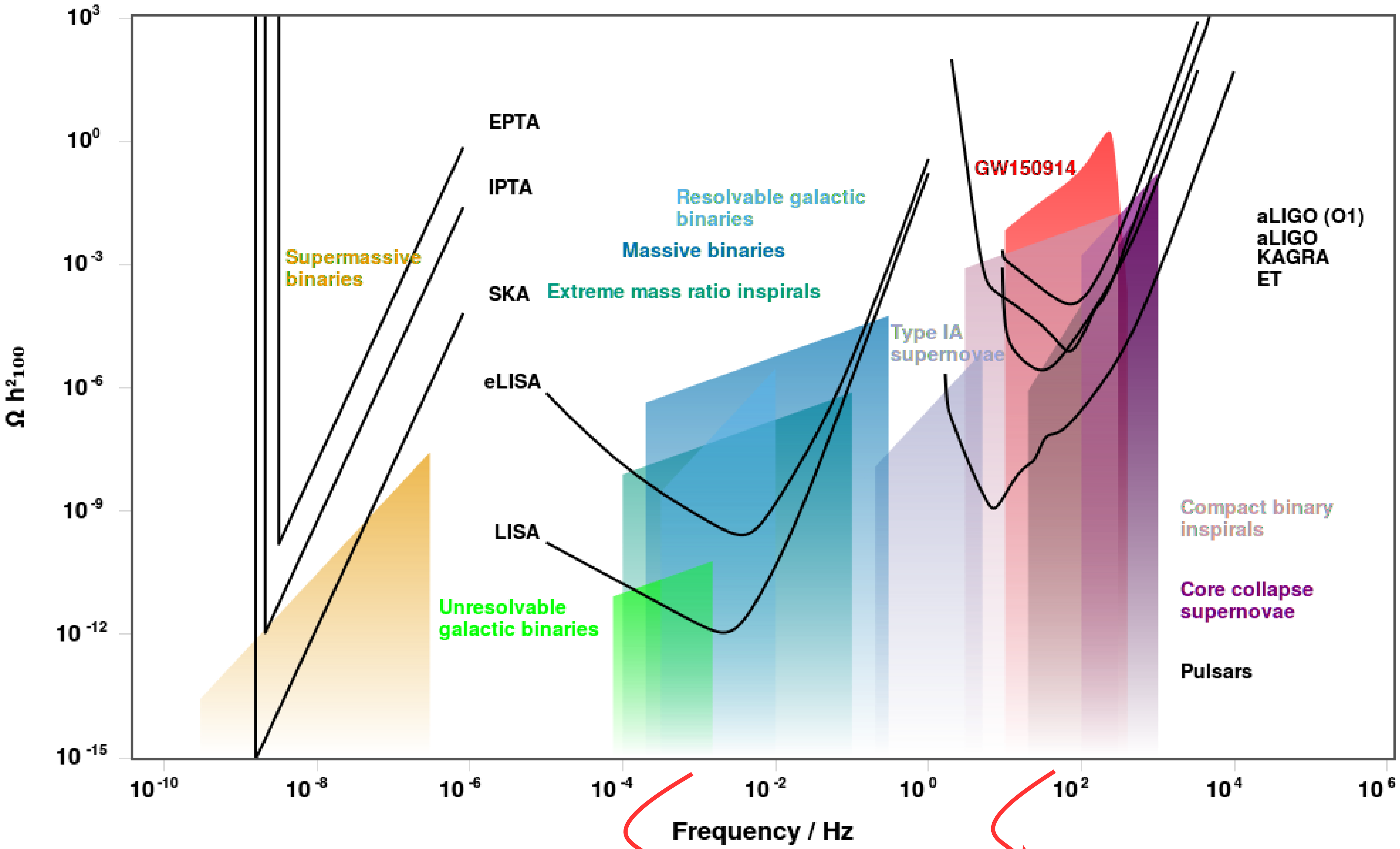
Very solid reasons for a GW detector in that range!

Besides astrophysical sources, possible pre-BBN cosmological GW sources (inflation, topological defects, phase transitions...)



Besides astrophysical sources, possible pre-BBN cosmological GW sources (inflation, topological defects, **phase transitions**...)

LISA probes the EW phase transition



T ~ 100 GeV   T ~ 10^7 GeV

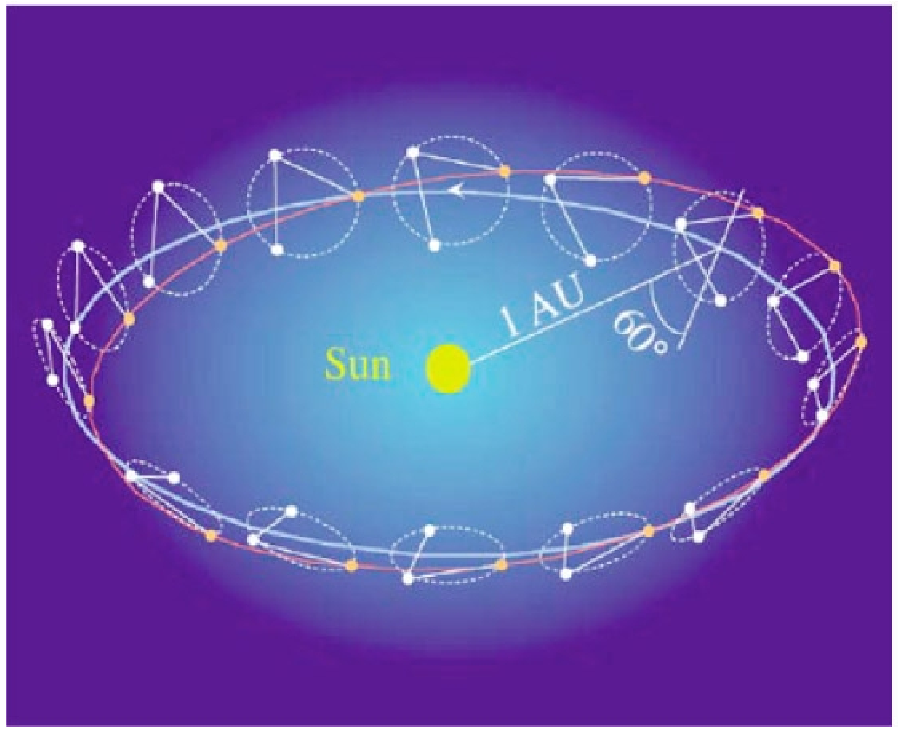
https://www.elisascience.org/

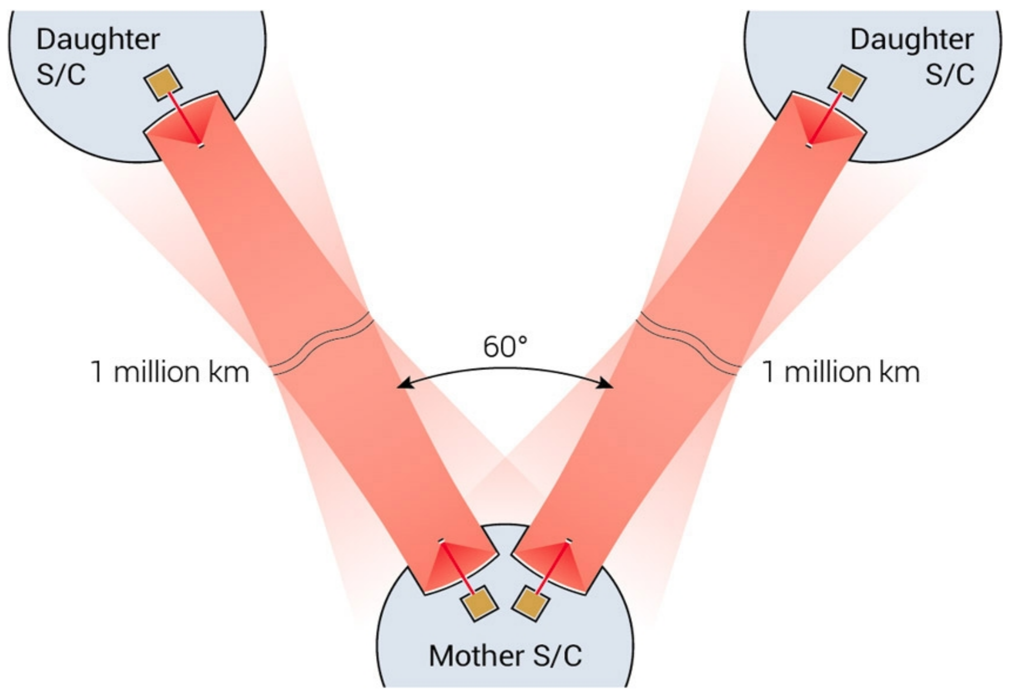
The LISA Mission

(Laser Interferometer Space Antenna)

A brief status report

Thanks to G. Nardini





https://www.elisascience.org/

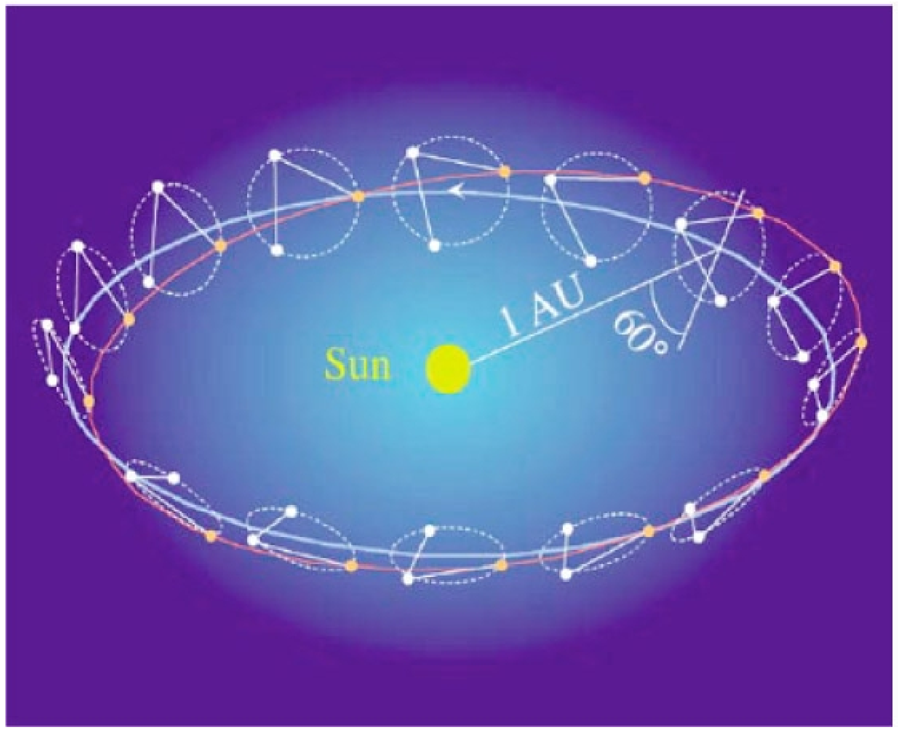
The LISA Mission

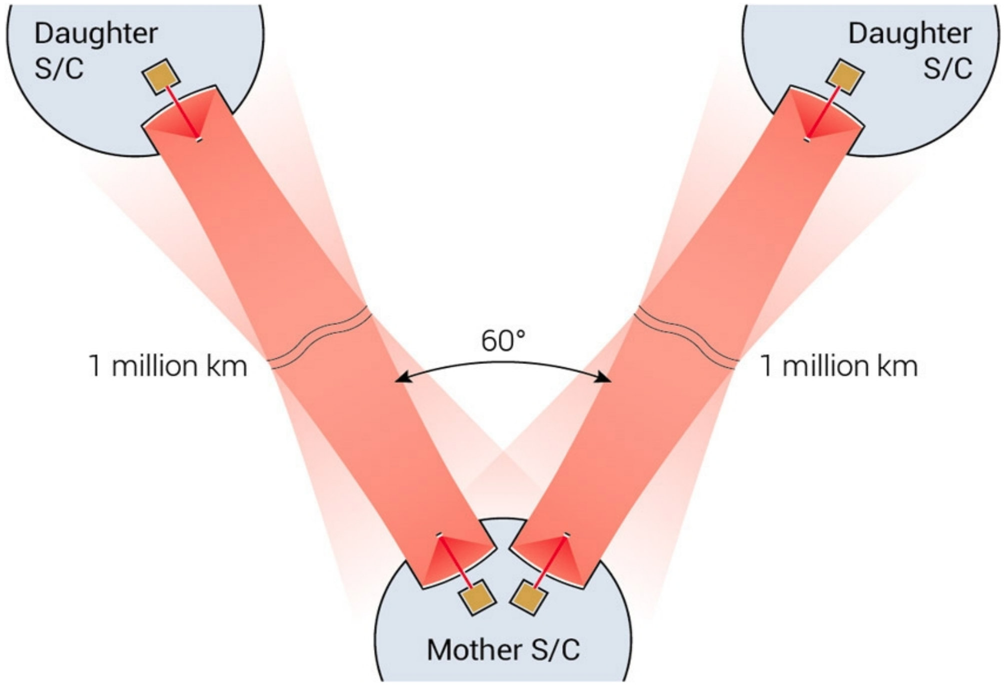
(Laser Interferometer Space Antenna)

A brief status report

Thanks to G. Nardini

2011 (after NASA leaves the project): eLISA/NGO





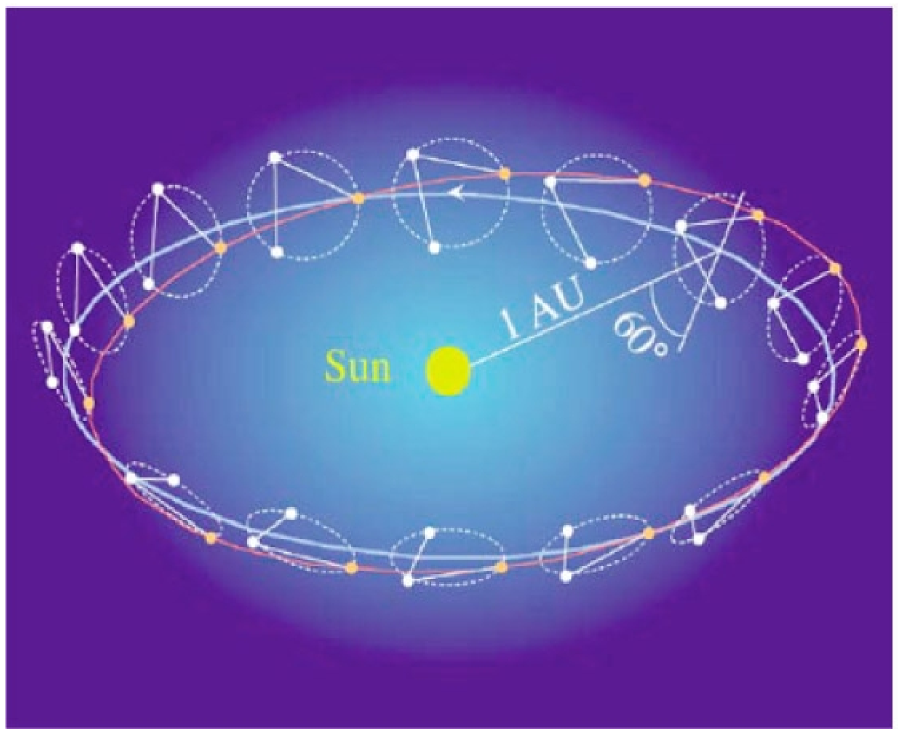
The LISA Mission

(Laser Interferometer Space Antenna)

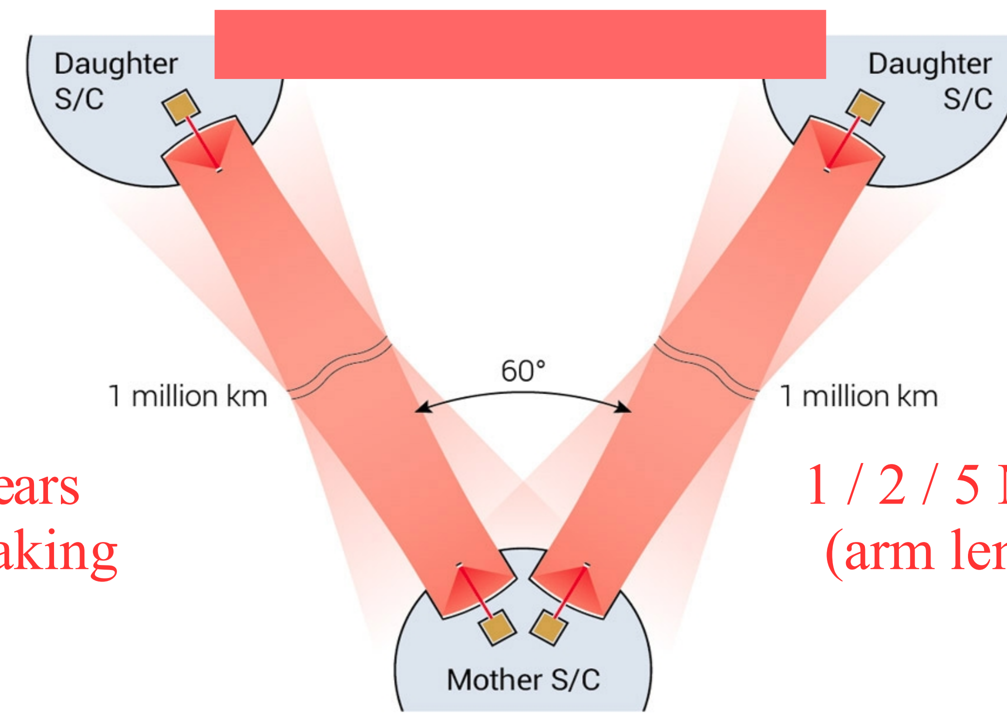
A brief status report

Thanks to G. Nardini

2015: Many open issues



Possible 3rd arm



2 / 5 Years of data taking

1 / 2 / 5 MKm (arm length)

Reanalysis of costs + NASA & Japan (re)joining

ESA opens L3 Mission Call: "The Gravitational Universe"

https://www.elisascience.org/

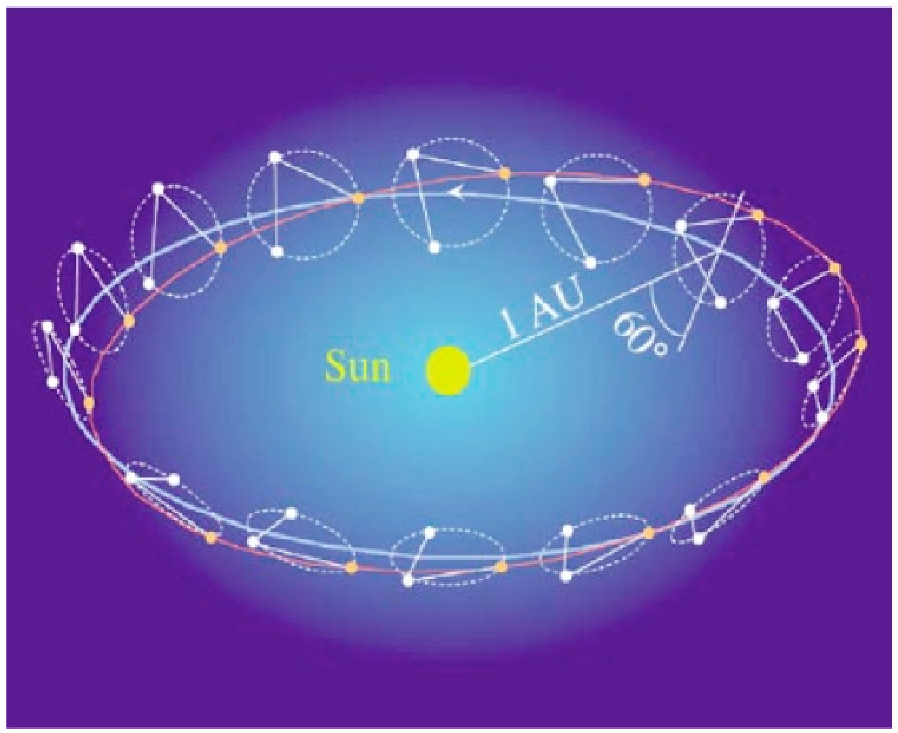
The LISA Mission

(Laser Interferometer Space Antenna)

A brief status report

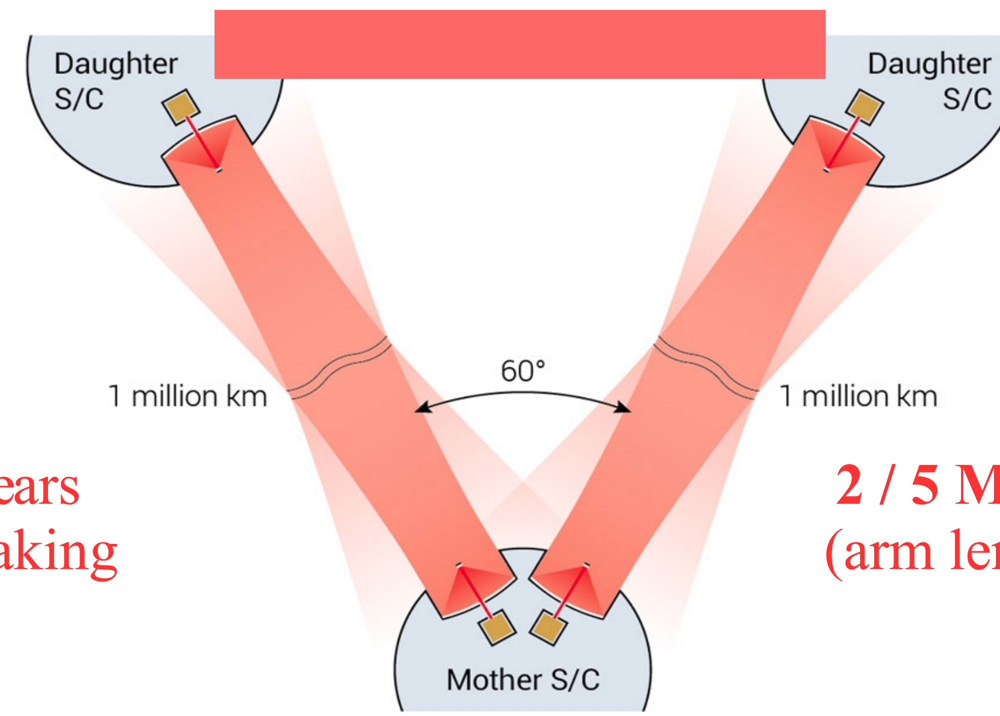
Thanks to G. Nardini

2016: Open issues converge



3rd arm YES!

2 / 5 Years
of data taking



2 / 5 MKm
(arm length)

Reanalysis of costs + NASA & Japan (re)joining

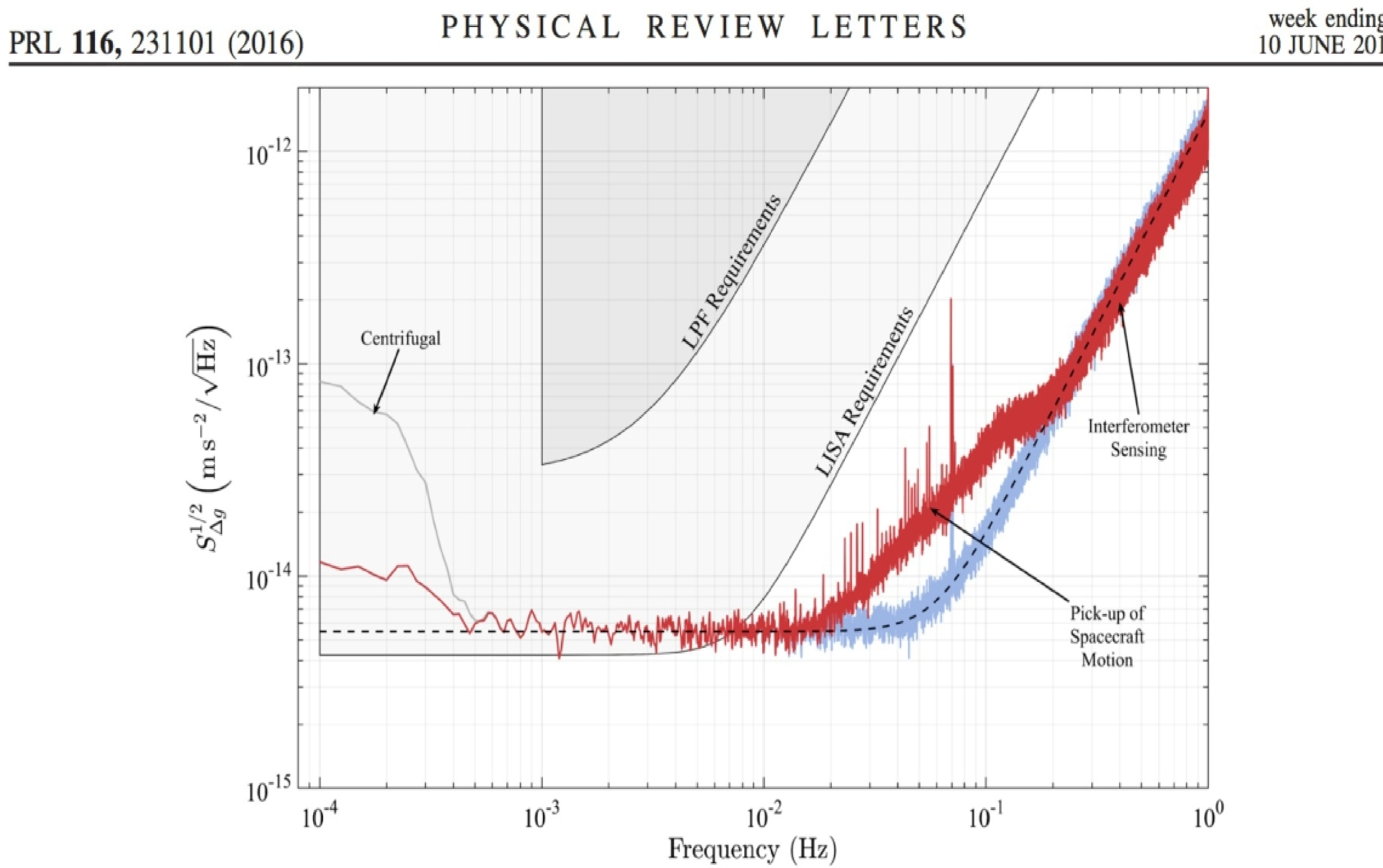
ESA opens L3 Mission Call: “The Gravitational Universe”

+ GW150914 Makes GW Guaranteed “Unexplored” Physics

+ Success of LISA PathFinder Mission

The LISA Mission
PathFinder

Test of the technology to achieve LISA strain sensitivity



https://www.elisascience.org/

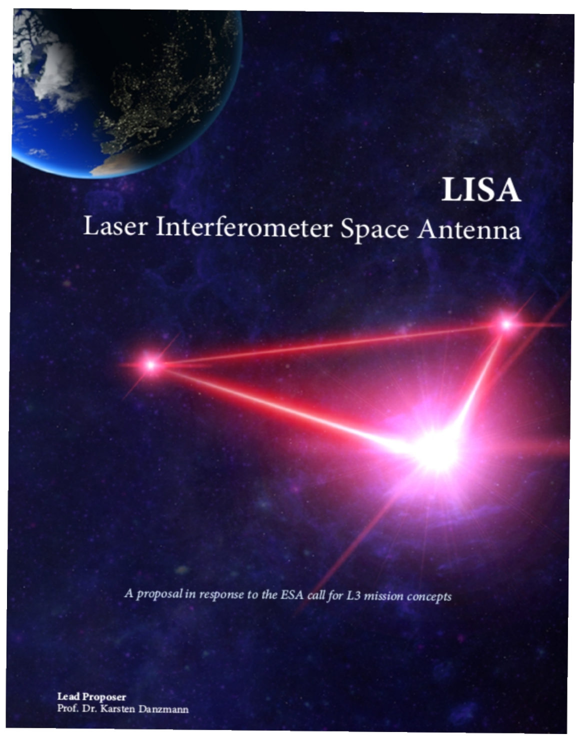
The LISA Mission

(Laser Interferometer Space Antenna)

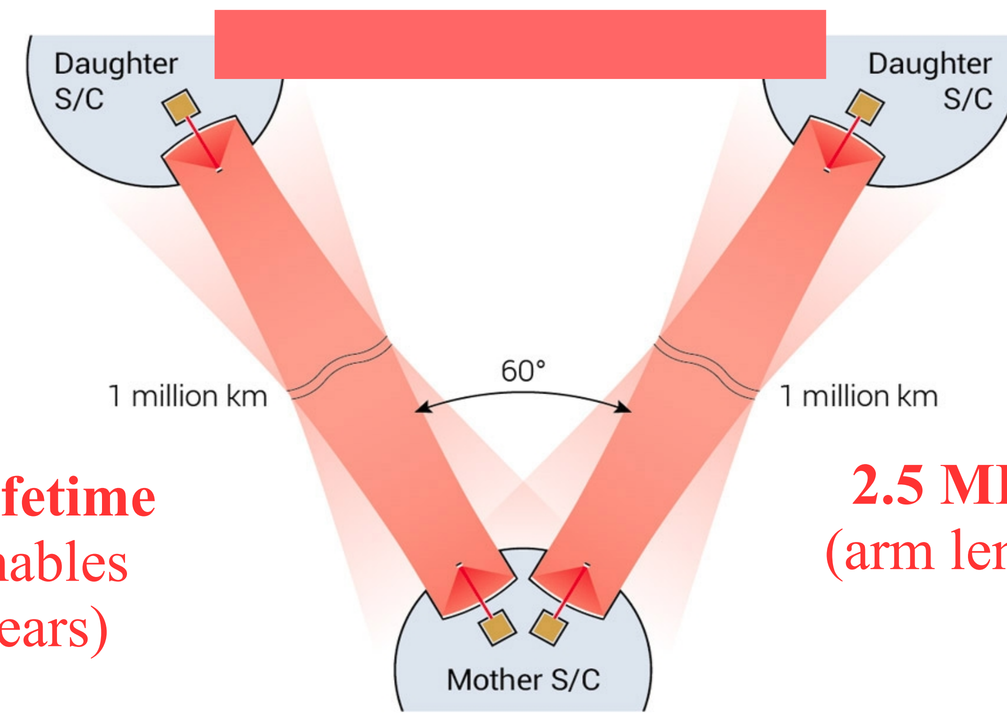
A brief status report

Thanks to G. Nardini

2017: LISA proposal to ESA



LISA Collaboration, 1702.00786



4 years of lifetime
(w. consumables
up to 10 years)

2.5 MKm
(arm length)

Proposed Launch date **2028**

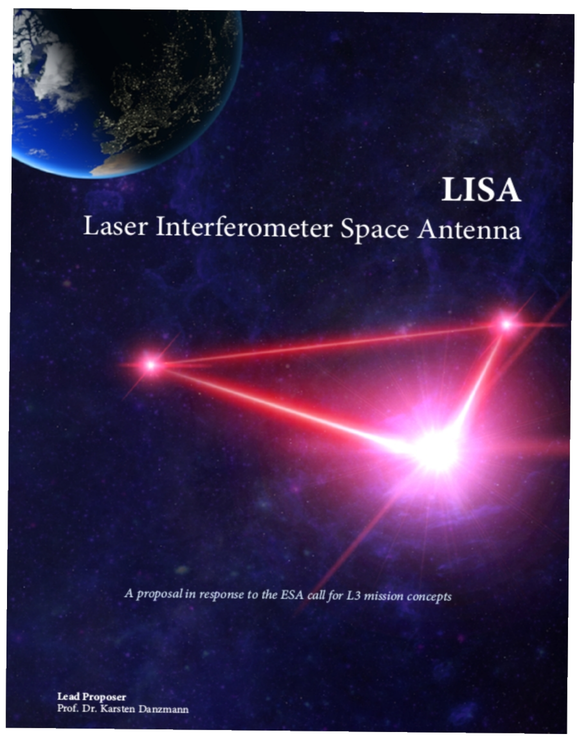
The LISA Mission

(Laser Interferometer Space Antenna)

A brief status report

Thanks to G. Nardini

2017: LISA proposal to ESA



LISA Collaboration, 1702.00786

From the proposal:

Audley et al, arXiv:1702.00786

SI7.2 : Measure, or set upper limits on, the spectral shape of the cosmological stochastic GW background

OR7.2: Probe a broken power-law stochastic background from the early Universe as predicted, for example, by first order phase transitions [21] (other spectral shapes are expected, for example, for cosmic strings [22] and inflation [23]). Therefore, we need the ability to measure $\Omega = 1.3 \times 10^{-11} \left(f/10^{-4}\,\mathrm{Hz}\right)^{-1}$ in the frequency ranges $0.1\,\mathrm{mHz} < f < 2\,\mathrm{mHz}$ and $2\,\mathrm{mHz} < f < 20\,\mathrm{mHz}$, and $\Omega = 4.5 \times 10^{-12} \left(f/10^{-2}\,\mathrm{Hz}\right)^{3}$ in the frequency ranges $2\,\mathrm{mHz} < f < 20\,\mathrm{mHz}$ and $0.02 < f < 0.2\,\mathrm{Hz}$.

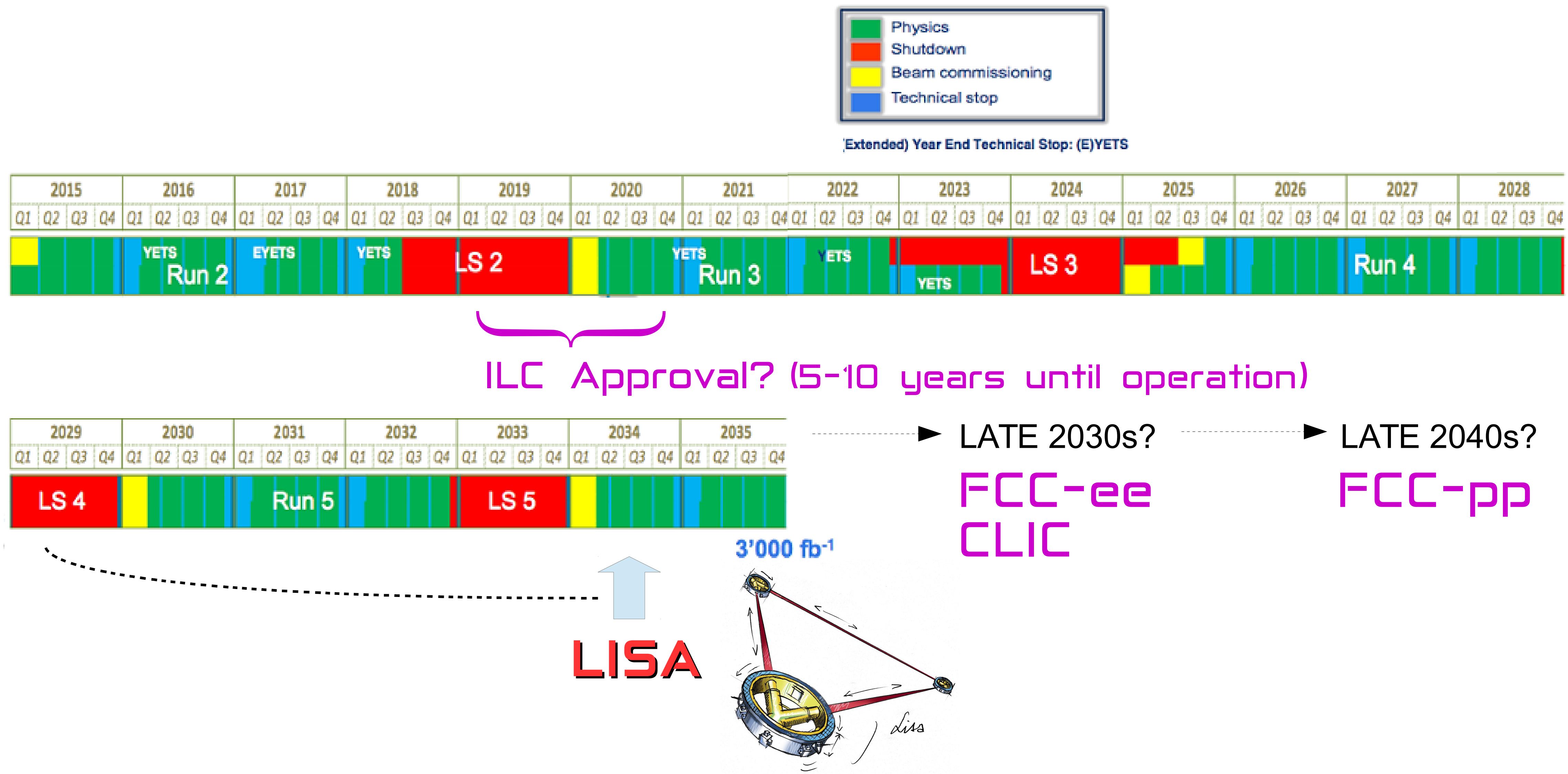
Launch date **2028-2034**

LISA Mission selected by ESA (Summer **2017**)

+ (On Jan 22 2018, LISA passed ESA's Mission Definition Review)

GW – Collider complementarity

Timeline: LISA GW Observatory in the Context of High-Energy Colliders



After LHC, LISA is next step in exploration of EW scale physics

...and now,

to the Physics!

GW from the EW Phase Transition

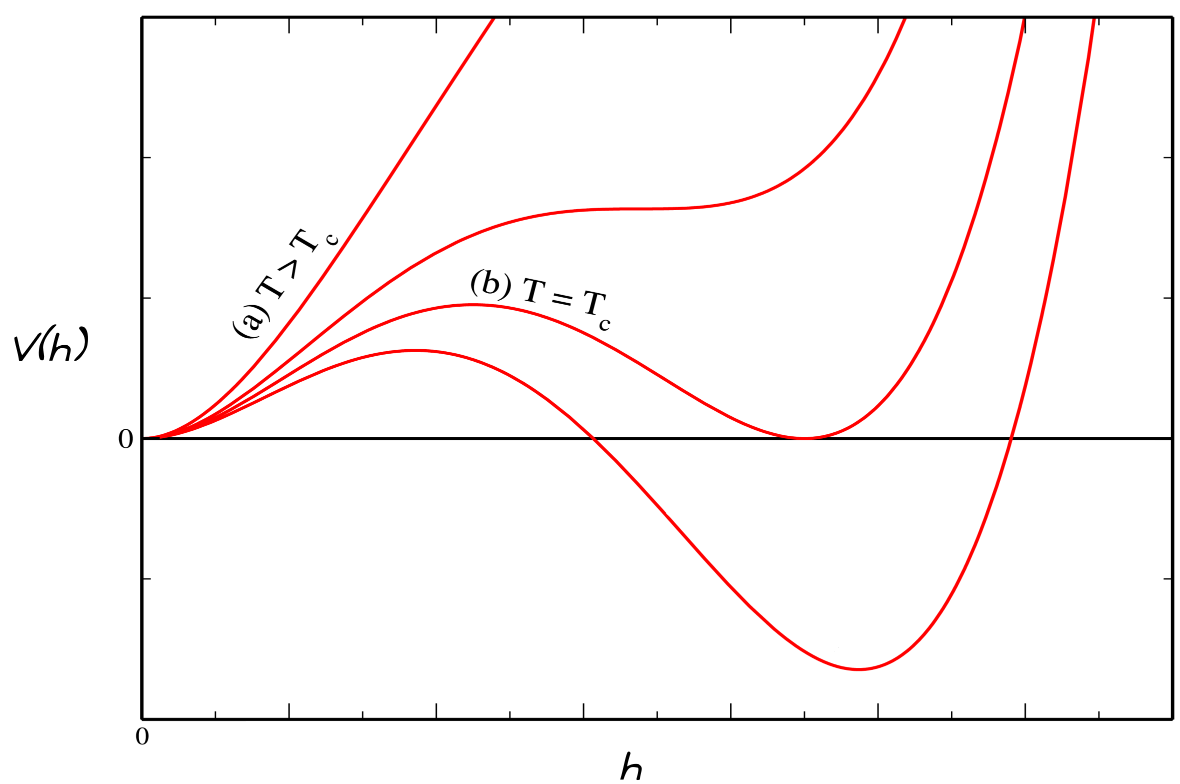
Finite-Temperature Higgs Effective Potential

$$V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm loop}(h) + V_T(h,T)$$

Tree-level potential | Loop corrections | Thermal corrections

First Order EW Phase Transition

$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T)$ Discontinuous



GW from the EW Phase Transition

First Order EW Phase Transition

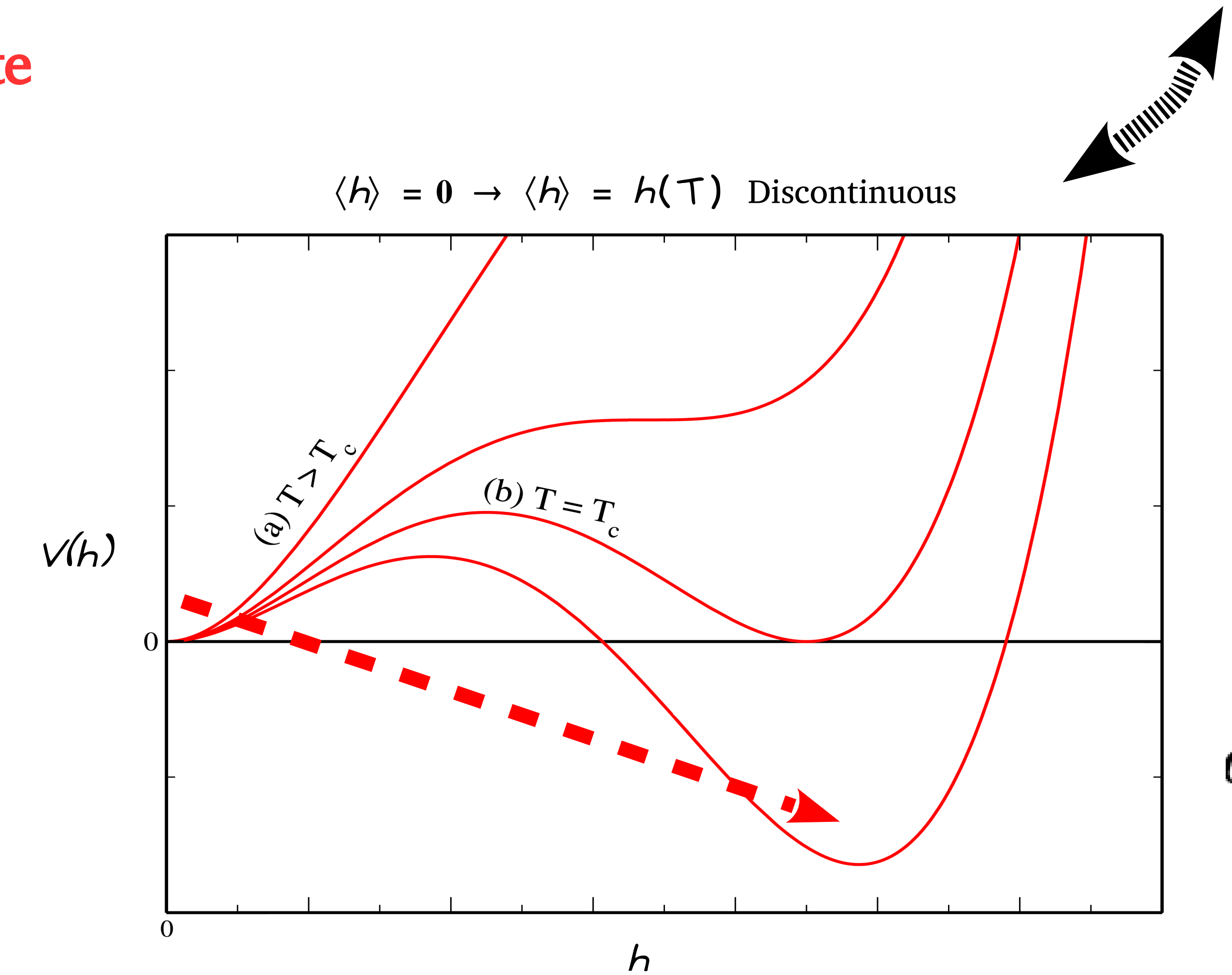
$\Rightarrow$ **Bubbles nucleate**

Finite-Temperature Higgs Effective Potential

$$V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm loop}(h) + V_T(h,T)$$

Tree-level potential | Loop corrections | Thermal corrections

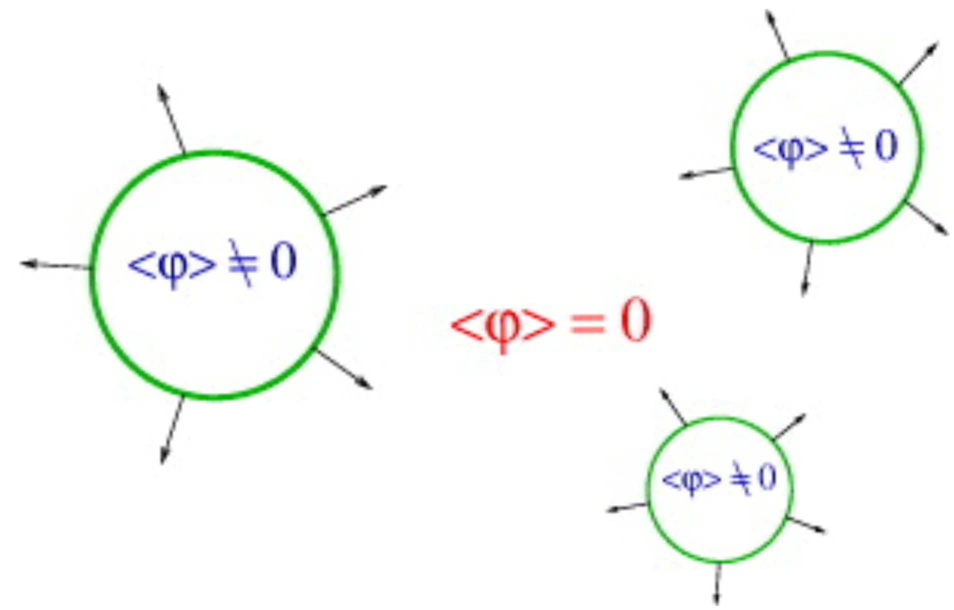
$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T)$ Discontinuous



$$\alpha_T = \left. \frac{\rho_{{\rm vac},u} - \rho_{{\rm vac},b}}{\rho_{{\rm rad},b}} \right|_{T=T_n}$$

GW from the EW Phase Transition

First Order EW Phase Transition



⇒ Bubbles nucleate

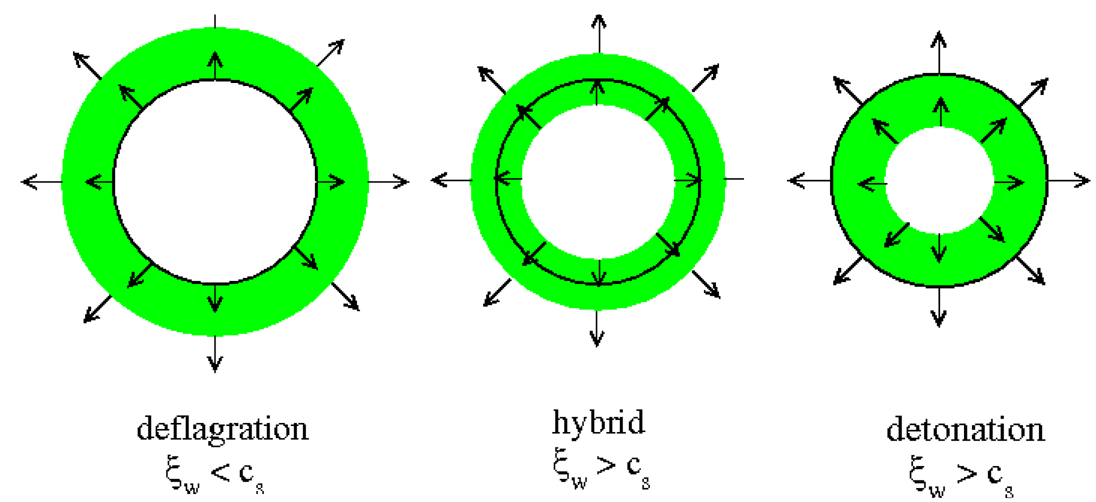
⇒ **Bubbles expand**
(in plasma → create fluid waves)

Fluid Dynamics

*Laine, Phys. Rev. D**49** (1994) 3847*
*Espinosa, Konstandin, No, Servant, JCAP **1006** (2010) 028*

→ Available Phase Transition energy into fluid shells
(Kinetic + Thermal energy)

$$\partial_\mu T^{\mu\nu}_{Plasma} = 0 \qquad v(r,t) = v(\xi = r/t)$$

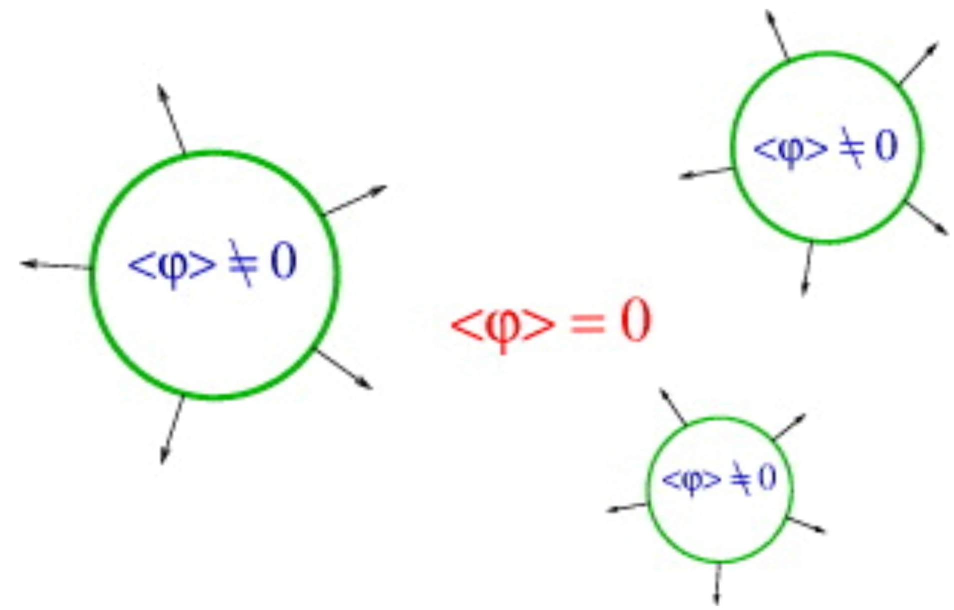


GW from the EW Phase Transition

First Order EW Phase Transition

$\Rightarrow$ Bubbles nucleate

$\Rightarrow$ **Bubbles expand**
(in plasma → create fluid waves)

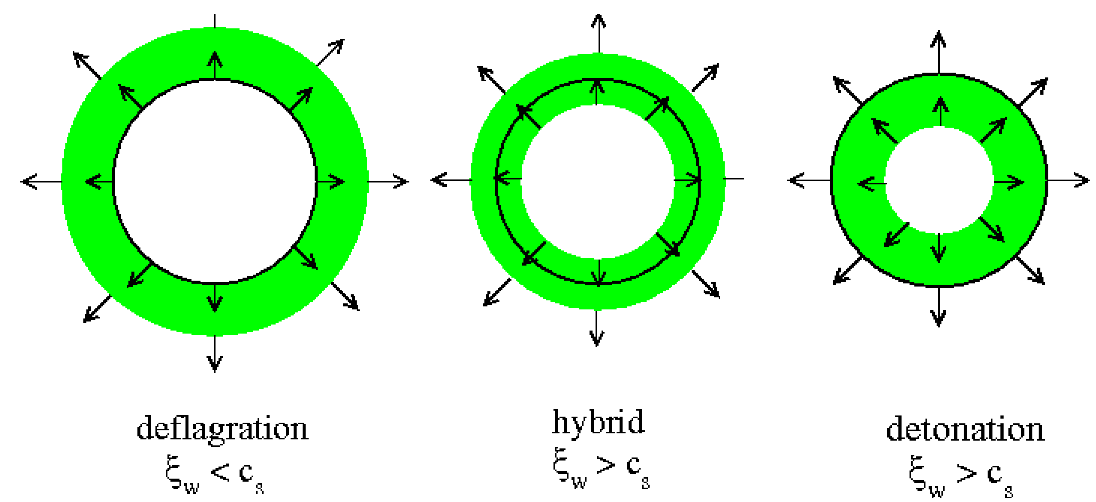


Fluid Dynamics

*Laine, Phys. Rev. D**49** (1994) 3847*
*Espinosa, Konstandin, No, Servant, JCAP **1006** (2010) 028*

Available Phase Transition energy into fluid shells
(Kinetic + Thermal energy)

$$\partial_\mu T^{\mu\nu}_{Plasma} = 0 \qquad v(r,t) = v(\xi = r/t)$$



CHARACTERIZED BY α_T T_* v_w

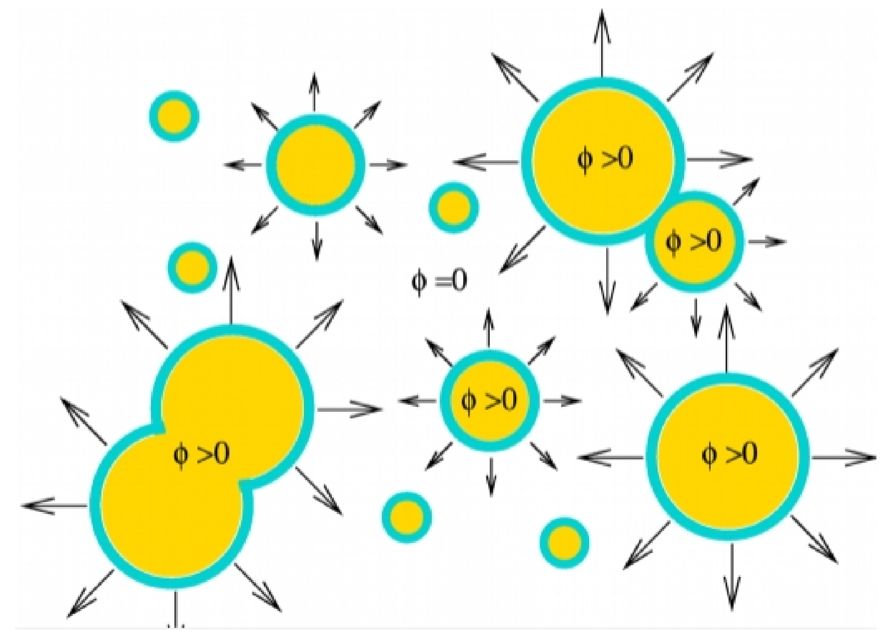
GW from the EW Phase Transition

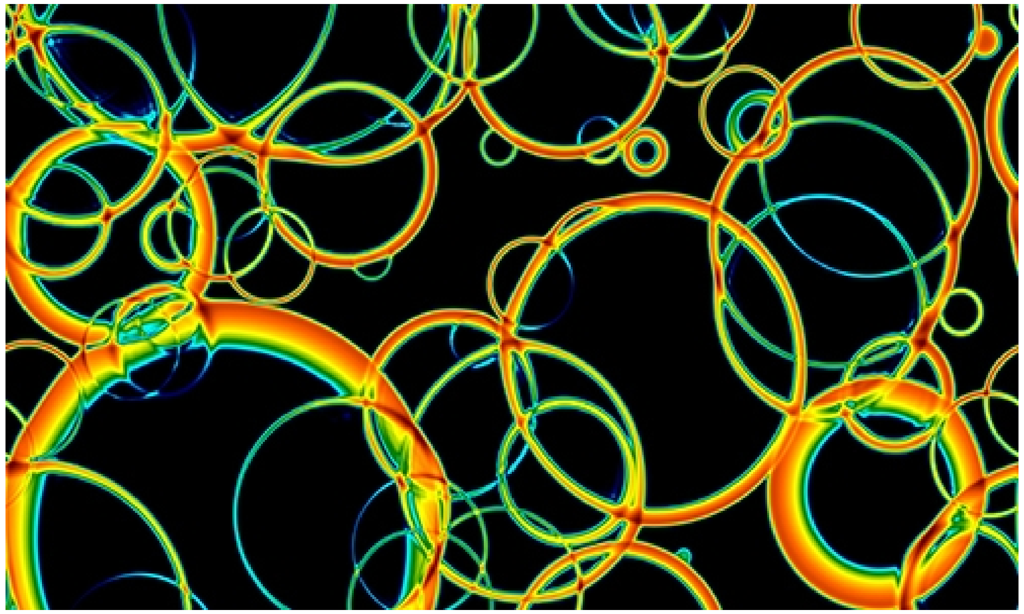
First Order EW Phase Transition

⇒ Bubbles nucleate

⇒ Bubbles expand
(in plasma → create fluid waves)

⇒ **Bubbles (& fluid) collide**





Courtesy of D. Weir

Hindmarsh, Huber, Rummukainen, Weir, Phys. Rev. Lett ***112*** *(2014) 041301*
Hindmarsh, Huber, Rummukainen, Weir, PRD ***92*** *(2015) 123009*

Bubble collisions & subsequent fluid motion source GWs

GW from the EW Phase Transition

First Order EW Phase Transition

⇒ Bubbles nucleate

⇒ Bubbles expand
(in plasma → create fluid waves)

⇒ **Bubbles (& fluid) collide**

Bubble collisions & subsequent fluid motion source GWs

Relevant parameters for GW generation

$$T_* \quad \alpha_T \quad \frac{\beta}{H_*} \quad v_w$$

$\frac{\beta}{H_*}$ = duration of phase transition

GW from the EW Phase Transition

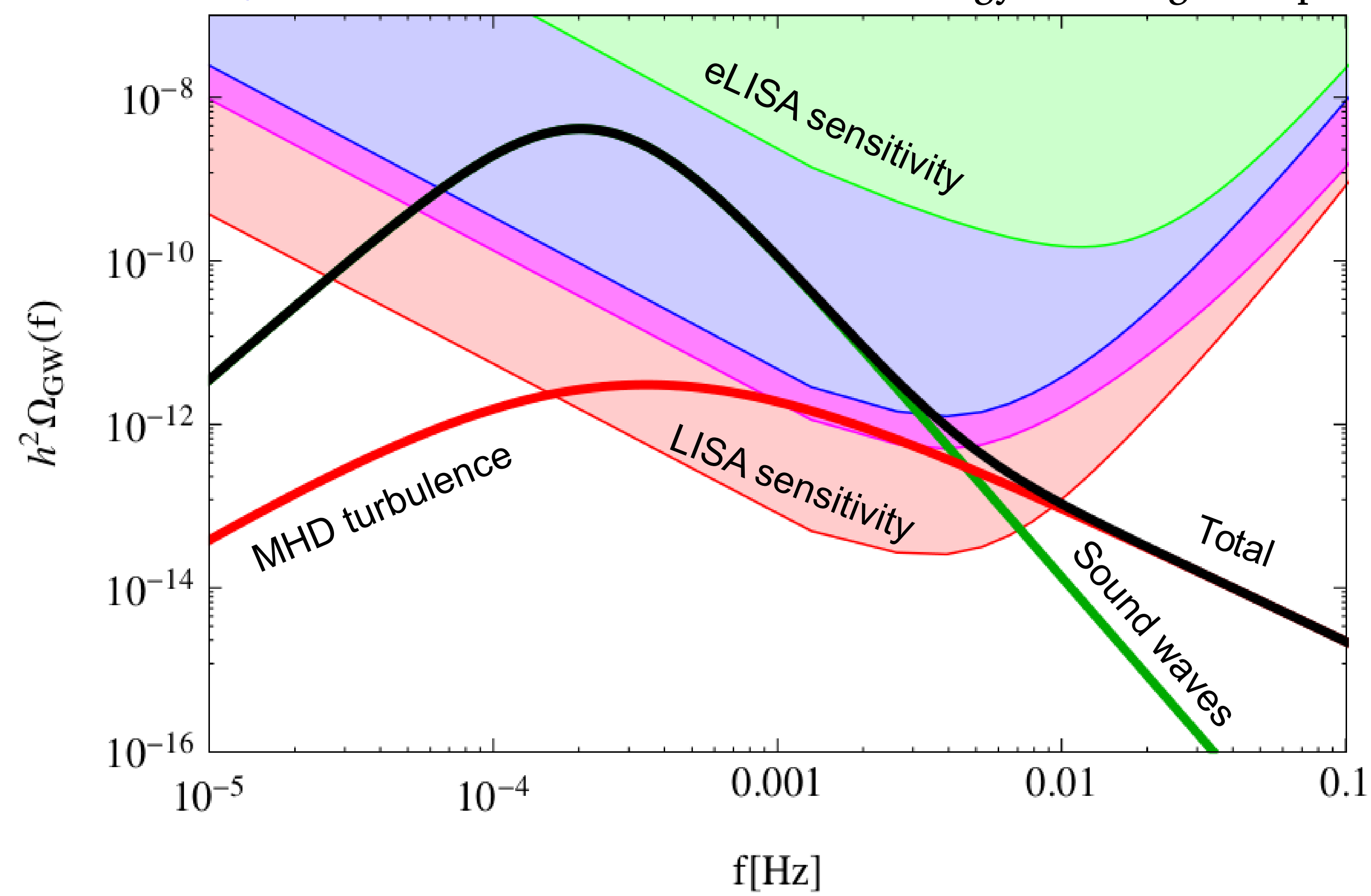
First Order EW Phase Transition

⇒ Bubbles nucleate

⇒ Bubbles expand
(in plasma → create fluid waves)

⇒ Bubbles (& fluid) collide

Caprini et al, JCAP **1604** (2016) 001 LISA Cosmology Working Group



GW from Sound Waves

Hindmarsh, Huber, Rummukainen, Weir, Phys. Rev. Lett **112** (2014) 041301
Hindmarsh, Huber, Rummukainen, Weir, Phys. Rev. **D92** (2015) 123009

$$h^2\Omega_{\rm sw}(f) = 2.65\times 10^{-6}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}} v_w\, S_{\rm sw}(f)$$

$$f_{\rm sw} = 1.9\times 10^{-2}\,{\rm mHz}\,\frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

GW from Turbulence

Caprini, Durrer, Servant, JCAP **0912** (2009) 024

$$h^2\Omega_{\rm turb}(f) = 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

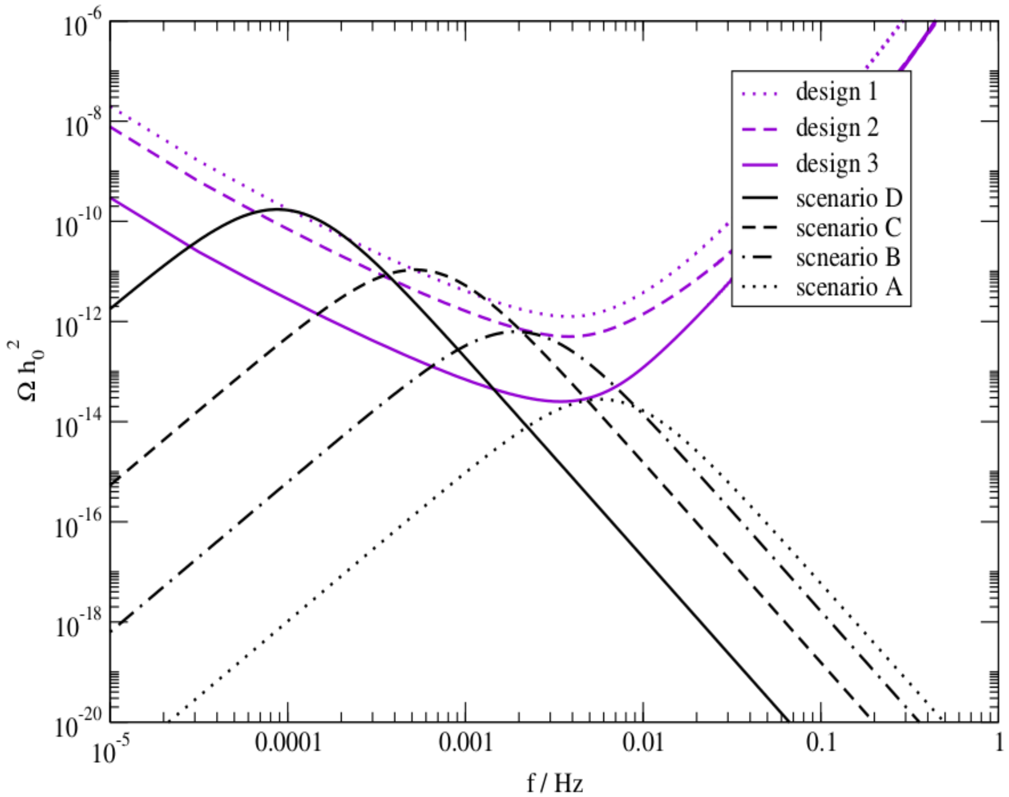
$$f_{\rm turb} = 2.7\times 10^{-2}\,{\rm mHz}\,\frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

(also work by Gogoberidze, Kahniashvili, Kosowsky)

One quick last slide on BSM Models...

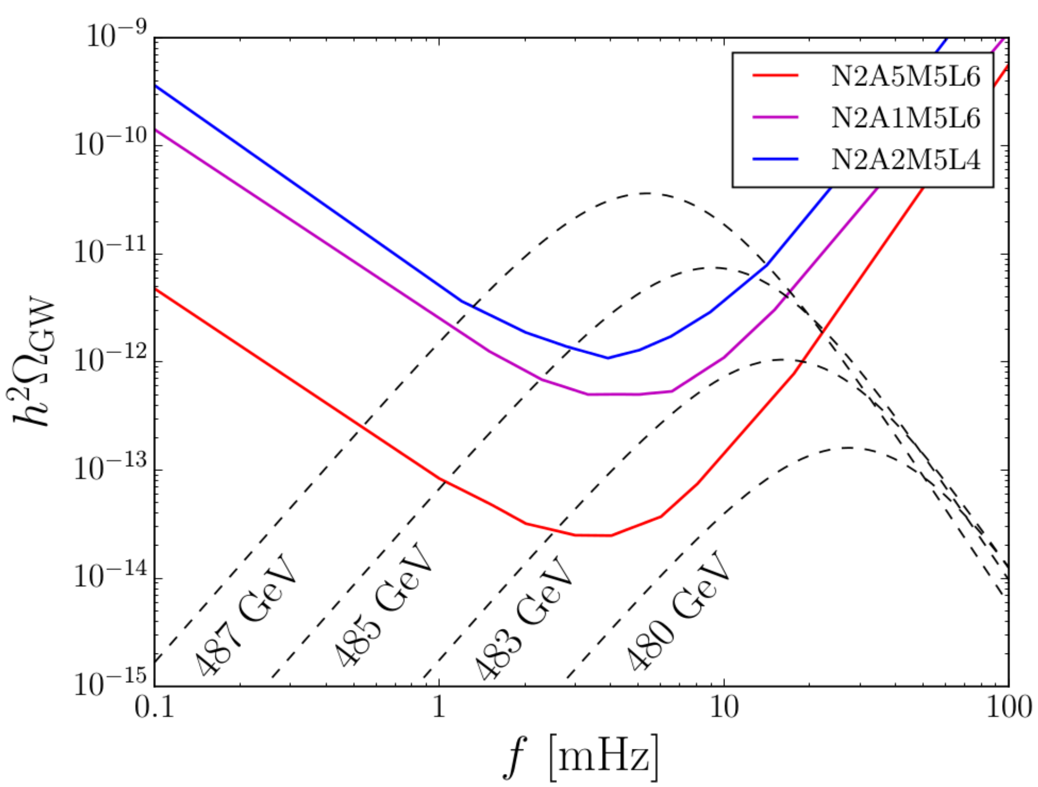
NMSSM

*Huber, Konstandin, Nardini, Rues, JCAP **1603** (2016) 036*

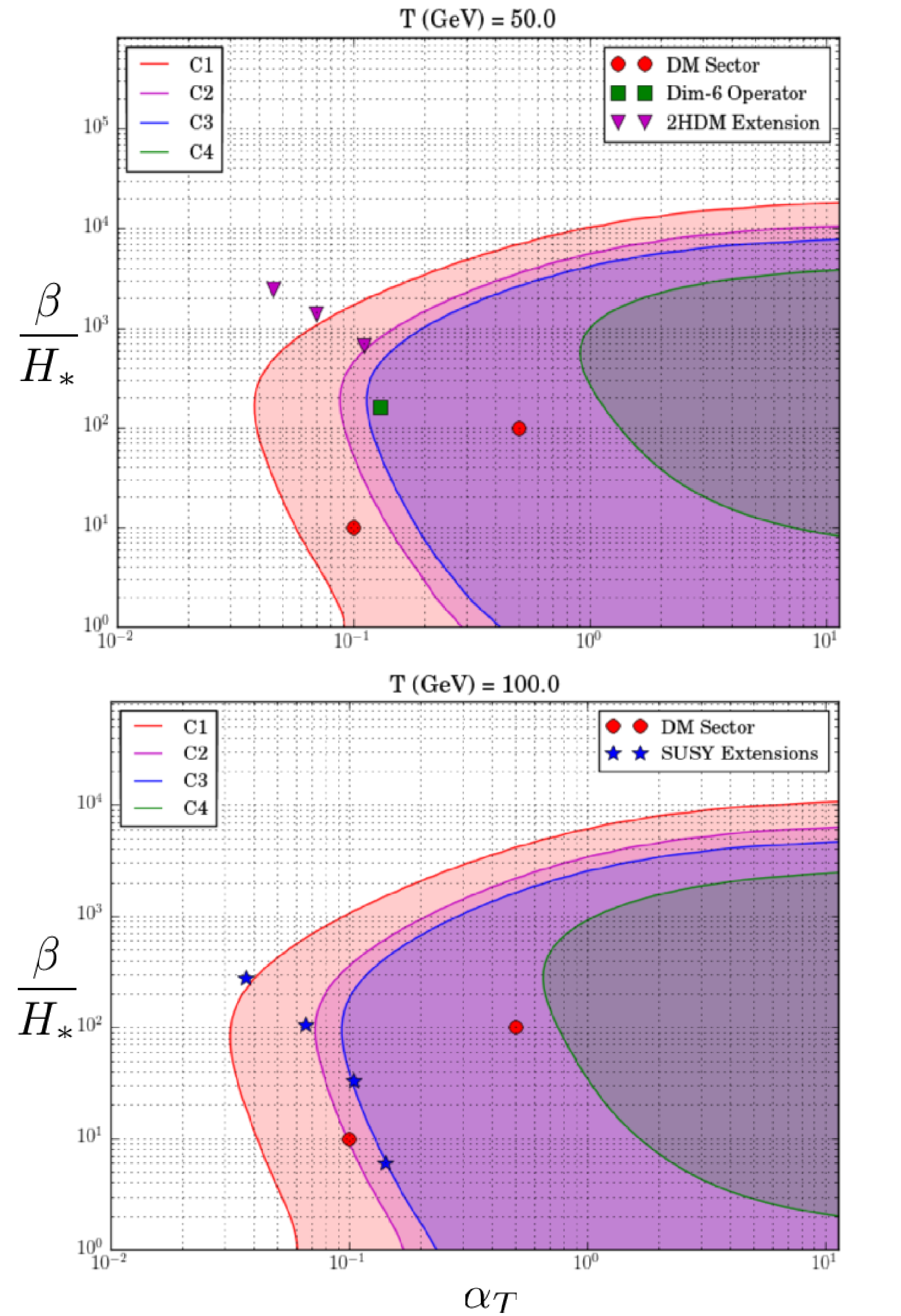


2HDM

*Dorsch, Huber, Konstandin, No, JCAP **1705** (2017) 052*



*Caprini et al, JCAP **1604** (2016) 001* LISA Cosmology Working Group



"Every time humans have opened new eyes on the Universe, we have discovered something unexpected that revolutionized how we saw the Universe and our place within it."

LIGO Press Conference
February 11th, 2016

"Every time humans have opened new eyes on the Universe, we have discovered something unexpected that revolutionized how we saw the Universe and our place within it."

LIGO Press Conference
February 11th, 2016

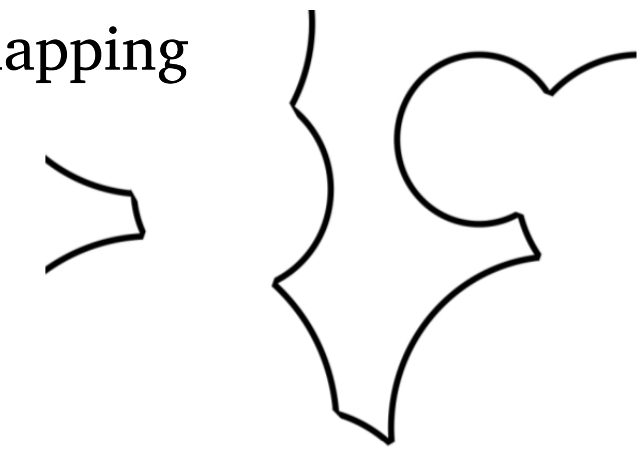

KEEP
CALM
AND
BACKUP
YOUR
WORK

GWs from Phase Transitions

Vacuum Phase Transition

Available Energy → ϕ Kinetic Energy

- GW from collisions of infinitely thin bubble shells
  Kosowsky, Turner, Watkins, Phys. Rev. ***D45*** *(1992) 4514*
  Kosowsky, Turner, Watkins, Phys. Rev. Lett. ***69*** *(1992) 2026*
- **Envelope Approximation:** GW sourced by envelope of overlapping bubbles in bubble collisions
  Kosowsky, Turner, Phys. Rev. ***D47*** *(1992) 4372*



$$h^2\Omega_\phi \simeq 1.29 \times 10^{-6} \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\alpha_T}{1+\alpha_T}\right)^2 \left(\frac{g_*}{100}\right)^{-1/3}$$

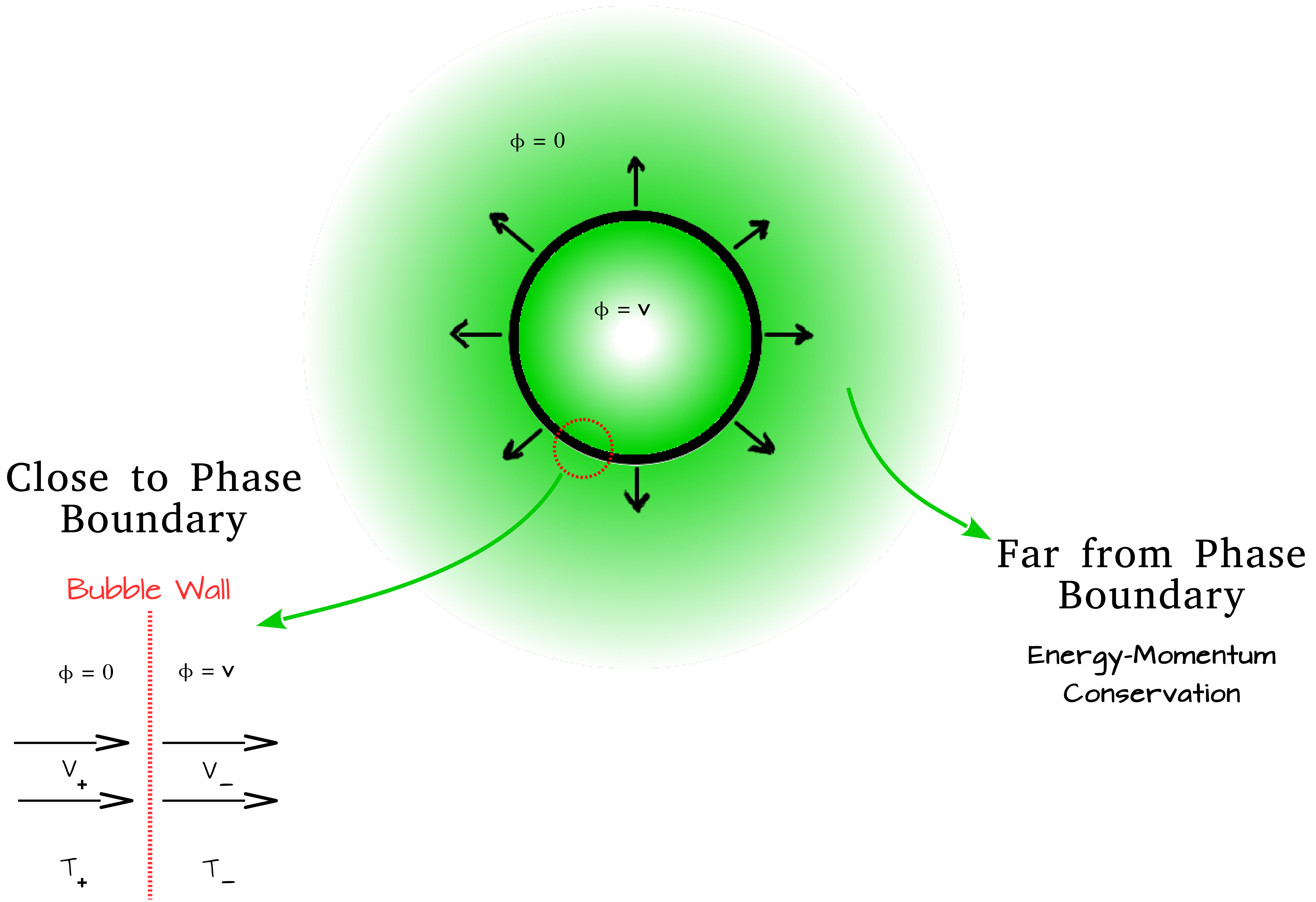
$$f_\phi = 3.8 \times 10^{-3}\mathrm{mHz} \left(\frac{\beta}{H_*}\right) \left(\frac{T_*}{10^2\ \mathrm{GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6}$$

Huber, Konstandin, JCAP ***0809*** *(2008) 022*
Weir, Phys. Rev. ***D93*** *(2016) 124037*
Jinno, Takimoto, Phys. Rev. ***D95*** *(2017) 024009*

$$h^2\Omega_\phi(f) \propto \begin{cases} \left(\frac{f}{f_\phi}\right)^3 & (f < f_\phi) \\ \left(\frac{f}{f_\phi}\right)^{-1} & (f > f_\phi) \end{cases}$$

Dynamics of Thermal Plasma

Expanding bubbles perturb plasma



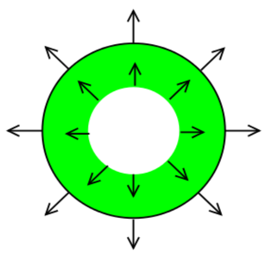
Dynamics of Thermal Plasma

Solutions for Fluid Motion

$$\frac{1-\xi v(\xi)}{1-v^2(\xi)}\left[\frac{\mu^2}{c_s^2}-1\right]\partial_\xi v = 2\frac{v(\xi)}{\xi}$$

$$\mu(\xi, v) \equiv \frac{\xi - v(\xi)}{1-\xi v(\xi)}$$

$$c_s = 1/\sqrt{3}$$



detonation
$\xi_w > c_s$

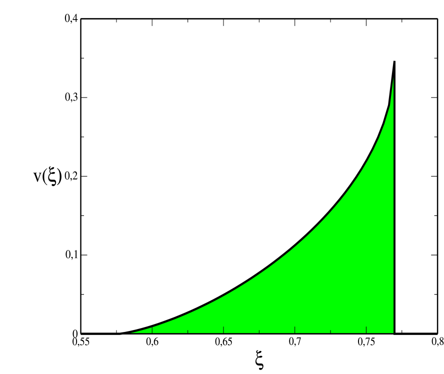
DETONATIONS

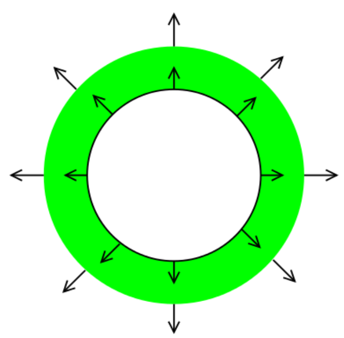
$v_+ > v_-$

Supersonic $v_W > c_s$

Fluid at Rest in Front of Wall $v_+ = v_W$, $T_+ = T_N$

Rarefaction Wave Behind Wall $T_- > T_+$





deflagration
$\xi_w < c_s$

DEFLAGRATIONS

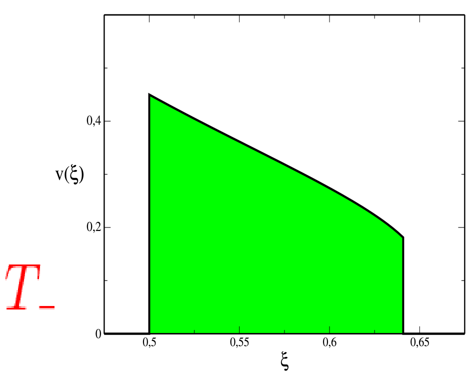
$v_+ < v_-$

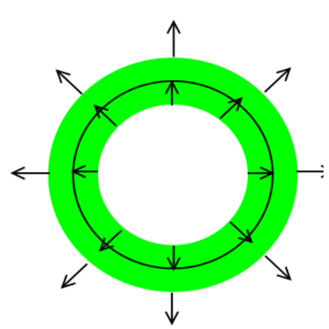
Subsonic $v_W < c_s$

Fluid at Rest Behind Wall $v_- = v_W$

Compression Wave in Front of Wall $T_+ > T_N > T_-$

Ends in a Shock Front





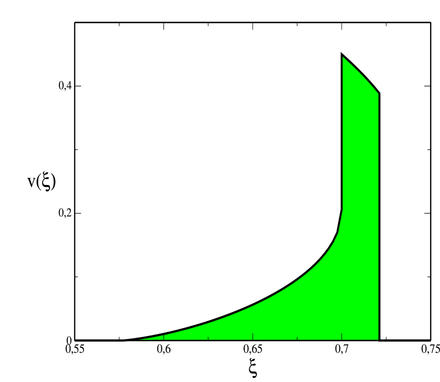
hybrid
$\xi_w > c_s$

HYBRIDS

$v_+ < v_-$

Supersonic $v_W > c_s = v_- > v_+$

Both Compression & Rarefaction Waves

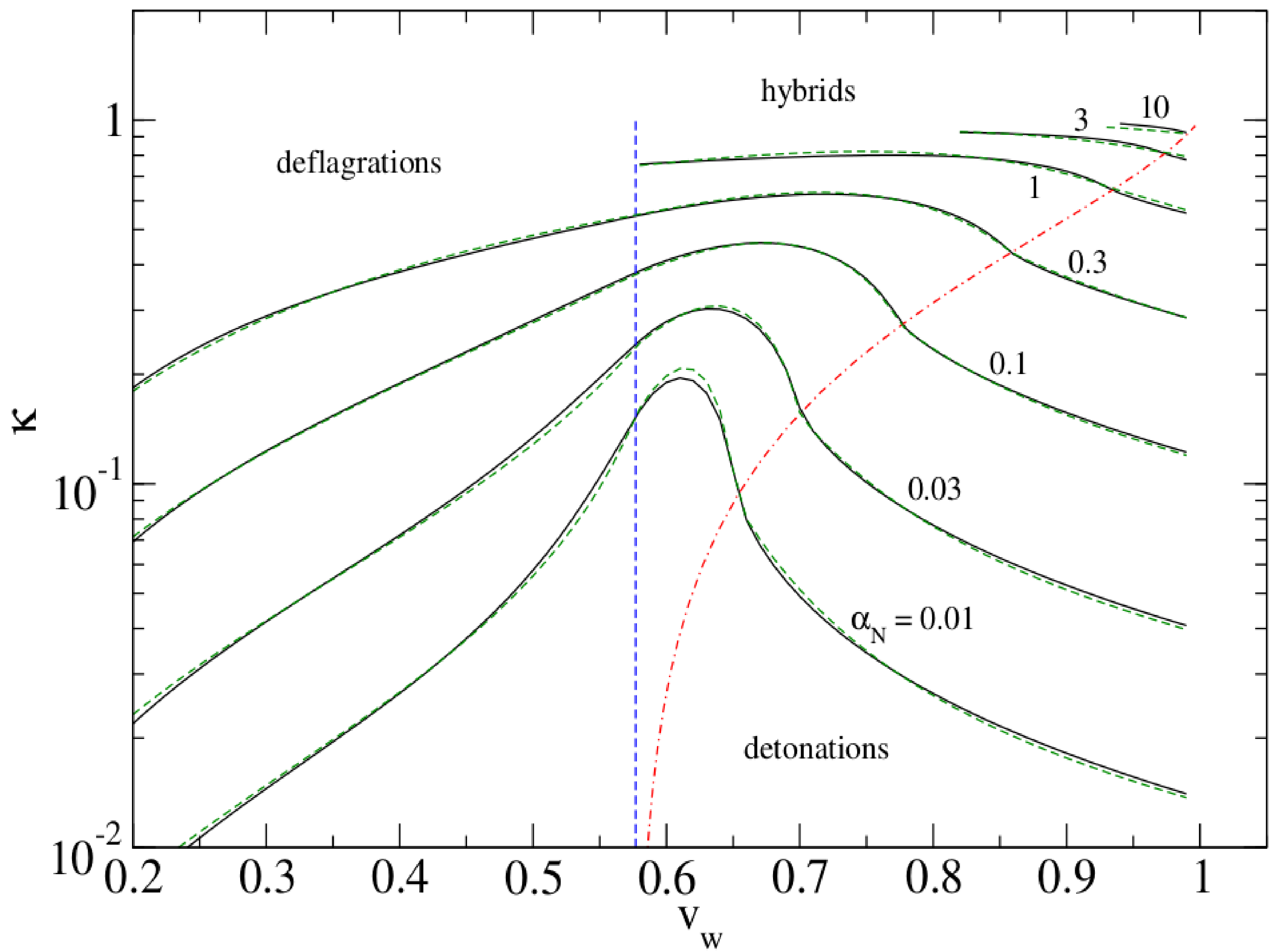


Energy Budget of the Phase Transition

Controls **Energy Budget**

$$\kappa = \frac{3}{\epsilon\, v_W^3} \int w(\xi)\, v(\xi)^2\, \gamma(\xi)^2\, \xi^2\, d\xi < 1$$

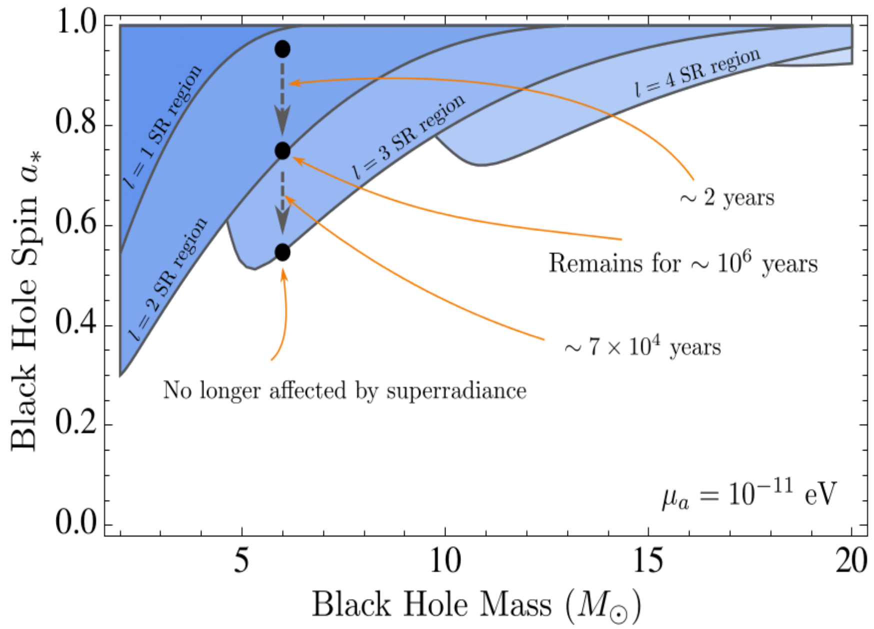
Energy not transformed into plasma bulk motion ($1-\kappa$)
used to increase plasma thermal energy



BSM GW Astronomy

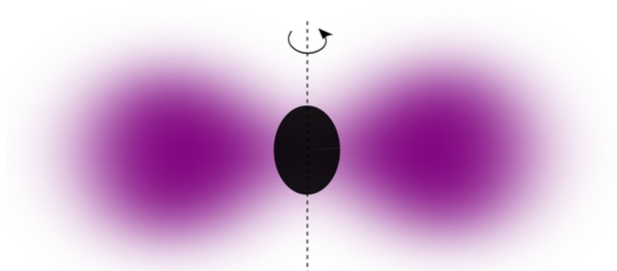
Light Fields around BH

(& Superradiance)



Arvanitaki, Dubovsky, Phys. Rev. D**83** (2011) 044026

Arvanitaki, Baryakhtar, Huang, Phys. Rev. D**91** (2015) 084011



GWs from Exotic Compact Objects

Boson Stars

If a light scalar field has weak self interactions, can condense.

Supported from collapse by uncertainty principle: cannot be localized below inverse mass. Total mass:

$$M_{BS} \approx \left(\frac{10^{-10}\ \text{eV}}{m_B}\right) M_\odot$$

Compactness:

$$M/R < 0.08$$

Fermion Stars

Supported from collapse by fermion degeneracy pressure. Chandrasekhar mass

$$M \lesssim \frac{M_P^3}{m_F^2}$$

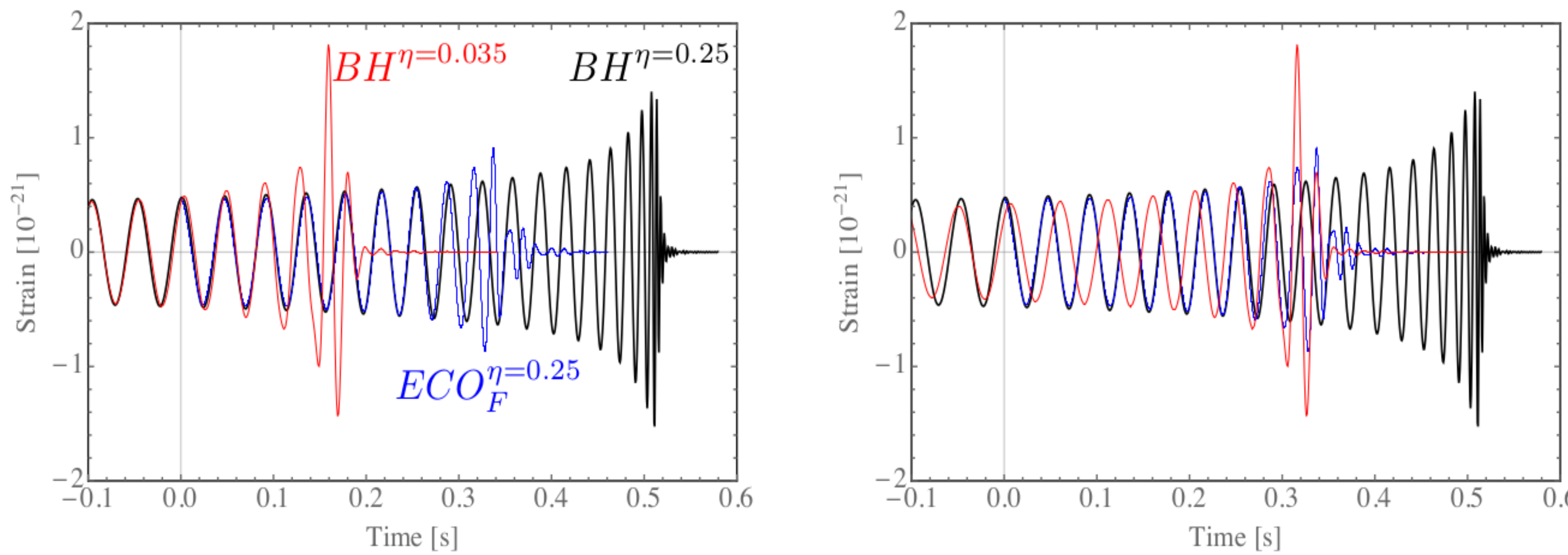
Thus:

$$M \lesssim \left(\frac{250\ \text{MeV}}{m_F}\right)^2 10 M_\odot$$

Compactness

$$M/R < 0.16$$

Courtesy of M. McCullough



Giudice, McCullough, Urbano, JCAP **1610** (2016) 001