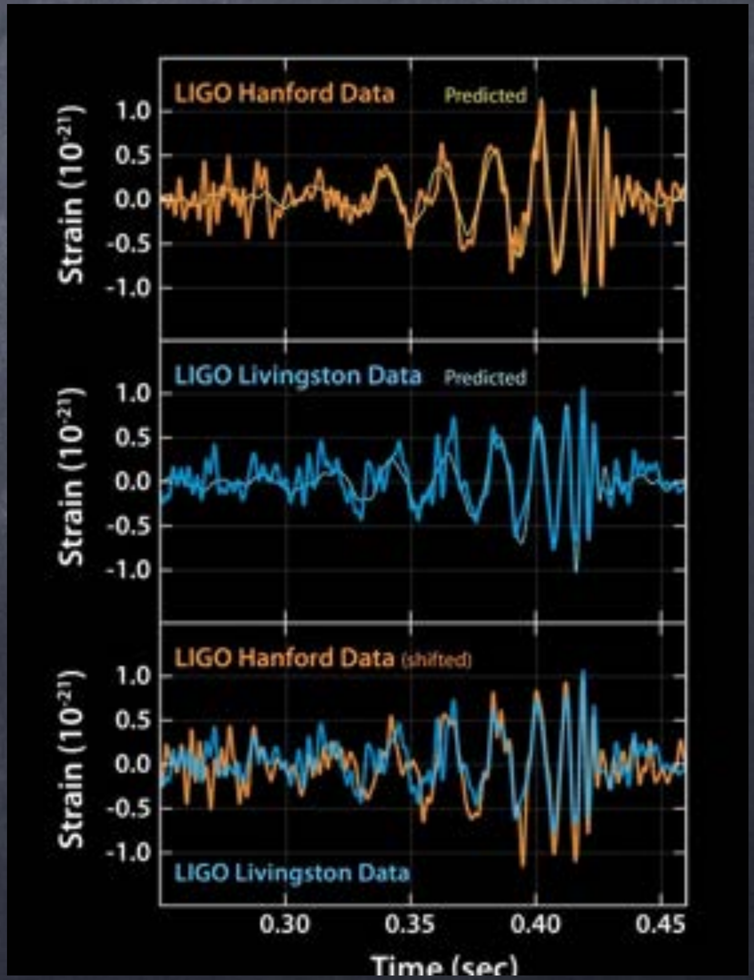
Gravitational Waves, and GW150914

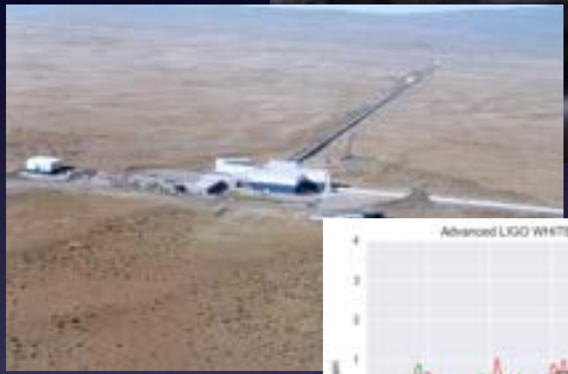
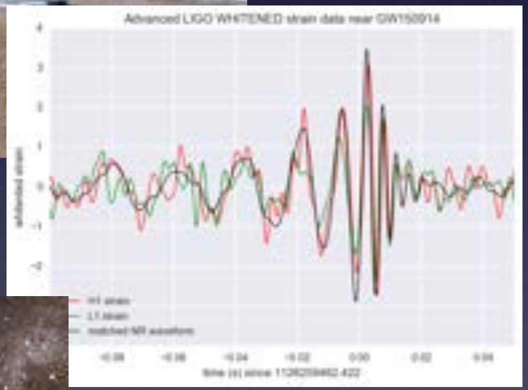
Tsvi Piran

The Hebrew University

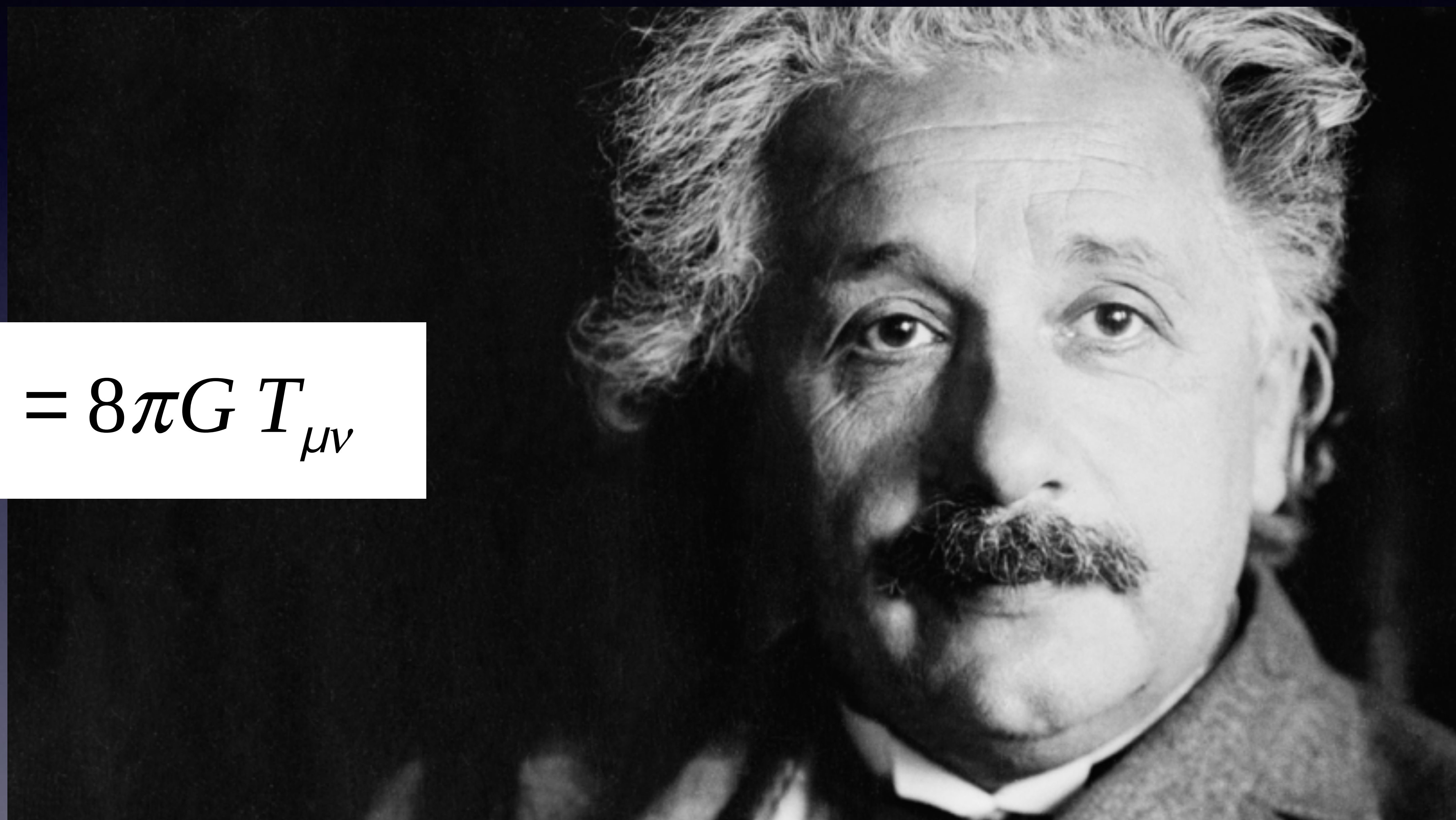


Outline

- General Relativity in a nut shell
- Gravitational waves
- Compact binary mergers and the Chirp
- GW Interferometers
- GW150914
- Physical implications
- Astrophysical considerations
- Conclusions

1915 – General Relativity



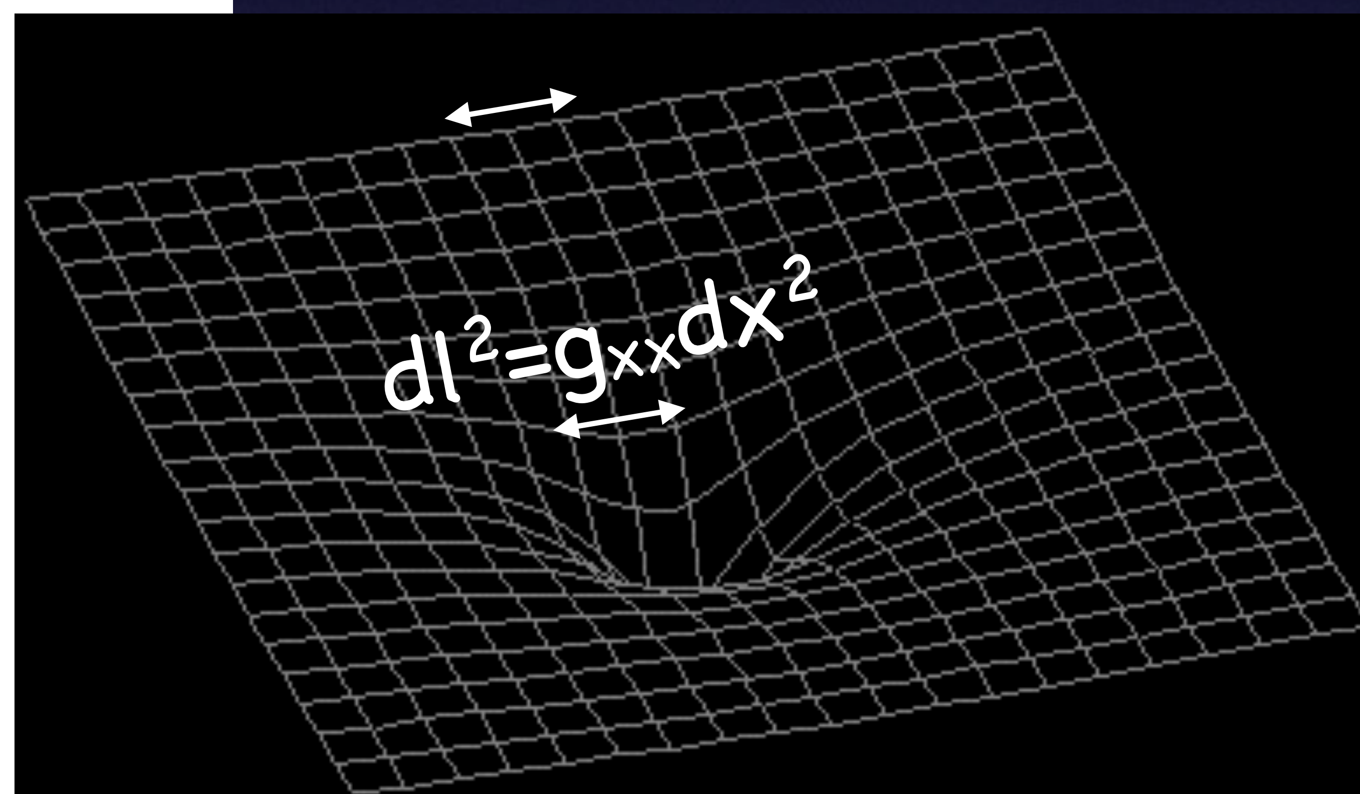
$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Spacetime is curved

Ricci scalar

the metric

$$g_{\mu\nu} \equiv \begin{pmatrix} g_{tt} & g_{tx} & g_{ty} & g_{tz} \\ g_{tx} & g_{xx} & g_{xy} & g_{xz} \\ g_{ty} & g_{xy} & g_{yy} & g_{yz} \\ g_{tz} & g_{xz} & g_{yz} & g_{yz} \end{pmatrix}$$



Einstein's Equation
Matter curves Space

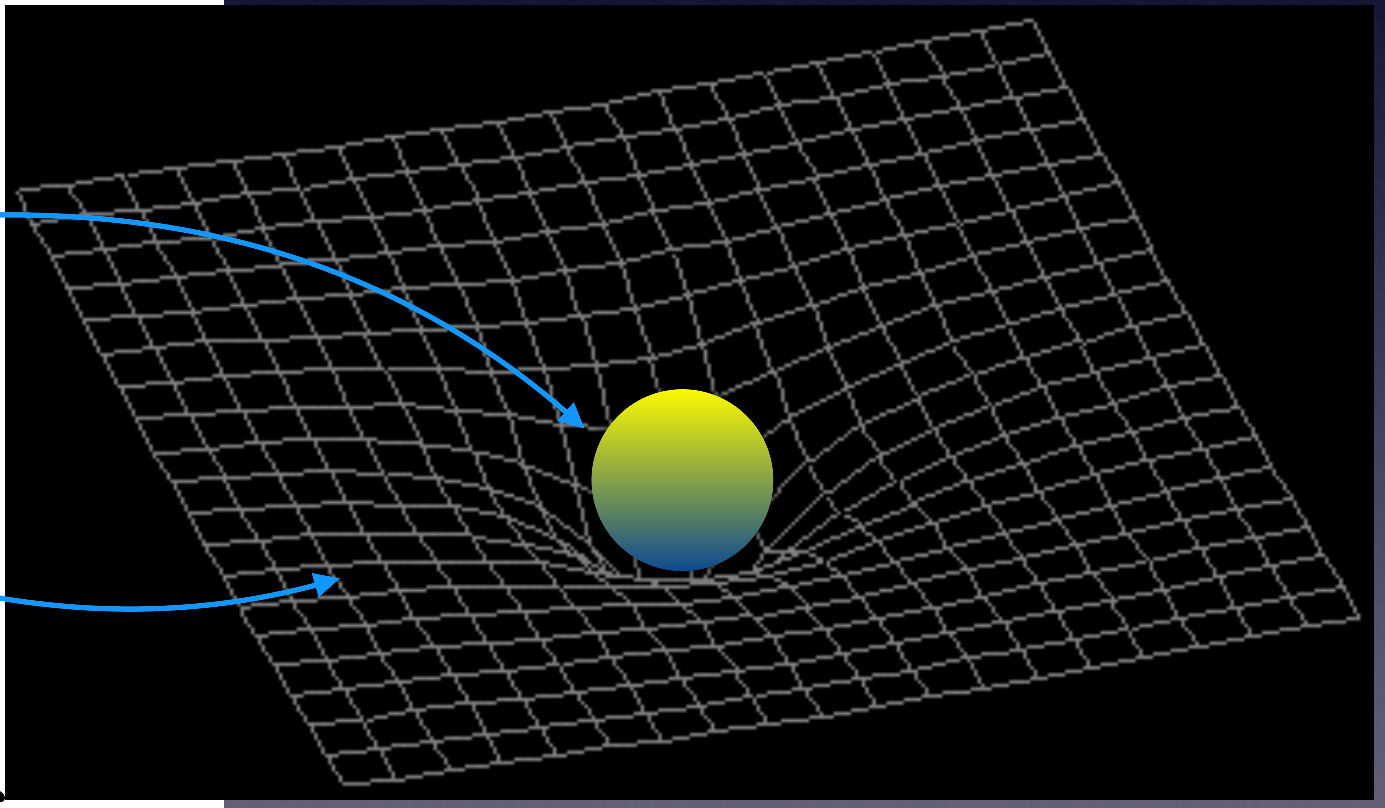
Newton's constant

metric

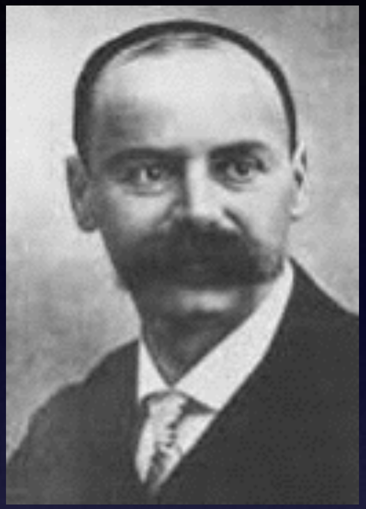
$$G_{\mu\nu}(g_{\mu\nu}) = 8\pi G\, T_{\mu\nu}$$

Einstein's tensor

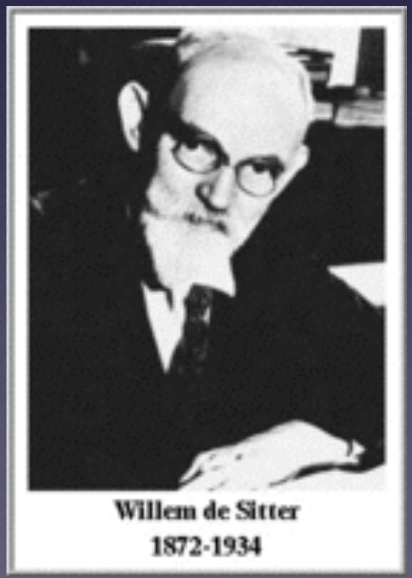
Energy-momentum tensor

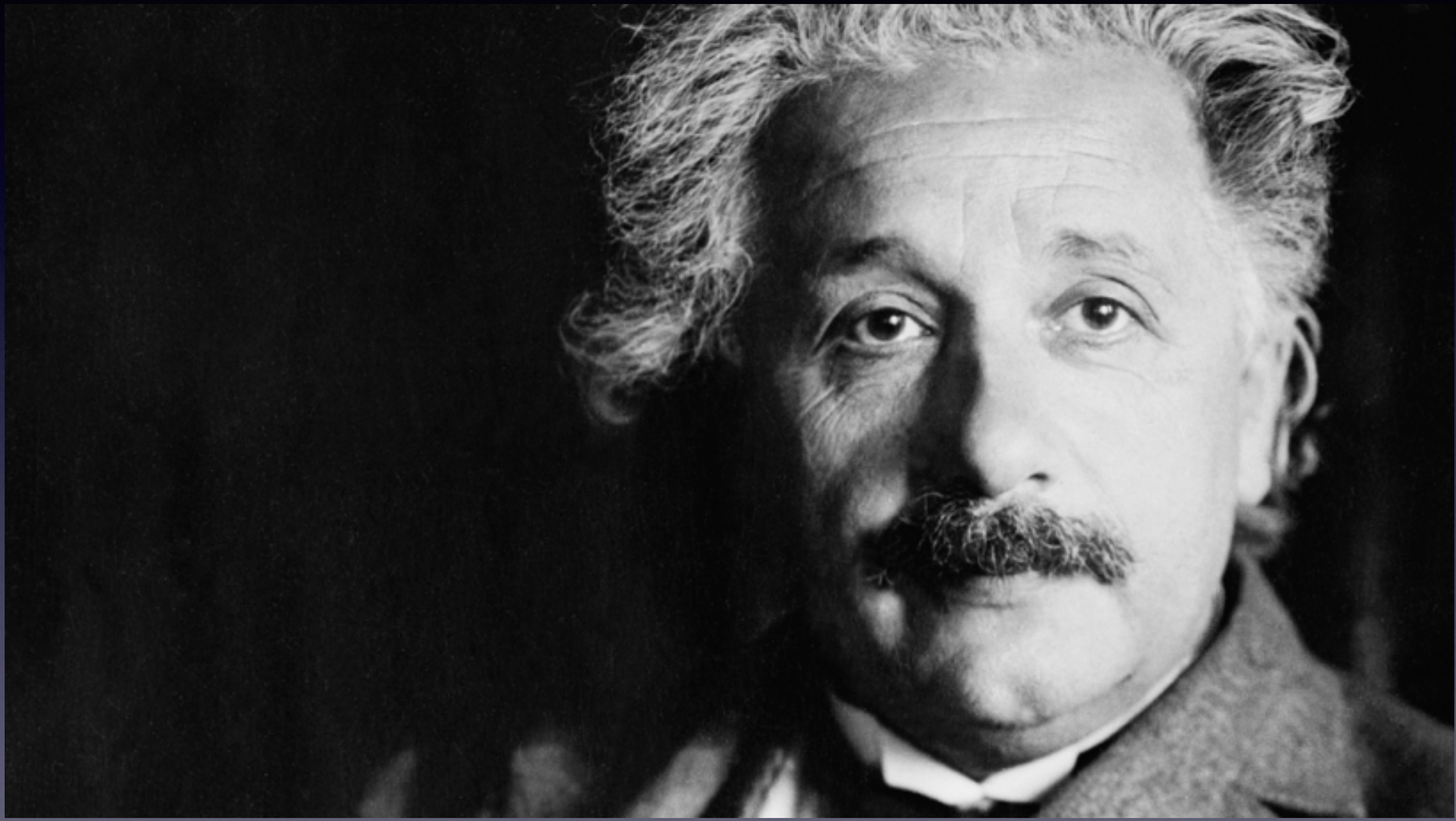


1916 – Gravitaiontal waves



Karl Schwartzchild





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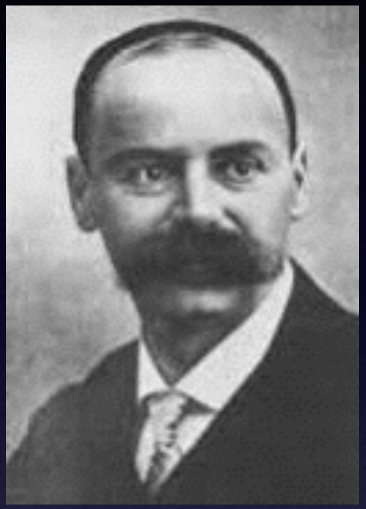

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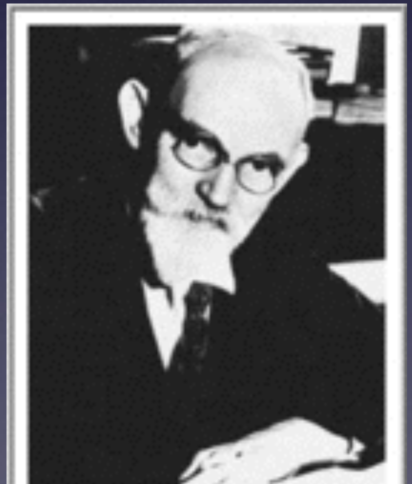
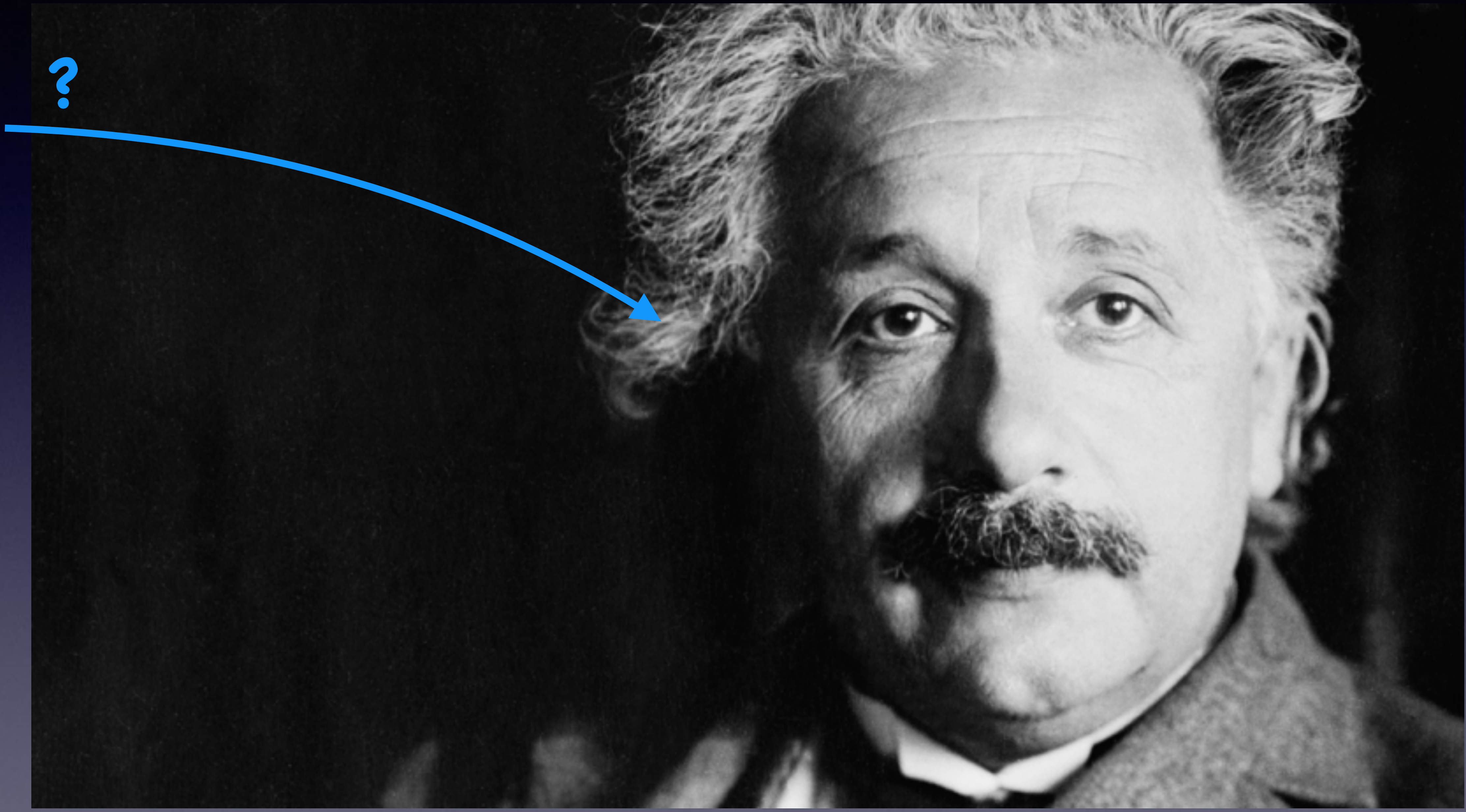


Willem de Sitter
1872-1934



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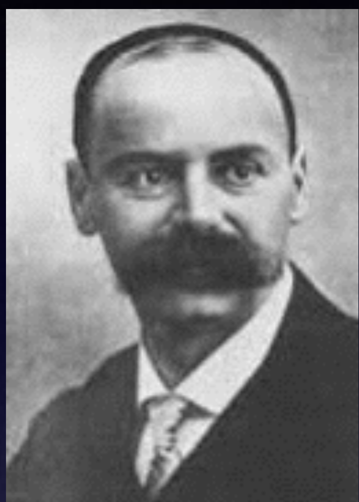

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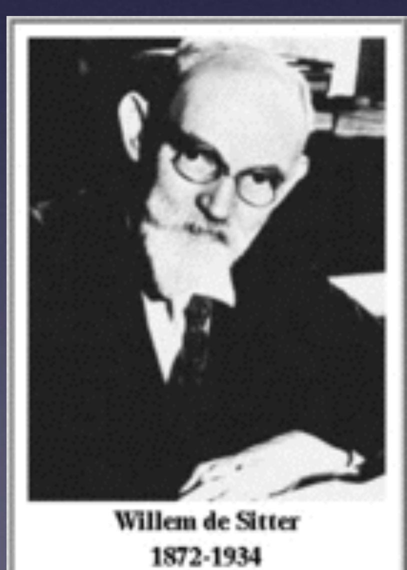

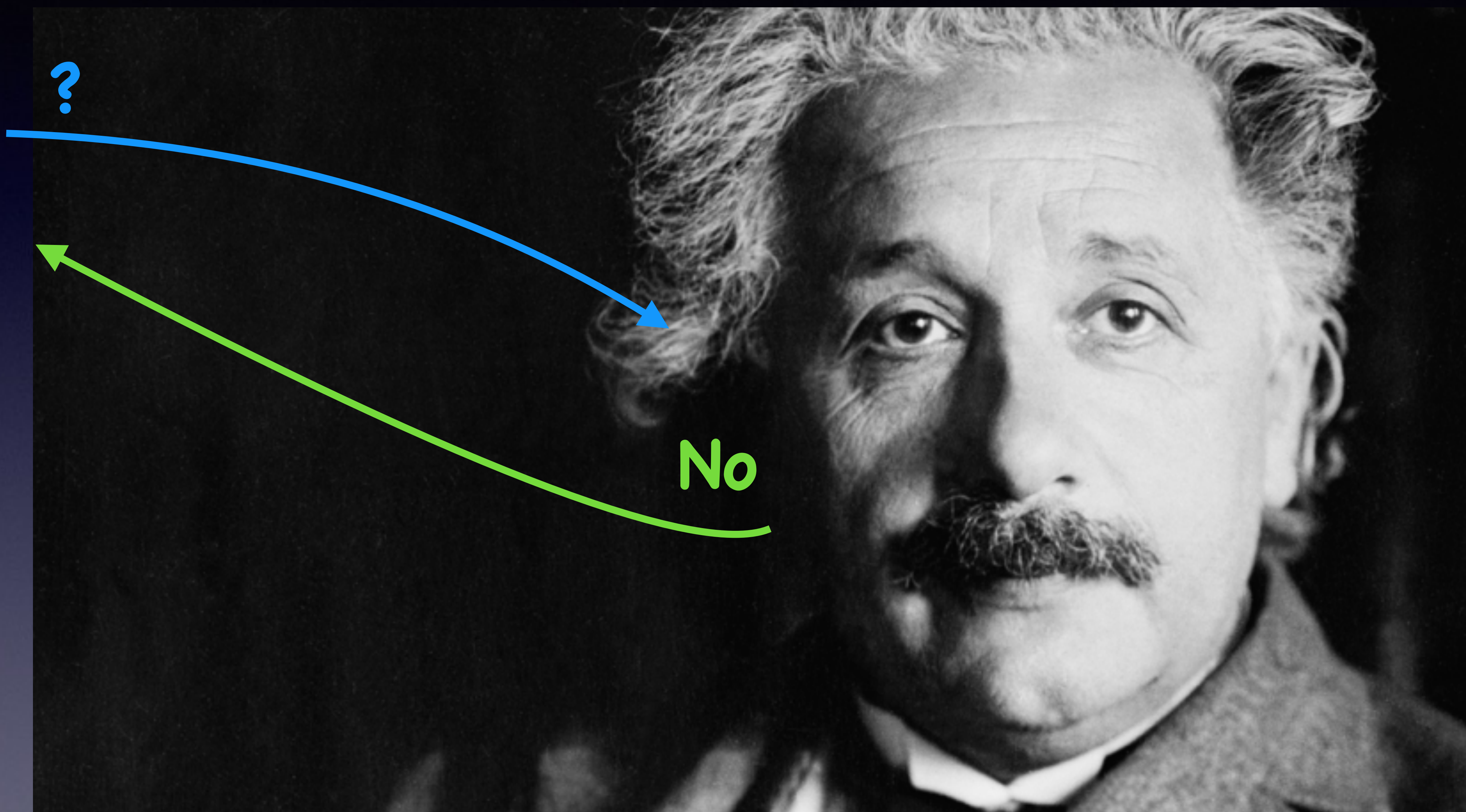

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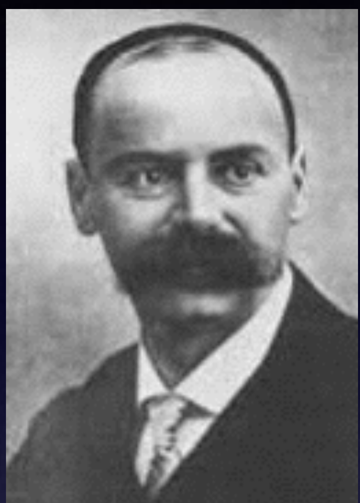

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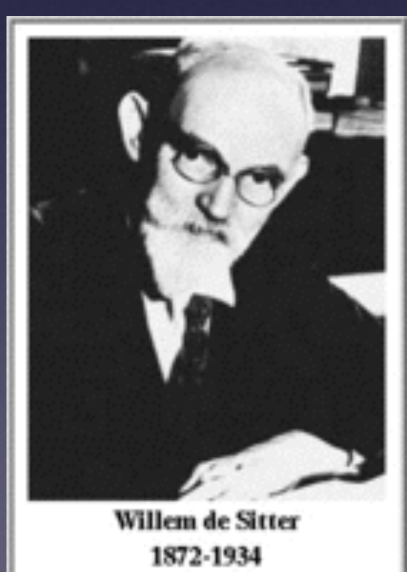
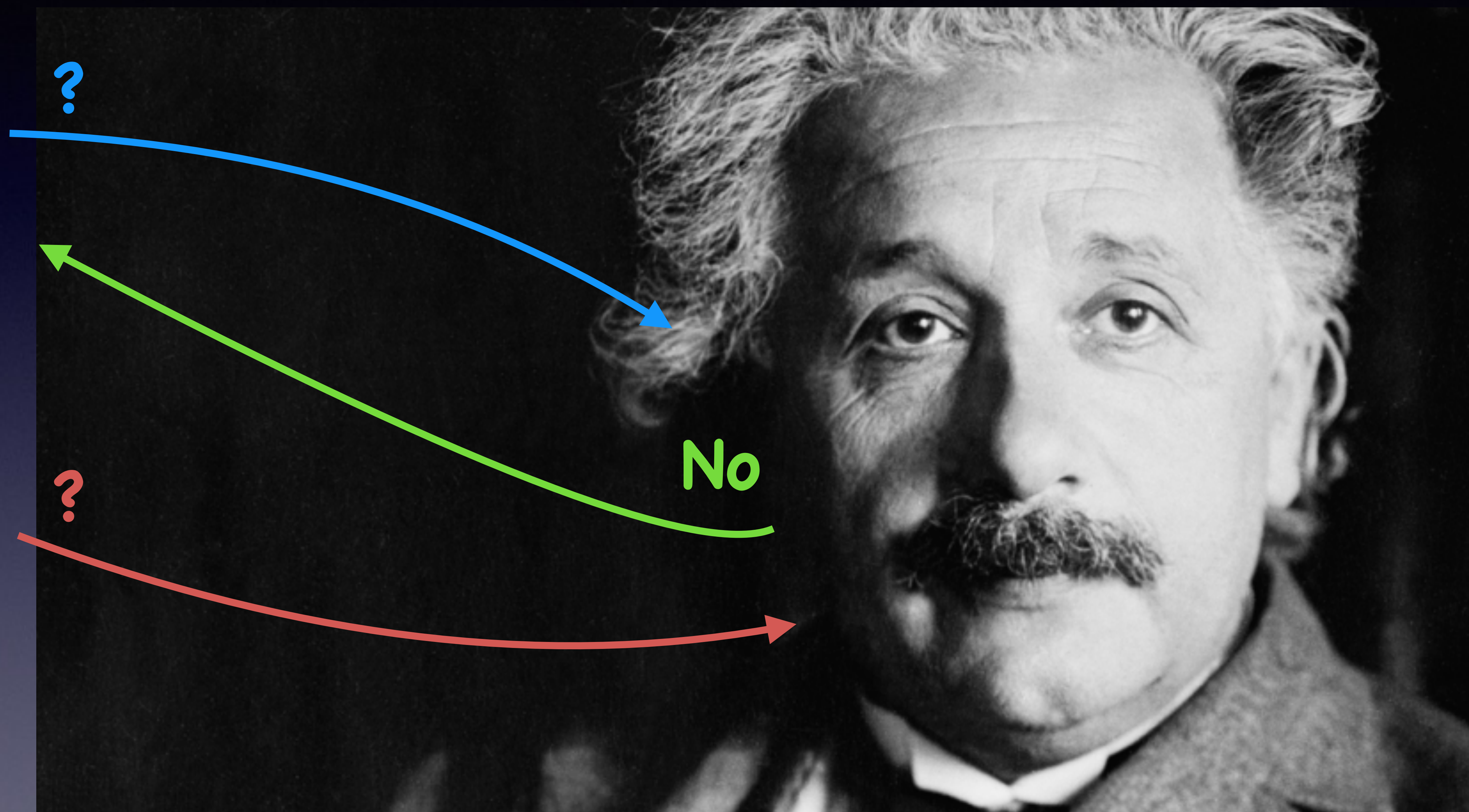
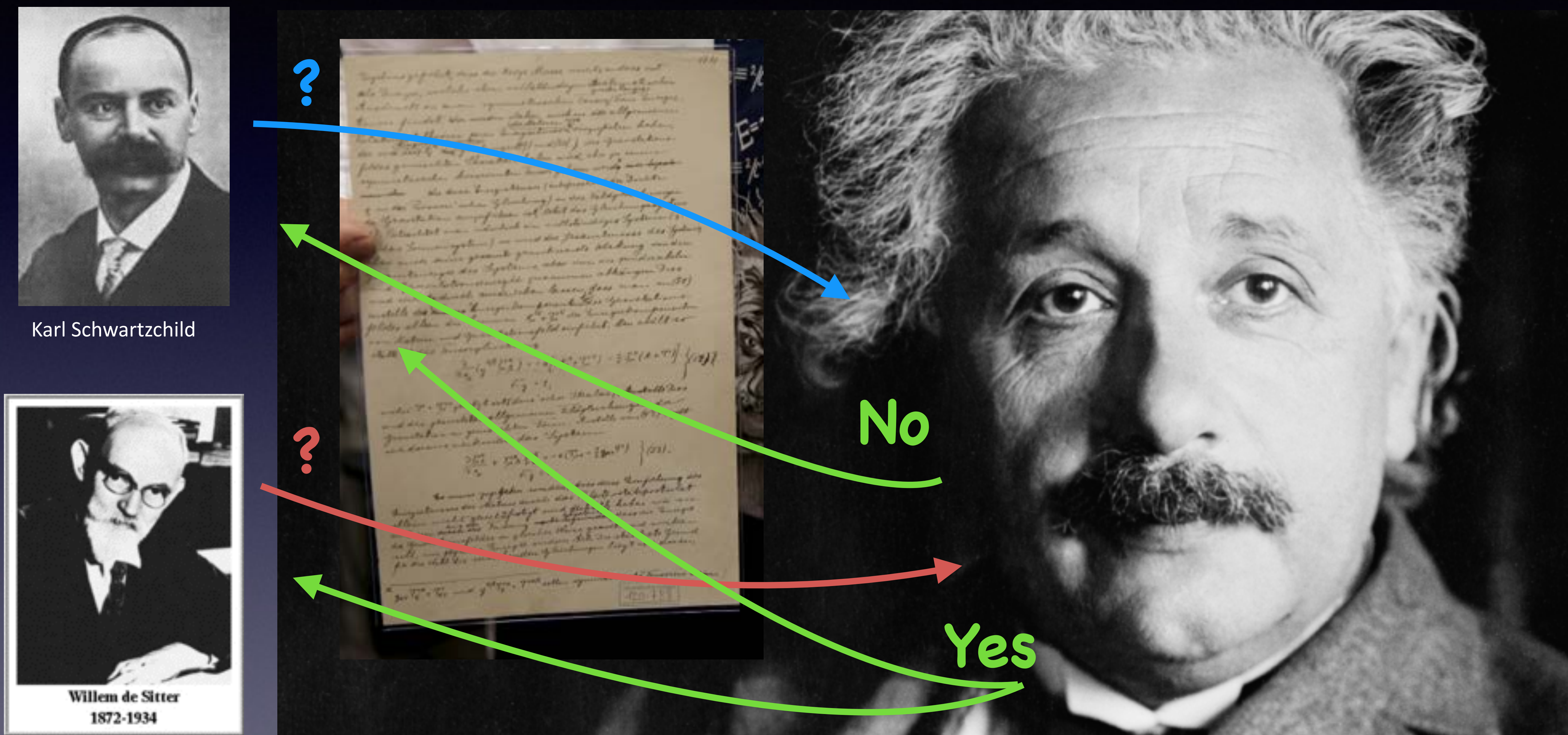




1916 – Gravitaiontal waves



Gravitational Waves

flat space metric

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu} \qquad \eta_{\mu\nu} \equiv \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$|h_{\mu\nu}| \ll 1$$

Linearization=> Waves

$$G_{\mu\nu} \approx \frac{1}{2}\left(-\frac{\partial^2}{c^2\,\partial t^2} + \nabla^2\right)h_{\mu\nu} = 0$$

Gravitational Waves

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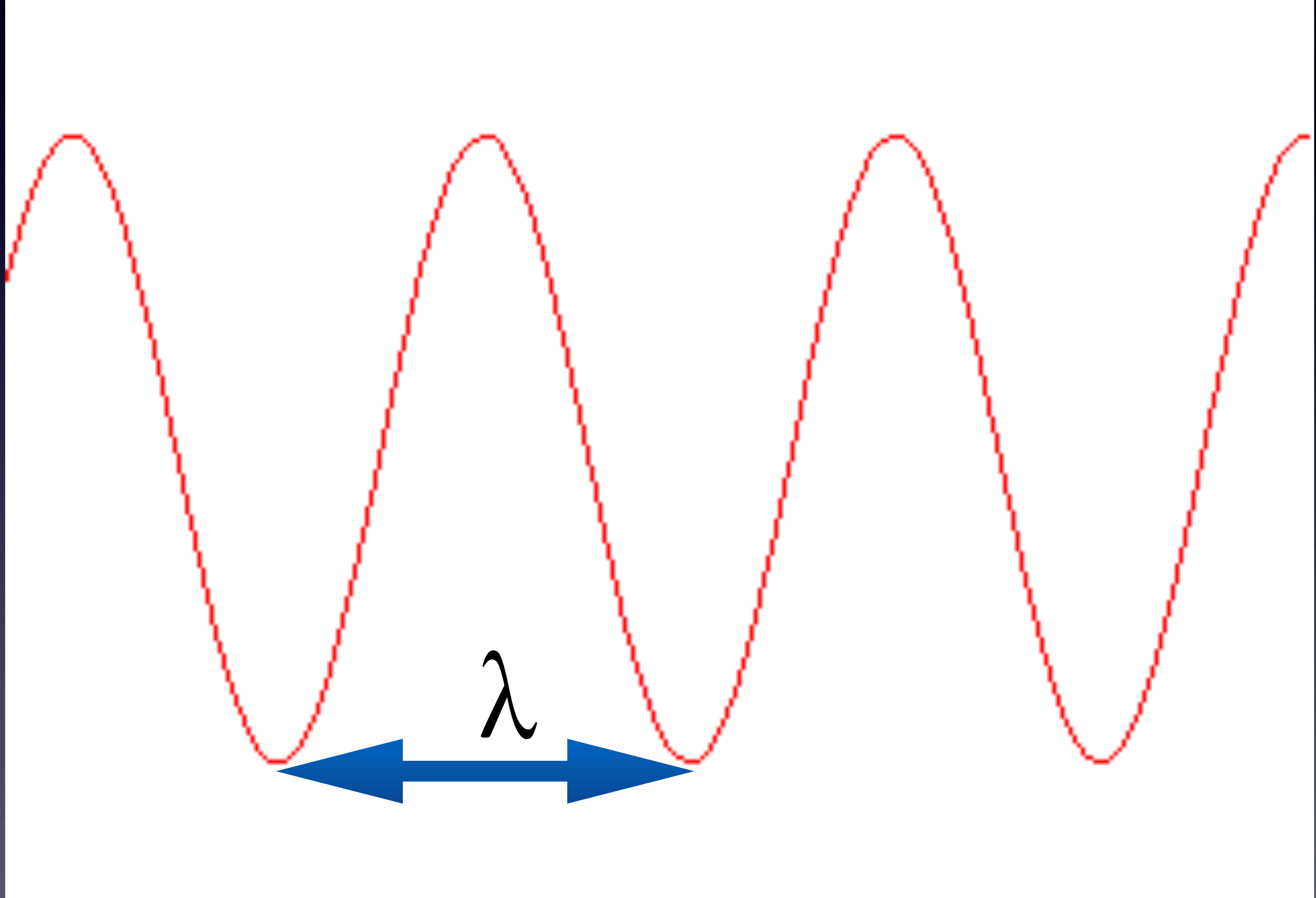
Linearization=> Waves

$$G_{\mu\nu} \approx \frac{1}{2}\left(-\frac{\partial^2}{c^2\,\partial t^2} + \nabla^2\right)h_{\mu\nu} = 0$$

speed of light

A conceptual problem*

Space is locally flat -> h=0 ??



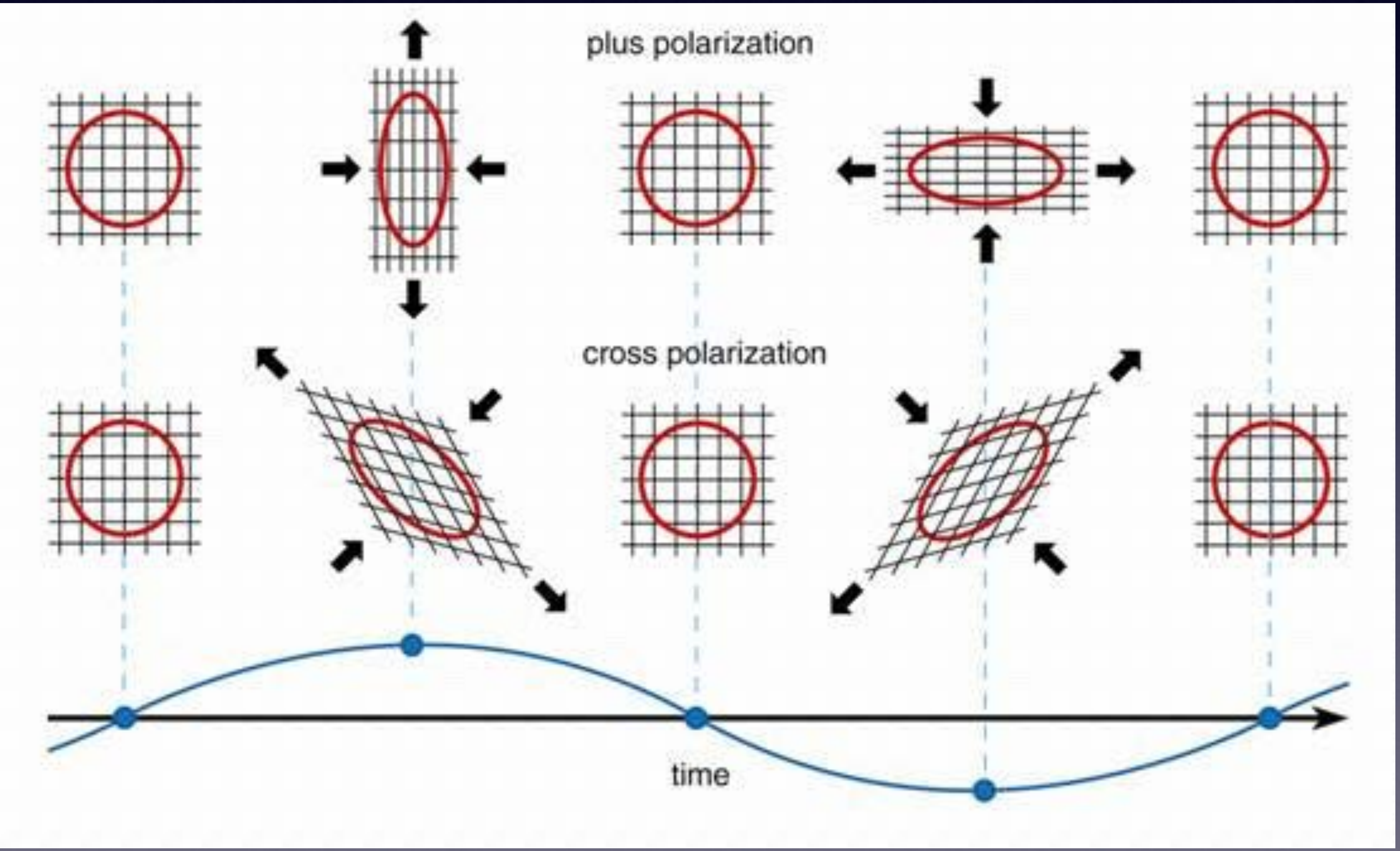
Space is locally flat on a scale << λ
But curved on scale λ

*Don't worry - This is a subtle point. The rest of the talk doesn't depend on it.

Tow Polarization modes

$$dl_x = h_+ dx$$

$$dl_y = -h_+ dy$$



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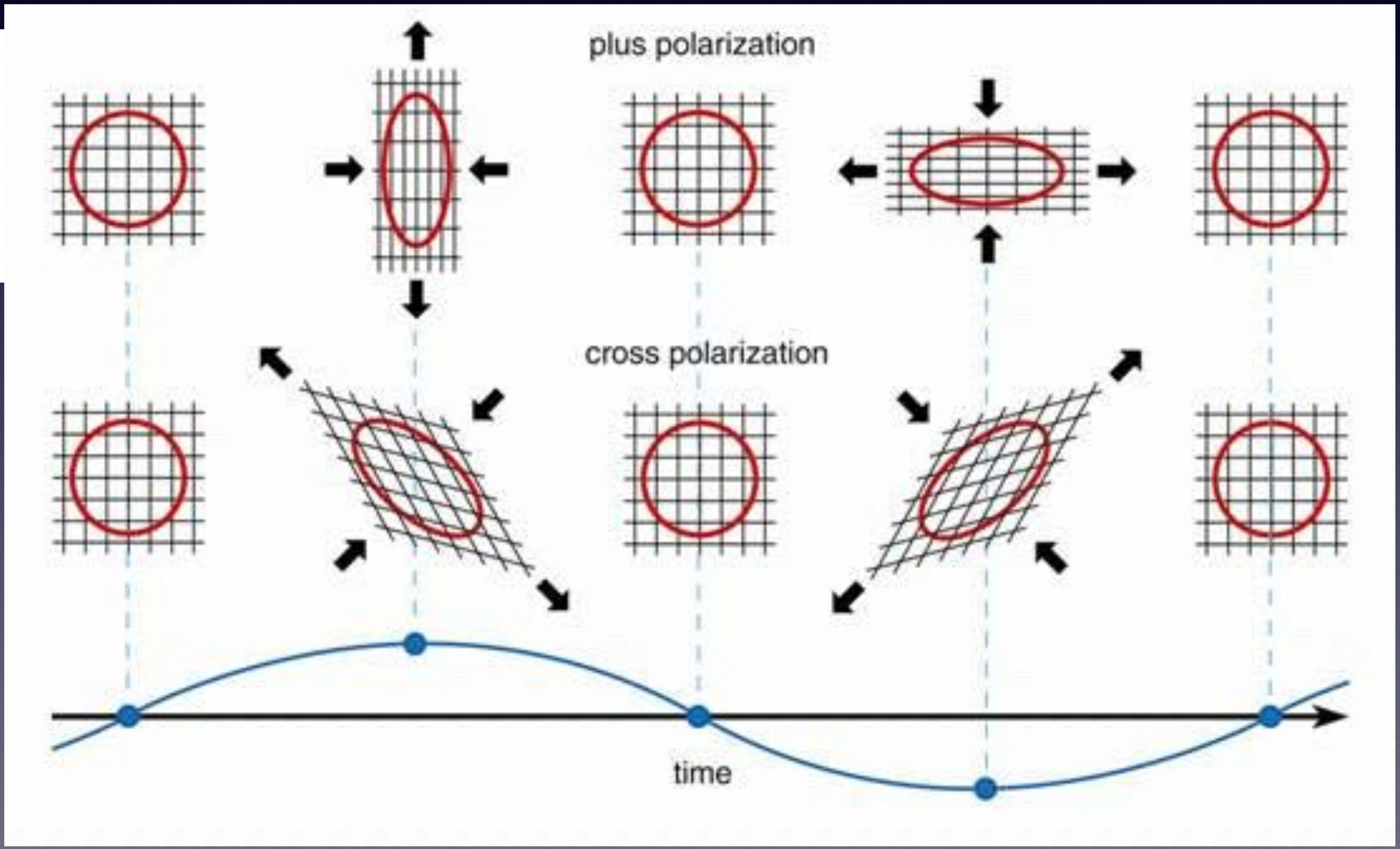

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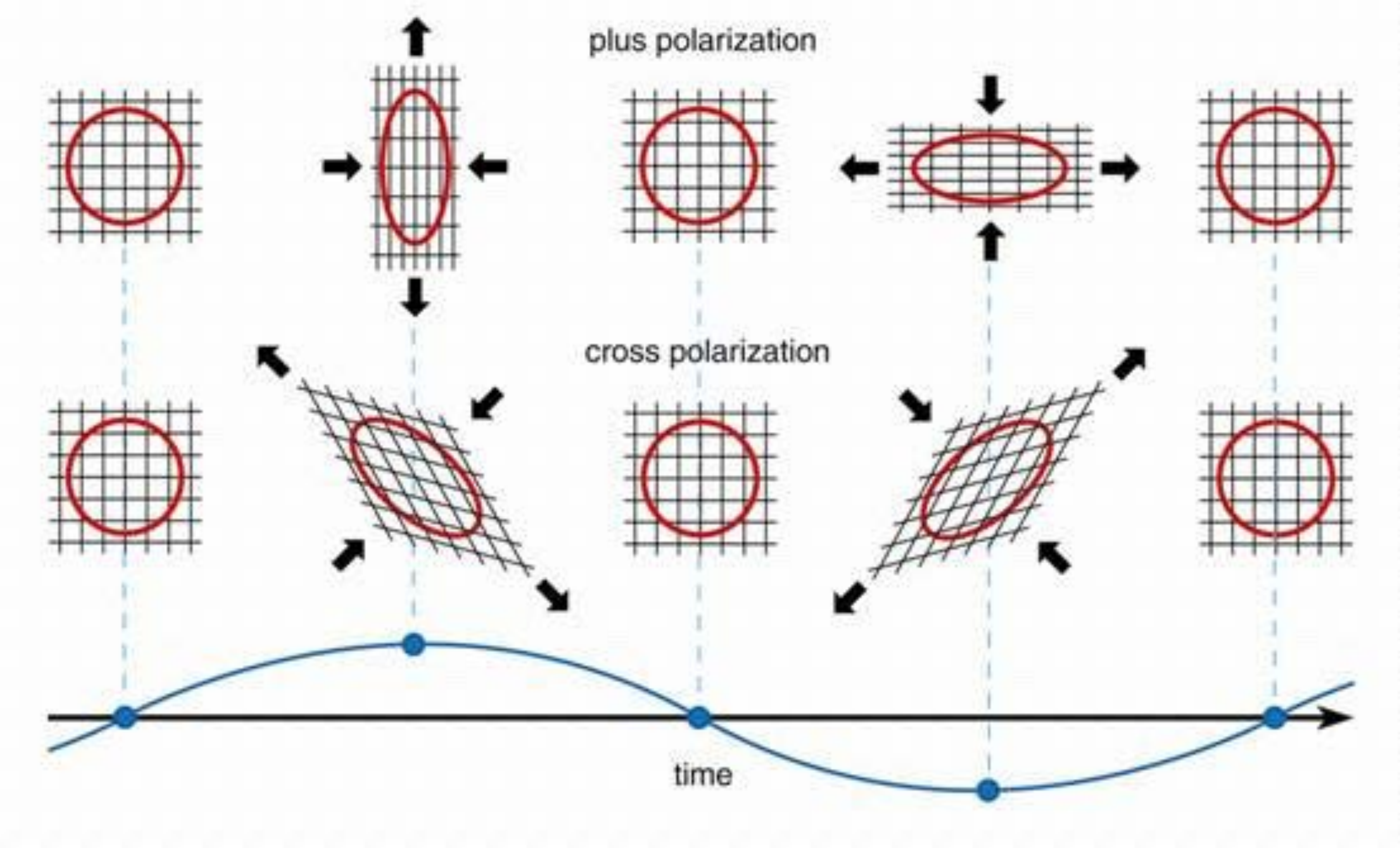

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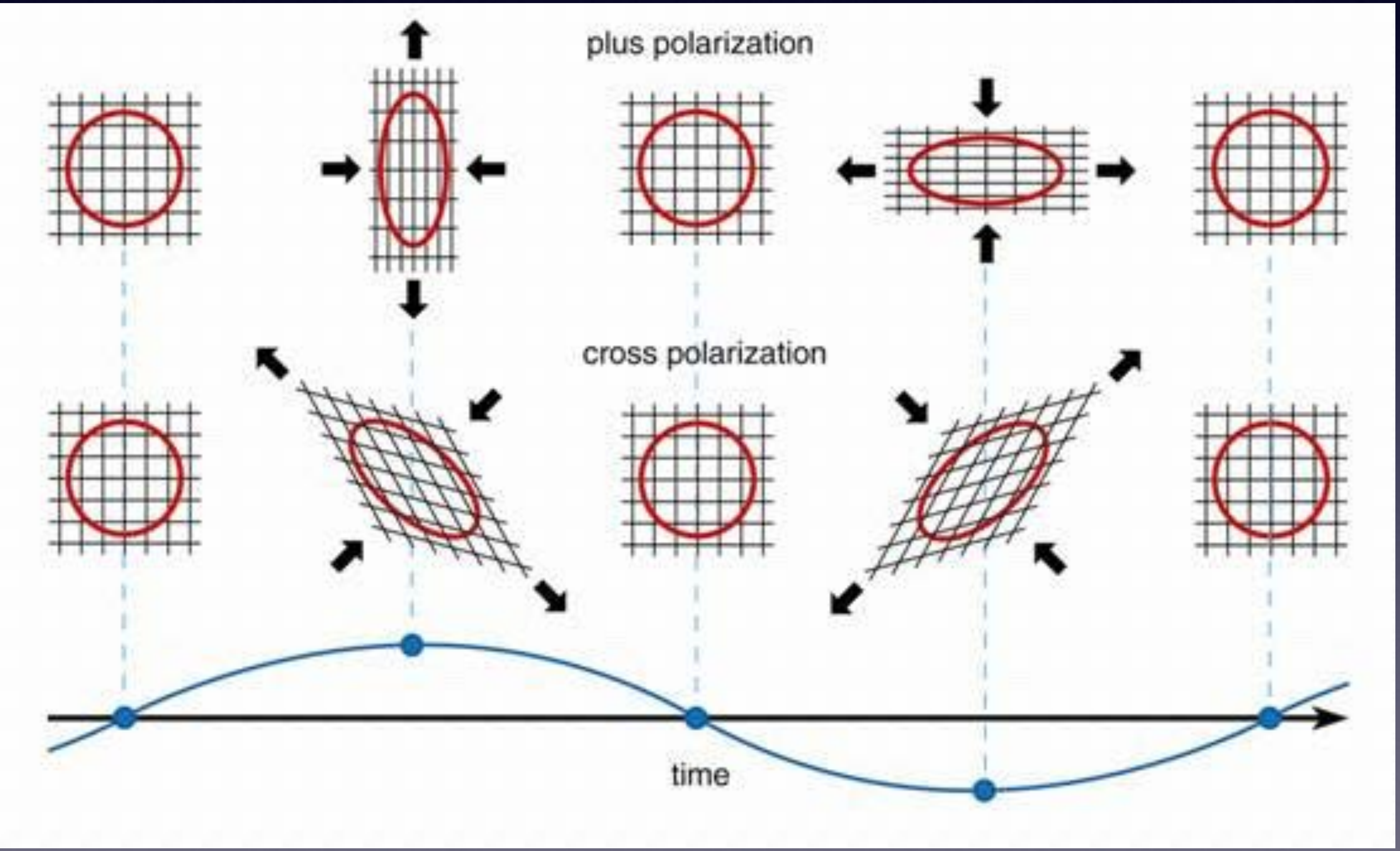


Energy Flux

$$F = \frac{c^3}{G}\left(\dot{h}_+^2 + \dot{h}_x^2\right)$$

Energy Flux

$$F = \frac{c^3}{G}(\dot{h}_+^2 + \dot{h}_x^2)$$

$$\sim 4 \cdot 10^{38} \, ergs/(cm^2 \sec)$$

Generation of Gravitational Waves

matter

$$G_{\mu\nu} \approx \frac{1}{2}\left(-\frac{\partial^2}{\partial t^2} + \nabla^2\right)h_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

The quadrupole Formula

3rd time derivative

reduce quadruple moment

$$L_{GW} = \frac{1}{5}\frac{G}{c^5}\dddot{Q}^2$$

the EM dipole formula

$$L_{em} = \frac{\ddot{d}^2}{c^3}$$

The quadrupole Formula

3rd time derivative

reduce quadruple moment

$$L_{GW} = \frac{1}{5}\frac{G}{c^5}\dddot{Q}^2$$

the EM dipole formula

$$L_{em} = \frac{\ddot{d}^2}{c^3}$$

Wrong but correct!!!

The quadrupole Formula

$$L_{GW} = \frac{1}{5}\frac{G}{c^5}\dddot{Q}^2$$

reduce quadruple moment - non symmetric

massive

$$L_{GW} \approx \frac{G}{c^5}\frac{M^2L^4}{T^6} \approx \frac{G}{c^2}\frac{M^2}{T^2}\left(\frac{v}{c}\right)^4$$

fast

The GW problem

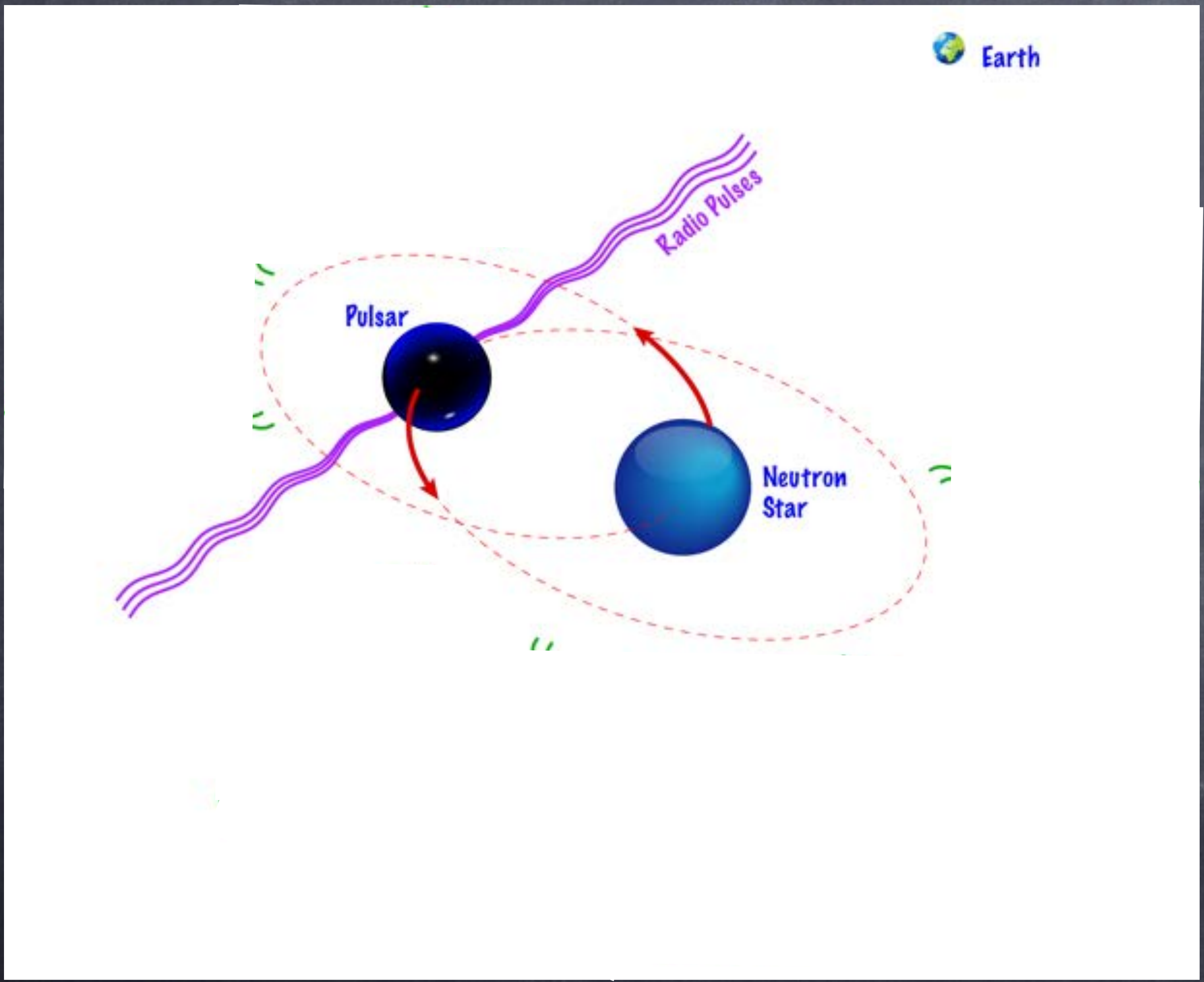
$$\frac{dl}{l} \equiv h \approx \varepsilon \frac{r_g}{d}$$

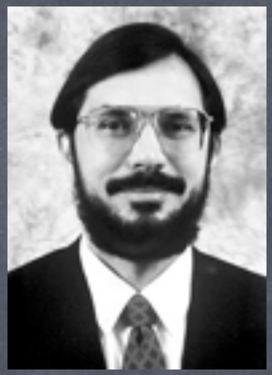
gravitational radius
~1 km for a solar mass

efficiency

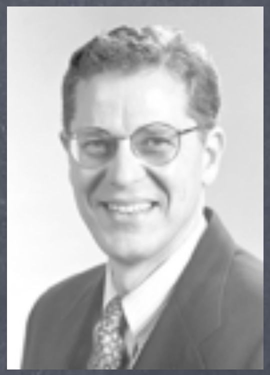
distance
~10^{17} km galactic
~10^{21}–10^{23} km extragalactic

1975 – Binary Neutron Stars



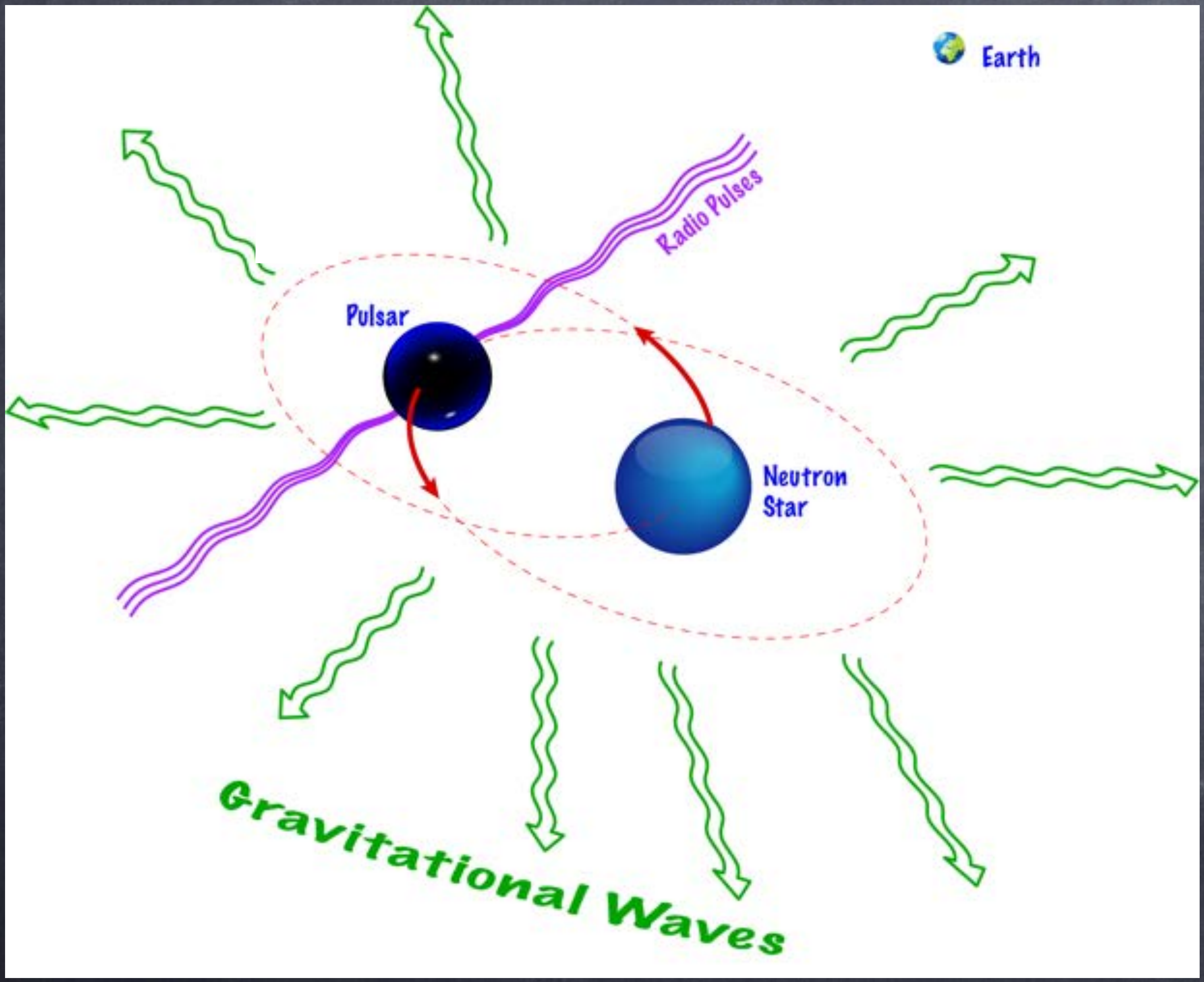


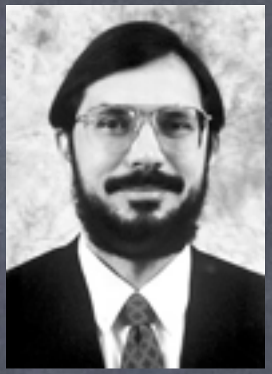
R. Hulse



J. Taylor

1975 - Binary Neutron Stars





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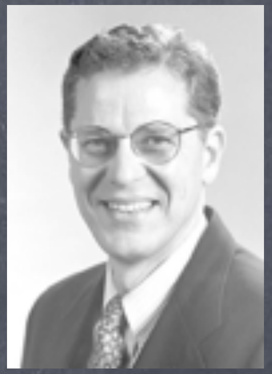
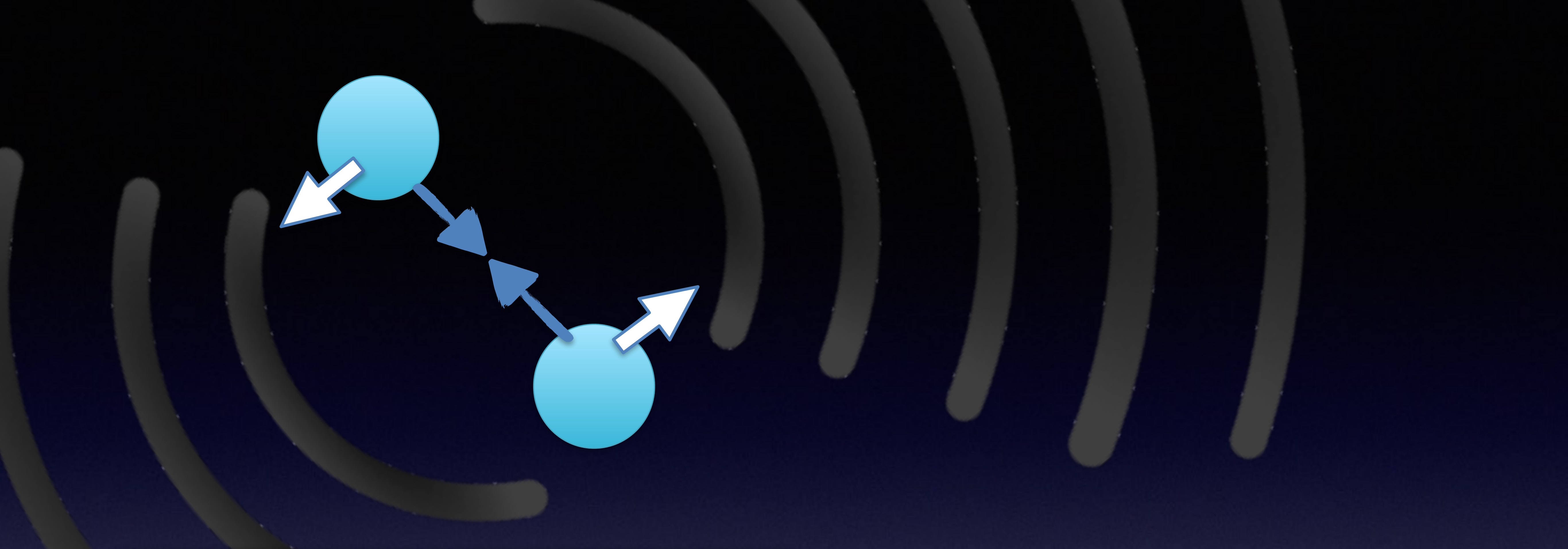


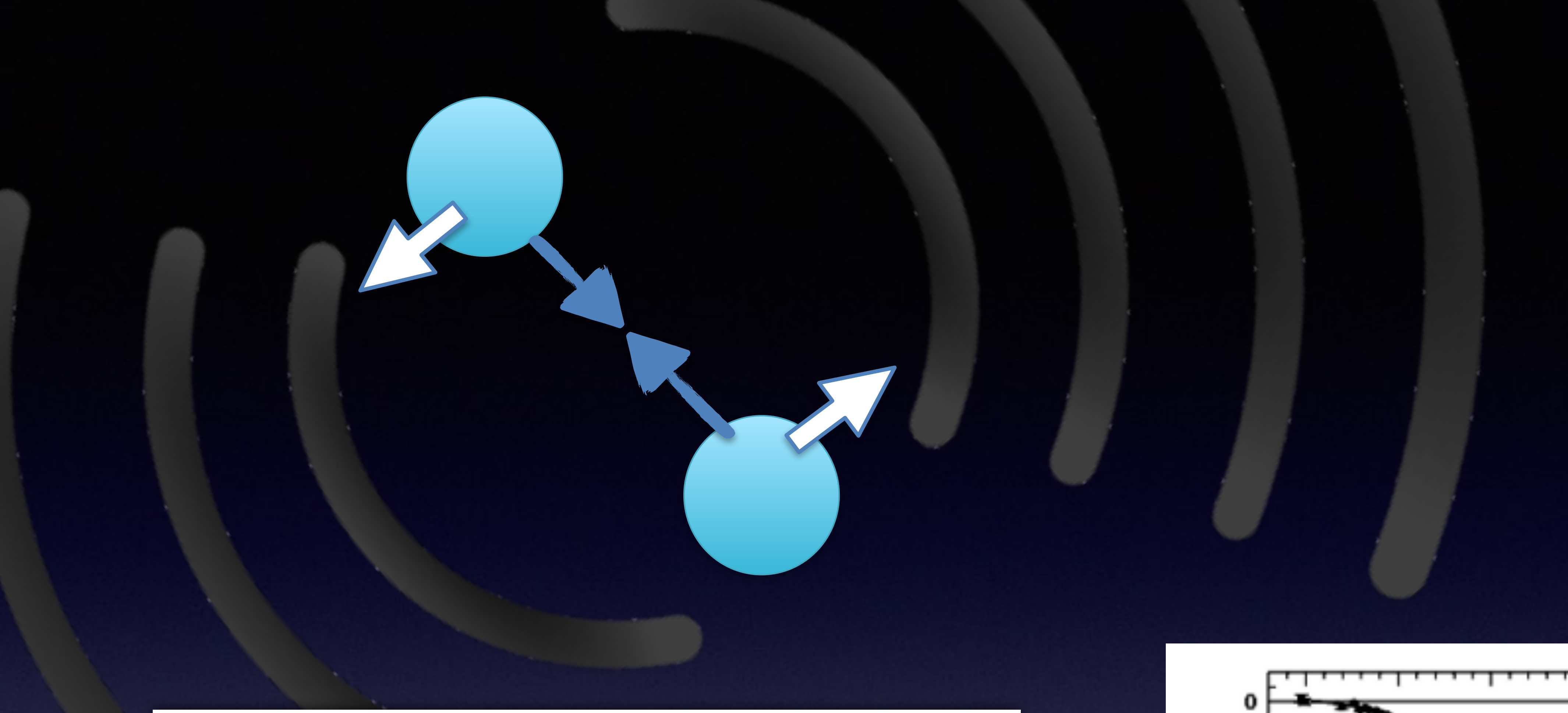
J. Taylor



$$E = -\frac{GM\mu}{2a}$$

$$\frac{dE}{dt} = -L_{GW} = -\frac{1}{5}\frac{G}{c^5}\dddot{Q}^2$$

$$\frac{1}{a}\frac{da}{dt} = -\frac{192}{15}\frac{G^3}{c^5}\frac{M^2\mu}{a^4}$$



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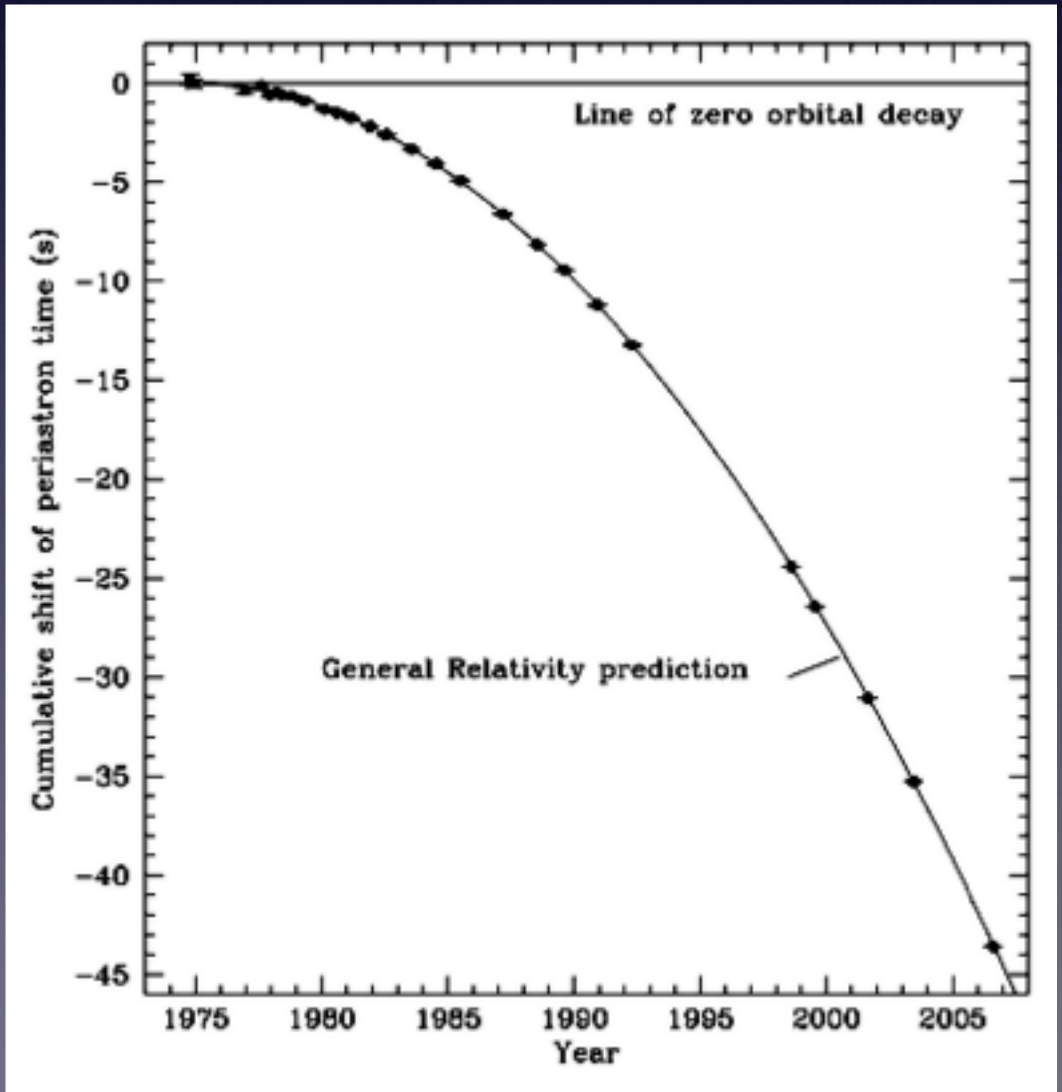
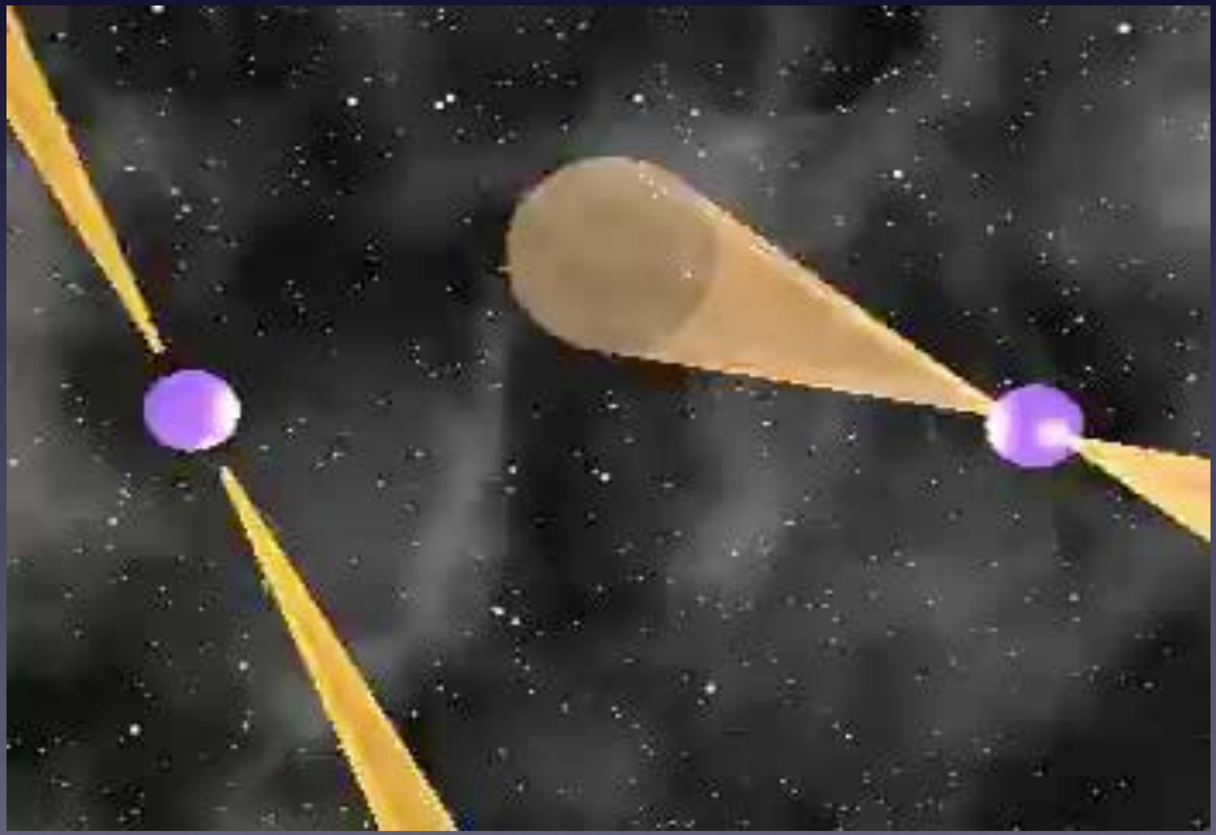
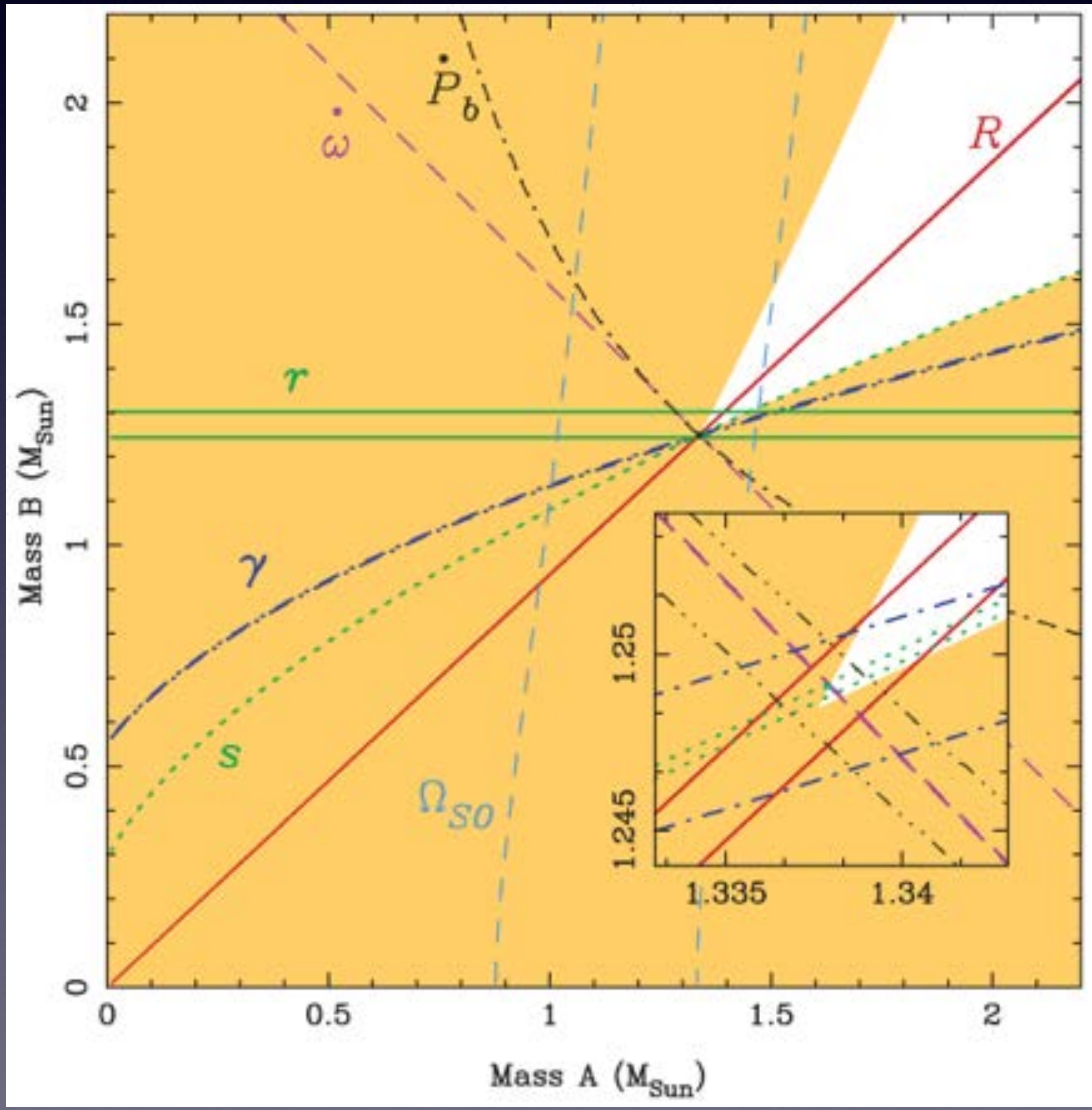
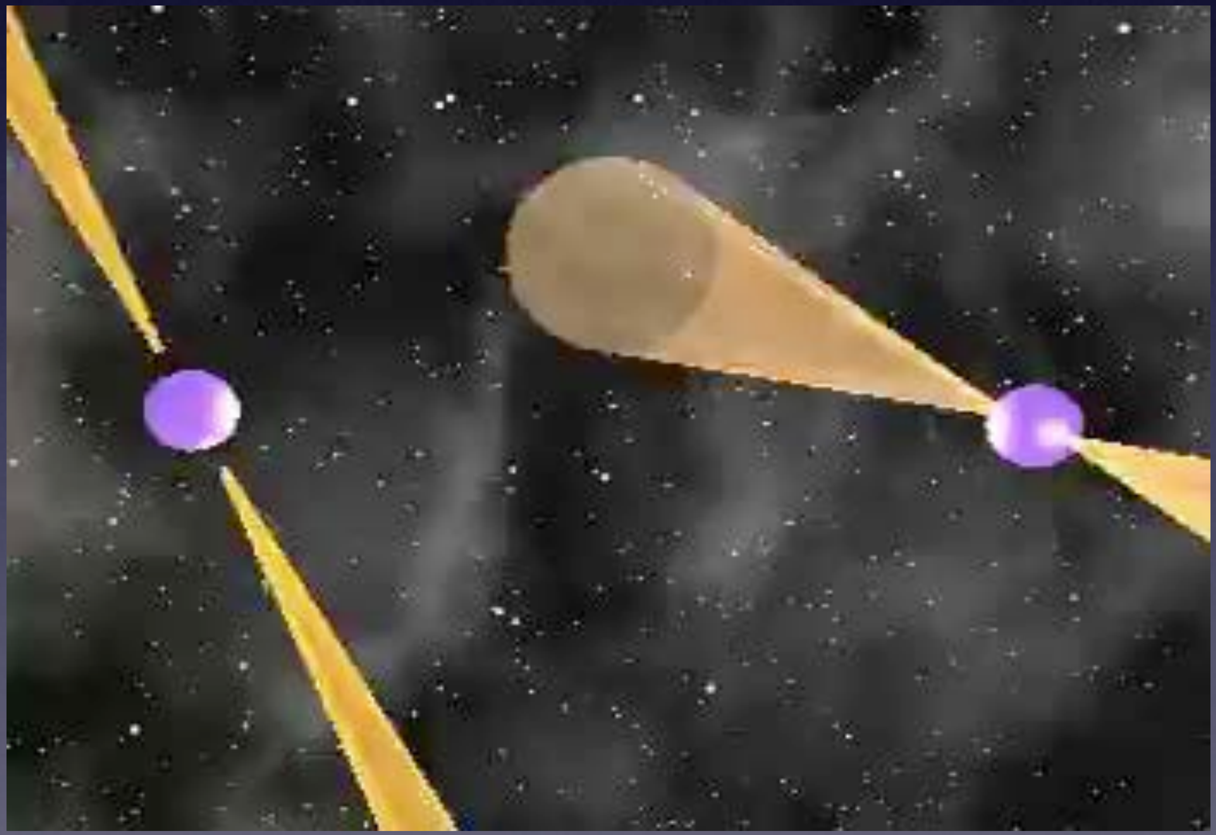


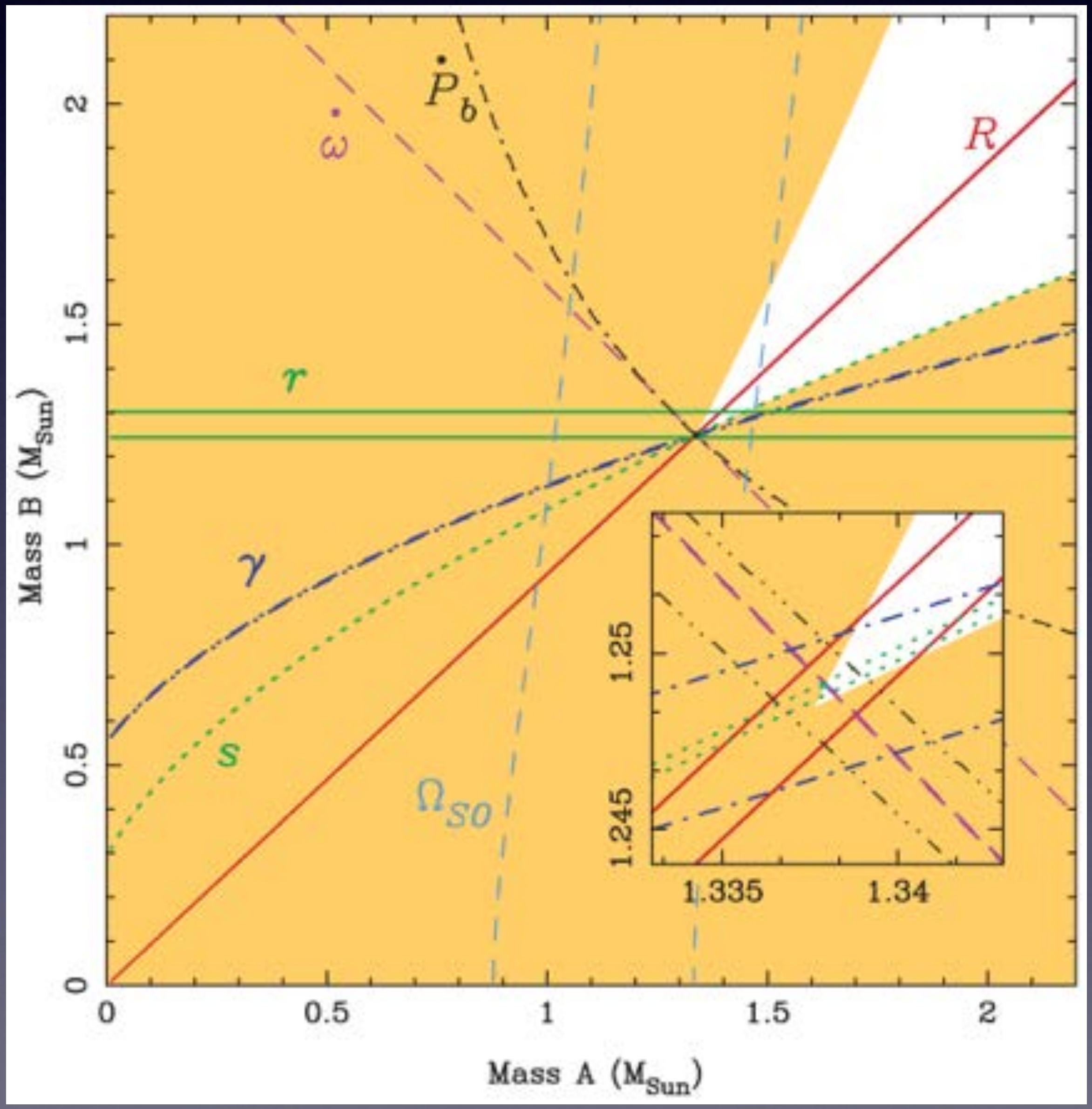
Consistency - the double pulsar



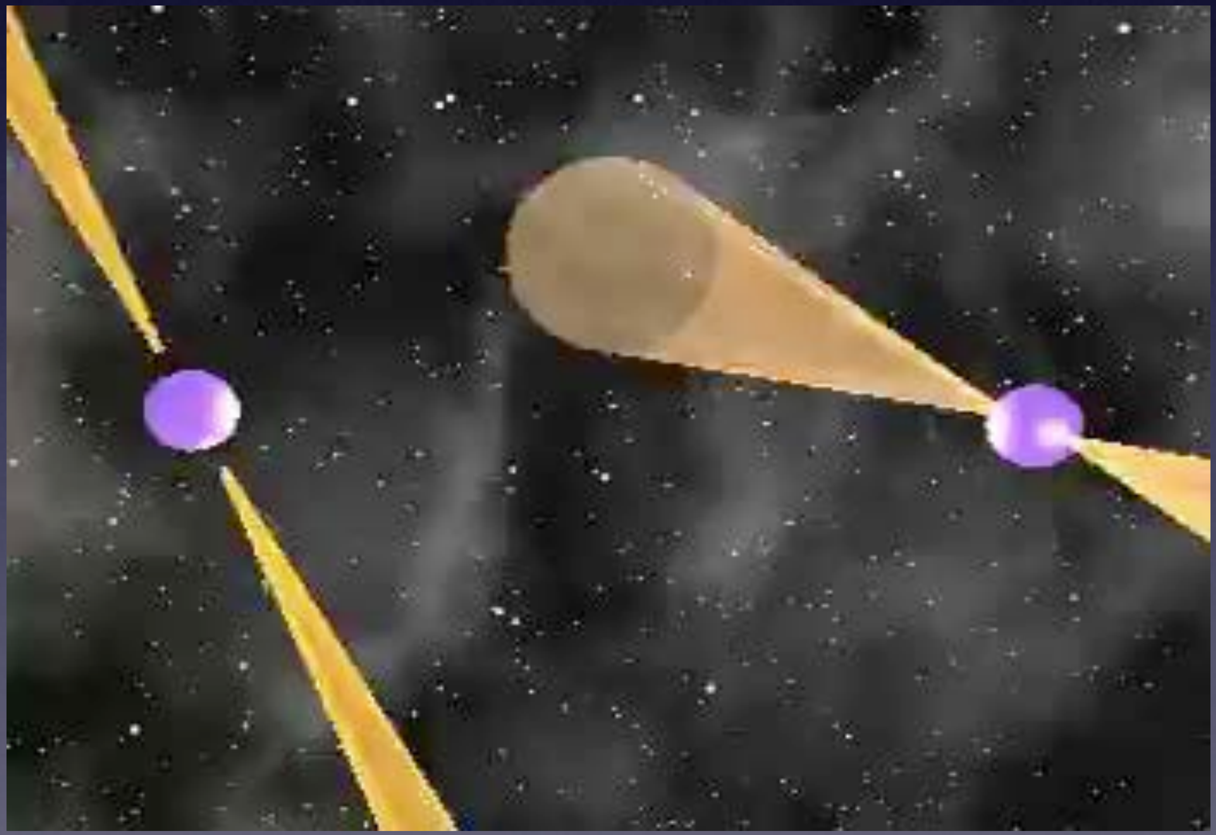


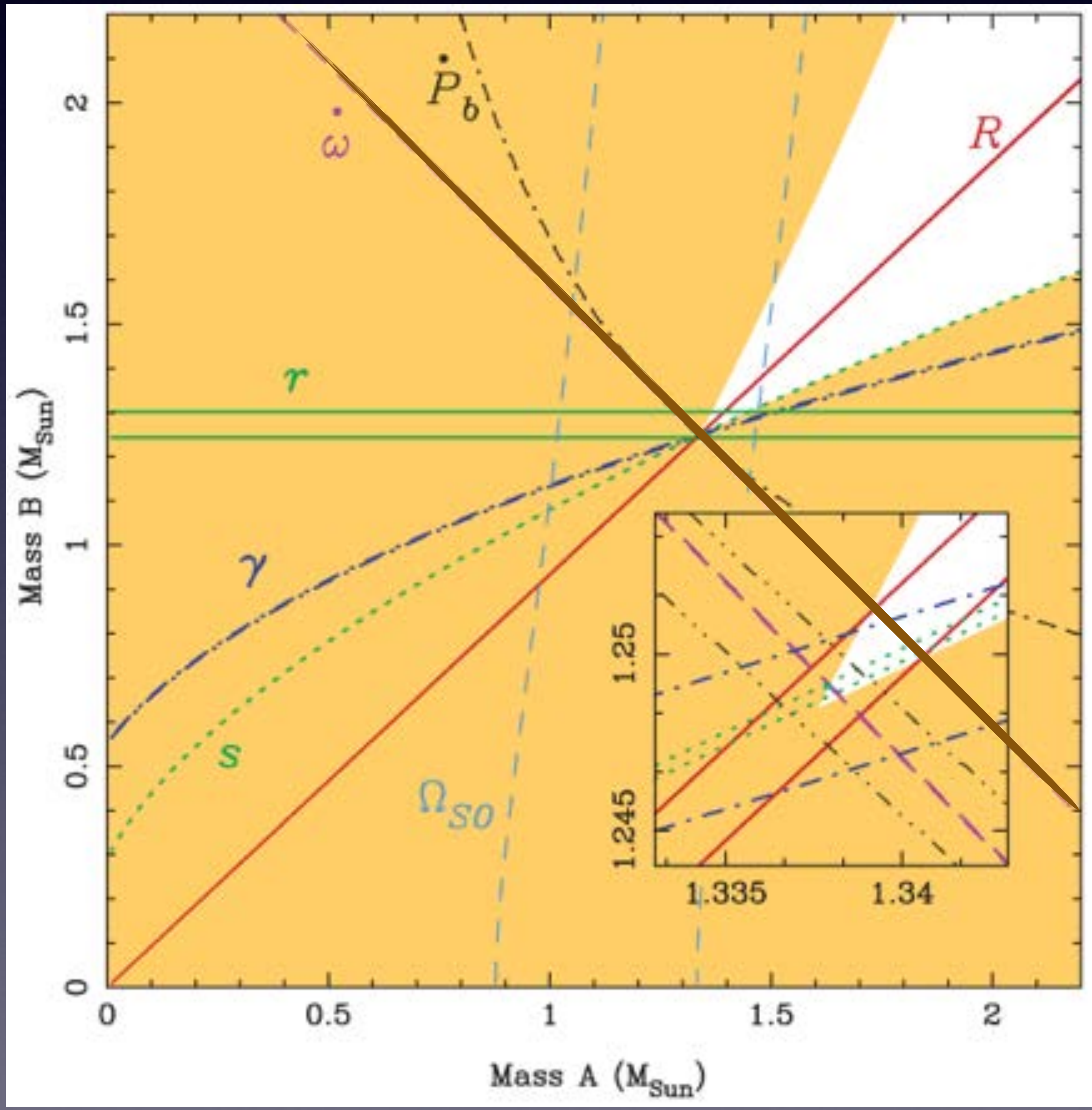
Consistency - the double pulsar



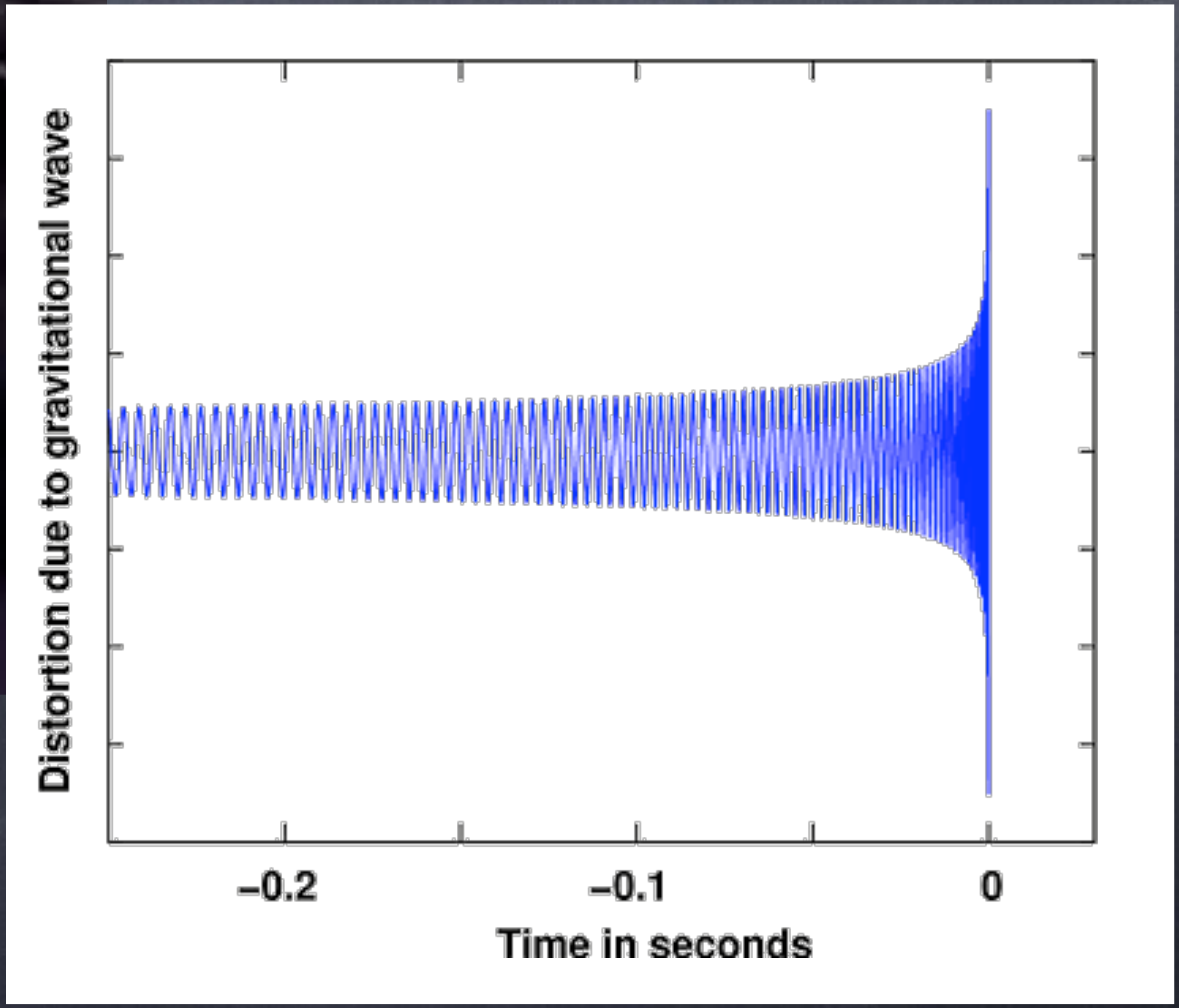


Consistency - the double pulsar



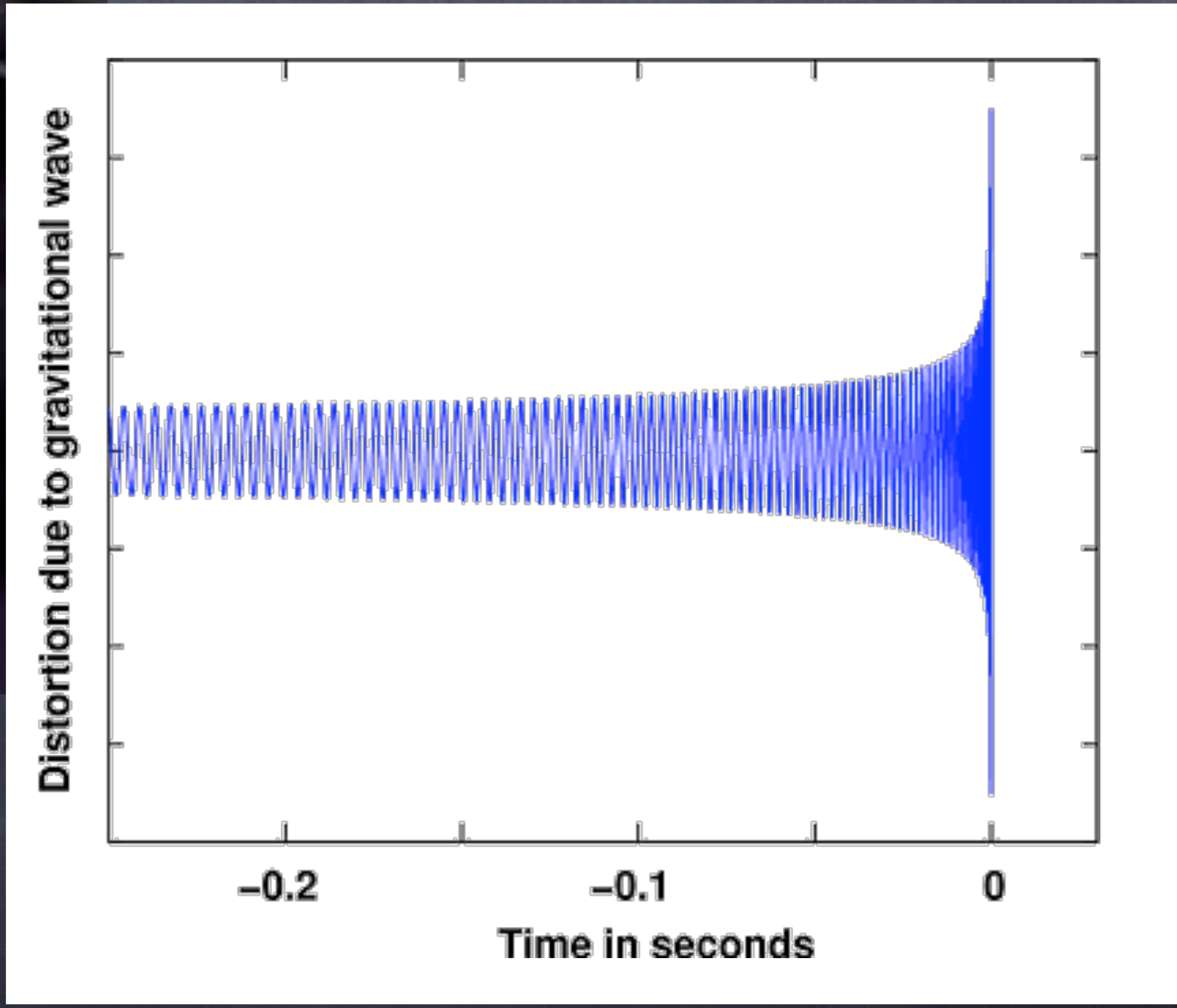


The Chirp



Distortion due to gravitational wave
−0.2
−0.1
0
Time in seconds

The Chirp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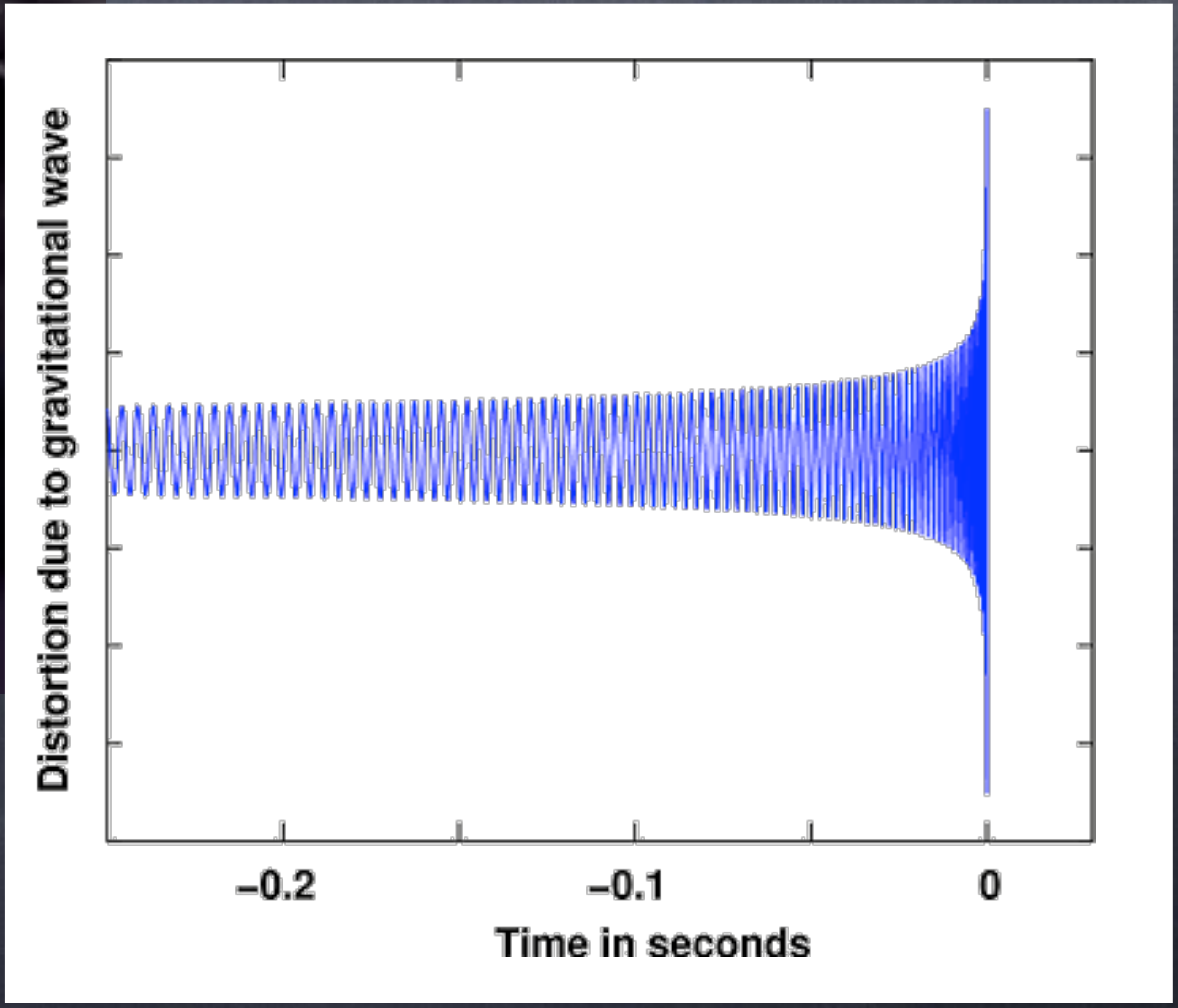

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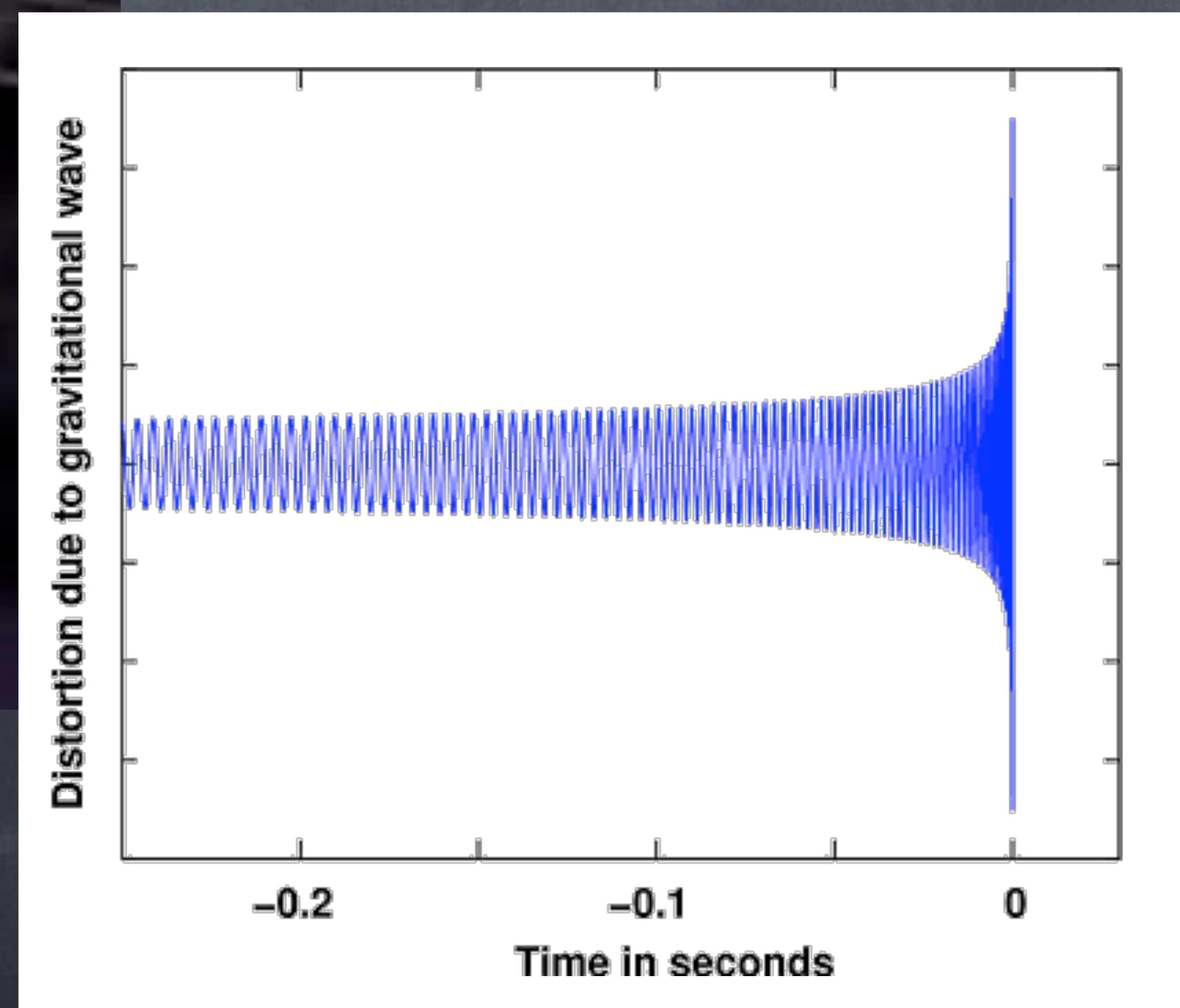
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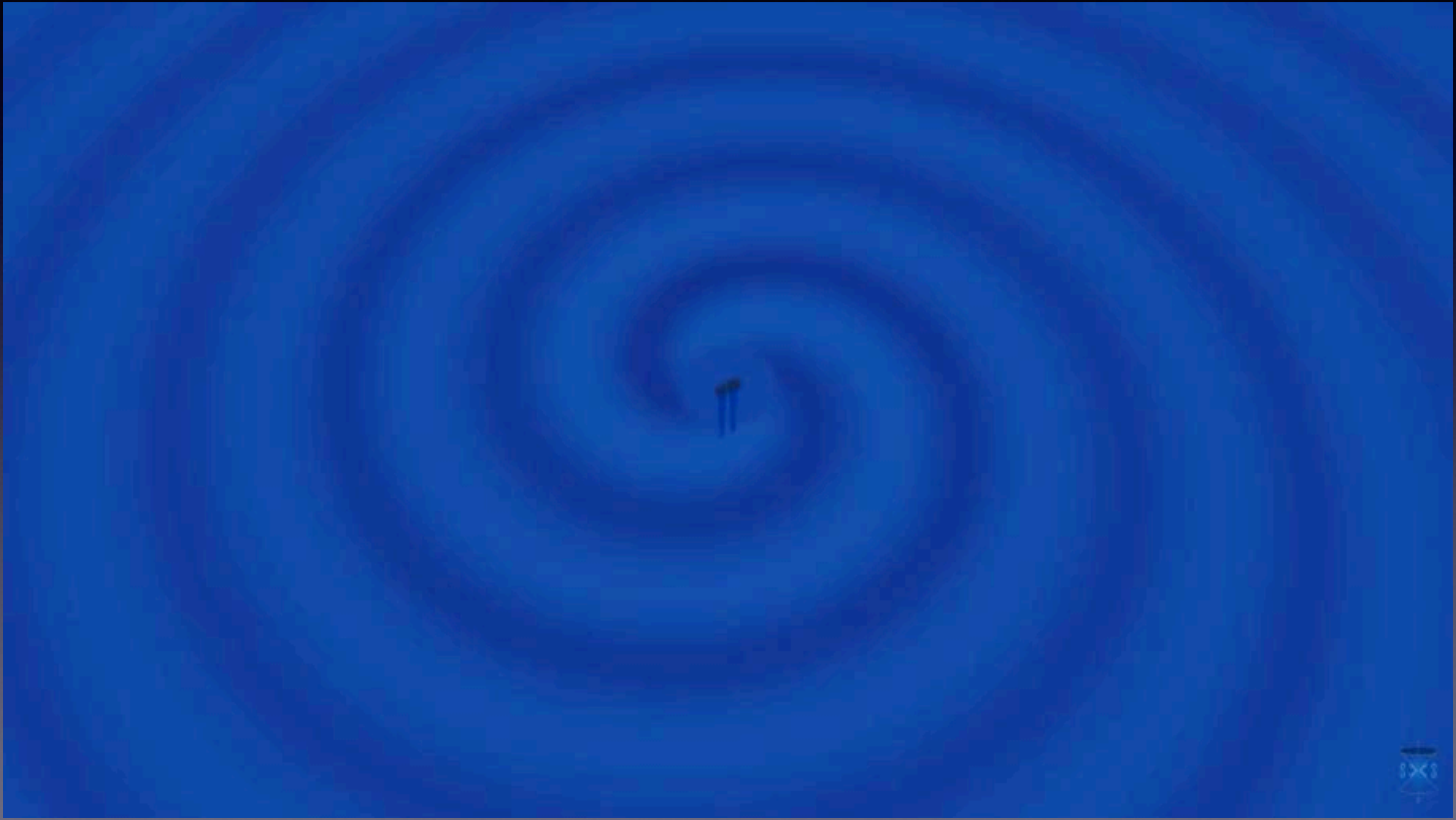
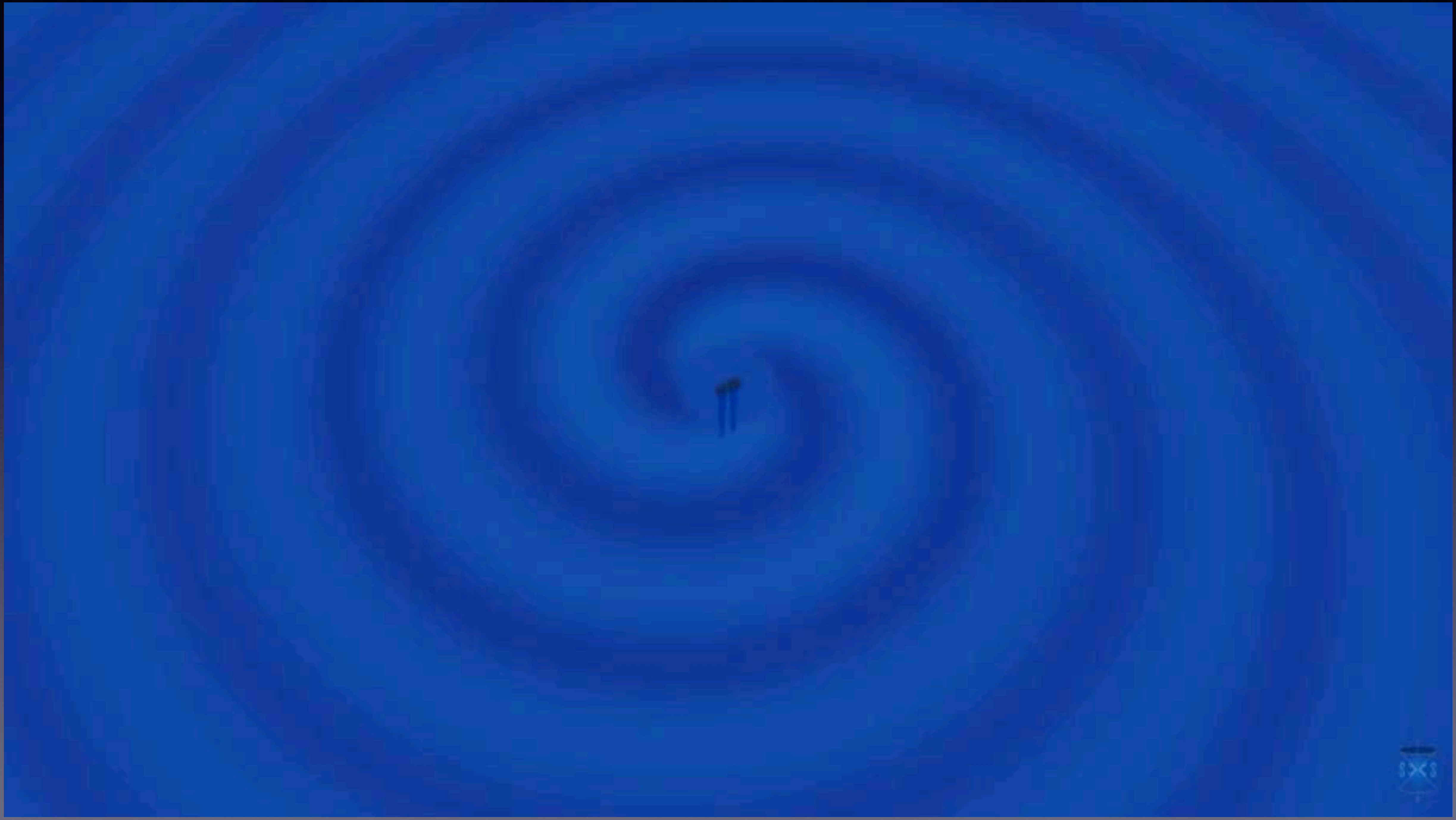


Source: ALIGO



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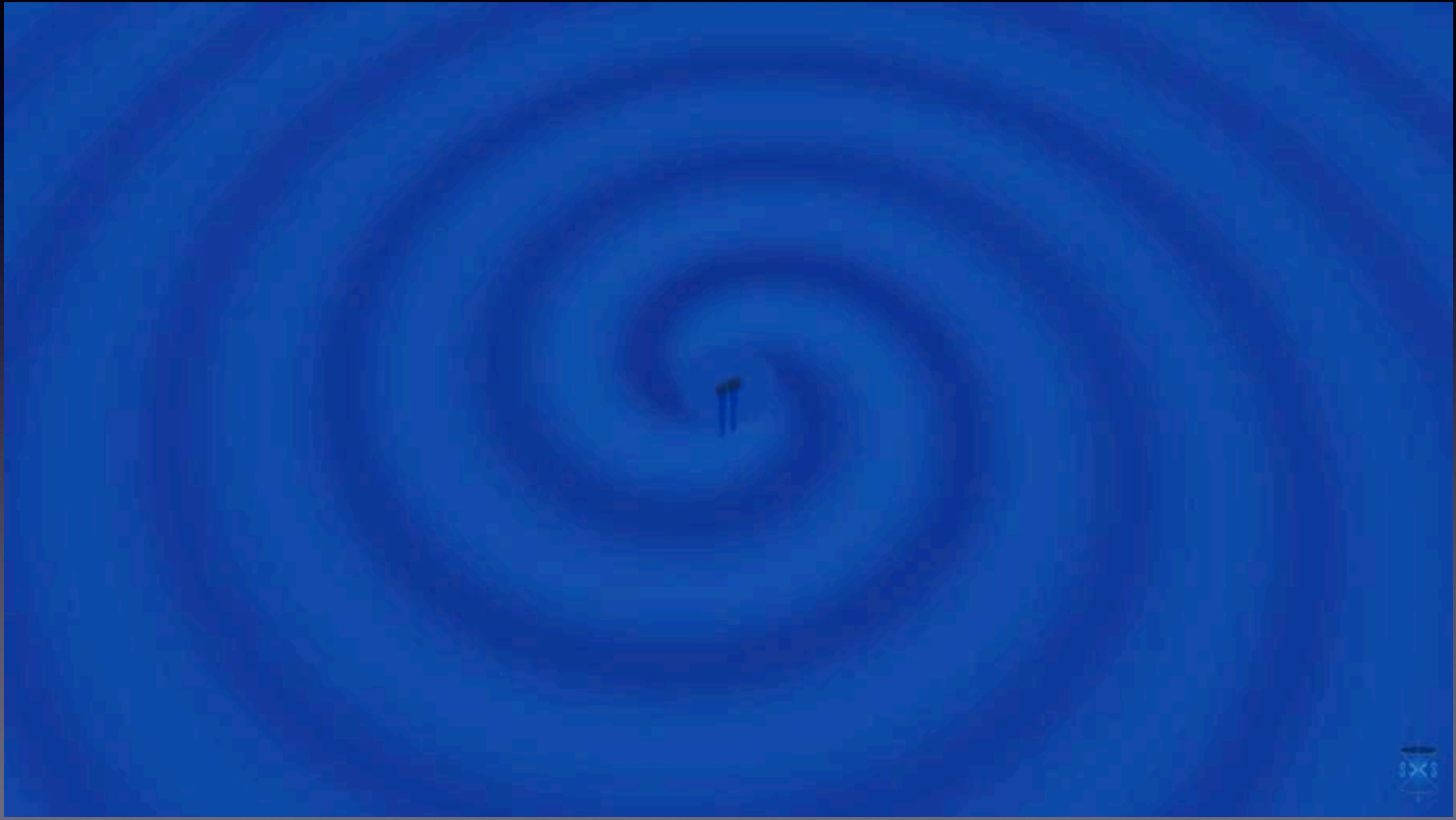

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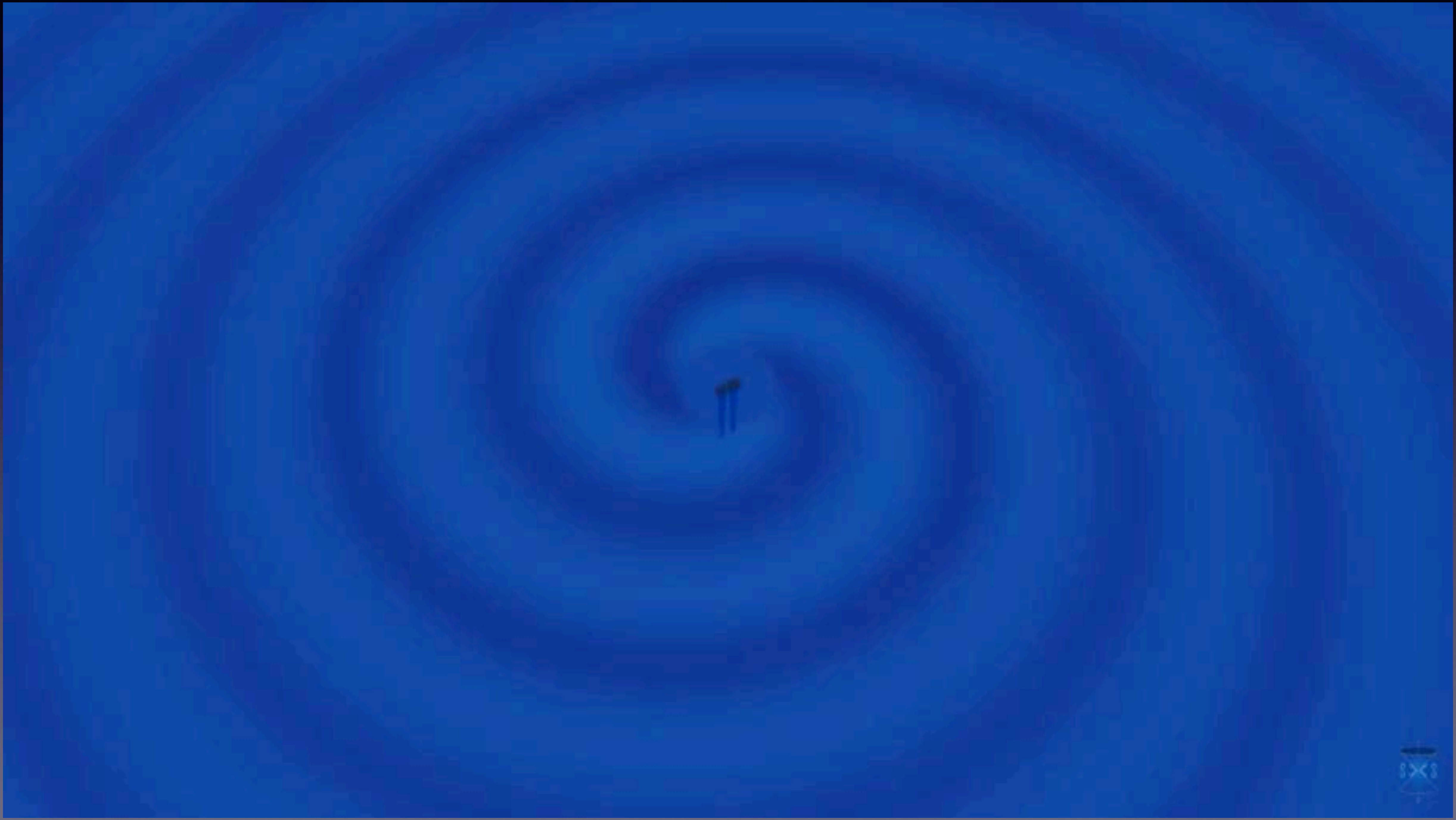
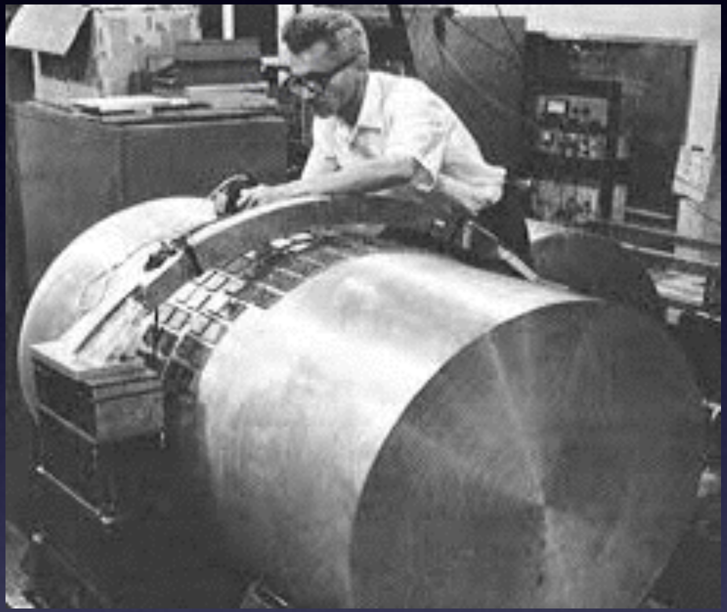
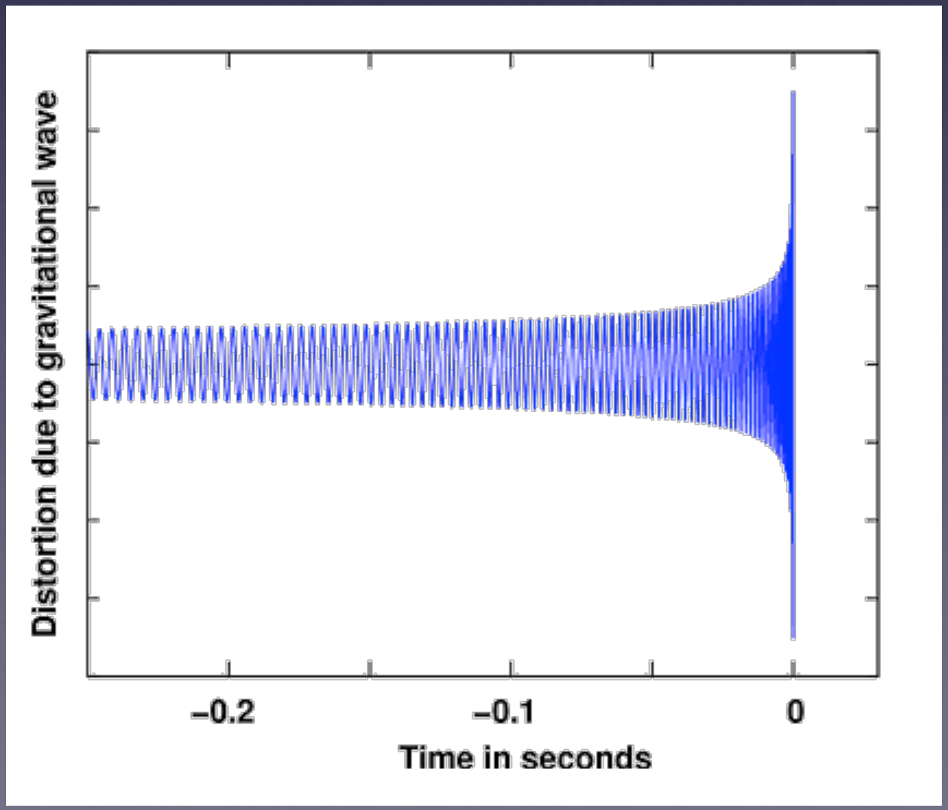


Source: ALIGO

GW Interferometers





Les Houches 1982


CENTRE DE PHYSIQUE DES HOUCHES

RAYONNEMENT GRAVITATIONNEL

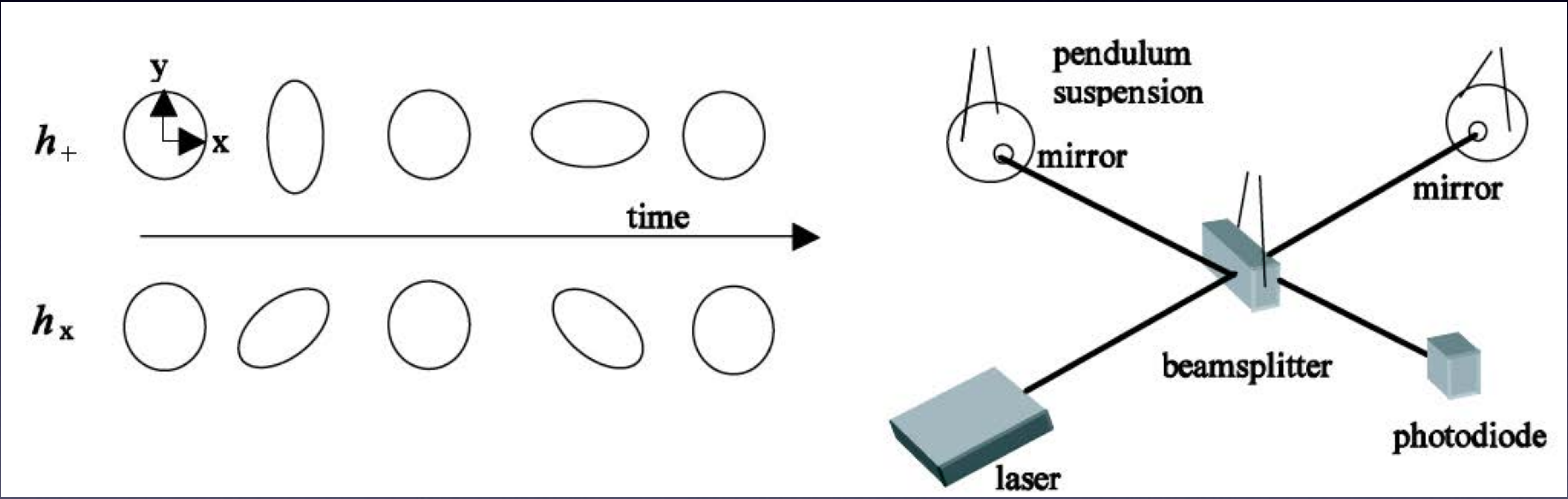
GRAVITATIONAL RADIATION

Ron Drever

Gravitational Radiation. Proceedings, Summer School, Nato Advanced Study Institute, Les Houches, France, June 2-21, 1982

N. Deruelle (ed.) (Poincare Inst.) , T. Piran (ed.) (Hebrew U.)

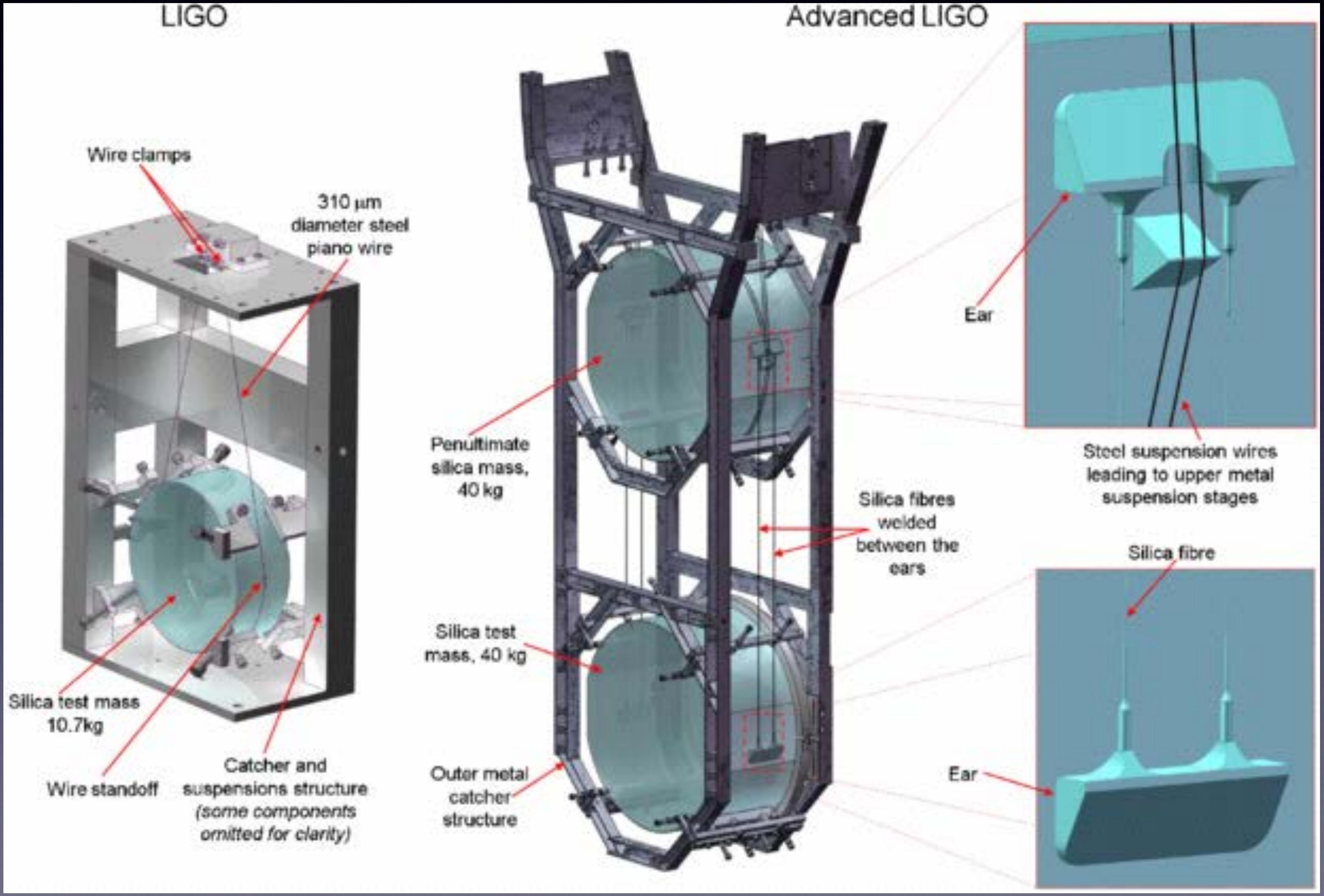
GW Interferometer

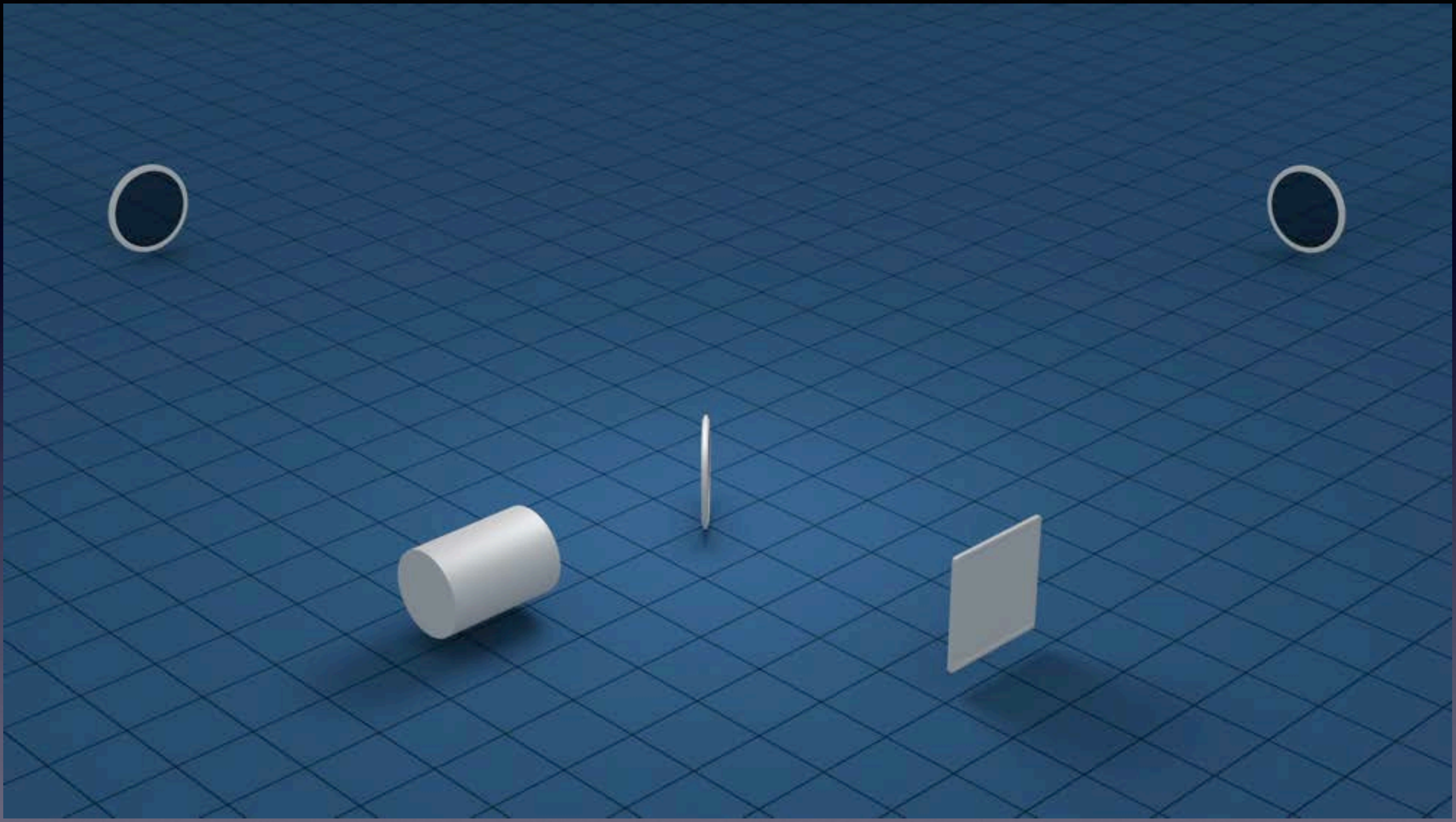


Source: Hogan et al.

Adv LIGO

Suspension


LIGO
Advanced LIGO
Wire clamps
310 μm diameter steel piano wire
Silica test mass 10.7kg
Wire standoff
Catcher and suspensions structure (some components omitted for clarity)
Penultimate silica mass, 40 kg
Silica test mass, 40 kg
Outer metal catcher structure
Silica fibres welded between the ears
Ear
Steel suspension wires leading to upper metal suspension stages
Silica fibre
Ear



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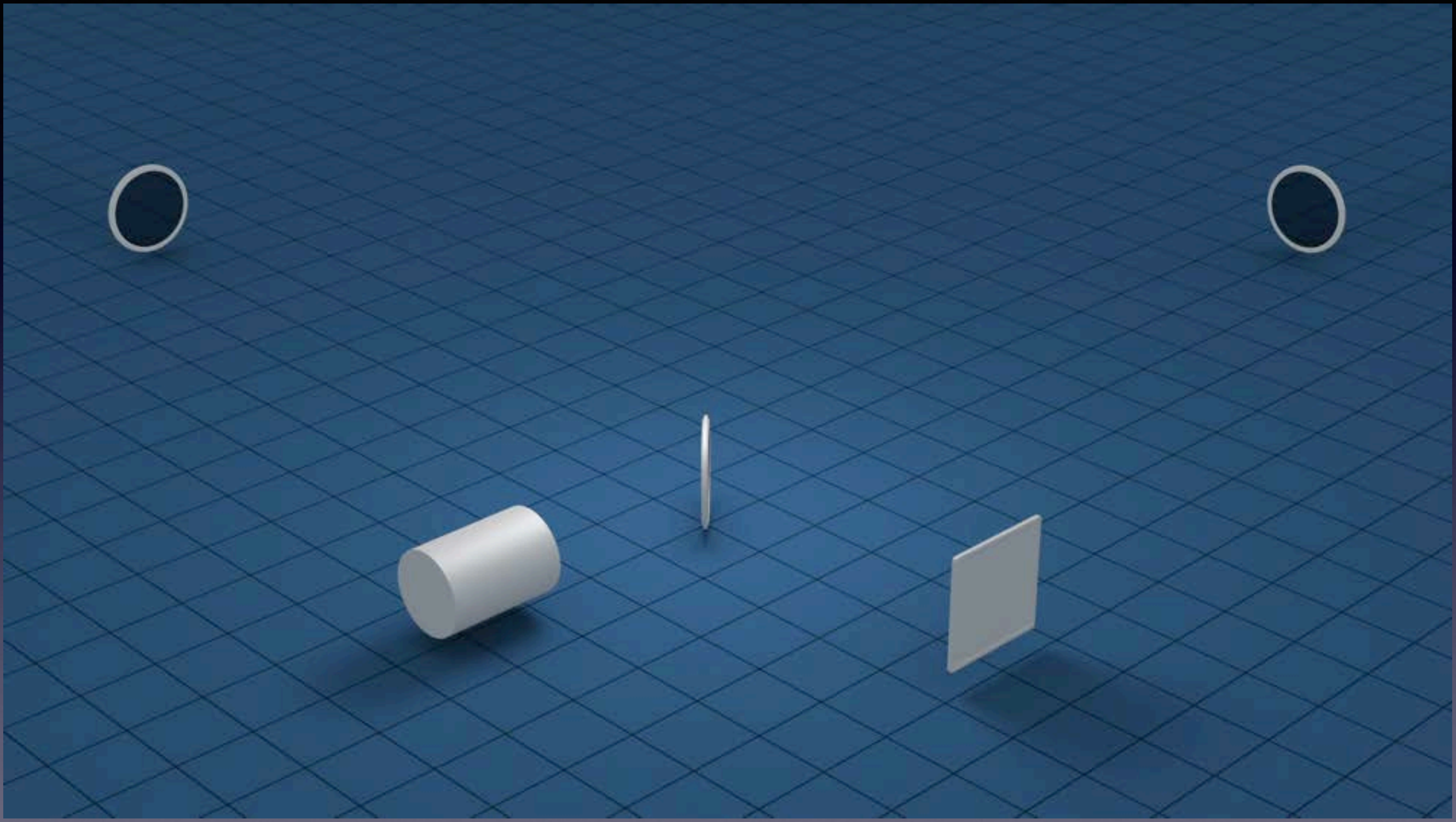

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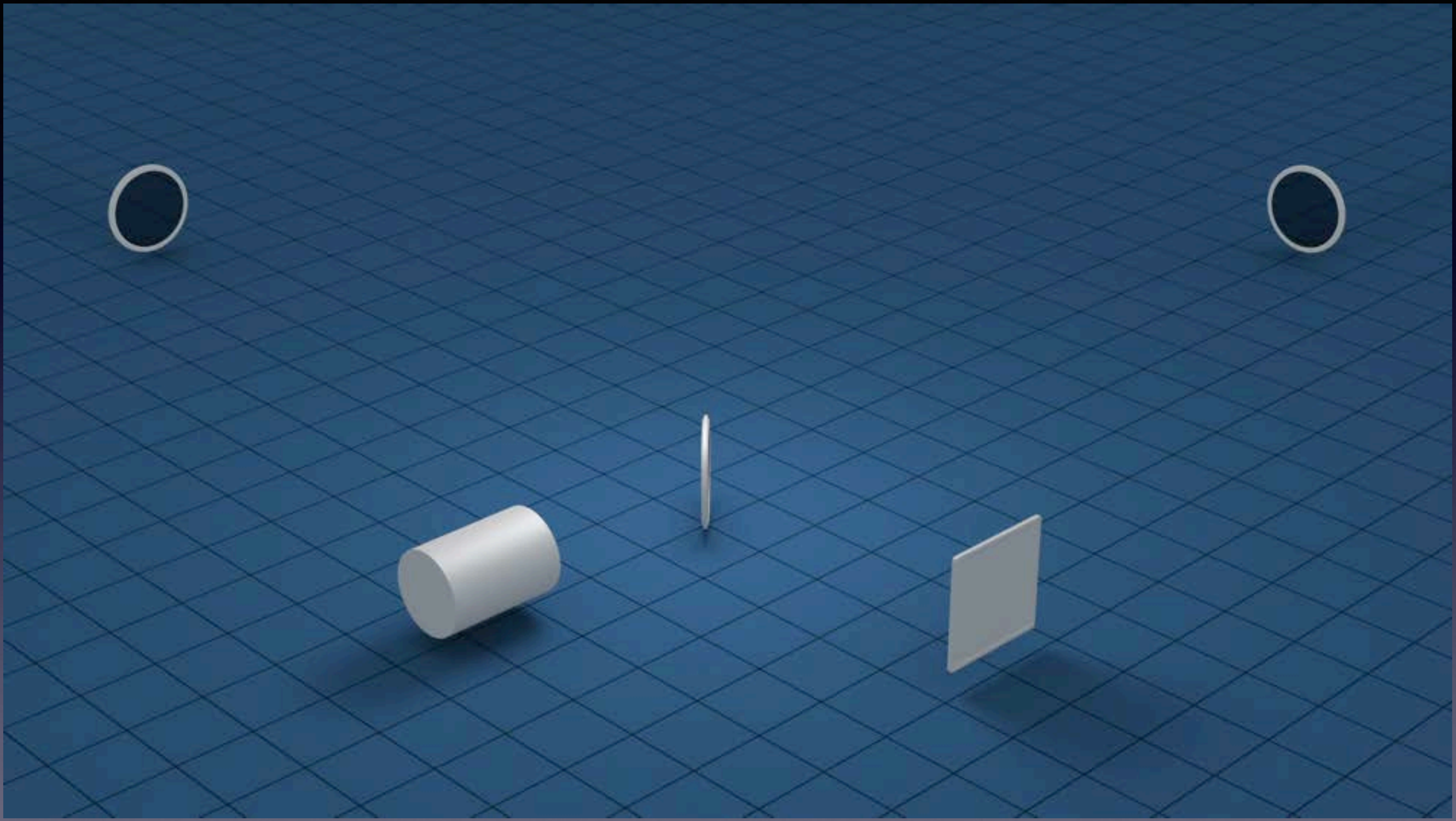
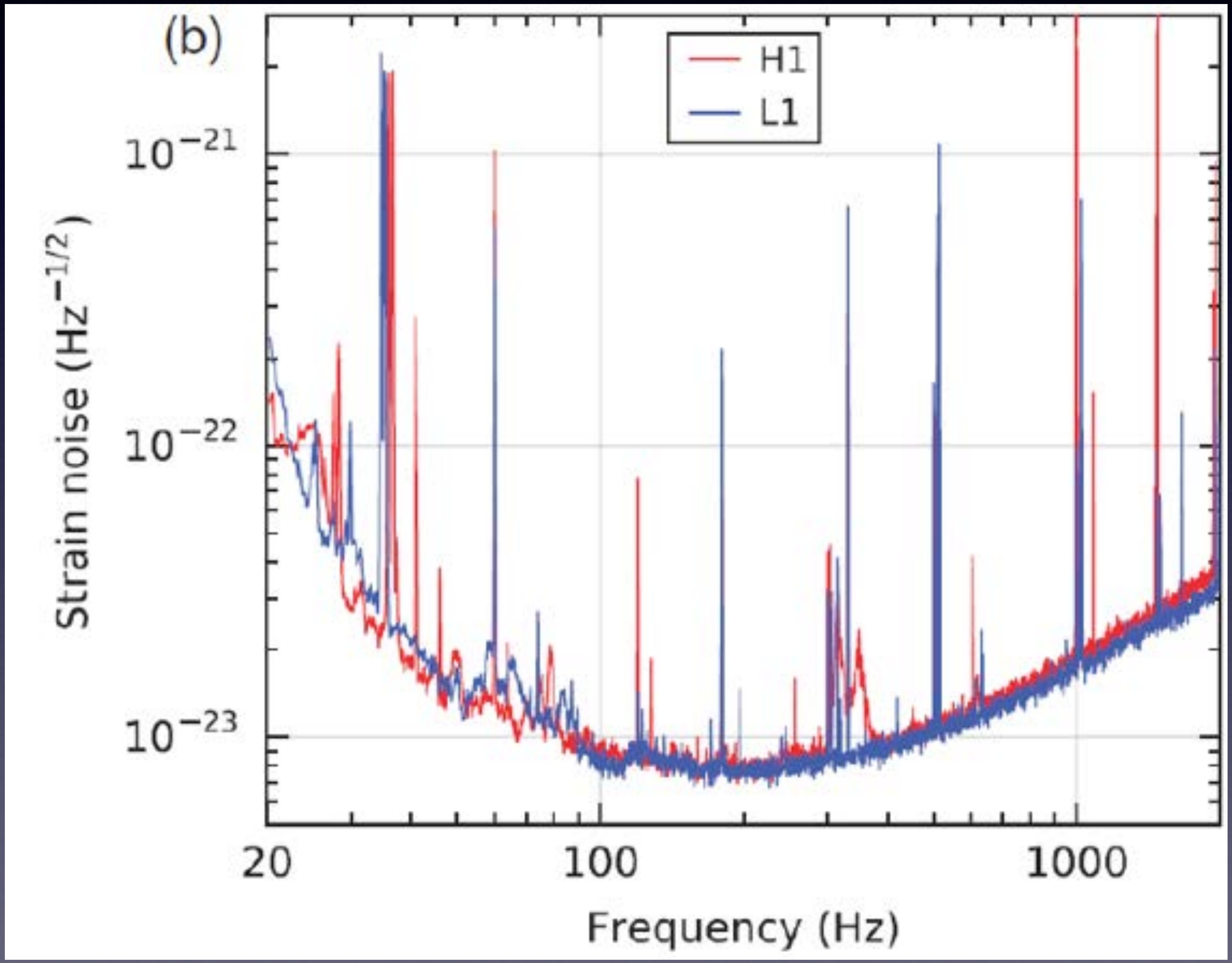


Source: ALIGO

LIGO Virgo and KAGRA

Adv LIGO sensitivity

- >150Hz shot noise
- Narrow features
  - Mirror suspension
  - power grid



Source: ALIGO

Adv LIGO's goal

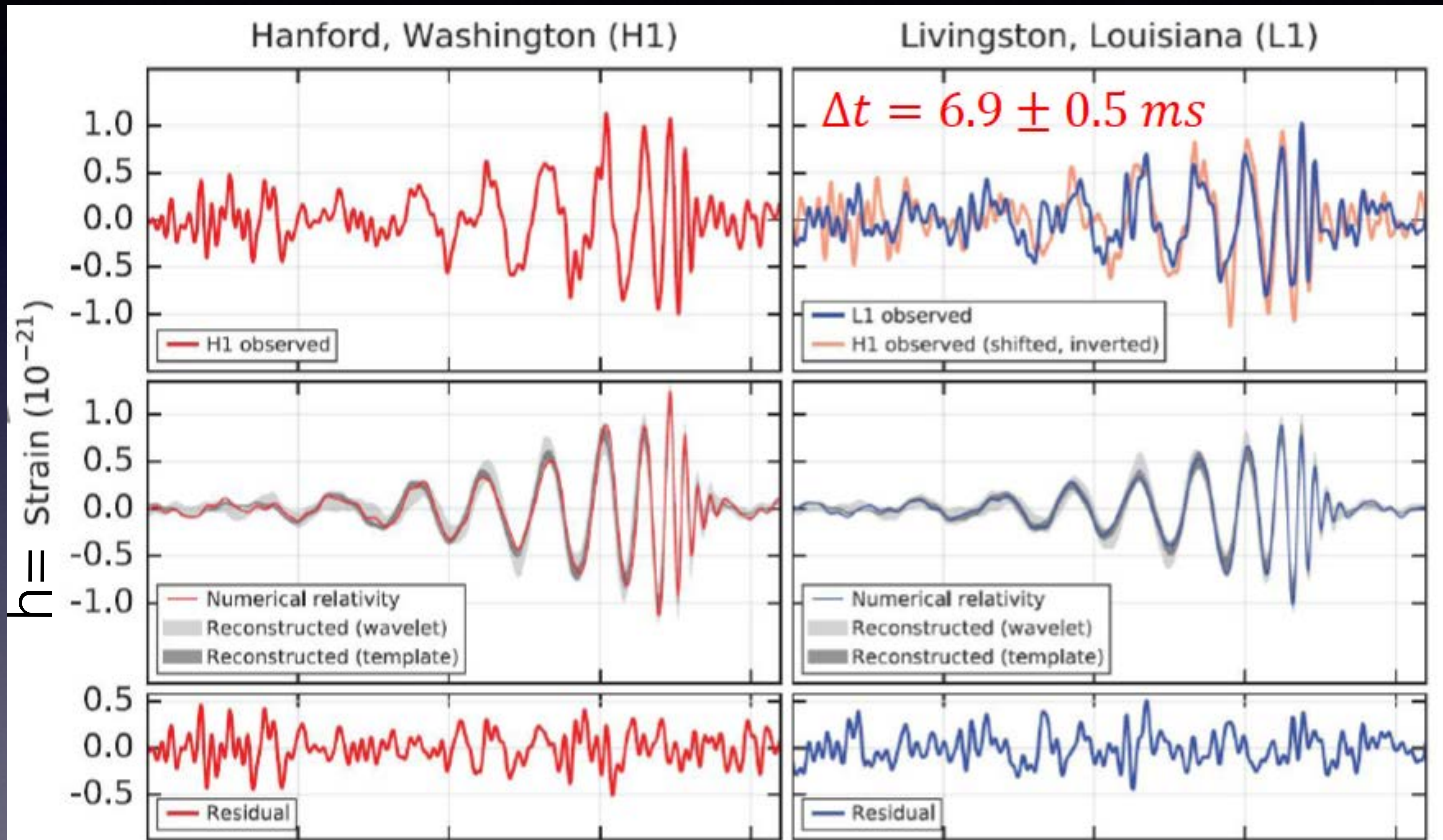
- Binary ns–ns exist
- ns^2 merger rate up to 300 Mpc 1–400 yr^{-1}

=> Reach sensitivity to detect ns^2 merger from 300Mpc by 2018

Adv LIGO was switched on for the first scientific Run on Sept 12 2015

Abbott, B. P., et al. (LIGO Scientific Collaboration, Virgo Collaboration). Observation of gravitational waves from a Binary Black Hole Merger. Phys. Rev. Lett., 116, 061102, 2016.

GW150914

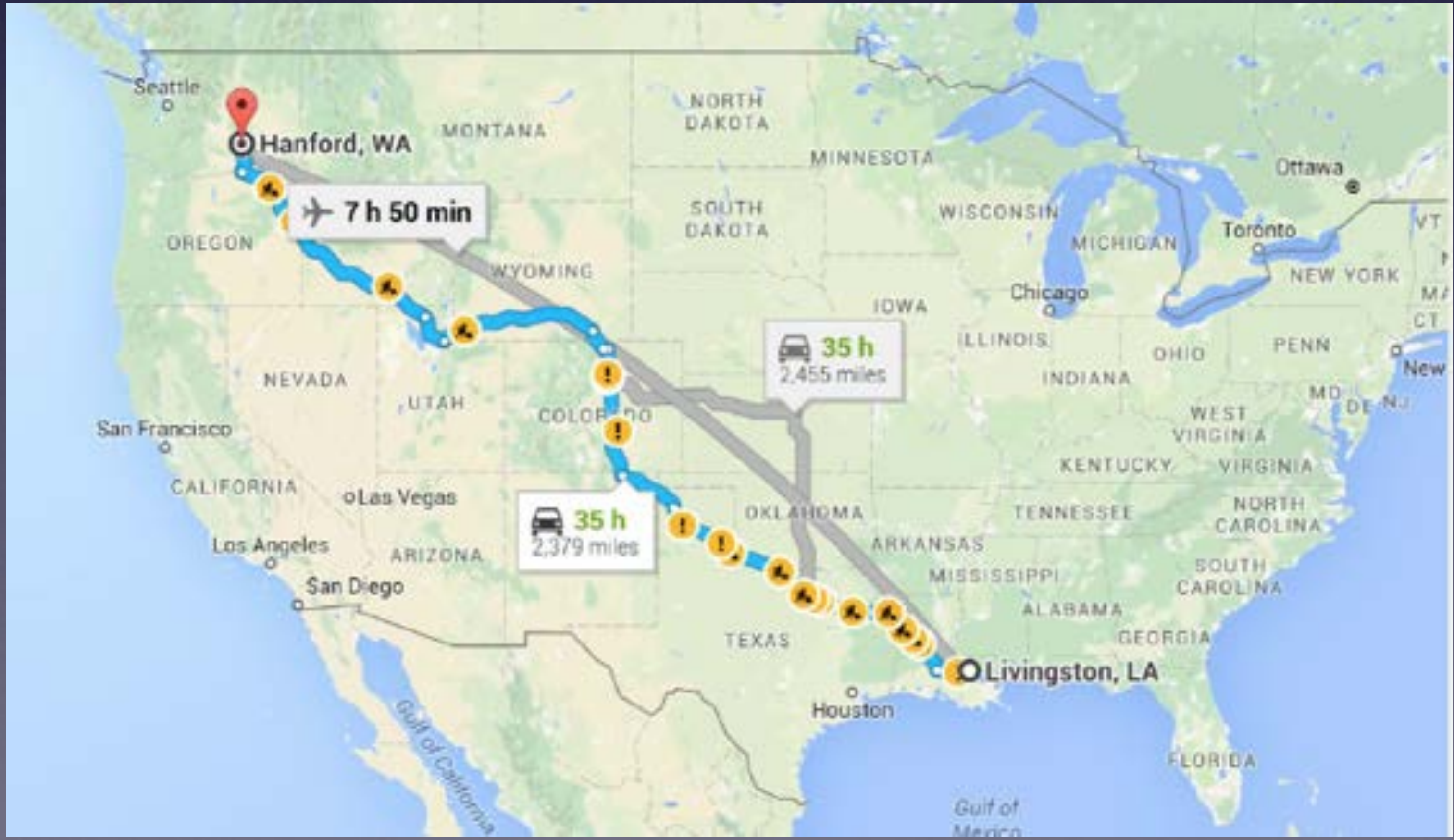


Abbott, B. P., et al. (LIGO Scientific Collaboration, Virgo Collaboration). Observation of gravitational waves from a Binary Black Hole Merger. Phys. Rev. Lett., 116, 061102, 2016.

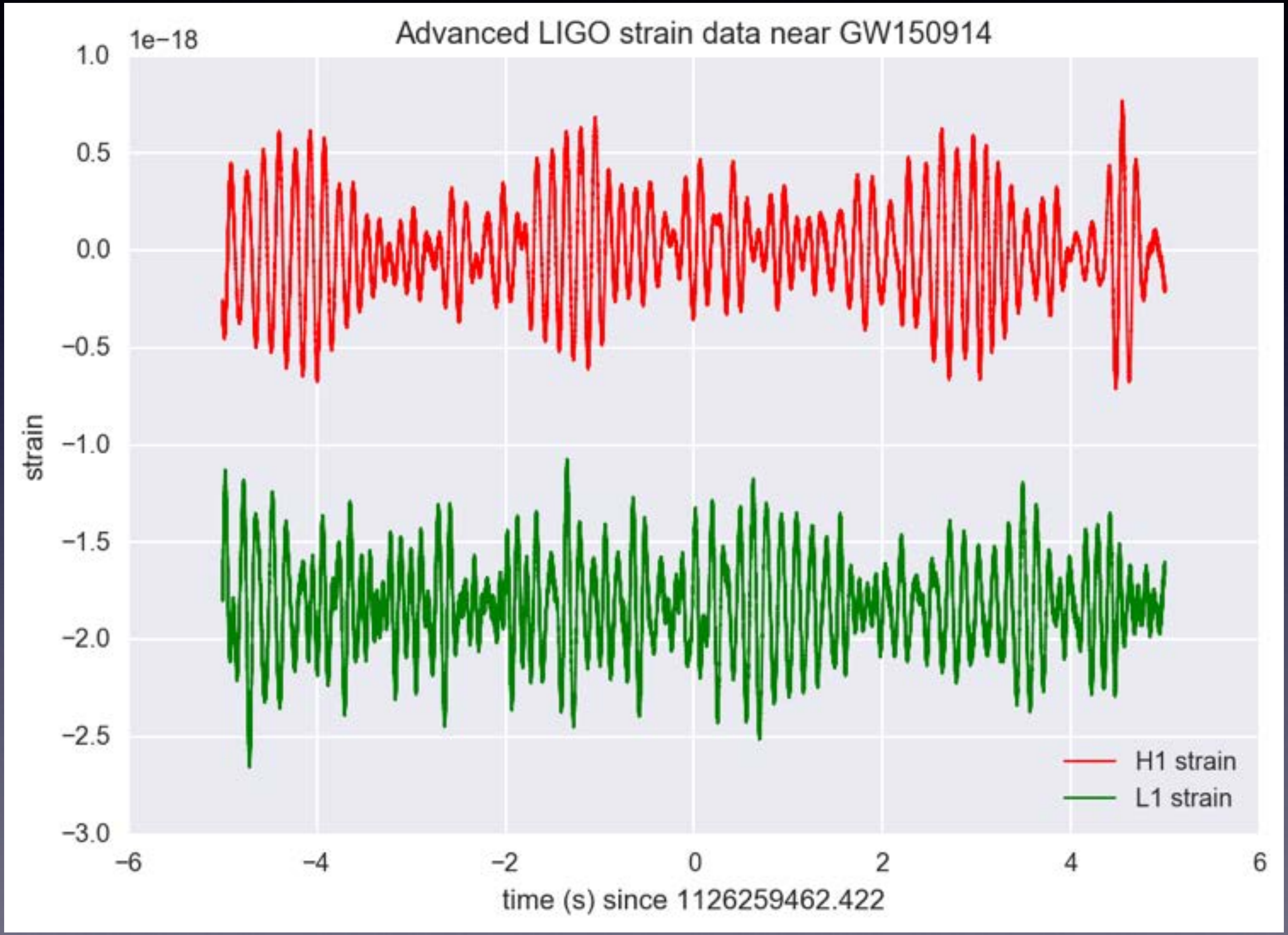
Source: ALIGO

The Detection

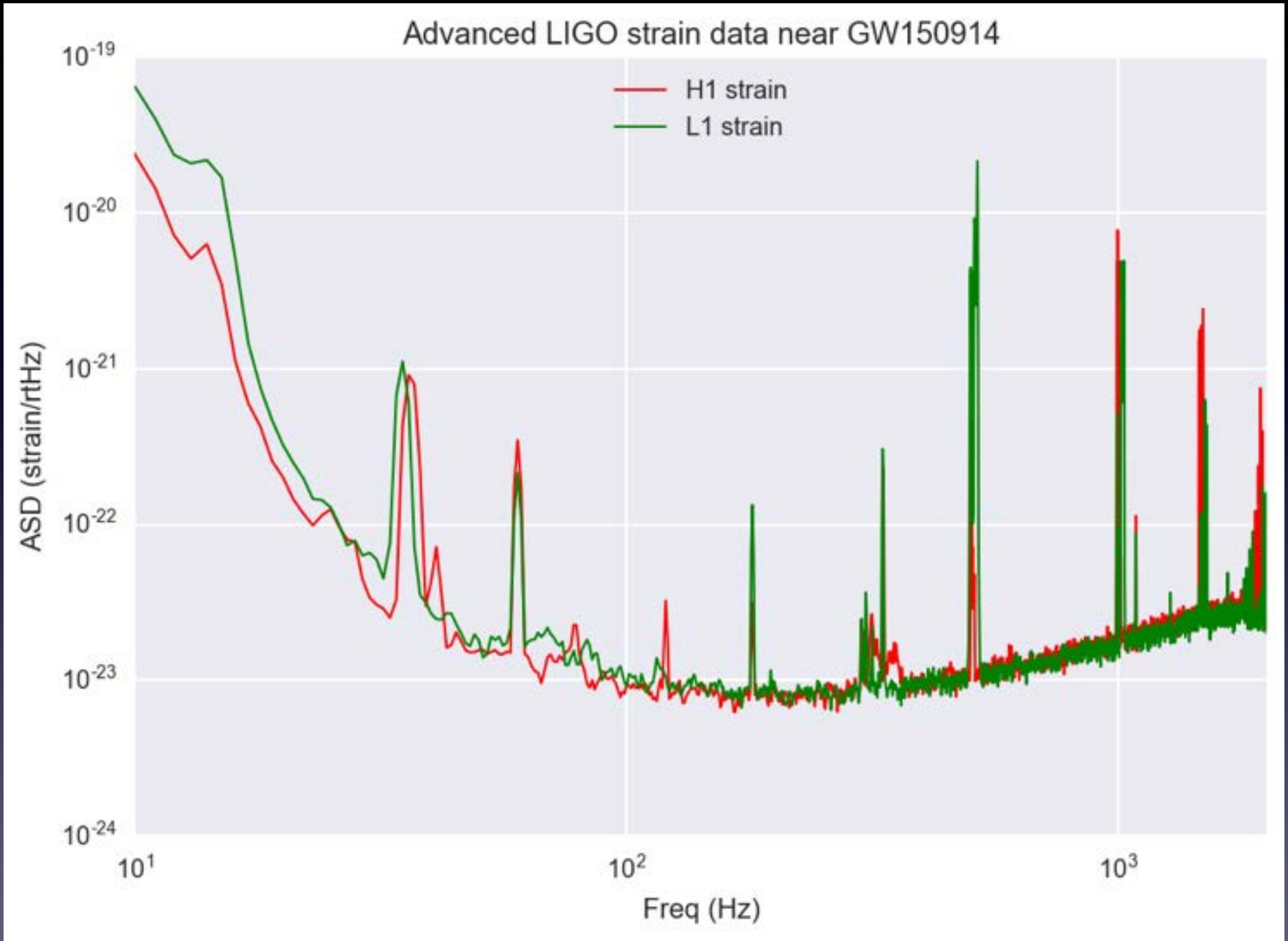
- 2 Active detectors on Sept 14, 2015
  - Hartford H1
  - Livingston L1
- Sensitivity band 35-250 Hz
- Detection by online burst-search algorithm
- Detection reported 3 minutes later
- Observation period - 16 days



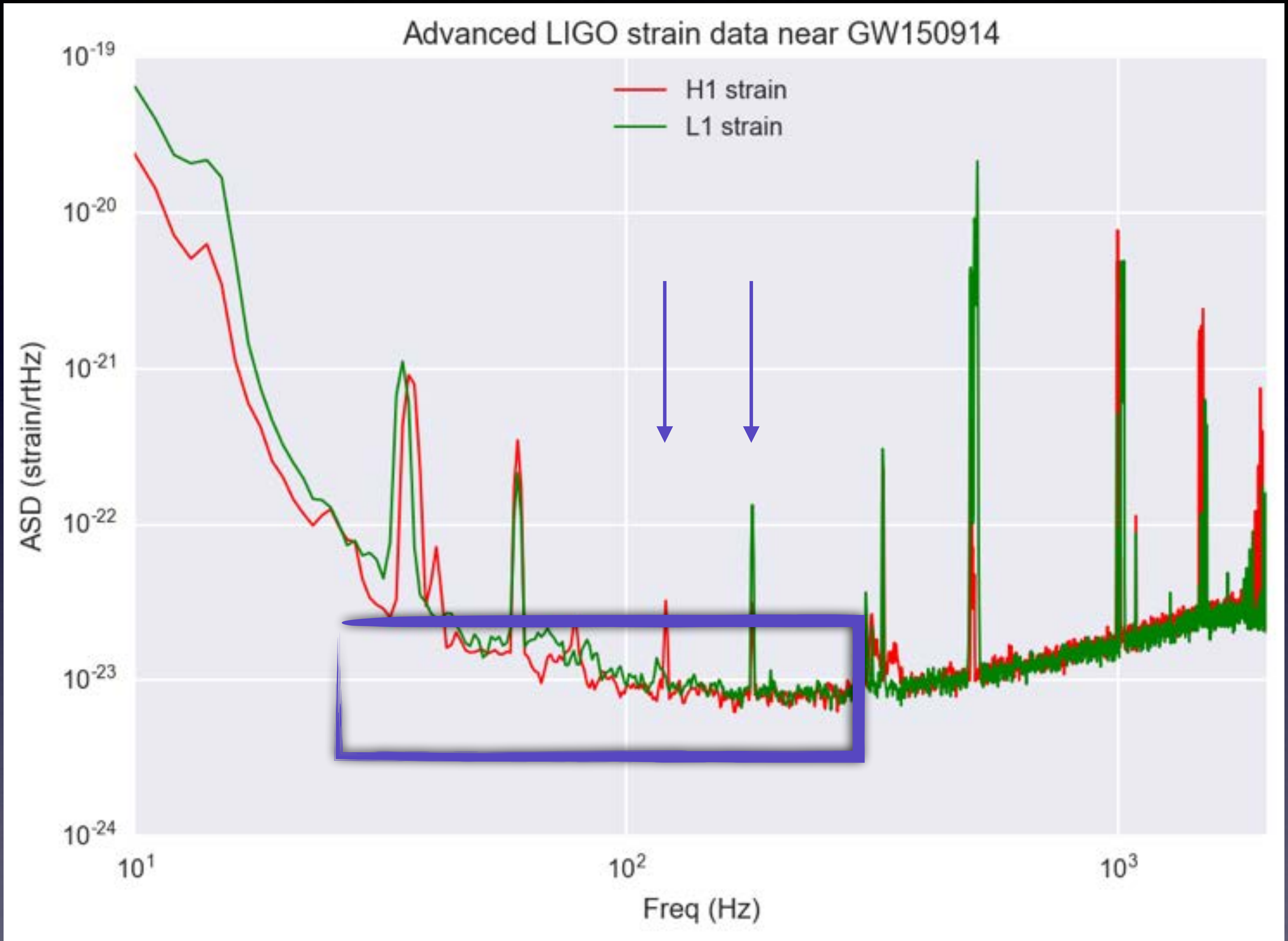
The Raw Data



https://github.com/minrk/ligo-binder



Averages over 32 seconds of data
=> entirely dominated by instrumental noise.



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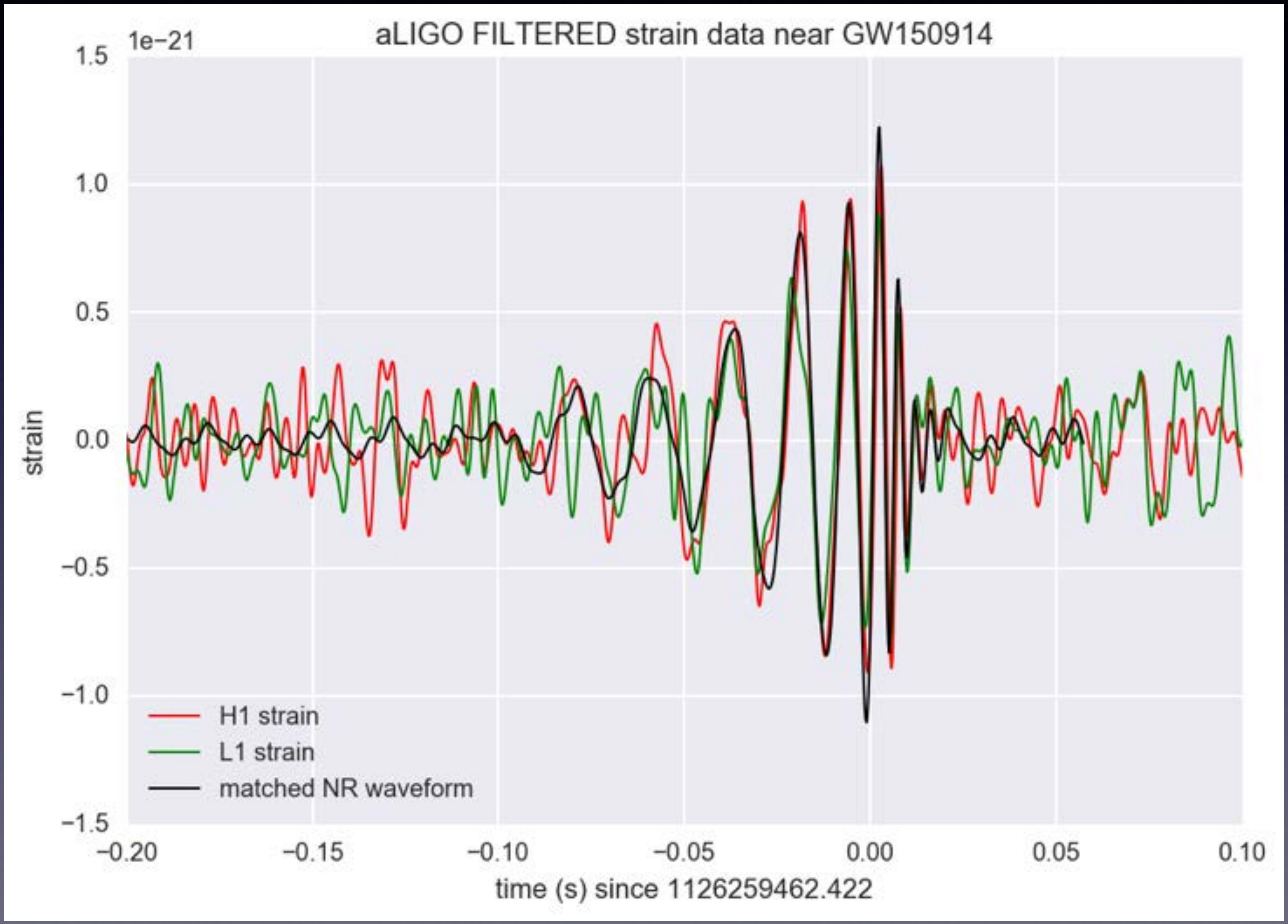
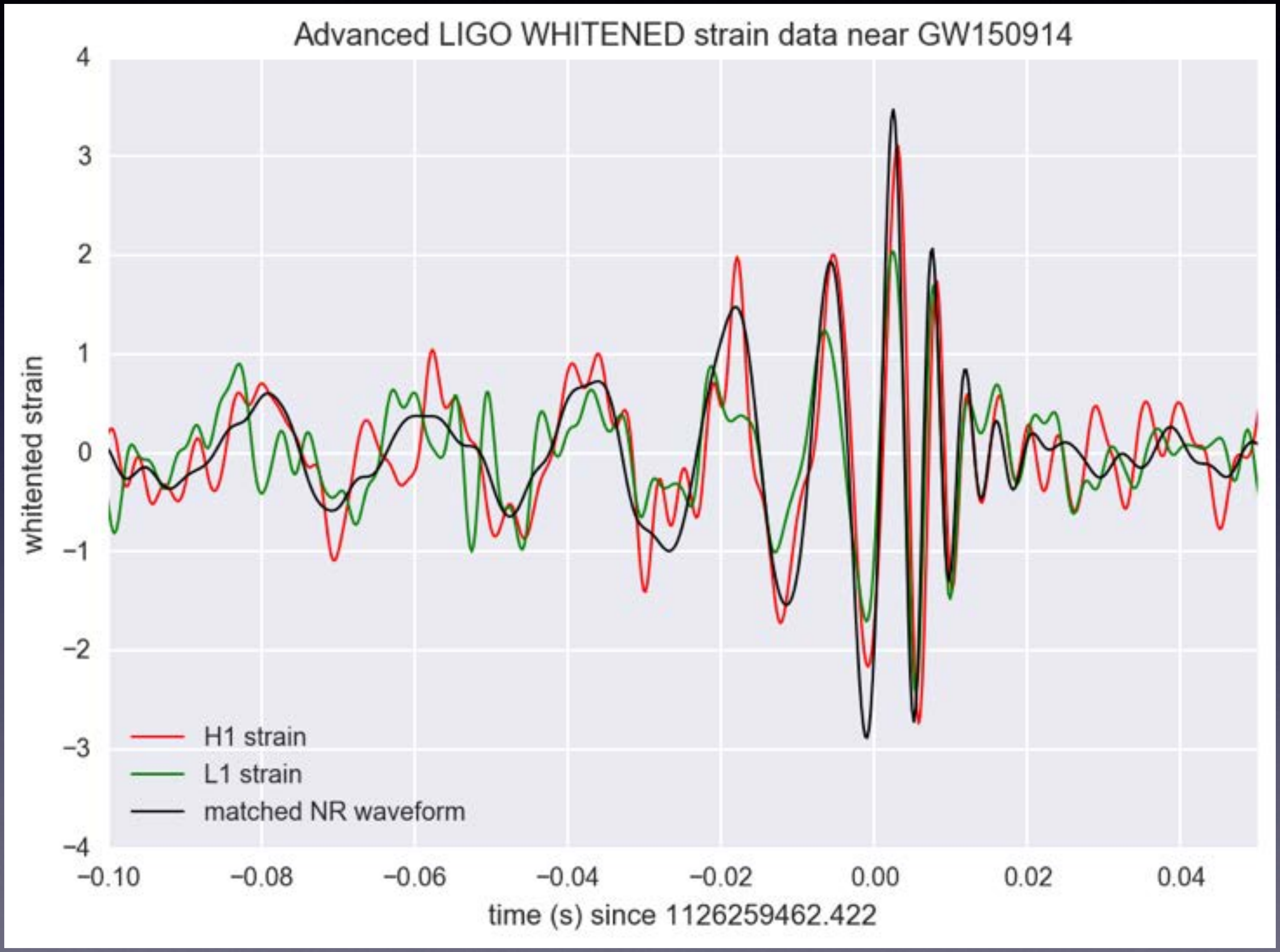
Filtered data + NR template

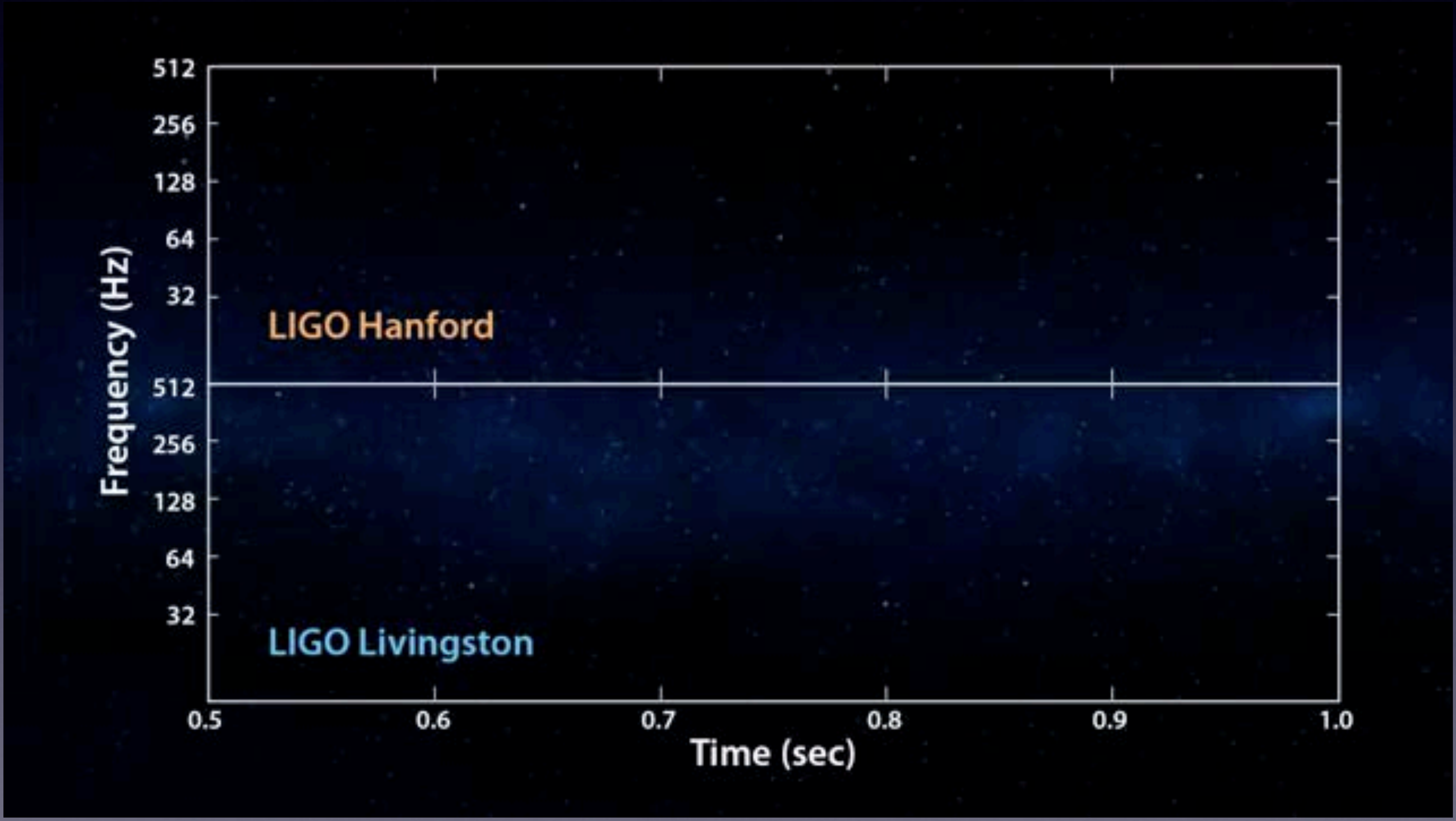


Filtered data + NR template



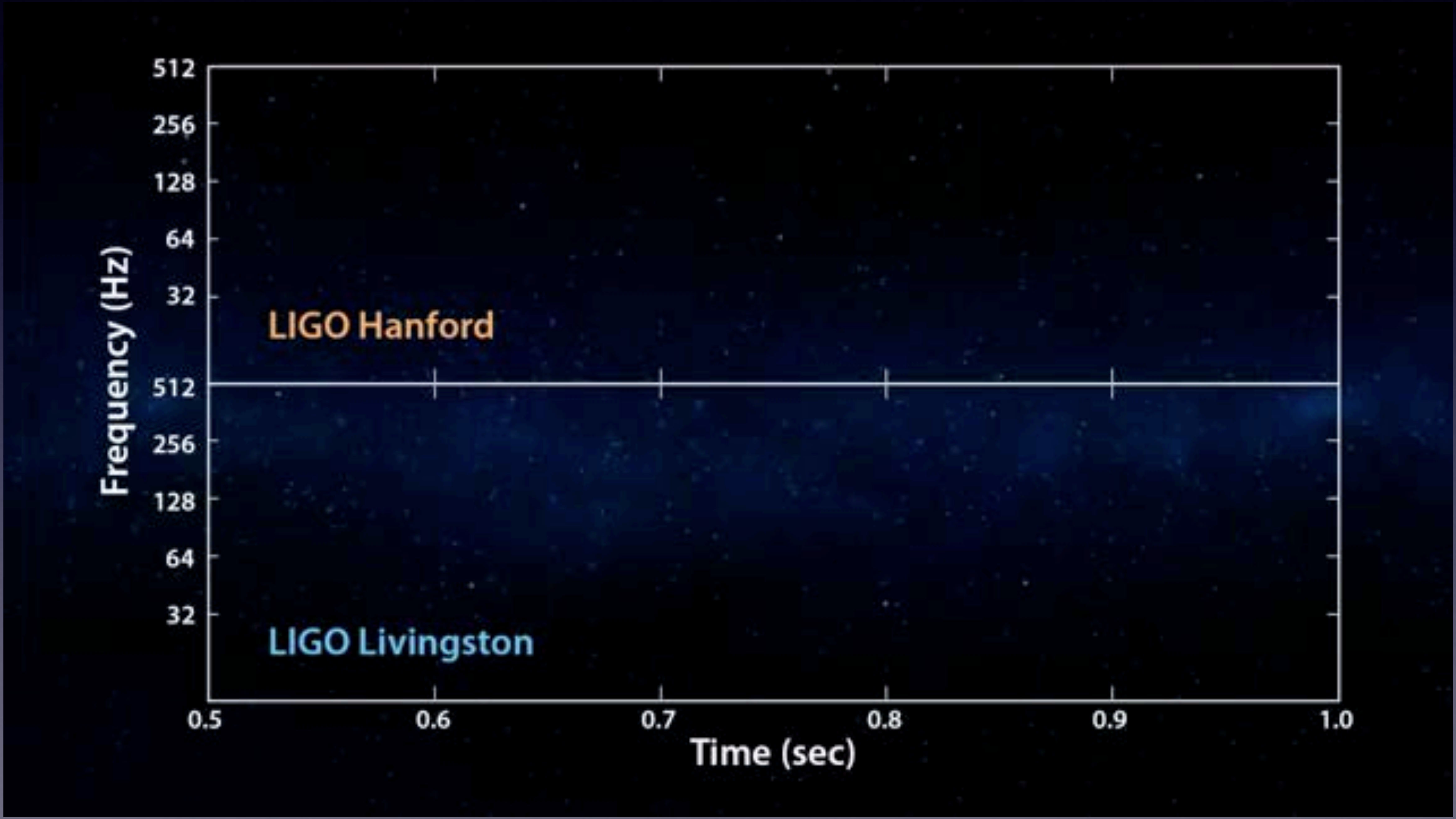
Unites of σ of the noise

The light and sound show



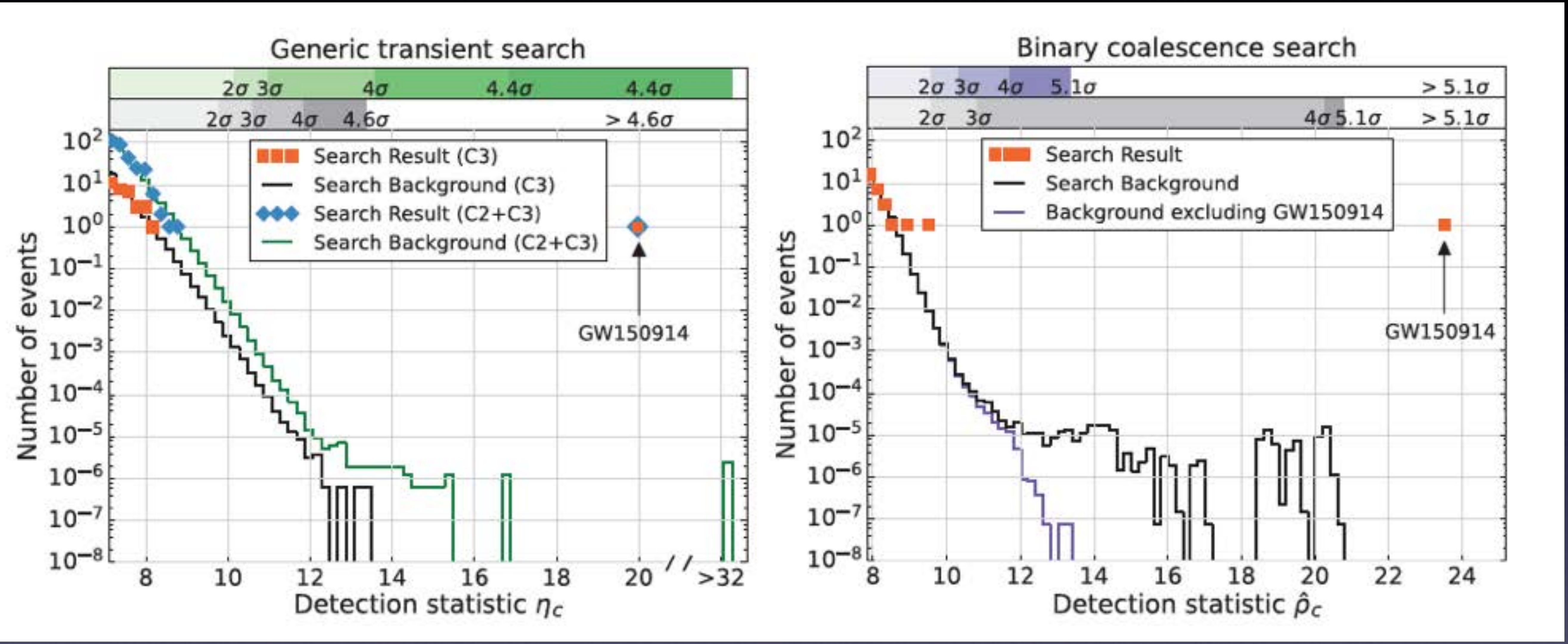
Source: ALIGO

The light and sound show



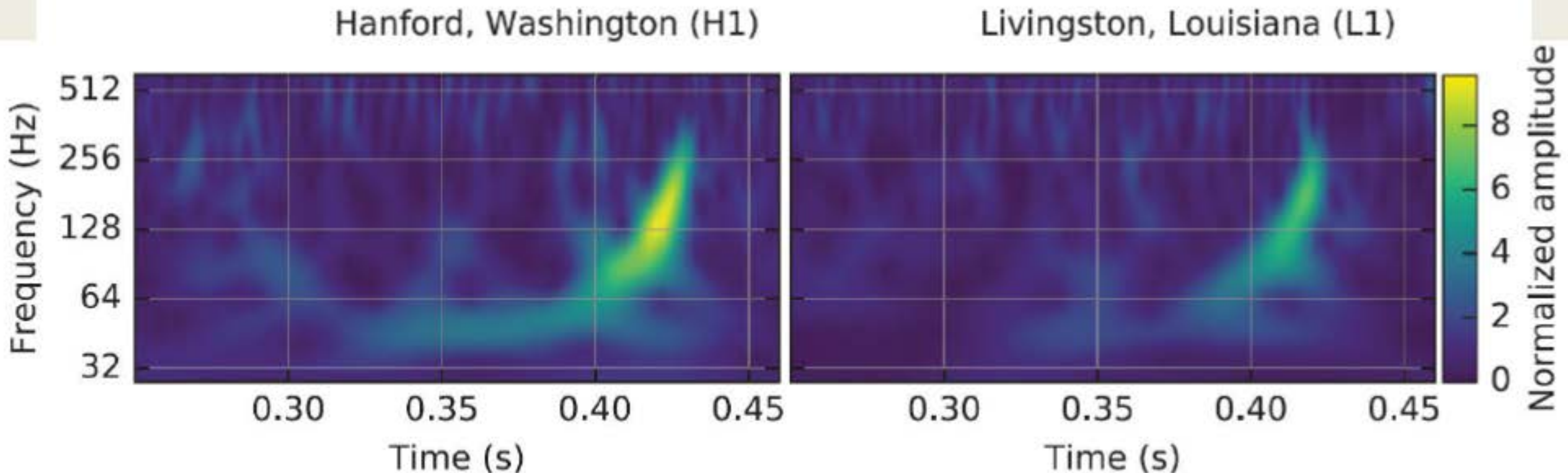
Source: ALIGO

Noise Estimates



- C1 – "blip glitches" and "narrow band"
- C3 – Events with $M_{chirp} > 1\ M_{\odot}$
- All the rest

Frequency-time domain



Source: ALIGO

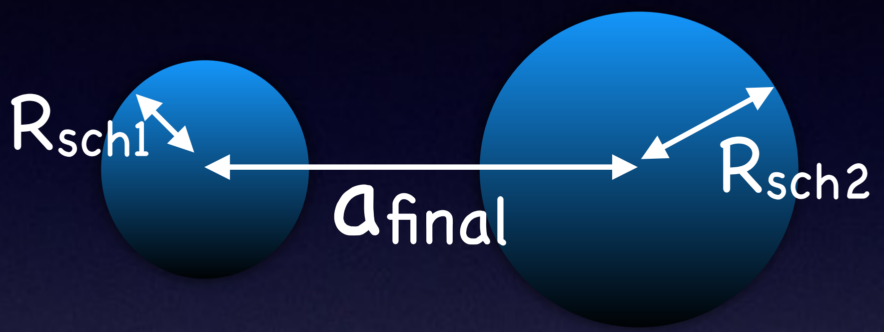
$$M_{chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

$$M_{chirp} \simeq 40\mathrm{M}_{\odot}(f/50Hz)^{-11/5}[\dot{f}/(500Hz/\mathrm{sec})]^{3/5}$$

$$M_{tot} \geq 4^{3/5} M_{chirp} \simeq 70\mathrm{M}_{\odot}$$

Identifying the source

- $f_{final} = 150$ Hz $= 2\ f_{orb}$



=> $a_{final} \simeq 350$ km

- $R_{sch1} + R_{sch} = 250\ GM_{tot}/c^2 \geqq 210$km
- ns-ns - M_{tot} too high
- BH-ns - high mass ratio - much lower f

=> BH-BH

Distance

- $h \simeq R_{sch}/D \simeq 10^{-21}$
- $R_{sch} \simeq 100$ km

=> $D \simeq 3.2$ Gpc

- More detailed analysis $D \simeq 410$ Mpc

Flux

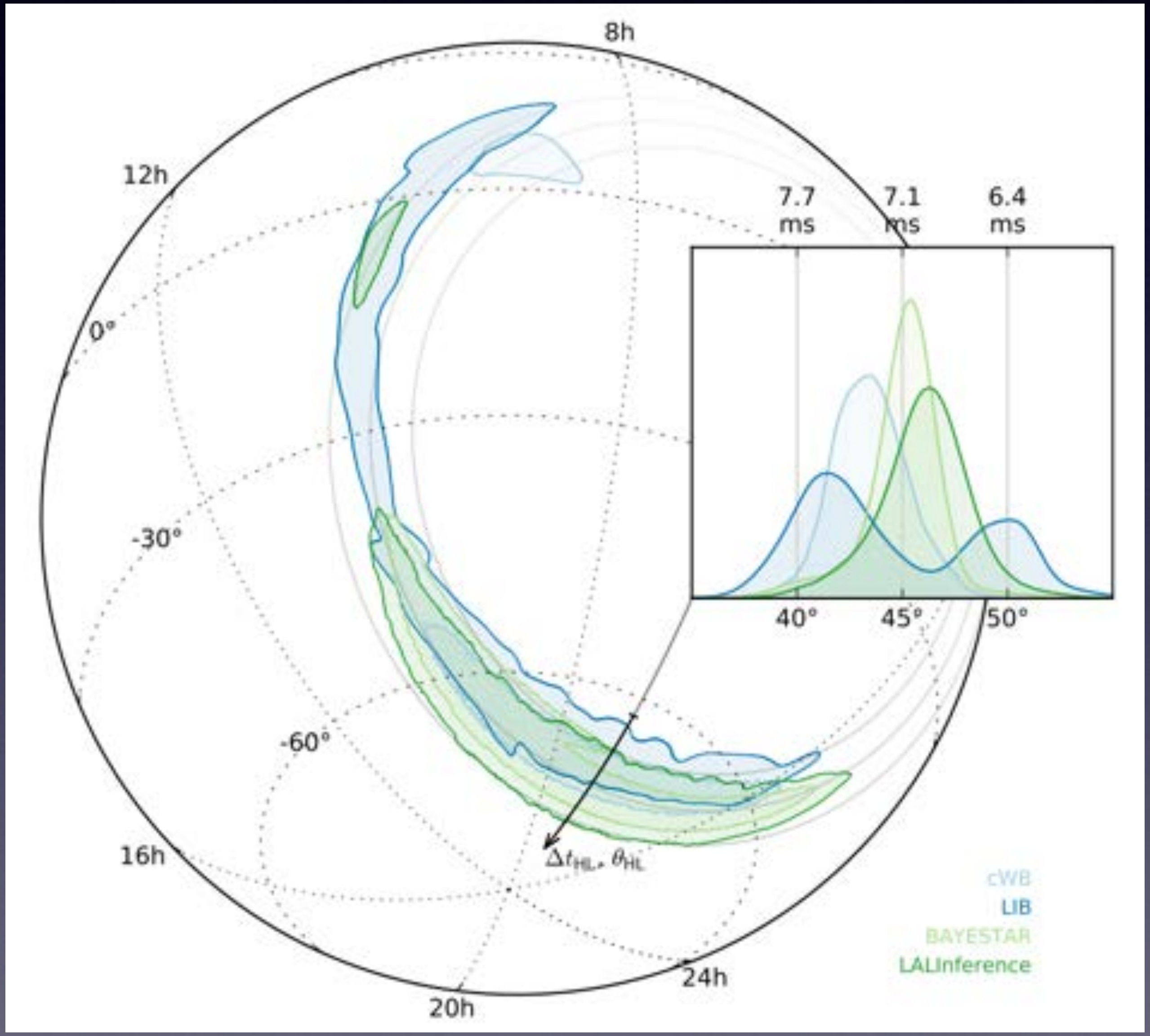
- $h \simeq R_{sch}/D \simeq 10^{-21}$
- $f \simeq 350$ Hz

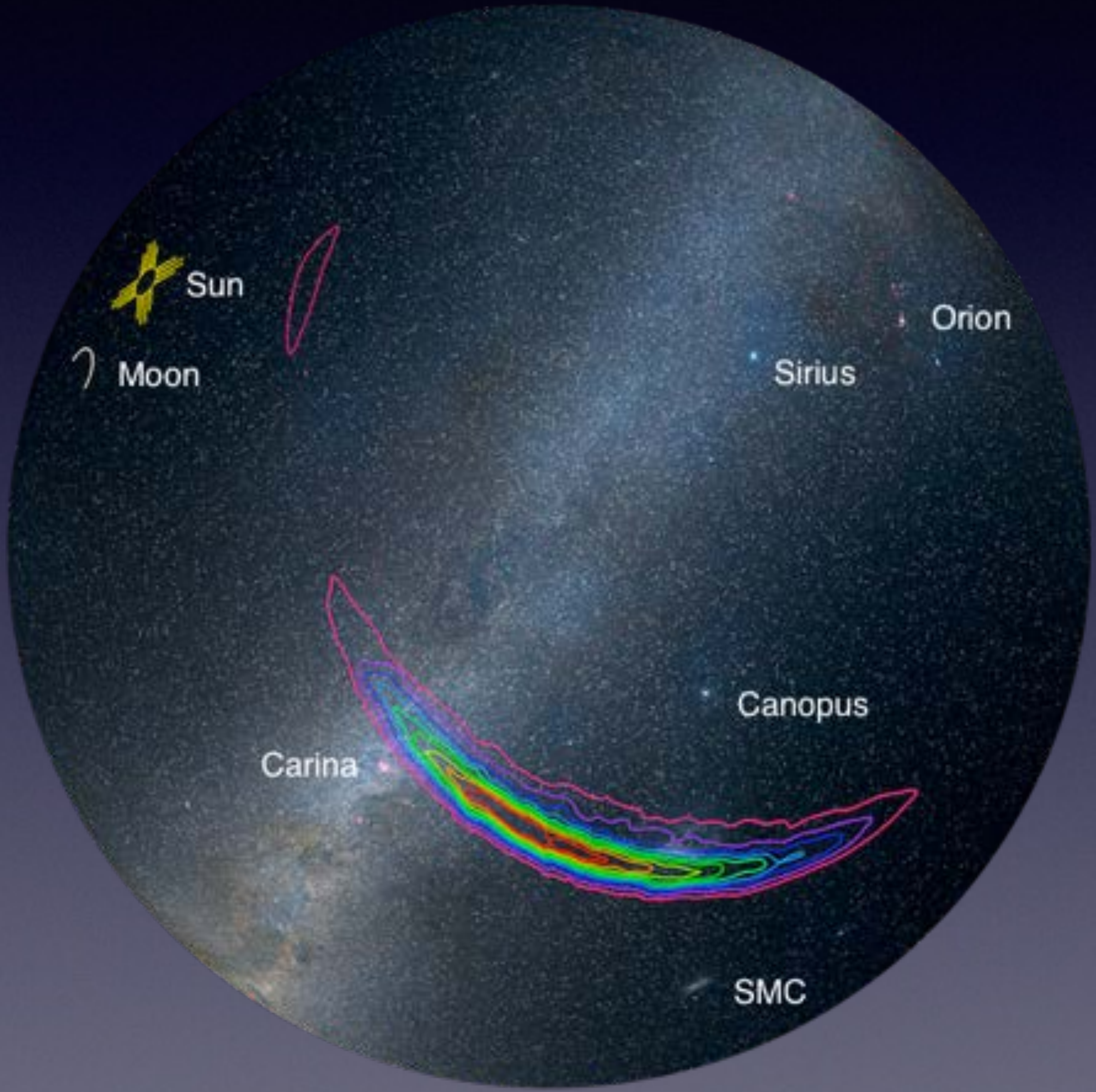
=> $F \simeq 0.3$ ergs/cm^2 sec (Sun's flux is 10^6)

System Parameters

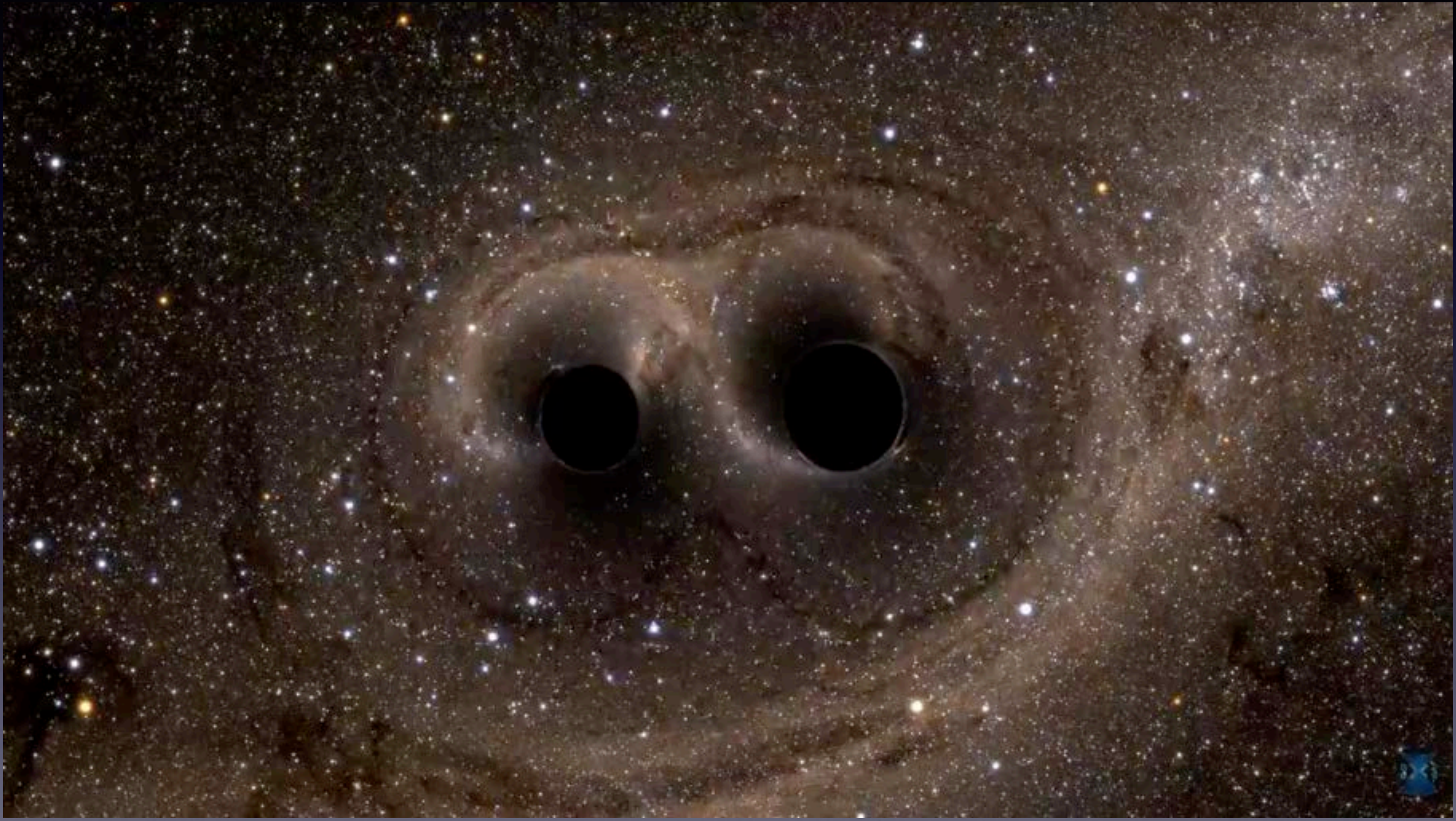
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Sky Localization





Merging Black Holes



Source: ALIGO

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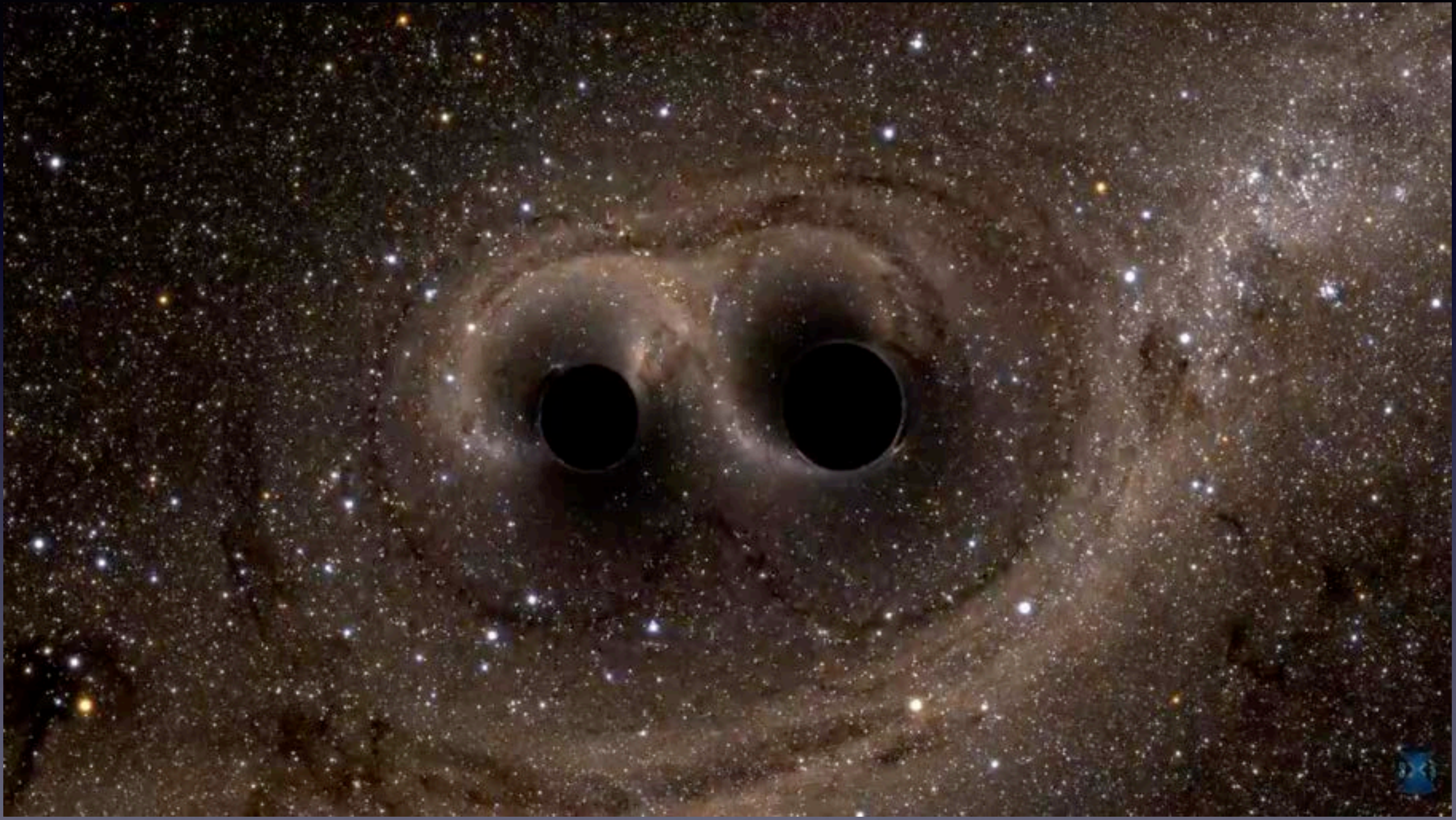

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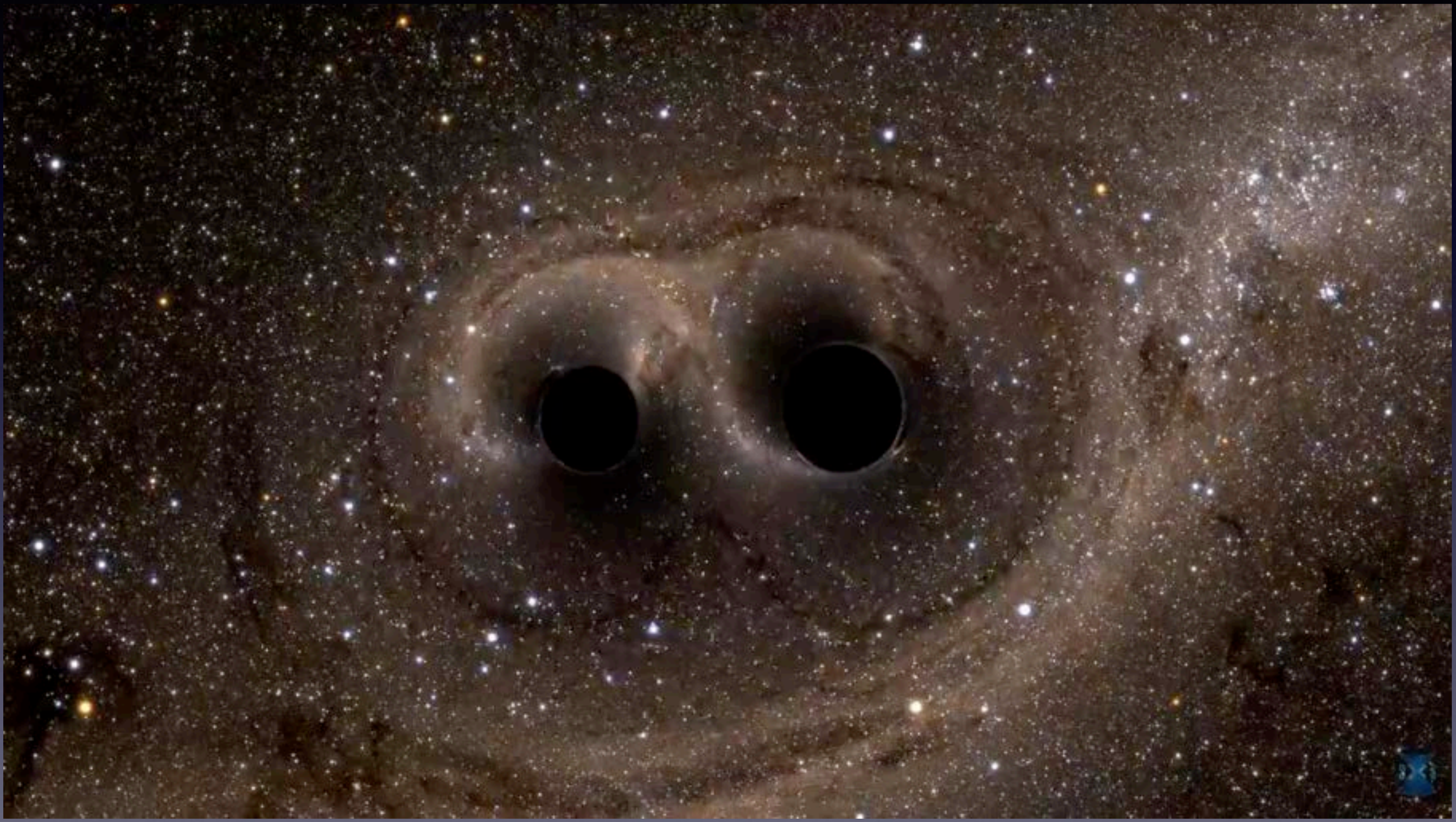

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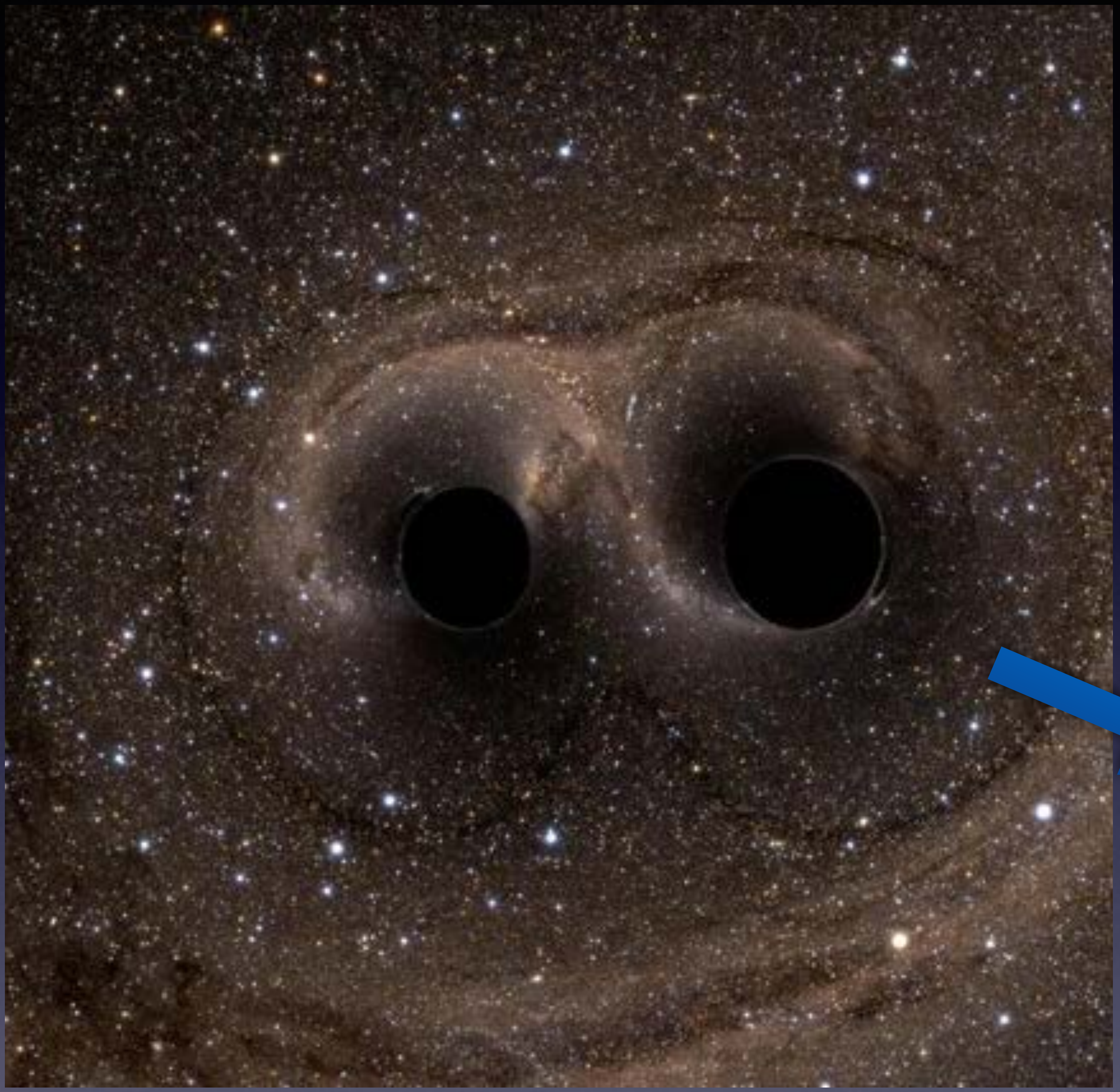
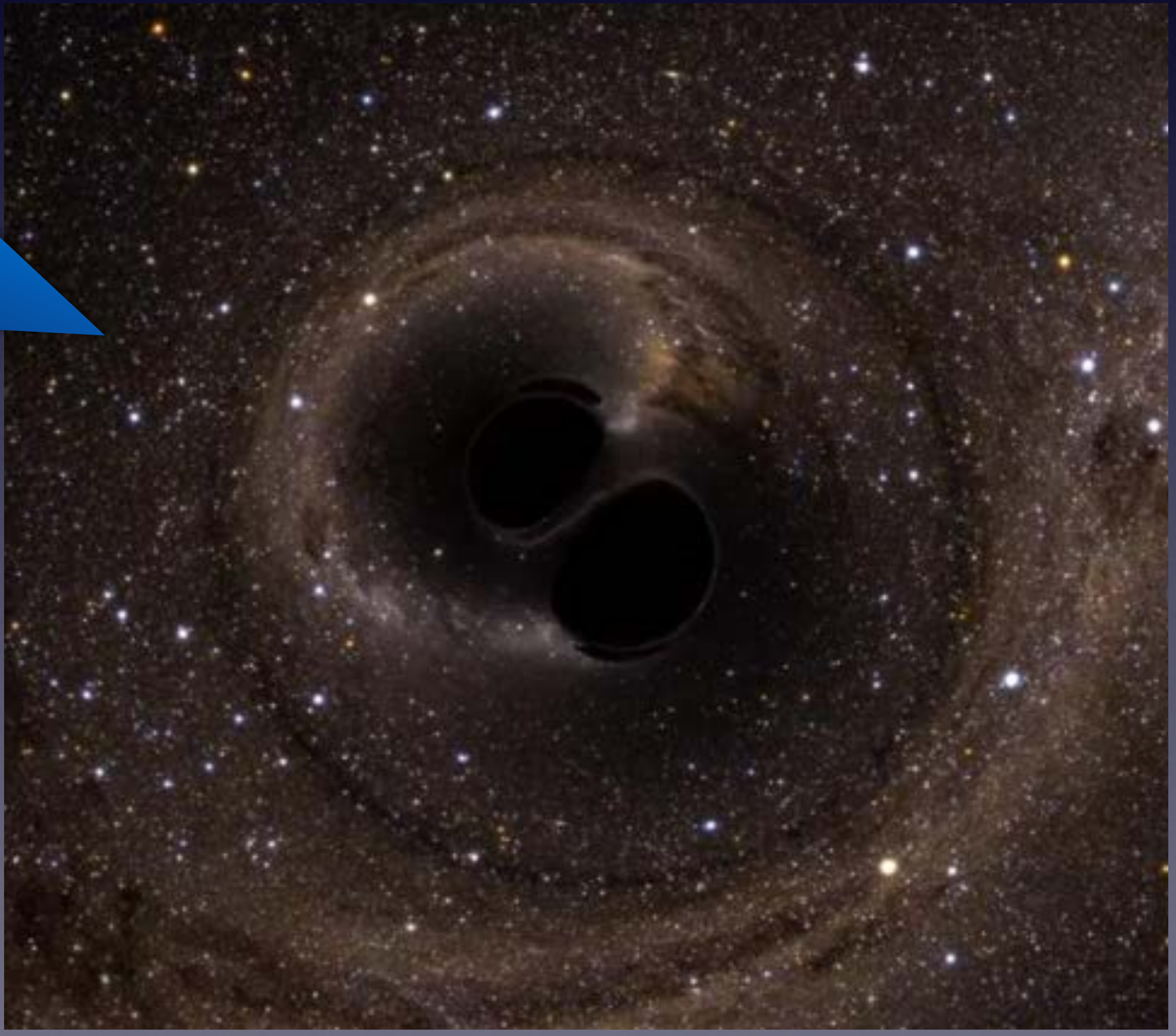




Some Physical Implications

- Black holes exist (? - we need the ringdown)
- Speed of gravitons (Blas) $c(1-10^{-15}) < v_g < 1.7c$
- Upper limit on the gravitons mass from dispersion (Will, ALIGO) $(v_g / c)^2 = (1-(c/f\lambda_g)^2 \quad => m_g < 1.2 \cdot 10^{-22}\,\mathrm{eV}$
- Upper limit on the gravitons mass from screening (Bicudo) $e^{-d/\lambda_g} \quad => m_g < 1.2 \cdot 10^{-32}\,\mathrm{eV}$

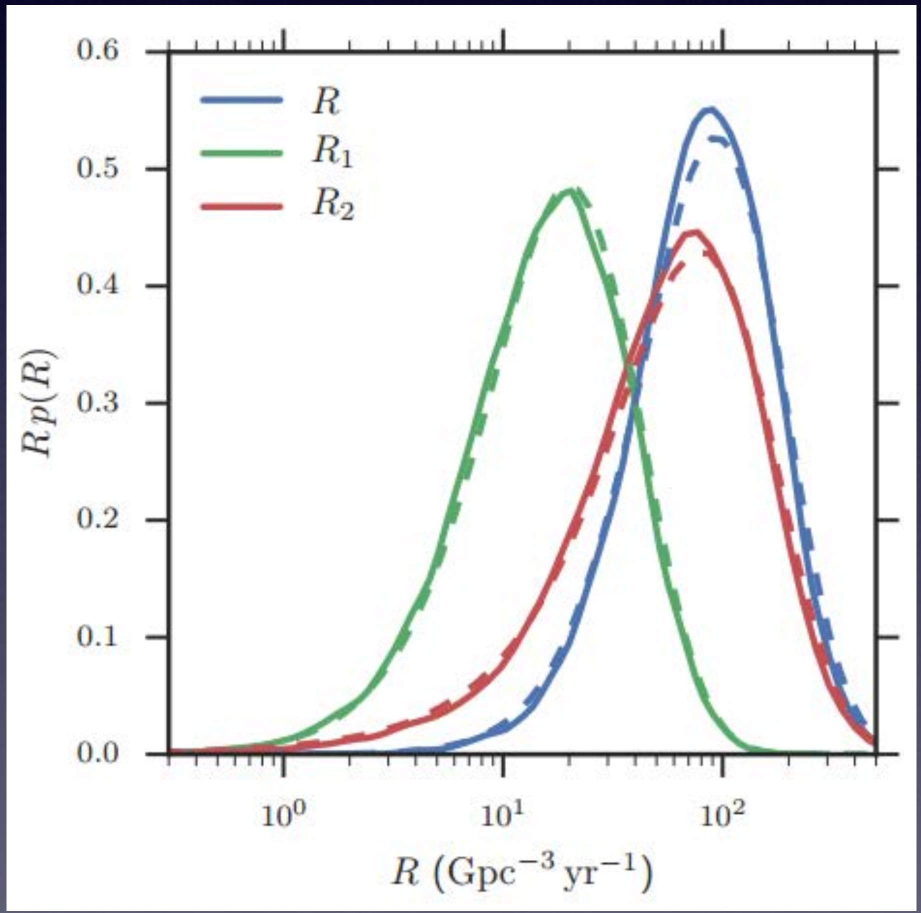
Event rate

- One event detected in two weeks of observations => 25 yr^{-1}
- Detection horizon ~700 Mpc

=> 14_{-12}^{+39}/(Gpc^3 yr)

+ A second marginal event => 83_{-63}^{+168}/(Gpc^3 yr)

- Consistent" with "predictions" (2-400) but no one (see however Kinugawa et al., 2013) predicted 30-30 M_o event.



GW150914 is unusually significant; only ~ 8% of the distribution of sources will be more significant. However, it is not so significant as to call into question the assumption that BBH coalescences are distributed uniformly in co-moving volume and source time.

Counterparts

- No optical
- No Swift
- No Intergal (X-ray & soft Gamma)
- No Fermi (GeV)
- No VHE neutrinos

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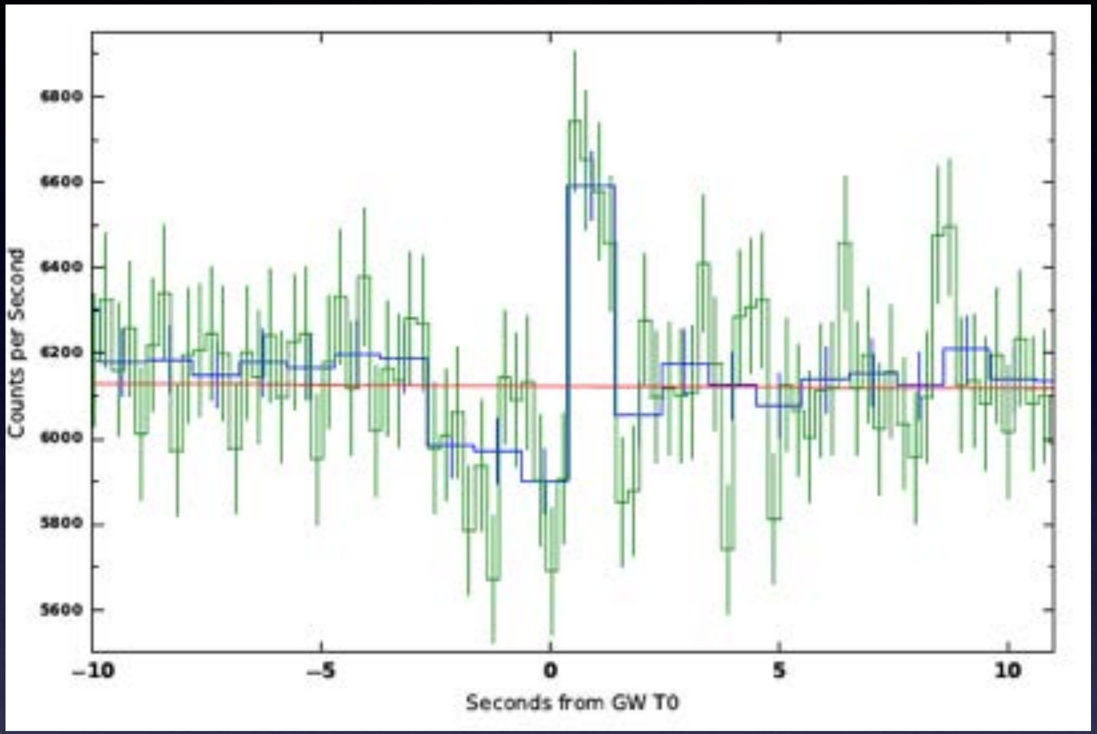
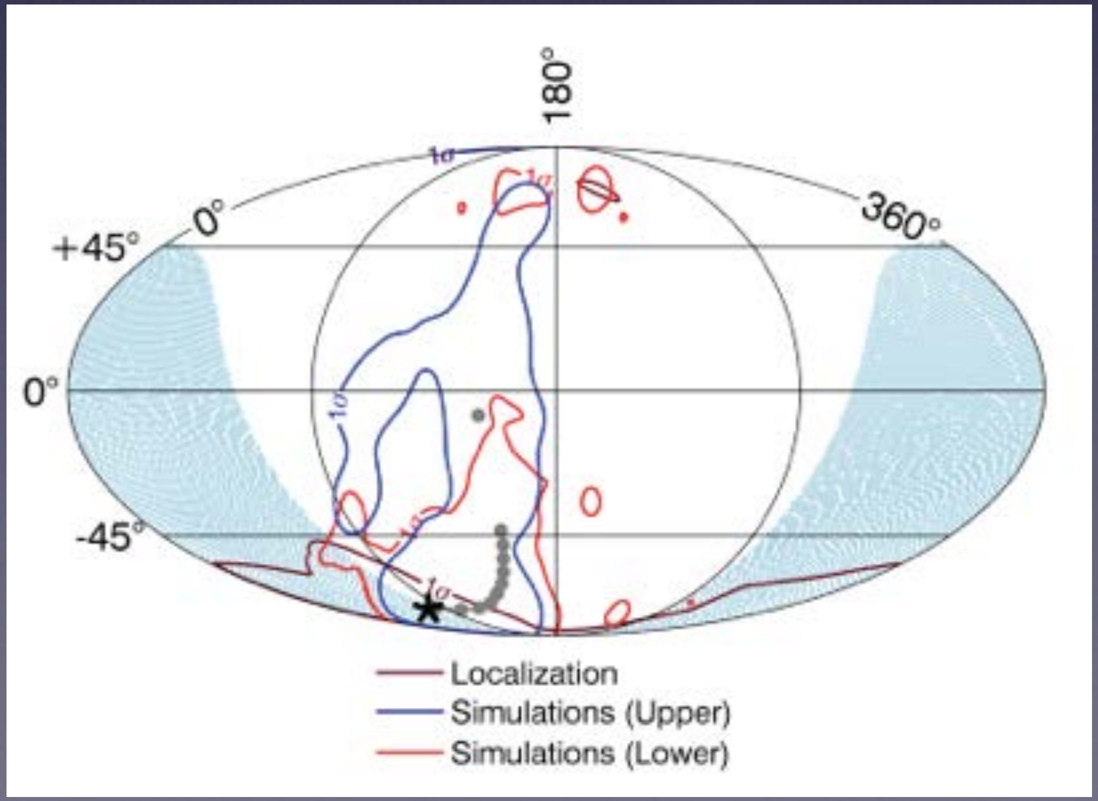
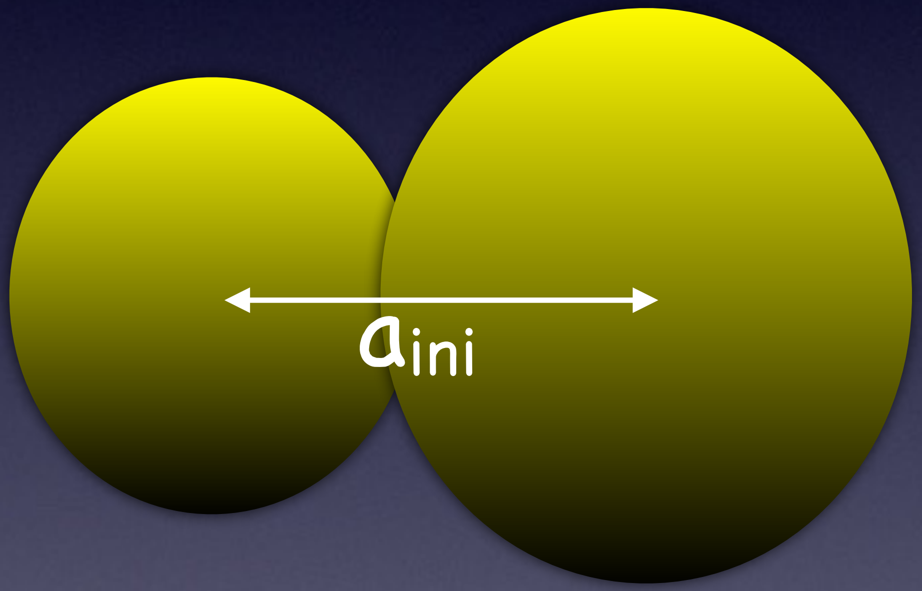
? Fermi GBM (~MeV)
(chance 0.0022 ?)
[N explanations N>>1]





The Origin?

$$t_{merge} = \frac{5}{256}\frac{c^5}{G}\frac{a^4}{M^2\mu}$$



- To merge in a Hubble time $a_{ini} < 10^{12}$ cm
- But two stars with $M > 30 M_\odot$ must be more than 10^{12} cm apart
- Models predicted $M_{BH} \sim 5\ M_\odot$
- Pop III stars that are smaller (different composition) !

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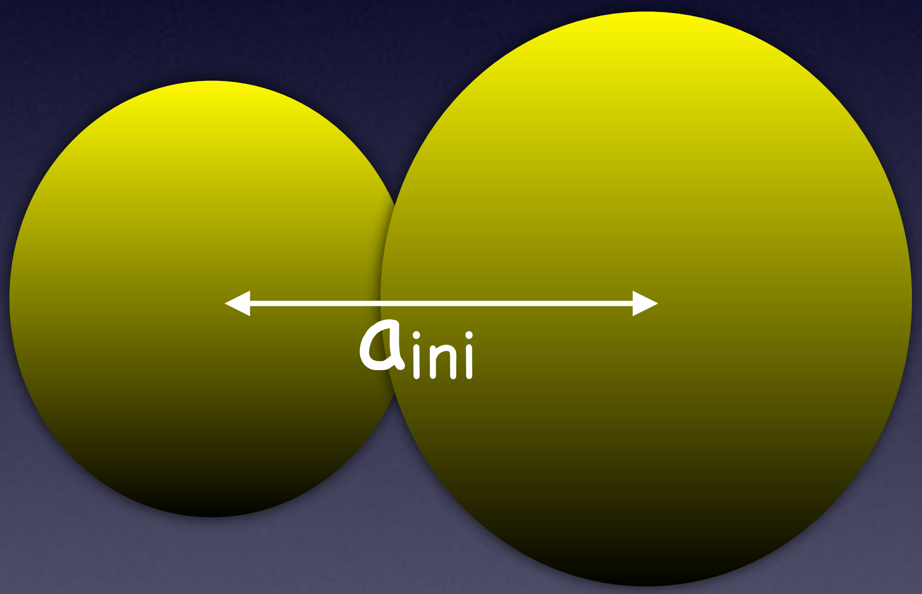

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Possible Indirect Confirmation of the Existence of Pop III Massive Stars by Gravitational Wave
Tomoya Kinugawa, Kohei Inayoshi, Kenta Hotokezaka, Daisuke Nakauchi, Takashi Nakamura 2013


1609


1912


1609


1932


1912


1609


60ies


1932


1912


1609


60ies

1932

1912

1609

1987


60ies

1932

1912

1609

1987

early 2000


60ies

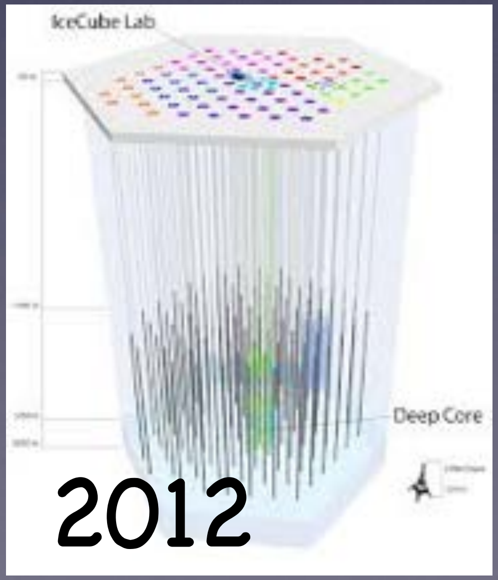

1932


1912

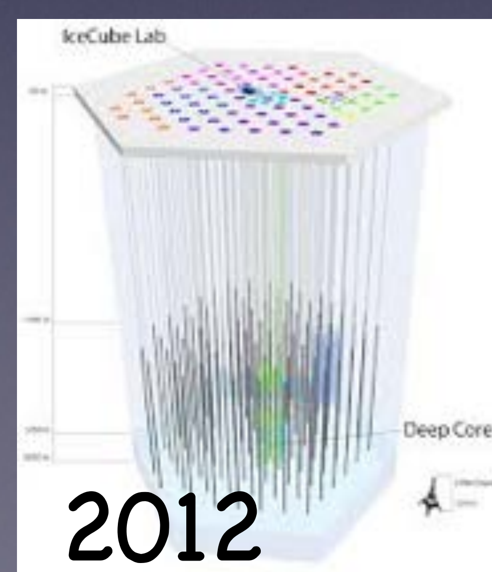

1609


1987


early 2000


IceCube Lab
Deep Core
2012

The Last Window



Summary

- 100 years after Einstein's prediction Advanced LIGO detected GW from a distant astronomical source
- An unexpected discovery of a merger of 2 Black Holes with 30 solar masses each
- This opens the last window on the Universe - focusing on the densest and most extreme objects