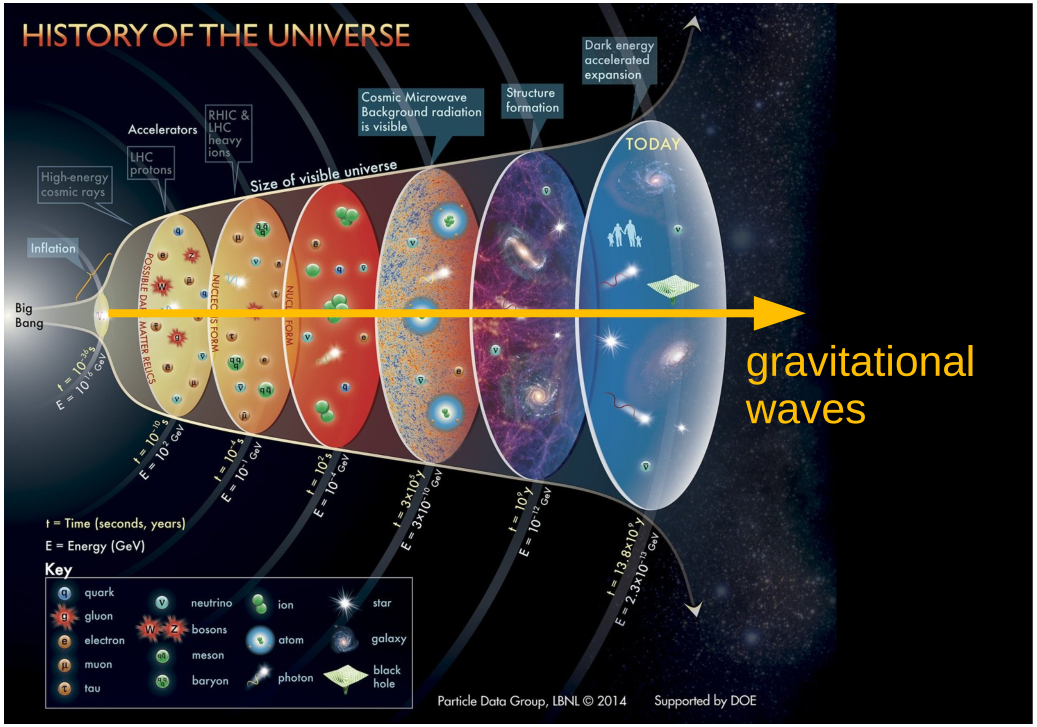
Gravitational wave physics

what we know and what we want to know



Valerie Domcke
CERN

Academic training lectures
April 2024

Outline

1) What we know

- Motivation
- What is a GW?
- LIGO: signal & detection
- LIGO: some highlights

Literature:
- M. Maggiore, GWs, Vol I
- C. Caprini, D. Figueroa, Cosmological backgrounds of GWs, arxiv: 1801.04268

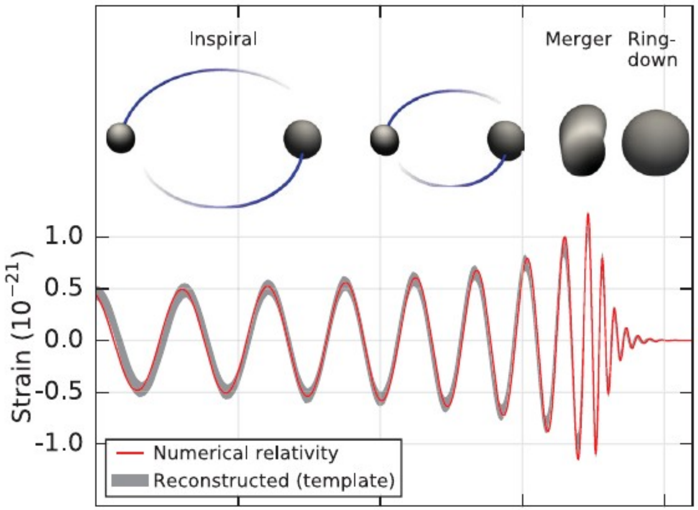
2) Current frontier

- GW background
- Pulsar timing arrays
- BSM searches with GWS

3) What we want to know

- Going to space & underground
- New opportunities at new frequencies

transient and stochastic signals



LIGO Livingston, USA

2015: first direct observation of GWs, collision of two black holes a billion years ago

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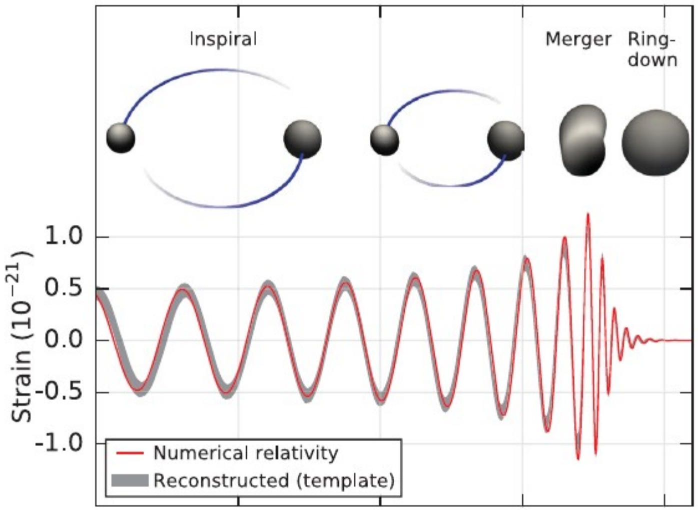

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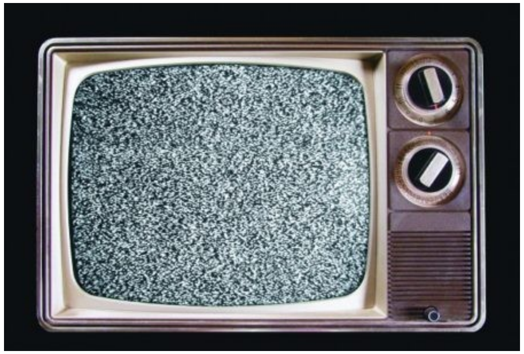
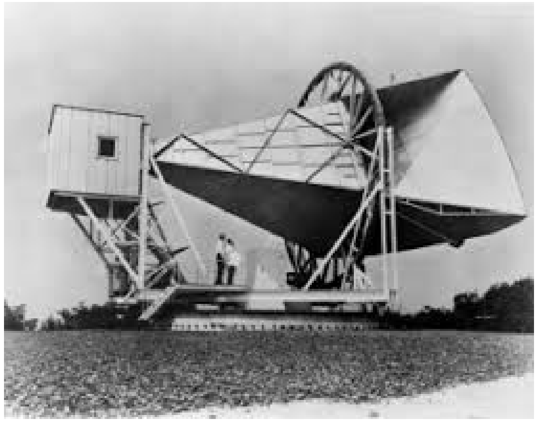


next challenge:
stochastic gravitational wave background

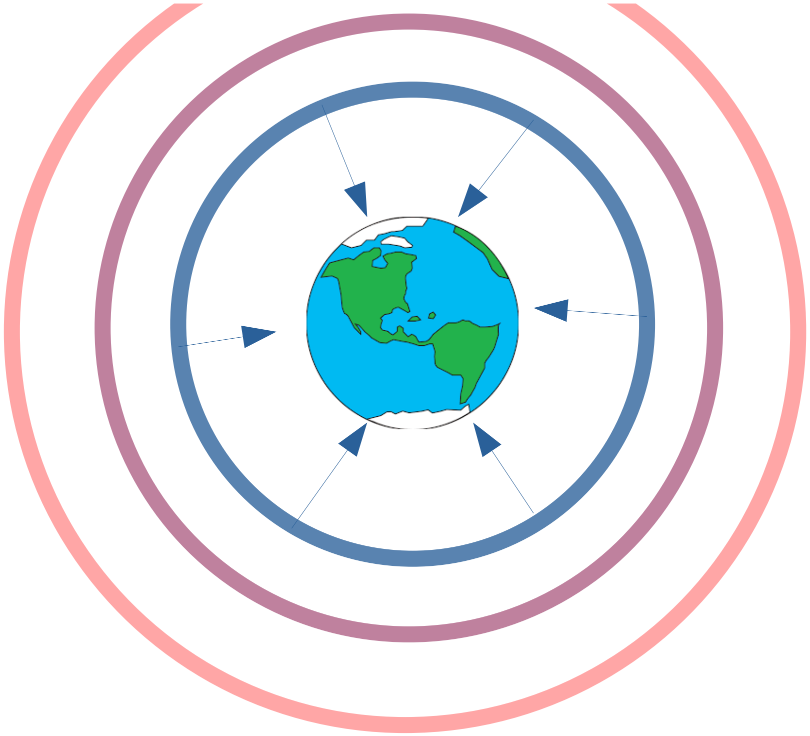
analagous to CMB



Penzias, Wilson `64

astrophysical and cosmological contributions

possible hint by PTAs (pulsar timing arrays) stochastic gravitational wave background (SGWB):



astrophysical sources:

unresolved mergers
of compact objects (BH, NS, ..)

cosmological sources:

SM: inflation, thermal fluctuations
→ very small

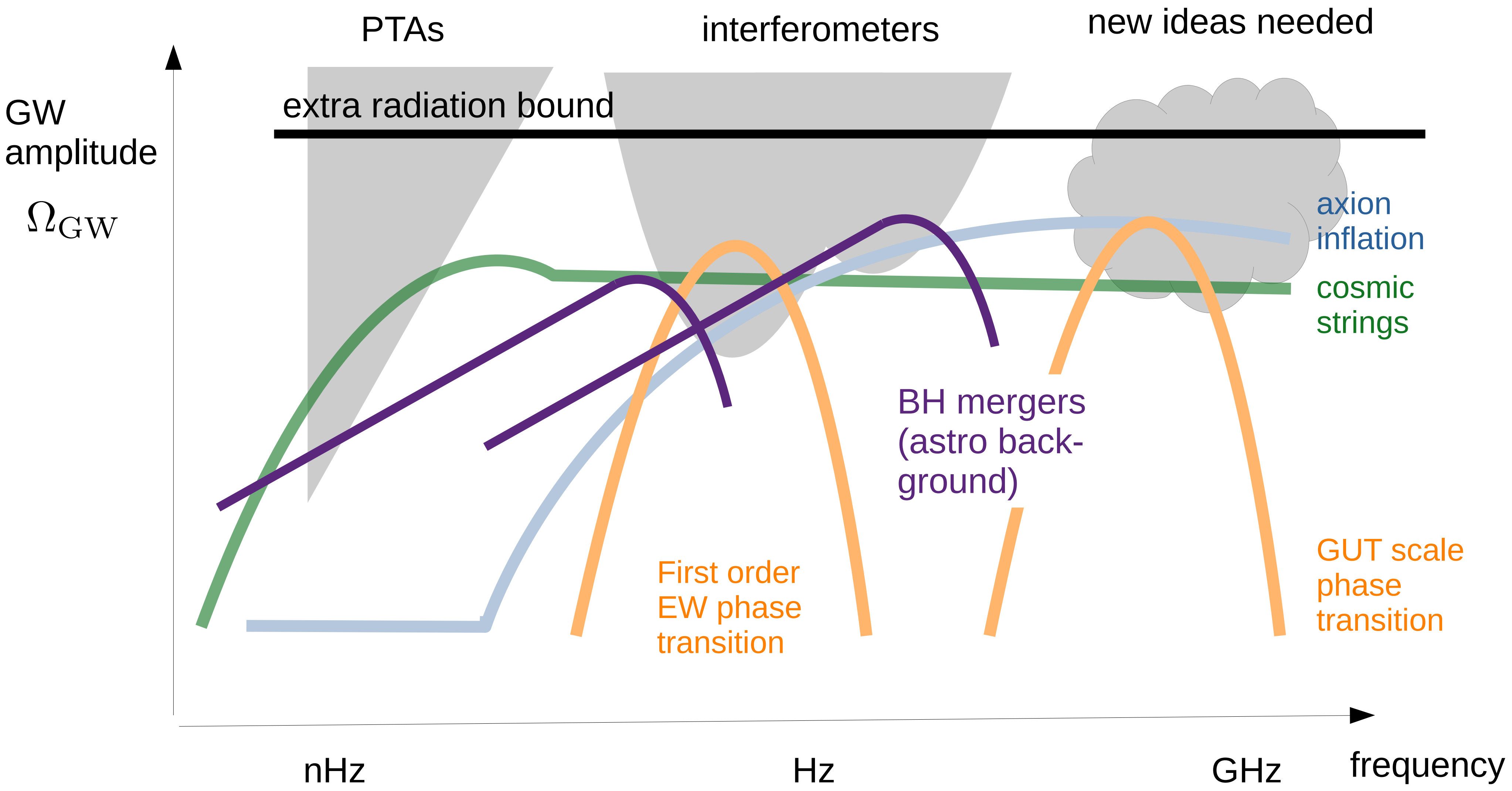
BSM: inflation, (p)reheating,
phase transitions, ...

$$f \sim \text{mHz}\ (0.01/\epsilon_*)\,(T_*/100\ \text{GeV})$$

primary observable:

$$\Omega_{GW} = \frac{1}{\rho_c}\frac{\partial \rho_{GW}(f,\tau)}{\partial \ln f}$$

A possible landscape of GW backgrounds



Deciphering the SGWB (I)

Characteristic frequencies of relic GWs:

$$f_* = (\epsilon_* H_*^{-1})^{-1}$$

emitted frequency

causal horizon

$\epsilon_* \lesssim 1$
size of the universe relative to horizon

$$f_0 = f_* \frac{a(t_*)}{a(t_0)}$$

observed frequency
= redshifted emitted frequency

scale factors parametrize expansion of the universe

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Expansion history according to ΛCDM : $H^{-1} \propto t^2\,, \quad a \propto t^{1/2}\,, \quad T \propto t^{-1/2}$

$$\mathrm{f}_0 \simeq 1 \text{ Hz } \epsilon_*^{-1} \left(\frac{T_*}{10^8 \text{ GeV}}\right)$$

$$t_* \simeq 10^{-22}\text{s } \epsilon_* \left(\frac{\text{Hz}}{f_0}\right)^2$$

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1 : 1 frequency → time / energy mapping for transient cosmological events.

GW detectors as probe of early universe cosmology, probe of BSM physics complementary to colliders.

Deciphering the SGWB (II)

GW propagation in the expanding universe:

$$(\partial_t^2 - \partial_{\vec{x}}^2)h_{\mu\nu} + \underline{2a\,\partial_t a\,\partial_t h_{\mu\nu}} = \frac{16\pi G}{c^4}T_{\mu\nu}$$

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Observed GW carries information about source and expansion history:

$$h_{ij}(\tau, x) = \int d^3k\, \underbrace{h_\lambda(\vec{k})}_{\text{source}}\, \underbrace{T_k(\tau)}_{\text{expansion}}\, e_{ij}^\lambda(\hat{k})\, e^{-i(k\tau - \vec{k}\vec{x})}$$

source   expansion $T_k(\tau) = a(\tau_*)/a(t_0)$

for experts:
τ : conformal time
k : comoving frequency

Cosmological GW signals depend on source properties and cosmic history

Extra radiation bound

radiation energy after electron decoupling:

photons, neutrinos, BSM

$$\rho_{rad} = \frac{\pi^2}{30}\left(2 + \frac{7}{4}\left(\frac{4}{11}\right)^{4/3}(3.046 + \Delta N_{eff})\right)T^4$$

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at BBN or CMB decoupling:

$$\rho_{GW}(T) < \Delta\rho_{rad}(T) \quad \Rightarrow \quad \left(\frac{\rho_{GW}}{\rho_\gamma}\right)_{T_{BBN,CMB}} \leq \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\Delta N_{eff} \simeq 0.05$$

→ at BBN, CMB decoupling ~ 5 % GW energy density allowed

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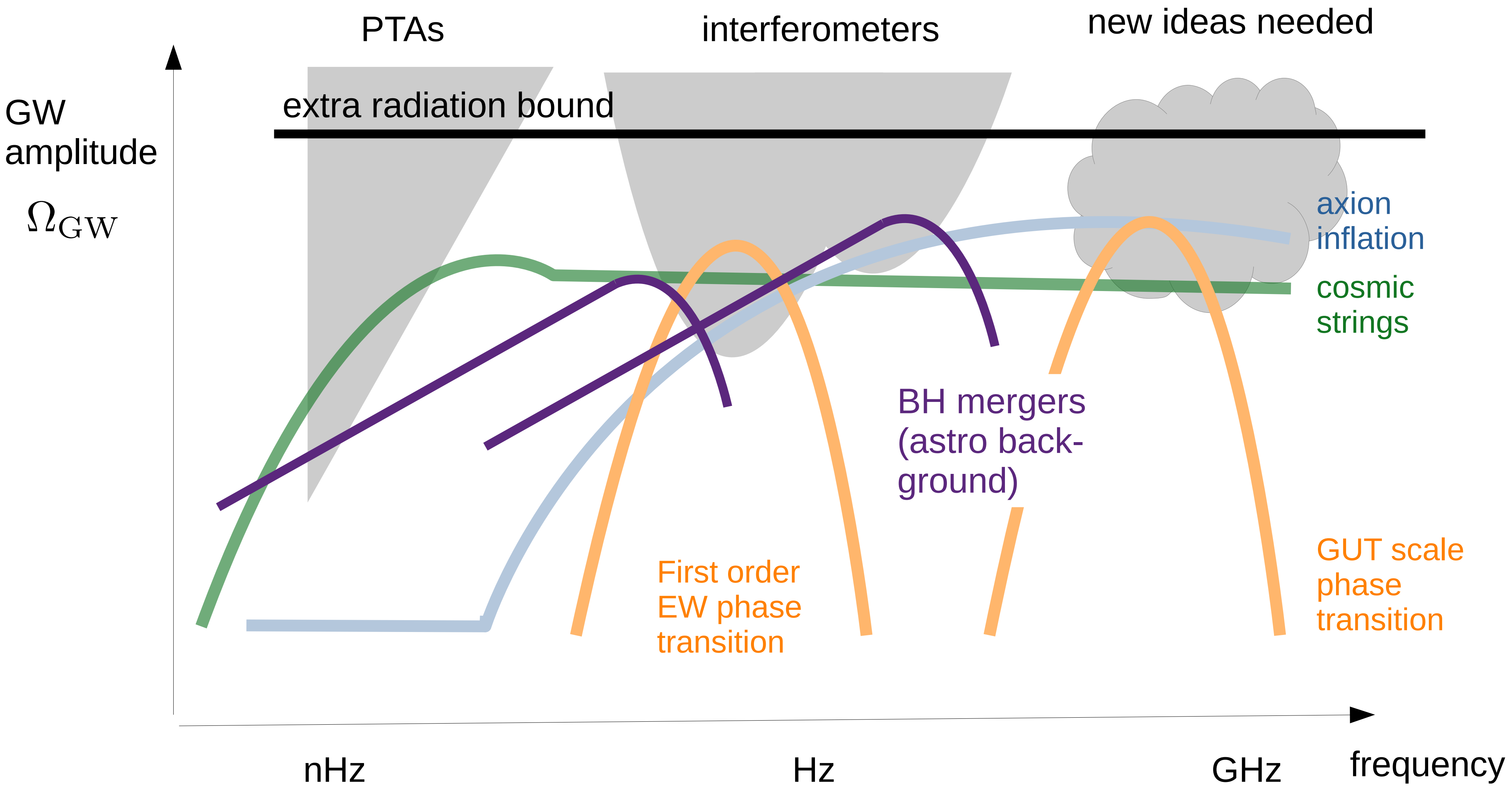
today:

$$\frac{\rho^0_{GW}}{\rho^0_c} = \Omega^0_\gamma \left(\frac{g^0_s}{g_s(T)}\right)^{4/3} \frac{\rho_{GW}(T)}{\rho_\gamma(T)} \leq 10^{-5}\Delta N_{eff} \simeq 10^{-6}$$

note: constraint on *total* GW energy

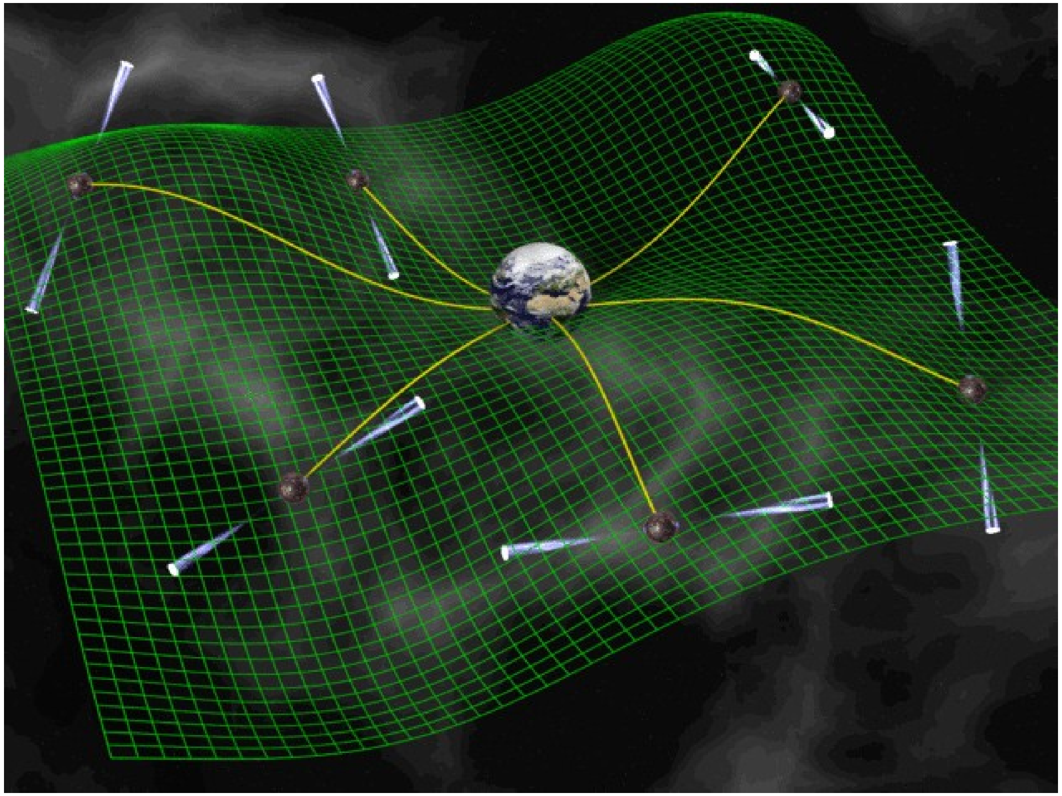
→ today, energy fraction < 10^{-6} (for GWs present at BBN / CMB decoupling)

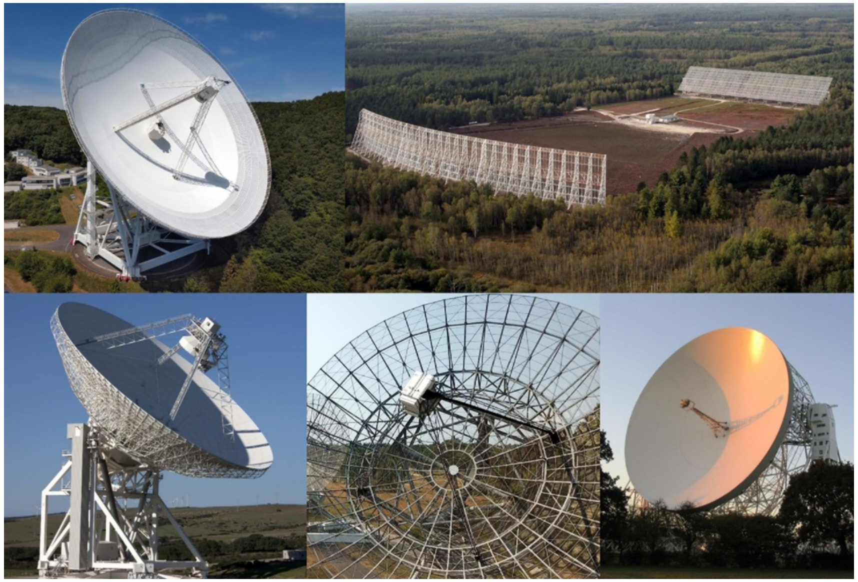
A possible landscape of GW backgrounds



Pulsar timing arrays

- rotating neutron stars act as lighthouses in the galaxy
- measure arrival time of pulses on earth
- search for shifts in arrival time due to passing GWs

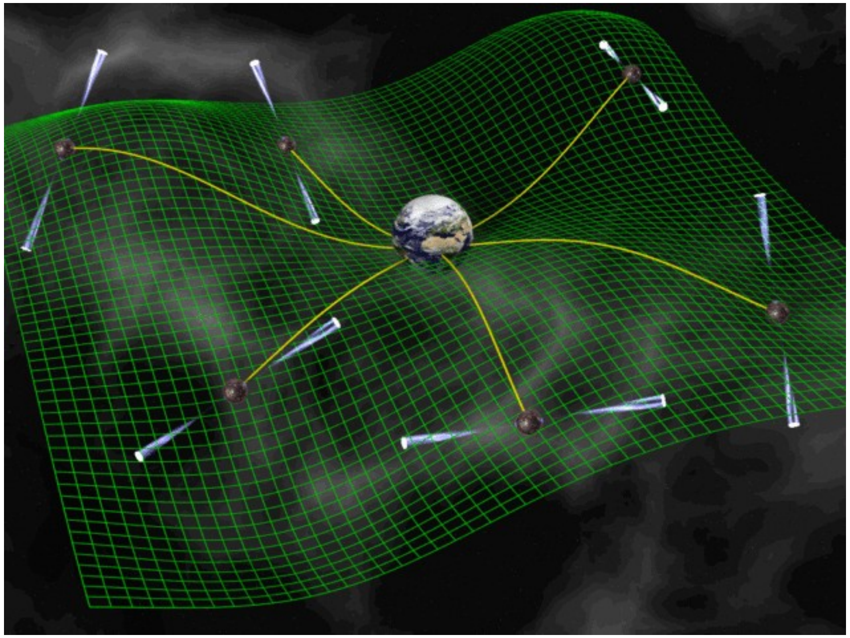




- data from EPTA + InPTA, NanoGrav, PPTA, CPTA
- combination through IPTA

Pulsar timing arrays

- search for delays in pulse arrivals
- 2020: evidence for common stochastic noise component across all pulsars
- 2023: evidence for Hellings-Down correlation (i.e. gravitational waves)



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IPTA `22, 2201.03980

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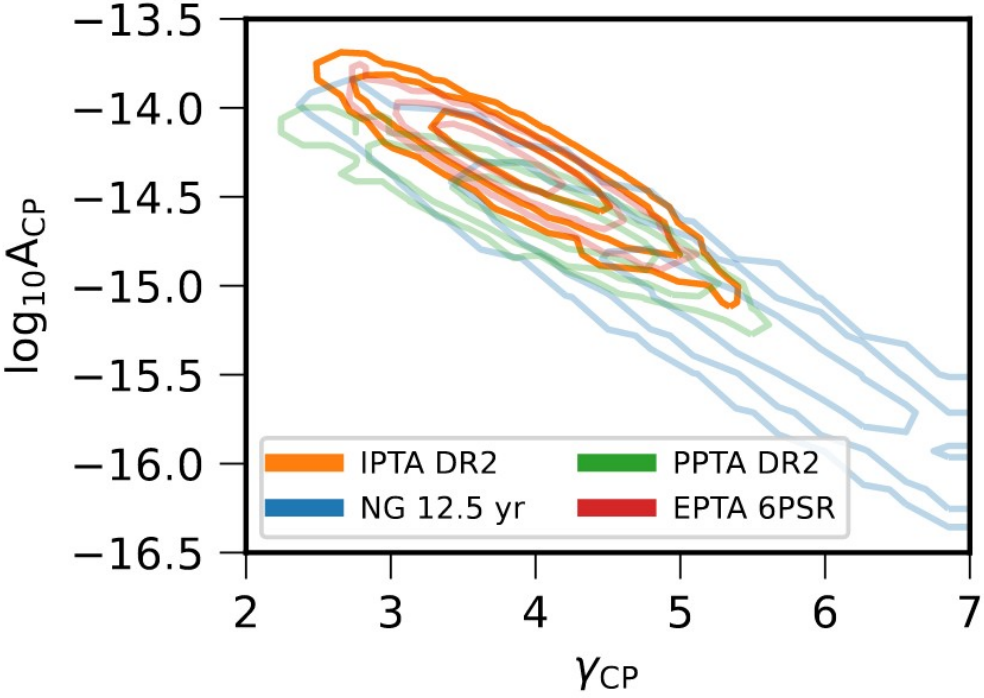

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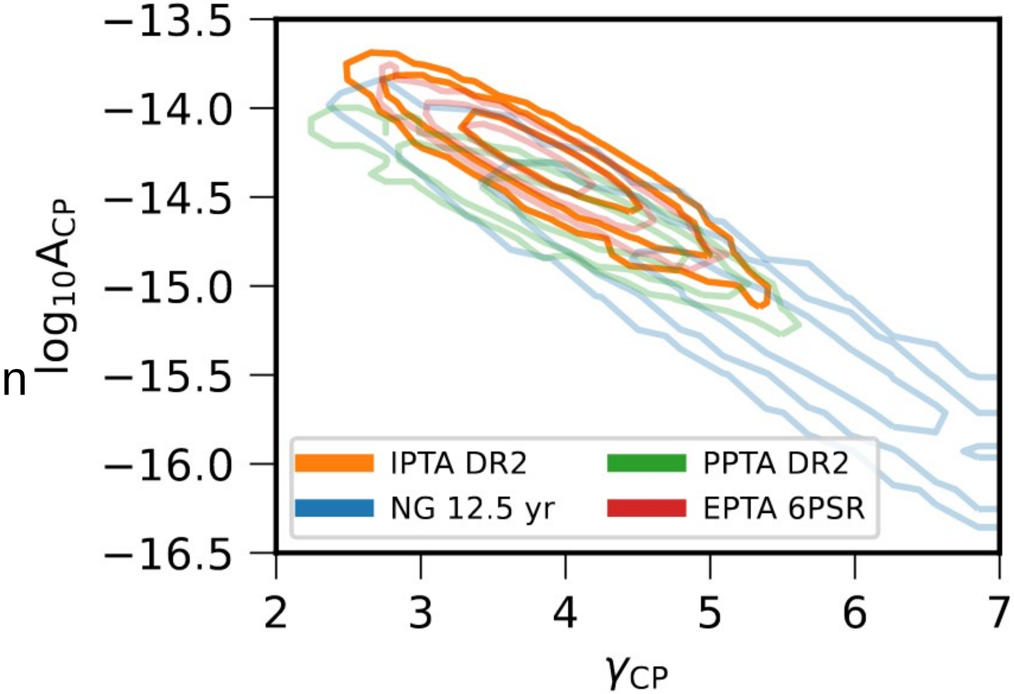

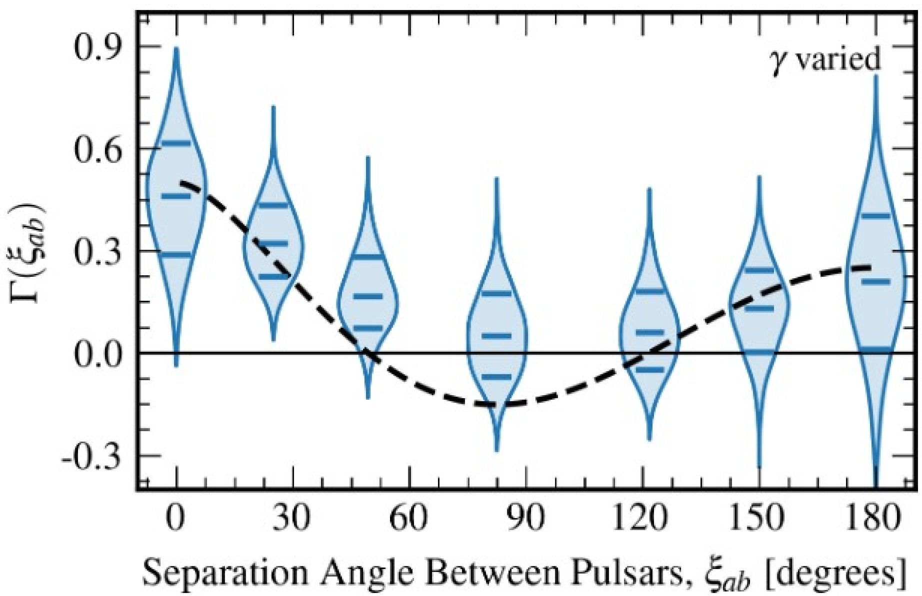

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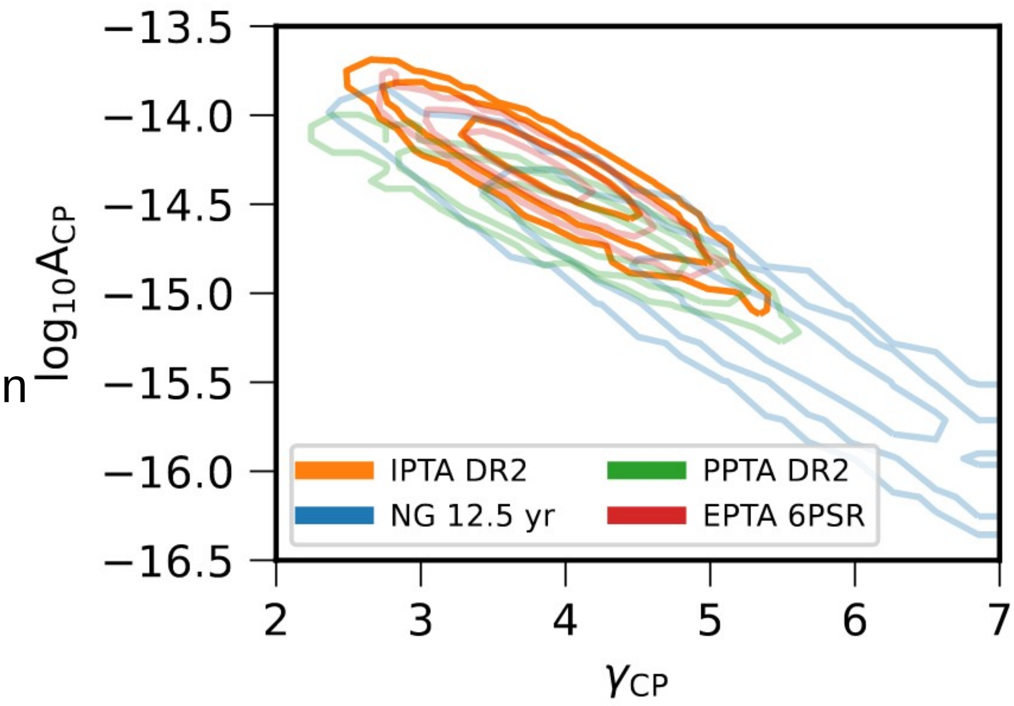
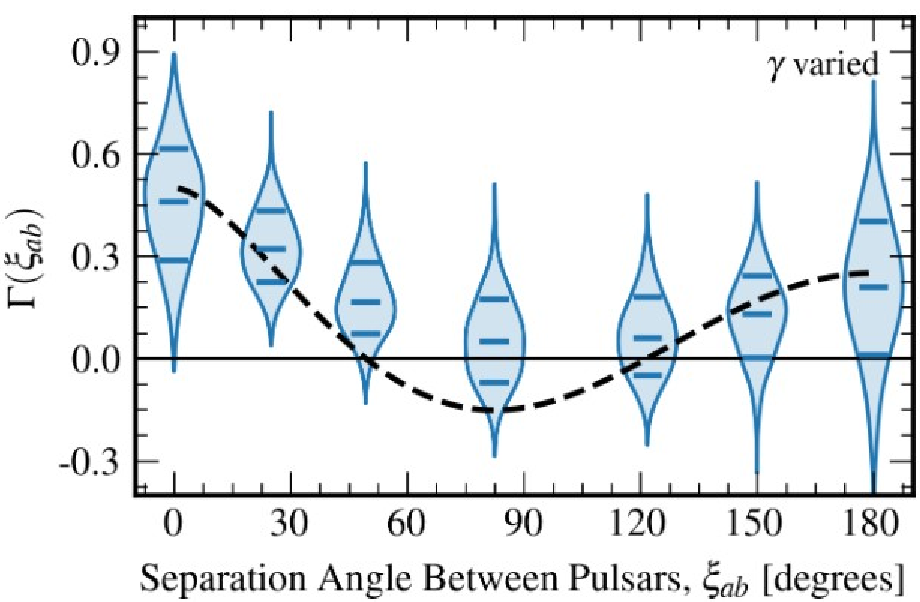
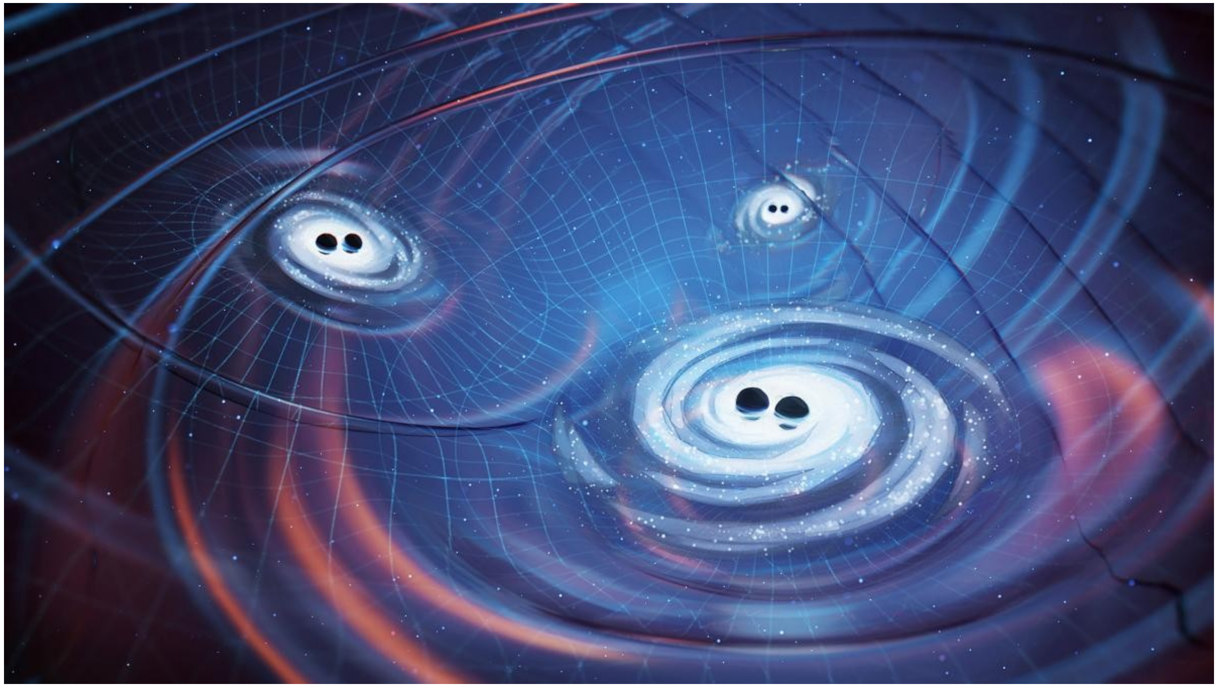




- likely origin: supermassive BH binaries
- SGWB or individual source?
  → frequency dependence, anisotropy
- cosmological or astrophysical?
  → anisotropy

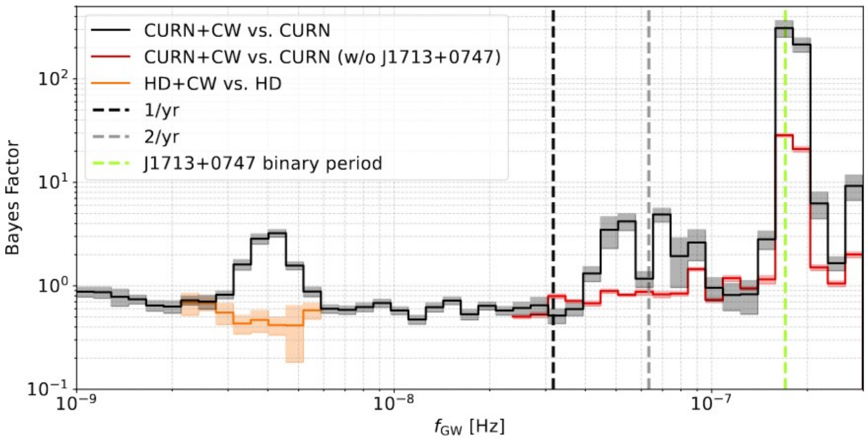
Supermassive black hole binaries?



- Merger of supermassive black holes in the center of galaxies (galaxy merger)
- Probe of astrophysical environment in the center of galaxies (last parsec problem)
- Probe of star & galaxy formation models

astrophysical or cosmological ?

NANOGrav 15 individual source search



currently no convincing evidence for
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astrophysical or cosmological ?

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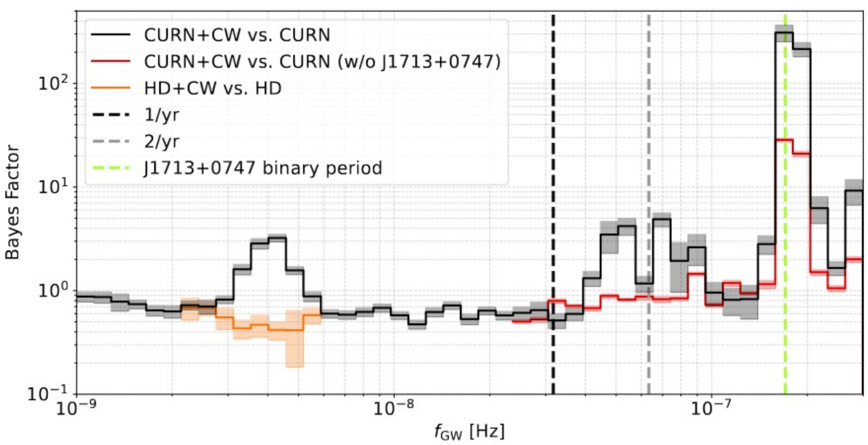

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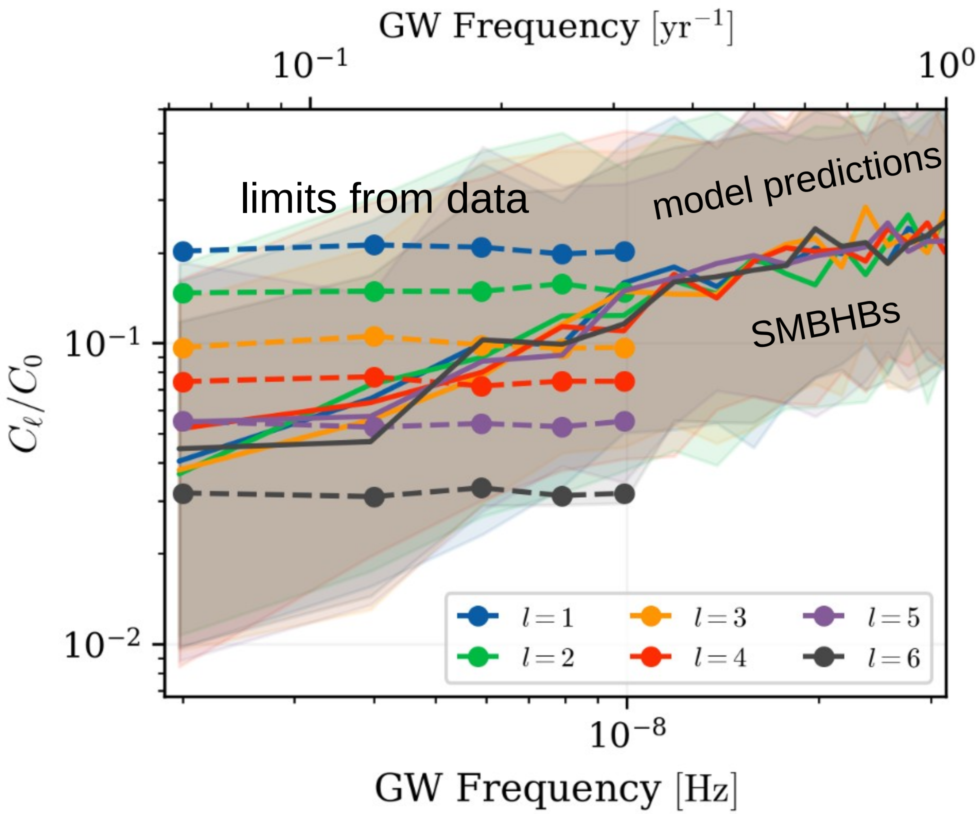
NANOGrav 15 anisotropy search



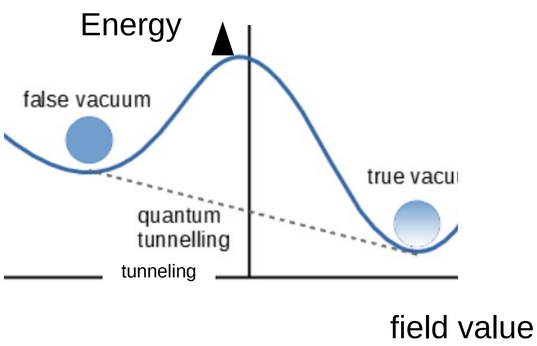
sensitivity to anisotropies is reaching SMBHB predictions

stay tuned!

example : first order phase transition

Electroweak symmetry breaking: Cross-over in the SM, new physics in the Higgs sector can make it 1st order

.. and beyond: extended symmetry groups (eg GUTs) spontaneously broken in cooling Universe



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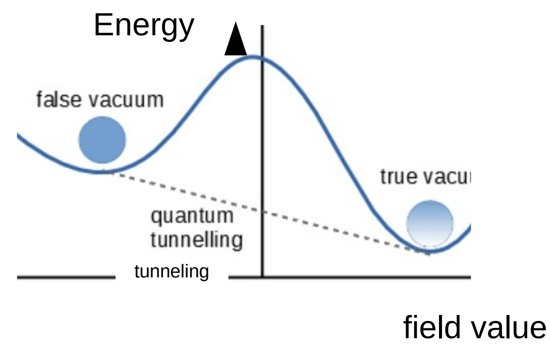

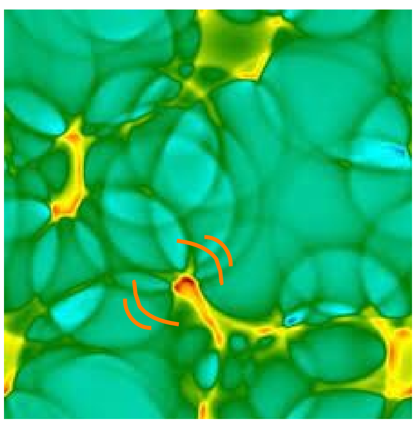

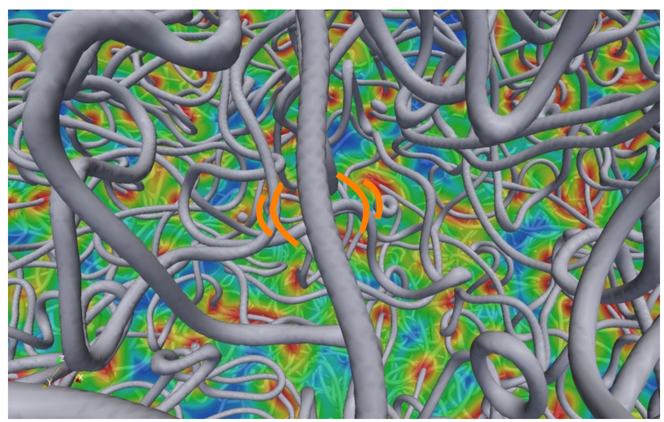

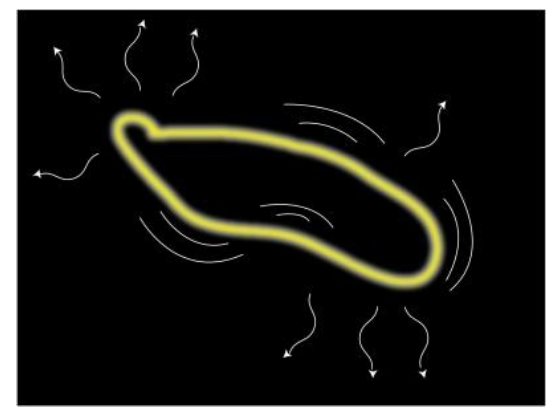

1st order PT sources GWs

topological defects formed during PT radiate GWs

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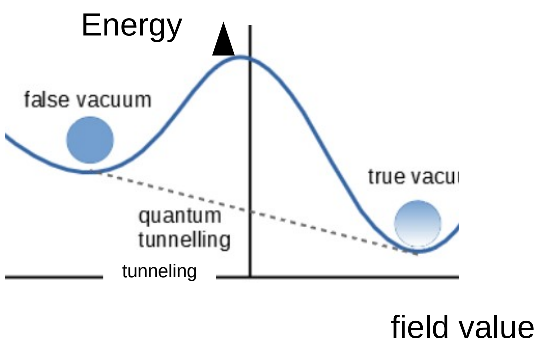
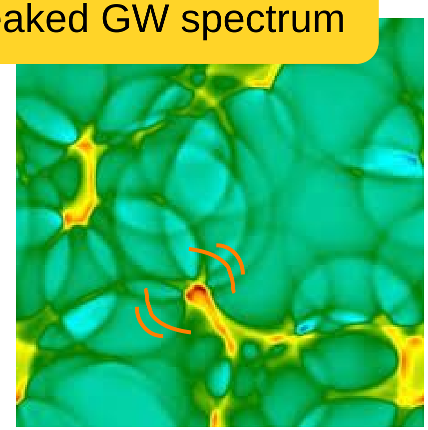
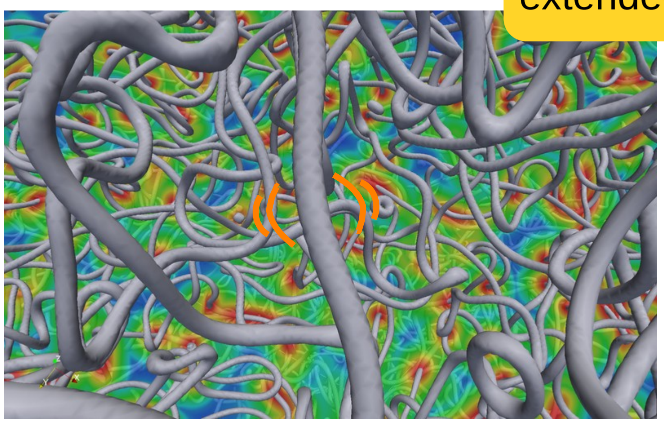
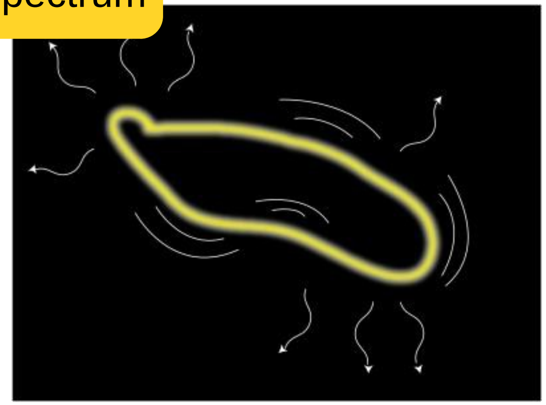


transient event → peaked GW spectrum





persistent source → extended GW spectrum



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Conclusions and outlook

Detecting and mapping out the stochastic GW background will be a next milestone in GW astronomy

Opportunities from so far unexplored regions of astronomy and cosmology

Many challenges: small signal, signal versus noise discrimination, large uncertainties / model dependence in predictions, foregrounds

Next lecture: Prospects to push the limits of sensitivity and frequency range