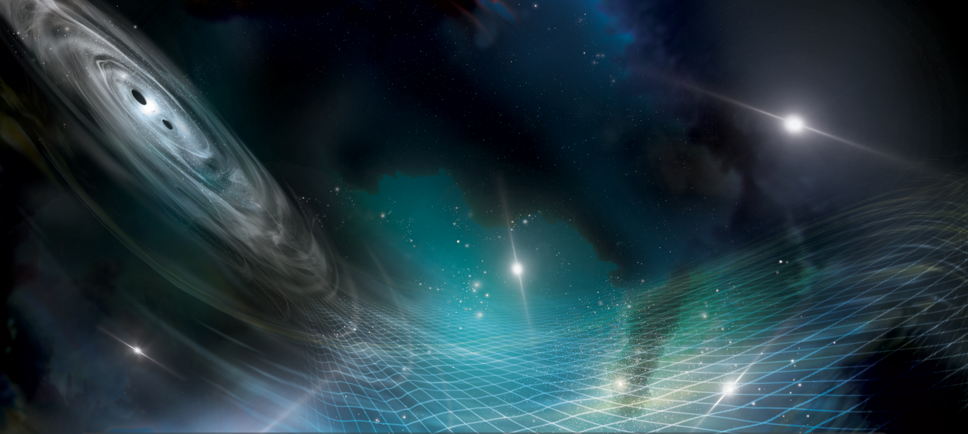

Gravitational Waves

Kai Schmitz (NANOGrav New Physics Working Group)

University of Münster, Institute for Theoretical Physics

ISAPP School | KIT / Bad Liebenzell | September 20, 2024

Literature

- M. Maggiore, *Gravitational Waves. Vol. 1: Theory and Experiments*, Oxford University Press (2007), ISBN-13: 978-0198570745.
- M. Maggiore, *Gravitational Waves. Vol. 2: Astrophysics and Cosmology*, Oxford University Press (2018), ISBN-13: 978-0198570899.
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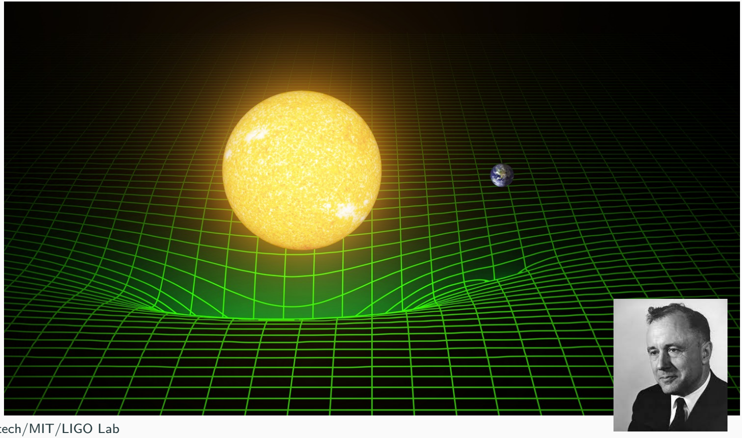
- C. Caprini, D. G. Figueroa, *Cosmological Backgrounds of Gravitational Waves*, Class. Quant. Grav. **35** (2018) 163001, [arXiv:1801.04268].
- J. D. Romano, N. J. Cornish, *Detection methods for stochastic gravitational-wave backgrounds: a unified treatment*, Living Rev. Rel. **20** (2017), [arXiv:1608.06889].

Theory

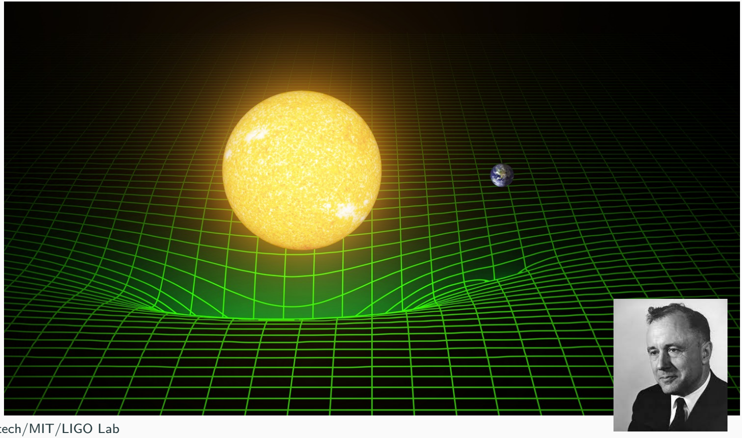
General relativity (GR) in 12 words



John Archibald Wheeler:

"Spacetime tells matter how to move; matter tells spacetime how to curve."

General relativity (GR) in 12 words



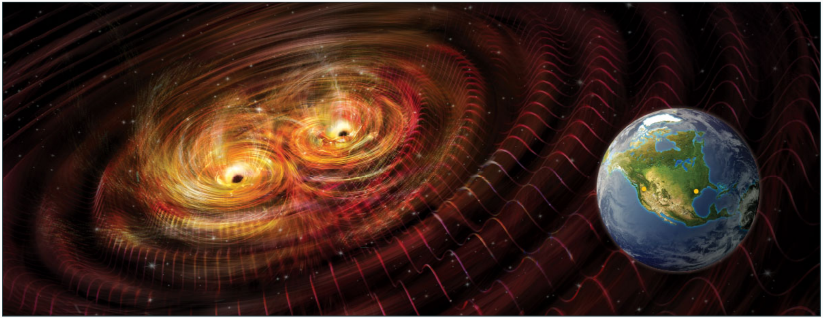
John Archibald Wheeler:

"Spacetime tells matter how to move; matter tells spacetime how to curve."

Gravitational waves (GWs) are ripples in spacetime

Waves propagating at the speed of light; stretch and squeeze distances on spacetime

GW science: the first century



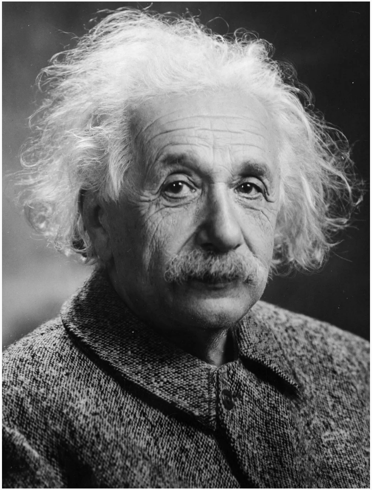
[Nicolle Rager Fuller for sciencenews.org]

- 1916: Albert Einstein predicts GWs based on his general theory of relativity
- 2016: LIGO/Virgo Collaboration announces the detection of GW150914
- 2017: Rainer Weiss, Barry Barish, and Kip Thorne receive Nobel Prize in Physics

→ Milestone in fundamental physics, triumph of general relativity

→ Discovery of a new class of astrophysical objects: heavy black holes in binaries

Headaches over theoretical details



Einstein to *Physical Review* (1936)

"Dear Sir,

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.

Respectfully,
Albert Einstein"

Consider small perturbations $h_{\mu\nu}$ around Minkowski; work at linear order in $h_{\mu\nu}$

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

$$g^{\mu\nu} = \eta^{\mu\nu} - h^{\mu\nu} \, ,$$

$$h^{\mu\nu} = \eta^{\mu\rho}\eta^{\nu\sigma} \, h_{\rho\sigma} \, ,$$

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

Linearized GR

Theory of a symmetric tensor field $h_{\mu\nu}$ propagating on a flat Minkowski background

Linearized GR

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

Linearized GR

Theory of a symmetric tensor field $h_{\mu\nu}$ propagating on a flat Minkowski background

- A priori, $h_{\mu\nu}$ has got ten independent components; but how many are physical?
- General covariance $\rightarrow$ symmetries of linearized GR $\rightarrow$ gauge GWs away?!

Symmetries of linearized GR

Global symmetries: Finite rotations, boosts, and translations
Lorentz symmetry + spacetime translations → Poincaré symmetry

---

Symmetries of linearized GR

Global symmetries: Finite rotations, boosts, and translations

Lorentz symmetry + spacetime translations → Poincaré symmetry

---

Gauge symmetry: Infinitesimal coordinate transformations

$$h_{\mu\nu} \to h'_{\mu\nu} = h_{\mu\nu} - (\partial_\mu \xi_\nu + \partial_\nu \xi_\mu), \qquad |\partial_\mu \xi_\nu| \lesssim |h_{\mu\nu}| .$$

Symmetries of linearized GR

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- Equivalent to gauge transformation in electrodynamics, $A_\mu \to A_\mu - \partial_\mu \chi$
- Use gauge freedom to eliminate unphysical degrees of freedom

Physical degrees of freedom

Four-vector potential A_μ in electrodynamics

Lorenz gauge	$(-1$ DOF$)$:	$\partial^\mu A_\mu = 0$
Temporal gauge	$(-1$ DOF$)$:	$A_0 = 0$

Radiation gauge

- $A_0 = 0, \quad \partial^i A_i = 0$
- $4 - 1 - 1 = 2$ physical DOFs, e.g., polarization states with $\pm$ helicity

Physical degrees of freedom

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Radiation gauge

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---

Metric perturbations $h_{\mu\nu}$ in linearized GR

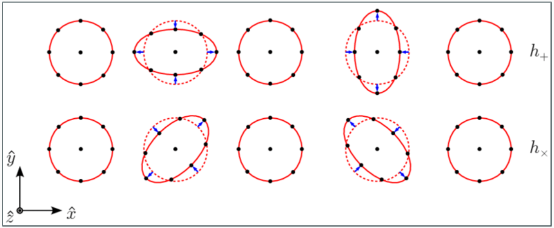
Lorentz gauge (−4 DOF): $\partial^\mu \bar{h}_{\mu\nu} = 0, \ \bar{h}_{\mu\nu} = h_{\mu\nu} - {}^1\!/_2\, \eta_{\mu\nu} h, \ h = \eta^{\mu\nu} h_{\mu\nu}$

Synchronous gauge (−4 DOF): $h = 0, \ h_{0i} = 0$

Transverse-traceless (TT) gauge

- $h_{0\mu} = 0, \quad h = 0, \quad \partial^i h_{ij} = 0$
- $10 - 4 - 4 = 2$ physical DOFs, e.g., $+$ (plus) and $\times$ (cross) polarization states

Response of test masses in the $x-y$ plane to a GW moving along the z axis



$$h_{ij}^{\mathrm{TT}}(t,z) = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix} \cos\left[\omega\left(t-\frac{z}{c}\right)\right]$$

https://www.youtube.com/watch?v=uH91gSI4ELs

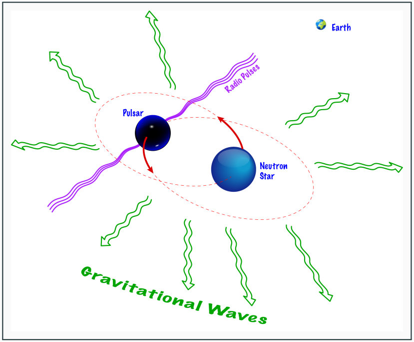
Experiments

First experimental attempts

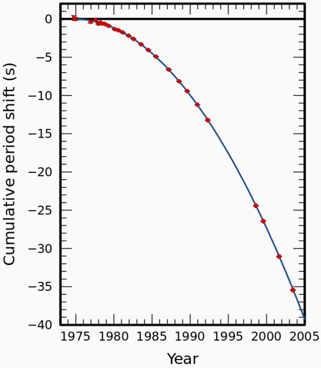
Resonant detectors developed by Joseph Weber (*"Weber bars"*)

- Idea: GWs excite resonant oscillations of large aluminium cylinders
- First "signals" from 1968, but not confirmed by other experiments
- 70s: Ronald Drever, Kip Thorne, Rainer Weiss design GW laser interferometers

First, indirect detection of GWs



© Shane L. Larson, NASA

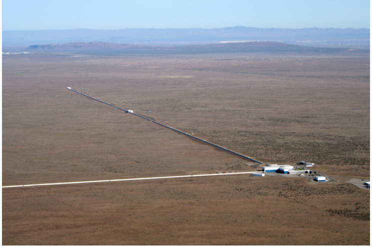


Hulse–Taylor pulsar

- Binary system consisting of a pulsar and a neutron star
- Orbital period decreases because of GW emission
- 1993 Nobel Prize in Physics awarded to Russell Hulse and Joseph Taylor

Laser Interferometer Gravitational-Wave Observatory (LIGO)

Hanford, Washington

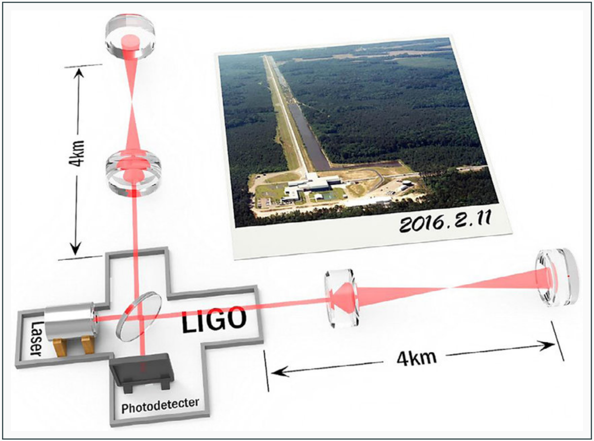


Livingston, Louisiana

LIGO fact sheet

- More than 40 years from the idea to the realization of “Advanced LIGO” in 2015
- Today, more than 1000 scientists from over 20 countries
- Two interferometers to better exclude local noise effects
- Time delay provides information about the direction of the signal

LIGO measurement principle

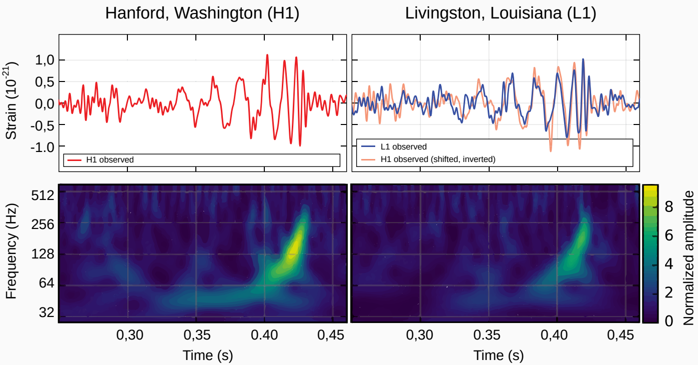


❶ Laser beam is split, runs along two interferometer arms, and is reflected by mirrors

❷ GWs stretch and squeeze length of the interferometer arms (by 1/1000 of the radius of a proton)

❸ Photodetector measures temporal variation in the phase difference between both beams

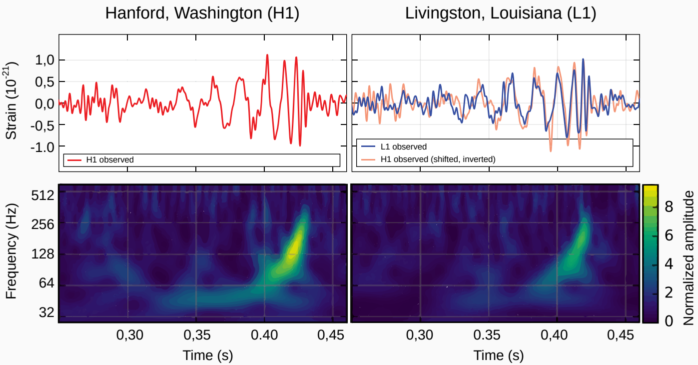
[LIGO/Virgo Collaboration: 1602.03837]



GW150914: First *direct* detection of GWs

- Coalescence of two black holes: $36\,M_\odot + 29\,M_\odot \to 62\,M_\odot$

[LIGO/Virgo Collaboration: 1602.03837]



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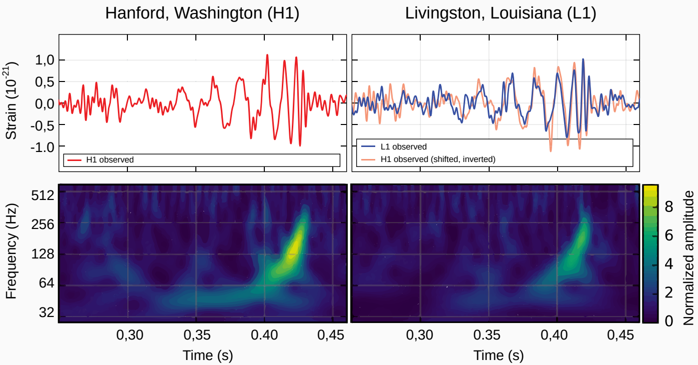
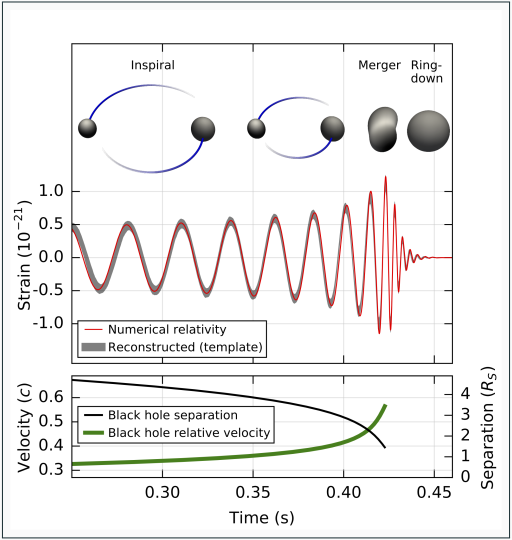


GW150914: First *direct* detection of GWs

- Coalescence of two black holes: $36\,M_\odot + 29\,M_\odot \to 62\,M_\odot$ (?)
- Event at a distance of 1.3 Gly; no plants on earth at time of emission
- Signal propagates for 1.3 Gyr; homo sapiens measures just at the right time

GW150914



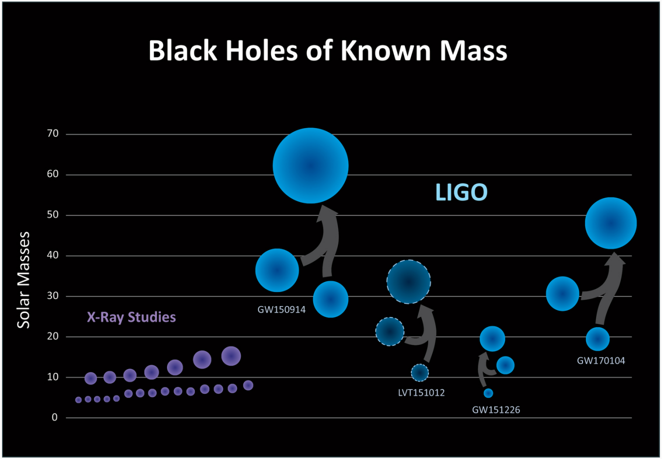
© LIGO / VIRGO Collaboration, Observation of gravitational waves from a binary black hole merger, Phys. Rev. Lett. 116, 061102 (2016)

2017 Nobel Prize in Physics

"For decisive contributions to the LIGO detector and the observation of gravitational waves"

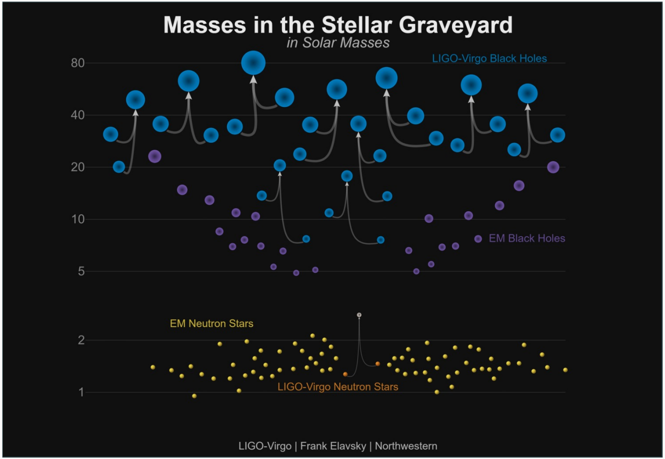
Rainer Weiss (1/2)	Barry C. Barish (1/4)	Kip S. Thorne (1/4)
* 1932 in Berlin	* 1936 in Nebraska	* 1940 in Utah
MIT, Massachusetts	Caltech, California	Caltech, California

Catalog of GW events observed by Advanced LIGO and Advanced Virgo as of June 2017: First binary-black-hole mergers



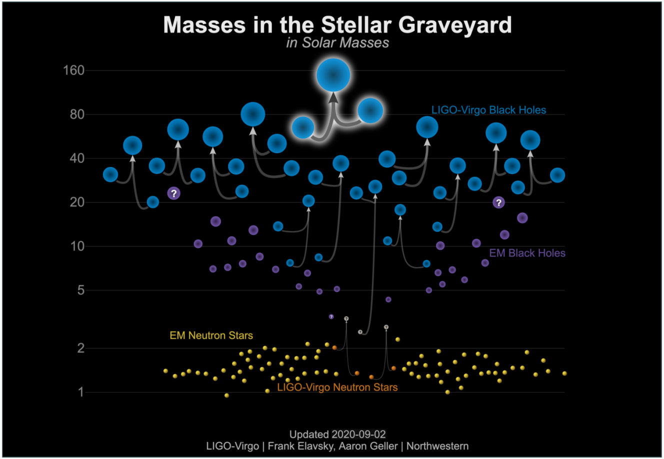
Glorious start into the age of GW astronomy

Catalog of GW events observed by Advanced LIGO and Advanced Virgo as of December 2018: First binary-neutron-star merger (plus EM counterpart)



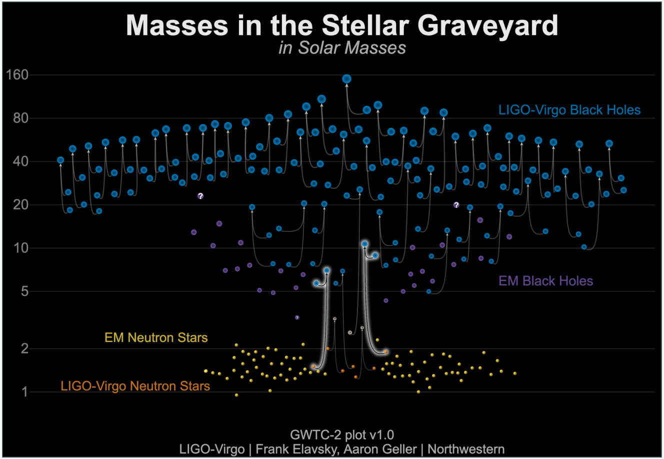
Glorious start into the age of GW astronomy

Catalog of GW events observed by Advanced LIGO and Advanced Virgo as of September 2020: First intermediate-mass black hole



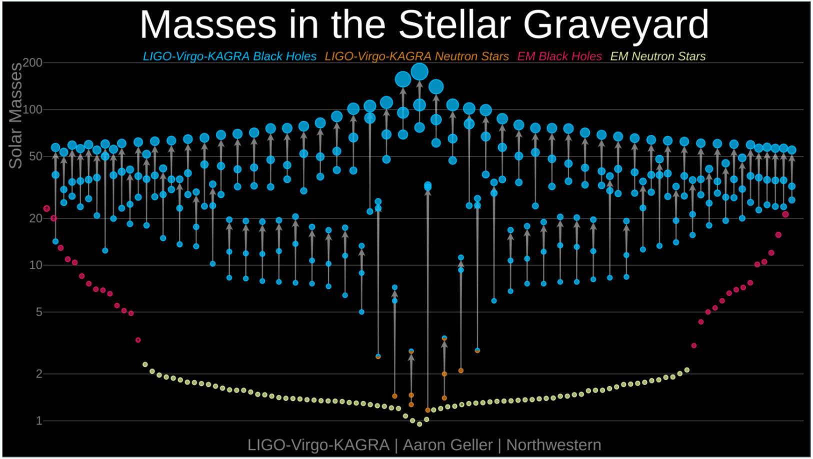
Glorious start into the age of GW astronomy

Catalog of GW events observed by Advanced LIGO and Advanced Virgo as of June 2021: First neutron-star–black-hole mergers



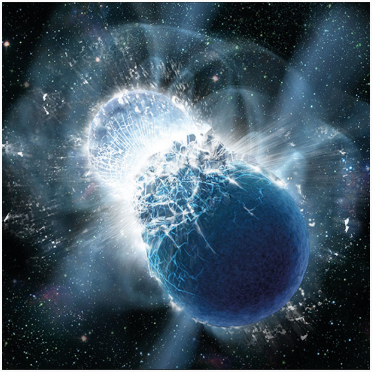
Glorious start into the age of GW astronomy

Catalog of GW events observed by Advanced LIGO and Advanced Virgo as of November 2021: GWTC-3, total of 90 events



One milestone after another

GW170817:
Coalescence of two neutron stars



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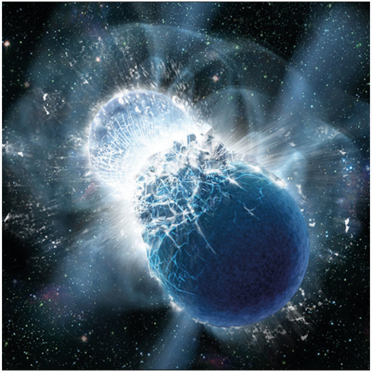

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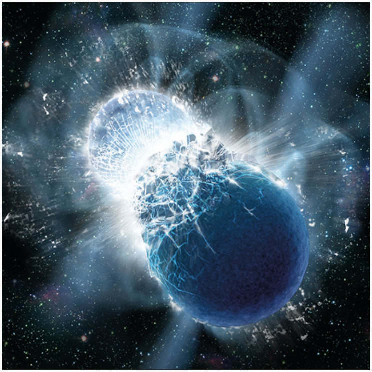
GW200105 und GW200115:
Neutron star eaten by a black hole

© Carl Knox / OzGrav, ARC Centre of Excellence

One milestone after another

GW170817:
Coalescence of two neutron stars



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GW200105 und GW200115:
Neutron star eaten by a black hole

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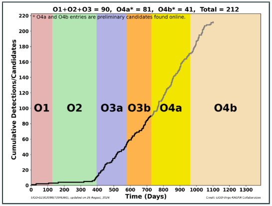
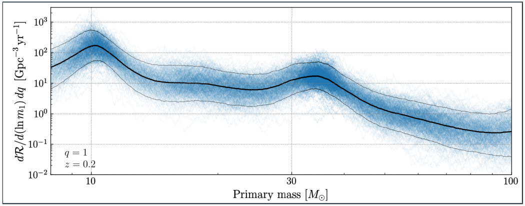
Wealth of opportunities: Gravitational, astro, particle, nuclear physics
→ Tests of GW under extreme conditions, search for new physics, ...

Large number of events

More than 200 events / candidates! [2302.07289]

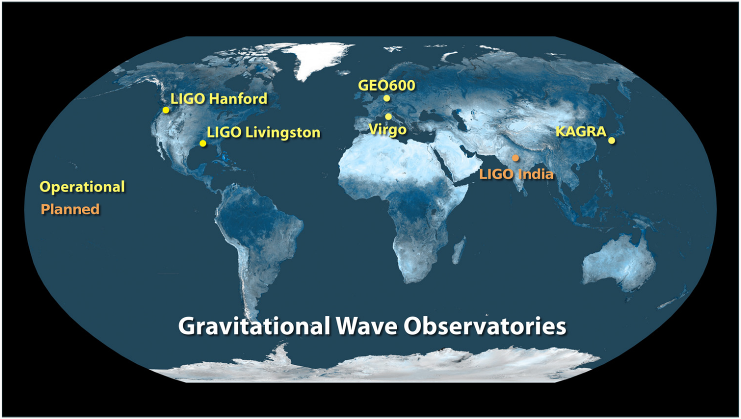




Begin to explore population statistics

- Merger rate = progenitor formation rate + delay time distribution
- Identify different populations: BHs from stellar collapse, primordial BHs?
- Features in mass and spin distributions? → cosmological parameters

Global network of GW detectors



© Caltech/MIT/LIGO Lab

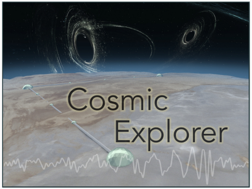
Ground-based laser interferometers:

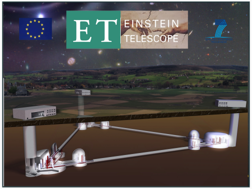
Generation 1: GEO600, LIGO, TAMA, Virgo

Generation 2: Advanced LIGO / Virgo

Generation 2.5: KAGRA, underground and cryogenic

Ground

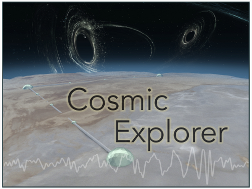


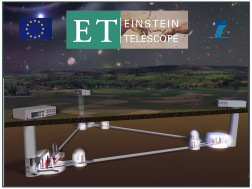


$f \sim 10 \cdots 1000\,\mathrm{Hz}$

Frontiers of GW astronomy in the 21st century

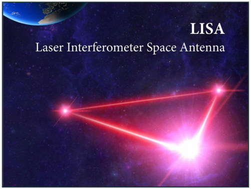
Ground

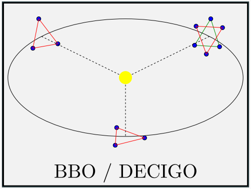




$f \sim 10 \cdots 1000\,\mathrm{Hz}$

Space

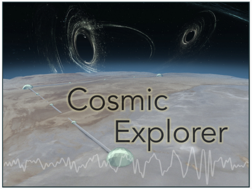


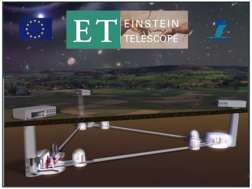


$f \sim 1 \cdots 1000\,\mathrm{mHz}$

Frontiers of GW astronomy in the 21st century

Ground





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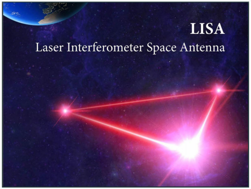
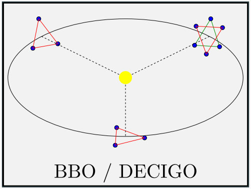
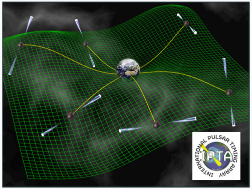
Space





$f \sim 1 \cdots 1000\,\mathrm{mHz}$

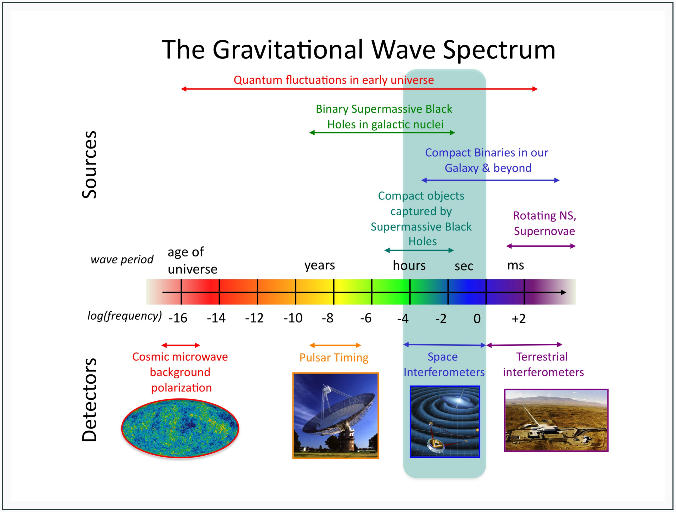
Sky



$f \sim 1 \cdots 10\,\mathrm{nHz}$

GW spectrum

Just like electromagnetic radiation, GWs reach us across a vast frequency spectrum



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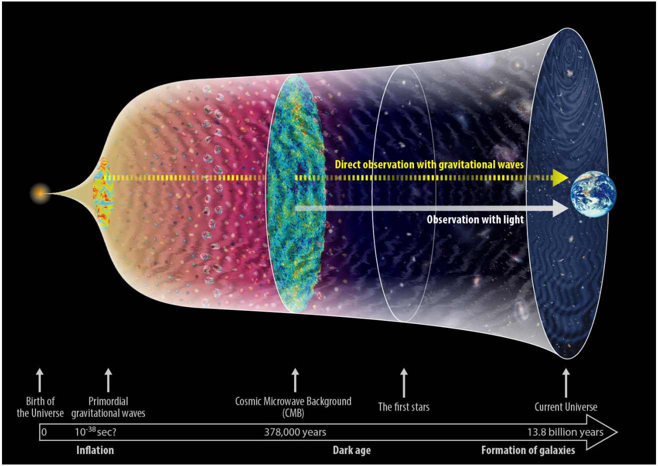
GW echo from the Big Bang

Access to the very early Universwe

[National Astronomical Observatory of Japan, gwpo.nao.ac.jp]



→ Universe becomes transparent to photons only 380,000 after the big bang
→ GWs travel freely through the primordial plasma; messengers from even earlier times

Characterization of a GWB signal

GWs are tensor perturbations of the metric; specifically, in a flat FLRW universe

$$ds^2 = -dt^2 + a^2(t)\left(\delta_{ij} + h_{ij}\right) dx^i dx^j\,, \qquad \partial_i h_{ij}^{\mathrm{TT}} = 0\,, \quad h_{ii}^{\mathrm{TT}} = 0$$

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Strain power spectral density S_h and characteristic strain amplitude $h_c = \sqrt{2fS_h}$

$$\left\langle h_{ij}^{\mathrm{TT}} h_{ij}^{\mathrm{TT}} \right\rangle = 2\left\langle h_+ h_+ \right\rangle + 2\left\langle h_\times h_\times \right\rangle = 4\int_0^\infty df\, S_h(f) = 2\int_0^\infty \frac{df}{f}\, h_c^2(f)$$

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Energy density power spectrum on a logarithmic frequency scale, in units of ρ_{crit}

$$\Omega_{\mathrm{gw}}^{\mathrm{tot}} = \frac{\rho_{\mathrm{gw}}^{\mathrm{tot}}}{\rho_{\mathrm{crit}}} = \int_0^\infty \frac{df}{f}\, \Omega_{\mathrm{gw}}(f)\,, \qquad \Omega_{\mathrm{gw}}(f) = \frac{1}{\rho_{\mathrm{crit}}} \frac{d\rho_{\mathrm{gw}}(f)}{d\ln f} = \frac{4\pi^2 f^3}{3H_0^2}\, S_h(f)$$

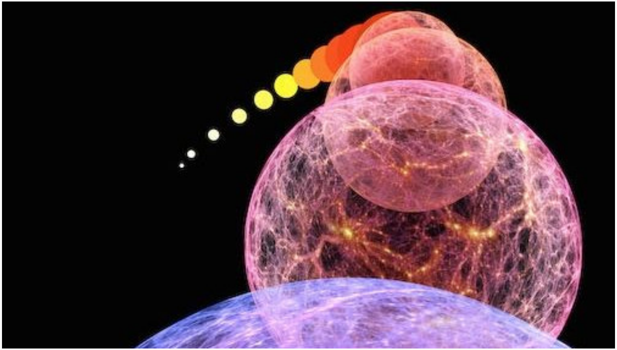
Multiply by h^2, where $H_0 = 100\,h\,\mathrm{km/s/Mpc}$, so that $h^2\Omega_{\mathrm{gw}}$ is independent of H_0

❶ BSM scenario: Cosmic inflation

Big questions: What set the initial conditions of the Hot Big Bang: homogeneity, isotropy, spatial flatness? What seeded the temperature fluctuations in the CMB?

❶ BSM scenario: Cosmic inflation

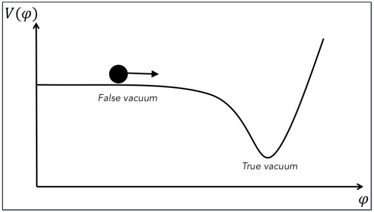
Big questions: What set the initial conditions of the Hot Big Bang: homogeneity, isotropy, spatial flatness? What seeded the temperature fluctuations in the CMB?



Cosmic inflation: Stage of exponentially fast expansion before the Hot Big Bang

- Requires form of dark energy, e.g., potential energy of a scalar "inflaton" field
- Inflaton and metric fluctuations $\rightarrow$ primordial scalar and tensor perturbations

Background dynamics



Klein–Gordon equation

$$\ddot{\phi}(t) + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

Friedmann equation

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 \approx \frac{V}{3M_{\mathrm{Pl}}^2}$$

Slow-roll inflation

- Scalar inflaton field ϕ slowly rolls down scalar potential, $\ddot{\phi} \ll 3H\dot{\phi}, dV/d\phi$
- $V(\phi) \approx \mathrm{const} \approx$ slowly decaying cosmological constant $\rightarrow$ exponential expansion

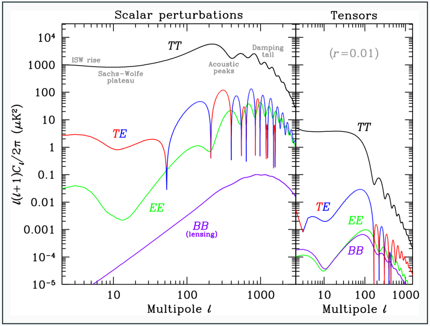
Perturbation theory

Vacuum continuously sources perturbations in the inflaton field and in the metric

[Guth 1981] [Linde 1982] [Albrecht & Steinhardt 1982]

CMB observables

[Review of Particle Physics (2020), pdg.lbl.gov]



Primordial scalar + tensor perturbations source temperature + polarization anisotropies

$$\mathcal{P}_\mathcal{R}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} \approx \frac{1}{8\,\epsilon}\left(\frac{H_k}{\pi\, m_\text{Pl}}\right)^2, \qquad \mathcal{P}_h(k) = r\,A_s\left(\frac{k}{k_*}\right)^{n_t} \approx 2\left(\frac{H_k}{\pi\, m_\text{Pl}}\right)^2$$

with the slow-roll parameter $\epsilon = -\dot{H}/H^2$ measuring the deviation from dS expansion

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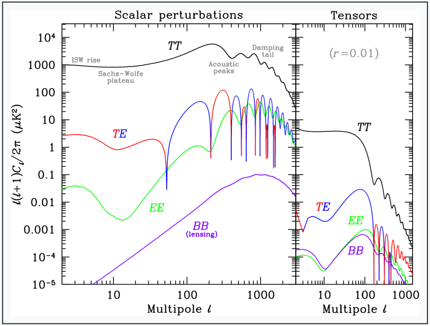

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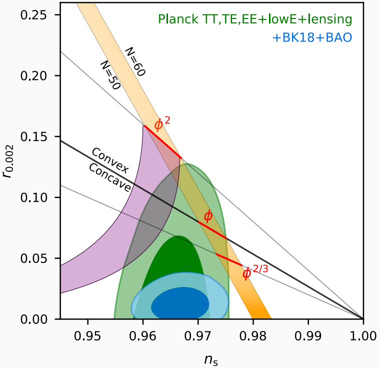
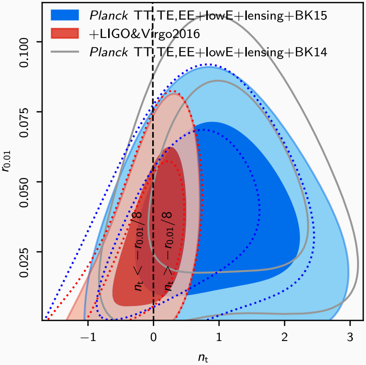
Consistency relation in single-field slow-roll inflation: $\boxed{n_t = \frac{d\ln \mathcal{P}_h}{d\ln k} \approx -2\,\epsilon = -\frac{r}{8}}$

Observational constraints

Scalar spectral index versus $r_{0.002}$

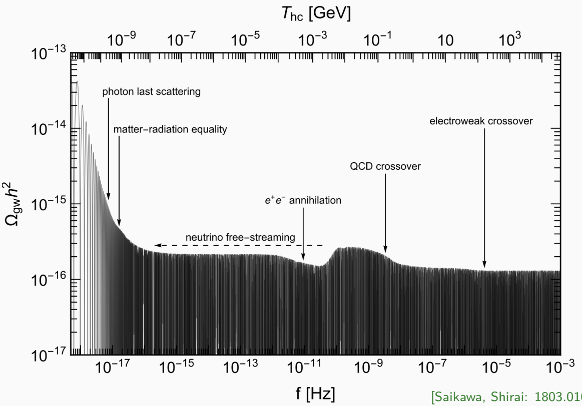


Tensor spectral index versus $r_{0.01}$



- Future CMB polarization experiments (e.g., LiteBIRD) will probe $r \gtrsim 10^{-4 \cdots 3}$
- In absence of a GW signal, tensor index only poorly constrained by CMB
- Tighter constraints if power law naively extrapolated to higher frequencies

Logbook of the expansion history



[Saikawa, Shirai: 1803.01038]

Scale-invariant GW spectrum from inflation, redshifted to the present epoch

- Cosmic logbook encoding the entire expansion history of the early Universe
- Major events in the early Universe leave their imprint in the SGWB signal
- Approximately flat plateau at $\Omega_{\rm gw} \sim \Omega_{\rm r}/24\, rA_s \sim 2 \times 10^{-16}\,(r/0.044)$

❷ BSM scenario: Primordial black holes

Big questions: Are some of the black holes seen by LVK of primordial origin? To what extent do PBHs contribute to dark matter? How do galactic SMBHs form?

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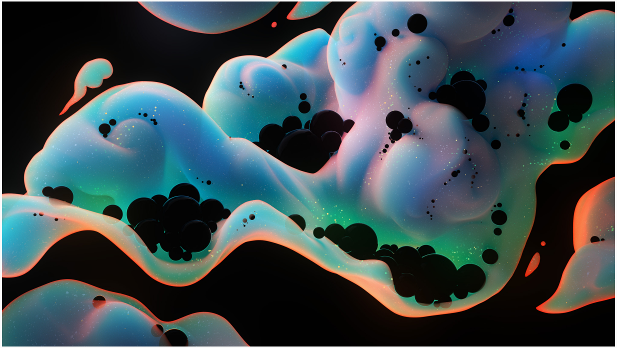
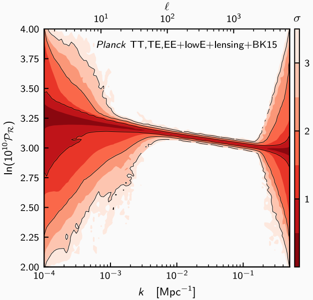


PBHs: Form in the gravitational collapse of large overdensities in the early Universe

- Typical scenario: Scalar perturbations enhanced during ultra-slow-roll inflation
- Enhanced scalar perturbations $\rightarrow$ GWs at second order in perturbation theory

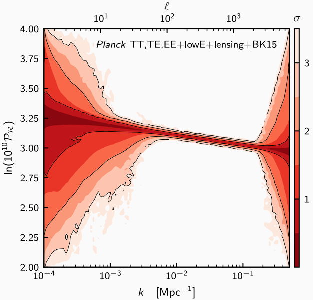
Enhanced curvature perturbations



[PLANCK Collaboration: 1807.06211]

Primordial scalar power spectrum only well known at CMB scales

$$\mathcal{P}_\mathcal{R} = \frac{1}{24\pi^2}\frac{1}{\epsilon}\frac{V}{m_\mathrm{Pl}^4} \simeq (2.10 \pm 0.06) \times 10^{-9} \qquad \text{at} \qquad k_\mathrm{CMB} = 0.05\,\mathrm{Mpc}^{-1}$$



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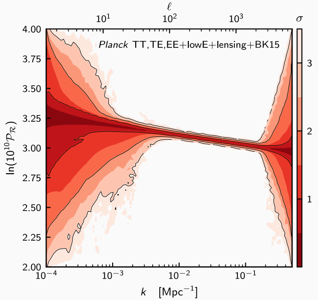
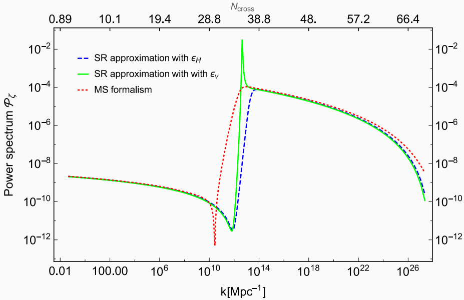
- Standard slow-roll inflation + constant red tilt → even smaller $\mathcal{P}_\mathcal{R}$ on small scales

Enhanced curvature perturbations



[PLANCK Collaboration: 1807.06211]



[Drees, Xu: 1905.13581]

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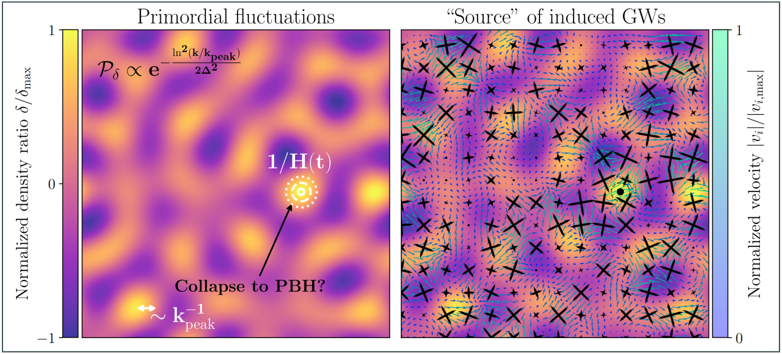
- Standard slow-roll inflation + constant red tilt → even smaller $\mathcal{P}_\mathcal{R}$ on small scales
- Strong assumption! Many inflation models give rise to $\mathcal{P}_\mathcal{R} \gg \mathcal{P}_\mathcal{R}(k_{\rm CMB})$ at large k

Scalar-induced GWs (SIGWs) at second order in perturbation theory

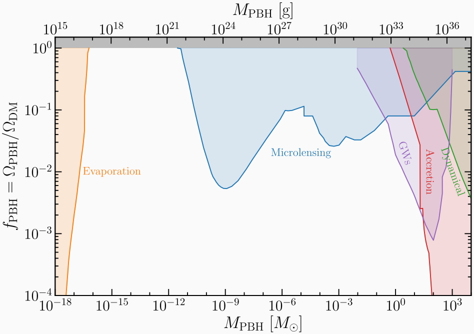
[2402.17388]

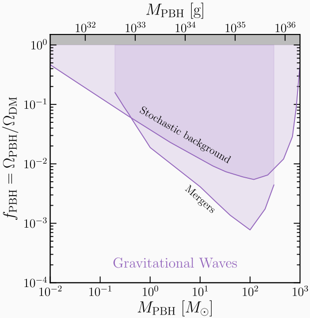


Cosmological perturbation theory

- Scalar and tensor modes couple to each other at second order, $h_{ij} \leftrightarrow \partial_i\Phi\partial_j\Phi$
- Enhanced density modes leave (re-enter) Hubble horizon during (after) inflation
- Collapse into PBHs and source SIGWs upon horizon re-entry during radiation era

Associated PBH formation





[Green, Kavanagh: 2007.10722]

Collapse of horizon mass when overdense regions re-enter the causal horizon

- Statistics of primordial density perturbations translate into PBH mass fraction
- Part of dark-matter (DM) relic density; up to 100 % for asteroid-scale masses
- DM mass fraction $f_{\rm PBH} \sim 10^{-3}$ and masses of $\mathcal{O}(10)\, M_\odot$ → LIGO / Virgo!?

❸ BSM scenario: Phase transition

Big questions: How are the Higgs mechanism and the quark–hadron transition realized in the early Universe? Are there other fundamental forces beyond the Standard Model?

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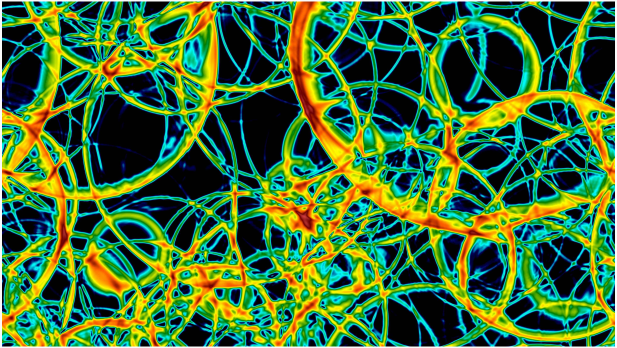
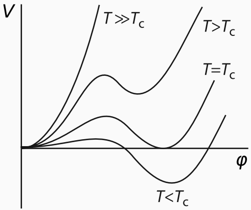


Cosmological phase transitions: Changes in the quantum field theory vacuum structure

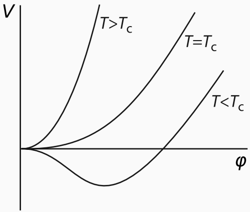
- SM predicts smooth crossovers; strong first-order phase transitions require BSM
- GWs from bubble collisions, sound waves, and magnetohydrodynamic turbulence

First-order phase transitions

First-order phase transition



Second-order phase transition



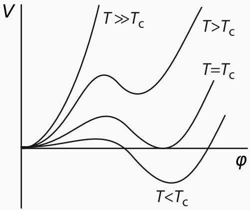
[Kinnunen, Baarsma, Martikainen, Törmä: 1706.07076]

GWs from strong first-order phase transitions (SFOPTs)

- Barrier in the effective potential of the order parameter (scalar field)
- Thermal jump or quantum tunneling → bubble nucleation in position space
- Bubbles expand, accelerate, transfer energy to the surrounding plasma, and collide

First-order phase transitions

First-order phase transition



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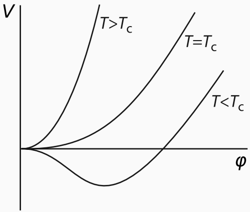

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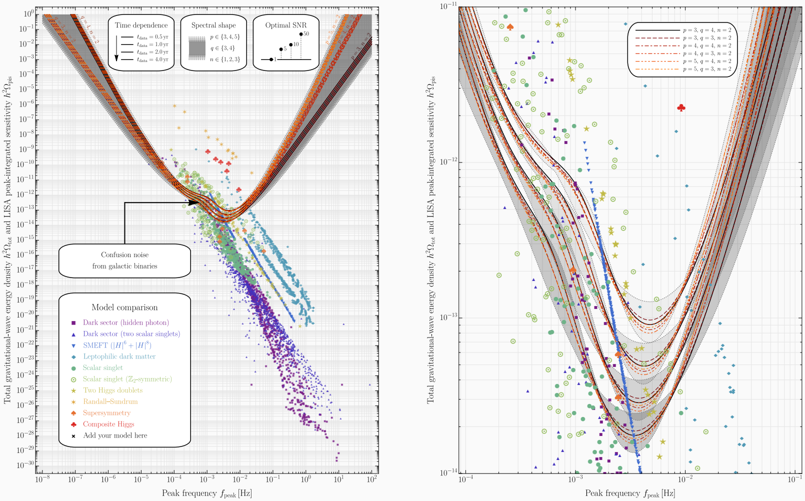
Three sources of GWs

- $\Omega_{\rm b}$: Bubble collisions, gradient energy in the scalar field
- $\Omega_{\rm s}$: Sound waves, compression and rarefaction waves in the bulk plasma
- $\Omega_{\rm t}$: Magnetohydrodynamic turbulence, vortical motion in the bulk plasma

LISA sensitivity to GWs from sound waves

[**KS**: 2005.10789]



Peak-integrated sensitivity: LISA sensitivity projected onto $f_{\rm peak} - h^2\Omega_{\rm tot}$ plane

❹ BSM scenario: Cosmic defects

Big questions: How are the tiny SM neutrino masses generated? What is the origin of the matter–antimatter asymmetry? Is the SM embedded in a grand unified theory?

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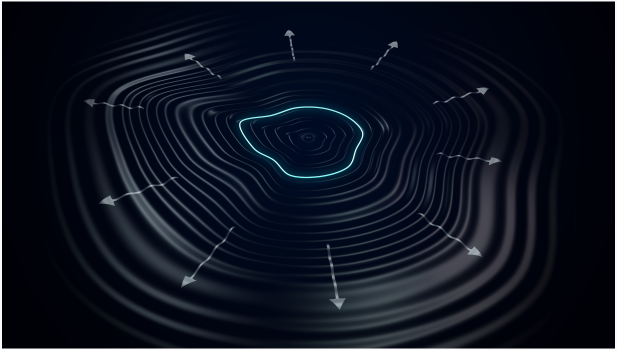
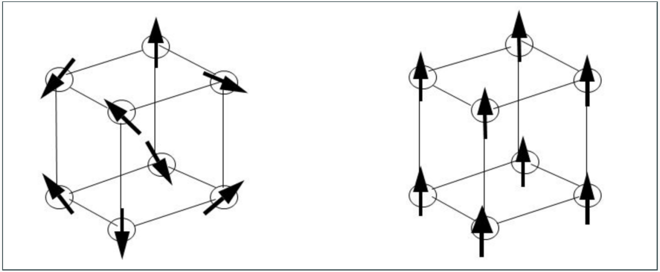


Cosmic strings / domain walls: Defects after spontaneous breaking of GUT symmetries

- Typical scenario: $U(1)_{B-L}$ breaking $\rightarrow$ neutrino masses, leptogenesis, and strings
- Dynamics and decay of defect networks yield anisotropic stress and hence GWs

Magnetic domains in a ferromagnet

[wikimedia.org]

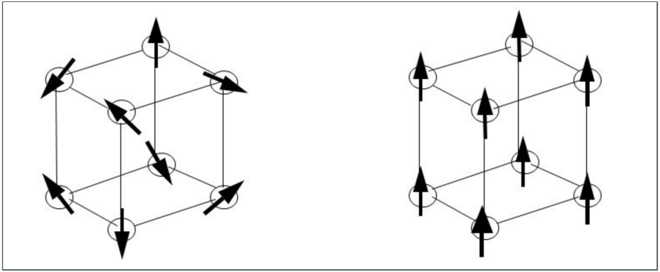


Magnetization in a ferromagnet

- Phase transition at the Curie temperature: paramagnet $\rightarrow$ ferromagnet
- Magnetic dipoles align spontaneously due to exchange interaction
- Translation and rotation invariance spontaneously broken
- Magnetic domains, regions of uniform magnetization, separated by domain walls
- Domain walls are stable, unless an external force (magnetic field) is applied

Magnetic domains in a ferromagnet

[wikimedia.org]



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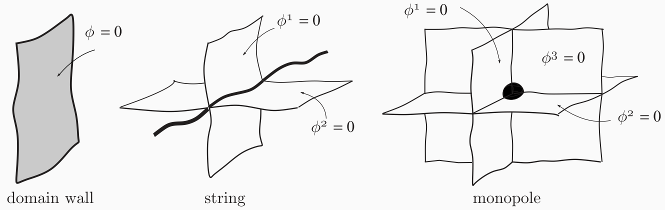
Similar phenomenology after phase transitions in the early Universe!

Topological defects in the early Universe

[Viatcheslav Mukhanov: Physical Foundations of Cosmology, Cambridge University Press (2005)]



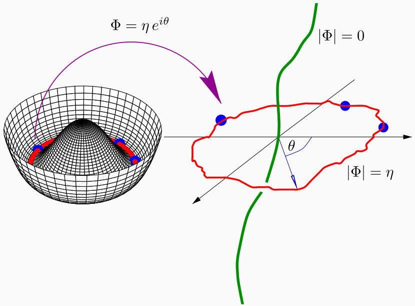
Consider spontaneous symmetry breaking in an N-dimensional scalar field space:

$$V(\Phi) = \frac{\lambda}{4}\left(\Phi^2 - v^2\right)^2, \qquad \Phi = \frac{1}{\sqrt{N}}\left(\phi_1, \phi_2, \cdots, \phi_N\right)^T$$

- Scalar fields transform under $SO(N)$ global or local gauge symmetry
- $\mathbb{Z}_2 \rightarrow$ domain walls; $U(1)$, $SO(2) \rightarrow$ cosmic strings; $SU(2)$, $SO(3) \rightarrow$ monopoles
- Solitonic solutions of classical equations of motion for the gauge and Higgs fields
- Formal description in terms of topology of vacuum manifold $\mathcal{M}(\Phi) \rightarrow$ stability

Cosmic strings

[Ringeval: 1005.4842]



Properties

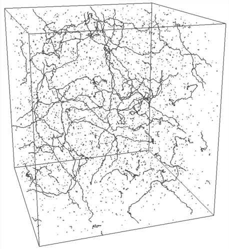
- Topological defects after spontaneous $U(1)$ breaking in the early Universe
- Global / local $U(1)$ symmetry restored (never broken) at the core of strings
- Condensed matter analog: magnetic field vortices in a superconductor

Relevant parameters

- $G\mu$: String tension = energy per unit length, in units of $G = 1/M_{\rm P}^2$
- α: Size of string loops at the time of formation, in units of H^{-1}

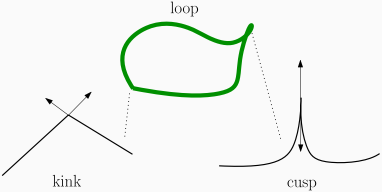
Gravitational waves from cosmic strings

[Allen, Martins, Shellard: ctc.cam.ac.uk/outreach]



Infinite strings and string loops;
scaling regime: $\rho_{\rm cs} \propto \rho_{\rm crit} \propto H^2$

[Gouttenoire, Servant, Simakachorn: 1912.02569]



Gravitational waves from

- Cusps
- Kinks
- Kink–kink collisions

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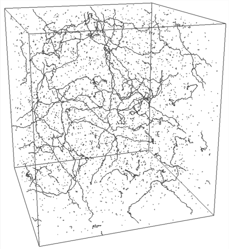

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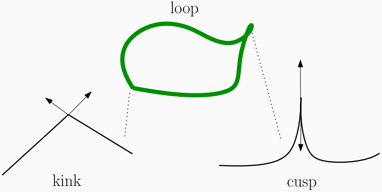

Gravitational waves from

- Cusps
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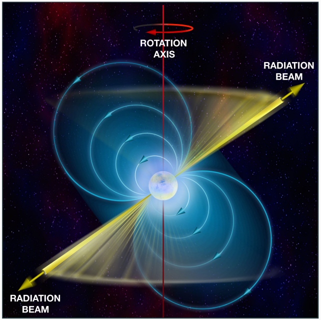
- Nambu–Goto action: infinitely thin strings, no particle emission
- Abelian-Higgs model: short-lived loops, decay into massive particles
- Nonminimal models: Metastable strings, current-carrying cosmic strings, ...

[Vachaspati, Vilenkin: PRD 31 (1985) 3052] [LISA Cosmology Working Group, Auclair et al.: 1909.00819]

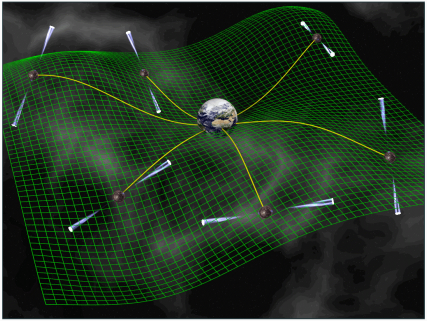
Latest developments

Pulsar timing arrays (PTAs)

Array of pulsars across our MW spiral arm → GW detector of galactic dimensions!



[nrao.edu]



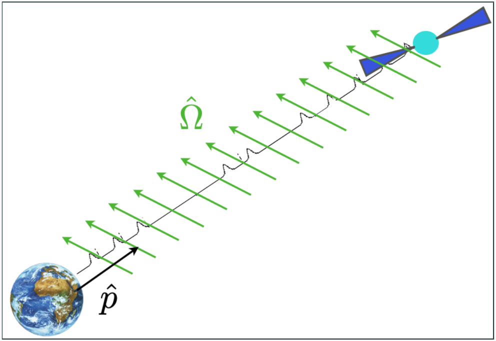
[MPIfR]

Pulsars: **Highly magnetized rotating neutron stars**

- Beamed radio pulses emitted from magnetic N and S poles → cosmic lighthouses
- Stable rotation with periods as short as a few milliseconds → celestial clocks

Look for tiny distortions in pulse times of arrival (TOAs) caused by nanohertz GWs

GW imprint in PTA data



GWs red/blue-shift the train of pulses from a pulsar

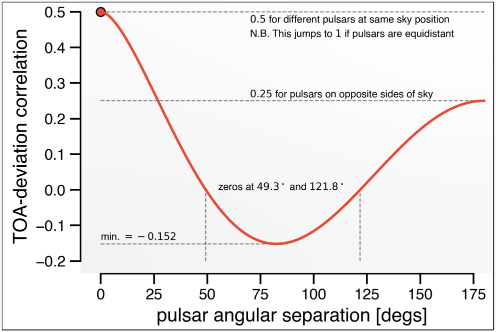
Example: Monochromatic GW moving in direction $\hat{\Omega}$

$$Z = \frac{1}{2} \frac{\hat{p}^i \hat{p}^j}{1 + \hat{\Omega} \cdot \hat{p}} \left[h_{ij} \left(t_{\rm obs}, \boldsymbol{x}_{\rm earth} \right) - h_{ij} \left(t_{\rm em}, \boldsymbol{x}_{\rm pulsar} \right) \right]$$

Main PTA observable: **Timing residual** $R_a(t) = \int_0^t dt' \, Z(t')$ for each pulsar a

Cross-correlation analysis

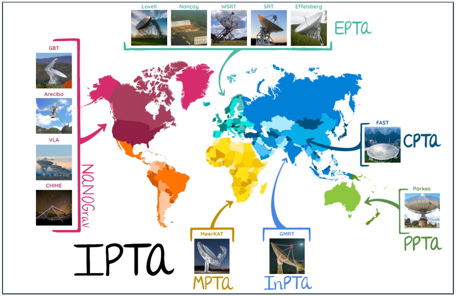
[Hellings, Downs: ApJ 265 (1983) L39] [2105.13270]



Timing-residual cross power spectrum: Correlation coefficients × power spectrum

$$\langle R_a R_b \rangle = \Gamma(\xi_{ab}) \int_0^\infty df \, P_g(f)$$

- **Hellings–Downs curve:** $\Gamma(\xi_{ab}) = \frac{3}{2} x_{ab} \ln x_{ab} - \frac{x_{ab}}{4} + \frac{1}{2}\,, \quad x_{ab} = \frac{1}{2}(1 - \cos\xi_{ab})$
- **Common power spectrum:** $P_g(f) = h_c^2/(12\pi^2 f^3) \overset{\text{ansatz}}{\to} A^2/(12\pi^2 f_{\text{yr}}^3)\,(f/f_{\text{yr}})^{-\gamma}$



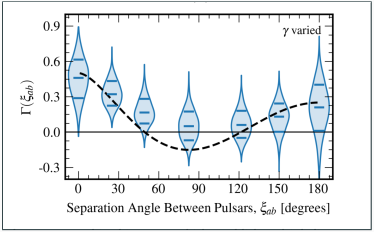
EPTA: European PTA
CPTA: Chinese PTA
PPTA: Parkes PTA
InPTA: Indian PTA
MPTA: MeerKAT PTA
NANOGrav: North American Nanohertz Observatory for Gravitational Waves

18 papers on the arXiv on June 29, 2023

[2306.16213]	NANOGrav	GWB	[2306.16222]	NANOGrav	Continuous GW
[2306.16214]	EPTA	GWB	[2306.16223]	NANOGrav	Analysis pipeline
[2306.16215]	PPTA	GWB	[2306.16224]	EPTA	Data set
[2306.16216]	CPTA	GWB	[2306.16225]	EPTA	Noise model
[2306.16217]	NANOGrav	Data set	[2306.16226]	EPTA	Continuous GW
[2306.16218]	NANOGrav	Noise model	[2306.16227]	EPTA	Implications
[2306.16219]	NANOGrav	New physics	[2306.16228]	EPTA	ULDM
[2306.16220]	NANOGrav	SMBHBs	[2306.16229]	PPTA	Noise model
[2306.16221]	NANOGrav	Anisotropies	[2306.16230]	PPTA	Data set

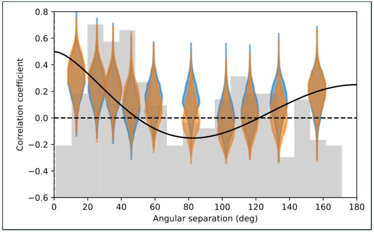
Evidence for HD correlations $\Gamma(\xi_{ab})$

2306.16213: NANOGrav



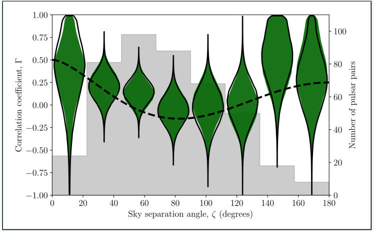
68 pulsars, 16 yr of data, HD at $\sim 3 \cdots 4\,\sigma$

2306.16214: EPTA+InPTA



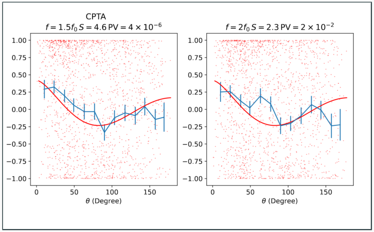
25 pulsars, 25 yr of data, HD at $\sim 3\,\sigma$

2306.16215: PPTA



32 pulsars, 18 yr of data, HD at $\sim 2\,\sigma$

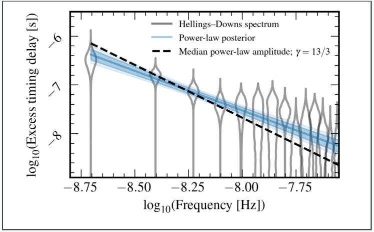
2306.16216: CPTA



57 pulsars, 3.5 yr of data, HD at $\sim 4.6\,\sigma$

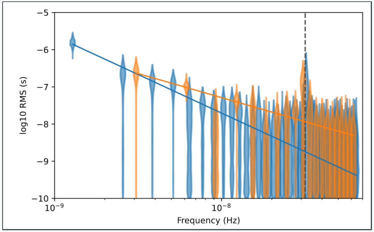
Common power spectrum $\sqrt{\Delta f \, P_g(f)}$

2306.16213: NANOGrav



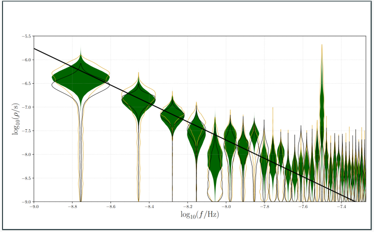
68 pulsars, 16 yr of data, HD at $\sim 3 \cdots 4\,\sigma$

2306.16214: EPTA+InPTA



25 pulsars, 25 yr of data, HD at $\sim 3\,\sigma$

2306.16215: PPTA



32 pulsars, 18 yr of data, HD at $\sim 2\,\sigma$

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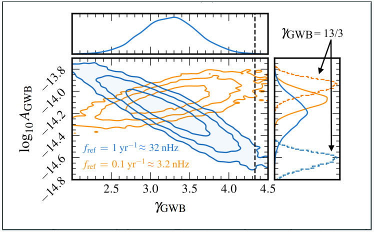
57 pulsars, 3.5 yr of data, HD at $\sim 4.6\,\sigma$

Power-law parameters A and γ

2306.16213: NANOGrav



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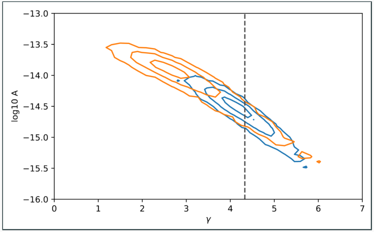

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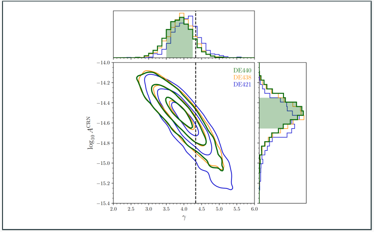

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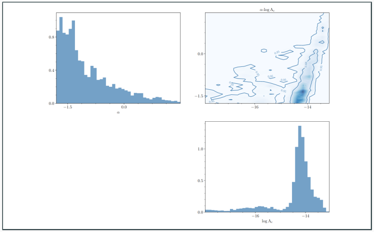
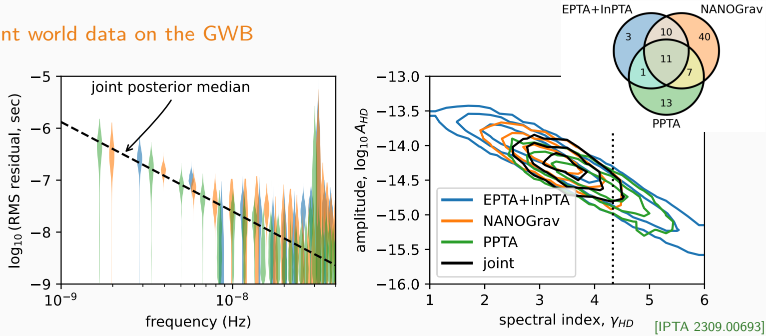


57 pulsars, 3.5 yr of data, HD at $\sim 4.6\,\sigma$

IPTA comparison

Current world data on the GWB

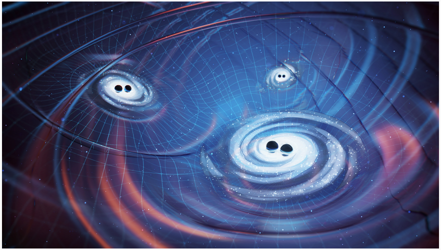


[IPTA 2309.00693]

- Results from regional PTAs are consistent with each other (1σ posteriors overlap)
- Joint posterior = naive product (properly normalized) of individual posteriors
- Proper data combination and combined data analysis → IPTA DR3

Interpretations

❶ Supermassive black-hole binaries



❶ SMBHBs (realistic)

- No SMBHB mergers directly observed as of yet $\rightarrow$ data-driven field thanks to PTAs
- Viable explanation, several open questions $\rightarrow$ unexpected corners of parameter space?

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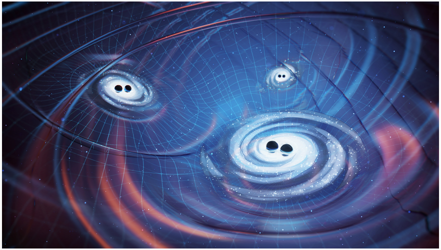
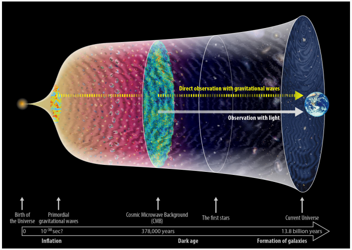


❷ GWs from the Big Bang



❶ SMBHBs (realistic)

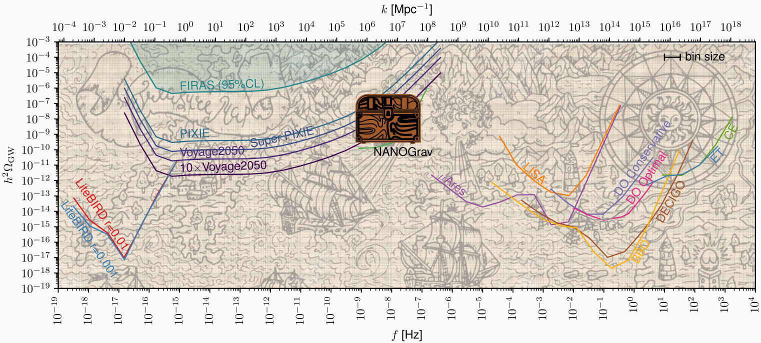
- No SMBHB mergers directly observed as of yet → data-driven field thanks to PTAs
- Viable explanation, several open questions → unexpected corners of parameter space?

❷ New physics (speculative)

- Logical possibility: PTA signal is not of SMBHB origin or receives several contributions
- **Probe** and **constrain** cosmology at early times as well as particle physics at high energies

Outlook

Off to new shores!



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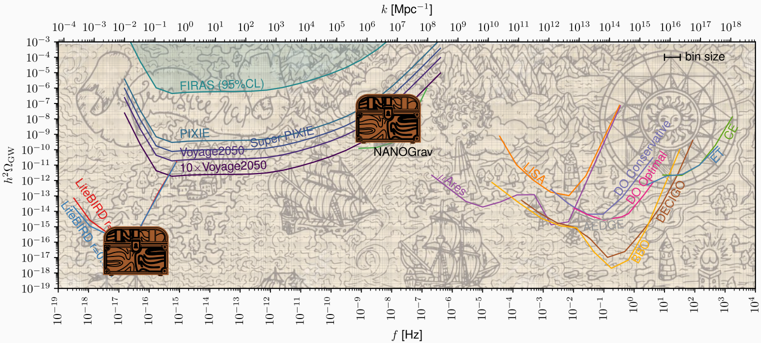

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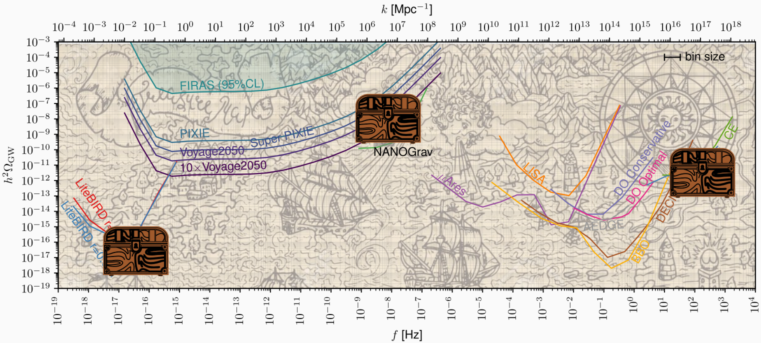

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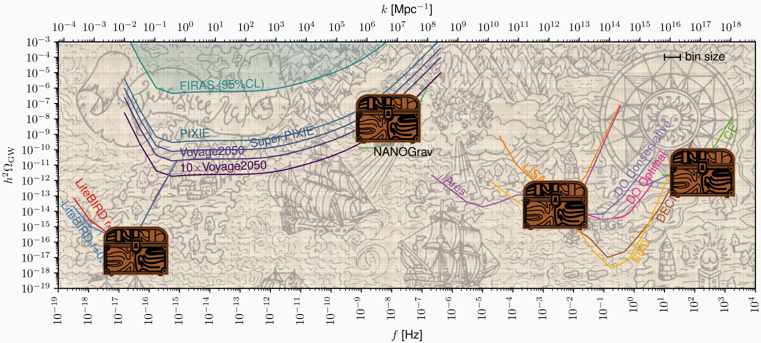

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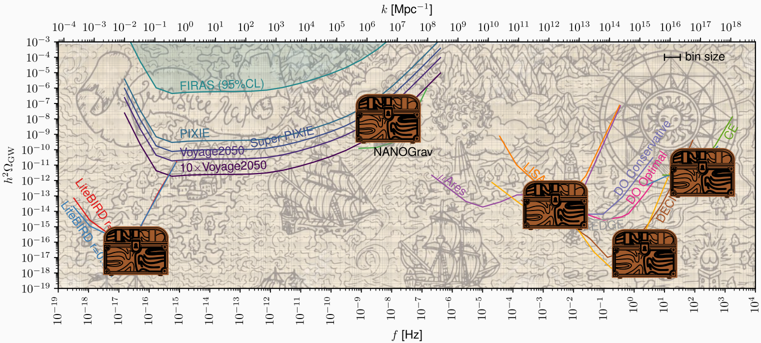

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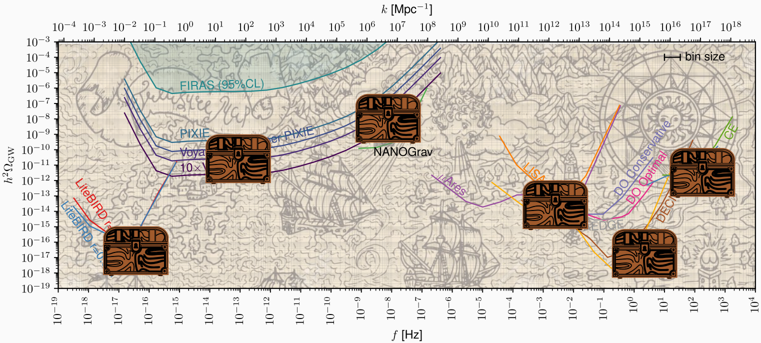
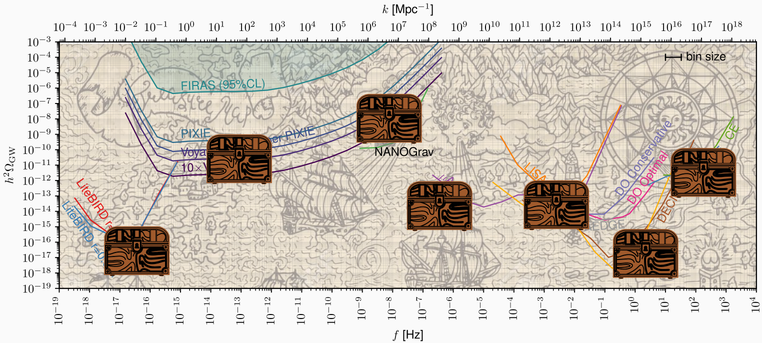
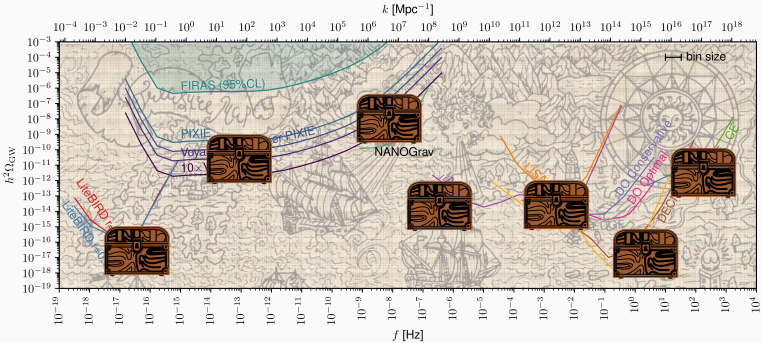


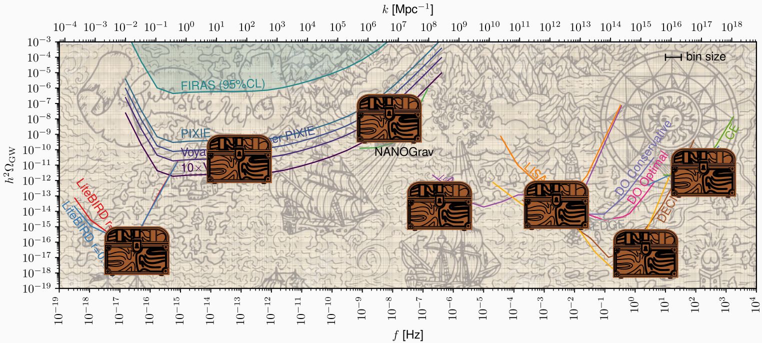

k [Mpc⁻¹]
bin size
FIRAS (95%CL)
PIXIE
Super PIXIE
Voya
10×
NANOGrav
LiteBIRD
LiteBIRD
LISA
DO Conservative
DO Optimal
DECI
CE
EDGE
h²Ω_GW
f [Hz]



The 21st century will be the century of GW science

- New window onto the Universe $\rightarrow$ astrophysics, cosmology
- Novel probe of fundamental physics $\rightarrow$ particle physics, gravity

Off to new shores!



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Thanks a lot for your attention!